Hurricanes and typhoons in the global climate system

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Motivation: TCs as rare, albeit significant contributors to climate

Re-analyses very likely under-estimating the role of TCs in producing precipitation and moisture transports.

What is the role of model resolution, model physics, DA?
Motivation II: a changing risk from TCs

2017 North Atlantic Hurricane Season

Total storms: 17
- 17 tropical storms (39+ mph)
- 10 hurricanes (74+ mph)
- 6 major hurricanes (111+ mph)

Accumulated Cyclone Energy (ACE) index = 226

Thanks to Jo Camp
TC observations are just a mess... (K. Hodges, 2018)

Number of storms each year for the IBTrACS (NH) (pressure)

P. Loizou, 2018, unpublished
There is a constant effort to re-visit and complete TC observations.

Analyses of long time series (basically NATL) show that substantial decadal variability is present and needs to be considered in risk estimates and management actions.

Vecchi and Knutson 2008

Careful with fitting linear trends...

Vecchi and Knutson 2011
Main finding: re-analyses are able to credibly reproduce TCs in the higher categories, but are challenged in the TD, TS and CAT1 categories.

We created a complementary TC database that can be used to assist risk assessment, by:
1. increasing the sample size and
2. providing physically based estimates of model uncertainty.
There is no trace of TC trends in the re-analyses: Re-analyses are inherently wrong, but consistent!
There is no trace of TC trends in the re-analyses: there is, however, substantial and interesting variability

IBTrACS

ERA1

MERRA

MERRA2

NCEP

JRA25

JRA55

NA NORTH ATLANTIC (P)

WP WEST PACIFIC (P)
Power spectra of TC time series in different basins, from 3 data sets

IBTrACS, NCEP, JRA55

**NATL**

**EPAC**

**CPAC**

**WPAC**

**NIND**

**TOTAL**

P. Loizou, 2018, unpublished
Natural variability of TCs

Some evidence of TC variability in the ENSO frequency range. There is also evidence of decadal variability, but the time series are too short for robustness.

Can GCMs help in understanding whether or not this is a robust feature of the climate system?
Natural variability of TCs

North Atlantic

Some evidence of TC variability in the ENSO frequency range. There is also evidence of decadal variability, but the time series are too short for robustness.

Can GCMs help in understanding whether or not this is a robust feature of the climate system?
Tropical Cyclones “emerge” at high resolution

Results finally confirmed by the US CLIVAR Hurricane Working Group (HWG), via a systematic multi-model intercomparison:

- TC tracks and interannual variability in frequency are credibly represented at 20km;
- however, intensity is still underestimated by some of the GCMs at this resolution
- HRCM played a strong role in the first HWG; even stronger role in next phase

Distribution of the number of TCs per year
ENSO-TC: track density anomalies

Match well

Overpronounced variability

Bell et al. J. Clim 2012
TCs and ENSO in CLIVAR HWG exercise

Figure 11. Difference of TC genesis density in El Niño and La Niña in models and observations. The genesis density is defined as the mean TC formation per $5^\circ \times 5^\circ$ box per year.

From Shaevitz et al. 2014
PRIMAVERA: decadal variability in unforced runs

M. Roberts, P. L. Vidale, K. Hodges, unpublished
Both NA and WP basins exhibit **TC variability in the decadal range**, for periods of up to 50 years.

These two simulations impose constant anthropogenic forcing, that is: we have denied the climate change of the last 65+ years.

The existence of such natural variability makes the interpretation of climate change complicated.
Variability of TC ACE in GCMs forced with high resolution SSTs (HadISST2.2)
What will happen to TCs in the future?

Typhoons will migrate poleward … and a NA hurricane reduction

Fig. 2. Tropical cyclone track density, same as figure 1, for (a) HiGEM present-day simulation (b) The same as for (a) but North Atlantic (c) 2CO2 - present-day simulation (d) North Atlantic 2CO2 - present-day simulation (e) 4CO2 - present-day simulation and (f) North Atlantic 4CO2 - present-day simulation. Stippling shows where changes are outside the range of 5×30-year present-day simulations.

Bell et al. J. Clim. 2012, idealised HiGEM simulations

GPI-based estimates agree in the Pacific, albeit not in the Atlantic

2012 UPSCALE MODELLING CAMPAIGN

GPI

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.

Roberts et al. 2015. Journal of Climate, RCP 8.5 scenario
Tropical Cyclones “emerge” at high resolution

From US CLIVAR to CMIP6-HighResMIP TC simulations

Hurricane Working Group (2015)

Our main question: is this a robust result? We need a multi-model, multi-resolution, ensemble approach

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

1950 Historic forcings highresSST-present 2014 Future forcings highresSST-future 2050

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)

Constant 1950’s forcing control-1950

PRIMAVERA, 2018

Shaevitz et al. 2015. Journal of Climate
Models in PRIMAVERA running HighResMIP protocol

<table>
<thead>
<tr>
<th>Institution</th>
<th>MOHC, UREAD, NERC</th>
<th>EC-Earth KNMI, SHM, BSC, CNR</th>
<th>CERFACS</th>
<th>MPI-M</th>
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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
Tropical Cyclone **track density**: 65 year climatologies (storm transits per month per 4 degree unit area)

![Model Tropical Storm Track Density](image)

Roberts et al. 2018, in preparation
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

HadGEM3, from 100 to 10km resolution

Roberts et al. 2018, in preparation
It seems that at higher resolution the models tend to have a larger increasing trend in precipitation per TC and a larger decreasing trend in the number of tropical cyclones days per year.

What are the mechanisms by which resolution influences the latter?
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 variability are credibly represented at 20km.

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

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)

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

Roberts et al. 2018, in preparation
Is using single ensemble members per GCM enough to robustly represent interannual variability?

Multiple GCM resolutions of ensembles, 2 tracking algorithms

At least 6 ensemble members needed in the North Atlantic to understand skill in simulating interannual variability.

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.
Summary

• We have made substantial progress in understanding the role of resolution (dynamics) in the representation of the hydrological cycle in GCMs. As we increase resolution:
  — less water is recycled on land and more water is transported from ocean to land
  — the role of physical parameterisations is therefore reduced
  — cyclones play a role, but so do mountains
• Tropical Cyclones emerge in high-resolution GCMs:
  — The good and the bad:
    • 50-20km resolution: credible representations of track density and interannual variability
    • Structures are credible at ~20km, but TCs still too large in most GCMs.
    • Intensity at ~20km still not sufficient to capture all CAT4,5 in most GCMs (but there are notable exceptions with full spectrum represented)
    • We need ensemble size of at least 5 to robustly represent interannual variability
  — TC-ENSO relationship credibly represented in historical simulations
  — Poleward shift of TCs seen in climate change projections by GCMs capable of resolving TCs
• We are working towards sub-10km GCMs: expect better skill in terms of intensity.
• Much work left to do on post-tropical cyclones, extra-tropical transition, structures, etc.
Precipitation attributed to Post-Tropical Cyclones (from ERA-I)

**METHOD:**
Cyclone-associated precipitation is computed by defining 10° radial caps around PTC centres at 6-hourly timesteps (following Hawcroft et al., 2012).

**METHOD:**
Attribute 6-hourly heavy precipitation events (95th percentile exceedances) to PTC transits (following Pfahl and Wernli, 2012).

- **PTC-associated precipitation**
- **PTC contribution to total precipitation**
- **Fraction of 95th percentile exceedances attributable to PTCs**