日英気候共同研究
UK-Japan Climate Collaboration

Met Office | NATURAL ENVIRONMENT RESEARCH COUNCIL

Joint Weather & Climate Research Programme
A partnership in climate research

PRIMAVERA

Global Climate Modelling at High Resolution

From UPSCALE to PRIMAVERA and HighResMIP

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Malcolm Roberts Met Office

Matthew Mizielinski, Jo Camp, Lizzie Kendon
(Many Met Office groups involved in model development and elsewhere)

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

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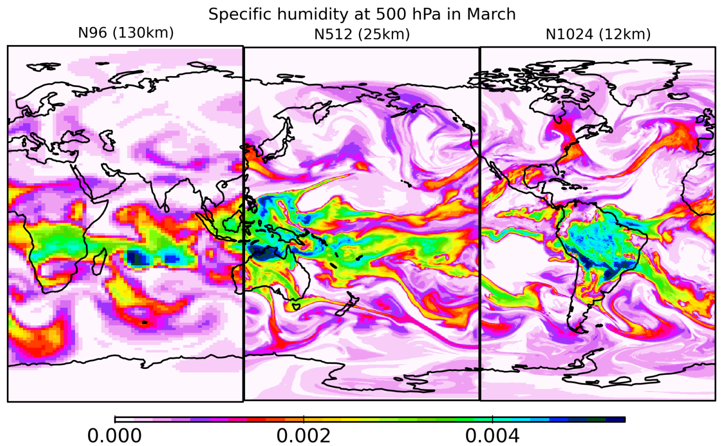
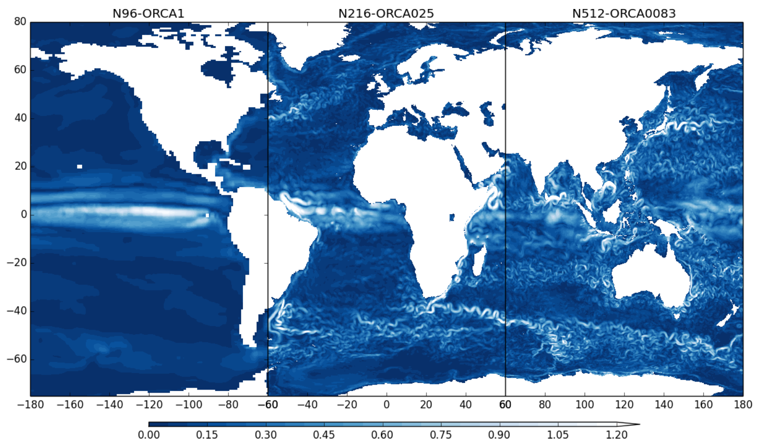
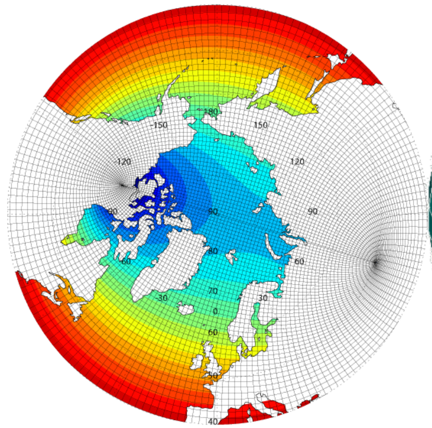


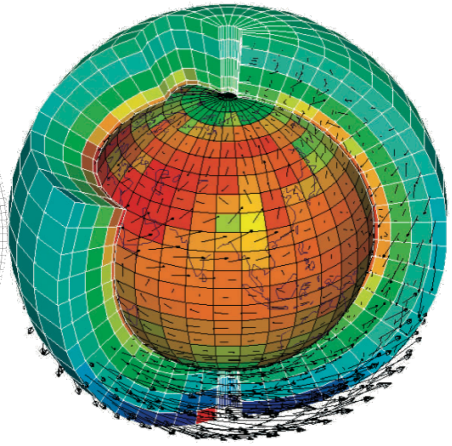


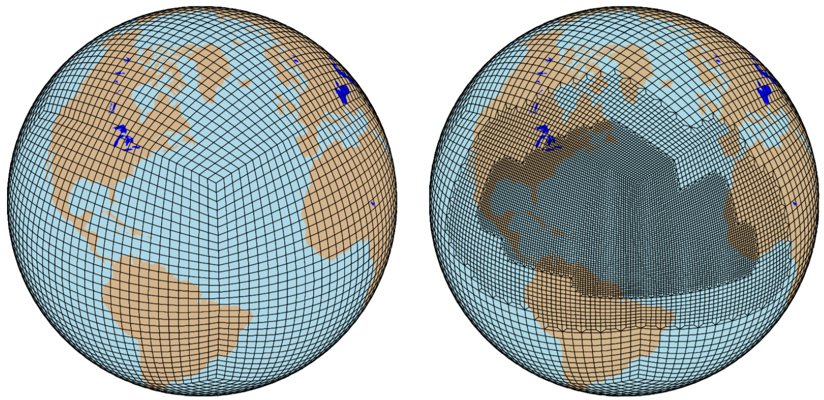
Emerging processes in the atmosphere and ocean as model resolution is increased

Outline

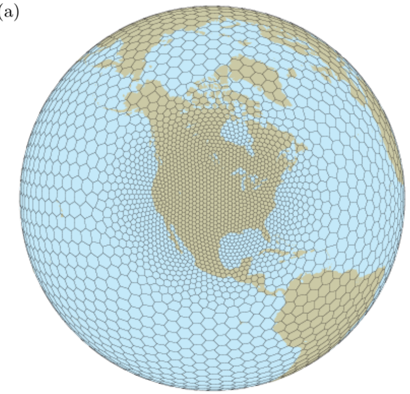
- Scientific motivation for investigating weather and climate at the global scale with high-resolution
  - Why bother with something so expensive and painful?
- A pinch of GCM engineering and aspects of High-Performance Computing
- Examples of multi-scale processes and their interactions in the climate system



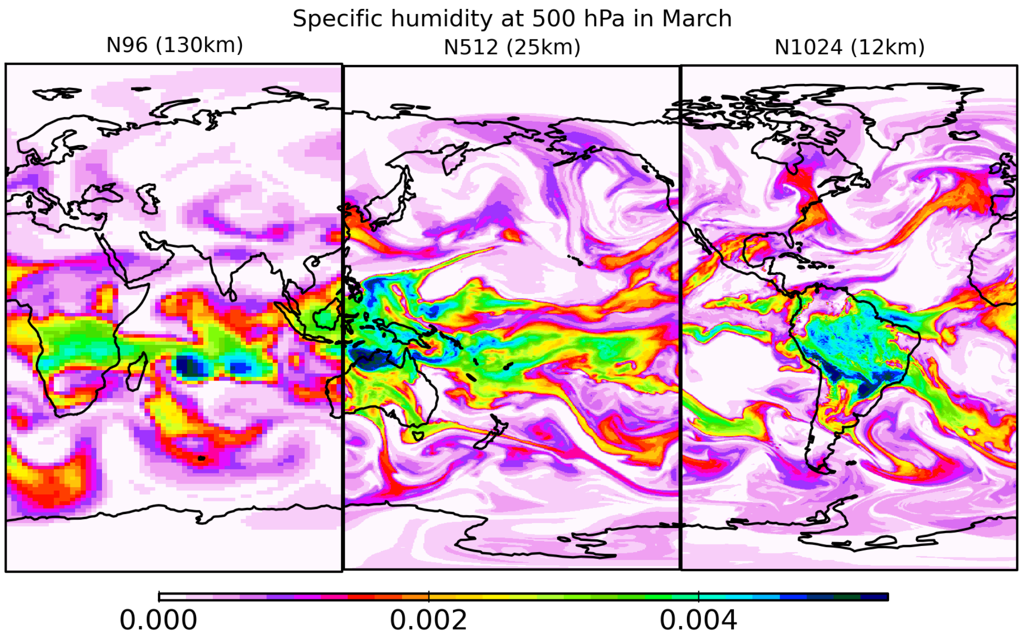




(a) (b)



What happens when we increase resolution in the atmospheric model?



Example 1: global radiative balance and the global hydrological cycle

What changes with resolution?

In our (HadGEM) case, the energy budget is insensitive.

Hopefully, some important things do depend on resolution.

<u>The global hydrological cycle</u>

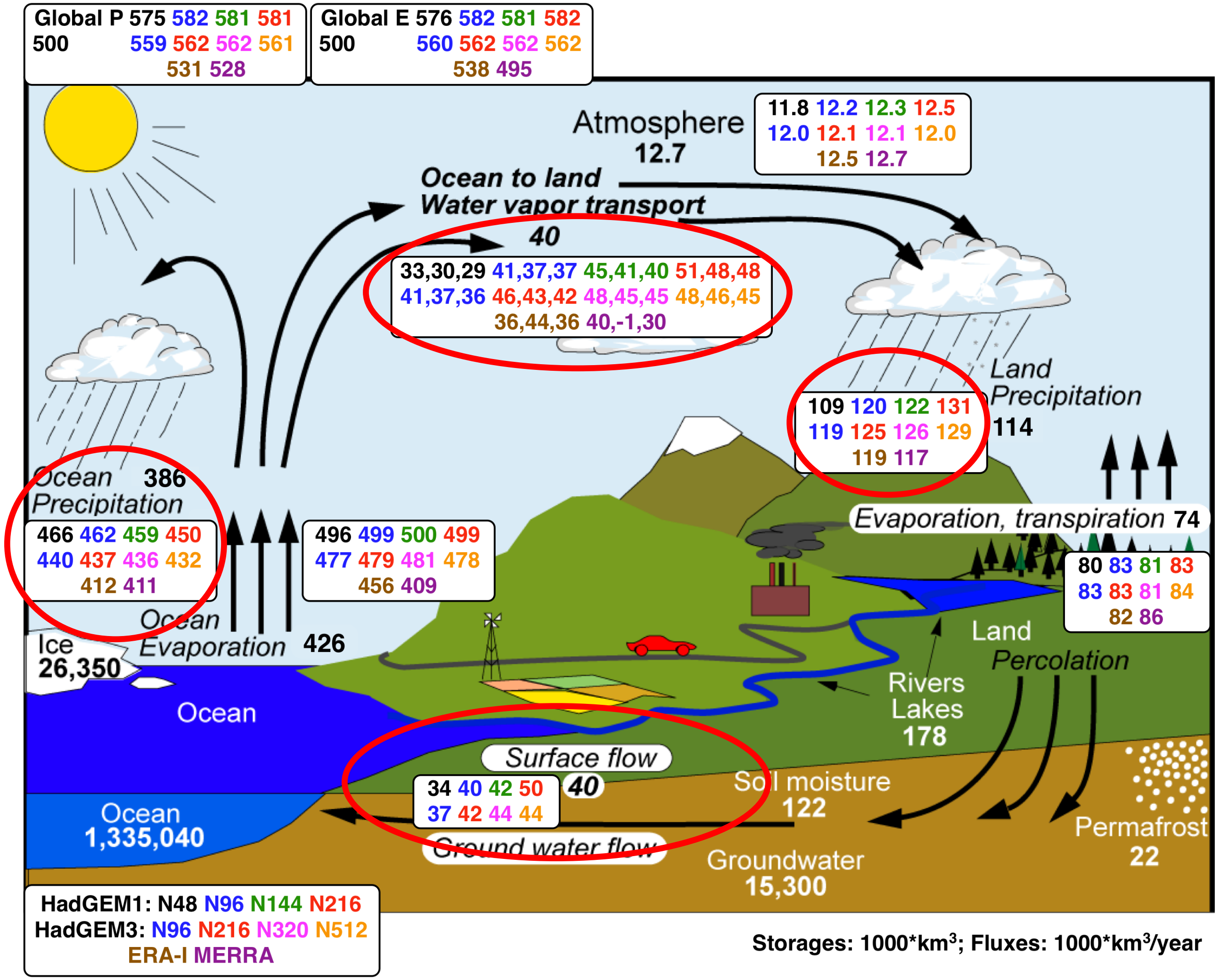


Figure adapted from Trenberth et al, 2007, 2011

- 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

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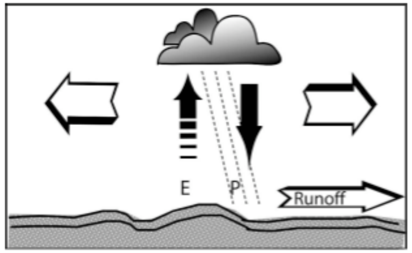
Demory et al., Clim. Dyn., 2014

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



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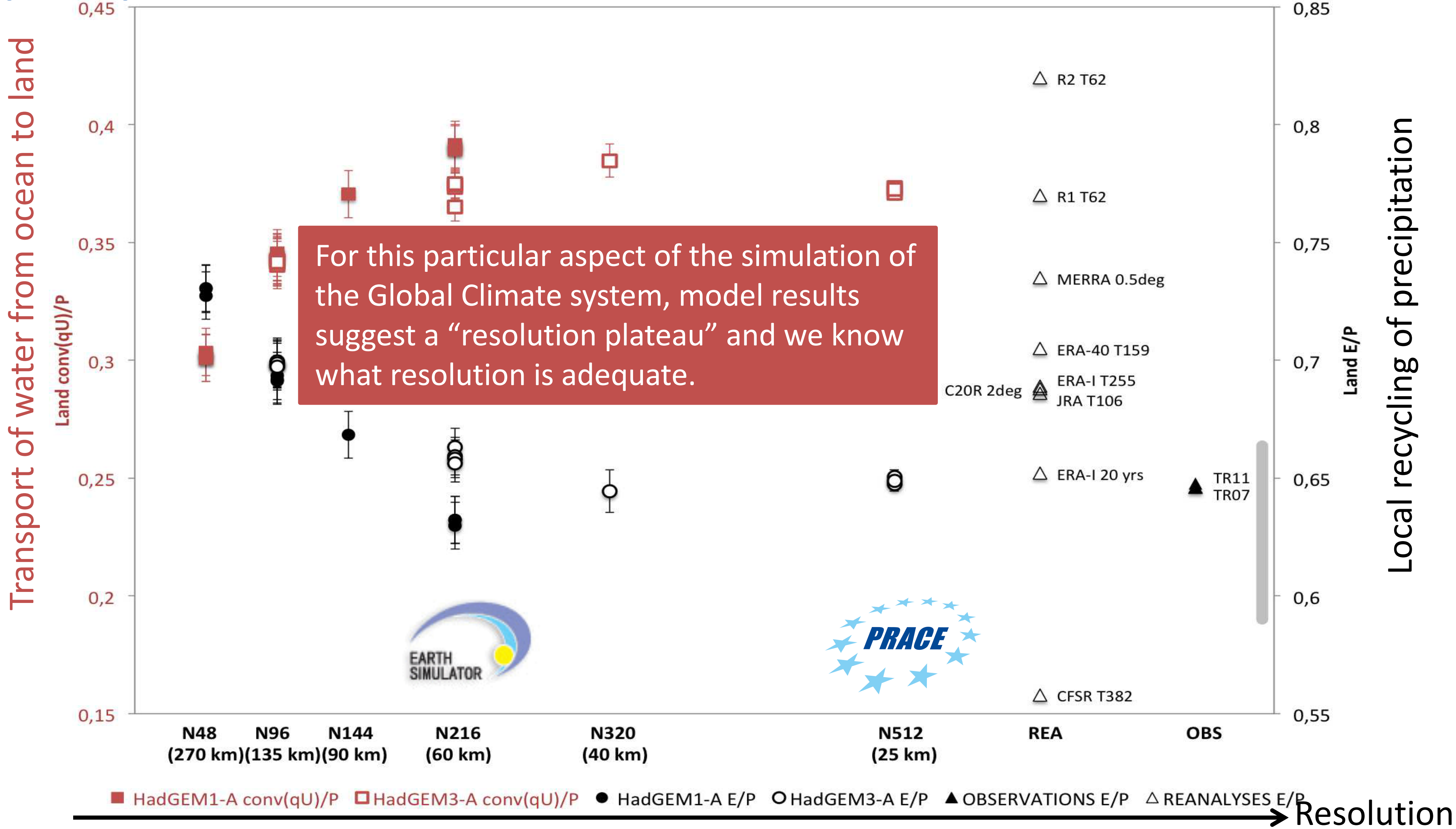


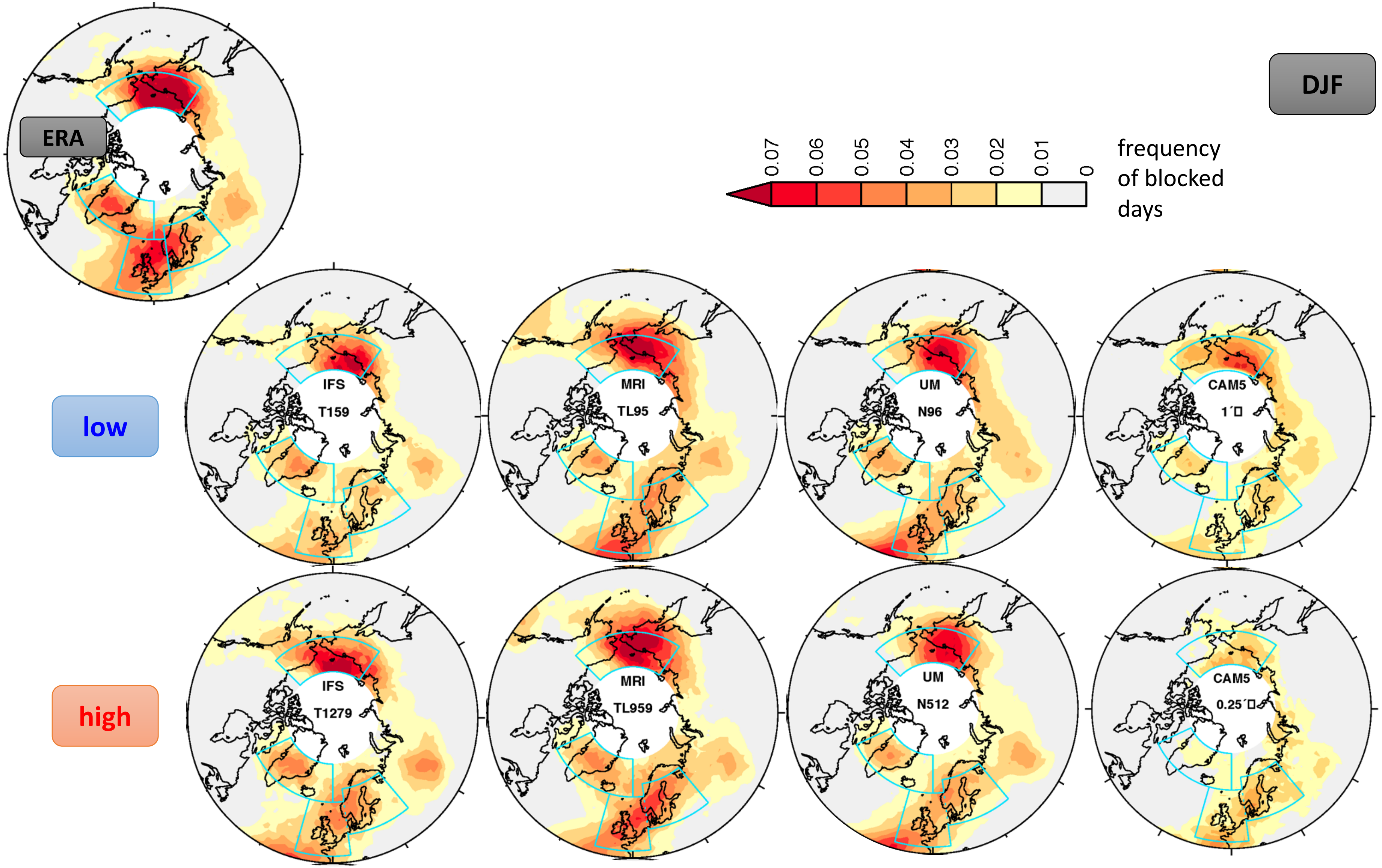
For this particular aspect of the simulation of the Global Climate system, model results suggest a “resolution plateau” and we know what resolution is adequate.

High local recycling
Low transport

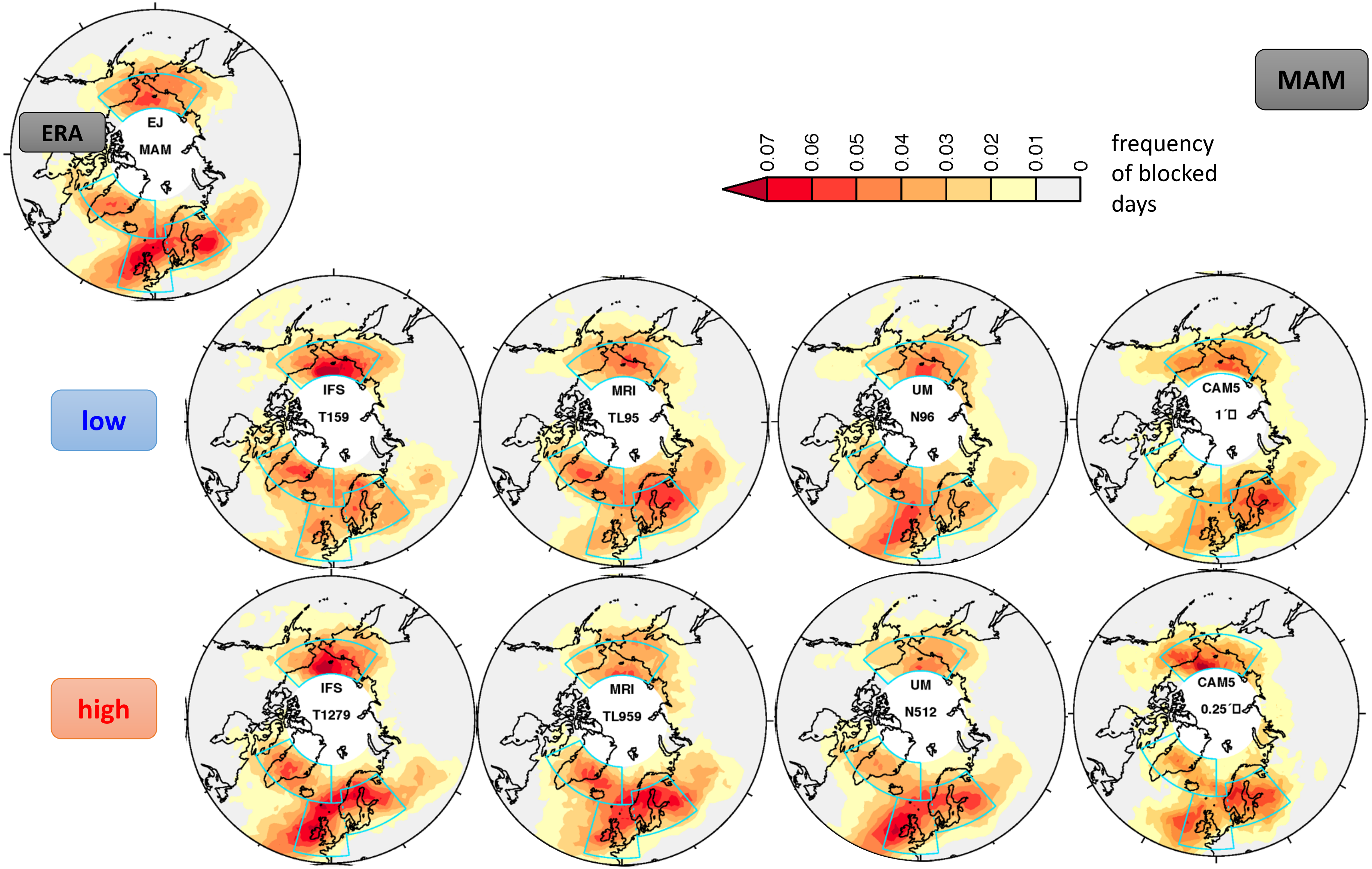
Lower local recycling
Higher transport

Demory et al, Clim. Dyn., 2014

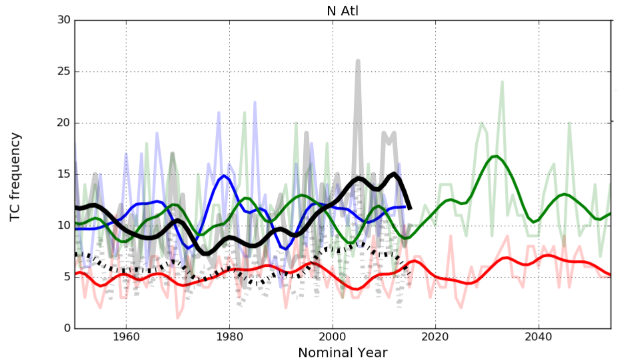
Blocking climatologies in a multi-model ensemble



Blocking climatologies in a multi-model ensemble



Blocking in high-resolution A-GCMs
Schiemann et al. J. Clim. 2016



Weather-resolving (N216)60km-ORCA025-ORCA12

Aim: decadal variability of weather

Science Question(s)

What is the role of the climate decadal variability in governing the distribution/frequency of weather?

Is the global hydrological cycle more credibly represented if we resolve weather features?

Role of ocean mesoscale in air-sea interactions and fluxes → climate variability (e.g. ENSO)

Centennial scale, ensembles of 5

Typical turnaround: 1MY=0.7-2.1 days

75 NEXC-S nodes (~2400 cores)

204 NEXC-S nodes (~6528 cores)

Phenomena

Cyclones and their transports

Jets

Atmospheric waves

Ocean eddies, boundary currents and storm tracks

Air-sea fluxes

Projects/Collaborations

CLIVAR Dynamics Panel

HighResMIP

Analyses

Eulerian and Lagrangian budgets of atmospheric moisture

Cyclone tracking

SST-wind coupling

Spatial filtering of synoptic scales

Publications

Bell et al. 2013, 2014

Demory et al. 2013

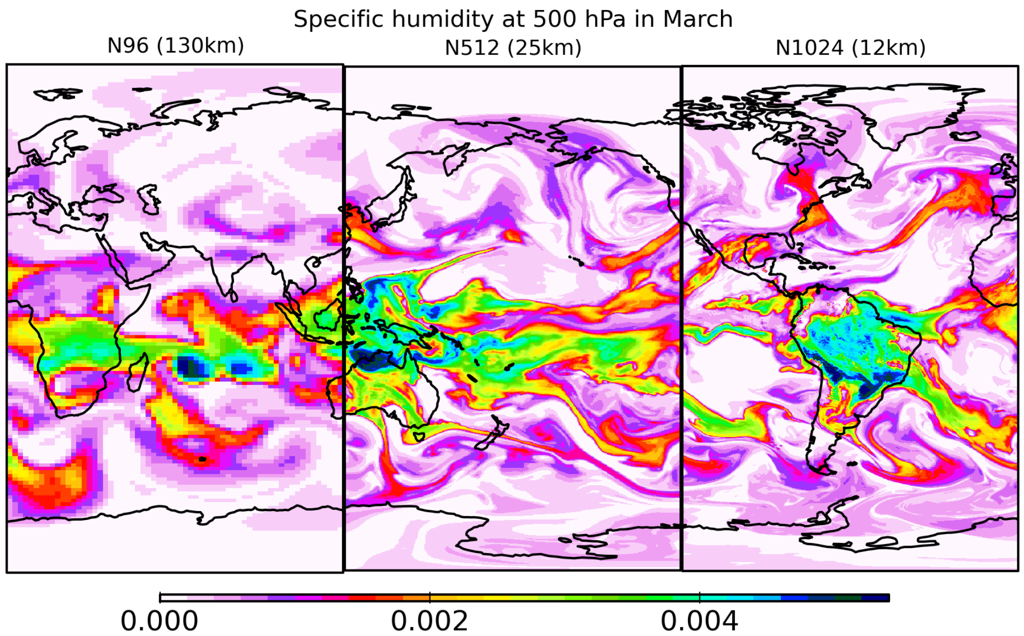
Dawson et al. 2013

Roberts et al. 2009, 2016

Custodio et al. 2017

Vidale et al. in preparation

What happens when we increase resolution in the atmospheric model?



Example 2: simulating precipitation variability, understanding the connection between atmospheric physics and atmospheric dynamics

Sahel decadal rainfall variability and the role of model horizontal resolution

M. Vellinga et al. GRL, 2016

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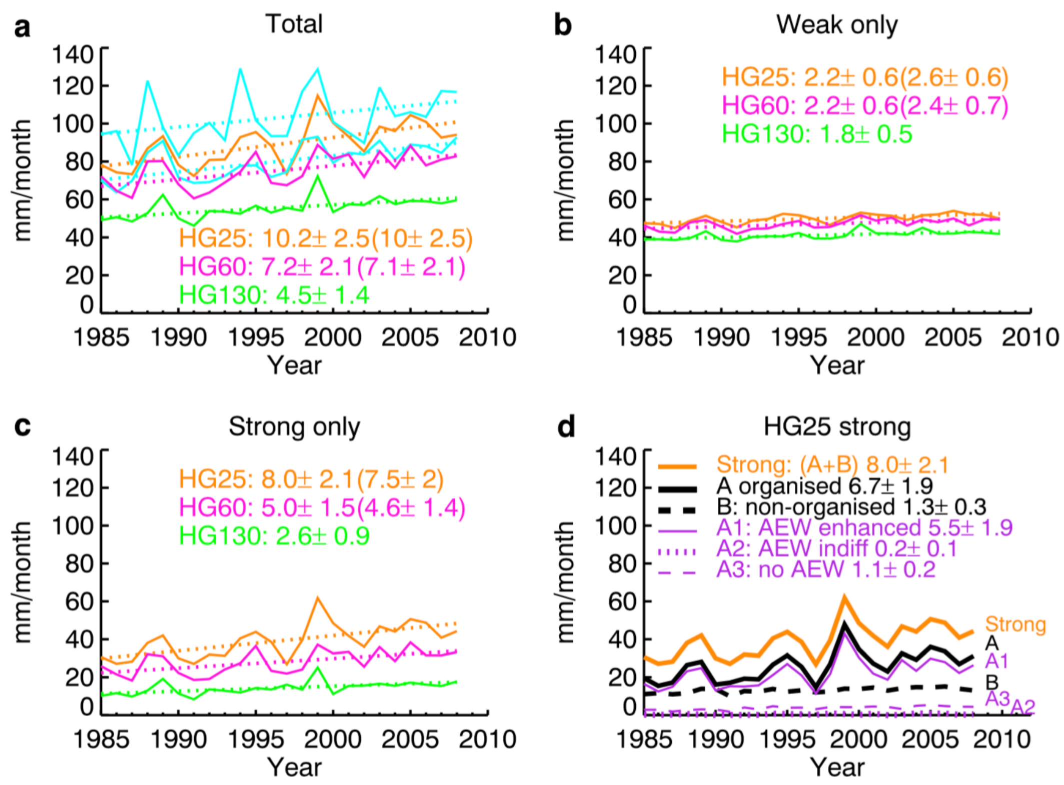

1. The decadal trend is mostly found in <u>high-intensity precipitation</u>
2. Standard resolution (135km) GCM cannot represent the decadal trend
   - **62% of moisture is lost via export** to higher latitudes
3. High resolution GCM produces
   - low-level moisture convergence
   - organised+travelling convection
   - **<u>more efficient</u> conversion to precipitation**

At <u>low</u> resolution: 62% of moisture transported away form region
→ No decadal precipitation recovery

At <u>high</u> resolution: only 37% of moisture transported away form region
→ Good simulation of decadal precipitation recovery
→ Minimal resolution to simulate decadal precipitation recovery in the Sahel

Reason for increased efficiency: coupling between physics and dynamics

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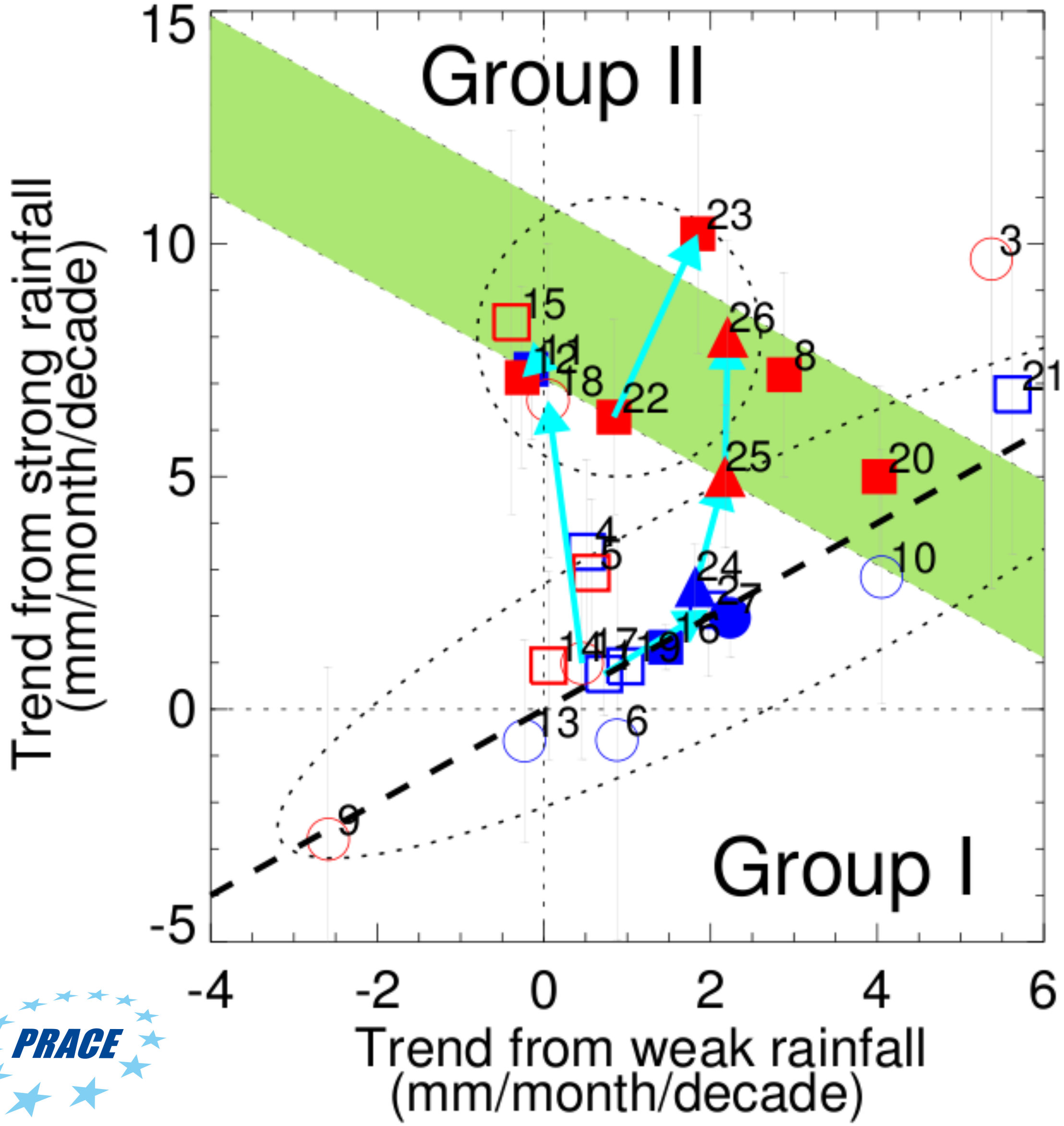
3hrly Sahel rainfall events from climate simulations at different resolutions: the decadal <u>trend can only be represented by High Resolution GCMs</u>

Vellinga et al (2016) GRL

One of the many reasons that have led us to propose a HighResMIP protocol

Trends in Sahel rainfall for CMIP5 AMIPII models and GA3.

Solid red = significant trend from heavy events
Solid blue = sig. trend from weak rainfall events
Green shading = observed trend
24 → 25 → 26 = N96 → N216 → N512 GA3



2012 **UPSCALE** MODELLING CAMPAIGN

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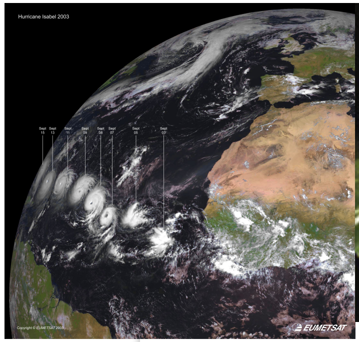

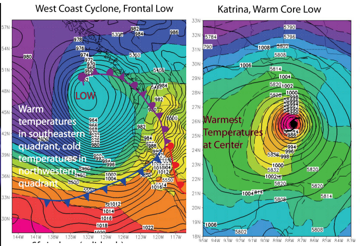

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Cyclone-resolving

(N512)25km-ORCA025-ORCA12

Aim: intense cyclones (e.g. CAT5 hurricanes)

Science Question(s)

What is the role of model resolution in determining storm intensity?

How, and how strongly, do storms interact (UPSCALE) with the rest of the climate system?

What is the role of air-sea interactions in governing climate variability?

Multi-decadal to Centennial scale, ensembles of 3-5

Typical turnaround:
1MY=2.1-2.5 days

120 NEXC-S nodes (~3840 cores)
266 NEXC-S nodes (~8512cores)

Phenomena

Cyclones, particularly Tropical Cyclones
AEWs
Ocean eddies
Air-sea interactions
Atmospheric Blocking
Heat Waves

Projects/Collaborations

CLIVAR Hurricane Working Group
PRIMAVERA/HighResMIP
CLIVAR Dynamics Panel
MO-CSSP (DREAM, FASCINATE)
H2020 COPERNICUS (WISC)
US NSF proposal on TCs
CSIRO/UNSW/Monash

Analyses

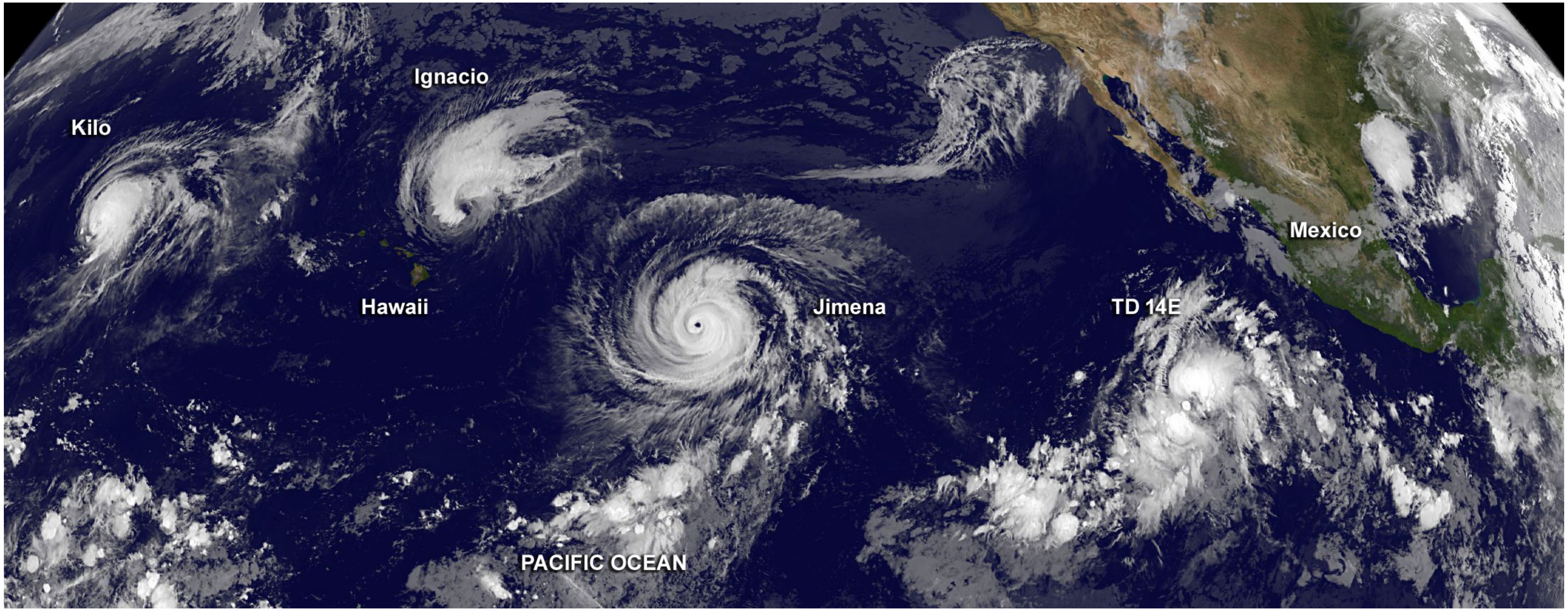
Blocking (Eulerian and Lagrangian)
Feature Tracking and attribution
(eddies in the atmosphere-ocean, eddy transports, eddy-mean flow interactions, storm surge)
Planetary wave resonance
Rossby-wave sources
EOTs

Publications

Strachan et al. 2013
Johnson et al. 2015
Roberts et al. 2015
Shaevitz et al 2014
Daloz et al 2015
Walsh et al. 2015
Tous et al. 2016
Schiemann et al. 2014, 2017
Guo et al. 2017

The rare charm of Tropical Cyclones

- Causing extreme impact, including substantial loss of life
- Yet, they illustrate the problem of <u>scale interactions</u> within the climate system
- A tough phenomenon: rare events that require high resolution and high sample size for any significance

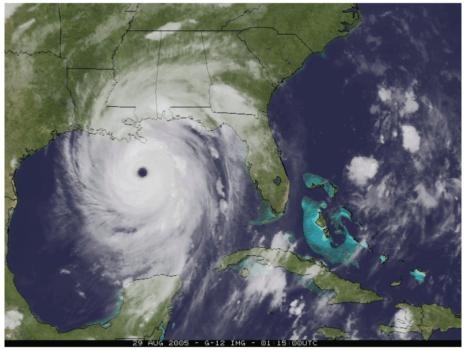


This GOES-West satellite image shows four tropical cyclones in the North Western, Central and Eastern Pacific Ocean on September 1, 2015. In the Western Pacific (far left) is Typhoon Kilo. Moving east (to the right) into the Central Pacific is Hurricane Ignacio (just east of Hawaii), and Hurricane Jimena. The eastern-most storm is Tropical Depression 14E in the Eastern Pacific.

Evolution of N. Atlantic hurricane frequency in past 100+ years: connections with C-Atlantic SSTs.

2005 was a true record year: 15 hurricanes (incl. Katrina), 28 named storms … and some of the most intense storms in US history.

Katrina damage = 1600 dead; 75-200 bn U$. **Harvey (2017): 75-125 bn U$… Irma?**

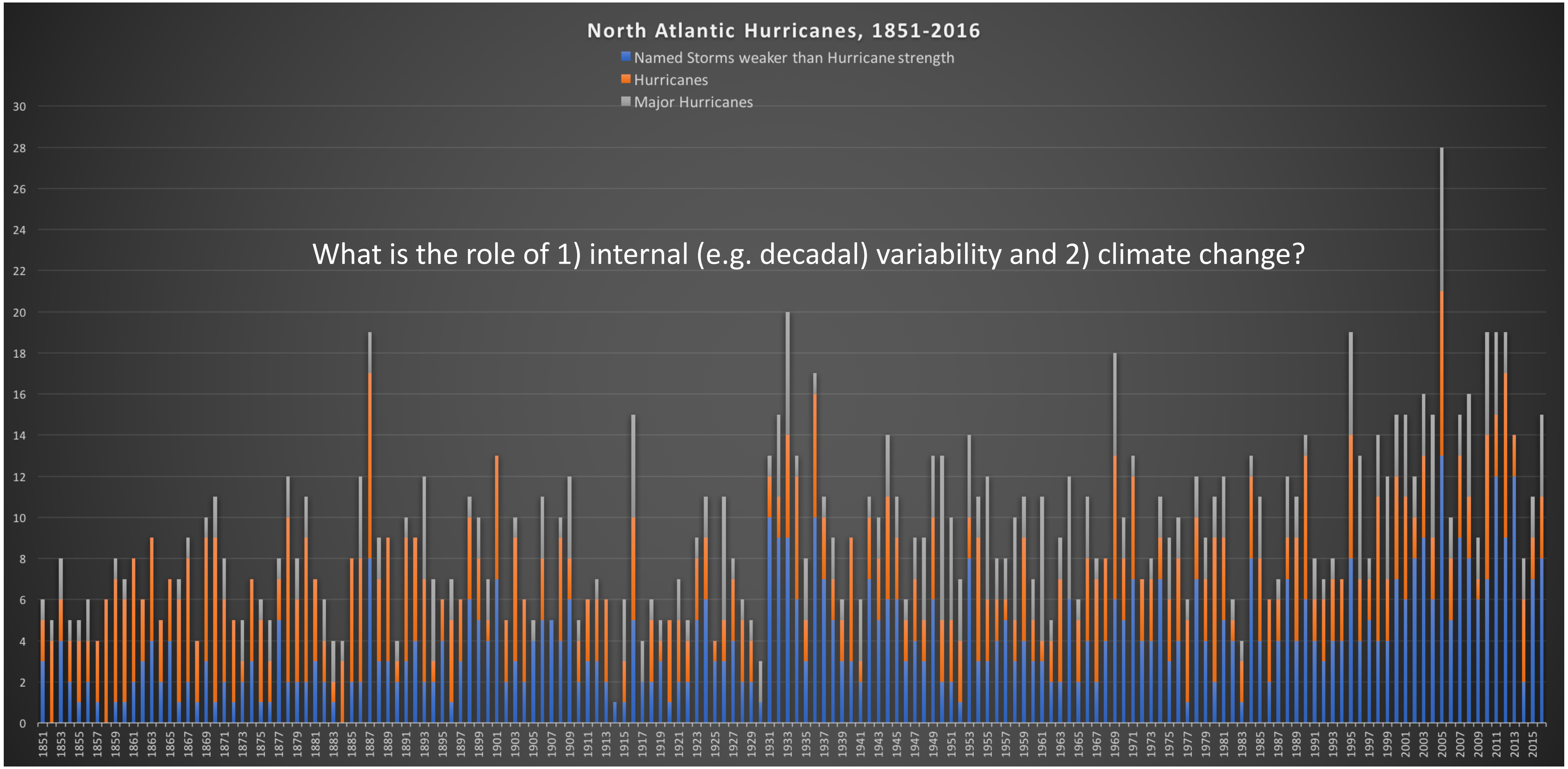


But what about before 1850, or 1950 (for the Pacific) ?

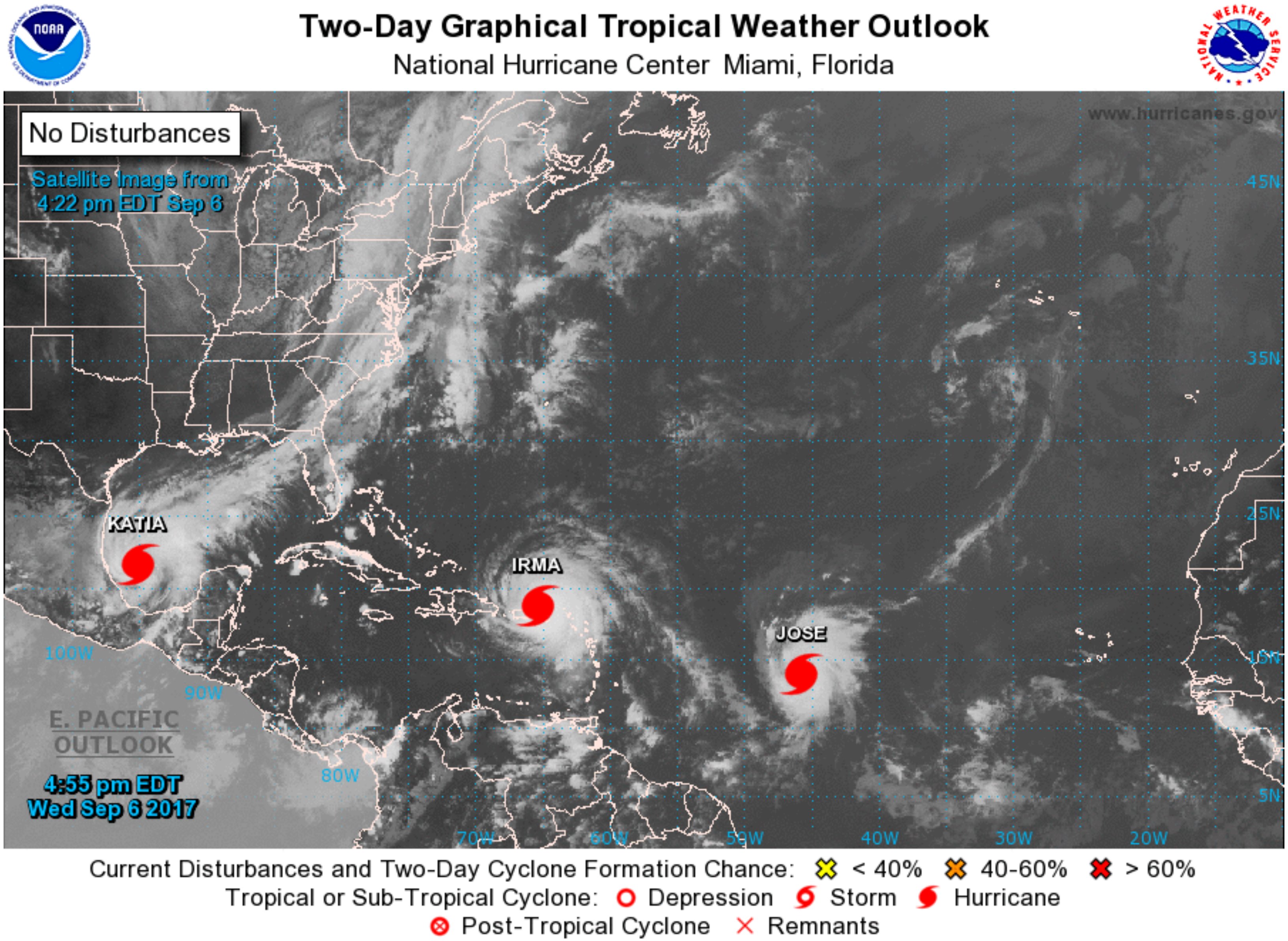
Short/inhomogeneous records of **extremely rare** events:

we need models to <u>complement</u> observations

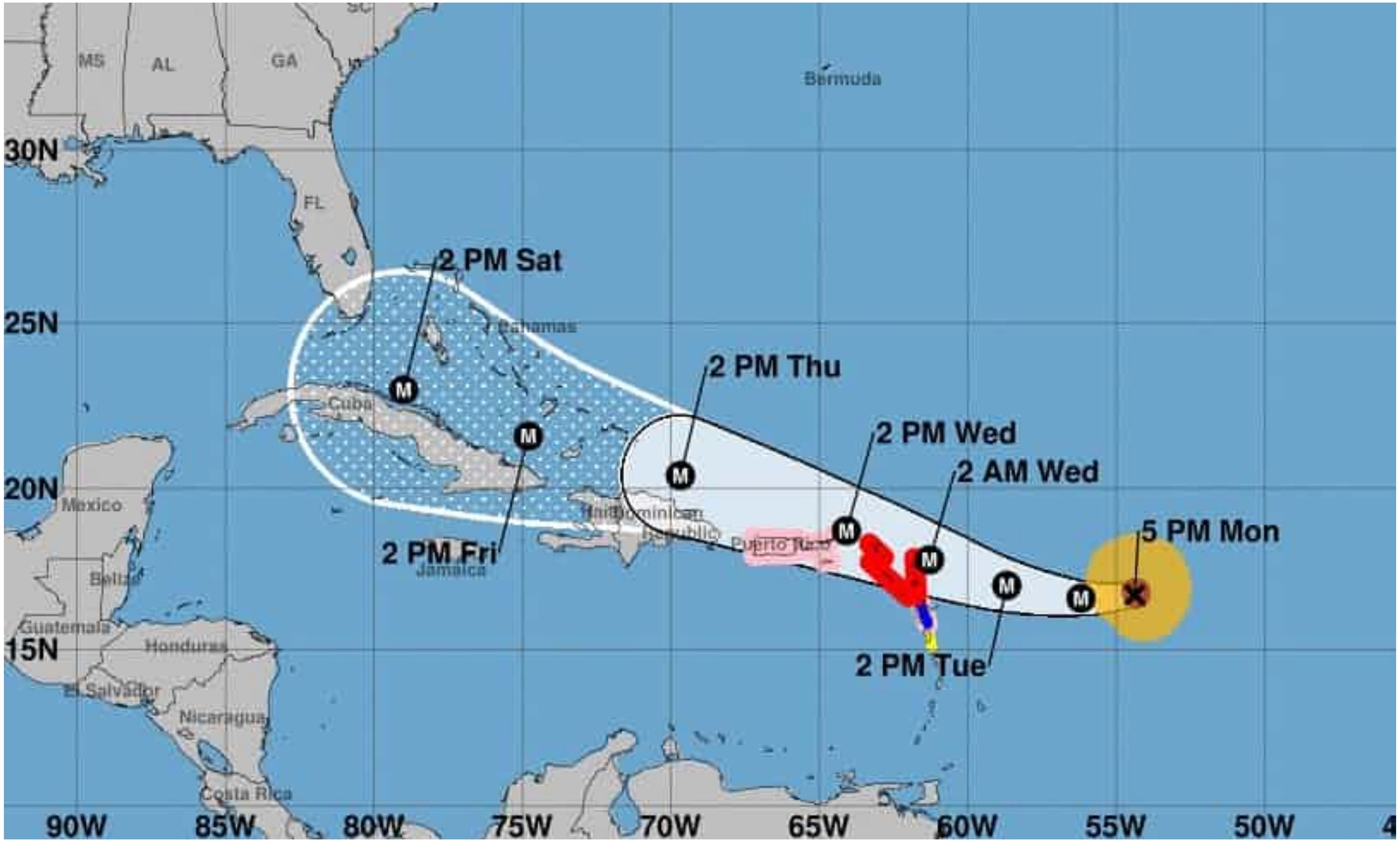
And yet, coarse GCMs, especially those used for long (e.g. IPCC) integrations, cannot fully represent tropical cyclones



6 Sep NA Atlantic image



Irma will graze Cuba and may enter the Gulf this week



Irma: ECMWF ensemble forecast on 6 Sep 2017

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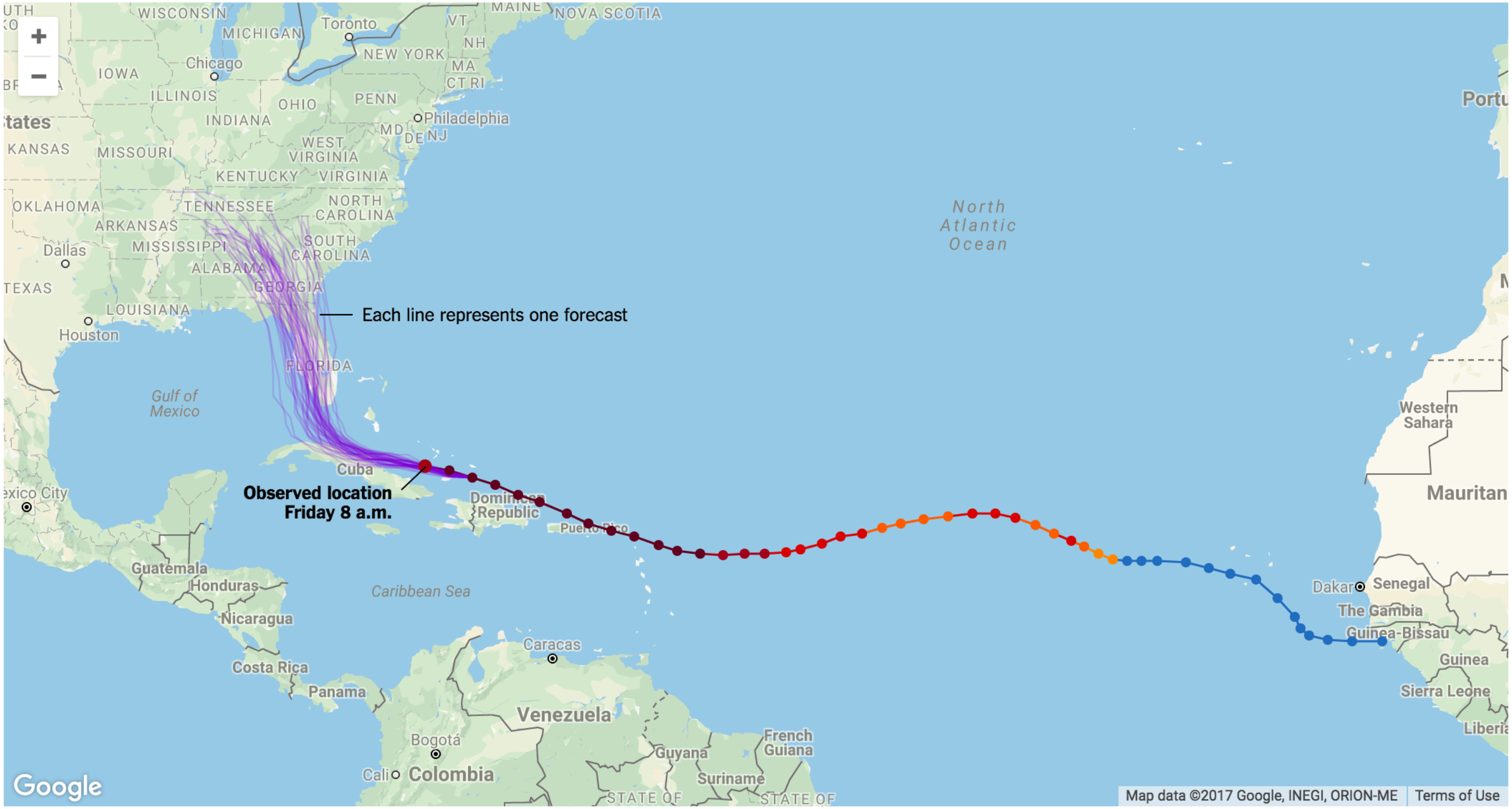

Source: European Center for Medium-Range Weather Forecasts, National Weather Service

Current situation, 10 Sep 2017

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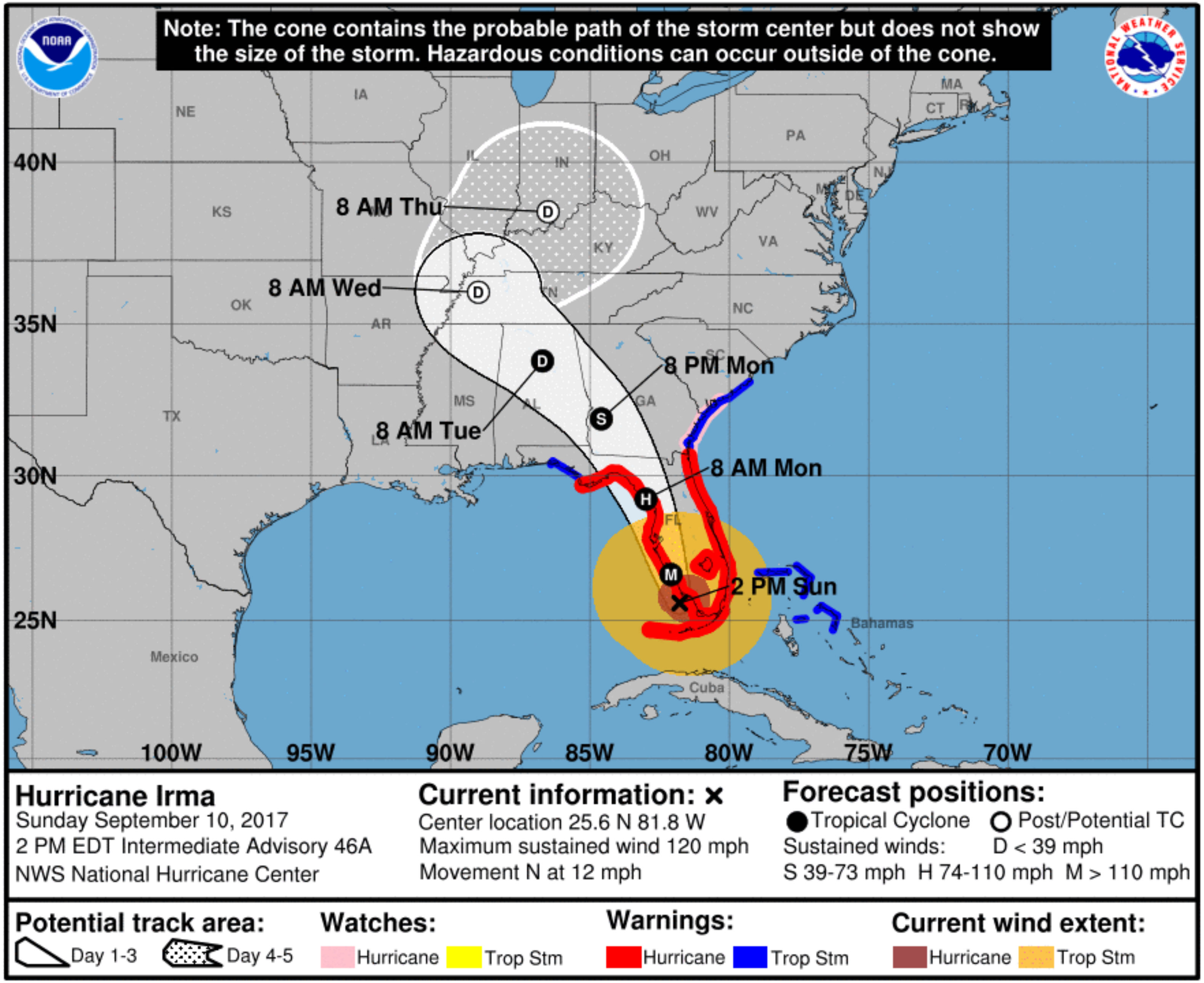
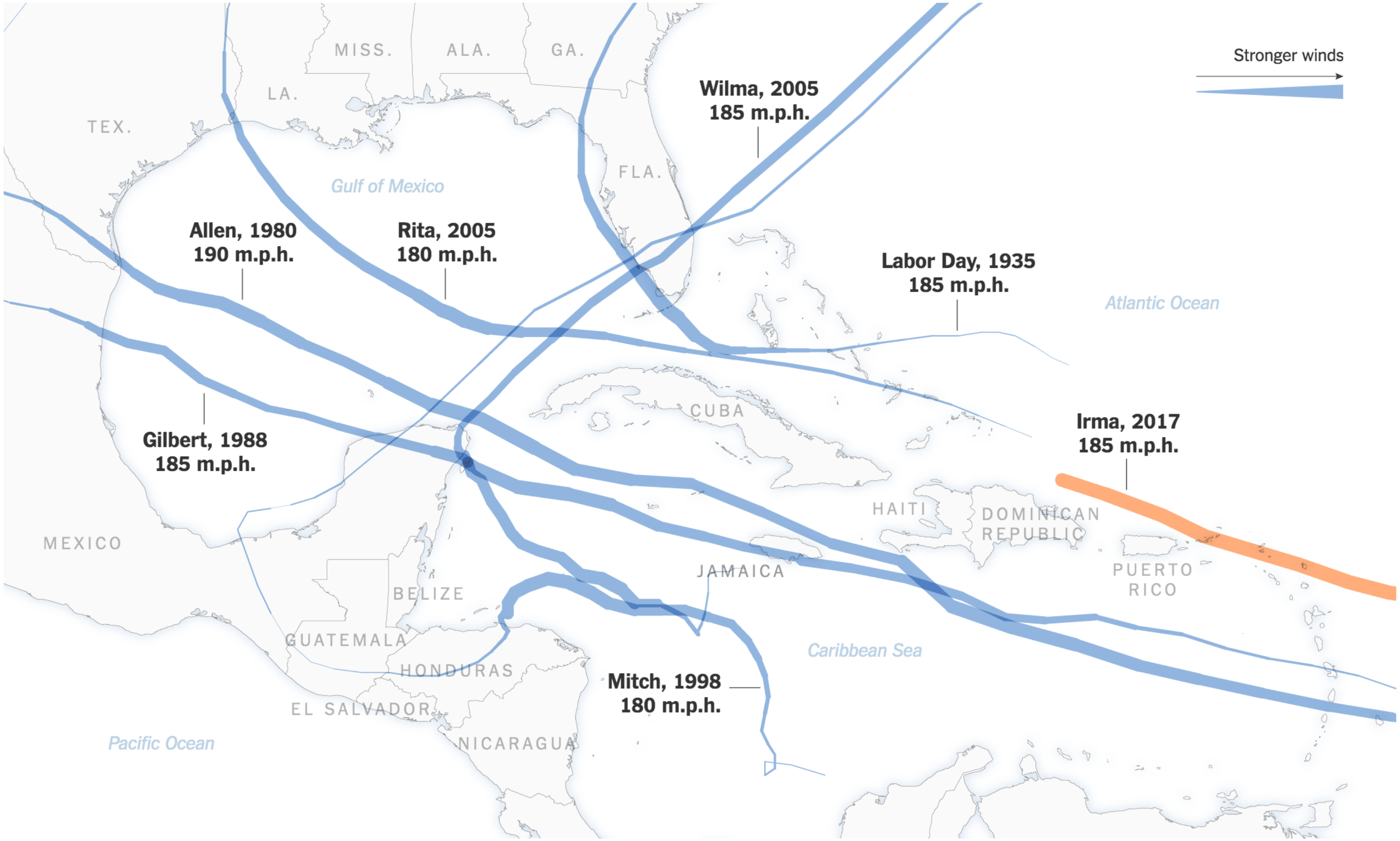


Historical context



Sources: Hurricane Research Division, National Oceanic and Atmospheric Administration

Contribution of Tropical Cyclones to precipitation and moisture flux over China

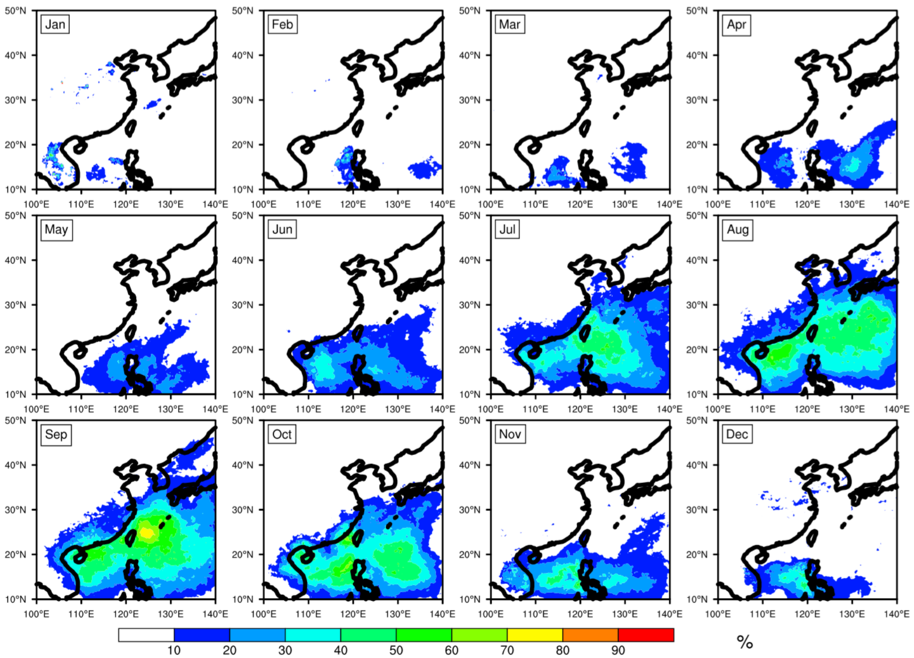


FIG. 2. Monthly mean fractional contribution of TC rainfall amount to the total rainfall calculated using TRMM 3B42 rainfall data. Units: %.

Precipitation: along the coast, where most people live, 20-50% of precipitation can be attributed to Tropical Cyclones in the Jun-Oct season

Moisture flux: Tropical Cyclones in the Jun-Oct season contribute significantly, and <u>opposite</u> to large scale + monsoon.

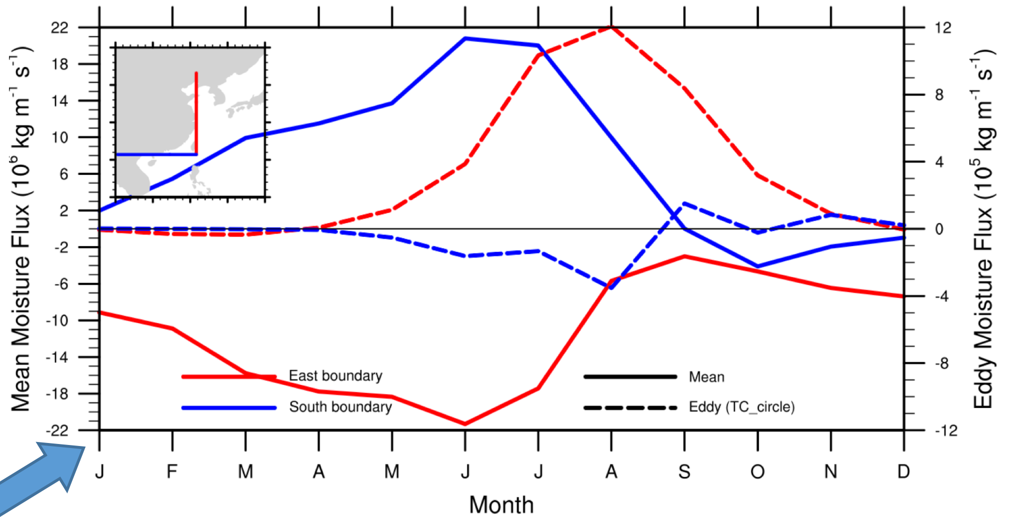


FIG. 5. Seasonal cycle of monthly mean vertically integrated moisture flux passing through the southern (blue) and eastern (red) boundaries. Mean flow moisture fluxes are shown as solid lines and TC eddy moisture fluxes as dash lines. The inner panel shows the definition of the southern and eastern boundaries. Units: kg/m/s.

<u>Notes</u>:

- 2-month delay in seasonal cycle of contributions, relative to larger scales.
- ERA-I TCs are significantly weaker than real TCs, so very likely underestimated contribution to moisture flux. Need High-Res GCMs to understand further.

University of Reading

L. Guo et al., J. Clim. 2017

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What will happen to TCs in the future?

Typhoons will migrate poleward … and a NA hurricane reduction

580 JOURNAL OF CLIMATE VOLUME 28

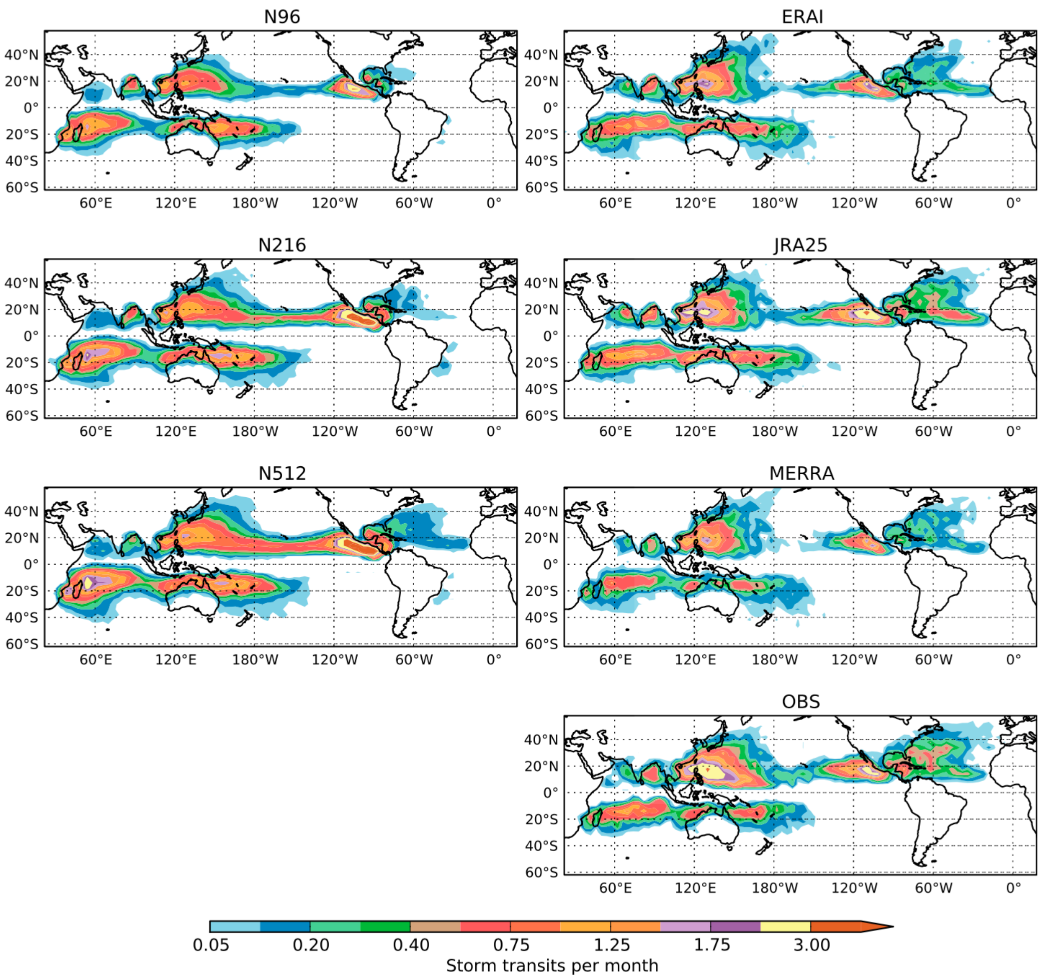

FIG. 4. Track density (transits per month per unit area equivalent to a 4° spherical cap) for (left) model ensembles (top)–(bottom) N96, N216, and N512; (right) reanalyses (top)–(next to bottom) ERA-Interim, JRA-25, and MERRA; and (bottom) observed hurricanes over the period 1986–2010. The Northern Hemisphere period is set to May–November and the Southern Hemisphere period is set to October–May.

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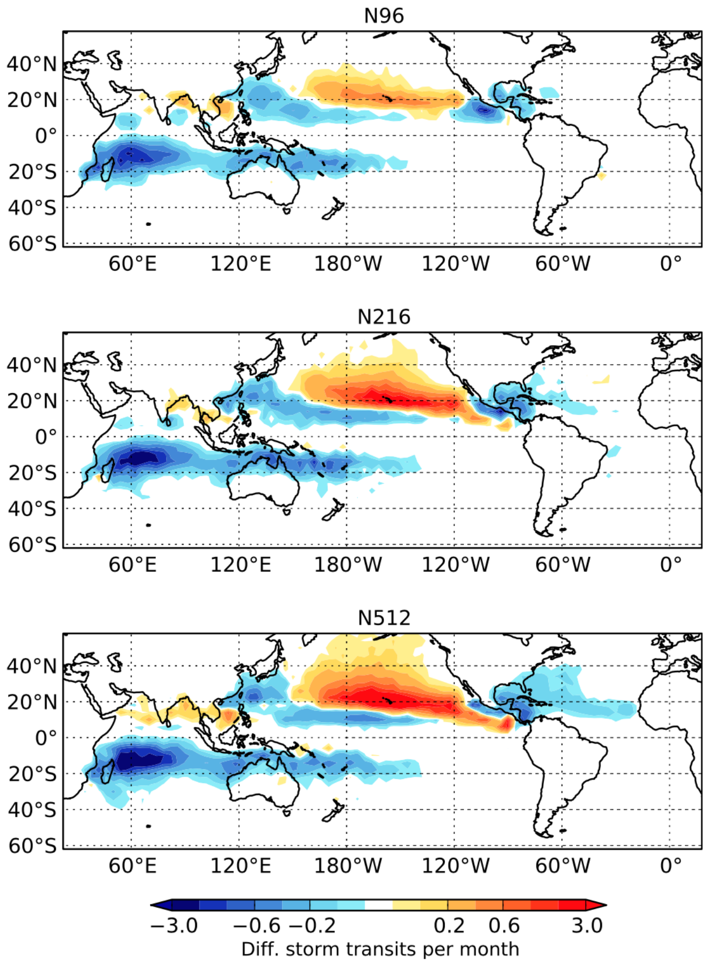

FIG. 12. Change in tropical cyclone track density (storm transits per month per unit area equivalent to a 4° spherical cap) between the future climate and present climate integrations for the whole 1986–2010 period and for the whole ensemble at each model resolution: (top)–(bottom) N96, N216, and N512.

2012 UPSCALE MODELLING CAMPAIGN

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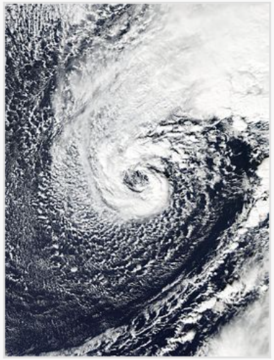
Roberts et al. 2015. Journal of Climate

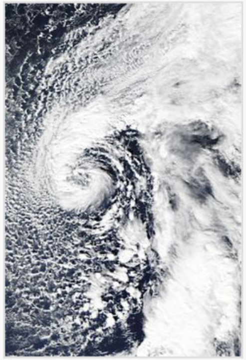
Hurricane Alex, January 2016

a preview of things that do not obey the textbooks

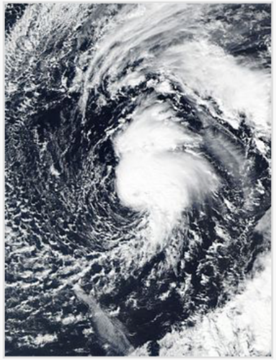
Structural evolution of Hurricane Alex from a non-tropical low into a hurricane



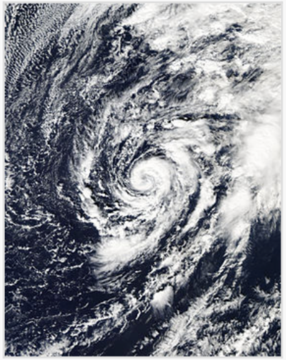
The precursor occluded cyclone on January 10



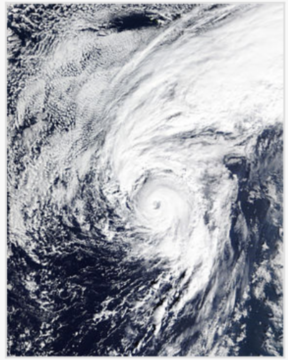
The cyclone becomes increasingly separated from frontal boundaries on January 11



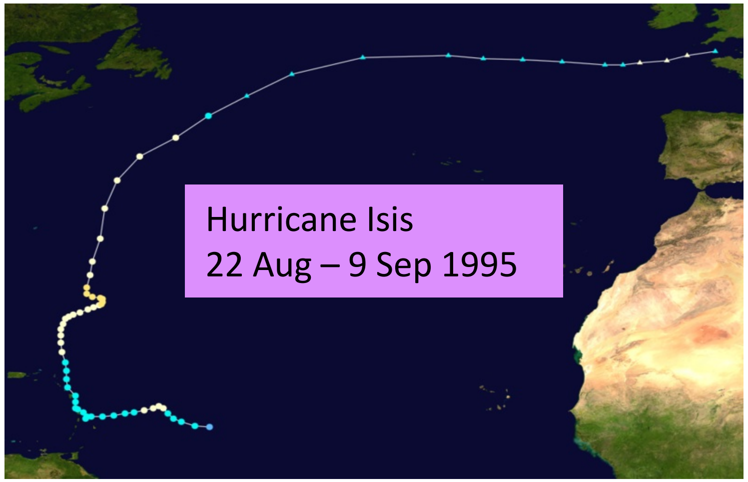
Convection develops atop the circulation center on January 12



The system hours before being classified as a subtropical cyclone, on January 13



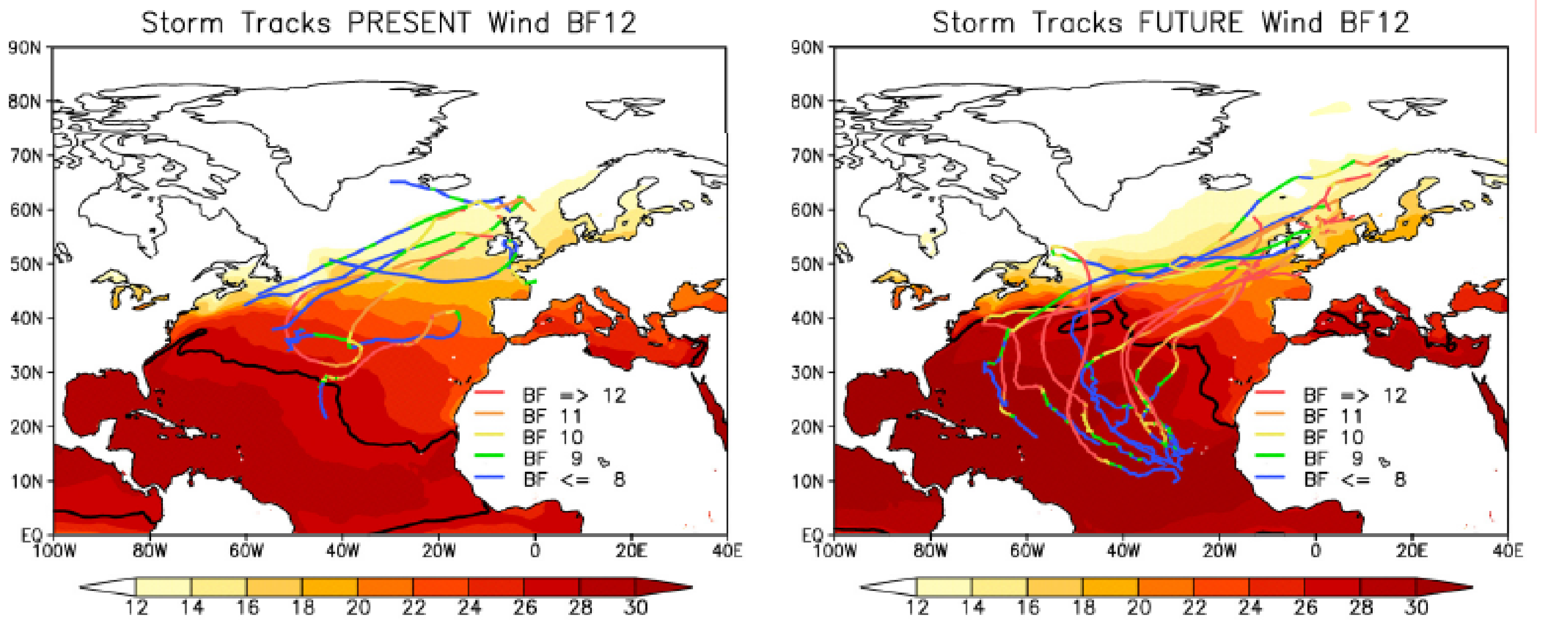
Alex develops a well-defined eye and core structure, as it becomes a hurricane on January 14



From Wikipedia, 2016

Origin of severe autumn storms near Europe

The origin, nature and impact of storms making landfall in Europe is one of the key questions in our Horizon 2020 PRIMAVERA project



Haarsma et al. (2013) suggested that in the future more of the storms impacting Europe will

1) have a tropical origin
2) have a different structure

Both leading to more extreme precipitation

Haarsma et al GRL 2013

Tropical Cyclones "emerge" at high resolution

TC tracks and interannual variability in frequency are credibly represented at 20km; however, intensity is still underestimated by some of the GCMs

Results finally confirmed by a **systematic** multi-model intercomparison

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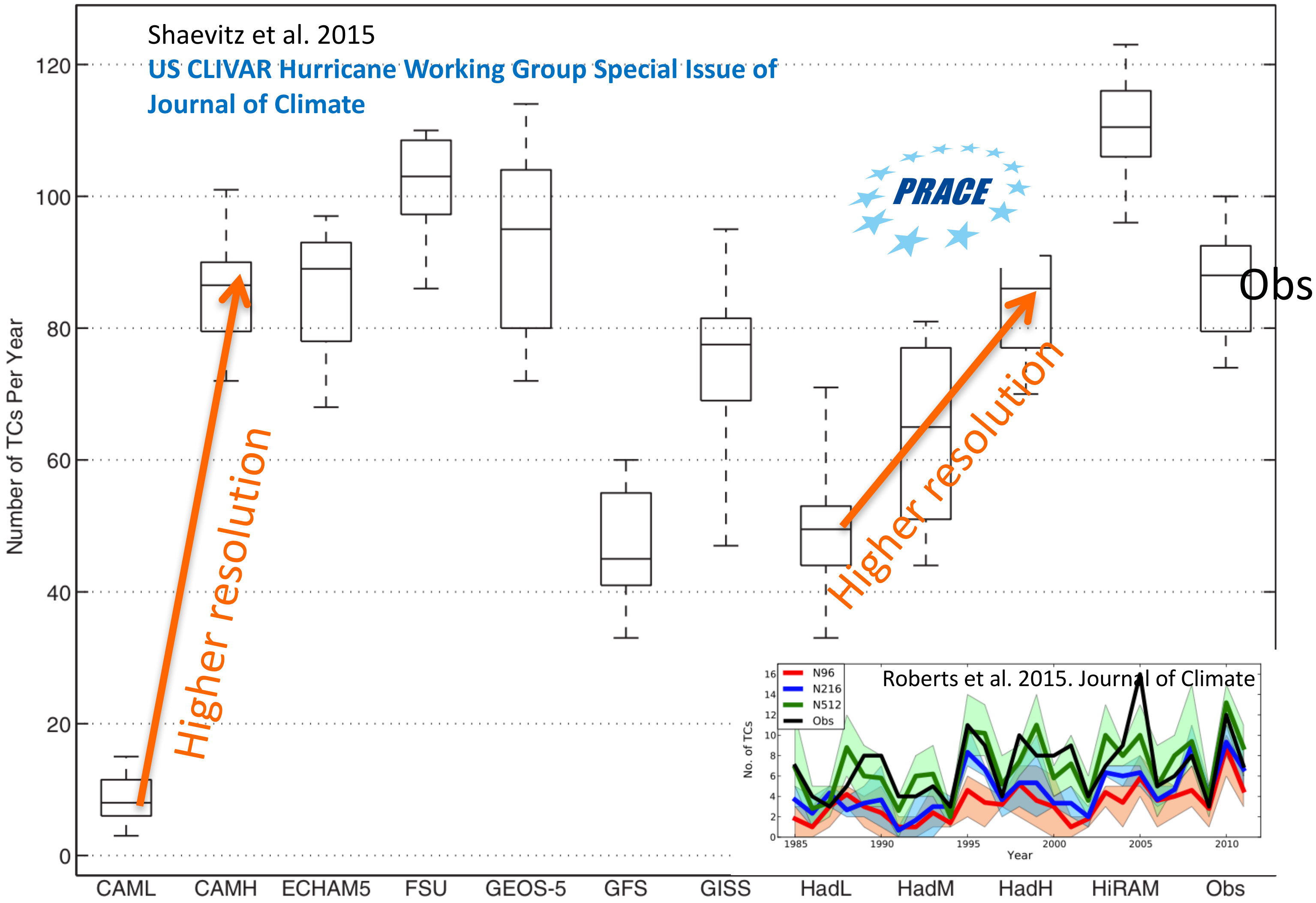
Multi-model representation of the number of TCs per year and its variability



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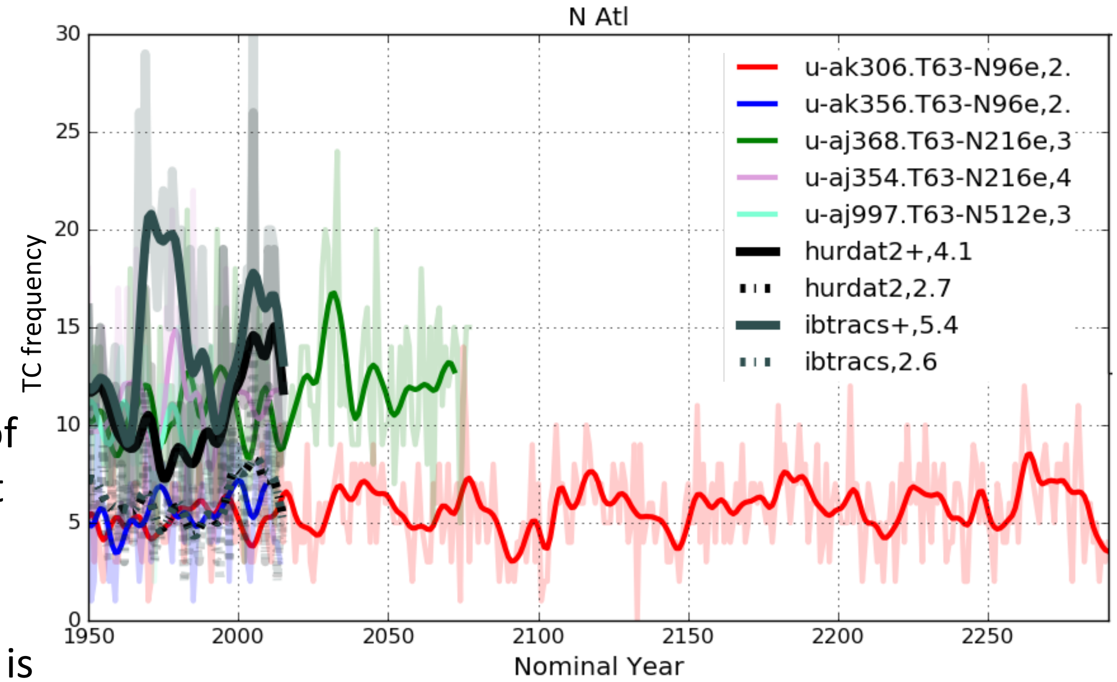
PRIMAVERA: Initial analysis with HadGEM3 GA7/GC3.1

- Coupled atmosphere-ocean HighResMIP
  - control-1950
    - N96-ORCA1 (u-ak306)
    - N216-ORCA025 (u-ak368)
    - N512-ORCA025 (u-aj997)
  - hist-1950
    - N96-ORCA1 x 6 (u-ak356)
    - N216-ORCA025 x 3 (u-ak354)
    - N512-ORCA025 x 3 (not shown)

➢ N216-ORCA025 has event reminiscent of recent observed period, with coincident AMO phase

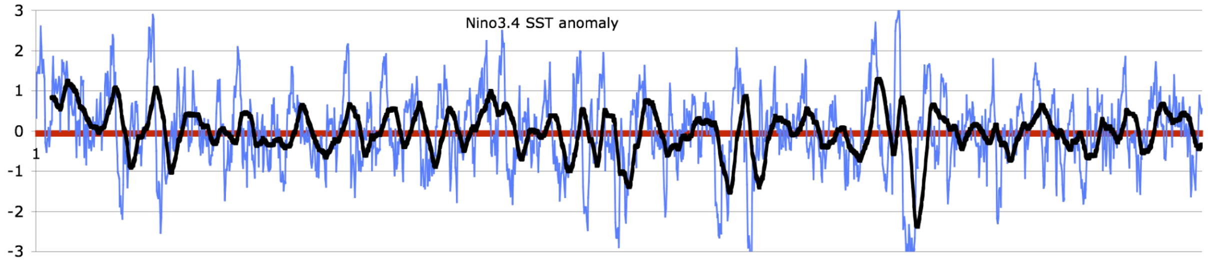
➢ N96-ORCA1 has some longer period variability too, though much weaker (as is the mean), and no decade-long large anomalies

➢ aim to understand drivers of internal variability and contrast with transient-forcing simulations



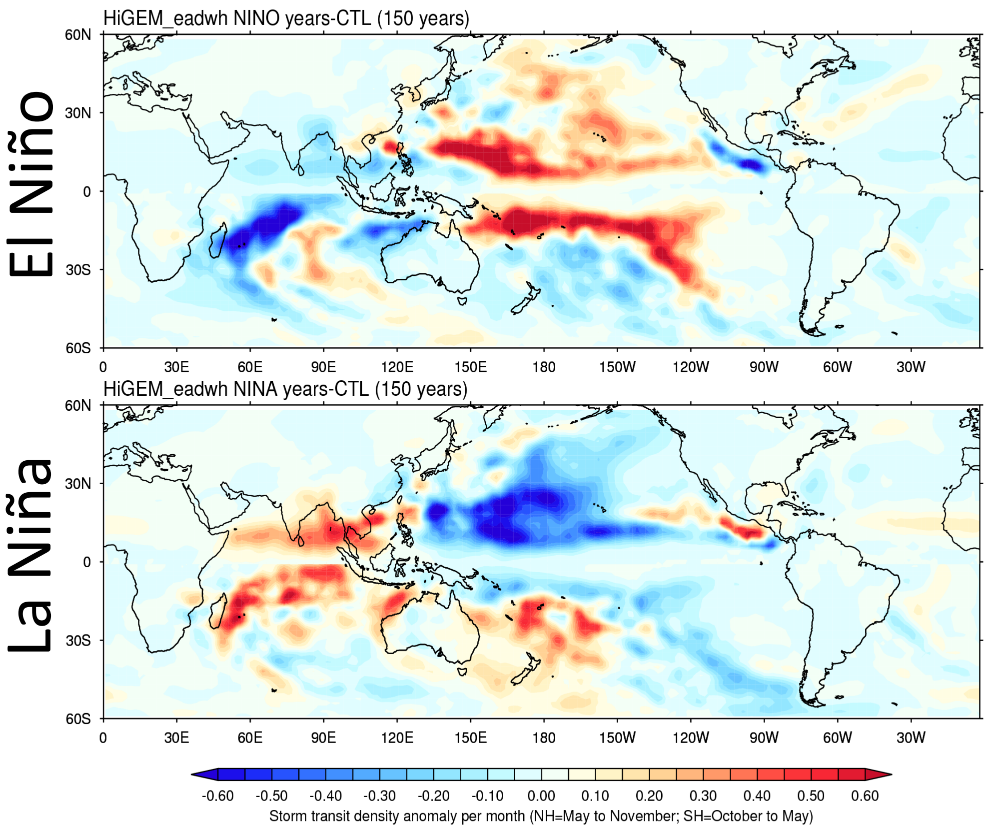
M. Roberts, P. L. Vidale, K. Hodges, unpublished

The impact of natural variability example: ENSO



Nino 3.4 SST anomaly HiGEM (150 year simulation)

Change in simulated (TC) storm track density with ENSO



HiGEM – 150 years

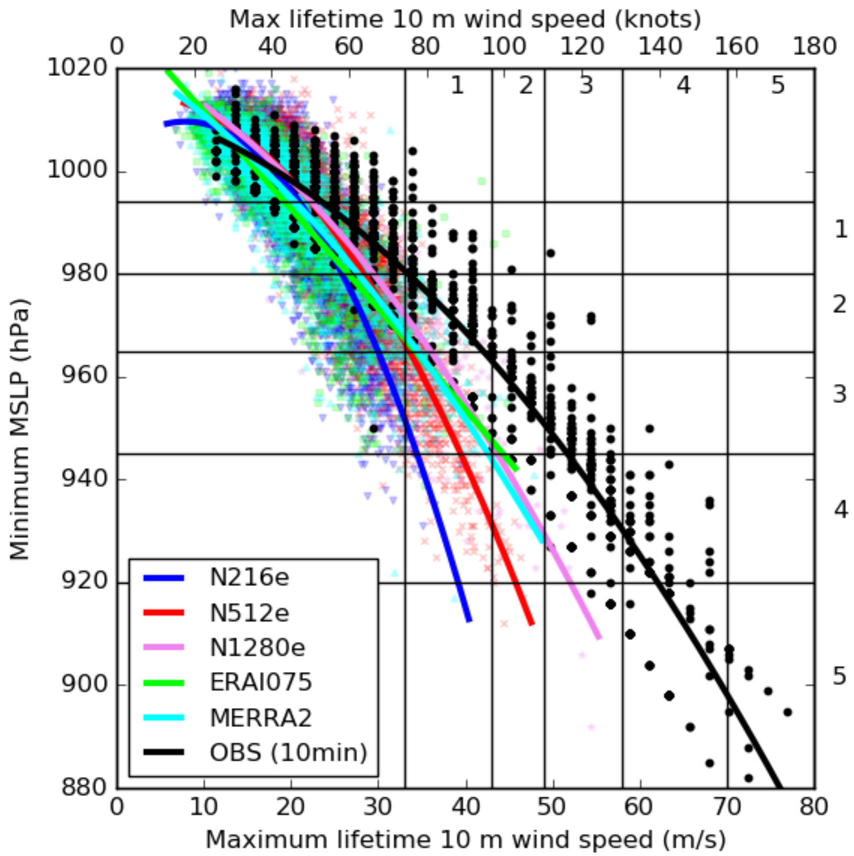
- HiGEM: significant skill in simulating El Niño/La Niña conditions
- Under El Niño (La Niña), there is an eastward (westward) shift in tracks to the central Pacific Ocean (East Asia)
- Potential predictability at the seasonal to interannual scale
- R. Bell et al. J. Clim. 2015

Hurricane intensity

- Atmosphere-only, HighResMIP
  - N216, N512
    - 1950 – 2014
    - daily ¼° HadISST SST and sea-ice
    - EasyAerosol
  - N1280
    - 2005 – 2010
    - standard convection parameterisation
    - Reynolds daily SST and sea-ice
    - GLOMAP-MODE aerosol

➢ **max. wind speed underestimated,** slight improvement with resolution increase

➢ probably over-deepening in terms of MSLP (lack of coupling)

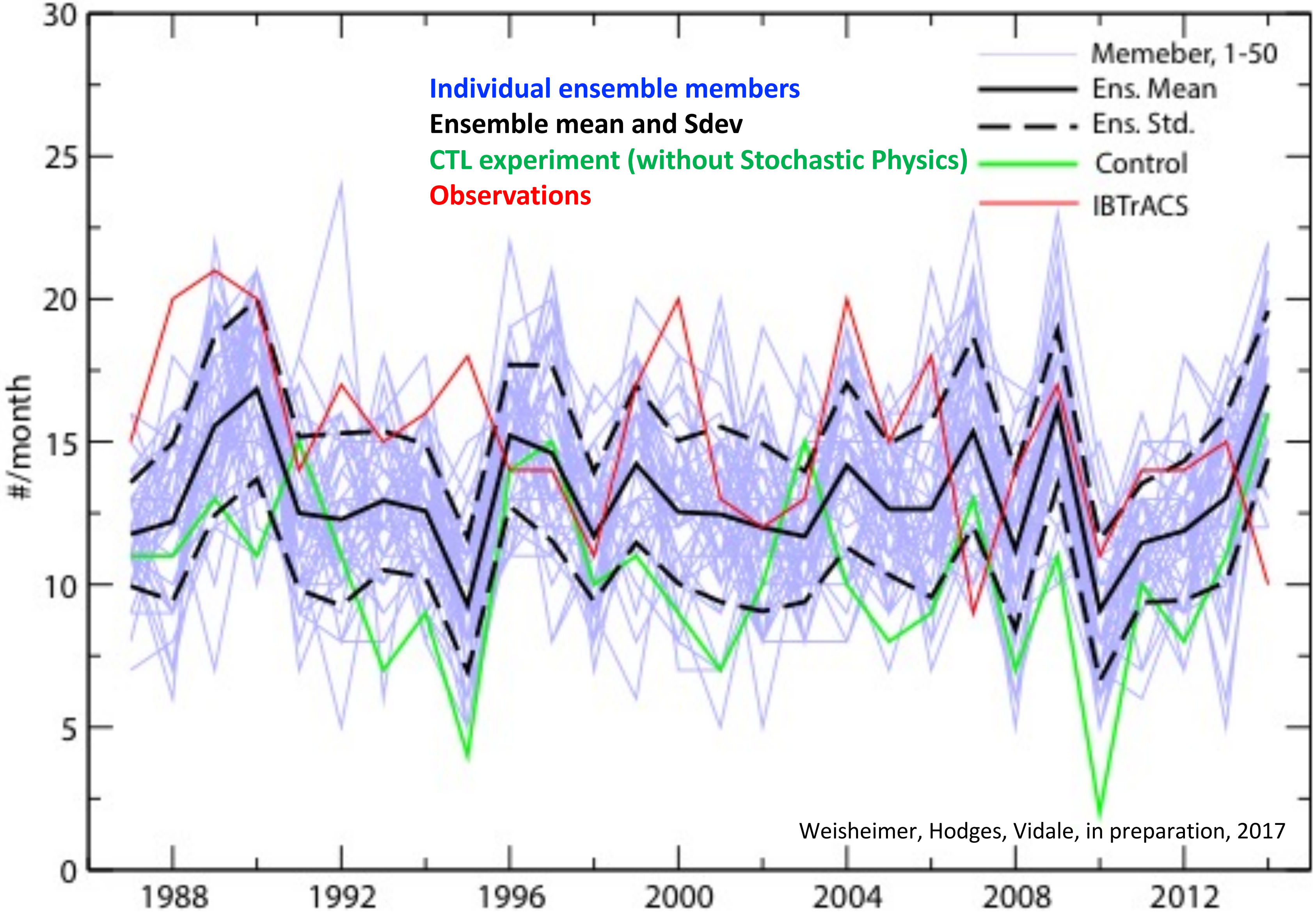


M. Roberts, P. L. Vidale, K. Hodges, unpublished

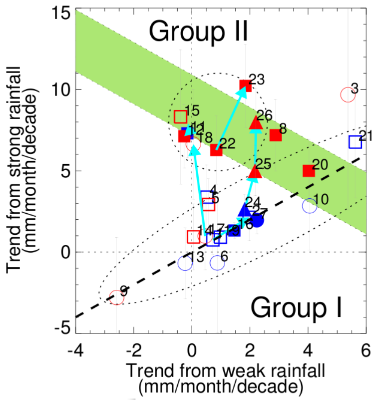
It is not all about resolution: **impact of stochastic physics** on the number of simulated Tropical Cyclones in ECMWF-IFS.

NEARLY EQUIVALENT TO A DOUBLING OF RESOLUTION

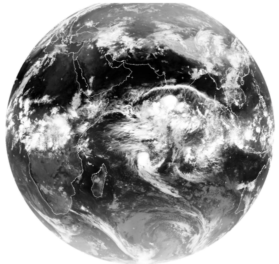
National Centre for Atmospheric Science
NATURAL ENVIRONMENT RESEARCH COUNCIL



Consistent with result achieved with the Unified Mode (GA7 and GC3 formulations)



Vellinga et al. 2016



Convective system-resolving (N1280)10km-ORCA025-ORCA12

Aim: MCSs and their propagation

Science Question(s)

What is the role of convective organisation + propagation in governing regional climate variability?

How is tropical cyclogenesis initiated?

Is climate sensitivity affected by how we simulate convection? What is the role of stochastic physics?

Can we simulate extreme events if we remove the equilibrium assumptions associated with convective parameterisation?

Decadal scale, ensembles of 3

Typical turnaround: 1MY=14.4 days

320 NEXC-S nodes (~10’240 cores)

420 NEXC-S nodes (~13’440 cores)

Phenomena

AEWs and MCSs

Cyclones, particularly the genesis of Tropical Cyclones

Air-sea interactions

Atmospheric Blocking

Diurnal cycle

Extreme precipitation

Projects/Collaborations

CLIVAR Hurricane Working Group

PRIMAVERA/HighResMIP

CLIVAR Dynamics Panel

ECMWF/Oxford

NERC ParaCon

CSSP-HiResCity

Analyses

Extreme value statistics

Catchment-scale model evaluation

Diurnal cycle of convection and precipitation

Surface-atmosphere coupling strength

Publications

Vellinga et al. 2016

Roberts et al. 2009

Birch et al. 2015

Ackerley et al (submitted)

Precipitation propagation: evidence of organisation at high resolution.

GCM comparison with TRMM

Met Office | NATURAL ENVIRONMENT RESEARCH COUNCIL

Joint Weather & Climate Research Programme

A partnership in climate research

PRACE

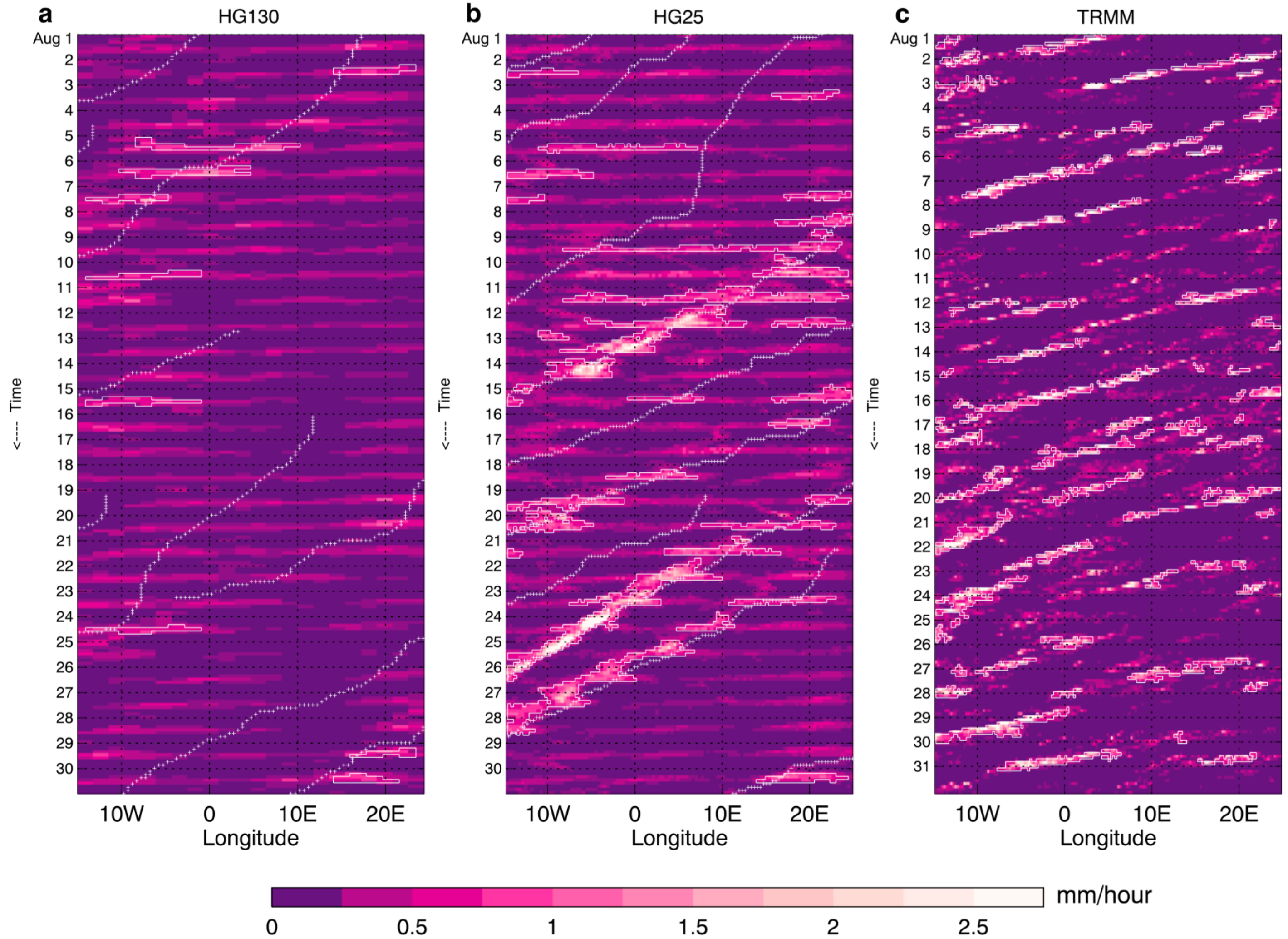


Figure 2. Examples of typical rainfall sequences. Meridionally averaged (10–20°N) 3-hourly rainfall shown as a function of longitude (horizontal) and time (vertical, positive down) for single members of (a) HG130, (b) HG25, and (c) TRMM. Organized rainfall objects are outlined by white contours; African easterly wave tracks in the models are shown by white crosses.

M. Vellinga et al. GRL, 2016

Precipitation spectra

AGCM comparison with TRMM

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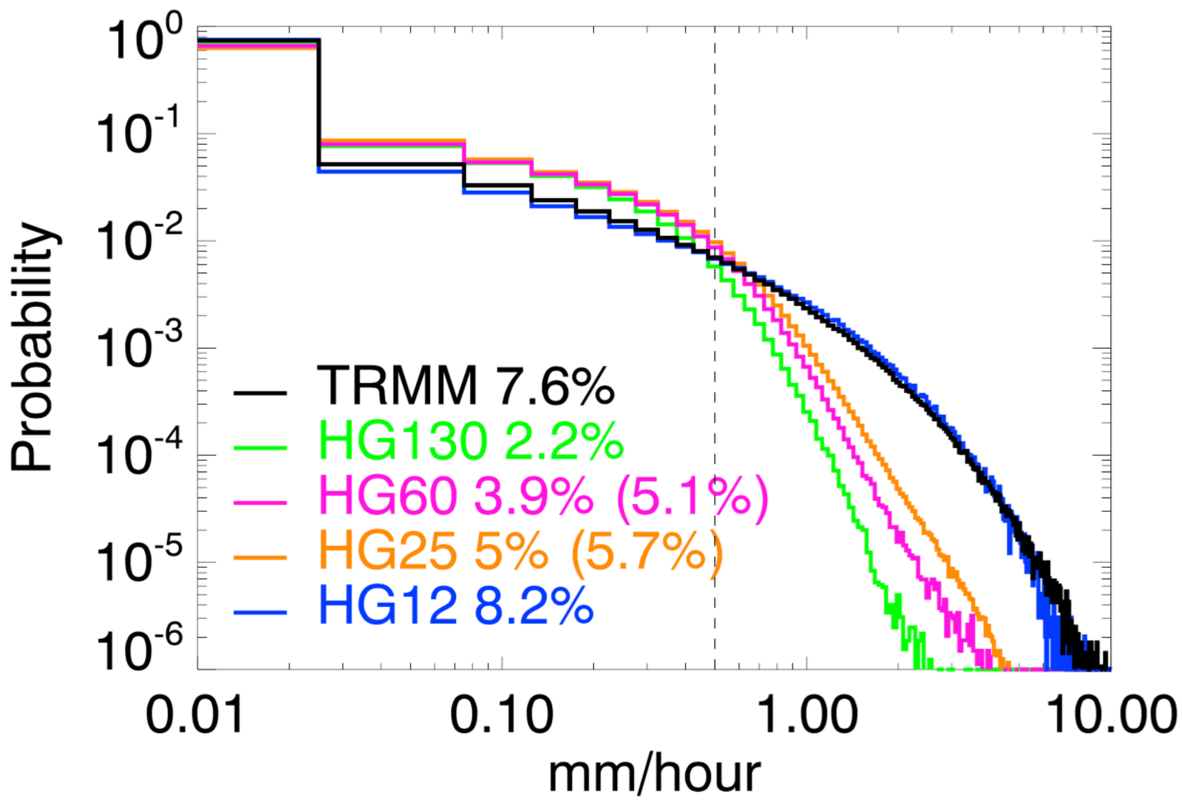
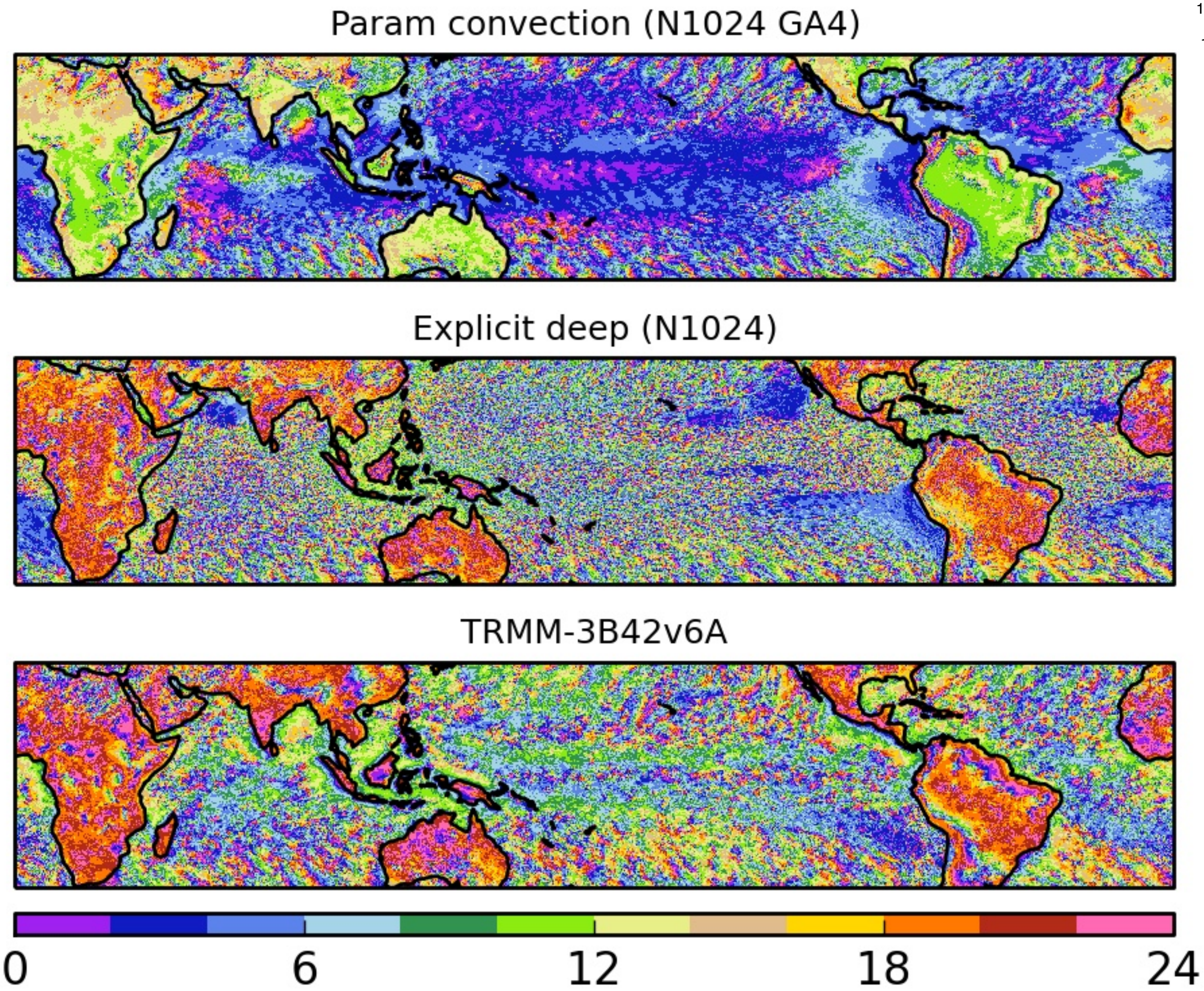


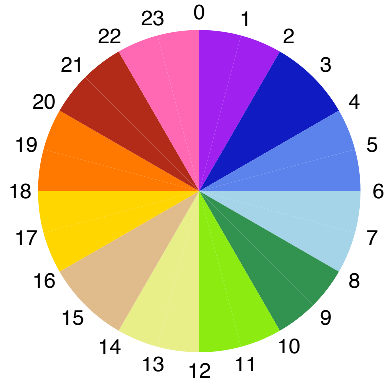
2012 **UPSCALE** MODELLING CAMPAIGN

Figure 3. Distributions of 3-hourly meridional mean Sahel rainfall in July–September. TRMM is for years 1998–2013 and is shown in black. The HG130, HG60, and HG25 models use all ensemble members for years 1985–2011. HG12 uses one realization for years 2008–2011. Numbers in the legend are the probability for an event >0.5 mm/h (dashed line) in each of the distributions; number in brackets is the probability when rainfall is first aggregated onto the HG130 grid.

M. Vellinga et al. GRL, 2016

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



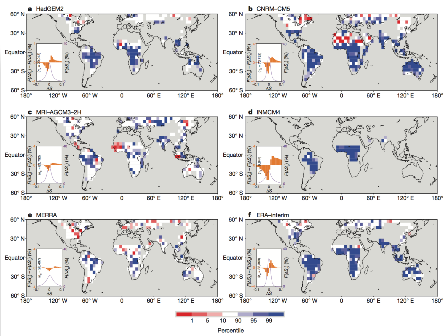


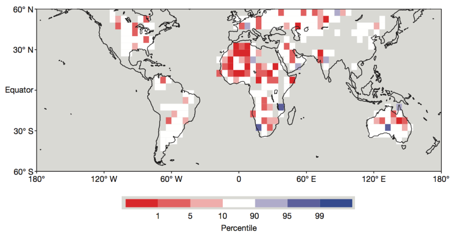
2012
UPSCALE
MODELLING
CAMPAIGN

Birch et al. 2015

Plots R. Schiemann

JWCRP High-Resolution Climate Modelling Programme





Future Development:

Convective system-resolving (N2560)5km

Aim: Land-Atmosphere and Ocean-Atmosphere coupling

Science Question(s)

Is climate sensitivity affected by how we simulate convection and its organisation?

Can we simulate extreme events if we remove the equilibrium assumptions associated with convective parameterisation?

Is land-atmosphere coupling dependent on precipitation occurring over DRY spots?

Seasonal-Annual scale, ensembles?
Typical turnaround: 1MY=30 days

900 NEXC-S nodes (~100’000 cores)

Phenomena

Convection, particularly associated with:

TCs
mesoscale circulations
diurnal cycle

Extreme precipitation

Projects/Collaborations

PRIMAVERA/HighResMIP

NERC convection programme

CASIM

ECMWF/Oxford

CEH

Analyses

Propagation of AEWs and convective systems

L-A / O-A coupling

Non-Gaussian precipitation distributions

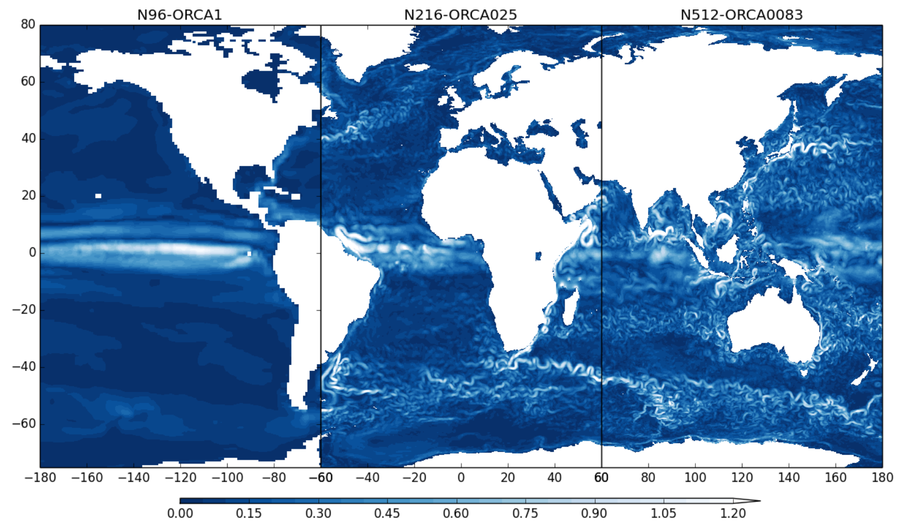
Moist thermodynamics

(Aerosol-cloud-microphysics-rainfall interactions)

Publications

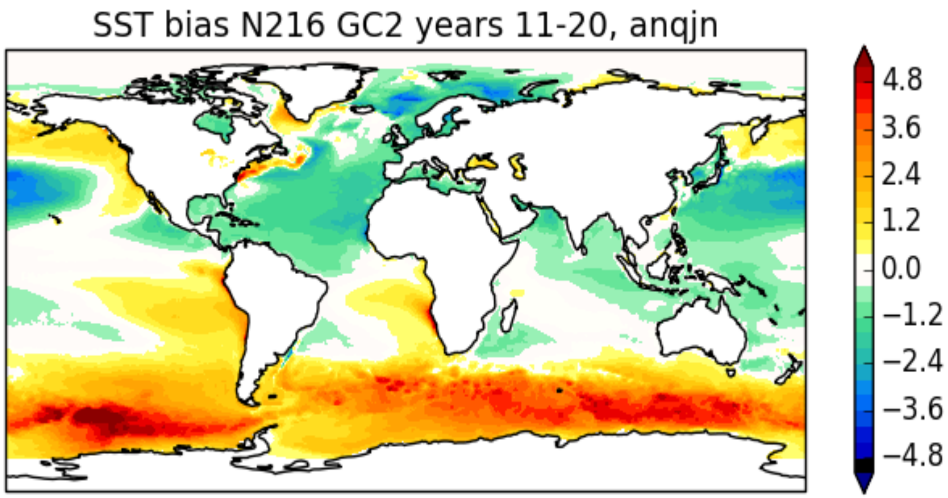
McCoy et al. (submitted)

What happens when we increase resolution in the ocean model?



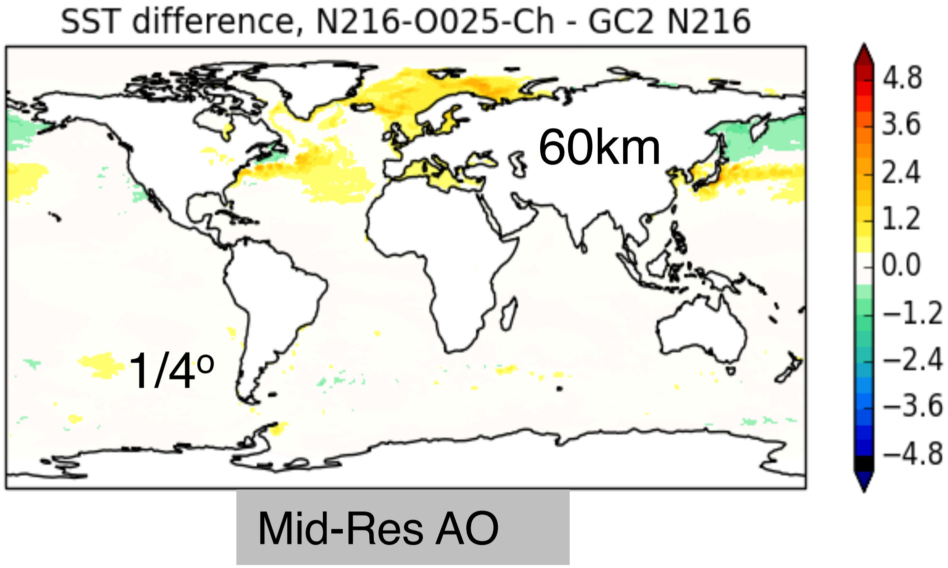
Example 3: SST biases and simulated oceanic transports

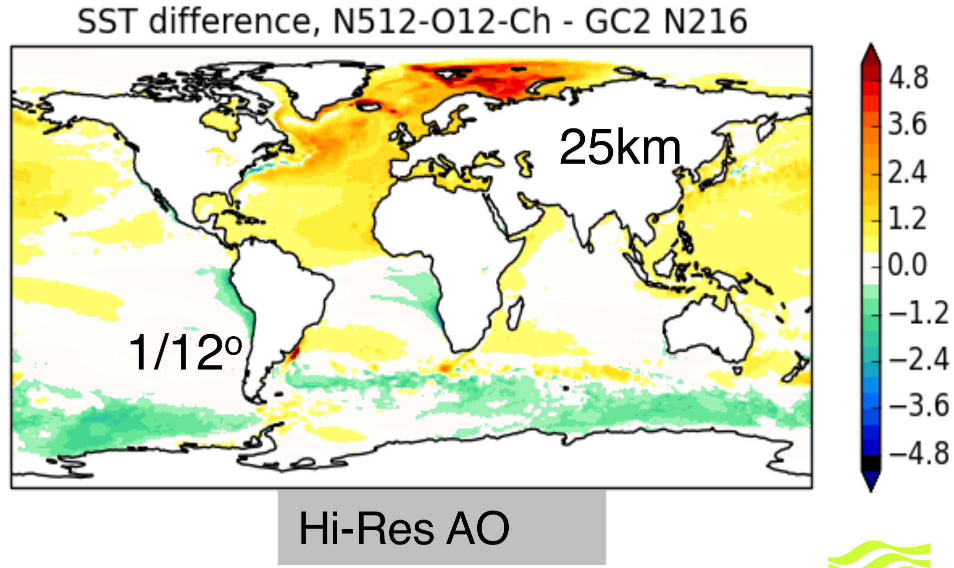
HadGEM GC2 configuration, and High-Resolution variants
SST bias in N216 GC2, and relative change, over years 11-20



Impact of increasing the ocean model resolution from ¼ degree to 1/12 degree:

Significant warming in the North Atlantic due to increased overturning and heat transport





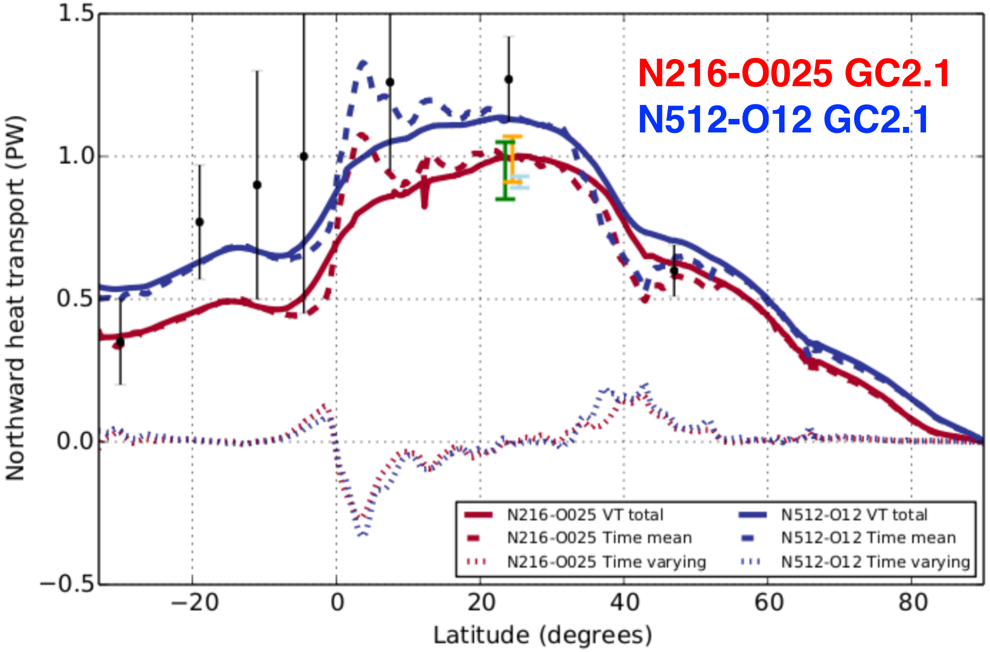
M. Roberts and CHARISMA team, GRL, 2016; Hewitt et al., 2016 (in prep for GMD)

Met Office

M. Roberts and CHARISMA team, GRL 2016
Hewitt et al, 2016 (in prep for GMD)

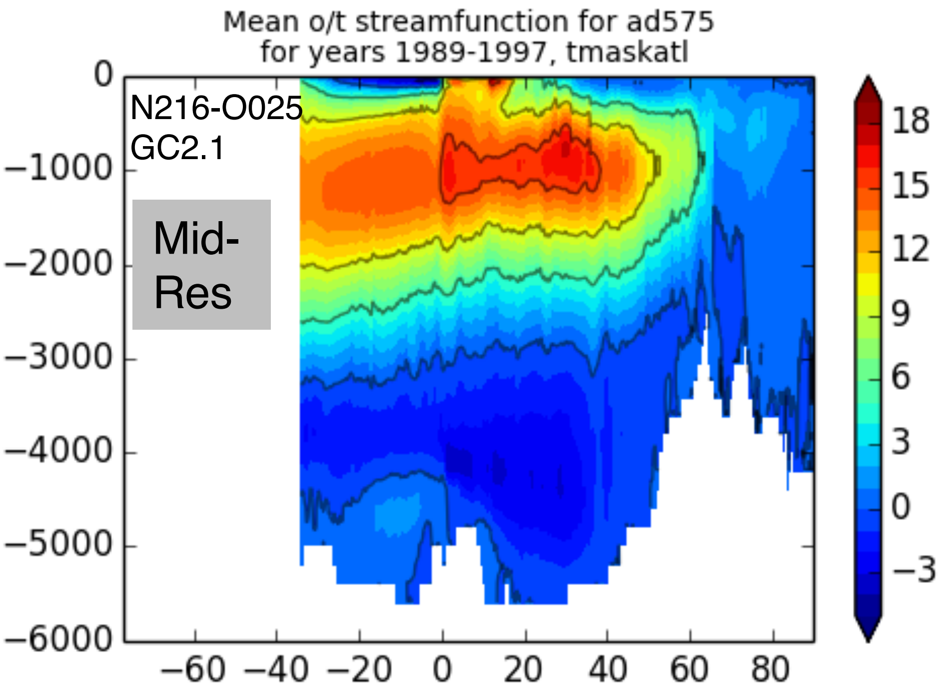
Years 11-20 mean ocean northward heat transport

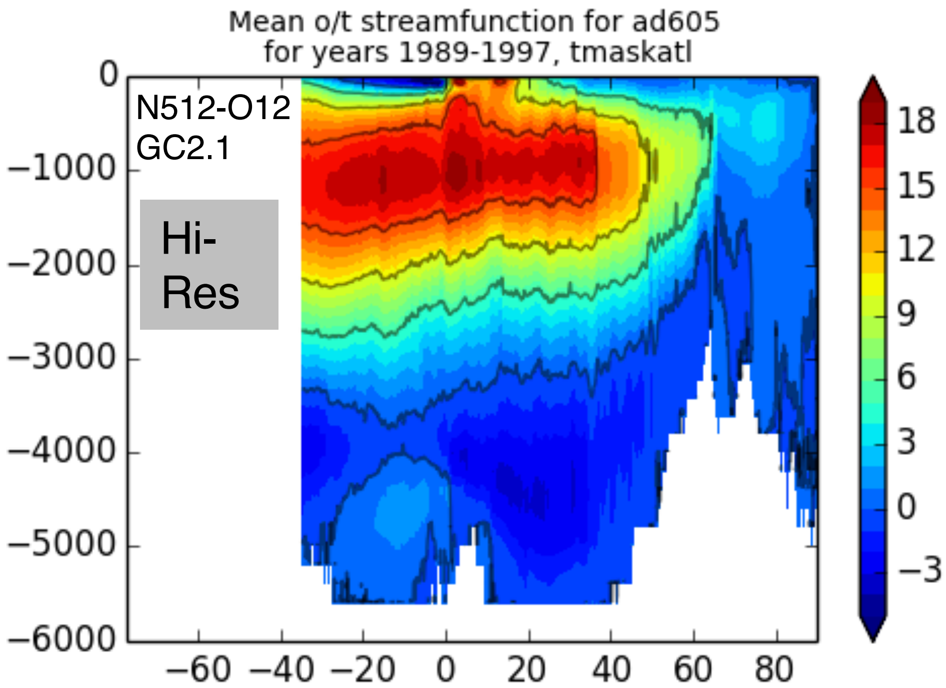
Met Office



Northward ocean heat transport in the North Atlantic from both models, together with observational estimates from Ganachaud and Wunsch (2003). The coloured bars indicate the range of heat transport from additional longer simulation (see text for details)

Increased northward heat transport consistent with increased overturning strength





http://www.primavera-h2020.eu

Strategy:

- Develop a new generation of well-evaluated high-resolution global climate models, capable of simulating and predicting regional climate with unprecedented fidelity
- Coordinated multi-model approach, within Europe and via CMIP6
- Lead and deliver a new protocol: CMIP6-HighResMIP
  - to **develop and run multi-model ensembles of global atmosphere-only and coupled simulations beyond current resolution frontiers**
- Co-design with end-users in 3 key sectors: energy, transportation, insurance

The analysis challenge:

- Minimum HighResMIP set will require 670 million core hours (ARCHER), 8 PB data
  - Our previous project, UPSCALE: 144M core hours (HERMIT) = 260M (ARCHER), 400 TB data
- Fast (parallel), specialised process-based analysis will be a crucial component, in order to extract science in time for CMIP6
  - Need large, dedicated analysis server, e.g. CEDA-JASMIN
  - Need to strongly enhance our parallel analysis capability

PRIMAVERA: open science questions

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A partnership in climate research

- What processes emerge as we increase resolution in the ocean and in the atmosphere?
- Do these finer scale processes, missing in IPCC-class GCMs, affect the simulation of the <u>global</u> climate system?
- Can we produce more trustworthy predictions of climate change if we increase our models' resolution?
  - Are unresolved (missing) processes involved in:
    1. **Teleconnections**, e.g. ocean → land water transport, ENSO
    2. **Decadal variability**, e.g. Sahel rainfall recovery
  - Can we compute robust predictions of the risk of extremes?
    - Hurricanes/typhoons, flooding/drought, windstorms, heatwaves

Roadmap:

UK-Japan Climate Collaboration, HiGEM	UK JWCRP **High Resolution Global Climate Modelling**	PRACE EU-PRACE **UPSCALE**	EU-Horizon 2020 **PRIMAVERA**
2005-2007	2008-	2012-2013	PIs: M. Roberts and P.L. Vidale

PRIMAVERA

Malcolm Roberts, Met Office (coordinator)
Pier Luigi Vidale, Univ. of Reading (scientific coordinator)

PRocess-based climate s**IM**ulation: **A**d**V**ances in high resolution modelling and **E**uropean climate **R**isk **A**ssessment

Goal: **to develop a new generation of advanced and well-evaluated high-resolution global climate models, capable of simulating and predicting regional climate with unprecedented fidelity, for the benefit of governments, business and society in general.**

HighResMIP is a key deliverable in PRIMAVERA

Core integrations in PRIMAVERA will form much of the European contribution to CMIP6 HighResMIP, which is led on behalf of WGCM by PRIMAVERA PIs.

PRIMAVERA core experiments (HighResMIP) and "Frontiers" simulations

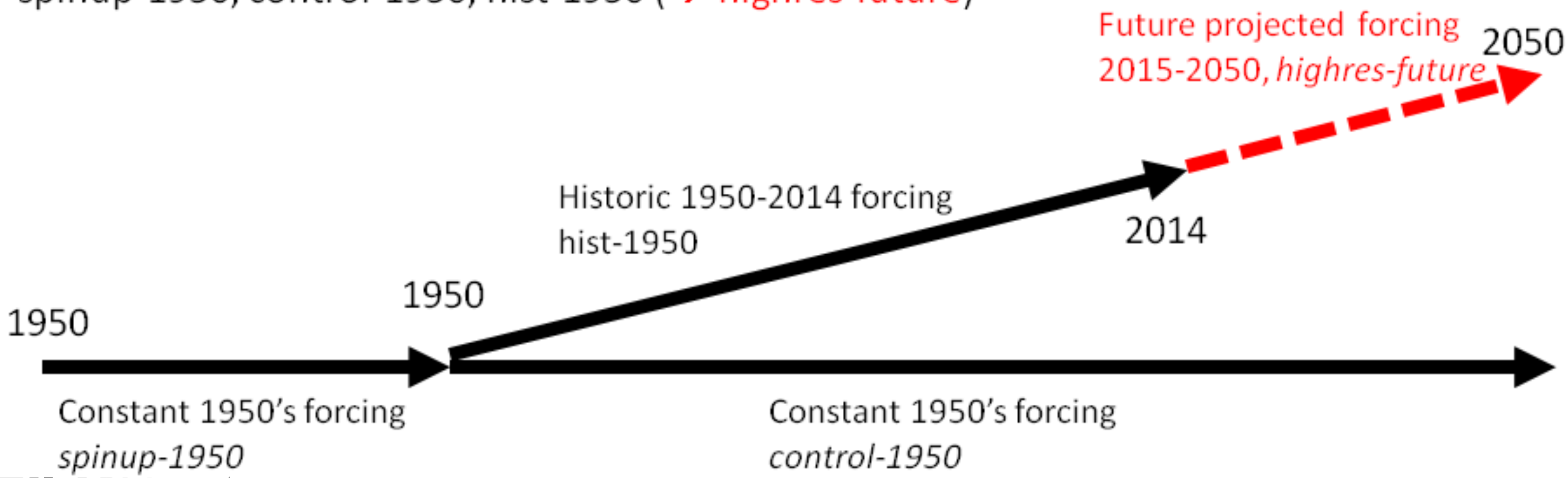
Institution	MO NCAS	KNMI IC3 SMHI CNR	CERFACS	MPI	AWI	CMCC	ECMWF
Model names	MetUM NEMO	ECEarth NEMO	Arpege NEMO	ECHAM MPIOM	ECHAM FESOM	CCESM NEMO	IFS NEMO
Atmosph. Res., core	60-25km	T255-799	T127-359	T63-255	T63-255	100-25km	T319-799
Atmosph. Res., FCM	10-5km						T1279-2047
Oceanic Res., core	¼ o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

PRIMAVERA simulations to be submitted to CMIP6-HighResMIP

Atmosphere-land-only, 1950-2014 (→ 2050)
Forced by observed SST and sea-ice and historic forcings (→ projected)
highresSST-present (→ highresSST-future)

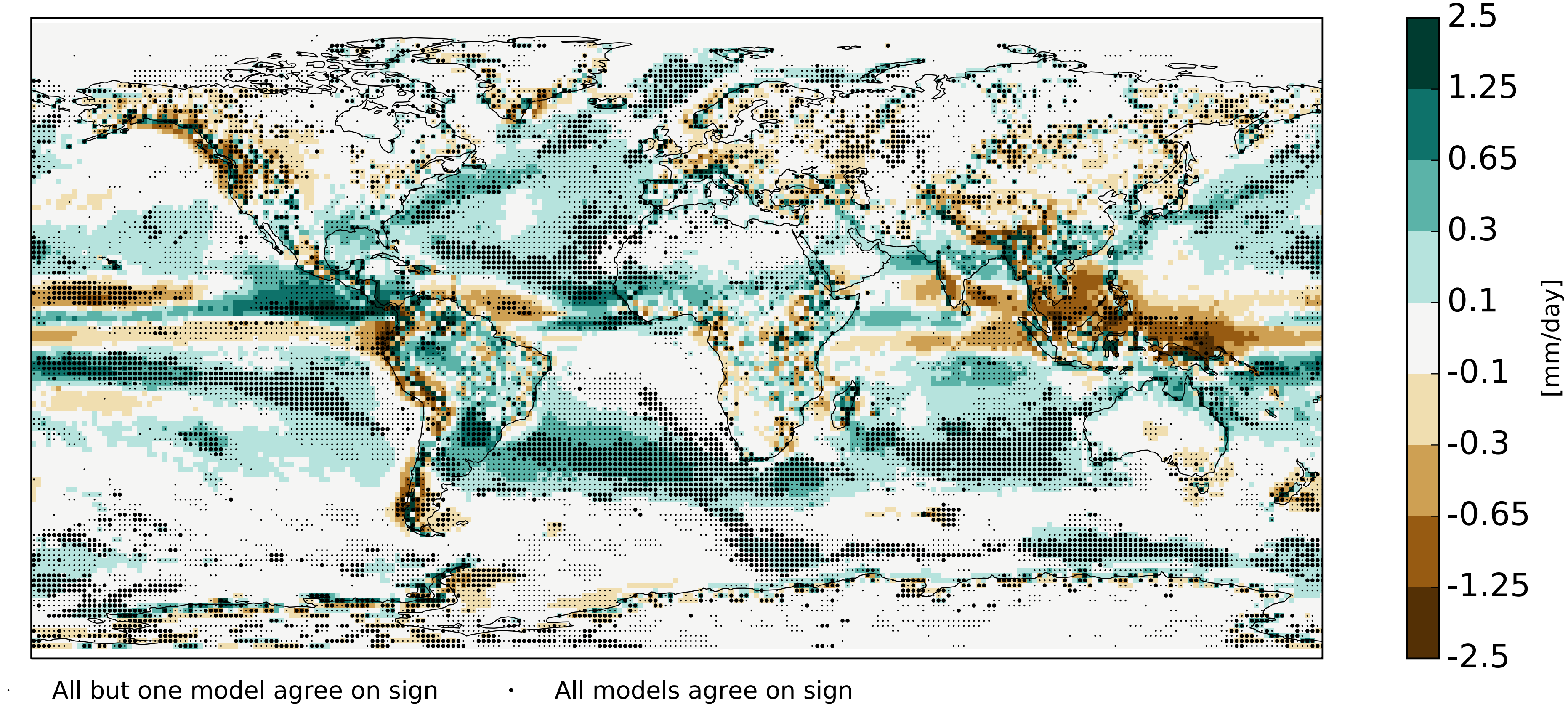
Generating up to 8PB of data, to be analysed for the next IPCC report (AR6)

Coupled climate, 1950-2014 (→ 2050)
Forced by constant 1950 and historic forcings (→ projected)
Initial coupled spin-up period ~ 30-50 years from 1950 EN4 ocean climatology
spinup-1950, control-1950, hist-1950 (→ highres-future)



The value of a coordinated multi-model approach

Sensitivity of annual precipitation to model resolution

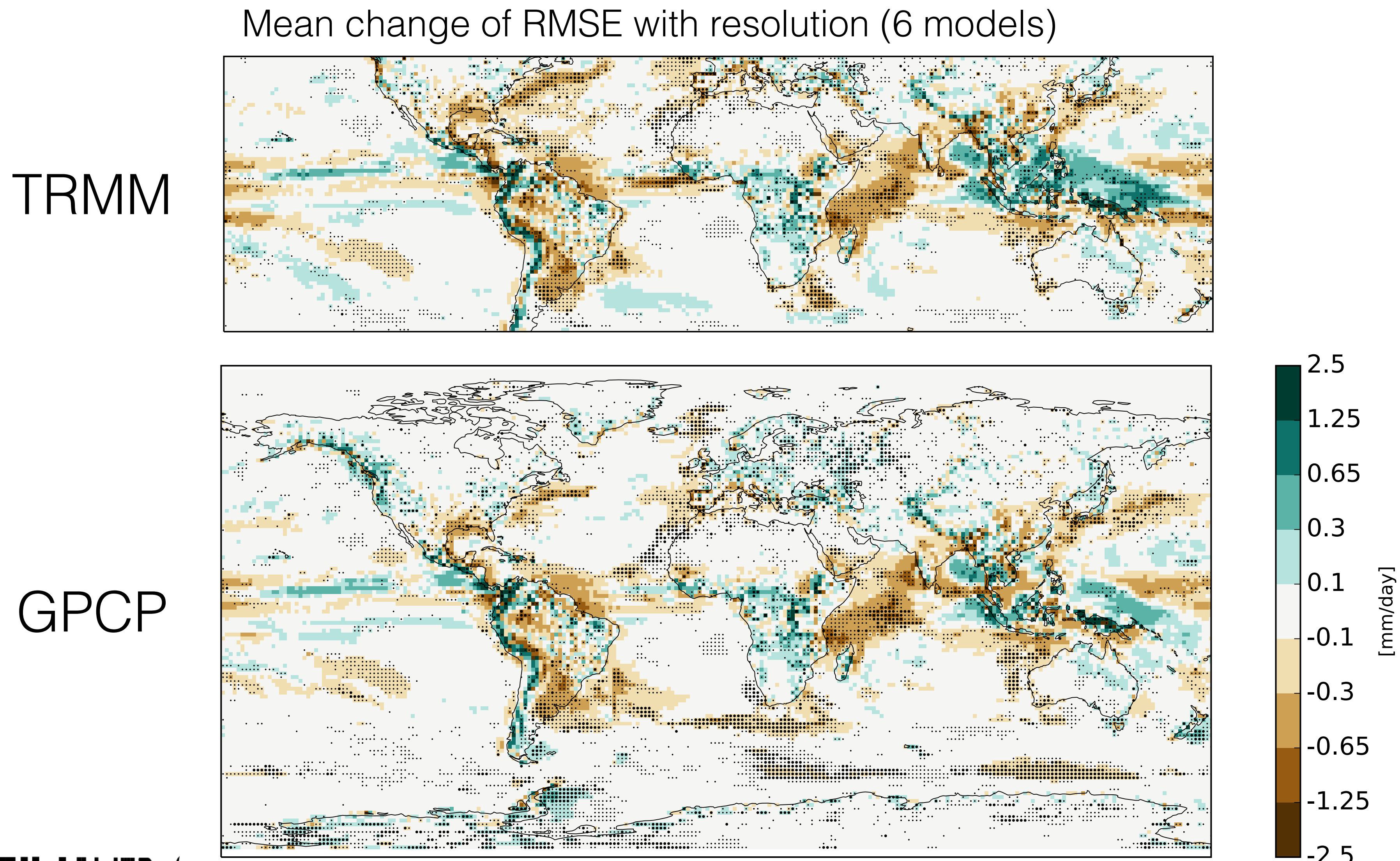


Increase of precipitation:
over orography, storm tracks, Amazon basin, la Plata basin, Sahel, North East India…

Systematic drying:
over the maritime continent, eastern Europe, in regions shadowed by orography…

B. Vanniere, NCAS, in preparation

What does it mean in term of bias reduction?



B. Vanniere, NCAS, in preparation

Demory et al (2014) revisited with a **multi-model approach**, to establish the **robustness** of our previous findings.

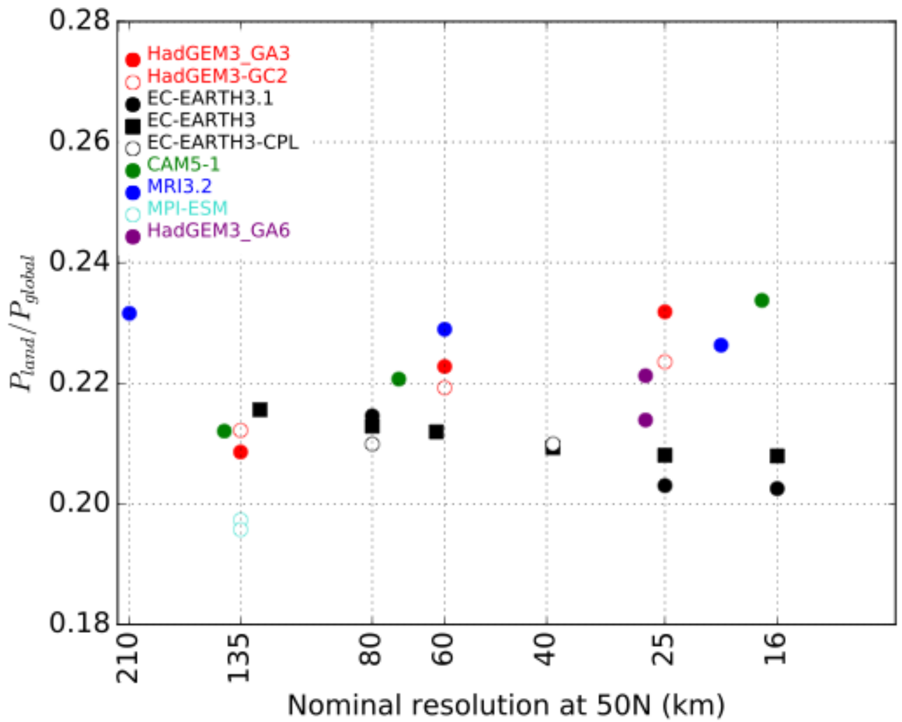


Figure 1 I Ratio of land to global precipitation as a function of model resolution at 50°N. Plain circles stand for atmosphere-only experiments and open circles for coupled experiments.

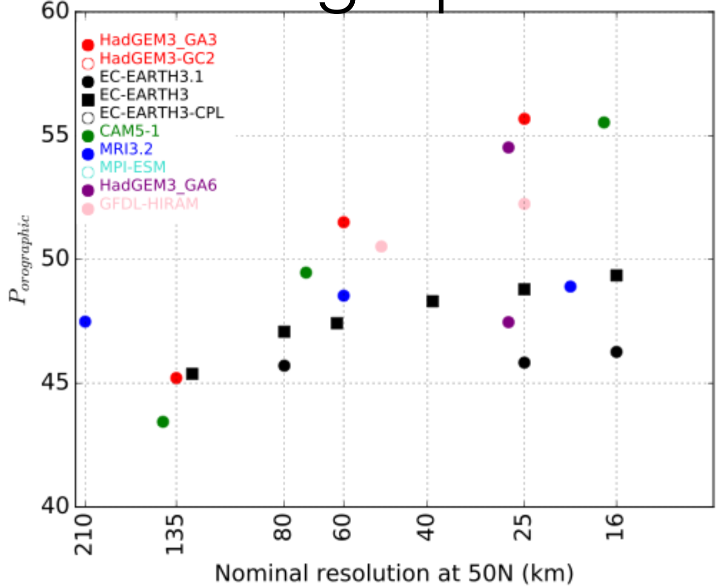
- It is interesting to note that two different behaviours arise depending on model formulation : in finite differences/volumes models (HadGEM3, CAM5-1) the land to global precipitation ratio increases with resolution whereas it decreases in spectral models (EC-Earth3,EC-Earth3.1, MRI3.2).
- Coupling does not modify this behaviour.
- The purple circles stand for two experiments testing the sensitivity to the resolution of orography : the control (top) uses HadGEM3_GA6 on grid N480, the perturbed experiment (bottom) uses the same atmospheric resolution but N96 orography.

PRIMAVERA

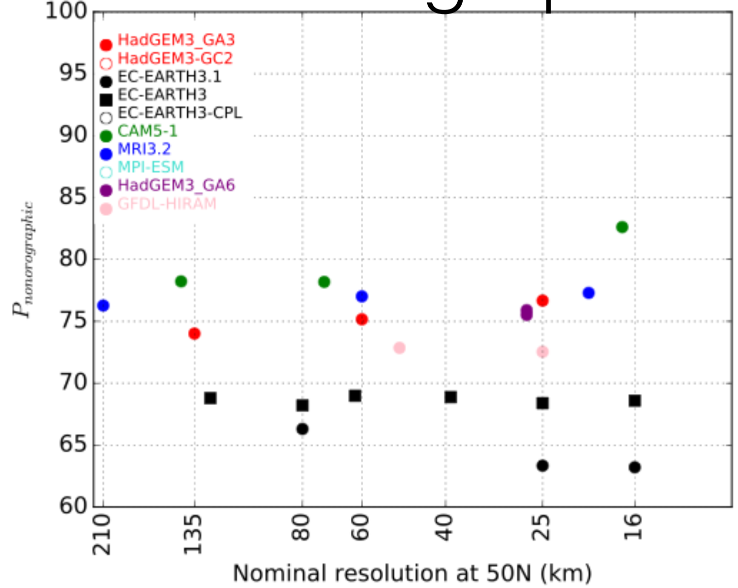
B. Vanniere, NCAS, in preparation

Identifying orographic precipitation in models. Technique 2: metric based on Sinclair's model (1994) for orographic precipitation.

Orographic



Non-orographic

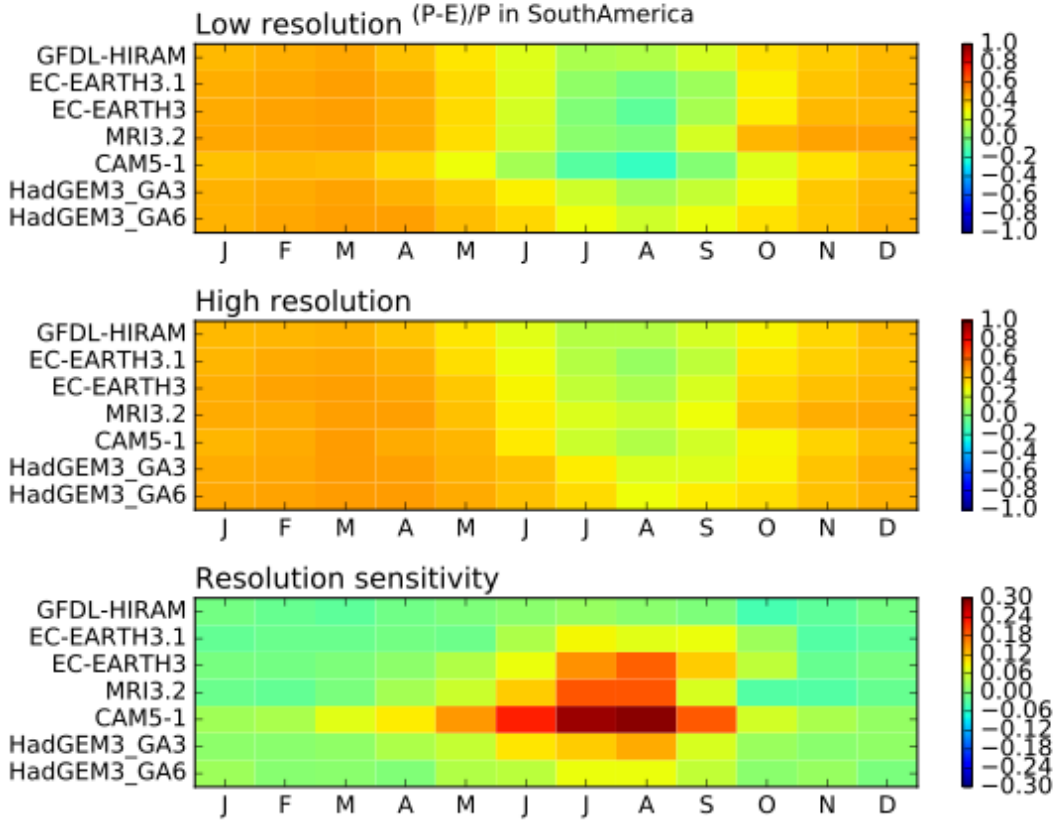


- Regions identified as giving orographic precipitation represent 20% of land area and ~40% of land precipitation.
- It represents for most models most of the increase of precipitation with resolution.
- In HadGEM-GA6 experiments, the metric attributes all the precipitation change to orographic precipitation, suggesting that the differences in precipitation non orographic regions cancel out (see south America).
- The amplitude of the orographic precipitation change is less in GA6 than in GA3. Suggesting that part of the increase can be attributed to the atmospheric model resolution (rather than to the resolution of the orography). Role of mesoscale features in initiating microphysics leading to orographic precipitation?
- NB: Orographic precipitation in EC-EARTH3 increases with resolution, but global precipitation too. So the effect of orography itself might not be as strong as it looks…

B. Vanniere, NCAS, in preparation

Illustration of a systematic increase of moisture advection to land:

JJA moisture convergence in S. America



(P-E)/P over land represents the fraction of local precipitation due to moisture convergence.
All models simulates an increase of this ratio in JJA in South America.

B. Vanniere, NCAS, in preparation

Summary of Global Climate Modelling at the Petascale

- From High Resolution to High Fidelity: beautiful pictures are not enough.
- Focus on producing and understanding:
  i) trustworthy, ii) traceable and iii) reproducible results.
  - **Emerging processes** and **scale interactions**
    - Intense cyclones (tropical, extra-tropical)
    - Eddies and their transports
    - Convective organisation
  - QUESTION: what is the impact of emerging processes on the larger scales?

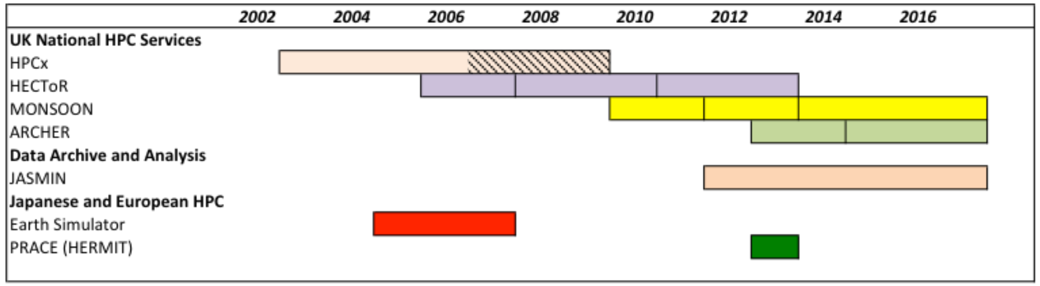
  $\Rightarrow$ need high-resolution global climate simulations over centennial time scales
- International collaboration on the workflow from simulation to analysis is key to scientific outputs:
  - From PRACE-UPSCALE to PRIMAVERA and HighResMIP
  - WCRP, US CLIVAR Hurricane Working Group, ENES
  - EPECC
- Scientific leadership:
  - Now leading a new protocol for CMIP6: HighResMIP

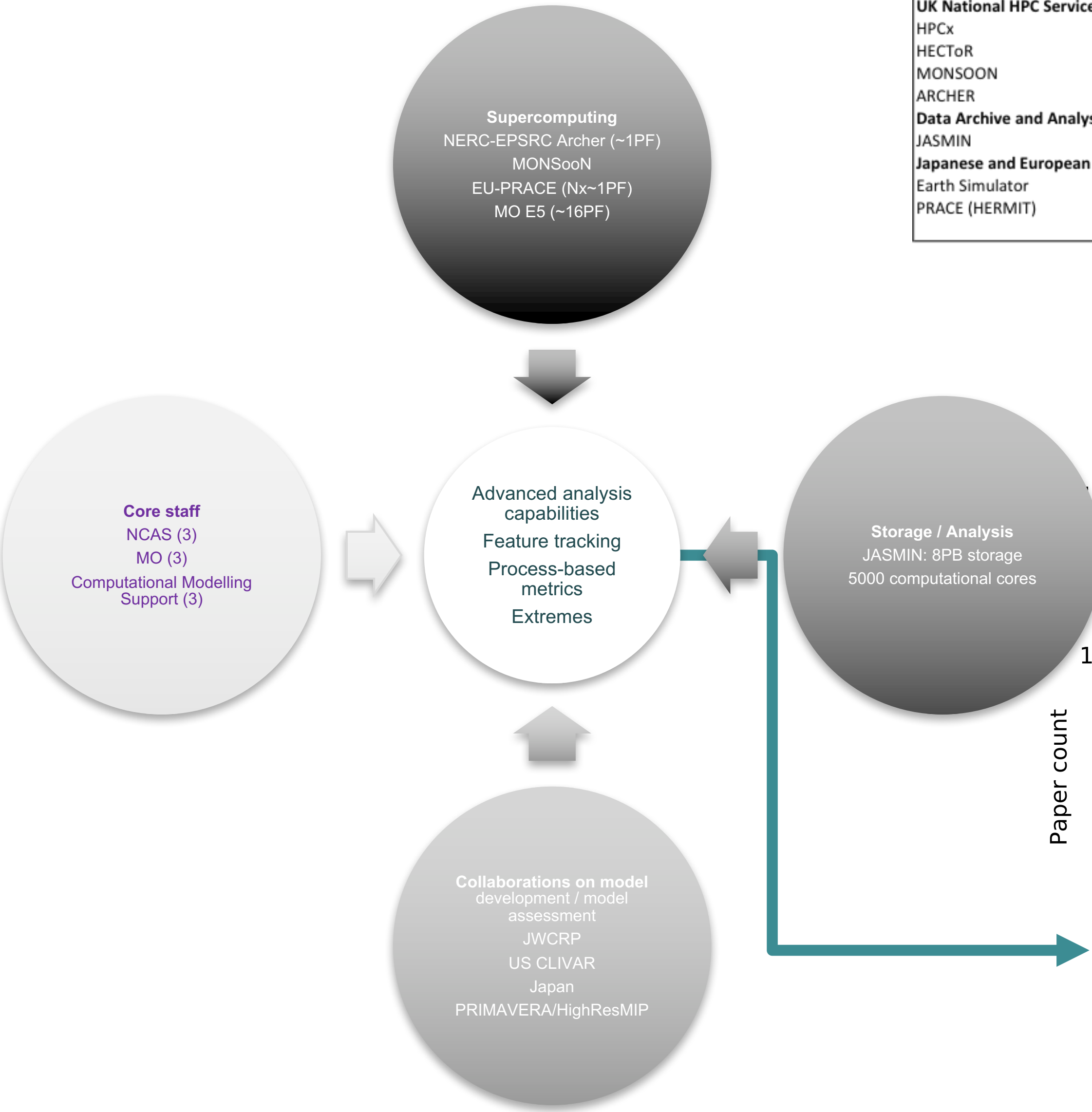
Resources / Investments

The UK's JWCRP High Resolution global Climate Modelling has required large, sustained investments over decadal time scales

Joint Weather and Climate Research Programme

A partnership in climate research





Publication timing lags experimental design/execution by several years, which is a challenge for University academics. Publication impact, however, is high.