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Coupled Chemistry-Meteorology/ Climate Modelling (CCMM): status and relevance for numerical weather prediction, atmospheric pollution and climate research

(Geneva, Switzerland, 23-25 February 2015)

WEATHER CLIMATE WATER

WORLD METEOROLOGICAL ORGANIZATION

GLOBAL ATMOSPHERE WATCH

WWRP WORLD WEATHER RESEARCH PROGRAMME

WCRP World Climate Research Programme

cost EUROPEAN COOPERATION IN SCIENCE AND TECHNOLOGY

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PREFACE

The global coupled atmosphere–ocean–land–cryosphere system exhibits a wide range of physical and dynamical phenomena with associated physical, biological, and chemical feedbacks that collectively result in a continuum of temporal and spatial variability. We realize that the traditional boundaries between atmospheric, oceanic and earth sciences are by and large artificial. This has sparked a new area of research for seamless weather and climate prediction. This was actively discussed at the World Weather Open Science Conference (WWOSC) in Montreal organized by the World Meteorological Organization (WMO) and Environment Canada in 2014 and on the 17th WMO Congress in Geneva in 2015. The concept extends beyond weather and climate prediction to chemical weather and chemical climate. As for physical and dynamical processes, there is a continuum of chemical phenomena and interactions with the physical and dynamical state of the atmosphere across all time and spatial scales.

The development of numerical models that couple meteorology with atmospheric chemistry and aerosol dynamics within an integrated model system has undergone a rapid evolution in recent years. The motivation is that meteorology has a strong impact on air quality, and in return atmospheric composition has a potentially strong feedback to weather and climate. Relevant questions for the broader communities are related to the impact of air constituents on both air quality and incoming radiation, the modification of weather (cloud formation and precipitation) by natural and anthropogenic aerosol particles, and the impact of climate change on the frequency and strength of such effects and air quality.

The WMO Commission for Atmospheric Sciences (CAS) is working to integrate atmospheric composition, weather and climate research in order to achieve a comprehensive description and understanding of the Earth System. The Global Atmosphere Watch (GAW) Programme has taken up the challenge to promote an increased emphasis on atmospheric composition modelling within GAW, and the increased collaboration with the World Weather Research Programme (WWRP) is an important component to achieve this. The last CAS-17 Session identified 'Aerosols: impacts on air quality, weather and climate' as one of the CAS six key priorities/emerging challenges and opportunities for the decade.

The World Climate Research Programme (WCRP) which under the joint sponsorship of WMO, the International Council for Science (ICSU) and the Intergovernmental Oceanographic Commission (IOC of UNESCO), facilitates analysis and prediction of Earth System variability and change on climate time scales for use in an increasing range of practical applications of direct relevance, benefit and value to society. Several initiatives of WCRP are moving towards seamless modelling, such as the WCRP Chemistry-Climate Model Initiative (CCMI) and (jointly with WWRP) the Working Group on Numerical Experimentation (WGNE) specific online integrated modelling study on Aerosol Effects on Numerical Weather Prediction (NWP).

The European COST Action ES1004: "European Framework for Online Integrated Air Quality and Meteorology Modelling (EuMetChem)", involved 25 European countries and 11 research organizations outside of Europe, provided a substantial progress in seamless coupled meteorology-atmospheric composition modelling. This CCMM Symposium was initiated by EuMetChem as its final event concluding five years activities of the EuMetChem international community and giving a new impulse for further worldwide coordination in this important area of research and integrated services.

The symposium aimed to review the current research status of online coupled meteorology (weather and climate) and atmospheric chemistry modelling, and to assess the processes relevant for the interactions between atmospheric physics, dynamics and composition. In addition, scientific issues and emerging challenges were highlighted that require proper consideration to improve the reliability and usability of these models for the three scientific communities: air quality, numerical weather prediction and climate modelling. A synthesis of scientific progress was provided as well as recommendations for future research directions and priorities in development, application and evaluation of online coupled models.

The main outcome from the CCMM Symposium was reported at the 17th World Meteorological Congress and reflected in the Congress' resolutions for the future research and development directions for the years 2016-2019. The Congress noted that active interaction between the meteorological, environmental and climate communities is required to ensure the development of new generation seamless/coupled meteorology- chemistry models and their applications for numerical weather prediction, atmospheric pollution and climate studies.

Prof. Øystein Hov
President
WMO Commission for
Atmospheric Sciences (CAS)

Prof. Guy Brasseur
Chair of the Joint Scientific
Committee of the World Climate
Research Programme (WCRP JSC)

EXECUTIVE SUMMARY

Online coupled meteorology atmospheric chemistry models have undergone a rapid evolution in recent years. Although mainly developed by the air quality modelling community, these models are also of interest for numerical weather prediction and climate modelling as they can consider not only the effects of meteorology on air quality, but also the potentially important effects of atmospheric composition on weather. This report provides the main conclusions from the Symposium on "Coupled Chemistry-Meteorology/Climate Modelling: Status and Relevance for Numerical Weather Prediction, Air Quality and Climate Research" and an overall outcome of the European COST Action ES1004: European Framework for Online Integrated Air Quality and Meteorology Modelling (EuMetChem). It also contains the symposium abstracts and a review of the current research status of online coupled meteorology and atmospheric chemistry modelling, a survey of processes relevant to the interactions between atmospheric physics, dynamics and composition, and highlights selected scientific issues and emerging challenges, which require proper consideration to improve the reliability and usability of these models for three scientific communities: air quality, numerical meteorology modelling (including weather prediction) and climate modelling. It presents a synthesis of scientific progress in the form of answers on eight key questions and recommendations for future research directions and priorities in the development, application and evaluation of online coupled models.

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CHAPTER 1. INTRODUCTION

The development of numerical models that couple meteorology with atmospheric chemistry and aerosol dynamics within one integrated model system has undergone a rapid evolution in recent years. The motivation for this development is the recognition that meteorology has not only a strong impact on air quality, but that in return weather and climate respond to changes in atmospheric composition. Of particular importance are the interactions between weather/climate and aerosols, which are key air pollutants and at the same time affect the radiative balance of the atmosphere and the formation of clouds and precipitation.

The European COST Action ES1004 EuMetChem (European Framework for Online Integrated Air Quality and Meteorology Modelling; 2011-2015) aimed at developing a strategy and framework for online integrated modelling by identifying relevant interactions, parameterizations and feedback mechanisms and considering chemical data assimilation in integrated models. The status of integrated modelling has extensively been summarized by Baklanov et al. (2014) and a large number of regional model systems have been thoroughly evaluated in the joint European – North American Air Quality Model Evaluation International Initiative (AQMEII-2) (Galmarini et al. 2015). The action included experts not only from Europe but also from other continents (Figure 1) to take advantage of the global expertise in this dynamic research field.

Figure 1. Participants from European COST countries (red dots) and external institutions/experts (yellow dots) contributing with their expertise to the COST Action ES1004 EuMetChem

The Symposium on "Coupled Chemistry-Meteorology/Climate Modelling (CCMM): status and relevance for numerical weather prediction, atmospheric pollution and climate research", was initiated by EuMetChem as its closing event and was strongly supported by WMO. It brought together more than 100 experts (Figure 2) from three different research communities interested in CCMM modelling, that is air quality (AQ), numerical weather prediction (NWP) and climate change (CC), with the aim to review the current status of CCMM modelling and assess the processes relevant for the interactions between atmospheric physics, dynamics and composition. In addition, it highlighted scientific issues and emerging challenges that require proper consideration to improve the reliability and usability of these models for AQ, NWP, and CC. It presented a synthesis of scientific progress and provided recommendations for future research directions and priorities in the development, application and evaluation of seamless online coupled models.

Symposium on: Coupled Chemistry-Meteorology/Climate Modelling (CCMM): status and relevance for numerical weather prediction, atmospheric pollution and climate research

Website: http://www.eumetchem.info/ccmm.html
What: More than 100 scientists and experts from 36 countries from 5 continents discussed the current research status, main gaps and priorities in the development, application and evaluation of CCMMs for the three communities numerical weather prediction, atmospheric pollution and climate research.
Where: World Meteorological Organization (WMO), Geneva, Switzerland
When: 23-25 February 2015
Initiated, organized and supported by:

- European Cooperation in Science and Technology (COST) Action ES1004 EuMetChem: 'European Framework for Online Integrated Air Quality and Meteorology Modelling' (http://www.eumetchem.info/)
- WMO Commission for Atmospheric Sciences (CAS), including Global Atmosphere Watch (GAW) and World Weather Research Programme (WWRP),
- World Climate Research Programme (WCRP)

Figure 2. Short summary of the CCMM symposium

The main focus of the symposium was on aerosols and their feedbacks with weather and climate and the following specific topics were covered:

- Coupled chemistry-meteorology (weather and climate) modelling (CCMM): approaches and requirements
- Key processes of chemistry-meteorology interactions and their descriptions
- Aerosol effects on meteorological processes and Numerical Weather Prediction (NWP)
- CCMM for air quality and atmospheric composition
- CCMM for regional and global climate modelling
- Model validation and evaluation
- Data requirements, use of observations and data assimilation
- Outlook and future challenges.

Eight key scientific questions were formulated for discussions on the symposium:

1. What are the advantages of integrating meteorological and chemical/aerosol processes in coupled models?
2. How important are the two-way feedbacks and chains of feedbacks for meteorology, climate, and air quality simulations?
3. What are the effects of climate/meteorology on the abundance and properties (chemical, microphysical, and radiative) of aerosols on urban/regional/global scales?
4. What is our current understanding of cloud-aerosol interactions and how well are radiative feedbacks represented in NWP/climate models?

5. What is the relative importance of the direct and indirect aerosol effects as well as of gas-aerosol interactions for different applications (e.g. for NWP, air quality, climate)?
6. What are the key uncertainties associated with model predictions of feedback effects?
7. How to realize chemical data assimilation in integrated models for improving NWP and air quality simulations?
8. How the simulated feedbacks can be verified with available observations/datasets? What are the requirements for observations from the three modelling communities?

The following areas were suggested to consider as targeted CCMM possible applications:

- Chemical Weather Forecasting (CWF)
- Numerical Weather Prediction (NWP) for precipitation, visibility, thunderstorms, etc.
- Integrated Urban Meteorology, Environment and Climate Services
- Sand and Dust Storm Modelling and Warning Systems
- Wild fire atmospheric pollution and effects
- Volcano ash forecasting, warning and effects
- High Impact Weather and Disaster Risk
- Effects of Short-Lived Climate Forcers
- Earth System Modelling and Projections
- Data assimilation for CWF and NWP
- Weather modification and geo-engineering

Additional to the main oral and poster sessions (see Annex 2) a plenary discussion session was organized and seven brain-storming teams reported their outcomes on the main above mentioned specific topics. Reports of these groups are presented in the following Chapter.
The overall outcomes of the CCMM symposium and answers on the key questions are presented in Chapter 3 and conclusions and recommendations are in Chapter 4.

More CCMM symposium materials (programme, abstracts, list of participants) and EuMetChem overview can be found in the Annexes. Selected scientific papers presented at the symposium are contributing to the joint CCMM/EuMetChem special issue of the two journals Atmospheric Chemistry and Physics (ACP) and Geoscientific Model Development (GMD) (Baklanov et al., 2015).

Most of the presentations of the symposium are available from the following website: http://www.eumetchem.info/ccmm.html.

CHAPTER 2. REPORTS FROM CCMM SESSIONS AND BRAIN-STORMING GROUPS

2.1 SESSION 1 - COUPLED/INTEGRATED CHEMISTRY-METEOROLOGY SYSTEMS

Gregory Carmichael, Alexander Baklanov, Georg Grell and Peter Suppan

Summary of presentations

Formally, Session 1 was represented by five oral talks and one poster, however many other presentations of the symposium also reported on the status and architecture of differently integrated or coupled meteorology-chemistry modelling systems. The session's presentations focused on describing the current state of the integrated models. Alexander Baklanov et al. gave an overview of the current status and further opportunities of online coupled meteorology-chemistry modelling based on outcomes of the EuMetChem COST Action ES1004. Rohit Mathur et al. based on the US Environmental Protection Agency (EPA) studies with Weather Research Forecast -Community Multiscale Air Quality (WRF-CMAQ) model, analysed how well coupled models can simulate multi-decadal trends in tropospheric aerosol burden and its radiative effects. Johannes Flemming et al. reported on the current status of atmospheric chemistry integration in the European Centre for Medium-Range Weather Forecasts (ECMWF) Integrated Forecasting System (IFS). Eigil Kaas et al. analysed the existing approaches of numerical treatment of the transport problem in Environment – High Resolution Limited Area Model (Enviro-HIRLAM) and other online coupled atmospheric models. Astrid Manders-Groot et al. reported on the advantages and disadvantages of offline versus online approaches in modelling the radiative impacts of aerosols. Alexander Mahura et al. outlined in his poster the current experience of the HIRLAM community in science-education in online integrated modelling of aerosol-chemistry-meteorology effects using Enviro-HIRLAM. Additionally, Mark Jacobson presented his studies of coupling wind and solar energy systems with feedback to the online coupled air pollution, weather, climate, and the Gas, Aerosol, TranspOrt, Radiation, General Circulation, Mesoscale, Ocean Model (GATOR-GCMOM).

The discussion included a summary of the advantages of online and offline approaches. While offline approaches have some ease of use and flexibility for certain applications, online approaches offer advantages when combining chemistry and meteorology and studying aerosol feedbacks.

There are a growing number of online models covering spatial scale from urban to global. There are also various modes of carrying out online coupling. These include the use of couplers and full integration into a single code. At least two ways of online coupling can be distinguished: online integrated and online access coupling. Online integrated meteorology chemistry models handle meteorology and chemistry using the same grid in one model and using one main timestep for integration. Online access models use independent meteorology and chemistry models that might even be using different grids, but exchange information from meteorology to chemistry and back to meteorology on a regular and frequent basis using special couplers (Baklanov et al., 2014). These approaches also have advantages depending on end use. Numerical experiments at ECMWF (Flemming et al.) show that adding online chemistry in the code is more efficient than coupling, especially at higher resolution applications. Additionally, coupling may introduce inconsistencies, unless the coupled modelling systems use identical physical parameterizations, and numerical algorithms for large-scale advection.

Furthermore, for numerical weather prediction applications, while adding chemistry to meteorological models can increase costs by 5-10 times, this needs to be contrasted with the costs associated with increases in spatial resolution for weather models (which are typically a factor of 10).

Currently, there is growing interest in including aerosols in coupled models. There is also stronger interest in composition assimilation in coupled models and various approaches are being explored.

In general, the community is gaining important increased understanding of the linkages and the underlying processes of importance.

- Online modelling approach is a prospective way for future single-atmosphere modelling systems with advantages for applications at all time scales of NWP, AQ and climate models.

- AQMEII and episode studies help assess the importance of including the meteorology and chemistry (especially aerosols and O_3) interactions in online coupled models for specific episodes.

- A variety of integrated online modelling systems is needed for different applications. Different model versions should feed different targets with respect to temporal as well as spatial scales, but also to processes under focus.

- For NWP: full scale gas chemistry may not be important, it can be simplified focusing mostly on chemistry influencing aerosol formation and cloud interactions; inclusion of aerosol feedbacks may improve numerical weather prediction in very polluted episodes (such as during intense forest fire events, dust outbreaks, or in and near megacities). For a global average and NWP annual statistics the effects are not strong. Even though NWP might not depend on detailed chemical processes, considering the cloud and radiative effects of aerosols can be important for fog, visibility and precipitation forecasting.

- For AQ: online coupling improves AQ forecasting, full chemistry is needed; aerosol feedbacks effects are not always relevant, they need to be studied further. For AQ forecasting, the key issue is usually the ground-level concentration of pollutants, whereas for weather and climate studies model skill is typically based on screen level temperature, wind speed and precipitation.

- For chemical weather forecasting and prediction of atmospheric composition in a changing climate, the online integration definitely improves AQ and chemical atmospheric composition projections.

- For climate studies: suitable only for understanding the forcing and feedback mechanisms, it is still too expensive to include the full chemistry in climate runs. Chemistry is important, the model needs to be optimised and simplified. For climate modelling, feedbacks from greenhouse gases (GHGs) and aerosols become extremely important. However in some cases (e.g. for long-lived GHGs on global scale), fully online integration of full-scale chemistry and aerosol dynamics is not critically needed.

Main challenges and gaps in the field

There is still the need to sort out the strengths and weaknesses of the various approaches with respect to the type of modelling system (differently coupled versus fully integrated) and the physical and chemical parameterizations employed that describe the processes studied. This is especially true as related to indirect effects. Present studies show significant inconsistencies and uncertainties with indirect effects. Further work is needed to better understand the sensitivity of results to domains and resolution, spin-up, meteorological forcing and feedbacks, and physical and chemical parameterizations that are used. A WMO Working Group for Numerical Experimentation (WGNE) on the impact of aerosols on NWP has been established by operational centers to look at sensitivity derived from different modelling systems. There is a need for best practices to be articulated/agreed to. The data requirements, use of observations and data assimilation need to be better understood and articulated.

Recommendations for future research

Migration from offline to online integrated modelling systems is recommended as only the latter approach can guarantee a consistent treatment of processes and allow two-way interactions of physical and chemical components of CCMM systems, particularly for CWF and NWP communities. Online integrated models, however, need optimized integration architectures and harmonized formulations of all processes influencing meteorology and chemistry. In particular, the following steps should be taken in further development of CCMM systems:

- Create a unified central database of chemical mechanisms, where mechanism owners can upload relevant codes and provide updates as necessary.

- Enable interfacing of this database using, e.g. the Kinetic Pre-Processor (KPP) to develop a set of box model intercomparisons including evaluation against smog chamber data and more comprehensive mechanisms and moreover an analysis of the computational cost.

- A major challenge for most online models is the adequate treatment of indirect aerosol effects. Its implementation with affordable computational requirements and evaluation against laboratory/field data would greatly facilitate this transition.

- The understanding and therefore the parameterization of aerosol–radiation–cloud–chemistry interactions is still incomplete and further research on the model representations of these interactions is needed.

- The most relevant properties to be considered when developing integrated models and especially for considering feedback mechanisms are conservation, shape-preservation and prevention of numerical mixing or unmixing. Eulerian flux-based schemes are well suitable for mass conservation. Recently several semi-Lagrangian schemes have been developed that are inherently mass conservative. Such schemes are applied in some integrated models, e.g. Enviro-HIRLAM.

- A detailed analysis of the numerical properties of integrated models is recommended. A particularly relevant set of tests has been described by Lauritzen and Thuburn (2011), which shifts the focus from traditional, but still important, criteria such as mass-conservation to the prevention of numerical mixing and unmixing. Not maintaining the correlations between transported species is similar to introducing artificial chemical reactions in the system.

- A clear trend towards integrated model development is becoming perceptible with several modelling systems that can be considered as online integrated models with main relevant feedbacks implemented. Complementing those, there are several ones that are built using an online integrated approach, but some major feedbacks are not included yet. A third group of models, the online access models, is characterised by applying an external coupler between meteorology and chemistry. All the information is passed through the coupler. Depending on the approach used, wind and mass consistency problems may arise in the last case. In this sense, online integrated models are desirable to avoid consistency problems. For some applications it is also important to include emissions as a part of the integrated system.

- Numerical performance is an important issue for online models. The current parallelisation is based on well-established MPI and OpenMP programming models. Beyond these approaches there is no clear trend towards new parallelisation paradigms, even though supercomputers are experiencing a huge increase in computing power achieved mainly through an increase in the number of computing units rather than an increase in clock frequency. New processor types such as GPU's and MIC's are only beginning to be explored.

- Until recently, because of the complexity and the lack of appropriate computer power, air chemistry and weather forecasts have developed as separate disciplines, leading to the development of separate modelling systems with significant differences in treating physical processes. Boundary layer parameterizations or convective parameterizations are rarely the same. Much work is involved to develop these parameterizations. Even more complex are physical processes representations that must involve both disciplines (such as microphysics or radiation parameterization) that have the capability to allow for interaction of meteorology and complex chemistry. It would be of great value to have a code repository that included computer code for such parameterizations. This code should be somewhat standardized. As an example a parameterization should be at a minimum a self-contained module with a clear description of what is input, output and where to find documentation.

- Educational outreach is important. Community modelling systems such as WRF, WRF-Chem, and/or CMAQ offer a help desk as well as professionally taught tutorials. The enormous complexity of the coupled modelling systems may require expertise in many areas when choosing the setup of the modelling system. Potential users can not only learn the use of the models in less time in such tutorials, but they also may learn who to contact with questions on separate parts of the modelling system (such as data assimilation, or different chemical mechanisms), where to find documentation and what to do and what not to do.

- To adopt newer technologies, a conversion program that transfers existing code to the new technology would be advantageous. The transferred code would need to be still readable and maintainable. This would be very useful since a coupled meteorology chemistry model takes several decades of work to develop, and without software based support, transfers can take years to be completed reliably.

- Need to develop more systematic approaches to answer the question of what level of complexity is needed for a specific application? This is also a task of the WGNE group for impacts of aerosols on numerical weather prediction. To study the aerosol indirect effect initial studies will require cloud resolving simulations, since unresolved clouds – especially convection – traditionally does not know how to interact with aerosols. After establishing trustworthy cloud resolving simulations from complex modelling systems – that also need to be verified with observations – we can start developing ideas on how to include the indirect effect in the treatment of non-resolved clouds. We can also try to determine what complexity is needed in the chemistry and aerosol modules through systematic simplification.

- We need to identify a suitable field experiment (past or future) to be able to verify the complex modelling simulations described above. Need for better metrics for the evaluation of prediction (performance and feedbacks) for applications (can't rely solely on NWP skill score). An international test bed for evaluation of urban- and mesoscale online CCMM models is needed. A first step in this direction has been taken by the AQMEII consortium for the regional scale, but extension for higher resolving models is important. At the European level, model evaluation activities are currently conducted for AQ under the Forum for Air quality Modelling (FAIRMODE) initiative. To integrate the meteorology community could help to ensure that model results are correct for the right reasons. Further WGNE like activities are needed to evolve/develop and evaluate the system.

2.2 SESSION 2 - KEY PROCESSES AND INTERACTIONS

Paul Makar, Bernhardt Vogel, Renate Forkel and Yang Zhang

Summary of presentations

Zhang et al. worked on reducing the uncertainty in the aerosol indirect effect parameterizations by examining key processes using WRF/Chem3.4.1 with CAM5 physics and aerosol package. The model improvement included: (1) modifications to the ZM deep cumulus parameterization to accounts for microphysics and aerosol impacts; (2) incorporation of three new heterogeneous ice nucleation parameterizations for mix-phase clouds; (3) incorporation of a new dust emission module; (4) implementation of new particle formation modules for urban, non-urban and above PBL chemistry; (5) incorporation of a more advanced aerosol activation parameterization based on Fountoukis and Nenes (2005) parameterizations including those of Fountoukis and Nenes (2005), Barahona and Nenes (2007) (BN07), Kumar et al. (2009) (K09), and Barahona et al. (2010) (B10) (FN) series. The model simulations were conducted over East Asia with triple-nested domains at 36, 12 and 4 km. They showed better results with the modified deep cumulus parameterization that accounts for microphysics and aerosol impacts. They also found that the original aerosol activation parameterization, AR-G2000, underpredicts cloud droplet number concentrations (CDNC) whereas the FN series overpredicts them but with a lower bias. For the two ice nucleation parameterizations tested, they showed that the Neimand (2012) parameterization predicts higher nucleated ice crystal number concentrations and shows better performance for radiation and cloud variables than the Meyers 1992 parameterization because of the inclusion of the effects of dust particles on ice crystal formation. A six-year evaluation showed good agreement for most meteorological variables and column mass abundance of SO_2, CO, NO_2, HCHO and TOR, but the performance of surface chemical predictions had higher biases due to several reasons, e.g. underestimations of anthropogenic emissions and natural dust emissions and uncertainties in the spatial and vertical distributions of the anthropogenic emissions. They also found that aerosol in East Asia can reduce near surface temperature (T2), shortwave radiation (SWD), planetary boundary layer height (PBLH), increase cloud condensation nuclei, CDNC, cloud liquid water path, cloud optical depth, shortwave cloud forcing (SWCF), either increase or decrease precipitation. Aerosol indirect effects dominate over aerosol direct effects for most variables (e.g. CDNC, precipitation). Both effects are important for some variables (e.g. T2, PBLH, SWD, SWCF).

Forkel et al.’s work on multi-model case studies on aerosol feedbacks within COST1004 looked at two short-term case studies. The two selected episodes, the Russian heat wave and wildfires episode in July/August 2010 and an episode in October 2010 which includes enhanced cloud cover and rain and Saharan dust transport to Europe, were selected on behalf of their potential for direct and indirect aerosol effects on meteorology. Four different configurations of WRF-Chem and simulations with COSMO-MUSCAT and COSMO-ART (contributed by Univ. Murcia, UPM-ESMG, Univ. Lubljana, KIT/IMK-IFU, IFT Leipzig, and EMPA) simulations without aerosol-meteorology interactions and including the direct aerosol radiative effect were performed by all contributors. Additional simulations including the direct aerosol effect as well as aerosol-cloud interactions for grid scale clouds depending on simulated aerosol fields (“indirect aerosol effect”) were supplied for the four different WRF-Chem configurations. As some results were still in the “uploading stage” at the time of the conference, only some preliminary results could be shown. Direct effect results submitted thus far for the October episode showed large variability between the two models submitted for the effect on near surface PM10. Mean near surface temperatures were decreased due the direct aerosol effect by up to 0.2 K for WRF-Chem during this episode while deviations between -0.1 K and 0.05 K were found for COSMO-MUSCAT. In contrast, differences in cloud liquid water path (CLWP) were found to be more pronounced for COSMO-MUSCAT. The results indicate that, except for extreme aerosol hotspots like the Russian forest fire plumes, the variability of the response of the different models (or model configurations) to aerosol meteorology interactions can be of the same magnitude as the simulated aerosol effects. The variation in model response is still more pronounced for cloudy areas when both the direct and the indirect effects are considered.

Kallos et al. used Regional Atmospheric Models/Integrated Community Limited Area Modelling Systems (RAMS/ICLAMS) for feedback studies, switching parts of this 2-way interactive nesting model to see responses to feedbacks, with a focus on the April 2004 dust event over the East Mediterranean using observations at the Crete site for a reference. They compared the Meyeres, Philips, Purppacher and Klett ice nuclei (IN) schemes, all four schemes behave similarly within the first four minutes – a more key issue is to get the chemical speciation of IN correct: soot is much more efficient as IN than dust, for example. A sulphate aerosol sensitivity study showed significant impacts on clouds, lower level cloud development, enhanced formation of ice at 5 km, lower cloud tops – yet the spatial distribution of precipitation is similar. They noted that dust and aerosols are always present in the Mediterranean, with a contribution of anthropogenic aerosols to loading – mixed phase aerosols with fractions of insoluble species are typical and CCN/IN feedbacks are important.

Krakovska et al. examined possible ways of improving mixed stratus cloud/fog formation. Bin microphysics models are believed more accurate, but less efficient – moment schemes are faster but less accurate – they are looking for a compromise solution. Their analysis of the system of equations for IN showed that very fast collectional growth occurs as ice/droplets grow, on time scales of seconds, compared to deposition growth on time scales of minutes to hours. They have derived equations that simplify the system, with one dimensionless free parameter instead of four. They plan to try out their system in feedback models in upcoming work.

Lehmann et al. described an automatic mechanism-analysis system which determines the key reaction pathways in complex chemical mechanisms; a means of identifying which of the longer-lived species are the most important towards a given process within a large mechanism. The system builds pathways step by step, avoids combinatorial explosion issues in complex mechanisms by leaving out small reaction rate reactions, and has been applied to methane oxidation, mesosphere HNO_3 production, Martian chemistry and exoplanet chemistry for red dwarf stars in contrast to Sun-like stars. The algorithm could be used for complex tropospheric reaction mechanisms.

Makar et al. mentioned some of the key findings of AQMEII-2 with regards to feedbacks (e.g. annual temperature forecast bias was improved using feedbacks, and Russian fires and similar large sources of pollutants were identified as cases in which the feedback effect dominates. Ongoing work with Environment Canada's GEM-MACH model in 3-level nested mode for a large innermost domain for a month-long set of no-feedback, direct and direct + indirect effect simulations improved model performance relative to surface observations for $PM_{2.5}$ and NO_2 for the combined feedback simulation with the direct effect simulation coming in second, but the direct effect O_3 results were better than for the combined feedbacks. The feedback effect was largest for $PM_{2.5}$, followed by NO_2 and then O_3. Feedbacks were shown to alter the turbulent kinetic energy (mostly through the direct effect), and plume altitude and direction changes on the very local scale were linked to these turbulence changes and changes in wind direction. Feedbacks were shown to influence downwind deposition of SO_2, suggesting that acid deposition may be altered by feedback effects. Changes in O_3 were linked to feedback-induced changes in cloud cover, but a lack of improvement in correlation coefficients for O_3 suggests that the cloud radiative properties and/or formation algorithms still need work.

Nikovic et al. examined the modelling of cold cloud formation due to atmospheric dust. They found that the DeMott et al. parameterization for IN worked better than the Meyers et al. 1992 parameterization during their construction of the DREAM dust model for the NCEP NMM weather model, with good correlation of major peaks for ice nucleation particles. The Calima field experiment (summer 2013 off the west coast of Africa) was used for evaluation, with good plume placement from the Sahara to cloud optical thickness from MODIS for IN; model IN were placed at about 11 km altitude for the maximum and compared to MIRA55 IWC a correlation R of 0.84 was found. Good agreement was found with lidar observations as well. In the Q/A, it was noted that Atkinson et al. 2013 has a parameterization showing K-feldspar dust has several orders of magnitude greater IN efficiency compared to kaolinite, suggesting that the mineral composition of dust is a key factor in accurately simulating IN processes. Speyer et al. noted that wood burning for domestic heating has become more prevalent in Greece in recent years, with a consequent increase in the intensity of smog events. COSMO-ART was used with the RADM2 extended gas-phase mechanism and TNO/MACCII 2009 emissions including residential wood burning (RWB), with a revision to the RWB to better improve the temporal allocation of the emissions. The model results showed that PM_{10} was mostly PM_1, and RWB is 80 to 90% of that, consistent with the obs. For feedback effects all of the aerosols examined had a negative impact on total radiation and air temperature – though under cloudy conditions, the backscattering of clouds counteracts the effects of aerosols. Shortwave radiation impacts of RWB included increases in aerosol optical depth (AOD) and decreases on the order of -0.75W/m^2 in the Athens plume. They noted that the organics are mostly underestimated, so these model values are likely a lower limit. Temperature decreases of -0.1K were seen, but much of the Athens plume was over the ocean, where the temperature at 2 m may be more influenced by sea-surface temperatures than local radiative forcing.

Stenchikov et al. simulated radiative and meteorological effects of air pollution over the Arabian Peninsula using a 25 km resolution global model (HIRAM, C360 cubed sphere domain using finite volume advection), coupled with the LM3 land use model for ecosystem dynamics and hydrology. Comparisons between global averages and the Arabian Peninsula region with the inclusion of dust showed the importance of dust for the region (SW global dust effect -1.5 Wm^{-2} compared to -13.99 Wm^{-2} in the region; LW global 0.183 global, 2.18 W m^{-2} in the region). AERONET observations sometimes showed radiative forcing associated with dust reaches -70Wm^{-2}, but soot and other components sometimes enter from airmasses originating over land. WRF/Chem was used for local studies, nested over the region, to examine dust storms, with very good comparisons for surface time series of both PM10 and fine mode over a few month time period. Current work centers on meteorological and chemical properties of the dust/feedback processes. Their work to date has shown that dust produces a profound impact on radiative balances.

Posters

Nuterman et al. used Enviro-HIRLAM to look at heat waves with and without indirect effects. Their simulations showed an increase in total cloud cover for the European region, mostly over the oceans – cloud cover over the land decreased in some areas. Their feedback simulations had better precipitation scores than the no-feedback simulations.

Riger et al. simulated a Saharan dust event using ICON-ART, adding IN to a 2 moment microphysics model. Their simulations showed good agreement for the magnitude of transported ozone in the dust event to the Jungfraujoch mountain site, with the timing of the peak deviating by a few hours from observations. With the IN feedbacks, lower ice crystal numbers were found with higher levels of mineral dust.

Ruhnke et al. investigated convective transport processes with ICON-ART for three case studies: (1) O_3-depleting brominated substances (fast convective transport in tropics were shown to be important for overall budget of these species); (2) Comparison between HALO aircraft observations and model-generated temperatures and relative humidities; (3) Antarctic vortex flow splitting using a linearized O_3 mechanism; the vortex splitting mechanism was well simulated, but the arrival time was a week earlier than observed.

Main challenges and gaps in the field

- Both Zhang et al. and Makar et al. have suggested that the accurate vertical distribution of pollutants remains a significant uncertainty. Previous work in AQMEII-2 suggested that feedback effects can have a strong influence on plume rise and dispersion, or, equivalently, the process of plume rise and dispersion is very sensitive to the radiative balance and the resulting changes in stability and wind direction. Current plume rise parameterizations assume no radiative properties of the plume aside from an initial temperature of emission – this is clearly inadequate based on feedback research, and the accuracy of pollutant dispersion may be improved with revised plume rise algorithms which take the radiative properties of the aerosols in the plume into account.

- Large variations in the forecasts between different fully coupled models have been seen in AQMEII-2 and COST ES1004 model intercomparisons have been noted. These are attributed to either differences in model parameterizations for feedbacks or other processes. In that respect, the multiple WRF/Chem in the most recent COST experiment may be useful, to put bounds on the impact of the different parameterizations on the model results. Beyond that, it may be possible to use operator mass tracking (keeping track of the change in mass across different operators in the models) during a short test run to examine the models' response to feedbacks and how they are implemented.

- Zhang et al., Kallos et al., Stenchikov et al., Krakovska et al. and Nikovic et al. noted the importance of dust composition towards accurate IN simulation. However, most current generation fully coupled AQ models have a single "species" for dust, and emissions algorithms for wind-blown dust give very different results. Work is needed to define the minimum number of dust types needed for accurate IN simulations and/or a minimum set of transportable dust properties (number concentration, surface area, surface tension/aging, etc.) to be used in IN calculations. The theoretical formulations for different IN parameterizations also vary in terms of what they require as inputs, e.g. supersaturation, temperature, sometimes area, solubility). Laboratory work is needed with multiple dust types to build a database of properties.

- Krakovska et al. and Lehmann et al. have showed analytical means for reducing the complexity of IN microphysics and gas-phase chemistry – both methodologies need testing in, or using test cases from, fully coupled models.

- Zhang et al. indicated "what aerosol activation / droplet nucleation processes – which of the different methods is more correct? More data is needed for evaluation". In addition, they attributed large biases in cloud variables to uncertainties in cloud dynamics and thermodynamics, as well as aerosol-cloud interactions.

- Speyer et al. noted that the original MACC emissions for wood burning were inadequately temporally allocated compared to observations. This issue is a common one for more than one source of emissions. Both the AQMEII-1 (mostly uncoupled models) and AQMEII-2 experiments (fully coupled models) showed less accurate performance for the same models used in Europe compared to their use in North America. The performance differences are usually ascribed to quality of the emissions data – but this issue has been known for about a decade now, and remains unresolved. A challenge to the community – resolve it! A COST Action with the aim of collecting a common European emissions database with equivalent accuracy to those used in North America might be one possible means of doing this.

Answers to the relevant key questions

What are the advantages of integrating meteorological and chemical/aerosol processes in coupled models?

Ultimately, a better representation of the atmosphere in a model is the main advantage – the real atmosphere includes these processes; so should our models. Is there any scientific reason to have uncoupled models?

How important are the two-way feedbacks and chains of feedbacks for meteorology, climate, and air quality simulations?

Under the right circumstances and locally they are very important e.g. Saharan dust, near large plumes, usually in the 10's and up to 100 W m^{-2} influences on the radiative budget. Compare that magnitude to that of GHG influences etc.

What are the effects of climate/meteorology on the abundance and properties (chemical, microphysical, and radiative) of aerosols on urban/regional/global scales?

1st order: this is known from offline models: the deposition of aerosols depends on turbulence, the dispersion of aerosols depends on advection, the removal and creation of aerosols depend on cloud processing and radiation, the formation of secondary aerosols depends on temperature, UV radiation, relative humidity, and PBL mixing; the emissions of precursor gases can be temperature and radiation dependent.

2nd order: direct effect feedbacks have been shown to influence atmospheric turbulence, changing, in turn, the aerosol dispersion in three dimensions. Indirect effect feedbacks change the amount and radiative properties of clouds, in turn changing the light reaching the surface, in turn changing the oxidation and formation of secondary aerosols near the surface. These "second order" effects dominate as the aerosol concentrations increase. Quantification of these second order effects is an issue – are they important for weather forecasting? They seem to be important, for longer-term comparisons, and deviations from the mean aerosol loading, but not as large as model-model differences.

What is our current understanding of cloud-aerosol interactions and how well are radiative feedbacks represented in NWP/climate models?

Cloud-aerosol interactions are poorly represented in most of the models. The indirect effect parameterizations seem to be very sensitive to the details of implementation. AQMEII-2 models employing the same theoretical approach for CCN sometimes had very different results (most single cloud studies show clear aerosol effect – atmospheric system is more complex; compensating processes seem to occur). Most models do not treat aerosol interactions with deep and shallow cumulus clouds. Large uncertainties also exist in ice nucleation parameterizations and most of them are not linked to aerosol properties. IN scatter in the lab data is very large and thus is a topic for more research.

What is the relative importance of the direct and indirect aerosol effects as well as of gas-aerosol interactions for different applications (e.g., for NWP, air quality, climate)?

The direct and indirect effects sometimes act in opposition, in terms of their impact on both meteorological and air-quality predictions. Usually, the direct effect could be important for radiation and PBL variables, and the indirect effect is the dominant process, particularly for cloud and precipitation predictions, but the cross-model variability in indirect effect implementation complicates intercomparisons of relative impact.

What are the key uncertainties associated with model predictions of feedback effects?

1. Indirect effect implementation details. IN processes and parameterizations are less well defined than CCN parameterizations, though the CCN parameterizations are very sensitive to implementation details.

2. So far, indirect effect is only implemented in the description of grid scale clouds. For subgrid cumulus clouds only a few models include parameterizations, which are still quite undeveloped.

3. Direct effect – defining optical properties (depending on aerosol mixing rules, etc.) is still an issue.

4. Feedback effects seem to have a crucial importance in the vicinity of large emission sources (Saharan dust, forest fires, large plume emissions), but the parameterizations for these emissions sources do not always include feedback effects explicitly, and for forest fires, the parameterizations for plume rise are many and variable in their accuracy. In order to get feedbacks "right" we may need better parameterizations for these sources… or we may need to include feedbacks explicitly into their formulation.

5. Related cloud and precipitation formation processes such as cloud dynamics and thermodynamics for all types of clouds, particularly, cumulus and ice clouds contain large uncertainties.

How the simulated feedbacks can be verified with available observations/datasets? What are the requirements for observations from the three modelling communities?

1. First some advice from those communities would be appreciated: what are the measures of significance of a model change, relative to observations, typically employed in these communities?

2. Plume rise needs to be revisited in a feedback context. Redo Brigg's classic plume rise experiments, this time with instrumentation designed to examine radiative impacts due to the composition of the plume on its dispersion.

3. Databases of radiative and microphysical properties of different aerosol types are needed for parameterization construction. Measurement intensives should attempt to include characterization of these properties as an objective. Measurements of CCN, CDNC, CWP and other properties for all types of clouds including warm, cumulus, ice, and mix-phase clouds are needed to constrain the current parameterizations used for cloud and precipitation formation processes and aerosol-cloud interactions.

4. Evaluation protocol for feedback evaluation should be developed, including performance statistics, comparison of spatial, temporal, and vertical profiles, and analysis of long-term trends and their correlation of relevant variables using surface measurements (e.g. PM2.5, visibility, and precipitation) and satellite data (e.g. AOD, SWD, COT).

5. Comparison of model simulations with and without feedbacks with observations (e.g. shortwave radiation, CDNC) can indirectly show the advantage of inclusion of the feedbacks in reproducing observations.

2.3 SESSION 3 - CCMMS FOR CLIMATE STUDIES

M. Gauss, M. Hegglin, A. Ekman, M. Rixen and Ø. Hov

Summary of presentations

The oral presentations of Session 3 focused mainly on the use of global chemistry-climate and Earth system models for the study of chemistry-climate interactions. Most of these simulations run on multi-decadal to century timescales, but at lower resolution than e.g. regional climate models, typically 2 degrees horizontally, because of their complexity, spatial coverage, and the associated computing cost. A number of them are coupled to the ocean and sometimes also to the biosphere.

Specific sensitivity studies on chemistry-climate interactions have investigated the impact of aerosol emission reductions on short-term climate warming (Ø. Hov), also with a more specific focus on Arctic climate (A. Ekman), the impact of stratospheric aerosol/geoengineering on surface or stratospheric climate (P. Colarco), and the impact of the stratospheric ozone hole on Southern hemisphere surface climate (M. Hegglin).

Chemistry-climate interactions and model performance in chemistry-climate models have been tested extensively against observations and, more recently, also in detailed analyses of model sensitivity studies using different emission scenarios. Examples for model evaluation using chemical trace gas observations, presented in Session 3, were based on OH distributions (P.K. Patra) as well as CO, NO_2, and O_3 long-term trends (T. Doumbia). The differences and uncertainty in observational datasets used for testing model performance were highlighted several times, pointing out the need for high-quality and well-characterized Earth observations.

The session included a number of examples that used varying model setups to investigate key processes determining chemistry-climate interactions in models:

- The large number of pathways through which aerosols can influence cloud microphysics, in particular ice formation processes (A. Possner).
- Use of monthly aerosol climatologies versus the use of prognostic modules to assess the effect of emission changes on meteorology downstream of the changes (P. Nabat, M. Schultze).
- Use of nudged chemistry-climate models with and without ozone depleting substances (ODS) to test our knowledge of long-term ozone changes, chemistry and emissions, highlighting in particular the uncertainties in emission data bases (M. Hegglin).

The three posters displayed in Session 3 addressed key questions as to how changes in aerosol emissions affect climate, and how climate policies will affect air pollution and its impacts on health: past changes in Arctic aerosol due to air quality legislation have been studied in particular, highlighting the fact that the climate response can occur far away from the emission change. The presented studies of climate policy effects on air pollution accounted for changes in air quality due to emissions change and climate change.

The following research tools and data were used in the studies presented by the posters:

- NorESM, EMEP emissions, past decades: to study the impact of European aerosol emission reductions on Arctic climate (Ekman et al.).
- COSMO-CLM, Aerosol-climatologies, past decades: to study the impacts of different aerosol climatologies on the European climate during the last decades (Schultze et al.).
- CCSM4/WRF-Chem/CMAQ, RCP4.5/8.5, future decades*:* to study urban health impacts of global climate scenarios (DECUMANUS project) (San Jose et al.).

Main challenges and gaps in the field

The main challenges identified in Session 3 concerned the comparability between models and observations (e.g. do we have representative observations to define past composition changes and variability? how can we compare models and observations in a fair way? etc.), and also the detailed understanding of mechanisms behind different chemistry-climate couplings.

In particular, the observational data is not considered sufficient to test the representation of trends in tropospheric aerosol and ozone, and their impact on regional climate in the past. Furthermore, the formulations of complex microphysical processes in cloud/aerosol interactions suitable for resolution of global CCMs need improvement.

Answers to the relevant key questions

In this Section we give answers to the relevant key questions, based only on the presentations and discussions of Session 3. Combination with answers collected in other sessions may give a more complete picture of our current understanding.

What is the relative importance of the direct and indirect aerosol effects as well as of gas-aerosol interactions for different applications (e.g. for NWP, air quality, climate)?

- The direct effect is better understood than indirect effects. But the question as to which effect is of highest relevance depends on the region and the season.
- Extreme events seem to be better represented in NWP models with explicit descriptions of aerosol-cloud interactions.
- Both the direct and indirect effects are important for climate applications, but the largest uncertainty comes from the indirect effect, in particular aerosol effects on ice clouds.
- Using aerosol climatologies instead of predicted aerosols may cause significant errors in retrievals of different gases, e.g. CO_2.

What are the key uncertainties associated with model predictions of feedback effects?

- Measuring feedback processes in reality (and verifying them in models) is a challenge and so is the quantification of uncertainties; key uncertainties may lie in cloud-aerosol couplings, as this will potentially have a large impact on climate.
- Biosphere-atmosphere couplings will also respond to climate change and are not fully understood.
- Radiative forcing is a poor measure for regional climate response.

How can the simulated feedbacks be verified with available observations/datasets?

- Nudged climate simulations help verification, although some of the feedback effects will be supressed by the nudging.
- Free-running simulations where feedbacks are switch on/off feedbacks can be compared in terms of skill scores.
- There is a need for process-oriented evaluation, going beyond the comparison against observed mean values.

What are the requirements for observations from the three modelling communities?

- We do need co-located and simultaneous meteorology and chemistry measurements.
- Innovative designs for global measurement systems (existing technological platforms such as commercial aircraft, cell phones, cars, etc.) should be further exploited.

- Measurements should be made at carefully selected locations to ensure spatial representativeness.

How important are the two-way feedbacks and chains of feedbacks for meteorology, climate, and air quality simulations?

- Within the climate community, which was the focus of Session 3, two-way feedbacks are of crucial importance to correctly capture climate sensitivity.

- Important feedbacks for climate and the other modelling communities have been identified by COST Action ES1004 (see webpage of COST ES1004 WG2).

What are the effects of climate/meteorology on the abundance and properties (chemical, microphysical, and radiative) of aerosols on urban/regional/global scales?

- Less precipitation and higher windspeeds will lead to higher aerosol loadings

- Changes in humidity alter wet scavenging and resuspension of aerosol

- Changes in circulation/wind patterns will alter aerosol transport and abundances

- Climate change caused by changes in aerosols affects other chemical constituents such as tropospheric and stratospheric ozone

- Changes in cloudiness affect photolysis rates

What is our current understanding of cloud-aerosol interactions and how well are radiative feedbacks represented in NWP/climate models?

- Cloud-aerosol interactions are not yet fully understood, in particular for ice clouds and mixed-phase clouds (including mid-level and Arctic clouds), as was discussed in several papers at the CCMM symposium.

Recommendations for future research

Based on the presentations of Session 3 and subsequent discussions, the following recommendations were identified for future research:

- Improve our understanding of indirect effects (e.g. BC on clouds):
    - The details of implementation of the indirect effect have a large impact on model results, and hence should be a focus of future research;
    - Complete analysis of indirect effects will require simulations on high resolution and aerosol representations in convective schemes.

- Develop CCMs with prognostic aerosol:
    - Level of sophistication of such modules needs to be defined;
    - For example, what is the tradeoff between a more complex aerosol representation on one side and model resolution, or the atmosphere-ocean coupling on the other?
    - Consistency between resolution and parameterizations needs to be assessed.

- Test model performance in terms of relevant physical, chemical, and radiative processes and mechanisms (in contrast to just testing mean performance):
    - In particular, NWP models are tuned to perform well without feedbacks, leaving room for improvement towards more realistic model behaviour.

- Test model performance in terms of tropospheric dynamics/meteorology and their effect on composition (and vice-versa):
    - Important especially in the field of inverse modelling of emission sources.

2.4 SESSION 4 - CCMMS FOR AIR QUALITY AND ATMOSPHERIC COMPOSITION

Jose M. Baldasano, Véronique Bouchet, Rohit Mathur, Ana Miranda and Nicolas Moussiopoulos

Summary of presentations

Presentations in this session focused on studies with online models and 2-way feedbacks and examined the benefits of the approach in improving the quality of the AQ and atmospheric composition results.

S. Galmarini summarized results from the AQMEII study; phase 1 of the study used offline models whereas phase 2 inter-compared online models with feedbacks. For some metric examined, the online systems compared better with measurements. Other key findings from the analysis include: (i) ability to simulate surface O_3 and $PM_{2.5}$ is generally better than NO_2; (ii) ensemble model estimates provide better estimates of air quality than individual models; (iii) based on the models participating in AQMEII, ~5 models were needed to capture 85% of the observed variance in O_3 and $PM_{2.5}$.

C. Carnevale presented a modelling case study for the Po Valley which examined how aerosol feedback effects change for different emission control strategies. Emission reductions were found to impact local meteorological conditions, primarily through modulation of temperature.

M. Prather focused on two areas. First, he emphasized the incommensurability associated with comparing model grid estimates with point observations and re-emphasized the need to consider the spatial representativeness of the measurements. In the approach presented, contiguous fields were created through krigging from surface observations and analysis of results suggested that there is a limit to how close model simulations of air quality can get to point measurements – for surface O_3, that limit was suggested to be 6ppb. Secondly, the study focused on extreme air quality events produced by the ACCMIP-5 suite of global climate models (GCMs), and showed that there is a large variability across the models though episode length was generally comparable.

S.T. Rao's presentation stressed on the need to consider intrinsic or the irreducible uncertainty in model calculations in both meteorological and air quality model analysis and interpretation. The study examined uncertainty in model predictions arising from the specification of the initial meteorological state of the model simulation. Results suggest that the uncertainties in the initial state persist throughout the three-week simulations examined and at their lowest are of the order of 10% or 4-5 ppb for surface O_3. Studies of this nature are needed to develop quantitative measures of the confidence level of models in air quality analysis.

F. Tummon's presentation sought to explain the evolution of free tropospheric ozone levels over the past 20 years which exhibit an increase even though surface emissions of precursors have been decreasing. Diagnostic modelling was performed using several tagged O_3 species identifying locations of where the O_3 molecule originated from. The modelling identified changes in stratospheric circulation with more upwelling in the tropics and more downwelling in the mid-latitudes. Model results suggest a slightly increasing trend in stratospheric input into the European troposphere.

Poster presentations on modelling studies for Istanbul (H. Toros), Cuba (F. Hernandez) and Asia (I. Inomata) also emphasized the continued need for improvement in emission inventories for CCMM applications for air quality across the globe.

A spring birch pollen episode was simulated using an online modelling system (A. Kurganskiy). Improvements are underway to better model meteorology taking into account urban effects. The poster by N. Moussiopoulos described an approach to simulate urban areas, which is based on an urban increment methodology. This approach is now applied to online systems.

Answers to the relevant key questions

How important are the two-way feedbacks and chains of feedback for meteorology, climate, and air quality simulations? What is the relative importance of aerosol radiative effects for air quality applications?

- Accounting for feedback effects can influence the assessment of impact of emission changes on air quality.

- Ensemble estimates present a viable means to balance the diversity and accuracy of existing CCMMs for air quality applications.

What are the key uncertainties associates with model predictions of feedback effects?

- CCMMs appear to be able to capture the long-term trends in air pollution and associated direct feedback effects but not the absolute magnitude. This may be associated with the ability of CCMMs to represent the burden of primary (emissions) and secondary (formation pathways) aerosols in the troposphere.

- Predictions of natural aerosols (wildfires, dust) need to be improved. For current anthropogenic emission levels in N. America and Europe, these events are likely to show the largest impacts of feedback effects.

- While increasing number of models include aerosol-cloud interactions, systematic assessments of the algorithms included against measurements is lacking. There is significant heterogeneity in the complexity of model process formulations for aerosol-cloud interactions reflecting the uncertainty in this field.

Main challenges and gaps

CCMMs are now being increasingly applied in a variety of air quality and atmospheric composition studies. These evolving studies are highlighting the opportunities to advance the state of CCMMs and their use in such assessments. A few key application areas and associated challenges are summarized below:

1. Urban/stable boundary layer: the modulation of the urban heat island resulting from aerosol effects on radiation in urban areas with high pollution has received little attention to date. Opportunities exist to advance our understanding of interactions between atmospheric chemistry and dynamics in urban areas through application and further evolution of CCMMs.

2. Finer scale model applications require frequent coupling between the dynamical and chemical components of the atmospheric system. CCMMs provide the framework for such coupling. The benefits of CCMM applications that enable coupling at fine temporal scales to enable these fine spatial resolution air quality studies needs to be further demonstrated.

3. Application of CCMMs to study changes in stratosphere-troposphere exchange and impacts on "background" O_3.

4. Integrating emerging satellite observations with CCMMs to better describe trends (space and time) in atmospheric composition.

5. Improving estimates of pollution scavenging and deposition – does inclusion of aerosol-cloud interaction processes in CCMMs improve the estimates of pollution deposition (amounts and spatial distributions)?

6. Need to evolve the way we compare grid based models with point observations
   - Spatial representativeness of observations must be considered
   - There is a limit to how close a simulation can get to a point observation.

Recommendations for future research

- Continue intercomparisons both at global and regional scale for AQ, NWP and climate (should also consider intercomparisons that are cutting across all three fields);

- Need some specifically defined experiment that looks at chemistry-cloud-microphysics at different scales;

- Need for (field experimental) data to evaluate online coupled models;

- Improving the numerical and computational efficiency of the models as complexity of applications grows (e.g. scales).

2.5 SESSION 5 - CCMMS FOR NWP AND METEOROLOGY

Nicholas Savage, Saulo Freitas, Sylvain Joffre and Vincent-Henri Peuch

Summary of presentations

The session included 11 oral presentations and five posters. Since the additional computing costs of using upgraded aerosol schemes have to be justified for operational NWP by improvements in forecasting skill, most of the papers addressed cases studies of enhanced aerosol load (dust storms or biomass burning) when major effects of aerosol influence are expected. One paper (G. Thompson) focused on a simpler and thus a lower cost approach to the aerosol parameterization problem while attempting to represent fundamental first-order aerosol processes. This added three more tracers (water-friendly aerosols, ice-friendly aerosols and number concentration of cloud droplets). This resulted in an increase of 16% in computing costs.

Three papers presented the activities of the WMO WGNE group to evaluate the impact of aerosols on NWP. The goal is to evaluate the impact of aerosols on weather prediction using modelling runs involving eight regional and global models to simulate three strong or persistent events of aerosol pollution in three different but characteristic parts of the world. This activity is one relevant extension of some of the activities of the COST Action ES1004.

A number of papers discussed the applications of Coupled Chemistry-Meteorology Models. Applications presented included solar power forecasting, aircraft icing, volcanic ash, pollen, air pollution and aviation meteorology (visibility).

It has to be noted also that challenges and advances in other applications (CCMM for climate or for air quality) are also relevant for NWP: mainly radiation dimming as well as cloud processes and microphysics, but also detailed and reliable description of the land surface and its temporally varying properties (snow, ice, SST, vegetation ...) is of quite large importance. This is also an additional incentive for further cooperation between the three modelling communities here.

Main challenges and gaps in the field

The cloud schemes used in operational NWP are frequently much simpler than those used in research – this makes it a challenge to create transferable solutions. We need to be able to develop more traceable hierarchies of configurations to allow the simplified versions used in NWP to be benchmarked more easily against the more sophisticated schemes and quantify the benefits for specific NWP systems with more sophisticated schemes.

There are also differences in objectives between NWP and research. In the case of NWP, the approach is "outputs" based: if outputs (i.e. indicators of forecast skill) are not improved, there is little drive to adopt a certain scheme (together with its central processing unit (CPU) burden). In research, the drive is "input" based. The aim is to answer the question: "does my model represent, with sufficient fidelity, the aerosol and associated processes which are currently known to be critical for the coupling between aerosols and the physical properties of the atmosphere?" In contrast NWP will only adopt more expensive schemes if it is proven that the added sophistication (and computational cost) has a sufficiently large impact on the skill of the model in forecasting parameters of interest to their customers or is considered at least as a credible stepping stone for future progress.

There is no consistency between modellers over what we mean by "direct effect" or "indirect effect". These are typically assessed by doing sensitivity studies (on/off pairs of runs), but there is a lot of inconsistency between models as to what assumptions about aerosols are in use when the "direct" or "indirect" effects are off in the model. For the radiative transfer schemes, some models have zero aerosol, others use a climatology. For cloud and precipitation schemes, the picture is even more unclear. At the very least, modelling studies need to be clear what assumptions about aerosols are made in the runs where direct/indirect effects are not linked to the prognostic aerosols and ideally intercomparison should use a harmonized approach and nomenclature to the aerosols representation they are using in the case where prognostics aerosols are not used in the radiation and/or cloud schemes.

The magnitude of the modelled effects is very variable – different models have different impacts, with the sign of the impacts not being consistent in some cases. Also strong geographical differences are seen: some parts of the world seem to have more significant feedbacks than others. All of this makes it a challenge to provide consistent answers to the key questions posed. There is clearly a need for much more extensive, co-ordinated and systematic research on this topic and for the reasons for the differences between models to be better understood. Some of the differences may be related to the point above about the lack of a consistent baseline in the studies. Finally, they is a need to move from case studies to assessment of impact of overall skill scores (by season, regions…).

Answers to the relevant key questions

What are the advantages of integrating meteorological and chemical/aerosol processes in coupled models?

Meteorological processes such as precipitation, thunderstorms, radiation, clouds, fog, visibility and PBL structure all depend on atmospheric concentrations of chemical components, especially aerosols, because of their effects on atmospheric radiation, physics and/or microphysics. In general, having interacting aerosols is potentially relevant for episodes in relation to health effects, aviation forecasts, radiation and temperature. However, its relevance for operational NWP applications remains to be demonstrated. For cloud properties, most probably having online aerosols is an advantage, while for precipitation the benefits are not yet clear. It is also unclear whether the advantages seen for short-term episodes of high aerosol loading are also present when evaluated over a longer-term period. It is important to have detailed information on aerosols (loading, aerosol types, profile, mixing state, etc.) for retrieval of CO2 concentrations and possibly other satellite retrievals. If retrievals of parameters such a temperature and humidity can be improved this could have further benefits for NWP. However, this has not yet been demonstrated.

Several studies show the effects of having aerosols included with direct effect on surface temperature and radiation during episodes. The effect over more extended periods of time however is not so clear. There were also effects on wind speed which interacted with local stratification and consequently on convection, cloud formation and precipitation.
Integration of meteorological and chemical/aerosol processes into a single forecasting system is most probably important for atmospheric chemical transport model (ACTM) (air quality/chemistry) and climate applications. As to short-range limited area NWP models, the essential aspect is to be able to obtain reliable (3D) real-time aerosol concentrations, either based on analyses of observations in an integrated model or provided by global or regional ACTM model simulations. This can be presently used for aerosol direct radiative effects, in the future for improved parameterizations of cloud microphysics for precipitation.

An additional benefit of the coupled approach would be for meteorological data assimilation in particular assimilation of radiative properties that depends on chemical composition. This assumes that the modelling system can outperform pollutant concentration climatologies when forecasting concentrations of aerosols and radiatively-active gases and was demonstrated in some talks (e.g. B. Vogel, G. Grell and H. Vogel). It is clear that enhanced retrieval of satellite data and direct assimilation of radiances is likely to improve both weather and chemical weather forecasts.

Some improvements in model skill for predicting standard weather variables such as screen level temperature, cloud and winds have been shown. In many cases, some improvement for these variables is seen, but certainly not all the time, and also depending on application of interest. For example, the integration may be more relevant for issues such as aircraft and surface icing and light precipitation. It is also important that the "benchmarking" NWP system used must be at the state of the art: it is easy to "beat" a system which does not assimilate large amounts of meteorological data.

How important are the two-way feedbacks and chains of feedbacks for meteorology, climate, and air quality simulations?

The processes that are particularly critical for online coupling between the chemical and meteorological components include (1) advection, convection and vertical diffusion (which control the transport and dispersion of chemical species and hence critically affect surface concentrations); (2) cloud microphysics (which determines cloud life cycle, interactions between clouds and aerosols and affects soluble chemical species); (3) radiative transfer (which is determined by meteorological parameters and radiatively-active chemical compounds); and (4) turbulent fluxes at the surface (which influences transport and distribution of chemical species). The importance of these interactions depends on the NWP parameters being considered and the meteorological conditions. While the importance for surface short-wave radiation of aerosol loading is clear, there is more uncertainty over the importance of aerosol representation for cloud forecasting – but it seems quite probable that it is important to represent these as well. In the case of precipitation the importance is not clear yet.

Research studies have shown that meteorology and chemistry feedbacks can be important but there are still many unanswered questions. Generally, there is strong evidence for the importance of some of the chains of interactions – for example increased AOD lowering surface temperature, giving a lower boundary layer and increasing primary pollutant concentrations at the surface. However, the importance of these chains is less clear under "normal" conditions than during strong events as considered in many papers. There also seems to be emerging evidence that the importance of these processes is not just dependant on aerosol loading but also on the region. Two presentations (poster by Jena and oral by Grell) indicated that the cloud aerosol interaction may be more important in the tropics. The relative importance of online integration and of the priorities, requirements and level of details necessary for representing different processes can vary greatly between applications, i.e. NWP, AQ, or climate and Earth system modelling. Most current NWP models do not incorporate detailed aerosol processes, even though aerosols – via radiative and microphysical processes, can affect fog formation, visibility and precipitation, and thus forecasting skill.

The impact of modified NWP forecasts of 3D meteorological variables like temperature, cloud condensate content, precipitation and wind on the real-time AQ forecasts could be estimated by the coupled/integrated ACTM community. For weather prediction by Short- to Medium-Range Numerical Weather Prediction models, the 3D real-time aerosol would most probably be important in specific cases of high aerosol concentrations. The task of the NWP community is first of all to make sure the radiation and microphysics parameterizations will be able to optimally use this information when obtained either as climatological fields or as forecast fields from another model.

What are the effects of meteorology on the abundance and properties (chemical, microphysical, and radiative) of aerosols on urban/regional/global scales?

Many processes and inputs (emissions) depend on meteorological conditions: wind/turbulence for dust and sea salt emissions or dry deposition; temperature for volatile organic compound (VOC) emissions; cloud processes for aqueous chemistry and wet deposition. The importance of wind speed in dust parameterizations was highlighted by one paper (Rémy), which showed how the changes in boundary layer stability fed back onto low level wind speed and thus to dust emissions. However, these parameterizations are very uncertain and vary greatly between models.

What is our current understanding of cloud-aerosol interactions and how well are radiative feedbacks represented in NWP/climate models?

Short-wave radiation is perhaps the best represented, LW not that well, cloud-aerosol interactions poorly. The results tend to be very much model-specific.

What is the relative importance of the direct and indirect aerosol effects as well as of gas-aerosol interactions for different applications (e.g. for NWP, air quality, climate)?

For NWP, most probably, the direct radiative aerosol effect has the most importance; the indirect one comes second, while gas-aerosol interactions are not important. The definition and specification of indirect effects is a complicated issue and deserves attention as well as requiring clear diagnostics for evaluation.

What are the key uncertainties associated with model predictions of feedback effects?

For NWP: (1) How to parameterize the SW and LW radiation transfer; (2) How to obtain reliable real-time external aerosol. There are a lot of uncertainties around the indirect aerosol effects, but perhaps for NWP they are not "key" as it is not so easy to find how to take these into account, and the importance of doing so is unknown from the NWP perspective.

How can the simulated feedbacks be verified with available observations/datasets? What are the requirements for observations from the three modelling communities?

Until we have a common definition of "simulated feedbacks" it is difficult to say how to verify them: the presentation by Johannes Flemming showed we cannot use the standard 500hPa height anomalies, etc. Radiation measurements at the surface could be used more widely for validation of NWP and climate models, which always parameterize the radiation fluxes and include them in the model output. For NWP, there is the question of developing model diagnostics and validation for high resolution, where quite a lot of work is being done. This is perhaps applicable for the two other modelling communities as well.

Note that in many papers, people took what is available, but no one really addressed “best wishes” for new or enhanced observations. This lack of observations is a challenge for many of the intermediate steps in the chains of interacting processes. As well as providing more observations, it would be very helpful if Met Services and institutes could provide more access to datasets such as SW radiation, cloud observations etc. More vertical information in the boundary layer is also key as often the largest modelled changes are not at the surface but are higher up.

Operational models still rely on observations and network design mainly developed in the 60-70s, when NWP was in its infancy, models had very coarse resolution, physical parameterizations very simplistic and measuring technology less advanced. It would be very timely to globally assess and revisit our operational observing strategies to provide the necessary data to current high-resolution state-of-the-art operational NWP models. Furthermore, NWP models include complex physical processes and interactions (e.g. at the surface), so that to really drill down into the processes more sites with co-located observations of visibility, cloud, radiation, vertical profiles of T, RH and winds and aerosol properties would be highly desirable. Such a task should fit the mandate of international organizations such as WMO and EUMETNET.

Recommendations for future research

Some recommendations for future research are:

- Research on the impact of online modelling of aerosols on visibility forecasting and observational constraints on the causes of light extinction and on parameterizations for calculating extinction given model parameters.
- Developing diagnostic and validation methodologies to more explicitly separate the different effects of the intertwined feedback processes.
- More collaboration between operational centres and research communities. This needs to be focussed on providing schemes that have an impact that is proven to be valuable enough to justify the cost of their implementation (even for relatively modest increases in computational cost).
- Coupling with oceans – both the impact of aerosols on SST in prognostic aerosol models and links to biogeochemistry especially DMS.
- More evaluation of aerosol properties routinely. We need more than PM10 or PM2.5 but also optical, chemical and microphysical properties.
- To make it easier to compare the indirect effects across models, a global reference set of aerosols and their properties would be very useful. This could perhaps be developed from MACC/Copernicus reanalysis or other long model runs.
- Developing methods to use chemical observation as tracers in order to gain information on winds. This has been done with stratospheric ozone for Upper Troposphere-Lower Stratosphere winds, but there is potential also in the troposphere especially in the tropics (carbon monoxide or dust).
- Further research to better understand the importance of including more accurate representation of aerosol properties in satellite retrievals.

2.6. SESSION 6 - MODEL EVALUATION

K. Heinke Schlünzen, Dominik Brunner, S.T. Rao and Stefano Galmarini

Summary of presentations

At the symposium nearly all presentations included some elements of model evaluation. Sensitivity studies evaluating the impact of a new methodology (changed parameters/process descriptions/initial data/boundary data) on model performance, for example, used evaluation to determine, if the new methodology is leading to model results closer to reality. Most evaluations presented were operational evaluations; some were diagnostic, but very few dynamic or probabilistic evaluations, using definitions by Dennis et al. (2010). No paper (except ~ Brunner et al.) focused on evaluation concepts with stated objectives (application purposes, target values).

Presentations mostly highlighted advantages of online models, often for situations with very high aerosol levels, but rarely disadvantages of online coupling were shown. These are, however, possible, if an online coupled model explicitly simulates processes that are already implicitly considered by other parameterizations of the model. Thus, a careful check of all parameterizations is needed to avoid modelling a process twice.

Some papers addressed that the robustness of the results needs to be quantified, especially for sensitivity studies. This is relevant to distinguish true signals from noise (S.T. Rao et al., Bernhard Vogel et al.).

Main challenges and gaps in the field

Evaluation always helps to better understand the abilities (case study verified by the model) or restrictions of a model (falsification of the model with respect to the selected case study). Concerning the generic evaluation concept (Schlünzen and Sokhi, 2008) that is needed to be applied for model evaluation there is no difference for online or offline models, or for purely meteorology or chemistry transport models. There is no need for a new generic concept for evaluating coupled models, but the scientific processes to be evaluated as well as the benchmark tests to be applied need to be driven by the model purpose (fit for purpose). Therefore, the following general recommendations are true for online as well as offline models:

1. Based on the generic evaluation concept (Schünzen and Sokhi, 2008) an evaluation concept needs always to be developed towards a scope (= purpose of the model application). This scope (purpose) needs to be clearly stated, including the target parameters (e.g. PM10 annual average values and/or exceedances for daily values; deposition values), the scale they are needed for (e.g. urban background, nitrification in rural areas, urban traffic situations), as well as the application purpose (assessment in hindcast mode, AQ or/and weather forecast, emergency response, etc.). It cannot be expected that one model is equally well applicable for calculating all the different target parameters at all possible scales and for all application purposes.

2. The scientific evaluation should include essential model qualities and the test cases should be defined, preferably covering operational, dynamic, diagnostic and a probabilistic evaluation (Dennis et al., 2010). For dynamic evaluation, robust methods are needed that are able to separate true signals from the internal variability of the atmosphere.

3. The uncertainty of observation data to be used in evaluation needs to be specified (including their representativeness) and should be considered in the evaluation. Satellite data cannot be used blindly, since they typically depend on a priori assumptions for the atmosphere which might not be consistent with the actual pollutants situation. If satellite data are used, averaging kernels (if provided) need to be accounted for or forward operators or other ways of reproducing a signal seen from

the satellite need to be consistently applied in the evaluation. Satellite data need to be properly mapped onto the model grid (space and time) accounting for the spatial and temporal resolution of the satellite data.

4. Quality measures internally assume Gaussian (error) distribution, which is not generally true. Error-distribution-independent measures should be used like hit rates or contingency tables. In the case of hit rates the allowed deviation (relative, absolute) needs to be defined and consistently used in the community to make evaluation results comparable. The same is true for contingency tables, where acceptable class ranges need to be defined.

Additional answers to the relevant key questions from the point of evaluation

What are the advantages of integrating meteorological and chemical / aerosol processes in coupled models?

For evaluation no (dis)advantages.

What are the key uncertainties associated with model predictions of feedback effects?

No sufficient evaluation has been performed to answer this question, especially due to the absence of specific observation datasets. A key challenge for evaluating feedback effects is to distinguish real impacts from "meteorological noise". Tiny effects can grow to large differences in meteorological evolution due to the chaotic nature of weather (butterfly effect). This may lead, for example, to spatial shifts in cloud and precipitation patterns resulting in locally large differences between simulations with and without feedbacks. Real effects, however, have to be identified as systematic changes over larger domains and/or longer time periods or in multi-case applications rather than as localized single case effects.

How to realize chemical data assimilation in integrated models for improving NWP and air quality simulations?

Understanding and quantifying the uncertainty of observation data is important for both data assimilation and model evaluation.

How can the simulated feedbacks be verified with available observations/datasets? What are the requirements for observations from the three modelling communities?

Required measurements / instrumentation:

- Aerosol sizing: Optical Particle Counters (OPC) and Mobility Particle Size Spectrometers (SMPS, DMPS)

- Aerosol composition: analysis of filter sample, filterpack, Aerosol Mass Spectrometers (AMS), Elemental Carbon/Organic Carbon (EC/OC) analyzers

- Aerosol optical properties: aethalometer, nephelometer

- Aerosol nucleation: Condensation Particle Counters (CNC/CPC), size resolved CCN, Zurich Ice Nucleation Chamber (ZINC), Tandem Differential Mobility Analyzers (TDMA)

- Radiation: downward and upward SW & LW radiation, diffuse/direct components
- Aerosol remote sensing: AOD, absorption AOD, Angstrom Exponent, fine fraction

- Cloud properties: cover, optical depth, liquid/ice water path, droplet/ice number concentration

- Radiative fluxes in the atmosphere (and at the surface)
- Turbulent fluxes in the atmosphere (and at the surface)
- Information on PBL height / stratification (time dependent, spatially resolved).

Datasets need to come with quantified uncertainties including spatial and temporal representativeness.

Satellite data can be particularly valuable for evaluating direct and indirect feedback effects, as shown e.g. by Quaas et al. (2009), and should be included more systematically in future evaluation studies.

2.7 SESSION 7 - DATA ASSIMILATION

Christian Seigneur and Johannes Flemming

There is increasing experience in the assimilation into CCMM of composition observations obtained from ground-based networks and satellite sensors. Data assimilation can, therefore, be used to improve air quality forecasts and to produce re-analyses of three-dimensional fields of chemical and aerosol concentrations. The main challenges of chemical data assimilation (CDA) with CCMM, however, do not differ from the challenges of CDA with chemical transport models.

Summary of presentations

Three presentations and one poster were made on CDA.

Greg Carmichael (University of Iowa) presented a 4D-Var assimilation system for aerosols with WRF PLUS/DA. His group and the WRF community have made substantial developments to also include the tangent and linear formulation of the aerosol scheme, the emissions and dry deposition (see Guerrette and Henze, GMDD, 2015 for details).

Arlindo da Silva (NASA GSFC, talk given by Peter Colarco) presented the GEOS-5 aerosol assimilation and forecasting system. NASA CDA related activities are aerosol forecasting, campaign support, biomass burning emission prediction as well as reanalysis (MERRAero). Peter Colarco pointed out the importance to correctly deal with the biases in the different observing systems for aerosols for the assimilation.

Johannes Flemming presented the global MACC data assimilation system at ECMWF. At ECMWF there is currently no evidence that the joint assimilation of composition and meteorology is beneficial. However, there is a benefit of the CDA for the simulation of composition-weather feedbacks as CDA can improve the realism of the composition fields used in these studies.

A poster by Prodromos Zanis (AUT) showed the improvement by the assimilation of satellite data on surface ozone concentrations in Europe in the MACC reanalysis.

Main challenges and gaps in the field

A main challenge of CDA is the limited information content of the current chemical and aerosol observations. For example, satellite data typically provide integrated observations (e.g. AOD, or total column values for gases), but not the 3D model concentration fields. Many species relevant to atmospheric chemistry and air quality are simply not observed (for example, few volatile organic compounds are observed). There are significant data gaps in terms of spatial coverage, because of the interference of clouds in the case of satellite data and because of the limited coverage of ground-based monitoring networks. Observation systems for the same species (e.g. AOD satellite products) show often systematic biases. There is, therefore, the need to calibrate different observations from different systems before they can be fed into CDA systems.

Up to now, there has been little positive experience in assimilating both meteorological and chemical data into CCMM. The lack of accuracy and coverage of the atmospheric composition observations is probably the main reason for this issue. Further, the correct definition of the error cross-correlations between meteorological and composition fields is a challenge.

Future research

Direction of future research with CDA will focus on a better exploitation of existing observations networks and satellite products. In particular, additional profile observations from lidars, ground based remote sensing or sondes may help to complement the total column observations provided by satellite products. New observing systems such as geostationary instruments for atmospheric composition observations will open new research opportunities.

The impact of chemical data assimilation could be improved, if not only directly observed concentration fields and surface fluxes can be updated within the CDA framework. To achieve this, variational data assimilation systems need to better represent the relevant processes. This may require the development of adjoint and tangent linear formulation of the relevant processes (emission, dry deposition, chemical conversion) of the assimilating model.

Improved representation of atmospheric composition by CDA will be essential for the successful simulation of weather/composition feedbacks in CCMM in the future.

CHAPTER 3. MAIN OUTCOMES FROM THE CCMM SYMPOSIUM

A summary of the key issues and recommendations regarding Coupled Chemistry-Meteorology/Climate Modelling: status and relevance for numerical weather prediction, atmospheric pollution and climate research based on the symposium presentations, discussions and conclusions of the brain-storming teams (see the previous chapter), is presented briefly in this chapter[a]. The outcomes of the CCMM symposium are organized around eight key questions.

1. What are the advantages of integrating meteorological and chemical/aerosol processes in coupled models?

Meteorological processes such as precipitation, thunderstorms, radiation, clouds, fog, visibility and PBL structure are all affected by atmospheric concentrations of chemical components, especially aerosols. Considering the effects of aerosols may thus not only be relevant in air quality modelling but also in the prediction of tomorrow’s temperatures and precipitation and in sensitive applications such as cloud and fog forecasting for aviation. However, its relevance for operational NWP applications has not yet been demonstrated except for short episodes associated with high aerosol concentrations such as dust outbreaks or intense biomass burning (Rémy et al., 2015; Freitas et al., 2016). For cloud properties, having online aerosols is most probably an advantage while for precipitation the benefits are not yet clear. It is also unclear whether the advantages that have been demonstrated for short-term episodes with extreme aerosol loading are still present in more common situations relevant for daily weather prediction.

A proper representation of aerosols in NWP models may also be beneficial for the assimilation of satellite observations since aerosols affect the path of light through the atmosphere and may therefore affect the retrieval of temperatures, water vapour, ozone and other parameters from satellite observed radiances.

Several case studies have shown the benefits of including aerosols in NWP models for the prediction of surface temperature and radiation during episodes of high aerosol concentrations. Aerosols have also been shown to affect wind speeds through their interaction with local stratification and convection, and to influence cloud formation and precipitation. The effects over more extended periods of time could be important under changing emission scenarios, but need to be examined in more detail.

Integration of meteorological and chemical/aerosol processes into a single forecasting system is assumed to be most important for atmospheric chemical transport (ACT) modelling (air quality/atmospheric composition) and climate applications. As to short-range limited area NWP models, the essential aspect is to be able to obtain reliable (3D) real-time aerosol concentrations. This can be presently used for aerosol direct radiative effects, and in the future for improved parameterizations of cloud microphysics for precipitation.

Some improvements in model skill for predicting standard weather variables such as screen level (normally 2 m above displacement height) temperature, cloud and winds have been shown. In many cases there are improvements for these variables but certainly not under all meteorological situations, and the improvement also depends on the application. For example, the integration may be more relevant for issues such as aircraft and surface icing and light precipitation than for heavy precipitation.

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[a] A short version was submitted to BAMS on 31 January 2016 as: ’Coupled Chemistry-Meteorology/Climate Modeling: status and relevance for numerical weather prediction, atmospheric pollution and climate research’, by Alexander Baklanov, Dominik Brunner, Gregory Carmichael, Johannes Flemming, Saulo Freitas, Michael Gauss, Øystein Hov, Rohit Mathur, K. Heinke Schlünzen, Christian Seigneur, Bernhard Vogel. Corresponding author: Gregory Carmichael, University of Iowa, USA, E-mail: gcarmich@engineering.uiowa.edu

A technical advantage of online coupled systems is the reduced amount of work needed to maintain and further develop the model, since processes like advection or diffusion can be calculated with the same methods for e.g. water vapour or other concentration and even the same code can be used.

2. How important are the two-way feedbacks and chains of feedbacks for meteorology, climate, and air quality simulations?

The processes which are particularly critical for online coupling between the chemical and meteorological components include (i) advection, convection and vertical diffusion (which control the transport and dispersion of chemical species and hence critically affect surface concentrations); (ii) cloud microphysics (which determines cloud life cycle, interactions between clouds and aerosols and affects soluble chemical species); (iii) radiative transfer (which is determined by meteorological parameters and radiatively active chemical compounds); and (iv) turbulent fluxes at the surface (which influences transport and dry deposition of chemical species). The importance of these interactions depends on the meteorological parameters being considered and the prevalent conditions. While the importance of aerosol loading for estimating surface shortwave radiation is clear, there is more uncertainty in quantifying its effects on cloudiness – but it seems quite probable that it is important to represent these as well. In the case of precipitation the importance (e.g. the impact direction) is not clear yet.

Research studies have shown that meteorology and chemistry feedbacks can be important but there are still many unanswered questions. There is strong evidence for the importance of some chains of interactions – for example increased aerosol loadings lowering surface temperature thereby reducing boundary layer depth and increasing primary pollutant concentrations at the surface. However, the importance of these chains is less clear under normal conditions than in the strong events considered in many studies such as Xing et al. (2015). There is also emerging evidence that the importance of these processes is not only dependent on aerosol loading but also on the region. Grell and Freitas (2014) and Chinmay Jena et al. (see WMO CCMM, 2016) indicated that the cloud aerosol interaction may be more important in the tropics.

The relative importance of online integration and of the priorities, requirements, and level of detail necessary for representing different processes can vary greatly between applications, i.e. NWP, AQ, or climate and Earth system modelling. Most current NWP models do not incorporate detailed aerosol processes, even though aerosols – via radiative and microphysical processes, can affect fog formation, visibility and precipitation, and thus forecasting skill. The impact of modified NWP forecasts of 3D meteorological variables on real-time AQ forecasts could be estimated by online coupled ACT models. For weather prediction by Short to Medium Range NWP models, the 3D real-time aerosol would most probably be important in specific cases of high aerosol concentrations. The task of the NWP community is first of all to make sure the radiation and microphysics parameterizations will be able to optimally use this information when obtained as climatological fields or as forecast fields from another model. Under particular circumstances, the two-way feedbacks can be very important: Saharan dust and biomass burning aerosols have been reported to be able to reduce downward shortwave radiation by several 10s and up to 100 W m^{-2} locally with correspondingly large effects on surface temperatures and vertical stability.

Within the climate community two-way feedbacks are of crucial importance to correctly capture climate sensitivity. Important feedbacks for climate and the other modelling communities have been identified by the COST Action ES1004 (webpage of COST ES1004 WG2 at http://www.eumetchem.info).

When new processes and feedbacks mechanisms are incorporating in CCMMs it is important to remember that in NWP and climate models there are already parameterizations in an implicit manner of the general physical and dynamical effects of chemical trace gases and aerosols, therefore implementing more detailed chemistry processes would also mean modifying existing parameterizations in the models.

3. What are the effects of meteorology on the abundance and properties (chemical, microphysical, and radiative) of aerosols on urban/regional/global scales?

Many processes relevant for air quality depend on meteorological conditions. Examples are the importance of wind and turbulence for the release of dust and sea salt aerosols, of humidity for dry deposition, temperature for VOC emissions, cloud processes for aqueous chemistry and wet deposition, moisture and temperature for fire emissions. The importance of wind speed in dust emission parameterizations was recently highlighted by Rémy et al. (2015) who showed how the changes in boundary layer stability may feed back on low level wind speed and thus on dust emissions. The formation of secondary aerosols depends on temperature, UV radiation and relative humidity. So far these effects could already be accounted for in offline-coupled models. What online coupled models are considering in addition are direct feedbacks, such as the modification of radiation by aerosols and gases, and indirect feedback effects, such as the modification of physical properties of clouds followed by modifications of radiation and precipitation. In addition this implies changes of the light reaching the surface and changes of the oxidation and formation of secondary aerosols near the surface. These second-order effects become important as the aerosol concentrations increase. Quantification of these second-order effects is relevant to the question as to whether they are important for weather forecasting. This seems to be the case for longer term comparisons, and for large deviations from the mean aerosol loading, but the effects are often in the range of model-model differences and therefore difficult to demonstrate (Kong et al., 2014).

For climate the following effects were highlighted: (i) less precipitation and higher wind speeds lead to higher aerosol dust and sea salt emissions; (ii) changes in humidity alter wet scavenging and resuspension of aerosol; (iii) changes in circulation/wind patterns alter aerosol transport and abundances; (iv) climate change caused by changes in aerosols affects other chemical constituents such as tropospheric and stratospheric ozone; (v) changes in cloudiness affect photolysis rates; (vi) long-term dry and hot climates increase flammability of vegetation, fire emissions and predisposing higher injection layers.

4. What is our current understanding of aerosol-cloud interactions and how well are radiative feedbacks represented in NWP/climate models?

Generally speaking, short-wave radiation in existing modern CCMMs is perhaps the best represented radiative feedback process, while long-wave radiation is less well represented, and cloud-aerosol interactions are poorly described. However, the level of sophistication differs from one model to another.

The indirect effects seem to be very sensitive to the complexity of the chosen parameterizations and to detail of the implementation. The models participating in phase 2 of the Air Quality Modelling Evaluation International Initiative (Galmarini and Hogrefe, 2015) employing essentially the same theoretical approaches for cloud condensation nuclei (CCN) sometimes had very different results. Idealized model studies on isolated clouds show a clear aerosol effect while in case of real world simulations the atmospheric feedback is more complex and compensating effects may occur. Laboratory data of particles' capability to act as ice nuclei show large scatter, so this is a topic for more research.

With respect to climate modelling cloud-aerosol interactions are also not yet fully understood, in particular for ice clouds and mixed-phase clouds including mid-level and Arctic clouds.

5. What is the relative importance of the direct and indirect aerosol effects as well as of gas-aerosol interactions for different applications (e.g., for NWP, air quality, climate)?

For NWP, the direct radiative aerosol effect is most probably the most important feedback mechanism. The indirect one comes second (or first according to some authors), while gas-aerosol interactions are rated not important (but they are important if we consider secondary aerosol formation). Aerosols are very important for cloud microphysics, therefore they might be important for precipitation forecast. The definition and specification of indirect effects is a complicated issue that deserves further attention and requires clear diagnostics for evaluation. The direct and indirect effects sometimes act in opposite direction in terms of their impact on both weather and air-quality predictions. For specific aerosol episodes under cloudy conditions the indirect effect can be the dominant process, but the cross-model variability in the implementation of the indirect effect complicates intercomparisons of the relative impact. For climate studies the question as to which effect is of highest relevance depends on the region and the season. Both the direct and indirect effects are important for climate applications, but the largest uncertainty comes from the indirect effect, in particular aerosol effects on ice clouds. Using aerosol climatologies instead of predicted aerosols may cause significant errors in satellite retrievals of different gases such as ozone.

Accounting for feedback effects can influence the assessment o the impact of emission changes on air quality. Ensemble estimates present a viable means to balance the diversity and accuracy of existing CCMMs for air quality applications.

6. What are the key uncertainties associated with model predictions of feedback effects?

The treatment of the indirect effect is one of the key uncertainties. Ice nucleation processes and parameterizations are less well defined than CCN parameterizations.

For the direct effect accurate estimation of aerosol optical properties is largely dictated by the accurate prediction of aerosol composition, size-distribution and mixing state and the knowledge of the refractive index of the individual species.

Feedback effects seem to have a crucial importance in the vicinity of large emission sources (Saharan dust, forest fires and other large plume emissions), but the parameterizations for these emissions sources do not always include feedback effects explicitly, and for forest fires, the parameterizations for plume rise are many and variable in their accuracy. In order to get feedbacks “right” better parameterizations for these sources are needed or feedbacks need to be explicitly included into their formulation.

For different applications different key uncertainties were identified.

For NWP: (1) How to parameterize the short-wave and long-wave radiation transfer; (2) How to obtain reliable real-time external aerosol. There are a lot of uncertainties around the indirect aerosol effects, but perhaps for NWP they are not "key" as it is not so easy to take these into account, and the importance of doing so is unknown from the NWP perspective.

For Climate: (1) Measuring feedback processes in reality (and verifying them in models) is a challenge and so is the quantification of uncertainties; key uncertainties may lie in cloud-aerosol couplings, as this will potentially have a large impact on climate; (2) Biosphere-atmosphere couplings will also respond to climate change and are not fully understood; (3) Radiative forcing is a poor measure for regional climate response.

7. How can chemical data assimilation (DA) be implemented in integrated models to improve NWP and air quality simulations?

During the last decade, experience in assimilation of chemical and aerosol observations from ground-based and satellite instruments into CCMM has grown significantly (Bocquet et al., 2015). Chemical DA has been implemented in several CCMM such as IFS, WRF/Chem and GEOS-5. Chemical DA is used to initialize air quality forecasts and for retrospective analysis of atmospheric composition. It has been shown that corrections to emissions as part of the DA procedure can help to improve the impact of the observations especially in forecast applications. A main challenge of chemical DA is the limited information content of the atmospheric composition observations because:

- Many modelled species, such as organic compounds or aerosol species, are not directly observed.
- Vertically integrated observations, such as aerosol optical depth or total column, have to be distributed to model levels.
- Spatial and temporal coverage is limited because of network design, viewing geometry or cloud cover masking.
- There are biases between different observing systems, which should be removed before the assimilation.

Although the importance of assimilating atmospheric composition data in CCMM to get realistic chemical fields has been demonstrated, there is little experience in assimilation of both meteorological and chemical observations into CCMM. Future research should address:

- Cross-correlations between chemical and meteorological background errors (e.g. wind versus chemical species and species versus species).
- New observing systems such as lidars and geostationary instruments for atmospheric composition observations.

8. How can the simulated feedbacks be verified with available observations/datasets? What are the requirements for observations from the three modelling communities?

No robust evaluation has been performed to answer these questions, due to the paucity of simultaneous measurements of aerosol chemical, optical, and radiative properties. However, radiation measurements at the surface could be used more widely for validation of NWP and climate models, which always parameterize the radiation fluxes and include them in the model output. For NWP, and possibly also for the other two modelling communities, there is the question of developing model diagnostics and validation for high resolution, where quite a lot of work is being done.

Nudged climate simulations help verification, although some of the feedback effects will be suppressed by the nudging. Free-running simulations where feedbacks are switch on/off can be compared in terms of skill scores. There is also a need for process-oriented evaluation, going beyond the comparison against observed mean values.

Modellers usually take the observations that are available without specifically addressing the requirements for new or enhanced observations. This lack of observations is a challenge for many of the intermediate steps in the chains of interacting processes. Thus some advice from those three communities would be beneficial: what are the measures of significance of a model change, relative to observations, typically employed in these communities? As well as providing more observations, it would be very helpful if meteorological services and institutes could provide better access to datasets such as shortwave radiation or cloud observations that are not routinely reported to the international weather centers. More vertical profiling in the boundary layer is also a key as often the largest modelled changes are not at the surface but higher up in the atmosphere.

There is a need for co-located and simultaneous meteorology and chemistry measurements at locations carefully selected to ensure spatial representativeness. To really drill down into the processes, more sites with co-located observations of visibility, cloud, radiation, vertical profiles of temperature, relative humidity as well as winds and aerosol properties would be highly desirable. Innovative designs for global measurement systems (existing technological platforms such as commercial aircraft, cell phones, cars, etc.) should be further exploited. Such a task should fit the mandate of international organizations such as WMO and EUMETNET.

In particular the following measurements/instrumentation can be mentioned:

- Aerosol sizing: Optical Particle Counters (OPC) and Mobility Particle Size Spectrometers (SMPS, DMPS)
- Aerosol composition: analysis of filter sample, filterpack, Aerosol Mass Spectrometers (AMS), Elemental Carbon/Organic Carbon (EC/OC) analyzers
- Aerosol optical properties: aethalometer, nephelometer
- Aerosol nucleation: Condensation Particle Counters (CNC/CPC), size resolved CCN, Zurich Ice Nucleation Chamber (ZINC), Tandem Differential Mobility Analyzers (TDMA)
- Radiation: downward and upward SW & LW radiation, diffuse/direct components
- Aerosol remote sensing: AOD, absorption AOD, Angstrom Exponent, fine fraction
- Cloud properties: cover, optical depth, liquid/ice water path, droplet/ice number concentration
- Radiative fluxes in the atmosphere (and at the surface)
- Turbulent fluxes in the atmosphere (and at the surface)
- Information on PBL height / stratification (time dependent, spatially resolved).

CHAPTER 4. CONCLUSIONS AND RECOMMENDATIONS

Migration from offline to online integrated modelling systems is recommended as only the latter approach can guarantee a consistent treatment of processes and allow two-way interactions of physical and chemical components, particularly for AQ and NWP communities. Applications that may benefit from CCMM are numerous and include: Chemical Weather Forecasting (CWF); Numerical Weather Prediction for precipitation, visibility, thunderstorms, etc.; Integrated Urban Meteorology, Environment and Climate Services; Sand and Dust Storm Modelling and Warning Systems; Wild fire atmospheric pollution and effects; Volcano ash forecasting, warning and effects; High Impact Weather and Disaster Risk; Effects of Short-Lived Climate Forcers; Earth System Modelling and Projections; Data assimilation for CWF and NWP; and Weather modification and geo-engineering. Online integrated models, however, need harmonized formulations of all processes influencing meteorology and chemistry.

Based on the presentations of the symposium as well as the discussions following them (e.g. WWRP, 2015), we have identified the following recommendations for future research in the main three communities.

For meteorological studies and specifically NWP the following research is needed:

- Research on the impact of online modelling of aerosols on visibility forecasting, observational constraints on the causes of light extinction and on parameterizations for calculating extinction given model parameters.
- Developing diagnostics and validation methodologies to more explicitly separate the different effects of the intertwined feedback processes.
- More collaboration between operational centers and research communities. This needs to be focused on providing schemes that have an impact that is proven to be valuable enough to justify the cost of their implementation (even for relatively modest increases in CPU).
- Coupling with oceans – this is important for both, atmosphere and ocean: the impact of aerosols on sea surface temperature can only be considered with prognostic aerosol models and links to biogeochemistry in the ocean are relevant to determine especially DMS emissions.
- More evaluation of aerosol properties routinely, not only for the indicators PM10 and PM2.5 but also for optical, chemical and microphysical properties.
- A global reference set of aerosols and their properties would be very useful for make it easier to compare the indirect effects across models. This could perhaps be developed from the Copernicus Atmosphere Monitoring Service (CAMS) reanalyses or other long-term model runs, e.g. within the ongoing EU project BACCHUS.
- Further research is needed to better understand the importance of including more accurate representation of aerosol properties in satellite retrievals.

For air quality and atmospheric composition studies the following research needs are stressed:

- Experiments are needed that are specifically defined to looks at chemistry-cloud-microphysics at different scales.
- There is need for (field experimental) data to evaluate online coupled models.
- The numerical and computational efficiency of the models need to be improved as the complexity of applications grows (e.g. scales).
- Intercomparisons both at global and regional scale for AQ, NWP and climate should continue; intercomparisons that are cutting across all three fields should be considered.

For climate research the following main developments in CCMMs are needed:

- Improve our understanding of indirect effects (e.g. BC on clouds).
    - The details of implementation of the indirect effect have a large impact on model results, and hence should be a focus of future research.
    - Complete analysis of indirect effects will require simulations on high resolution and aerosol representations in convective schemes.

- Develop CCMs with prognostic aerosol.
    - Level of sophistication of such modules needs to be defined. E.g., what is the tradeoff between a more complex aerosol representation on the one side and model resolution, or the atmosphere-ocean coupling, on the other side?
    - Consistency between resolution and parameterizations needs to be assessed.

- Test model performance in terms of relevant physical, chemical, and radiative processes and mechanisms (in contrast to just testing mean performance).
    - In particular, NWP models are tuned to perform well without feedbacks, leaving much room for improvement towards more realistic model behaviour.

- Test model performance in terms of tropospheric dynamics/meteorology and their effect on composition (and vice-versa).
    - Important especially in the field of inverse modelling of emission sources.

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Annex 1

EuMetChem Overview of Online Meteorology-Composition Modelling

Abstract

The COST Action - European framework for online integrated air quality and meteorology modelling (EuMetChem) is focusing on a new generation of online integrated Atmospheric Chemical Transport (ACT) and Meteorology (Numerical Weather Prediction and Climate) models with two-way interactions between different atmospheric processes including chemistry (both gases and aerosols), clouds, radiation, turbulent mixing, emissions, meteorology and climate. Two major application areas of the integrated modelling are considered: (i) improved numerical meteorology and weather prediction (NWP) and chemical weather forecasting (CWF) with short-term feedbacks of aerosols and chemistry on meteorological variables, and (ii) two-way interactions between atmospheric pollution/composition and climate variability/change. The framework consists of four Working Groups (WGs) namely: (1) Strategy and framework for online integrated modelling; (2) Interactions, parameterizations and feedback mechanisms; (3) Chemical data assimilation in integrated models; (4) Evaluation, validation, and applications. Establishment of such a European framework (involving also key American experts) enables the EU to develop world-class capabilities in integrated ACT/NWP-Climate modelling systems, including research, education and forecasting.

COST Action ES1004 Overview

Motivation to start the COST Action EuMetChem arose from results of offline coupled Numerical Weather Prediction (Meteorological) and Air Quality Models and the online coupled models (Figure A.1). Experimental studies and research simulations had shown that atmospheric processes (meteorological weather, including precipitation, thunderstorms, radiation, clouds, fog, visibility and PBL structure) depend on concentrations of chemical components (especially aerosols) in the atmosphere. Furthermore, meteorological data assimilation (in particular assimilation of radiances) depends on the chemical composition. Last not least, studies also had shown that air quality forecasts loose accuracy when ACT models are run offline. However, a new generation of online integrated meteorology and chemistry modelling systems is becoming available for predicting atmospheric composition, meteorology and climate change.

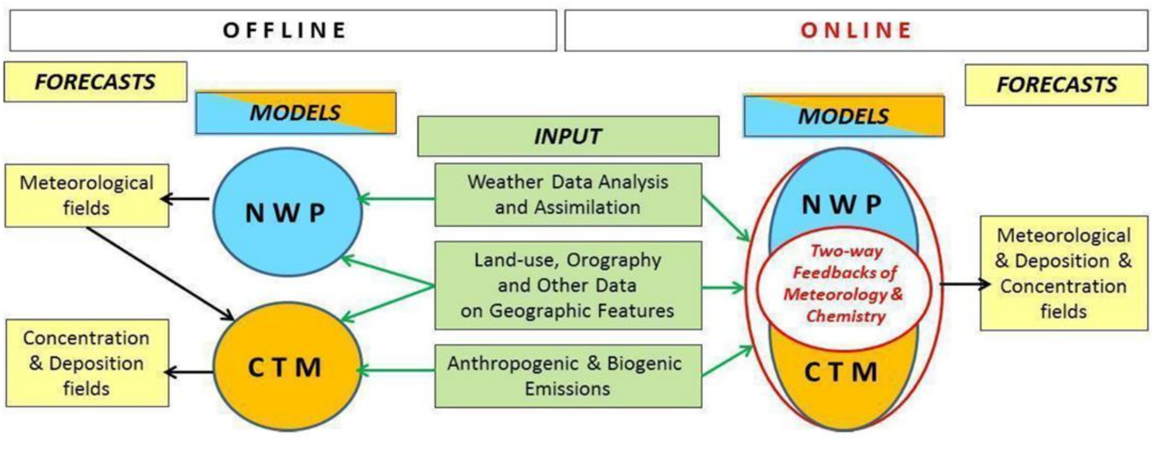

Figure A.1. Schematic diagramme of (left) offline and (right) online coupled NWP and ACT modelling approaches for AQ and meteorology simulation. Figure from Baklanov et al. (2014). CTM – a chemical transport model.

Historically, Europe has not adopted a community approach to modelling and this has led to a large number of model development programmes, usually working independently such as the AQ and NWP communities. A strategic framework is needed that will help to provide a common goal and direction to European research in this field while having multiple models. The COST Action was initiated to integrate, streamline and harmonize the interaction between atmospheric chemistry modellers, weather modellers and end users. It will lead to strongly integrated and unified tools for a wide community of scientists and users.

The EuMetChem action aimed on the new generation of online models, using integrated ACT and Meteorology (Numerical Weather Prediction and Climate) modelling with two-way interactions between different atmospheric processes including chemistry (both gases and aerosol), clouds, radiation, boundary layer, emissions, meteorology and climate. Overall objective was to set up a multi-disciplinary forum for online integrated air quality/meteorology modelling and elaboration of the European strategy for a new generation integrated ACT/NWP-Climate modelling capability/framework.
The main topics were:

- Online versus offline modelling: advantages and disadvantages
- Analysis of priorities, particularly focusing on interaction/feedback mechanisms
- Chemical data assimilation in integrated models
- European strategy/framework/centre for online integrated modelling
- Evaluation and validation framework of online ACT/NWP-Climate models
- Collection of suitable datasets for model development and evaluation.

The EuMetChem Action involves teams from 23 European COST countries: Austria, Bulgaria, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Israel, Italy, Malta, Netherlands, Norway, Poland, Portugal, Serbia, Slovenia, Spain, Sweden, Switzerland, Turkey, United Kingdom and several institutions from non-COST countries (Argentina, Brazil, Canada, Egypt, Russia, Ukraine, USA) and international organizations (ECMWF, JRC, WMO) contributing with their expertise. The chair of the Action is Prof. Alexander Baklanov, Danish Meteorological Institute (now at WMO), the vice-chars are Prof. Sylvain Joffre, Finnish Meteorological Institute, and Prof. K. Heinke Schlünzen, University of Hamburg, Germany and the grant holder representative is Prof. Nicolas Moussiopoulos, AUTH, Greece.

EuMetChem research activities are organized within the following four WGs:

- WG1 Strategy and framework for online integrated modelling (coordinated by Dr Peter Suppan, Karlsruhe Institute of Technology and Prof. Jose M. Baldasano, Barcelona Supercomputing Center, advised by Dr Georg Grell, NOAA).

- WG2 Interactions, parameterizations and feedback mechanisms (coordinated by Dr Michael Gauss, met.no, Dr Alberto Maurizi, Institute of Atmospheric Sciences and Climate, Italian National Research Council and since March 2014 Dr Renate Forkel, Karlsruhe Institut für Technologie, advised by Prof. Yang Zhang, North Caroline University).

- WG3 Chemical data assimilation in integrated models (coordinated by Prof. Christian Seigneur, CEREA, Université Paris-Est, France and Dr Hendrik Elbern, University of Cologne, advised by Prof. Greg Carmichael, University of Iowa).

- WG4 Evaluation, validation, and applications (coordinated by Dr Dominic Brunner, Empa, Swiss Federal Laboratories for Materials Science and Technology, Dr Stefano Galmarini, JRC EC, Ispra and Prof. Heinke Schluenzen, University of Hamburg, advised by Dr S.T. Rao, US EPA).

Online coupled meteorology atmospheric chemistry models have undergone a rapid evolution in recent years. Developments of the coupled atmosphere-chemistry models and consideration of aerosol feedbacks are realized in different research communities, first of all in the air quality modelling, numerical weather prediction and climate modelling as they can consider not only the effects of meteorology on air quality, but also the potentially important effects of atmospheric composition on weather. Relative importance of online integration and of the priorities, requirements and level of details necessary for representing different processes and feedbacks can greatly vary for these related communities.

Some outcomes of the EuMetChem COST Action ES1004 are:

- Joint overall review paper with all participants and a wider community involved (Baklanov et al., 2014)
- Two Summer schools on CCMM: in Odessa, Ukraine (2011) and in Aveiro, Portugal (2014), the last one with more than 200 applications and 52 accepted students from 25 countries of four continents and with publication of training materials (Miranda et al., 2014)
- Participation in the join AQMEII Phase2 model exercise coordinating its European efforts and performing various modelling runs (Galmarini and Hogrefe, 2015)
- Multiple publications and workshops (See Publications of EuMetChem below)
- Action was attractive to many scientists outside the Action (including overseas)
- Attraction to WMO for participation in the final CCMM conference
- Triggering of WMO initiative on seamless prediction (Chapter 12 in WWRP, 2015)
- Integrated Special Issue of ACP/GMD journals on "Coupled chemistry–meteorology modelling: status and relevance for numerical weather prediction, air quality and climate communities" (Baklanov et al., 2015).

The EuMetChem overview of CCMMs below is a short compilation[b] of the findings from the COST ES1004 Action with recommendations for scientists, users and international organizations to take on these results after the Action. The summary below and the conclusions and recommendations shall also help non-scientists interested in this quickly developing field to understand the results of this Action and which steps should be taken next (e.g. needed research).

1. Introduction into coupled meteorology-chemistry modelling

Coupling of atmospheric dynamics, pollutant transport, chemical reactions and atmospheric composition for modelling environmental impacts, climate change, weather forecasts and air quality will remain one of the most challenging tasks over the next decades as they all involve strongly integrated processes. It is well accepted that weather has a profound impact on air quality (AQ) and atmospheric transport of hazardous materials. It is also recognised that

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[b] Based mostly on the EuMetChem paper: Baklanov, A., Schlünzen, K., Suppan, P., Baldasano, J., Brunner, D., Aksoyoglu, S., Carmichael, G., Douros, J., Flemming, J., Forkel, R., Galmarini, S., Gauss, M., Grell, G., Hirtl, M., Joffre, S., Jorba, O., Kaas, E., Kaasik, M., Kallos, G., Kong, X., Korsholm, U., Kurganskiy, A., Kushta, J., Lohmann, U., Mahura, A., Manders-Groot, A., Maurizi, A., Moussiopoulos, N., Rao, S. T., Savage, N., Seigneur, C., Sokhi, R. S., Solazzo, E., Solomos, S., Sørensen, B., Tsegas, G., Vignati, E., Vogel, B., and Zhang, Y.: Online coupled regional meteorology chemistry models in Europe: current status and prospects, Atmos. Chem. Phys., 14, 317-398, doi:10.5194/acp-14-317-2014, 2014.

atmospheric composition can influence both weather and climate directly by changing the atmospheric radiation budget or indirectly by affecting cloud formation and precipitation. Until recently however, because of the scientific complexities and lack of computational power, atmospheric chemistry and weather forecasting have developed as separate disciplines, leading to the development of separate modelling systems that are only loosely coupled. This is particularly true for regional scale models, whereas for global scale and in particular stratospheric modelling, the development and availability of online coupled models is more advanced.

The dramatic increase in computer power during the last decade enables us to use high spatial resolutions (e.g. < a few km) in numerical weather prediction (NWP) and meteorological modelling. Fronts, convective systems, local wind systems, and clouds are being resolved or partly resolved. Furthermore, the complexity of the parameterization schemes in the models has increased as more and more processes are considered. Additionally, this increased computing capacity can be used for closer coupling of meteorological models (MetM) with atmospheric chemical transport models (CTM) either offline or online. Offline modelling implies that the CTM is run after the meteorological simulation is completed, while online modelling allows coupling and integration of some of the physical and chemical components to various degrees.

In recognition of the rapid development of coupled meteorology and chemistry modelling, Action ES1004 (EuMetChem) in the European Cooperation in Science and Technology (COST) Framework was launched in February 2011 to develop a European strategy for online integrated air quality (AQ) and meteorology modelling (see the web-site: www.eumetchem.info). The Action does not aim at determining or designing one best model, but to identify and review the main processes and to specify optimal modular structures for online Meteorology Chemistry (MetChem) models to simulate specific atmospheric processes. Furthermore, the COST Action develops recommendations for efficient interfacing and integration of new modules, keeping in mind that there is no one best model, but that the use of an ensemble of models is likely to provide the most skilful simulations (Baklanov et al., 2014). The WMO Working Group for Numerical Experimentation (WGNE) recently initiated also a specific online coupled modelling case study on Aerosol Effects on Numerical Weather Prediction (see the web-site: www.wmo.int/wgne/).

These coupled models are distinguished with respect to the extent of online coupling: online integrated and online access coupling. Online integrated meteorology chemistry models handle meteorology and chemistry using the same grid in one model and using one main timestep for integration. Online access models use independent meteorology and chemistry models that might even be using different grids, but exchange information from meteorology to chemistry and back to meteorology on a regular and frequent basis. The frequency of data exchange needs to increase as the time scale of the relevant processes becomes smaller. In contrast to online access models, offline models do not exchange data, but merely provide, e.g. meteorology information to drive the chemistry model. The ultimate stage is the online integration of CTM and MetM to produce a unified modelling system with consistent treatments of processes such as advection, turbulence and radiation for both meteorological and chemical quantities. Such an integration allows online integrated meteorology chemistry simulations with two-way interactions (also referred to as feedbacks). Climate modelling is also expanding its capability through the use of an earth system modelling approach that integrates the atmosphere, hydrosphere (including both fresh water and oceans) and biosphere with high spatial and temporal resolution. Climate modelling, however, does not require the implementation of near-real-time data assimilation, which is crucial for the skill of NWP and can also help improve AQ forecasts.

For performing a simulation, the input data need to be tailored to the specific requirements of the atmospheric model. For this purpose several programs are employed for each model, that pre-process data, e.g. meteorology measurements on model grids as initial data, land use data consistent with the model land use categories and emission data in agreement with the used chemical mechanism. Specific programs are also needed for providing output data from an atmospheric model.

Combining two modelling systems for operational applications, each of which have high CPU time and memory requirements, still poses many problems in practice and thus is not always feasible at all NWP or chemical weather forecasting centres. Nevertheless, one can argue that such gradual migration towards ever stronger online coupling of CTMs with MetMs poses a challenging but attractive perspective from the scientific point of view for the sake of both high-quality meteorological and chemical weather forecasting (CWF). While NWP centres, as well as entities responsible for AQ forecasting, are only beginning to discuss whether an online approach is important enough to justify the extra cost (Baklanov, 2010; Grell and Baklanov, 2011; Kukkonen et al., 2012; Zhang et al., 2012a,b), the online integrated approach is already used in many research and pre-operational/operational atmospheric models. Most of the times these systems are run at a lower resolution than the NWP resolution for weather applications. However, for some tracers they may even be run at the same (high) resolution.

For NWP/CWF centres, an additional benefit of the online approach would be its possible application for meteorological data assimilation (Hollingsworth et al., 2008). This assumes that the modelling system can outperform pollutant concentration climatologies when forecasting concentrations of aerosols and radiatively active gases. The retrieval of satellite data and direct assimilation of radiances is likely to improve both weather and chemical weather forecasts.

Online coupled meteorology and chemistry models were initially formulated in 1980s but mostly have been developed in recent years (see an historical overview by Zhang, 2008). Nowadays these models are becoming increasingly popular in Europe. Historically, Europe has not adopted a community approach to modelling and this has led to a large number of model development programmes, usually working almost independently, thereby yielding results tailored for specific applications (Baklanov et al., 2011). However, a strategic framework could help to provide a common goal and direction to European research in this field, while still having various models as part of a European model ensemble. The task is manifold since it requires scientific knowledge and practical experience in Met and AQ modelling and forecasting, numerical analysis, atmospheric physics, chemistry and data assimilation. That framework has somewhat be provided also by the MACC project with the integration of global and regional modelling, and the establishment of a multi-model ensemble for European AQ forecast within the Copernicus Atmosphere Monitoring Service (CAMS).

The focus on integrated systems is timely, since recent research has shown that meteorology and chemistry feedbacks are important in the context of many research areas and applications, including NWP and AQ forecasting, as well as climate and Earth system modelling. However, the relative importance of online integration and of the priorities, requirements, and level of details necessary for representing different processes can vary greatly between applications. Under these circumstances tailored solutions may be required for the three communities: (i) AQ forecasting and assessments, (ii) NWP and Met modelling, (iii) climate and earth system modelling.

For example, current NWP models do not incorporate detailed chemical processes, even though aerosols – via radiative and microphysical processes, can affect fog formation, visibility and precipitation, and thus forecasting skill. For climate modelling, feedbacks from greenhouse gases (GHGs) and aerosols are extremely important, though in most cases (e.g. for long-lived GHGs), online integration of full scale chemistry and aerosol dynamics is not critically needed. For CWF and prediction of atmospheric composition in a changing climate, online integration is expected to improve AQ and atmospheric chemical composition simulations and projections (e.g. Moran et al., 2010). The AQ, Met and climate modelling communities have different targets with respect to temporal and spatial scales, as well as to the processes involved in such modelling. For AQ forecasting, the key issue is usually the ground-level concentrations of pollutants, whereas for weather and climate models, skill is typically based on temperature, precipitation and wind. Since short-lived pollutants influence climate and air quality conditions, the AQ community is interested in online modelling to understand the feedback mechanisms and to design air quality policies that can maintain future air quality at acceptable levels under changing climate conditions (Alapaty et al., 2011).

Several applications are likely to benefit from online modelling, although they do not clearly belong to one of these three main communities mentioned above. These include bioweather forecasting, pollen warnings, forecasting of hazardous plumes from volcanic eruptions, forest fires, oil and gas fires, dust storms, assessment of methods in geoengineering that involve changes in the radiation balance (e.g. input of sulfate aerosols, artificially increased albedo) and consequences of nuclear war or leaks of radioactive material.

2. Potential direct impact and feedback processes relevant in meteorology chemistry coupling

Direct impacts of meteorology on chemistry or vice versa as well as feedback processes are varied. Their calculation only became possible only with the introduction of online meteorology chemistry models. Traditionally, aerosol feedbacks have been neglected in Met and AQ models mostly due to a historical separation between these communities, as well as a limited understanding of the underlying interaction mechanisms and associated complexities. Such mechanisms may, however, be important on a wide range of temporal and spatial scales (hours to decades and local to global). Field experiments and satellite measurements have shown that chemistry dynamics feedbacks exist among the Earth system components including the atmosphere (e.g. Kaufman and Fraser, 1997; Rosenfeld, 1999; Rosenfeld and Woodley, 1999; Givati and Rosenfeld, 2004; Jacobson, 2005; Lau and Kim, 2006; Rosenfeld et al., 2007, 2008).

The potential impacts of aerosol feedbacks can be broadly explained in terms of four types of effects: direct, semi-direct, first indirect and second indirect. For example, the reduction in solar radiation reaching the Earth by aerosols is an example of direct effect (Jacobson et al., 2007). Changes in surface temperature, wind speed, relative humidity, clouds and atmospheric stability that are caused by absorbing aerosols are examples of the semi-direct effect (Hansen et al., 1997). A decrease in cloud drop size and an increase in cloud drop number as a result of aerosols in the atmosphere are named first indirect effect (Twomey, 1977). These changes might enhance cloud albedo. An increase in liquid water content, cloud cover and lifetime of low level clouds and suppression or enhancement of precipitation are examples of the second indirect effect (Albrecht, 1989). However, this simplified classification is insufficient to describe the full range of two-way, chains and loops of interactions between meteorological and chemical processes in the atmosphere. It should also be noted that these definitions are not always consistently used throughout the literature.

The main meteorology and chemistry/aerosol interacting processes and effects, which could be considered in online coupled MetM-CTMs, are summarised in Tables 1 and 2. The order in Table 1 does not reflect their importance or relevance, since their actual relevance depends on the model application. In addition to looking at the meteorological parameters affecting chemistry, it is also worth mentioning effects of altered meteorology on meteorology, in order to better understand chains and loops of interactions. For example, clouds modulate boundary layer outflow/inflow by changes in the radiative fluxes as well as alterations of vertical mixing and the water vapour modulates radiation. The temperature gradient influences cloud formation and controls turbulence intensity and the evolution of the atmospheric boundary layer (ABL). Similar feedback mechanisms exist for altered chemistry impacts on chemistry. For example, biogenic emissions affect the concentrations of ozone and secondary organic aerosols. The polymerisation of organic aerosols produces long chain secondary organic aerosol (SOA) with lower volatility.

Table 1. Meteorology's impacts on chemistry

Temperature	Modulates chemical reaction and photolytic rates
	Modulates biogenic emissions (isoprene, terpenes, dimethyl sulfide, etc.)
	Influences biogenic emissions (isoprene, monoterpenes)
	Influences the volatility of chemical species
	Determines aerosol dynamics (coagulation, condensation, nucleation)
Temperature vertical gradients	Determines vertical diffusion intensity
Temperature & humidity	Affect aerosol thermodynamics (e.g. gas-particle partitioning, secondary aerosol formation)
Water vapour	Modulates OH radicals, size of *hydrophilic aerosol*
Liquid water	Determines wet scavenging and atmospheric composition
Cloud processes	Affects mixing, transformation and scavenging of chemical compounds
Precipitation	Determines the wet removal of trace gases and aerosol
Land surface parameterization (soil type and vegetation cover, soil moisture, leaf area)	Affects natural emissions (e.g. dust, BVOCs, CO2) and dry deposition
Lightning	Determines free troposphere NOx emissions
Radiation	Determines photolysis rates and influences many chemical reaction rates
	Determines isoprene emissions
Wind speed and direction	Determines horizontal transport and vertical mixing of chemical species
	Influences dust and sea-salt emissions
ABL height	Influences concentrations

On a more general level, a number of chains and loops of interactions take place and should be properly simulated in an online coupled model. These may include: (a) a loop feedback starting with temperature that affects chemistry and thus chemical concentrations (Table 1): the changes in chemical concentrations will in turn affect radiative processes (Table 2), which will then affect temperature to close the loop; (b) a chain feedback starting with aerosol that affects radiation (Table 2) and thus photolysis and chemistry (Table 1), (c) a chain feedback starting with temperature gradients that affects turbulence mixing (Met-Met feedback), thus affecting surface-level pollutant concentrations (Table 1) and boundary layer outflow/inflow (Met-Met feedback); (d) a chain feedback starting with aerosols that affect cloud optical depth through influence of droplet number on mean droplet size (Table 2): the resulting changes in cloud formation will then affect the initiation of precipitation (Met-Met feedback); and (e) a chain feedback starting with aerosol absorption of sunlight which results in changes in the temperature profile of the atmosphere and vertical mixing (Table 2) and thereby changes in the cloud droplet formation, which affects cloud liquid water and thus cloud optical depth (Met-Met).

Against the backdrop of the separate development of MetMs and CTMs together with the continued increase in computing power, a more detailed modelling description of physical and chemical processes and their interactions calls for a strategic vision. Such a vision will help to provide shared goals and directions for the research and operational communities in this field, while still having a multiple model approach to respond to diverse national and world-wide mandates.

Table 2. Chemical species' impacts on meteorology

Aerosols	Modulate radiation transfers (SW scattering/absorption, LW absorption, LW scattering by large particles like dust)
	Affect boundary layer meteorology (temperature, humidity, wind speed and direction, ABL height, stability)
	Extraordinary high concentrations can affect stability and wind speed
	Influence cloud formation, since they act as cloud condensation nuclei
Aerosols physical properties (size distribution, mass and number concentrations, hygroscopicity)	Influence cloud droplet and crystal number and hence cloud optical depth and hence radiation
	Modulate cloud morphology (e.g. reflectance)
	Influence precipitation (initiation, intensity)
	Affect haze formation and atmospheric humidity
	Influence scattering /absorption
Soot deposited on ice	Influences albedo
Radiatively active gases	Modulate radiation transfers

3. Major challenges and needs

3.1 Interacting processes and feedback mechanisms

The focus on integrated systems is needed, since recent research has shown that interactions between meteorology and chemistry and feedback mechanisms are important in the context of many research areas and applications, which can broadly be separated into the fields of NWP, air quality/CWF and climate/earth system modelling. The relative importance of online integration and the level of detail necessary for representing different processes and feedbacks will vary greatly between the three mentioned application fields, as was also confirmed in an expert poll conducted among the members of the EuMetChem COST Action (Baklanov et al., 2014; Kong et al., 2014).

The processes which are particularly critical for online coupling between the chemical and meteorological components include (i) advection, convection and vertical diffusion (which control the transport and dispersion of chemical species and hence critically affect surface concentrations); (ii) cloud microphysics (which determines cloud life cycle, interactions between clouds and aerosols and affects soluble chemical species); (iii) radiative transfer (which is determined by meteorological parameters and radiatively active chemical compounds); (iv) turbulent fluxes at the surface (which influences transport and distribution of chemical species).

Convection and condensation schemes need to be updated to take the aerosol–microphysical interactions into account, and the radiation scheme needs to be modified to include the aerosol effects more accurately. The interactions of aerosols with gas phase chemistry and their impacts on radiation and cloud microphysics depend strongly on their physical and chemical properties. Several processes such as nucleation, coagulation, condensation, evaporation, sedimentation, in-cloud and below-cloud scavenging, and deposition at the surface need to be taken into account by the models. The aerosol–cloud interaction schemes used in models are still very uncertain, sometimes giving substantially different forcing and thus need to be improved and further developed (for example, for ice forming nuclei, interaction with cirrus clouds, contribution of different anthropogenic and biogenic/natural aerosol particles for cloud evolution). On the other hand, the inclusion of aerosol effects in convective parameterizations is only beginning to receive attention.

Online coupling imposes additional requirements on the setup and implementation of radiation parameterizations. Most of these requirements reflect the need to maintain physical and numerical consistencies between the various modules and computational schemes of the model, against the increased frequency of interactions and the multitude of simulated effects. The complexity of the treatment of the effect of simulated aerosol concentrations on shortwave and longwave radiation fluxes differs strongly among the models. A final recommendation on how complex the parameterization needs to be is currently not possible.

Finally, emissions and deposition also interact in a specific way with the meteorological part within online coupled models. The most interesting emissions are those which depend on meteorology as they could potentially be treated more accurately and consistently than in offline models. Natural emissions (e.g. isoprene, terpenes and pollen) strongly depend on meteorology and are in general already calculated online even in offline models using the meteorological input driving the CTM model. Sea spray is the dominant aerosol source over the oceans and therefore, its proper quantification is highly relevant for a coupled model. Wind-blown dust refers to particles from a broad range of sources. Due to their direct relationship with meteorology, such emissions must be calculated online.

A large variety of chemical mechanisms are currently in use in online coupled models. Nevertheless, the most commonly used mechanisms have converged in terms of the state of the science included in their formulation. Modifications of the chemical mechanisms, which not only affect gas phase chemistry but also the coupling with aqueous-phase and aerosol mechanisms, have faced practical difficulties in the past, requiring significant reprogramming. Methods of updating chemical mechanisms make updates much easier as illustrated in the MECCA module (Sander et al., 2005). Therefore, the following actions are recommended:

- Create a unified central database of chemical mechanisms, where mechanism owners can upload relevant codes and provide updates as necessary. Versions should be numbered and chemical mechanisms should be open.

- Enable interfacing of this database using, e.g. the Kinetic Pre-Processor (KPP) to develop a set of box model intercomparisons including evaluation against smog chamber data and more comprehensive mechanisms and moreover an analysis of the computational cost.

3.2 Numerical and computational aspects

The most relevant properties to be considered when developing integrated models and especially for considering feedback mechanisms are conservation, shape-preservation and prevention of numerical mixing or unmixing. Traditionally, Eulerian flux-based schemes are more suitable for mass conservation. Recently however, several semi-Lagrangian schemes have been developed that are inherently mass conservative. Such schemes are applied in some integrated models.

A detailed analysis of the numerical properties of European integrated models is recommended. A particularly relevant set of tests has been described by Lauritzen and Thuburn (2011), which shifts the focus from traditional, but still important, criteria such as mass-conservation to the prevention of numerical mixing and unmixing. Not maintaining the correlations between transported species is similar to introducing artificial chemical reactions in the system.

A clear trend towards integrated model development is becoming perceptible with several modelling systems that can be considered as online integrated models with main relevant feedbacks implemented. Complementing those, there are several ones that are built using an online integrated approach, but some major feedbacks are not included yet. A third group of models, the online access models, is characterised by applying an external coupler between meteorology and chemistry. All the information is passed through the coupler. Depending on the approach used, wind and mass consistency problems may arise. In this sense, online integrated models are desirable for a better representation of feedback processes.

Numerical performance is also an important issue for online models. The current parallelization is based on well-established MPI and OpenMP programming models. Beyond these approaches there is no clear trend towards new parallelization paradigms, even though supercomputers are experiencing a huge increase in computing power achieved mainly through an increase in the number of computing units rather than an increase in clock frequency. New processor types such as GPU’s and MIC’s are only beginning to be explored.

To adopt newer technologies, a conversion program that transfers existing code to the new technology would be advantageous. The transferred code would need to be still readable and maintainable. This would be very useful since a coupled meteorology chemistry model takes several decades of work to develop, and without software based support, transfers can take years to be completed reliably.

3.3 Data assimilation

Experience with chemical data assimilation (CDA) in integrated online models is still limited (see an overview in Bocquet et al., 2015). Most applications of CDA use CTMs, rather than online coupled models, to improve the simulated concentration fields or model parameters such as emissions. First efforts have been made with integrated systems (IFS-MOZART and WRF-Chem) to assimilate chemical and meteorological observations in online integrated models. There is some evidence that CDA can also improve the assimilated meteorological variables, for example the assimilation of ozone can have a positive effect on the assimilated wind fields (Semane et al, 2009). CDA will be beneficial in online coupled model if it improves the realism of the chemical fields which are used to simulate the interaction between atmospheric composition and meteorology. The easiest approach is the adjustment of initial conditions through CDA in a manner similar to meteorological data assimilation. Optimal interpolation, variational approaches, EnKF or hybrid techniques combining the advantages of both variational and EnKF techniques are applicable. Other methodologies such as inverse modelling of emission fields appear as a promising technique to improve the skill of online integrated models and may have a stronger impact for short-lived pollutants than CDA has on initial conditions. However, it is debatable whether the results of inverse modelling should be used directly to correct emission fields or only to provide insights for the development of improved emission inventories.

3.4 Evaluation of methodologies and data

There is a crucial need for more advanced evaluation of methodologies and output data. Model validation and benchmarking are important elements of model development as they help identifying model strengths and weaknesses. Model validation has a long tradition in the NWP and AQ modelling communities, and many concepts can be applied to online integrated models as well. The MetM community has the necessary tools, for example, to analyse whether including certain feedbacks or not has a positive effect on weather forecast skill. Demonstrating these benefits however, requires running a model with and without feedbacks over extended periods of time - rather than for selected episodes - in order to draw statistically significant conclusions.

Evaluating whether relevant feedback processes are treated accurately by a model is challenging. The effects of aerosols on radiation and clouds, for example, depend on the physical and chemical properties of the aerosols. Thus, comprehensive measurements of aerosol size distributions, chemical composition, and optical properties are needed. Such observations should ideally be collocated with detailed radiation measurements (e.g. WMO GAW, AERONET), with aerosol lidars probing the vertical distribution and with radiosondes providing profiles of temperature and humidity. Evaluating indirect aerosol effects on clouds and precipitation is even more challenging and requires additional detailed observations of cloud properties such as cloud droplet number concentrations. Measurements from polarimetric radars, disdrometers, and cloud particle imagers can provide information on hydrometeor phases and size distributions but are only sparsely available. Online integration can also be beneficial for AQ modelling. Dense observational networks are available for the validation of classical air pollutants such as O_3 or NO_x and satellite observations of AOD and NO_2. Aircraft data also represent an important resource for observations of trace gases and aerosols for evaluation and possibly data assimilation.

4. Future directions, perspectives and recommendations

It is clear that the online modelling approach is a prospective way for future single-atmosphere modelling systems, providing advantages for all three communities, Met modelling including NWP, AQ modelling including CWF, and climate modelling. However, there is not necessarily one integrated online modelling approach/system suitable for all communities.

Comprehensive online modelling systems, built for research purposes and including all important mechanisms of interactions, will help to understand the importance of different processes and interactions and to create specific model configurations that are tailored for their respective purposes.

Regarding CWF and AQ modelling the online approach will certainly improve forecast capabilities as it allows a correct way of jointly and consistently describing meteorological and chemical processes within the same model timesteps and grid cells. This also includes harmonised parameterizations of physical and chemical processes in the ABL. There are many studies and measurements supportive of this conclusion (Grell et al., 2004; Grell, 2008; Zhang, 2008; Korsholm et al., 2009; Grell and Baklanov, 2011; Forkel et al., 2012; Saide et al., 2012; Zhang et al., 2013). In particular, due to the strong nonlinearities involved, offline coupling can lead to inaccuracies in chemical composition simulations.

For meteorological modelling, the advantages of online approaches are less evident and need to be further investigated and justified. It is clear that online models for short-term applications like NWP do not require full comprehensive chemistry (which would increase the CPU cost tremendously). Rather, the main improvements for NWP that are possible through an online integrated approach will be related to improvements in (i) meteorological data assimilation (first of all remote sensing data, radiation characteristics, which require detailed distributions of aerosols in the atmosphere) and (ii) description of aerosol–cloud and aerosol–radiation interactions, yielding improved forecasting of precipitation, visibility, fog and extreme weather events. While these improvements might not be statistically significant as averaged over longer periods of time, it is clear that for specific episodes and for urban weather forecasts, there are large potential benefits. In summary, meteorology modelling including NWP should benefit from including such feedbacks as aerosol–cloud–radiation interactions, aerosol dynamics along with simplified chemistry (with a focus on aerosol precursors and formation, e.g. sulfur chemistry).

For climate modelling, the feedbacks (forcing mechanisms) are the most important and the main improvements are related to climate–chemistry/aerosols/clouds interactions. However, the online approach is not strictly necessary for all purposes in this field. Many GCMs or RCMs are using an offline approach for describing GHG and aerosol forcing processes (by chemistry/aerosol parameterizations or prescription or reading outputs of CTMs). For global climate, in the EU project MEGAPOLI, a sensitivity study compared online vs. offline approaches and showed that for long-lived GHG forcing the online approach did not give large improvements (Folberth et al., 2011). On the other hand, for short-lived climate forcers, especially aerosols and for regional or urban climate, the outcome was very different, with online modelling being of substantial benefit. The online approach for climate modelling is mostly important for studies of short-lived climate forcers, which represent one of the main uncertainties in current climate models and are in particular at the core of political and socio-economic assessments of future climate change mitigation strategies. It will be impossible to answer the main questions about aerosol short-lived climate forcers and mitigation strategies without employing fully online coupled modelling systems that include aerosol dynamics and feedbacks.

Based on several overview analysis of the models (Zhang, 2008; Grell and Baklanov, 2011; Kukkonen et al., 2012; Zhang et al., 2012a,b; Baklanov et al., 2014), we suggest aiming at eventually migrating from separate MetM and CTM systems to online integrated coupled meteorology chemistry models. Only this type of model allows the consideration of two-way interactions (i.e. feedbacks) in a consistent way. The integration has not only the advantage of a single-atmosphere model, for instance where water vapour and other atmospheric gases are no longer treated numerically differently simply because of historical separation of the different disciplines. Furthermore, the integration has the advantage of saving computational resources, since several processes (e.g. vertical diffusion) have to be described in both MetMs and CTMs. Moreover, it will also reduce the overall efforts in research and development, maintenance and application leading to cost savings for both types of models.

The main recommendations are briefly summarised in the following sections. If a recommendation is mainly relevant for one type of the application (Meteorology or Chemistry simulations), this is explicitly mentioned.

4.1 Emissions and depositions

Emission and deposition are both close-to-surface processes and dependent on meteorology processes. In order to improve their treatment in MetChem models the following is needed:

- Time dependence of anthropogenic emissions should be better described, and open-ocean ship emissions should be better characterised (time, amount, compounds). Currently their parameterizations still have large uncertainties (Jalkanen et al., 2012).

- Accurate characterisation of land use, soil moisture and vegetation should be used for more accurate representations of meteorologically-dependent emissions.

- Emissions and heat fluxes from forest fires and volcanic eruptions need to be better known and improved in the models.

- Treatment of anthropogenic VOC emissions need to be improved/updated, both because of their contributions to O_3 and SOA formation.

- Emissions of primary aerosols and in particular their number and size distributions and physical properties (hydrophilic/hydrophobic) need to be better represented, both for atmospheric composition and for interaction with meteorology.

- Ammonia emissions should be calculated online with a more accurate representation of temporal variation, and account should be taken of their interactions with soil/vegetation (bi-directional fluxes, deposition or emission).

- Dry and wet deposition processes are directly driven by meteorology and, therefore, more accurate representations of their interplays with chemistry and meteorology are needed.

- Accurate parameterizations of land surface processes and accurate land use/land cover datasets are needed because of their profound impacts on both natural emissions and dry deposition fluxes.

4.2 Model formulations

Migrate from offline to online integrated modelling systems is recommended as only the latter approach can guarantee a consistent treatment of processes and allow two-way interactions of physical and chemical components of Met-Chem systems, particularly for CWF and NWP communities. Online integrated models, however, need harmonised formulations of all processes influencing meteorology and chemistry. In particular the following model treatments need to be considered:

- Our parameterization/understanding of aerosol–radiation–cloud–chemistry interactions is still incomplete and further research on the model representations of these interactions is needed.

- Key aerosol properties (size distribution, phase, hygroscopicity, mixing state and optical depths) and processes (chemistry, thermodynamics for SOA and dynamics) need to be better represented for AQ simulations.

- Cloud properties (droplet number concentrations, size distribution, optical depths), processes (microphysics, dynamics, wet scavenging, aqueous phase chemistry) and cloud–aerosol interactions for all types of clouds (in particular for convective and ice clouds) need to be better represented.

- A major challenge for most online models is the adequate treatment of indirect aerosol effects. Its implementation with affordable computational requirements and evaluation against laboratory/field data would greatly facilitate this transition.

- As more meteorological and chemical variables are assimilated into a model, one must be cautious about possible diminishing returns and possible antagonistic effects due to the interactions between meteorological variables and chemical concentrations. Consequently, the development of optimal methods for data assimilation is warranted.

4.3 Real-time application

To achieve the objective of online coupled meteorology and chemistry simulation in forecast models some specific aspects should be considered:

- National weather centres should consider progressively including aerosol-chemistry interactions into NWP systems which will lead to potential improvements and extending them to CWF using online coupled models for cross evaluations, benefitting both disciplines.

- The online integrated approach is well suited for applications where a frequent integration between meteorology and chemistry models is required to properly account for the effects of mesoscale events in high-resolution CTMs.

- The online coupling of meteorology, physics and emissions and their accurate representations are essential for CWF; the implementation of aerosol feedbacks is important mostly for specific episodes and extreme cases.

4.4 Model evaluation

For online models the evaluation can no longer be conducted for meteorology or chemistry separately. Interacting processes will need specific attention to avoid the situation where the "right" results are obtained for the wrong reasons. In this regard, efforts should focus on conducting dynamic evaluation to establish the models' credibility in accurately simulating the changes in weather and air quality conditions observed in the real world. To achieve this, attention should be given to:

- An international test bed for evaluation of urban models and mesoscale models for online MetChem models. A first step into this direction has been taken by the AQMEII consortium for the regional scale, but extension for higher resolving global models is important.

- Special variables (e.g. shortwave and longwave radiation, photolytic rate of NO_2, AOD, COT, CCN, CDNC, precipitation) should be included routinely into a model evaluation for online coupled models. Reliable measurements are needed on a routine basis.

- Routine, long-term measurements of aerosol size distributions, chemical composition and optical properties in operational ground-based networks are urgently needed to verify meteorology/climate–chemistry feedbacks.

- Ground-based and satellite remote-sensing measurements of aerosol and cloud properties (e.g. optical depths, CCN, IN, CDNC and SW and LW radiation) are very important to study aerosol indirect effects and should be included for validation of meteorology chemistry feedbacks.

- Last but not least, there is a need to evaluate routinely the atmospheric mixing processes in models, in particular within the ABL, using measurements on fluxes of meteorological parameters and chemical species in all three directions.

4.5 Data needs for assimilation

An important growing aspect of online chemical modelling has been the development of data assimilation systems that include also chemical species and particulate. Several global and regional models currently provide analysis of gases and aerosols. As an example, among others, the MACC system incorporates retrieved observations of ozone, CO, SO2, NO2 and aerosol optical depth in its analysis to provide initial conditions for the prediction of these species. Currently the emissions are not part of the analysis but are specified either from established inventories or from satellite observations as it's the case for the emissions of biomass burning aerosols, CO and other species from wild fires (GFAS, Kaiser et al 2012). Estimation of emissions through data assimilation will be the next step for global models. It has already been successfully tried by regional models and in offline models (Bocquet et al., 2015). Several data assimilation techniques are used in the analysis of atmospheric constituents such as 3D and 4D-Var, Ensemble Kalman filter and OI. Independently of the specific assimilation framework, any analysis requires input data which have specific characteristics of timeliness and accuracy. In particular, especially for chemical weather forecasting, the data to be fed in the assimilation system need to be in near-real time (NRT) and have a characterization of the observation errors at the pixel level. Several data sources are needed to ensure resilience of the system and wealth of observation-based information. Currently most centres rely on satellite data for the analysis of the atmospheric composition. Efforts are also under way to use ground-based (CO2, PM, etc.) and aircraft measurements. At the same time there is the need for accurate measurements to verify the model prediction.

These could have a longer data latency that the data to be used in the analysis. However it is important that these observations are also delivered timely, to ensure the possibility of a routine verification of the chemical model prediction. Validation datasets are mostly those coming from ground-based observing network such as GAW, AERONET, EARLINET/ACTRIS, MPLNET, etc. Aircraft data also provide invaluable independent observations for validation (MOSAIC for example, now IAGOS). High quality, validated datasets are essential also for the verification of the chemical models run in climate configuration.

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Uphoff, M., D. Grawe, O. Ross and K.H. Schlünzen, 2013: *Relevance of Photolysis Frequencies Calculation Aspects to the Ozone Concentration Simulation*, ITM 2013, Miami, FL, USA, 26-30 August 2013.

Annex 2

CCMM SYMPOSIUM PROGRAMME

Motivation and aims

The development of numerical models that couple meteorology with atmospheric chemistry and aerosol dynamics within one integrated model system has undergone a rapid evolution in recent years. The motivation for this development is that meteorology has not only a strong impact on air quality, but in return atmospheric composition has a potentially strong feedback to weather and climate. Relevant questions for the broader communities are related to the impact of air constituents on both air quality and incoming radiation, the modification of weather (cloud formation and precipitation) by natural and anthropogenic aerosol particles, and the impact of climate change on the frequency and strength of such effects and air quality.

The symposium aims to review the current research status of online coupled meteorology (weather and climate) and atmospheric chemistry modelling, and to assess the processes relevant for the interactions between atmospheric physics, dynamics and composition. In addition, it will highlight scientific issues and emerging challenges that require proper consideration to improve the reliability and usability of these models for the three scientific communities: air quality, numerical weather prediction and climate modelling. It will present a synthesis of scientific progress and provides recommendations for future research directions and priorities in development, application and evaluation of online coupled models.

Initiated and supported by

European Cooperation in S&T(COST) Action ES1004: http://www.eumetchem.info/,
World Meteorological Organization (WMO) Commission for Atmospheric Sciences (CAS) and
World Climate Research Programme (WCRP).

Key Topics

Main focus is on Aerosols and their feedbacks/forcing, with the following scopes and frameworks:

- Coupled chemistry-meteorology (weather and climate) modelling: approaches and requirements;
- Key processes of chemistry-meteorology interactions and their descriptions;
- Aerosol effects on meteorological processes and Numerical Weather Prediction (NWP);
- CCMM for air quality and atmospheric composition;
- CCMM for regional and global climate modelling;
- Model validation and evaluation;
- Data requirements, use of observations and data assimilation;
- Outlook and future challenges.

Registration and Abstract submission

Abstract submissions and registration	1 December 2014 DEADLINE
Notification of acceptance	15 December 2014
Registration	http://eumetchem.info

Key scientific questions

- What are the advantages of integrating meteorological and chemical/aerosol processes in coupled models?
- How important are the two-way feedbacks and chains of feedbacks for meteorology, climate, and air quality simulations?
- What are the effects of climate/meteorology on the abundance and properties (chemical, microphysical, and radiative) of aerosols on urban/regional/global scales?
- What is our current understanding of cloud-aerosol interactions and how well are radiative feedbacks represented in NWP/climate models?
- What is the relative importance of the direct and indirect aerosol effects as well as of gas-aerosol interactions for different applications (e.g., for NWP, air quality, climate)?
- What are the key uncertainties associated with model predictions of feedback effects?
- How to realize chemical data assimilation in integrated models for improving NWP and air quality simulations?
- How the simulated feedbacks can be verified with available observations/datasets? What are the requirements for observations from the three modelling communities?

CCMM Possible Applications

- Chemical weather / air quality forecasting and reanalyses
- Numerical Weather Prediction (NWP) for precipitation, visibility, thunderstorms, etc.
- Integrated Urban Meteorology, Environment and Climate Services
- Sand and Dust Storm Modelling and Warning Systems
- Wild fire atmospheric pollution and effects
- Volcano ash forecasting, warning and effects
- High Impact Weather and Disaster Risk
- Effects of Short-Lived Climate Forcers
- Earth System Modelling and Projections
- Data assimilation for air quality and NWP
- Weather modification and geo-engineering

Programme Committee

Øystein Hov (NO) - Chair
Greg Carmichael (US) - Co-Chair
Sylvain Joffre (FI) - Co-Chair
Alexander Baklanov (WMO)
Bernhard Vogel (DE)
Dominik Brunner (CH)
Georg Grell (US)
Michel Rixen (WCRP)
Rohit Mathur (US)
Saulo Freitas (BR)
S.T. Rao (US)
Stefano Galmarini (JRC, EU)
Veronique Bouchet (CA)
Vincent-Henri Peuch (ECMWF)

Organizing Committee

Alexander Baklanov (WMO) - Chair
K. Heinke Schlünzen (DE) - Co-Chair
Ana Isabel Miranda (PT)
Christian Hogrefe (US)
Christian Seigneur (FR)
Jose M Baldasano (ES)
Michael Gauss (NO)
Michel Rixen (WCRP)
Nicolas Moussiopoulos (GR)
Paul Makar (CA)
Peter Suppan (DE)
Renate Forkel (DE)

Agenda

Monday 23/2/2015

8:30 **Registration opens**

8:50 **Symposium Opening**

Welcome from WMO, Deon Terblanche, Research Director

Session 1: Coupled chemistry-meteorology systems

Greg Carmichael (chair), Georg Grell (rapporteur)

9:10 **Alexander Baklanov**

Online coupled meteorology-chemistry modelling: review of current status and further opportunities

9:30	**Rohit Mathur**	How Well Can Coupled Models Simulate Multi-Decadal Trends in Tropospheric Aerosol Burden and its Radiative Effects across the Northern Hemisphere?
9:50	**Johannes Flemming**	Atmospheric Chemistry in ECMWF's Integrated Forecasting System.
10:05	**Eigil Kaas**	Numerical treatment of the transport problem in on-coupled atmospheric models
10:20	**Astrid Manders-Groot**	Modelling the radiative impacts of aerosols: off-line versus on-line approach
10:35	**Coffee break**	

Session 2: Key processes and interactions

Bernhard Vogel (chair), Paul Makar (rapporteur)

11:00	**Yang Zhang**	Online-Coupled WRF-CAM5 Modeling over East Asia: Multi-Year Evaluation, Model Improvement, and Aerosol Indirect Effects
11:20	**Renate Forkel**	The EuMetChem multi-model case studies on aerosol feedbacks
11:35	**George Kallos**	Links and Feedbacks between Aerosol, Radiation, Cloud and Precipitation in the RAMS/ICLAMS Modelling System
11:50	**Svitlana Krakovska**	Towards improving parameterizations of mixed stratus cloud/fog formation in climate models and NWP
12:05	**Ralph Lehmann**	Determination of pathways in chemical reaction systems: an algorithm and applications to atmospheric chemistry
12:20	**Lunch break**	

Session 2 continued

Renate Forkel (chair), Yang Zhang (rapporteur)

13:20	**Paul Makar**	Coupled Chemistry-Meteorology: Simulations at 2.5km Resolution
13:35	**Slobodan Nickovic**	Modelling of cold cloud formation due to atmospheric dust

13:50 **Orestis Speyer**
Investigation of direct radiative effects of aerosols due to changes in domestic heating fuel

14:05 **Georgiy Stenchikov**
Radiative and Meteorological Effects of Air Pollution and Dust over the Arabian Peninsula

Session 3: CCMMs for climate studies

Annica Ekman (chair), Michel Rixen (rapporteur)

14:20 **Michaela Hegglin**
The IGAC/SPARC Chemistry-Climate Model Initiative

14:40 **Øystein Hov**
Climate-chemistry interactions in an Earth System Model (NorESM)

14:55 **Coffee break and Poster Session with guided poster show**

Session 3 continued

Øystein Hov (chair), Michaela Hegglin (rapporteur)

16:30 **Thierno Doumbia**
Evolution of the Chemical Composition of the Atmosphere over the Past Three Decades: Comparisons of Chemistry-Climate Model Simulations with Observations

16:45 **Peter Colarco**
The NASA Goddard Earth Observing Chemistry-Climate Model and its application to aerosol-chemistry-climate interactions

17:00 **Pierre Nabat**
Aerosol modeling in a regional climate models: prognostic scheme or monthly climatologies, which consequences on regional climate?

17:15 **Prabir Patra**
Diagnosing inter-hemispheric OH distribution and transport in chemistry and transport models

17:30 **Anna Possner / Ulrike Lohmann**
Uncertainties in climate prediction: The influence of aerosol particles on clouds and climate

17:50 END Presentations Day 1

18:00 Icebreaker Reception

Tuesday 24/2/2015

Session 4: CCMMs for air quality and atmospheric composition

Rohit Mathur (chair), Nicolas Moussiopoulos (rapporteur)

9:00 **Stefano Galmarini**
Ensemble summary of the AQMEII Phase 2 model evaluation activities and the role and relevance of international model evaluation studies

9:20 **Giovanna Finzi**
Impact of pollutant emission reductions on summertime aerosol feedbacks: a case study over the Po Valley

9:35 **Michael Prather**
Evaluation of Present and Future Surface Ozone as Simulated by Chemistry-Climate Models

9:50 **S.T. Rao**
Discussion on inherent uncertainties in atmospheric modeling: altering the initial state

10:05 **Fiona Tummon**
Diagnosing changes in European tropospheric ozone over the past 50 years

10:20 **Ashraf Zakey**
Climate change impacts on surface ozone: Using the Online integrated climate-chemistry model (EnvClimA)

10:35 **Coffee break**

Session 5: CCMMs for NWP and meteorology

Alexander Baklanov (chair), Sylvain Joffre (rapporteur)

11:00 **Saulo Freitas**
Evaluating the Impact of Aerosols on Numerical Weather Prediction

11:20 **Heike Vogel**
Impact of mineral dust particles on the forecast of temperature and photovoltaic power

11:35 **Georg Grell**
Evaluating the impact of aerosols on numerical weather prediction: The use of an aerosol aware convective parameterization

11:50 **Samuel Rémy**
Evaluating aerosol impacts on Numerical Weather Prediction in an extreme dust event

12:05	**Oriol Jorba**
	Direct radiative effect of mineral dust on meteorology for dust outbreak events over the Mediterranean in summer 2012
12:20	**Lunch break**
	Session 4 continued
	Saulo Freitas (chair), Nick Savage (rapporteur)
13:20	**Bernhard Vogel**
	Dynamic aerosol in numerical weather forecast: nice to have or necessary?
13:40	**Laura Rontu / Emily Gleeson**
	Aerosols in the HARMONIE NWP model - aerosol radiative effects and further perspectives
13:55	**Bent Sass**
	Integrated Meteorology-Aerosol-Chemistry Modelling for NWP Applications: Present Status, Future Steps and Challenges
14:10	**Manu Anna Thomas**
	Development of prognostic aerosol-cloud interactions in a chemistry transport model coupled to a regional climate model
14:25	**Gregory Thompson**
	A study showing impacts of aerosols on clouds and precipitation associated with a large winter cyclone
14:40	**Velle Toll**
	Aerosol direct radiative effect during summer 2010 wildfires in Russia simulated with NWP model HARMONIE
14:55	**Coffee break and Poster Session with guided poster show**

Session 6: Model evaluation

	Heinke Schlünzen (chair), Stefano Galmarini (rapporteur)
16:30	**Dominik Brunner**
	Fit for purpose? Application and evaluation of coupled chemistry and meteorology models
16:50	**Ashok Luhar**
	Evaluation of tropospheric chemistry in the Australian ACCESS-UKCA climate model
17:05	**Sara Basart**
	Extensive Comparison between a set of European Dust Regional Models and Observations in the Western Mediterranean for the Summer 2012 Pre-ChArMEx/TRAQA Campaign

17:20 **Mark Jacobson**

Coupling wind and solar energy systems with feedback to a coupled air pollution, weather, climate, and ocean model, GATOR-GCMOM

17:40 **END Presentations Day 2**

19:30 **Conference Dinner**

21:00 **End Dinner**

Wednesday 25/2/2015

Session 7: Data assimilation and data requirements

Christian Seigneur (chair), Johannes Flemming (rapporteur)

9:00 **Greg Carmichael**

Improving Air Quality (and weather) Predictions via Application of New Data Assimilation Techniques Applicable to Coupled Models

9:20 **Arlindo da Silva**

The GEOS-5 Aerosol Forecasting and Data Assimilation System

9:35 **Sushil Kumar Dash**

Impacts of Aerosols and Changing Climate on Indian Summer Monsoon and Extreme Events

9:50 **Coffee break**

10:20 **Plenary discussion on outcome**

Moderators: Øystein Hov, Greg Carmichael, Alexander Baklanov

Short reports by chairs or/and raporters for each topics

- Summary of papers and posters of the session,
- Main challenges and gaps in the field,
- Answers on the relevant key questions (see in the 2nd announce),
- Recommendations for future research.

12:10 **End of the CCMM Symposium**

12:10 **Lunch break**

13:00 **COST EuMetChem MC Meeting (COST internal only)**

16:10 Farewell

16:20 **End COST Action**

Poster Sessions

All posters are displayed during all days.
Guided poster tour at Monday and Tuesday

Monday 23/2/2015 – 15:15-16:15

Session 1: Coupled chemistry-meteorology systems

Greg Carmichael (chair), Georg Grell (rapporteur)

#1 **Alexander Mahura**

Science-Education: Online Integrated Modelling of Aerosol-Chemistry-Meteorology Effects using Enviro-HIRLAM

Session 2: Key processes and interactions

Bernhard Vogel (chair), Paul Makar (rapporteur)

#2 **Roman Nuterman**

Improvement of Enviro-HIRLAM weather forecasting through inclusion of cloud-aerosol interactions

#3 **Daniel Rieger**

Feedback between Natural Aerosol and Cloud Microphysics within ICON-ART

#4 **Roland Ruhnke**

Investigating convective tropospheric transport processes and large scale stratospheric dynamics with ICON-ART

Session 3: CCMMs for climate studies

Annica Ekman (chair), Michael Gauss (rapporteur)

#5 **Annica Ekman**

Impact of European aerosol emission reductions on Arctic climate

#6 **Markus Schultze**

Impacts of different aerosol climatologies on the European climate during the last decades

#7 **Amir Yadghar**

An integrated GIS-based air quality and climate change modeling methodology

#8 **Roberto San Jose**

Hight resolution urban health impacts of global climate scenarios: DECUMANUS project

Session 5: CCMMs for NWP and meteorology

Saulo Freitas (chair), Sylvain Joffre (rapporteur)

#9 **Chinmay Kumar Jena**

Changes on monsoon precipitation over South Asia due to anthropogenic aerosols: A case study using WRF-Chem model

#10 **Alexander Kirsanov**

Quasi-operational use of the COSMO-Ru7-ART Chemical-Transport Model at the Hydrometcenter of Russia

#11 **Alexander Mahura**

Enviro-HIRLAM Modelling of Regional and Urban Meteorology and Chemistry Patterns for Summer 2009 Paris Campaign

#12 **Julia Palamarchuk**

Aerosol effects on the physical weather in the Harmonie model

#13 **Emily Gleeson**

Aerosols in HARMONIE Radiative Effects and further Perspectives

Session 6: Model evaluation

Heinke Schlünzen (chair), Stefano Galmarini (rapporteur)

#14 **Marina Astitha**

Discussion on inherent uncertainties in atmospheric modeling: altering the initial state

#15 **Sara Basart**

The SDS-WAS North Africa-Middle East-Europe Regional Node activities: Different approaches to dust forecast evaluation

#16 **Virginie Buchard**

Evaluation of surface PM 2.5 in the NASA MERRA Aerosol Reanalysis over the United States

#17 **Jacek Kaminski**

New air quality observations from Sentinel, GEMS and TEMPO missions

#18 **Werner Thomas**

European ceilometer and lidar networks - aerosol retrieval, transport phenomena and future applications

Tuesday 24/2/2015 – 15:15-16:15

Session 4: CCMMs for air quality and atmospheric composition

Rohit Mathur (chair), Nicolas Moussiopoulos (rapporteur)

#19 **Serdar Bagis**
Modelling of Air Pollution Distribution with Chimere And WRF-Chem: A Case Study for Istanbul

#20 **Pelin Cansu Cavus**
Air Pollution Modelling Studies for Metropolitan Area of Istanbul

#21 **Deniz Hazel Diren**
A Case Study for Urban Effects on Meteorological Parameters by Enviro-HIRLAM

#22 **Fonseca Hernandez**
An air quality forecasting system based on WRF-Chem over Cuba: preliminary results.

#23 **Goran Gasparac**
Air quality modeling during stable atmospheric conditions

#24 **Sachin Ghude**
Influence of springtime biomass burning in South Asia on regional Air Quality: A regional model based study

#25 **I Yayoi Inomata**
Temporal variation of particulate polycyclic aromatic hydrocarbon concentrations in Northeast Asia

Session 4 cntd. **Jose M Baldasano (chair), Ana Isabel Miranda (rapporteur)**

#26 **Alexander Kurganskiy**
Birch pollen modeling for Denmark: spring 2006 episode.

#27 **Silvana Maldaner**
Simulating the contaminants dispersion in a shear-dominated stable boundary layer

#28 **Nicolas Moussiopoulos**
Using regional online coupled model results for estimating concentration increments in urban areas by means of a statistical approach

#29 **Varun Sheel**
Distribution of trace gases over South Asia: role of CCMs

#30 **Cardoso da Silveira**
Modeling the concentration of contaminants in stable wind meandering situation employing the advection-diffusion equation and asymptotic diffusivities

#31 **Huseyin Toros**
A Case Study of Online Enviro-HIRLAM and WRF-CHEM Model using global

emission data during an air pollution episode in Istanbul

#32 **Prodromos Zanis**

Evaluation of the dust scheme in the regional climate model RegCM4 using the dust satellite product LIVAS over Europe and North Africa

Session 7: Data assimilation and data requirements

Christian Seigneur (chair), Johannes Flemming (rapporteur)

#33 **Kuvar Satya Singh**

Impact of radiance data assimilation for prediction of a land-falling Bay of Bengal cyclone using mesoscale model

#34 **Prodromos Zanis**

Evaluation of MACCII near surface ozone reanalysis over Europe

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Rapporteurs / Brain storming Teams for each of the seven Sessions/Topics
(more persons are welcome to join):

1. Coupled chemistry-meteorology systems:

Greg Carmichael (chair), Georg Grell, Peter Suppan, Alexander Baklanov (rapporteurs)

2. Key processes:

Bernhard Vogel (chair), Paul Makar, Renate Forkel, Yang Zhang (rapporteurs),

3. CCMMs for climate studies:

Øystein Hov (chair), Michel Rixen, Michael Gauss, Annica Ekman, Michaela Hegglin (rapporteurs)

4. CCMMs for air quality and atmospheric composition:

Rohit Mathur (chair), Veronique Bouchet, Nicolas Moussiopoulos, Jose M Baldasano, Ana Isabel Miranda (rapporteurs)

5. CCMMs for NWP and meteorology:

Saulo Freitas (chair), Sylvain Joffre, Vincent-Henri Peuch, Nick Savage (rapporteurs)

6. Model evaluation:

Heinke Schlünzen (chair), Dominik Brunner, S.T. Rao, Stefano Galmarini, Christian Hogrefe (rapporteurs)

7. Data assimilation:

Christian Seigneur (chair), Johannes Flemming (rapporteur).

Annex 3

CCMM SYMPOSIUM LIST OF PARTICIPANTS

Hassan ABDULRAHMAN
Mohammad ABDULRAHMAN
Abdulhamid Ali ALRAEESI
Noel J. AQUILINA
Marina ASTITHA
Eleni ATHANASOPOULOU
Serdar BAGIS
José BALDASANO
Sara BASART
Veronique BOUCHET
François BOUYSSEL
Dominik BRUNNER
Virginie BUCHARD
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Greg CARMICHAEL
Claudio CARNEVALE
Pelin Cansu CAVUS
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Sushil Kumar DASH
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Thierno DOUMBIA
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Giovanna FINZI
Johannes FLEMMING
Jochen FOERSTNER
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Renate FORKEL
Saulo FREITAS
Stefano GALMARINI
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Paul MAKAR

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Peter SUPPAN

Dimiter SYRAKOV

Werner THOMAS

Manu Anna THOMAS

Gregory THOMPSON

Velle TOLL

Huseyin TOROS

Fiona TUMMON

John VAN AARDENNE

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Bernhard VOGEL

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Jason WILLIAMS

Ashraf ZAKEY

Prodromos ZANIS

Yang ZHANG

WMO Secretariat:

Alexander BAKLANOV

Geir BRAATHEN

Michel RIXEN

Paolo RUTI

Deon TERBLANCHE

Group photo of participants attending the Coupled Chemistry-Meteorology/Climate Modelling (CCMM): status and relevance for numerical weather prediction, atmospheric pollution and climate research symposium, Geneva, Switzerland, 23-25 February 2015

Annex 4

CCMM SYMPOSIUM ABSTRACTS

MONITORING AND FORECASTING DUST HAZE OVER WEST AFRICA USING SATELLITE IMAGERIES AND NUMERICAL WEATHER PREDICTION OUTPUT

Abdou Adam Abdoul-Aziz Abebe, Abdelkrim Ben Mohamed, Ilboudo Goama and Saley Diori

Abstract

Dust Haze occurrence over the sub-Saharan Africa is an annual phenomena, which has attracted quite a lot of attention from both forecasters and scientists. Between November and March, observations show that large dust plumes are transported from both the Sahara and Sahel towards West African countries and across the Atlantic Ocean. Predicting Dust haze generation should be an important application of meteorology to development in this area both for economic and social aspects. The main objective of the present study is to develop methodologies for better interpretation and use of NWP and Satellite products in forecasting Dust Haze generated by the predominant mechanism associated with pressure gradient tendency; improve knowledge and techniques required to exploit potential predictability of Dust Haze; verification of weather forecasts. One should however keep in mind that atmospheric soundings are needed when other generation mechanisms are concerned.

DISCUSSION ON INHERENT UNCERTAINTIES IN ATMOSPHERIC MODELLING: ALTERING THE INITIAL STATE

Marina Astitha, S.T. Rao, Jaemo Yang and Huiying Luo

Abstract

It is well known that the reducible and irreducible uncertainties in coupled meteorology-chemistry models are affecting the accuracy of the meteorological and atmospheric chemistry predicted values. Reducible (i.e. structural and parametric) uncertainties are attributable to our incomplete or inadequate understanding of the relevant atmospheric processes and errors in model input data. Improving or altering the physical and chemical parameterizations included in the models is used to reduce the structural and parametric uncertainties. Inherent or irreducible uncertainties stem from our inability to properly characterize the atmosphere with appropriate initial conditions. When the initial state of the atmosphere is unknown, its future state cannot be predicted with great accuracy. There is an emerging need for properly assessing the inherent modelling uncertainties in order to improve the prediction accuracy of modelling systems. This work focuses on the assessment of inherent uncertainties in atmospheric and air quality models by evaluating the impacts of different initial conditions on weather parameters and their consequent effect on atmospheric pollutant concentrations. We will discuss the effects of different model initializations in cloud formation, precipitation and atmospheric pollutant deposition in continental U.S. Support for the modelling efforts is given by data collected from surface measurement networks as well as satellite products and field experiments.

MODELLING OF AIR POLLUTION DISTRIBUTION WITH CHIMERE AND WRF-CHEM: A CASE STUDY FOR ISTANBUL

Serdar Bagis and Huseyin Toros

Abstract

Air quality is of vital importance because of its negative impact on human health. Large urban areas together with the industrial activity surrounding and within them are of the main causes of air pollution. Knowledge of air quality distribution will be take precautions in time for reduce the worse whether effects in populated areas. Istanbul is one of the most densely populated cities in Europe with a population exceeding 14 million. The position of the city, on two continents and separating Black and Marmara seas makes it difficult to model its weather. Another problem is the rapid growth of the city, the industrial zones once at the city limits are now wrapped by residential areas. Air quality models try to simulate the dispersion of pollutants. In this paper we investigate the performance of Chimere and of WRF-chem models on base pollutant such as NO2, SO2, PM10, PM2.5 etc. The results will help understand the quality of the available emission inventory as well as which model performs better.
Acknowledgement: This work was supported by TUBITAK-111Y319 and COST Action ES1004. The authors are grateful to the Ministry of Environment and Urbanism of Turkey, Environment Department of Istanbul Greater Metropolitan and Turkish State
Meteorological Service for meteorological and air pollution data.

ONLINE COUPLED METEOROLOGY-CHEMISTRY MODELLING: REVIEW OF CURRENT STATUS AND FURTHER OPPORTUNITIES

Alexander Baklanov and COST ES1004 EuMetChem partners

Abstract

Online coupled meteorology atmospheric chemistry models have undergone a rapid evolution in recent years. Although mainly developed by the air quality modelling community, these models are also of interest for numerical weather prediction and climate modelling as they can consider not only the effects of meteorology on air quality, but also the potentially important effects of atmospheric composition on weather. Two ways of online coupling can be distinguished: online integrated and online access coupling. Online integrated models simulate meteorology and chemistry over the same grid in one model using one main timestep for integration. Online access models use independent meteorology and chemistry modules that might even have different grids, but exchange meteorology and chemistry data on a regular and frequent basis. This paper is an overall outcome of the European COST Action ES1004: European Framework for Online Integrated Air Quality and Meteorology Modelling (EuMetChem). It offers a review of the current research status of online coupled meteorology and atmospheric chemistry modelling, a survey of processes relevant to the interactions between atmospheric physics, dynamics and composition; and highlights selected scientific issues and emerging challenges that require proper consideration to improve the reliability and usability of these models for the three scientific communities: air quality, numerical meteorology modelling (including weather prediction) and climate modelling. It presents a synthesis of scientific progress and provides recommendations for future research directions and priorities in the development, application and evaluation of online coupled models.

EXTENSIVE COMPARISON BETWEEN A SET OF EUROPEAN DUST REGIONAL MODELS AND OBSERVATIONS IN THE WESTERN MEDITERRANEAN FOR THE SUMMER 2012 PRE-CHARMEX/TRAQA CAMPAIGN

S. Basart and the Charmex team

Abstract

The present analysis focuses on the model capability to properly simulate long-range Saharan dust transport for summer 2012 in the Western Mediterranean. An exhaustive comparison of model outputs against other models and observations can reveal weaknesses of individual models, provide an assessment of uncertainties in simulating the dust cycle and give additional information on sources for potential model improvement. For this kind of study, multiple and different observations are combined to deliver a detailed idea of the structure and evolution of the dust cloud and the state of the atmosphere at the different stages of the event. The present contribution shows an intercomparison of a set of 7 European regional dust model simulations (NMMB/BSC-Dust, ALADIN, Meso-NH, RegCM, CHIMERE, COSMO/MUSCAT; MOCAGE and BSC-DREAM8b). The model outputs are compared against a variety of both ground-based and airborne in situ and remote sensing measurements performed during the pre-ChArMEx/TRAQA field campaign which included in particular several AERONET sites, the airborne lidar LNG, sounding with a ULA and with the new balloon-borne optical particle counter LOAC showing large particles (>15 μm), the CARAGA network of weekly deposition samples, etc. The models are also compared with satellite aerosol products (including MSG/SEVIRI, MODIS, POLDER and CALIOP), which provide a description of the spatial AOD distribution over the basin. These observational datasets provide a complete set of unusual quantitative constraints for model simulations of this period, combining data on aerosol optical depth, vertical distribution, particle size distribution, deposition flux, and chemical and optical properties. Acknowledgements are addressed to OMP/SEDOO for the ChArMEx data portal and to CNES for balloon operations and funding. The other main sponsors of the campaign were ADEME and INSU under the umbrella of the programmes PRIMEQUAL and MISTRALS. LOAC was developed with funding from ANR.

THE SDS-WAS NORTH AFRICA-MIDDLE EAST-EUROPE REGIONAL NODE ACTIVITES: DIFFERENT APPROACHES TO DUSTFORECAST EVALUATION

Sara Basart, Enric Terradellas, Jose M. Baldasano, Emilio Cuevas, Slodovan Nickovic, Angela Benedetti, Goran Pejanovic, Oriol Jorba, Malcolm E. Brooks, Arlindo Da Silva, Sarah Lu and Francesco Benincasa

Abstract

The World Meteorological Organization Sand and Dust Storm Warning Advisory and Assessment System (WMO SDS-WAS) project searches to enhance the ability of countries to deliver timely and quality sand and dust storm forecasts, observations, information and knowledge to users through an international partnership of research and operational communities. One of the activities performed in the North Africa, WMO SDS-WAS Middle East and Europe (NAMEE) Regional Center (http://sds-was.aemet.es/) is to establish a protocol to routinely exchange products from dust forecast models as the basis for a common model evaluation of aerosol optical depth (AOD) using ground-based (AERONET) and satellite (MODIS) observations. A multi-model median, generated after interpolating the models fields to a common grid mesh (at 0.5º x 0.5º), is also included in the evaluation. The aim of this work is to present different approaches and to test the use of different observational products in the evaluation system. It is also intended to find out which approach and which observational data better reflect the model performance. The good results obtained by the SDS-WAS NAMEE Regional Center and the demand of many national meteorological services promoted the developing of operational dust services. On June 2014, the First Specialized Center for Mineral Dust Prediction of the WMO, the Barcelona Dust Forecast Center (http://dust.aemet.es/), was publicly presented. The Center operationally generates and distributes predictions for NAMEE region. The numerical dust forecasts are based on the NMMB/BSC-Dust model developed at Barcelona Supercomputer Center (BSC-CNS).

THE IMPACT OF CLIMATOLOGICAL AND PROGNOSTIC AEROSOLS ON GLOBAL NWP PERFORMANCE

Malcolm Brooks, James Manners, Jane Mulcahy, Tom Riddick, David Walters and Jonathan Wilkinson

Abstract

In recent years, we have investigated the impact of a speciated prognostic aerosol scheme on global NWP performance in the Met Office Unified Model (Mulcahy et al., ACP 2014). In regions of high aerosol loading and variability, these successfully show how prognostic/interactive aerosols can affect the model forecast. In regions of lower aerosol loading, however, the results highlight a change in the mean climatology. The impact of this change on the model fields can be as large as - or even larger than - is seen in regions of high aerosol loading. This has motivated us to adopt a three dimensional speciated aerosol climatology that influences the model physics in a consistent manner to the full prognostic aerosol scheme. We present the impact of these climatologies and show that they both improve global NWP performance and provide a better platform for "seamless" model development between systems with prognostic and climatological aerosol. We argue that such a climatology is critical in assessing the true cost/benefit of interactive prognostic aerosol schemes on NWP model performance. Finally we present our plans to adopt of an internally mixed modal aerosol scheme and the benefits and challenges that this presents.

FIT FOR PURPOSE? APPLICATION AND EVALUATION OF COUPLED CHEMISTRY AND METEOROLOGY MODELS

Dominik Brunner, Stefano Galmarini, Christian Hogrefe, Renate Forkel, Michael Gauss, K. Heinke Schluenzen and Alexander Baklanov

Abstract

A number of regional scale coupled chemistry and meteorology model (CCMM) systems have been developed over the past two decades. Although they have reached a certain level of maturity, important questions remain regarding their fitness for purpose with respect to different applications of interest to both the research community and to operational centres. This is on the one hand due to the complexity of the atmospheric processes considered, and on the other hand due to difficulties in suitably evaluating the models with respect to a given application. An important asset of CCMMs is the possibility to account for interactions between chemistry and meteorology, notably for the feedbacks of aerosol direct and indirect radiative effects onto meteorology. CCMMs may therefore improve numerical weather prediction in particular under highly polluted conditions and may improve regional scale climate simulations in regions affected by high anthropogenic or natural aerosol loads. Such improvements have been demonstrated for single cases such as Saharan dust events but much more extensive evaluations are needed to clarify whether the models are adding sufficient benefit to be used widely for numerical weather prediction and regional climate modelling considering the large additional computational costs. Online coupled, fully integrated models are also expected to improve air quality simulations since atmospheric transport can be simulated more accurately and in a more consistent manner than in offline models. However, demonstrating these benefits through model evaluation is challenging since differences between simulated and observed air pollutant concentrations are often large and not only affected by the quality of transport but also by many other factors that makes it difficult to isolate one effect from the other. Here, we briefly review the different applications of CCMMs in the three main areas numerical weather prediction, air quality modelling and regional climate modelling, and outline the specific needs for evaluation and the associated challenges. We provide an overview of model evaluation studies conducted so far for individual models and of coordinated multi-model intercomparisons such as the Air Quality Model Evaluation International Initiative (AQMEII) phase 2. Finally, we identify the future needs in terms of model evaluation strategies and validation data sets required to make these models fit for their respective purpose.

EVALUATION OF SURFACE PM 2.5 IN THE NASA MERRA AEROSOL REANALYSIS OVER THE UNITED STATES

V. Buchard and A. da Silva

Abstract

MERRAero is the first aerosol reanalysis produced at NASA Global Modelling Assimilation Office (GMAO) using meteorological fields from the MERRA reanalysis. This reanalysis is based on a version of the GEOS-5 model radiatively coupled to Goddard Chemistry, Aerosol, Radiation, and Transport (GOCART) aerosols and includes assimilation of bias corrected Aerosol Optical Depth (AOD) from the MODIS sensor on both Terra and Aqua satellites. In this presentation, we use surface fine particulate matter (PM 2.5) measurements collected by the US Environmental Protection Agency (US EPA) and the IMPROVE networks in the United States as independent validation for MERRAero. Focusing on a 10 years period (from 2003-2012), we first, make an assessment of MERRAero AOD against independent ground-based retrievals from AERONET network. Over this period, MERRAero shows relatively good agreement with AERONET AOD at 550 nm. While we constrain the total column aerosol loading in MERRAero, the assimilation of AOD however, does not correct errors in either aerosol vertical placement or composition, implying that surface PM 2.5 is much harder to estimate. The model was able to better capture monthly mean measurements from IMPROVE network, composed essentially of rural stations. Comparisons with the EPA chemical speciation network provides much understanding of which species MERRAero predicts well and for which there is some discrepancy when compared with EPA.

AIR POLLUTION MODELLING STUDIES FOR METROPOLITAN AREA OF ISTANBUL

Pelin Cansu Cavus, Deniz Diren and Huseyin Toros

Abstract

Air pollution is the most important social and ecological problem all over the world. Various scientific studies have linked air pollution to a variety of health problems. Air pollution also damages environment. Sources of emissions are large stationary fuel combustion sources, industrial and other processes manufacturing facilities and mobile sources including highway vehicles. These situations show that air pollution is affected by industry and urbanization. Actually, big cities which have huge urbanization rate are imperilment regions. Istanbul is a big example these imperilment cities because of much urbanization and industrial power. Therefore, models help humanity spatial and temporal distribution of pollution in cities. This study aims to show that, the model’s results and prediction for metropolitans area of Istanbul. WRF and WRF/Chem models are used for air pollution and meteorological condition with some different parameters. The model results have also includes effects of coastal region and effects of urbanization. Final step is validation; using for sure that the model represents the real system to a sufficient level of accuracy. Real data is used for validation step and real data and models result compare which each other. The study will include compared results.
Acknowledgement: This work was supported by TUBITAK-111Y319 and COST Action ES1004. The authors are grateful to the Ministry of Environment and Urbanism of Turkey, Environment Department of Istanbul Greater Metropolitan and Turkish State Meteorological Service for meteorological and air pollution data.

IMPROVING AIR QUALITY (AND WEATHER) PREDICTIONS VIA APPLICATION OF NEW DATA ASSIMILATION TECHNIQUES APPLICABLE TO COUPLED MODELS

Gregory R. Carmichael and Pablo E. Saide

Abstract

Ambient aerosols are important air pollutants with direct impacts on human health and on the Earth's weather and climate systems through their interactions with radiation and clouds. Their role is dependent on their distributions of size, number, phase and composition, which vary significantly in space and time. There remain large uncertainties in simulated aerosol distributions due to uncertainties in emission estimates and in chemical and physical processes associated with their formation and removal. These uncertainties lead to large uncertainties in weather and air quality predictions and in estimates of health and climate change impacts. Despite these uncertainties and challenges regional-scale coupled chemistry-meteorological models such as WRF-Chem have significant capabilities in predicting aerosol distributions and explaining aerosol-weather interactions. In this talk we explore the hypothesis that new advances in on-line, coupled atmospheric chemistry/meteorological models, and new emission inversion and data assimilation techniques applicable to such coupled models, can be applied in innovative ways using current and evolving observation systems to predictions of aerosol distributions at regional scales.

IMPACT OF POLLUTANT EMISSION REDUCTIONS ON SUMMERTIME AEROSOL FEEDBACKS: A CASE STUDY OVER THE PO VALLEY

C. Carnevale, G. Finzi, A. Pederzoli, E. Turrini, M. Volta

Abstract

This study presents an evaluation of the impact by future pollutant anthropogenic emission reductions on summertime aerosol direct feedbacks. The fully coupled on line Wrf/Chem model has been used to examine the air quality and meteorology response over the Po valley region to 2020 emission reductions, with respect to a simulation base case (2013). Future changes in cloud (i.e. cloud fraction) and optical properties (albedo, short net radiation flux) are also analysed. The model domain is a 6x6 km2 resolution grid covering Northern Italy; the simulation period covers two summer months (July-August 2013). The work is divided into two parts. In the first, model results from the baseline simulation (1st July-31st August 2013) are evaluated by comparing Wrf/Chem output to observations provided by Regional and AERONET networks. Monthly maps of modelled AOD and cloud fraction are also compared to satellite retrievals from OMI. The comparison shows that the model is able to capture the temporal and spatial distribution of most variables; the correlation between modelled and observed data is the main source of error for all parameters. In the second part, a Maximum Feasible Reduction (MFR) scenario at 2020 have been simulated; direct aerosols feedbacks for both the baseline simulation and the MFR 2020 have been computed and analysed. In the 2013 baseline simulation, the net surface solar radiation decreases due to aerosol direct effects, except for some very localized areas over the Alps where the radiation flux increases. This warming is associated to the increased albedo over the same areas, which causes multiple reflections between these highly reflecting surfaces and the absorbing aerosol layers above. Changes in meteorological variables are also visible: the direct effect of aerosols reduces PBL height, 2-m temperature and wind speed. The perturbations in pollutant concentrations are mainly due to the changes in meteorology caused by the direct aerosol feedbacks. Maps of monthly O3, NO2 and SO2 show that the concentrations decrease in the areas with the highest PBL height and lowest wind speed. The emission reductions in the MFR 2020 lead to a sensible change in the aerosol direct feedbacks for all variables; the highest feedbacks reductions are visible over Lombardy (mainly over the Milan area) and the Veneto region.

AN OPERATIONAL SHORT-TERM FORECASTING SYSTEM FOR PLUME DISPERSION

Tomas Chor, Gilca Palma, Sandra Saad, Marcos de Morais, Luiz Gozzo

Abstract

We present an operational system designed to provide short-term concentration forecasts for pollutants being emitted by an industrial stack. The computation of the plume dispersion is done with CALPUFF, which is one of the preferred/recommended models by the United States Environmental Protection Agency (US-EPA). The meteorological boundary conditions needed by CALPUFF are provided by daily runs of the Weather Research and Forecast (WRF) model. Wind forecast is compared with ground level data in order to test its validity. The system outputs the average of the concentrations for each hour in the period and peaks of concentration. This approach could help industrial facilities avoid peak concentrations on its surroundings, diminish pollution-related complaints in cases where the facility is close to a populated area and also avoid high hazardous levels of pollutants within the factory itself. This can be done by the facility by reducing the level of emissions during hours in which the forecast output predicts above-acceptable concentration in sensitive areas. These concentrations depend on the emissions and on the synoptic conditions of the atmosphere.

THE NASA GODDARD EARTH OBSERVING CHEMISTRY-CLIMATE MODEL AND ITS APPLICATION TO AEROSOL-CHEMISTRY-CLIMATE INTERACTIONS

Peter Colarco, Valentina Aquila, Anne Douglass and Arlindo da Silva

Abstract

The NASA GEOSCCM is the Goddard Earth Observing System Chemistry-Climate Model. GEOSCCM is a global model integrated within the Goddard Earth Observing System (GEOS-5) core Earth system modelling framework, which includes components for atmospheric circulation, composition, and physics, oceanic circulation and biogeochemistry, land and ice processes, and data assimilation. GEOSCCM focuses especially on atmospheric chemistry and aerosols, and their interactions with other components of the Earth system. A hierarchy of complexities is implemented, including stratospheric-tropospheric and stratospheric-only chemistry mechanisms, and bulk, modal, and sectional aerosol microphysics schemes. Aerosol-chemistry, aerosol-chemistry-radiation, and aerosol-cloud interactions are active areas of investigation. GEOSCCM is used at a variety of temporal and spatial scales, from long-term, climate-scale integrations through high-spatial resolution global cloud permitting simulations used to drive observing system simulation experiments. In this presentation we highlight features of the GEOSCCM and the connections of our modelling efforts to NASA and other remote sensing data sets (e.g. OMI on Aura, OMPS-LP on Suomi-NPP). We present particular examples of the radiative feedback of dust aerosols on the climate system, and aerosol-chemistry-radiation interactions due to perturbations of the stratospheric aerosol layer (i) by volcanic eruptions or (ii) by proposed sulfate injection geo-engineering scenarios.

IMPACTS OF AEROSOLS AND CHANGING CLIMATE ON INDIAN SUMMER MONSOON AND EXTREME EVENTS

S.K. Dash, M.P. Singh and S.T. Rao

Abstract

Today, air pollution is a serious concern in several countries all over the world. In addition, the 2014 IPCC report has reiterated the need to address climate change on a global basis. It is also recognized that atmospheric composition can profoundly influence weather and climate directly by changing the atmospheric radiation budget or indirectly by affecting cloud formation and precipitation. Recent observational and modelling studies indicate that climate change can lead to devastating impacts on the Indian summer monsoon and extreme weather events. Modelling the coupled evolution of atmospheric dynamics, pollutant transport, chemical reactions and atmospheric composition will remain one of the most challenging tasks in environmental simulation modelling, climate change studies, weather forecasting, and air quality conditions over the next decades as they all involve strongly-integrated processes. To address the above mentioned challenges, a three-day workshop will be held during January 12-15, 2015 in Delhi, India bringing together scientists with wide experience in air quality, weather, and climate related issues from India, Europe, Japan, and North America to discuss the current status, identify research gaps, and prepare a research agenda to help improve our understanding of air quality and climate change interactions, and utilise the output from atmospheric models to effectively project the future characteristics of Indian summer monsoon circulation and rainfall. The workshop is focused on four theme areas, such as Aerosols and monsoon dynamics, Weather extremes in changing climate, Impact of air quality and climate change on human health and Geo-engineering of climate. On the first two days of the workshop, there will be invited talks from the experts in the field. On the third day, a series of panel discussions is proposed to be held to identify research issues. Following the workshop, a small team of scientists will meet for a day to prepare an action plan for implementing recommendations of the workshop. It is envisioned that lead scientists identified from different countries will coordinate this research effort. This paper presents a summary of the recommendations made by the workshop participants and actions being taken at the national/international levels.

A CASE STUDY FOR URBAN EFFECTS ON METEOROLOGICAL PARAMETERS BY ENVIRO-HIRLAM

Deniz Hazel Diren, Pelin Cansu Cavus and Huseyin Toros

Abstract

Urbanization is one of the most important issues of this century. By the population growth, city areas are getting larger. This situation causes some impacts on the environment. The reduction in air quality is the most popular one. Not only the air pollution but also the meteorological conditions that affected from urban air can damage the health, environment and social life. It can be said that, urban heat island issue has importance in this instance. Istanbul is a megacity where the millions of people live in. The impacts of metropolitan area on weather can be observed in Istanbul clearly. In this study, urban heat islands and meteorological parameters which affected by urbanization will be analysed with the Enviro-HIRLAM online integrated NWP-ACTM model. It is aimed to determine how the meteorological conditions are changed and show the urban heat islands occur. The results will be discussed.
Acknowledgements: This study is a background of the online integrated air quality and meteorology modelling project funding by the TUBITAK Project 111Y319 and COST Action ES1004.

EVOLUTION OF THE CHEMICAL COMPOSITION OF THE ATMOSPHERE OVER THE PAST THREE DECADES: COMPARISONS OF CHEMISTRY-CLIMATE MODEL SIMULATIONS WITH OBSERVATIONS

T. Doumbia, K. Sindelarova, C. Granier, S. Tilmes, H. Worden, L. Emmons, A. Hilboll, A. Richter and A. Colette

Abstract

Global chemistry-climate models have been used to simulate the evolution of the atmospheric composition over the past decades. These simulations have been performed using the Community Atmosphere Model version 4 included in the NCAR Community Earth System Model. We have analysed the long-term changes as well as the interannual variability of several atmospheric compounds with a focus on ozone, carbon monoxide and nitrogen dioxide. We have investigated the behaviour of these species by focusing on three regions, Europe, North America and Asia. In Europe and North America, surface emissions have decreased significantly since the 1980s, which have led to a decrease in the concentrations of several tropospheric compounds. On the contrary, emissions in Asia have dramatically increased, particularly during the past two decades, which has resulted in large increases in the atmospheric content of several species. We have used in-situ observations of O3, CO and NO2 from different monitoring networks to analyse the model results in different stations in the regions under consideration. We will also discuss the comparison of the model results with remote sensing observations from MOPITT, OMI, GOME, GOME-2 and SCIAMACHY instruments. The model simulations were performed in free-running and specified dynamic modes. The run with specified dynamic was forced by the Modern Era Retrospective Analysis for Research and Applications (MERRA) provided by the NASA Global Modelling and Assimilation Office. The free-run mode has three ensemble members with prescribed sea surface temperature and perturbed spin-up climate conditions. We will discuss comparison of tropospheric concentration of atmospheric compounds calculated by different model runs.

ATMOSPHERIC CHEMISTRY IN ECMWF'S INTEGRATED FORECASTING SYSTEM

J. Flemming, V. Huijnen, J. Arteta, O. Stein, Q. Errera, A. Inness, B. Monge-Sanz, R. Engelen and V.-H. Peuch

Abstract

ECMWF has extended in recent years its Integrated Forecasting System (C-IFS) with modules for atmospheric composition. The system is run in pre-operational mode to provide atmospheric composition forecast and analyses and will become the main global modelling system for the operational Copernicus Atmosphere Monitoring Service (CAMS). We will discuss in more detail the on-line integration of chemistry modules in C-IFS. C-IFS can apply multiple chemistry schemes for tropospheric and stratospheric chemistry. We will discuss example how the chemistry module interact with the NWP radiation, transport and land surface modelling as well as data assimilation.

AN AIR QUALITY FORECASTING SYSTEM BASED ON WRF-CHEM OVER CUBA: PRELIMINARY RESULTS

Mariam Fonseca Hernandez, Yandy Gonzalez Mayor, Adrian Hernandez Ferrer and Osvaldo Cuesta Santos

Abstract

This paper describes the implementation of the chemistry module of the Weather Research and Forecasting (WRF-Chem) model over Cuba, at the Institute of Meteorology of Cuba. Anthropogenic surface emissions database used as input for this model are mainly based on some public global international databases like EDGAR (Emission Database for Global Atmospheric Research), RETRO (REanalysis of the TROpospheric chemical composition over the past 40 years) and GEIA (Global Emissions Inventory Activity). Most of the data offered by these databases are based on monthly estimations. Some local point emissions are also used to complement and calibrate this set of data. Despite the low resolution of the area global emissions and the weak density of the local point emissions, it has been found that WRF-Chem simulates quite well the diurnal variation of the chemical species concentrations over the Cuban region.

THE EUMETCHEM MULTI-MODEL CASE STUDIES ON AEROSOL FEEDBACKS

Renate Forkel, Dominik Brunner, Alexander Baklanov, Heinke Schluenzen, Michael Gauss, Alessandra Balzarini, Roci Baro, Marcus Hirt, Pedro Jimenez-Guerrero, Oriol Jorba, George Kallos, Xin Kong, Ana Miranda, Christina Mitsakou

Abstract

The importance of different processes and feedbacks in online coupled chemistry-meteorology models for air quality simulations and weather prediction is investigated in COST Action ES1004 (EuMetChem). In order to analyse the aerosol direct and indirect effects and the response of different models to aerosol-meteorology interactions case studies for two episodes were performed with different models as a coordinated exercise of Working Groups 2 and 4 of EuMetChem. The participating models were COSMO-ART, COSMO-Muscat, EnviroHIRLAM, NMMB/BSC-CTM, RAMS/ICLAMS, WRF-CMAQ, and WRF-Chem with different chemistry and physics options. The two considered episodes are the Russian heat wave and wildfires episode in July/August 2010 and a period in October 2010 with enhanced cloud cover and rain and including an of Saharan dust transport to Europe. These episodes had been identified during the previous AQMEII phase2 exercise and were selected for the current exercise on behalf of their strong potential for direct and indirect aerosol effects on meteorology. However, multiple simulations which are needed to analyse the importance of aerosol radiative effects and different feedback processes were only available for WRF-Chem. Therefore, this additional exercise was initiated in order to investigate these processes in more detail and with a larger number of models. The chosen common setup for all participating models and a unified output strategy allow analysing the model output with respect to similarities and differences in the model response to the aerosol direct effect and aerosol cloud interactions. The paper gives an overview on the rationale of the simulation strategy and an outline of the selected episodes and some examples of aerosol meteorology interactions and their representation within different models.

EVALUATING THE IMPACT OF AEROSOLS ON NUMERICAL WEATHER PREDICTION

Saulo Freitas and participants

Abstract

The Working Group on Numerical Experimentation (WMO, http://www.wmo.int/pages/about/sec/rescrosscut/resdept_wgne.html) has organized an exercise to evaluate the impact of aerosols on NWP. This exercise will involve regional and global models currently used for weather forecast by the operational centres worldwide and aims at addressing the following questions: a) How important are aerosols for predicting the physical system (NWP, seasonal, climate) as distinct from predicting the aerosols themselves? b) How important is atmospheric model quality for air quality forecasting? c) What are the current capabilities of NWP models to simulate aerosol impacts on weather prediction? Toward this goal we have selected 3 strong or persistent events of aerosol pollution worldwide that could be fairly represented in current NWP models and that allowed for an evaluation of the aerosol impact on weather prediction. The selected events includes a strong dust storm that blew off the coast of Libya and over the Mediterranean, an extremely severe episode of air pollution in Beijing and surrounding areas, and an extreme case of biomass burning smoke in Brazil. The experimental design calls for simulations with and without explicitly accounting for aerosol feedbacks in the cloud and radiation parameterizations. In this presentation we will summarize the results of this study focusing on the evaluation of model performance in terms of its ability to faithfully simulate aerosol optical depth, and the assessment of the aerosol impact on the predictions of near surface wind, temperature, humidity, rainfall and the surface energy budget.

ENSEMBLE SUMMARY OF THE AQMEII PHASE 2 MODEL EVALUATION ACTIVITIES AND THE ROLE AND RELEVANCE OF INTERNATIONAL MODEL EVALUATION STUDIES

S. Galmarini, C. Hogrefe, R. Mathur and S.T. Rao

Abstract

The role of internationally coordinated model evaluation activities is presented to underline the relevance and advancements produced over the years by such collaborative activities in many fields from atmospheric dynamics to dispersion to atmospheric composition. The Air Quality Model Evaluation International Initiative is a good example of such activities. In its second phase AQMEII has addressed the evaluation of coupled air quality models and results of this phase will be presented. In its third phase it has promoted the improvement of regional scale air quality models and will tackle the evaluation of global versus regional scale air quality models. The advantages of the international collaboration will be emphasized but be will also discuss the drawbacks and aspects that require improvement in such collaborative activities.

AIR QUALITY MODELLING DURING STABLE ATMOSPHERIC CONDITIONS

Goran Gasparac, Amela Jericevic and Branko Grisogono

Abstract

During November 2011, persistent stable meteorological conditions lead to relatively high PM10 concentrations over Pannonian basin. The particular situation was characterized as an interruption by strong NE bora flow that initiated the re-suspension of crustal elements into the air. Using monitored air quality and meteorological data, backward air mass trajectories and the results of NWP WRF model, PM10 contributions were investigated at urban and rural stations in Croatia, Hungary and Serbia. Regional EMEP model was used for simulation of long range, trans-boundary transport of PM10 concentrations and the composition of particulate matter. Within the research with the NWP WRF model, various tests were made with implementation of the new, improved mixing length in MYJ PBL scheme. Modified mixing length was later implemented in the WRF Chem model and was tested together with original WRF Chem to evaluate the contribution of local anthropogenic sources. Using high-resolution complex atmospheric chemistry models it was possible to analyse the main processes contributing to the high PM concentration on regional and local scale and to compare the performance of modified and original model.

INFLUENCE OF SPRINGTIME BIOMASS BURNING IN SOUTH ASIA ON REGIONAL AIR QUALITY: A REGIONAL MODEL BASED STUDY

Sachin Ghude, Chinmay Jena, D.M. Chate and G. Bieg

Abstract

In this study, for the first time, the influence of springtime (MAM) biomass burning in South Asia on regional ozone (O3) distribution has been evaluated using a regional chemical transport model (WRF-Chem) and the Fire Inventory from NCAR (FINNv1). Model results are compared with satellite retrievals of tropospheric column amounts of carbon monoxide (CO) from MOPITT and nitrogen dioxide (NO2) from OMI. With daily varying emissions, the model captures reasonably well the satellite-derived temporal variations in CO and NO2 (index of agreement (R) for CO is 0.83 and for NO2 is 0.76), indicating the effectiveness of the model in estimating the overall fire impact on a regional scale. Simulated tropospheric NO2 concentration shows better agreement with the magnitude of observed NO2 when FINNv1 NOx emissions are reduced by a factor of 2.2 over the model domain. A clear increase in CO and NO2 levels over Burma (35-60%), Central India (15-30%), the Indo-Gangetic (15-25%) region and the Bay of Bengal (15-40%) are simulated with fire emissions. The model results are also used to quantify the net O3 production from fires. Calculated O3 productions are up to 4 ppb h-1 over inland and up to 0.1 ppb h-1 over marine regions respectively. Our model-based analysis yields average enhancement ratios O3/CO of 0.12 ppbv/ppbv and a total O3 production of about 3.5 Tg from South Asia during the spring season. The findings demonstrate that the springtime fire emissions in South Asia have a noticeable impact on regional air quality in this region.

AEROSOLS IN THE HARMONIE NWP MODEL - AEROSOL RADIATIVE EFFECTS AND FURTHER PERSPECTIVES

Emily Gleeson, Serguei Ivanov, Jan Masek, Kristian Pagh Nielsen, Laura Rontu and Velle Toll

Abstract

The HARMONIE mesoscale numerical weather prediction model is based on ALADIN nonhydrostatic dynamics and AROME or ALARO physical parametrizations. Presently, the direct radiative effect of climatological aerosols is considered in HARMONIE. New possibilities for the introduction of real-time, possibly three-dimensional, aerosol information into the NWP models are evolving based on coupling to atmospheric chemistry transport models and using aerosol data assimilation. The sensitivity of the shortwave and longwave radiation fluxes in HARMONIE to changes in aerosol concentration, vertical distributions and the definition of aerosol optical properties has been studied in order to understand the need and possibility of using enhanced aerosol data for operational weather forecasts. Studies on aerosol direct radiative effects performed within MUSC, the single-column framework of HARMONIE, will be described. A comparison of three different radiation schemes - IFS, HIRLAM and ALARO – has shown significant sensitivity of radiation fluxes to aerosol changes, but also differences between the results of the schemes. The development of a new aerosol radiative transfer parametrization scheme, applicable together with the HIRLAM radiation scheme in HARMONIE, will be reported.

SOURCES OF REACTIVE BROMINE IN POLAR REGIONS AND ITS IMPLICATIONS FOR OZONE IN THE TROPOSPHERE

Paul T. Griffiths, A. T. Archibald, N.L. Abraham, X. Yang and J.A. Pyle

Abstract

The aerosol loading over Antarctica shows a seasonal cycle, which has a maximum in winter at many coastal sites [Wagenbach et al. 1998], which is surprising given the fact that the nearest open water is often hundreds of km more distant in that season because of the extension of sea ice. More generally, studies over the last decade have generally concurred that a large proportion of sea salt aerosol in the atmosphere over the Antarctic continent and the surrounding sea ice zone, and in the Antarctic ice sheet, derives ultimately from the sea ice surface. In light of these facts, Yang et al. (2008) suggested snow could provide a source of (depleted) sea-salt aerosol if wicked from the surface of ice. They suggest that rapid depletion of bromide via acid displacement from the aerosol will constitute a source of photochemical Bry. Given the large sea ice extent in polar regions, this may constitute a significant source of gas phase bromine in the polar lower atmosphere. While bromine release from blowing snow is perhaps less likely to trigger sudden ODEs, it may make a contribution to regional scale processes affecting ozone levels. In this poster, we consider the production of bromine from sea-salt aerosol from a mixture of snow and sea ice during periods of strong wind. We present results from the recent reimplementation of Yang's blowing snow in the UK Met Office Unified Model. We present results from a combination of box models and the UM-UKCA to quantify the effect of bromine release in the boundary layer and its effect on ozone at the regional scale. This work is performed as part of the NERC-funded BLOWSEA project which in later stages will draw on new data from the recent Polarstern cruise by members of the British Antarctic Survey.

THE IGAC/SPARC CHEMISTRY-CLIMATE MODEL INITIATIVE

Michaela Hegglin

Abstract

Increasingly, the chemistry and dynamics of the stratosphere and troposphere are being studied and modelled as a single entity in global models. These chemistry-climate models (CCMs) are used to make predictions of air quality, the stratospheric ozone layer, and climate under different future emission scenarios, but also to study the complex interactions and feedbacks between chemistry and climate. In order to increase our confidence in these predictions, CCMI is coordinating and carrying out a comprehensive evaluation of the performance of the CCMs in a concerted international effort. In this activity, the CCMs dynamics, chemistry, and radiation are tested thoroughly using process-oriented validation diagnostics that are derived from observations. The testing of the dynamical performance of the models has already been a key component of CCMI's predecessor activity, SPARC CCMVal, and will be extended to include key aspects of tropospheric dynamics that are relevant to chemistry-climate interactions.

CLIMATE-CHEMISTRY INTERACTIONS IN AN EARTH SYSTEM MODEL (NORESM)

Øystein Hov, Michael Gauss, Dirk Jan Leo Olivié, Øyvind Seland, et al.

Abstract

The climate response of chemical trace gas and aerosol emissions calculated in a coupled atmosphere-ocean-biogeochemistry model will be described under various assumptions. The model is the Norwegian Earth System Model (NorESM), which includes a state-of-the-art aerosol-cloud scheme, gaseous chemistry with methane and ozone, and an isopycnic coordinate ocean component. It has contributed to the climate model diversity in the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) (2013/14).

TEMPORAL VARIATION OF PARTICULATE POLYCYCLIC AROMATIC HYDROCARBON CONCENTRATIONS IN NORTHEAST ASIA

Yayoi Inomata, Mizuo Kajino, Keiichi Sato, Jun-ichi Kurokawa, Hajime Akimoto Kazuichi Hayakawa, Toshimasa Ohara, Tsuyoshi Ohizumi, Ning Tangc and Hiromasa Ueda

Abstract

We investigated the temporal variation of particulate phase polycyclic aromatic hydrocarbon (PAHs) concentrations in Northeast Asia, using the aerosol chemical transport model, Regional Air Quality Model version 2 for Persistent Organic Pollutants (RAQM2-POP ver2). The emission inventory, Regional Emission Inventory in Asia for POPs version, REAS-POP ver2, was updated to investigate the recent temporal and spatial variation for the period from 2000 to 2008. China was the largest particulate phase PAHs emission country, which contributes to more than 95% of total emission in the northeast Asia. The emission of PAHs was rapidly increased with clear seasonal variation, low in summer and high in winter in China. The areas of highest emissions were in China, especially in eastern China, Chongqing, Sichuan province. The increased emission was significant in eastern China. Annual emissions of 9PAHs were increased to 1.4 times during the period from 2000 to 2008. Emission in winter season (December) was 1.3-1.5 times higher than those in summer season (July). By using RAQM/REAS-POPs ver2, we investigated the temporal variation of particulate phase PAH concentrations at Noto site, Japan. This site is located to the coastal site of Sea of Japan and effective to investigate the transboundary transport of particulate phase PAHs in northeast Asia. At the Noto site, particulate phase PAH concentrations are clear seasonal variation with high in autumn-spring and low in summer from September 2004 to March 2010. The highest concentration was observed in March 2008 during this period.

COUPLING WIND AND SOLAR ENERGY SYSTEMS WITH FEEDBACK TO AN AIR POLLUTION, WEATHER, CLIMATE, AND OCEAN MODEL, GATOR-GCMOM

Mark Z. Jacobson

Abstract

Summary of Saturation Wind Potential

Global simulations were run accounting for kinetic energy extraction by wind turbines to examine the maximum wind potential over land and worldwide. As the number of wind turbines increases over large geographic regions, power extraction first increases linearly then converges to a saturation wind power potential. Thus, there is no fundamental barrier to obtaining half (5.75TW) or many times more of world's all-purpose 2030 power demand from wind. In terms of surface air temperature, wind turbines slow surface winds, reducing evaporation, warming the ground at first but reducing latent heat release, cooling the air. Thus, those two impacts cancel. However, the reduction in water vapor, a greenhouse gas, cools the air and ground further, resulting in wind turbines causing a net cooling worldwide.
More information can be found at:
http://web.stanford.edu/group/efmh/jacobson/Articles/I/windfarms.html

Can Walls of Offshore Wind Turbines Dissipate Hurricanes?

Simulations of Hurricanes Katrina, Isaac, and Sandy were run with a 3-D global-regional nested model that accounted for energy extraction by wind turbines to examine impacts of arrays of offshore turbines on hurricane winds and storm surge. Results are discussed.
More information can be found at:
http://web.stanford.edu/group/efmh/jacobson/Articles/I/WindHurricane/WindHurric.html

CHANGES ON MONSOON PRECIPITATION OVER SOUTH ASIA DUE TO ANTHROPOGENIC AEROSOLS: A CASE STUDY USING WRF-CHEM MODEL

Chinmay Jena, Sachin D. Ghude and Rajesh Kumar

Abstract

Aerosols from local anthropogenic emissions play a very important role in the surface temperature, radiation, and monsoon circulations. Anthropogenic aerosols are found to affect the precipitation in South Asia through direct and indirect aerosol radiative forcing. In this study, we have used the regional Weather Research and Forecasting model coupled with chemistry (WRF-Chem v3.6.1), to understand the changes in the Indian summer monsoon precipitation by the anthropogenic aerosols. The simulations were carried out for a period from March to September 2010. The study uses the WRF-Chem. model covering the domain of south Asia at 30 km x 30 km horizontal resolution. The model uses HTAP version 2 anthropogenic emissions, MOZART-4 gas phase chemistry linked to the MOSAIC aerosol scheme. The model results show a decreasing precipitation in the local anthropogenic emissions source region while slightly increasing precipitation outside of the emission source regions. The increase in precipitation corresponds to a decrease in the cloud base level or lifting condensation level. The changes can be associated with both radiative and microphysics interaction with the meteorology. Analysis of vertical cloud properties suggests that the increased cloud droplet number and prolonged cloud lifetime/reduced precipitation efficiency due to the local aerosol emissions are responsible for the precipitation reduction over South Asia.

NUMERICAL TREATMENT OF THE TRANSPORT PROBLEM IN ON-COUPLED ATMOSPHERIC MODELS

Eigil Kaas

Abstract

On-line chemical-dynamical coupling of atmospheric models require introduction of many more prognostic variables, sometimes several hundred, representing the concentrations of the individual chemical species and aerosols characteristics. This poses a number of severe challenges regarding numerical methodologies for solving the transport problem in an accurate and consistent manner, which is, at the same time, efficient on modern HPC systems. Recently several attempts have been made to meet these challenges. This presentation will first briefly review relevant properties of transport schemes in atmospheric chemical transport models such as mass-conservation, monotonicity/positive definiteness, consistency, computational efficiency, realistic mixing diagnostics etc. The presentation will then discuss how the desired properties are met in the main on-line coupled models applied in Europe: C-IFS, COSMO-ART/ICOS-ART, Enviro-HIRLAM/HARMONIE, SILAM, The Unified Model, and WRF-Chem. These models and the numerical treatment within them are quite different, and the presentation aims at categorizing strengths and weaknesses of each model/scheme. The general conclusion is that there are still challenges ahead of us regarding numerical treatment of the transport problem in on-line couple models.

LINKS AND FEEDBACKS BETWEEN AEROSOL, RADIATION, CLOUD AND PRECIPITATION IN THE RAMS/ICLAMS MODELLING SYSTEM

G. Kallos, J. Kushta, C. Spyrou, C. Kalogeri, N. Bartsotas and N. Barranger

Abstract

Airborne particles of anthropogenic and/or natural origin have certain direct and indirect effects in the atmosphere. Aerosols interact strongly with solar and terrestrial radiation in several ways. By absorbing and scattering the solar radiation aerosols reduce the amount of energy reaching the surface. Aerosols enhance the greenhouse effect by absorbing and emitting outgoing long wave radiation. Forcing by dust and other natural aerosols exhibits large spatial and temporal variability. This is due to their lifetime and diverse optical properties. In this presentation we discuss the complex direct, semi-direct and indirect links and feedbacks between natural aerosols, radiation budget and the meteorological and chemical state of the atmosphere. The results of a fully coupled atmospheric modelling system (RAMS/ICLAMS) are discussed. The capabilities of this modelling system include the online coupling between chemical and meteorological processes, as well as the explicit treatment of cloud condensation, giant and ice nuclei (CCN, GCCN, IN), and size and humidity dependent optical properties for aerosols. The results from this work show that the presence of mineral dust leads to a linear reduction in solar radiation and nonlinear increase in net downward longwave radiation that is larger during daytime than night time. The magnitude of change in the radiation budget is determined by the vertical structure of the dust cloud and mainly its height. The perturbations in the radiation budget affect the air temperature and moisture vertical profile, leading to a cloud base lifting and redistribution of condensates. The explicit activation of aerosols as CCN and IN causes changes in the spatiotemporal patterns of the precipitation field during and after the event. These influences are caused more by the indirect rather than the direct and semi-direct effects. The changes in the diffuse and direct components of the radiation budget lead to a net negative effect on the photolysis rates that, in turn, alter the pollutants distribution. Ozone concentration, in particular, is affected by dust in a non-monotonous way determined by the availability of ozone precursors.

EVALUATION OF MACCII NEAR SURFACE OZONE REANALYSIS OVER EUROPE

E. Katragkou, P. Zanis, A. Tsikerdekis, J. Kapsomenakis, D. Melas, H. Eskes, J. Flemming, V. Huijnen, A. Inness, M.G. Schultz, O. Stein and C. Zerefos

Abstract

This work is an extended evaluation of near surface ozone reanalysis for the period 2003-2013 produced within the European Funded project MACC-II (Monitoring Atmospheric Composition and Climate). Measurements at rural locations from the European Monitoring and Evaluation Program (EMEP) and the European Air Quality Database (AirBase) were used for the evaluation assessment. Overall, the modelled near surface ozone shows negative bias in winter over northern Europe and positive bias during warm months. With respect to the seasonal cycle, MACC reanalysis reproduces fairly well the photochemically driven broad spring-summer maximum of surface ozone of the sub-regions at central and south Europe, however it does not capture adequately the early spring peak in most of the subregions of the European domain. The diurnal range of surface ozone, which is as an indication of the local photochemical production processes, is reproduced fairly well in the MACC reanalysis, with a tendency for a small overestimation during the warm months for the subregions of central and south Europe. The impact of assimilation and the bias correction of the Microwave Limb Sounder (MLS) data used for assimilation until 2007 are also discussed.

TOWARDS IMPROVING PARAMETERIZATIONS OF MIXED STRATUS CLOUD/FOG FORMATION IN CLIMATE MODELS AND NWP

V. Khotiaintsev, R. Bardakov and S. Krakovska

Abstract

Many recent studies have shown that formation of low stratus clouds (fogs) cannot be properly presented and predicted by current forecasting and climate models. At the same time with expanding urban areas and sources of anthropogenic aerosols cases with dense and dangerous low clouds or fogs could increase too. It could became a real hazard at negative temperatures since leads to formation of hoar including icing of transportation facilities particularly aviation and electrical power lines. Presented research is devoted to study of microphysical processes in homogeneous cloud/fog from IN activation up to its complete glaciation. Simplified model includes water vapour, uniform overcooling and hang in the air water droplets, uniform rounded growing by deposition and gravity collection ice crystals formed on activated IN at fixed in initial time supersaturation and temperature. RH, number and sizes of water droplets and sizes of ice crystals are changed due to condensation/evaporation and gravity collection. Such simplification of cloud description allows analysing microphysical processes in mixed cloud/fog analytically with conclusions confirmed and illustrated by numerical experiments. It was found that ice crystals growth can be presented by the one differential equation of the first order (instead of four) with the one parameter as combination of some dimensional values. This parameter regulates transition from dominated depositional growth of ice crystals to the growth by gravity collection. In a whole expectedly ice crystals grew up to maximum sizes with complete evaporation or sweeping of water droplets. Characteristic times of ice crystals' growth by different processes and their sizes in dependence of the found transitional parameter are estimated numerically. We expect that proposed transitional parameter could be included in bulk parameterizations of NWP and climate models for better representation of cloud ice evolution.

QUASI-OPERATIONAL USE OF THE COSMO-RU7-ART CHEMICAL-TRANSPORT MODEL AT THE HYDROMETCENTER OF RUSSIA

Alexander Kirsanov, Gdaly Rivin, Anastasia Revokatova, Galina Surkova, Alexander Kislov, Irina Kuznetsova and Irina Shalygina

Abstract

COSMO-ART is a fully on-line coupled regional model system consisted of the non-hydrostatic model COSMO (Consortium for Small Scale Modelling) combined with the chemical model ART (Aerosols and Reactive Traces Gases). COSMO-ART simultaneously calculates the meteorological variables and chemical transformations at each time step, which makes possible to utilize all meteorological fields in the chemical-transport model and to consider feedbacks of air pollution on meteorological processes. At the Hydrometcenter of Russia since April 2011, OSMO-Ru7 mesoscale weather forecast system has been in operational practice. Since December 2011, COSMO-Ru7-ART model system issues quasi-operational daily air quality forecast on 48 hours. Visualisation and representation of the forecast data is done in user-preferred format. Evaluation of these forecasts has been done using the observation data received from the SEMSMC (State Ecological Monitoring System of Moscow-City). The results were obtained on improving short-term forecast of carbon monoxide concentration over the Moscow region and on representing forest fires impact on the pollutants concentration.

BIRCH POLLEN MODELLING FOR DENMARK: SPRING 2006 EPISODE

A.R. Kurganskiy, A.G. Mahura, R.B. Nuterman, A.A. Baklanov, A. Rasmussen, E. Kaas and S.P. Smyshlyaev

Abstract

Modelling of birch pollen temporal and spatial evolution in the atmosphere has very high interest in recent years. Birch pollen is biological aerosol that can cause allergic reactions among people suffered from respiratory diseases such as rhinitis. Among European countries, in Denmark the number of allergic patients has been increased twice over the past few decades. This fact shows importance of operational birch pollen forecasting for Danish population especially during spring season. The pollen emission is strongly meteorology dependent, so it is essential to simulate and forecast pollen pollution episodes by online-coupled meteorology-air pollution models. The Enviro-HIRLAM (Environment - High Resolution Limited Area Model) online-coupled meteorology-chemistry model was employed to simulate birch pollen emissions, atmospheric transport, dispersion and deposition for European domain with focus on Denmark. For Denmark the spring of 2006 was characterized by abundant birch pollen concentrations and long-range transport episodes. In order to assess pollen sources the birch forest map has been derived using 3 databases: Global Land Cover, European Forest Institute and Tree Species Inventory. The derived map has 15 km resolution over European domain and represented by fraction of birch trees in a forest in each grid cell. The simulated concentration fields were compared with observations at 2 Danish measurement sites: Copenhagen and Viborg. The evaluation procedure showed good consistency of modelling results with observations for both Danish measurement stations.

DETERMINATION OF PATHWAYS IN CHEMICAL REACTION SYSTEMS: AN ALGORITHM AND APPLICATIONS TO ATMOSPHERIC CHEMISTRY

Ralph Lehmann

Abstract

Numerical models of increasing complexity have been created in order to simulate chemical processes. The growing number of chemical species and reactions included in such models provides the opportunity of a better approximation of reality. However, at the same time, it becomes more difficult to understand the complicated interplay of the processes involved. This motivates the development of automated analysis tools. A typical question is: How, i.e. by which reaction sequences, is a certain species of interest produced (or destroyed)? An algorithm for the automatic determination of such reaction sequences (pathways) will be presented. Under the assumption that a chemical reaction system is given and reaction rates are known (from a chemical model run), the algorithm constructs all significant pathways and calculates a rate for each of them. Up to now the algorithm has been applied to analyse the chemistry in the stratosphere (ozone formation and destruction, methane oxidation), the mesosphere (ion chemistry), the atmosphere of Mars (CO2 formation), and the atmospheres of potential extra-solar planets.

EVALUATION OF TROPOSPHERIC CHEMISTRY IN THE AUSTRALIAN ACCESS-UKCA CLIMATE MODEL

A.K. Luhar, M. T. Woodhouse, M. Thatcher, P. F. Uhe, J. Noonan

Abstract

The Australian Community Climate Earth-System Simulator (ACCESS, see http://www.accessimulator.org.au, Bi et al., 2013) forms the basis for the current and future Australian contributions to CMIP and IPCC activities. It is coupled to a detailed interactive chemistry and aerosol scheme based on the UKCA model (http://www.ukca.ac.uk) for computing the radiative feedbacks of ozone and methane within the coupled climate system. Other components of ACCESS include a land surface model and an ocean model. An evaluation of ACCESS-UKCA tropospheric chemistry is presented here, with sea-surface temperatures prescribed. The model includes an explicit isoprene chemistry mechanism, and describes essential background inorganic chemistry involving Ox, NOx, HOx, CO cycles, together with near-explicit degradation of methane, ethane and propane. CO2, H2, N2, O2, and CH4 are used as global constants. The model simulations are conducted at 1.875 degrees x 1.25 degrees resolution, with 85 vertical levels extending to 85 km in height. Annually-varying anthropogenic emissions are derived from the ACCMIP database, and natural emissions are based on previous studies. Aircraft NOx emissions and interactive lightening NOx emissions are also included. We run ACCESS-UKCA in both free-running and nudged modes, making use of ECMWF's ERA-Interim reanalyses. Nudged simulations allow meaningful comparisons against specific observations at a point in space and time, while free-running simulations allow evaluation of the performance of the model from a climatological perspective. Comparisons are made against both in-situ and satellite observations of chemical species, particularly for O3, CO and CH4, in order to test the performance of ACCESS-UKCA. The evaluation results are discussed, and potential reasons for disagreement are elucidated. Future work will see UKCA used within the fully-coupled atmosphere-ocean configurations for chemistry-climate process studies and long-term climate simulations.

Reference:

Bi, D., Dix, and co-authors (2013), The ACCESS Coupled Model: Description, Control Climate and Evaluation. Australian Meteorological and Oceanographic Journal, 63, 41-64.

SCIENCE-EDUCATION: ONLINE INTEGRATED MODELLING OF AEROSOL-CHEMISTRY-METEOROLOGY EFFECTS USING ENVIRO-HIRLAM

Alexander Mahura, Roman Nuterman and Julia Palamarchuk

Abstract

For advanced level research and development of complex and modern modelling systems, a specific approach is required to attract more perspective well-motivated young scientists. It should allow within a short period of time to evaluate student's background level, research skills, capabilities, etc. To learn more about new potential science-oriented developers, it is often not enough just to read individual CV. Thus, a special event such as Young Scientist Summer School (YSSS) can be organized, where young researchers could have opportunity to attend lectures and participate in practical exercises showing their personal skills in doing research. For that, practical exercises are developed as independent small-scale research projects. Developed approach was realized in 2008, 2011 and 2014 YSSS schools organized in Zelenogorsk, RU (by NetFAM et al; http://netfam.fmi.fi/YSSS08), Odessa, UA (MUSCATEN et al; http://www.ysss.osenu.org.ua), and Aveiro, PT (COST Action EuMetChem et al; http://aveirosummerschool2014.web.ua.pt). The main focus of these YSSSs was on online integrated modelling of meteorological and chemical transport processes for weather, air quality, and climate applications. During YSSS-2014 two research projects - "URBAN: Influence of Metropolitan Areas on Meteorology (& Chemistry)" and "AEROSOL: Impact of Aerosols on Meteorology" - were focused on evaluation of urban/aerosol effects on formation and development of meteorological and chemical fields over selected urban areas and Europe. The Environment - HIgh Resolution Limited Area Model (Enviro-HIRLAM) was applied with/without changes for urban areas and chemical species/aerosols effects. Main items of small-scale research projects include: Introduction with background discussions; Analysis of meteorological situations; Learning practical technical aspects; Performing model simulations; Visualization of results; Evaluation of possible impact on temporal-spatial variability of simulated meteorological and chemical fields; Team presentation on results and findings. Outline and detailed description of developed approach, key project items, schedules, preparatory steps, requirements for successful completion and project defense, team independent work and under supervision are presented and discussed.

ENVIRO-HIRLAM MODELLING OF REGIONAL AND URBAN METEOROLOGY AND CHEMISTRY PATTERNS FOR SUMMER 2009 PARIS CAMPAIGN

Alexander Mahura, Roman Nuterman, Iratxe Gonzalez-Aparicio and Alexander Baklanov

Abstract

The evaluation of regional and urban meteorological and chemical patterns due to influence of the Paris metropolitan area was performed employing an urbanized version of the Enviro-HIRLAM (Environment - HIgh Resolution Limited Area Model). It is a fully online-coupled Atmospheric Chemistry Transport - Numerical Weather Prediction (ACT-NWP) modelling system developed for regional-, meso- and urban scale different environmental applications. The studied period covers July 2009 when the FP7 EU MEGAPOLI Paris Campaign took place within the Paris metropolitan area and surroundings. Model setup included selection of boundaries for nested modelling domains and projection, horizontal and vertical resolutions, chemical and meteorological initial and boundary conditions, different types of emissions (anthropogenic for gases and aerosols from sources - for EU domain - TNO-MACC for year 2009, biogenic (IS4FIRES by FMI), natural - including interactive sea-salt and mineral dust emission modules), chemical and aerosol modules. The model is urbanized based on the Building Effects Parameterization module which describes different types of urban districts such as industrial commercial, city centre, high density and residential with its own characteristics. Boundary and initial conditions for the downscaling runs are taken from ECMWF and further from the inner domains of nested model runs (with 15, 5, and 2 km horizontal resolutions). The Paris megacity effects on formation and development of meteorological fields (for air temperature, wind speed, relative humidity, total cloud cover, boundary layer height, surface temperature) are evaluated on a diurnal cycle. Enviro-HIRLAM simultaneously with meteorological parameters simulated atmospheric transport, dispersion, deposition, and transformations of chemical species. The effects of urbanization on variability of spatio-temporal concentration patterns of selected chemical species were also studied for the Paris metropolitan area and surroundings. Results of comparative analysis based on different Enviro-HIRLAM model runs: reference/control vs. modified/urbanized are presented.

COUPLED CHEMISTRY-METEOROLOGY: SIMULATIONS AT 2.5 KM RESOLUTION

P.A. Makar, W. Gong, C. Stroud, M. Moran, S. Gravel, A. Akingunola, J. Zhang, S.M. Li, K. Hayden, R. Staebler, J. Liggio and J. Brook

Abstract

As part of phase 2 of the Air-Quality Model Evaluation International Initiative (AQMEII-2), a 15 km resolution, 12-aerosol size bin, direct + indirect aerosol/weather feedback version of Environment Canada's Global Environmental Multiscale Modelling Air-quality and CHemistry (GEM-MACH) model was implemented. Following this work in which several models were compared for feedback and no-feedback simulations, the GEM-MACH model was reconfigured to run on a nested domain with a highest resolution nest of 2.5 km, for a domain covering the Canadian provinces of Alberta and Saskatchewan. The higher resolution had the advantage of avoiding the need for a convective parameterization; the model's microphysics was used to simulate cloud formation in feedback and no-feedback modes, without the need for convective parameterizations. This in turn would be expected to result in a stronger signal from feedbacks, in contrast to the previous lower resolution simulations. Here, the model results in feedback and no-feedback modes will be compared, both to each other, and to ground network and aircraft observations of PM2.5 and atmospheric gases for a one-month period. The comparisons will show the effects of feedbacks on mesoscale high-resolution forecast accuracy.

SIMULATING THE CONTAMINANTS DISPERSION IN A SHEAR-DOMINATED STABLE BOUNDARY LAYER

Silvana Maldaner, Viliam Cardoso, Gervasio Annes Degrazia and Daniele M. Aimi

Abstract

In this study, the performance of a Lagrangian Stochastic particle model to simulate the pollutants dispersion in a shear-dominated stable boundary layer is presented. Therefore, atmospheric dispersion data, lagrangian time scales and velocity variances, for a shear-dominated stable boundary layer, are employed to simulate the Hanford observed contaminants concentrations data. The parameterizations that were used are based on the local similarity and Taylor's statistical diffusion theory. The simulation results show that the lagrangian model can reproduce satisfactorily the contaminant dispersion data in a shear-dominated stable boundary layer.

MODELLING THE RADIATIVE IMPACTS OF AEROSOLS: OFF-LINE VERSUS ON-LINE APPROACH

Astrid Manders, Bas Henzing, Arjo Segers, Antoon Visschedijk, Erik van Meijgaard and Martijn Schaap

Abstract

Aerosols play an important role in the radiative balance of the atmosphere. They scatter or absorb radiation, depending on the aerosol composition, and determine cloud properties including albedo and lifetime. In addition, aerosols have an impact on human health and ecosystems; their concentrations at ground level are subject to legislation. The regional chemistry-transport model (CTM) LOTOS-EUROS has a long tradition in performing emission scenario simulations for air quality and air quality forecasts. It can be used to assess the impact of emission scenarios on radiation in two ways: firstly by calculating the optical properties of the modelled aerosol and using a radiation module (RRTM_sw) to determine the radiative impact,without feedback to the meteorology, and secondly by using the semi-online coupled model RACMO2 (regional climate)-LOTOS-EUROS, including feedbacks . The advantage of the first approach is that the same meteorology can be re-used and that the CTM can run stand-alone, the advantage of the second approach is that a more complete and consistent analysis can be made, including temperature and cloud properties. Results from both approaches are compared for a case study on the impact of emission reductions from 1990 to 2005.

HOW WELL CAN COUPLED MODELS SIMULATE MULTI-DECADAL TRENDS IN TROPOSPHERIC AEROSOL BURDEN AND ITS RADIATIVE EFFECTS ACROSS THE NORTHERN HEMISPHERE?

Rohit Mathur, Jia Xing, Jonathan Pleim, David Wong, Christian Hogrefe, Chuen-Meei Gan and Chao Wei

Abstract

Though aerosol radiative effects have been recognized as some of the largest sources of uncertainty among the forcers of climate change, the verification of the spatial and temporal variability of the magnitude and directionality of aerosol radiative forcing has remained challenging. Significant and contrasting changes in tropospheric aerosol burden have occurred over the past two decades as a result of changing patterns of emissions of primary aerosol and gaseous precursors. During this period, SO2 and NOx emissions across the US have reduced by about 66% & 50%, respectively. In contrast, anthropogenic emissions have increased dramatically across Asia. These changes provide an opportunity for conducting a systematic investigation of the processes regulating aerosol distributions, their optical properties, and verification of their simulated radiative effects for past conditions relative to measurements. We conduct multi-decadal simulations for the 1990-2010 period with the two-way coupled WRF-CMAQ modelling system over a domain covering the northern hemisphere and a nested finer resolution continental U.S. domain. Simulated aerosol size and composition and size are used to estimate their optical properties which are then used in the radiation calculations impacting both photolysis rates and atmospheric dynamics. Model results (aerosol burden and composition, radiation, temperature) over North America, Europe, and Asia are analysed in conjunction surface, aloft and remote sensing measurements to contrast the differing trends in aerosol-radiation interactions in these regions over the past two decades. Both model and measurements indicate significant reductions in tropospheric aerosol burden across North America and an associated increase in shortwave radiation at the surface. In contrast, an increase in tropospheric aerosol burden and reduction in surface shortwave radiation in noted across large portions of Asia during the past two decades. Simulated trends in aerosol composition, tropospheric burden, and radiative effects are compared with those inferred from available measurements. Model simulations with and without aerosol radiative effects are analysed to assess the impacts of these interactions on severity of air pollution episodes.

USING REGIONAL ONLINE COUPLED MODEL RESULTS FOR ESTIMATING CONCENTRATION INCREMENTS IN URBAN AREAS BY MEANS OF A STATISTICAL APPROACH

N. Moussiopoulos, J. Douros, E. Chourdakis, S. T. Ortiz, Rahela Zabkar, Marcus Hirtl and Renate Forkel

Abstract

The simple methodology presented in this study is implemented in the form of a computational tool that allows for the efficient assessment of the urban increment of PM10 and NO2 caused by traffic, as well as other local sources, such as space heating (domestic and commercial), industrial activities, etc. and aims at the determination of an urban concentration increment on top of the regional scale background, for urban areas in the entire European region. This approach builds on earlier attempts to provide estimates of the urban increment for various pollutants, by improving key aspects concerning the treatment of the meteorological parameters. The method operates by establishing a functional relationship between the concentration increment and the local meteorological conditions, the city characteristics, the urban emissions and regional background concentrations. In the frame of the current application, regional background concentrations originated from the WRF-Chem online coupled model, taking into account only the direct aerosol effect. In order to describe the development of the atmospheric boundary layer the method utilizes estimates for the atmospheric boundary layer height that were also produced by WRF-Chem. The results demonstrate the capability of this simple approach to assess the urban increment with satisfactory accuracy, thus providing a tool for fast but still reliable quantitative assessments of urban air quality that can subsequently be used in calculations of exposure and health impact assessment. Additionally, scenario calculations for the urban increments are possible, based on scenario emissions and respective modelled regional background concentrations, a feature that can take advantage of the improved estimates of online coupled models and which will be particularly useful for urban air quality assessment.

AEROSOL MODELLING IN A REGIONAL CLIMATE MODELS: PROGNOSTIC SCHEME OR MONTHLY CLIMATOLOGIES, WHICH CONSEQUENCES ON REGIONAL CLIMATE?

P. Nabat, S. Somot, M. Mallet, M. Michou and D. Saint-Martin

Abstract

Aerosols interact with shortwave and longwave radiation with ensuing consequences on radiative budget and regional climate. At least two different possibilities exist to include aerosols in a regional climate model (RCM). On the one hand, many RCMs use monthly aerosol optical depth (AOD) climatologies, thus representing the main patterns of the spatial and temporal aerosol variability at the monthly and interannual scales. On the other hand, some RCMs are now able to include a prognostic aerosol scheme, which enables to represent aerosol variations at high frequency. In the present work, we use the ALADIN-Climate RCM to evaluate the impact on regional climate of using a prognostic aerosol scheme instead of monthly AOD climatologies. For this purpose, two simulations have been carried out for the 1979-2013 period over the Mediterranean region, which is subject to high and frequent aerosol loads, the first one with a prognostic aerosol scheme including the five main aerosol species (desert dust, sea-salt, sulfate, black carbon and organic matter), and the second one with monthly AOD fields averaged from the first simulation. The results show differences both on mean regional climate and on daily climate variability, notably in terms of surface radiation and temperature. These differences could be due to a correlation between high aerosol loads and cloud cover, or more generally between aerosols and synoptic conditions. For example, dust outbreaks over the Mediterranean region are generally associated to southwesterly winds, bringing also high cloud cover, thus reducing the aerosol dimming. As a consequence, this work highlights the importance of the choice of the aerosol modelling in a RCM.

MODELLING OF COLD CLOUD FORMATION DUE TO ATMOSPHERIC DUST

S. Nickovic, S. Petkovic, G. Pejanovic and Fabio Madonna

Abstract

Formation of cold clouds is enhanced upon the availability of ice nuclei (IN) to begin condensation of atmospheric water vapour. Cold clouds contribute at global scale with 60% in average in precipitation and their presence significantly affects the atmospheric radiation properties. It is expected that better description of the IN process should substantially improve cloud parameterization in climate and numerical weather prediction models. Recent observations demonstrate that mineral dust is the dominant source of residual particles found in cloud ice. In this project we employ the regional dust DREAM model based on horizontal resolution at least order of magnitude higher than global models, to study IN caused by mineral dust. DREAM has been already deployed in a study related to IN process (Klein et al, 2010), also in model experiments using several IN parameterization schemes in support of the IN field experiment CALIMA over Canaries. The model has been recently extended by adding the major dust mineral fractions as tracers in order to facilitate studies related to dust mineralogy impacts to weather and climate including IN. In this study, we will present IN concentration parameterized using the DREAM-simulated dust concentration, water moisture and temperature. We will show preliminary results of simulated IN, validated against lidar dust profiles and cloud radar data on ice cloud water observed in the Potenza EARLINET site. This study is an initial step in improving a cloud physics parameterization using IN as an input variable parameter in an integrated dust-atmospheric modelling system.

IMPROVEMENT OF ENVIRO-HIRLAM WEATHER FORECASTING THROUGH INCLUSION OF CLOUD-AEROSOL INTERACTIONS

R.B. Nuterman, U.S. Korsholm, K.P. Nielsen, B.H. Sass, A.A. Baklanov and E. Kaas

Abstract

During the summer of 2010, there were a number of severe weather events, such as floods, heat waves and droughts across Middle East, most of Europe and European Russia. In particular, heat waves followed by wildfires in Europe and Russia led to substantial increase of atmospheric aerosols concentration. In order to study aerosols indirect effects on meteorology, the online-coupled air quality and meteorology model Enviro-HIRLAM (Environment - HIgh Resolution Limited Area Model) has been employed. The model includes aerosol microphysics HAM-M7 scheme, tropospheric sulphur cycle chemistry, wet scavenging and dry-deposition schemes, aerosol activation scheme and cloud processing with respect to precipitation and radiation. Several emission inventories have been used, i.e. anthropogenic (by TNO) and wildfires (by FMI, http://is4fires.fmi.fi) as well as interactive sea-salt, dust and DMS emissions. The Enviro-HIRLAM modelling domain with horizontal resolution of 0.15o x 0.15o and 40 vertical hybrid levels covers Europe, North of Sahara, and Central Russia. Boundary and initial conditions for meteorological fields and atmospheric tracers have been produced by ECMWF IFS and MOZART models, respectively. The model runs have been performed for July and August of 2010. The model shows good correlation of particulate matter (PM) concentrations on diurnal cycle as well as day-to-day variability, but one always has negative bias of PM. The Enviro-HIRLAM is able to capture concentration peaks both from short-term and long-term trans boundary transport of PM. The cloud-aerosol interaction processes led to increase (with local maxima up to 90%) of total cloud cover except several inland areas, where cloud cover decreased by almost 10 fold. The similar patterns were observed for cloud water content at average cloud base for the entire modelling domain. The reference Enviro-HIRLAM model (without cloud-aerosol interactions) tends to overpredict both frequency and amount of stratiform and convective precipitation but inclusion of cloud-aerosol interactions generally improves the model performance.

DIRECT RADIATIVE EFFECT OF MINERAL DUST ON METEOROLOGY FOR DUST OUTBREAK EVENTS OVER THE MEDITERRANEAN IN SUMMER 2012

Vincenzo Obiso, Oriol Jorba, Sara Basart and Jose Maria Baldasano

Abstract

Aerosols interact with the atmospheric system scattering and absorbing solar radiation, with a significant impact on atmospheric energy and hydrologic processes. Radiative forcing associated with these perturbations affects climate and meteorology. In this contribution, we analyse model results of the Direct Radiative Effect (DRE) of mineral dust over the western-Mediterranean during summer 2012. For that, the NMMB/BSC Chemical Transport Model (NMMB/BSC-CTM) is applied on a regional domain. The NMMB/BSC-CTM is a new on-line chemical weather prediction system coupling atmospheric and chemistry processes. In the radiation parameterization, mineral dust is treated as a radiatively active substance interacting both on short and longwave radiation. The impact of the mineral dust outbreaks on meteorology is discussed by comparing model forecasts with atmospheric analysis and meteorological observations. The analysis focuses in the vertical structure of the atmosphere and the resulting surface meteorological conditions.

OVER-VIEW OF FARMERS PERCEPTION ON THE EFFECT OF CLIMATE CHANGE IN AGRICULTURAL PRODUCTION AT FEDERAL CAPITAL TERRITORY ABUJA, NIGERIA

Michael Adedotun Oke

Abstract

The implications of climate change have being reflected in the agricultural sectors, thus it affects livestock, crop production, post harvesting, transportation, storage systems and managerial strategies with the labouring, different communal crises and agricultural activities in the six area council of the Federal Capital Territory Abuja, Nigeria. The objectives of this project is to interview the practicing small holders farmers and commercial farmers and to gain insight, receive the necessary information about their perception on the effect of climate change on agricultural practices, to offer solutions and suggestions. Different farmers were visited to gain insight. Group discussions were made, different opinions were collected and analysed and pictures were taken to ascertain these studies. The findings show that climate change have effect on the prices of the agricultural produce, non availability of agricultural labouring, poor transportation of agricultural produce from the farm to the markets and it is noted in the destruction of crops and poor yields as a result of rapid drought during the dry seasons where the cattle farmers move with their cattle in search of greener pastures, which they destroy farm land and the various communal clashes. Suggestions were made to provide pastures for their cattle and adequate weather information dissemination, planting to improve agricultural varieties and provision of goods roads.

Keywords: climate, Gwagalada, farmers, change, agricultural production, Federal Capital Territory

AEROSOL EFFECTS ON THE PHYSICAL WEATHER IN THE HARMONIE MODEL

Iuliia Palamarchuk, Sergey Ivanov, Alexander Baklanov, Igor Ruban and Hanna Pavlova

Abstract

Modern numerical weather prediction (NWP) models are able to represent a wide spectrum of atmospheric processes and transformations in explicit manner. Chemical transport (CTM) models explore physical atmospheric fields as drivers for simulating numerous chemical reactions and conversions on temporal scales from seconds to years with appropriate accuracy. The high resolution limited area Harmonie model allows as well to consider feedbacks from chemical and aerosol effects to physical variables. To highlight the impact of aerosols on atmospheric conditions, sensitivity experiments were performed with modified concentrations in set of aerosol types (sea salt, soot, land aerosols, desert aerosols). The area of interests covered the Atlantic-Europe-Northern Africa region. The Harmonie runs were carried out on the model grid with horizontal resolution 25 x 25 km for the period 11-16 August 2010. Results showed that all simulated atmospheric variables are sensitive to the aerosol presence. This effect appears in a form of mesoscale cells irregularly distributed over the whole domain. Largest influence is revealed along high gradients frontal zones. Shortwave radiation fluxes are mainly increased at the top of the atmosphere, while decreasing in fluxes occurs near the surface. The aerosol impact on the air temperature and specific humidity fields is most prominent within the planetary boundary layer (PBL) with a maximum near its top. This fact partly may be addressed to higher aerosol concentrations within the PBL. Variations in physical atmosphere values due to aerosols are associated with the intensity of vertical flows and dynamics. Thus, aerosols act as a trigger reorganizing a chain of complex interactions and transformations in the atmosphere on mesoscales. However, aerosol induced changes in weather parameters averaged over the domain are negligible.

DIAGNOSING INTER-HEMISPHERIC OH DISTRIBUTION AND TRANSPORT IN CHEMISTRY AND TRANSPORT MODELS

P.K. Patra, M.C. Krol and TransCom-CH4, NOAA, AGAGE and HIPPO teams

Abstract

Uncertainties in the representation of meteorology and chemistry are difficult to disentangle in the chemistry-transport models. These uncertainties greatly limit our ability to predict the future changes in atmospheric composition and their climate impacts. We have implemented chemical tracers in the CCSR/FECGC/NIES atmospheric general circulation based chemistry transport model, i.e. JAMSTEC ACTM, for simulating SF6, CH4, CH3CCl3, HFC-134a, Radon-222 etc. for evaluating the transport of chemical species at synoptic to annual time scales in comparison with observed concentrations around the globe. We have established from the model transport intercomparison experiment (TransCom-CH4; Patra et al., ACP, 2011) that inter-hemispheric transport biases uniformly affect the simulation of chemical species when the emissions and chemistry are kept common among the models. We also have prepared an optimized set of methyl chloroform (CH3CCl3) emissions for the period of 1980 to 2013 using monthly varying OH from Spivakovsky et al. (JGR, 2000). The OH field is scaled down by 8% to obtain 5 years of lifetime for CH3CCl3 for the decade of 2000s and successfully simulate the growth and decay of CH3CCl3 concentration in the atmosphere (A lower amount of OH would fail to simulate the CH3CCl3 concentration decay rate during 2000s, and higher amount of OH lead to greater than observed seasonal cycle amplitude. Using the ACTM simulations we estimate that the amount of OH in the northern hemisphere (NH) compared to the southern hemisphere (SH) should be close to 1 (Patra et al., Nature, 2014). We will present these recent results obtained using ACTM, and propose validation schemes for model transport and chemistry.

EVALUATION OF PRESENT AND FUTURE SURFACE OZONE AS SIMULATED BY CHEMISTRY-CLIMATE MODELS

Michael J. Prather, Jordan, Schnell and the ACCMIP group

Abstract

For future air quality, four major factors drive change: (1) global emissions that alter composition and baseline levels of surface O3; (2) global climate changes that also alter these baselines (via T, H2O, convection); (3) climatic changes in meteorological regimes that lead to air quality extreme (AQX) episodes; and (4) changes in the efficacy of local emissions to produce pollution within a governance region. While all factors can be part of a coupled system, separate verification is needed. In this study, we focus on factor (3), evaluating the ability of the models in the Atmospheric Chemistry & Climate Model Intercomparison Project to reproduce the observed present-day climatology (diurnal/seasonal cycles, AQX episode size) of surface O3 in North America (NA) and Europe (EU). We can characterize future AQ within NA and EU, as well as for south Asia (SA) where we lack suitable observations to verify models. The chemistry-climate models simulated the 2090s decade for RCP8.5 climate using both current and 2100 emissions for air pollutants. Most models simulate the observed climatology well, albeit biased high over most of the probability distribution from baseline (30th percentile) to AQX threshold (100 worst days per decade). For RCP8.5, the model ensemble mean shows an increase of ~10% in the mean annual maximum daily 8-h average ozone (MDA8) over all domains, with largest changes in winter months. For RCP8.5 holding 2000s pollutant emissions, the modelled NA shows a small increase (+1%) in annual mean MDA8 while EU and SA show small decreases (-2% and -3%, respectively). Also for RCP8.5, models show average shifts in the mean size (S) and duration (D) of the large AQX episodes: S = -28% & D = -17% in EU; D = -7% & S =+21% in NA; but S = +54% & D = +15% in SA. For RCP8.5 with 2000s pollutants, we find similar but smaller changes occur. We conclude that future changes in AQX episodes are driven more so by changes in precursor emissions rather than climate.

EVALUATING AEROSOL IMPACTS ON NUMERICAL WEATHER PREDICTION IN AN EXTREME DUST EVENT

Samuel Remy, Angela Benedetti, T. Haiden, L. Jones, M. Razinger, J. Flemming, R.J. Engelen, V.H. Peuch and J.N. Thepaut

Abstract

The WMO-sponsored Working Group on Numerical Experimentation (WGNE) set up a project aimed at understanding the importance of aerosols for numerical weather prediction (NWP). Within the framework of that project, we report on a new mechanism whereby the radiative effect of dust aerosol on surface fluxes acts to increase the dust loading of the atmosphere via modification of boundary-layer stability, thereby acting to enhance the radiative aerosol effect. This positive feedback between dust aerosol and boundary layer stability occurred during a series of dust storms in the Sahara and the Eastern Mediterranean in April 2012, which were studied using the Monitoring Atmospheric Composition and Climate - Interim Implementation (MACC-II) system.

FEEDBACK BETWEEN NATURAL AEROSOL AND CLOUD MICROPHYSICS WITHIN ICON-ART

D. Rieger, K. Deetz, H. Vogel, A. Seifert, R. Ruhnke and B. Vogel

Abstract

The integrated modelling framework ICON-ART [1] (ICOsahedral Nonhydrostatic - Aerosols and Reactive Trace gases) extends the numerical weather prediction modelling system ICON by modules for gas phase chemistry, aerosol dynamics and related feedback processes. The nonhydrostatic global modelling system ICON [2] is a joint development of German Weatherservice (DWD) and Max Planck Institute for Meteorology (MPI-M) with local grid refinement. It will be used for numerical weather prediction, climate projections and for research purposes. Analogous to its predecessor COSMO-ART [3], ICON-ART is designed to account for feedback processes between meteorological variables and atmospheric trace substances. Up to now, ICON-ART contains the dispersion of volcanic ash and sea salt aerosol as well as ozone-depleting stratospheric trace substances [1]. The generic infrastructure allows an easy implementation of further monodisperse and polydisperse aerosol species. Very recently, we have extended ICON-ART by a mineral dust emission scheme with global applicability and nucleation parameterizations which allow the cloud microphysics to explicitly account for prognostic aerosol distributions. We present first results of the impact of natural aerosol (i.e. sea salt aerosol and mineral dust) on cloud properties and precipitation.

[1] Rieger, D., et al. (2014), ICON-ART - A new online-coupled model system from the global to regional scale, submitted to Geosci. Model Dev.

[2] Zangl, G., et al. (2014), The ICON (ICOsahedral Non-hydrostatic) modelling framework of DWD MPI-M: Description of the non-hydrostatic dynamical core. Q.J.R. Meteorol. Soc., doi: 10.1002/qj.2378.

[3] Vogel, B., et al. (2009), The comprehensive model system COSMO-ART - Radiative impact of aerosol on the state of the atmosphere on the regional scale, Atmos. Chem. Phys., 9, 8661-8680.

INVESTIGATING CONVECTIVE TROPOSPHERIC TRANSPORT PROCESSES AND LARGE SCALE STRATOSPHERIC DYNAMICS WITH ICON-ART

Roland Ruhnke, Jennifer Schrieter, Christian Stassen, Daniel Rieger, Ingeborg Bischoff-Gauss, Heike Vogel and Bernhard Vogel

Abstract

We have extended the global ICON (ICOsahedral Nonhydrostatic) modelling framework. ICON is a joint development by the German Weather Service (DWD) and the Max-Planck-Institute for Meteorology (MPI-M). We added modules for gas-phase chemistry and aerosol dynamics (ART, Aerosols and Reactive Trace gases) [1]. ICON allows a regional grid refinement with two-way interactions between the different horizontal grids. It is used by DWD for numerical weather predictions and will be used by MPI-M for climate projections [2]. The extended modelling framework ICON-ART is developed in an analogous way to its predecessors COSMO-ART [3], so that aerosol and chemical composition feedbacks can be considered in a comprehensive way. Up to now, ICON-ART accounts for volcanic ash tracers, radioactive tracers, sea salt and mineral dust aerosols. Additionally, several gaseous tracers have been introduced. For the dynamics (transport and diffusion) of aerosol and gaseous tracers, the original ICON tracer framework is used. For the model physics, numerical time integration follows a process splitting approach separating physical processes. Each process is called independently via an interface module. Currently, the processes of emission, dry and wet deposition, sedimentation, and first order chemical reactions are included.

We will present a simulation of the transport of ozone depleting short-lived trace gases from the surface into the stratosphere as well as of long-lived tracers. The simulated tracer distributions are used to investigate the ability of ICON-ART to simulate convective vertical transport in the troposphere as well as of large-scale stratospheric dynamics. Where applicable the ICON-ART results will be compared to observations and to results of the global chemistry-climate model EMAC.

[1] Rieger, D., et al. (2014), ICON-ART - A new online-coupled model system from the global to regional scale, submitted to Geosci. Model Dev.

[2] Zangl, G., et al. (2014), The ICON (ICOsahedral Non-hydrostatic) modelling framework of DWD MPI-M: Description of the non-hydrostatic dynamical core. Q.J.R. Meteorol. Soc., doi: 10.1002/qj.2378.

[3] Vogel, B., et al. (2009), The comprehensive model system COSMO-ART - Radiative impact of aerosol on the state of the atmosphere on the regional scale, Atmos. Chem. Phys., 9, 8661-8680.

ASSESSING SAHARAN MINERAL DUST USING TWO ONLINE MODELS

E. Sa, C. Gama, S. Basart, H. Martins, A.P. Fernandes, A.I Miranda and J.M. Baldasano

Abstract

During the last years there has been an increasing interest in the study of atmospheric aerosols given their confirmed impact on human health. Dust events may greatly increase the ambient air levels of PM recorded in air quality monitoring networks. This is especially relevant in Southern Europe, Eastern Asia and in some Atlantic islands. The transport of Saharan dust into Europe has a clear seasonality, being more frequent from February to June and from late autumn to early winter, although dust events can be distributed throughout the year. The Mediterranean countries are mostly affected by Sahara dust episodes. Over the last decade, air pollution has become a major problem in Portugal mainly due to the high concentration of particulate matter (PM) in the atmosphere, which surpassed the daily limit values. An abundant type of natural atmospheric aerosol is related with the suspension and long-range transport of mineral dust and for this reason the mineral dust contribution to the air quality concentrations of PM is relevant for the air quality management. Air quality models are powerful tools to predict the fate of aerosols after their release into the atmosphere and the application of online models allows the understanding of the aerosol feedback effects. The aim of this study is to conduct a model intercomparison between the online Weather Research and Forecasting with Chemistry model (WRF/Chem Ver. 3.5) and the NCEP Non-hydrostatic Multiscale Model/Barcelona Supercomputing Center (NMMB/BSC-Dust v2.0). This intercomparison aims at investigate direct and indirect aerosol feedback. The study was performed over Europe, under the guidance of the AQMEII-Phase 2 international initiative, and also over Portugal. The case study focuses on the atmospheric aerosols from the Saharan Dust episode in October 2010. The results from both simulations were compared with air quality data from stations of the AERONET and EARLINET networks. Preliminary results show a good agreement between both online models and with observations.

INTEGRATED METEOROLOGY-AEROSOL-CHEMISTRY MODELLING FOR NWP APPLICATIONS: PRESENT STATUS, FUTURE STEPS AND CHALLENGES

Bent H. Sass, Alexander Baklanov, Francois Bouyssel and the HIRLAM-ALADIN Working Meetings Team

Abstract

Scientific development, improving computing capacities and societal needs for better forecasts to mitigate effects of severe weather and air pollution episodes have made the time ripe for a clear leap towards stronger integration or coupling of meteorology-chemistry-aerosol processes. This was one of the reasons for launching the COST Action ES1004 EuMetChem (European framework for online integrated air quality and meteorology modelling - 2011-2015; http://eumetchem.info) to address strategically the issue. Following 1st (Sep 2013, Toulouse, France) and 2nd (Sep 2014, Copenhagen, Denmark) joint HIRLAM-ALADIN working meetings the strategy for online integrated Meteorology-Aerosol-Chemistry modelling for Numerical Weather Prediction (NWP) was developed including elaboration of joint plans and strategy for building joint online coupled baseline system. Overview of the COST EuMetChem and WMO activities on online integrated modelling for NWP applications and numerical systems developed at Meteo-France for air quality modelling, NWP and climate research was done. Developments and plans on chemistry/ aerosols/ radiation/ clouds/ microphysics interactions, etc. and some practicalities regarding development of an operational coupled model were discussed. Further planning, scientific coordination of activities, international collaboration, external possible projects/proposals, students/university collaboration were discussed.

IMPACTS OF DIFFERENT AEROSOL CLIMATOLOGIES ON THE EUROPEAN CLIMATE DURING THE LAST DECADES

Markus Schultze, Burkhardt Rockel and Hans von Storch

Abstract

As summarized in the 5th Assessment Report of the IPCC the effects of aerosols on the Earth's energy budget are one of the largest uncertainty in a changing climate. Despite a better understanding of aerosol processes since the last report, it remains unclear how complex these processes have to be represented within the climate models to consider their effects in a sufficient way. Within the nonhydrostatic regional climate model COSMO-CLM the aerosol climatology of Tanre from 1984 is widely used to simulate the direct effect of aerosols on radiative processes. Apart from a very low spatial resolution and a missing temporal variability this climatology is dominated by high values of Aerosol Optical Depth (AOD) over Northern Africa, which are caused by an overestimation of Saharan dust. To investigate the impacts of different aerosol distributions on the meteorological fields the Tanre aerosol climatology is replaced by the more realistic climatologies of Tegen from 1997 and AEROCOM from 2006 with monthly mean values of AOD. In addition a control simulation without any aerosol feedbacks was performed from 1980 to 2010. We found a partly near surface cooling, which is strongly linked to AOD, and a broad mid-troposphere warming for all simulations in comparison to the control simulation. A decrease in convective precipitation is mainly caused by a stabilization of stratification and less evapotranspiration through surface cooling. The horizontal differing mid-troposphere warming induces a drop in surface pressure and therefore leads to changes in circulation patterns, which are still under investigation. The largest impacts of direct and semi direct aerosol effects was found in summer season. As the next step the fully online coupled model system COSMO-ART will be used to compile an up to date aerosol climatology with a high spatial and temporal resolution. Gas phase chemistry and aerosol dynamics are taken into account within this model system. In addition to the direct aerosol effect on radiation, interactions of aerosols and cloud microphysics (indirect effect) are considered. It will be a main focus of the study to investigate, whether a decrease in anthropogenic aerosol load in Europe during the last decades enhances the GHG induced near surface warming.

DISTRIBUTION OF TRACE GASES OVER SOUTH ASIA: ROLE OF CCMS

Varun Sheel, Lokesh Sahu, M. Kajino and Valerie Thouret

Abstract

Anthropogenic emissions in Asia are increasing due to rapid urbanization and industrial growth. Trace gases like CO and O3 emitted in the Asian region are susceptible for long rang transport and are known to affect the remote regions of the atmosphere. We study the seasonality in the vertical distribution of CO and O3 over Asia using the MOZAIC aircraft data, and a state of the art chemistry climate model (CCM). The objective of this study was to investigate the effect of convection and biomass burning, on the variability of these trace gases. While the PBL CO is predominantly influenced by strong winds, bringing regional background air from marine and biomass burning regions, under calm conditions CO levels are elevated by local emissions. Back trajectories and fire count map indicate the role of long-range transport and regional biomass burning on the lower tropospheric O3. On the other hand, in the free troposphere, seasonal variation reflects the impact of long-range transport associated with the ITCZ and biomass burning. The inter-annual variations were mainly due to transition from El Nino to La Nina conditions.

THE GEOS-5 AEROSOL FORECASTING AND DATA ASSIMILATION SYSTEM

Arlindo da Silva, Peter Colarco, Anton Darmeno, Virginie Buchard, Cynthia Randles and Oreste Reale

Abstract

GEOS-5 is the latest version of the NASA Global Modelling and Assimilation Office (GMAO) earth system model. GEOS-5 contains components for atmospheric circulation and composition (including data assimilation), ocean circulation and biogeochemistry, and land surface processes. In addition to traditional meteorological parameters, GEOS-5 includes modules representing the atmospheric composition, most notably aerosols and tropospheric/stratospheric chemical constituents, taking explicit account of the impact of these constituents on the radiative processes of the atmosphere. The assimilation of Aerosol Optical Depth (AOD) in GEOS-5 involves very careful cloud screening and homogenization of the observing system by means of a Neural Net scheme that translates MODIS radiances into AERONET calibrated AOD. These measurements are further quality controlled using an adaptive buddy check scheme, and assimilated using the Local Displacement Ensemble (LDE) methodology. An Ensemble Kalman Filter (EnKF) is currently in development, including assimilation of radiances and LIDAR (attenuated) backscatter. GEOS-5 aerosols are driven by daily QFED biomass burning emissions derived from MODIS fire radiative power retrievals. In this talk we will highlight the main results from the MERRA-2 reanalysis (including aerosols), discuss the application of GEOS-5 forecasts for several NASA field campaigns, and post-mission data analysis. In particular, we will discuss the impact of assimilated and interactive aerosols on Tropical Cyclogenesis and on the assimilation of meteorological IR and microwave sensors.

MODELLING THE CONCENTRATION OF CONTAMINANTS IN STABLE WIND MEANDERING SITUATION EMPLOYING THE ADVECTION-DIFFUSION EQUATION AND ASYMPTOTIC DIFFUSIVITIES

Viliam Cardoso da Silveira, Silvana Maldaner, Daniela Buske and Gervasio Annes Degrazia

Abstract

The aim of this study is to simulate the pollutants dispersion in the Planetary Boundary Layer (PBL) in stable low wind conditions (< 2 m/s) and taking into account the wind meandering. The advection-diffusion equation is solved considering the Generalized Integral Laplace Transform Technique (GILTT). This technique combines a series expansion with one integration. In the expansion is used a trigonometric base obtained from a Sturm-Liouville auxiliary problem. The integration is performed in all range of the transformed variable using an orthogonality property. In the present analysis, were utilized asymptotic eddy diffusivities to parameterize the turbulence effects occuring in regions near of the ground. To validity the present methodology the classical diffusion experiment called Idaho National Engineering Laboratory (INEL) was utilized. This experiment was accomplished in stable and low wind speed conditions. The results show a reasonable concordance between the observed and simulated concentration data. Thus, this model can be applied to regulatory applications in air quality.

IMPACT OF RADIANCE DATA ASSIMILATION FOR PREDICTION OF A LAND-FALLING BAY OF BENGAL CYCLONE SIDR USING MESOSCALE MODEL

K.S. Singh and M. Mandal

Abstract

Land-falling tropical cyclones (TCs) are one of the most devastating weather phenomena in the nature. The devastations are mainly due to strong winds, heavy rainfall and associated storm surges. Therefore accurate prediction of land-falling tropical cyclones track, intensity changes near their landfall is of great importance for effectively warning the public and reducing economy damage and deaths. In this study, prediction of a very severe cyclone Sidr that formed over the Bay of Bengal during 2007 were investigated using a customized version of the WRF model. Four numerical experiments were conducted, three with data assimilation and one without data assimilation. Assimilation experiments were performed with the WRF-3DVAR to evaluate the impact of directly assimilating the radiances of AMSU-A, AMSU-B, HIRS, MHS and AIRS on the analysis and prediction of a Bay of Bengal cyclone. The lateral boundary condition is prepared from the Global Forecasting System (GFS) forecast at every 3 hourly interval. The model predicted track and intensity of the storms are compared with the India Meteorological Department (IMD) best-fit track. Results indicate that the track, intensity and landfall of the storm are well predicted by the model in radiance data assimilations. The improvement in predictions is mainly due to the better initial condition of the middle troposphere. The magnitude and spatial distribution of precipitation is also better predicted by model with 3DVAR experiments. The results indicate that the direct radiance data assimilation may have good potential for real-time prediction of cyclones, air quality modelling and climate research and encourage further investigation with larger number of cyclones and other applications.

INVESTIGATION OF DIRECT RADIATIVE EFFECTS OF AEROSOLS DUE TO CHANGES IN DOMESTIC HEATING FUEL

Orestis Speyer, Eleni Athanasopoulou, Evangelos Gerasopoulos, Dominik Brunner, Heike Vogel and Bernhard Vogel

Abstract

For the past 5 years, Greece has been experiencing a major financial crisis which, among other side effects, led to a shift in the fuel used for residential heating from fossil fuels towards bio-fuels, primarily wood. As a consequence, severe winter smog episodes became more frequent, which led to the setup of a large experiment measuring mass concentrations, chemical composition and physicochemical properties of aerosols in big cities of Greece. Synergistically, COSMO-ART (regional aerosol model coupled online with meteorology) applications were performed over Greece with a high horizontal resolution (~2.8 km), during the winter of 2013 - 2014. A base-case simulation was performed with the standard TNO-MACC II anthropogenic emission inventory for 2009 and compared against specialized measurements in Greece. Their synergy resulted in a refined emission database, with respect to the temporal distribution and chemical composition of aerosol emissions from domestic heating. New model results are significantly improved, especially during the days with intense heating demand (T_{min}<8°C). During the studied period, PM_{10} concentrations presented numerous night-time spikes (ca. 23 times), reaching or exceeding 150 μgm^{-3} in 2 cases. The vast majority of this mass was in the submicron aerosol fraction (PM_1) and consisted mainly (90%) of organics. The 80% of PM_1 organics originated from biomass burning, as revealed both from online chemistry measurements with an Aerosol Chemical Speciation Monitor (ACSM) and from the model outputs. Black Carbon (BC) also showed elevated concentrations, multiple times the concentrations typically found in megacities worldwide and the biomass burning-related BC equalled the rest of all other sources. The modification of the radiative budget by the smog plume above Greece, and primarily Athens is also studied. Primary results show that the positive effect of the peak night-time concentrations on the long-range radiation and the radiative cooling of the residual plume during the day hours, counteract.

RADIATIVE AND METEOROLOGICAL EFFECTS OF AIR POLLUTION AND DUST OVER THE ARABIAN PENINSULA

Georgiy Stenchikov, Jos Lelieveld, Paul Kucera, Duncan Axisa and Sergey Osipov

Abstract

Located in the centre of the northern subtropical dust belt, the Arabian Desert is the third largest region of dust generation where extreme dust pollution episodes are frequent. The Arabian Peninsula experiences rapid economic and population growth accompanied by intense industrialization and urbanization, mostly in the coastal areas, which are affected by anthropogenic pollution of local, African, Asian and European origin, and also subject to high relative humidity, especially in summer, and frequent dust outbreaks. These factors in combination with the high temperature and intense insolation provide unique conditions for atmospheric photochemistry and air pollution processes that have yet been inadequately investigated. In this study we focus on in-depth analysis of the combined effects of anthropogenic pollution and dust on air-quality and meteorological processes in the southwest of the Arabian Peninsula. We have conducted simulations using a comprehensive regional Weather Research Forecast model fully coupled with the aerosol/chemistry calculations, WRF-CHEM, and take advantage of available aircraft observations conducted by the NCAR team during the observation campaign in August of 2009. We have found that the model reproduces the aerosol loading and size distribution quite well compared to aircraft observations, and estimated aerosol impact on radiation fluxes and meteorology, as well as analysed abundance, spatial distribution, and transport of gaseous anthropogenic pollutants.

DEVELOPMENT OF PROGNOSTIC AEROSOL-CLOUD INTERACTIONS IN A CHEMISTRY TRANSPORT MODEL COUPLED TO A REGIONAL CLIMATE MODEL

M. A. Thomas, M. Kahnert, C. Andersson, H. Kokkola, U. Hansson, C. Jones, J. Langner and A. Devasthale

Abstract

For an accurate evaluation of aerosol (direct and indirect) radiative forcing, the recent generation of models aim for a tight coupling between chemistry transport models (CTM) and regional climate models so as to have a better representation of aerosol microphysical processes, aerosol-cloud interactions and also, the capability to run at higher spatial resolution compared to global models. Here, we present the results from a working version of the coupling between a CTM with a detailed aerosol dynamics model and a regional climate model. This coupling is done by first forcing the regional climate model, RCA4 by ERA lateral boundaries (LBCs) and SST using the standard CDNC (cloud droplet number concentration) formulation (hereafter, referred to as the 'stand-alone RCA4 version'). In this simulation, the CDNCs are assigned fixed numbers based on if the underlying surface is warm-continental or cold-oceanic. The meteorology from this simulation is then used to drive the chemistry transport model, MATCH which is coupled online with the aerosol dynamics model, SALSA. CDNC fields obtained from MATCH-SALSA are then fedback into a new RCA4 simulation. In this new simulation, all parameters remain the same as in the first run except for the CDNCs provided by MATCH-SALSA. Simulations were carried out with this model set up for the period 2005-2012 over Europe and the differences in cloud microphysical properties and fluxes as a result to the local CDNC changes and possible responses of the land surface to changes in radiation are discussed.

A STUDY SHOWING IMPACTS OF AEROSOLS ON CLOUDS AND PRECIPITATION ASSOCIATED WITH A LARGE WINTER CYCLONE

Gregory Thompson

Abstract

Aerosols influence cloud and precipitation development in complex ways due to myriad feedbacks at a variety of scales from individual clouds through entire storm systems. This talk will describe the implementation, testing, and results of a newly modified bulk microphysical parameterization with explicit cloud droplet nucleation and ice activation by aerosols. Idealized tests and a high-resolution, convection-permitting, continental-scale, 72-h simulation with five sensitivity experiments showed that increased aerosol number concentration results in more numerous cloud droplets of overall smaller size and delays precipitation development. Furthermore, the smaller droplet sizes cause the expected increased cloud albedo effect and more subtle longwave radiation effects. Although increased aerosols generally hindered the warm-rain processes, regions of mixed-phase clouds were impacted in slightly unexpected ways with more precipitation falling north of a synoptic-scale warm front. Aerosol impacts to regions of light precipitation, less than approximately 2.5 mm per hour, were far greater than impacts to regions with higher precipitation rates. Comparisons of model forecasts with five different aerosol states versus surface precipitation measurements revealed that even a large-scale storm system with nearly a thousand observing locations did not indicate which experiment produced a more correct final forecast, indicating a need for far longer-duration simulations due to the magnitude of both model forecast error and observational uncertainty. Last, since aerosols affect cloud and precipitation phase and amount, there are resulting implications to a variety of end-user applications such as surface sensible weather and aircraft icing.

AEROSOL DIRECT RADIATIVE EFFECT DURING SUMMER 2010 WILDFIRES IN RUSSIA SIMULATED WITH NWP MODEL HARMONIE

Velle Toll, Marko Kaasik, Ketlin Reis, Riinu Ots, Aarne Mannik, Marje Prank and Mikhail Sofiev

Abstract

The aerosol direct radiative effects during the Russian wildfires in summer 2010 have been simulated with numerical weather prediction model HARMONIE using external aerosol data from the atmospheric chemical transport model SILAM and MACC IFS reanalyses. The highest values of aerosol optical depth (at 550 nm) in the European part of Russia were more than 4 during intense fire period. The simulated decrease in downwelling shortwave radiation is more than 200 W/m2 and the decrease in near ground air temperature more than 3°C, strongly influencing atmospheric conditions near the surface. Considering the aerosol direct radiative effect in the meteorological simulations brought simulated temperature closer to the observations (daily average 2 m temperature was overestimated by up to 5°C without considering aerosol direct radiative effect). Stabilization of the planetary boundary layer through the aerosol direct radiative effect was simulated (the simulated decrease in the planetary boundary layer height was up to 2000 m). The stabilization effect is in agreement with sounding data and its relevance is possible feedback on the aerosol distribution near the surface. In addition, during the intense wildfire period on August 8, 2010, a severe derecho-type thunderstorm swept over the Baltic countries and Finland and aerosol influence on the storm is simulated. The modelling results suggest that the thunderstorm was weakened through the direct radiative effect. The weakening of the storm is expected as atmospheric instability was decreased.

A CASE STUDY OF ONLINE ENVIRO-HIRLAM AND WRF-CHEM MODEL USING GLOBAL EMISSION DATA DURING AN AIR POLLUTION EPISODE IN ISTANBUL

Huseyin Toros and Suleiman Mostamandy

Abstract

The main objective of this study is to evaluate the performance of Enviro-HIRLAM and WRF-CHEM using global emission data in air pollution atmospheric conditions in Istanbul in mid of January 2013. For this purposes we run the model from 10 to 20 January of 2013, due to high PM10 values during 14-16 January 2013. The assessment has been performed for selected relevant air pollution parameters (PM10), meteorological parameters, such as temperature, inversion, pressure, wind speed and relative humidity with online running of Enviro-HIRLAM and WRF-CHEM. The result also compares with measurement of some air pollution parameters. Analysis of results showed that both Enviro-HIRLAM and WRF-Chem models produced PM10 concentrations up to 10 and 6 times lower compared with measurements, correspondingly. Spatial distribution of PM10 looks reasonable for both models (see below Figures). Perhaps problem with initial condition of emissions, which is present some time averaged value.
Acknowledgement: This work was supported by TUBITAK-111Y319 and COST Action ES1004. The authors are grateful to the Ministry of Environment and Urbanism of Turkey, Environment Department of Istanbul Greater Metropolitan and Turkish State Meteorological Service for meteorological and air pollution data

EVALUATION OF THE DUST SCHEME IN THE REGIONAL CLIMATE MODEL REGCM4 USING THE DUST SATELLITE PRODUCT LIVAS OVER EUROPE AND NORTH AFRICA

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Abstract

Aiming to evaluate and test the sensitivity of the dust scheme used in the regional climate model RegCM4, we have conducted a series of simulations, changing in each experiment some key variables that modify the dust production of the model. The evaluation of the modelled dust aerosol optical depth (AOD) is based on the pure dust product that it is derived by CALIPSO observations, spanning in the period 2007-2013. Techniques for the discrimination of the dust component from other aerosol types have been recently developed in the framework of the LIVAS (LIdar climatology of Vertical Aerosol Structure for space-based lidar simulation studies- http://lidar.space.noa.gr:8080/livas/). A set of five yearly RegCM4 simulations have been carried out for the year 2008. The dust parameter modifications were applied in the parameterization of dust emission size distribution and in soil erodibility, which mainly controls the dust production in the model. After the selection of the optimized set-up in the dust scheme parameters, a six years experiment was conducted for the period 2007-2012 and evaluated with the CALIPSO satellite retrieved dust AOD from LIVAS. The spatial analysis shows a small negative bias across the western part of the Sahara, a positive one in the Central-Eastern Sahara and an almost zero bias across Europe, while the temporal monthly correlation for the entire domain is 0.73. The simulated annual cycle of dust AOD from RegCM4 is also discussed with respect to LIVAS dust AOD for different sub-regions of the model domain.

DIAGNOSING CHANGES IN EUROPEAN TROPOSPHERIC OZONE OVER THE PAST 50 YEARS

Fiona Tummon, Laura Revell, Andrea Stenke, Timofei Sukhodolov, Eugene Rozanov and Thomas Peter

Abstract

In recent decades, the negative impacts of tropospheric ozone on human and ecosystem health have led to policy changes to reduce emissions of ozone precursor gases such as nitrogen oxides (NOx) and carbon monoxide (CO). Although emissions of these species in Europe and North America have significantly decreased since the early 1990s, observational data indicate that free tropospheric ozone over Europe has not decreased as expected. Previous studies suggest that transport of stratospheric ozone to the troposphere may have increased from the late 1980s until the early 2000s. However this is also a period over which ozone precursor emissions have increased significantly from the Asian region. Given the relatively long lifetime of ozone in the free troposphere (approximately 20-30 days), the burden over one continent can be affected by emissions from another. Thus, both changes in ozone transport from the stratosphere and long-range transport from Asian source regions may have affected ozone in the free troposphere over Europe over the past three decades. SOCOL (SOlar Chemistry Ozone Links), an online-coupled global chemistry climate model, is used to investigate tropospheric ozone trends over Europe from 1960 to 2010. To fully disentangle the effects of both long-range transport and input from the stratosphere, three simulations are run with ozone tracers from 21 different atmospheric regions. In addition to a standard reference run, two sensitivity simulations are run: one with emissions of NOx and CO held constant at 1960 levels, and one with methane (CH4) held at constant 1960 levels, in addition to the NOx and CO. Preliminary results suggest that the influence of stratospheric ozone transport is small in all three simulations and remains largely constant over time, except for the contribution from the tropical lower stratosphere, which decreases over the entire simulation period. In contrast, the contributions from the tropical and northern mid-latitude boundary layer and free troposphere increase over time, but only in the simulations with all ozone precursor emissions. This would indicate that changes in source gas emissions have affected ozone concentrations in the European free troposphere most strongly and suggest that the contribution of stratospheric ozone to European ozone trends is very small.

IMPACT OF EUROPEAN AEROSOL EMISSION REDUCTIONS ON ARCTIC CLIMATE

V. Varma, A.M.L. Ekman, O. Seland, T. Iversen, A. Kirkevag, I. Riipinen, H. Struthers and H.-C. Hansson

Abstract

Anthropogenic aerosols are short-lived atmospheric constituents, which play a dualistic role in the earth system. They act as a forcing agent for the Earth's climate and are environmental pollutants with potentially adverse impacts on fresh water, soils, vegetation and human health. Due to the environmental pollution characteristics, emissions of anthropogenic aerosols and precursors have already been reduced in large parts of the world, including Europe. The changes in the magnitude and spatial patterns of global aerosol emissions have occurred especially during the last two decades of the 20th century and are projected to continue over the 21st century. Of particular relevance for the Arctic are the reductions in sulphate from industrial activities, domestic heating, and power production that have taken place in Europe since 1980. In this study, the CMIP5-version of the Norwegian Earth System Model (NorESM1-M) is used to simulate the climate with different emission scenarios for aerosols and their precursors. The purpose is to study in detail how selected aerosols may have affected the radiative balance, the global climate in general, and the Arctic climate in particular. A three-member ensemble of reference transient simulations for the historical period 1850-2005, where greenhouse gas concentrations and aerosol emissions varied with time according to best estimates, are compared to various aerosol sensitivity experiments. In the experiments, global and European SO2 and BC emissions are kept at levels corresponding to the years 1850 and 1980, respectively. Analysis of a sensitivity experiment where the global SO2 emissions were kept constant at 1850 levels shows a steep increase in the annual-mean global surface temperature of ~0.6°C from 1976 to 2005 whereas the experiment with global BC emissions kept at the 1850 level and the reference simulations show a smaller increase of up to ~0.4°C. In addition, results from the analyses of simulations with European SO2 and BC emissions fixed at 1980 levels will also be presented.

IMPACT OF MINERAL DUST PARTICLES ON THE FORECAST OF TEMPERATURE AND PHOTOVOLTAIC POWER

H. Vogel, J. Forstner, C. Kohler, B. Ritter, D. Rieger and B. Vogel

Abstract

Between April and June 2014 three mineral dust events have been observed over Germany. Due to the meteorological situation the dust was transported from the source region Sahara to central Europe. At Deutscher Wetterdienst (German weather service), additionally to the standard model chain, the model system COSMO-ART (Vogel et al., 2009, Bangert et al., 2012) was used in an operational mode. COSMO-ART describes online the temporal development of mineral dust particles and their feedback on radiation and cloud formation. Furthermore the two-moment scheme of Seifert and Beheng (2006) was activated instead of the standard bulk scheme that is usually used in COSMO for the operational weather forecast. Every 24 hours a simulation was started where for the initialization of the dust the concentrations from the previous run were used. With this model setup it was possible to forecast the dust load and to investigate the impact of the dust particles on radiation and cloud coverage. These parameters are important variables concerning the yield of solar energy. Due to the different meteorological situations the impact of the dust particles on the temperature forecast and on the photovoltaic energy yield could be analysed. Comparisons with the operational forecast shows that the dust load lead to a decrease of the global radiation in southern Germany above 100 W m-2 which is followed by a reduction up to 20 % of the photovoltaic power.

DYNAMIC AEROSOL IN NUMERICAL WEATHER FORECAST: NICE TO HAVE OR NECESSARY?

B. Vogel, E. Athanasopoulou, T. Schad, D. Rieger, I. Kraut and H. Vogel

Abstract

Current numerical weather forecast models treat the atmosphere as a dynamic mixture of nitrogen, oxygen, and water in gaseous, liquid, and solid state. Some of the trace substances as CO2, O3 and aerosol particles that are required to calculate the radiative fluxes are prescribed in time and space based on climatology. Natural and anthropogenic aerosol particles that differ substantially in time and space and in their chemical composition are known for a long time to absorb and to scatter short- and longwave radiation. They are a prerequisite in the formation of liquid clouds, serve as ice nuclei in case of heterogeneous freezing, and modify the formation of precipitation. However, so far it is not clear if a dynamic treatment of the feedback processes of aerosols with the state of the atmosphere would improve numerical weather forecast. In order to address this question we have developed the comprehensive online coupled model system COSMO-ART that is based on the operational weather forecast model COSMO used by several European countries and Russia. The model system includes atmospheric chemistry, aerosol dynamics and the feedback processes of aerosols with the atmospheric variables. We will present examples of applications of COSMO-ART for different kind of aerosols and weather systems and will elucidate the problems we are running in when distilling the role of aerosol particle for numerical weather forecast.

AN INTEGRATED GIS-BASED AIR QUALITY AND CLIMATE CHANGE MODELLING METHODOGY

Amir Yadghar and Majid Shafie-Pour

Abstract

Climate models aim to improve the understanding of Earth's climate by focusing on scientific analysis of the governing sets of processes that describe the climate over different conditions; evaluate strong methods to obtain higher spatial resolution for projections of climate change; and detect uncertainties in climate predications by real simulating. There are many potential effects of a changing climate. Water and air quality can be impaired, hurting human health. It can become more difficult to find and access water in certain areas. Airborne pollutants can deposit in areas where they previously hadn't been found. Strong models that can simulate of interaction ways of air pollutants with climate change are needed to assess and protect the human health and the environment. These models can be applied to estimate the effects of air quality policies in urban area on future climate conditions based on different scenarios. Coupling climate change models with air quality models are next step of modelling that makes scientists able to predict extreme climate events caused by air borne aerosols and air pollutants. This research proposes an integrated GIS-based air quality and climate change modelling methodology. The proposed model has a high spatial resolution which can be used in local and regional scale. The model is verified with different case studies. It can be widely used decision makers and authorities to assess different air quality policies and climate scenarios.

CLIMATE CHANGE IMPACTS ON SURFACE OZONE: USING THE ONLINE INTEGRATED CLIMATE-CHEMISTRY MODEL (ENVCLIMA)

A.S. Zakey and A. Baklanov

Abstract

The signature of climate change on European surface ozone was studied using the online integrated climate-chemistry model for Environmental applications (EnvClimA). The model domain has a horizontal resolution of 50 x 50 km and 18 vertical sigma levels. In this study, a 20-year simulation was preformed for the selected European domain for the reference (2000-2009) and future (2040-2049) periods. For both simulations, the initial and boundary conditions for the meteorological fields are provided every six hours from the global ECHAM5-r3 model. The chemical boundary conditions over Europe are provided also every six hours by the Danish Eulerian Hemispheric Model (DEHM). The anthropogenic emissions of nitrogen oxides, sulfur dioxide, ammonia, non-methane volatile organic carbon and carbon monoxide were taken from the IPCC-RCP4.5 future emission scenario. The EnvClimA results indicated zonal behaviour of average daily maximum concentrations for the surface ozone (O3). In winter, model has a substantial negative bias for both mean and daily maximum O3. This may be due to an underestimation of the winter air temperature over north-eastern Europe and due to feedback of O3 on the meteorological variables. Although the model spatial correlation is rather poor for diurnal average concentration, but for the average of daily maximum O3 concentrations the model showed correlation coefficients higher than 0.8 during summer. The model always showed the highest spatial correlation over central and southern Europe. The general pattern indicated an increase of surface ozone changes in southern Europe and a decrease in northern Europe for a chosen climate scenario. The change in surface ozone caused by climate change should also be related to anticipated changes in European precursor emissions. In this study it was found that changes in surface O3 due to climate change are much smaller than what can be expected from anthropogenic emission reductions over the same time period from previous studies.

ONLINE-COUPLED WRF-CAM5 MODELLING OVER EAST ASIA: MULTI-YEAR EVALUATION, MODEL IMPROVEMENT AND AEROSOL INDIRECT EFFECTS

Yang Zhang, Kai Wang, Xin Zhang, Ying Chen and Jian He

Abstract

Aerosol-cloud-radiation-climate feedbacks are important yet incompletely represented in most regional and global climate models and Earth system models. Accurate simulations of such feedbacks require robust parameterizations at various grid scales. The Weather Research and Forecasting Model with Chemistry version 3.4.1 (WRF/Chem v3.4.1) with physics packages from the Community Atmosphere Model version 5 (CAM5) (WRF-CAM5) is a regional climate model that has recently been developed to assess the robustness of CAM5 physics package for high-resolution modelling. In this work, to enhance the model's capability in reproducing aerosol interactions with various types of clouds at various grid resolutions, WRF-CAM5 is further improved by NCSU and collaborators at PNNL and applied over East Asia at a horizontal resolution of 36 km for six years during the period of 2001-2011 (i.e. 2001, 2005, 2006, 2008, 2010, and 2011) and at finer resolutions of 12 km over eastern China and 4 km over several urban airsheds for selected periods representing Asian spring dust storms and summer monsoons. In the improved WRF/CAM5, the aerosol indirect effects on cumulus and ice cloud formation are accounted for. The model offers two aerosol activation parameterizations and five heterogeneous ice nucleation parameterizations. A comprehensive evaluation has been performed for the 6 year baseline simulation results at 36 km using datasets from surface networks and satellites. The baseline results show an overall good performance for major meteorological variables, column abundances of CO, SO2, NO2, O3, and HCHO, and some surface concentrations such as PM10. However, relatively large biases exist for most cloud variables such as CCN, COT, LWP, IWPh, and CDNC, and some surface concentrations. Sensitivity simulations using more advanced aerosol activation and ice nucleation parameterizations are performed to demonstrate the improvement in model performance. Additional sensitivity simulations to separate aerosol direct and indirect effects are performed to quantify their relative importance in the overall aerosol effects on regional climate in East Asia and the responses of those effects to changes in emissions and resulting concentrations over a 10 year period.

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