A critical perspective on our ability to model

Circulation Extremes and Climate Change

Tim Palmer
University of Oxford

Why do we need trustworthy climate models?

- Mitigation
- Adaptation
- Geoengineering
- Attribution

Simulating climate extremes accurately is crucially important for all of these.
Are current generation models trustworthy enough?

Earth's Climate is a nonlinear system

$$\rho\left(\frac{\partial}{\partial t}+\mathbf{u}.\nabla\right)\mathbf{u}=\rho\mathbf{g}-\nabla p+\mu\ \nabla^{2}\mathbf{u}$$

In a nonlinear system, *a posteriori* bias correction is an unreliable way to correct for model inaccuracy.

In a nonlinear system, for a model to be trustworthy, model bias should be small compared with the sort of signals we wish to simulate/predict.

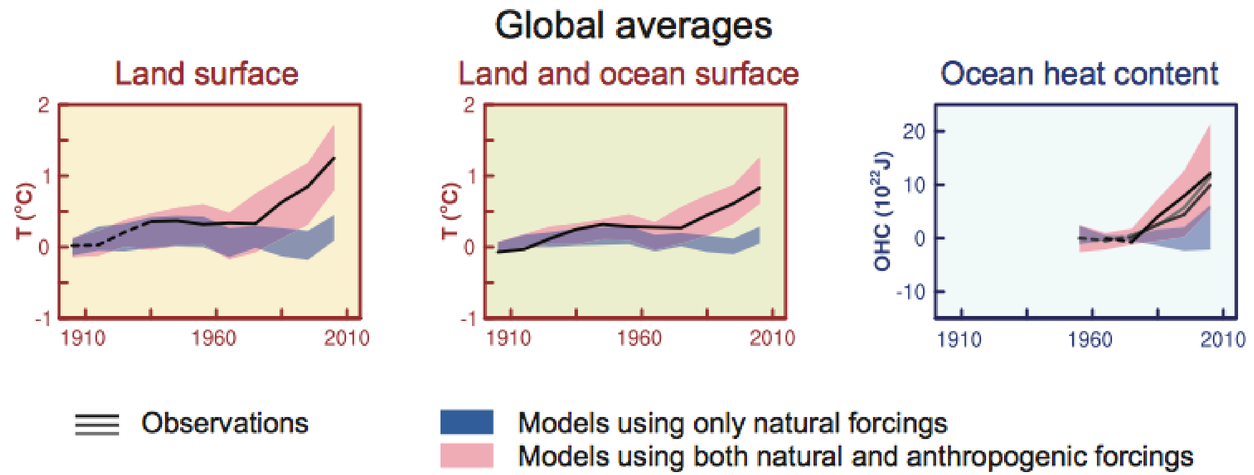
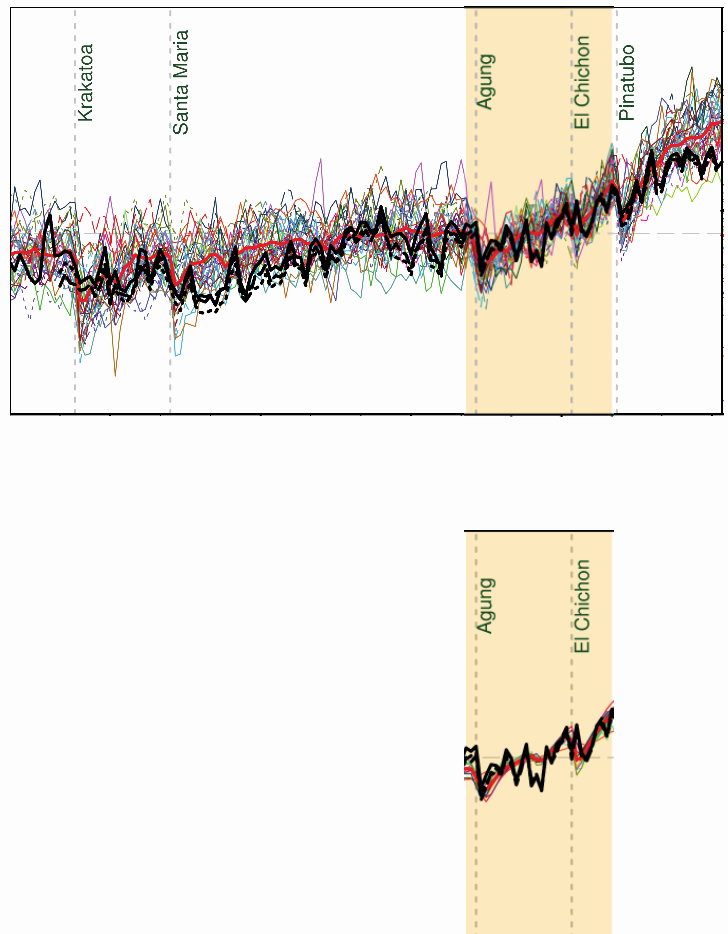


Figure SPM.6 | Comparison of observed and simulated climate change based on three large-scale indicators in the atmosphere, the cryosphere and the ocean: change in continental land surface air temperatures (yellow panels), Arctic and Antarctic September sea ice extent (white panels), and upper ocean heat content in the major ocean basins (blue panels). Global average changes are also given. Anomalies are given relative to 1880–1919 for surface temperatures, 1960–1980 for ocean heat content and 1979–1999 for sea ice. All time-series are decadal averages, plotted at the centre of the decade. For temperature panels, observations are dashed lines if the spatial coverage of areas being examined is below 50%. For ocean heat content and sea ice panels the solid line is where the coverage of data is good and higher in quality, and the dashed line is where the data coverage is only adequate, and thus, uncertainty is larger. Model results shown are Coupled Model Intercomparison Project Phase 5 (CMIP5) multi-model ensemble ranges, with shaded bands indicating the 5 to 95% confidence intervals. For further technical details, including region definitions see the Technical Summary Supplementary Material. {Figure 10.21; Figure TS.12}

AR5 SPM



AR5 Ch 9.

Figure 9.8 | Observed and simulated time series of the anomalies in annual and global mean surface temperature. All anomalies are differences from the 1961–1990 time-mean of each individual time series. The reference period 1961–1990 is indicated by yellow shading; vertical dashed grey lines represent times of major volcanic eruptions. (a) Single simulations for CMIP5 models (thin lines); multi-model mean (thick red line); different observations (thick black lines). Observational data (see Chapter 2) are Hadley Centre/Climatic Research Unit gridded surface temperature data set 4 (HadCRUT4; Morice et al., 2012), Goddard Institute for Space Studies Surface Temperature Analysis (GISTEMP; Hansen et al., 2010) and Merged Land–Ocean Surface Temperature Analysis (MLOST; Vose et al., 2012) and are merged surface temperature (2 m height over land and surface temperature over the ocean). All model results have been sub-sampled using the HadCRUT4 observational data mask (see Chapter 10). Following the CMIP5 protocol (Taylor et al., 2012b), all simulations use specified historical forcings up to and including 2005 and use RCP4.5 after 2005 (see Figure 10.1 and note different reference period used there; results will differ slightly when using alternative RCP scenarios for the post-2005 period). (a) Inset: the global mean surface temperature for the reference period 1961–1990, for each individual model (colours), the CMIP5 multi-model mean (thick red), and the observations (thick black: Jones et al., 1999). (Bottom) Single simulations from available EMIC simulations (thin lines), from Eby et al. (2013). Observational data are the same as in (a). All EMIC simulations ended in 2005 and use the CMIP5 historical forcing scenario. (b) Inset: Same as in (a) but for the EMICs.

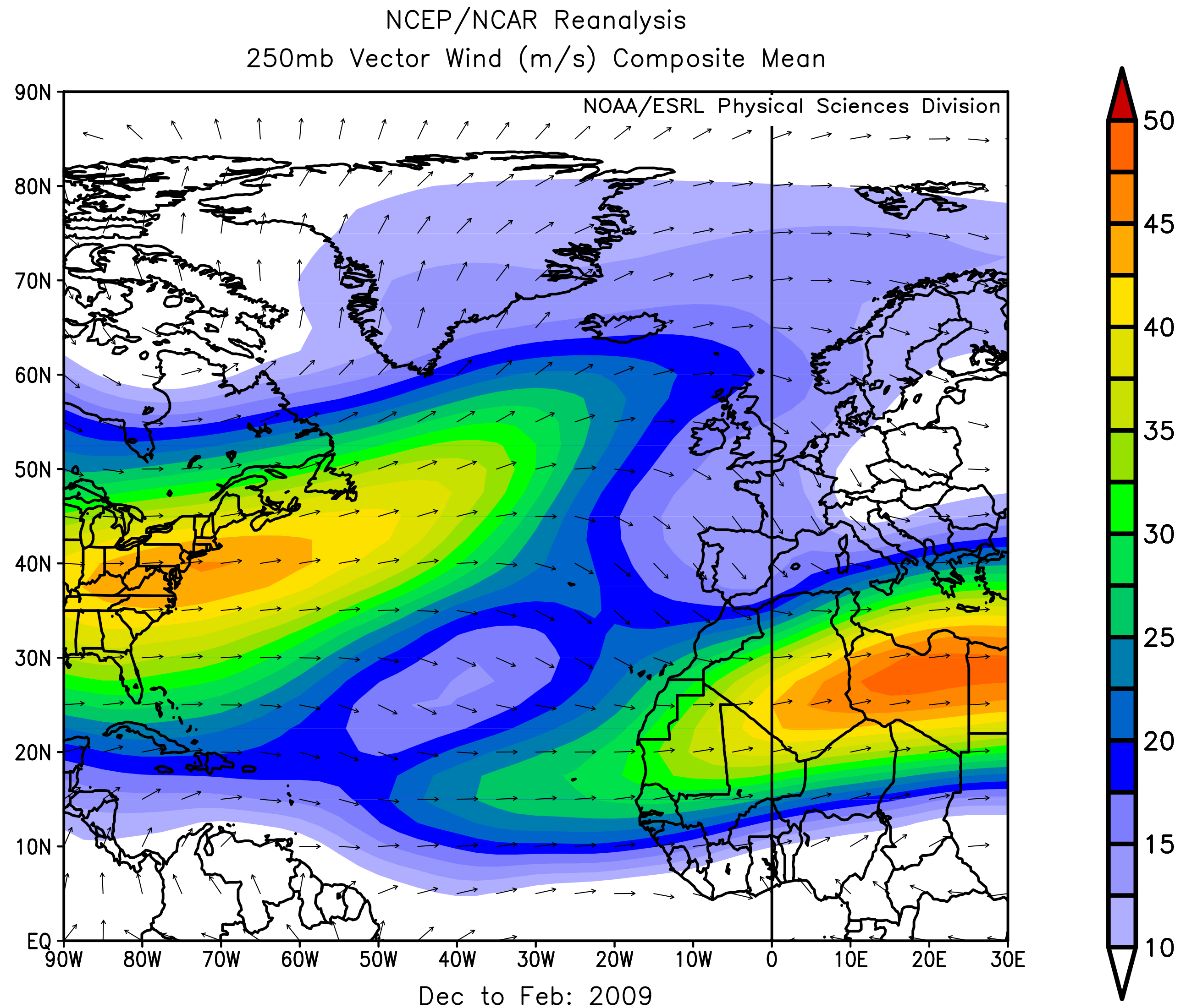
Attribution of eg Heat Waves

- Major heat waves tend to be associated with long-lived anticyclones (e.g. 2003).
- Does increased CO_2 increase the surface temperatures associated with a given long-lived anticyclone?
- Does increased CO_2 increase the frequency of occurrence of long-lived anticyclones?

Attribution of eg Winter Flooding Events

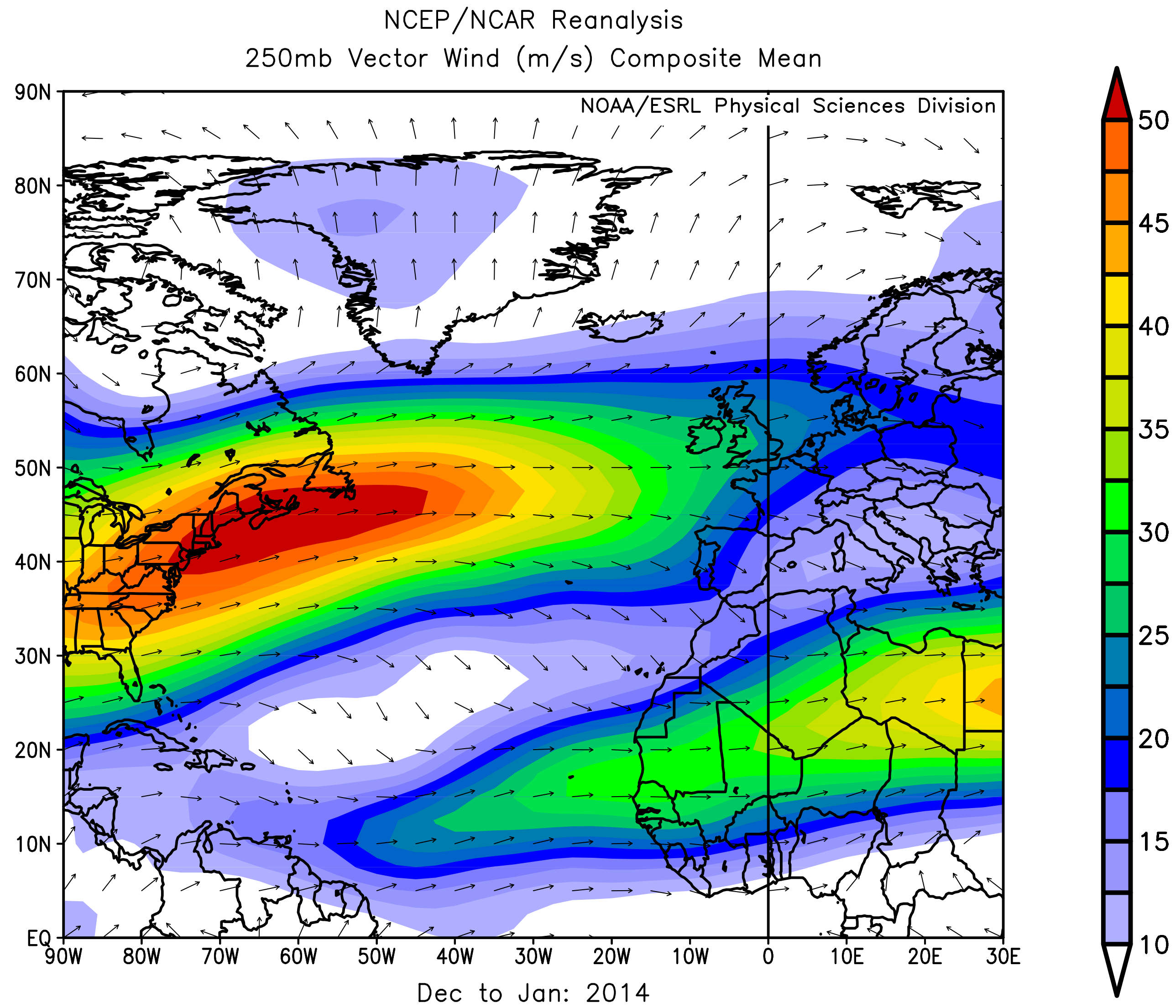
- Major winter flooding events tend to be associated with increased rainfall associated with enhanced cyclonic activity?
- Does increased CO_2 increase the rainfall associated with a given cyclone?
- Does increased CO_2 increase the frequency of occurrence of cyclonic activity?

Winter 2008/09 – a 'normal' year



Tim Woollings

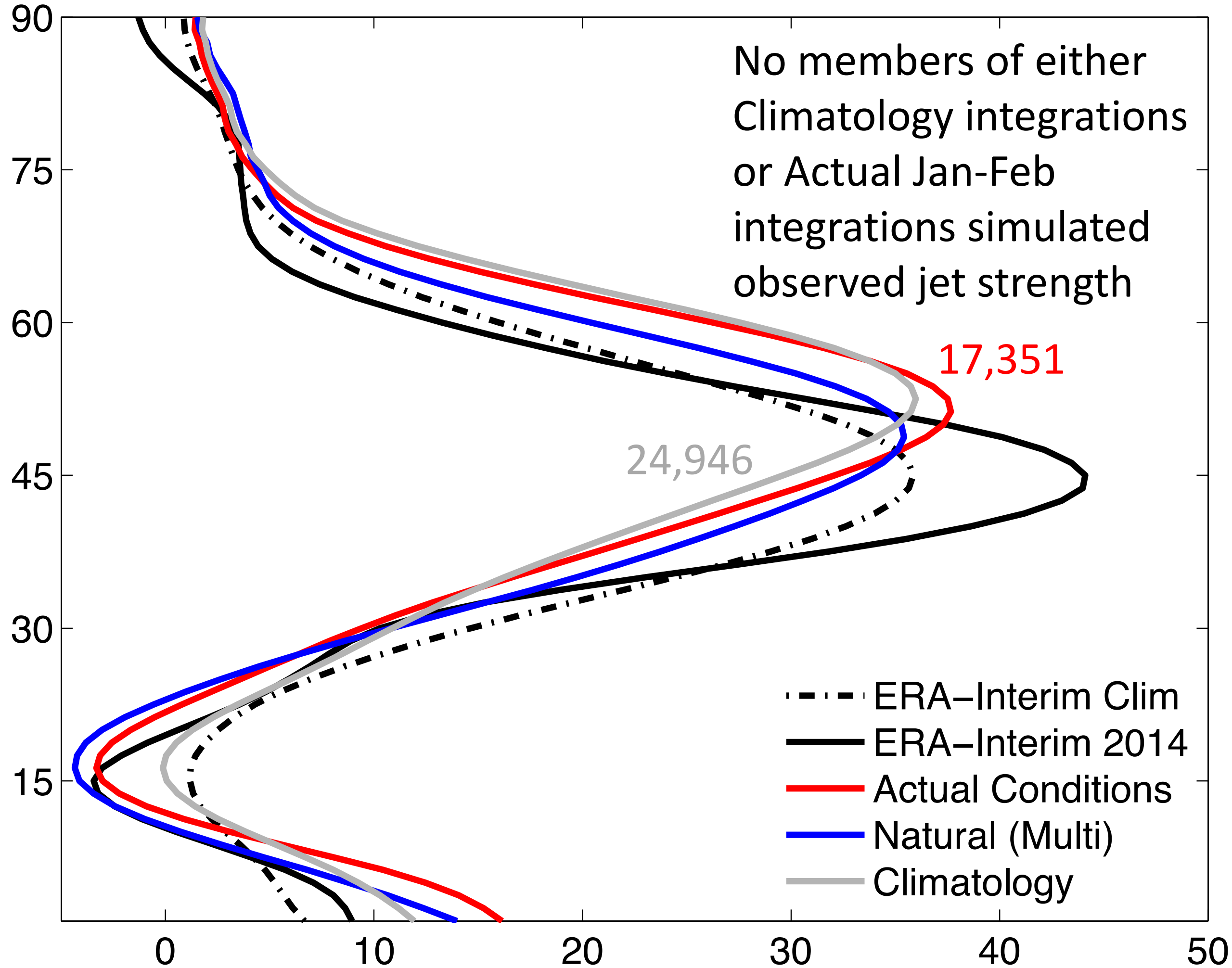
Winter 2013/14 – strong, straight jet



Tim Woollings

Do strong jets like this become more likely with climate change?

Does climate change increase the likelihood of a strong jet over E Atlantic?



Nathalie Schaller and Elizabeth Carr

From climateprediction.net study. Hadam3 + regional model, observed SSTs)

PV Gradient Across Tropopause

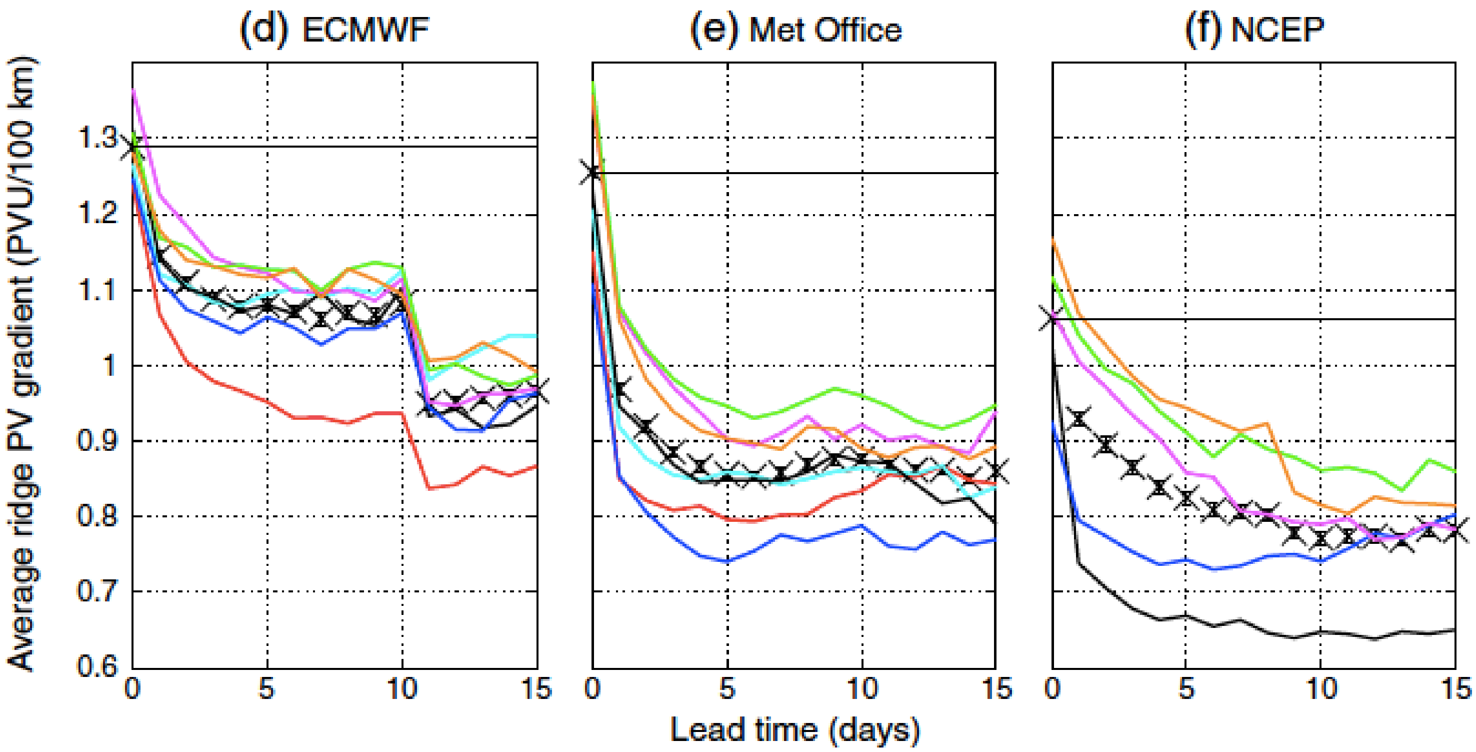


Figure 5. (a–c) Average ridge area and (d–f) the isentropic PV gradient flanking ridges as a function of forecast lead time for ECMWF, Met Office, and NCEP. Black markers with error bars (standard errors) are averages over all winter seasons with horizontal lines extending across all lead times from the analysis values. Colored lines are averages for the individual seasons where red is 2006/2007, cyan is 2007/2008, black is 2008/2009, blue is 2009/2010, magenta is 2010/2011, green is 2011/2012, and orange is 2012/2013. Note (as an example) that a fraction of the Northern Hemisphere of 0.05 is equivalent to an area of 1.275×10^7 km^2.

Gray et al, GRL, 2014

Ben Harvey, University of Reading

RW propagation – smooth PV step

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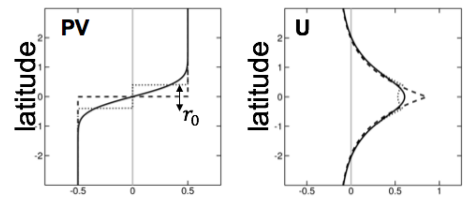
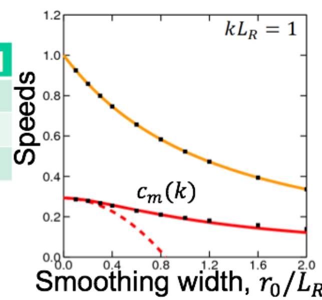
$$c_m \approx \int (U_s(y) - \phi_s(y))w(y)\,dy$$

- Putting some numbers in…
  - $r_0 = \frac{\Delta PV}{\max PV_y} \approx \begin{cases} 308\ km\ (analysis) \\ 381\ km\ (forecast) \end{cases}$
  - Also use: $L_R = 700\ km, \Delta PV = 4PVU$
  - Result:

	U_{max} [m/s]	c_m [m/s]	$c_{m,g}$ [m/s]
Sharp PV front:	70.0	20.5	45.3
$r_0 = 308\ km$:	50.9	17.7	38.2
$r_0 = 381\ km$:	47.6	16.8	36.0

- Typical phase error after 5 days = O(400km)





Dots = numerical simulation

Jet speed

RW speed

Amplitude error – what's its cause?

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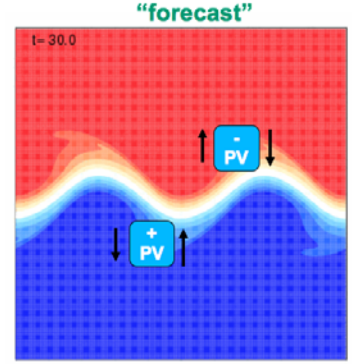
- Advection on the jet flank leads to a systematic accumulation of PV
  - The induced circulation acts to damp the Rossby wave
- Consistent with meridional dispersion of wave activity
- Diffusion at small scales acts to damp large scale waves via systematic accumulation of PV relative to the ridges and troughs

"forecast"



Tropical Biases in CMIP5 Multimodel Ensemble: The Excessive Equatorial Pacific Cold Tongue and Double ITCZ Problems*

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(Manuscript received 9 June 2013, in final form 30 October 2013)

ABSTRACT

Errors of coupled general circulation models (CGCMs) limit their utility for climate prediction and projection. Origins of and feedback for tropical biases are investigated in the historical climate simulations of 18 CGCMs from phase 5 of the Coupled Model Intercomparison Project (CMIP5), together with the available Atmospheric Model Intercomparison Project (AMIP) simulations. Based on an intermodel empirical orthogonal function (EOF) analysis of tropical Pacific precipitation, the excessive equatorial Pacific cold tongue and double intertropical convergence zone (ITCZ) stand out as the most prominent errors of the current generation of CGCMs. The comparison of CMIP–AMIP pairs enables us to identify whether a given type of errors originates from atmospheric models. The equatorial Pacific cold tongue bias is associated with deficient precipitation and surface easterly wind biases in the western half of the basin in CGCMs, but these errors are absent in atmosphere-only models, indicating that the errors arise from the interaction with the ocean via Bjerknes feedback. For the double ITCZ problem, excessive precipitation south of the equator correlates well with excessive downward solar radiation in the Southern Hemisphere (SH) midlatitudes, an error traced back to atmospheric model simulations of cloud during austral spring and summer. This extratropical forcing of the ITCZ displacements is mediated by tropical ocean–atmosphere interaction and is consistent with recent studies of ocean–atmospheric energy transport balance.

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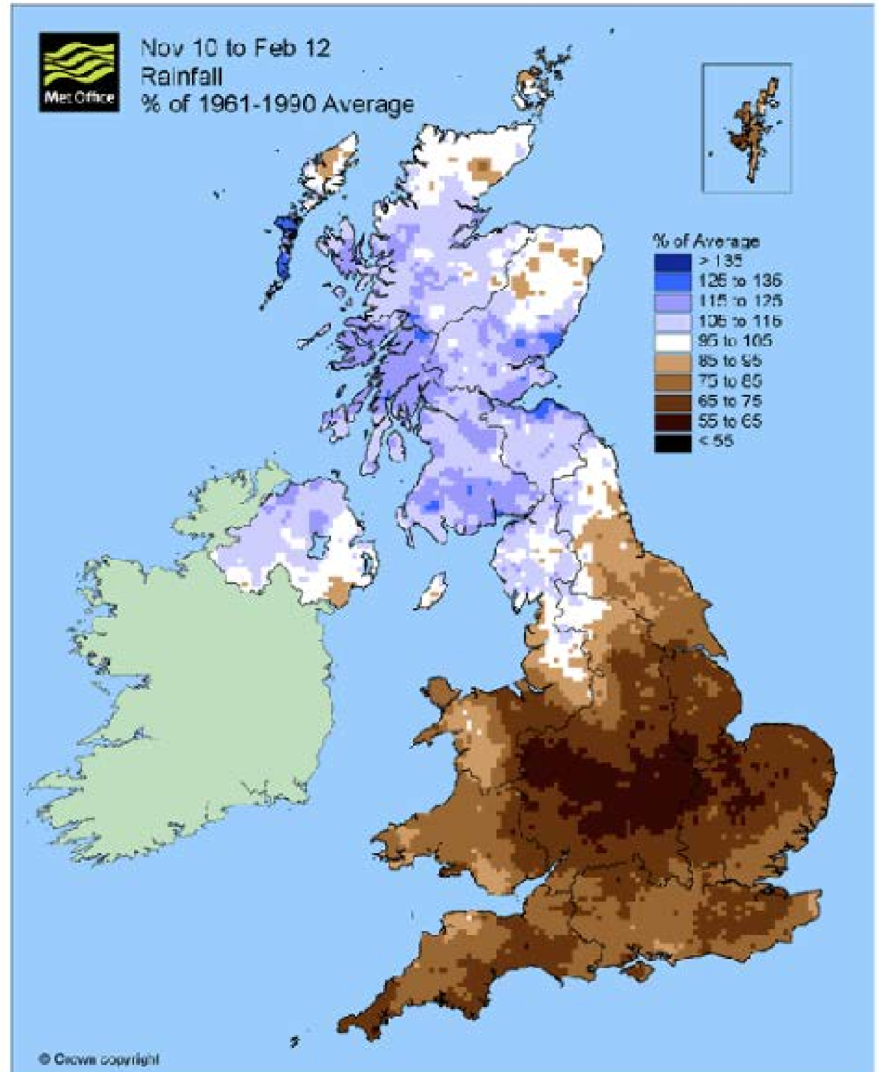
Why are we in drought?

13 03 2012

Rainfall amounts across many parts of the UK have been below average for the last two years. Importantly, this includes two dry winters – the periods when we would normally expect our rainfall to replenish river, reservoir and groundwater levels.

2010 was the eleventh-driest year in the series from 1910 and the driest since 2003. The dry weather continued during 2011 with large parts of central, eastern and southern England having well below average rainfall – several Midland counties – such as Shropshire, Nottinghamshire, Leicestershire and Warwickshire – had their driest year on record.



Map showing the rainfall seen between Nov 2010 and Feb 2012 compared to the long-term average for the same period

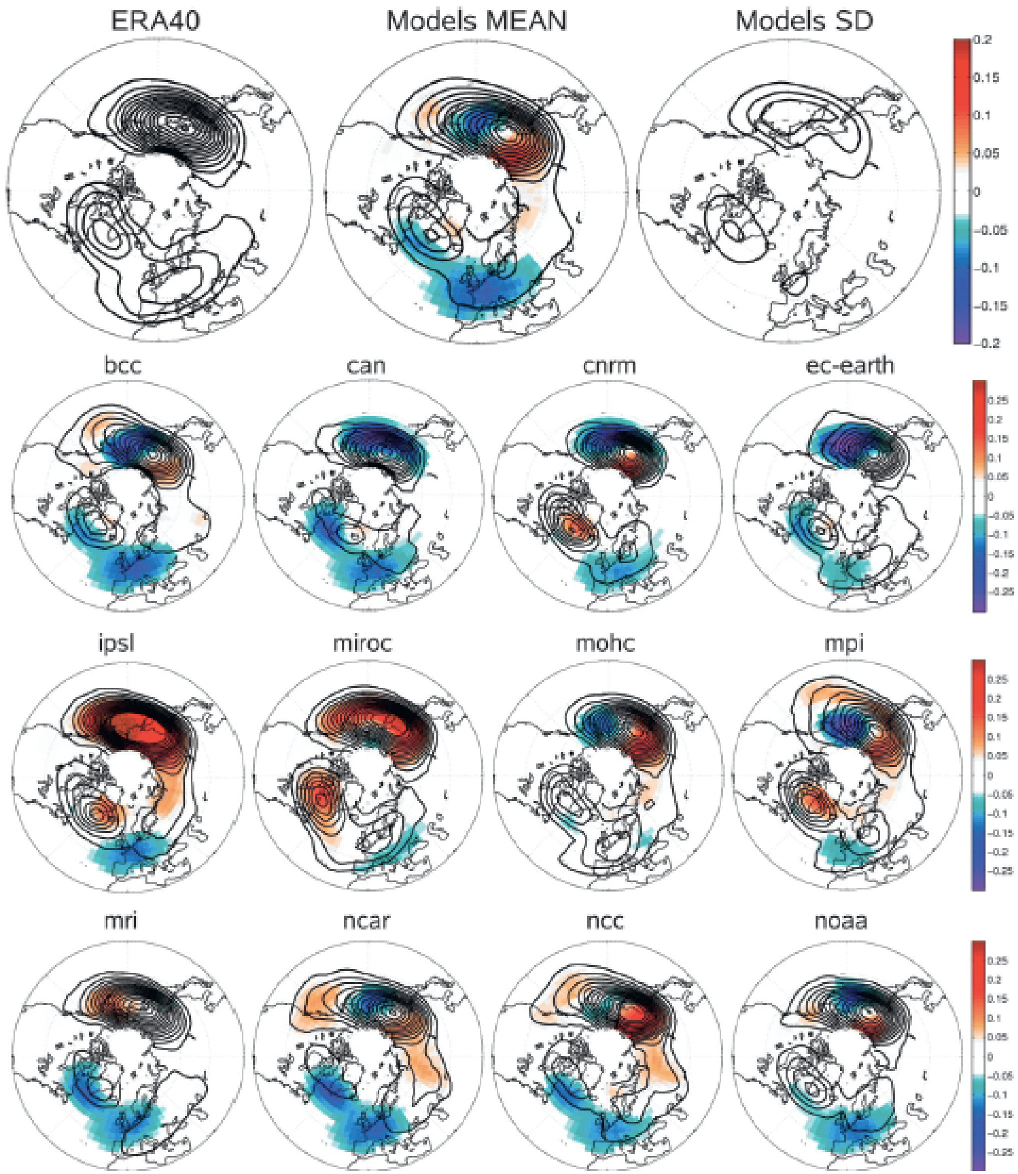
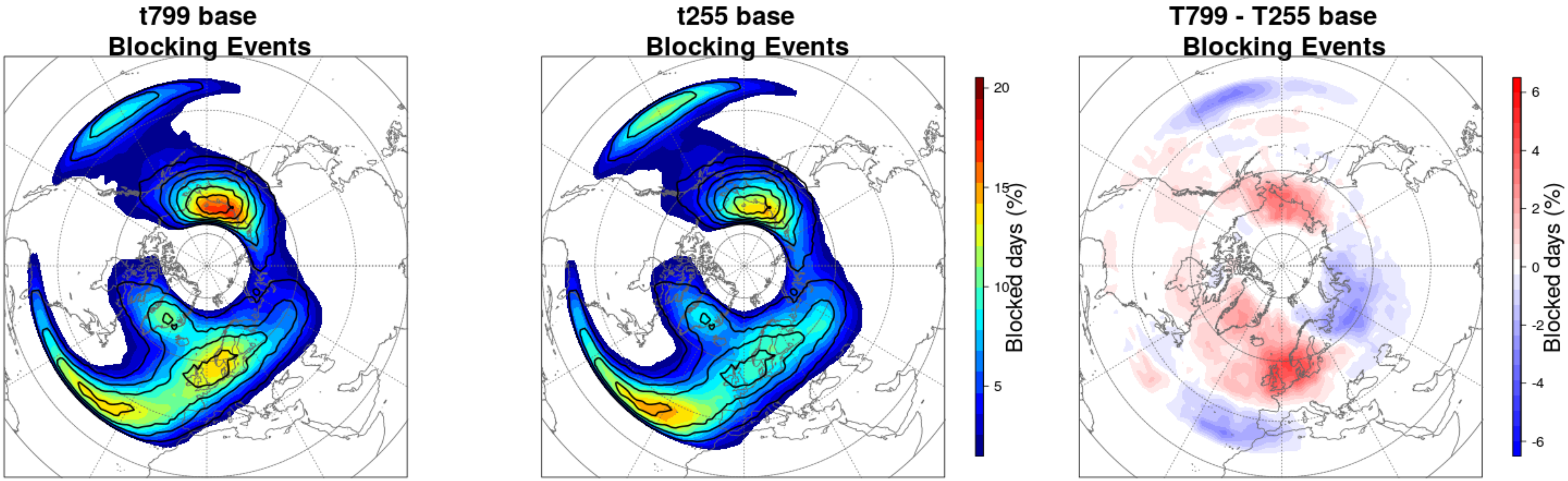


FIG. 1. (top) The 2D daily frequency of blocking (expressed in percentages; see section 2b for more details) during winter for ERA-40, the multimodel mean, and the intermodel standard deviation. The color shading represents the difference between the multimodel mean and the reanalysis. (bottom) The 2D daily blocking frequency for all the models considered (see Table 1 for details). Contours are every 0.05. The color shading represents the difference between each model and the reanalysis.



Paolo Davini. SPHINX PRACE

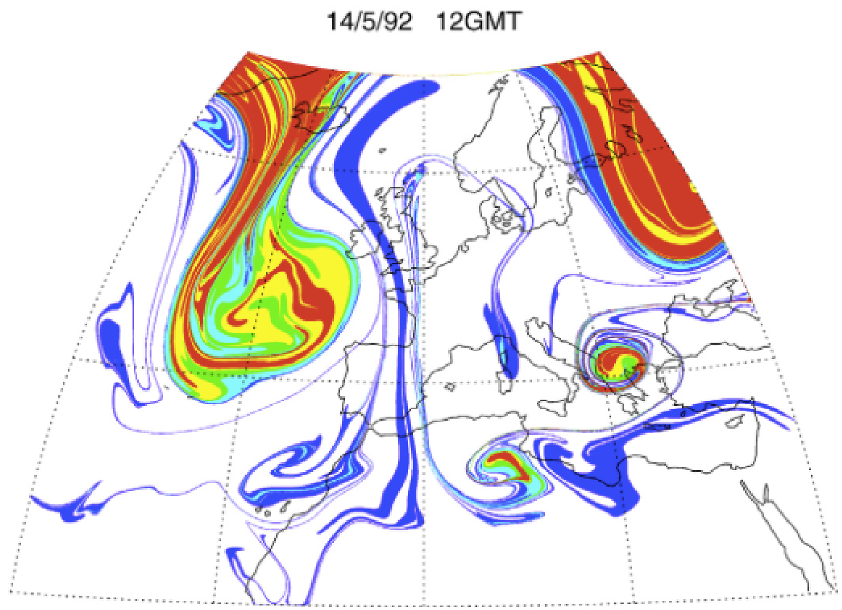


Figure 2 Estimated isentropic distribution of the (Rossby–Ertel) PV on the 320 K isentropic surface on 14 May 1992 at 1200 UT (Greenwich mean time), derived from observations as explained in the text. Over Europe the 320 K surface lies near jetliner cruising altitudes $z \sim 10$ km. The estimate used data from the operational weather-prediction analyses of the European Centre for Medium Range Weather Forecasts (ECMWF). Values from 1 PVU upwards are colored rainbow-wise from dark blue to red, with contour interval 1 PVU, where 1 PVU $= 10^{-6}$ m^2 s^{-1} K kg^{-1}. Courtesy W. A. Norton (personal communication); further details in Appenzeller et al. (1996). Figure 15(b) on p. 1450 of that paper checks that the wind field does, as expected from PV inversion, exhibit the usual tropopause jet structure around the periphery of the large high-PV region on the left. See *PV Mixability and Strong Jets* below.

LETTERS
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Importance of latent heat release in ascending air streams for atmospheric blocking

S. Pfahl[1]*, C. Schwierz[2], M. Croci-Maspoli[3], C. M. Grams[1] and H. Wernli[1]

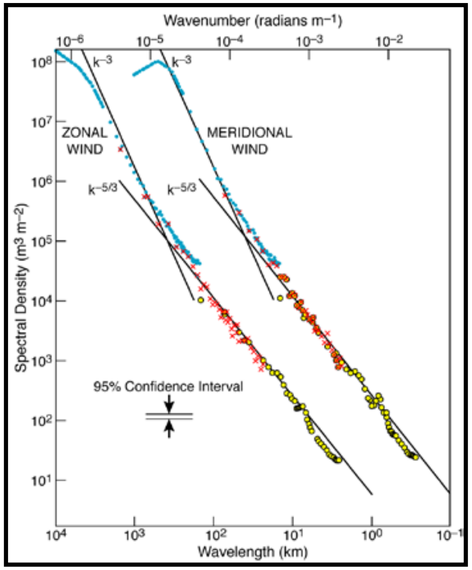
Atmospheric blocking is a key component of extratropical weather variability[1] and can contribute to various types of extreme weather events[2–5]. Changes in blocking frequencies due to Arctic amplification and sea ice loss may enhance extreme events[6,7], but the mechanisms potentially involved in such changes are under discussion[8–11]. Current theories for blocking are essentially based on dry dynamics and do not directly take moist processes into account[12–17]. Here we analyse a 21-year climatology of blocking from reanalysis data with a Lagrangian approach, to quantify the release of latent heat in clouds along the trajectories that enter the blocking systems. We show that 30 to 45% of the air masses involved in Northern Hemisphere blocking are heated by more than 2 K—with a median heating of more than 7 K—in the three days before their arrival in the blocking system. This number increases to 60 to 70% when considering a seven-day period. Our analysis reveals that, in addition to quasi-horizontal advection of air with low potential vorticity[12–15], ascent from lower levels associated with latent heating in clouds is of first-order importance for the formation and maintenance of blocking. We suggest that this process should be accounted for when investigating future changes in atmospheric blocking.

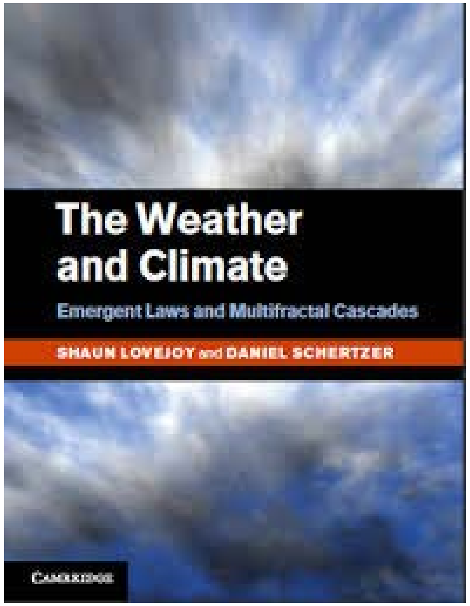
Atmospheric blocking refers to the formation of large-amplitude synoptic-scale quasi-stationary anticyclones in the extratropics, role of wave breaking[16] and the isentropic advection of air with low potential vorticity (PV) into the blocking region[12–15]. All these theories are essentially based on dry atmospheric dynamics, and diabatic processes have been considered only in an indirect way, for example, through the triggering of Rossby waves by tropical convection[13]. There are only few studies pointing to direct diabatic effects on blocking: substantial diabatic contributions to the intensification of two blocking systems in the Southern Hemisphere have been identified in ref. 20, whereas diabatic effects have been found to be of secondary importance for blocking formation over Siberia in ref. 21. Backward trajectory calculations from North Atlantic blockings during selected winters presented in refs 22,23 indicate that latent heating is often involved in the upward transport of air with low PV into the upper-tropospheric blocking. In this study, again a combined PV and Lagrangian approach is used to systematically assess the relevance of this diabatic mechanism for Northern Hemisphere blocking based on 21 years of ERA-Interim reanalysis data.

Different indices have been developed to identify blocking based on geopotential height, potential temperature (θ) or PV (see the methodological discussion in ref. 18). Here the approach of ref. 24 is applied, which identifies blocking as regions with anomalously low vertically integrated PV in the middle to upper troposphere that are quasi-stationary and exist for at least five days[4,24,25] (see Methods).

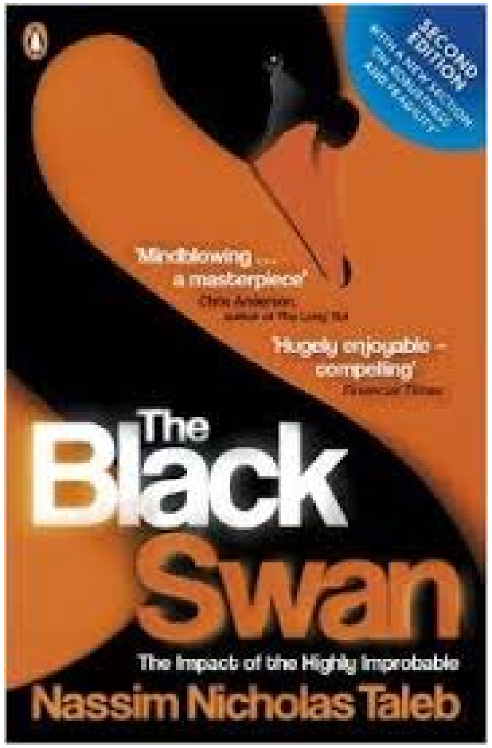
C. 20km models (+ ¼ degree ocean) can simulate 5-day blocks, but can they simulate long-lived blocks: e.g. multi-seasonal periods where most days were blocked?

Do we need convectively resolved global models to eradicate biases in the tropics?

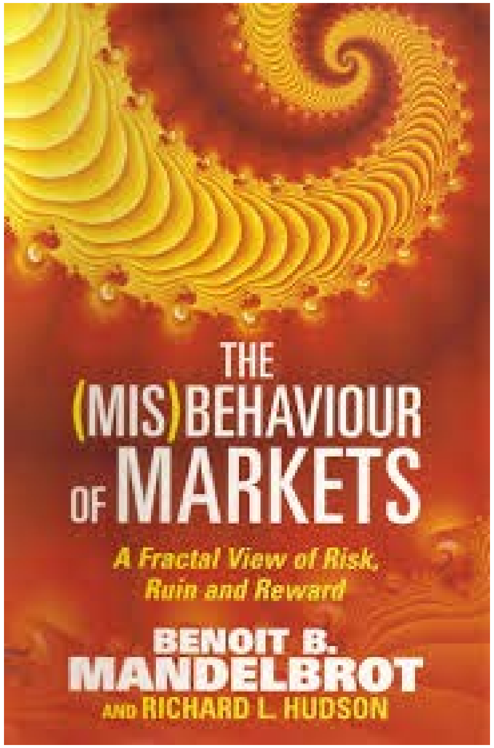




(Nastrom and Gage, 1985)

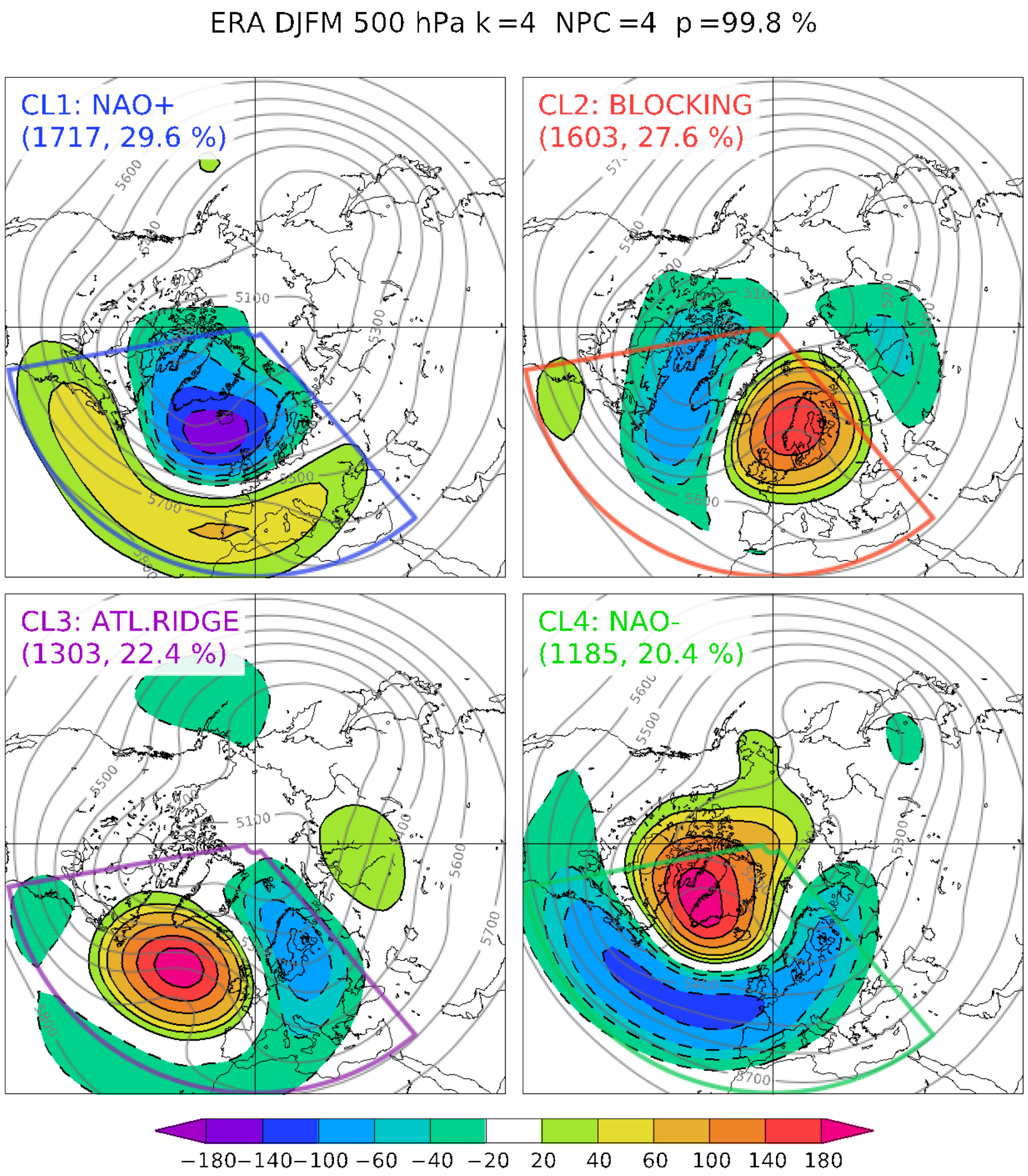


'Mindblowing . . . a masterpiece'
'Hugely enjoyable – compelling'
The Black Swan
The Impact of the Highly Improbable
Nassim Nicholas Taleb



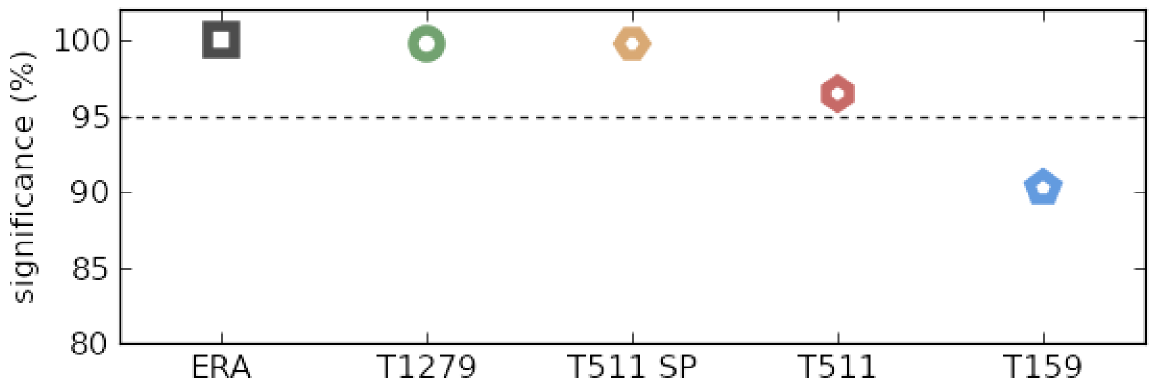
THE (MIS)BEHAVIOUR OF MARKETS
A Fractal View of Risk, Ruin and Reward
BENOIT B. MANDELBROT
AND RICHARD L. HUDSON

From Schertzer and Lovejoy, 1993

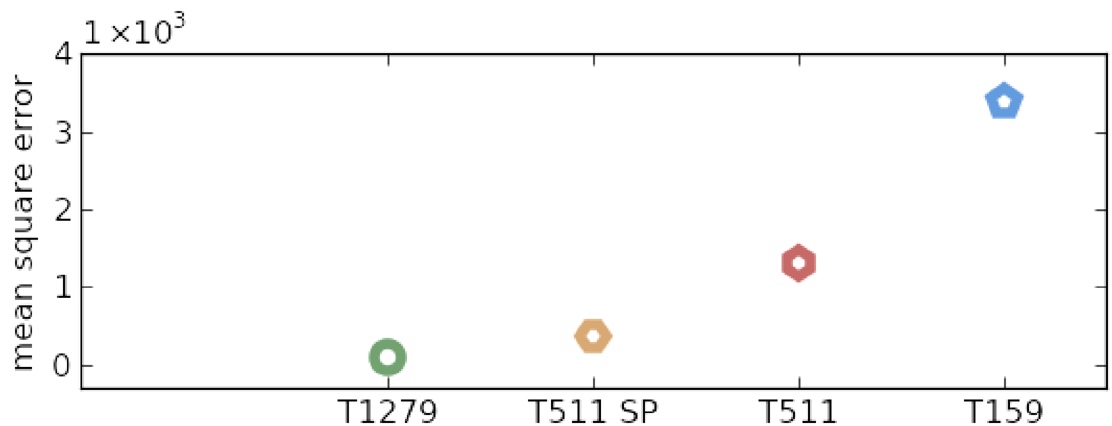


Dawson,
Corti Palmer,
GRL 2012

Athena: AMIP runs

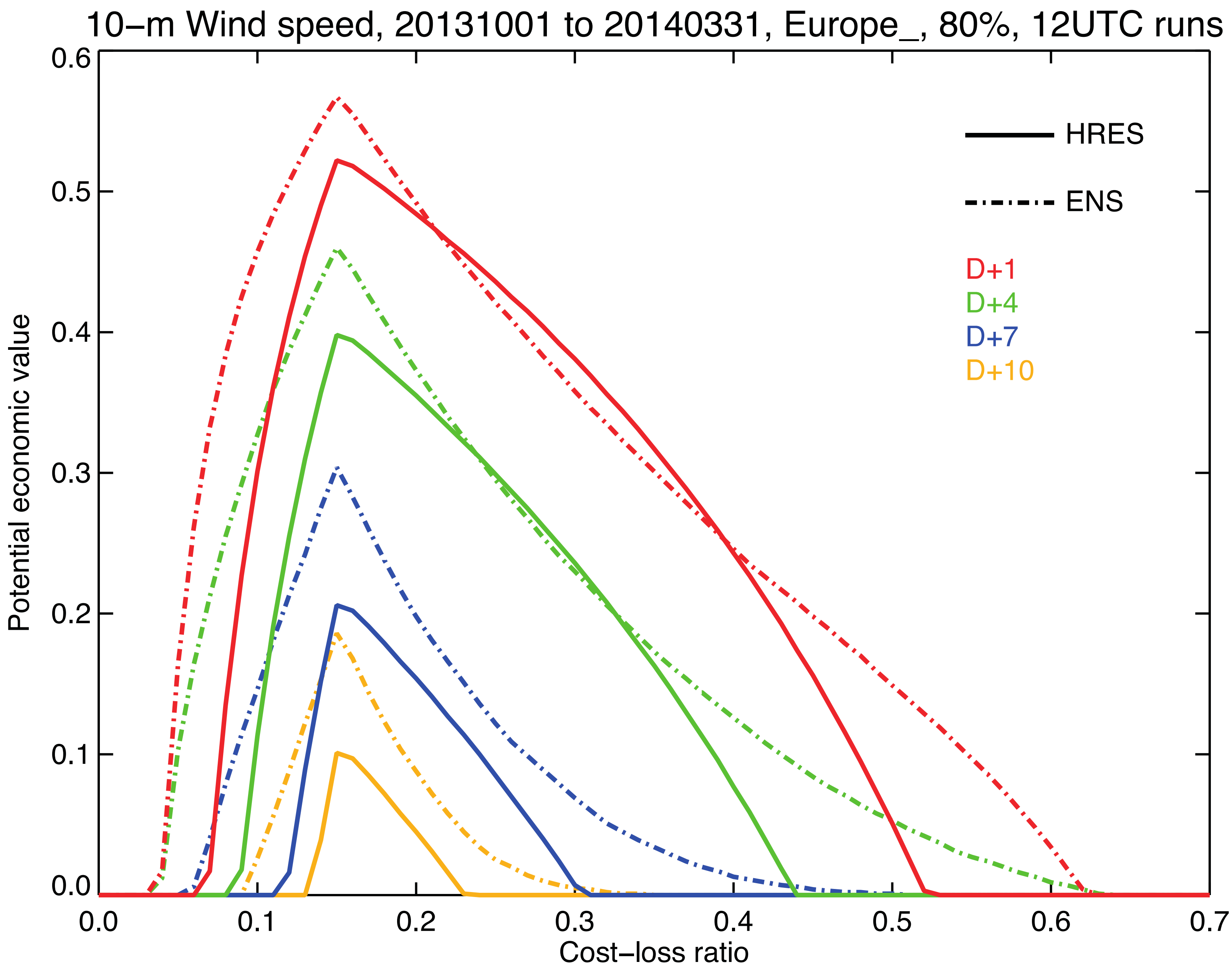


Probability that clusters are not produced from a chance sampling of a gaussian



Dawson,
Corti Palmer,
GRL 2012

RMS error of simulated clusters against ERA


10−m Wind speed, 20131001 to 20140331, Europe_, 80%, 12UTC runs
0.6
0.5
0.4
0.3
0.2
0.1
0.0
Potential economic value
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
Cost−loss ratio
HRES
ENS
D+1
D+4
D+7
D+10

Local effects such as thunderstorms, crucial for predicting global warming, could be simulated by fine-scale global climate models.

Build high-resolution global climate models

International supercomputing centres dedicated to climate prediction are needed to reduce uncertainties in global warming, says **Tim Palmer**.

The drive to decarbonize the global economy is usually justified by appealing to the precautionary principle: reducing emissions is warranted because the risk of doing nothing is unacceptably high. By emphasizing the idea of risk, this framing recognizes uncertainty in the magnitude and timing of global warming.

This uncertainty is substantial. If warming occurs at the upper end of the range projected including cloud systems and ocean eddies. The technical challenges will be great, requiring dedicated supercomputers faster than the best today. Greater international collaboration will be needed to pool skills and funds.

Against the cost of mitigating climate change — conceivably trillions of dollars — investing, say, one quarter of the cost of the Large Hadron Collider (whose annual budget is just under US$1 billion) to reduce by two types of circulation in the atmosphere: mid-latitude, low-pressure weather systems that transport heat from the tropics to the poles; and convection, which conveys heat and moisture vertically.

Global climate simulators calculate the evolution of variables such as temperature, humidity, wind and ocean currents over a grid of cells. The horizontal size of cells in current global climate models is roughly

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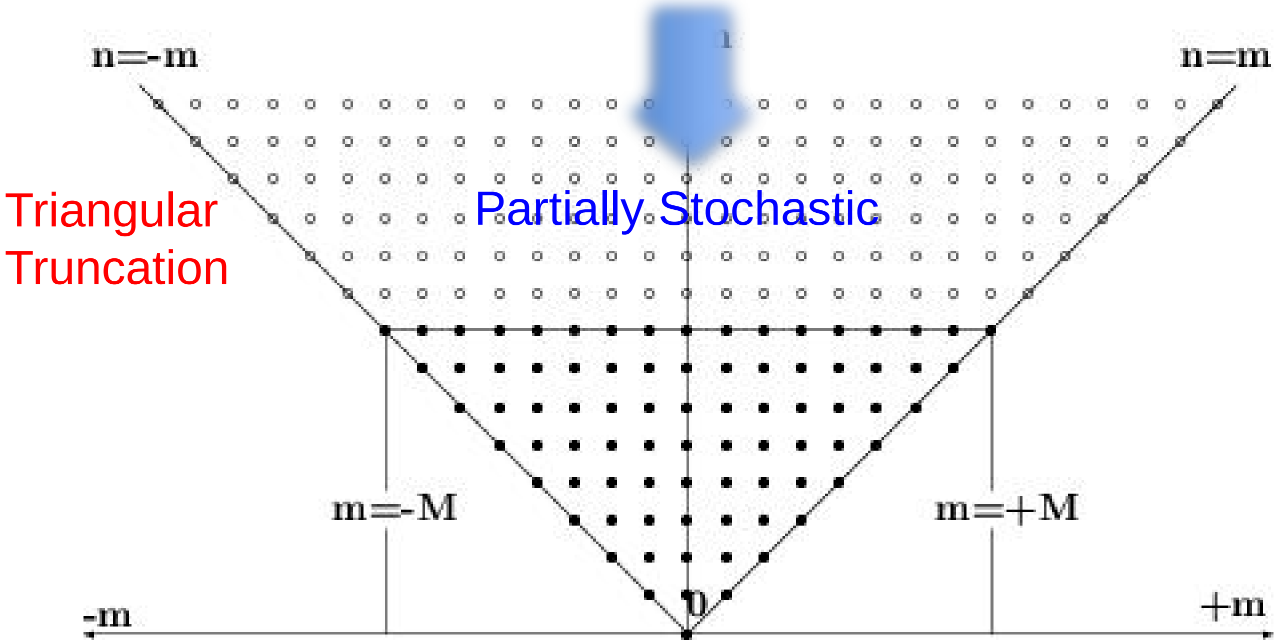
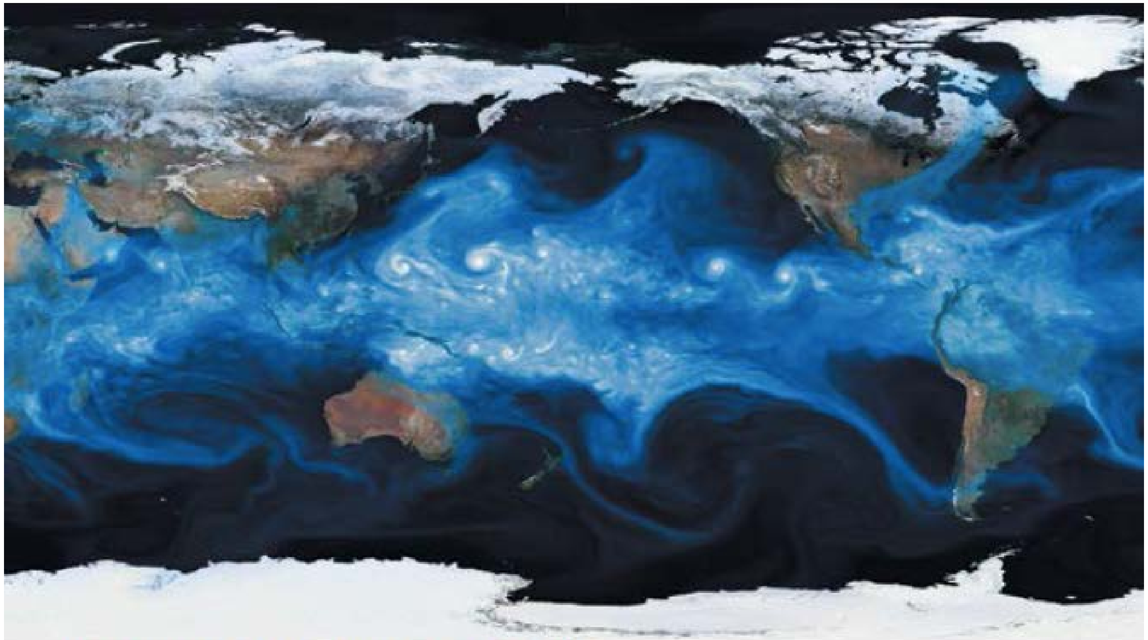
Stochastic Parametrisation



If parametrisation is partially stochastic, are we “over-engineering” our models (parametrisations, dynamical core) by using double precision bit-reproducible computations throughout?

Are we making inefficient use of computing resources that could otherwise be used to increase resolution?



A simulation of Earth's atmosphere generated by the Community Atmosphere Model.

Build imprecise supercomputers

Energy-optimized hybrid computers with a range of processor accuracies will advance modelling, from climate change to neuroscience, says Tim Palmer.

Today's supercomputers lack the power to model accurately many aspects of the real world, from the impact of cloud systems on Earth's climate to the processing ability of the human brain. Rather than wait decades for sufficiently powerful supercomputers — with their potentially unsustainable energy demands — it is time for researchers to

input — and with the same high level of precision. I argue that for many applications they do not.

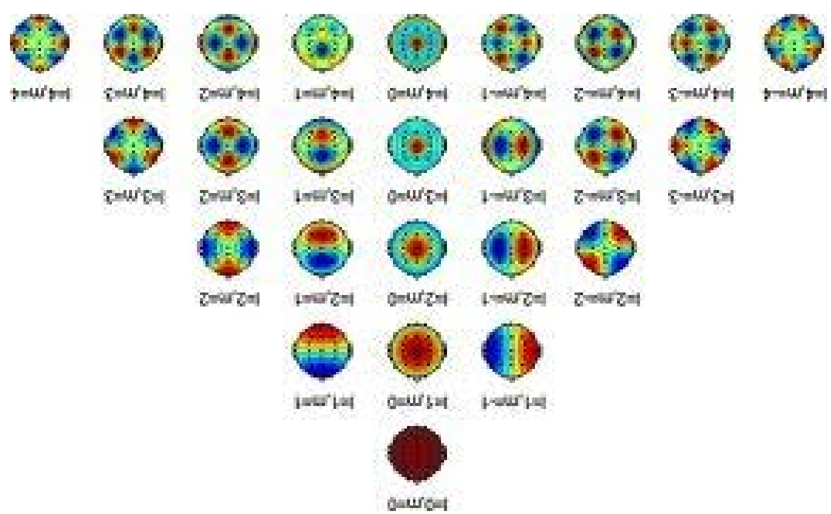
Energy-efficient hybrid supercomputers with a range of processor accuracies need to be developed. These would combine conventional energy-intensive processors with low-energy, non-deterministic processors, able to analyse data at variable levels of preci-

grid cells of 100 kilometres in width — can resolve large, low-pressure weather systems typical of mid-latitudes, but not individual clouds. Yet modelling cloud systems accurately is crucial for estimating reliably the impact of anthropogenic emissions on global temperature[1].

The resolution of this computational grid is determined by the available computing

E BERKELEY NAT'L LAB./DATA: MICHAEL NER (LBNL)/VISUALIZATION: PRABHAT

Greater Accuracy with Less Precision?

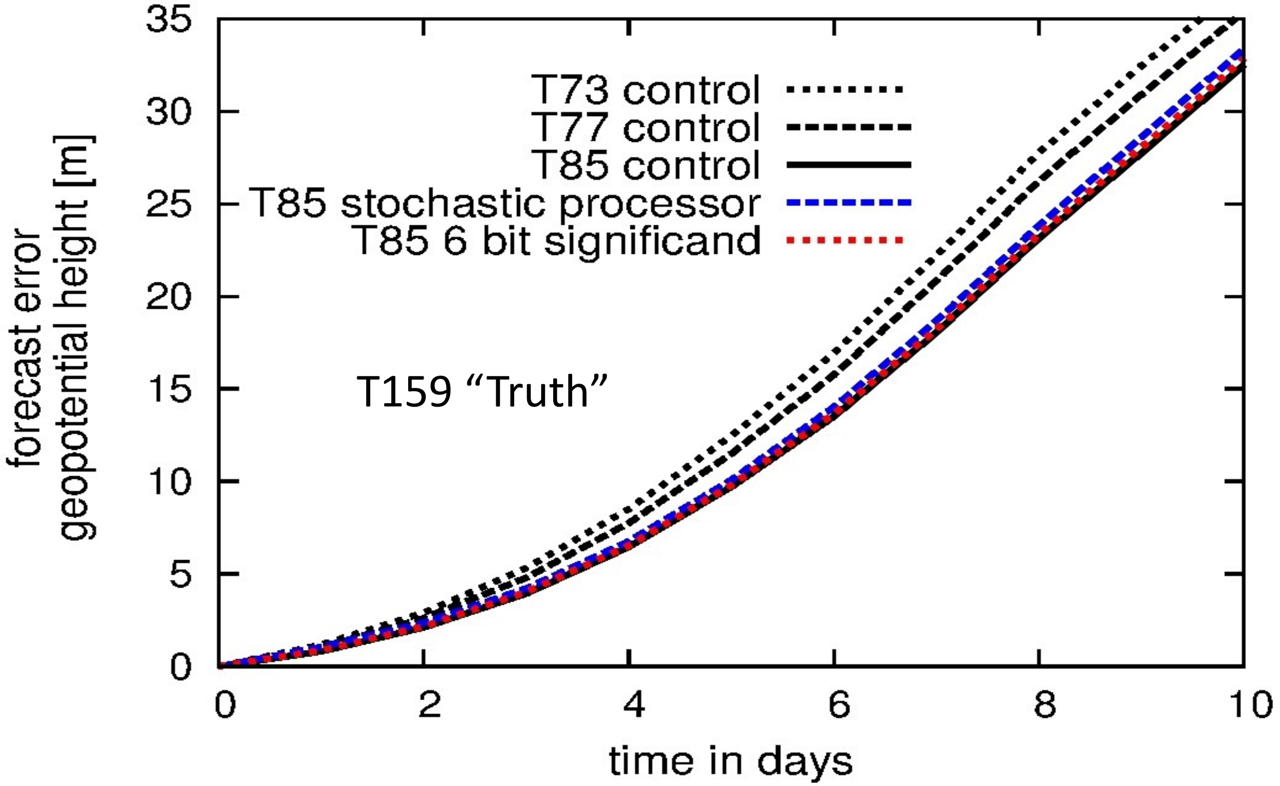


Use freed-up computing resource to extend simulator to cloud resolved scales?

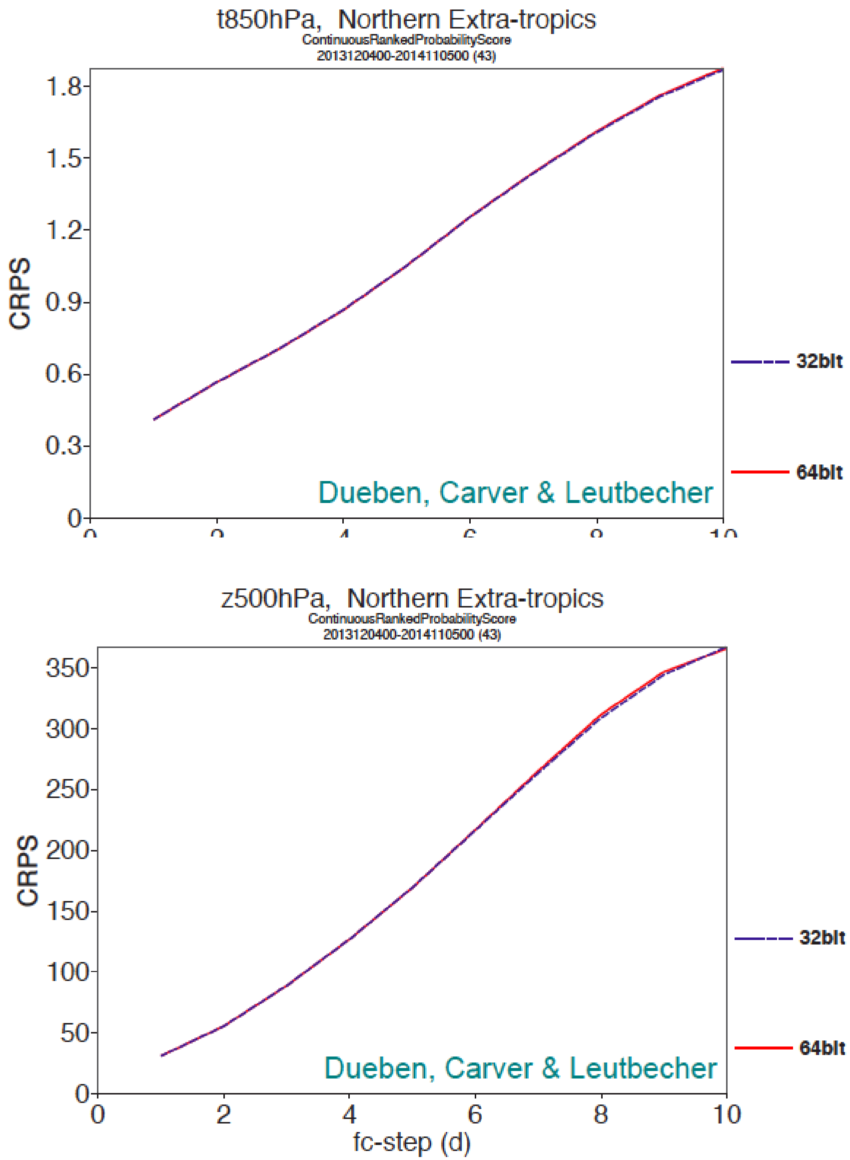
Decreasing precision, and determinism

More accurate "weather forecasts" with less precision
Reading IGCM

Düben and Palmer, 2014. MWR.



- The stochastic chip / reduced precision emulator is used on 50% of numerical workload:
  - All floating point operations in grid point space
  - All floating point operations in the Legendre transforms between wavenumbers 31 and 85.
- Imprecise T85 cost approx that of T73
- Scale dependent precision easy to code in a spectral model (potential advantage for the future?)



IFS: Single vs Double Precision

T399 20 member IFS

Can run 15 day T639 at single precision for cost of 10-day T639 at double precision

Conclusions

- Climate models are beginning to play a more and more important role in societal decision making.
- Being able to simulate extremes reliably is crucially important.
- Current generation climate models are still too coarse resolution to be trustworthy.
- We should pool resources to enable very high resolution models (e.g. 1km global) to be built.
- Small-scale variables do not need to be modelled with the same level of precision and determinism as large-scale variables – we could make much more efficient use of available computing resources.