UPSCALE

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

Porting and optimisation of the Met Office Unified Model on Petascale architectures

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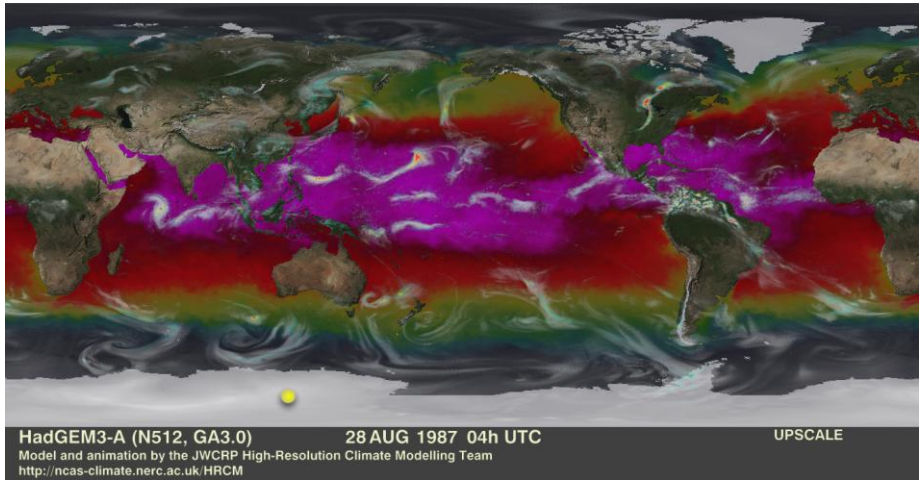
CRAY Inc



With many thanks to: P. Selwood, M. Carter, T. Davies, A. Lock, S. Webster, K. Williams, D. Walters, Met Office

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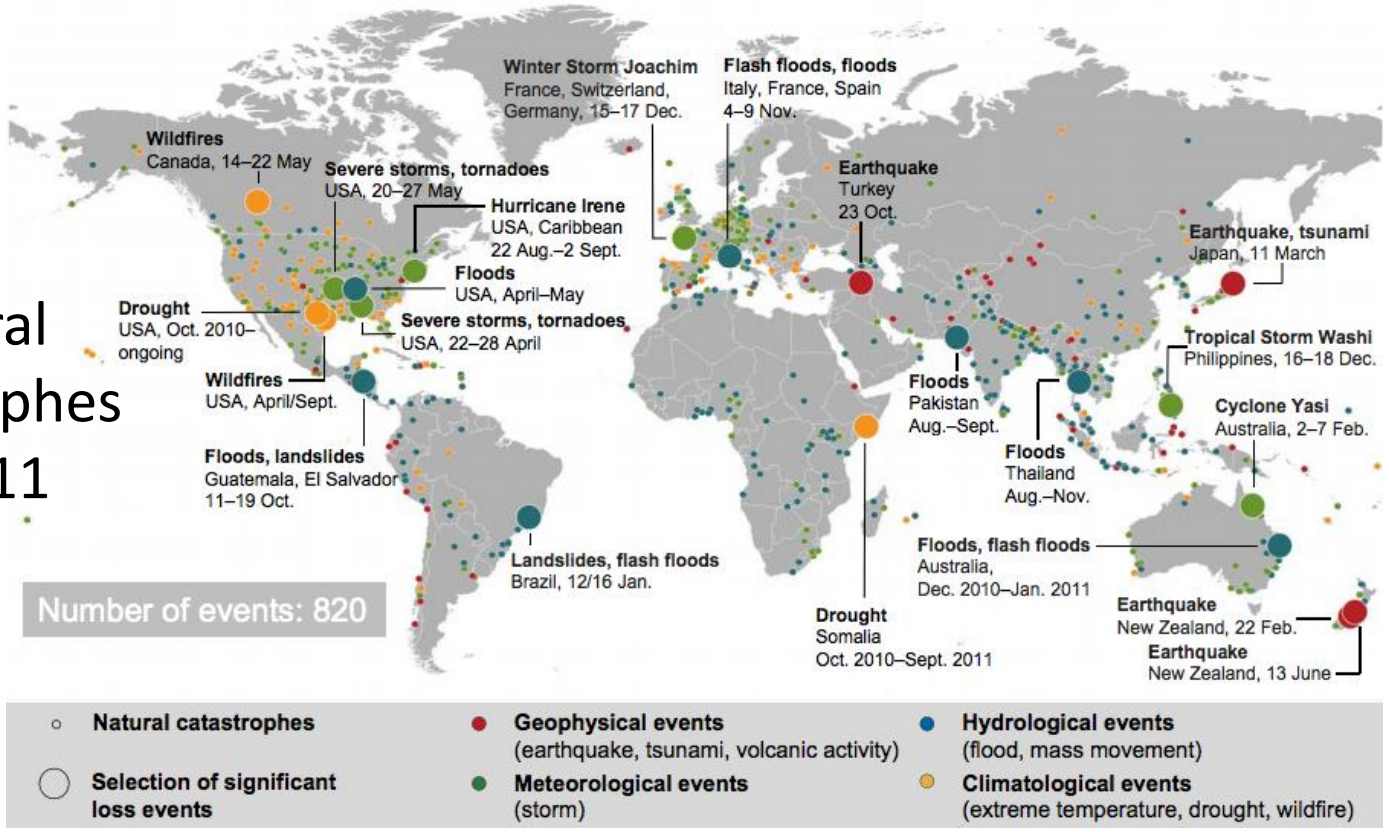
Joint Weather and Climate Research Programme

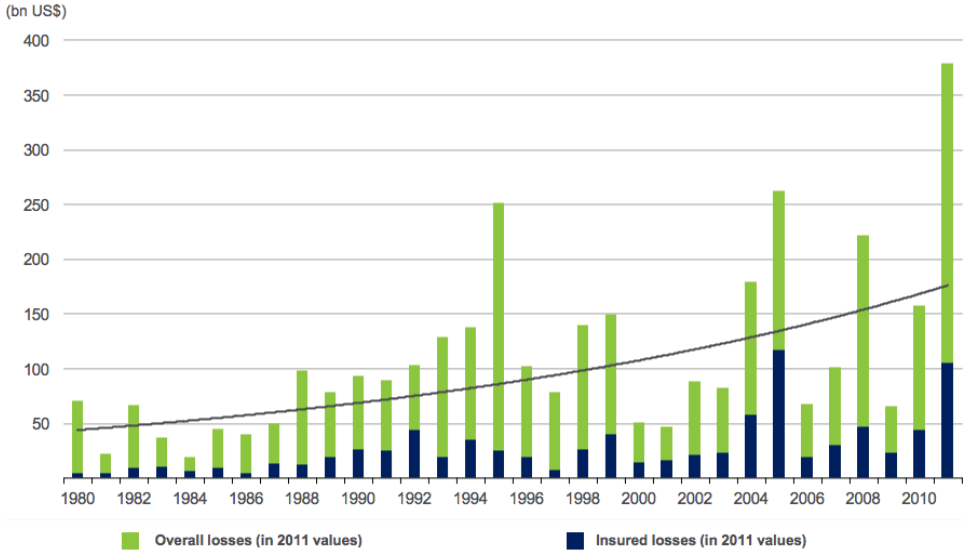
Knowledge Transfer Partnerships | Willis Research Network

* Willis Chair of Climate System Science and Climate Hazards

Natural Catastrophes of 2011



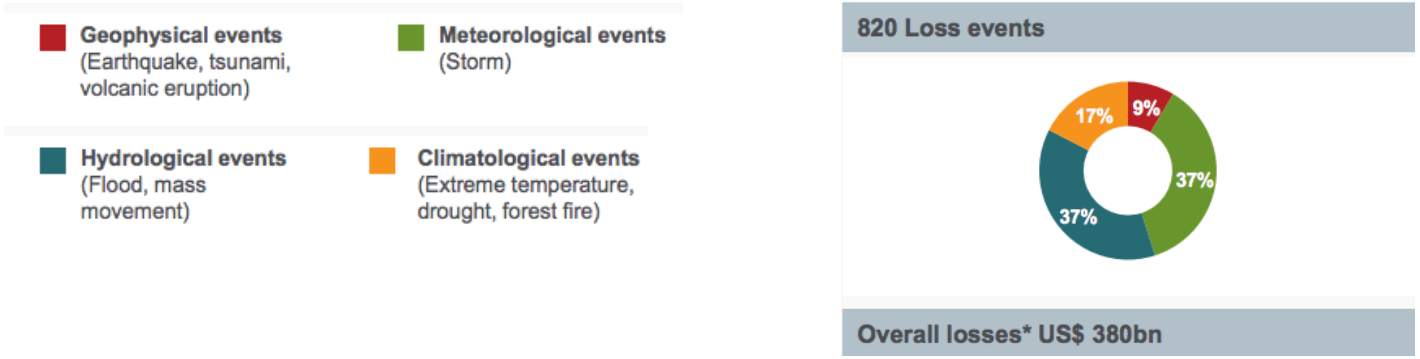
Comparing 2011 with previous years



Munich Re 2012

Motivations for a **Weather and Climate Hazards Laboratory**: Economic Impact of Weather-related Natural Catastrophes of 2011

- 2011= costliest year ever in terms of natural catastrophe
- **US$380bn** global economic losses / US$105bn insured losses (Munich Re)
- Although earthquake dominated loss in 2011 (Japan Tsunami prominent), still **90% of the number of natural catastrophes were weather-related**



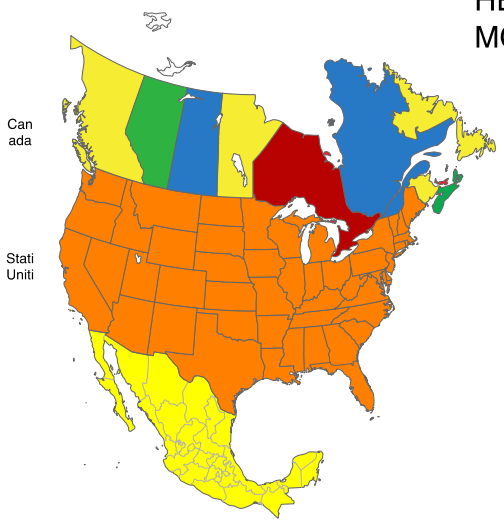
Munich Re 2012

- UK insurance and UK science share a need to understand the world around us and to understand how it is changing.
- Need for continuous engagement between the insurance industry and the scientific community to ensure industry has the best possible information to increase its market resilience to W&C risk

Knowledge Transfer Partnerships

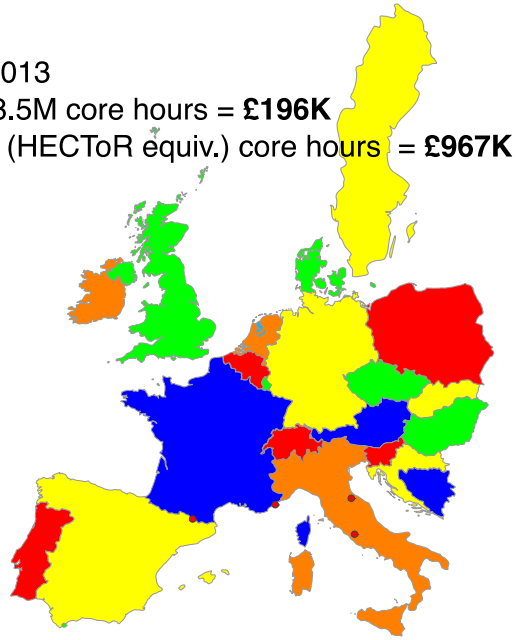
Willis Research Network

UK climate science winning High-Performance Computing resources around the world



USA, 2012-:
U. TEXAS: 100M core hours = **£2.4 million**
DOE: INCITE programme: TBA

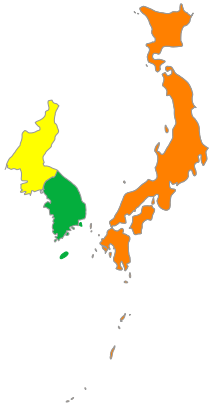
UK 2012-2013
HECToR: 8.5M core hours = **£196K**
MO: ~42M (HECToR equiv.) core hours = **£967K**



Europe (PRACE), 2011-2012
144M core hours = **£3.4 million**

Japan (Earth Simulator), 2006-2008
1.1 million core hours = **£957K**

Japan (K-machine), 2011
offer turned down for lack of personnel



Importance of UK High Performance Computing (HPC), from Beddington review

"if HMG is to fully benefit from the UK's world-leading expertise, the UK climate science community will need a **stable, dedicated high performance computing service that is developed with climate research needs in mind**, requiring effective collaboration between the Met Office and UK academic institutions."

Met Office

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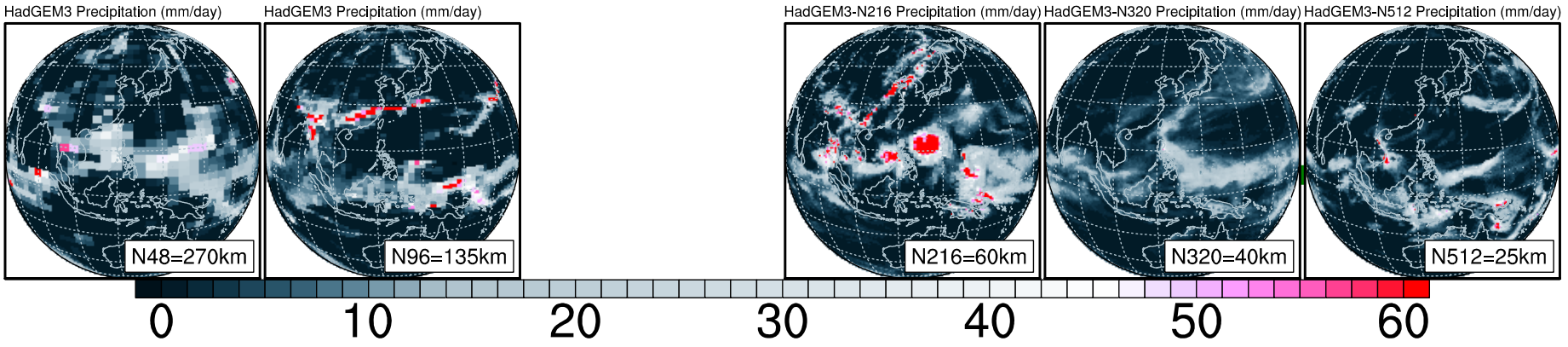
A partnership in climate research

From UJCC and HiGEM to the Met Office – NERC: Joint Weather and Climate Research Programme (JWCRP) in: **High-Resolution Climate Modelling**

M. Roberts, M Mizielinski (MO)
P.L. Vidale, R. Schiemann (NERC)

HadGEM3



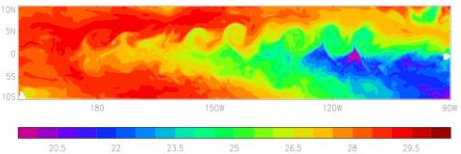
1.88^ox1.25^o, Δx_{50N} = 135 km

0.83^ox0.56^o, Δx_{50N} = 60 km

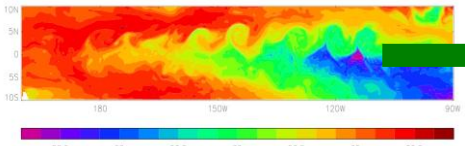
Double vertical resolution,
Model top at 85km

0.35^ox0.23^o, Δx_{50N} = 25km

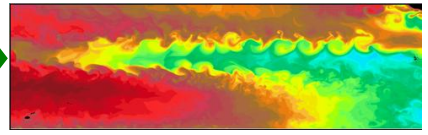
Current developments
N768=17km
N1024=12km



1^o NEMO ocean model, 75 layers



$¼^o$ NEMO ocean model, 75 layers



1/12° ocean model ?

Setup and "best practice" core counts on different architectures

Resolution		Number of cores				Notes
		NEC SX6	IBM P6	IBM P7	CRAY XE6	
N96 = 135km HG1-L38 HG3-L85		1*8 1*8	96	128		For HadGEM1: ES processors about 4x more powerful than P7
	Turnaround	1 sypd 10smo/day	3 sypd	3.5 sypd (EndGame)		
N216 = 60km HG1-L38 HG3-L85		11*8	192	3*32	1024	For HadGEM1: ES processors about 4x more powerful than P7
	Turnaround	1 sypd	8 smo/day	5 smo/day	13smo/day	
N512= 25km				64*32 40*32 (EG) 200*32 (L70 EG)	9408	
	Turnaround			7 smo/day 5.7 smo/day 2 sypd	6 smo/day	Ensemble of 5 runs, concurrent, up to 47K cores
N1024 = 12km				74*32		
	Turnaround			1.2 smo/day		

Changes in approach to parallelism between HadGEM1 and HadGEM3

- HadGEM1 (N216) could only scale on up to 11 Earth Simulator nodes (88 cores) ;
- efficient scaling over 3000 cores is the minimum requirement on PRACE TIER-0 machines.
- What has changed?
  - Various code optimisations
  - Hybrid parallelism: OpenMP (SM) on node; MPI across nodes; multithreading and its tuning
  - **IO server**
  - Model top at 85km: more expensive physics, need for shorter time step
- What has not changed?
  - Polar filtering and its global communications overhead. This will change with EndGame, which in fact already shows significantly better scalability.
  - Coupler and coupling strategy
  - NEMO ocean model has its own (incompatible!) IO server technology …

The PRACE UPSCALE grant

- UK on PRACE: weather-resolving Simulations of Climate for globAL Environmental risk (UPSCALE, PI: P.L. Vidale):
  - 144 Million core-hours (CRAY XE6), worth £3.4-8.1 million (big uncertainty in the actual cost estimates!)
  - 1 Jan 2012 → 1 Jan 2013
  - number 1 science project on TIER-0 supercomputing in Europe in 2011 (Paris PRACE planning meeting reported largest HPC grant ever globally?).
- Investigate:
  - weather in the climate system
  - extremes (hurricanes, typhoons, heat waves) and
    - the resolution dependence in their representation
    - how they are globally interconnected
    - how they are expected to change with climate change
  - how emerging processes affect the large scale
  - Can we use the output for ingestion in decision-making tools, e.g. “cat models” used in industry?

HLRS TIER-0 HERMIT and our climate production

- HLRS CRAY XE6 “HERMIT”:

Technical description (installation step 1)

Peak performance	1.045 PFlops
Cabinets	38 with 96 nodes each
Number of compute nodes	3552
Number of compute cores	per node 2 sockets with 16 cores each: 113 664
Number of service nodes	96
Processor compute nodes	Dual Socket AMD Interlagos @ 2.3GHz 16 cores each
Memory/node	32 GB and 64 GB
Disk capacity	2.7 PB
Node-node interconnect	CRAY Gemini
Special nodes	External Access Nodes, Pre- & Postprocessing Nodes, Remote Visualization Nodes
Power consumption	2 MW maximal

- We have been running:
  - two 26-year ensembles (5x) of HadGEM3-N512 (25km), nearly all completed:
    - First ensemble in current climate
    - Second ensemble for an RCP8.5 scenario.
  - Alternative formulation experiments: 5x N512
  - HadGEM3-N1024 (12km) developments: target of 3x10yrs… turned out to be impossible in 1yr!
- Our typical day:
  - 5xN512 hadGEM3 models in the queue: 23’520-47’040 cores concurrently busy (on average, 14’112 cores are always busy with our jobs)
  - 1TB flow back to the UK: stored and available 24/7 for community analysis on JASMIN service

Testing by Tom Edwards @ Cray

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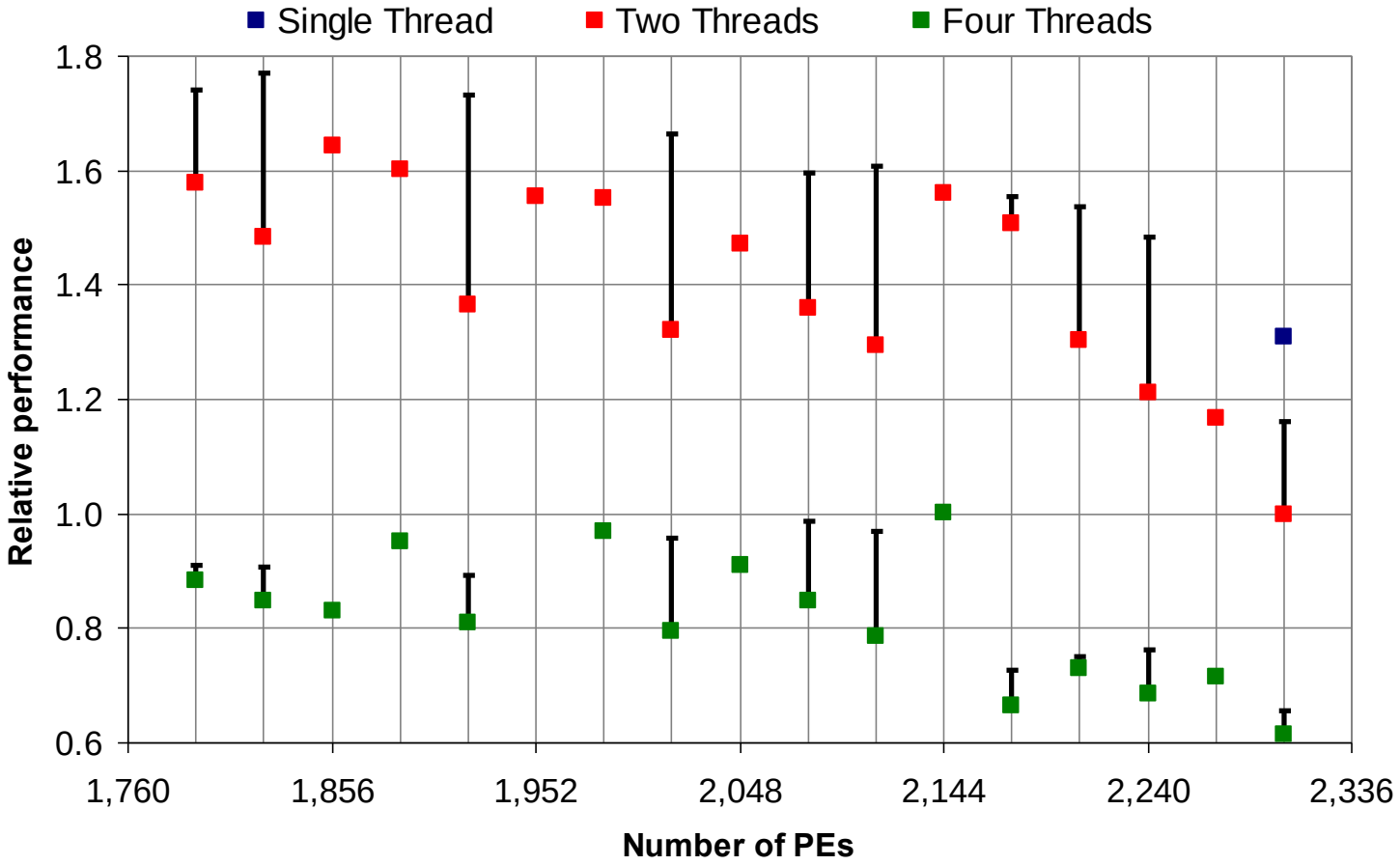
- Working array sizes (segment sizes) for radiation and diffusion routines
- Compiler optimisation levels on dynamics routines
- Processor & thread configuration (~100 tested)
- Lustre file system settings
- I/O server separation from computation

Threading



Relative performance of different processor configurations (the lower the number the faster the configuration) normalised to the 32x72x2 result. The number of PEs is number of MPI processes used (multiply this by the number of threads to get the total number of cores required. The black bars denote the range of observed performance for different decompositions with the same number of MPI tasks. The coloured points are the best performance for a given process count. Data provided by Tom Edwards.

Testing by TE: Segment sizes

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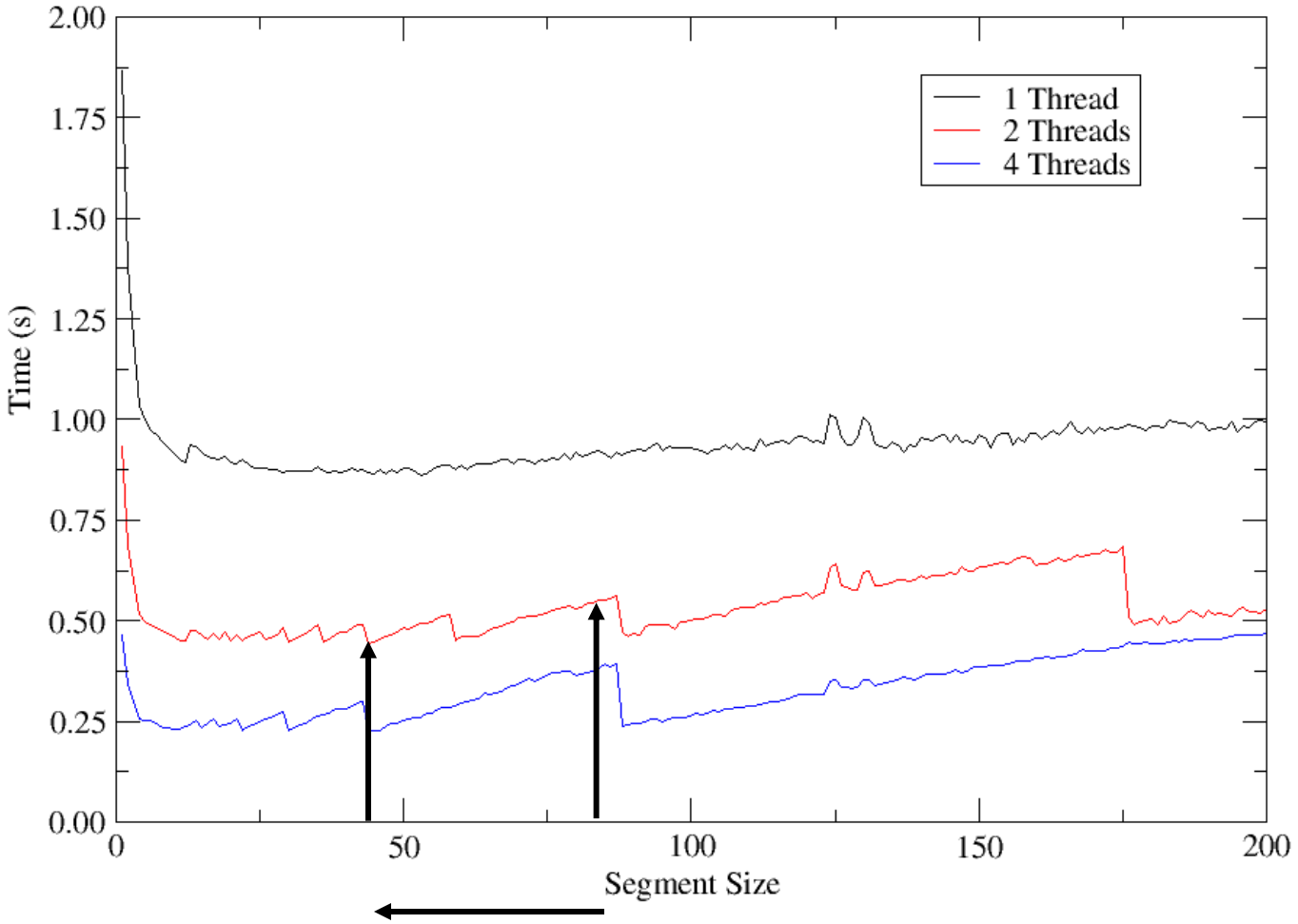
Long-wave segment size impact



25% improvement in radiation code cost (70% for 4 threads)

Testing by TE: IO server approach

12 IO servers working on our output

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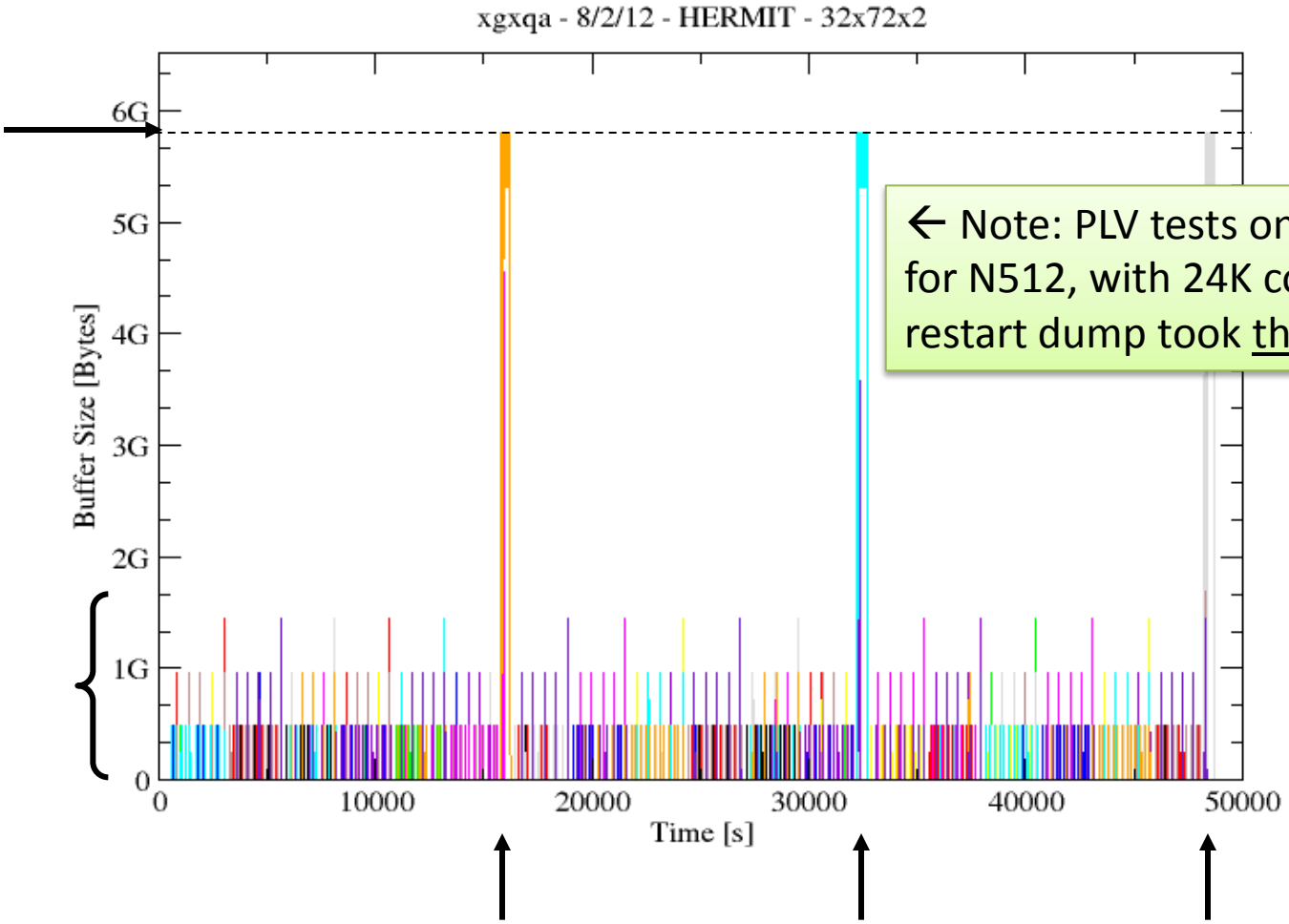
I/O server buffer size



← Note: PLV tests on HECToR: for N512, with 24K cores, a restart dump took three hours.

Frequent, low level I/O; 3 hourly and daily data

Output of end of month data (~30GB) and 58GB restart dump

Scaling: Hector phase 2b
(Cray XE6, Magny-Cours)

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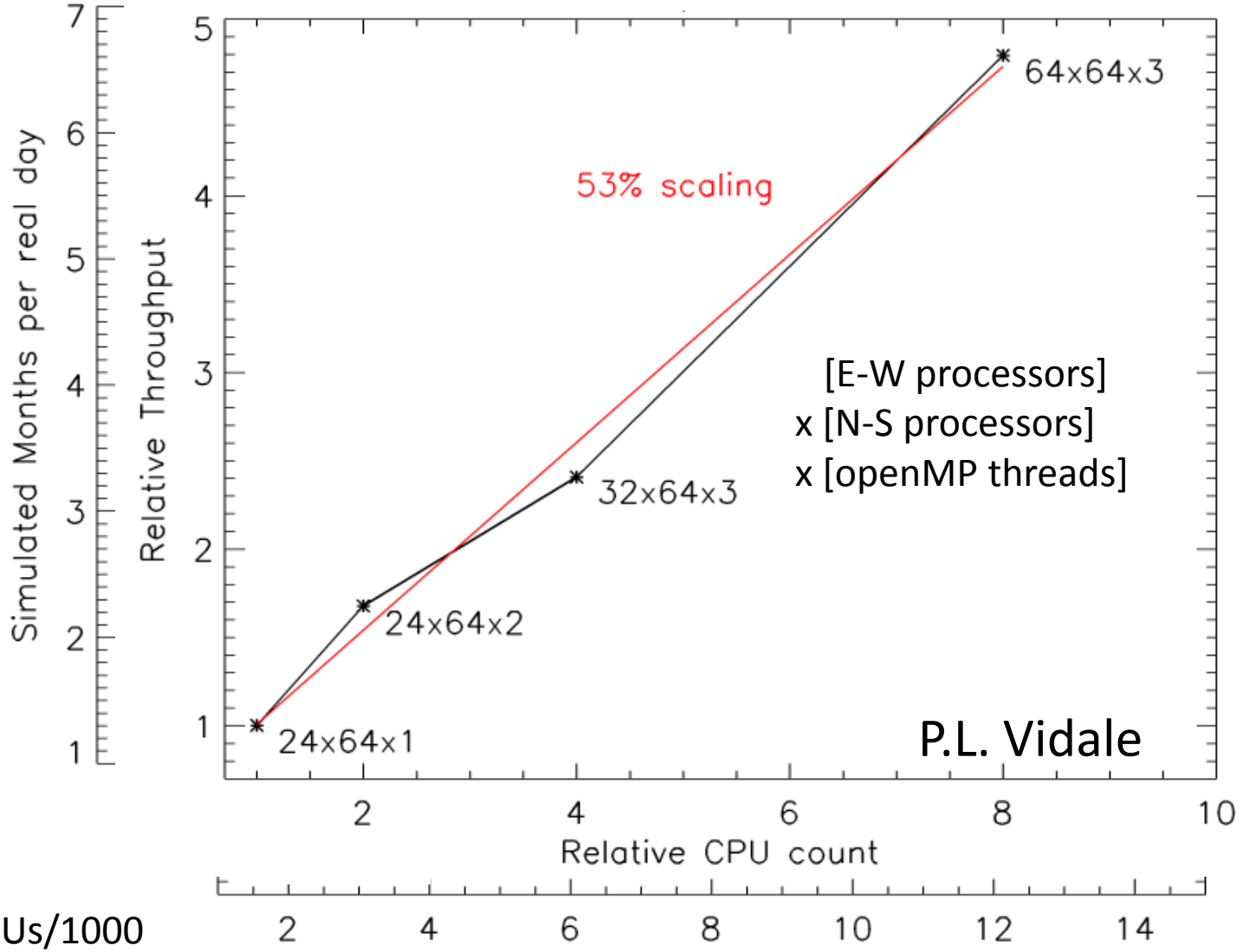

Scaling: Hermit (Cray XE6, Interlagos)

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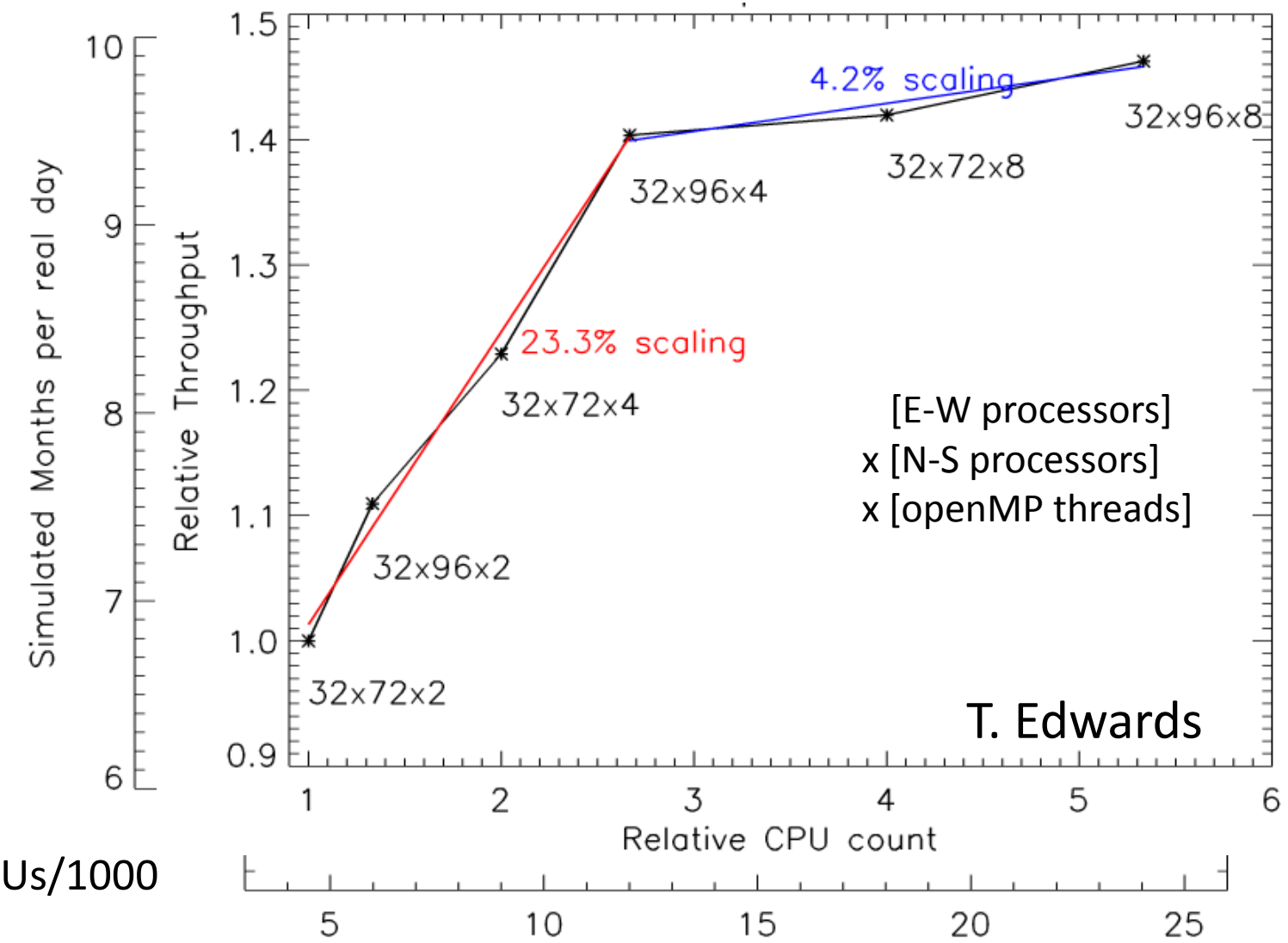
Excluding I/O



Scaling: Curie (Bull, Nehalem)

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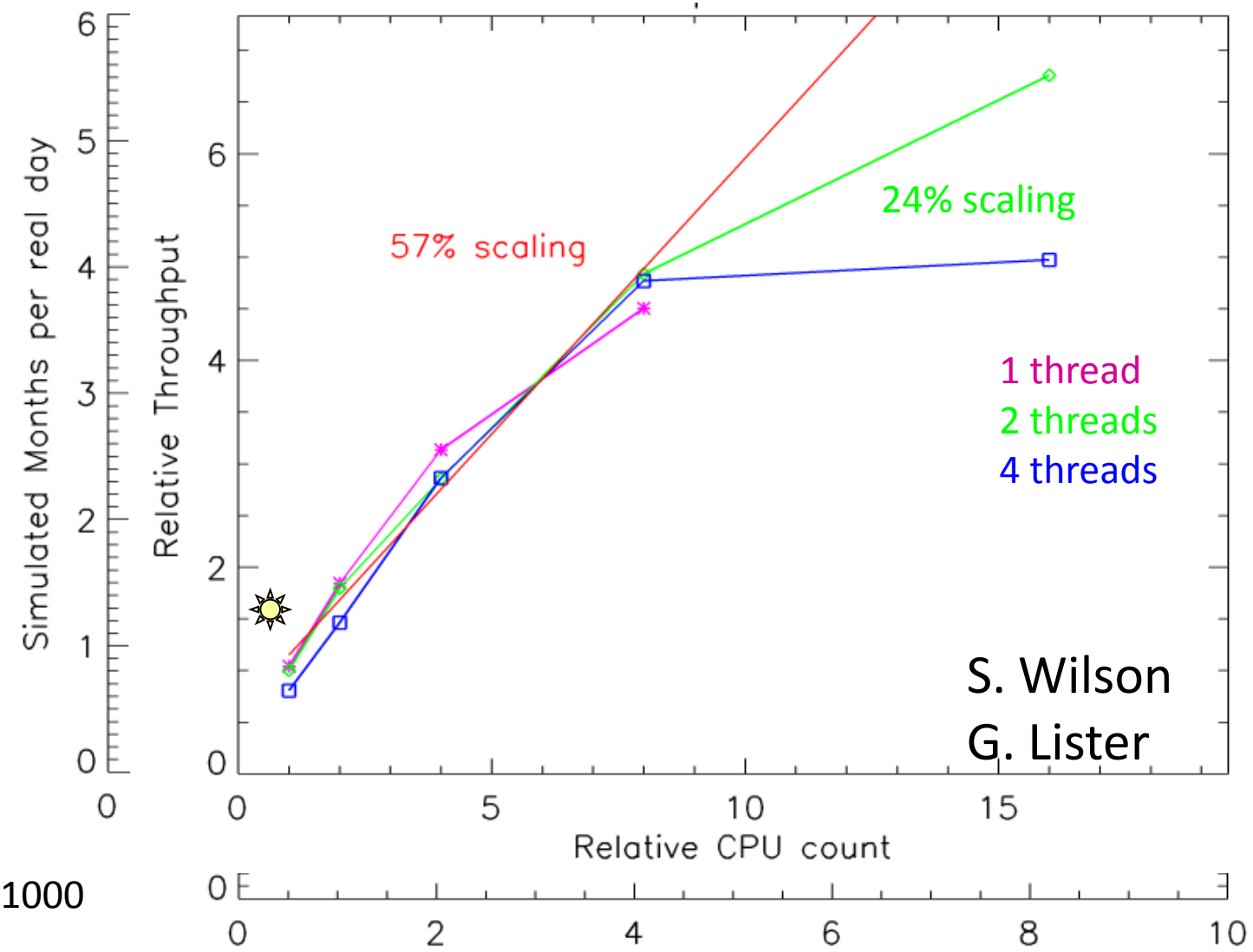

Data management

- I/O server and optimisation gives us a model which runs 5-6 months per day
- Each model run produces around 1 TB every running day (up to 5 models running at once depending on stability/queues)
- Data format conversion and compression reduces this to ~380 GB/model/running day
  ∴ ~1-1.5TB to be transferred per day
- Project expected to produce 250-300 TB

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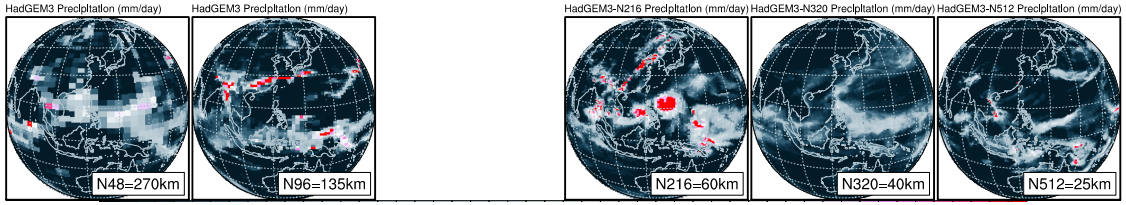
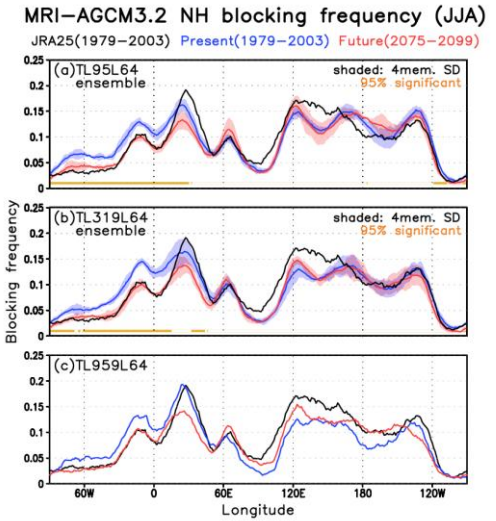
Two interconnected themes

1. High-resolution Global Climate Modelling:

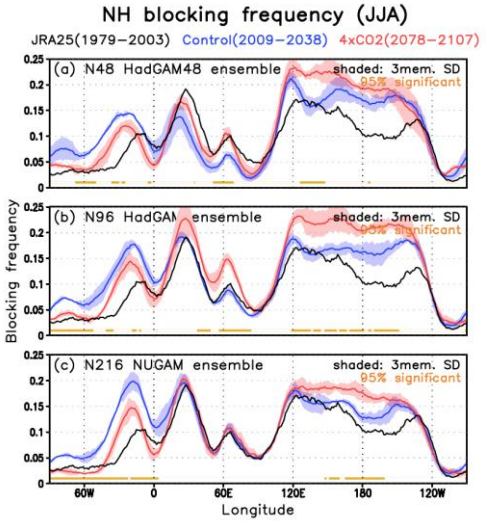
investigating the role of resolution, from 100km to 10km





Exploiting petascale computing on PRACE TIER-0 systems.
Long-term strategic partnership between NERC and the Met Office.
PIs: P.L. Vidale (NERC) and M. Roberts (Met Office)

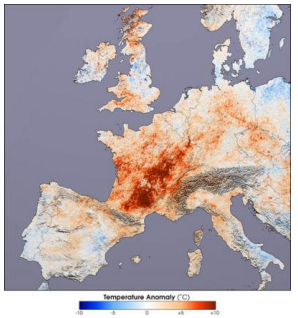
- Weather elements as the building blocks of climate:
  - Tropical and extratropical cyclones
  - Atmospheric blocking and heatwaves
  - Transports of energy and water by eddies / mean flow
- The global hydrological cycle: predictability at the continental to regional scales
- Hurricanes and typhoons in the climate system



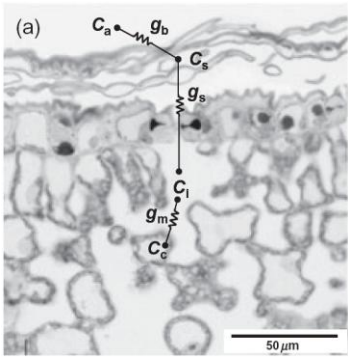
Matsueda and Palmer, GRL, 2011
Berckmans et al., ASL, 2012

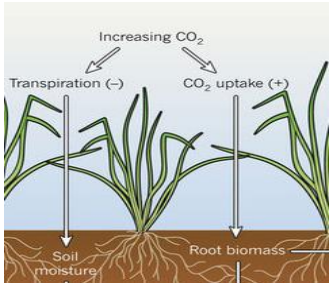
Two interconnected themes

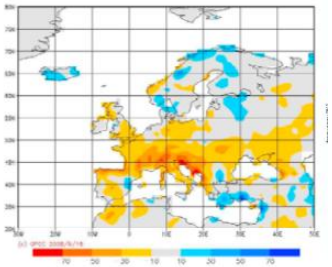
1. **High resolution global climate modelling**: from 100km to 10km
   - Weather elements as the building blocks of climate
     - Tropical and extratropical cyclones
     - Atmospheric blocking and heatwaves
     - Transports of energy and water by eddies / mean flow
   - The global hydrological cycle: predictability at the continental to regional scales
   - Hurricanes and typhoons in the climate system



1. **Land surface processes**: modelling and observations
   PIs: P.L. Vidale, A. Verhoef, E. Black
   - Photosynthesis and water resources: water stress, mesophyll and stomatal function
   - Soil physical processes:
     - Thermal transfer and the transport of water in its various phases
     - Sustainable energy production: soil heat pumps, energy crops
   - **Heatwaves** in Europe and North America: soil water as precursor or feedback?
   - Dynamic crop modelling with coupled GCMs



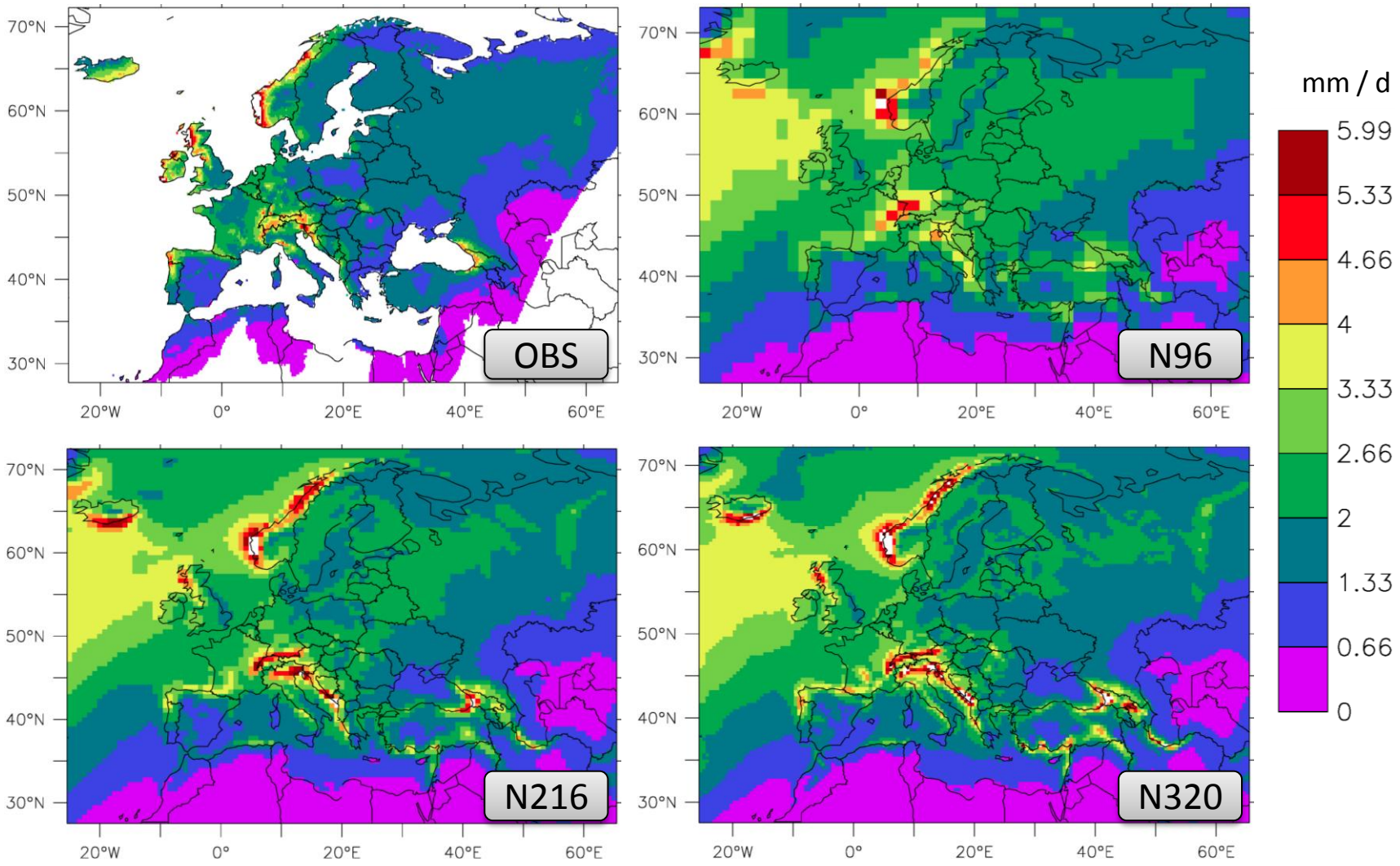




Van den Hoof et al., AFM, 2011
Egea et al. AFM, 2011
Black et al. ERL, 2012

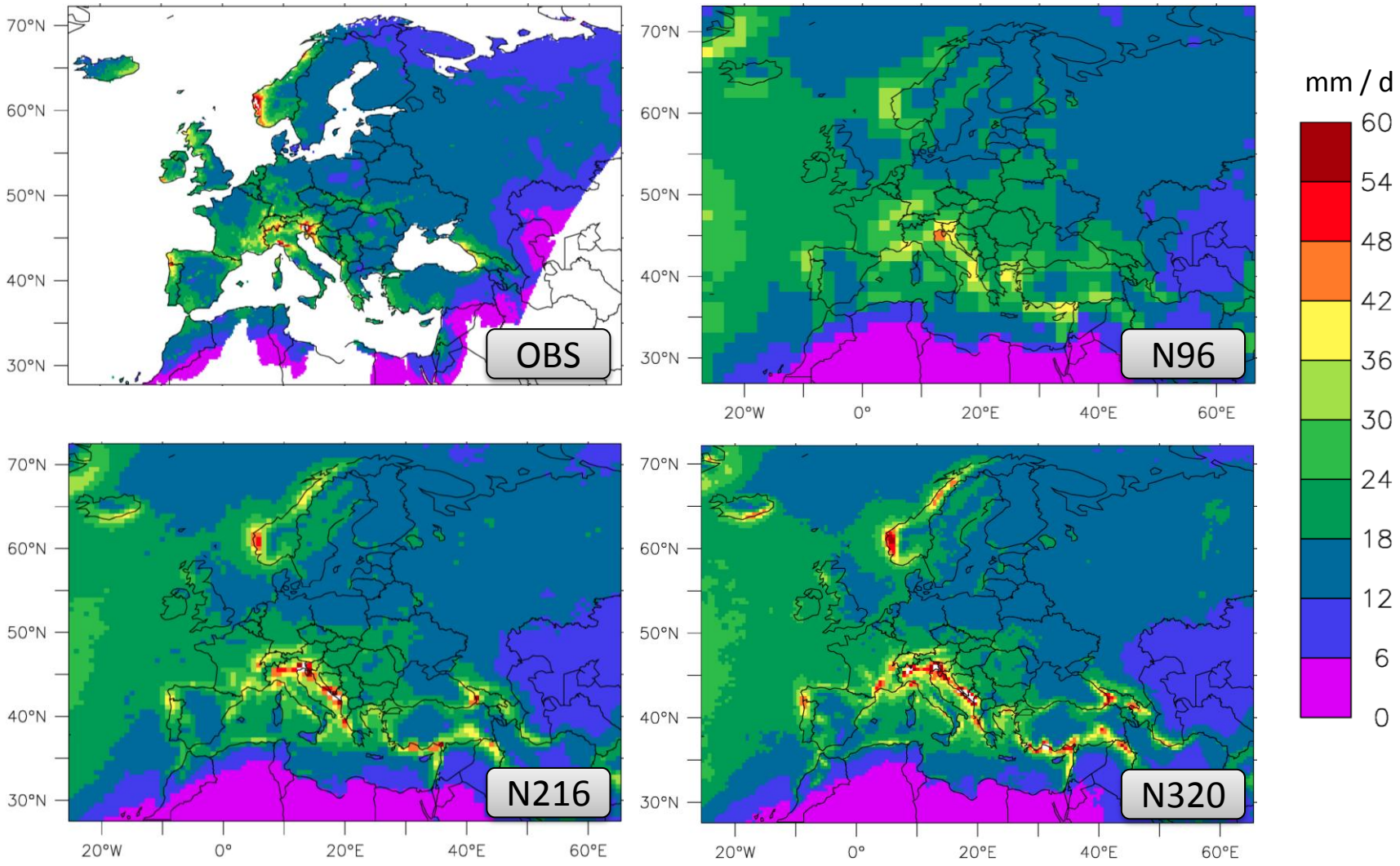
How good are global climate models at representing mean rainfall?

Europe (Mean)



How good are global climate models at representing extreme rainfall?

Europe (99% quantile)

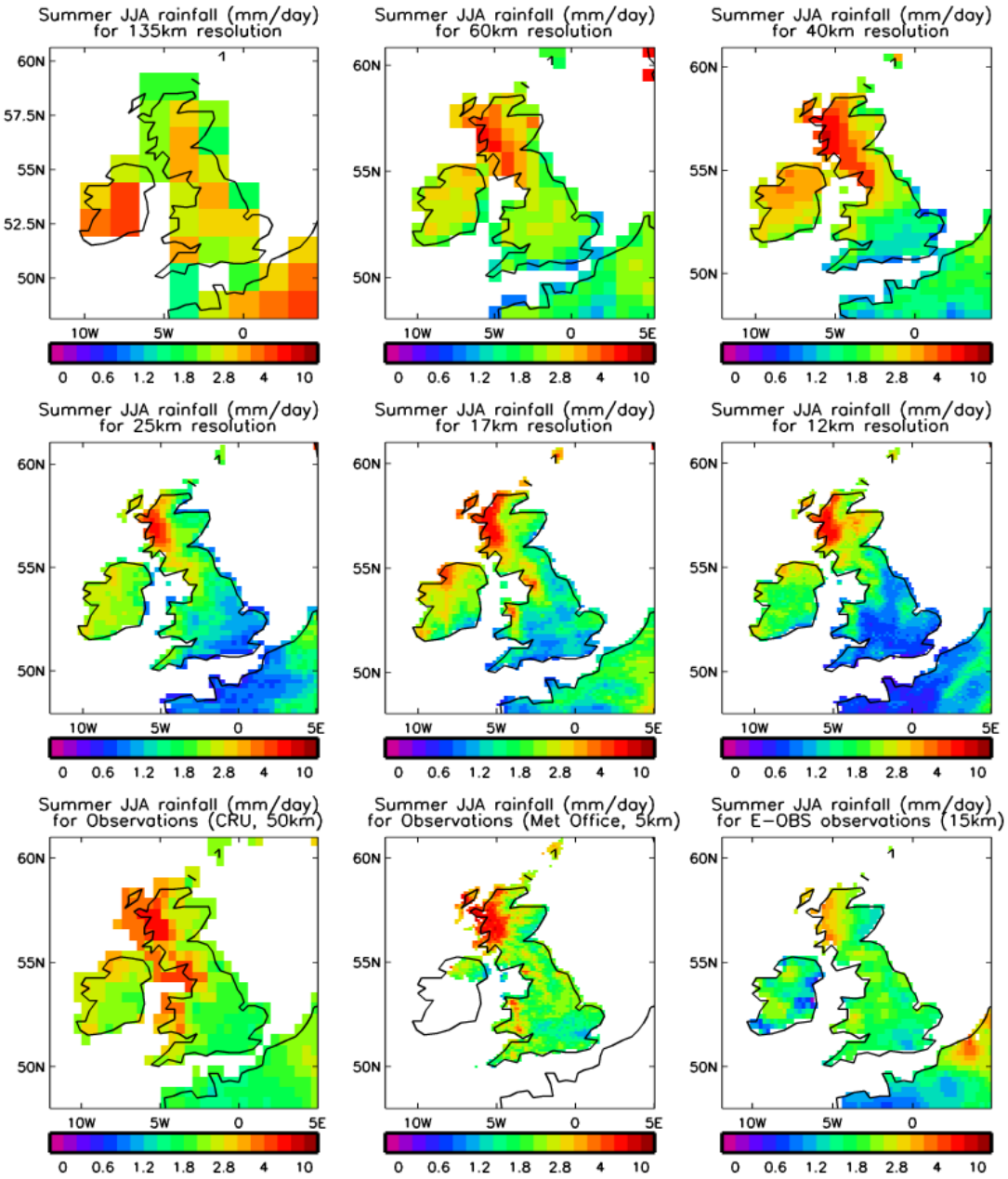


HadGEM3 N96 to N1024 precip over the UK

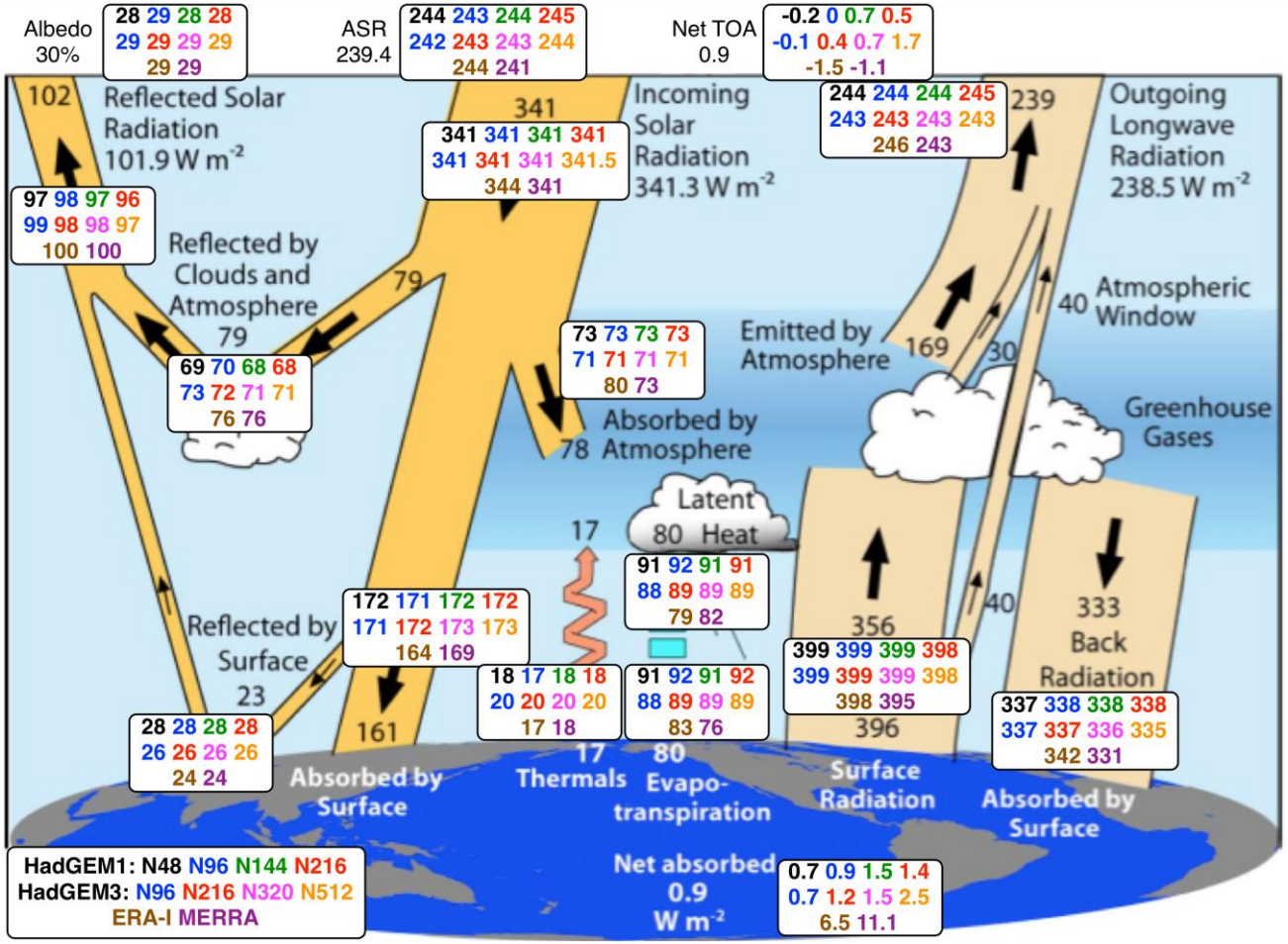
How good are <u>global</u> climate models at representing mean rainfall?

Average UK summer precipitation (mm/day) for JJA 2005.

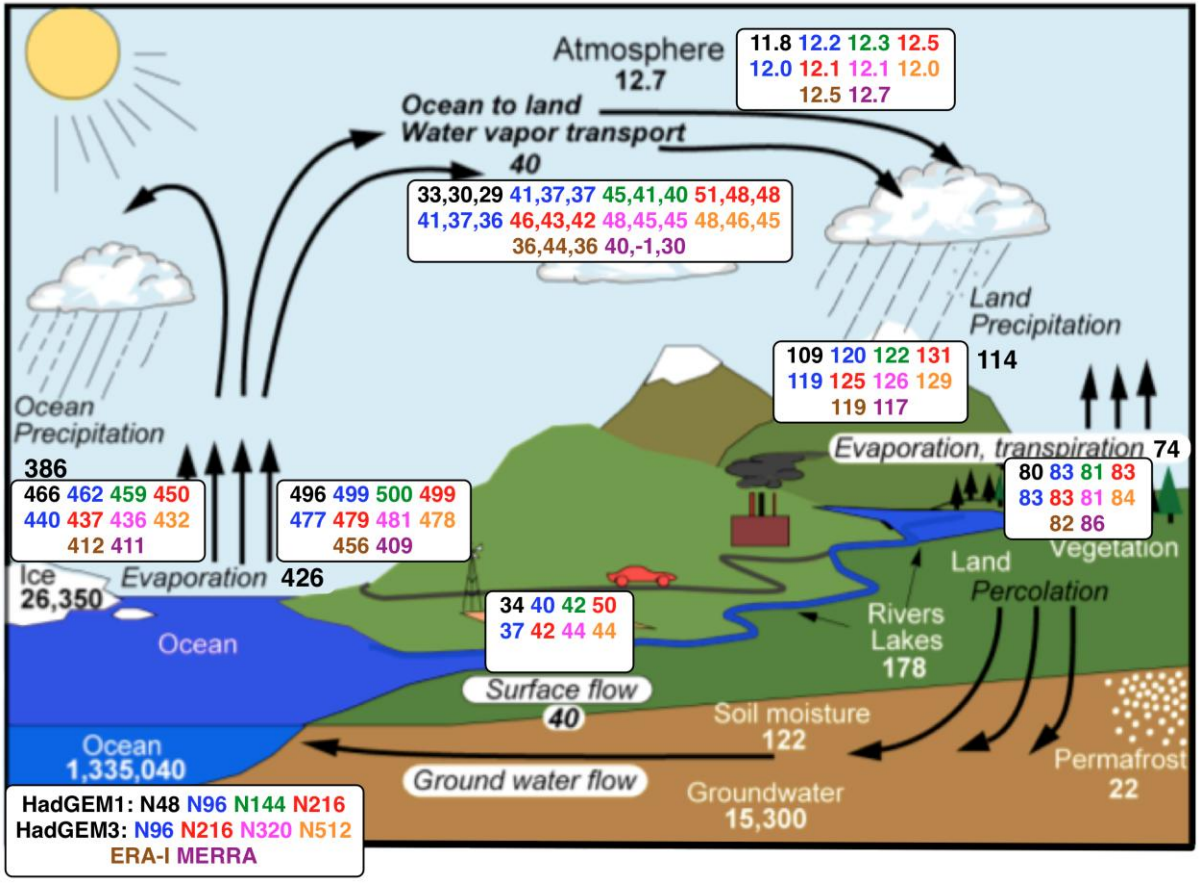
5 member ensemble averages, except N1024, which comprises only 3 members.



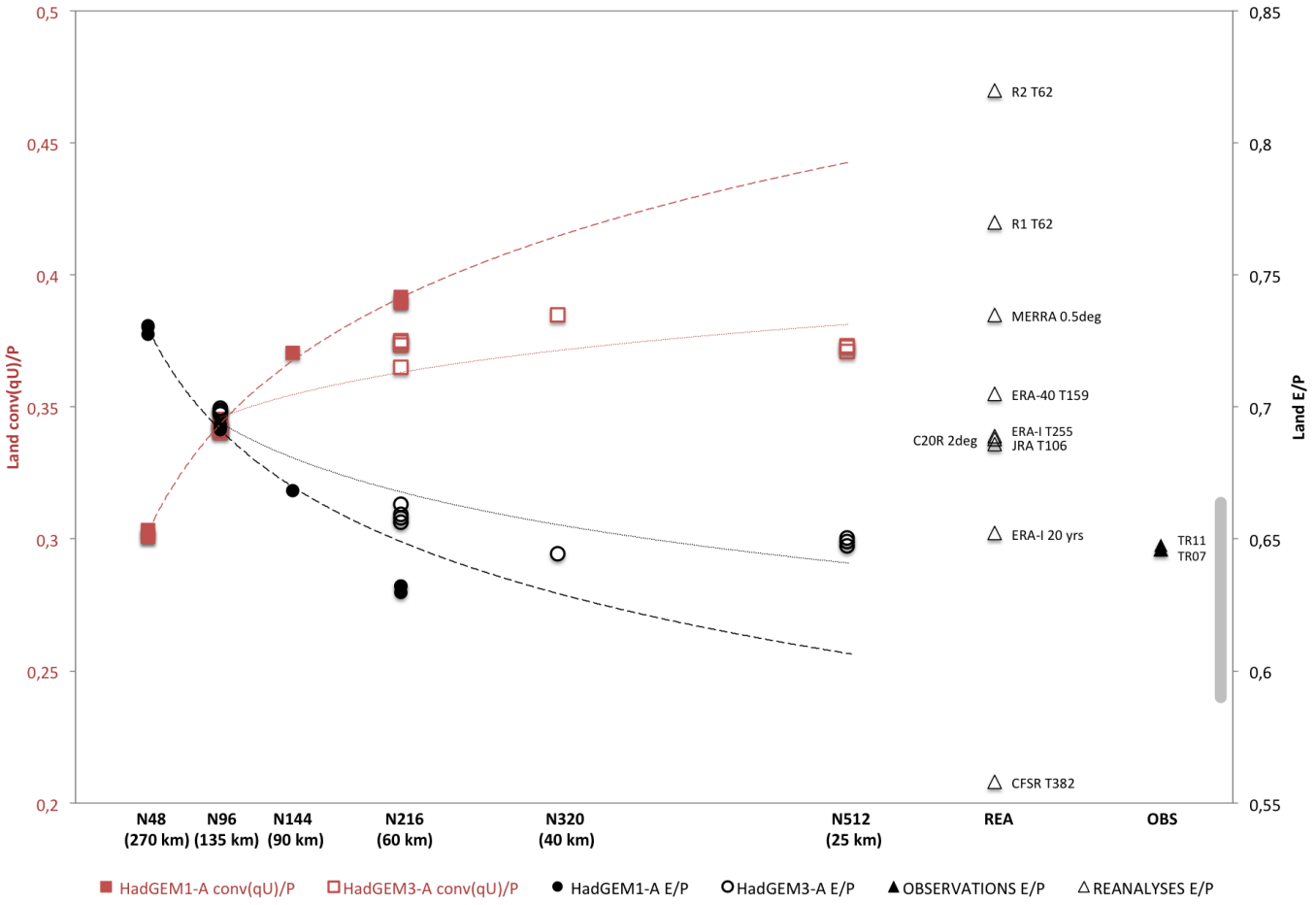
What changes with resolution?
Hopefully, important things are resolution-invariant.
Global energy budget



What changes with resolution?
Hopefully, important things depend on resolution.
Water cycle



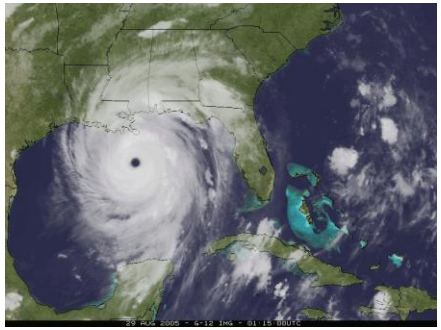
What changes with resolution?
Hopefully, important things are resolution-invariant.
And some are not: water cycle and land/sea contrast



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

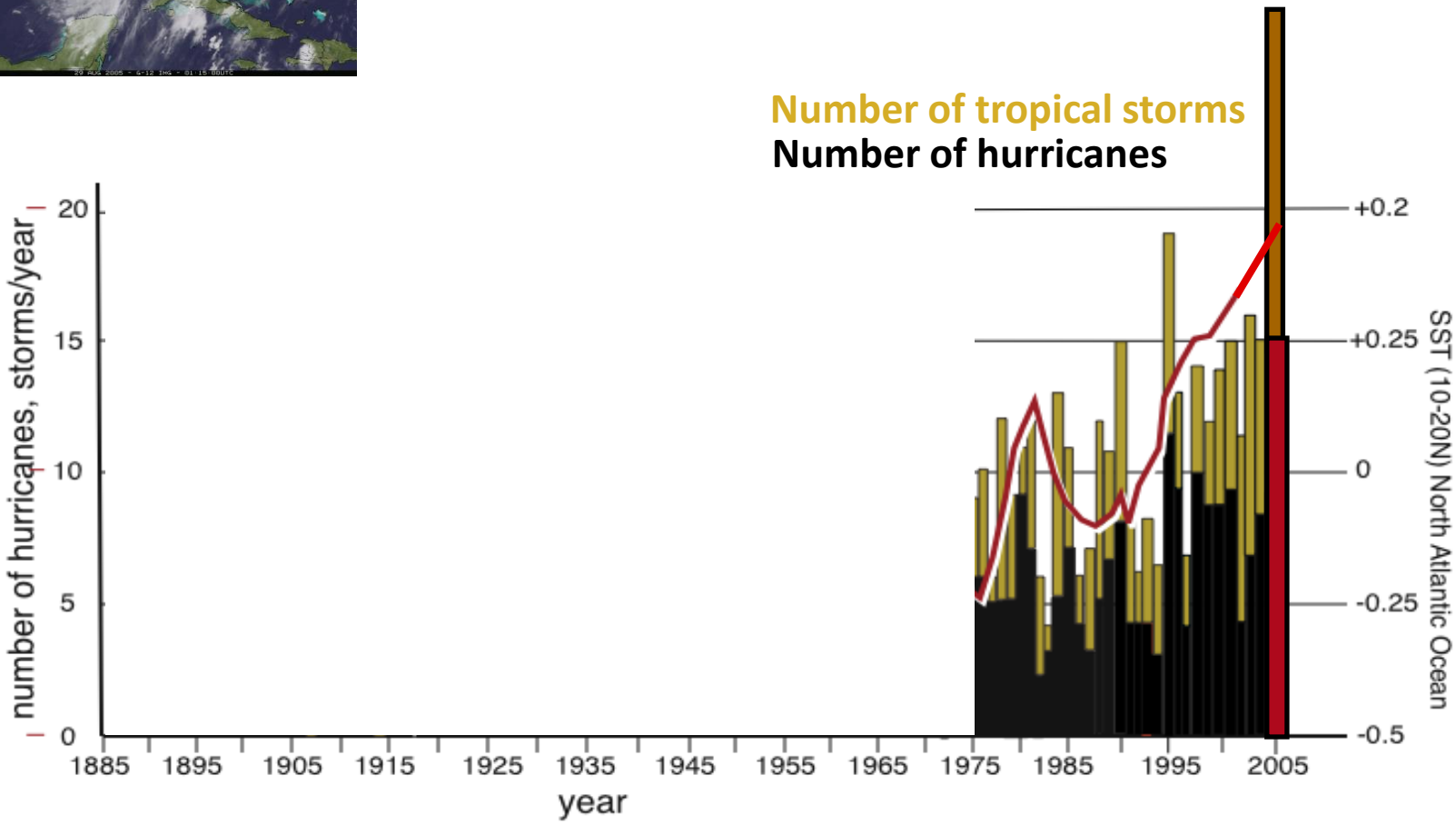
2005: 15 hurricanes (incl. Katrina), 27 named storms … and some of the most intense storms in US history.

Katrina damage = 1600 dead; 75-200 bn U$.



Short/inhomogeneous records of **extremely rare** events. We need models to:

1) Complement observations
2) Understand the drivers of variability in location, frequency, intensity etc.
3) Make trustworthy projections

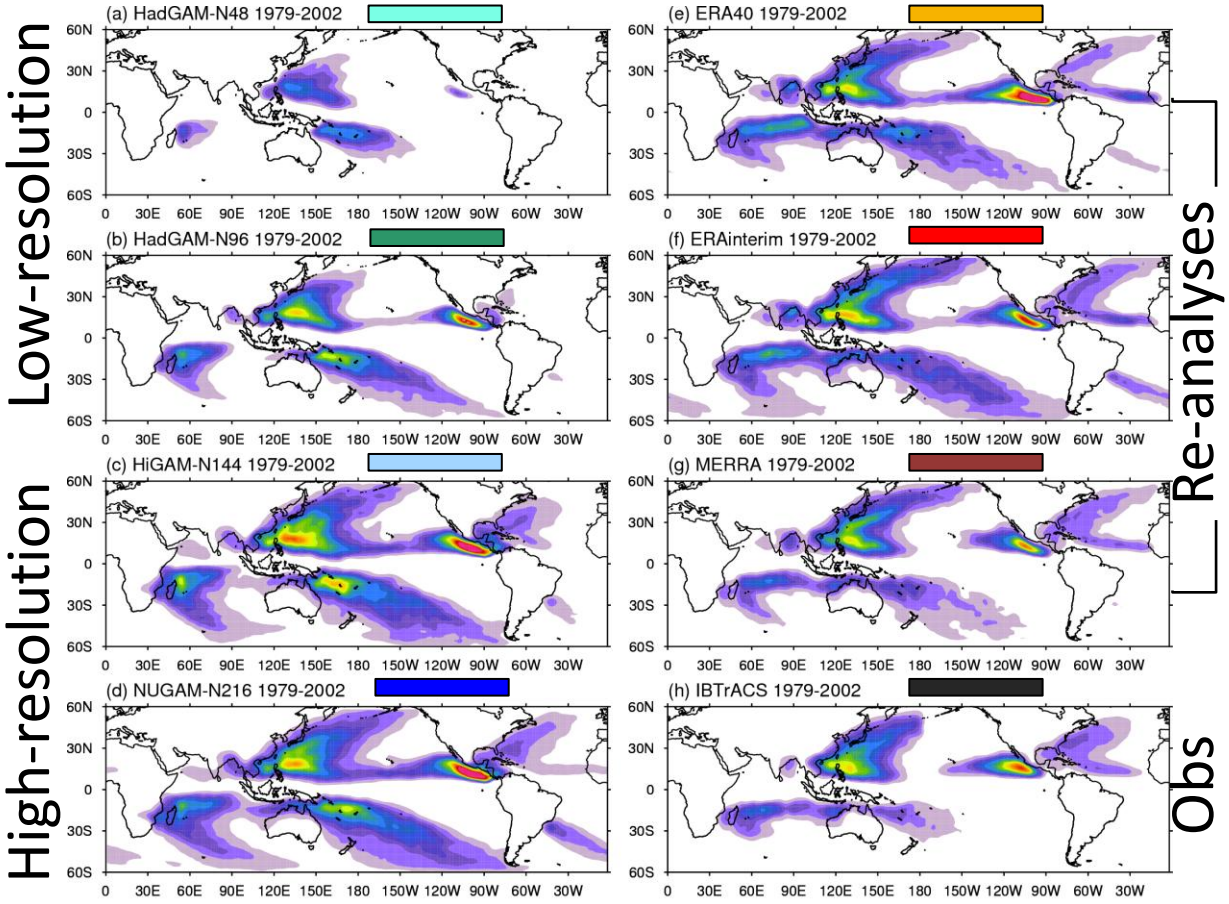


Courtesy of K. Trenberth

Atmosphere-only simulations

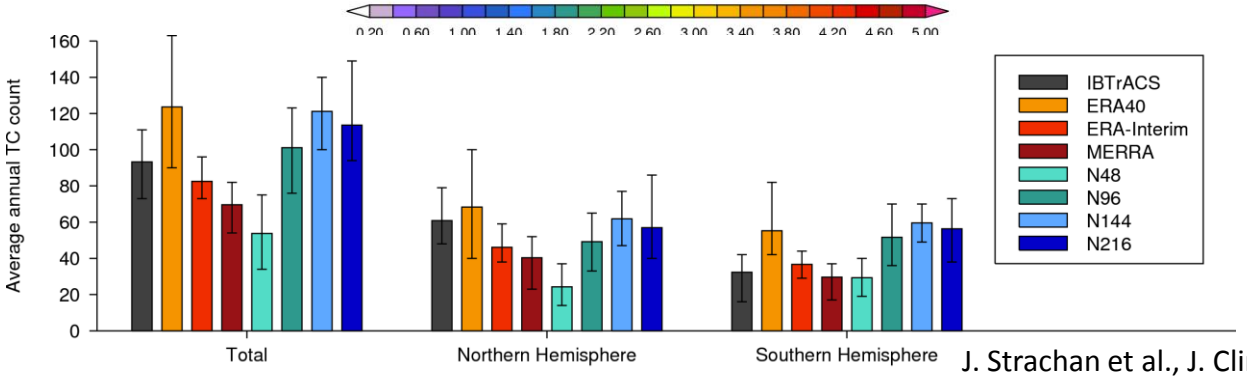
Geographical location of storms

Tropical cyclone track density (transits per unit area)



Number of tropical cyclones

Average annual storm count



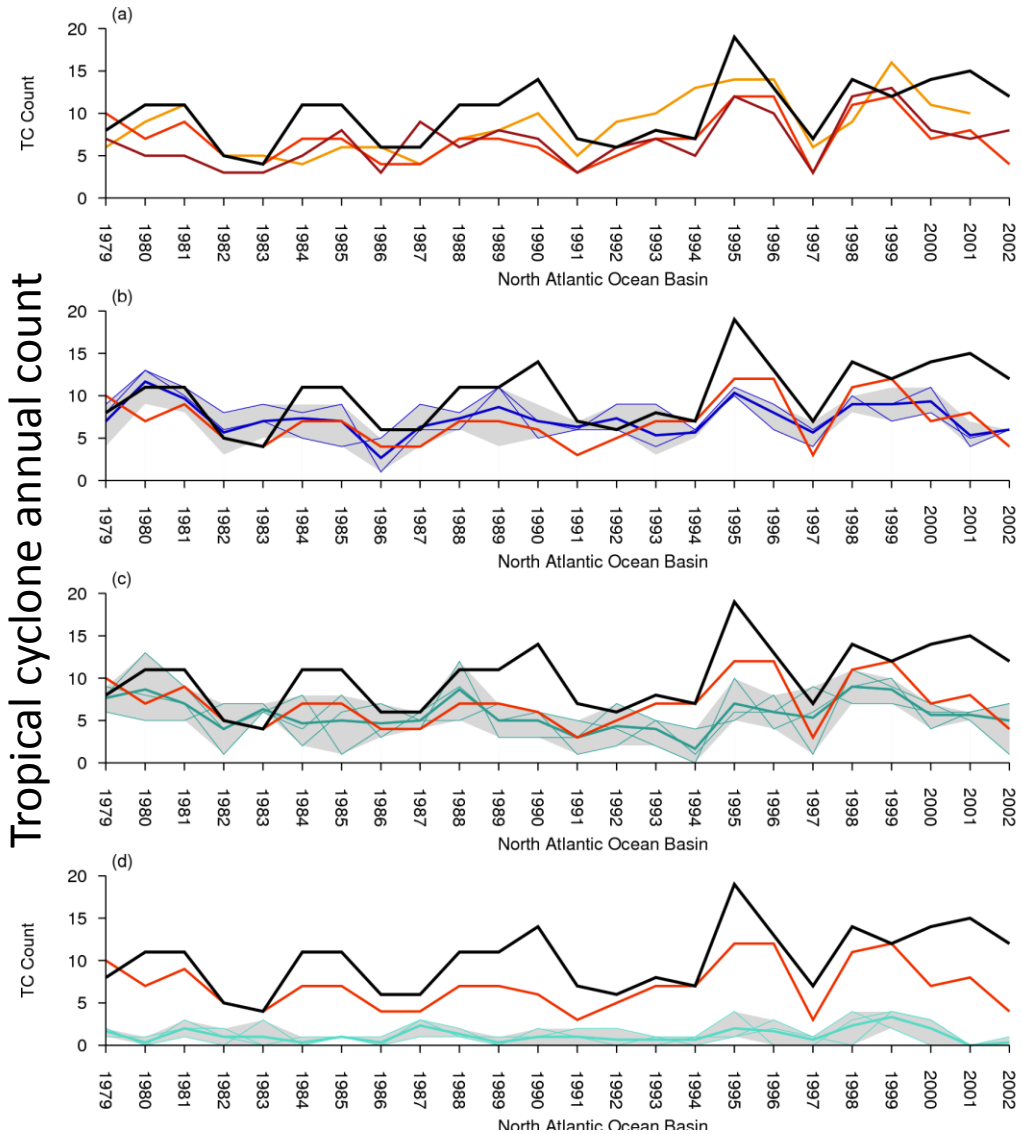
J. Strachan et al., J. Clim, in press

Tropical cyclone interannual variability

North Atlantic Ocean

High-resolution

Low-resolution



IBTrACS
ERA40
ERA-Interim
MERRA

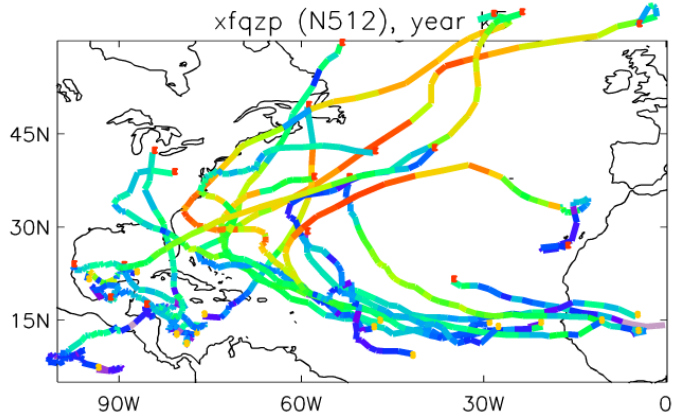
IBTrACS
ERA-Interim
N216 ensemble mean
N216 ensemble members
N96 ensemble mean
N96 ensemble members
N48 ensemble mean
N48 ensemble members
ensemble spread

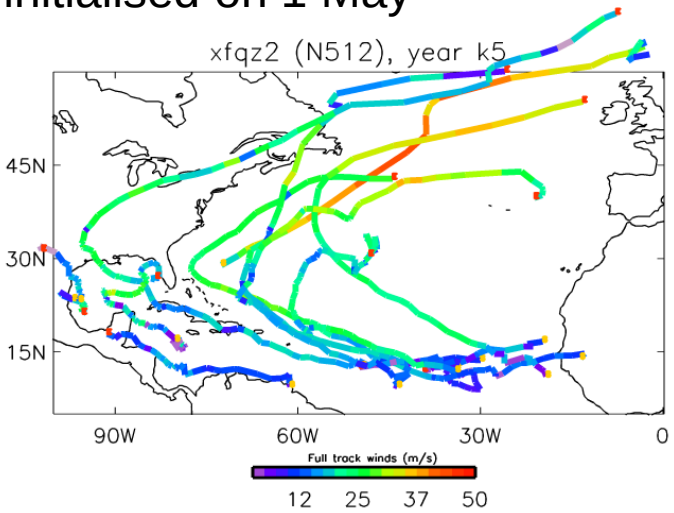
Correlations with IBTrACS

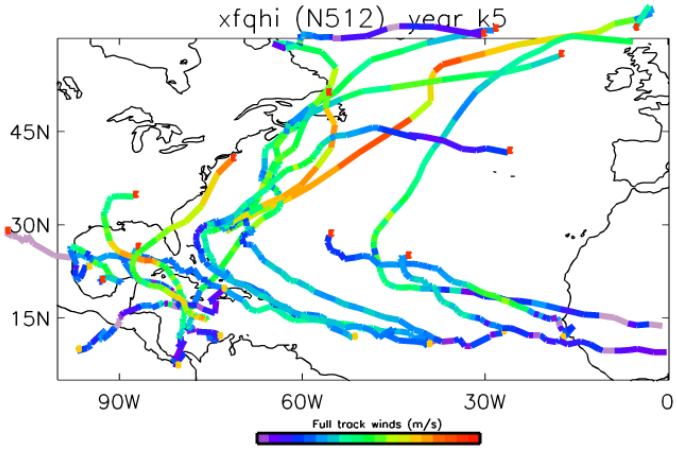
N48	= 0.41
N96	= 0.52
N144	= 0.55
N216	= 0.68
ERA40	= 0.59
ERA-I	= 0.78
MERRA	= 0.71

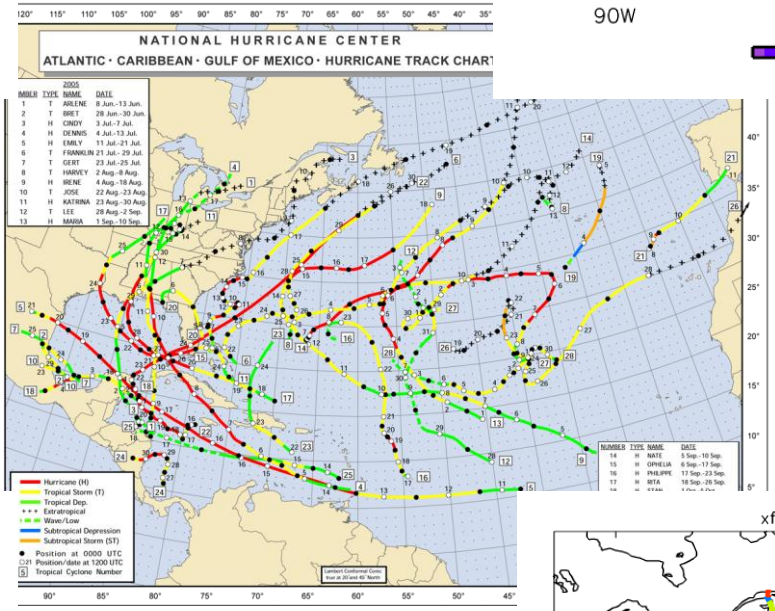
J. Strachan et al., J. Clim, in press

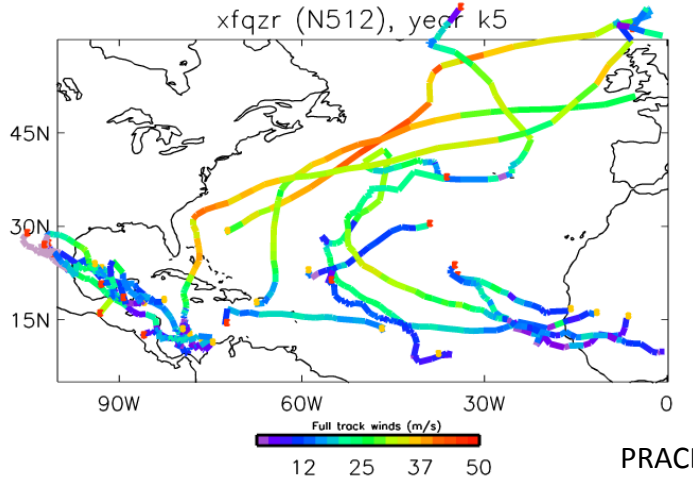
2005 Atlantic storm track at N512: 5 members initialised on 1 May

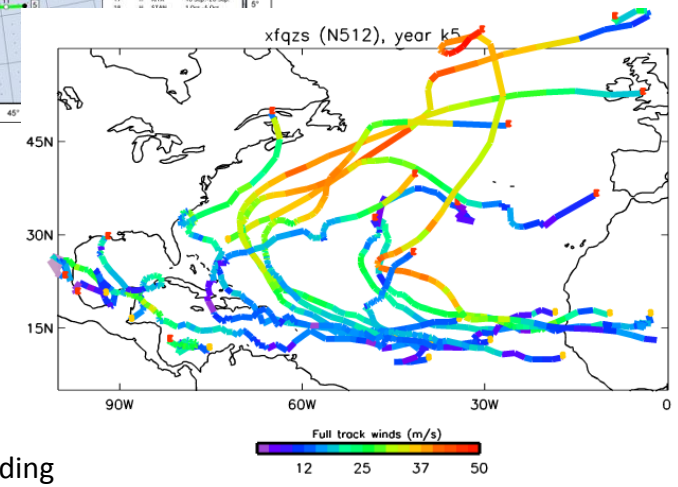












PRACE UPSCALE, Project PI: P.L. Vidale, Reading

TC correlations (1985-2011) vs HURDAT

Resolution Basin	N96 (2 member)	N216 (3 member)	N512 (3 member)
Atlantic	0.65, 0.37 (0.63)	0.54, 0.66, 0.44 (0.69)	0.65, 0.66, 0.52 (0.72)
W Pacific	0.70, 0.57 (0.68)	0.65, 0.49, 0.6 (0.7)	0.42, 0.44, 0.5 (0.55)
E Pacific	0.38, -0.12 (0.17)	0.47, 0.48, 0.46 (0.54)	0.4, 0.43, 0.51 (0.5)
Indian	-0.39, -0.04 (-0.30)	0.07, 0.0, -0.18 (-0.04)	0.21, -0.37, -0.3 (-0.23)

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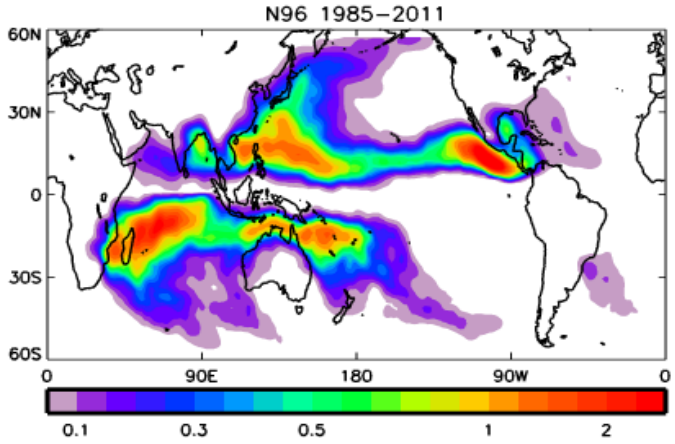
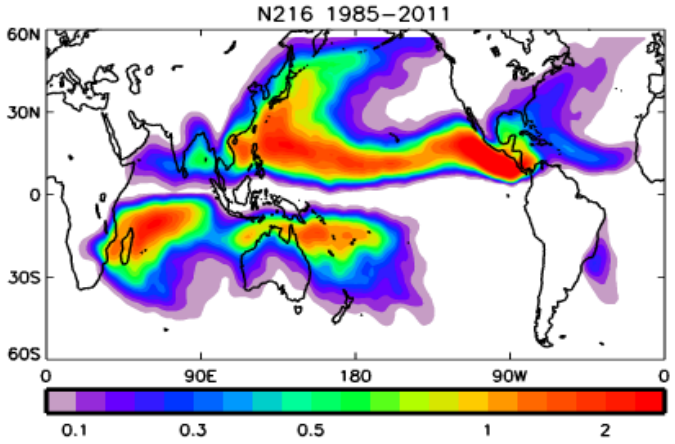
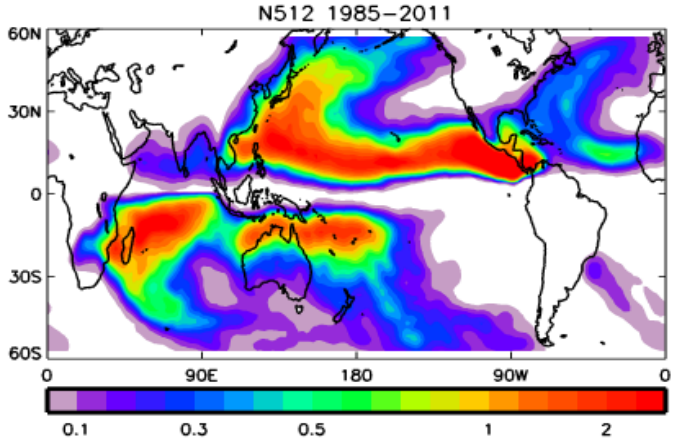
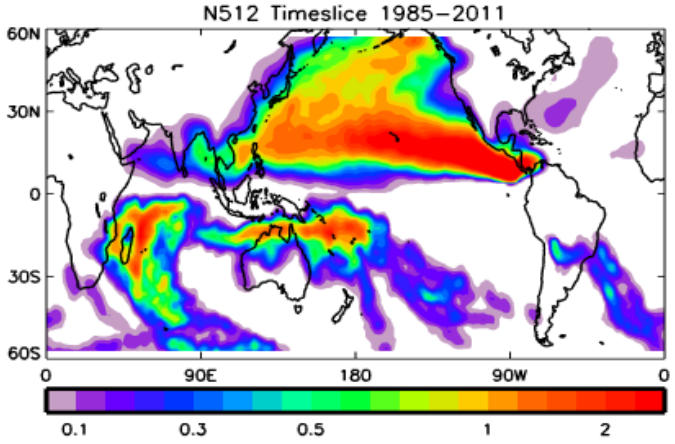
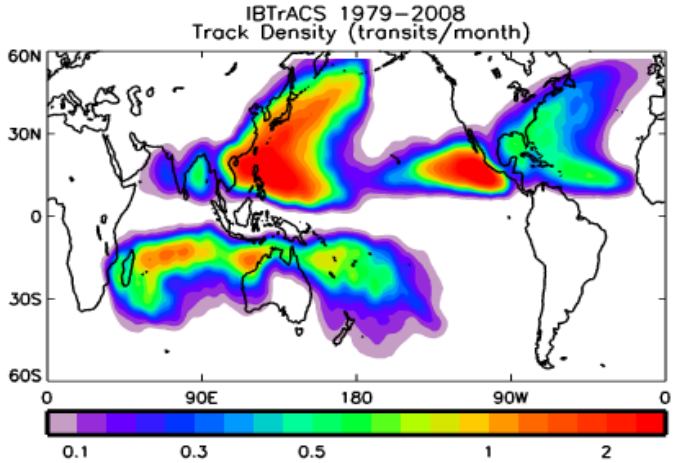

N96 1985–2011
60N
30N
0
30S
60S
0
90E
180
90W
0
0.1
0.3
0.5
1
2

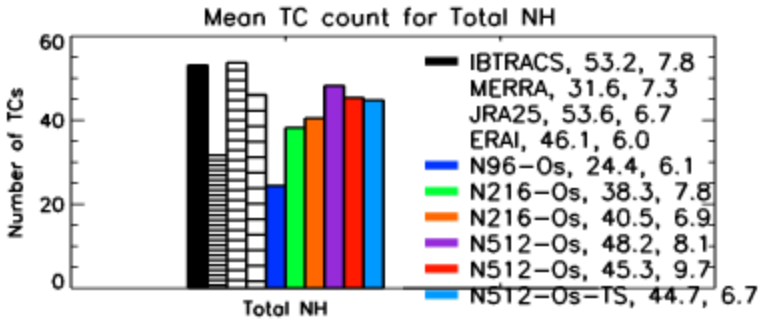

N216 1985–2011
60N
30N
0
30S
60S
0
90E
180
90W
0
0.1
0.3
0.5
1
2

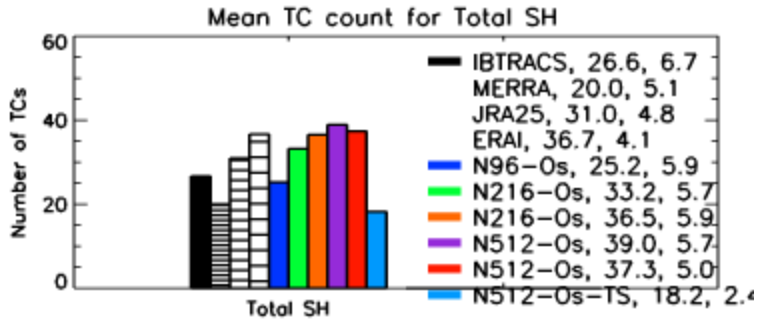

N512 1985–2011
60N
30N
0
30S
60S
0
90E
180
90W
0
0.1
0.3
0.5
1
2

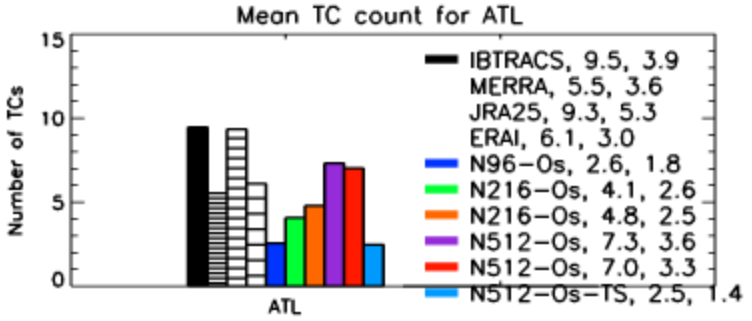

N512 Timeslice 1985–2011
60N
30N
0
30S
60S
0
90E
180
90W
0
0.1
0.3
0.5
1
2

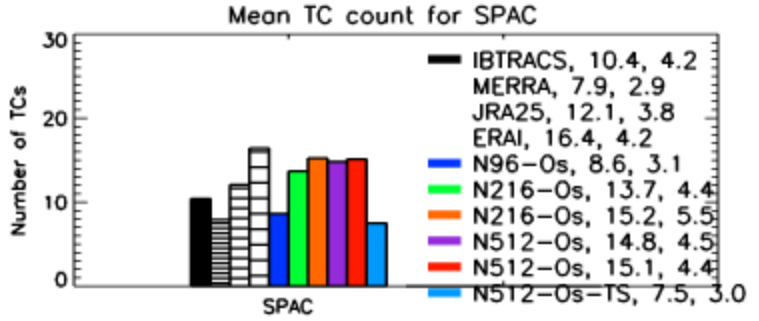

IBTrACS 1979–2008
Track Density (transits/month)
60N
30N
0
30S
60S
0
90E
180
90W
0
0.1
0.3
0.5
1
2

©



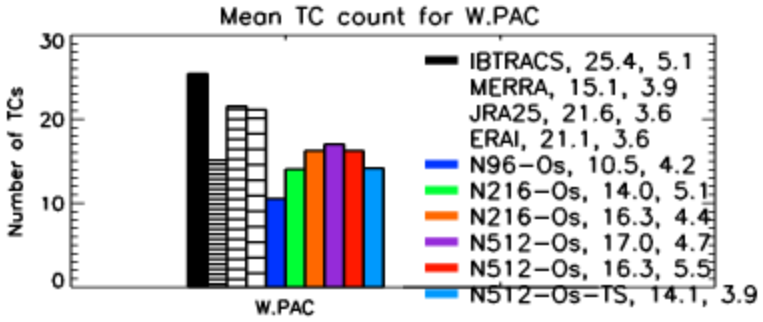


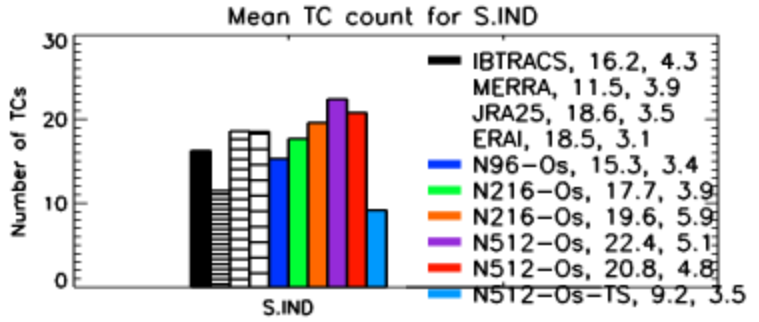


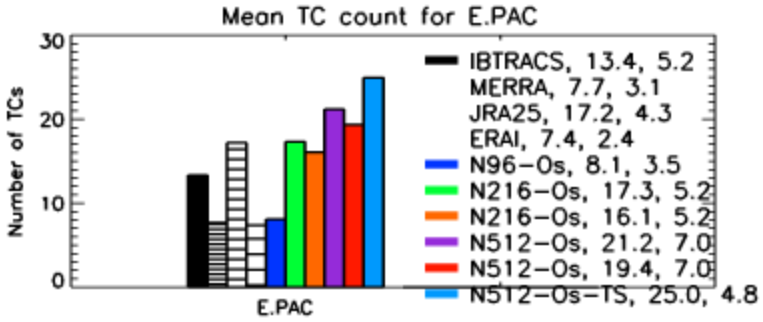


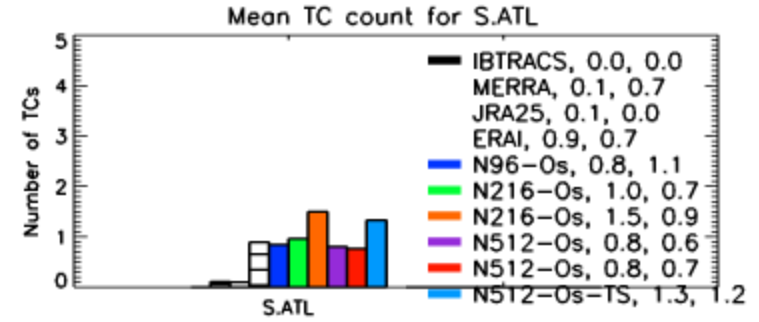
Os=OSTIA SST/sea-ice

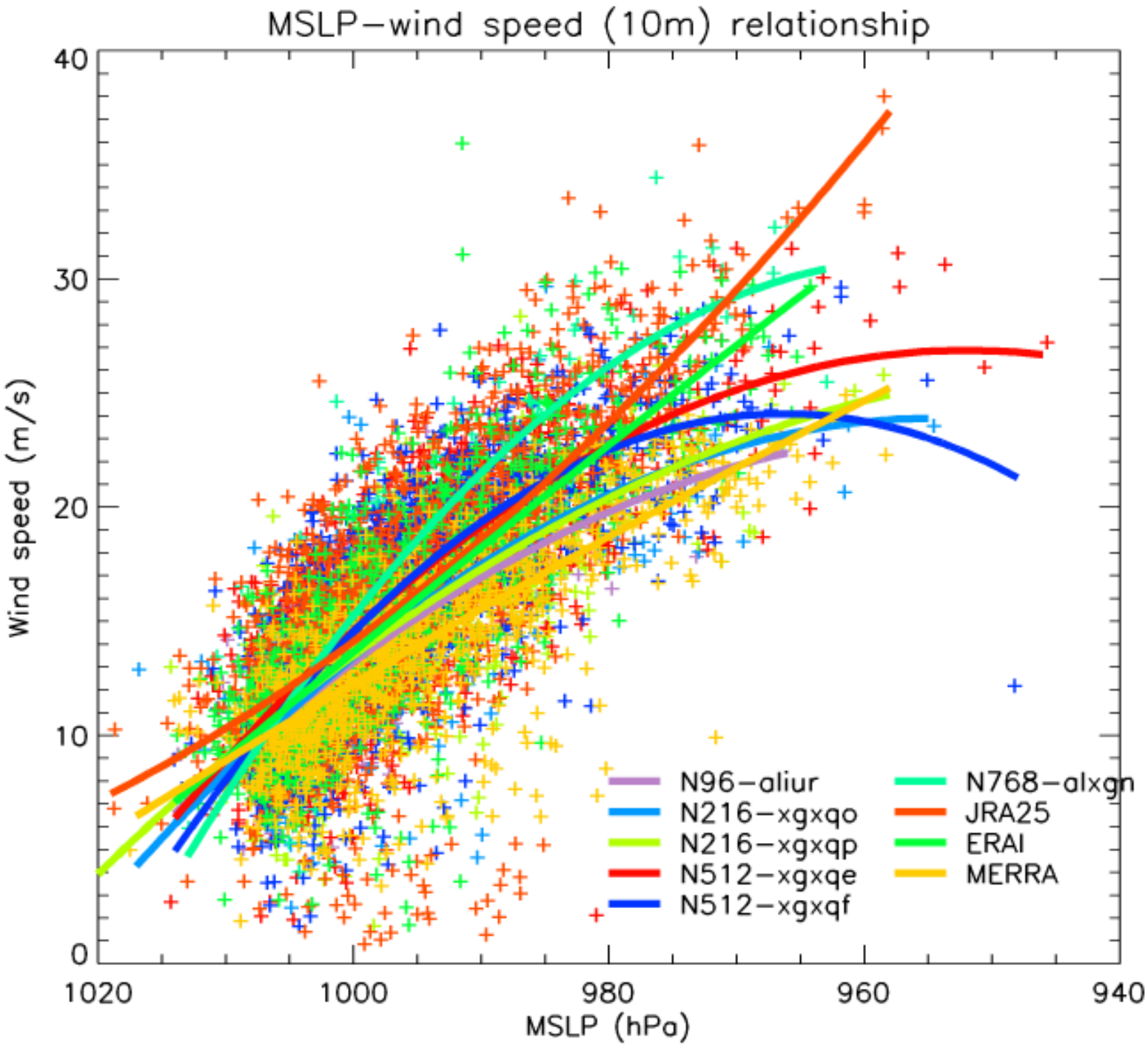
TS=timeslice

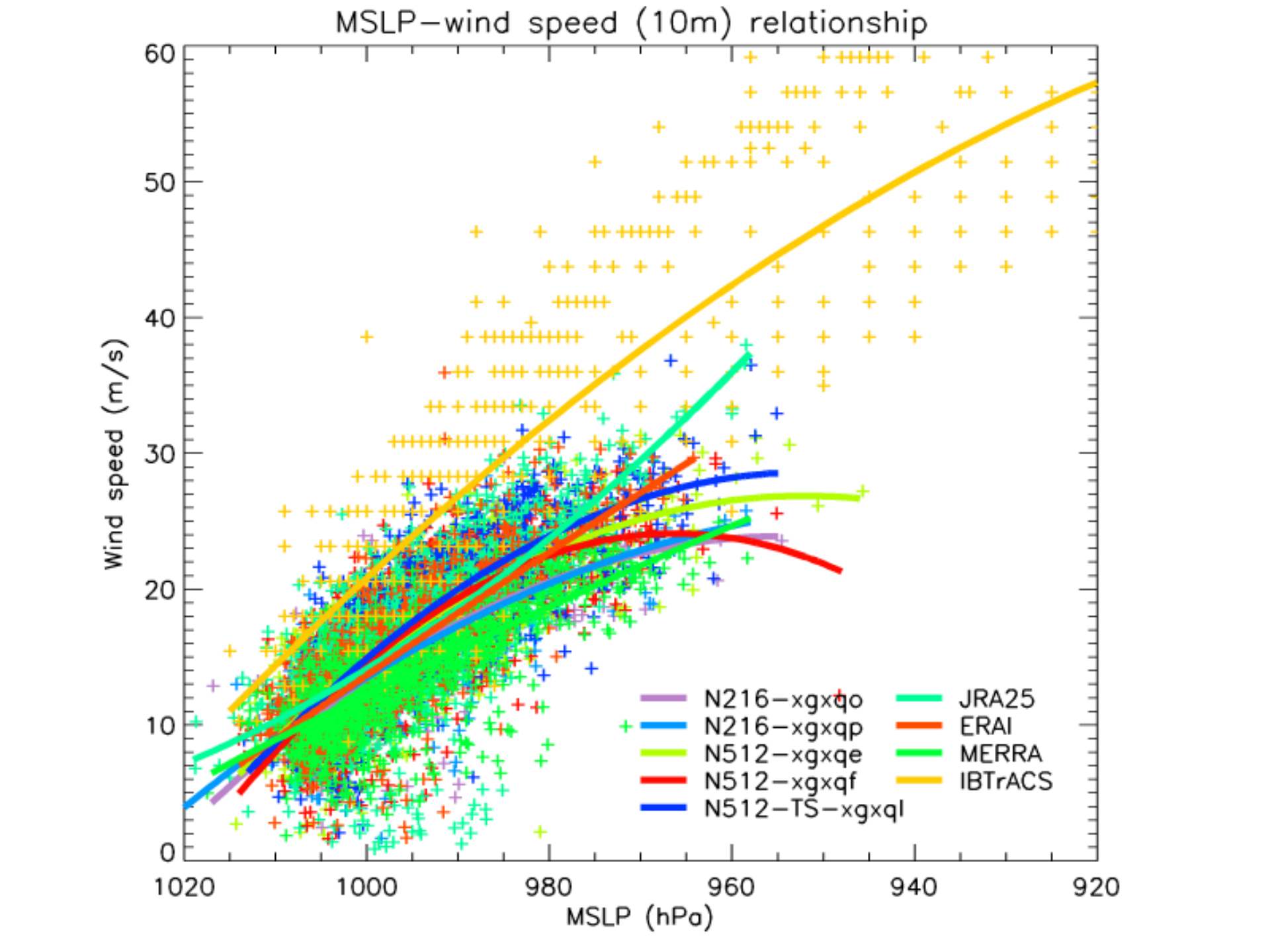


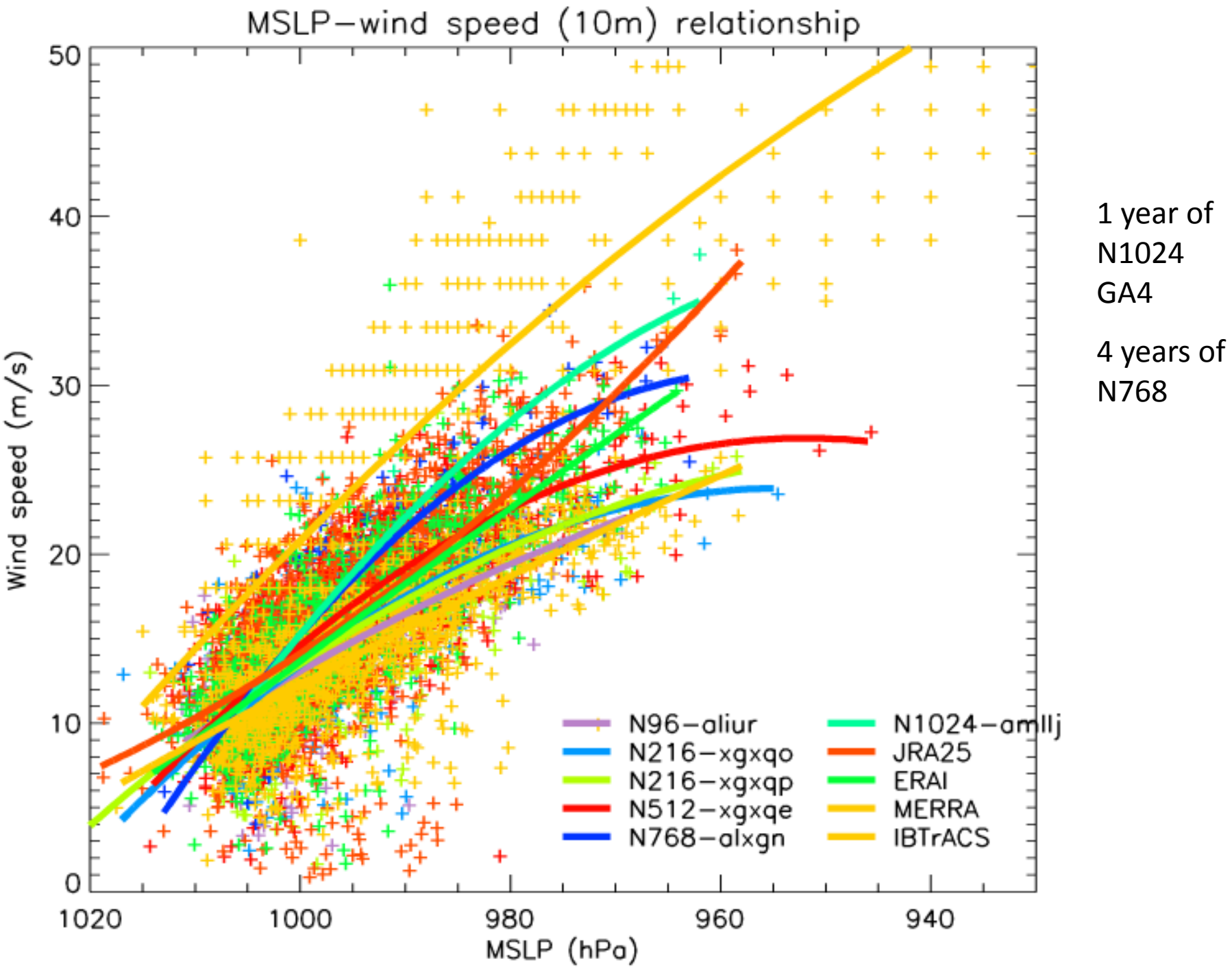







MSLP−wind speed (10m) relationship
Wind speed (m/s)
MSLP (hPa)
40
30
20
10
0
1020
1000
980
960
940
N96−aliur
N216−xgxqo
N216−xgxqp
N512−xgxqe
N512−xgxqf
N768−alxgn
JRA25
ERAI
MERRA


MSLP−wind speed (10m) relationship
Wind speed (m/s)
MSLP (hPa)
60
50
40
30
20
10
0
1020
1000
980
960
940
920
N216−xgxqo
N216−xgxqp
N512−xgxqe
N512−xgxqf
N512−TS−xgxql
JRA25
ERAI
MERRA
IBTrACS



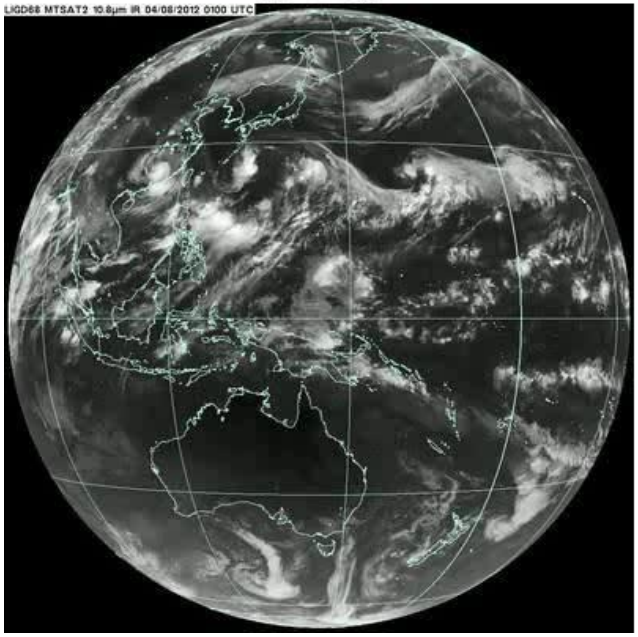
1 year of N1024 GA4

4 years of N768

Global N1024

- 12km at our latitudes, 19km at equator
- We ran it as:
  - Standard HadGEM3
  - Without convective parameterisation, but with 3D Smagorisnki (similar to a CASCADE setup)
- Single year driven by OSTIA SSTs, March to June so far

N1024: with and without convective parameterisation.

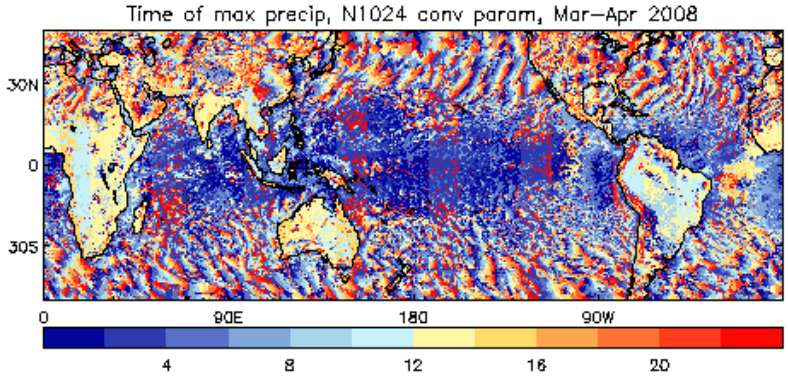


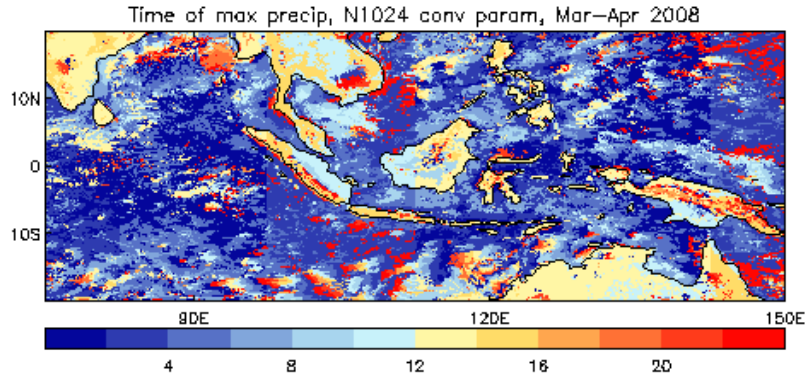
(top left) Hourly OLR from global N1024 with parameterised convection

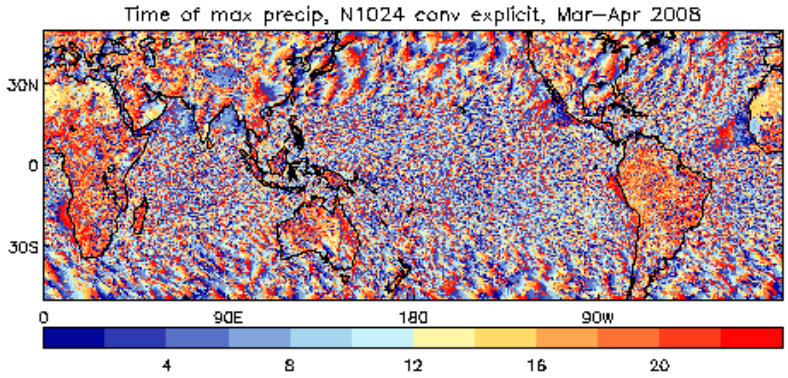
(top right) Hourly OLR from global N1024 with explicit convection (Smagorinsky)

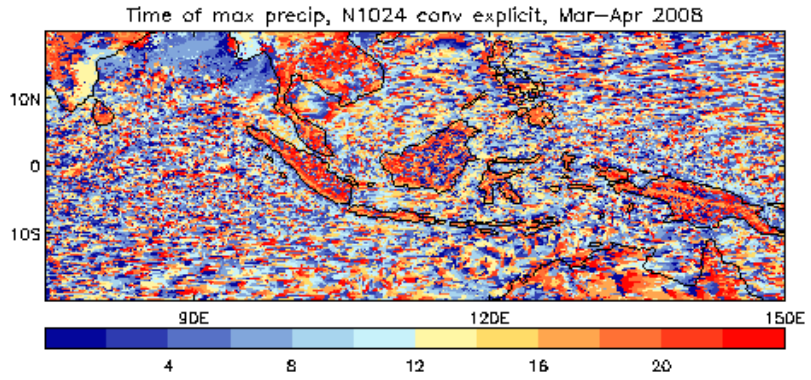
(bottom left) Hourly Infra-Red from MTSAT satellite

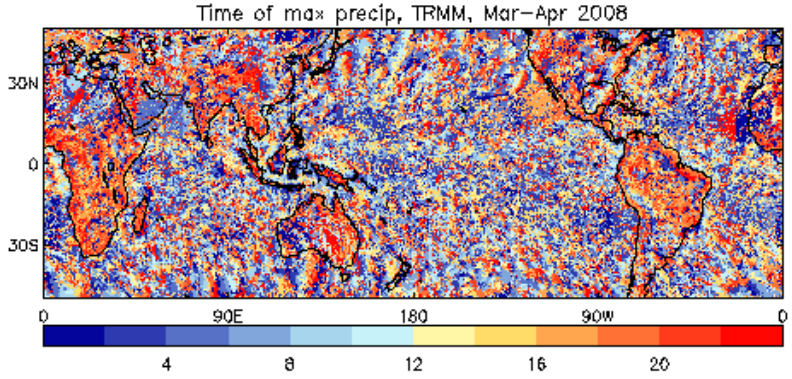
Diurnal cycle

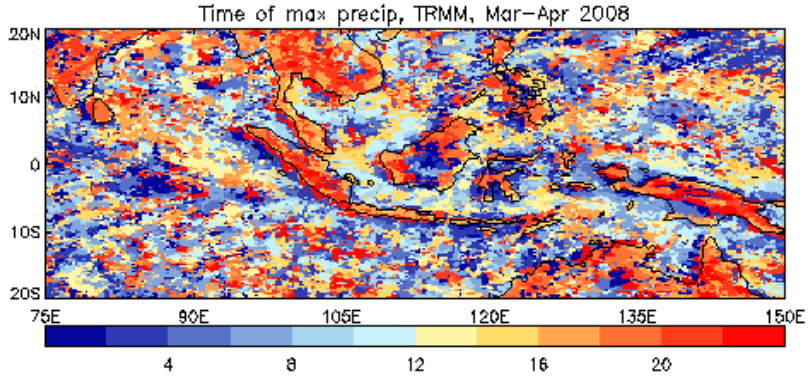












High-resolution Climate Modelling summary

- Significant increase in simulation capability in the last two years:
  - From 60km to 25km (and now 17 and 12km) AGCMs, mostly HadGEM3
  - Coupling to NEMO ¼ (ORCA25) now available with all models, up to N512 (25km)
  - Plans for coupling to NEMO 1/12
  - Scalability good on up to 12K cores (per ensemble member); weak scalability on O(100K) cores
- Significant improvements to simulated climate, with important processes emerging, e.g. ENSO, Tropical Cyclones, eddy transports
- Capability in High-Resolution Global Climate Modelling and in its application to the insurance industry:
  - Rapidly growing international markets, as exposure to weather and climate risk grows
    - HPC costs are just a small fraction of annual losses
    - Major economic opportunities for the UK
- Maintaining UK leadership requires investments in climate science and infrastructure, especially High-Performance Computing.

Thank you