Tropical Cyclones and resolution – Stochastic Physics sensitivity in CMIP6-HighResMIP GCMs

1: hurricanes in the global system

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2: HPC considerations

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8 MPI, DE
9
10 NCAS-CMS
11 CERFACS
12 AWI, DE
13 MRI, Japan
14 LBL, Berkley, USA

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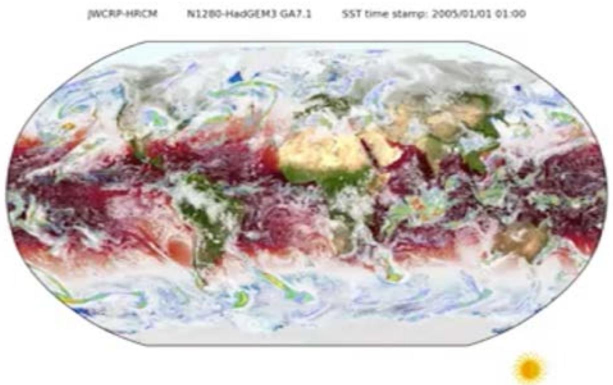
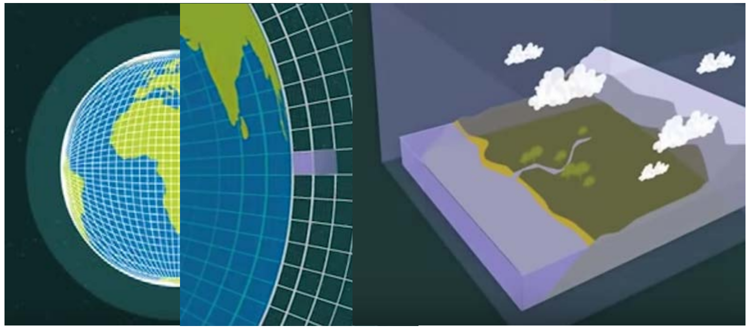
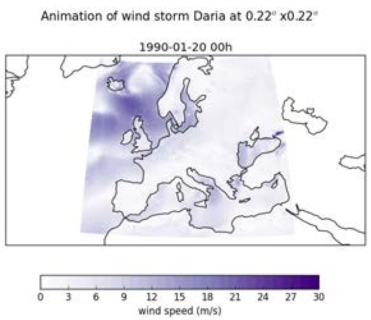
What is PRIMAVERA?



PRIMAVERA is a European Commission-funded (H2020) project about designing and running **new high resolution global climate models**,



There are 19 partner institutions, **developing and running 6 European GCMs…**



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assessing at the process level their **ability to simulate societally important processes,**

and thereby providing information to **support climate risk assessment activities** across Europe.

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CMIP6 HighResMIP

Global climate modelling at the frontiers

Collaboration is key for exploitation and understanding (national, European, international)

Multi model (6 atmos, 7 coupled)

Multi-resolution:

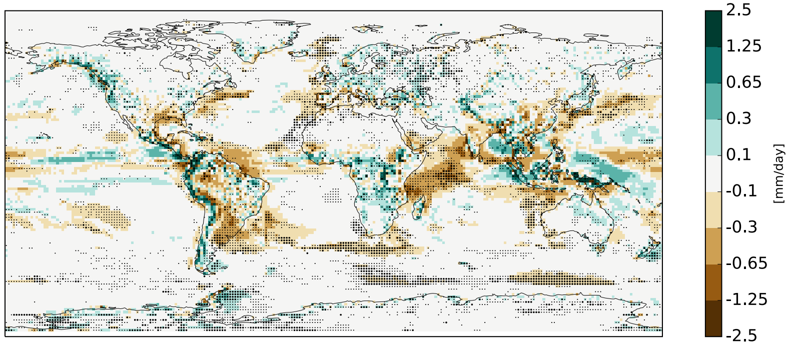
- Atmos: 200km - 25km (-10km)
- Ocean: 1˚, ¼˚, 1/12˚

Ensemble members (>=3, up to 13)

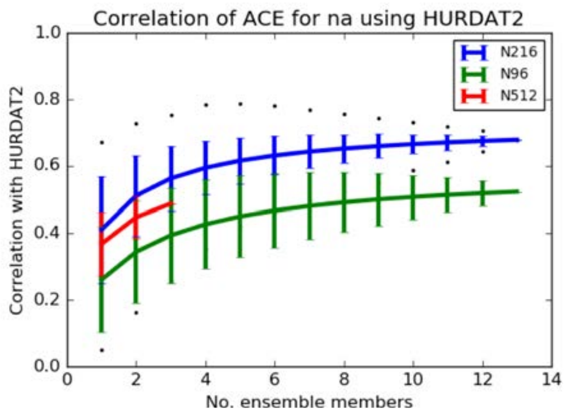
Long simulations (65/100+ years, 500-1000 years at lower resolutions)

Insights from physical model, simpler protocol

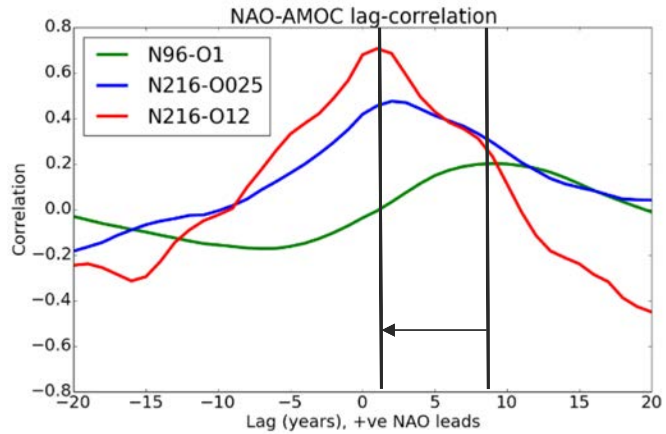
Multi-model (6)
Precip vs GPCP
high vs low
resolution
BIAS increases
BIAS decreases
Bigger dot – more
models agree



B. Vanniere, NCAS-Climate, in prep



Tropical cyclone interannual variability – correlation against Obs – for different #ensemble members and resolutions



Lag-correlation of NAO and AMOC - +ve = NAO leads
Note peak correlation increases and lag shortens with higher resolution

WEATHER AND CLIMATE PROCESSES EMERGE AT HIGH RESOLUTION

From Vidale et al. (2014), Introduction to the Scientific Case for PRIMAVERA (Horizon 2020)

A number of **processes emerge as we increase the resolution** of our weather and climate models.

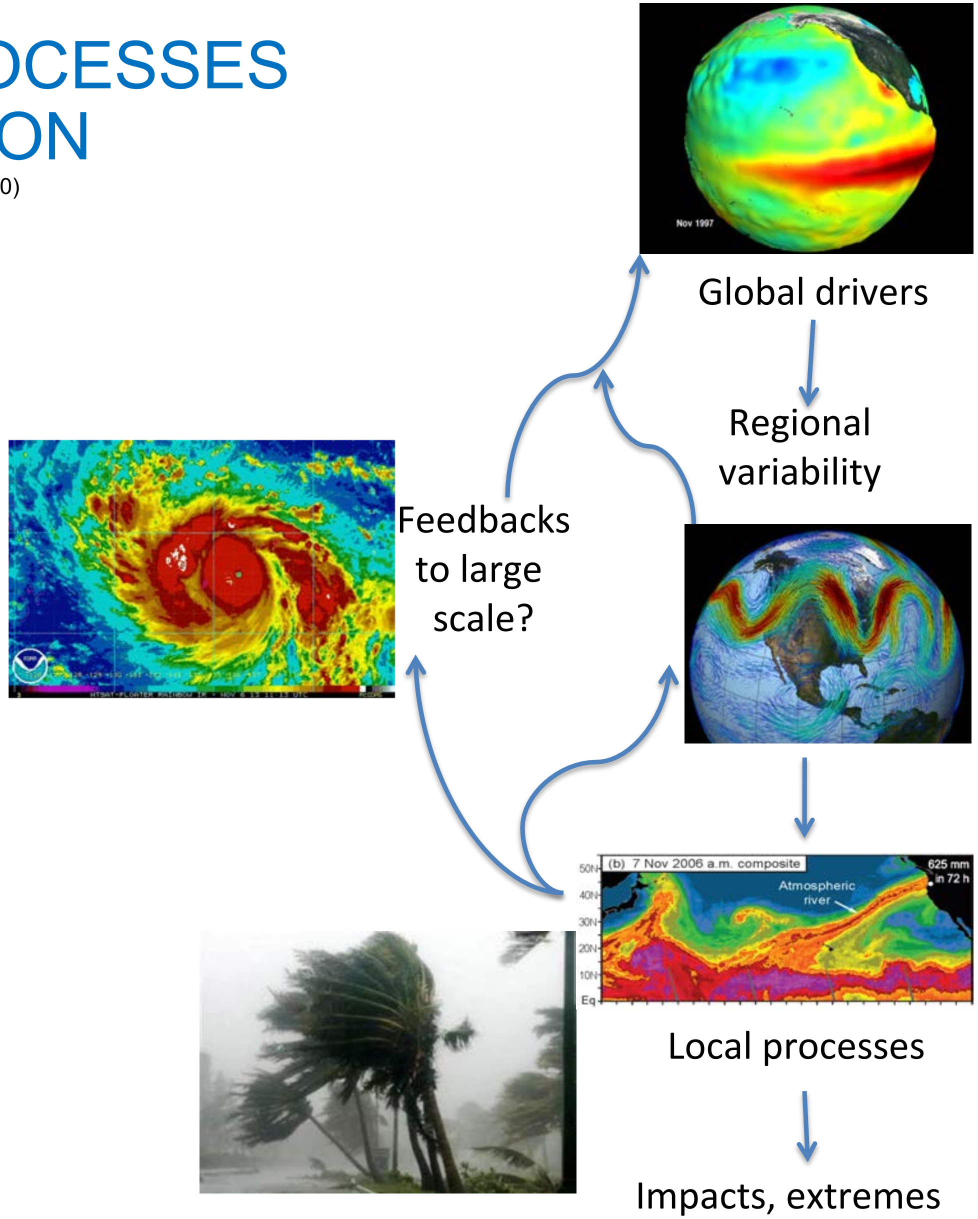
- … it has been robustly demonstrated that increasing resolution leads to systematically more credible simulations of key phenomena, such as El Niño Southern Oscillation (ENSO)[5], Tropical Instability Waves[6], the Gulf Stream and its influence on the atmosphere[7,8], the global water cycle[9], extra-tropical cyclones and storm tracks[10,11], tropical cyclones[12,13], tropical-extratropical interactions[14], and Euro-Atlantic blocking[15,16,17].

Processes at small scales, often in **remote regions of our planet, affect our local/regional weather and climate**

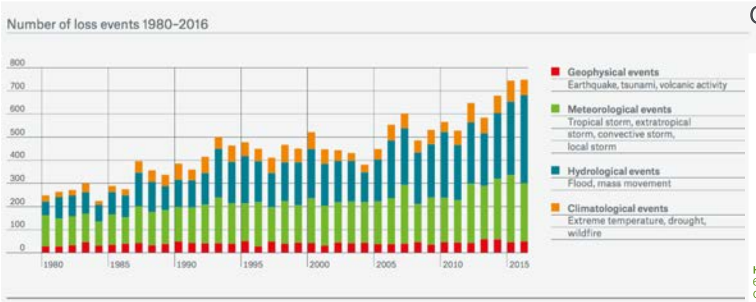
- A continuum of interactions exists between processes at scales from local to global that have a direct impact on European climate. For instance, it has been shown that the Indian monsoon has influence on Southern European summers[18]; that the Madden-Julian Oscillation affects the North Atlantic Oscillation[19]; that a significant number of Atlantic hurricanes undergo extra-tropical transition and morph into storms that impact Europe[14]; that European heat waves are influenced by processes in the Tropical Pacific ocean[20]; that resolving eddies in the Southern Ocean is key to simulating the Meridional Overturning Circulation[23].

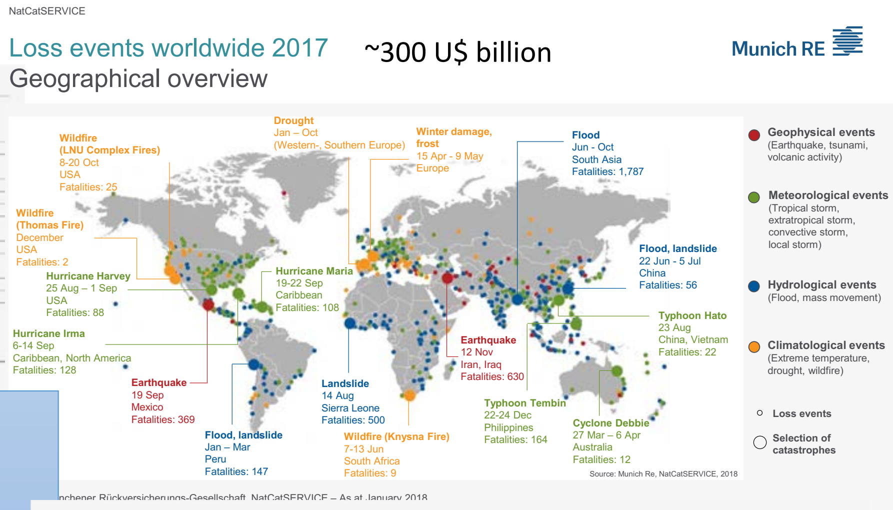
We **cannot really separate the relevant scales without breaking some key mechanistic chains**. Avoiding this danger is computationally expensive…

- In CMIP3 the typical resolution was 250km in the atmosphere and 1.5° in the ocean, while more than seven years later in CMIP5 this had only increased to 150km and 1° respectively. The benefits of higher resolution (~20km) have been abundantly demonstrated, albeit mostly outside the CMIP exercise, so that there has never been a systematic investigation of these benefits in the context of a multi-model assessment.



Recent natural catastrophes: comparing 2011 with other years





~300 U$ billion

Overseas Development work

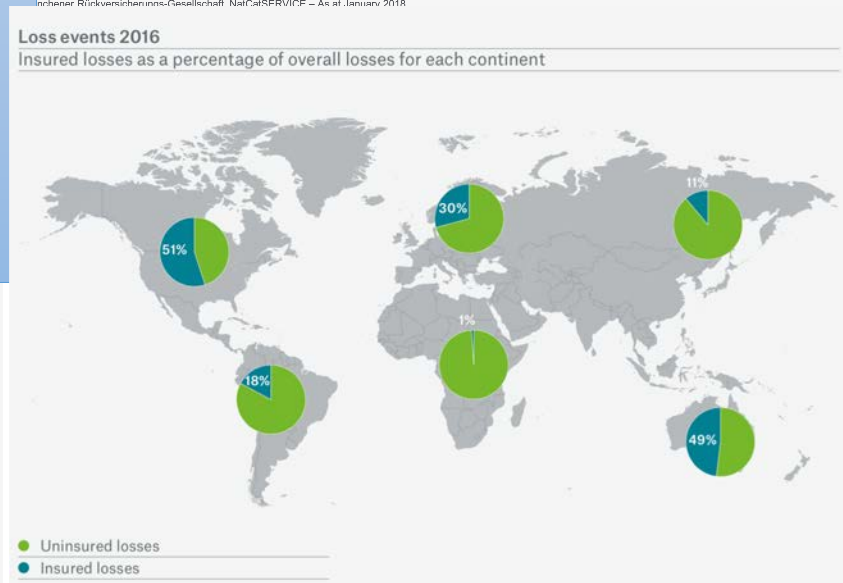
Global annual loss is:

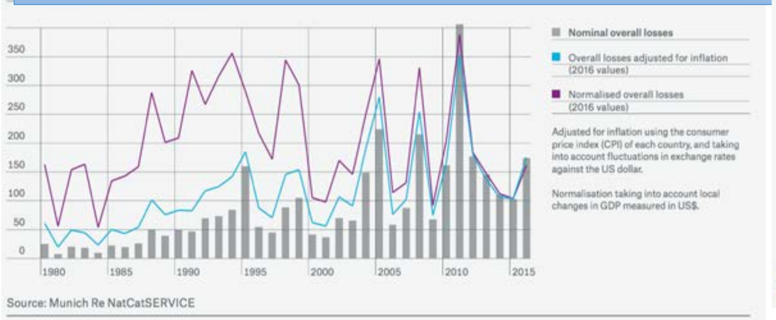
a) Mostly HydroMet

b) Uninsured (2/3)

c) Often governed by non-local processes

d) Located in developing countries, where <u>insurance cannot and will not operate</u>, because there is no suitable evidence base.





Munich Re 2011-2017

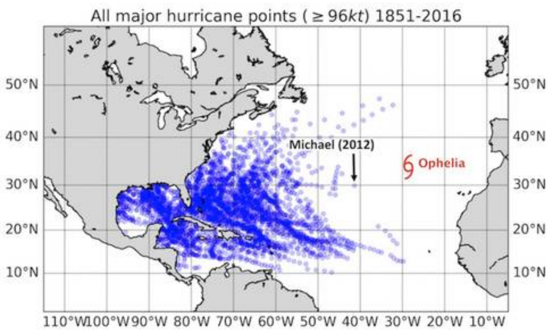
Europe is not just exposed from the financial and our involvement in overseas development aid

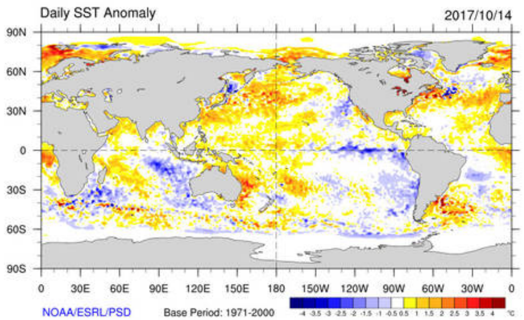
We are also physically at risk

Exactly as predicted by European (HR) climate models, intense cyclones with a tropical origin are, at times, making landfall in Europe. This is very rare, for now…

Post-tropical storm Ophelia (2017)

- Took a very easterly pathway
- Reached <u>category 3 intensity close to Europe</u>.
- Abnormally warm SST's: pattern governed by remote oceanic variability?





R. Haarsma, KNMI

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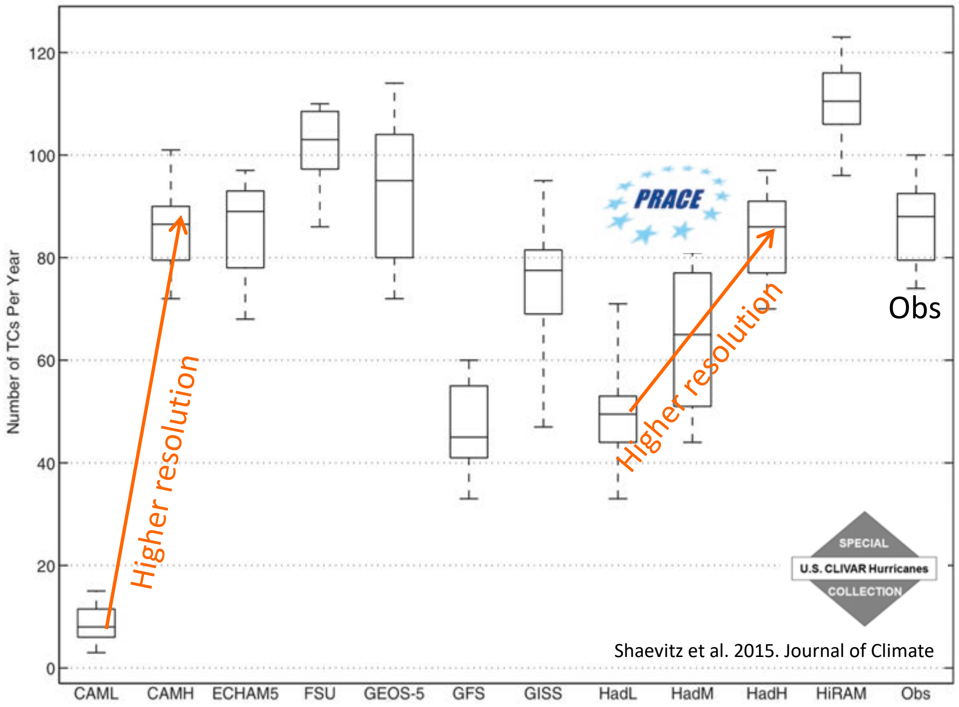
Tropical Cyclones “emerge” at high resolution

From US CLIVAR Hurricane Working Group (2015)



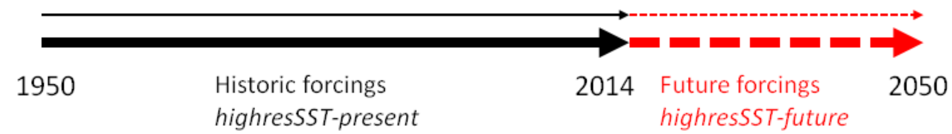
Is this a robust result?

to

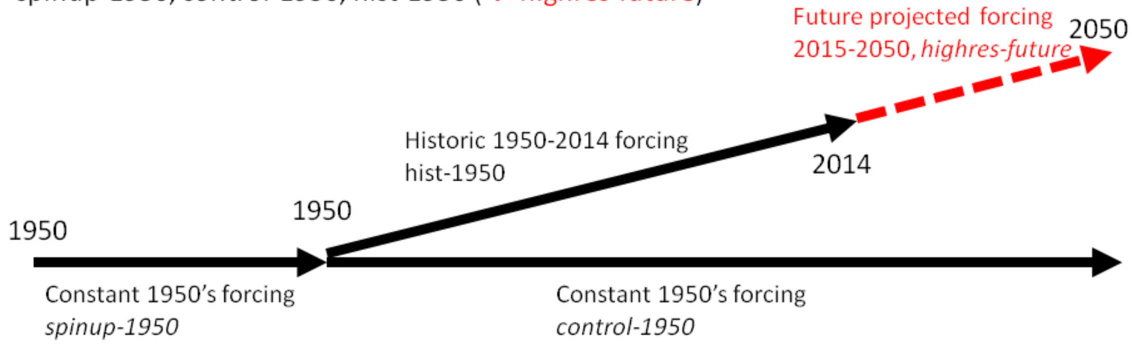
CMIP6-HighResMIP TC simulations

PRIMAVERA, 2018

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



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)



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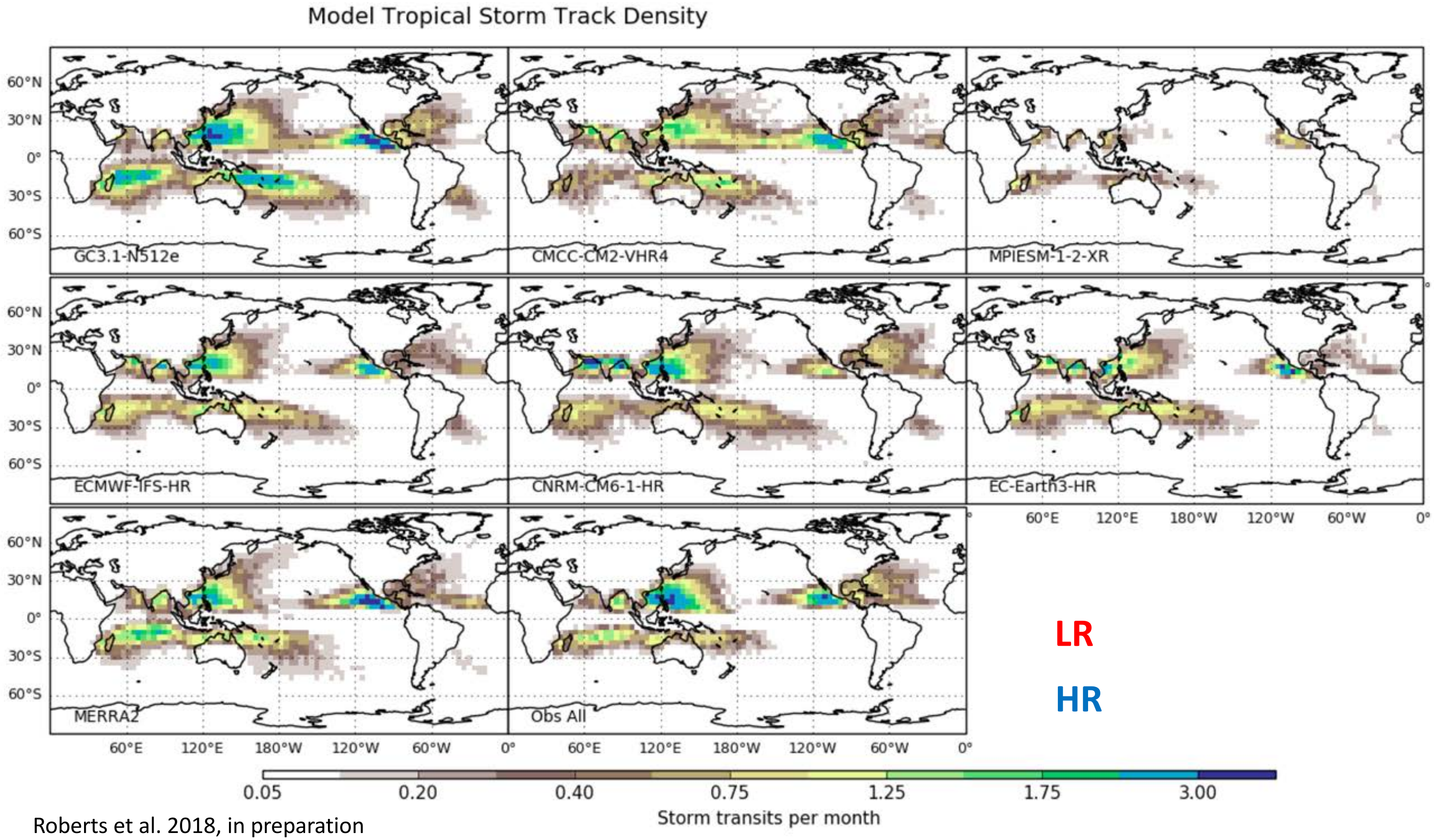
Tropical Cyclone **track density: 65 year climatologies**

(storm transits per month per 4 degree unit area)

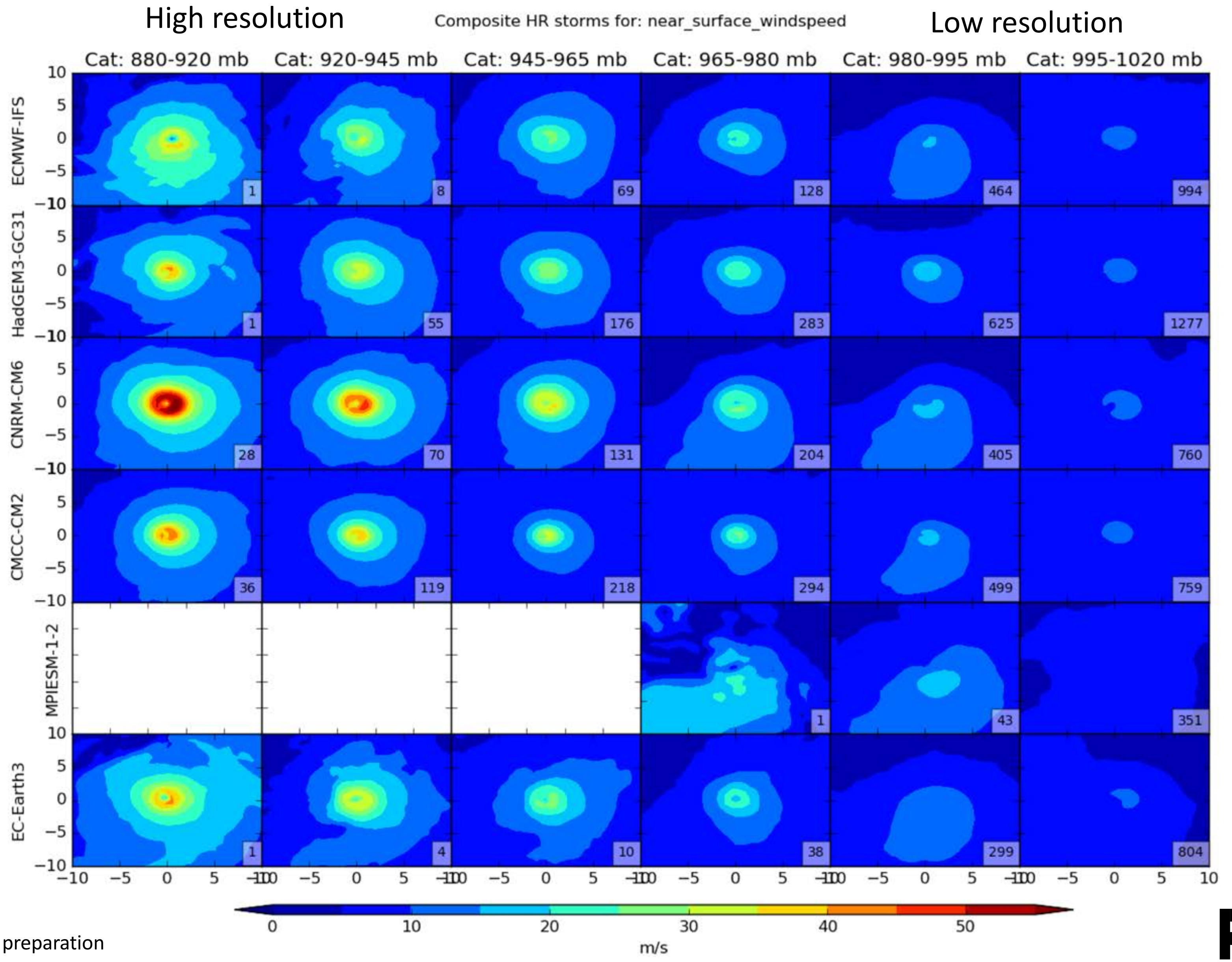


Roberts et al. 2018, in preparation

LR

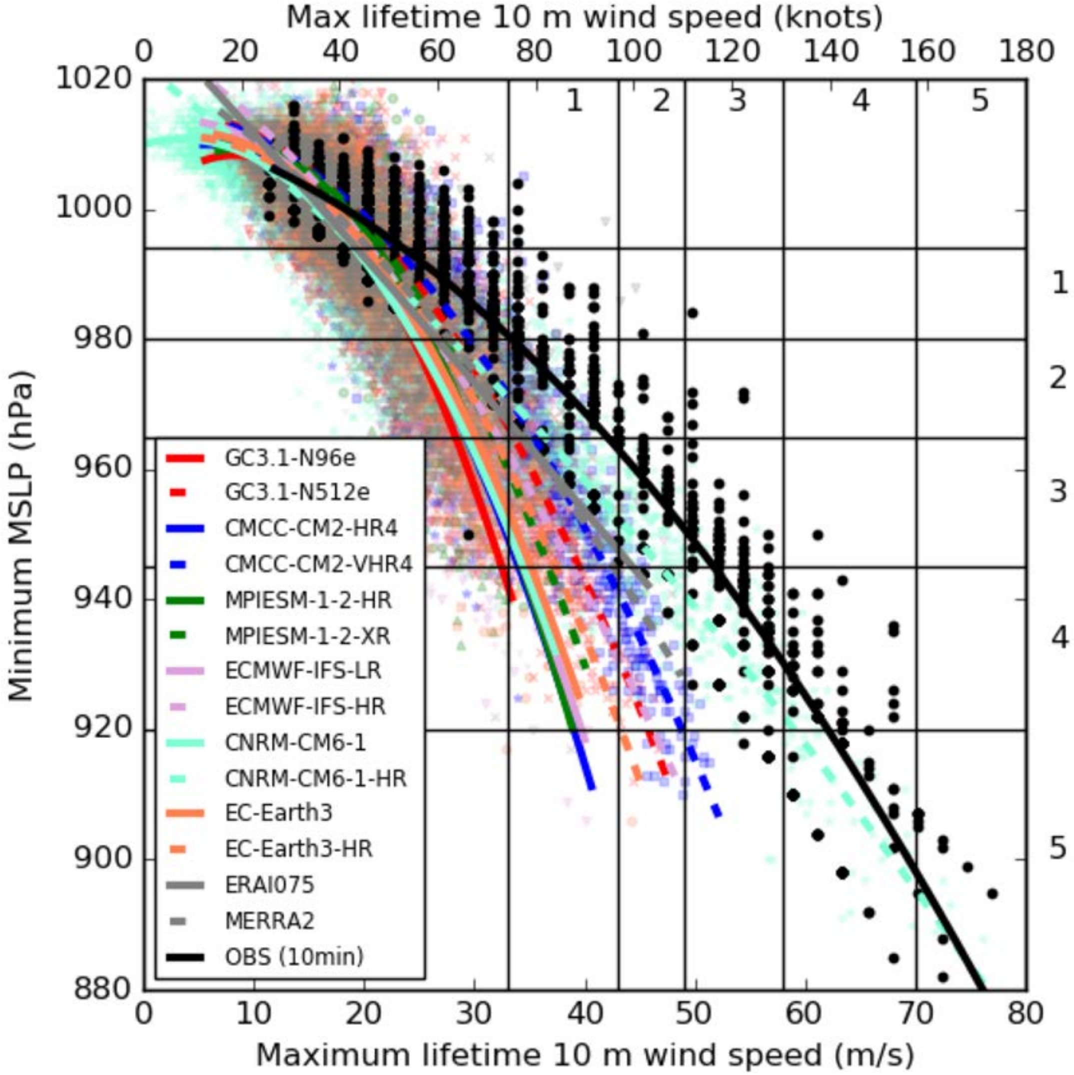
HR

IMAVERA



Roberts et al. 2018, in preparation

TC intensity using MSLP-10m wind
(instantaneous 6 hourly, not max/min over 6 hours)



Continuous lines are coarser GCMs

Dashed lines are higher resolution GCMs

Roberts et al. 2018, in preparation

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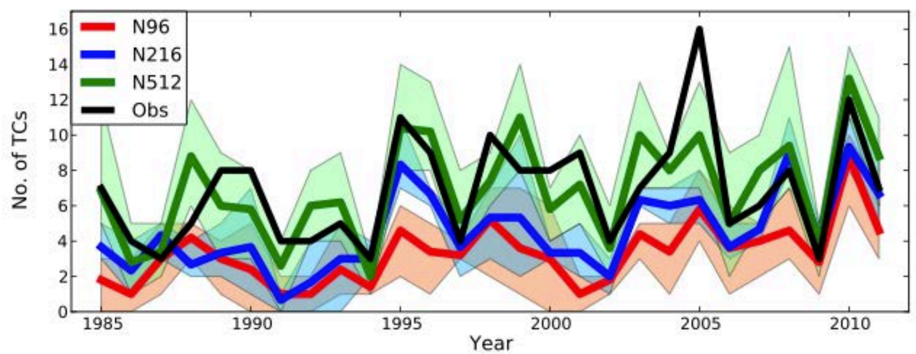
Interannual TC frequency correlation with observations (all/hurr) - 1 member

One of the most important results in the CLIVAR HWG experiment was this: **skill at representing interannual variability improves with model resolution.**

→ Key to seasonal prediction of hurricanes (and typhoons)

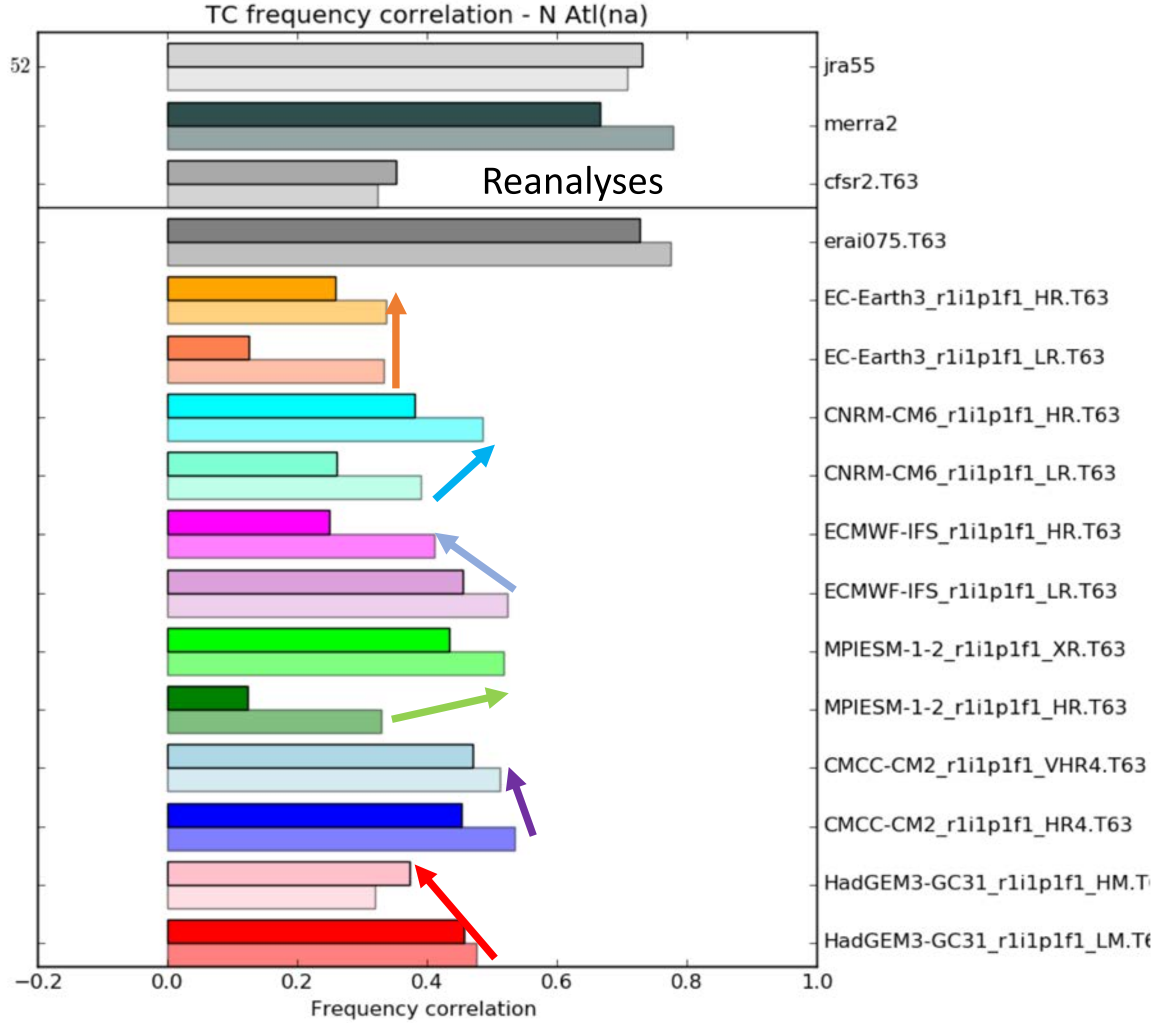
In 2015, as part of our work in the *US CLIVAR Hurricane Working Group*
using our 2012 PRACE-UPSCALE data:

TC frequency, track density and interannual



Roberts et al. 2015. Journal of Climate
Previously also shown in Zhao et al. (2010) and Strachan et al. (2011)

SPECIAL U.S. CLIVAR Hurricanes COLLECTION



Roberts et al. 2018, in preparation

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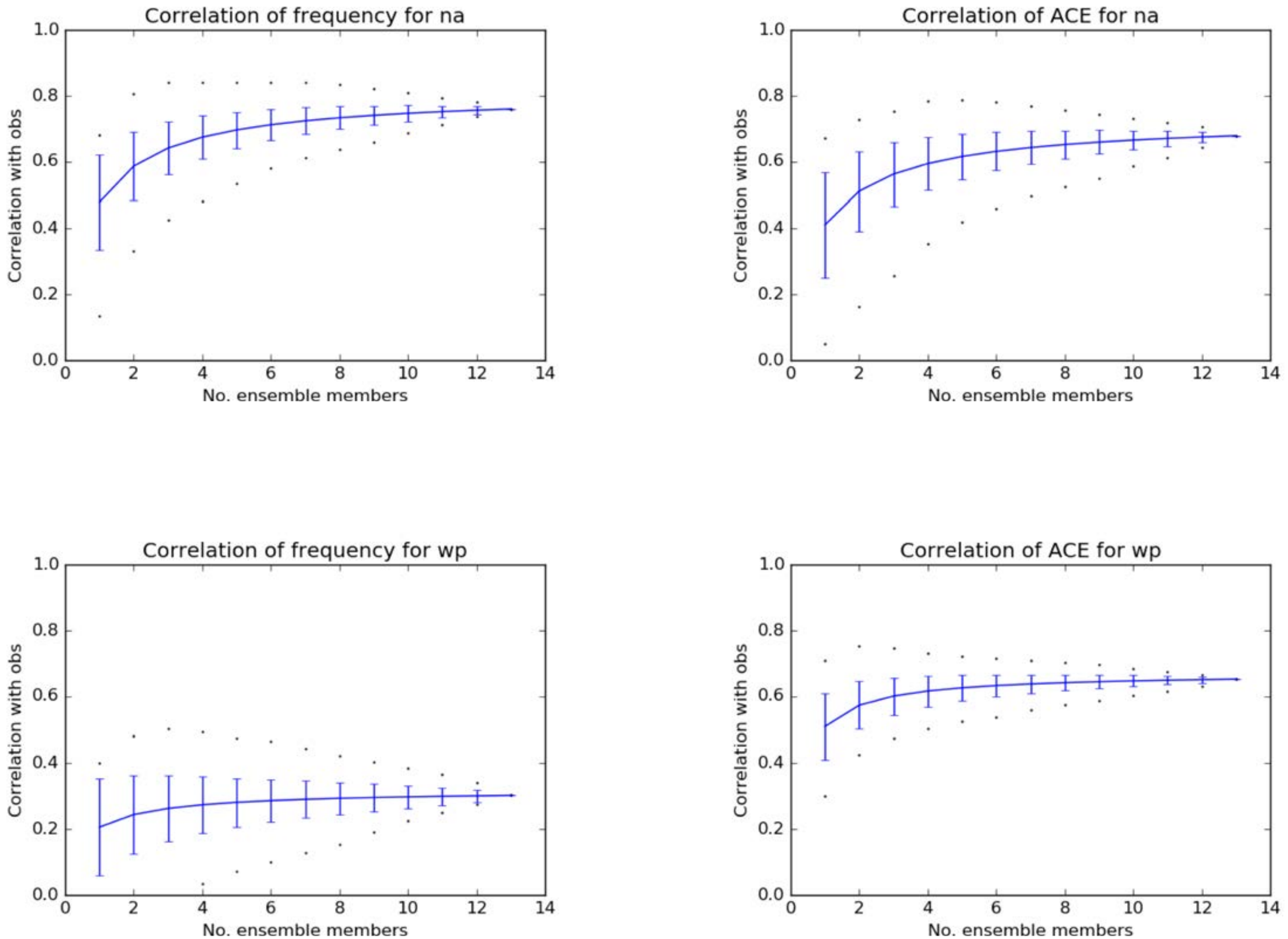
Is using single ensemble members per GCM enough to robustly represent interannual variability?



Roberts et al. 2018, in preparation

<u>Apparently not.</u>

At least **6 ensemble members needed** in the North Atlantic

3-4 ensemble members seem sufficient in the West Pacific.

We do have a heterogeneous ensemble in PRIMAVERA, but also small ensembles of each GCM. → need to revisit IV

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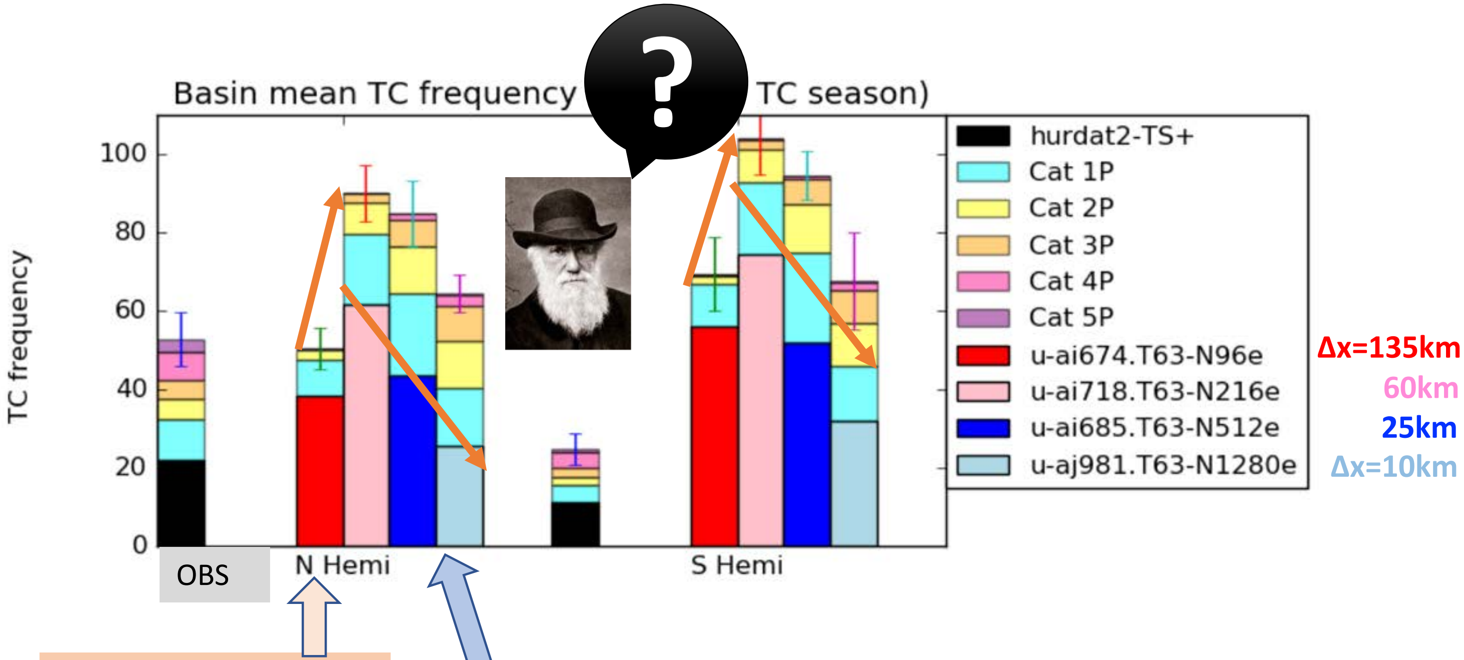
As we started our CMIP6 HighResMIP integrations, TC sensitivity to resolution started to look alarmingly different…



Between 135km and 60km, a familiar, albeit too large jump in frequency

However: from 60km to 10km a reduction towards observed values.

In the **previous generation** of GCMs the number of TCs per year increased with resolution, from nearly zero to the correct number.

This is no longer the case: the behaviour is quite opposite.

The only substantial change is the use of Stochastic Physics.

Questions:

1. is the use of SP spawning weak TCs all over the place?
2. are strong TCs emerging at higher resolution suppressing the too many weak ones?

Vidale et al. 2018, in preparation

A Stochastic Physics – Resolution equivalence?

CMIP6 (HighResMIP) GCMs have evolved since the time of the HWG experiments.

It has been suggesting that the use of Stochastic Physics is equivalent to increasing horizontal resolution

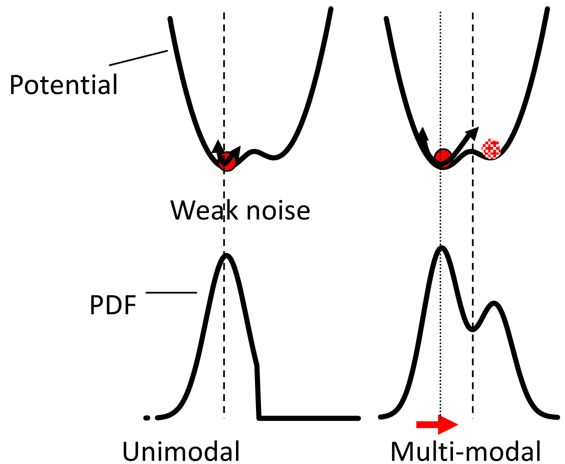
"The right results for the wrong reasons?"

Use of Stochastic Physics

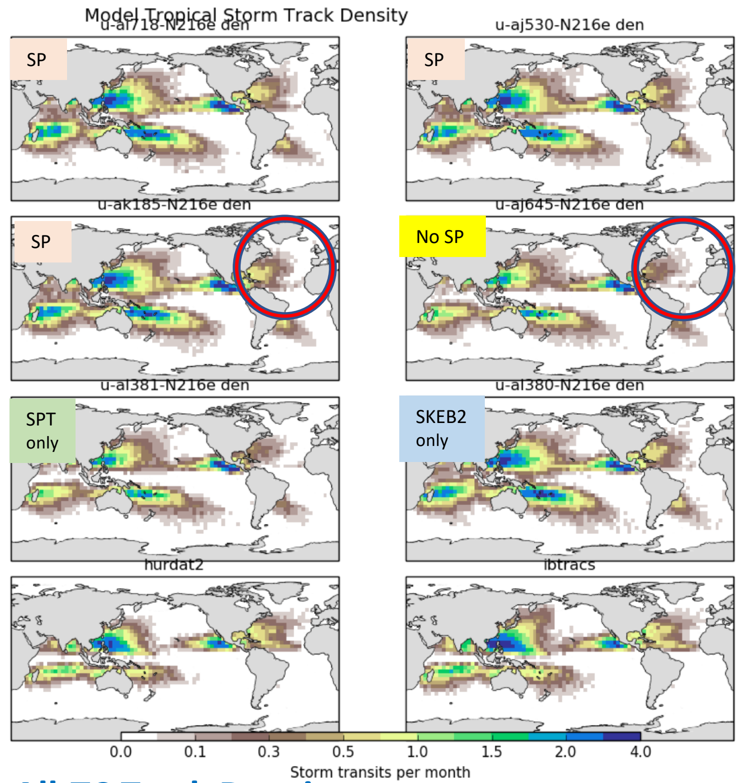
For the UM (PRIMAVERA/HighResMIP):
1. SPT (stochastic perturbation of tendencies)
2. SKEB2 (Kinetic Energy Backscatter)

For EC-Earth (Climate SPHINX):
3. SPPT (Stochastically Perturbed Parameterisation Tendencies)

Interesting for future computer architectures, because some of this can be achieved with custom-built hardware (see research in Tim Palmer's group, Univ. of Oxford)



Impact on TCs?



All-TC Track Density

Vidale et al. 2018, in preparation

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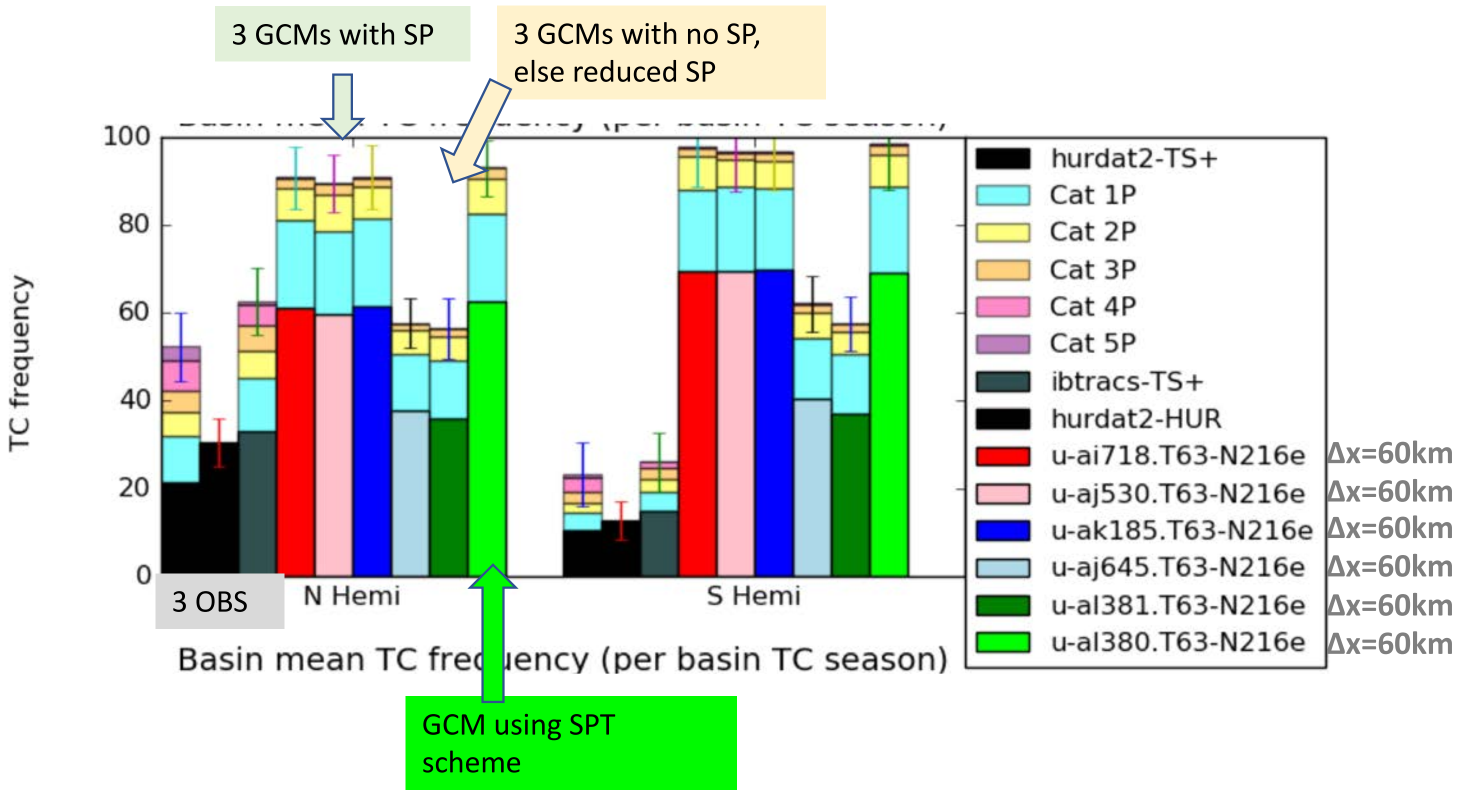
Sensitivity tests to understand the impact of Stochastic Physics on the simulation of Tropical Cyclones.

N216 (60km) UM integrations with and without SP



It is indeed that case that, if we <u>disable Stochastic Physics</u>, the annual TC frequencies go back to observed values, which is what we had in the previous generation of GCMs, in 2015.

Is this a robust result?

Analysis of results from other centres GCMs:

1. ECMWF-IFS in seasonal mode (not shown today)
2. EC-Earth Climate SPHINX

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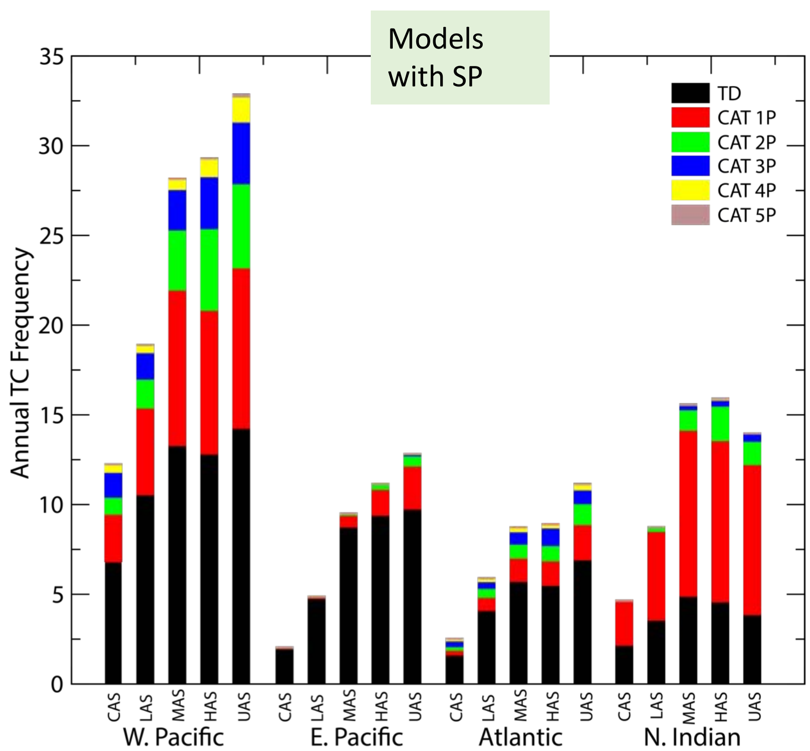
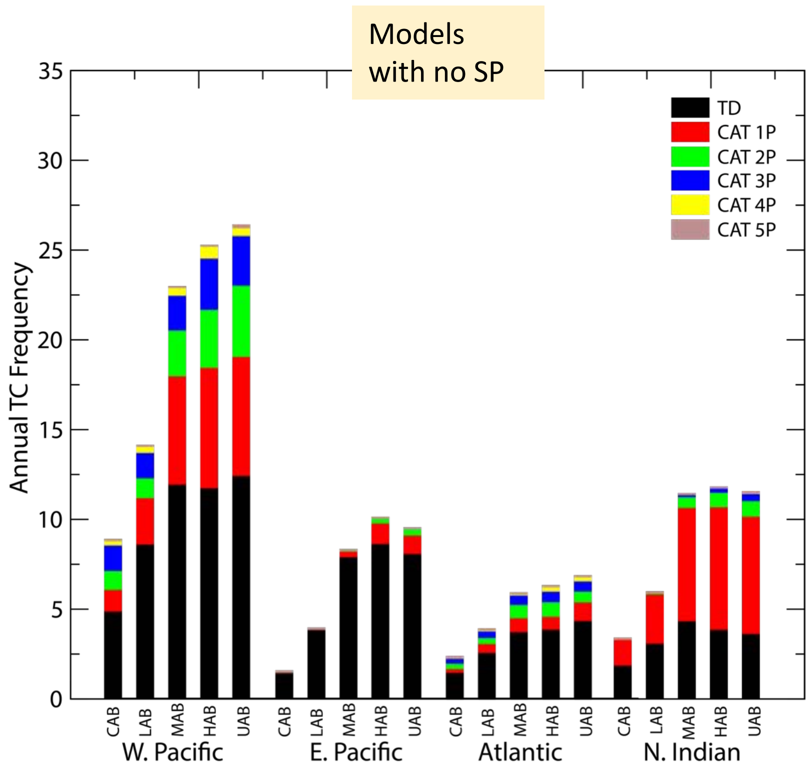
Sensitivity tests to understand the impact of Stochastic Physics on the simulation of Tropical Cyclones.

EC-Earth integrations with and without SP at multiple resolutions





Vidale et al. 2018, in preparation

Similar results:

<u>disabling Stochastic Physics</u>, the annual TC frequencies are reduced by ~30%, **albeit not equally at all resolutions.**

CA: T159	LA: T255	MA: T511	HA: T799	UA: T1279
10 ems	10 ems	6 ems	3 ems	1 em

EC-Earth data from Climate SPHINX, Davini et al. 2017

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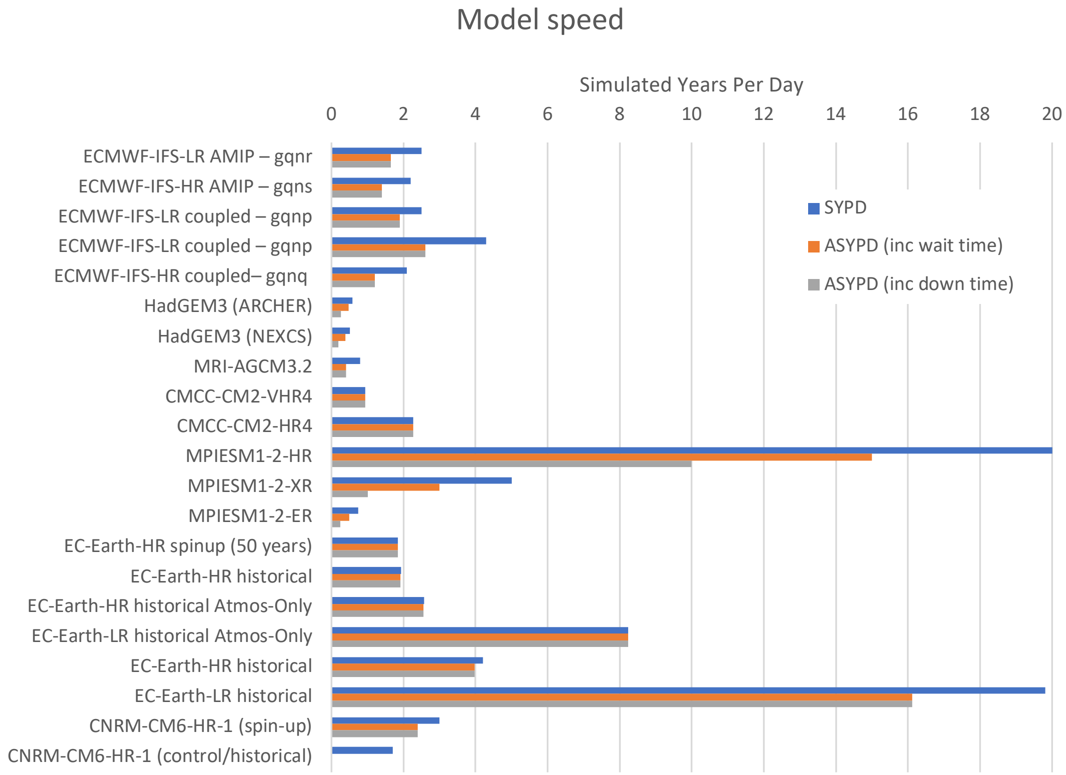
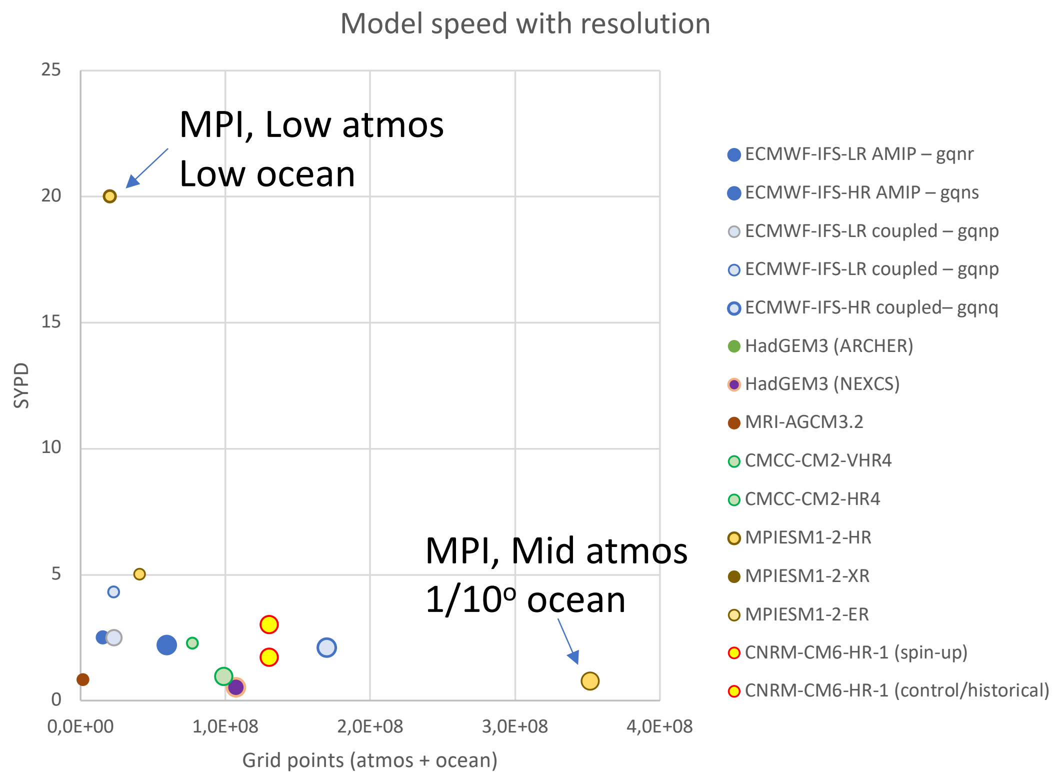
How much does PRIMAVERA cost in HPC?

Simulated Years Per DAY (SYPD)

Our requirement for climate research would be 10SYPD, but historically we have coped with 1 SYPD

In PRIMAVERA/HighResMIP, some of the 20km models are only sustaining 0.5 SYPD





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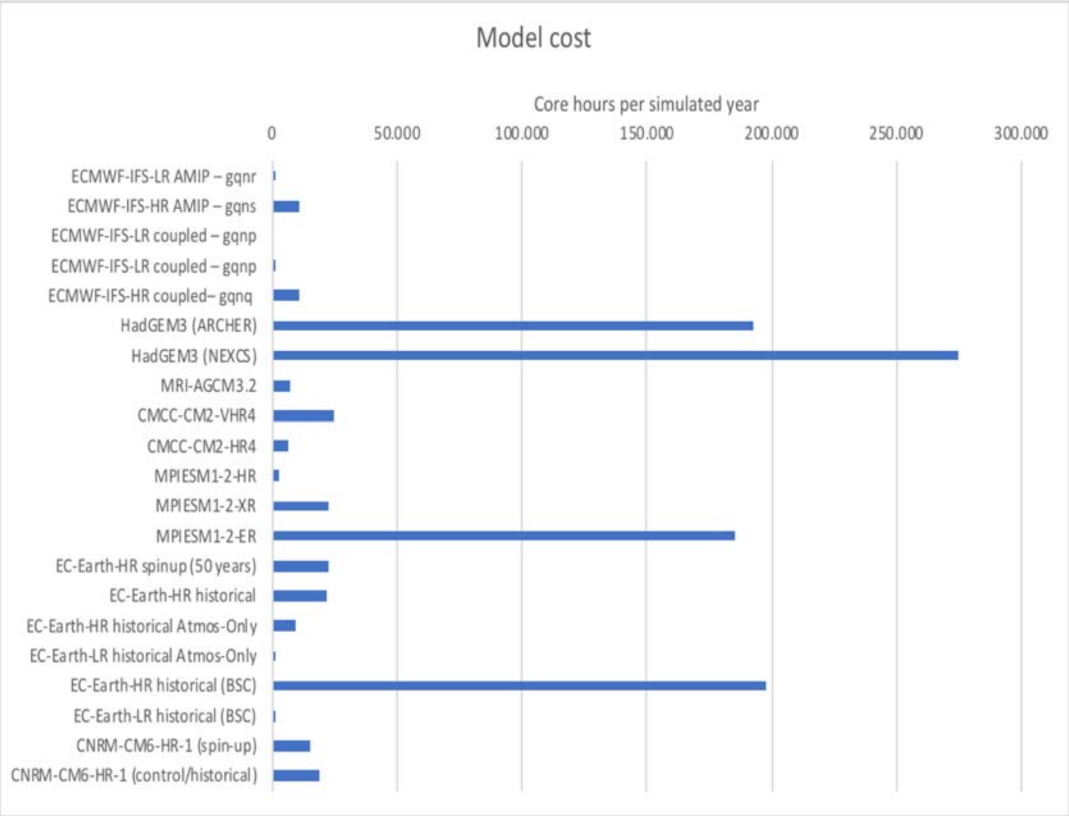
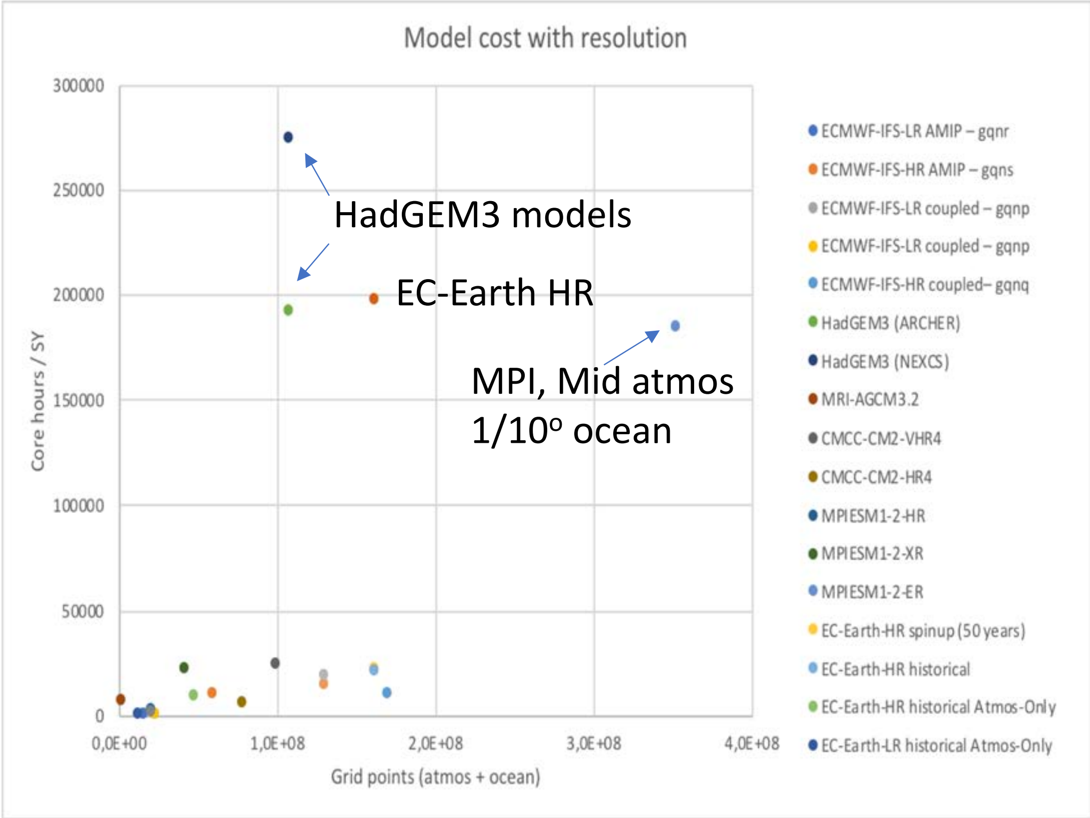
How much does PRIMAVERA cost in HPC?

Core Hours per Simulated Year





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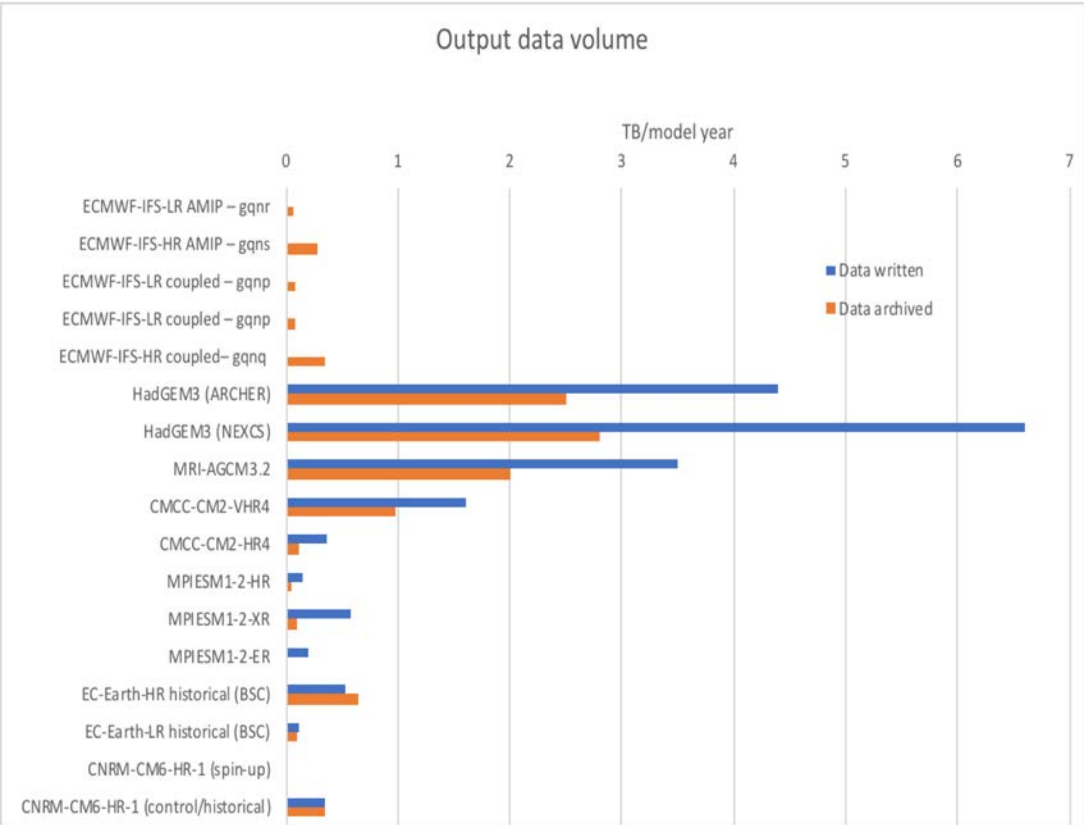
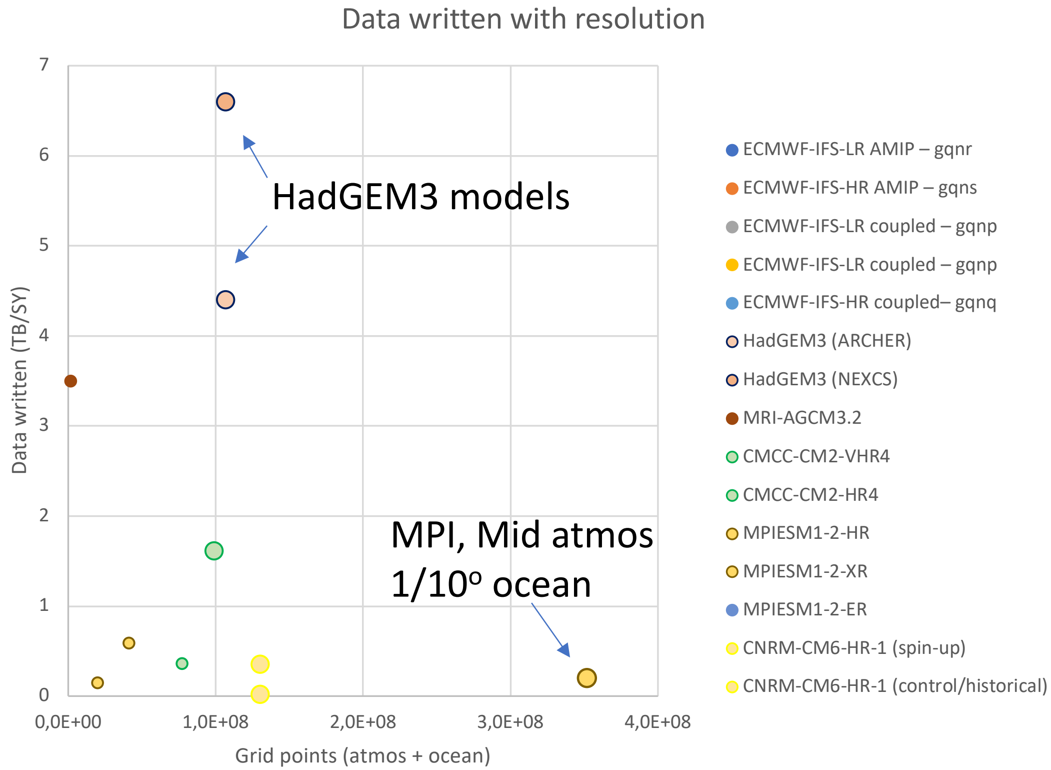
How much does PRIMAVERA cost in HPC?

Output Data Volumes





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How much does PRIMAVERA cost in HPC?
HighResMIP only: 100-20km globally

2017-2018 (1YR)	**85 years of simulation, 2 experiments per group**		
	LR	**HR**	**TOT**
HPC (core hours)			168 million
Written to disk			2.96 PB
Storage			1.46 PB
Energy costs			*~1E12 J = 0.287 GWh (only 2 models so far)*

100 years of simulation, 4 experiments per group	
	TOT
HPC (core hours)	396 million
Written to disk	6.96 PB
Storage	3.43 PB
Energy costs (GWh)	? 5-10 ?

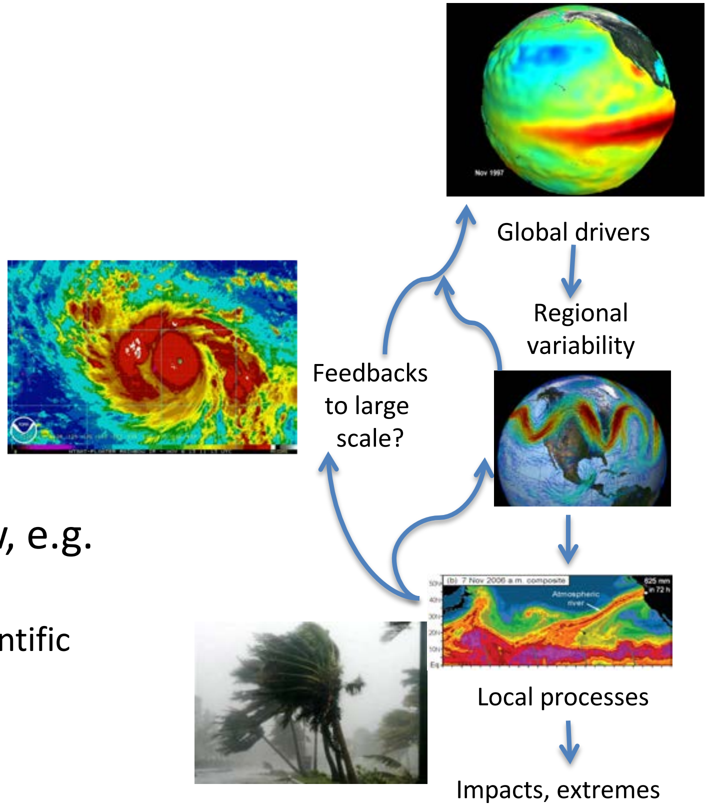
Notes:

1) Still missing data from EC-Earth, AWI.
2) This the MINIMAL protocol: 1 ensemble member per group.
   Some groups (e.g. UK) have run 3 ensemble members
3) We still have 35 additional years to run, then stream 2
4) *Ideally, stream 2 should run ensembles…*
5) ***FRONTIERS SIMULATIONS (5km global are not included)***

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?

  ⇒ need high-resolution global climate simulations over centennial time scales



- HPC costs are widely disparate: much can be attributed to HPC workflow, e.g. adapting to queues, amount of data written to disk etc.
  - 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
    - Extreme Earth
- Scientific leadership:
  - Now leading a new protocol for CMIP6: HighResMIP

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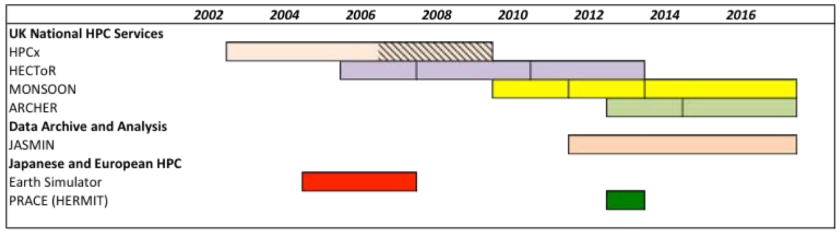
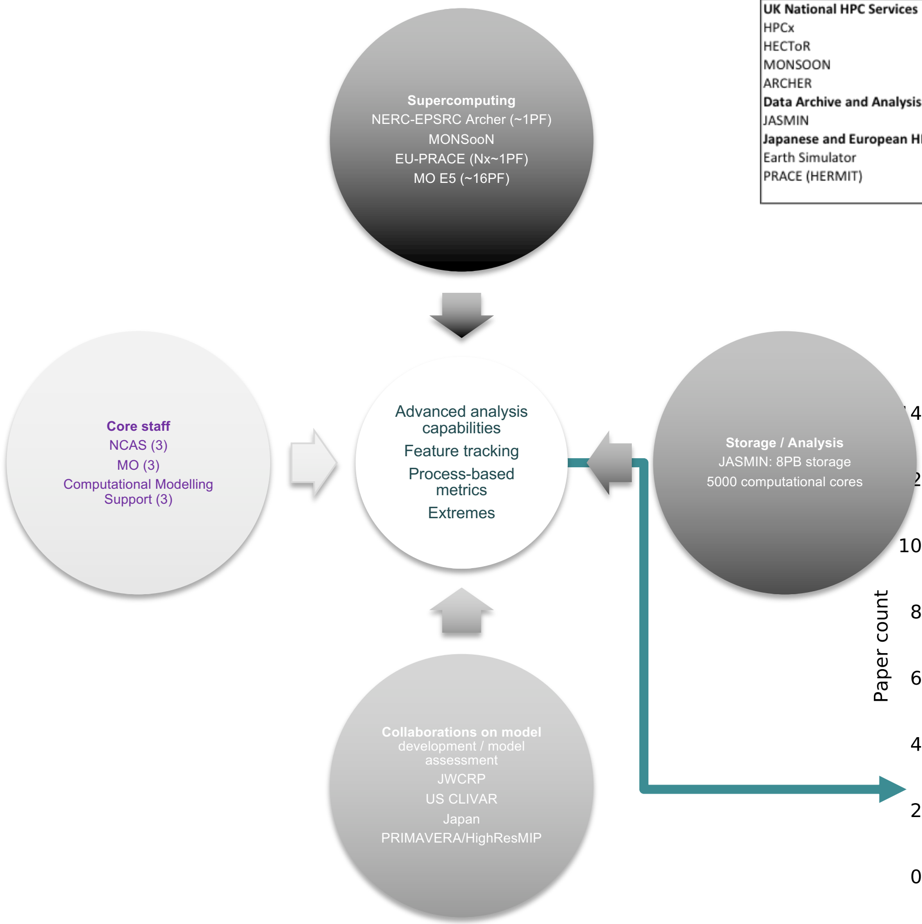
Resources / Investments

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

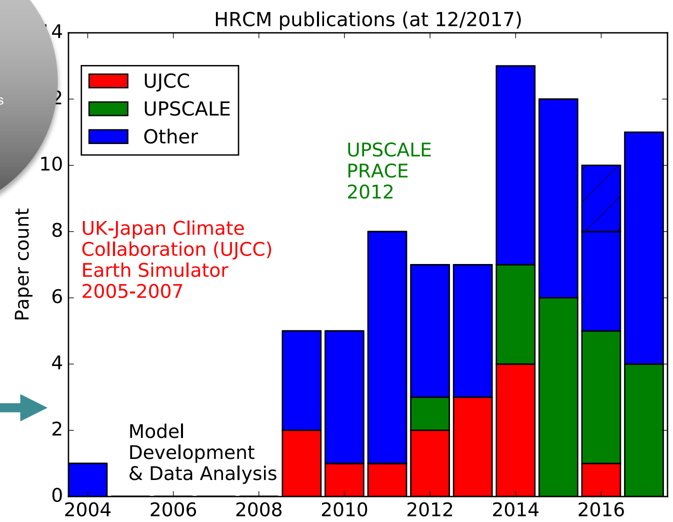
Joint Weather and Climate Research Programme

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.



Models in PRIMAVERA *running* HighResMIP protocol

Institution	MOHC, UREAD, NERC	EC-Earth KNMI,SHMI, BSC, CNR	CERFACS	MPI-M	AWI	CMCC	ECMWF
Model name	HadGEM3 GC3.1	EC-Earth3.3	CNRM-CM6	MPIESM-1-2	AWI-CM 1.0	CMCC-CM2	ECMWF-IFS
Model components	UM NEMO3.6 CICE5.1	IFS cy36r4 NEMO3.6 LIM3	ARPEGE6.3 NEMO3.6 GELATO6.1	ECHAM6.3 MPIOM1.63 MPIOM1.63	ECHAM6.3 FESOM1.4 FESIM1.4	CAM4 NEMO3.6 CICE4.0	IFS cycle43r1 NEMO3.4 LIM2
Atmos dynamical scheme (grid)	Grid point (SISL, lat-long)	Spectral (linear, reduced Gaussian)	Spectral (linear, reduced Gaussian)	Spectral (triangular, Gaussian)	Spectral (triangular, Gaussian)	Grid point (finite volume, lat-long)	Spectral (cubic octohedral, reduced Gaussian)
Atmos grid name	N96 , N216, N512 (L,M,H)	Tl255, Tl511	Tl127, Tl359	T127, T255	T63, T127	1x1, 0.25x0.25	Tco199, Tco399
Atmos mesh spacing 0N	208, 93, 39	78, 39	156, 55	100, 52	200, 100	100, 28	50, 25
Atmos mesh spacing 50N	135, 60, 25	71, 36	142, 50	67, 34	129, 67	64, 18	50, 25
Atmos nominal res (CMIP6)	250, 100, 50	100, 50	250, 50	100, 50	250, 100	100, 25	50, 25
Atmos model levels (top)	85 (85km)	91 (0.01 hPa)	91 (78.4 km)	95 (0.01 hPa)	95 (0.01 hPa)	26 (2 hPa)	91 (0.01 hPa)
Ocean grid name	ORCA	ORCA	ORCA	TP	FESOM (unstructured)	ORCA	ORCA
Ocean res nominal (km)	100, 25, 8 (L,M,H)	100, 25	100, 25	40, 40	50, 25	25, 25	100, 25
Ocean levels	75	75	75	40	47	50	75

6 different atmosphere-only GCMs

7 different coupled GCMs
(though some common components)

Range of resolutions: from 100km to 20km
… and further to sub-10km

HighResMIP: Haarsma et al., GMD, 2016

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