Global modelling of climate processes at high resolution – from one model towards multi-model

Met Office | Natural Environment Research Council

Joint Weather and Climate Research Programme

A partnership in climate research

Malcolm Roberts Met Office

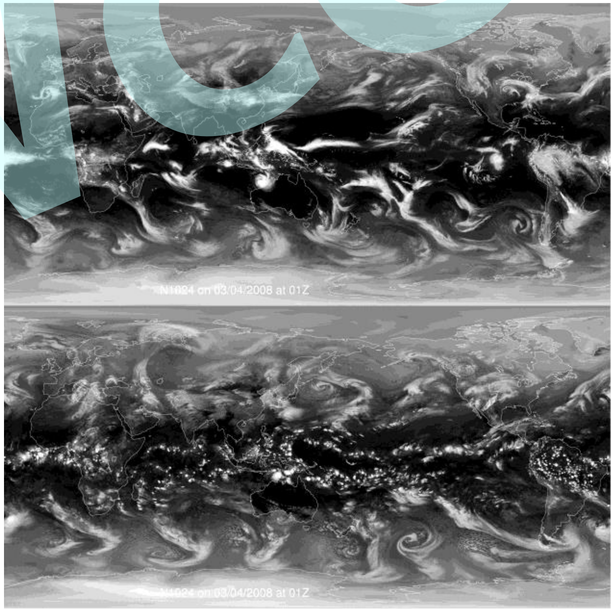
Matthew Mizielinski, Lizzie Kendon, Cathryn Birch
(with thanks to the many Met Office groups involved in model development and assessment)

University of Reading
National Centre for Atmospheric Science
NATURAL ENVIRONMENT RESEARCH COUNCIL
Willis Research Network

Pier Luigi Vidale

Willis Professor of Climate System Science and Climate Hazards
WCHL, Dept. of Meteorology, University of Reading, UK

Marie-Estelle Demory, Reinhard Schiemann, Jane Strachan

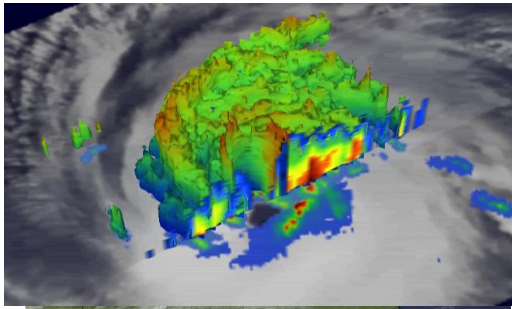
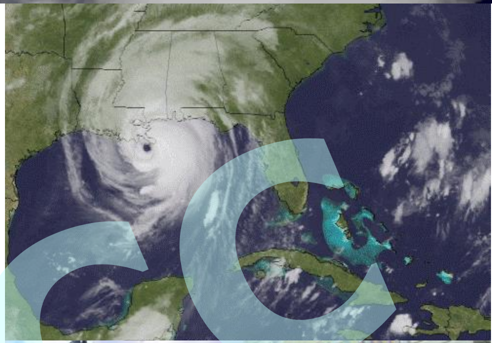


Workshop on High-Resolution Climate Simulation, Projection, and Application, Taipei, 19th Jan 2015

Outline

- Drive to traceable higher resolution global climate modelling
  - The PRACE-UPSCALE project
    - Science highlights:
      - Large-scale moisture transports
      - Hurricanes and typhoons in the climate system
  - The need for multi-model robustness
    - Multi-model process-based comparison
    - HighResMIP for CMIP6

- Enabling future GCM development: the drive to explicit convection at the global scale
  - Extreme rainfall in a regional 1.5km model

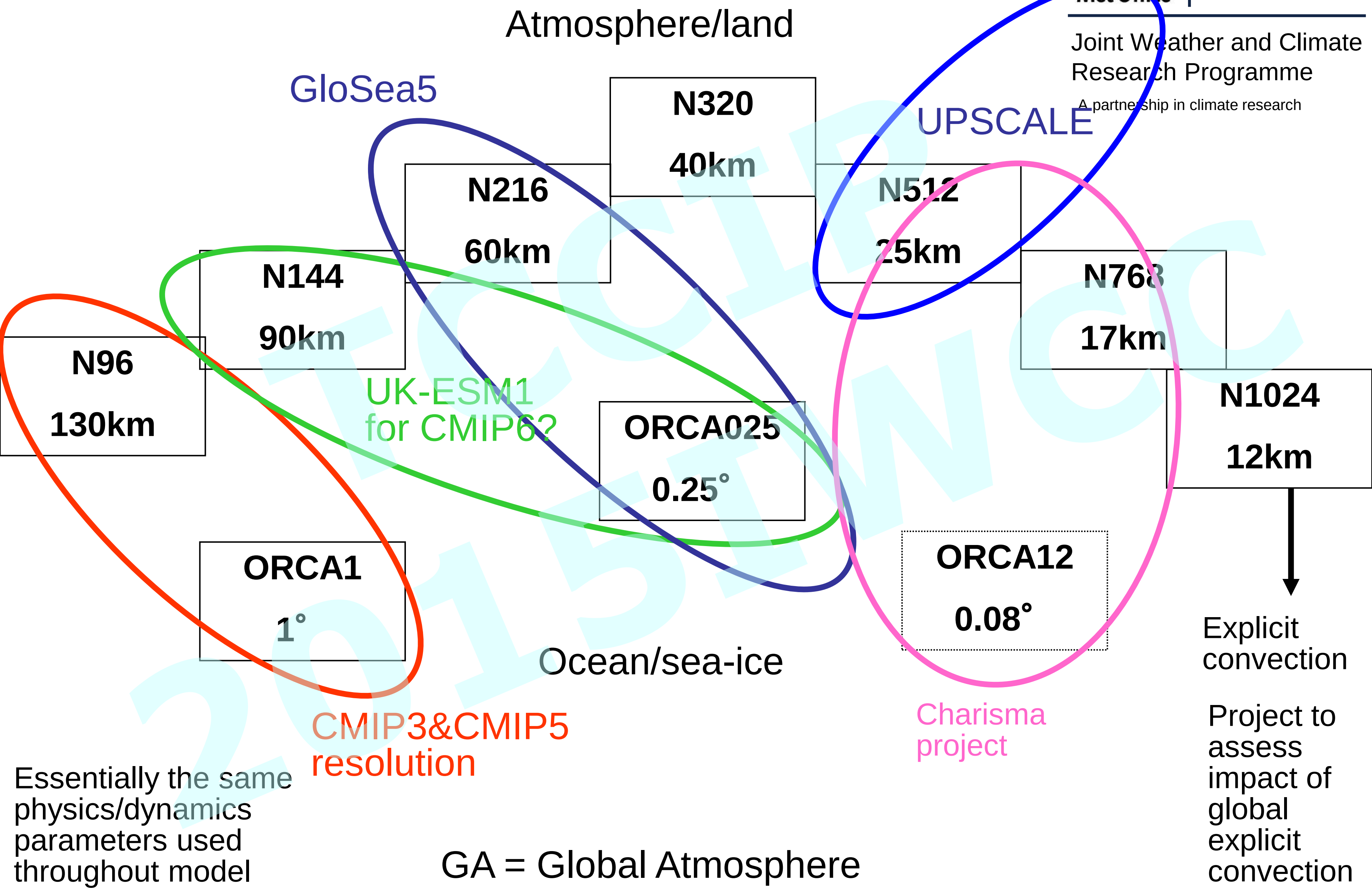



MetUM global atmosphere/coupled model climate configurations in use

Met Office | NATURAL ENVIRONMENT RESEARCH COUNCIL

Joint Weather and Climate Research Programme

A partnership in climate research

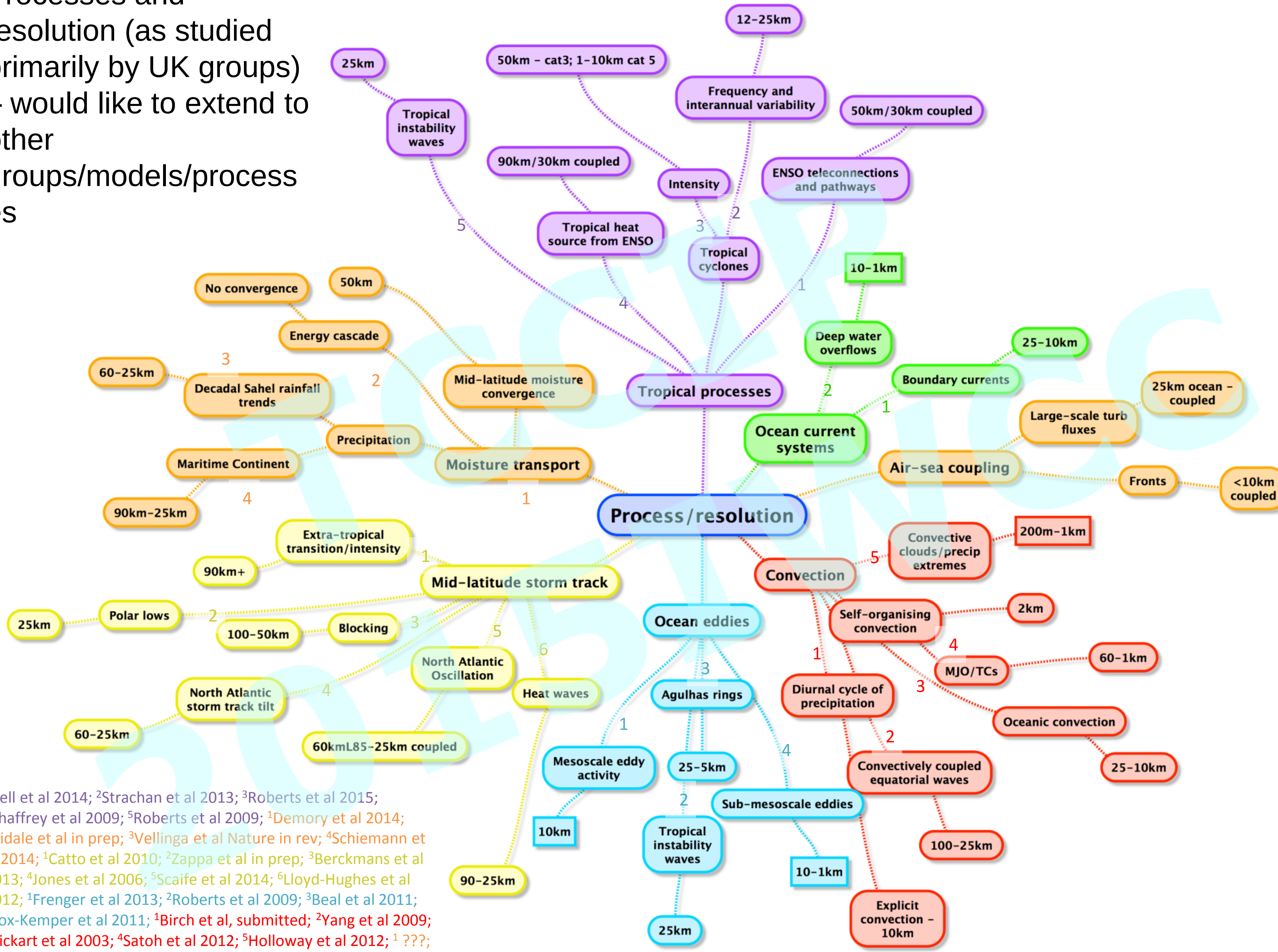


Essentially the same physics/dynamics parameters used throughout model hierarchy

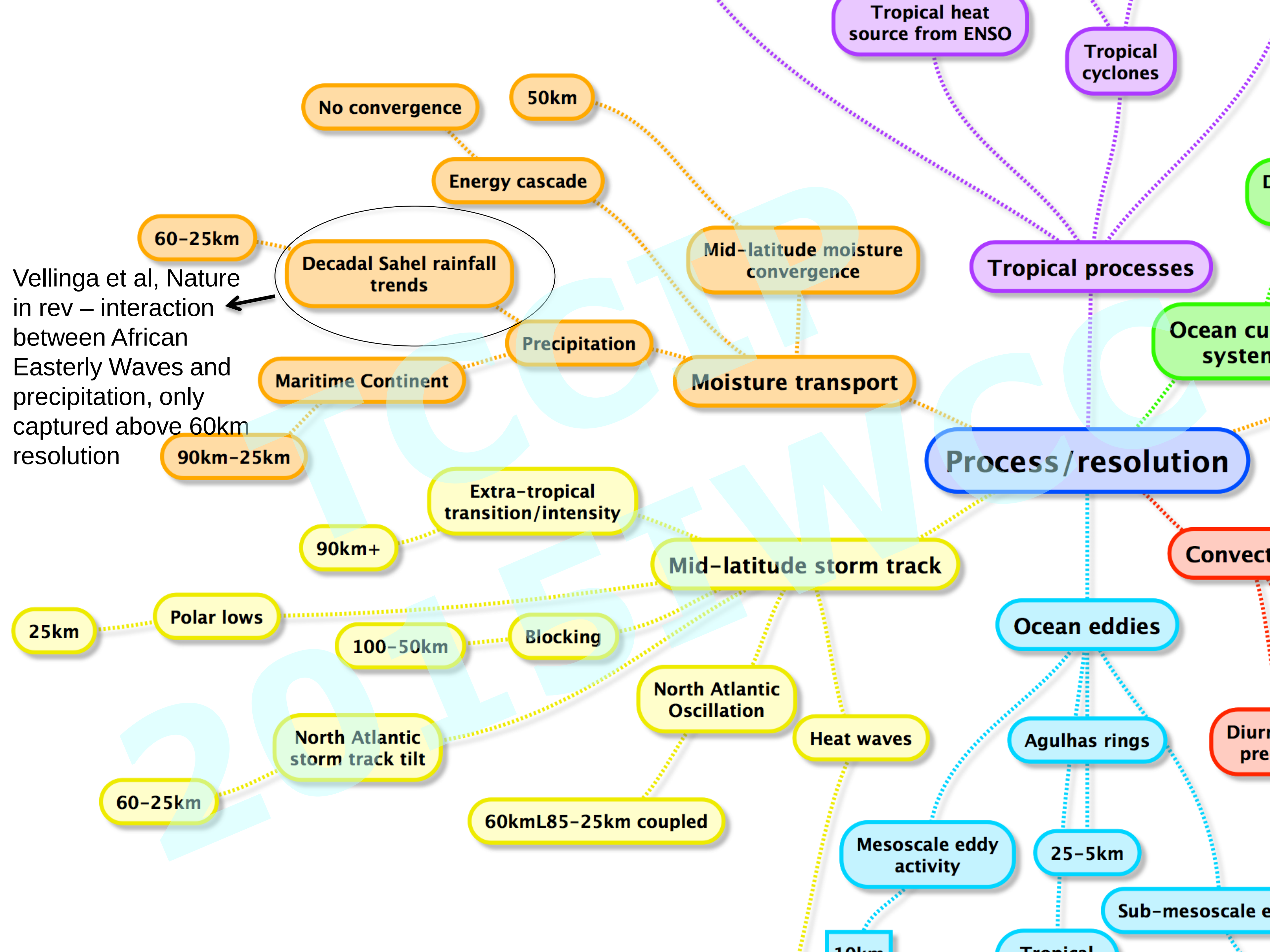
GA = Global Atmosphere

GC = Global Coupled

Processes and resolution (as studied primarily by UK groups) – would like to extend to other groups/models/processes



[1]Bell et al 2014; [2]Strachan et al 2013; [3]Roberts et al 2015; [4]Shaffrey et al 2009; [5]Roberts et al 2009; [1]Demory et al 2014; [2]Vidale et al in prep; [3]Vellinga et al Nature in rev; [4]Schiemann et al 2014; [1]Catto et al 2010; [2]Zappa et al in prep; [3]Berckmans et al 2013; [4]Jones et al 2006; [5]Scaife et al 2014; [6]Lloyd-Hughes et al 2012; [1]Frenger et al 2013; [2]Roberts et al 2009; [3]Beal et al 2011; [4]Fox-Kemper et al 2011; [1]Birch et al, submitted; [2]Yang et al 2009; [3]Pickart et al 2003; [4]Satoh et al 2012; [5]Holloway et al 2012; [1] ???; [2] ???; [1]Scaife et al 2011; [2]Beckmann and Doscher 1997

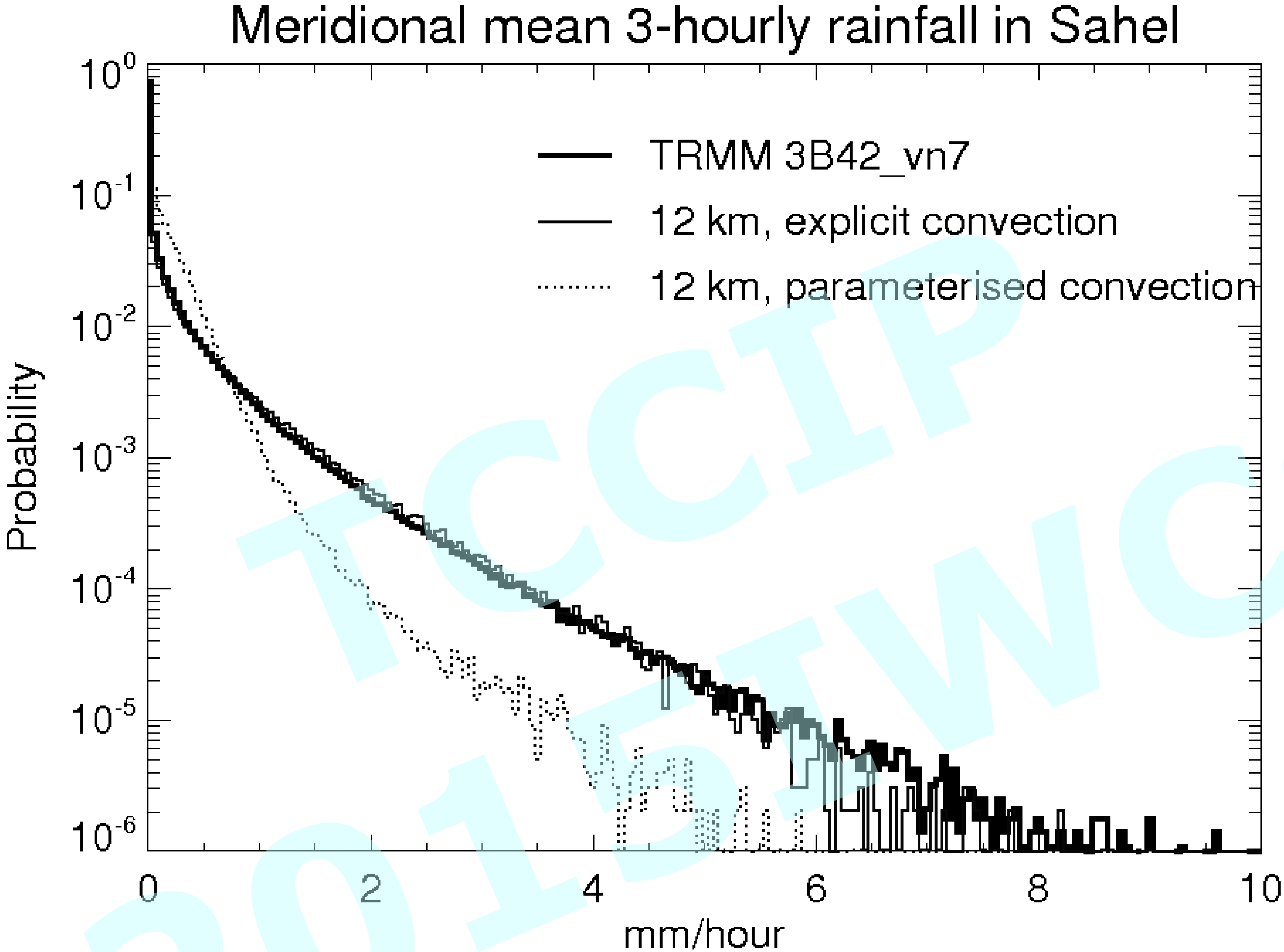


Tropical heat source from ENSO
Tropical cyclones
No convergence
50km
Energy cascade
60-25km
Decadal Sahel rainfall trends
Vellinga et al, Nature in rev – interaction between African Easterly Waves and precipitation, only captured above 60km resolution
Mid-latitude moisture convergence
Tropical processes
Precipitation
Maritime Continent
Moisture transport
90km-25km
Process/resolution
Extra-tropical transition/intensity
90km+
Mid-latitude storm track
25km
Polar lows
100-50km
Blocking
Ocean eddies
North Atlantic Oscillation
Heat waves
Agulhas rings
North Atlantic storm track tilt
60-25km
60kmL85-25km coupled
Mesoscale eddy activity
25-5km

NATURAL ENVIRONMENT RESEARCH COUNCIL

ther and Climate Programme

climate research



Parameterised model has higher probability of very light rain, while explicit model resembles the frequency of heavy rain found in TRMM

M. Vellinga et al, Nature, in rev

UPSCALE: UK on PRACE - weather resolving Simulations of Climate for globAL Environmental risk

PI: P.L. Vidale, NCAS-Climate, Reading

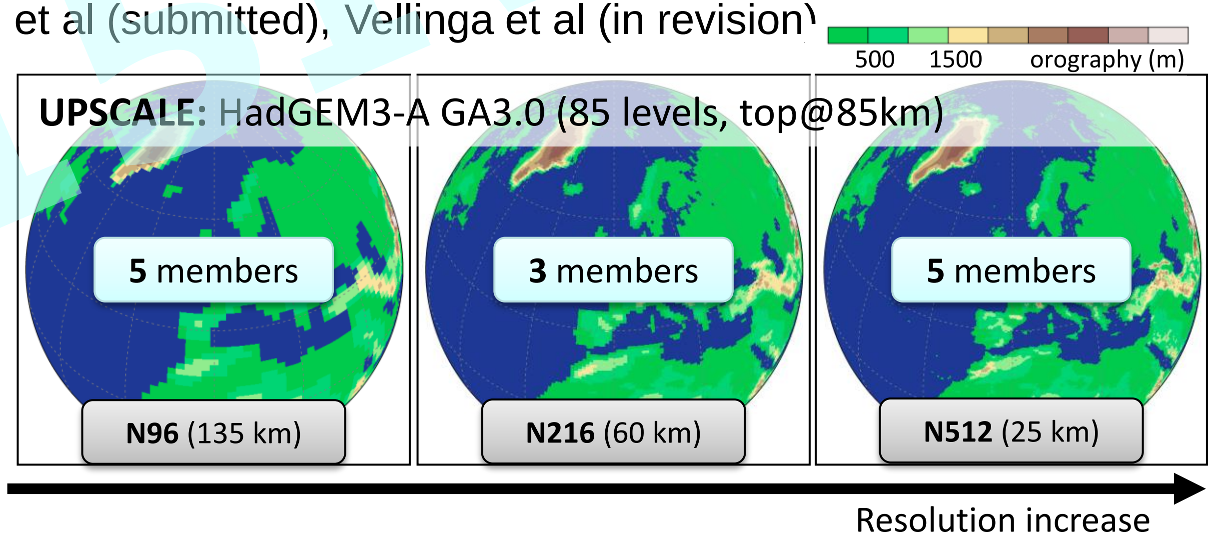
Met Office | NATURAL ENVIRONMENT RESEARCH COUNCIL

Joint Weather and Climate Research Programme

AIM: To increase understanding of climate processes and their resolution dependence

- Forced atmosphere-land integrations, 1985-2011, 3-5 ensemble members/resolution
- SST and sea-ice forcing from OSTIA 1/20° daily data
- CMIP5-defined forcings including historic aerosol emissions
- Timeslice future climate for 2100 with ΔSST from HadGEM2-ES using RCP8.5, 3 ensemble members/resolution
- Using PRACE HPC grant of 144M core hours on HLRS Stuttgart CRAY XE6
- 400TB data produced
- Demory et al (2013), Mizielinski et al (2014), Allan et al 2014 (in press), Roberts et al 2015 (in press), Vidale et al (in prep), Bush et al (submitted), Vellinga et al (in revision)

Essentially the same physics/dynamics parameters used throughout model hierarchy



PRACE-UPSCALE
Science Highlight 1

<u>Large-scale energy and moisture transports with resolution</u>:

1. Little change in energy budgets as model resolution is increased
2. Significant differences in moisture transports
   - Enhanced ocean to land moisture transport
   - Indications of convergence at resolutions finer than 60km

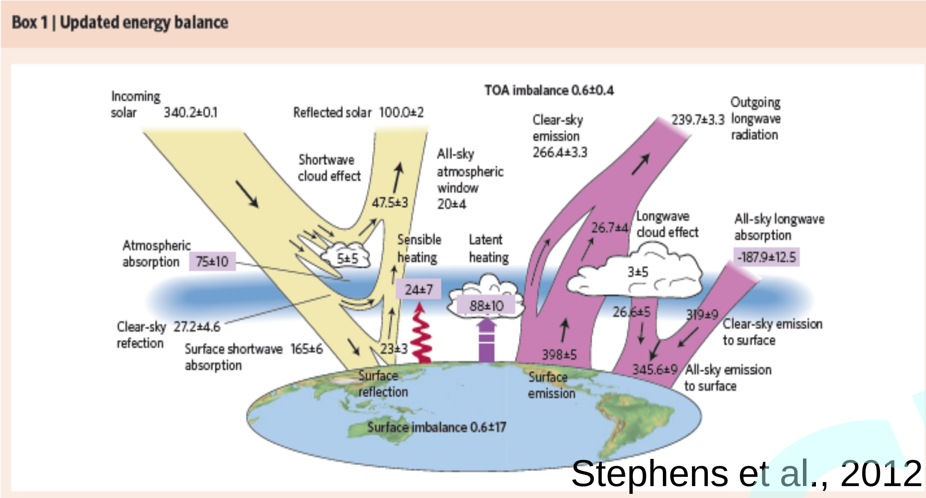
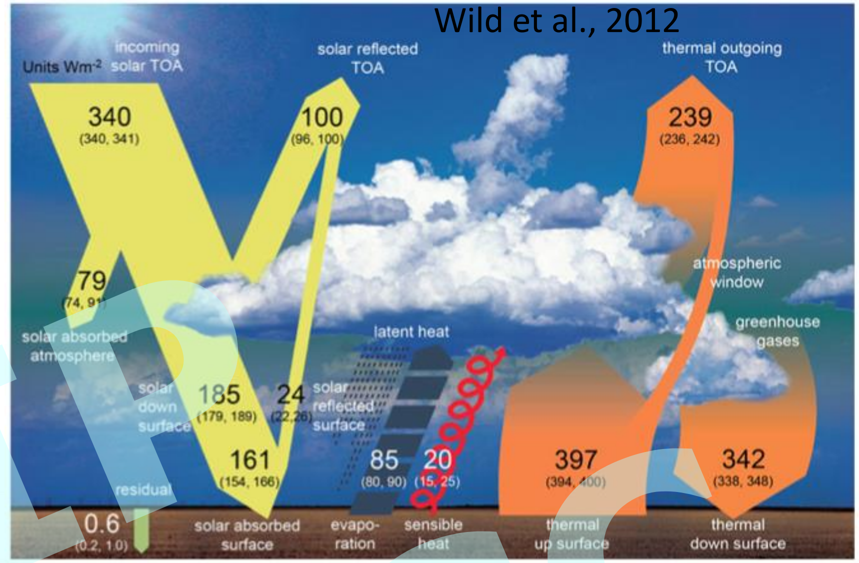
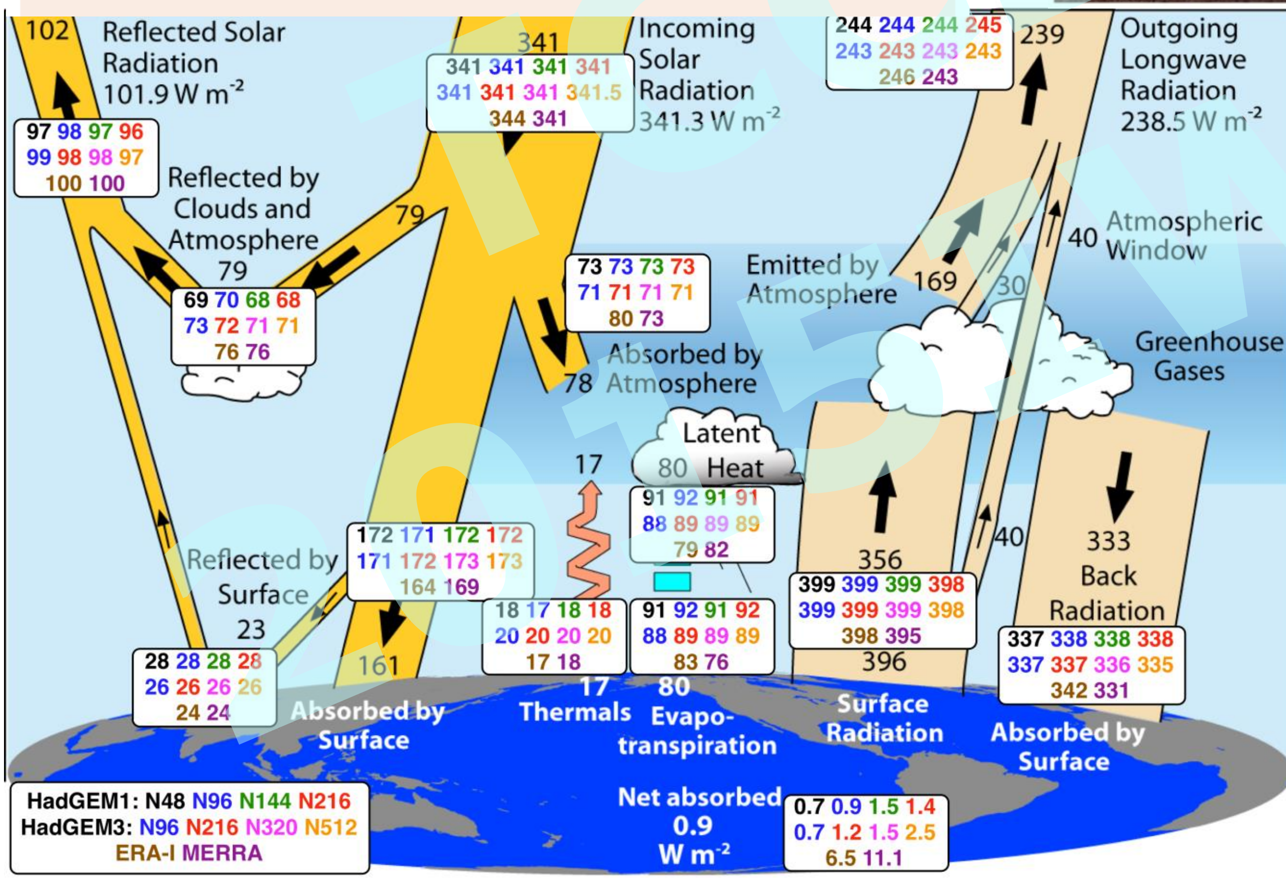


Figure B1 | The global annual mean energy budget of Earth for the approximate period 2000–2010. All fluxes are in Wm-2. Solar fluxes are in yellow and infrared fluxes in pink. The four flux quantities in purple-shaded boxes represent the principal components of the atmospheric energy balance.





Fluxes: W/m^2

Demory et al., Clim. Dyn., 2013

Figure adapted from Trenberth et al, 2009

What changes with resolution?

Expect small scale process changes with resolution, but does it affect the large-scale as well?

<u>The global hydrological cycle</u>

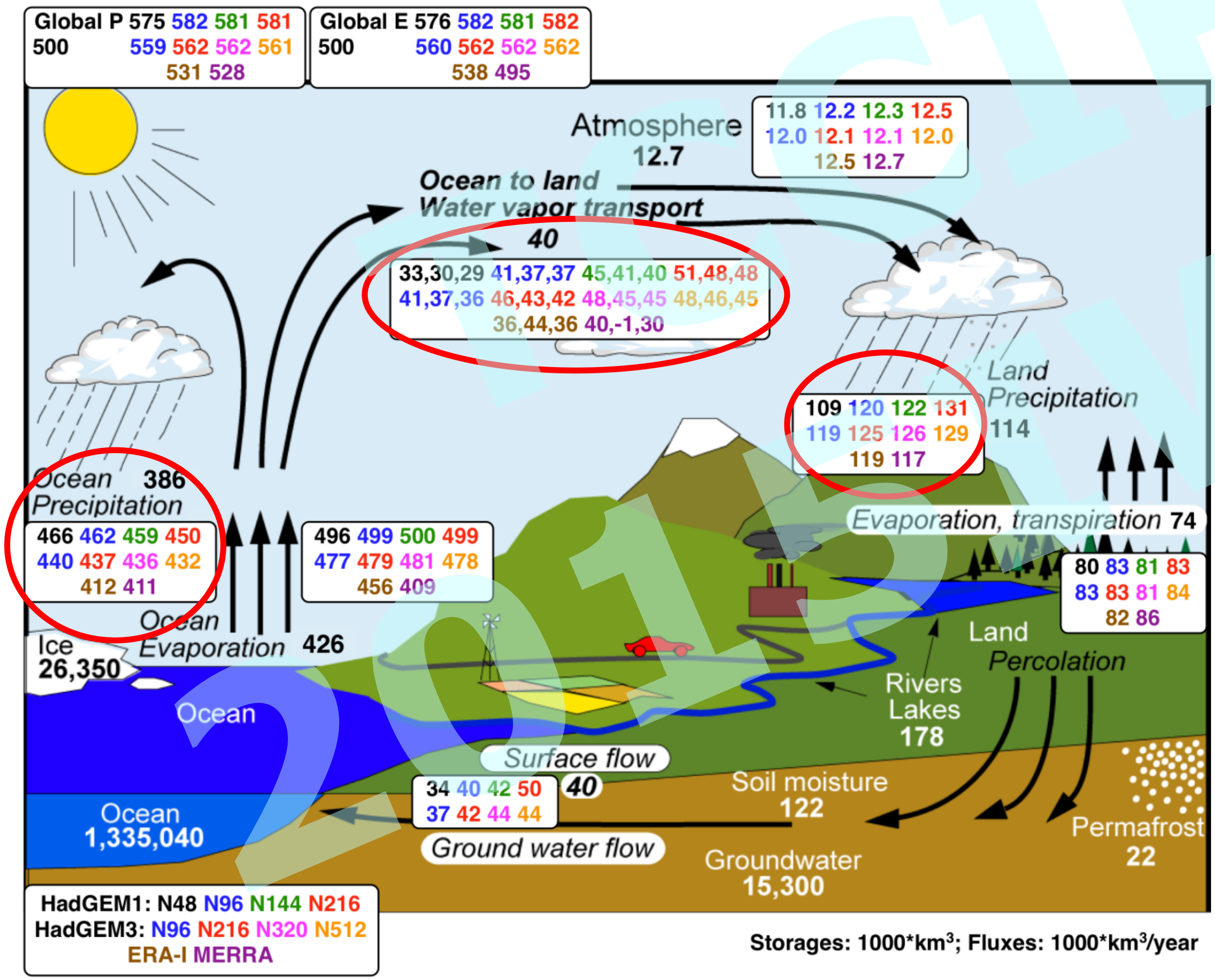


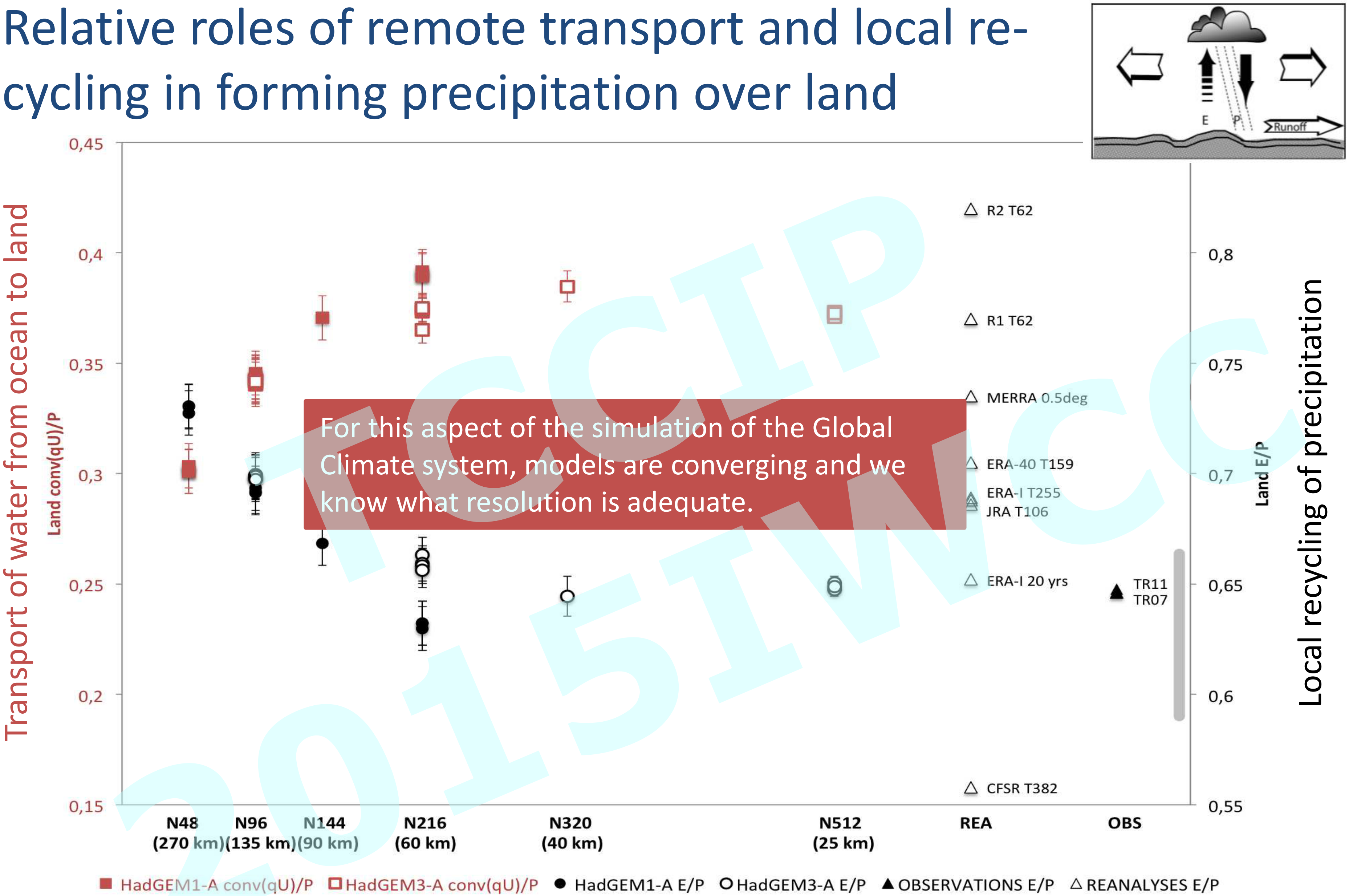
Figure adapted from Trenberth et al, 2007, 2011

- 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



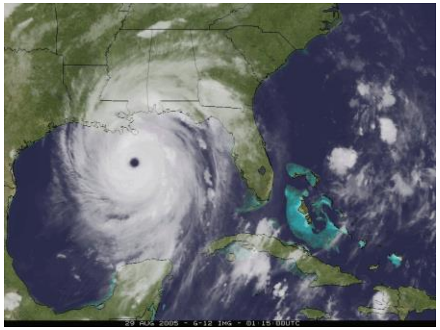
Resolution

High local recycling
Low transport

Lower local recycling
Higher transport

Demory et al, Clim. Dyn., 2013

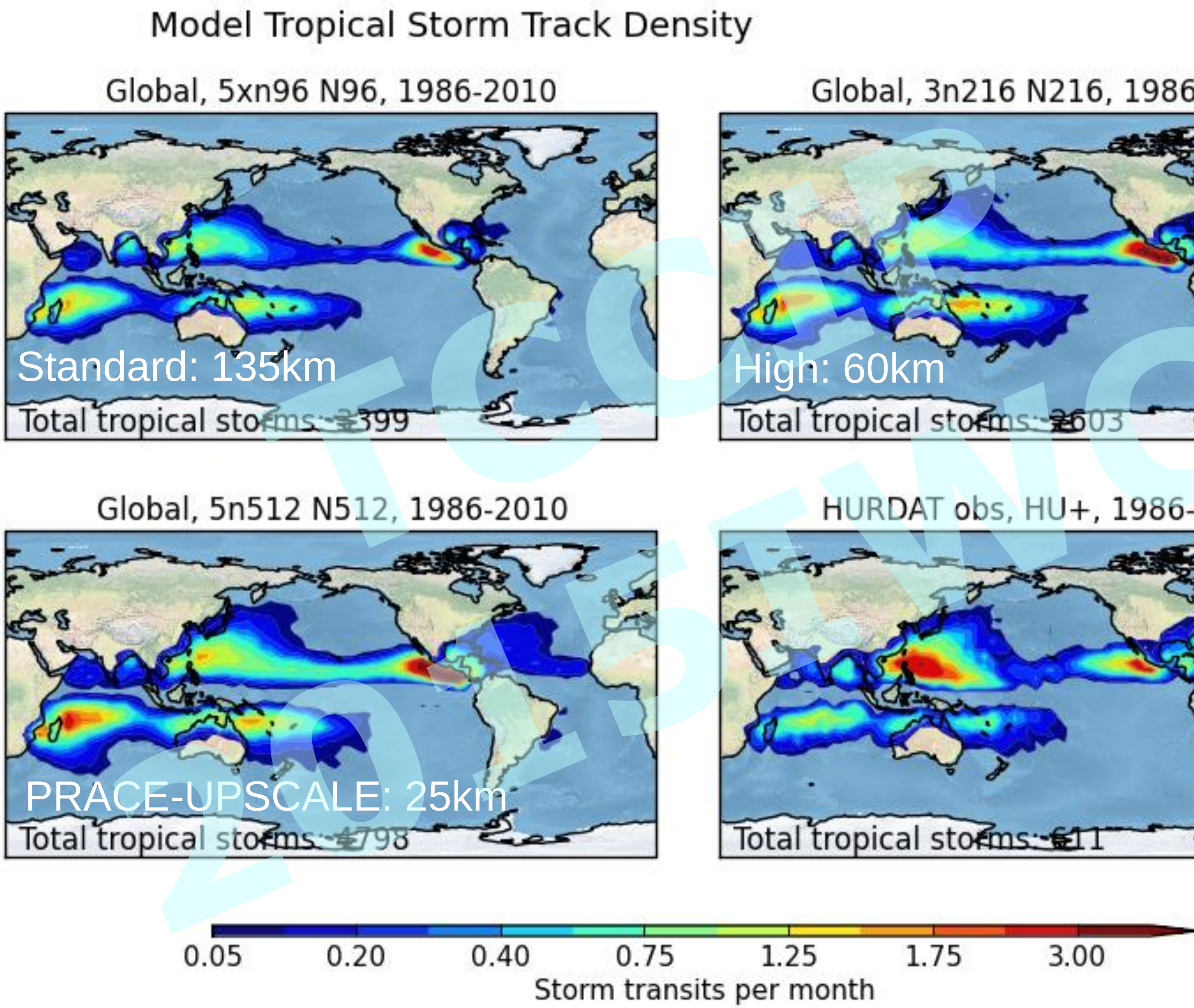
PRACE-UPSCALE
Science Highlight 2



<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?
3. how many more storms like Sandy, the storm that started in the tropics and then hit New York City in late 2012?

Storm Track density from model ensembles and observations



M. Roberts et al., MO, J. Clim, 2015

African Easterly Jet at different model resolutions

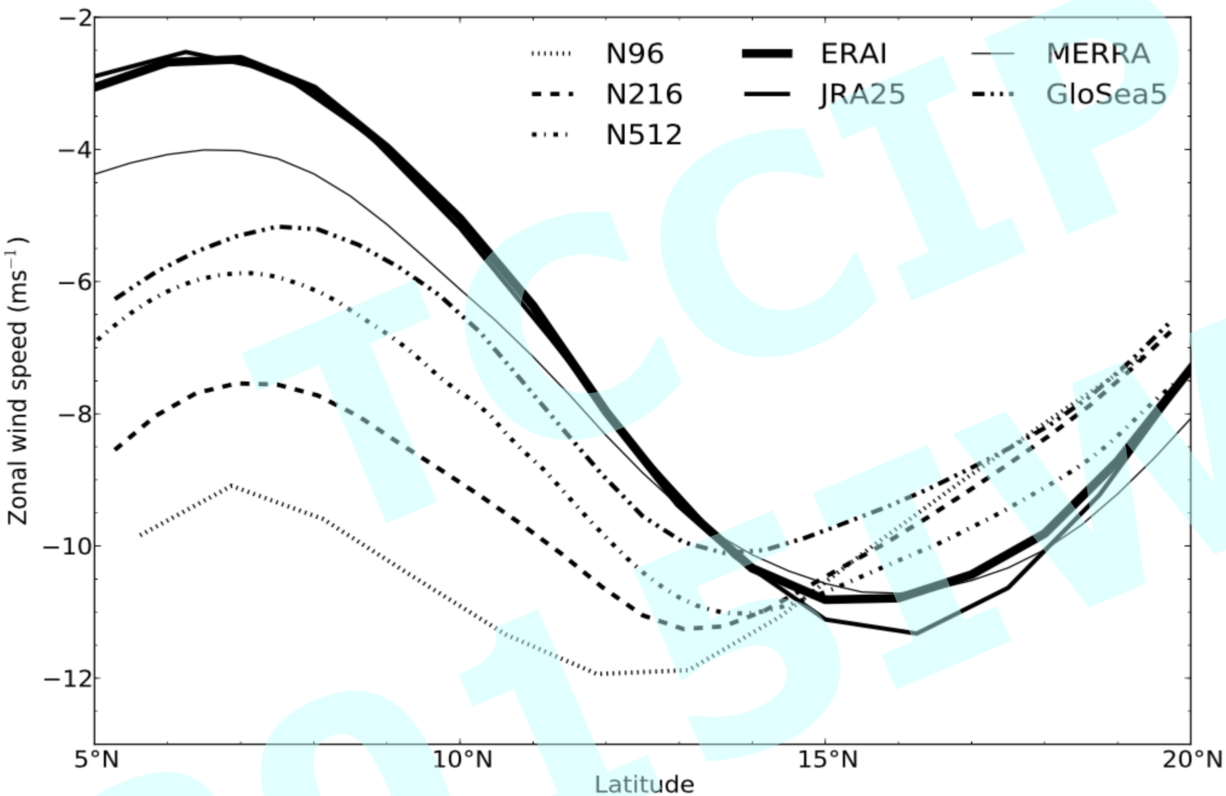
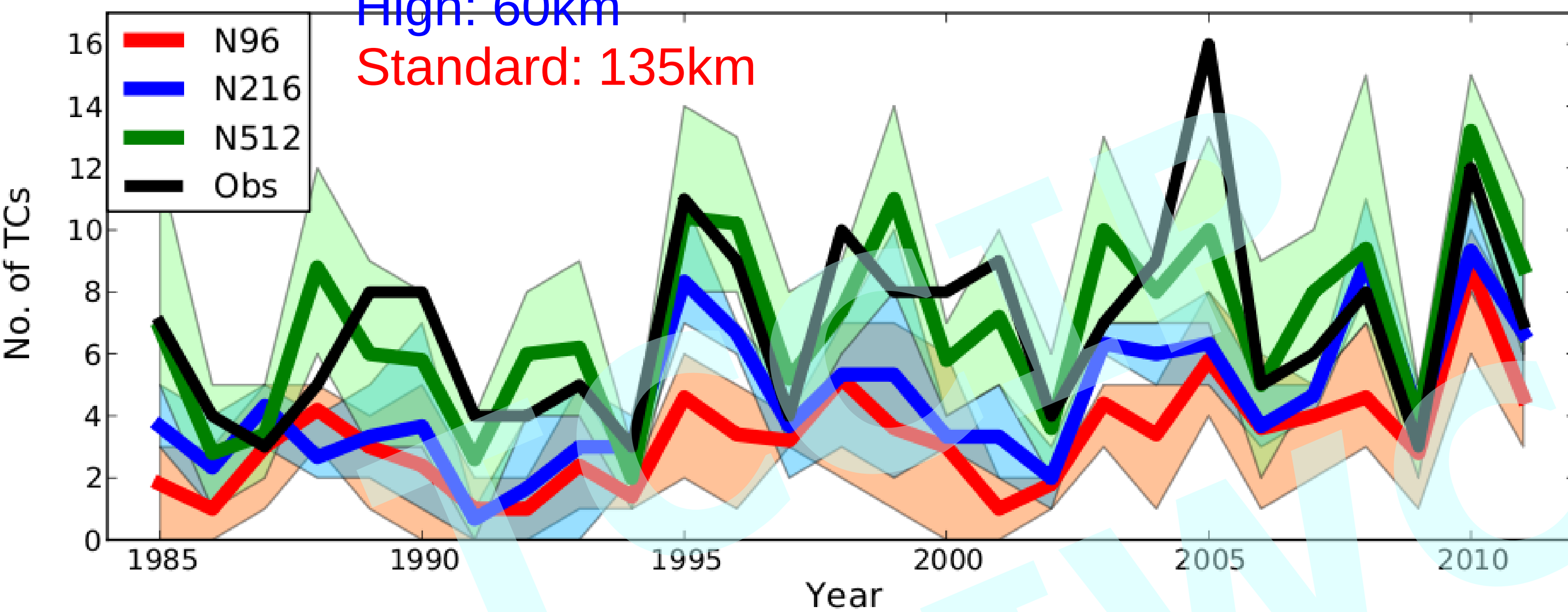
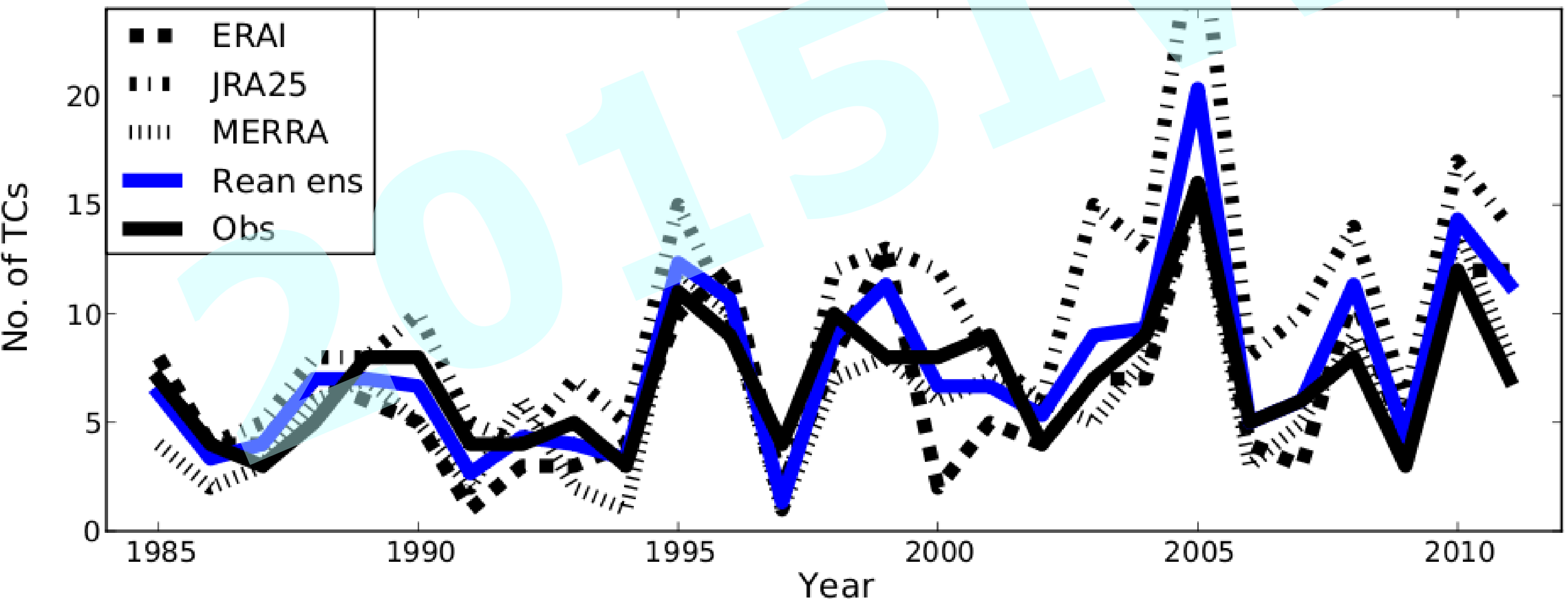


FIG. 7. Mean zonal wind at 15°W and 700hPa averaged over August-September 1986-2010 for models and reanalyses, and GloSea5 seasonal hindcast set (1996-2009). Note the latitude of the African Easterly Jet (minimum of the zonal wind) which shifts northwards with resolution.

M. Roberts et al., MO, J. Clim, 2015

Solid line = ensemble mean, shading = ensemble range





Met Office

NATURAL ENVIRONMENT RESEARCH COUNCIL

Veather and Climate
rch Programme
ship in climate research

Observed hurricanes

Correlation:

N96: 0.65

N216: 0.66

N512: 0.75

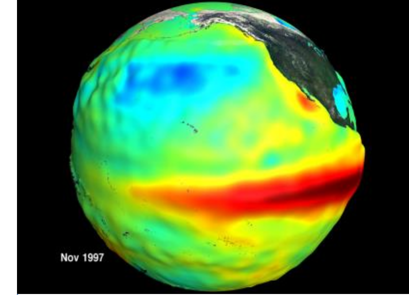
Roberts et al., J. Clim, 2015

HighResMIP

Rein Haarsma KNMI (lead)
Malcolm Roberts Met Office (co-lead)

- Important weather and climate processes emerge at sub-50km resolution
- They contribute significantly to both large-scale circulation and local impacts, hence vital for understanding and constraining regional variability
- How robust are these effects?
- Is there any convergence with resolution across models?

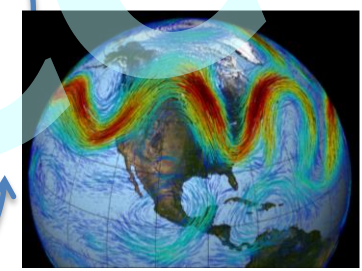
Need coordinated, simplified experimental design to find out

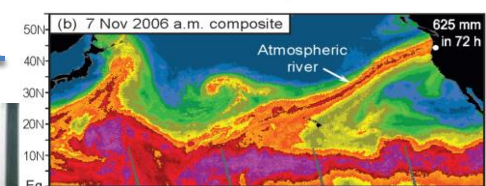


Global drivers

Regional variability

Feedbacks to large scale





Local processes

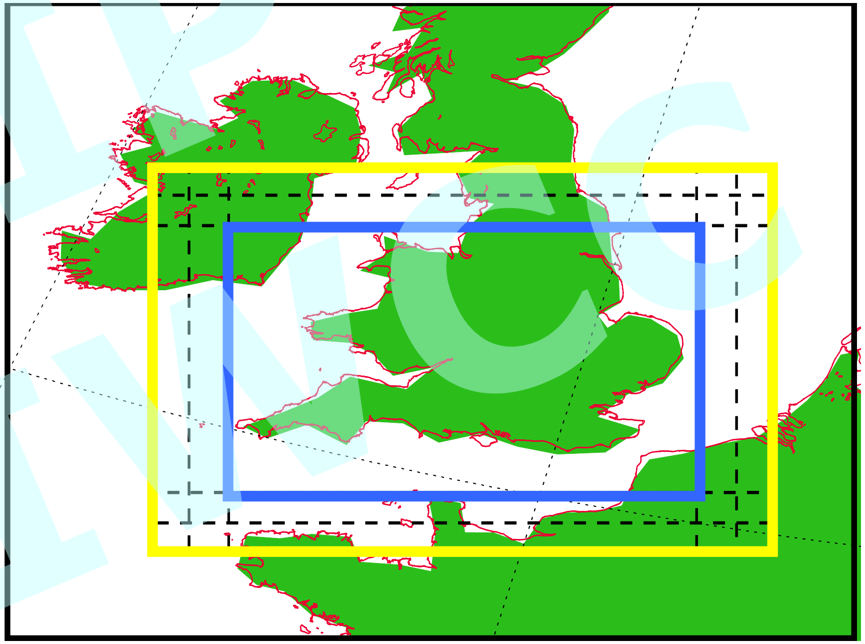
Impacts, extremes

Experimental protocol:
Global models – AMIP-style and coupled
Physical climate system only
Integrations: **1950-2050**
Ensemble size: >=1 (ideally 3)
Resolutions: **<25km HI and ~60-100km STD**
Aerosol concentrations specified

e.g. Zhao et al, 2009; Haarsma et al, 2013; Demory et al, 2013

Very high resolution climate model

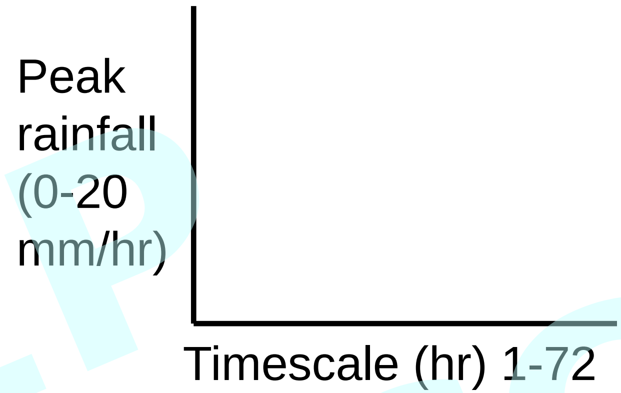
- Same formulation as UK weather forecast model
- Spans southern England and Wales at 1.5km resolution
- Driven by 12km regional climate model at boundaries
- Explicitly represents convection without need for parameterisation scheme
- Experiments now completed:

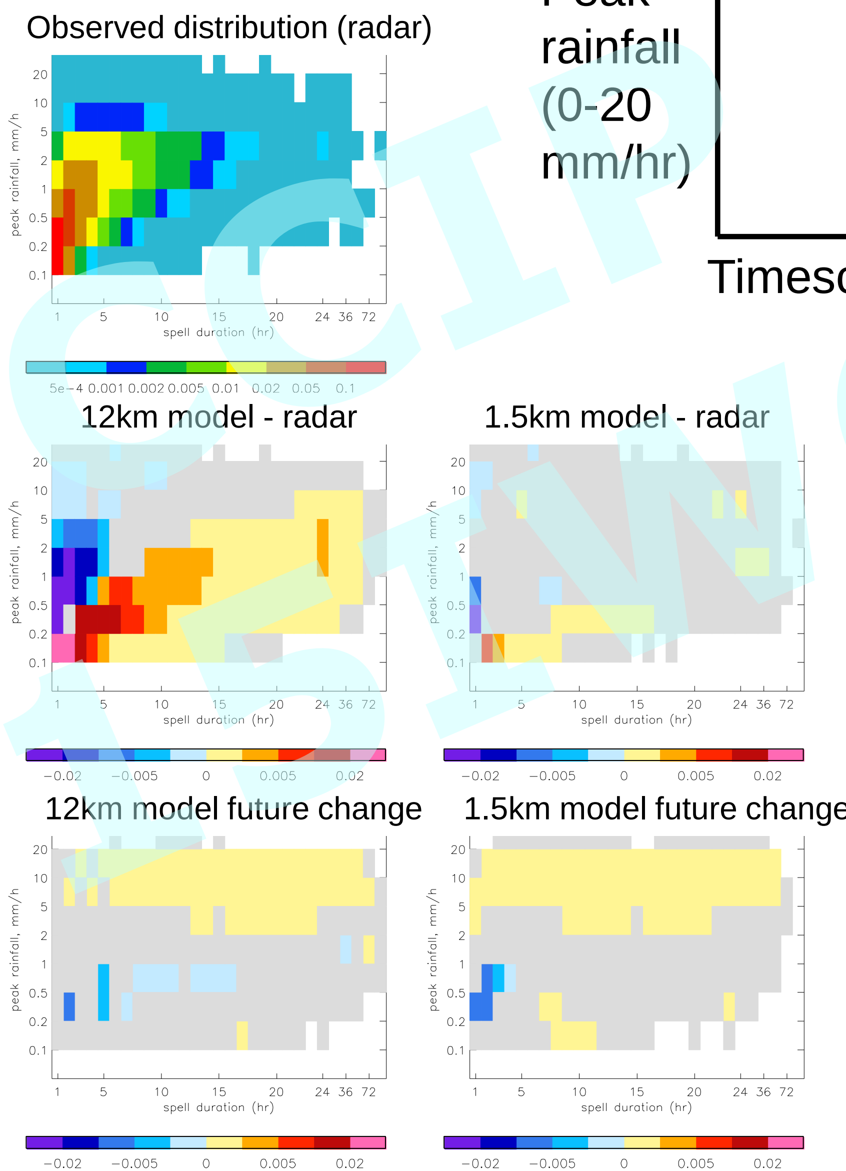


Expt	RCM boundary forcing	Years
Historic	ERA-interim	1989-2008
Control	60km GCM	1997-2009
Future	60km GCM	13y period ~2100 under RCP8.5

Kendon et al, 2012, 2014

Duration-intensity characteristics of rainfall for winter





In winter both models show increase in long-lived intense rainfall

Joint probability distribution of rain spell duration versus peak amount. [Rain > 0.1mm/h]

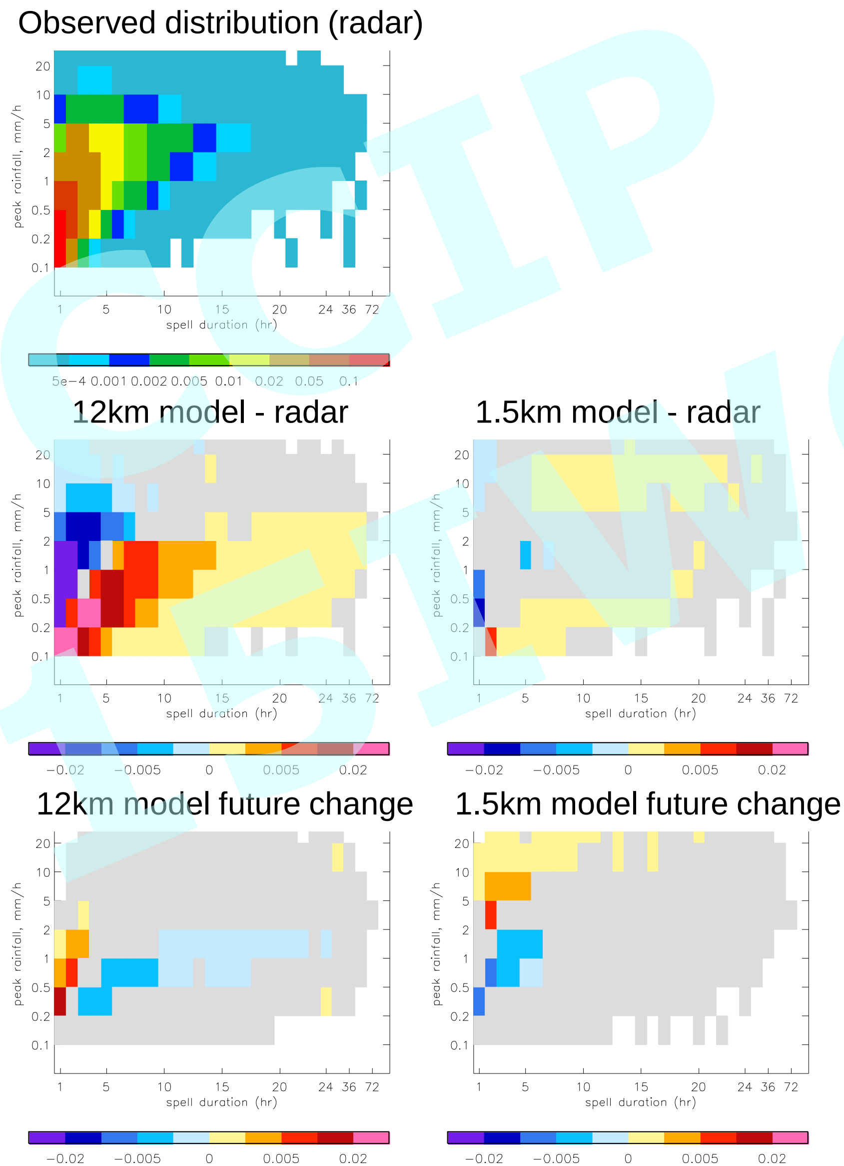
Grey = model biases and future changes not significant at the 1% level

Kendon et al, 2014, Nature Clim. Change

Duration-intensity characteristics of rainfall for summer

Met Office
Hadley Centre

In summer only high resolution (convection permitting) model shows increased rainfall intensity



Grey = model biases and future changes not significant at the 1% level

Kendon et al, 2014, Nature Clim. Change

Summary

Joint Weather and Climate Research Programme

A partnership in climate research

- PRACE-UPSCALE exploits national capability that we had been jointly developing since 2004.
  - 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 2006-2009 for climate research, is now the standard configuration of the GloSea5 seasonal prediction system
  - PRACE-UPSCALE@HERMIT: three peer-reviewed papers published so far, four are under review, dozens more in preparation
- 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
- Simulation of short duration rainfall extremes needs convection-permitting models
  - Even 1.5km resolution missed processes and has considerable biases
- Need both HPC and a well balanced <u>scientific and technical task force</u> in order to extract knowledge from our results and this requires **data+analysis services** of comparable power.

Future plans

- Analysis and understanding
  - Understanding where models converge, e.g. based on emerging processes
  - Scale interactions:
    - Clouds and climate – Grand Challenges
    - TCs and their contributions to global energy+water cycles
    - Planetary waves, blocking, feedbacks with land surface anomalies (heatwaves, droughts)
- Applications to study of climate change
  - Analysis of timeslice runs
  - Atmospheric rivers and precipitation extremes
- Future projects
  - Proposed EU Horizon 2020 project
    - Coupled, 2050 timescale, examine uncertainties due to resolution, aerosols, microphysics for regional climate projections
    - **Proposed HighResMIP submission for CMIP6 within (but not dependent on) this project**
  - Coupling the ORCA 1/12° ocean to N768 (17km) atmosphere
    - Eddy-resolving ocean, impact on coupling strength and modes of variability

PRIMAVERA

Met Office | NATURAL ENVIRONMENT RESEARCH COUNCIL

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
- Proposal for Horizon 2020 EU funding
- Develop a new generation of well-evaluated high-resolution global climate models, capable of simulating and predicting regional climate with unprecedented fidelity
  - More consistent, controlled comparison of different models configured in similar ways at different resolutions
- Provide flagship simulations for CMIP6
- Basis for HighResMIP as part of CMIP6 with other global groups
- European centres involved:
  - Met Office, Univ. of Reading, EC-Earth (KNMI, SMHI, IC3), MPI, CMCC (Italy), AWI (Germany), Univ. of Oxford, ECMWF, UCL (Belgium), Stockholm Univ., NOC-Southampton, ISAC-CNR (Italy)
- If funded, start ~mid-2015 for 4 years

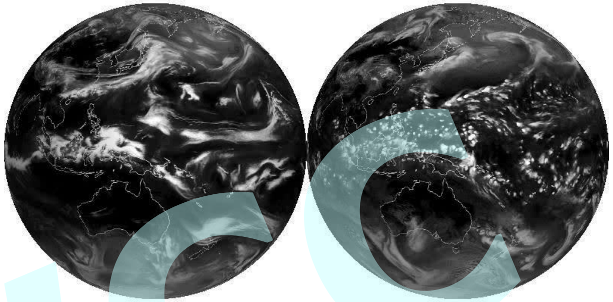
PRIMAVERA core integrations

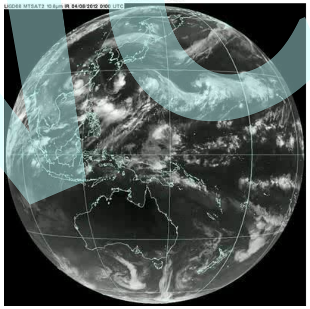
- AMIP-style
  - 1950-2050 (SSTs e.g. Mizuta et al, specified aerosol)
  - Low and high resolutions, ~N216 (60km) and ~N512 (25km)
  - Ensembles ~3
- Coupled AOIL (atmos-ocean-sea-ice-land)
  - 1950-2050
  - N216-ORCA025 and N512-ORCA025 (though couple of groups may use ORCA1 as well)
  - Fixed 1950's forcing vs all forcings (RCP4.5)
  - Ensembles ~3
- Intend to use aerosol concentrations (rather than emissions) to reduce spread between models and better understand processes
- Frontier integrations
  - Coupled model with 1/10° – 1/12° ocean, 100 years, 3-4 groups
  - Stochastic physics at low and high resolution
  - Unstructured mesh FESOM ocean/sea-ice coupled to ECHAM6
  - Horizontal resolution → allowing explicit convection ~6km → link to aerosol-cloud-microphysics-rainfall being developed in regional sub-km domains

Questions

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

- Some phenomena strongly tied to convection converge – at "high" resolution – to wrong solution
- We developed both a **standard HadGEM3-A version**, with parameterised convection and an **experimental version with explicit convection.**
- 12km is a minimal resolution to consider such a step
- Interested in both the local impact of a different representation of convection, and particularly whether it affects the large-scale





(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

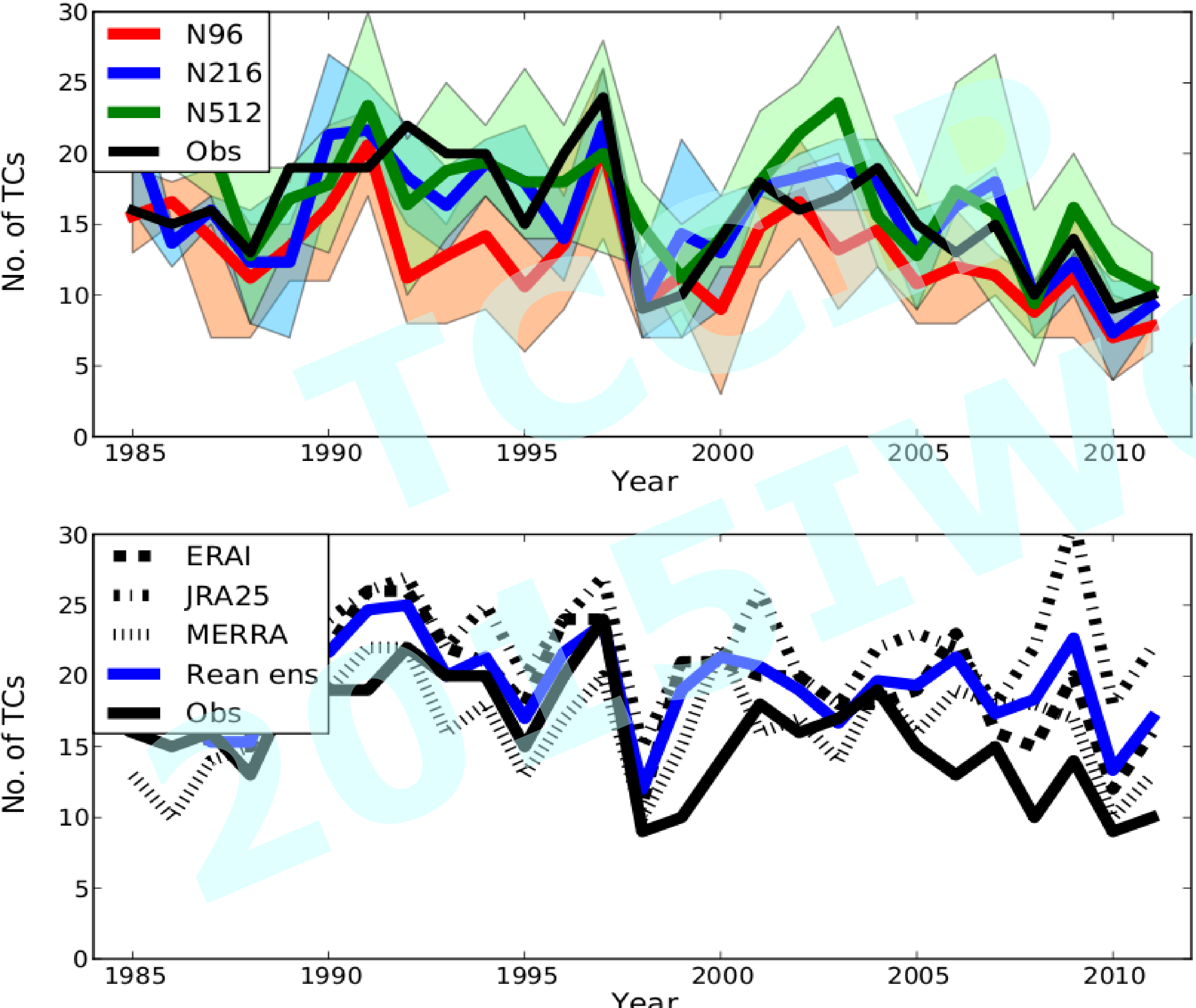
Met Office

NATURAL ENVIRONMENT RESEARCH COUNCIL

Joint Weather and Climate Research Programme

A partnership in climate research

W N Pacific



Correlation:

N96: 0.71

N216: 0.74

N512: 0.60

Roberts et al., MO