Joint Weather &
Climate
Research
Programme

Weather and Climate modelling at the Petascale: achievements and perspectives. *The roadmap to **PRIMAVERA***

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Presented on behalf of Professor Vidale by: Bryan Lawrence

Professor of Weather and Climate Computing, University of Reading, and
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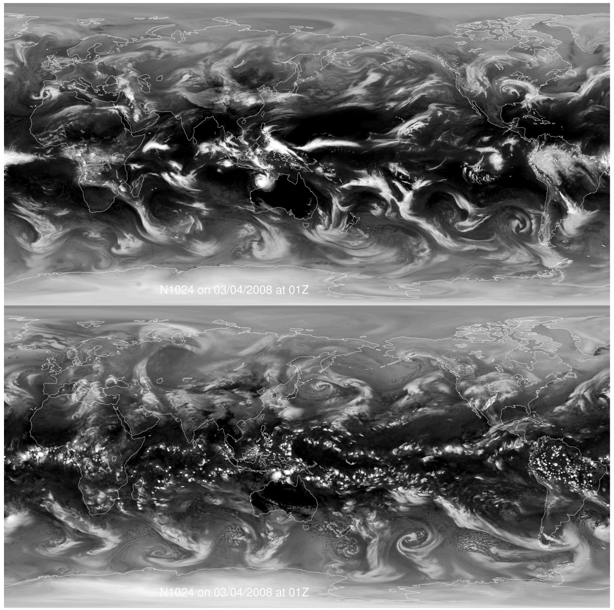

Malcolm Roberts

Met Office Hadley Centre, Exeter, UK

Matthew Mizielinski, Jo Camp, Lizzie Kendon

(with thanks to the many Met Office groups Involved in model development and elsewhere)

With thanks to colleagues from: AWI, KNMI,ECMWF, MPI, IC3, CMCC, SMHI

MetUM global atmosphere/coupled model climate configurations in use

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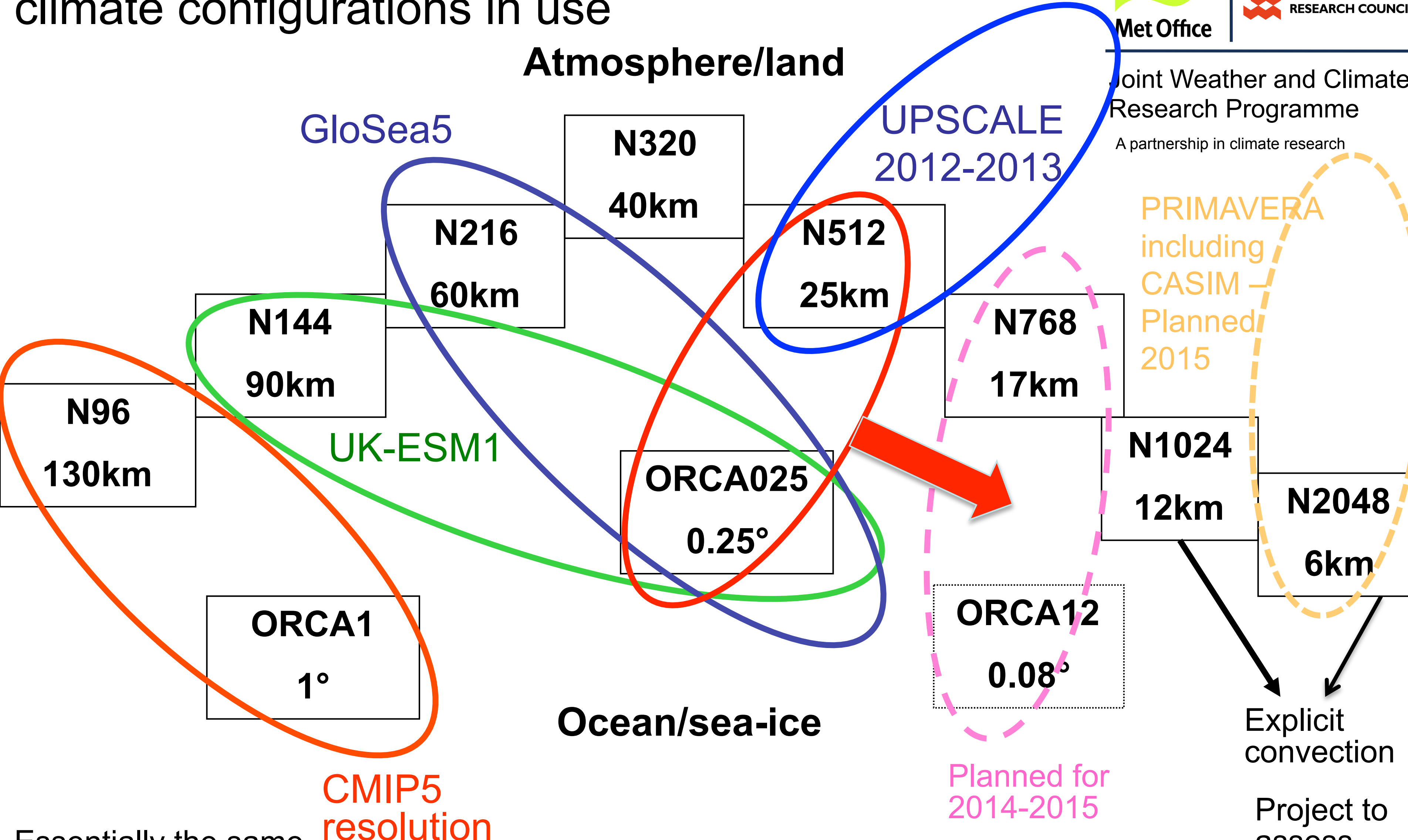
A partnership in climate research

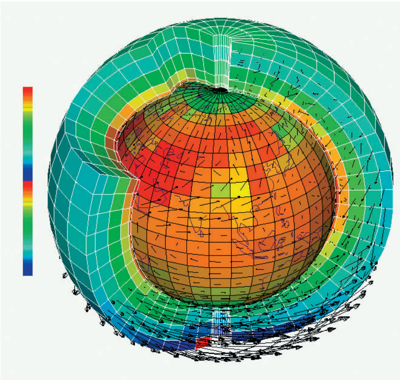


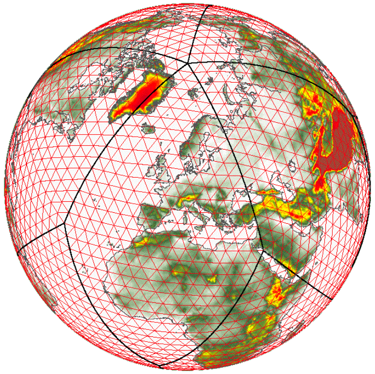
Essentially the same physics/dynamics parameters used throughout model hierarchy

Project to assess impact of global explicit convection

Model development and assessment philosophy

- No pretty models; rather a modelling system able to increase our understanding of the mechanisms that govern the climate system:
  - Not so important whether the model looks good or bad, but that it answers the question of **why** something happens in the climate system
  - While we develop, we prefer a bad result for the right reasons to a good result for the wrong reasons
- As much as it is feasible, only change one thing at a time, so that we can build a consistent and traceable chain of understanding
- Bottom line: **we do not tune our models** each time that we change resolution





HPC available to UK weather and climate scientists

Machine	Owner	PetaFlops	Year
HERMIT	HLRS (Germany) EU-PRACE	1	2012
Archer	EPSRC/NERC (UK)	1.6(2.6)	2014(Dec)
HORNET	HLRS (Germany)	4	2014
Cray® XC40	Met Office	16	2015-2017

1 PetaFlop = 1 quadrillion operations per second

World's #2 Machine	Owner	PetaFlops	Year
Titan	US DoE (Oak Ridge National Lab)	20 (!?!)	2014

Progress in our ability to exploit High Performance Computers

25km AGCM — ¼º OGCM, multi-decadal ensembles
Sustained turnaround: ~1yr/day for each ensemble member

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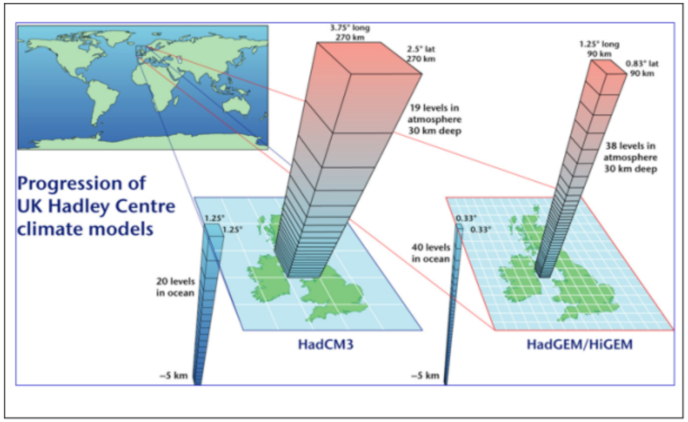
Year	Model	Machine	Type	Cores available	Cores per ensemble member, optimal	Cores used concurrently *(potential)*
2011	HadGEM3 GA3	HECToR (UK)	CRAY XT4	22,000	~1500	~1500 *(~1,500)*
2012	HadGEM3 GA3	HECToR (UK)	CRAY XE6	90,000	~6,000	~12,000 *(~30,000)*
2013	HadGEM3 GA3-4	HERMIT (DE-PRACE)	CRAY XE6	110,000	~6,000	~30,000 *(~50,000)*
2014	HadGEM3 GA7 and GC2 (+NEMO)	Archer (UK)	CRAY XC30	72,000 (118,000 from 12/14)	~6,500	~20,000 *(~80,000)*

The main limitation continues to be IO. Max rate of data flow to CEDA storage: 2-8 TB/day

Final archive size for each experiment: O(1PB)

Representation of orography: the importance of resolution

The upper figure shows the surface orography over the Alps at a resolution of ~150km, as in a low resolution climate model.



The lower figure shows the same field at a resolution of 25km (HadGEM3-N512), 5km and in the original SAR 30sec resolution.

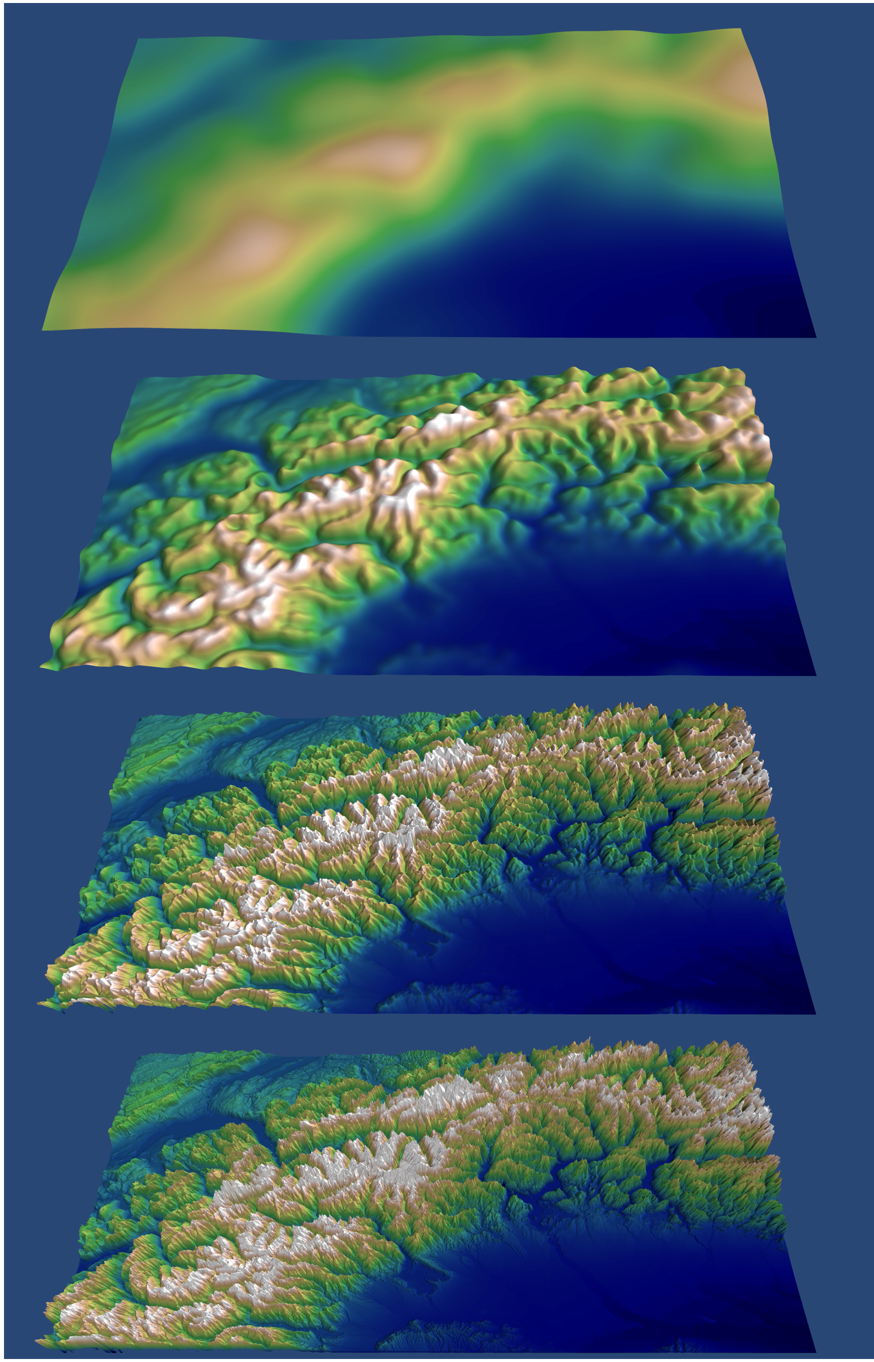
Remember that orographic processes are highly non-linear.

150km

25km

5km

SAR
30sec



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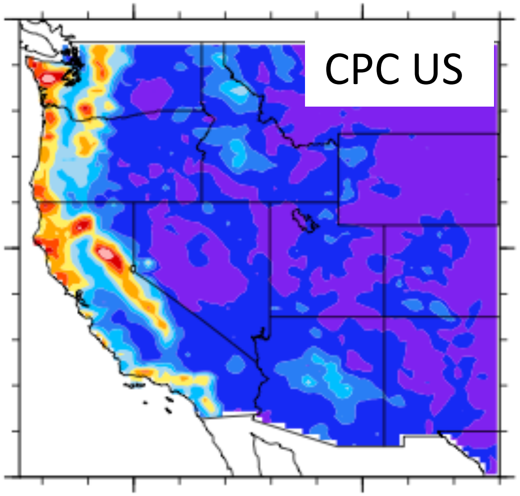
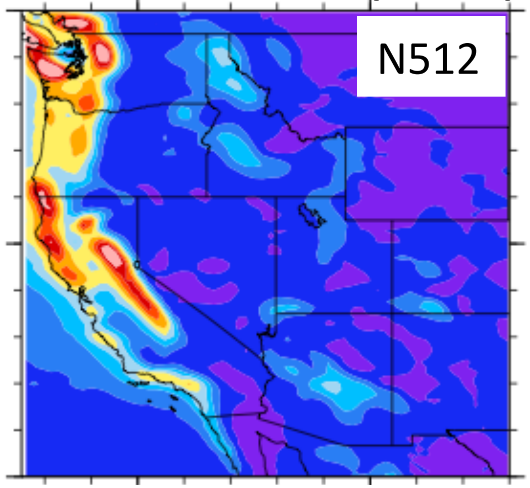
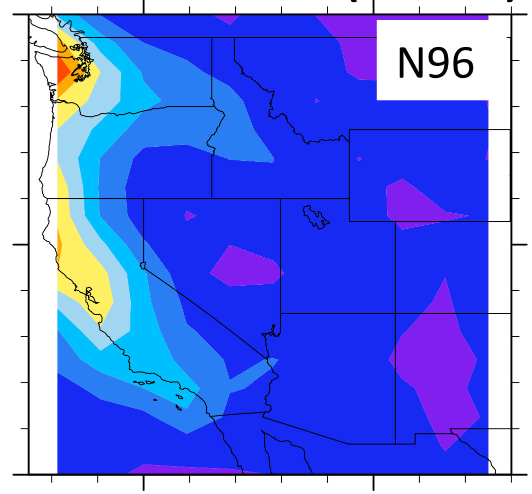
Events associated with ARs in California

99th percentile of daily precipitation in DJF

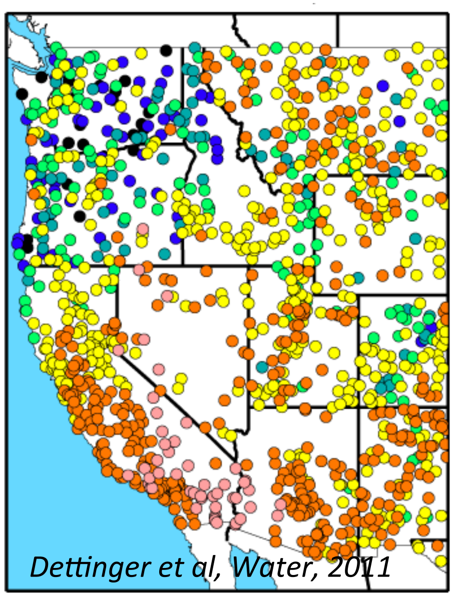
N512 (25 km) **N96 (135 km)**

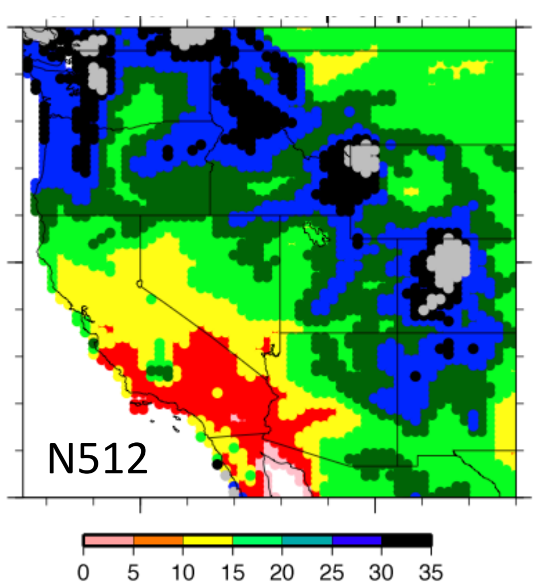


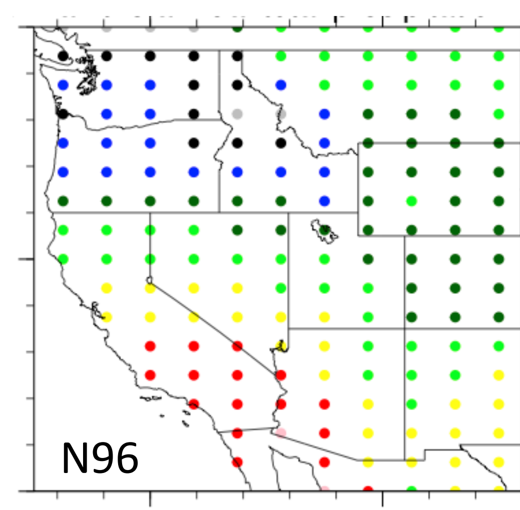




Average number of days necessary to obtain half the total annual precipitation







Demory et al (work in progress)

Box 1 | Updated energy balance

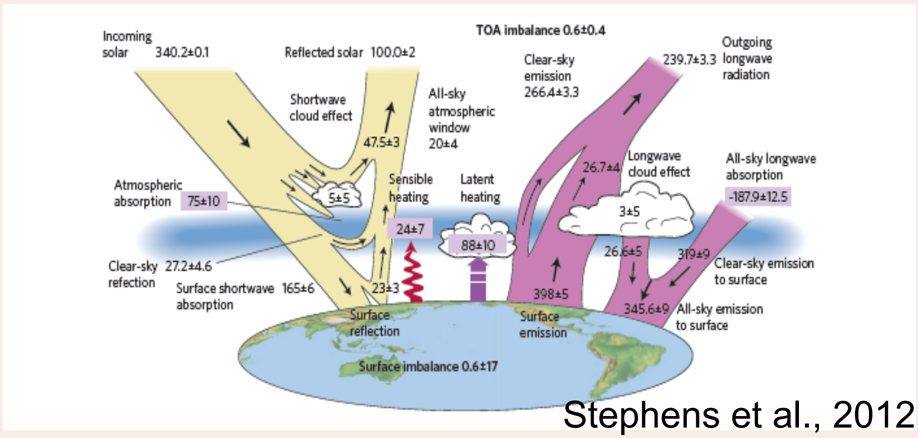
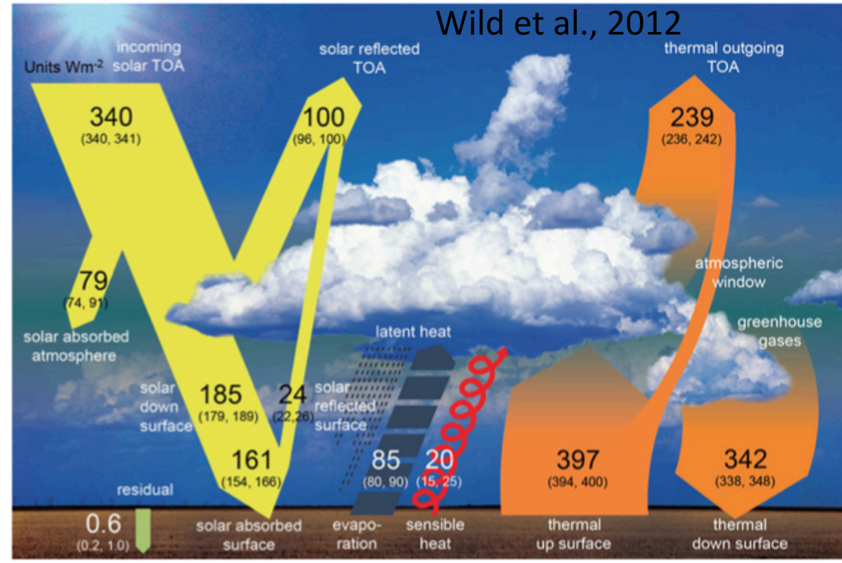
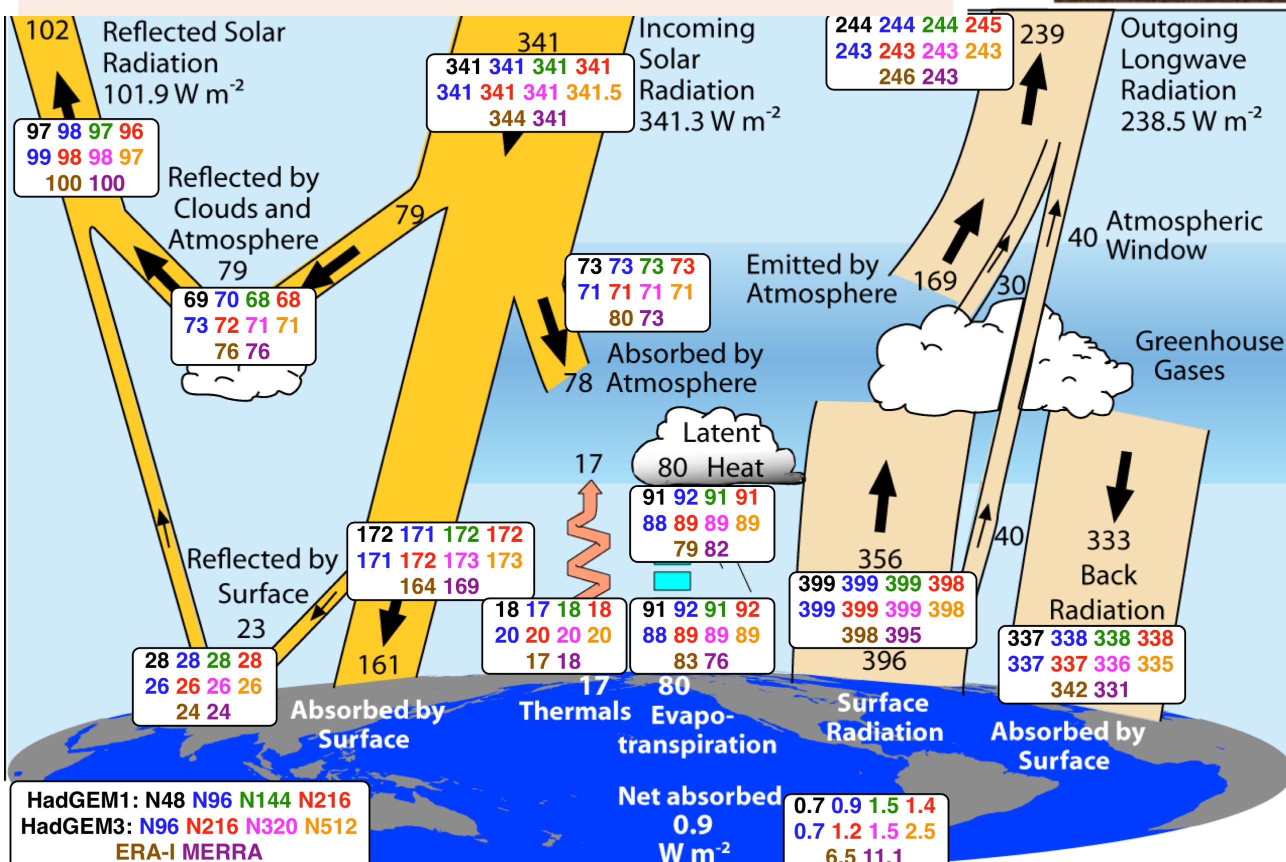


Figure B1 | The global annual mean energy budget of Earth for the approximate period 2000–2010. All fluxes are in Wm^{-2}. Solar fluxes are in yellow and infrared fluxes in pink. The four flux quantities in purple-shaded boxes represent the principal components of the atmospheric energy balance.





Fluxes: W/m^2

Demory et al., Clim. Dyn., 2013

Figure adapted from Trenberth et al, 2009

What changes with resolution?

Hopefully, some important things do depend on resolution.

<u>The global hydrological cycle</u>

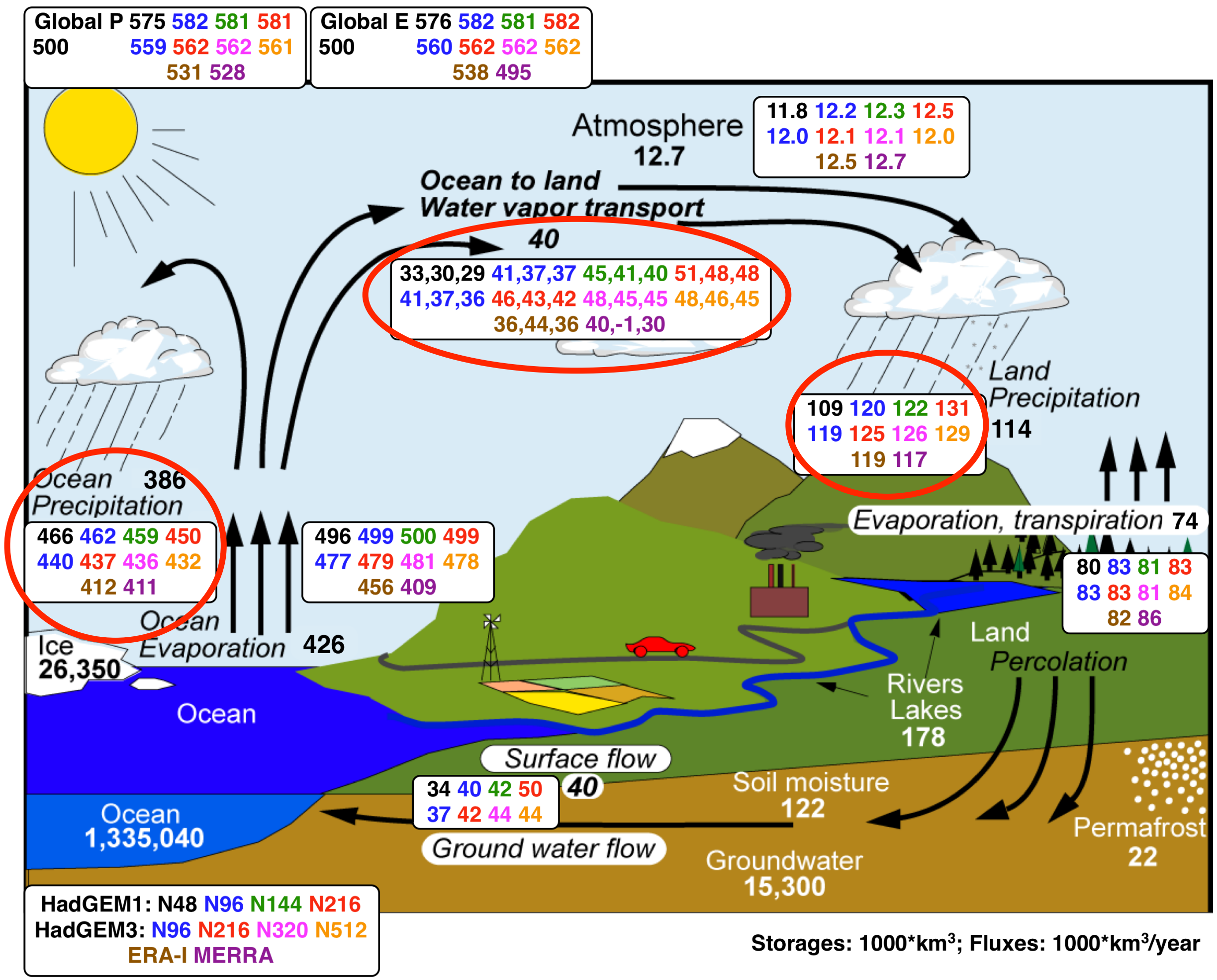


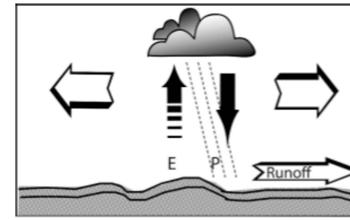
Figure adapted from Trenberth et al, 2007, 2011

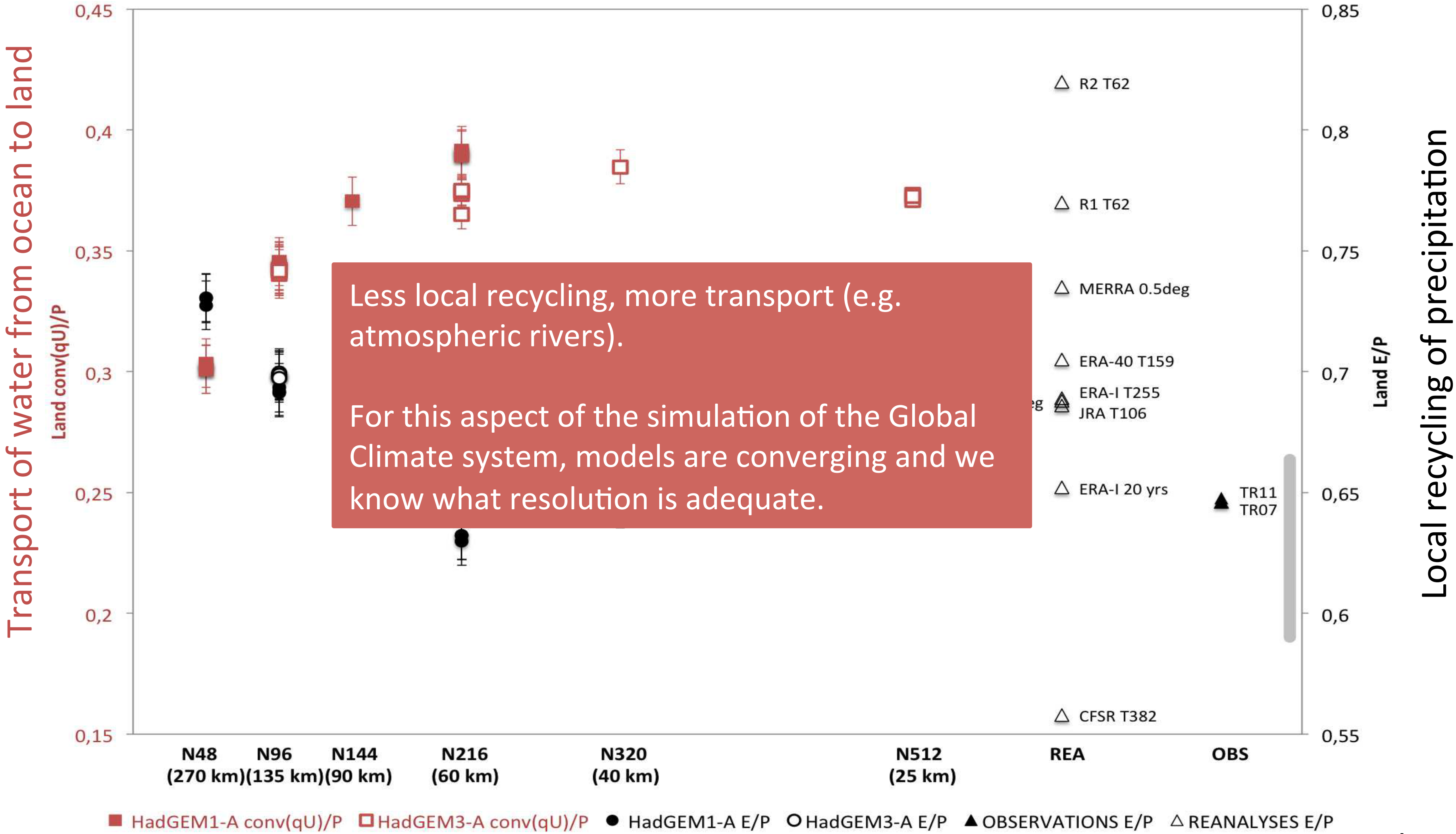
- Classic GCMs too dependent on physical parameterisation because of <u>unresolved</u> atmospheric transports
- Role of <u>resolved</u> sea→land transport larger at high resolution
- **Hydrological cycle more intense** at high resolution

Equivalent resolution at 50N:
270 km
135 km
90 km
60 km
40 km
25 km

Demory et al., Clim. Dyn., 2013

Relative roles of remote transport and local re-cycling in forming precipitation over land





Less local recycling, more transport (e.g. atmospheric rivers).

For this aspect of the simulation of the Global Climate system, models are converging and we know what resolution is adequate.

Resolution

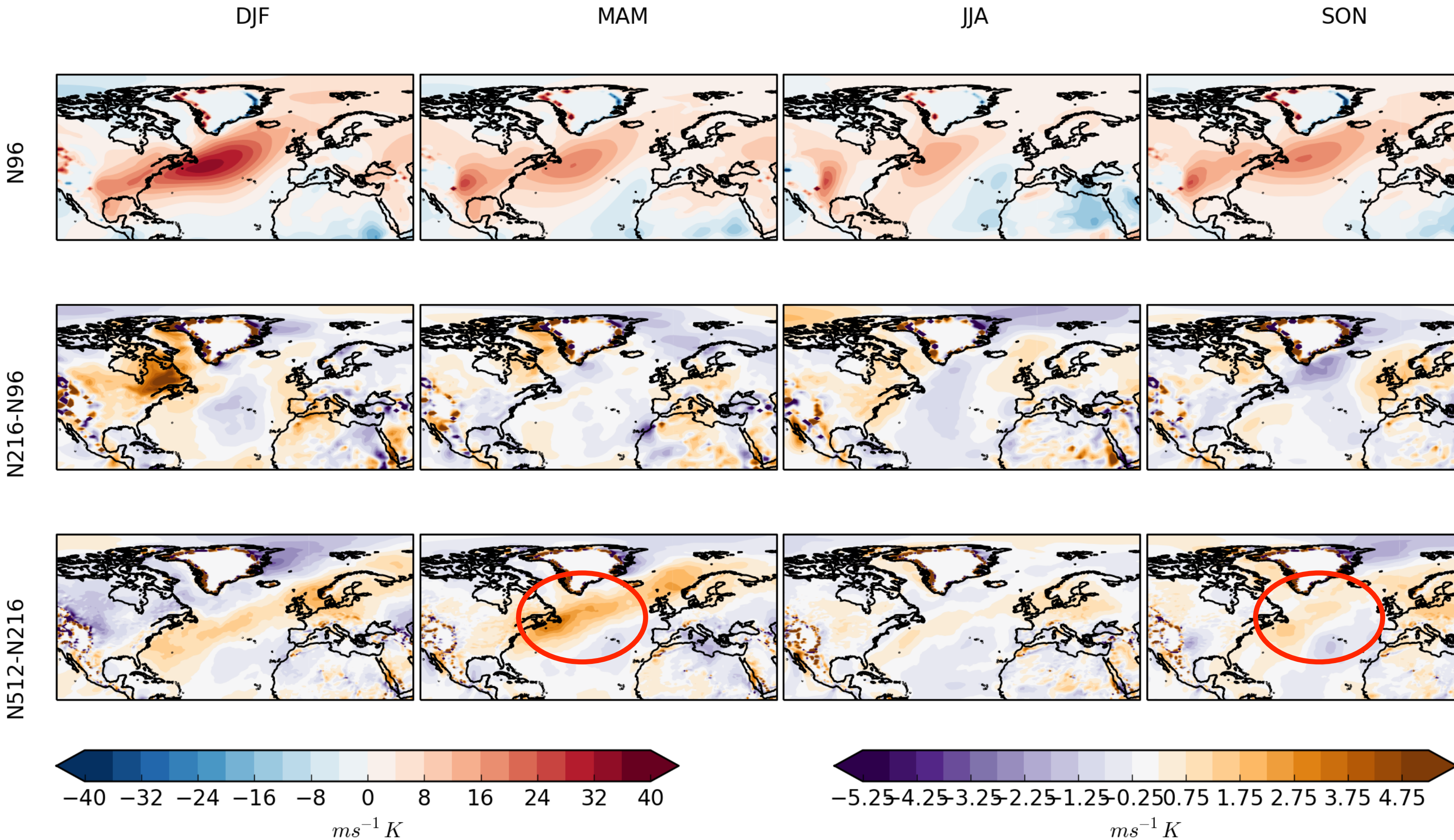
High local recycling
Low transport

Lower local recycling
Higher transport

Demory et al, Clim. Dyn., 2013

Meridional eddy heat flux, V' T '

L. Novak et al. 2014: "Our results suggest that <u>high</u> heat flux is conducive to a <u>northward</u> deflection of the jet, whereas <u>low</u> heat flux is conducive to a more <u>zonal jet</u>".



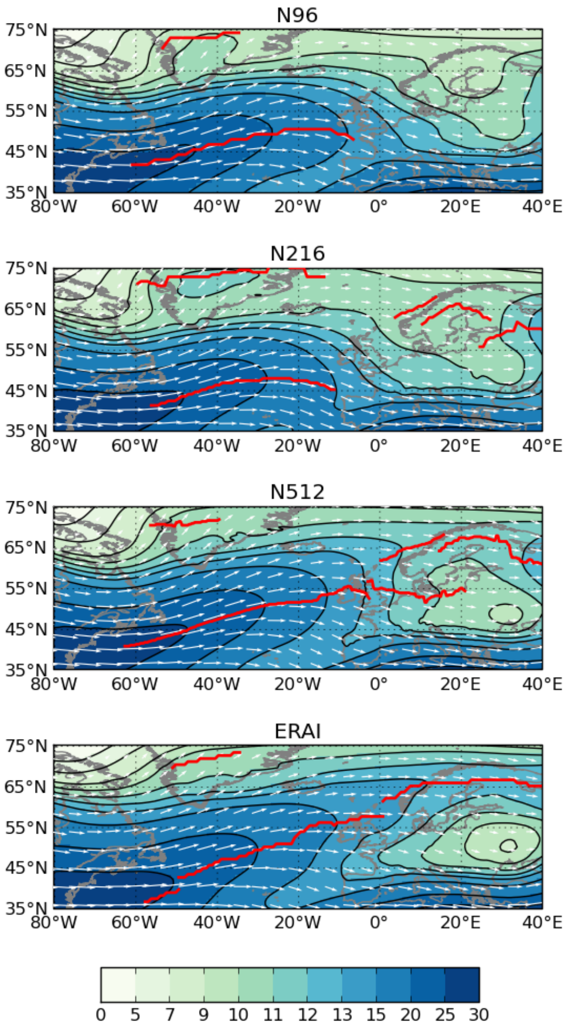
M. Mizielinski, with many thanks to L. Novak, Reading University

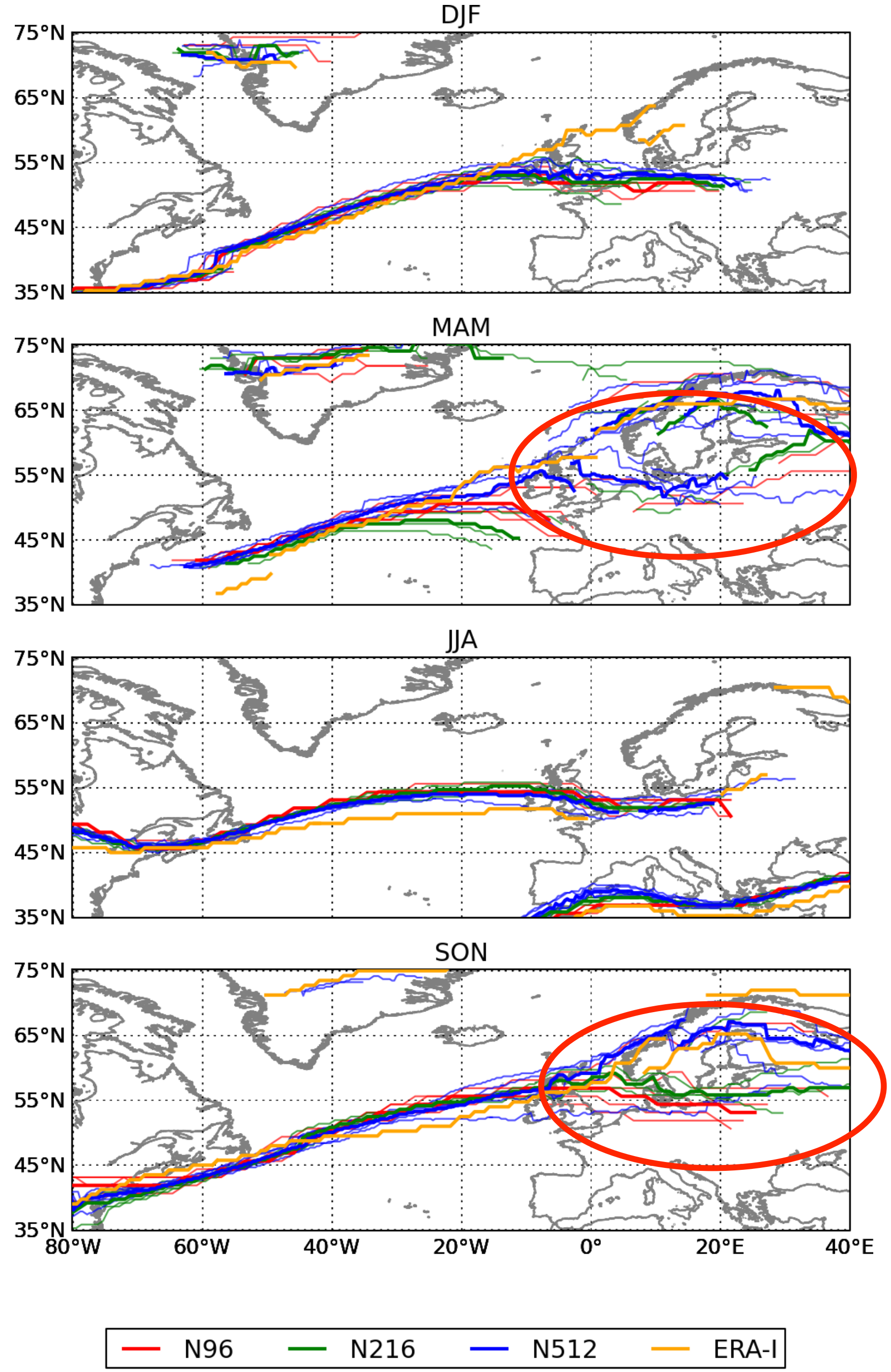
N96 = 135km N216 = 60km N512 = 25km

Atmospheric “eddie-driven” jets

governing European weather

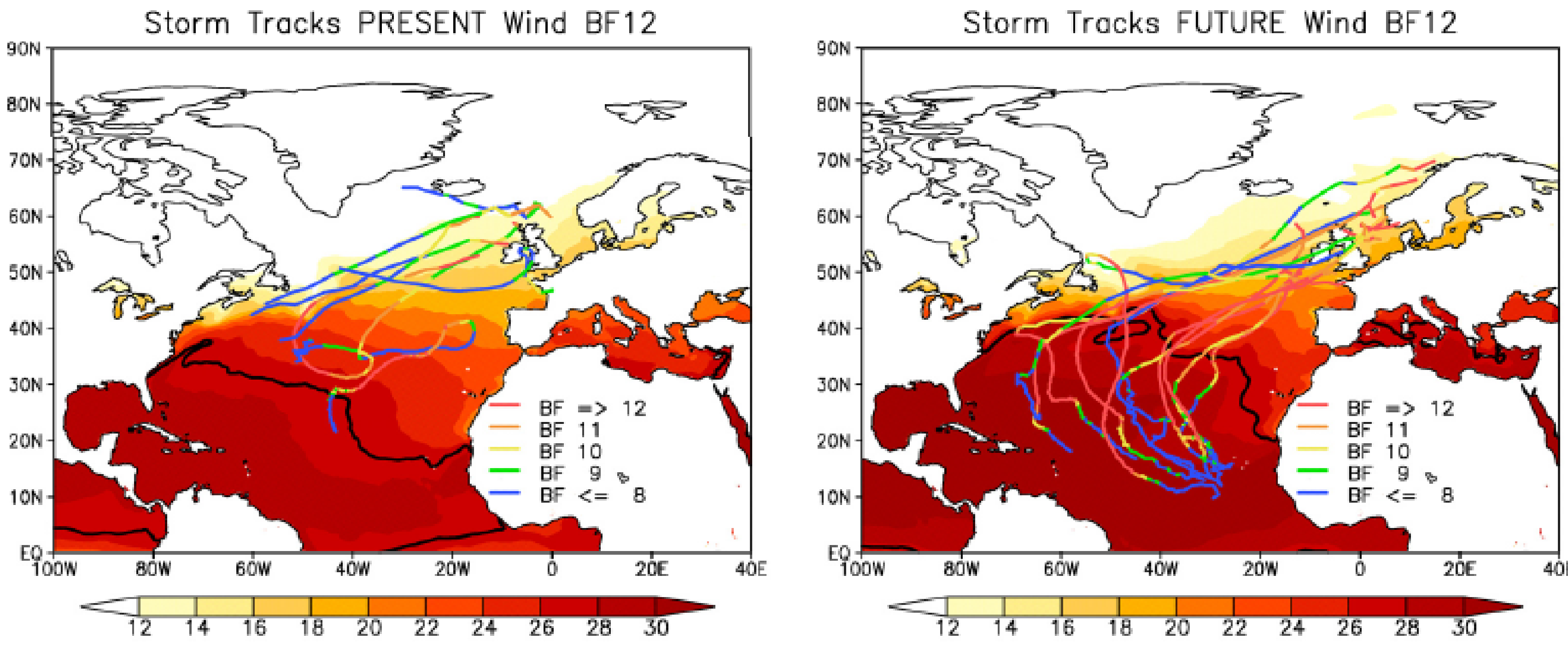
250hPa winds, ensemble



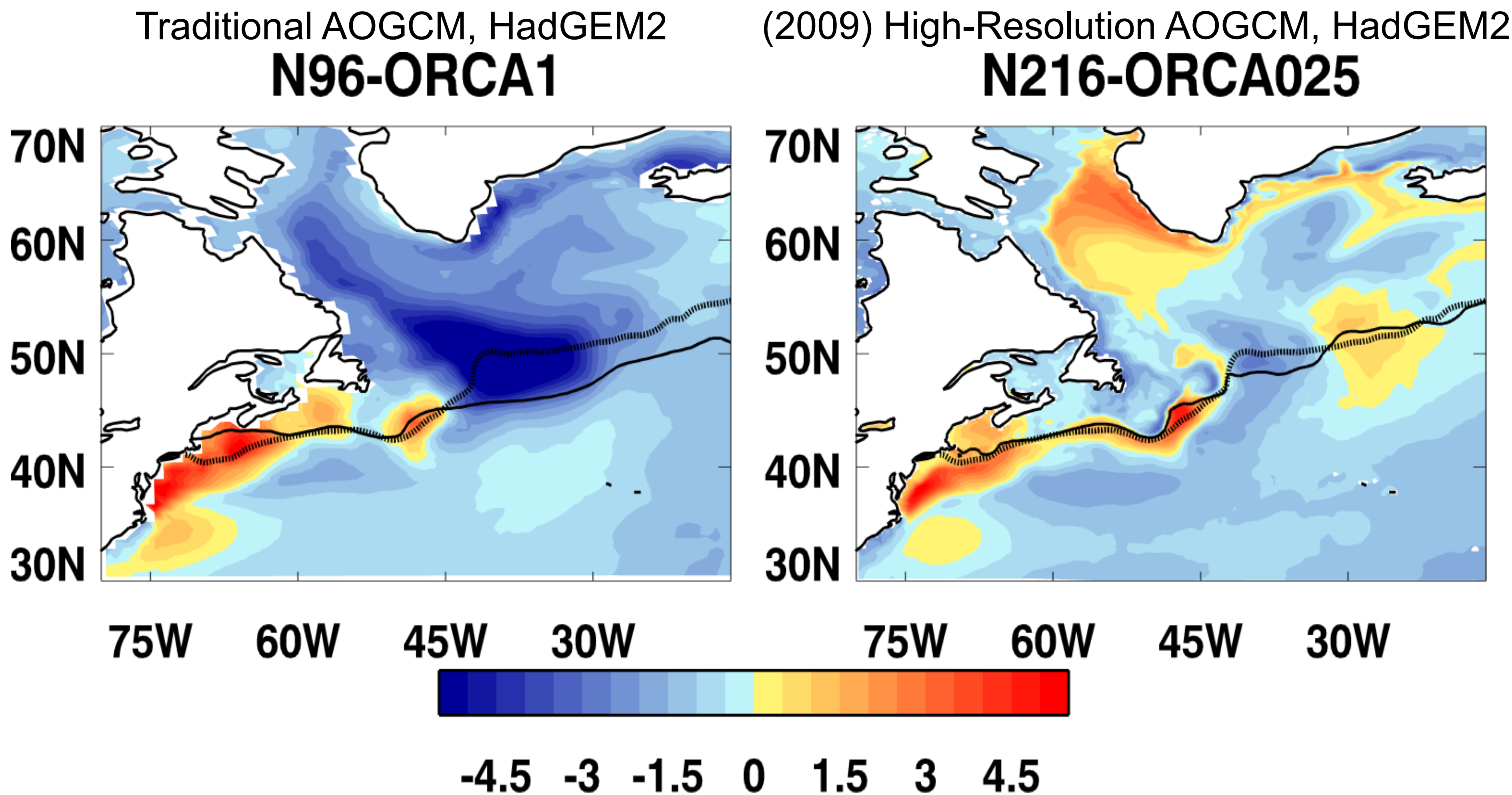


M. Mizielinski

Origin of severe autumn storms near Europe

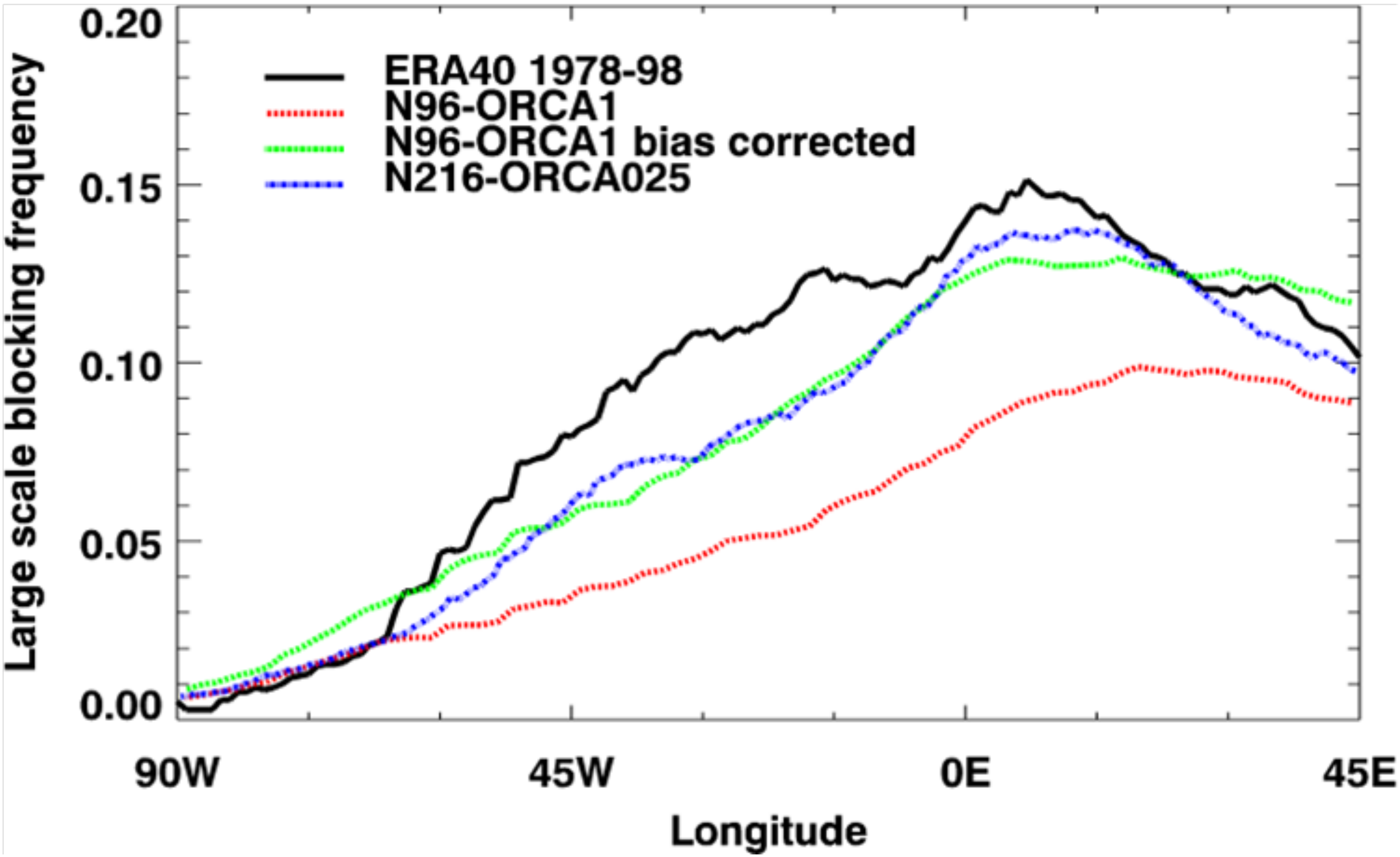


North Atlantic SST bias in coupled models



A. Scaife, GRL, 2011

Blocking frequency for Atlantic sector – important for large-scale extremes (hot summers/cold winters)



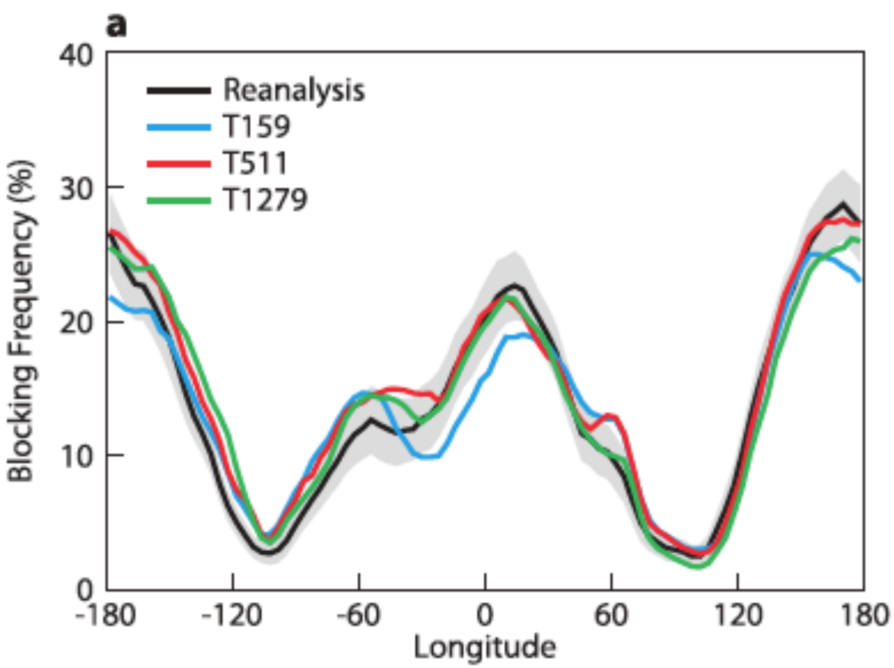
A. Scaife, GRL, 2011

Project Athena: Euro-Atlantic blocking and resolution
The role of mountains is key.

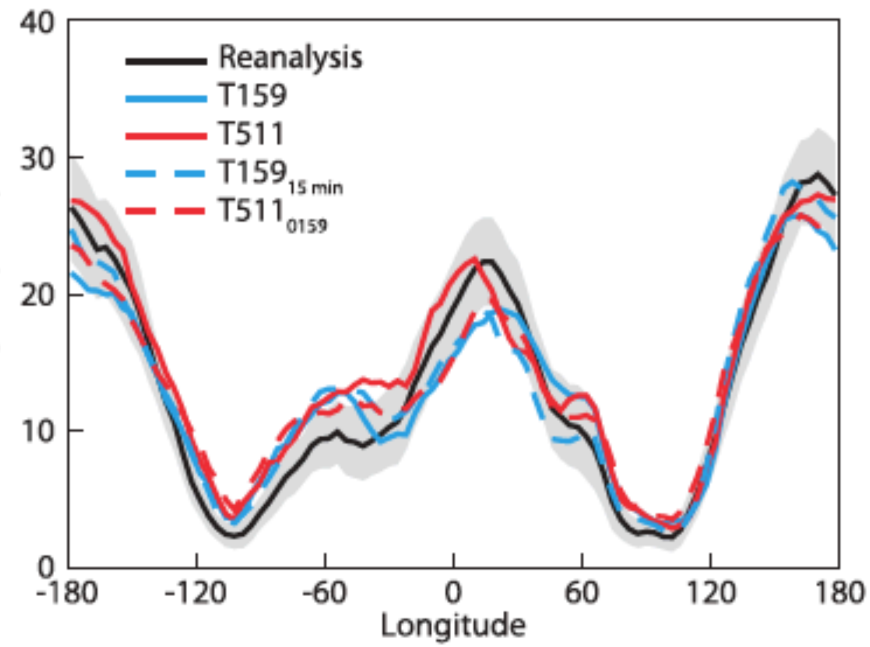
ALFRED-WEGENER-INSTITUT
HELMHOLTZ-ZENTRUM FÜR POLAR- UND MEERESFORSCHUNG

Equally, Jung et al. (2014), Geophys. Res Lett. argued that **small-scale atmospheric phenomena such as fronts, mesoscale cyclones, and topographic jets play an important role in driving the mean oceanic circulation** .
Representation of topography is also important.

Role of horizontal resolution



Role of topography



Jung et al. (2012), J. Climate

High-Resolution GCMs and ocean eddies
→ contribute to the mean state
→ sustain a more realistic ENSO

- Shaffrey et al (2009) and Roberts et al. (2009) found that ENSO is more credibly simulated with a high-resolution AOGCM.
- The correct mean state of the Tropical Pacific is sustained by meridional heat transport produced by TIWs
- Part of a larger investigation that aims to identify small-scale processes that emerge in high-resolution models and impact large-scale simulations

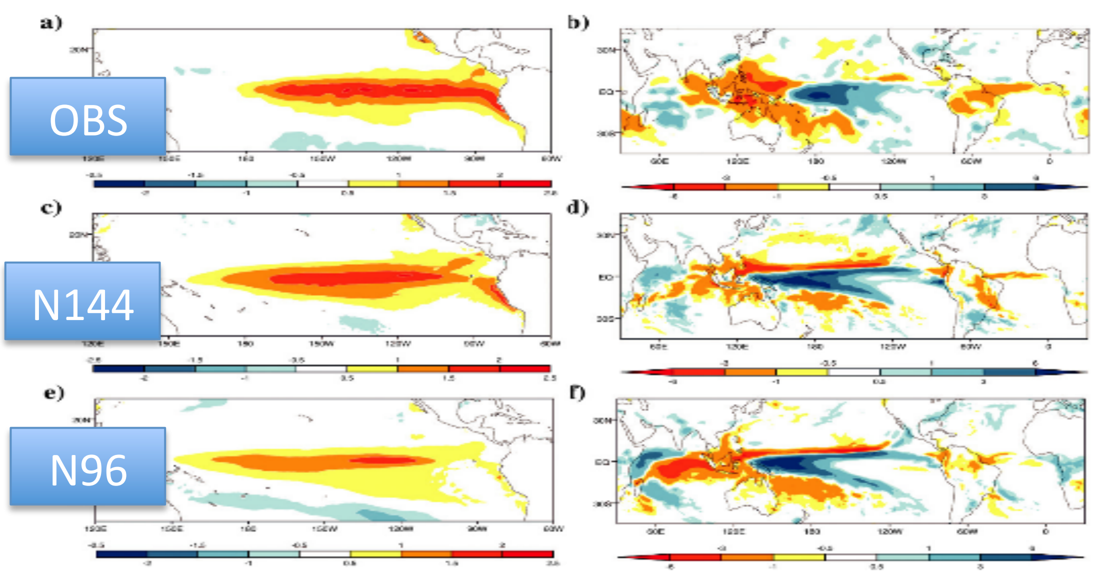
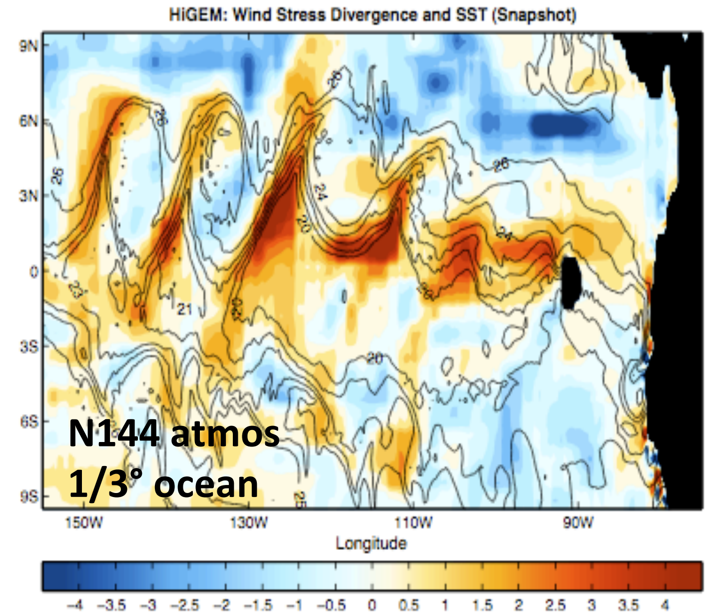
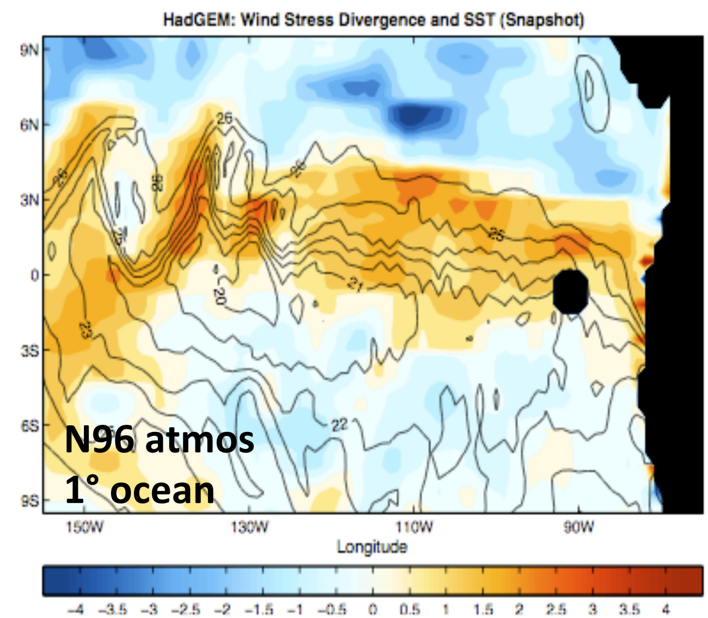


FIG. 20. El Niño DJF composite anomalies for SST (K) and precipitation (mm day^{-1}) from (a) the HadISST SST dataset and (b) the CMAP precipitation dataset and from (c),(d) HiGEM1.2 and (e),(f) HadGEM1.2.

Tropical Instability Waves

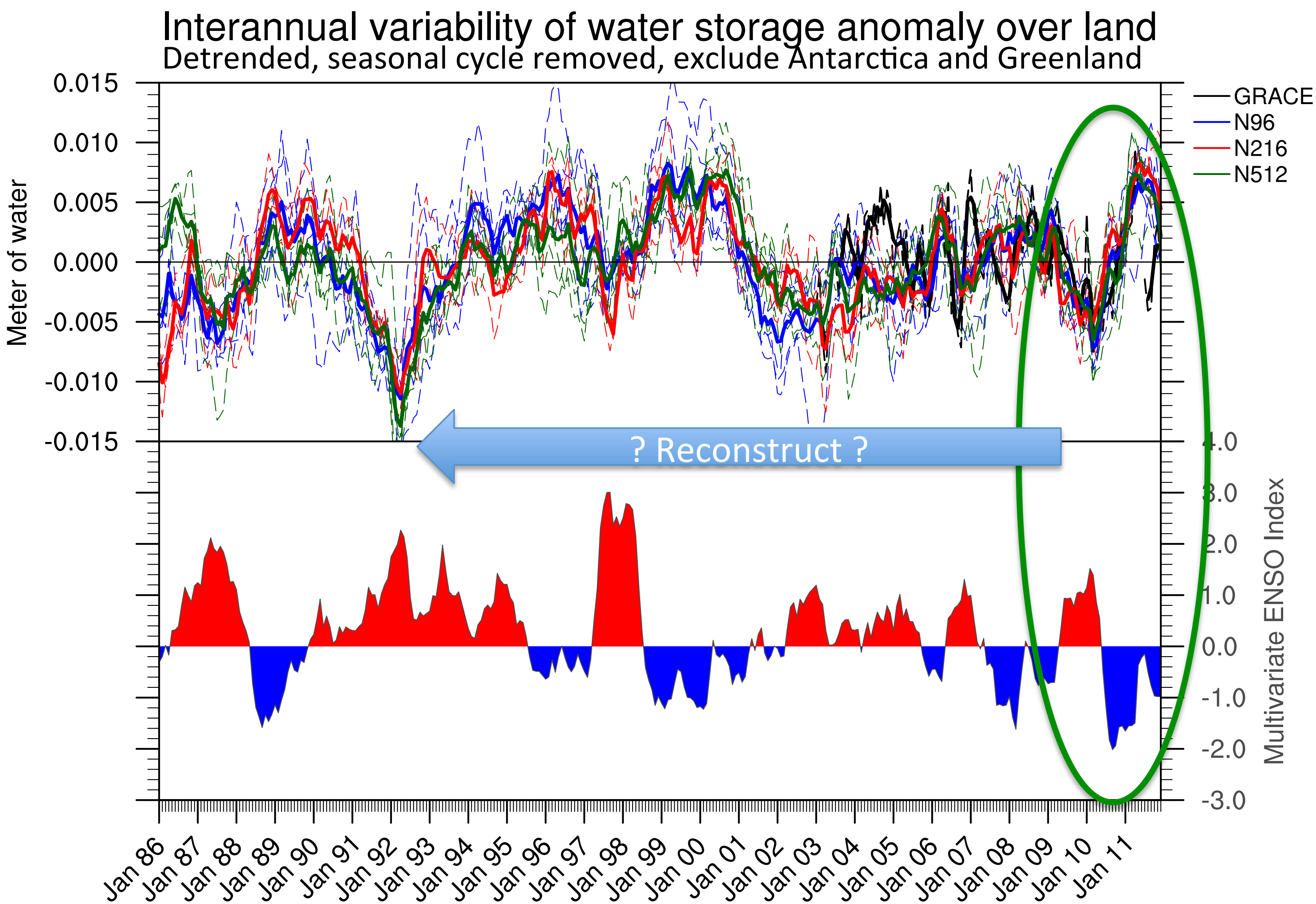




Shaffrey et al., 2009, J. Clim; Roberts et al., 2009, J. Clim

Terrestrial water storage interannual variability

Opportunities to assess GCMs at the process level using new observations. Example from GRACE.



Demory, Boening et al (work in progress)

A preview of future GCM capabilities

- In the future (going towards CMIP7) we expect to explicitly resolve many processes and to rely much less on parameterisations, which contain much empiricism.
- As an example of what expect of future GCMs, we have run HadGEM3 at 12km without parametrised convection. This has a dramatic impact on the quality of the diurnal cycle of precipitation, which is systematically wrong in standard (IPCC) GCMs:
  - Rain always at local noon
  - Rain a little every day
- Our (UPSCALE) 12km GCM corrects both errors above.

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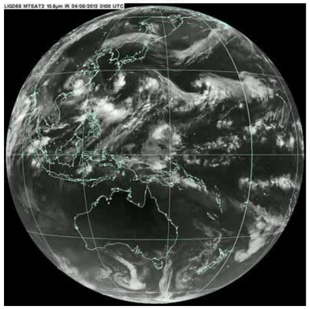
Enabling the development of next-generation forecasting systems.
N1024: a 12km GCM

- Ensembles of 5-yr simulations with multiple physics configurations, ranging GA3 to GA6.
- First time that a Global Climate Model leads its Numerical Weather Prediction (NWP) "parent" in resolution (current MO NWP still at 25km)
- We developed both:
  - **standard HadGEM3-A versions**, with parameterised convection and
  - **experimental versions with explicit convection.**





(top left) Hourly OLR from global N1024 with parameterised convection

(top right) Hourly OLR from global N1024 with explicit convection (Smagorinsky)

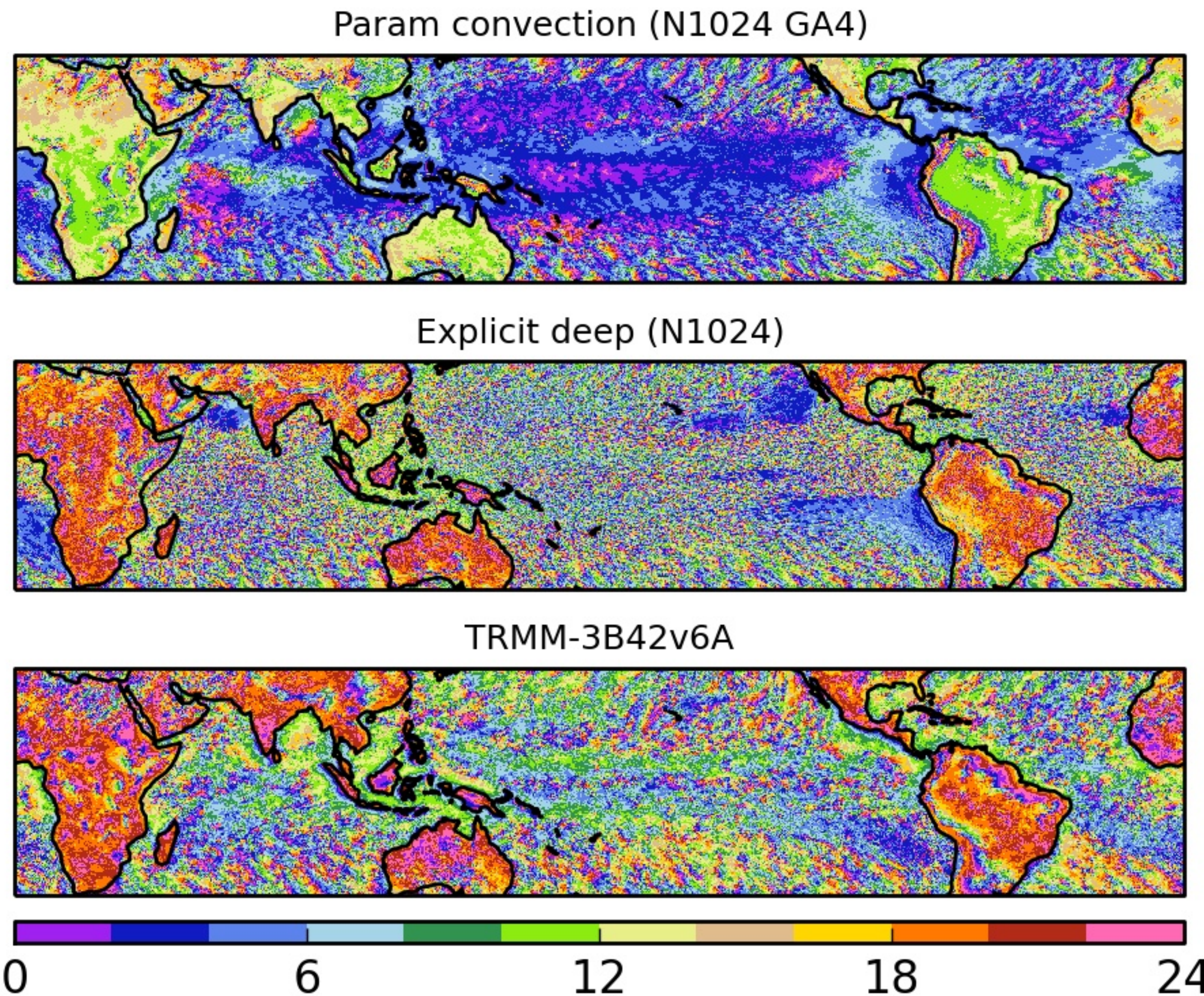
(bottom left) Hourly Infra-Red from MTSAT satellite

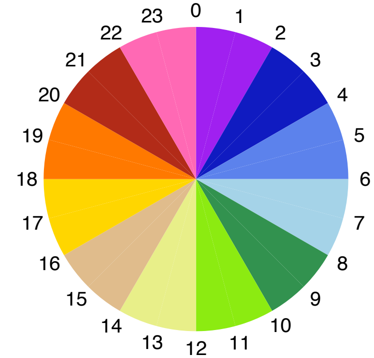
101 caveats of using explicit convection at 12km…
… but 6km soon and 4km in 2015

Consider the explicit convection version just as a process study:

- We don't represent convection at 12km (or even at 1km properly)!
- But the convective parameterisation has big issues too
- Probably the lowest resolution for which we can consider switching off the parameterisation – see CASCADE
- And mid-latitudes almost certainly not as good as with parameterisation

Local time of peak precipitation for 12km models (diurnal cycle) – Mar-Feb 08/09





M. Roberts et al.

thanks to R. Schiemann

JWCRP High-Resolution Climate Modelling Programme

Precipitation spectra, GCM comparison with TRMM

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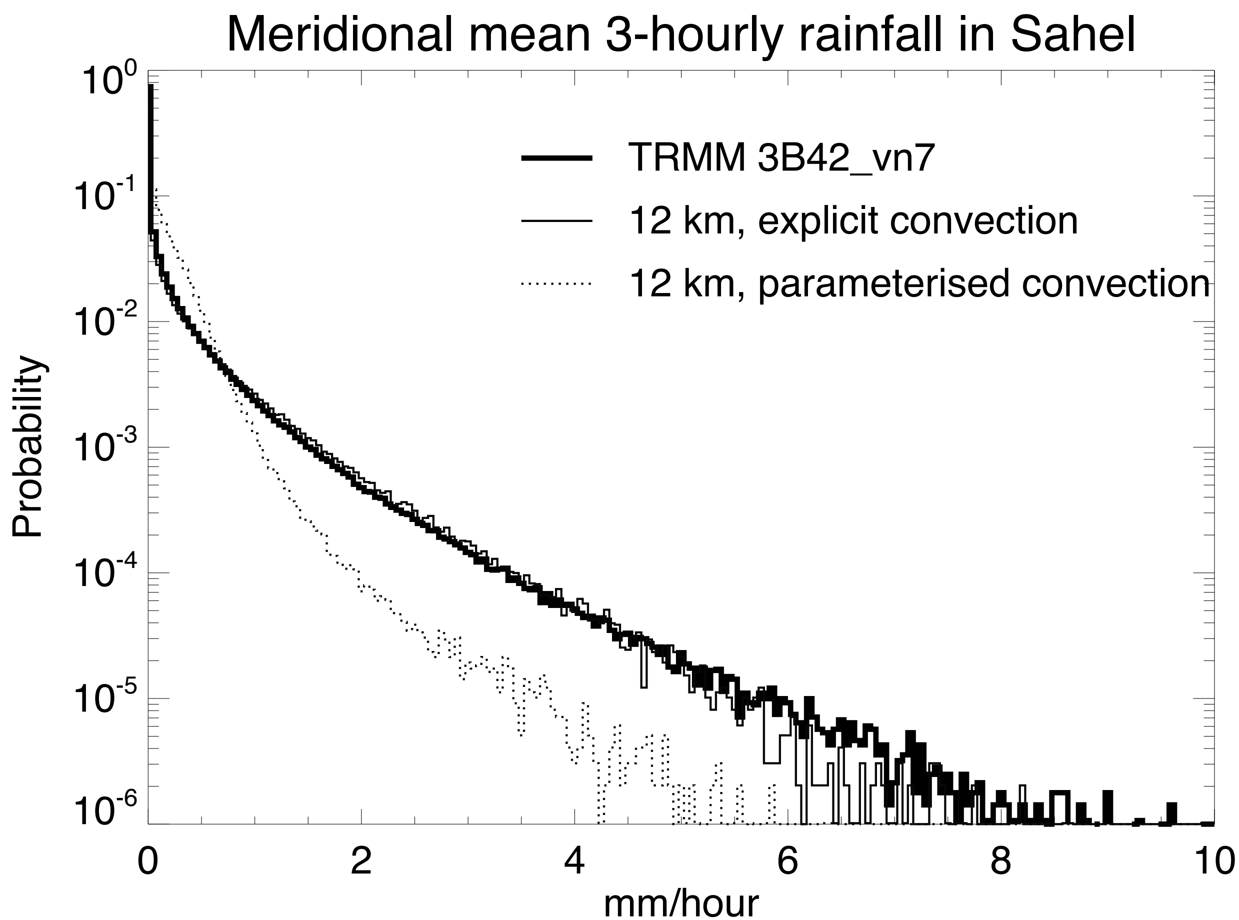
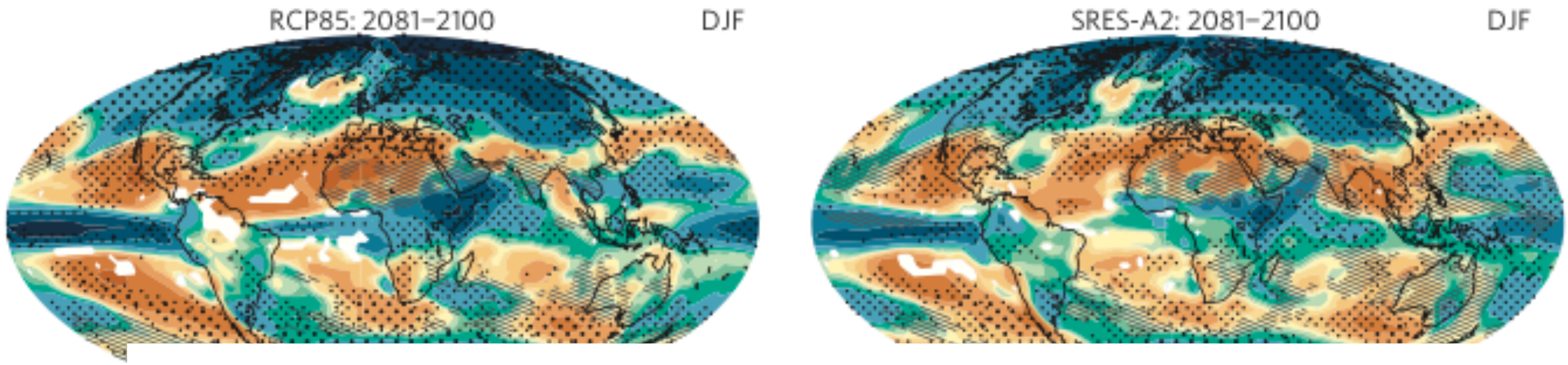


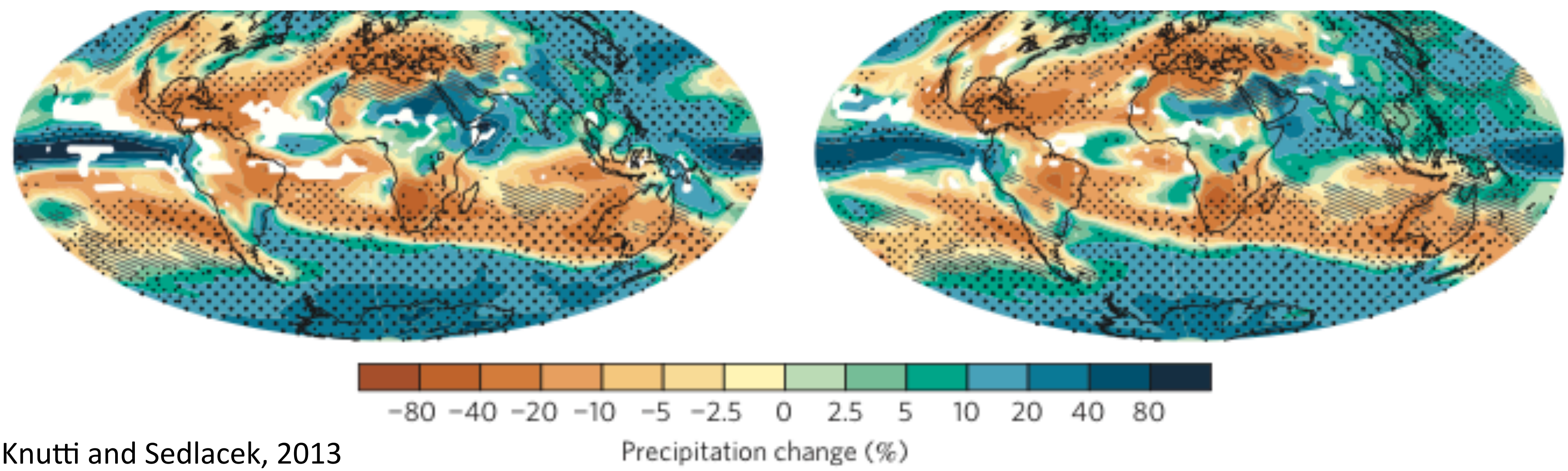
M. Vellinga, M. Roberts et al. 2014, unpublished

The updated **state of our ignorance**: level of agreement in CMIP5 (2013)

CMIP5 | CMIP3



Difficult to trust climate model projections of changes in the hydrological cycle, particularly at regional scale



Knutti and Sedlacek, 2013

From CMIP3 to CMIP6

Coupled Model Intercomparison Project, part of the Intergovernmental Panel on Climate Change (IPCC) process.

- In CMIP3 the typical resolution was 250km in the atmosphere and 1.5° in the ocean;
- more than seven years later, in CMIP5, this had only increased to 150km and 1° respectively.
- Current GCMs can operate in full climate mode (simulation length 10s to 100s of years, in ensemble mode), with mesh sizes of ~20km in the atmosphere and $1/4^{o}$ in the ocean.
  - the benefits of higher resolution (~20km) have been abundantly demonstrated, albeit mostly outside the CMIP exercise,
  - there has never been a systematic investigation of these benefits in the context of a multi-model assessment.

Readiness for CMIP6 and outlook for CMIP7

- PRIMAVERA now submitted to the EU's Horizon 2020 call
  - **PR**ocess-based climate s**IM**ulation: **A**d**V**ances in high-resolution modelling and **E**uropean climate **R**isk **A**ssessment
  - Coordinator: M. Roberts (MO)
  - Scientific Coordinator: P.L. Vidale (NCAS)
- <u>Overarching aim</u>:
  - To develop a new generation of advanced and well-evaluated <u>high-resolution</u> global climate models, capable of simulating and predicting regional climate with unprecedented fidelity.

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The roadmap to PRIMAVERA

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- We have some evidence of phenomena that, when simulated with current GCMs, are **insensitive to resolution**:
  - Global radiative budget
  - ENSO-driven ocean→land transports
  - MJO
- Some examples of phenomena that, in our GCMs are **resolution-dependent**
  - Emergence of backscatter in energy spectra
  - Precipitation distribution
  - Ocean → Land transports of water
  - Mid to high-latitude eddy transports → jets → weather
  - Storm intensities (tropical, extra-tropical)
  - Tropical Cyclone variability and response to drivers (e.g. ENSO, CC)
- **Most of these findings originate from a single model**. We need a systematic multi-model programme to investigate the robustness of our results. PRIMAVERA and HighResMIP.
- Coupled (AOGCM) and uncoupled (AGCM) responses are not always consistent. However, effectively spinning up a high-resolution ocean model remains a major obstacle for progress.

PRIMAVERA core experiments (HighResMIP) and "Frontiers" simulations

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Institution	MO NCAS	KNMI IC3 SMHI CNR	CERFACS	MPI	AWI	CMCC	ECMWF
Model names	MetUM NEMO	ECEarth NEMO	Arpege NEMO	ECHAM MPIOM	ECHAM FESOM	CCESM NEMO	IFS NEMO
Atmosph. Res., core	60-25km	T255-799	T127-359	T63-255	T63-255	100-25km	T319-799
Atmosph. Res., FCM	10-5km						T1279-2047
Oceanic Res., core	¼ ^{o}	¼^{o}	¼	0.4-¼^{o}	1-¼ spatially variable	¼	¼
Oceanic Res., FCM	1/12^{o}	1/12^{o}	1/12^{o}	1/10^{o}	1-1/14^{o} spatially variable	*(1/16^{o})*	

But it is not all about resolution…

- Recent developments in convective parameterisation have improved:
  - MJO: GFDL model (Benedict et al. 2013)
  - Diurnal cycle of precipitation: IFS model (Bechtold et al. 2013)
- And there are proposed schemes that are scale-aware:
  - Arakawa (2011)
  - Bechtold et al. (2013)

Summary of Global Climate Modelling at the Petascale

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- Much has changed in global climate modelling from the time when climate GCMs could not rival weather forecast (NWP) models in their ability to simulate the building blocks of climate;
- Not interested in downscaling; focus on emerging processes and <u>scale interactions</u>.
- Still a long way to go in how we:
  - Define and follow standard experimental protocols: proposal for HighResMIP
  - Assess our models as a community, using a process-understanding approach
  - Quantify the robustness of our findings and the trustworthiness of our model projections
- Running High-Resolution GCMs on Petascale HPC is trivial(-ish)
- <u>Data analysis remains the principal challenge</u>: we need a community approach, of the type used to exploit satellite missions.

Q&A

CHRM papers (13 published in 2013-2014)

One of the big success stories from UPSCALE is our having engaged ~20 expert research groups worldwide in analyses that exploit our simulations.

- **J. Clim**: M. Roberts et al., in press, on TCs in the UPSCALE campaign
- **BAMS**: K. Walsh et al., in press, reporting on the CLIVAR Hurricane Working Group experiments
- **JAMES**: Shaevitz et al., in press, reporting on the CLIVAR HWG experimental design
- **J. Clim**: Bell et al., published, on TCs and ENSO
- **J. Clim**: Daloz et al., in press, on emergent TC behaviour across a number of state-of-the-art GCMs
- **GRL**: R. Allan et al., on using high-res (UPSCALE) GCM to reconstruct the past history of the radiative budget
- **Nature** (submitted in late October): M. Vellinga et al., on the organisation of convection in West Africa