Weather and Climate modelling at the Petascale: achievements and perspectives

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National Centre for Atmospheric Science
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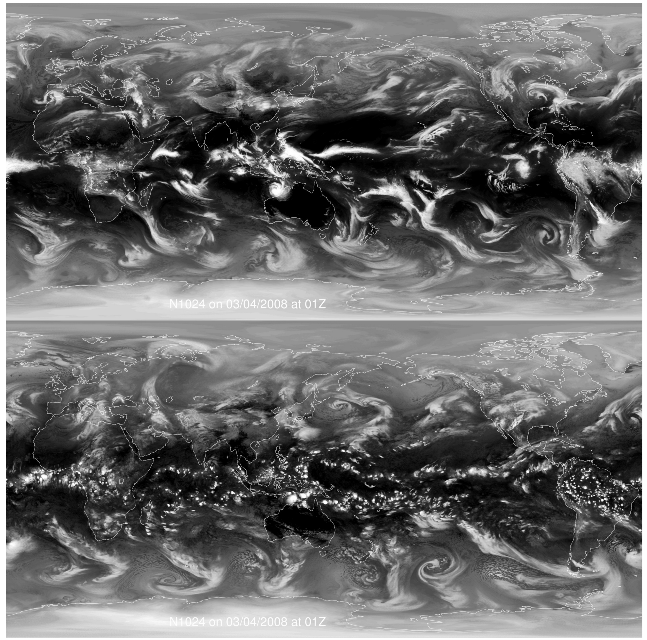
Willis Research Network



Malcolm Roberts

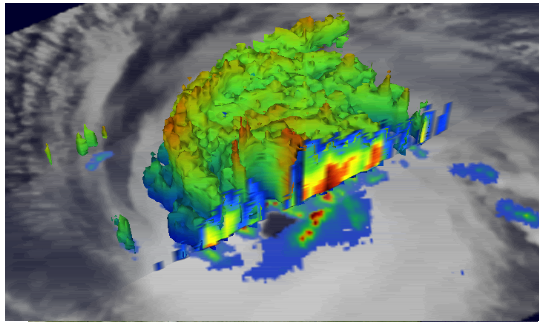
Matthew Mizielinski, Jo Camp, Lizzie Kendon
(with thanks to the many Met Office groups Involved in model development and elsewhere)

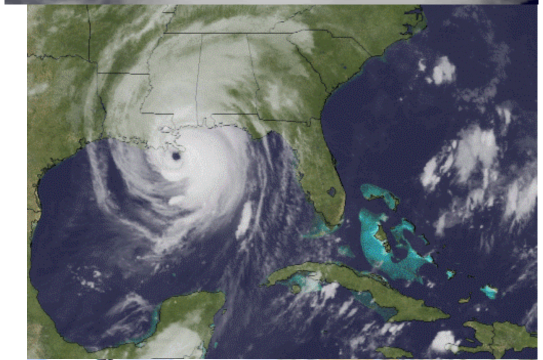
Met Office

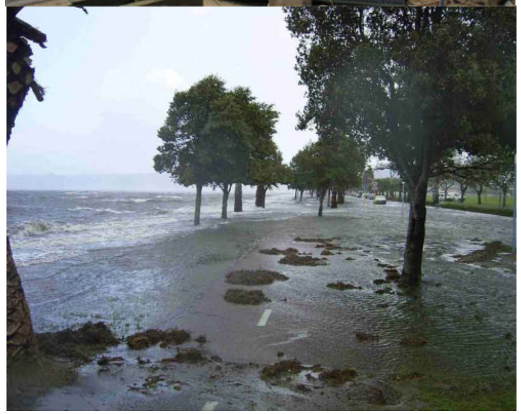
Outline

- The UK High-resolution Global Climate Modelling programme, **HRCM:**
  - Motivation
  - GCM developments and HPC

- The PRACE-UPSCALE project
  - Scalability achievements
  - Experimental design and goals
  - Science highlights:
    1. Global Energy and Hydrological Cycle
    2. Atmospheric eddies and jets
    3. European floods
    4. European heat waves
    5. Hurricanes and typhoons in the climate system
- Frontiers of Climate Modelling: the drive to explicit convection at the global scale

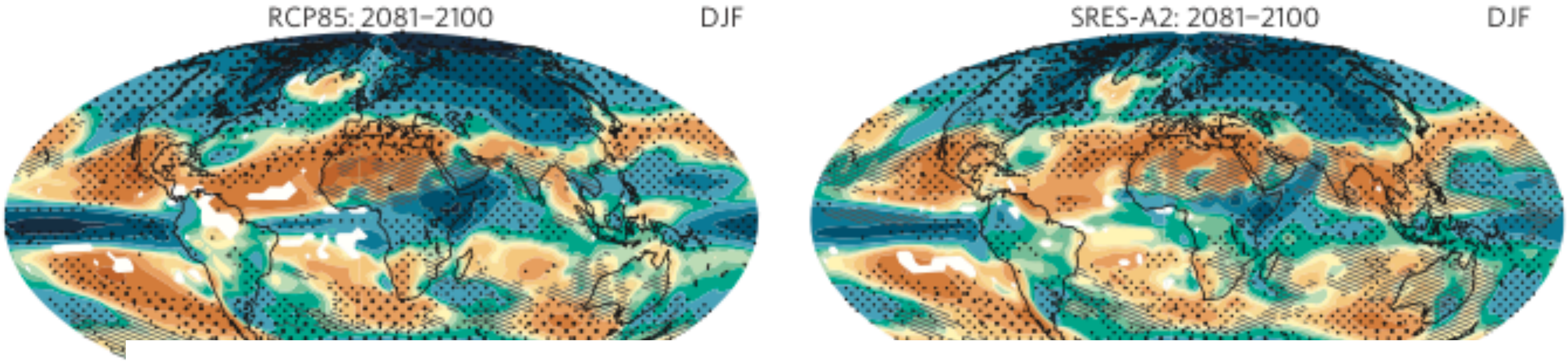




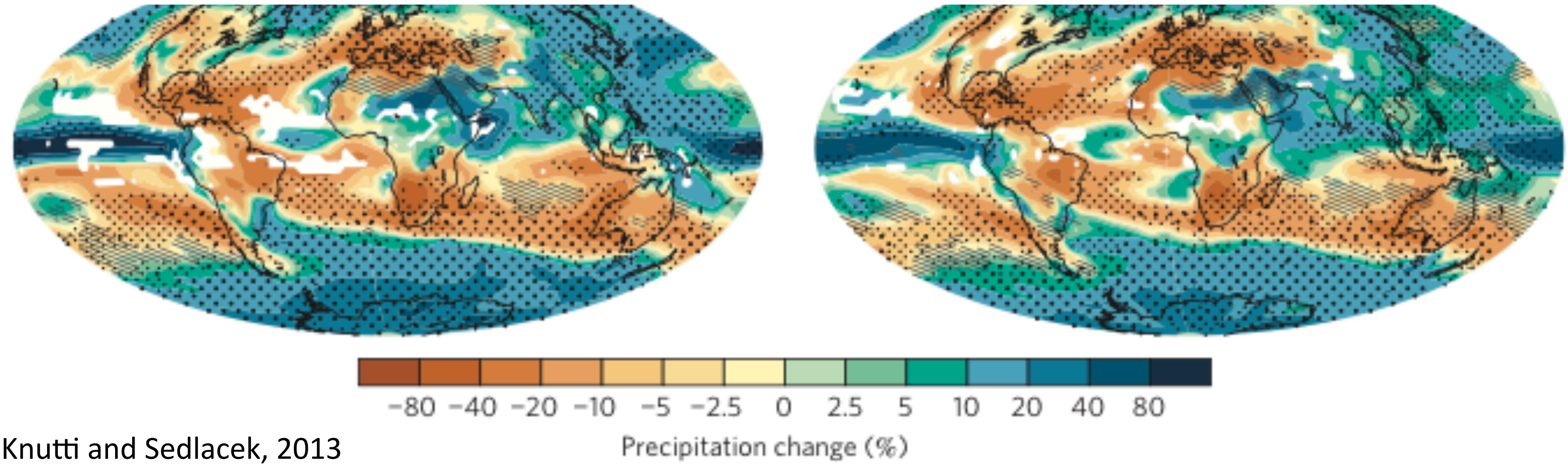


The updated **state of our ignorance**: level of agreement in CMIP5 (2013)

CMIP5 | CMIP3



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



Knutti and Sedlacek, 2013

Understanding of model uncertainty

Knutti and Sedlacek, 2013

Lack of convergence in model agreement attributed to:

1. Lack of accurate observations
2. Lack of process understanding
3. Limitation in model resolution **Our contribution**
4. Addition of new processes and components (Earth System Models) => new feedbacks not well understood
5. Lack of consensus on metrics of model performance (to separate better from worse models)
6. Limitation in prediction of climate change due to internal variability

Convergence in agreement for the right reasons

Our fleet: MetUM global atmosphere/coupled model climate configurations in use

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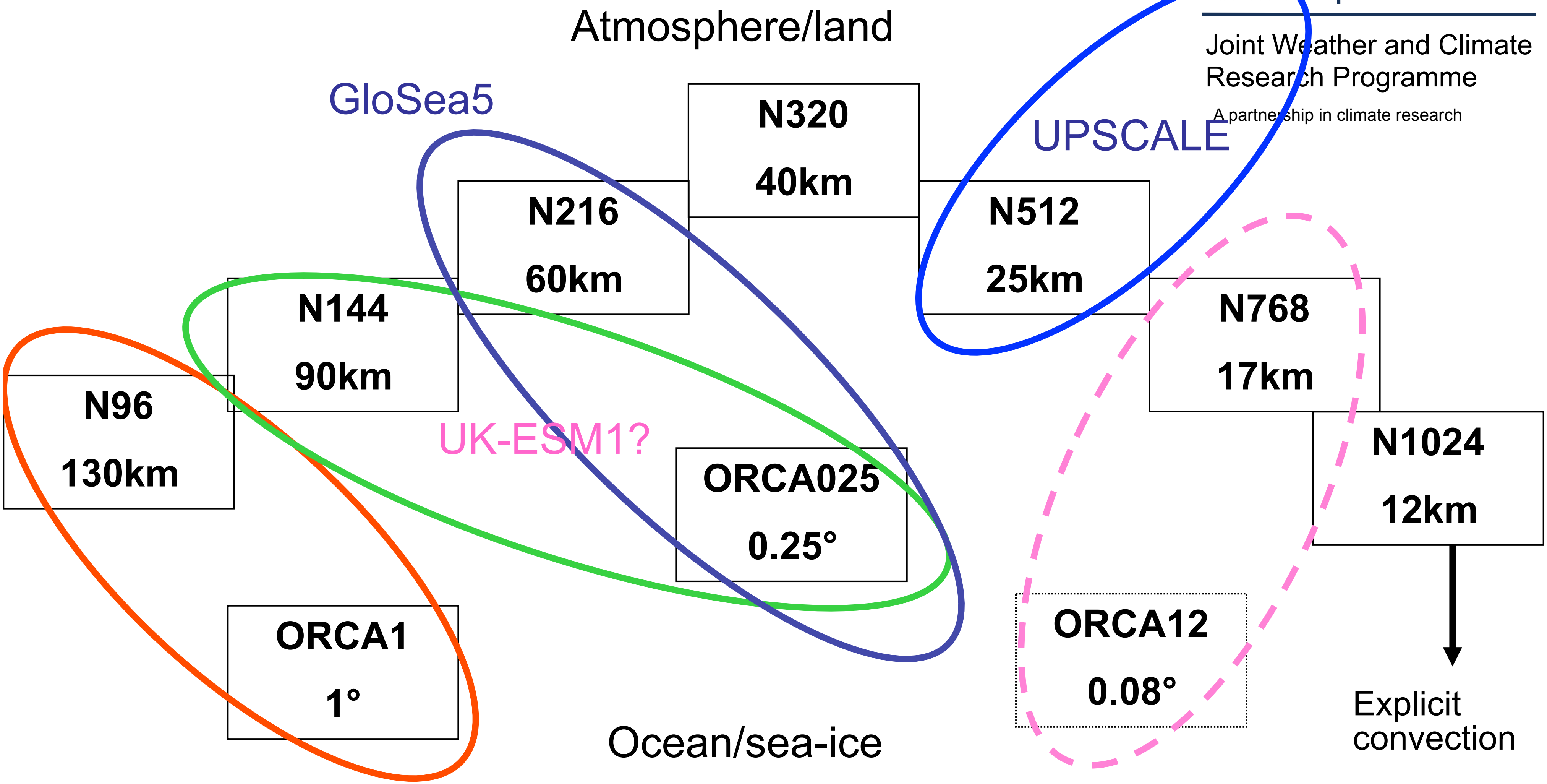
Joint Weather and Climate Research Programme

A partnership in climate research



CMIP5 resolution

Planned for 2014

Project to assess impact of global explicit convection

Essentially the same physics/dynamics parameters used throughout model hierarchy

The PRACE-UPSCALE Project

Joint Weather & Climate Research Programme
A partnership in climate research

UK on PRACE - weather resolving Simulations of Climate for globAL Environmental risk
Current "numerical mission" of the JWCRP High-resolution climate modelling team
PI: P.L. Vidale, NCAS-Climate, Reading

In 2011 we demonstrated our capability in effectively exploiting 4'800, and up to 12'000 CRAY XE6 cores. As an ensemble of GCMs, we could **concurrently use up to 60'000 cores.**

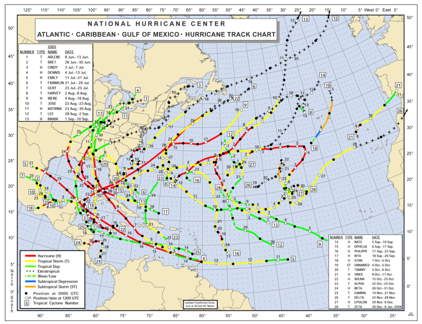
- Cf. with Earth Simulator: we never managed to effectively use more than 88 cores (out of 5'400 cores in total)

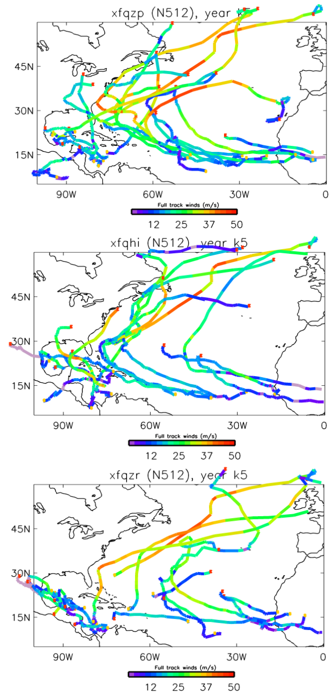
Produced 2-4TB data/day, transferred in real time to the UK, ended up with ~400TB of data

AWARD: **144 million core hours, for 1 year.**
Equivalent to: - 18x HadGEM2 submission to IPCC (= 8M core hours)
- half of the UK HECToR facility

Completed:

1. HadGEM3-A multi-decadal simulations at N96 (130 km) to N512 (25 km)
2. Development of a 12km (N1024) Global Climate Model





Present climate simulations

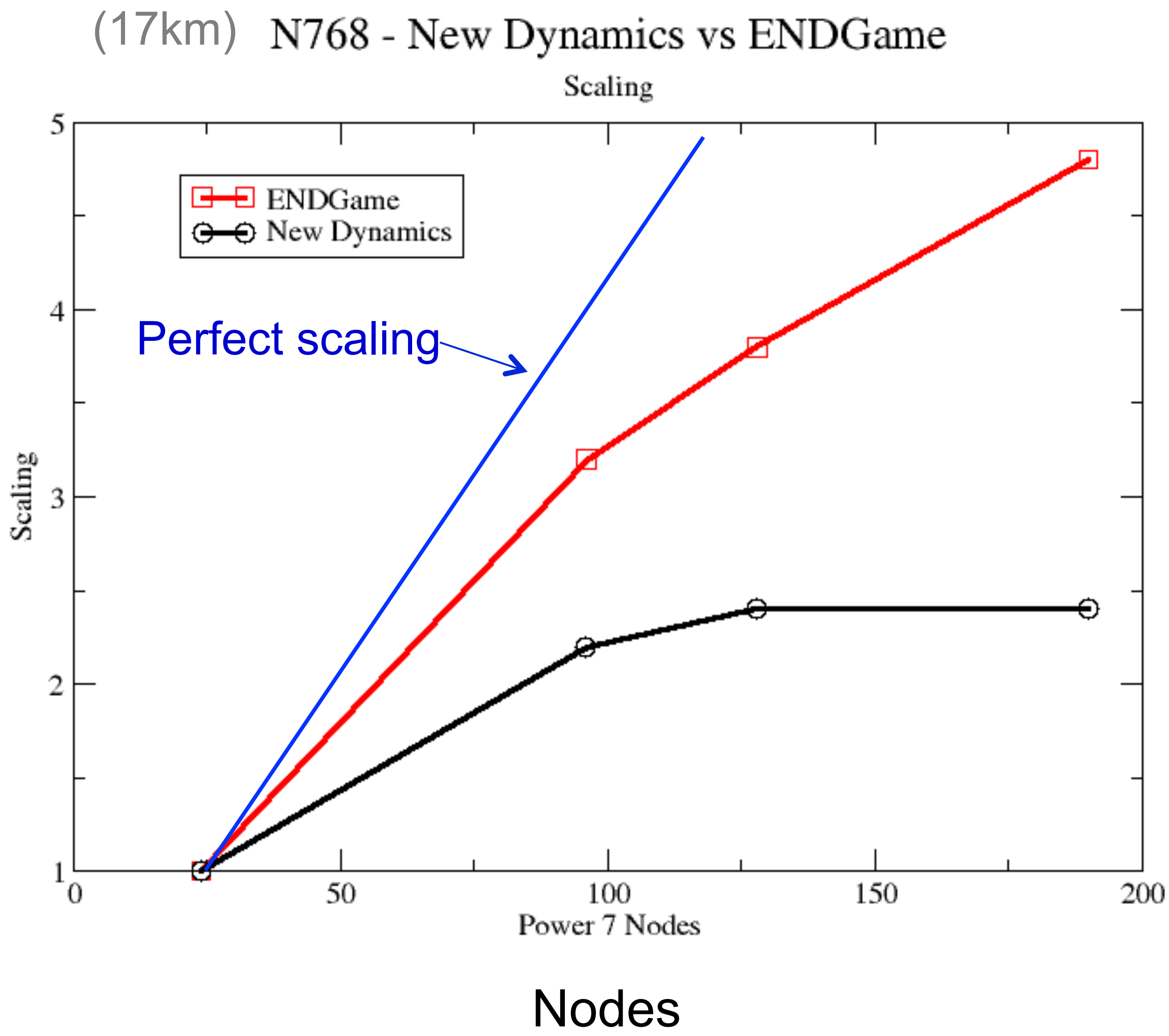
- forced with OSTIA SSTs
- 1985-2011 (27 years)
- 5 ensemble members, 27 years each

Future climate simulations

- 3 ensemble member, 27 years each
- following RCP8.5
- SST: daily OSTIA + HadGEM2-AO RCP8.5 2100 ΔSST

UPSCALE output available on JASMIN@CEDA

Progress in scalability from "New Dynamics" to "Endgame"



Slide: Nigel Wood

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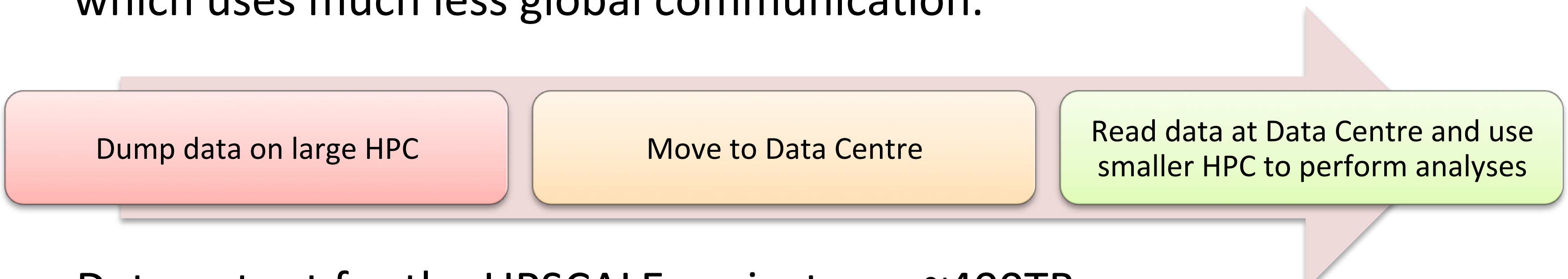
 ⟹ Algorithmic + code *scalability* is critical

“Best practice” setup core counts with new “EndGame” dynamical core
Time frame: 2012-

Resolution		Number of cores			Notes
		IBM P7	CRAY XE6	CRAY XC30	
N96 = 135km HG1-L38 HG3-L85		4*32 (EG)		192	Overall XC30 performance is 2.5x that of XE6
	Turnaround	3.5 syr/day		9 sypd	
N216 = 60km HG3-L85 Coupled O025		8*32 (EG) 36*32 (Coupled)			
	Turnaround	13 smo/day 2 sypd			
N512= 25km HG3-L85 HG3-L70 Coupled O0083		40*32 (EG) 200*32 (L70 EG) 140*32 (Coupled)	4’608 9’216	7’708 30K (L85)	Ensemble of 5 runs, concurrent, up to 150K cores
	Turnaround	5.7 smo/day 2 sypd 5 smo/day	5.3 smo/day 8 smo/day	1.2 sypd 5 sypd	**LIMITED BY OUTPUT SIZE** **Projection**
N1024 = 12km		75*32		50K (L85)	Projection
	Turnaround	32 days per day		1 sypd	**LIMITED BY OUTPUT SIZE**

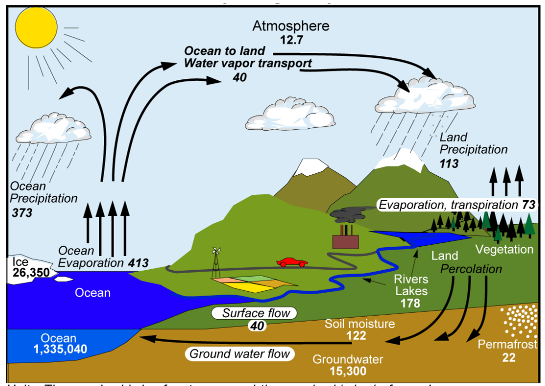
Data throughput and output is a big issue

- Earlier versions of our model could not scale because of the large data throughput requirements of our old dynamical core, “New Dynamics”
  - Breakthrough in scalability happened after we implemented our “IO server” technology, which reserves a number of nodes for data processing and frees all other nodes for number-crunching
- Data throughput is less of an issue with new dynamical core, “EndGame”, which uses much less global communication.



- <u>Data output</u> for the UPSCALE project was ~400TB:
  - we sustained 2-4 TB / day data transfers between HLRS (DE) and CEDA (UK); without this sustained transfer, the simulations would have stopped.
- We could have run a much larger ensemble if we could find more long-term storage and sustained larger transfer rates.

PRACE-UPSCALE
Science Highlight 1



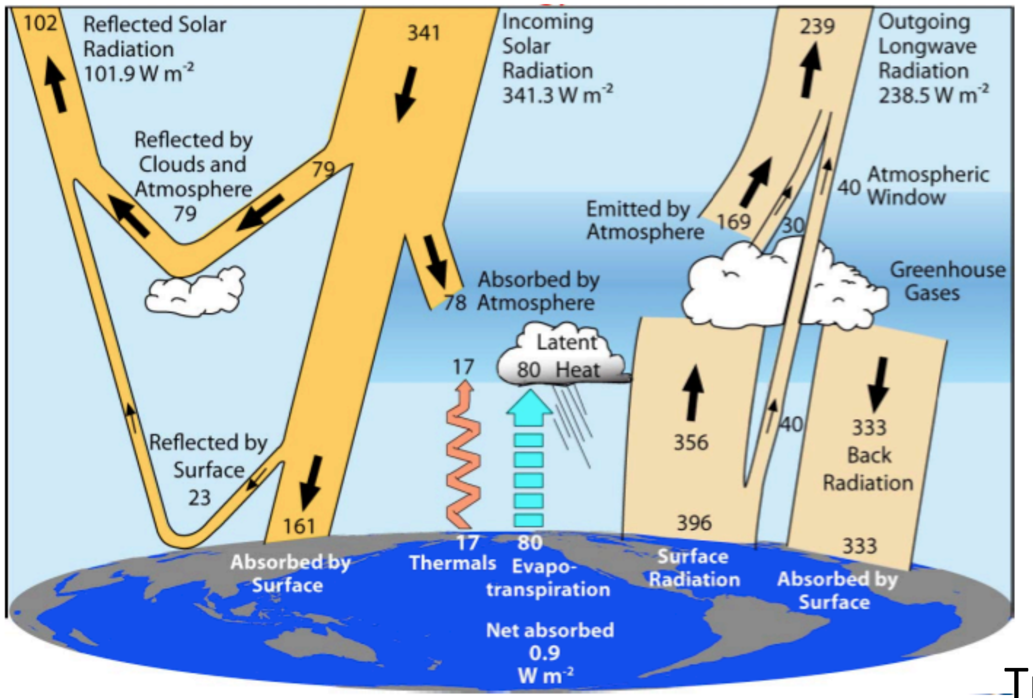
Units: Thousand cubic km for storage, and *thousand cubic km/yr* for exchanges

<u>The global water and energy balance</u>:

1. How much water is transported from the ocean to the land and then returned to the ocean as runoff?
2. What are the governing mechanisms?
3. Can increased understanding help us reduce IPCC model disagreement?

1a. Climate System Science: Energy and Water balance

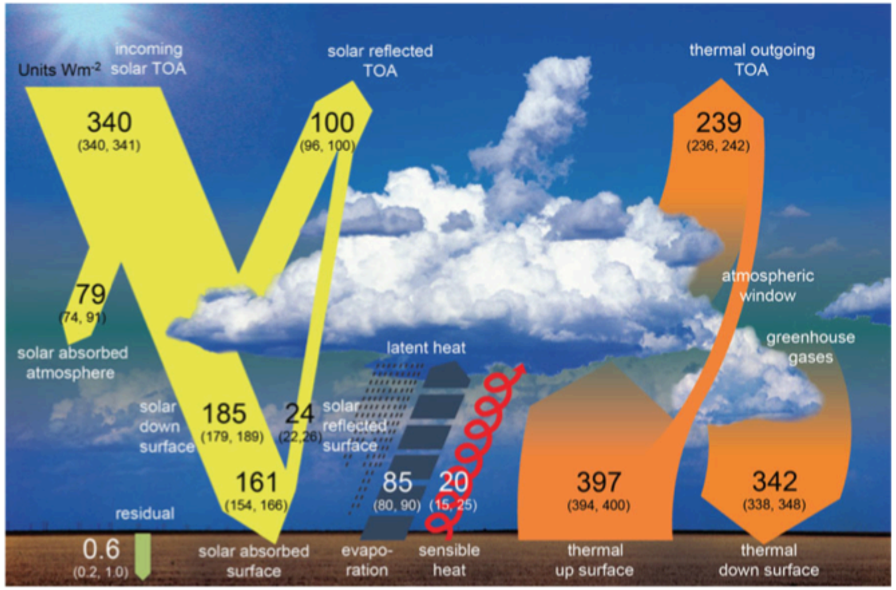
Hopefully, the simulation of some of the most fundamental aspects of the global climate system <u>should not depend</u> on model resolution



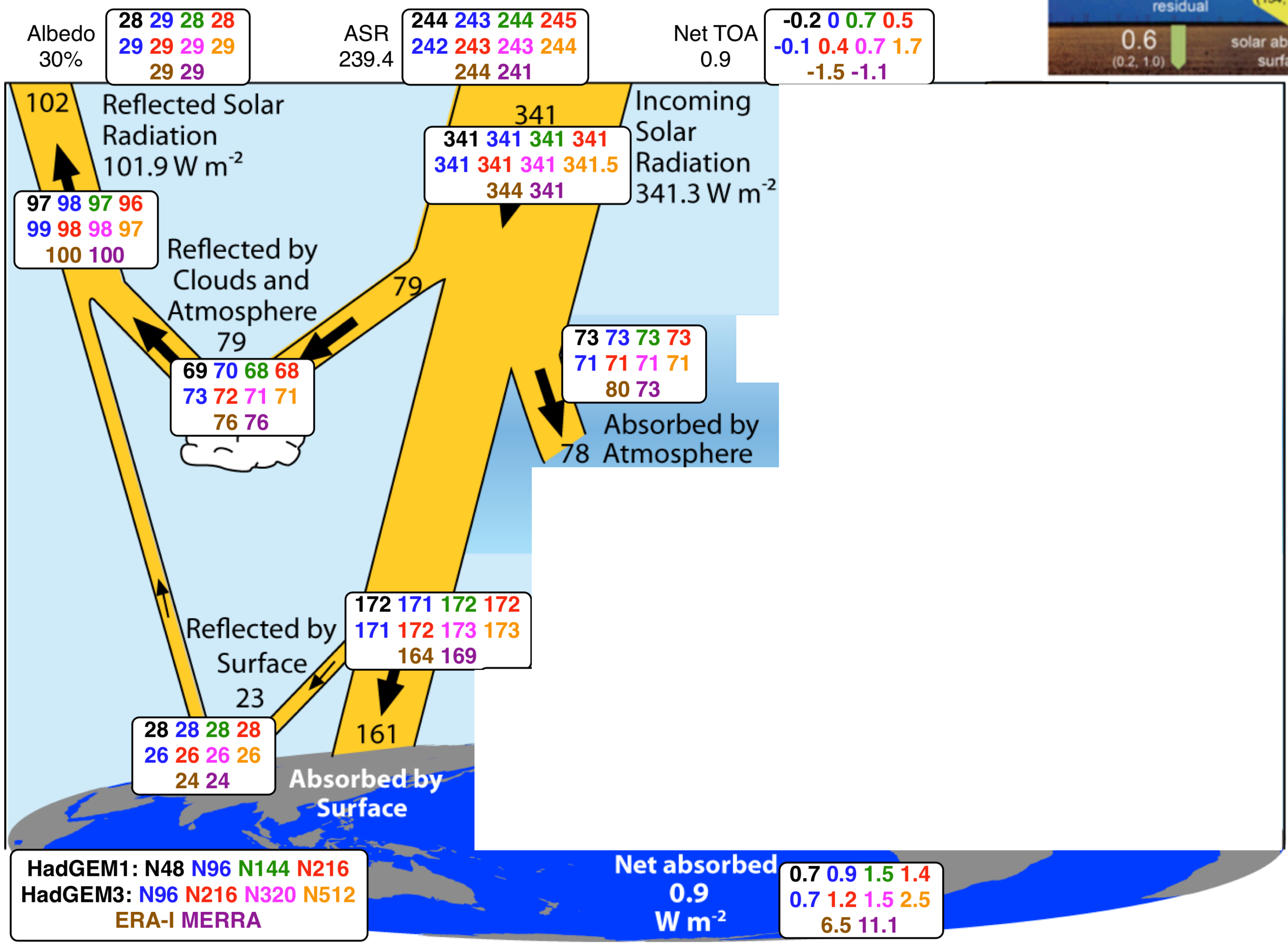
Trenberth et al., 2009

The global energy budget

Does not change with resolution



Wild et al., 2012



Fluxes: W/m²

Equivalent resolution at 50N:

270 km

135 km

90 km

60 km

40 km

25 km

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>

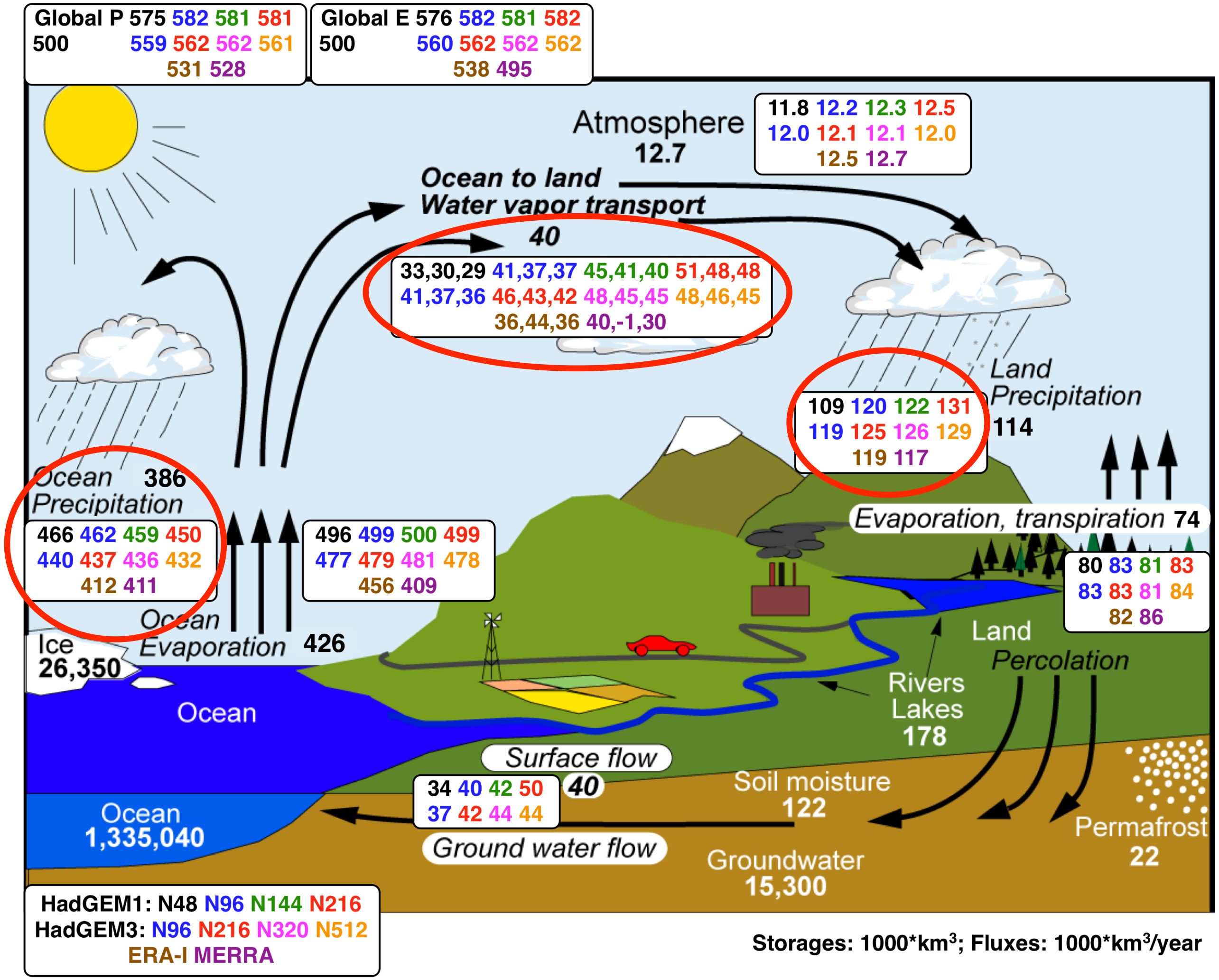


Figure adapted from Trenberth et al, 2007, 2011

- 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

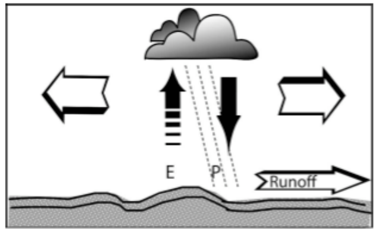
60 km

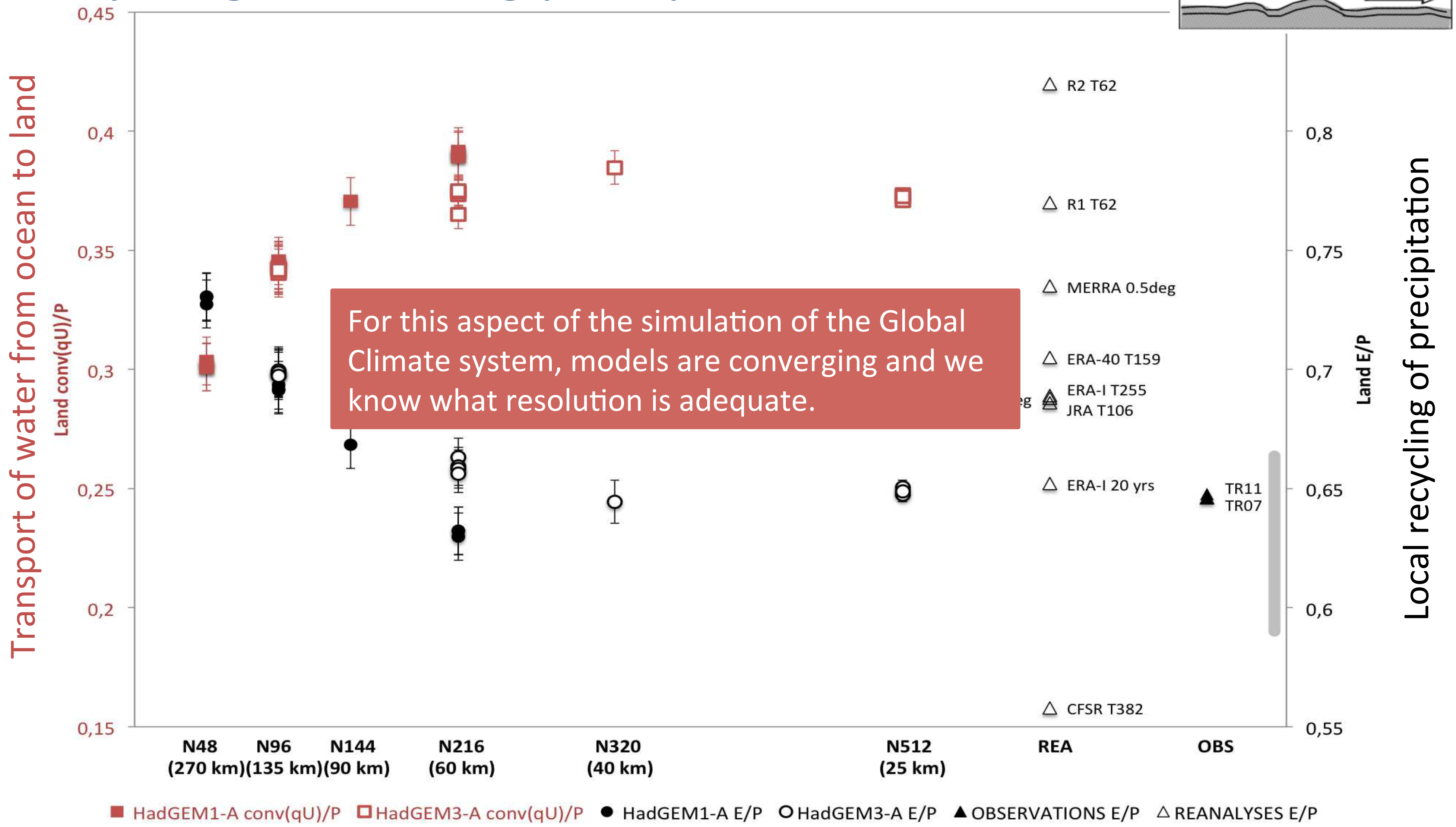
40 km

25 km

Demory et al., Clim. Dyn., 2013

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





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

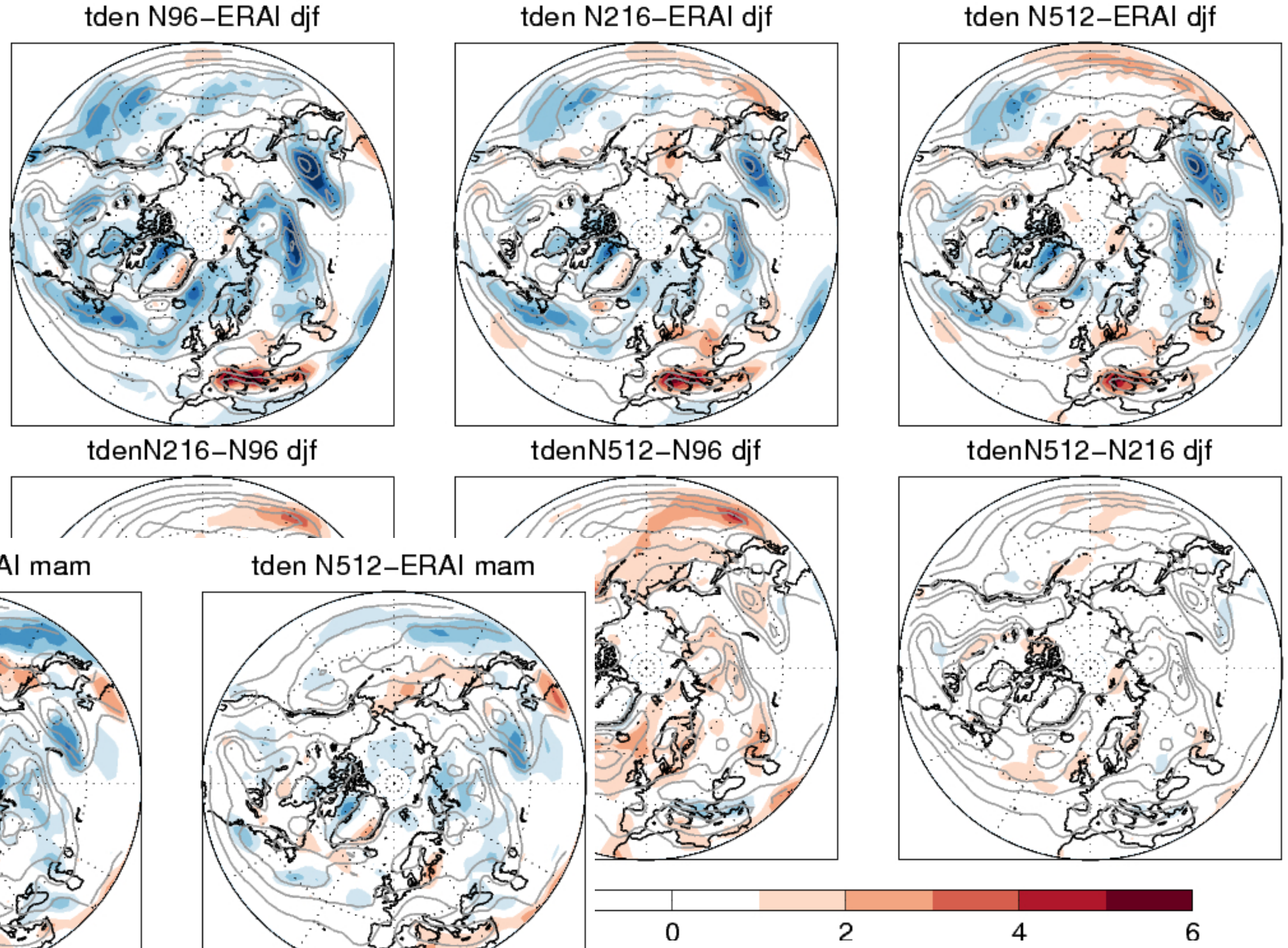
Lower local recycling
Higher transport

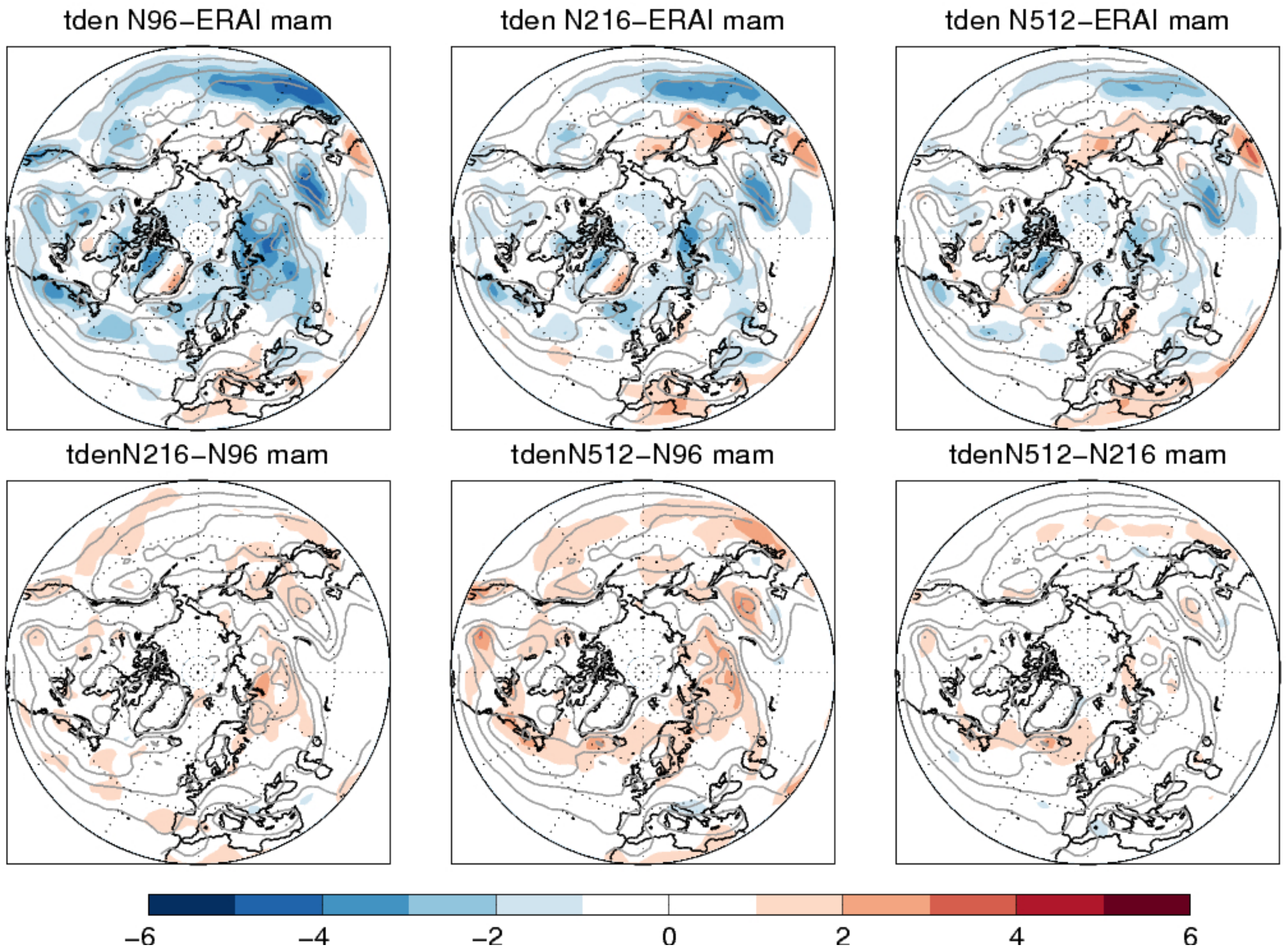
Demory et al, Clim. Dyn., 2013

UPSCALE

science hihghlight 2

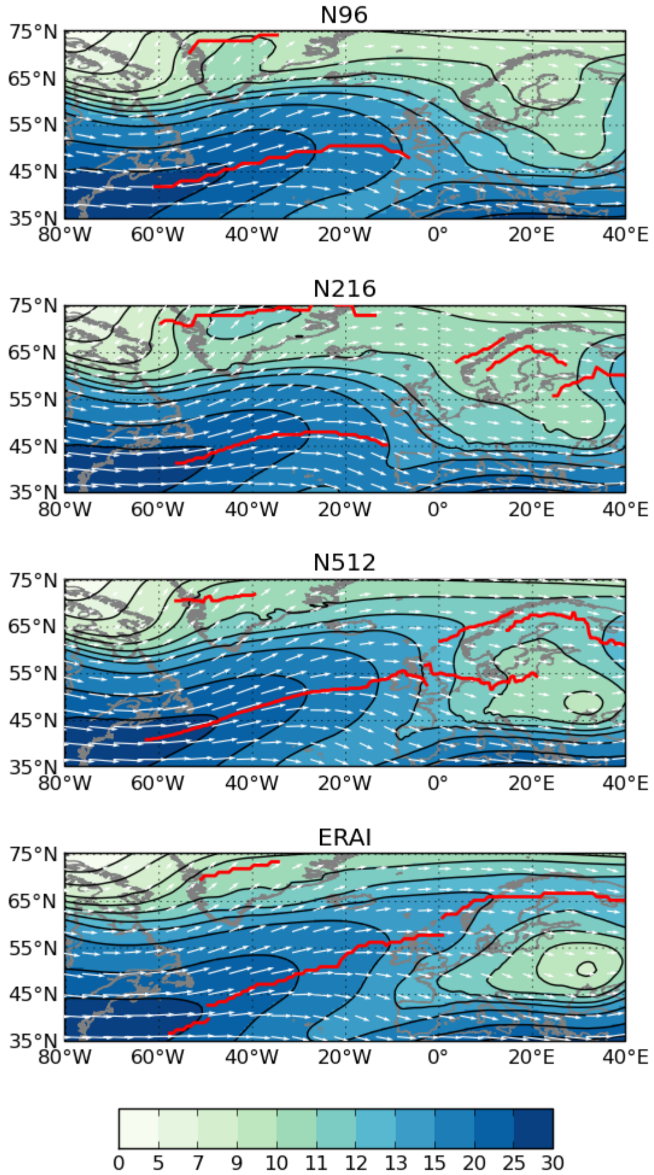
Atmospheric eddies ⇄ jets

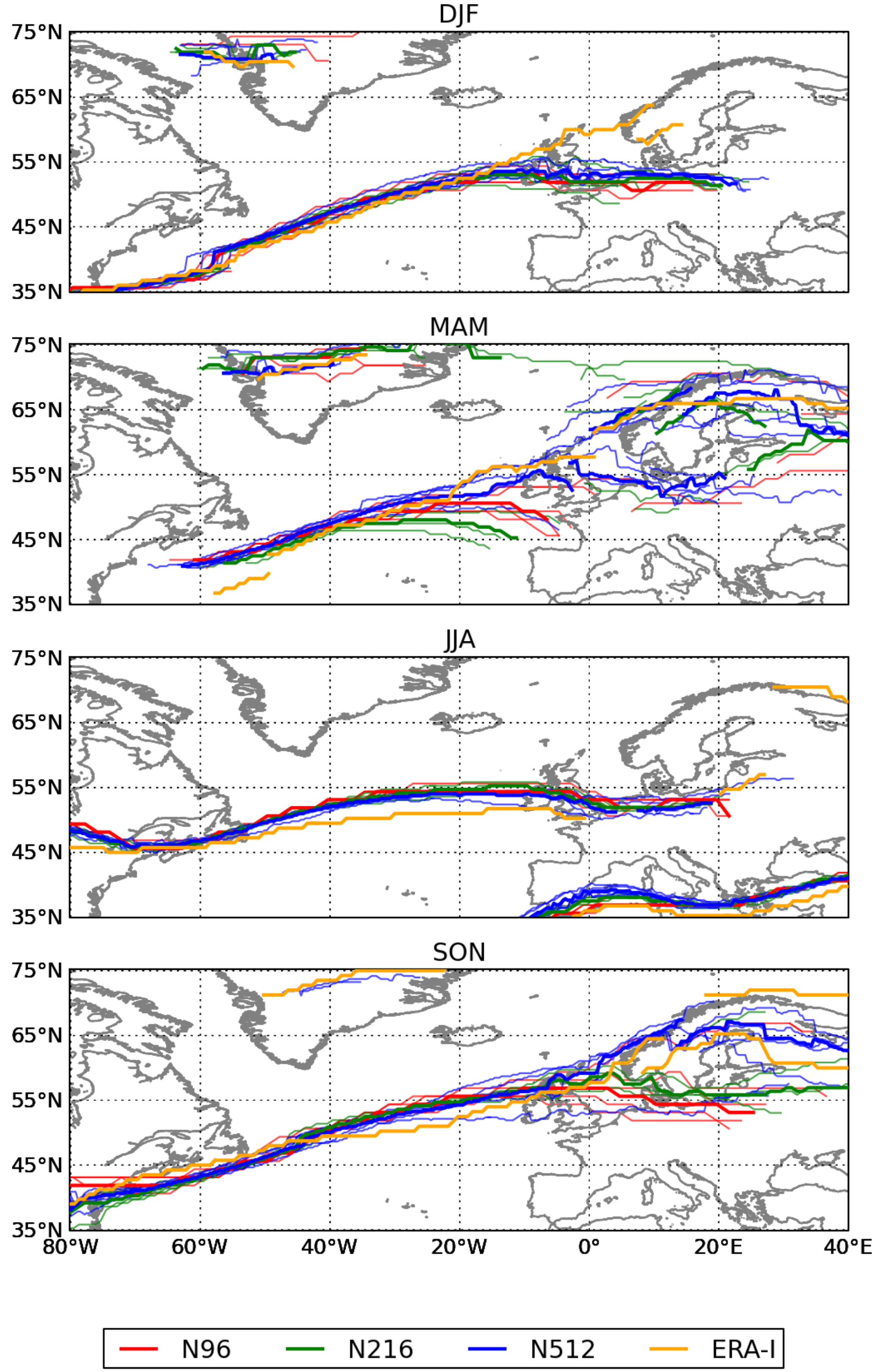




Atmospheric Jets

250hPa winds, ensemble





PRACE-UPSCALE
Science Highlight 3

Precipitation extremes:

1. how many more European floods like 2002, 2007, 2013, 2014 are likely and why ?
2. what is the relative role of the ocean and of the land ecosystems?
3. will these extreme episodes last longer and become more intense in the future?

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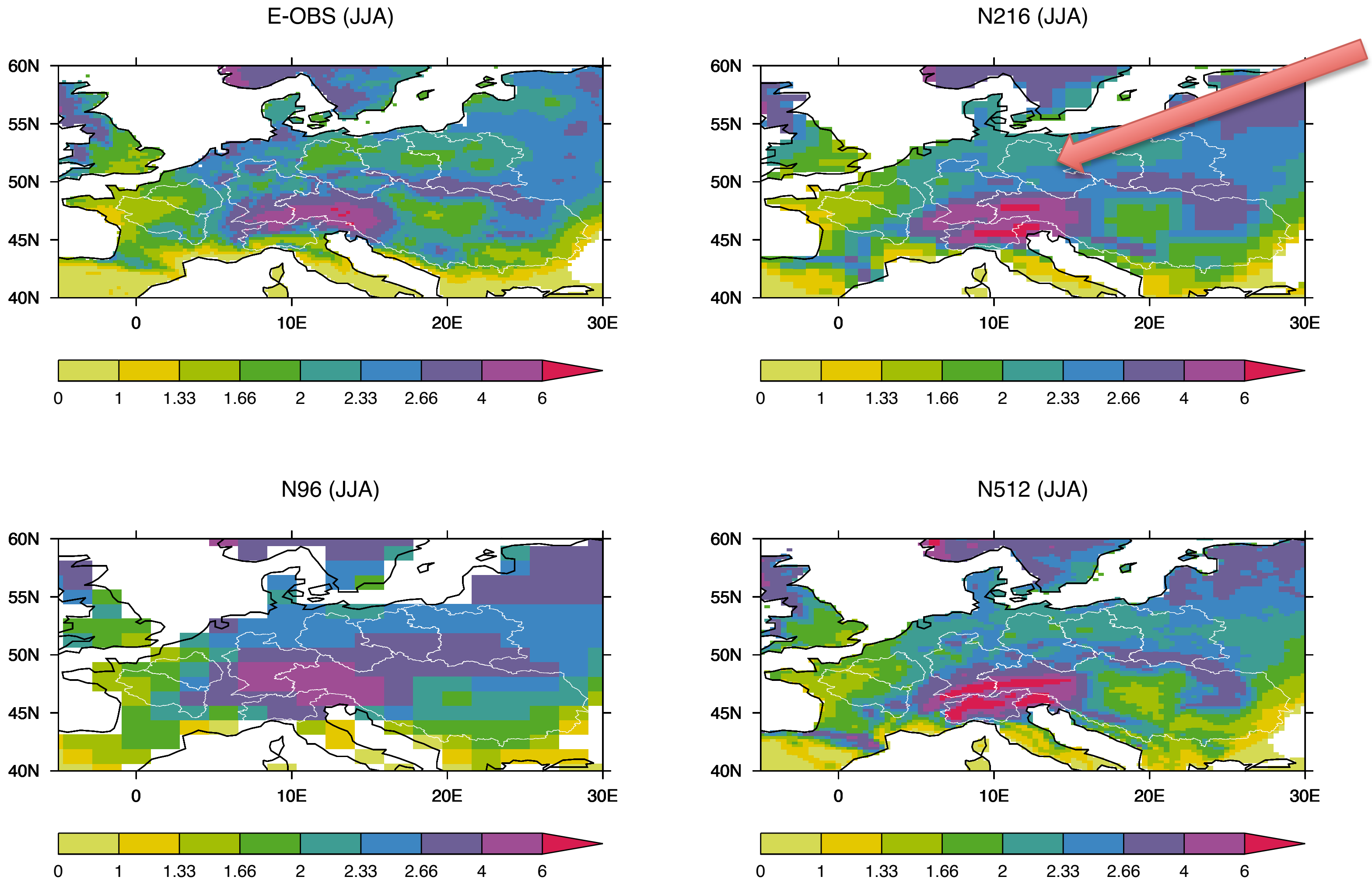
Joint Weather and Climate Research Programme



Elbe catchment

Reinhard Schiemann, NCAS-Climate, University of Reading.

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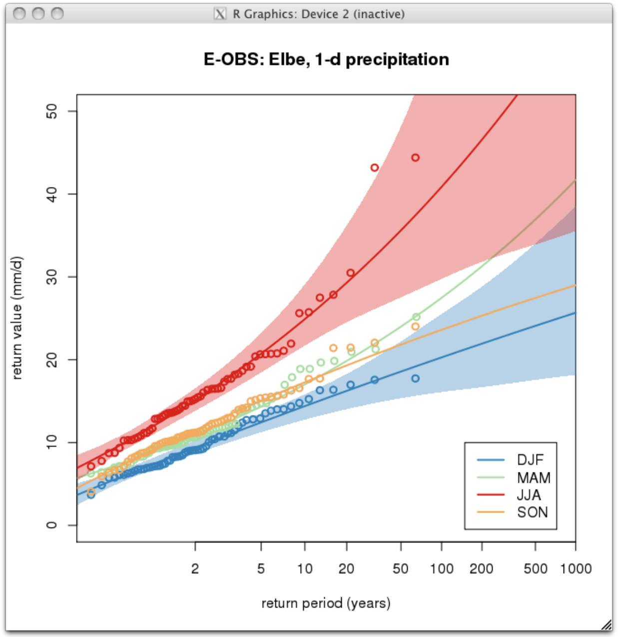
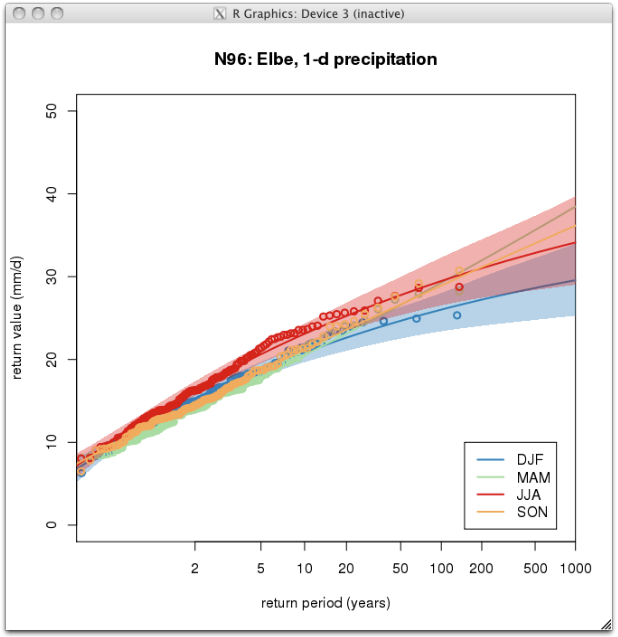
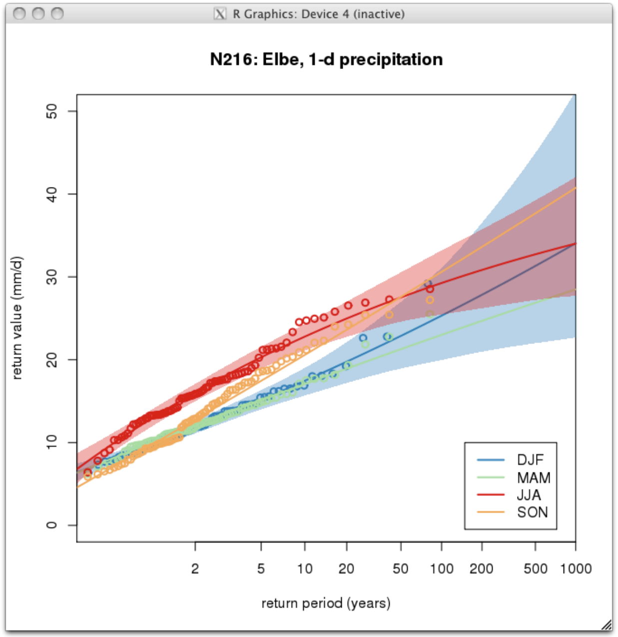
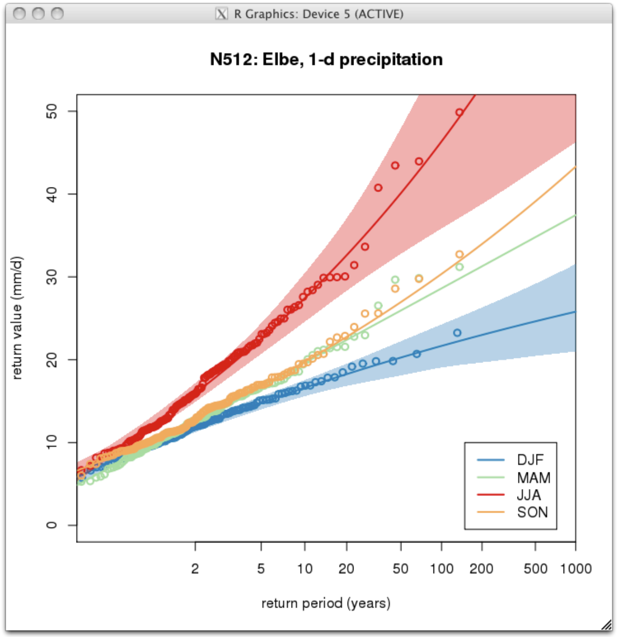




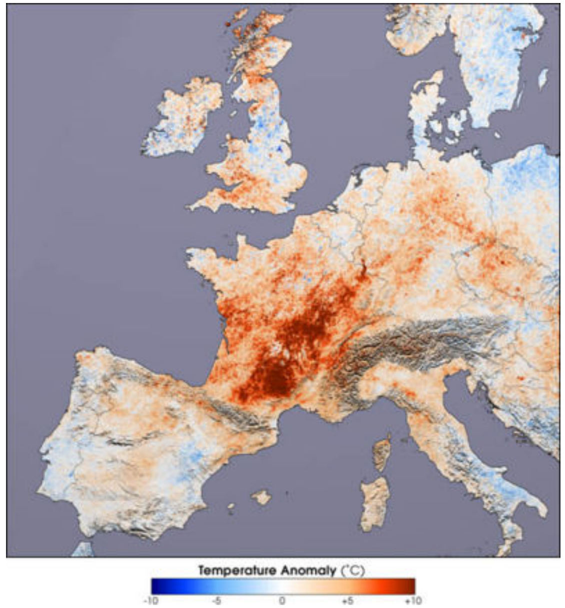




Reinhard Schiemann, NCAS-Climate, University of Reading.

Using gevXgpd R-package developed by Christoph Frei, Meteo Swiss

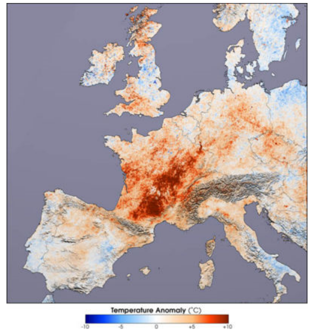
PRACE-UPSCALE Science Highlight 4

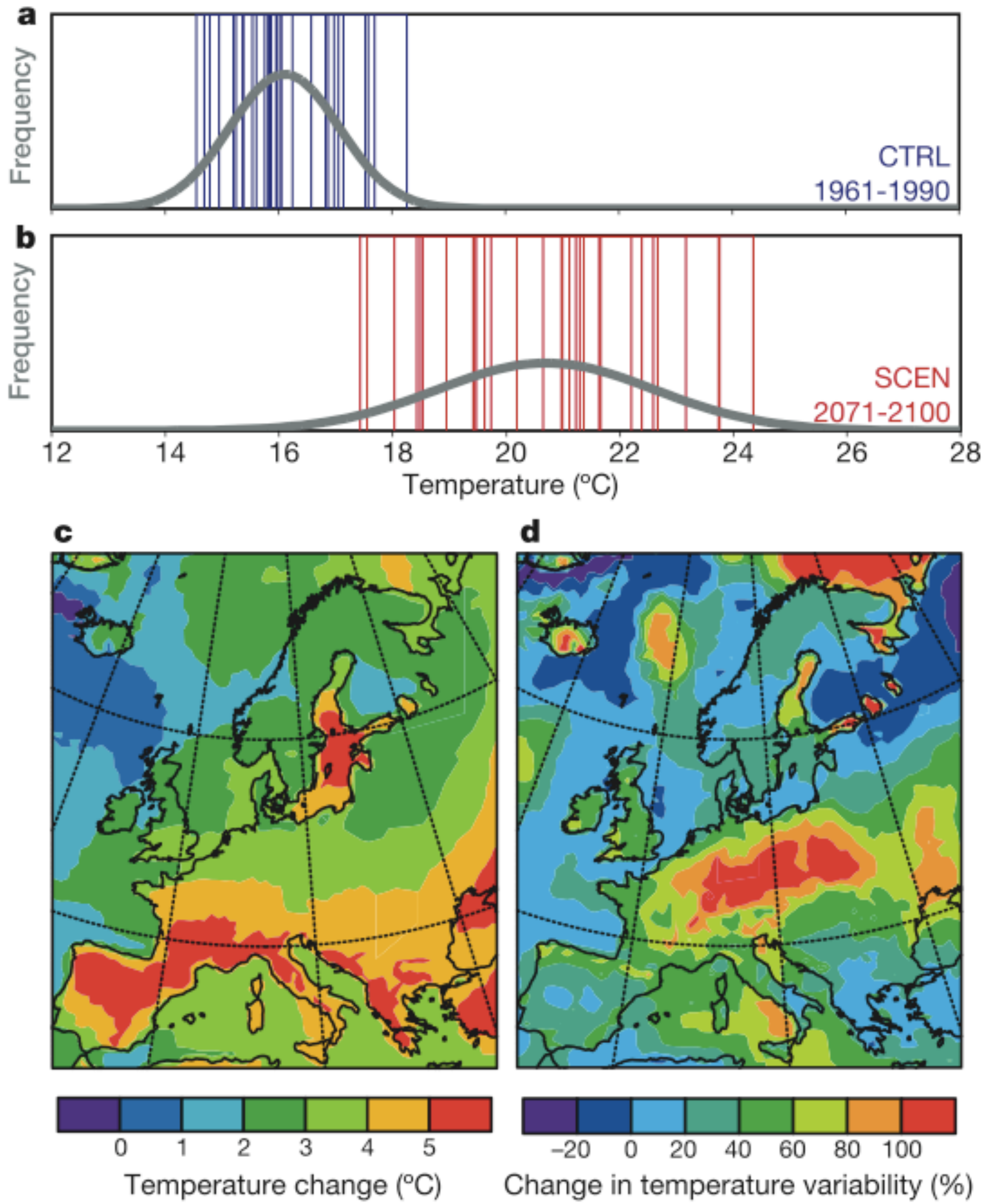


European heatwaves:

1. how many more European (or US) summers like 2003 are likely and why ?
2. what is the relative role of the ocean and of the land ecosystems?
3. will these extreme summer episodes last longer and become more intense in the future?

2003-type extreme summers how frequent and why? In the old times, only with regional models……



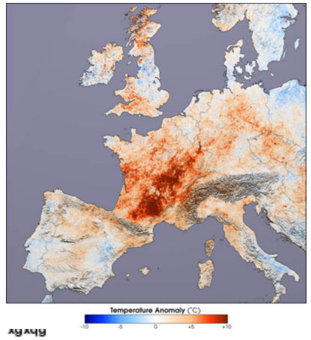


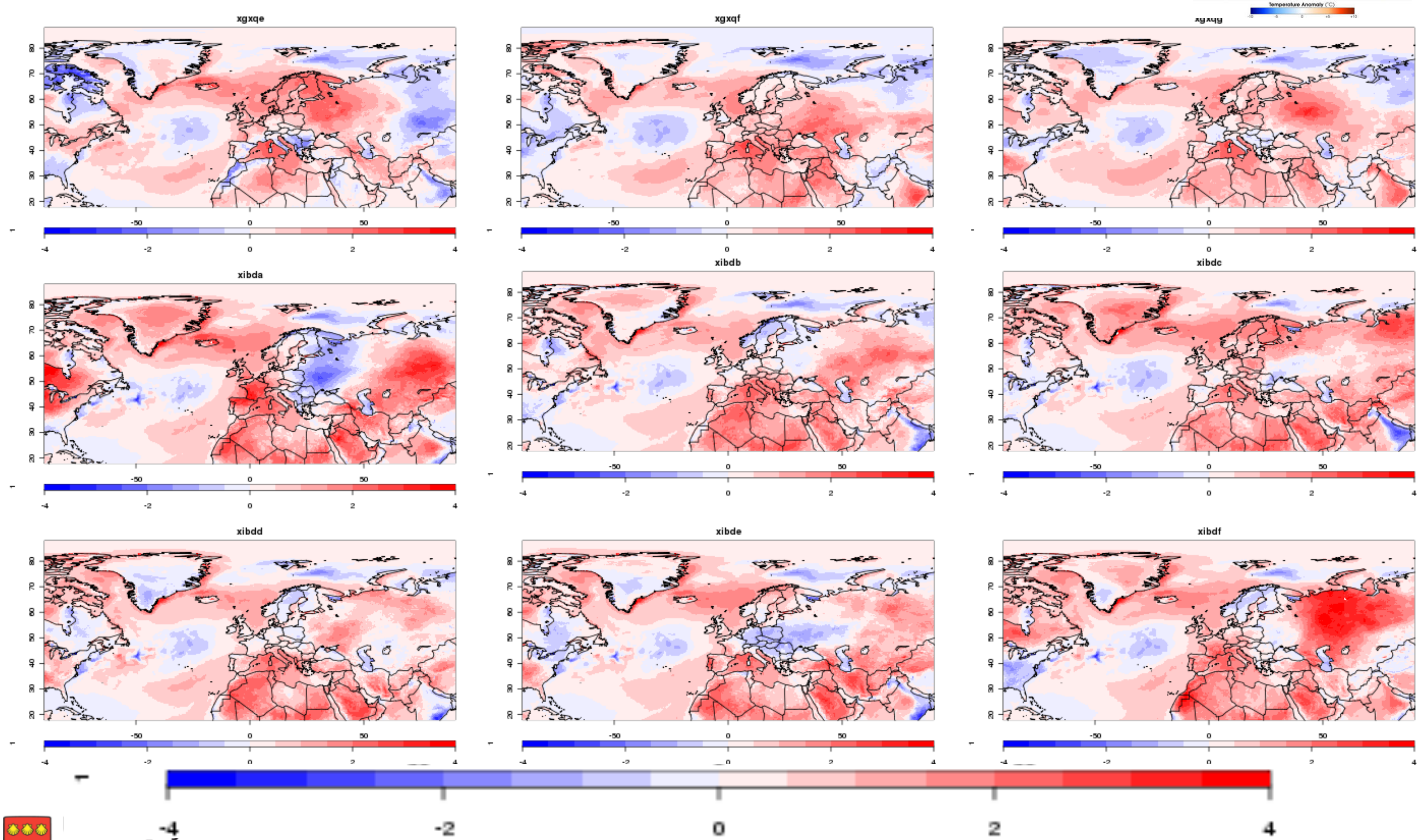
- Shift in mean and increase in interannual variability;
- This is crucial information for European decision makers;
- 2003 looks less special within a scenario distribution;
- Location of change in mean and location of change in variability are not the same
- How robust are these model results ?
- What are the active mechanisms ?

Schär et al., Nature 2004

2003 in the n512 UPSCALE GCMs:

JJA Temperature anomaly
in UPSCALE HadGEM3-N512 ensemble





Reading

E. Black, NCAS-Climate unpublished

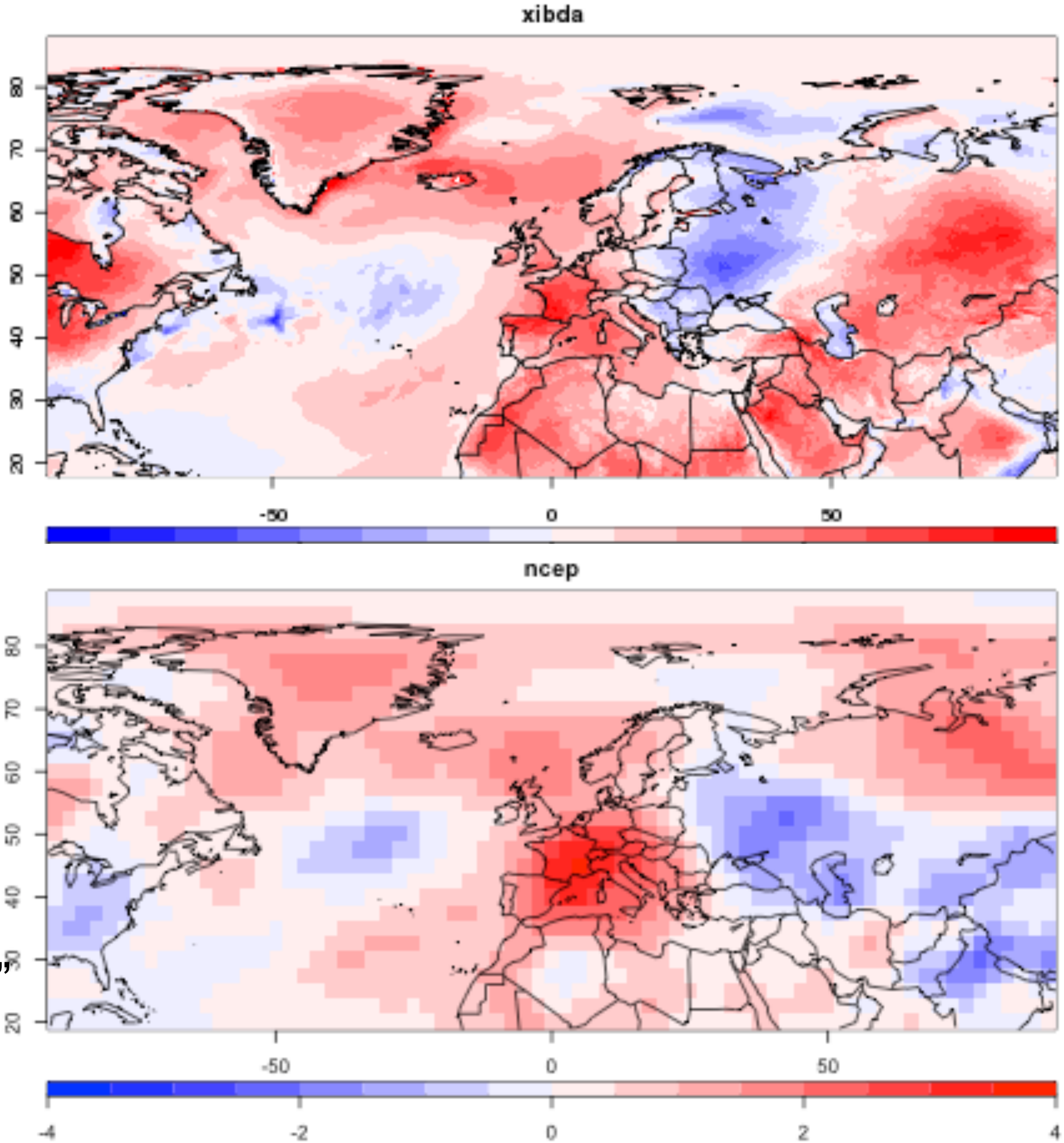
First place in the beauty contest…

xibda

NCEP

re-analysis,

“observations”



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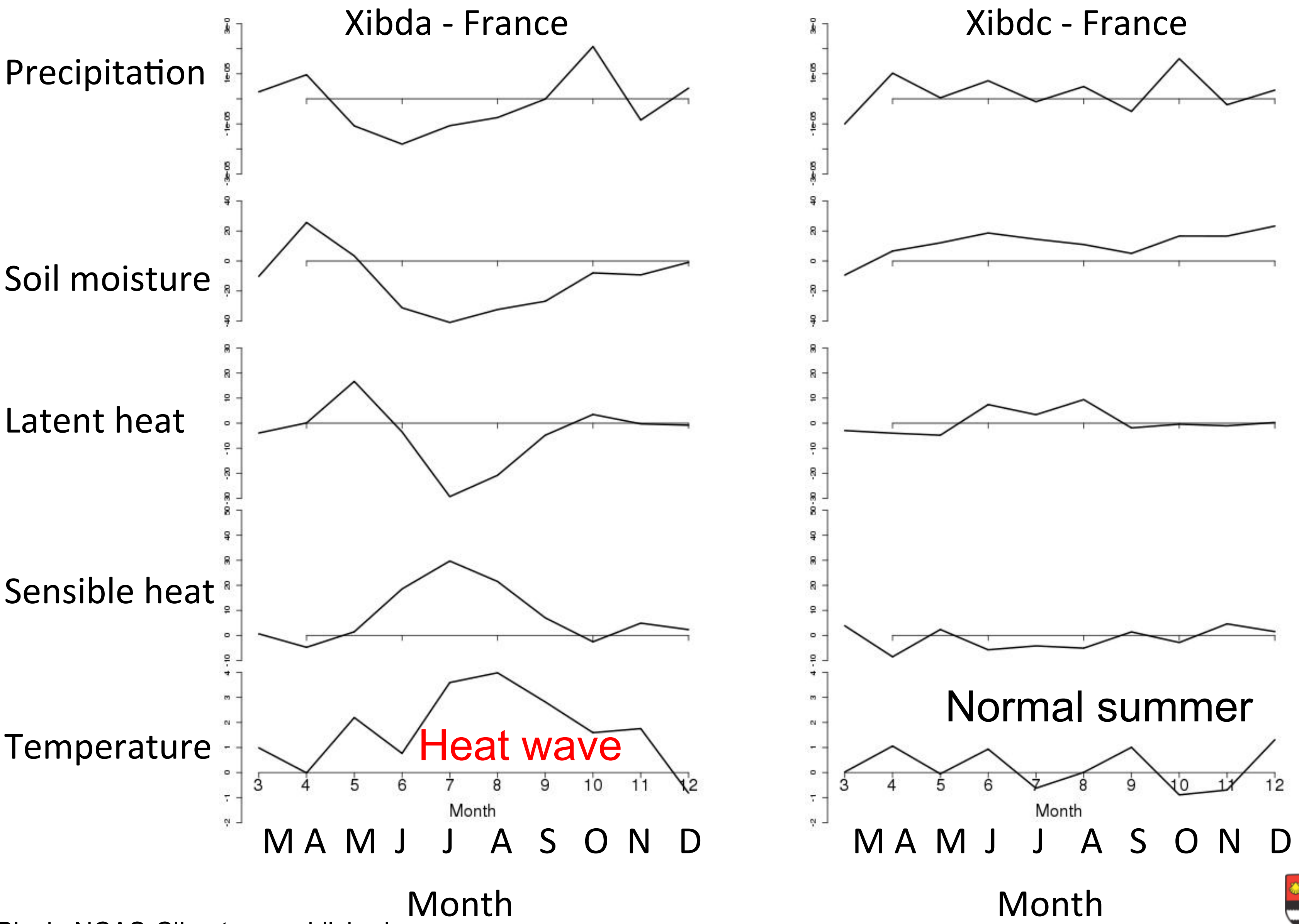
E. Black, NCAS-Climate unpublished

Hydrological pre-conditioning of European Heatwaves ?

Sequence of events in two ensemble members with identical, observed Sea Surface Temperatures (OSTIA)



E. Black, NCAS-Climate unpublished

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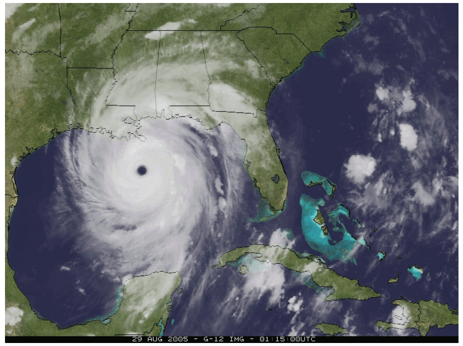
PRACE-UPSCALE
Science Highlight 5

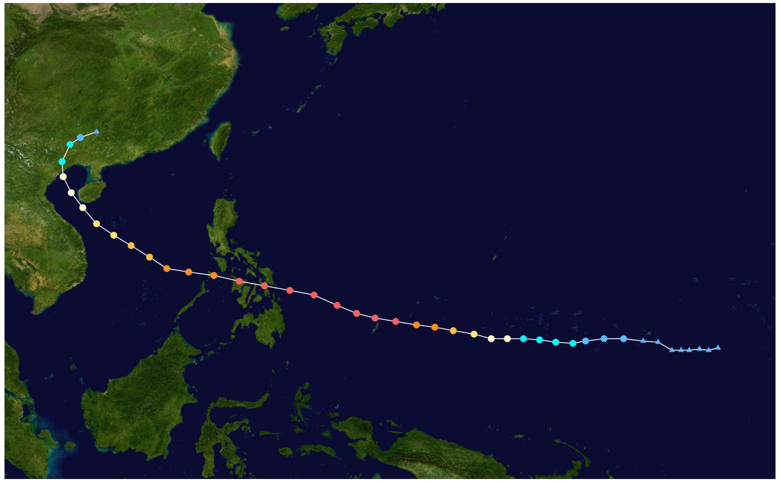


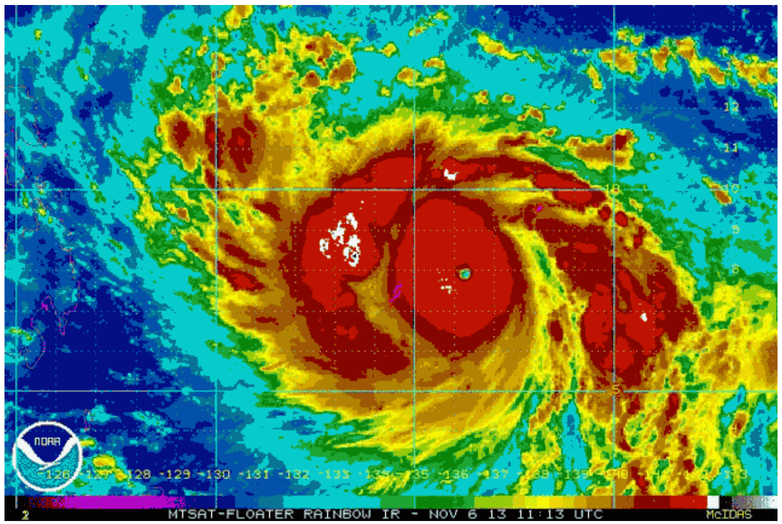
<u>Hurricanes and Typhoons</u>:

1. how many more years like 2005 (the year of Katrina), or 2011, can we expect?
2. will there be more/less storms in the future? more intense / less intense? Why was Haiyan (Philippines, 2013) so intense?
3. how many more storms like Sandy, the storm that started in the tropics and then hit New York City in late 2012?

Super-Typhoon Haiyan, 2-10 Nov 2013

- **25th tropical storm** to enter Philippine territory this year and reports suggest there have been sustained winds of some 315 km/h (195mph) with gusts of up to 375 km/h (235mph).
- At times it stretched **600km (372 miles) across**
- Officials estimate that:
  - up to **6,000 people** have died in Tacloban city and elsewhere.
  - Hundreds of thousands of people are displaced.
- Strongest?
  - <u>Fourth</u>: Typhoon Nancy in 1961, with 215 mph winds; Typhoon Violet in 1961, with 205 mph winds; and Typhoon Ida, in 1958, with 200 mph winds.
  - Atlantic hurricanes Camille, 1969 (200 mph), Wilma, 1985 (185mph).
- We do not trust wind estimates before ~1960.





UPSCALE Tropical Cyclones

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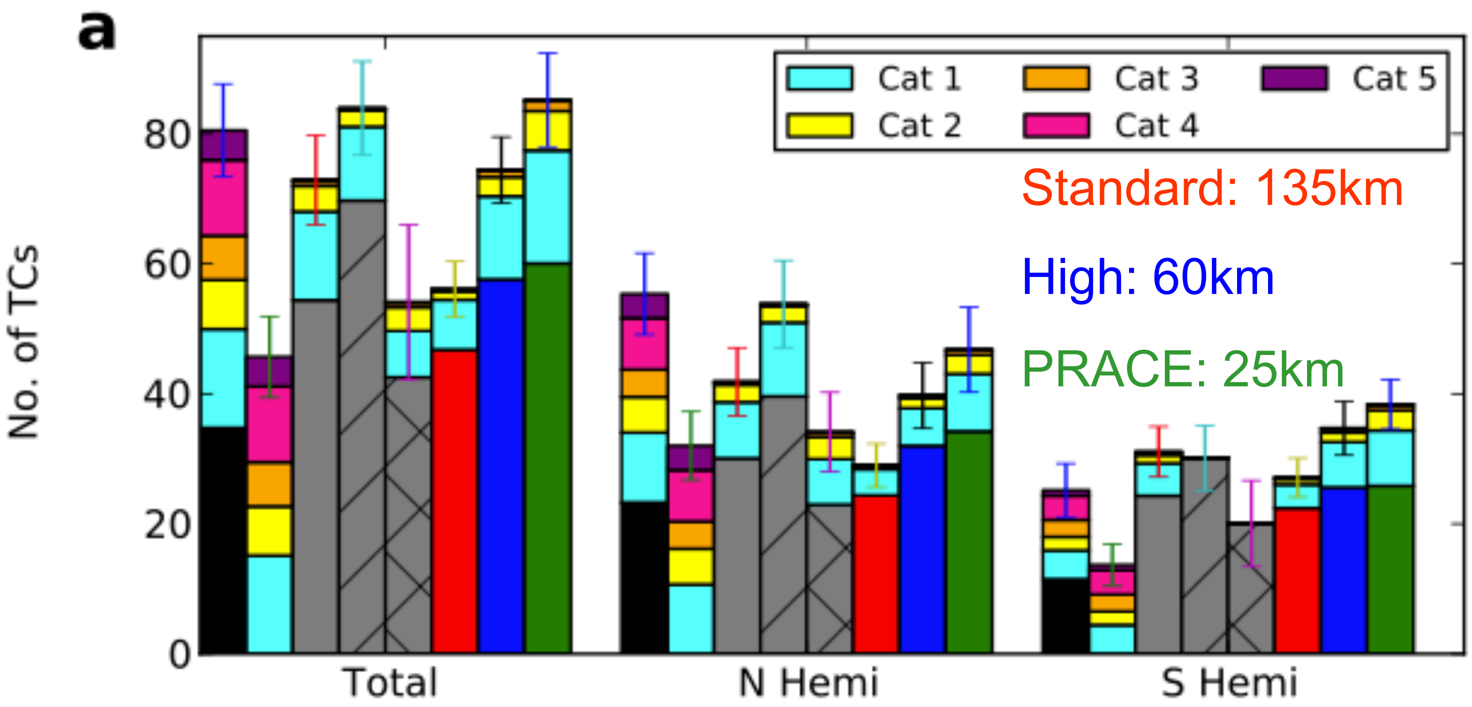
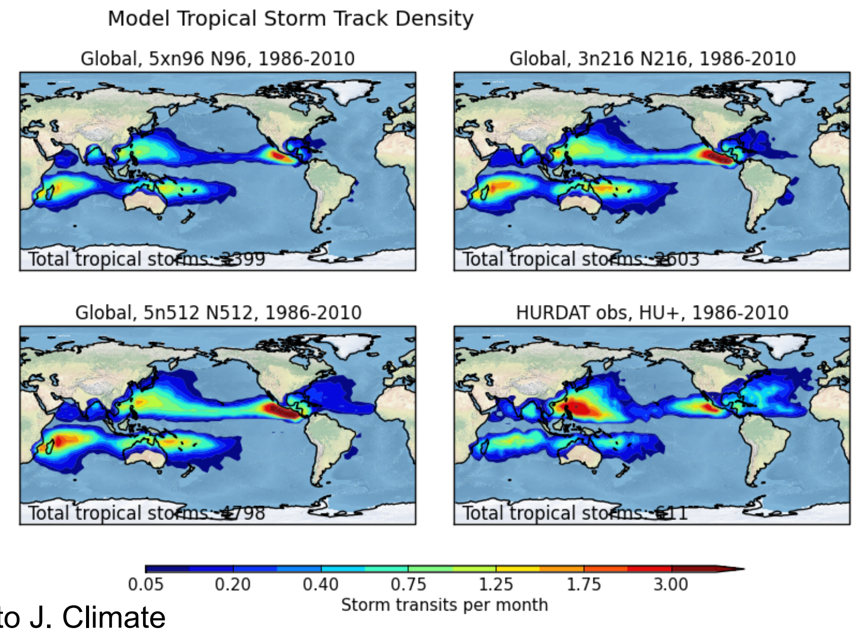


Frequency and strength of tropical cyclones 1986-2010



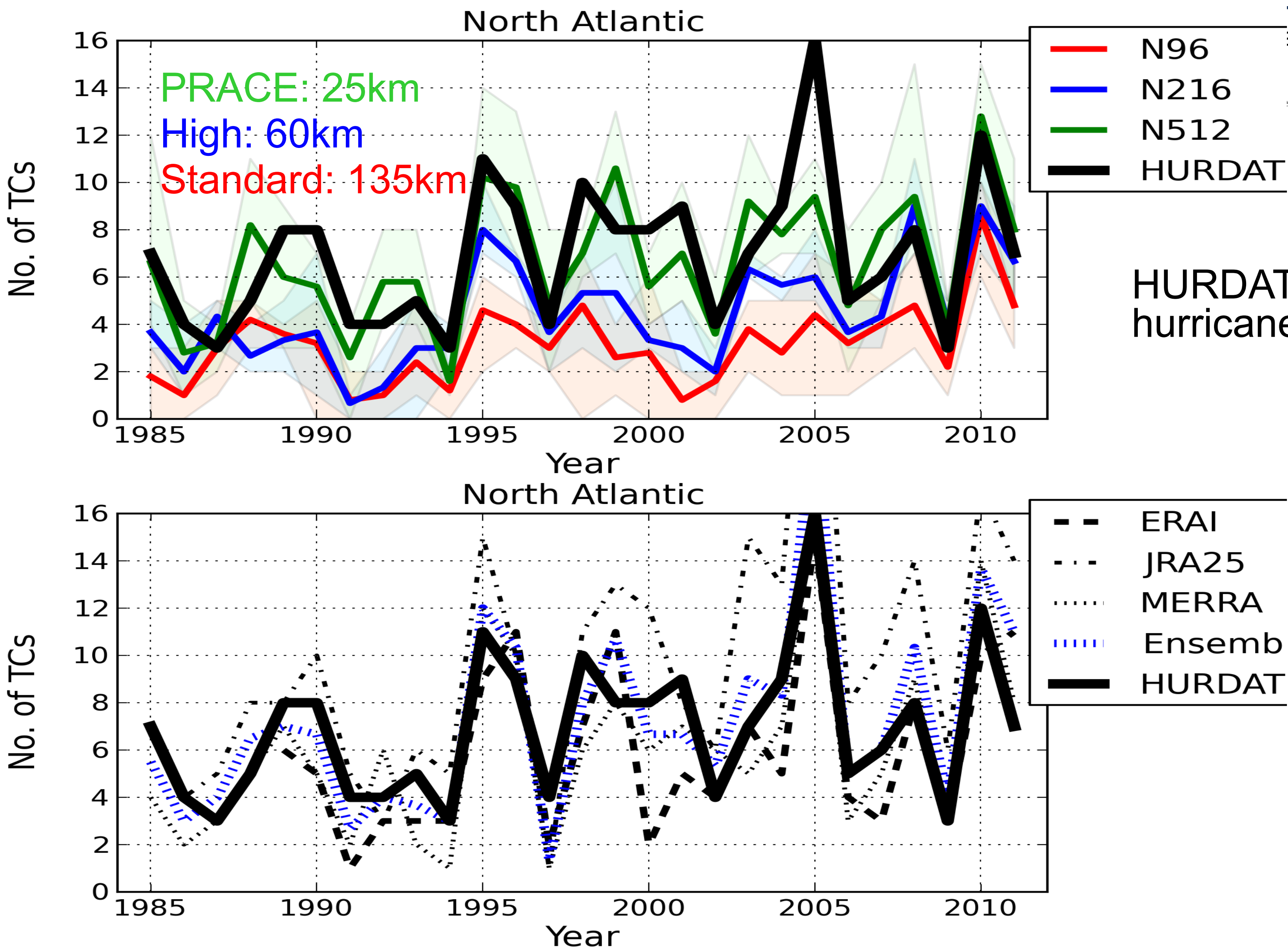
Geographical distribution (track density) is insensitive beyond 100km;

Interannual variability requires at least 50km

Intensity does not converge, even at 12km.

M. Roberts et al., submitted to J. Climate

Solid line = ensemble mean, shading = ensemble range



HURDAT hurricanes

M. Roberts et al., submitted to J. Climate

TC intensity for N512 - N1024, GA4 – GA6

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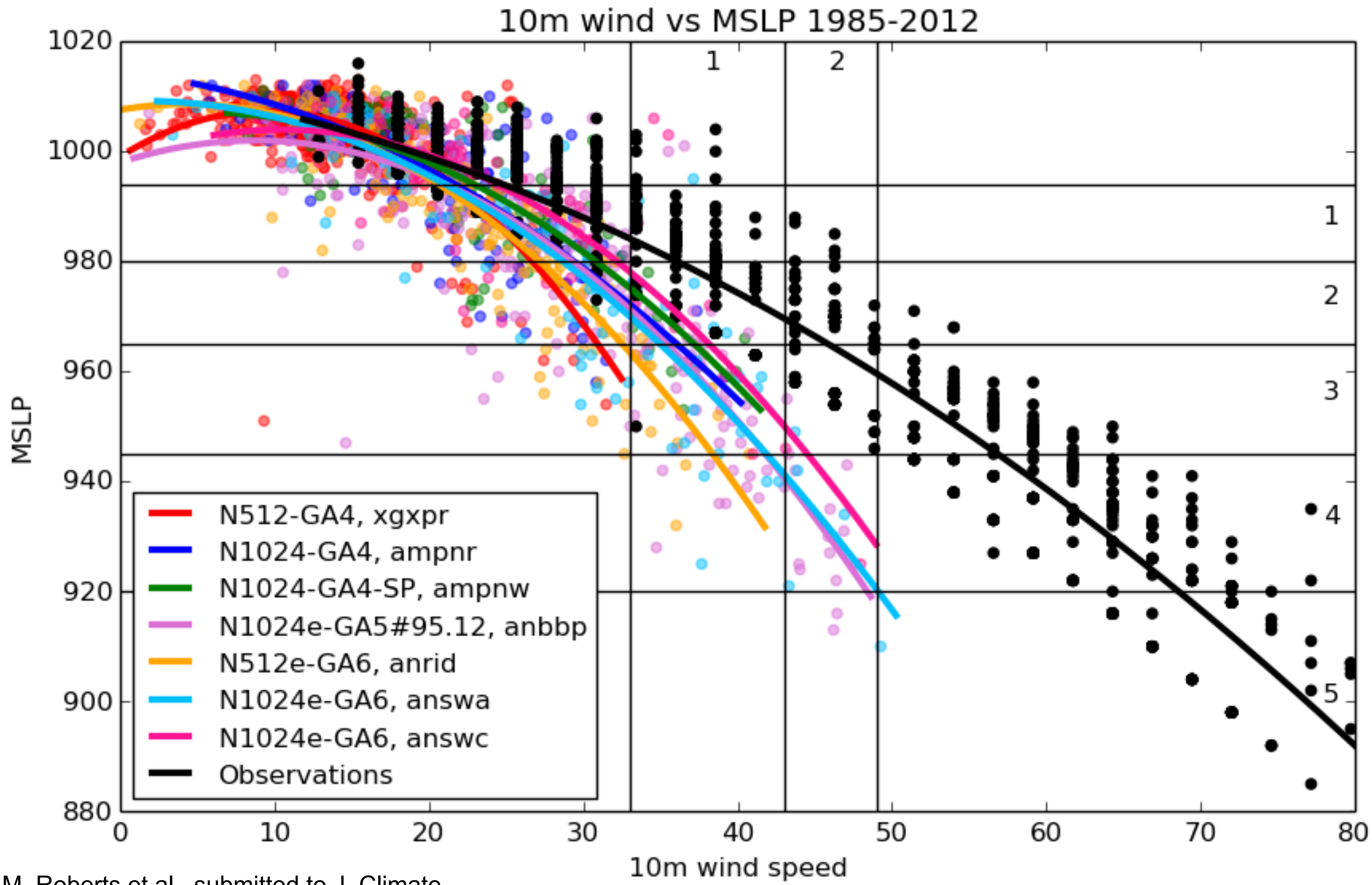
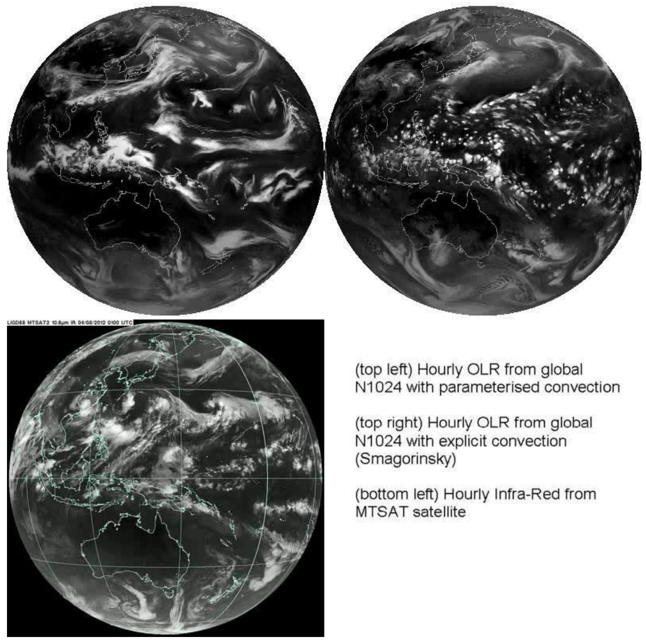


Hurricane intensity based on MSLP – not an official definition

M. Roberts et al., submitted to J. Climate

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

- First time that a Global Climate Model leads its Numerical Weather Prediction (NWP) "parent" in resolution (current MO NWP still at 25km)
    - Originally proposed in UPSCALE and planned for the PRACE supercomputer, but it required too much memory and could not be ported
- We developed both a **standard HadGEM3-A version**, with parameterised convection and an **experimental version 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

Consider the explicit convection version just as a process study:

•We don't represent convection at 12km (or even at 1km properly)!

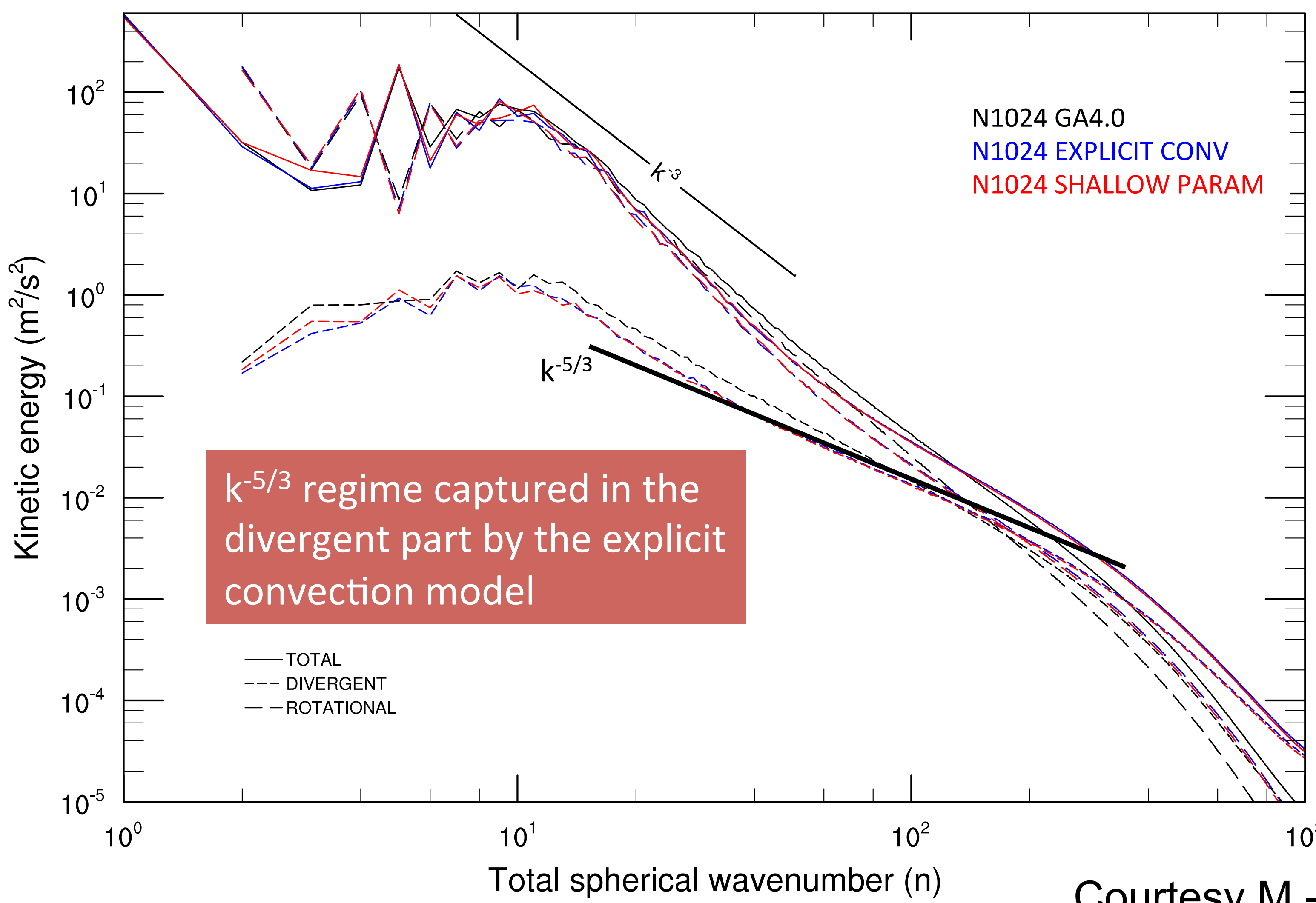
•But the convective parameterisation has big issues too

•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

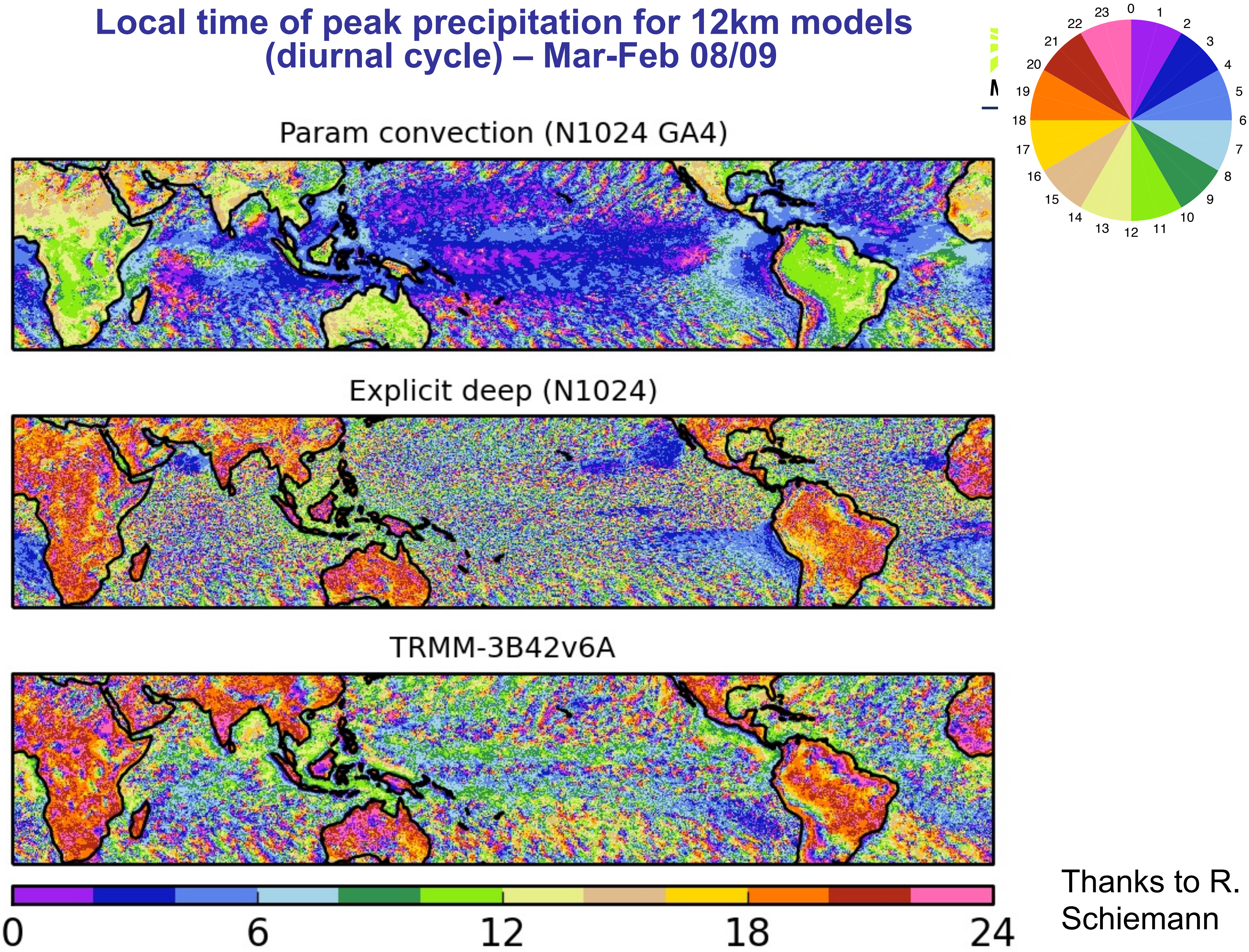
Kinetic energy spectrum at 200hPa in GA4 at N1024

Based on 6-hourly u, v at **200 hPa**



Courtesy M.-E. Demory

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



Thanks to R. Schiemann

Diurnal cycle cartoon

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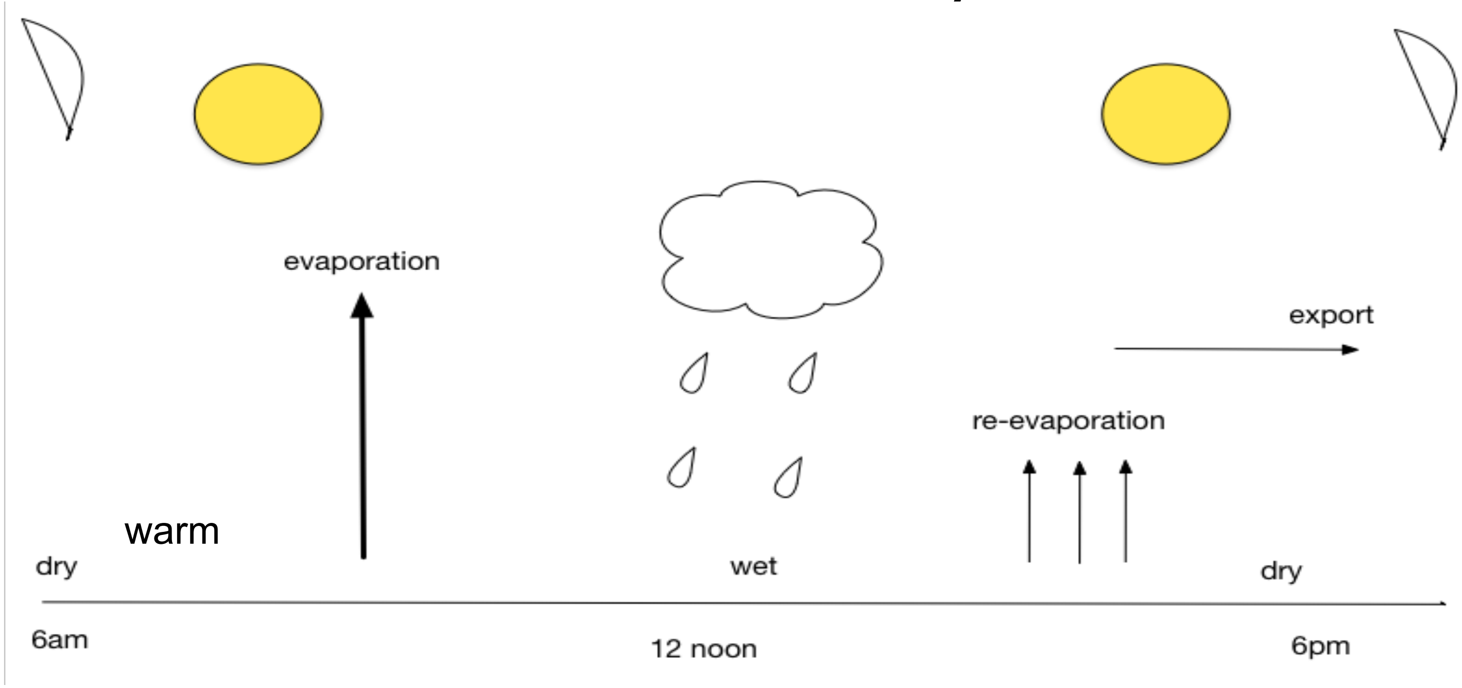
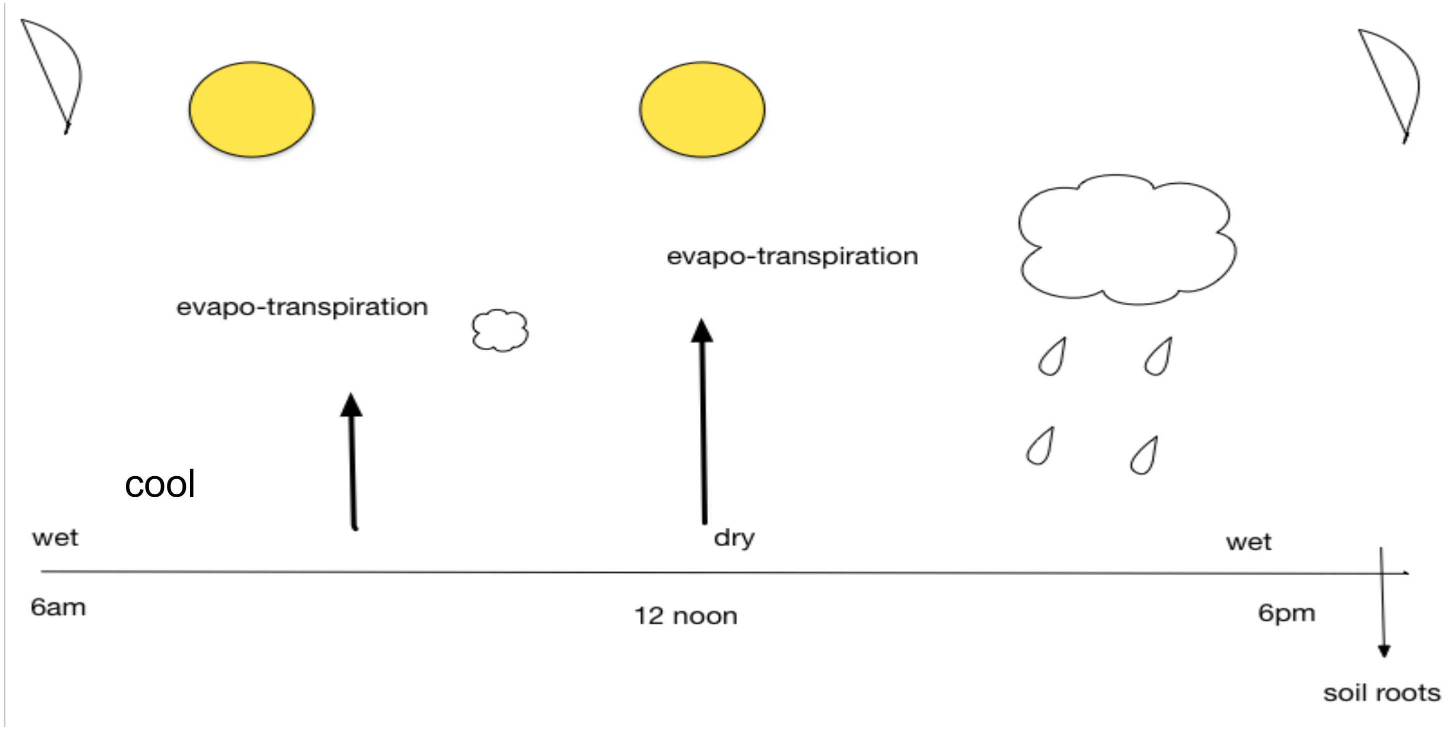


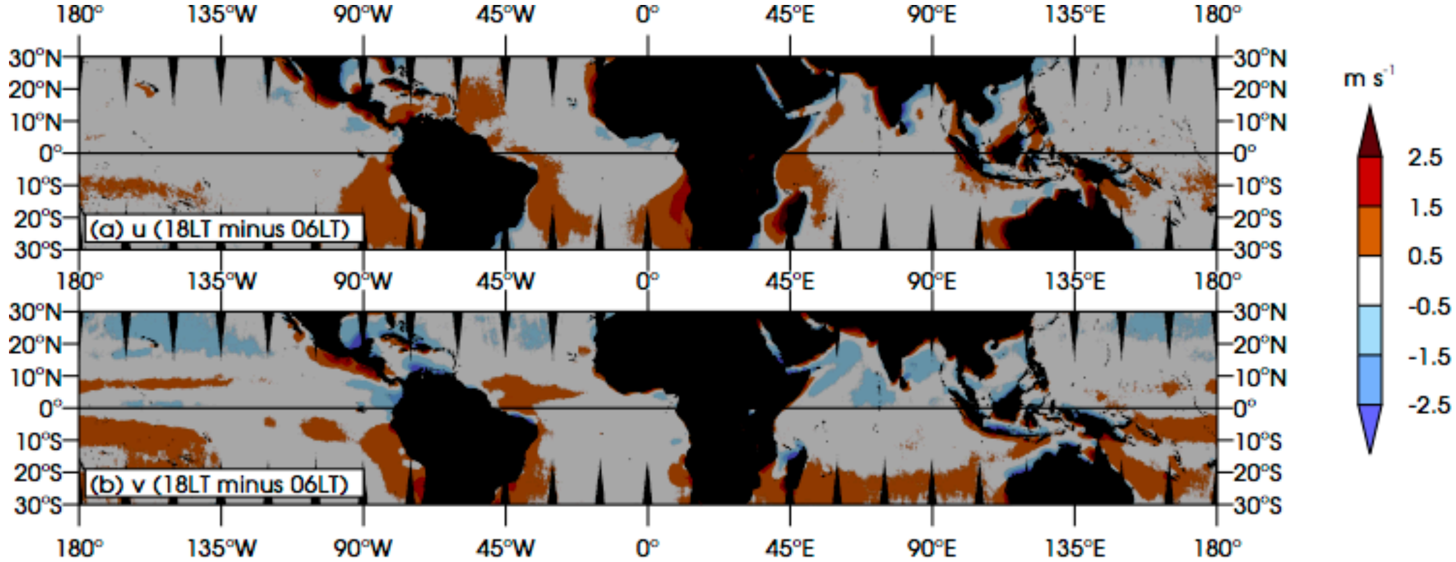
Parameterised convection

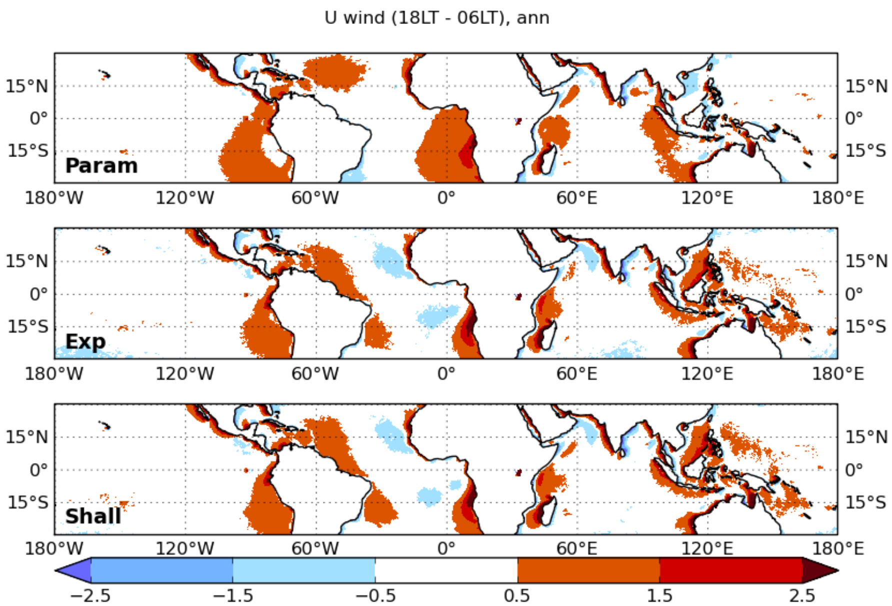


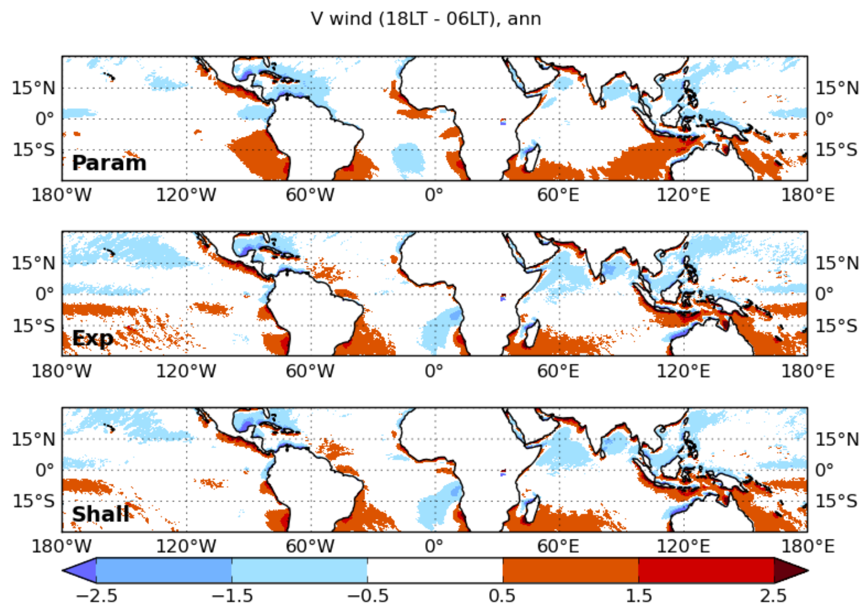
Explicit deep convection

Breezes in 12km models (diurnal cycle): in the tropics, a significant amount of precipitation is linked to breeze-type circulations.

QuikSCAT
“OBServations”

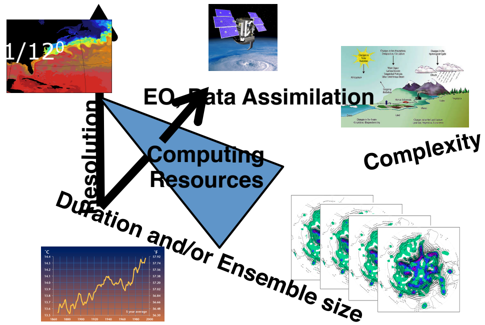






S. Peatman, M. Roberts et al., in preparation

Where would we like to be?



- Increasingly, Global Climate (or Earth System) Models should be seen as providing the same service and data volume of a cruise to the Antarctic, or of a satellite mission.
- **We are currently running our atmospheric GCMs using a mesh of 12km.**
- **Goals**:
  - Top priority: for real climate simulation, we need coupled atmosphere-ocean: **requires multi-year access to TIER-0 facilities**.
  - continue to build a hierarchy of multiple GCMs at resolution down to 1km, running for decades to centuries
    - Need massive improvements in scalability, from $O(10^4)$ to $O(10^6)$ cores per ensemble member
    - Computational cost 10x larger every time we double the resolution, this would help scalability
- However, data grows even faster: in fact, we could have run a much larger ensemble on HERMIT, but we would never have been able to store/process the data
  - **Future models could easily output O(PB) per wall-clock day.**

EU's Horizon 2020

PRIMAVERA: 2015-2020

Joint Weather and Climate Research Programme

A partnership in climate research

PRocess-based climate sIMulation: AdVances in high resolution modelling and European climate Risk Assessment

Joins efforts by five major European modelling groups:
UK-ESM (JWCRP), ECEarth (EU), Arpege (FR), ECHAM (MPI, DE), CESM (CMCC, IT)

- Scope: global, but special focus on processes affecting European climate, 1950-2050
- Aim: understanding and, when possible, reducing model divergence

Overarching objectives of PRIMAVERA:

- Develop a new generation of well-evaluated high-resolution global climate models, capable of simulating and predicting regional climate with unprecedented fidelity.
- Provide new high-resolution protocols and flagship simulations for the World Climate Research Programme's CMIP6 project, in support of the Intergovernmental Panel on Climate Change and in support of emerging Climate Services.
- Produce new, more robust and trustworthy projections of European climate for the next few decades based on improved global models and advances in understanding the drivers and processes that govern variability and change, including high impact events.
- Explore the frontiers of capability in numerical modelling to provide foundations for future generations of global climate and Earth-system models and for risk assessments of climate change and variability.

Summary

- PRACE-UPSCALE exploits national capability that we had been jointly developing since 2004.
  - We are world-leading in exploiting Peta-scale HPC and producing leadership-class simulations of the global climate system
- Fundamental Weather and Climate processes emerge at high resolution and affect the global climate system
  - Increased understanding of disagreement in IPCC-class GCMs
- **Concrete benefits lag developments**, with time scales of several years:
  - The 60km (N216) configuration developed on the Earth Simulator (simulations ran from 2006-2009) for climate research is now the standard configuration of the GloSea5 seasonal prediction system
  - Our Earth Simulator-era scientific publications are only starting to appear now
  - PRACE-UPSCALE@HERMIT: three peer-reviewed papers published so far, four are under review, dozens more in preparation
    - 18 groups from three continents analysing PRACE-UPSCALE data: this will continue for at least 5 years → substantial time lag between simulation and final publication
- The development of the N1024 GCM:
  - Provided a breakthrough in the simulation of the diurnal cycle
  - Leads NWP developments and informs the Met Office on what can be achieved with future HPC
- HPC is good, but not sufficient: we need to support a well balanced <u>scientific and technical task force</u>, combining Met Office and RCUK resources, in order to extract knowledge from our results and this requires **data+analysis services** of comparable power.

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