WORLD CLIMATE RESEARCH PROGRAMME

WCRP Satellite Working Group Report on " Update of Space Mission Requirements for WCRP "

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FINAL REPORT

January 15, 2003

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Introduction

The main objective of WCRP is to develop the fundamental scientific understanding of the physical climate system and climate processes, as needed to determine to what extent climate can be predicted and the extent of human influence on climate. To achieve this objective requires a comprehensive strategy that includes detailed process studies, analysis of all possible data available and modelling. Satellite observations are essential in providing global and reliable measurements of many different variables characterising the state and the variability of the climate components and their complex interactions.
Many Earth observation satellites of major importance for WCRP projects and modelling activities have been launched during the past decade (1992-2002) and an even larger number is planned or is under consideration for the forthcoming decade (2002-2012); In order, for the climate scientific research community, to take full advantage of this unprecedented large and diversified amount of data, a number of conditions must be met concerning both the space segment and the data management, implying a closer interaction between Space Agencies and the WCRP scientific community.
A review of past accomplishments and research progress was conducted by an informal Working Group set up by WCRP over the period September–December 2002; The findings and recommendations of the Group are given hereafter in terms of priorities for future space missions, requirements regarding data management and enhanced interaction with space agencies.

Priorities for space missions

For WCRP, the value of space missions comes mostly from the capability to produce globally integrated, high quality and reliable climate data products requiring the merged analysis of measurements from the whole constellation of operational and research/demonstration satellites.

The WCRP “space strategy” relies upon the availability of long term, stable and high quality observations as currently provided by operational satellites (such as meteorological series) complemented with innovative, process-oriented observations as provided by research satellites using new technologies and new observation techniques.
The strategy also aims at the transfer of appropriate research/precursor sensors to operational platforms after validation by the scientific community and at the integration of satellite data into long term climate products. This definitely requires an increased coordination and additional resources from space agencies.

Priority measurements from existing and planned research missions which need to be pursued include key oceanic parameters (ocean topography, ocean colour, sea surface temperature, surface winds), radiation measurements (solar irradiance, Earth radiation budget), atmospheric parameters (3-D wind field, atmospheric constituents, cloud characteristics and radiative properties, precipitation), cryospheric parameters (ice sheet variability and thickness, sea-ice characteristics and motion) and land parameters (vegetation index, biomass estimate).

Several options were identified by the Working Group to ensure the required continuity ranging from the extension of satellite lifetimes to the launch of sensor replicates at regular time intervals and the transition from research to operational platforms.

Among the various space missions currently under study but not yet approved by space agencies, the Working Group gave the highest priority for the approval of two key missions for the study of the Water Cycle and cloud radiative processes, namely, the international NASDA/NASA/ESA Global Precipitation Measurement (GPM) mission, complemented with the CNES/ISRO MEGHA-TROPIQUES mission for the determination of energy exchanges in the tropical zones. A similar high priority was also given for the approval of the ESA/CNES/Spain Soil Moisture and Ocean Salinity (SMOS) mission aiming at the determination of two important parameters for climate research.

The Working group also identified priority measurements and processes which would deserve particular attention by space agencies for the definition of the next round of space missions; These include improved characterisation of polar stratospheric clouds and aerosols, better understanding of upper troposphere/lower stratosphere interactions, high precision gravity field determination and snow cover depth estimation.

Data Management aspects

Data management is defined as an end-to-end system including data acquisition, processing, distribution and archiving. The Working Group identified a number of issues to be discussed and solved through bilateral negotiations between space agencies/operators and scientists in charge of WCRP projects and modelling activities. These issues include the following:

- Preferential access conditions to space data in particular for high resolution optical and radar space imagery.
- Generation, through a joint effort with appropriate resources, of globally integrated climate products in support to WCRP projects.
- Delivery of selected space data sets in near real time (ideally within 6 hours from measurement) for assimilation in global models.
- Definition of climate product quality specifications and full access to sensor calibration/product validation documentation.
- Definition of guidelines/recommendations for archiving and re-processing strategies.

Interaction with Space Agencies

The Working Group acknowledged the present interaction between WCRP and Space Agencies achieved through the WMO and CEOS channels and the IGOS Partnership. It recommended that this interaction be reinforced and proposed a three-level structure consisting of:

- A high level coordinating body that considers joint strategy, policy and plans and to which the WCRP Joint Scientific Committee presents its assessment of the current systems and its requirements for new activities/space missions.
- Routine contacts between WCRP projects and space agencies' programme management to review on-going research activities.
- Working contacts where space agencies' scientists/data specialists participate in WCRP-organised data analysis projects to produce merged, global climate products.

A systematic cross-participation of Space Agencies and WCRP members in respective advisory committees, whenever feasible, was strongly recommended by the Working Group.

Conclusions

Space observations from the current and planned missions will offer an unprecedented potential for climate research provided joint coordinated efforts be made between WCRP and Space Agencies to turn the separate sensor/satellite data into globally integrated products for climate research. This potential will be further enhanced with the approval of new priority space missions as recommended by the Working Group.

The Working Group stressed the urgent need to increase the resources for a more effective exploitation of current and planned satellite observations through increased international cooperation and provision of additional funding by Space Agencies.

The transition from research to operational systems should be considered by Space Agencies with a high priority and mechanisms to be rapidly identified to ensure the data continuity essential for meeting WCRP's objectives.

1 - Introduction / Purpose of the report

Observation of the complex evolving Earth System from space has become an essential tool for understanding the fundamental processes of the climate because only satellites can easily provide global coverage and span the whole range of space and time scales that these processes encompass. The World Climate Research Programme, as a major user of earth observation satellite data, has longstanding and well established relationships with space agencies, providing them with specific requirements of the climate research community in terms of space missions (e.g. observation priorities, specific data management needs, etc) as illustrated, in particular, in references 1&2 (CEOS Plenary 1992, document from P. Morel on "WCRP requirements for space observations" and 1996 letters from H. Grassl to space agencies on "WCRP space mission priorities").

It now seems timely to update these requirements. This is in line with a recommendation made in February 2002 by the Consultative Meeting on High Level Policy on Satellite Matters to "identify gaps in existing or planned satellite systems and possible weaknesses in data management activities for climate research purposes". To this end, a WCRP Satellite Working Group was set up with a view to making a preliminary assessment of the situation and recommendations to be presented at the next Consultative Meeting to be held in February 3-4, 2003 in Geneva. It is also planned to submit this report to WCRP governing committees.

This report, generated over the period September-December 2002, results from the synthesis of the contributions from the WG members (see list in Annex 4) and discussions which took place at a 2-day Workshop organised by WCRP on 6-7 November 2002 in Geneva. It takes into account work undertaken as part of the proposed WMO Space Programme. Consideration is also given to results from discussions at the CEOS Plenary, held on 20-21 November in ESRIN / Frascati, attended by Principals from major space agencies and at which the status of the 2nd GCOS Adequacy Report was presented and briefly discussed.

2- WCRP Objectives and Deliverables

WCRP objectives are to develop the fundamental scientific understanding of the physical climate system and climate processes needed to determine to what extent climate can be predicted and the extent of human influence on climate. The programme encompasses studies of the global atmosphere, oceans, sea and land ice, and the land surface which together constitute the Earth's physical climate system. WCRP studies are specifically directed to provide scientifically founded quantitative answers to the questions being raised on climate and the range of natural climate variability, as well as to establish the basis for predictions of global and regional climatic variations and of changes in the frequency and severity of extreme events.

WCRP addresses outstanding issues of scientific uncertainty in the Earth's climate system including transport and storage of heat by the oceans, the global energy and hydrological cycle, the formation of clouds and their effects on radiative transfer, and the role of the cryosphere in climate. These activities match the scientific priorities identified by the Intergovernmental Panel on Climate Change (IPCC), and provide the basis for responding to issues raised in the UN Framework on Climate Change

(UNFCCC). WCRP also lays the scientific foundation for meeting the research challenges posed in Agenda 21. Together with the International Geosphere-Biosphere Programme (IGBP) and the International Human Dimensions of Global Environmental Change Programme (IHDP), WCRP provides the international framework for scientific cooperation in the study of global change.

WCRP is actively supporting the planning of the ICSU/WMO/IOC/UNEP Global Observing System comprising the Global Climate Observing System (GCOS), and the Global Ocean Observing System (GOOS). WCRP's work on the physical aspects of climate is complementary to IGBP's work to describe and understand the interactions of the physical, chemical and biological processes of the total Earth System, the changes that are occurring in this system, and the manner in which they are influenced by human action. .

The main missions of WCRP are focussed on:

- The development of scientific understanding of the physical basis of the climate of the Earth's system,
- The development of scientific understanding of the processes leading to climate change,
- The articulation of that scientific understanding in numerical models of the Earth system,
- The use of those models to provide ensemble climate predictions
  - to estimate the likely scenarios of climate change
  - to estimate the uncertainties in those scenarios.

The means by which our understanding of the Earth's system is developed is through detailed study and analysis of all available *in situ* and space based observations aided by modelling. The great advantages of satellite data are to provide global measurements of many different variables with instruments whose measurement capabilities can be reliably characterised and validated.

A comprehensive model of the Earth's system must include modules representing the atmospheric dynamics, and associated energy and water cycles, natural and anthropogenic changes in atmospheric composition, the land biosphere, hydrosphere and cryosphere, ocean dynamics, ocean biosphere and ocean chemistry. Several WCRP projects (GEWEX, SPARC, CliC…) focus on the understanding of the processes underlying climate in their specialised areas and on the development and validation of specialised modules to represent these processes. Examples of such modules include regional weather models, chemical transport models, land SVATs, hydrological models, sea-ice models, ocean-surface wave models and so on. These modules may then be organised as components of an integrated Earth system model, or be used to develop parameterisations for integrated Earth system models. The WCRP project CLIVAR is concerned with assessing and exploiting the overall performance of integrated Earth system models on a range of time-scales from seasonal to inter-annual to decadal to centennial.

Scientific understanding is advanced through many different forms of analysis of the observational record. This ensemble of methodologies can be used to cross-check the results of the different approaches. To address the full range of non-linear interactions in the climate system, use is increasingly made of the method of data assimilation to estimate the true state of the system by combining non-linear models and observations which are non-linear in the model variables. This approach has been particularly valuable for using satellite data to document the state of the Earth's climate and helps document shortcomings in the model's representation of key climate processes. Testing of the performance of integrated Earth system models in this manner is now beginning. The contribution of satellite data to improving Earth system models helps WCRP meet one of its most important deliverables.

A second major benefit for WCRP is the use of satellite data in operational weather assimilation and in long re-assimilations of the instrumental record (re-analyses). These provide comprehensive gridded multi-variate datasets which are a major scientific resource both for direct study in themselves, and as a background for understanding the implications of new observations, and for driving specialised models.

WCRP's scientific activity is part of a continuum of scientific and operational activity including:

- weather forecasting on short medium time scales,
- forecasting on seasonal-interannual time scales,
- chemical weather forecasting,
- assessment of long-range transport of air pollutants,
- ocean forecasting on time scales of weeks to years,
- climate assessments and predictions
- development of methods for treaty verification.

Since the same models and assimilation systems are frequently used for research work and operational deliverables, many social and practical benefits flow from WCRP science on model and assimilation developments based on the use of satellite data. These benefits include:

- Extensive and internally consistent re-analyses of the free atmosphere for the period 1950 to the present.
- Dramatic improvements over the last decade in tropical cyclone forecasting, with major improvements in Northern Hemisphere and Southern Hemisphere extra-tropical forecast skill.
- Economic exploitation of the gains in the ability to forecast heavy floods, and other forms of severe weather in both the tropics and mid-latitudes, to optimise the use of natural, material and financial resources.
- Major improvements in seasonal forecast capability, as demonstrated in the 1997-98 ENSO event and in the ongoing 2002 ENSO event.
- Considerable progress in understanding of ozone chemical and dynamical processes in the stratosphere, improving forecasting capability (such as the October 2002 wave-number 2 sudden warming in the Southern hemisphere).
- Major contributions by WCRP to successive IPCC Assessment reports, which have set the agenda for the international debate on anthropogenic climate change and its prediction.

The space agencies current plans for new Earth Observation missions are providing an excellent response to the observational requirements identified by WCRP over the last decade. A great deal of work to prepare for effective exploitation of these new missions is underway in the WCRP community. WCRP scientists are devoting intense efforts to understanding and exploiting the powerful new satellite observing systems (e.g. precipitation radar, precise altimetry, advanced sounders and chemistry instruments, salinity radiometers, ice thickness altimeter, gradiometers…). Major improvements in scientific understanding and in forecast capability are expected from these new observing capabilities. Nevertheless, and unfortunately, a great deal of important and necessary work is not being funded.

In the course of this decade (2002-2012) computer developments will enable routine use of global weather prediction models and assimilation systems running at resolutions of 10-15 km. At somewhat lower resolutions, these models will be used to enable the transition from research to operations of comprehensive (globally on scales of about 50 km) and internally consistent environmental monitoring systems for greenhouse gases, reactive gases, aerosols, land biosphere, ocean dynamics and ocean biosphere. The development of these new capabilities will provide transparent monitoring methods, and will also drive further improvements in the component modules. These monitoring systems will be a key resource for GCOS in its support of UNFCCC.

The development of variational assimilation systems has provided a battery of sophisticated new tools to diagnose the shortcomings in meteorological analyses. Increasingly these new diagnostic methods are being extended to identify uncertainties in Earth-system models. Year by year in the coming decade the WCRP community, working with advanced diagnostics on advanced models which exploit the most advanced space observations, will provide substantially more refined specifications of observational requirements for further model and for analysis improvements. The space agencies will be expected to meet those new requirements in the following decade (2012-2022).

3- Contributions of existing and planned space missions to WCRP

3.1 Overall WCRP generic observational requirements

WCRP observational requirements from space for its main core projects (GEWEX, SPARC, CLIVAR, CliC) and modelling activities are quite demanding since they must satisfy several challenging objectives such as:

- To provide for long term monitoring to detect and attribute climate trends and changes through continuous, systematic, consistent and accurate observations
- To allow for short term studies of specific climate-related processes through experimental observations and long-term statistical studies of the interaction of multiple processes
- To provide global observations to appropriately initialise and validate models for climate prediction from seasonal through decadal and out to centennial timescales, including prediction of anthropogenic climate change

All the analyses made by WCRP experts have concluded that these objectives could only be met through a well-defined strategy where space contributions should result from the combination of three categories of space missions: operational missions, long term duration research missions and exploratory, short duration, process-oriented research missions.

One should also note that some key information needed for climate research must be inferred (i.e. through physical or empirical models, data assimilation techniques, statistical parameterisation…) from multi-source (space and non-space) measurements. Referring to the GCOS Plan for space-based observations (see ref. 3), the key generic observational parameters required by WCRP projects and modelling activities can be broadly categorised as follows:

- Global radiative properties including cloud amount/structure, solar irradiance, surface radiation fluxes, Earth radiation budget, multi-spectral albedo, aerosols
- Ocean characteristics including upper ocean biomass, ocean surface topography, sea-ice cover, sea surface temperature, sea surface salinity, marine geoid
- Ocean-Atmosphere interface including sea surface temperature, ocean wind vectors (speed and direction), ocean wave height, atmospheric surface pressure
- Atmospheric state variables including temperature profile, wind profile, liquid water/ice, precipitation, humidity profile
- Atmospheric composition including minor constituents, water vapour, ozone, aerosols
- Land-Atmosphere interface including vegetation characteristics, soil moisture, snow cover, snow water equivalent, ice sheet topography, ice sheet and glacier extent, land surface temperature, fire extent/temperature, land surface topography
- Land/Biosphere climate response including vegetation characteristics, land use change, land cover change

Detailed specifications of required space-time sampling, accuracy ranges and delivery times for the above-mentioned geophysical parameters have been made by expert groups (see ref. 4) and are regularly revised to account for progress made in the different research areas.

3.2 Contributions of existing and planned space missions

The last decade (1992-2002) has been characterised by the launch of a large number of Earth Observation satellites (*more than 60 between the beginning of 1992 and the end of November 2002*), a number nearly equally divided between operational satellites and research/experimental satellites (see ref.5- CEOS Earth Observation Handbook). That decade has seen the continuous performance improvement of operational polar and geo-stationary satellite series for meteorology and of multi-purpose high resolution imaging satellite series. It has also been characterised by the launch of a new generation of experimental satellites testing advanced instrument concepts/technologies and exploring new science areas and new application domains. More than a *hundred new sensors* have been put into orbit to observe the atmosphere, the oceans, the polar caps, the land surface, coastal zones and the interior of the Earth.

The Year 2002 has been a particularly important year for new Earth Observation satellite missions; At the end of December 2002, some 9 major satellites of relevance to climate research (Envisat, GRACE, Aqua, SPOT-5, FY-1D, NOAA-17, MSG-1, METSAT, ADEOS-2) from 8 different space agencies have been launched. One should mention, among the missions initially scheduled for a launch in December, the recent successful launch of the NASA ICESat on January 12, the forthcoming NASA SORCE mission, now scheduled for January 25 and the Canadian atmospheric chemistry mission, SCISAT-1, to be launched on 19 January 2003.

The next decade (2002-2012) will see the launch of a similar or even larger number of Earth Observation satellites than has taken place over the past decade; Current plans of space agencies, as from the recent CEOS Plenary meeting, indicate some 90 possible missions between 2002 and 2018!. This number will include operational satellite series with improved performances and *several tens of new research missions and advanced sensors, half of these new missions being planned to be launched within the next 5 years.* As an example, one should note that some 28 ozone profile sensors have been launched or are scheduled for launch over the period 2000-2015 on board 14 satellites.

Some highlights on the specific contributions to observational requirements listed in Section 3.1, of current (i.e. in orbit) and planned (i.e. fully approved and funded with defined launch date targets) space missions are given in Annex 1. The quality of space measurements for a large number of the geophysical parameters listed in 3.1 is generally satisfactory /acceptable, although not all of them can be derived yet from space (e.g. atmospheric surface pressure, land biomass, ocean salinity, snow water equivalent…) or sometimes only with marginal performance (see ref.4).

4- Space missions under consideration of relevance to WCRP

A number of space missions are currently under consideration (i.e. under study but not yet approved for full development) by several space agencies (NASA, ESA, NASDA, CNES, ISRO…) for launch in the 2006-2010 timeframe. These missions would contribute to a better understanding of key climate processes such as:

- The water cycle with the Global Precipitation Measurement (GPM) mission, a multiple satellite constellation concept, implemented between NASA, NASDA and ESA, embarking a dual-frequency precipitation radar and passive microwave imaging radiometers.

- The inter-tropical zone and convective processes with the CNES/ISRO cooperative mission MEGHA-Tropiques, scheduled for 2006 and embarking a microwave radiometer (MADRAS) and a microwave sounder (SAPHIR) plus ScaRaB for Earth radiation budget measurement.

- The cloud radiative and aerosol processes with EarthCare (Earth Clouds, Aerosols and Radiation Explorer) an ESA/NASDA mission embarking a backscatter lidar, a cloud profiler radar and a Fourier Transform spectrometer for measurement of cloud and aerosols properties, temperature and water vapour, radiation budget at TOA.

- The distribution of atmospheric water vapour in the troposphere and lower stratosphere with WALES (Water vapour And Lidar Experiment in Space), an ESA mission embarking a differential absorption lidar (DIAL), and ACE+

(Atmospheric and Climate Explorer), also an ESA mission to measure variations and changes in global atmospheric temperature and water vapour with a 4-satellite constellation and using GPS signal occultation techniques providing good accuracy and high vertical resolution for temperature and humidity across the tropopause.

- o The ozone and greenhouse gases circulation with GCOM-A1 (Global Change Observation Mission), a NASDA and ESA cooperative mission, with UV spectrometer (OPUS), solar occultation Fourier transform spectrometer (SOFIS) and stratospheric wind interferometer (SWIFT).

- The determination of the ocean surface salinity with the ESA-CNES SMOS (Soil Moisture and Ocean Salinity) and NASA/Aquarius demonstration missions which, both, will attempt to measure this important oceanic parameter in great demand for climate research. The combination of salinity and precipitation observations would provide new and important information on evaporation and precipitation estimates over the oceans.

- The measurement of the soil moisture in the upper layer with the ESA/CNES SMOS mission, based on a passive L-band 2-D interferometer technique.

- The study of land surface processes and the role of vegetation in the global carbon cycle with the ESA Spectra Earth Explorer mission, embarking an advanced hyper-spectral sensor (PRISM).

Final decisions on whether to proceed or not to the development phase for these various candidate missions will be taken in the 2003-2004 timeframe and will depend on available resources of space agencies and scientific priorities resulting from consultations of users' communities.

5- WCRP Priorities for Future Space Missions

The existing space missions, including operational and experimental/demonstration or precursor systems as briefly mentioned in Annex 1, already provide comprehensive and important data sets for the WCRP research community and the situation will be significantly enhanced with the forthcoming approved space missions to be launched over the next 5 years. In many cases, multiple measurements of the same variable will be generated using different techniques from a diversity of satellites, offering various space-time sampling strategies (polar, geo-stationary, inclined low orbit). However, this combination of missions will only meet part of the needs of the climate research community, which rather requires high level data products than individual measurements. Conditions required to gain full benefit from the diversity and the large number of missions/sensors have also been discussed by the Working Group and are reported in Section 6 on Data Management aspects and Section 7 on Interactions with Space Agencies.

For WCRP, the value of space missions comes mostly from the capability to produce globally integrated, high quality and reliable data products requiring the merged

analysis of measurements from the whole constellation of operational and research / demonstration satellites.

To this end, as an overall priority, the Working Group recommended that the WCRP "space strategy" should be established along the main following lines:

1- To ensure that operational agencies maintain the continuity of existing operational space systems (to-day, this seems to be guaranteed for the meteorological component till 2015/2020) and upgrade operational sensors as appropriate to achieve better performances and meet WCRP requirements for long term, consistent and well-calibrated data sets.

2- To encourage space agencies to develop new research/precursor sensors providing better quality space measurements (in terms of accuracy, resolution, coverage…) for those measurements already existing but requiring major improvements to meet WCRP specifications and/or to explore new techniques/technologies for measurements not yet derived from space but in great demand by WCRP scientists.

3- To support the progressive transfer of appropriate research/ precursor sensors to operational platforms when they have been validated by WCRP scientists. Since this is not always feasible (because of constraints of different nature imposed on operational entities), WCRP should encourage space agencies to consider means or mechanisms to ensure long term continuation, without gaps and possibly with some overlapping of these measurements whenever needed.

4- To ensure that more efforts and resources are devoted to the integration of satellite data into climate (i.e. global, long-term) products required by WCRP projects.

A number of high priority "generic" space missions and/or geophysical measurements have been identified (or confirmed) by the Working Group, but members strongly emphasized the need, firstly, to fully exploit and draw the lessons from existing and forthcoming space missions before being able to specify in detail the required performances of "third generation" missions.

The Working Group strongly supports the "GCOS Climate Monitoring Principles" related to satellite systems (see Annex 2). It stressed in particular:

- *The importance of the requirements for precise (cross) calibration of sensors and validation of products*
- *The need for in-orbit sensor redundancy (needed for some measurements)*
- *The need for a sound mission and/or sensor replacement strategy to generate long time measurement series required for change detection and assessment of trends.*

The Working Group also acknowledged the value of in-situ data collection and observing systems, as an essential complement to space systems and for the validation of space measurements.

Further specific recommendations or comments of the Working Group have been formulated as follows:

Continuity of existing operational missions/measurements

To-day, the situation seems satisfactory with operational polar and geo-stationary meteorological systems firmly guaranteed until 2015-2020 and progressively upgraded with a new generation of advanced platforms/sensors (METOP, NPOESS, DMSP, MSG…).
Continuity of operational multi-purpose high resolution imaging (optical and radar) missions is ensured for the next 10 years (SPOT and Landsat follow on, Radarsat-2…) but access to data remains an issue for the climate research community, in particular, the radar imagery important for the ice research community.

Continuity of existing research and precursor missions/measurements

The Working Group recommended that space agencies explore options and mechanisms in order to ensure the continuity (and possibly overlapping whenever justified) of the following priority missions and/or measurements currently available:

Precise Radar altimetry: Topex / Poseidon and Jason-1, complemented with simultaneous polar ERS/Envisat-type altimeter missions, have been demonstrated to be an essential tool for climate research; Jason-2, successor of Jason-1 is currently subject to favourable negotiations between USA and Europe but there is not yet any follow-on for a precise polar radar altimeter mission optimised for mesoscale circulation after Envisat. In principle, two (or better three) altimeter missions in appropriate orbits should operate simultaneously.

Ocean colour: This is currently provided by a variety of high sensitivity spectrometers (SeaWiFS, MODIS, MERIS, MOS…) on-board several research missions but continuity is not guaranteed until operational NPOESS/VIIRS (with equivalent accuracy?) is available. Moreover, MODIS, MERIS, and GLI can measure chlorophyll fluorescence, which will greatly improve the quality of ocean biomass measurements in optically-complex coastal waters as well estimates of primary productivity. This capability is not included in NPOESS/VIIRS.

Precise sea surface temperature, with 1 km at nadir or less: This is required by climate models and provided over the last 10 years by ATSR-1 and 2 instruments; No successor is currently planned after AATSR on Envisat (or possibly with NPOES/VIIRS?).

Ocean surface wind fields are currently provided with Quickscat and very soon with SeaWinds on ADEOS-2, recently launched; No gap should exist till operational METOP/ASCAT is launched in 2005 and back up solutions should be envisaged in case of partial/total failure of the current systems.

Total Solar Irradiance measurements have been performed for more than 20 years with adequate precision through various missions and sensors (ERB, ERBE, ACRIM 1,2&3, VIRGO…), always ensuring in-orbit redundancy. SORCE/TIM will be launched soon (January 2003) but options to provide in-orbit redundancy until the NPOESS timeframe should be explored.

Earth radiation budget at TOA provided with CERES and ScaRaB sensors should be further continued to ensure long term series with the same sensors.

Atmospheric chemistry instruments: The performance of new generation sensors recently launched on Envisat (MIPAS,GOMOS, SCIAMACHY), Terra (MOPITT)… will need, after an initial evaluation period (3 years or more?), to be reviewed and a decision made on which ones (identical or upgraded) should be re-flown on follow-on research missions or possibly be transferred to operational systems. There was also a strong recommendation for the continuing deployment of SAGE III, currently on-board METEOR 3M N1.

Continuity of firmly planned missions/measurements

Numerous missions are currently under development with firm launch date targets (see Annex 1). Most of them are research demonstration (i.e. for qualification of advanced technologies, validation of new measurement techniques, improvement of accuracies…) with a 2-3 year design lifetime (although with often a 5-year goal). This nominal lifetime may not be sufficient, in a number of cases, for change detection requiring long term monitoring (e.g. variability of ice sheets) or to allow complete and comprehensive validation/impact studies using data assimilation in operational forecasting models (e.g. global wind profiles).

The Working Group recommended that space agencies put in place a specific programme with appropriate resources/funding to allow, whenever justified:

- *Extension of useful lifetime (if technically feasible),or*
- *Launch of replicate mission or sensor(s) at appropriate time intervals, or*
- *Transition to operational missions*

The Working Group identified, in the short term, the following priority missions for consideration :

ADM-Aeolus which will provide for a nominal period of 3 years, and for the first time, consistent global wind profiles of primary importance for climate models, process studies and NWP using 4-DVAR assimilation.

ICESat which aims, in particular, at the determination of decadal variation of ice sheet thickness
and
Cryosat which will complement ICESat; Both missions are planned for a 3-year lifetime and should be operated in conjunction to provide combined sets of measurements over ice sheets.

Aura chemistry and Aqua Formation (Aqua, Cloudsat, CALIPSO, PARASOL) missions for the study of atmospheric chemistry processes and water cycle and cloud radiative processes. Decision would be taken after data from these missions have been evaluated.

Approval for missions under consideration

A number of missions are currently being studied at so-called Phase A / Definition level by space agencies in view of later selection for development. They are briefly listed under Section 4.

The Working Group noted that all these missions will make very important contributions to climate research.

A higher priority was given to missions for the study of water cycle and cloud radiative processes, namely:

Global Precipitation Measurement (GPM) mission, a follow-on of the successful TRMM. This international cooperative satellite constellation would provide global measurements of precipitation, its distribution and processes with sub-diurnal time resolution,

and

MEGHA-TROPIQUES, a CNES/ISRO cooperation to study the water cycle and energy exchanges in tropical zones.

The Working Group also stressed the urgent need for measurements of ocean salinity (as an important conservative tracer for the oceanic circulation and for understanding the water cycle) and soil moisture (for the study of large scale hydrological and terrestrial processes).

C*omplete approval of the Soil Moisture and Ocean Salinity (SMOS) mission,* an ESA Earth Explorer mission in cooperation with CNES and Spain and currently in detailed definition Phase (Phase B), was strongly recommended by the Working Group. The Working Group emphasised the need to fully validate the new proposed measurement technique (in particular as regard the horizontal resolution and achievable accuracy). SMOS would complement the recently approved NASA Aquarius mission for ocean salinity and allow for cross-comparison of results.

Need for new research missions/measurements

The Working Group identified additional scientific areas / measurements of primary interest for climate research and which now deserve particular attention by space agencies; Requirements cover improvements to existing measurements and requirements for new types of measurements:

Improved Characterisation of polar stratospheric clouds and aerosols (distribution, frequency, composition, particle size…).

Higher accuracy and resolution measurements in the Upper Troposphere/Lower stratosphere (UTLS), a critically important region to understand mass and trace gases transfers, particularly ozone and water vapour, and for which a mix of nadir sounding and limb-viewing passive instruments should be considered. New active techniques (radio occultation) for observing this part of the atmosphere have the potential for better vertical resolution and accuracy and should be developed.

High resolution gravity field mission in support to precise altimeter missions. The current GRACE mission and the forthcoming ESA/GOCE will provide accurate geoid models with less than 100 km half- wavelength; New missions should aim at 10 km or better.

Snow cover depth which needs to be known to reduce uncertainties in the determination of sea-ice thickness for which encouraging results are obtained using synergistic data from altimeter, SAR and passive microwave sensors. This would allow the total sea-ice mass balance to be derived for the first time with high accuracy.

High resolution, all-weather surface temperature measurements from passive microwave radiometers (working in combination with and having similar resolutions as infrared sensors), which are highly needed over cloudy regions.

6- Data Management aspects

Data management must be understood as an end-to-end system including data acquisition, processing, distribution and archiving activities. This has been the subject of many reports from several Working Groups (see ref. 6) and identified as one of the most crucial issues for climate research. Only a number of major aspects were discussed by the Working Group with the following findings and recommendations.

6.1 Access conditions and data utilisation (seen from a user's perspective)

Space agencies and/or space operators, responsible at national or regional level for the exploitation of Earth Observation satellites, are committed to define access conditions and utilisation principles for the data and products resulting from their space systems; The resulting "Data Policies" vary depending on the objectives set up for these space missions, namely, scientific research/application demonstration, operational for public services (e.g. meteorological missions) and/or commercial services (generally, multi-purpose, high resolution optical and radar satellites); It should be noted that some missions may combine several objectives.
Climate research needs access to data and products from *all* types of space mission; Research data and operational data for public services are usually made available free-of-charge or at marginal cost (COFUR) to the climate research community through various mechanisms (e.g. Announcements of Opportunity, direct negotiations between WMO and space agencies or space operators). An example of this mechanism is the recent Agreement, signed between WMO and ESA, providing access, for all WMO research programmes, to the ESA Envisat research ("category 1") data through an Announcement of Opportunity scheme; However, the current situation still requires improvements, for instance to provide access for monitoring purposes to large quantities of high resolution optical or radar imagery (e.g. for monitoring of sea-ice and ice sheets variability and processes).
High resolution imagery from commercial systems is hardly accessible to the climate research community because of their costs and constraints for the observation strategy (priority for requests is given to commercial users) ; Preferential rates for specific utilisation conditions may be negotiated with Commercial Distributors but it generally concerns only limited data sets (examples of limited scope Agreements exist to-day between SPOT IMAGE, EURIMAGE…and research communities for ERS/Envisat SAR and SPOT HRV high resolution imagery).

The Working Group recommended that further action be initiated by WCRP with space agencies and/or Commercial Distributors to negotiate access conditions for the provision of large quantities of high resolution space imagery essential for climate research but without undermining the commercial market.

6.2 Data processing and high level product generation

The climate research community requires long time series (years to decade) of a wide variety of global data and analysis products ranging from basic calibrated level 1 data to validated products at level 2 (geophysical product) or even at higher levels 3 or 4, the latter implying the use of multi-source data and models.
In general, data management systems of operational entities, such as meteorological offices, are not in a position to meet the needs of the climate research community, especially for the study of climate-related processes; They are tailored to provide, in near real-time, a limited number of standardised data products for forecasting purposes; On the other hand, climate research requires high quality data and well-validated products to detect small variations in Earth processes, and reduce or eliminate artefacts due to changes in sensor performance or in processing software;
Space agencies, in general, are not in a position to provide this wide variety of high quality products for various reasons such as budgetary constraints, lack of clear mandate, sometimes insufficient maturity of processing algorithms…etc. The few exceptions have resulted from successful negotiations between space agencies and scientists responsible for specific climate research projects (e.g. ISSCP cloud data sets) or from national efforts related to specific satellite programmes (e.g. WOCE data sets with Topex/Poseidon, ERS, NSCATT…).

The Working Group recommended that agreements between WCRP and Space Agencies be reached, as early as possible in the development phase of space missions of interest for climate research, in order to produce, through a joint effort, globally integrated climate products in support to WCRP projects. These agreements should identify required resources including possible sources of financing (national research budgets, European Research Framework Programmes…).

6.3 Data delivery

Data and products from operational and research space missions need to be assimilated in global models(meteorological, chemical, oceanic…models) with complementary in-situ measurements from other platforms. To facilitate this integration, satellite data should be accessible by data assimilation groups in near real time, ideally within 6 hours of the measurement. This would allow rapid comparison with other contemporaneous data, efficient delivery of products to users and offer potential for operational benefits during the lifetime of a research mission. It was noted that the “real time” requirement does not mean necessarily that all the data be made available all the time to everyone and that data from research satellites will not necessarily be adequate for inclusion in operational systems immediately but only after a period of evaluation and algorithm improvement.

The Working Group recommended that Space Agencies organise their data processing chains in order to make available in near real time (ideally within 6 hours from *measurement) those data appropriate for assimilation in global models. This requirement can also be met in such a way as to facilitate the retrospective re-processing needed to produce climate-quality versions of the data at a later time.*

6.4 Sensor Calibration and Product Validation

Accurate sensor characterisation and calibration, data quality assessment and product validation are vital for climate research and should be performed under the responsibility of space agencies throughout the lifetime of the mission. This should include the continuous monitoring of the instrument stability and data product evolution associated with the improvement of processing algorithms. These activities should be properly documented and regularly up-dated to allow complete traceability of the sensors and of products evolution. When several similar sensors are operating simultaneously on different platforms, cross-calibration should be performed to allow a sound comparison between products and the generation of consistent and coherent long-term records.

The Working Group recommended that WCRP provides to space agencies, for each space mission of interest to climate research, specifications for quality climate products required by the climate research community. Scientists should have access to the full sensor calibration and product validation documentation. The Working Group also recommends, whenever possible, the systematic use of in-situ vicarious validation sites operated under WCRP projects such as GEWEX, CliC…etc. The agencies should begin working together to achieve cross-calibration of similar sensors to allow for global integration of the observations.

6.5 Archiving Strategy and Re-processing of Historical Archives

Climate research requires long time series of data to allow appropriate studies of Earth processes and long term variability ("trends"). This implies the archiving and maintenance of very large archives of data and products over years to decades, together with the sensor calibration and data product quality assessment /validation documentation. One should realize that new generation space missions are generating a larger number of products (by a factor 10 or more) and much larger amounts of data (by a factor 100 or more) compared to their predecessors. New technologies for long term archiving have been developed but a strategy must be defined to identify which data and products should be archived to allow, in particular, re-processing with state of the art algorithms and updated calibration information; Easy access to archives is also an essential requirement for scientists. Here again, one should note that this is not a usual requirement for operational missions such as meteorology, primarily concerned with forecasting objectives, or even commercial space missions for which data are primarily acquired to meet priority customers' requests (Note: More and more commercial space operators are performing "background acquisition" i.e. acquisition without an identified customer, to constitute an archive which may become, in the medium to long term, an asset generating significant incomes).

The Working group recommended that WCRP generates guidelines/recommendations for archiving and re-processing strategies for each data product of interest to the climate research community and negotiates with relevant Space Agencies for their *implementation in the frame of their respective programmes. The Working Group suggested that delayed data access for retrospective re-processing should be designed to be as easy as the real-time access.*

7- Interactions with Space Agencies

7.1 Current situation

WCRP has longstanding relationships with major space agencies responsible for operational meteorological programmes and scientific research in the field of climate, either through the WMO channel or as a CEOS Associate Member. This situation is reflected when looking at the list of existing and firmly planned space systems which includes a wide variety of space missions directly inspired by WCRP programmes and scientific community.

One important new channel for this continuing relationship is the Consultative Group on High Level Policy on Satellite Matters set up in 2000. It involves WMO and Heads of Space agencies with the mandate to exchange views and formulate recommendations on priorities for future space systems and associated data management systems. This Group already met twice and the next meeting is scheduled for beginning of February 2003. Already a number of important recommendations have resulted from their fruitful discussions**..**

7.2 Proposed improved interaction structure

A more structured interaction between WCRP and Space agencies than exists at present should be explored, operating at various levels of responsibilities and forming a real working arrangement that can facilitate the cooperation among the space agencies to produce globally integrated, long-term homogeneous analysis products for climate research.

The Working Group proposed that the following structure be put in place, consisting of:

- *(i)* *A high level coordinating body that considers joint strategy, policy and plans and to which the WCRP Joint Scientific Committee presents its assessment of the current systems and its requirements for new activities/space missions, including space agencies' participation in joint data analysis projects organised by WCRP. This could possibly be achieved through the High Level Consultative Group.*

- *(ii)* *Routine contacts between WCRP projects (i.e. CLIVAR, GEWEX, CliC and SPARC) and space agencies' programme management to review on-going research programmes and issues where agencies' representatives are ex officio members of Scientific Steering Groups.*

- *(iii)* *Working contacts where space agencies' scientists/data specialists participate in WCRP-organised data analysis projects to produce merged, global climate products.*

7.3 Examples of specific concrete actions in the short-term

Bilateral Agreements between WMO and Space Agencies

The negotiation of specific bilateral agreements between WMO and Space Agencies would allow access to satellite data and products of *non-meteorological nature* (meteorological products are generally available without restrictions). Recent successful examples have allowed access to Fast Delivery products from ESA ERS and soon from Envisat for WMO projects. Similar approaches should be explored with Commercial Distributors whenever data from commercial missions are of interest to climate research programmes.

Participation in Senior Advisory Committees of Space Agencies

High level Advisory Committees of Space Agencies play an important role in the definition and selection of future missions. Members of these committees are usually selected “ad personam” for their scientific competence and knowledge in Earth Sciences. WCRP should encourage Space Agencies to invite appropriate representatives from its projects to participate in such committees to voice the specific requirements of the climate research community.
A possible immediate action could be to ask Space Agencies to describe their advisory structure and to indicate how they presently (or plan to) take into account the views of the climate research community.

Use of international fora (CEOS,IGOS)

International high level fora such as the Committee on Earth Observation Satellites (CEOS) and the Integrated Global Observing Strategy (IGOS) offer opportunities to Users’ organisations (so-called “Associates”) to express their requirements at the occasion of yearly plenary meetings attended by all Principals responsible for Earth Observation in their respective space agencies. WCRP, as an Associate member of CEOS, should clearly state its views/suggestions on Space Agencies programmes, so that they better serve climate research objectives (e.g. on mission priorities, new instrumentation, data management systems, data policy, data continuity, climate products requirements…). Active participation of experts from WCRP core projects in various specialised CEOS working groups (Cal/Val WG and its sub-groups per sensor family, WG on Information Systems and Services) would be extremely useful to inject WCRP specific requirements into CEOS.
The active participation of WCRP within IGOS (in particular within the Ocean/Atmospheric Chemistry/Water Cycle Themes) is a successful example of use of an international forum.

Participation of Space Agencies in WCRP Committees

To-day, representatives of major Space Agencies occasionally participate in key meetings of WCRP committees, such as the Joint Scientific Committee, Scientific

Steering Committees of WCRP core projects and modelling groups. This should be done on a systematic basis and institutionalised as proposed in section 7.2 above. In parallel, WCRP core projects should set up ad hoc Task Forces of limited duration or charge voluntary members to collect and formulate requirements for space data which would be discussed at the occasion of Steering Committees meetings together with representatives of Space Agencies.

Mobilisation of Climate research community

Climate change is now a major concern to general public, decision-makers and politicians. The climate research community was, in particular for the preparation of the Johannesburg Summit on Sustainable Development, heavily consulted by politicians and decision-makers on climate change issues. Climate scientists and experts should use these opportunities to sensitise decision-makers at national and international levels on the important role played by Space to better understand and predict climate variations and consequent implications on Society, Economy and Environment , the three pillars of Sustainable Development. This would provide a solid justification for requesting that more resources (staff and financing) be allocated to climate research to properly exploit the existing and forthcoming space assets representing tenths of billions of dollars/euros in terms of investments from national and regional public budgets

8- **Conclusions and Recommendations**

Current mission plans of Space Agencies will lead to the launch, during this decade, of a large constellation of operational and research / precursor Earth Observation satellites with advanced measurement capabilities.

The Working Group recognised that these space measurements, supplemented with data from in-situ observation networks and use of increasingly powerful models, will offer **an unprecedented potential for climate research provided joint coordinated efforts be made between WCRP and space agencies to turn the separate sensor/satellite data into globally integrated products for climate research.**

In order to get the full benefit of these large space investments, the Working Group made a number of specific recommendations in sections 5 and 6, as regard the space segment namely, the importance of ensuring continuity of existing and planned missions or measurements (Precise altimeter missions, Earth radiation measurements…), the identification of priorities for next space missions and measurements (precipitation/GPM, salinity and soil moisture/ SMOS), the need to explore further scientific processes crucial for climate understanding (troposphere/stratosphere interaction processes, cloud radiative processes…). The importance of protecting appropriate radio-frequencies for the next generation of microwave sensors was also highly stressed by the Working Group.

The Working group also made a number of specific recommendations concerning data management issues which deserve particular attention from Space Agencies (cross-calibration of sensors, validation of data products, archiving and re-processing strategies, generation of long records of key climate products identified by WCRP, delivery time…).

To improve the current situation, the Working Group recommended *a closer interaction between WCRP and Space Agencies and proposed a multi-level coordination structure,* allowing WCRP to have a more pro-active role with Space Agencies. This mechanism together with other existing ones (e.g. CEOS, IGOS) would contribute to harmonising space mission plans (e.g. minimise unnecessary duplications, fill observation gaps, organise in an efficient way cross-calibration of sensors, ensure mission continuity as necessary, generate climate products…) and data policies for access to data, in particular for high resolution space imagery important for some climate research community.

The Working Group stressed the *urgent need to increase resources for the exploitation and analysis of current and planned satellite observations*, including re-inforced international cooperation to analyse globally integrated (operational and experimental) data sets. Particular effort should be put on the development of physical algorithms and more rigorous models (e.g. radiative transfer models) for data interpretation and analysis.

Lastly, the Working Group expressed its concern for *the transition from research to operational systems* since many of required space observations are and will be performed in the context of research programmes from Space Agencies. *The Working Group recommended that some institutional mechanisms/specific programmes be set up by space agencies* to ensure the proper transfer of validated/mature observation systems to operational entities, as it is the case to-day for meteorological observations (recent examples are the ERS wind scatterometer and the ozone GOME demonstration instruments developed by ESA, which now will be embarked on the operational METOP series of Eumetsat).

Progress in climate research will largely benefit from the implementation of satisfactory solutions for the problem areas identified and discussed by the Working Group.

9- References

Reference 1 CEOS Plenary-1992, WCRP requirements for space observations

Reference 2 WCRP letters to Heads of space agencies-1996, Space mission priorities

Reference 3 GCOS Plan for space-based observation- 1995, GCOS-15, WMO/TD-684

Reference 5 WMO Satellite Report, Technical Document WMO/TD N° 1052

Reference 5 CEOS Earth Observation Handbook- 2002

Reference 6 Integration of Research and Operational satellite systems for climate research Space Studies Board / National Research Council- 2000

10- Annexes

Annex 1 Contributions of existing and planned space missions

Annex 2 GCOS Climate Monitoring Principles

Annex 3 Composition of WCRP Satellite Working Group

ANNEX 1

Contributions of existing and planned space missions

A summary of contributions of existing and planned space missions for the measurement/determination of geophysical parameters of importance for climate research is briefly outlined hereafter according to the two main relevant categories of space missions namely, operational meteorological missions providing routine weather services and scientific research/demonstration missions for studies of climate processes.

(i) Operational polar and geo-stationary meteorological satellites

The current generation of operational meteorological satellites provides the basic quality 3-D measurements on temperature, humidity and wind essential for numerical weather forecasting and for estimating energy and water transformation in the atmosphere and fluxes at the air-sea interface. These data are used to-day for climate research but they suffer from limitations (in terms of accuracy, coverage, horizontal and/or vertical resolutions and distributions, stability and consistency of data, revisiting frequencies, lack of measurements for some important parameters…) to meet stringent climate research requirements. Improvements are necessary and, fortunately, will be available in a near future with the new generation of operational satellites just launched (e.g. MSG-1) or under development for launch over the next 5/6 years.

The new (or improved) operational generation (polar METOP and NPOESS series and US DoD/DMSP series- although all DMSP data are not fully accessible-, geo-stationary MSG series…) will significantly improve the situation in many areas, drawing on the lessons learnt from previous missions. They will embark comprehensive sets of instruments with complementary and synergistic capabilities, including:

- A combination of second generation infra-red (IASI, CrIS) and microwave sounders (MHS, CMIS, ATMS) and multi-spectral high resolution cloud imagery to provide better accuracy (10% for humidity and 1°K for temperature), better vertical (1 km) resolution and all-weather capability (with radio occultation sensors such as GRAS with IASI on METOP and GPSOS with CrIS on NPOESS) for basic measurements such as data on water vapour column and profiles, cloud parameters, sea-ice characteristics…
- New multi-channel visible/infra-red imagers (VIIRS) to provide the highly demanded accurate sea (and land) surface temperature as well as ocean colour essential for studies of geo-biological processes. temperature and moisture profiles in the troposphere; This will also provide improved
- Improved ozone sensors (GOME-2, OMPS) to provide better information on vertical and horizontal distribution of ozone and atmospheric minor constituents.
- New sensors for aerosol composition using sensitive spectral polarimetric techniques (APS on NPOESS)

- Advanced wind scatterometer (ASCAT) to provide wind stress and wind field at the ocean surface with better spatial resolution and coverage, large-scale cryospheric features (sea-ice motion, land-ice motion) and vegetation cover information.
- Microwave multi-channel imaging radiometers (SSM/I, AMSR, CMIS) to provide all-weather sea surface temperature, water vapour, wind speed, sea-ice, land-ice and snow characteristics at medium/coarse resolution.
- Improved multi-spectral imaging radiometers (VIIRS) for global large-scale land and vegetation cover, extending long term series of current AVHRR measurements and complementing high and medium resolution imagery from operational land observation satellite series (Landsat / TM and ETM, SPOT / HRV and Vegetation).
- Total solar irradiance sensor (TSIS) on NOAA series and GERB (on MSG series) for Earth radiation budget.
- New multi-channel imaging radiometers, with improved radiometric, spectral, spatial and temporal resolution, on-board geo-stationary satellites (such as SEVIRI on MSG) to greatly improve the quality of observations of parameters such as atmospheric water vapour, surface temperature, cloud properties.

(ii) Experimental / Research / Exploratory / Precursor missions

The (about) 30 research and demonstration satellites launched during the past decade have "revolutionised" and opened totally new horizons about the capabilities and potential of Earth observation from space. An equal number of new experimental space missions will be put into orbit over the next decade bringing further impressive results. Only a brief summary of some "break-through" achievements and expected future improvements is given hereafter for the major disciplinary Earth science fields:

Oceanography

Satellites have become essential tools to monitor and understand the physical and bio geochemical processes that determine ocean circulation and the effects of the oceans on inter-annual to decadal climate change and to provide a number of key observations necessary for climate predictions.

During the past decade,

- Precise radar altimeter missions (Topex/Poseidon and Jason-1) have demonstrated their ability to provide global mean sea level and ocean surface dynamic topography with centimeter-level absolute accuracy. These missions were complemented with ERS-1 and 2, and now Envisat, providing polar coverage and ocean mesoscale variability. Use of improved Earth's gravity field models resulting from space missions such as CHAMP and GRACE will allow further refinement of accuracies.
- Global surface wind/wave fields (ERS/AMI wind/wave, QuickSCAT /SeaWinds) and accurate sea-surface temperature measurements (ERS/ATSR and Envisat /AATSR, Terra and Aqua/MODIS) are now available for a better assessment of atmosphere-ocean energy and momentum exchanges.
- A new generation of microwave radiometers (TRMM/TMI, Aqua/AMSR) are also providing outstanding results for all-weather sea surface temperature measurements. These sensors have revolutionized studies of air/sea interaction, such as the impacts of hurricane wakes on subsequent hurricanes.

- Synthetic Aperture Radar (ERS/SAR and Envisat / ASAR) have demonstrated their capability to detect surface frontal features, internal waves and to provide global 2-D wave spectra (wavelength and direction), in particular, for the latter, through data assimilation in wave models.
- Several missions have embarked on a new generation of high spectral sensitivity imaging spectrometers (OCTS/ADEOS-1, Envisat/MERIS, Terra and Aqua/MODIS, SeaStar/SeaWiFS, IRS/MOS…) for ocean colour and ocean primary productivity measurements in support of studies of oceanic bio-geochemical processes. Fluorescence measurements from MODIS have greatly improved chlorophyll estimates in coastal waters and show promise for improving estimates of primary productivity.

In the next decade,

- Further improvements are expected from the forthcoming missions which will provide additional measurements of sea surface temperature (ADEOS-2/GLI, Windsat/Coriolis and AMSR) and ocean colour (ADEOS-2/ GLI and POLDER and Oceansat-2/OCM).
- ESA/GOCE mission, complementing GRACE, will allow further precise determination of the global model of Earth's gravity field and geoid (accuracy of 1 mgal and 1cm at spatial resolution of 100 km) essential for higher accuracy ocean surface topography determination.
- The utilisation of signals-of-opportunities (bouncing off the ocean) from navigation satellites (GPS, GNSS, GLONASS) will also provide enhanced temporal and spatial observations of near surface winds, waves and sea level topography.

Cryosphere

The cryosphere plays an important role in global climate, in climate model response to global change and as an indicator of change in the climate system. For instance, polar sea-ice concentration, extent and large scale motion have been successfully monitored on a regular basis by passive microwave radiometers (SMMR and SSM/I) since 1978. The corresponding trend derived from these observations have revealed a decline in total sea-ice concentration in the Arctic by nearly 3% per decade equivalent to a total loss of 615,000 square kilometres of sea-ice.

During the past decade,

- A major "revolution" for the observation of polar caps has resulted from the use of space-borne active microwave sensors namely, Synthetic Aperture Radars (SAR), providing all-weather high resolution imagery essential for the study of small scale sea-ice and land-ice processes. ERS-1&2 and Radarsat-1 SAR have provided systematic observations of small scale sea-ice motion and deformation (fracture patterns) which cannot be resolved by lower resolution passive or optical sensors. These observations allow estimation of sea-ice thickness and age from sequential maps. Complete mapping at high resolution with Radarsat-1 of Antarctica has been achieved in 1997 for the first time. SAR has also proved to be useful for land-ice topography and phenomena like glacier surges. In March 2002, Envisat ASAR has been able to observe the collapse of the Larsen B ice shelf in the Antarctica Peninsula.
- Unprecedented results have been obtained using SAR interferometric techniques (InSAR) to measure centimetric ice motion, grounding line location and small scale topographic features. Velocity fields and surface relief of glaciers have been derived

from ERS-1 & 2 Tandem operations. Unfortunately these results remain mostly at demonstration level because of the limited quantities of SAR imagery delivered, free-of-charge, to scientists. SAR missions are generally driven by commercial objectives imposing mission planning restrictions ("on-demand" approach) and the cost of data is prohibitive for the systematic observation of large regions such as the Arctic, Greenland and Antarctica.

- Innovative techniques have been explored for cryospheric studies (sea-ice motion, deformation and type, variability in boreal freeze-thaw patterns, permafrost…) using the 50 km-resolution wind scatterometer on ERS. Melt regions on the Greenland ice are mapped daily with the SeaWinds wide-swath Ku-band scatterometer on QuikSCAT. Analysis of melt extent on the Greenland ice sheet using passive and active microwave sensor data have shown a very dramatic increasing melt trend since 1979 Promising results have also been obtained with space-borne radar altimeters to map ice sheet topography and estimate ice thickness.
- As mentioned previously, long time series of passive microwave radiometry have shown large-scale changes in sea ice cover in the Arctic, and new measurements from EOS Aqua AMSR have revealed impressive detail of the one pack, given the improved spatial resolution of the sensor.

In the near future,

- Important new satellites will be launched to support studies of cryospheric processes. These include the NASA/ICESat and the ESA Cryosat missions. ICESat (ICE, Clouds and Land Elevation satellite) will embark a fine resolution laser altimeter (GLAS) to map sea-ice and land-ice elevations and provide cloud parameters such as height and thickness. Cryosat will complement ICESat, in measuring sea-ice and land-ice mass fluctuations at large space and time scales using synthetic aperture and interferometric techniques in synergy with radar altimetry.
- The launch of new SAR missions namely, the Canadian Radarsat-2 and the Japanese ALOS (both with increased performances in terms of spatial resolution and polarimetry) together with Envisat ASAR, and in combination with the two forthcoming laser and radar altimeter missions, will allow to obtain highly accurate estimates of sea-ice volume and mass as well as their changes.

Atmosphere state variables/cloud-radiation/ atmospheric chemistry

This is also a domain where major progress have been realised in order to better understand the Earth's energy budget and water cycle, cloud radiative processes, atmospheric chemistry processes and their relations with the climate system and its predictability. Global observations of atmospheric variables and constituents and surface properties have greatly benefited from the operational polar and geo-stationary imaging and sounding sensors with continuously improved performances and capabilities as well as from new advanced research or precursor missions and sensors.

During the last decade,

The development of a new generation of research/precursor sensors and missions with enhanced horizontal and/or vertical, spectral and radiometric resolutions and, in particular, better calibration, has provided encouraging perspectives for:

- 3-D precipitation measurements over tropical regions with TRMM sensors (PR, TMI,VIRS), providing comprehensive data on distribution of rainfall and latent heating between 35°N and 35°S.
- Improved data on cloud parameters (amount, type, top temperature, height, albedo) and properties, water vapour and temperature profiles, surface temperature and albedo…;These improved data are coming from a large number of new generation instruments such as MODIS, MERIS, AIRS, MISR (with multi-directional capabilities), ASTER, AATSR, POLDER…flown on Terra, Aqua, Envisat, ADEOS-1 …etc.
- Atmospheric chemistry for which, since the early nineties, the UARS mission from NASA has enabled the systematic and comprehensive study of the stratosphere. Measurements of aerosols characteristics (type, size, horizontal distribution…) are currently provided from a variety of new instruments (MODIS, MERIS, MISR, GOME, AATSR, POLDER…), some using limb-sounding techniques giving data on upper troposphere and stratosphere with high vertical resolution (POAM, SCIAMACHY, GOMOS, SAGE…).
- Data on atmospheric trace gases are also provided, besides TOMS, by numerous missions since UARS in the 90's, with ADEOS-1 (IMG, ILAS), Terra (MOPITT), ERS-2 (GOME) and Envisat (SCIAMACHY, MIPAS, GOMOS).
- Ozone monitoring from space has been performed since 1978 with long-term missions such as TOMS and SBUV-2;UARS instruments, POAM-II and III, SAGE, GOME and now Envisat sensors (GOMOS, MIPAS, Sciamachy) are bringing higher accuracy, day and night data on total ozone column and profile (with improved vertical resolution) using new observing (occultation , limb-viewing) techniques. Despite the growing number of ozone sensors, better vertical resolution and accuracy are still needed, as well as cross-calibration of all these measurements, to correctly assess ozone trends.
- The Earth's radiation budget has been monitored since the mid sixties primarily with ERBE on-board ERBS and more recently with ScaRaB on METEOR , CERES on TRMM, Terra and Aqua, and with GERB on MSG-1; POLDER on ADEOS-2 will provide polarisation and directional effects of reflected solar light. Many meteorological sensors also contribute to ERB measurements at the top of the atmosphere (TOA).
- Total solar irradiance has been measured since the late seventies with electrically self-calibrating cavity sensors (ACRIM1,2 &3, VIRGO) with appropriate overlapping and in-orbit redundancy.

The next decade (2002-2012), will see further major improvements and innovative approaches with:

- The launch of a key international (USA, Canada, France) cooperative space mission to study cloud properties with the "Aqua formation" in 2004, including Cloudsat equipped with a Cloud Profiling Radar for the study of the cloud vertical structure and composition, CALIPSO with a multi-wavelength lidar for high resolution measurements of aerosols and cloud properties and completed with a micro-satellite, PARASOL, embarking POLDER instrument.
- The use of navigation satellite (GPS, GLONASS, GNSS) signals is being studied to derive high resolution and accuracy temperature profiles from the upper troposphere through the higher stratosphere and water vapour profiles in the lower troposphere.
- The approved ESA demonstration ADM-Aeolus mission will provide 3-D wind profiles, directly measured from space for the first time, with a Doppler wind lidar (ALADIN).Winds in the stratosphere will also be accessible from interferometric measurements resulting from the French-Canadian SWIFT mission.

- The NASA Aura mission, in cooperation with UK and the Netherlands, embarking advanced instrumentation (OMI, HIRDLS, TES, MLS), will provide in 2004, comprehensive measurements of atmospheric trace gases with emphasis on the upper troposphere and lower stratosphere. The Canada/USA SCISat-1 with the Atmospheric Chemistry experiment, ACE, will focus on Canada and the Arctic region.
- The continuity of solar irradiance measurements will be ensured with SORCE (SIM, SOLSTICE, TIM) due to be launched at the beginning of 2003 and later on with the NPOESS series.
- The continuity of ERB measurements will be ensured with the operational NPOESS series.

Land

During the last decade,

Major results for vegetation monitoring, have been obtained with optical coarse resolution sensors such as AVHRR on NOAA series and later with Vegetation on SPOT-4 and 5. Recent development of new sensors with moderate but high spectral resolution (MODIS on Terra and Aqua, MERIS on Envisat),the launch of SAR missions (ERS-1 and 2, J-ERS-1, Radarsat-1, Envisat) providing new interferometric (for generation of DEMs) and polarimetric (for vegetation discrimination) capabilities, the availability of multi-angle imaging capability with MISR on Terra, the innovative large scale soil moisture determination potential with C-band wind scatterometers on-board ERS-1 and 2..etc, have brought new perspectives and potential for land surface characterisation (bio-physical properties, biomass estimation, vegetation indices, land cover and cover change and possibly soil moisture).
C-band SAR missions have shown some capabilities for high resolution soil moisture measurements but with limitations for coverage and revisit frequency. Passive microwave with low frequency channels have also some soil moisture measurement capability but with a low resolution and limitation to bare soil or low vegetation cover.
Use of high resolution optical imagery (SPOT, Landsat, ASTER on Terra…) for climate research has been limited to studies of local processes.

The next decade will see further improvements with:

- The launch of more SAR missions (ALOS, Radarsat-2…) operating at different frequencies and with improved performances, in particular, multi-polarimetry and spatial resolution, allowing better vegetation classification and biomass estimation.
- The increasing availability of improved passive microwave radiometer data (AMSR recently launched on ADEOS-2…) for land cover and properties measurements.

ANNEX 2

GCOS Climate Monitoring Principles

Effective monitoring systems for climate should adhere to the following principles:*

1. The impact of new systems or changes to existing systems should be assessed prior to implementation.

2. A suitable period of overlap for new and old observing systems is required.

3. The details and history of local conditions, instruments, operating procedures, data processing algorithms and other factors pertinent to interpreting data (i.e., metadata) should be documented and treated with the same care as the data themselves.

4. The quality and homogeneity of data should be regularly assessed as a part of routine operations.

5. Consideration of the needs for environmental and climate-monitoring products and assessments, such as IPCC assessments, should be integrated into national, regional and global observing priorities.

6. Operation of historically-uninterrupted stations and observing systems should be maintained.

7. High priority for additional observations should be focussed on data-poor regions, poorly-observed parameters, regions sensitive to change, and key measurements with inadequate temporal resolution.

8. Long-term requirements should be specified to network designers, operators and instrument engineers at the outset of system design and implementation.

9. The conversion of research observing systems to long-term operations in a carefully-planned manner should be promoted.

10. Data management systems that facilitate access, use and interpretation of data and products should be included as essential elements of climate monitoring systems.

Furthermore, satellite systems for monitoring climate should adhere to the following specific principles:

11. Rigorous station-keeping should be maintained to minimize orbital drift.

12. Overlapping observations should be ensured for a period sufficient to determine inter-satellite biases.

13. Satellites should be replaced within their projected operational lifetime (rather than on failure) to ensure continuity (or in-orbit replacements should be maintained).

14. Rigorous pre-launch instrument characterization and calibration should be ensured.

15. Adequate on-board calibration and means to monitor instrument characteristics in space should be ensured.

16. Development and operational production of priority climate products should be ensured.

17. Systems needed to facilitate user access to climate products, metadata and raw data, including key data for delayed-mode analysis, should be established and maintained.

18. Continuing use of still-functioning baseline instruments on otherwise de-commissioned satellites should be considered.

19. The need for complementary in-situ baseline observations for satellite measurements should be appropriately recognized.

20. Network performance monitoring systems to identify both random errors and time-dependent biases in satellite observations should be established.

** The ten basic principles were adopted (in paraphrased form) by the Conference of the Parties to the UN Framework Convention on Climate Change through Decision 5/CP.5 of COP-5 at Bonn in November, 1999. The entire set was endorsed by WMO EC-LIV and is undergoing final review prior to submission to WMO Congress in May 2003.*

ANNEX 3

Composition of WCRP Satellite Working Group

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