Hurricanes and typhoons in the global climate system

Pier Luigi Vidale [1],

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all PRIMAVERA partners (models and analysis)

With many thanks to Suzana Camargo, Tom Knutson and Jim Kosssin

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[3]Koninklijk Nederlands Meteorologisch Instituut (KNMI),
[4]Centro Euro-Mediterraneo sui Cambiamenti Climatici S.c.a.r.l (CMCC),
[5]Barcelona Supercomputing Center (BSC), Barcelona, Spain,
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Co-funded by the European Union

Motivation: TCs as rare, albeit significant contributors to climate

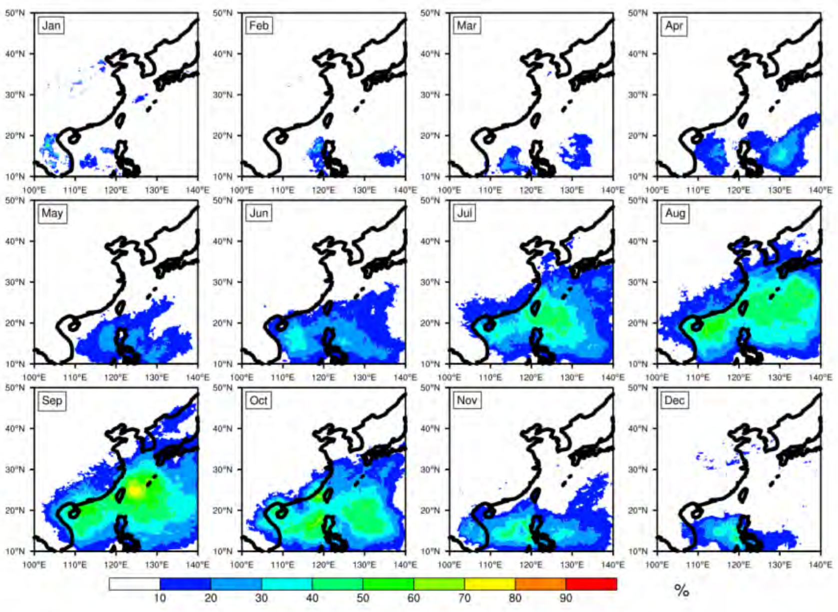


FIG. 2. Monthly mean fractional contribution of TC rainfall amount to the total rainfall calculated using TRMM 3B42 rainfall data. Units: %.

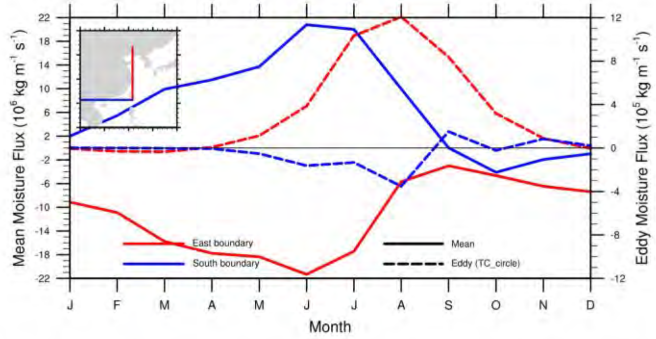
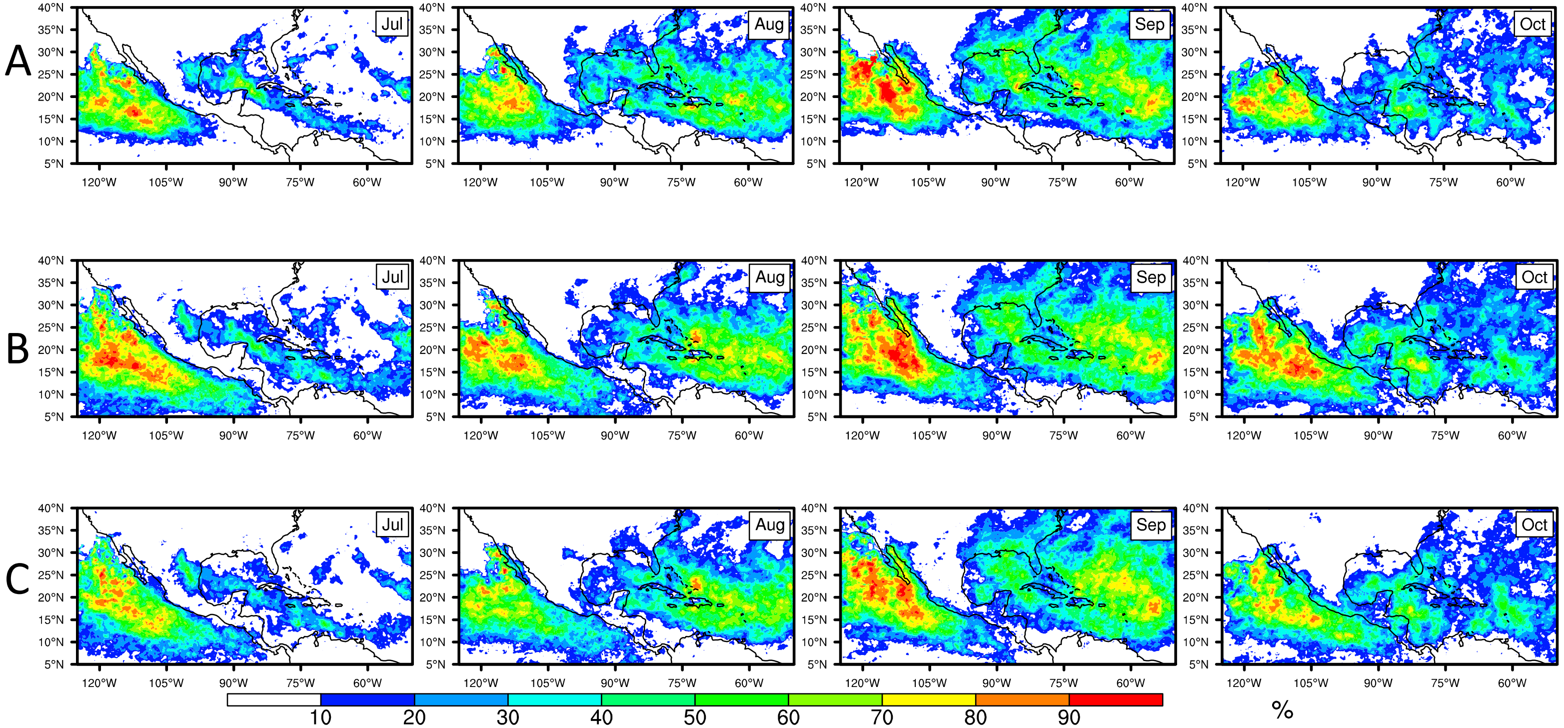


FIG. 5. Seasonal cycle of monthly mean vertically integrated moisture flux passing through the southern (blue) and eastern (red) boundaries. Mean flow moisture fluxes are shown as solid lines and TC eddy moisture fluxes as dash lines. The inner panel shows the definition of the southern and eastern boundaries.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

Guo et al. 2017



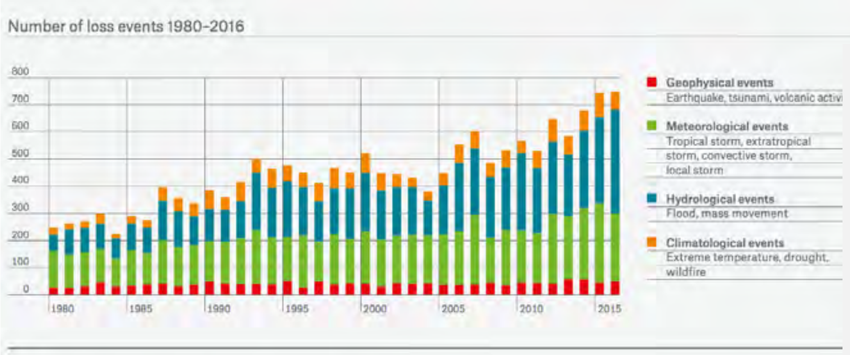
Contribution of TCs to the extreme rainfall (amount fraction) (%) from July to October, employing TCs tracks from (a) IBTrACS, (b) JRA-55 and (c) ERA-Interim. **Climatology for 1998-2015**

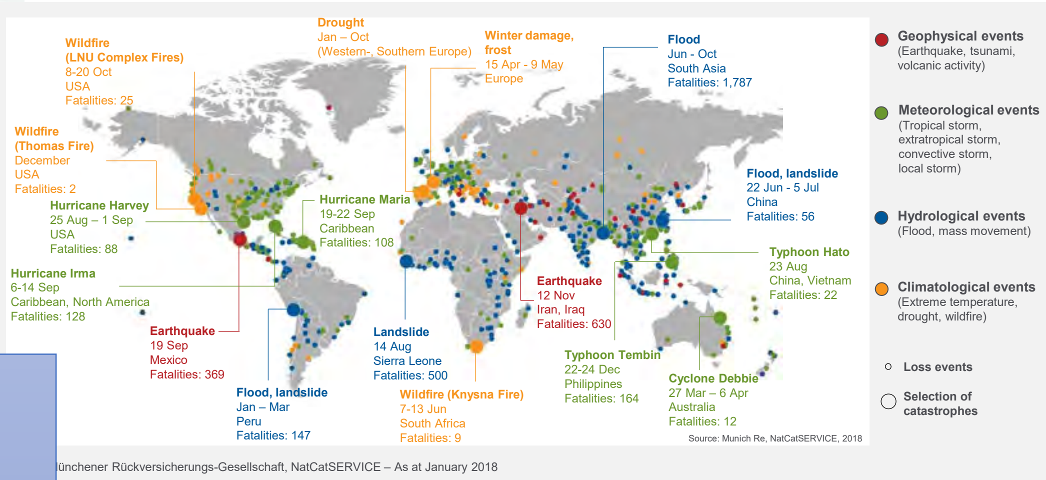
Franco-Diaz et al. 2019, submitted to Clim Dyn

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

What is the role of model resolution, model physics, initialisation (Data Assimilation)?

Recent natural catastrophes: comparing 2011 with other years



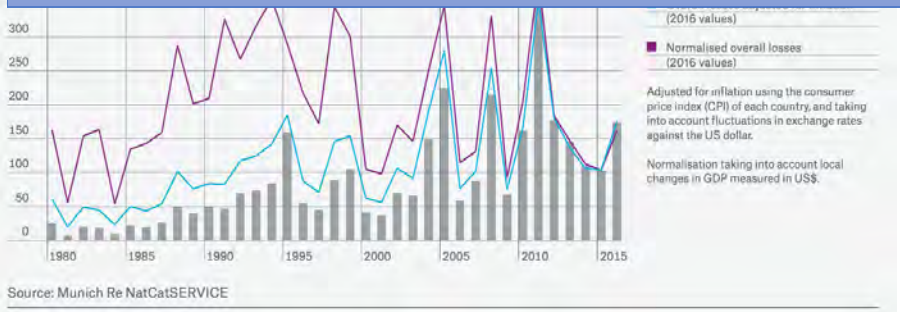


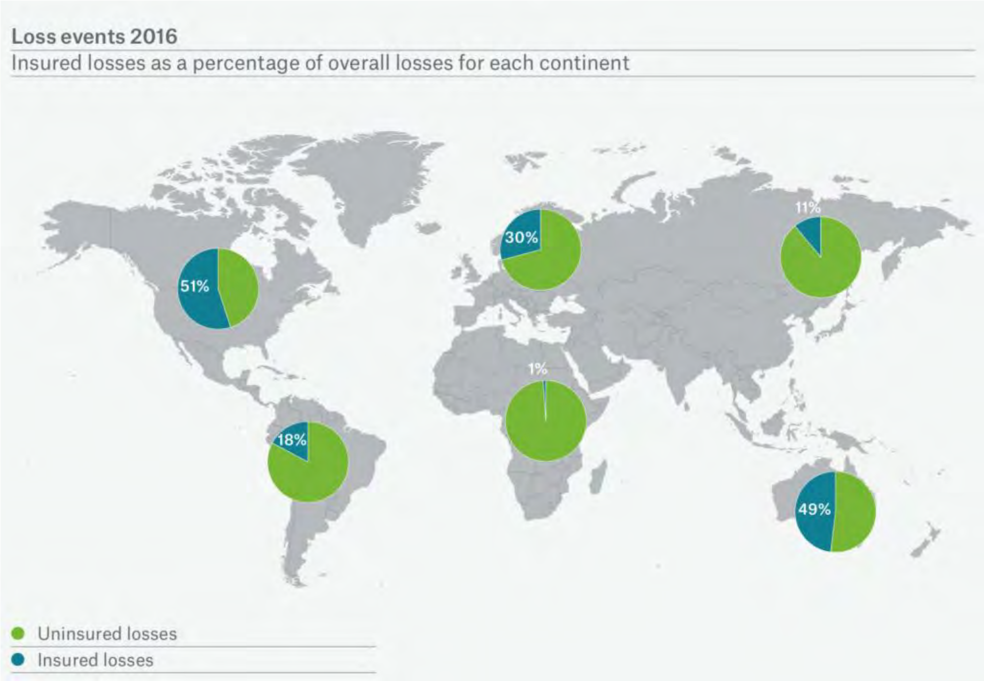
~300 U$ billion

Overseas Development work

Global annual loss is:

a) Order of 100 billion U$ each year
b) Mostly HydroMet
c) Uninsured (2/3)
d) Often governed by non-local processes
e) Located in developing countries, where <u>insurance cannot and will not operate</u>, because there is no suitable evidence base.

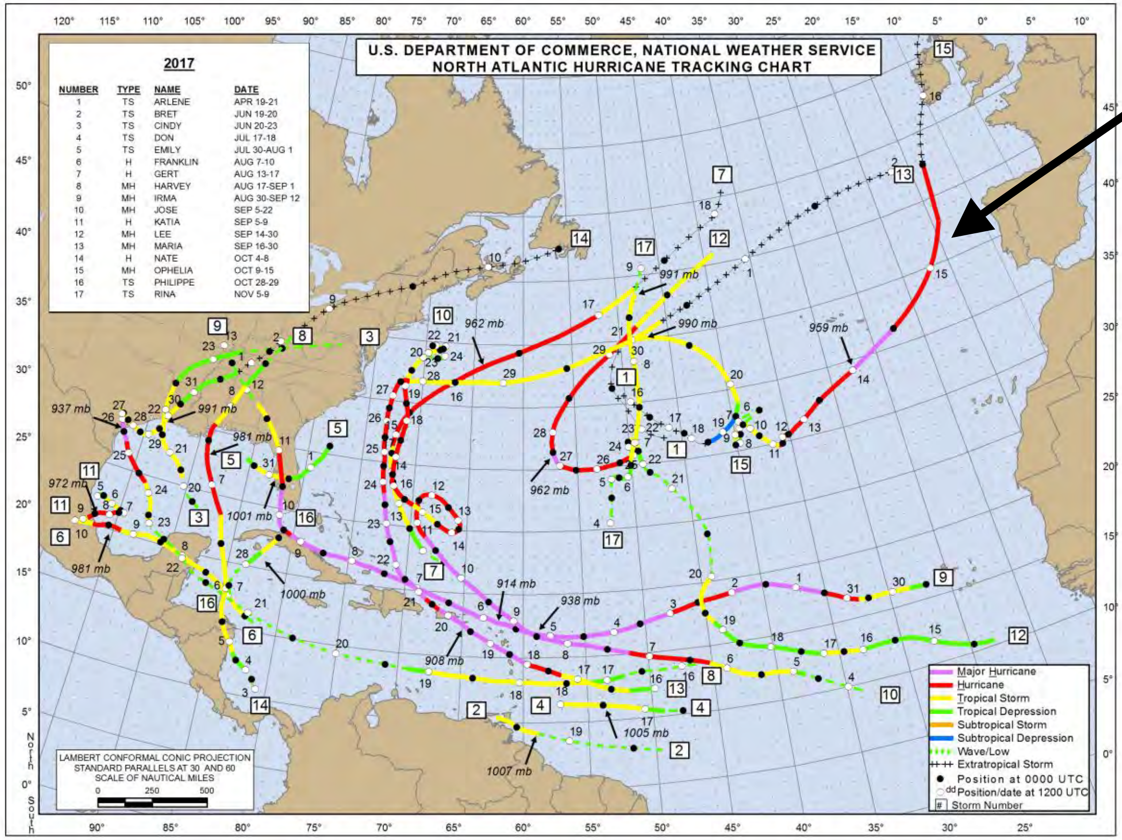


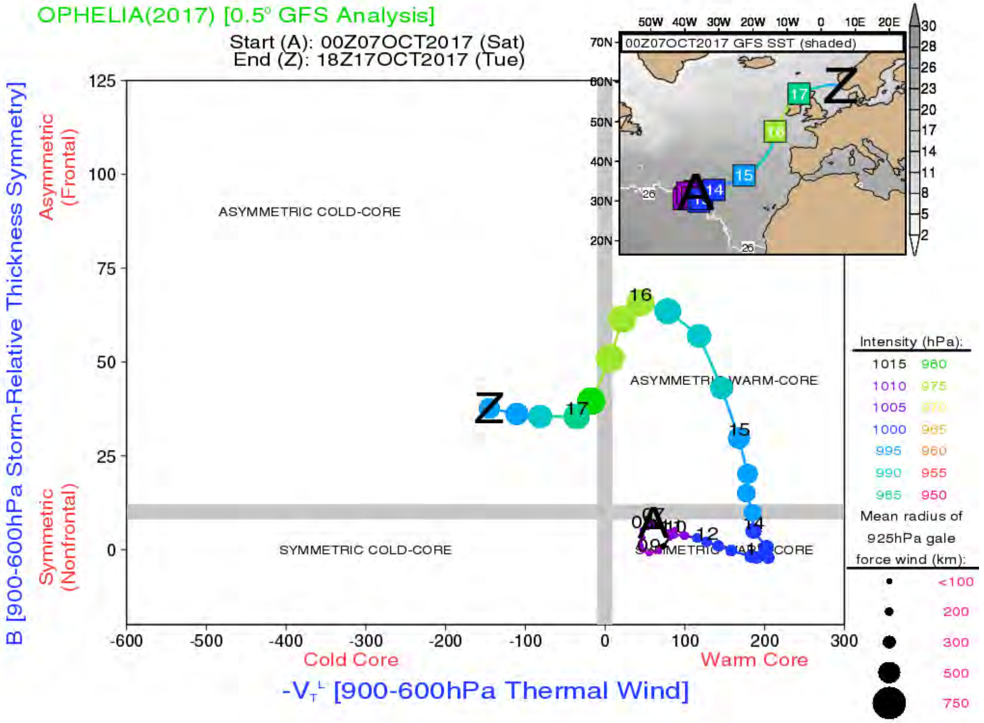


Munich Re 2011-2017

Europe example: ex-hurricane Ophelia (2017)

The easternmost Atlantic hurricane on record caused three fatalities and $65 million insured damages.






Cornwall, south-western UK (BBC)


County Kerry, Ireland (Irish Examiner)

Tropical-to-extratropical transition of cyclones exposes mid-latitude regions to hurricane-type hazards.

Early GCM studies: 70s-80s

"Hurricane-type vortices"

580 JOURNAL OF THE ATMOSPHERIC SCIENCES VOLUME 27

Tropical Circulation in a Time-Integration of a Global Model of the Atmosphere

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(Manuscript received 30 December 1969, in revised form 20 March 1970)

This is not in anyway a surprise, since the horizontal and vertical resolutions which are used in large-scale numerical models cannot satisfactorily describe the small-scale features of these phenomena. However, tropical cyclones have occasionally been observed to have dimensions over 2000 km, in particular in the western North Pacific. See for example the study of the super typhoon Tip (Dunnavan and Diercks, 1980). A numerical model with a resolution of 3° or less would therefore have the potential possibility of reproducing a vortex of this dimension, although it

basis carried out 10-day global forecasts 5 times a week from August 1, 1979 and daily from August 1, 1980. The following study is concerned with the period January 1, 1980–December 31, 1980. The numerical model has at times generated vortices with a structure and behaviour resembling intense tropical cyclones. The developments have mostly taken place around days 4 and 5 of the forecasts. Moreover, they have been found in areas and at times where tropical cyclones normally occur and they have shown a similar sensitivity to the sea-surface temperature as has been found in

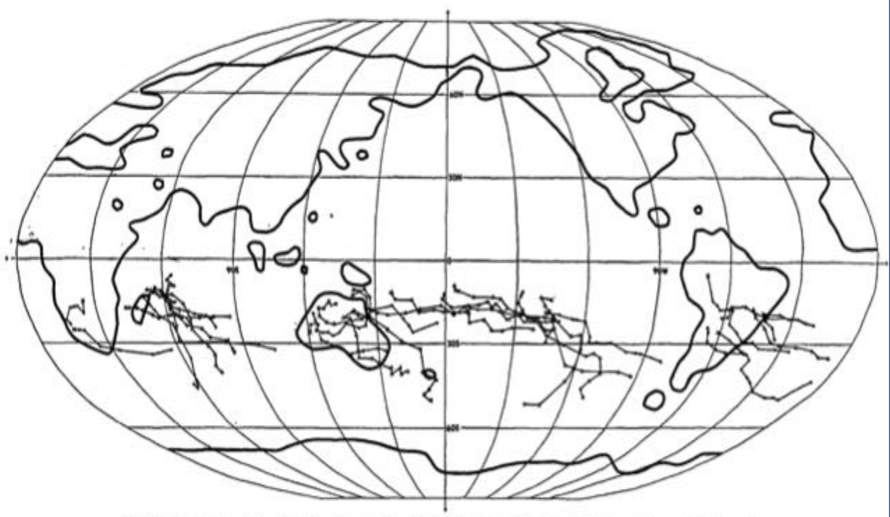
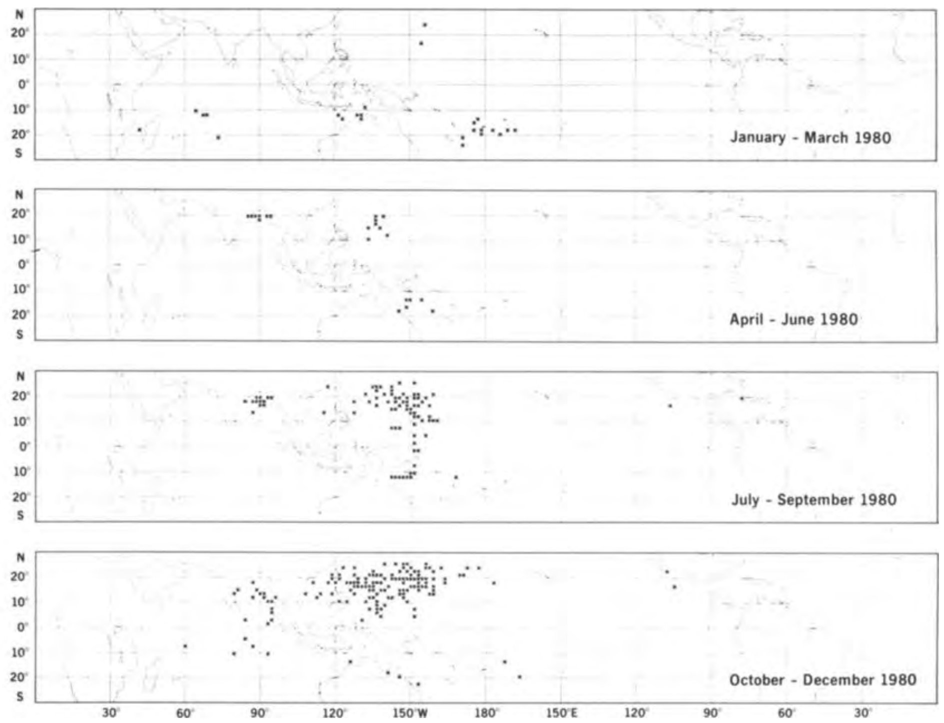


FIG. 5.14. Tracks of tropical cyclones from the points of origin indicated in Fig. 5.12. Symbols indicate positions at 1-day intervals.



Review: Camargo & Wing, 2016

Climate change and TCs

...cations may occur as a result of global warming. In... models suggest that a doubling of atmospheric CO_2 ...opical sea surface temperatures (SSTs) by as much as ...es, so this speculation would appear to have some ...

...(1987) attempted to examine this issue quantitatively ...the tropical cyclone as a Carnot heat engine in which ...put takes place at the temperature of the sea surface. ...idealized model, he suggested that the warmer SSTs ...$_2$ world would increase the maximum sustainable ...in tropical cyclones. He noted, however, that his anal-...

...ploying terrain-following sigma coordinates. Solar radia... top of the atmosphere varies seasonally but not diurnall... temperatures for land points are computed from a heat b... suming no heat storage in the ground, and both snow cov... moisture are predicted. The moist convective adjustment... Manabe et al. (1965) is used to parameterize convection.

Two versions of the model were used: a low resoluti... with spherical harmonics truncated rhomboidally at zo... number 15 (R15) and a high resolution version with tr... wavenumber 30 (R30). The latitude-longitude spacing o... form grids are 4.5° by 7.5° and 2.25° by 3.75°, respectiv...

Tellus (1996), 48A, 57–73
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TELLUS
ISSN 0280-6495

Will greenhouse gas-induced warming over the next 50 years lead to higher frequency and greater intensity of hurricanes?

By L. BENGTSSON*, M. BOTZET and M. ESCH, *Max-Planck-Institut für Meteorologie, Bundesstrasse 55, D-20146 Hamburg, Germany*

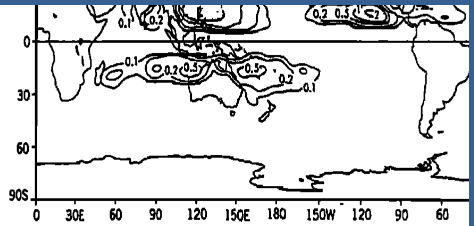
...the atmosphere, where low-level vorticity, low ...ear, and other dynamical parameters have a large ...n the climatology (Gray, 1968, 1982). McBride ...strated that the antecedent conditions, and the ...f the developing disturbance in the model, were ...by divergence rather than vorticity once again ...a different physical mechanism to that produc-... in the atmosphere. This strong reliance on an ...

vortices (and "storm days") than doubling of carb... ide. With this level of uncertainty in the control ru... that current climate GCMs are appropriate tool... ploring the relationship between greenhouse warm... tropical storm activity certainly seem to be over... tious.

In summary, there is no reason why GCM... not be able to simulate the tropical atmosphere an... ically the tropical cyclone climatology. However...

...ntended scope of BM90.

...s critical of our use of a six-month season for examining ...istics. Its use in BM90 resulted from our desire to develop ...objective, automated technique for distinguishing tropical ...ropical storms. As a first attempt, we assumed all storms ...red within a specified spatial and temporal domain were



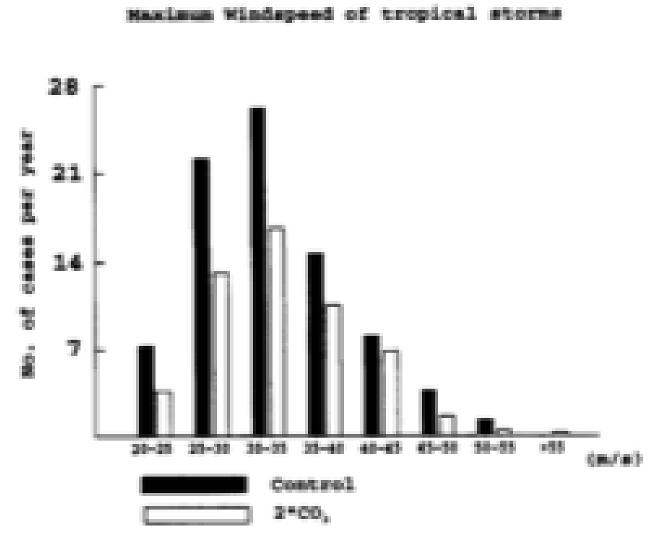


Fig. 5. Maximum windspeed obtained for each individual simulated tropical cyclone for present climate conditions (solid bars) and for the double CO_2 case (unfilled bars).

TC seasonal variability

April 1997 VITART ET AL. 745

Simulation of Interannual Variability of Tropical Storm Frequency in an Ensemble of GCM Integrations

F. Vitart
Program in Atmospheric and Oceanic Science, Princeton University, Princeton, New Jersey

J. L. Anderson and W. F. Stern
GFDL/NOAA, Princeton University, Princeton, New Jersey

1152 WEATHER AND FORECASTING Volume 17

Improving the Detection and Tracking of Tropical Cyclones in Atmospheric General Circulation Models

Suzana J. Camargo and Stephen E. Zebiak
International Research Institute for Climate Prediction, Lamont-Doherty Earth Observatory of Columbia University, Palisades, New York

(Manuscript received 25 February 2002, in final form 10 July 2002)

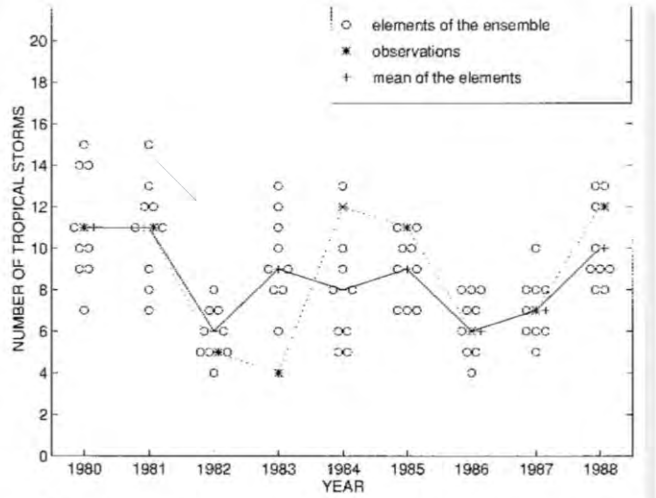


FIG 7. Ensemble simulation of number of tropical storms and observed number of tropical storms over the western North Atlantic. The solid line represents observed tropical storm numbers. The dotted line represents the mean tropical storm numbers of the elements of the ensemble. Each circle represents the tropical storm number of one element of the ensemble.

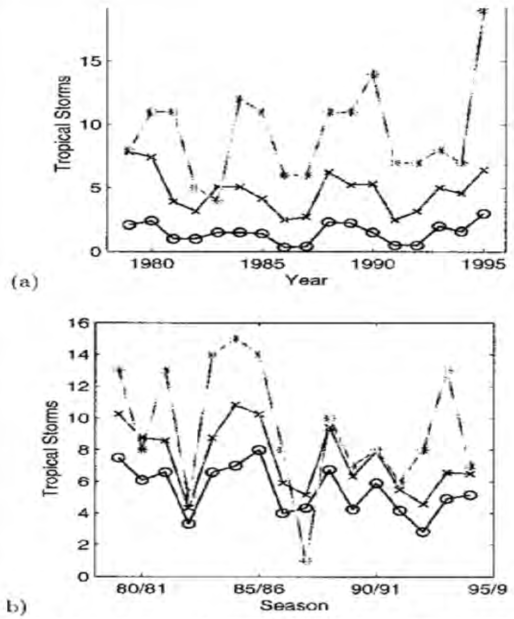


FIG 4. Ensemble mean number of storms per year detected usi[ng] [b]asin-independent thresholds (V), the basin-dependent threshol[ds] 3), and observations (*) for (a) the Atlantic and (b) the Australi[a]

Suzana Camargo

TC dynamical seasonal forecasts

3932 JOURNAL OF CLIMATE VOLUME 16

Seasonal Forecasting of Tropical Cyclone Landfall over Mozambique

FRÉDÉRIC VITART, DAVID ANDERSON, AND TIM STOCKDALE

European Centre for Medium-Range Weather Forecasts, Reading, United Kingdom

(Manuscript received 13 November 2002, in final form 19 June 2003)

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Experimental Dynamical Seasonal Forecasts of Tropical Cyclone Activity at IRI

SUZANA J. CAMARGO AND ANTHONY G. BARNSTON

International Research Institute for Climate and Society, The Earth Institute at Columbia University, Palisades, New York

(Manuscript received 7 December 2007, in final form 15 September 2008)

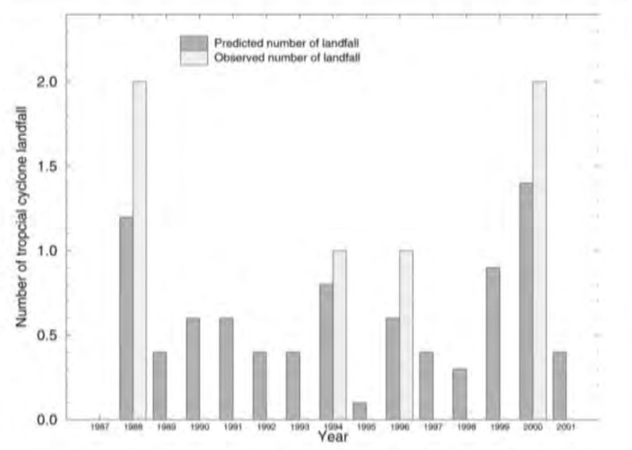


FIG 11. Interannual variability of the observed and predicted number of tropical storm landfalls over Mozambique. The predicted number of tropical storm landfalls has been calculated by taking the mean of the ensemble distribution, and multiplying it by 1.5, since the model simulates 1.5 less tropical cyclones than observed.

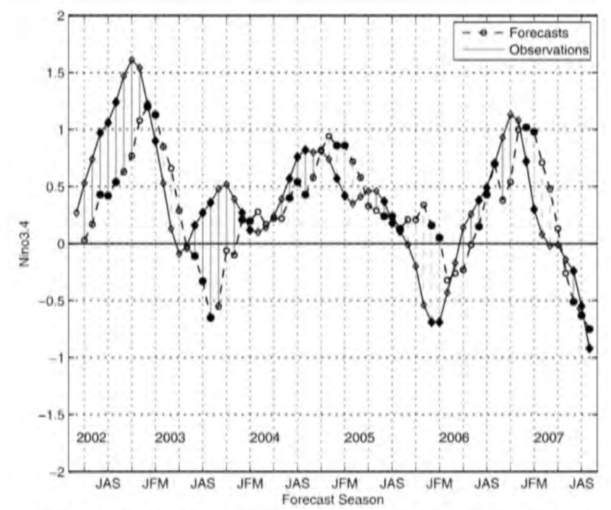
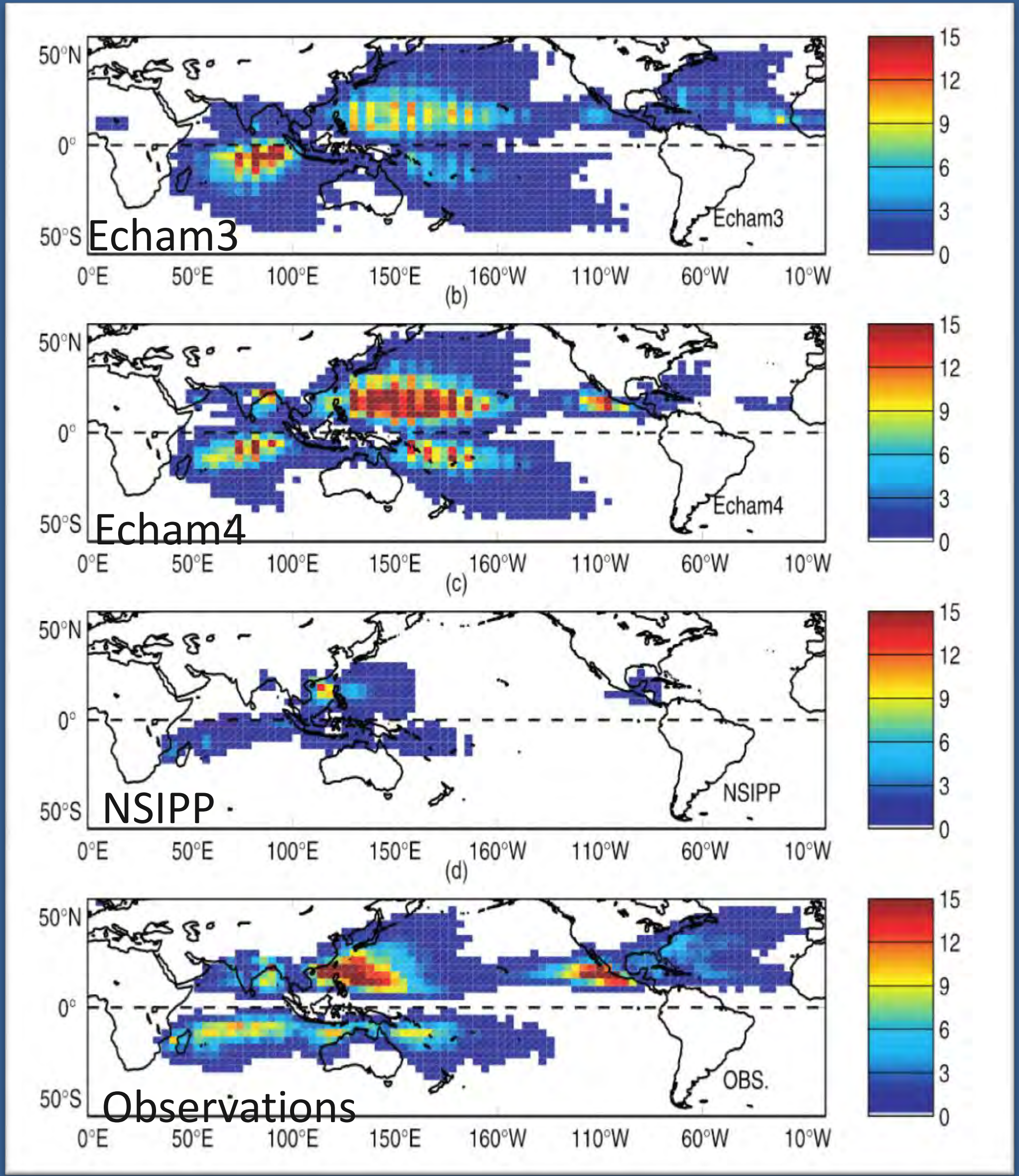
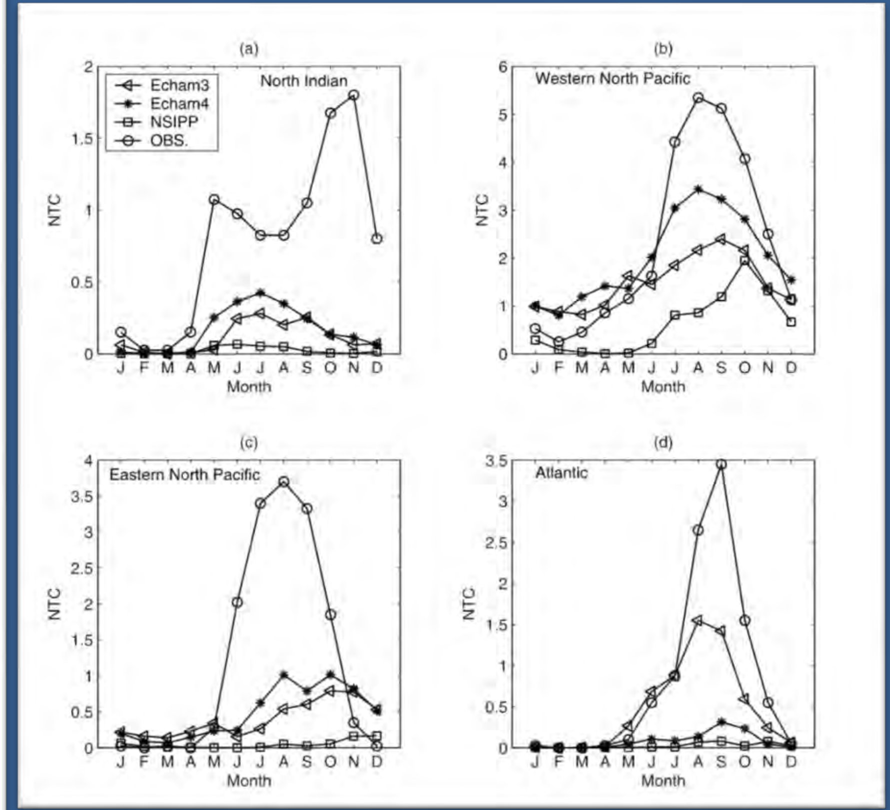


FIG. 6. Two-month lead IRI forecasts (circles) and observations (diamonds) of Niño-3.4 SST index anomalies. Seasons for which TCs are forecast are shown with filled symbols. The differences between the forecasts and observations are shown by solid (dotted) gray vertical lines when the observation was warmer (colder) than the forecast.

More recent GCM studies: 2000s



Track density



Number of tropical cyclones

Camargo, Barnston & Zebiak, Tellus, 2005

Suzana Camargo

North Atlantic TC variability in current high-res GCMs used for climate system research: <u>Atmosphere-only</u>

1 JANUARY 2013 STRACHAN ET AL.

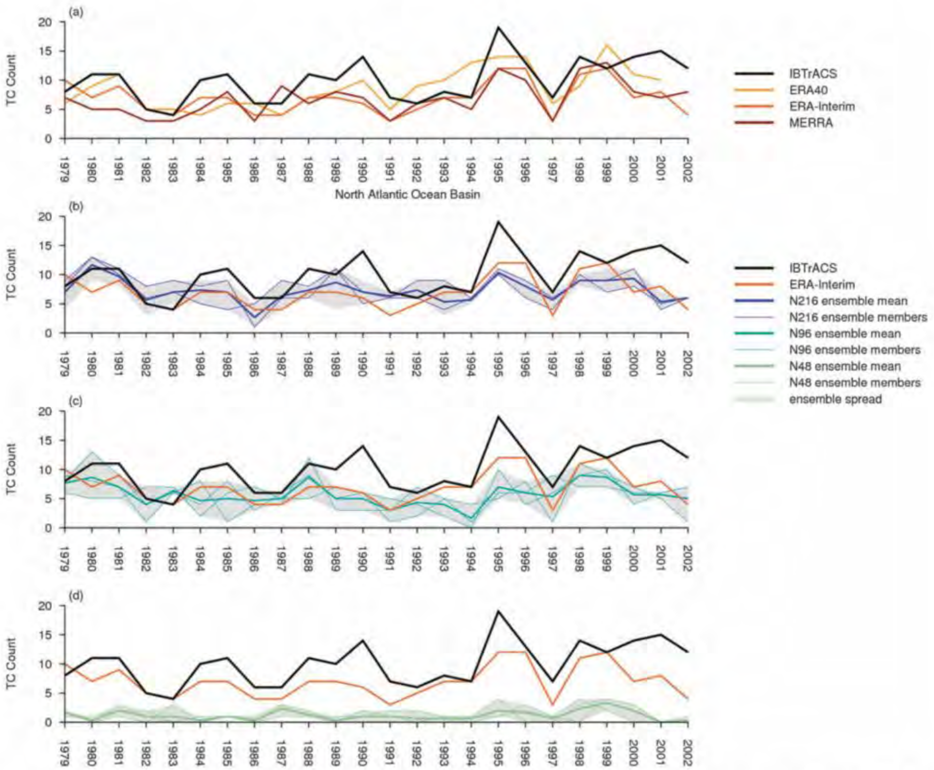


FIG. 7. Tropical cyclone interannual variability for North Atlantic basin for (a) reanalysis products; (b) the N216 GCM ensemble; (c) the N96 GCM ensemble; and (d) the N48 GCM ensemble. For (b)–(d) thick lines show the GCM ensemble mean, thin lines show the individual ensemble members, and the gray envelope shows the ensemble spread.

HadGEM1: Strachan et al. J. Clim. (2011-2013)

GFDL GCM:
Zhao et al.
J. Clim. (2009)

MBER 2009 ZHAO ET AL.

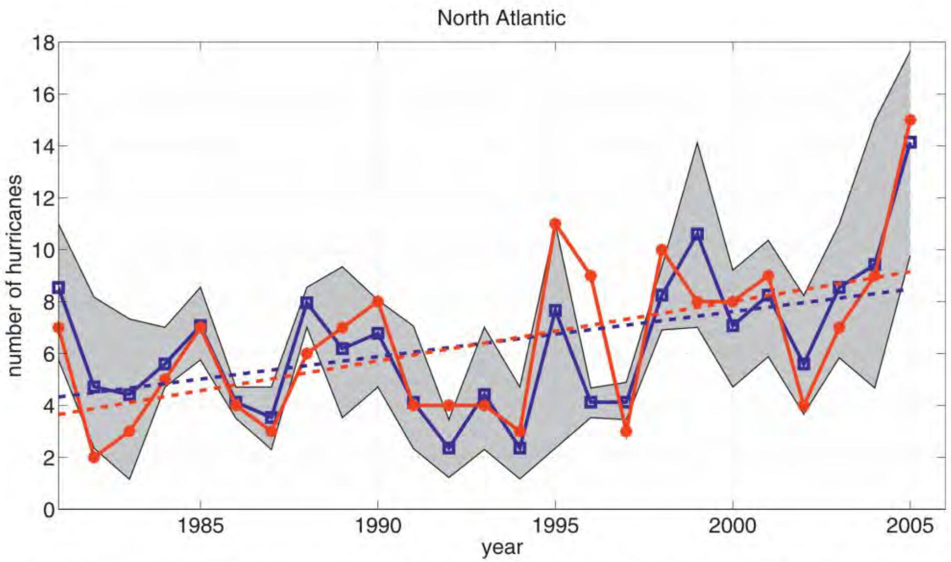
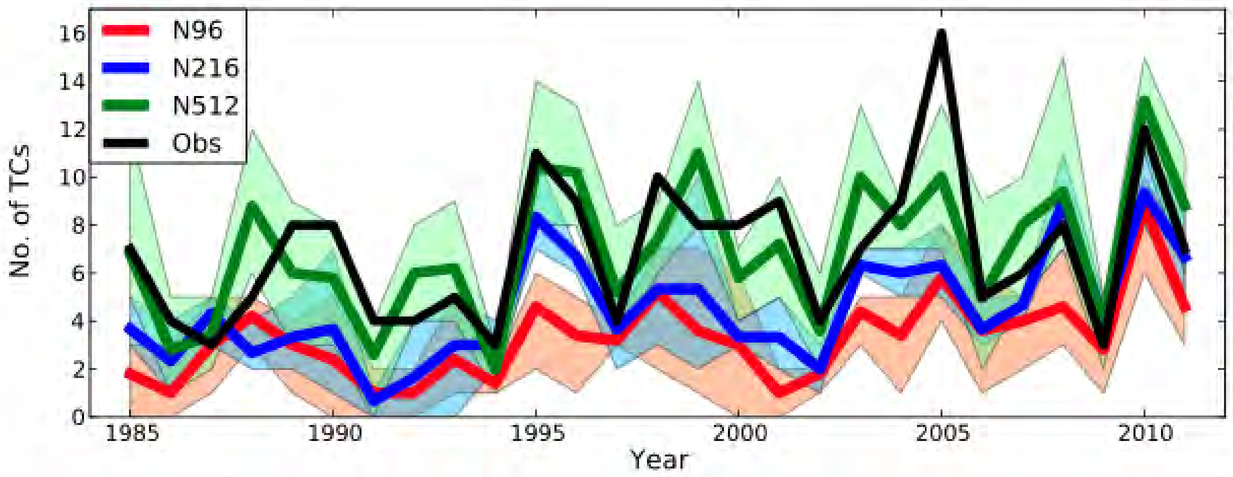


FIG. 7. Interannual variation of hurricane numbers for North Atlantic from 1981 to 2005. IBTrACS observations (Kruk et al. 2010) (red) and four-member ensemble mean (blue); shaded area shows the simulated maximum and minimum number for each year from the four-member integrations. Model time series are normalized by time-independent multiplicative factors so as to reproduce the observed total number. Dotted lines show observed and model (ensemble mean) linear trends.



HadGEM3: Roberts et al. J. Clim. (2015)

Continuing issues

- Mean biases in TC climatology:
  - Number, intensity, tracks, size
- Mainly attributed to:
  - Model low-resolution
  - Mean biases in model environment
- Dependency on model characteristics:
  - Model physics: convection scheme
  - Dynamical core
- "*Hurricane-type vortices*": if it walks like a duck and quacks like a duck…

Tropical Cyclones "emerge" at high resolution

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

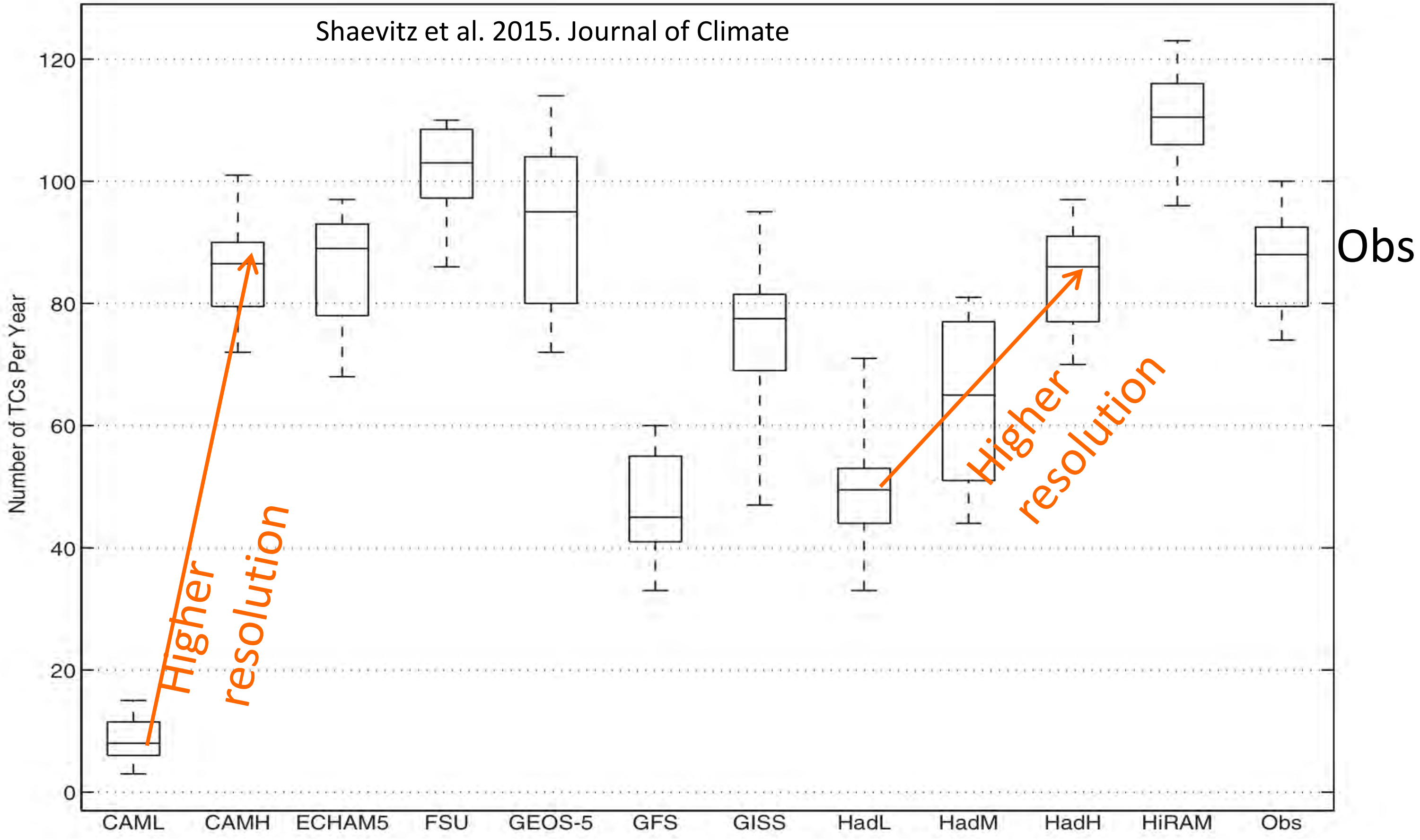
- TC tracks and interannual variability in frequency are credibly represented at 20km;
- however, intensity is still underestimated by some of the GCMs at this resolution
- HRCM played a strong role in the first HWG; even stronger role in next phase

Met Office | NATURAL ENVIRONMENT RESEARCH COUNCIL

Joint Weather & Climate Research Programme

A partnership in climate research

SPECIAL U.S. CLIVAR Hurricanes COLLECTION

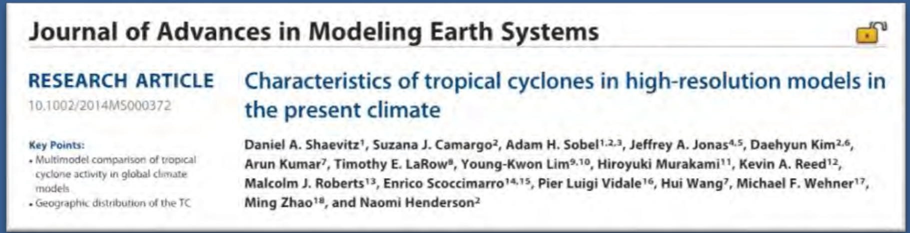


Shaevitz et al. 2015. Journal of Climate

Distribution of the number of TCs per year

PRACE

UPSCALE



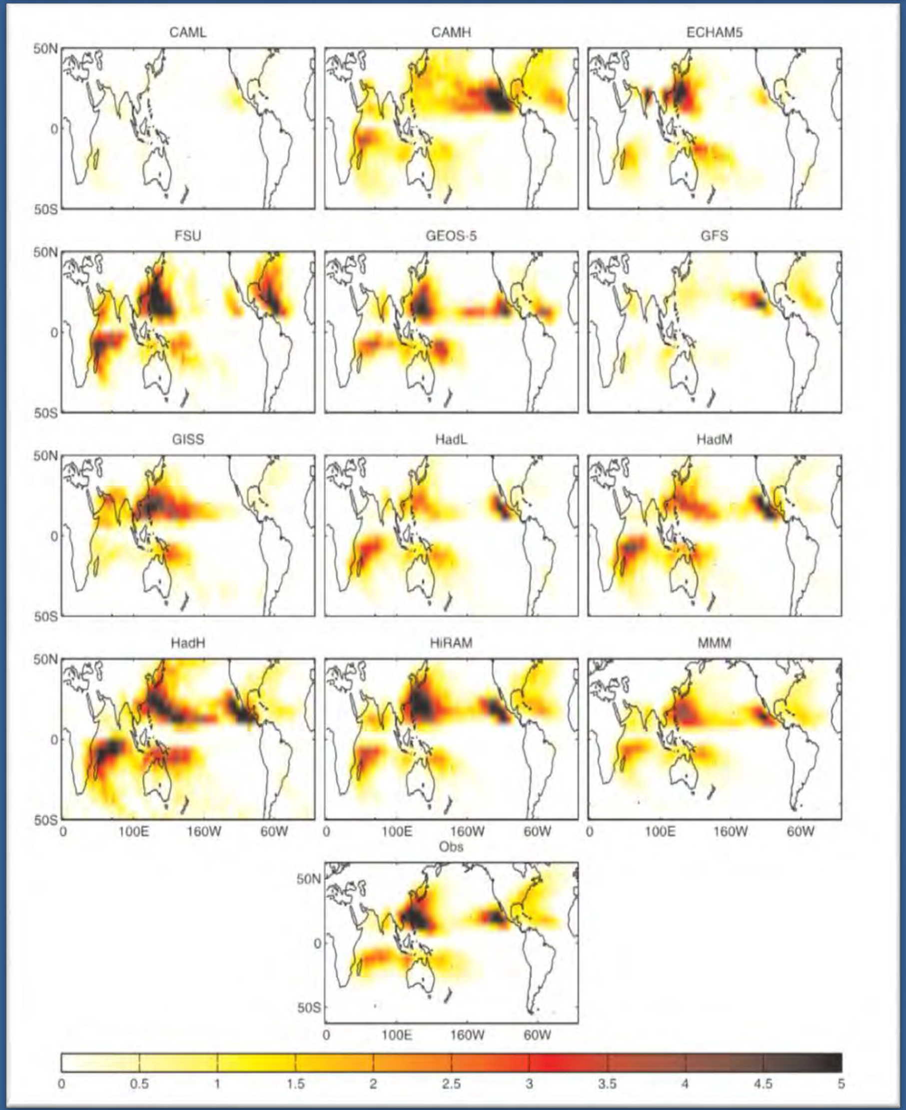
Journal of Advances in Modeling Earth Systems

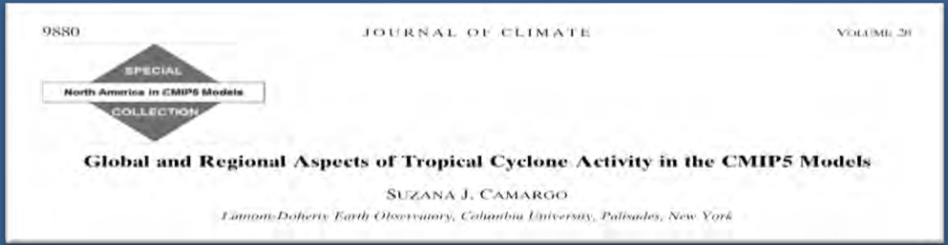
RESEARCH ARTICLE
10.1002/2014MS000372

Key Points:
- Multimodel comparison of tropical cyclone activity in global climate models
- Geographic distribution of the TC

Characteristics of tropical cyclones in high-resolution models in the present climate

Daniel A. Shaevitz[1], Suzana J. Camargo[2], Adam H. Sobel[1,2,3], Jeffrey A. Jonas[4,5], Daehyun Kim[2,6], Arun Kumar[7], Timothy E. LaRow[8], Young-Kwon Lim[9,10], Hiroyuki Murakami[11], Kevin A. Reed[12], Malcolm J. Roberts[13], Enrico Scoccimarro[14,15], Pier Luigi Vidale[16], Hui Wang[7], Michael F. Wehner[17], Ming Zhao[18], and Naomi Henderson[2]





9880 JOURNAL OF CLIMATE VOLUME 26

SPECIAL
North America in CMIP5 Models
COLLECTION

Global and Regional Aspects of Tropical Cyclone Activity in the CMIP5 Models

SUZANA J. CAMARGO

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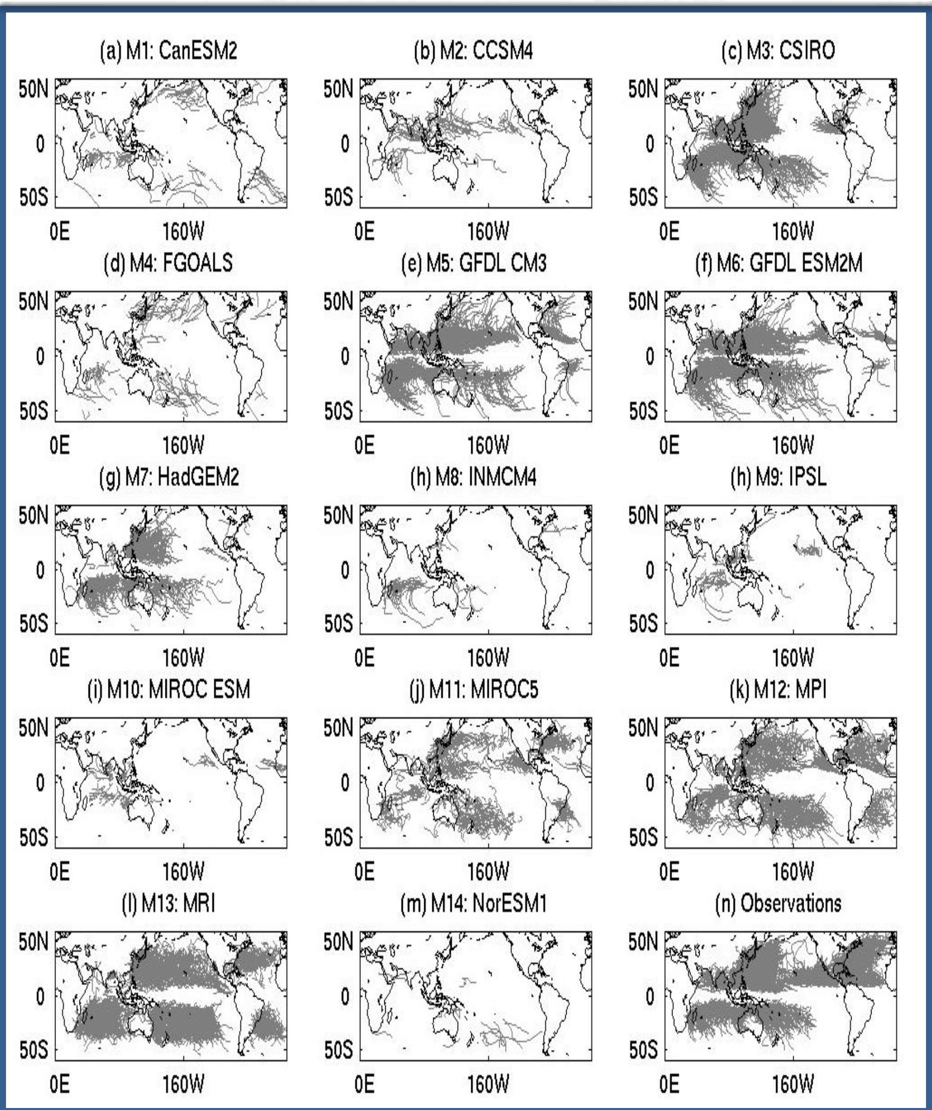


Suzana Camargo

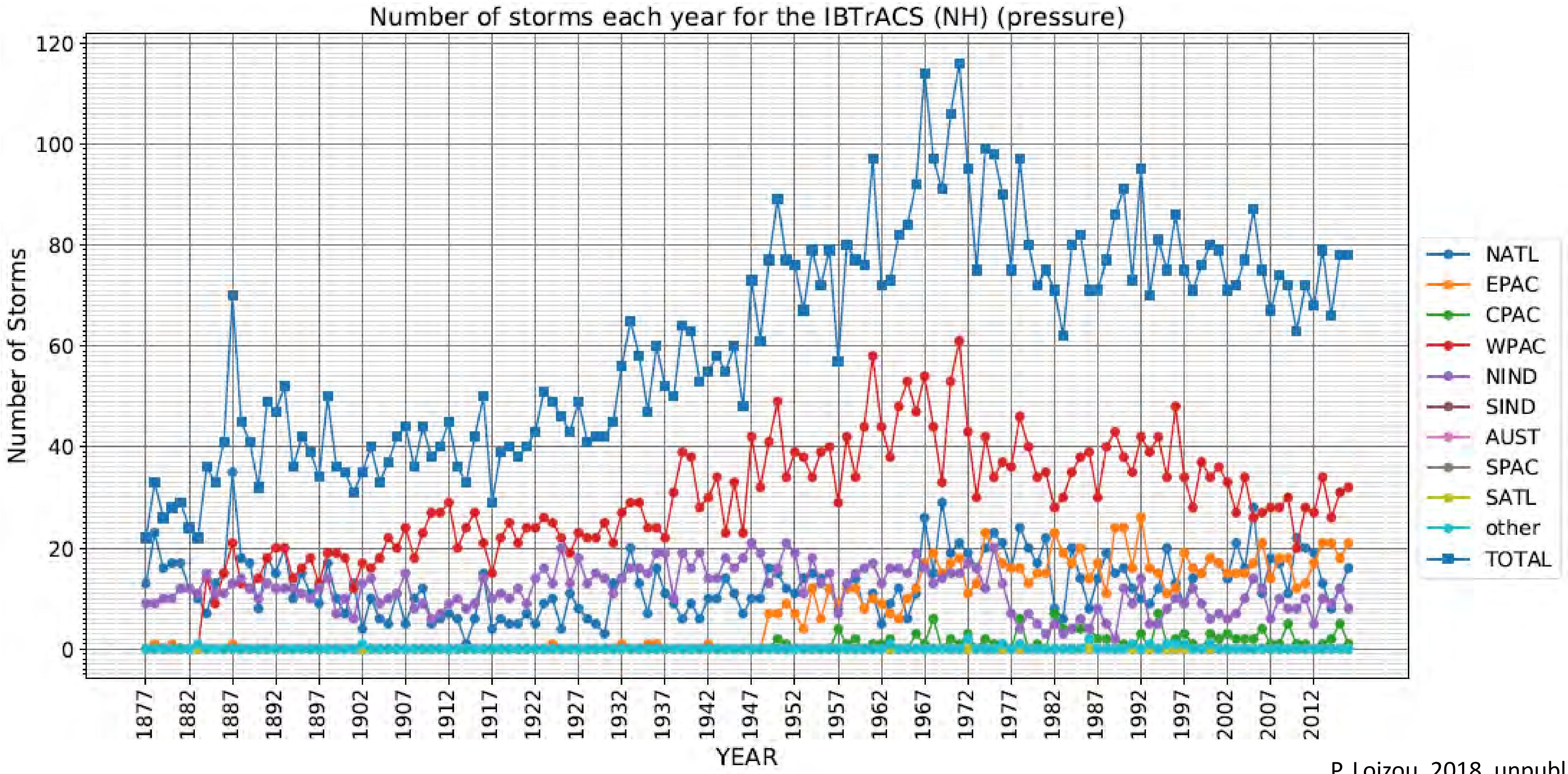
Track density

Tracks

What are the observed historical trends in key storm parameters and how well do the climate models resolve these?

TC observations are just a mess… (K. Hodges, 2018)

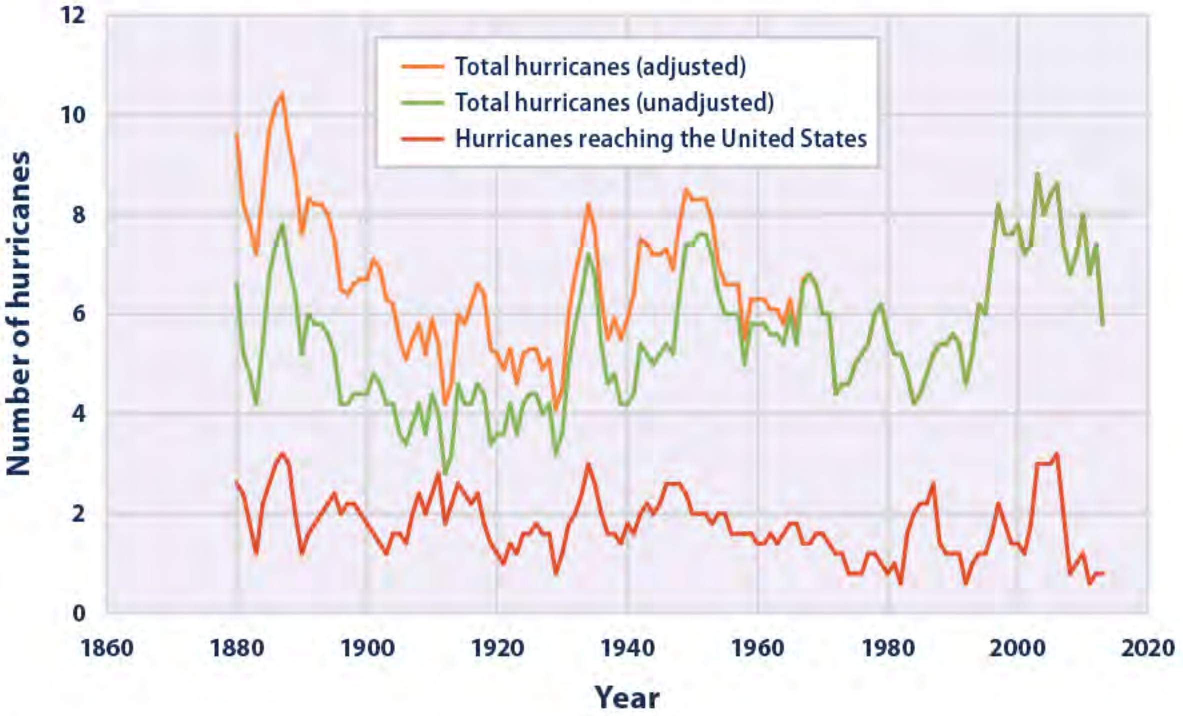
University of Reading



P. Loizou, 2018, unpublished

There is a constant effort to re-visit and complete TC observations

Careful with fitting linear trends…



Data sources:

- NOAA (National Oceanic and Atmospheric Administration). 2016. The Atlantic Hurricane Database Re-analysis Project. www.aoml.noaa.gov/hrd/hurdat/comparison_table.html.
- Vecchi, G.A., and T.R. Knutson. 2011. Estimating annual numbers of Atlantic hurricanes missing from the HURDAT database (1878–1965) using ship track density. J. Climate 24(6):1736–1746. www.gfdl.noaa.gov/bibliography/related_files/gav_2010JCLI3810.pdf.

For more information, visit U.S. EPA's "Climate Change Indicators in the United States" at www.epa.gov/climate-indicators.

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.

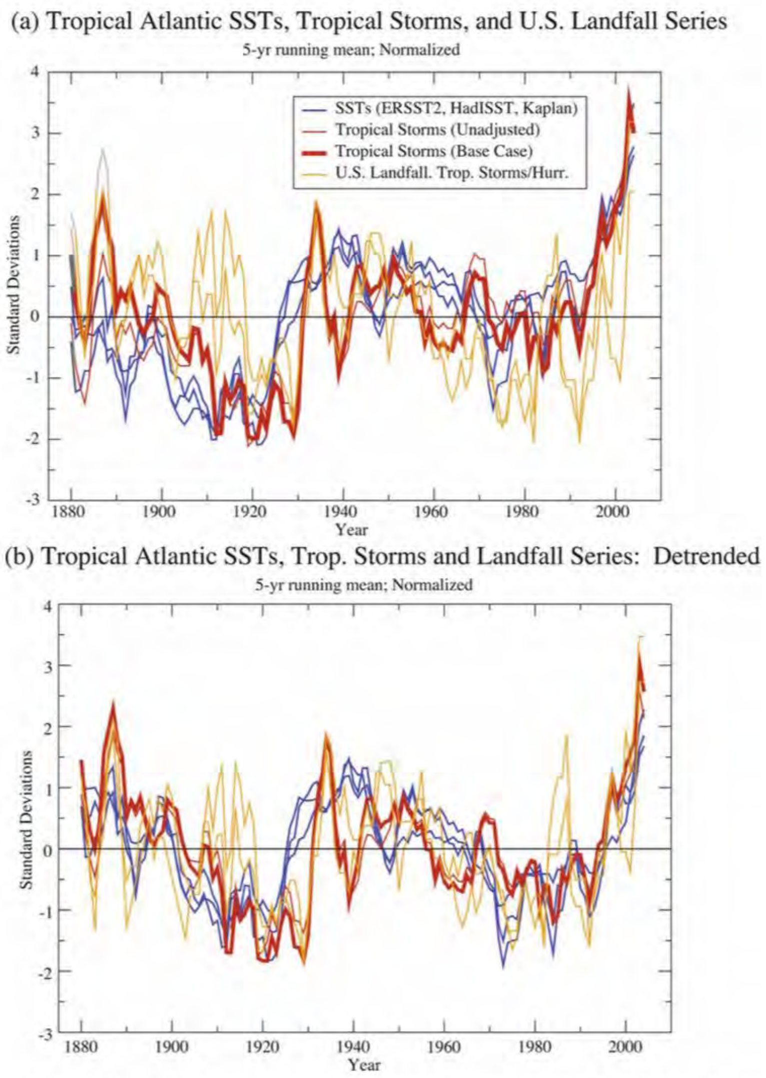


FIG. 10. (a) The 5-yr running mean normalized Atlantic MDR SST indices from three different reconstructions of SST (see text) overlaid on Atlantic TC counts. Blue curves are the three MDR SST reconstructions. The heavy red curve is the base-case TC count. The light red curve is the unadjusted TC count. The orange curves are U.S. landfalling tropical storm and hurricane count series from HURDAT. Curves in (b) have been detrended using ordinary least squares best fits.

Vecchi and Knutson 2011

Vecchi and Knutson 2008

TCs in 6 re-analyses

University of Reading

DATASET	PERIOD	MODEL RESOLUTION	DATA GRID
IBTrACS	1877-2017		
ERAI	1979-2016	TL255L60 (80 km)	512 × 256
MERRA	1979-2015	1/2° × 2/3° L72 (55 km)	540 × 361
MERRA-2	1980-2016	Cubed sphere (50 km)	576 × 361
NCEP	1979-2016	T382L64 (38 km)	720 × 361
JRA-25	1979-2013	T106L40 (120 km)	288 × 145
JRA-55	1958-2017	TL319L60 (55 km)	288 × 145

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.

15 July 2017 HODGES ET AL. 5255

TABLE 3. Storms that match and do not match with IBTrACS in the NH by storm category, for each reanalysis, storms identified by the objective detection method applied to the reanalysis tracks and, in parentheses, the direct matching method, performed in section 3a. Values are number per year.

Category		ERAI	JRA-25	JRA-55	NCEP-CFSR	MERRA	MERRA-2
TD	Match	2.91 (7.94)	3.26 (7.94)	5.24 (8.03)	3.50 (8.00)	2.29 (7.85)	3.48 (7.67)
	No match	5.56 (0.53)	5.21 (0.53)	3.24 (0.44)	4.97 (0.47)	6.18 (0.62)	4.91 (0.73)
TS	Match	11.85 (22.38)	18.62 (22.53)	18.32 (22.53)	14.76 (22.32)	9.85 (22.44)	14.24 (22.45)
	No match	11.85 (1.32)	5.09 (1.18)	5.38 (1.18)	8.94 (1.38)	13.85 (1.26)	9.73 (1.52)
CAT1	Match	8.74 (12.23)	11.18 (12.23)	11.17 (12.24)	10.09 (12.12)	7.74 (12.21)	9.76 (12.33)
	No match	3.44 (0.00)	1.00 (0.00)	1.00 (0.00)	2.09 (0.06)	4.44 (0.00)	2.55 (0.00)
CAT2	Match	5.29 (6.35)	6.15 (6.38)	6.00 (6.35)	5.82 (6.38)	4.76 (6.35)	5.64 (6.39)
	No match	1.06 (0.00)	0.21 (0.00)	0.35 (0.00)	0.53 (0.00)	1.59 (0.00)	0.73 (0.00)
CAT3	Match	6.15 (7.00)	6.91 (7.06)	6.82 (7.03)	6.71 (7.06)	5.82 (7.03)	6.42 (7.06)
	No match	0.88 (0.03)	0.12 (0.00)	0.21 (0.00)	0.32 (0.00)	1.21 (0.00)	0.64 (0.00)
CAT4	Match	5.97 (6.79)	6.76 (6.79)	6.71 (6.74)	6.47 (6.79)	5.76 (6.76)	6.48 (6.76)
	No match	0.82 (0.00)	0.03 (0.00)	0.09 (0.06)	0.32 (0.00)	1.03 (0.03)	0.33 (0.06)
CAT5	Match	1.09 (1.12)	1.12 (1.12)	1.12 (1.12)	1.12 (1.12)	1.03 (1.12)	1.09 (1.09)
	No match	0.03 (0.00)	0.00 (0.00)	0.00 (0.00)	0.00 (0.00)	0.09 (0.00)	0.00 (0.00)

There is no trace of TC trends in the re-analyses: there is, however, substantial and interesting variability

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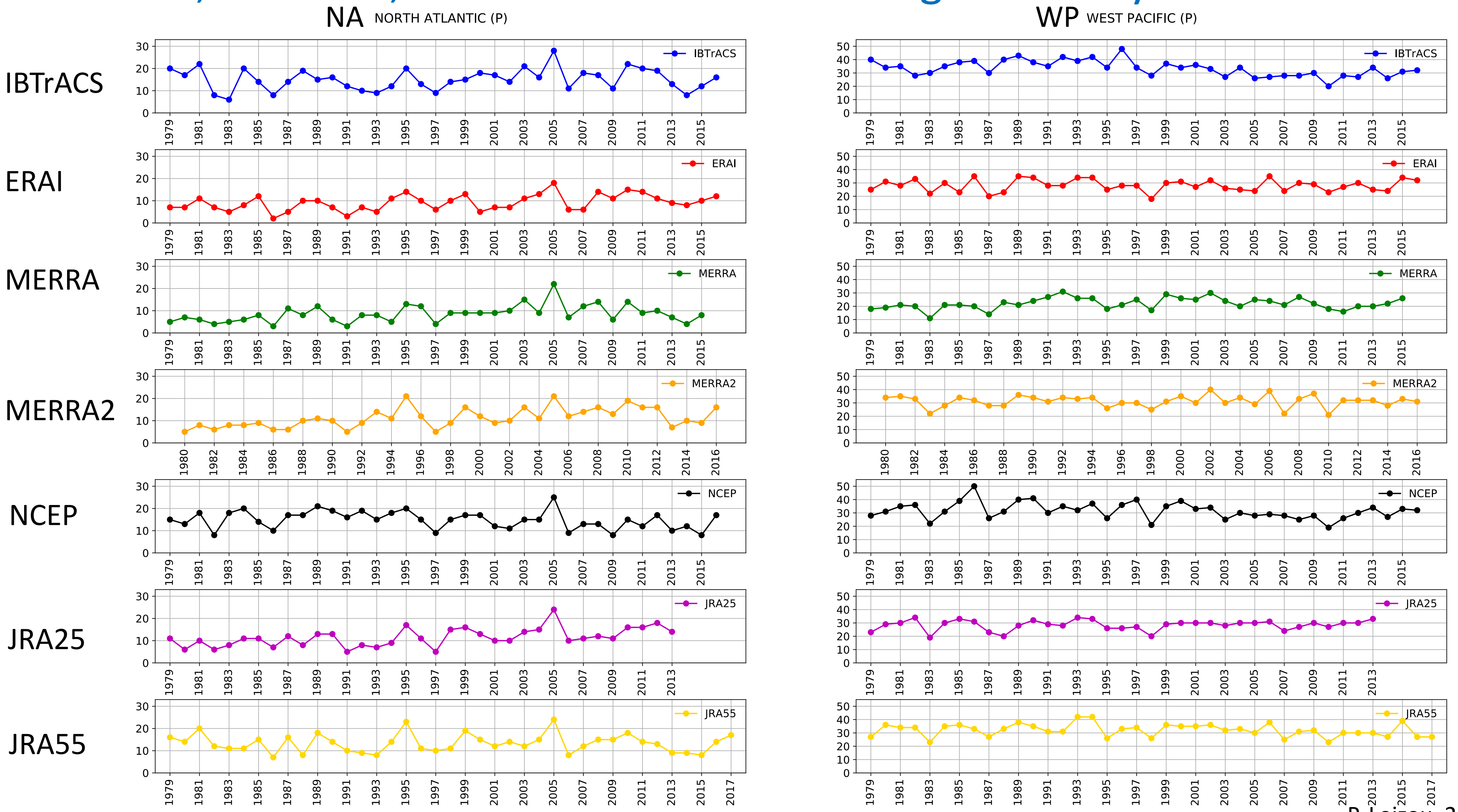
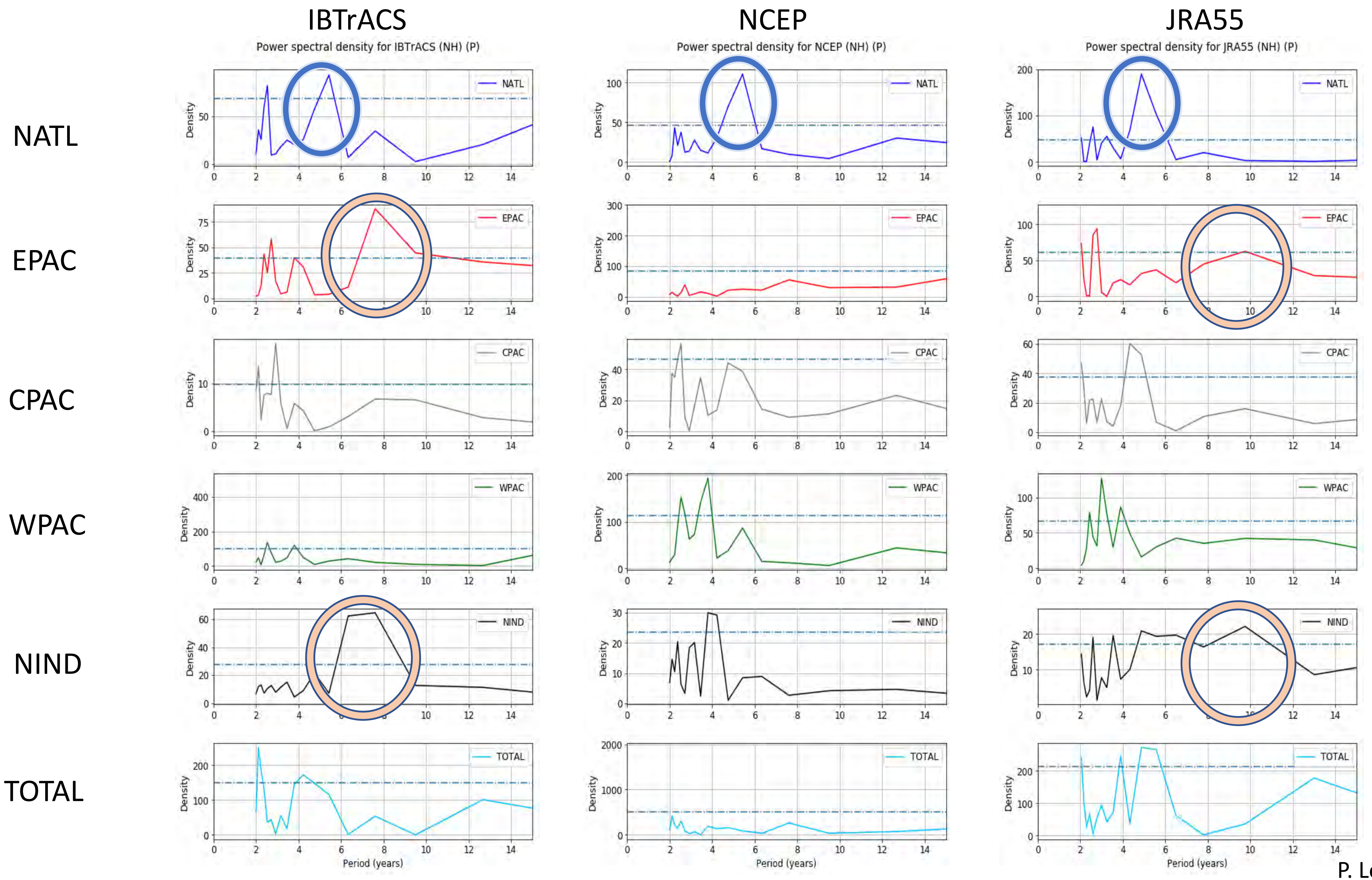


P. Loizou, 2018, unpublished

Power spectra of TC time series in different basins, from 3 data sets



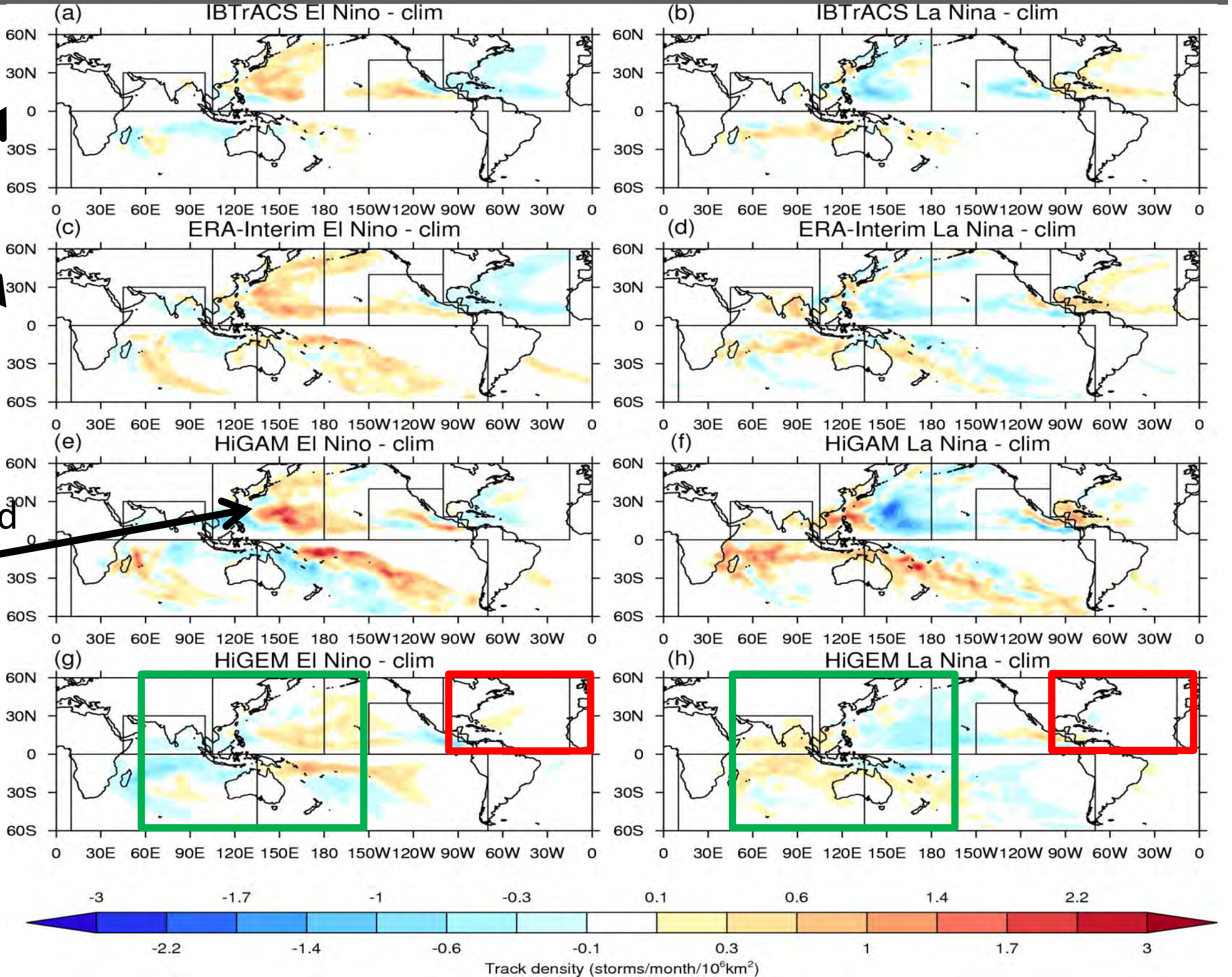
P. Loizou, 2018, unpublished

Will we see changes to the inter-dependency between La Niña / El Niño cycles and tropical storm intensity or frequency?

ENSO-TC: track density anomalies

Match well

Overpronounced variability



Bell et al. J. Clim 2012

TCs and ENSO in CLIVAR HWG exercise

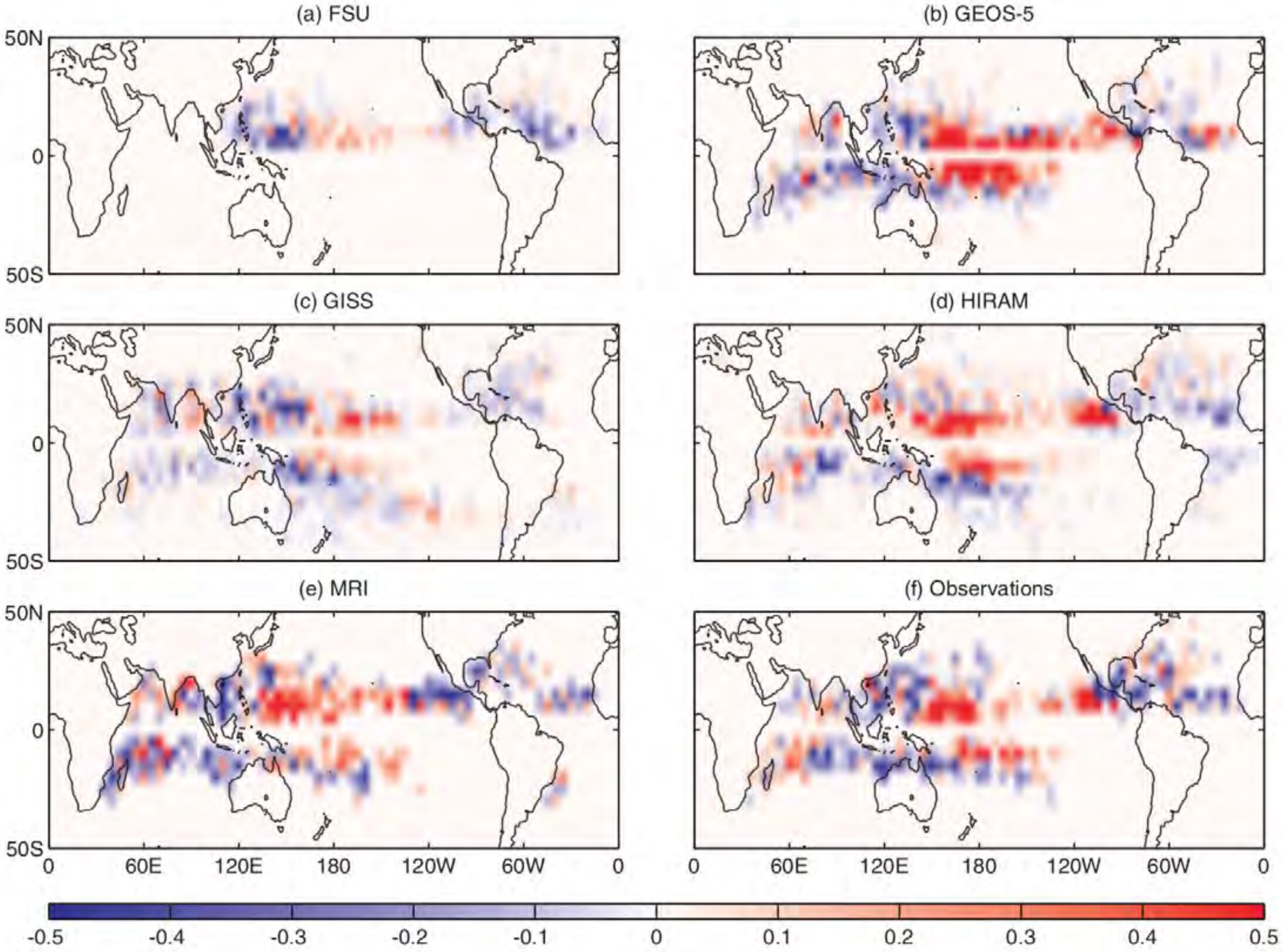
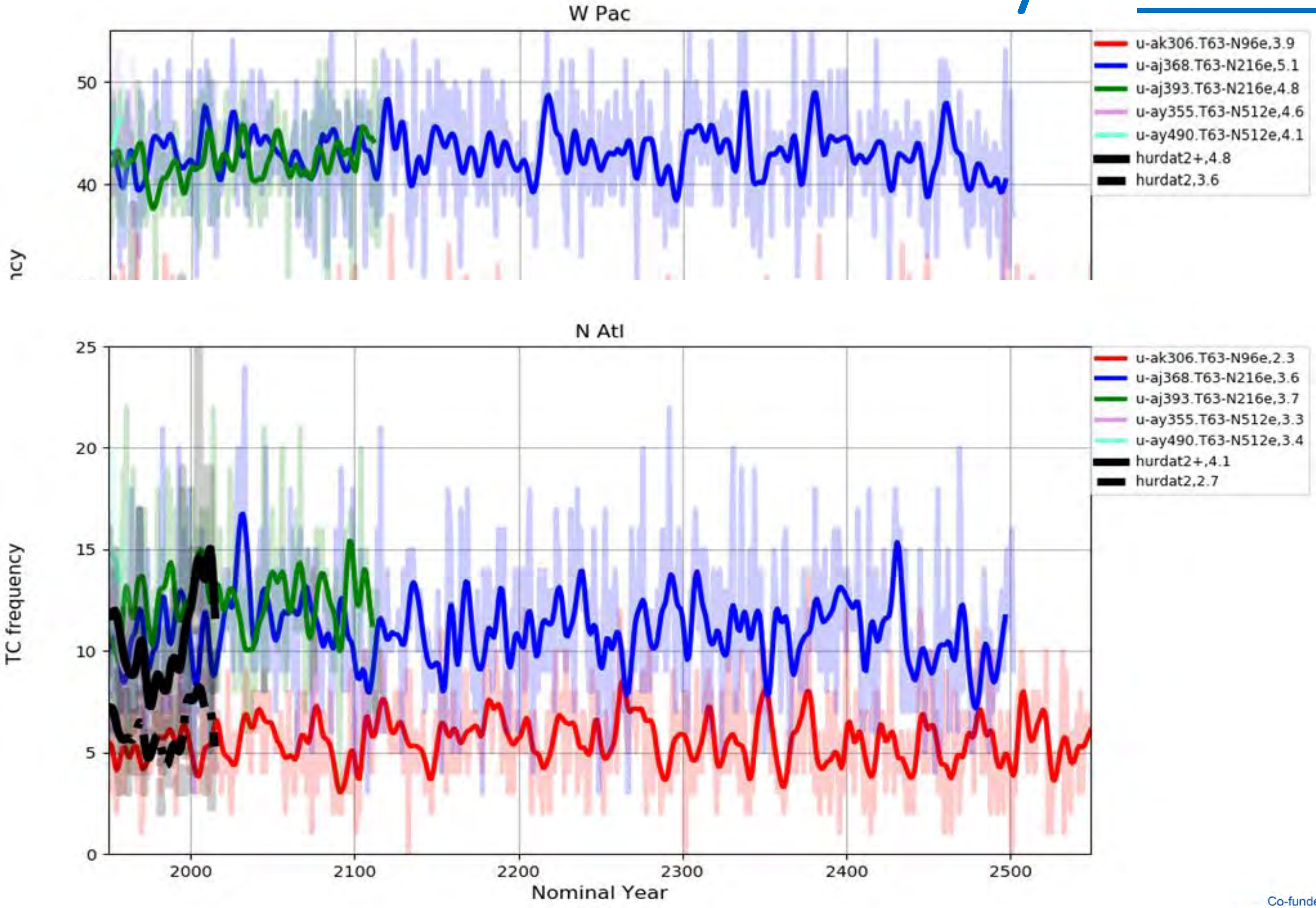


Figure 11. Difference of TC genesis density in El Niño and La Niña in models and observations. The genesis density is defined as the mean TC formation per 5° × 5° box per year.

From Shaevitz et al. 2014

PRIMAVERA: decadal variability in unforced runs



N96-ORCA1
N216-ORCA025
N216-ORCA12
N512-ORCA025
N512-ORCA12

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

Co-funded by the European Union

Power spectra of TC time series in different basins, from HadGEM3 simulations

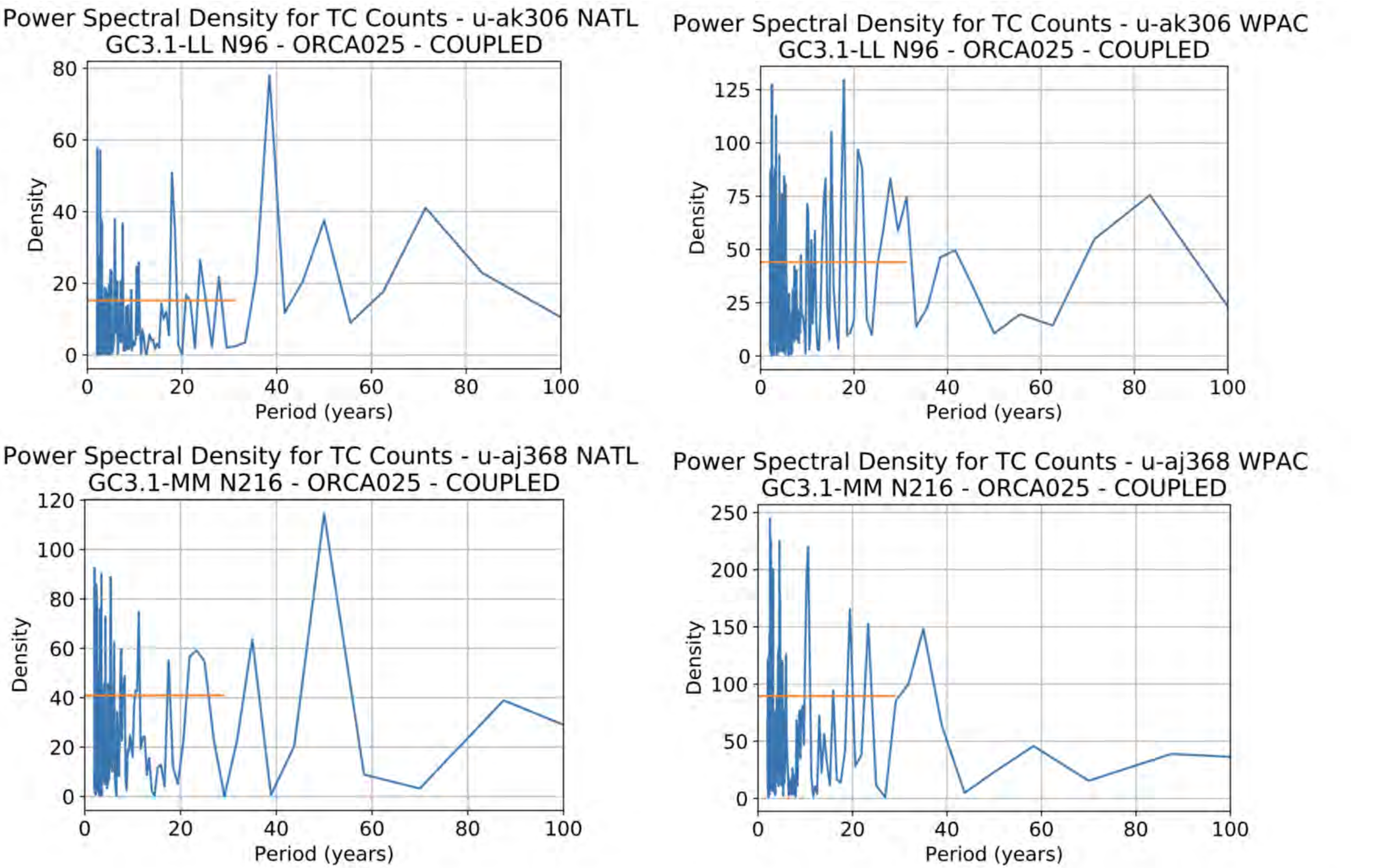


Figure 5: Results of the power spectrum analysis for the coupled model experiments. The two upper figures show the results for the N96- experiment for the NATL (on the left) and WPAC (on the right) regions. The two lower figures show the results for the N216-experiments for the same regions.

University of Reading

Loizou, 2018, unpublished

What are the projected changes to track paths, intensity, structure, frequency and potential seasonal extensions?

Is there regional variation in these climate model projections?

What will happen to TCs in the future?

Typhoons will migrate poleward … and a NA hurricane reduction

SPECIAL U.S. CLIVAR Hurricanes COLLECTION

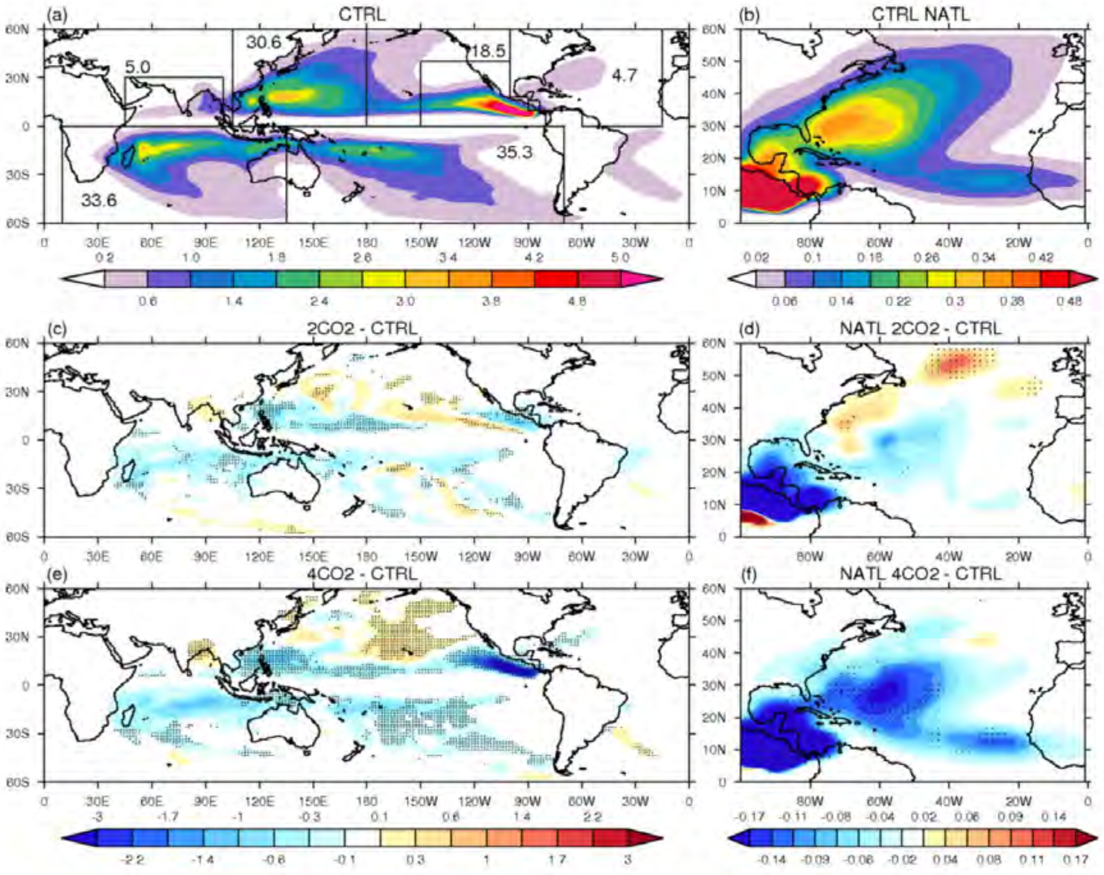
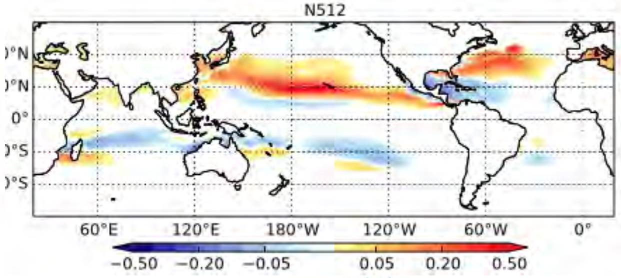


FIG. 2. Tropical cyclone track density, same as figure 1, for (a) HiGEM present-day simulation (b) The same as for (a) but North Atlantic (c) 2CO2 - present-day simulation (d) North Atlantic 2CO2 - present-day simulation (e) 4CO2 - present-day simulation and (f) North Atlantic 4CO2 - present-day simulation. 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



PRACE

UPSCALE

2012 UPSCALE MODELLING CAMPAIGN

JOURNAL OF CLIMATE

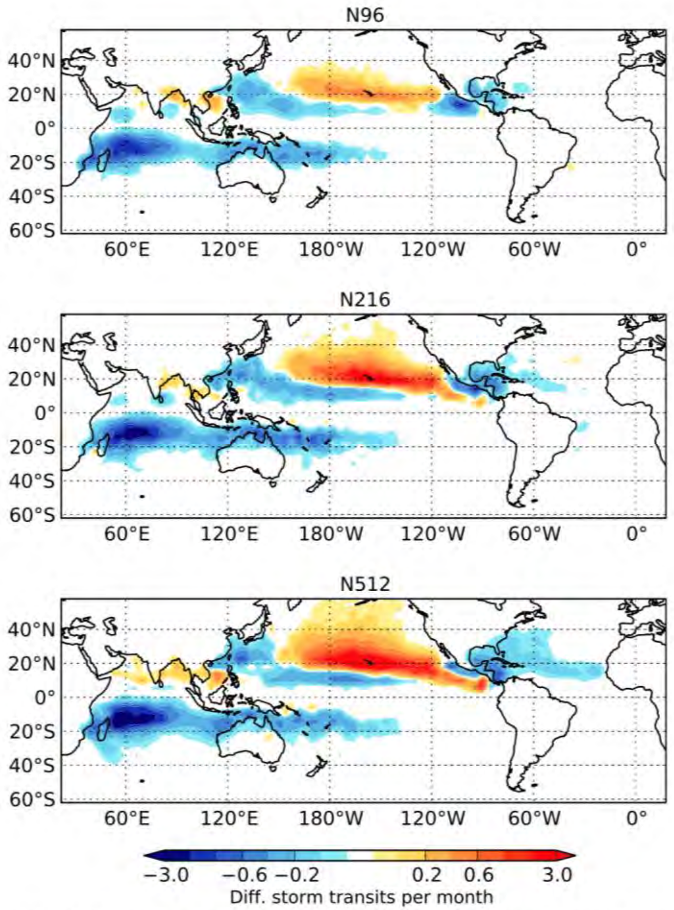
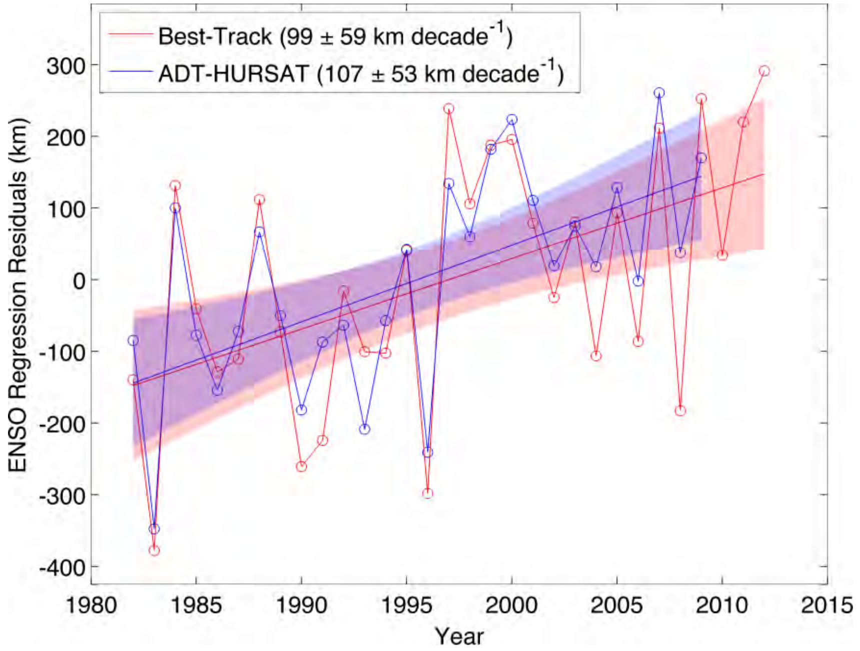


FIG. 12. Change in tropical cyclone track density (storm transits per month per unit area equivalent to a 4° spherical cap) between the future climate and present climate integrations for the whole 1986–2010 period and for the whole ensemble at each model resolution: (top)–(bottom) N96, N216, and N512.

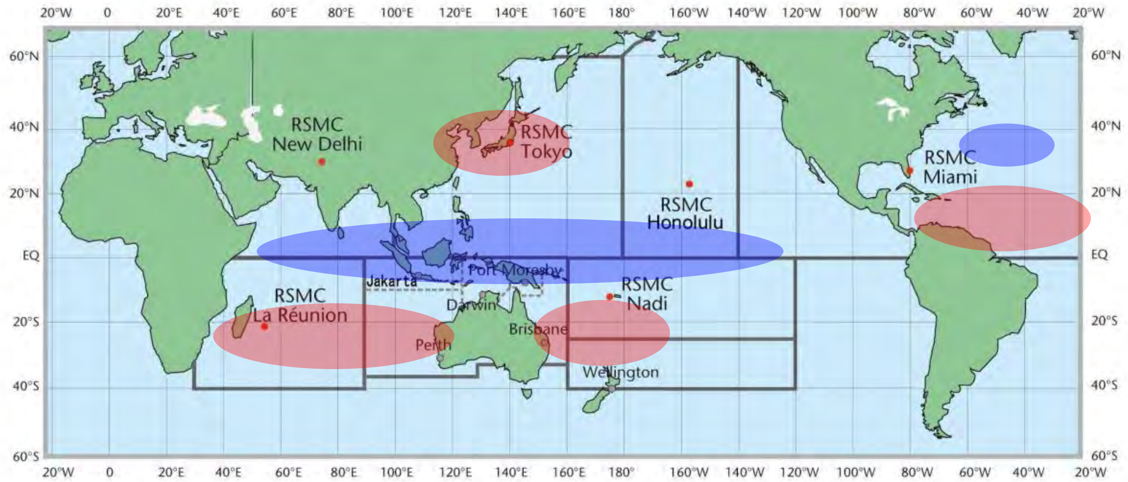
Roberts et al. 2015. Journal of Climate, RCP 8.5 scenario

Back to observations: annual-mean latitude of peak TC intensity



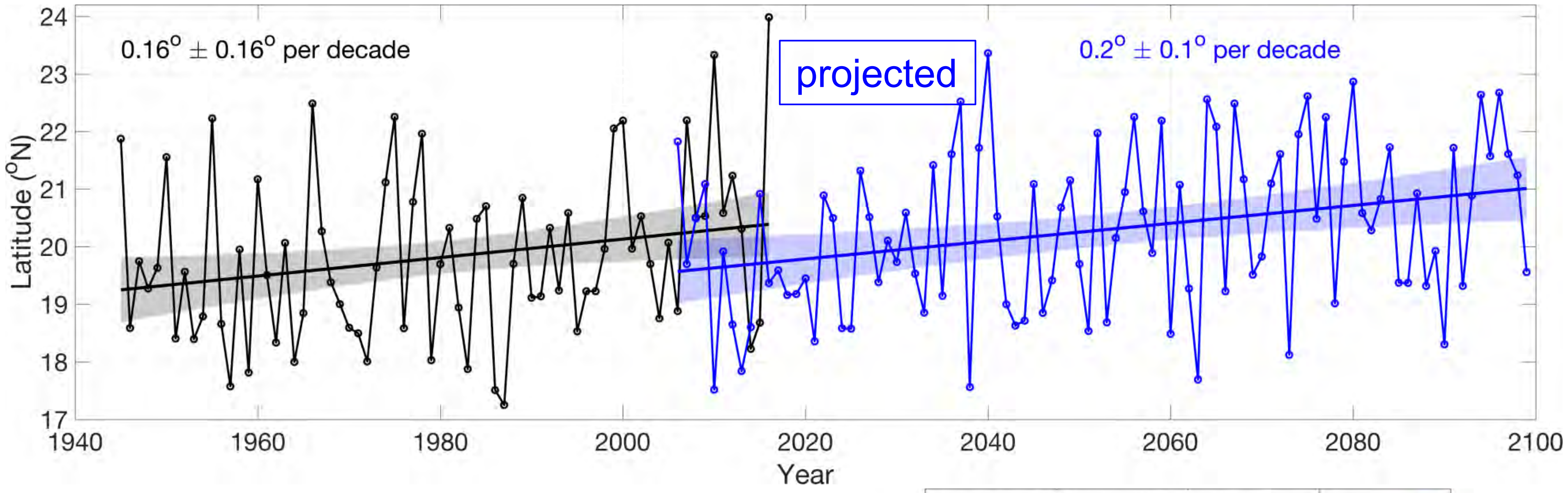
The migration rate is consistent with the independently-measured rate of tropical expansion, which has been partly attributed to human activity.

Kossin, J. P., K. A. Emanuel, and G. A. Vecchi, 2014: The poleward migration of the location of tropical cyclone maximum intensity. *Nature*, **509**, 349-352.



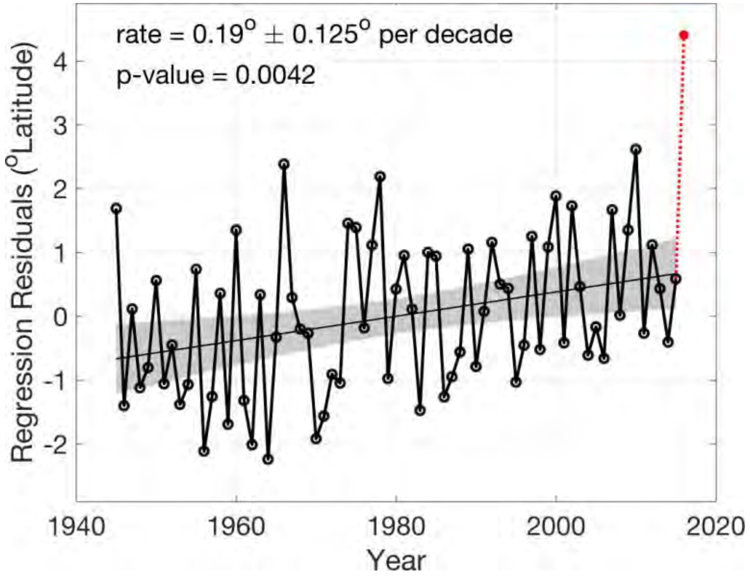
Jim Kossin

Longer-term observed trends and projections



Can we separate part of the trend from natural variability?

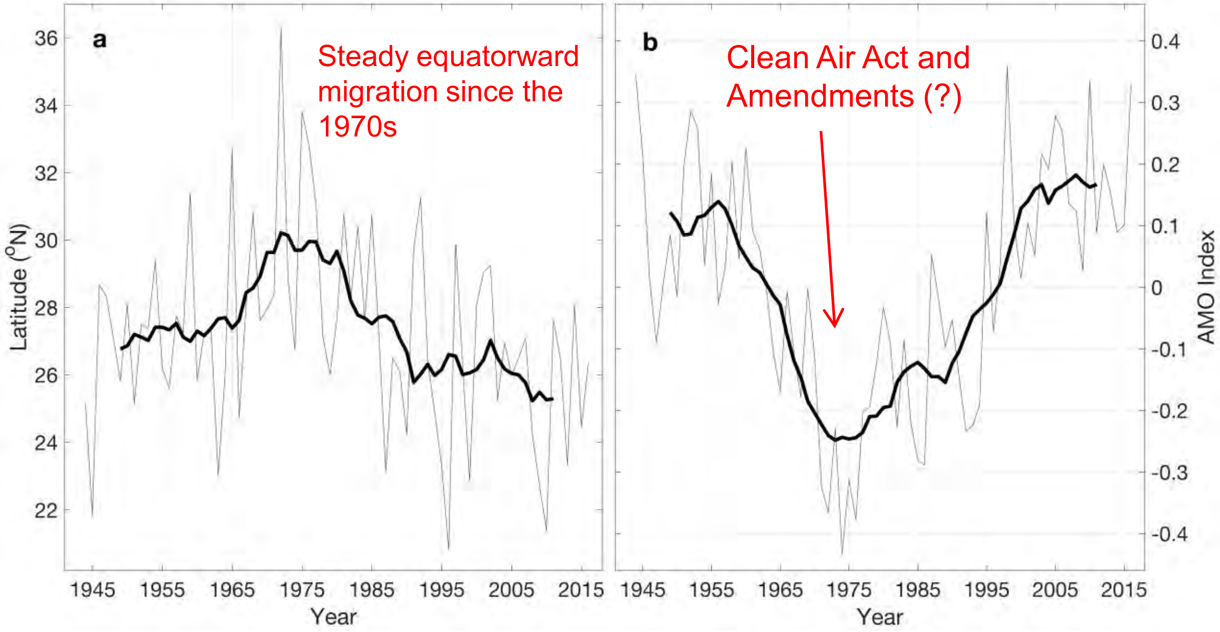
Western North Pacific known dominant modes of natural variability:
ENSO (inter-annual)
PDO (decadal)



Jim Kossin

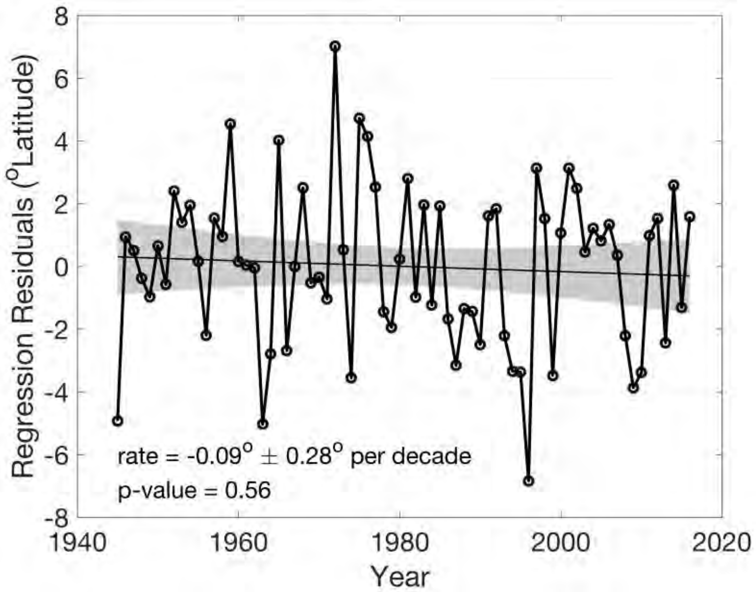
Kossin, J. P., K. A. Emanuel, and S. J. Camargo, 2016: Past and projected changes in western North Pacific tropical cyclone exposure. *J. Climate*, **29**, 5725-5739.

Back to observations: North Atlantic migration of TCs



No long-term trend.

But there is uncertainty about what's driving the Atlantic Multi-decadal Oscillation



Jim Kossin

Kossin, J. P., 2018: Comment on "Spatial and temporal trends in the location of the lifetime maximum intensity of tropical cyclones". *Atmosphere*, **9**, 241-244.

What will happen to TCs in the future? Models agree on an overall reduction.

What is still controversial:

a) regional distribution

b) changes by category

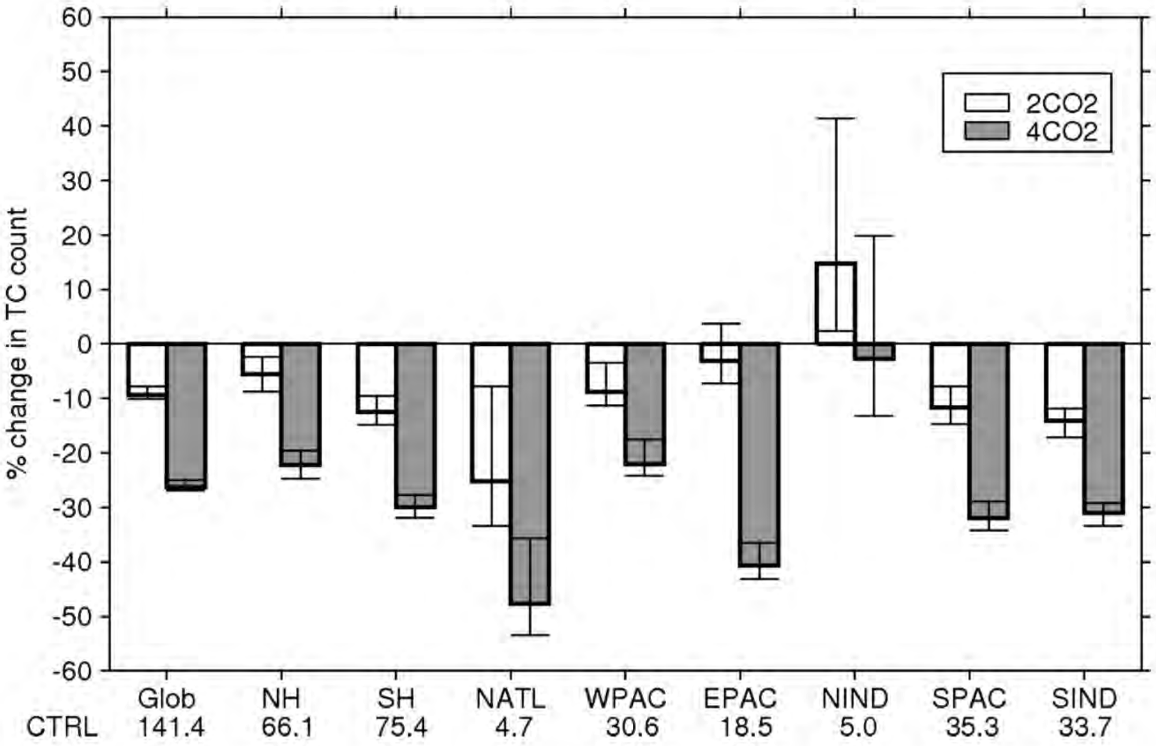


FIG. 3. Percentage change of annual tropical cyclone counts. The error bars denote the maximum and minimum 5×30-year present-day simulations. The present-day climatology is shown at the bottom.

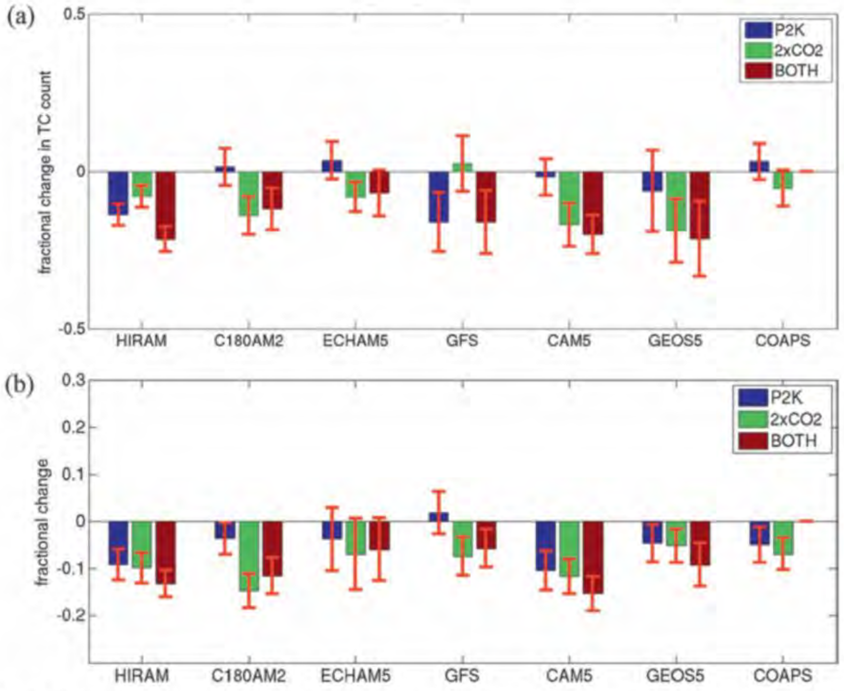


FIG. 3. Comparison between changes in (a) TC formation for various models for the 2K (P2K) and 2CO2 experiments vs (b) TC genesis as weighted by changes in midtropospheric vertical velocity, as described in the text. (From Zhao et al. 2013a.)

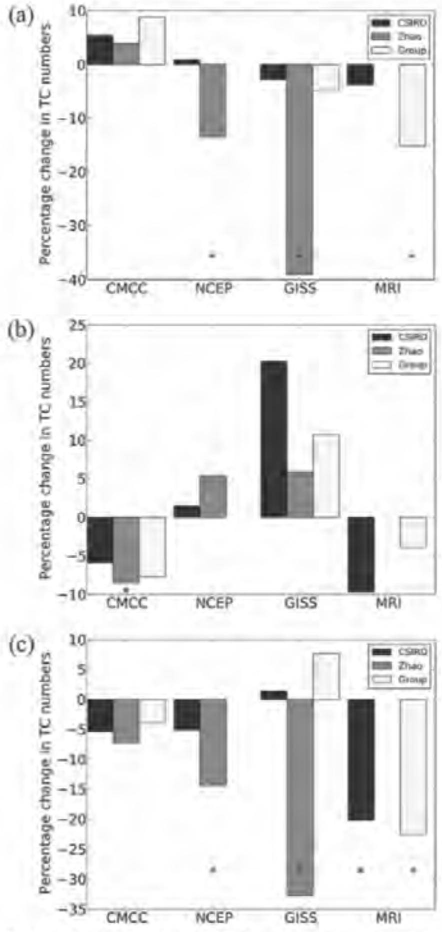


FIG. 6. Percentage change in TC numbers in each model for the three altered climate experiments relative to the present-day experiment, as tracked by the Commonwealth Scientific and Industrial Research Organisation (CSIRO), Zhao, and individual group tracking schemes, after homogenization in (a) duration, (b) wind speed, and (c) latitude of formation. Asterisks indicate statistical significance to at least the $p = 0.05$ level.

Projected changes in intensity due to anthropogenic climate change: still a controversial issue

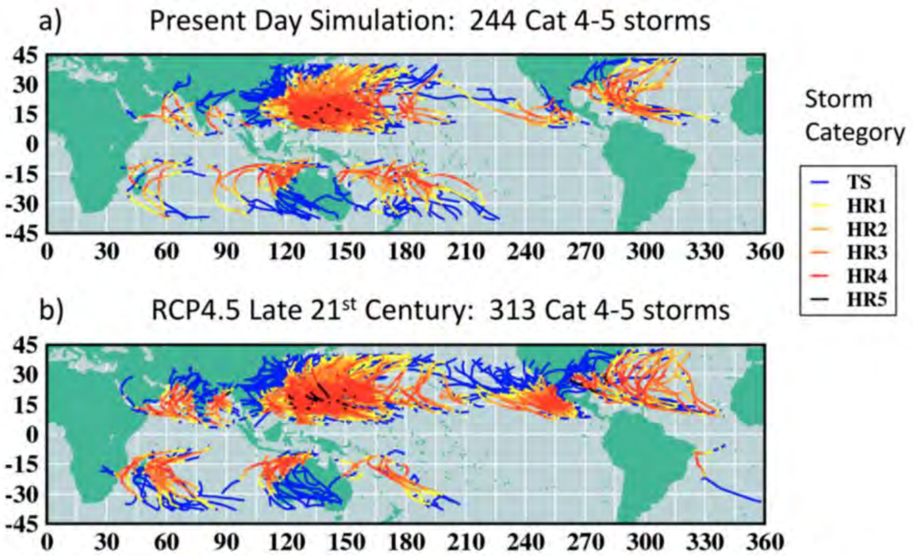


FIG. 7. Tracks of simulated cat 4–5 tropical cyclones for (a) present-day or (b) late-twenty-first-century (RCP4.5; CMIP5 multimodel ensemble) conditions. Simulated tropical cyclone tracks were obtained using the GFDL hurricane model to resimulate (at higher resolution) the tropical cyclone cases originally obtained from the HiRAM C180 global mode. Storm categories or intensities are shown over the lifetime of each storm, according to the Saffir–Simpson scale. The categories are depicted by the track colors, varying from tropical storm (blue) to category 5 (black; see legend).

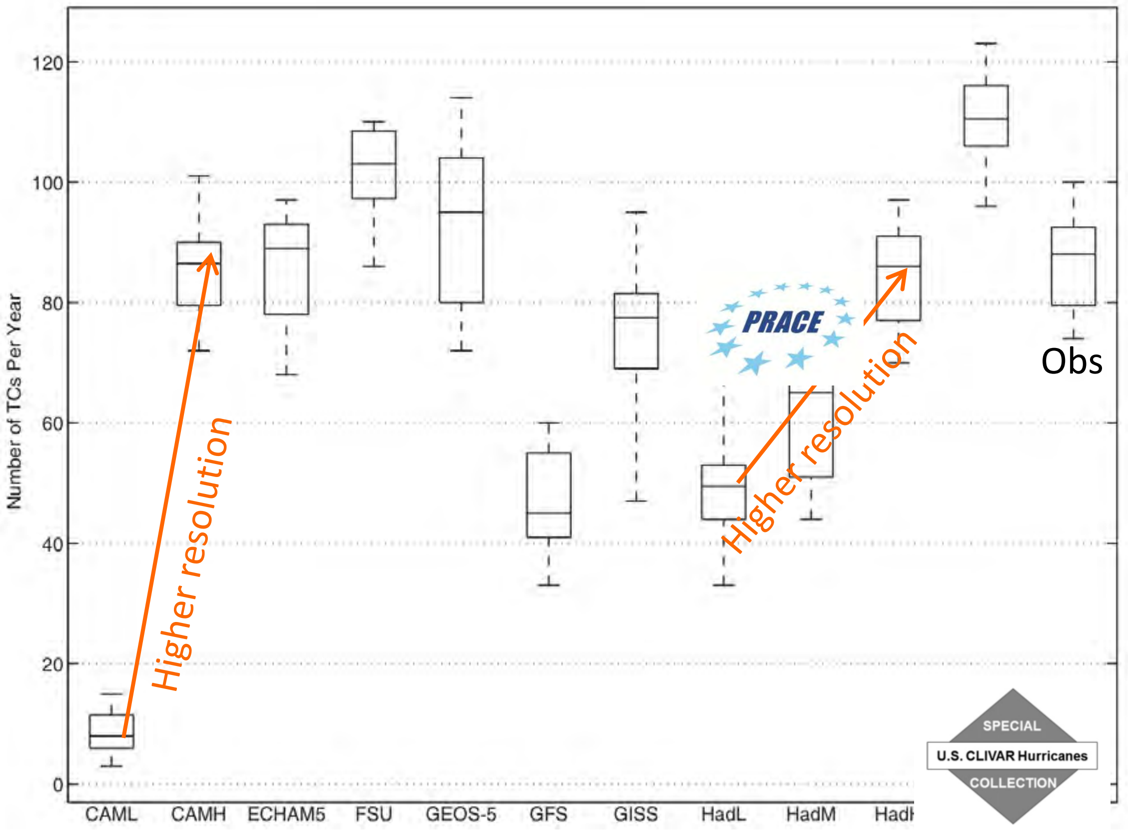
TABLE 3. Tropical cyclone activity (percent change) statistics from downscaling experiments for CMIP5 multimodel ensembles (future vs present day). The future scenarios use RCP4.5 averaged conditions for late twenty-first century and are compared to the "present-day" simulations for 1982–2005 climatological SST conditions. "Cat" refers to Saffir–Simpson intensity category (1–5) with "cat 0" signifying less than hurricane strength. Rain rate is the average rain rate within 100 km of the storm center, including all tropical cyclones (not just 10% rainiest). PDI is power dissipation index in units of $10^9\ m^3\ s^{-2}$. "Hur (wind > 65)" refers to hurricanes with surface wind speeds greater than or equal to $65\ m\ s^{-1}$. "Maxwnd_tc" and "maxwnd_hur" are percent changes of mean lifetime-maximum intensities for all tropical cyclones (wind speed $> 17.5\ m\ s^{-1}$) or hurricanes (wind speed $> 33\ m\ s^{-1}$). The p values, for a null hypothesis of no change from present to future, are given in the line below each percent change entry. These use a two-sided Mann–Whitney–Wilcoxon test for all frequency or days-of-occurrence metrics, and a one-sided test (for increase) for the intensity and rain rate metrics. Bold values indicate significance at the $p < 0.05$ level. "Inf" refers to cases where no occurrences were simulated in the present-day run while some were simulated in the future runs, indicating an infinite percent increase.

Variable	Global	North Atlantic	Northeast Pacific	Northwest Pacific	North Indian	South Indian	Southwest Pacific
No. of TC (cat 0–5)	**−16.4**	−9.4	**16.3**	**−34.5**	19.5	**−26.1**	**−36.6**
p value	**<0.01**	0.39	**0.02**	**<0.01**	0.07	**<0.01**	**<0.01**
No. of hur (cat 1–5)	**−16.6**	−17.5	**19.3**	**−31.6**	**25.6**	**−28.4**	**−40.6**
p value	**<0.01**	0.16	**0.01**	**<0.01**	**0.04**	**<0.01**	**<0.01**
No. of hur (cat 3–5)	1.8	2.7	**83.7**	**−16.9**	21.7	−8.3	**−50.6**
p value	[illegible]	0.76	**<0.01**	**<0.01**	0.14	0.42	**<0.01**
No. of hur (cat 4–5)	**28.3**	42.1	**337.5**	−6.5	200.0	63.6	**−58.3**
p value	**<0.01**	0.63	**<0.01**	0.59	−0.05	0.07	**0.01**
No. of hur (wind > 65)	**59.3**	125.0	Inf	16.7	Inf	Inf	0.0
p value	**0.01**	0.36		0.63			1.00
ACE	−13.1	−9.7	**44.2**	**−26.9**	23.2	**−28.8**	**−41.7**
p value	0.15	0.29	**<0.01**	**<0.01**	0.13	**<0.01**	**<0.01**
PDI	**−9.7**	−3.1	**52.7**	**−22.7**	28.6	**−26.6**	**−43.9**
p value	**<0.01**	0.53	**<0.01**	**<0.01**	0.08	**<0.01**	**<0.01**
maxwnd_ts	**3.6**	0.4	**8.2**	**7.4**	3.4	1.8	−5.6
p value	**<0.01**	0.41	**<0.01**	**<0.01**	0.07	0.20	0.98
maxwnd_hur	**4.1**	**4.5**	**7.8**	**5.5**	1.6	**3.3**	−3.1
p value	**<0.01**	**0.04**	**<0.01**	**<0.01**	0.23	**0.03**	0.88
Cat 4–5 days	**34.5**	175.4	**478.1**	9.7	**405.0**	55.4	**−52.5**
p value	**<0.01**	0.14	**<0.01**	0.50	**0.04**	0.39	**0.03**
Rain rate_tc (cat 0–5)	**14.3**	**17.3**	**17.2**	**20.8**	**10.5**	**8.5**	−1.2
p value	**<0.01**	**<0.01**	**<0.01**	**<0.01**	**0.01**	**0.03**	0.66
Rain rate hur (cat 1–5)	**13.4**	**20.5**	**14.4**	**15.5**	**12.8**	**11.1**	3.5
p value	**<0.01**	**<0.01**	**<0.01**	**<0.01**	**<0.01**	**<0.01**	0.58
Rain rate hur (cat 3–5)	**8.8**	**14.0**	**9.7**	**9.7**	**10.8**	**6.1**	10.6
p value	**<0.01**	**0.02**	**<0.01**	**<0.01**	**<0.01**	**<0.01**	0.65
Rain rate hur (cat 4–5)	**7.7**	9.4	**11.4**	**8.7**	21.4	−1.5	15.3
p value	**<0.01**	0.13	**<0.01**	**<0.01**	0.06	0.54	0.93
Delta SST (°C)		1.546	1.685	1.567	1.551	1.384	1.145

What are the present model limitations and how are these being (or could be) resolved?

Tropical Cyclones "emerge" at high resolution

From US CLIVAR Hurricane Working Group (2015)



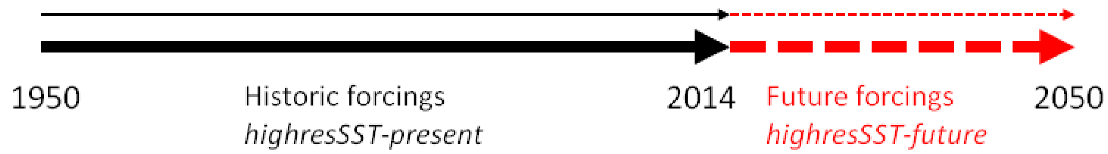
Shaevitz et al. 2015. Journal of Climate

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

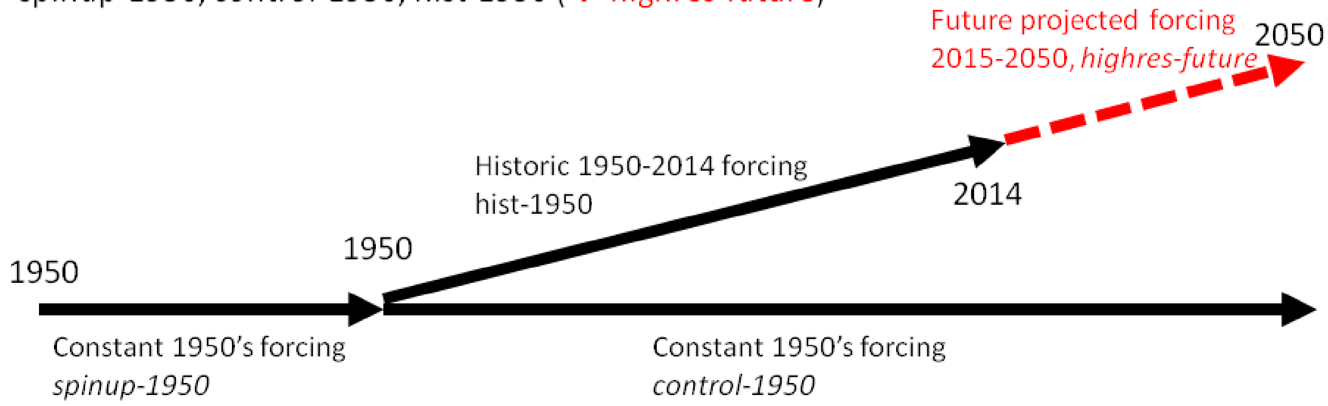
to CMIP6-HighResMIP TC simulations

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)



Co-funded by the European Union
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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

HighResMIP: Haarsma et al., GMD, 2016

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

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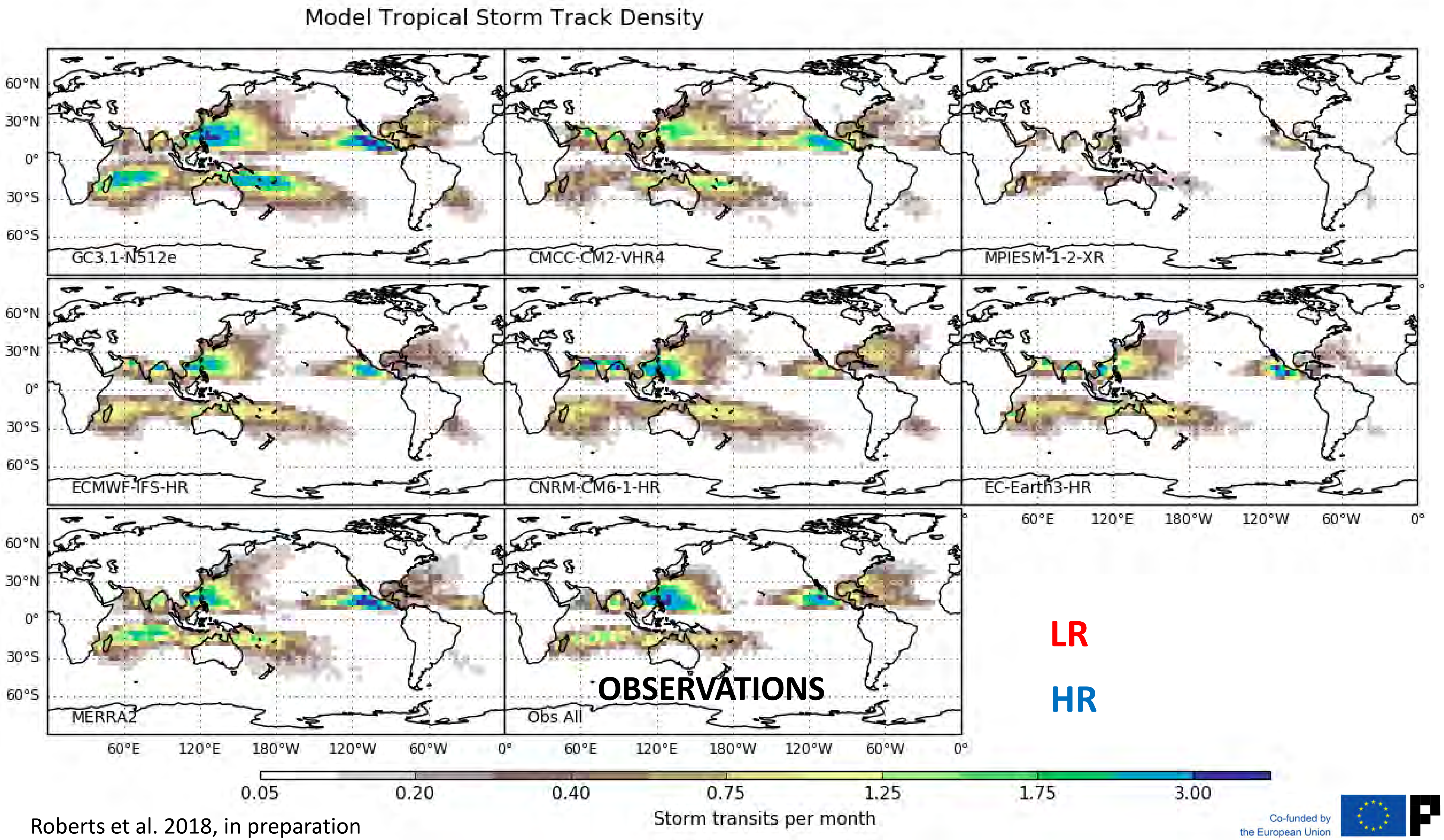
Tropical Cyclone **track density: 65 year climatologies**

(storm transits per month per 4 degree unit area)



Roberts et al. 2018, in preparation

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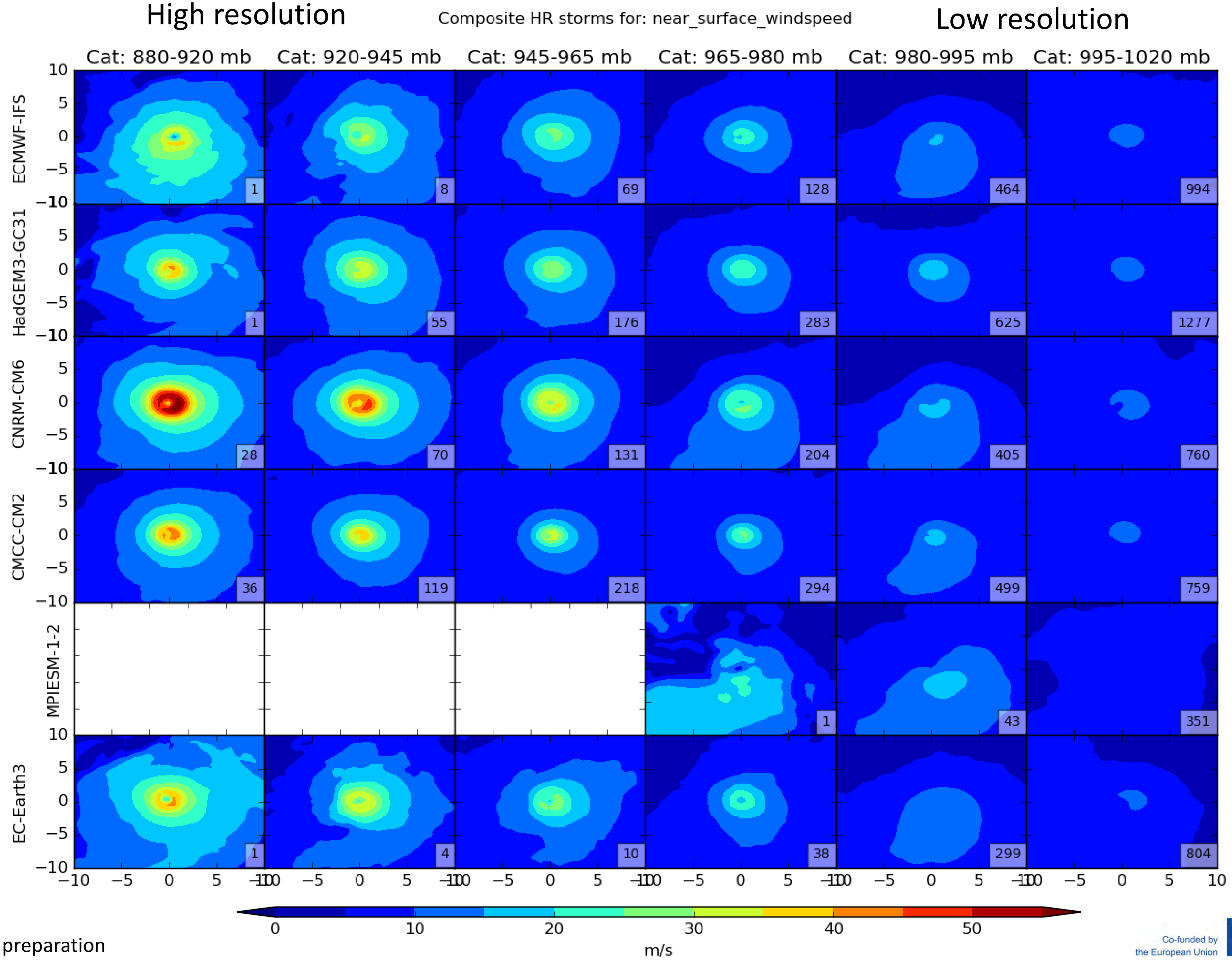
High resolution

Low resolution



Roberts et al. 2018, in preparation

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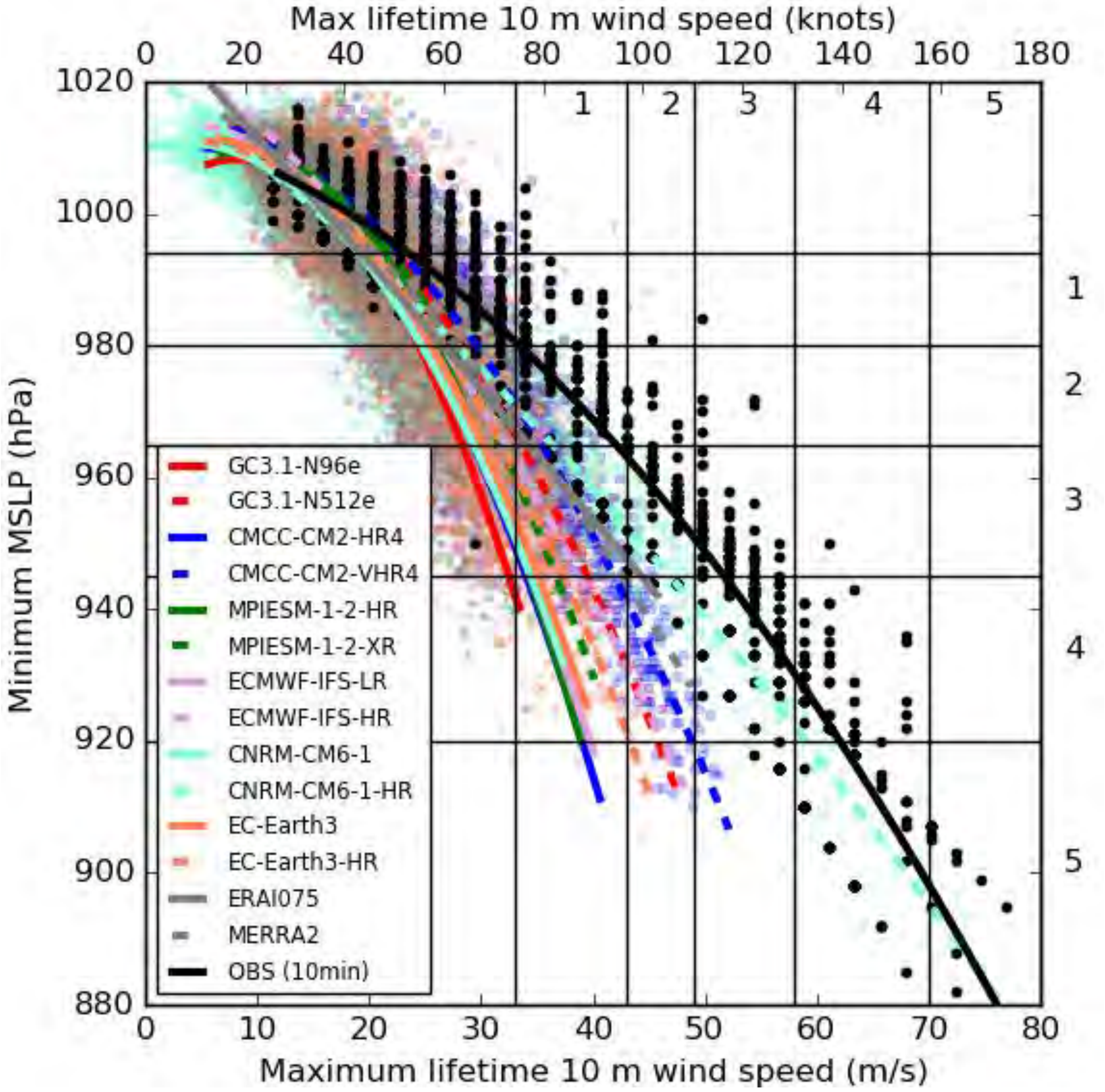
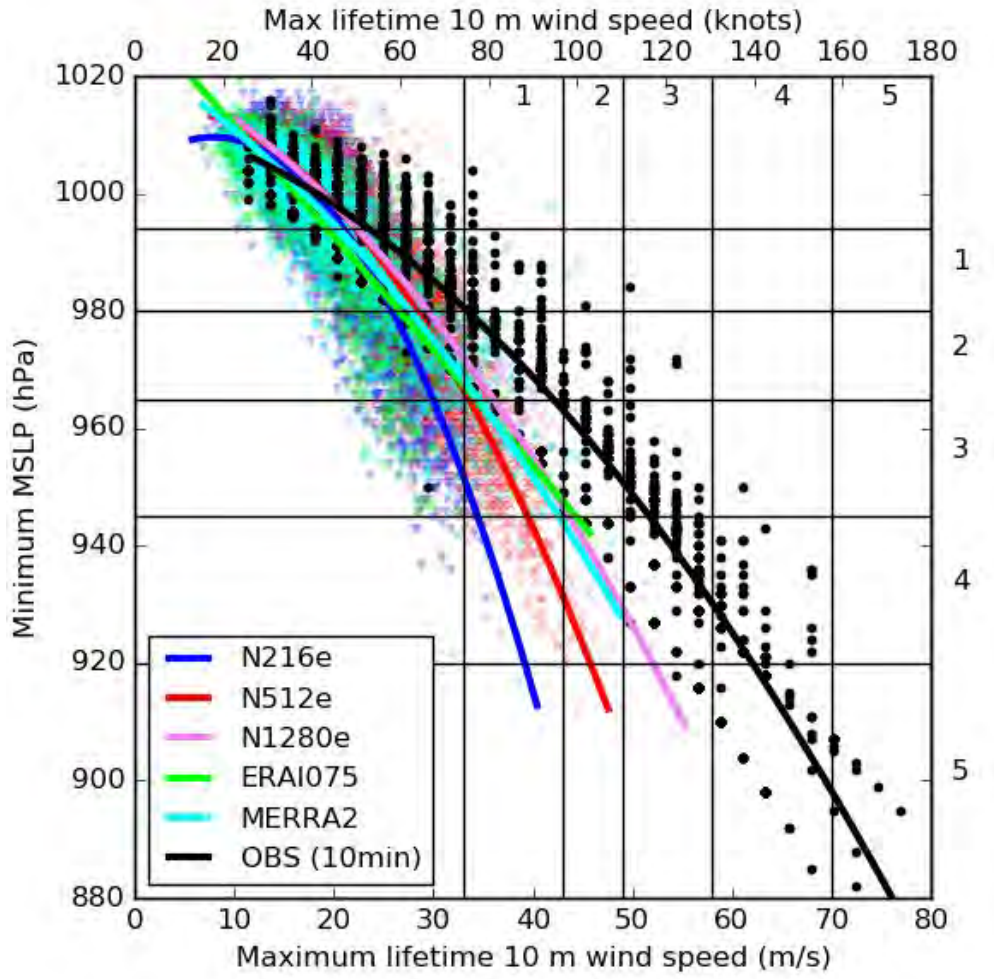
TC intensity using MSLP-10m wind
(instantaneous 6 hourly, not max/min over 6 hours)



Continuous lines are coarser GCMs

Dashed lines are higher resolution GCMs

HadGEM3, from 100 to 10km resolution



Roberts et al. 2018, in preparation

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PRIMAVERA

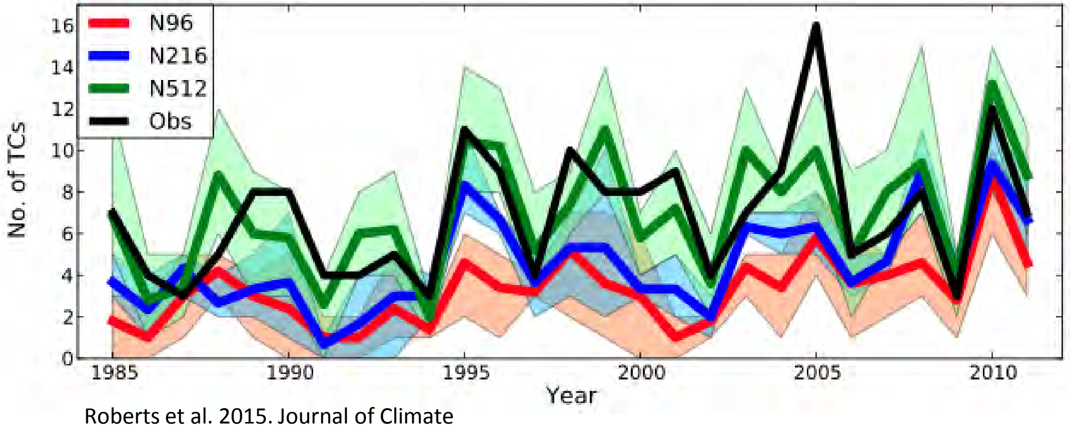
Interannual TC frequency correlation with observations (all/hurr) - 1 member

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

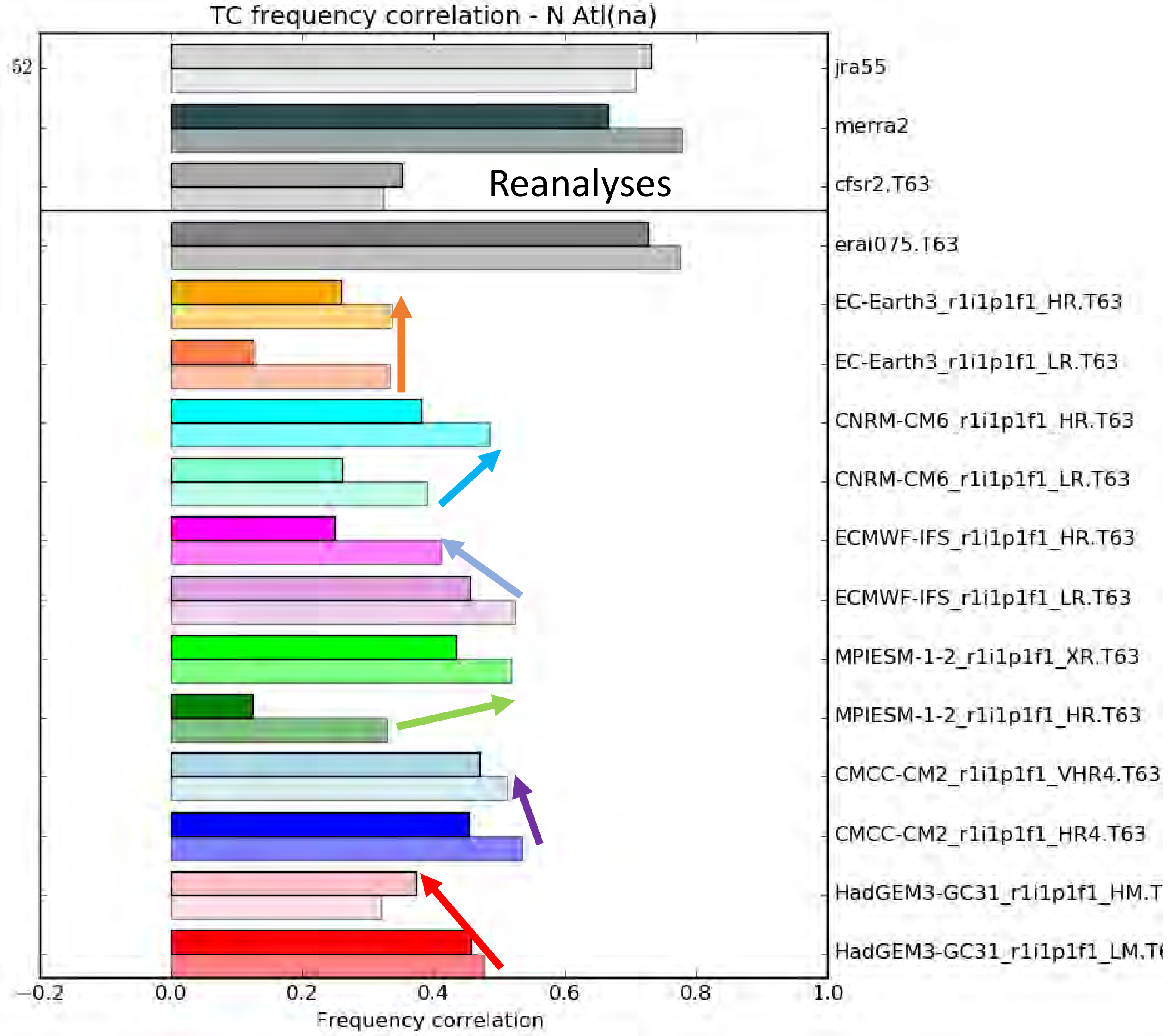
→ Key to seasonal prediction of hurricanes (and typhoons)

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)



Roberts et al. 2018, in preparation

SPECIAL
U.S. CLIVAR Hurricanes
COLLECTION

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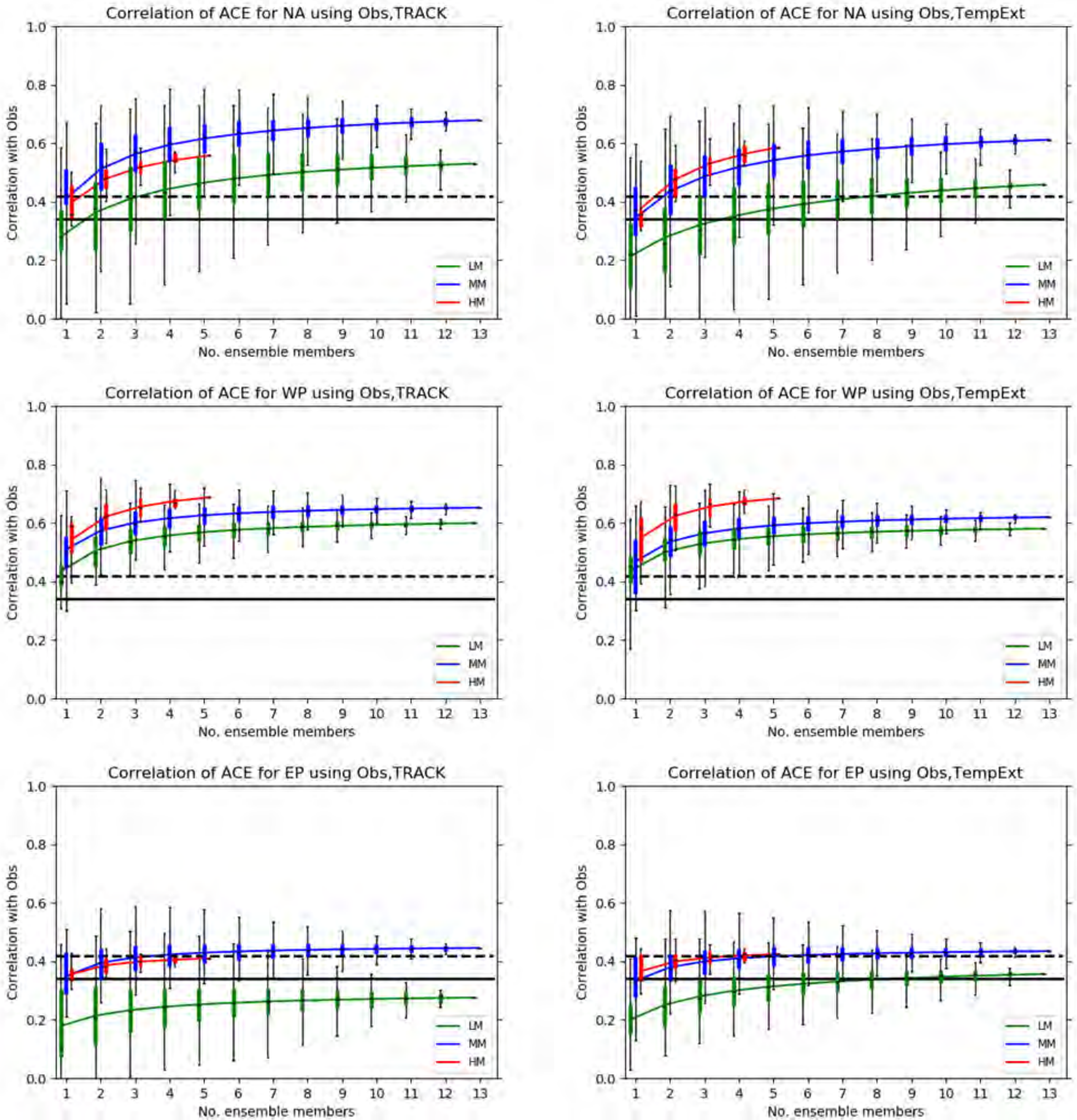

Is using single ensemble members per GCM enough to robustly represent interannual variability?

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

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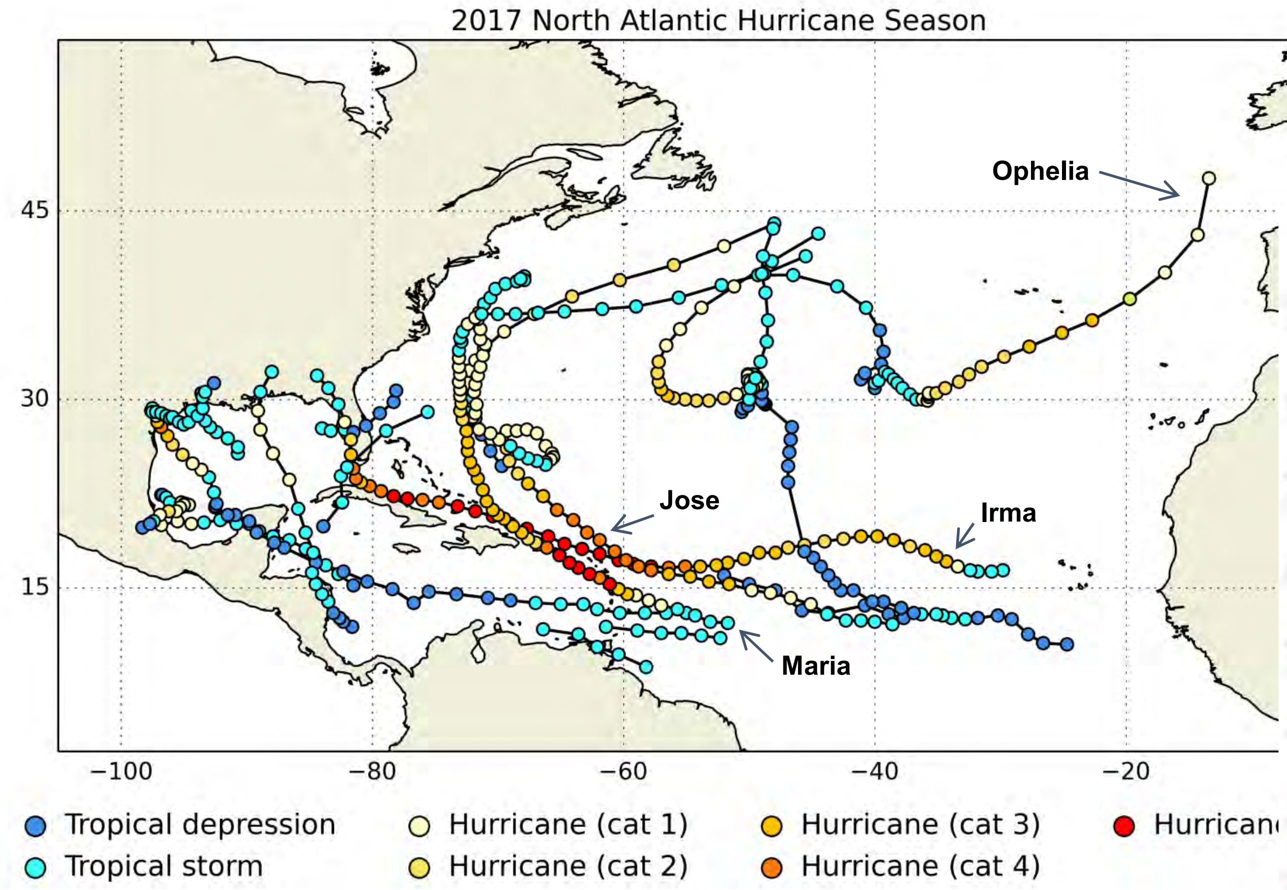
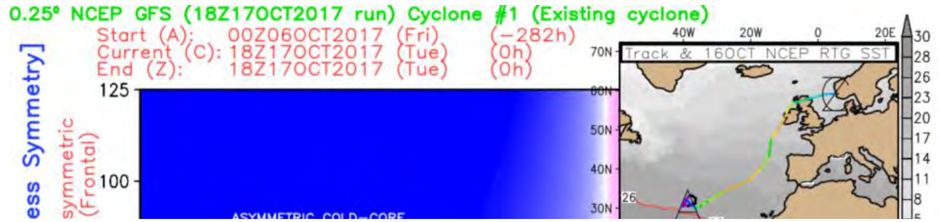
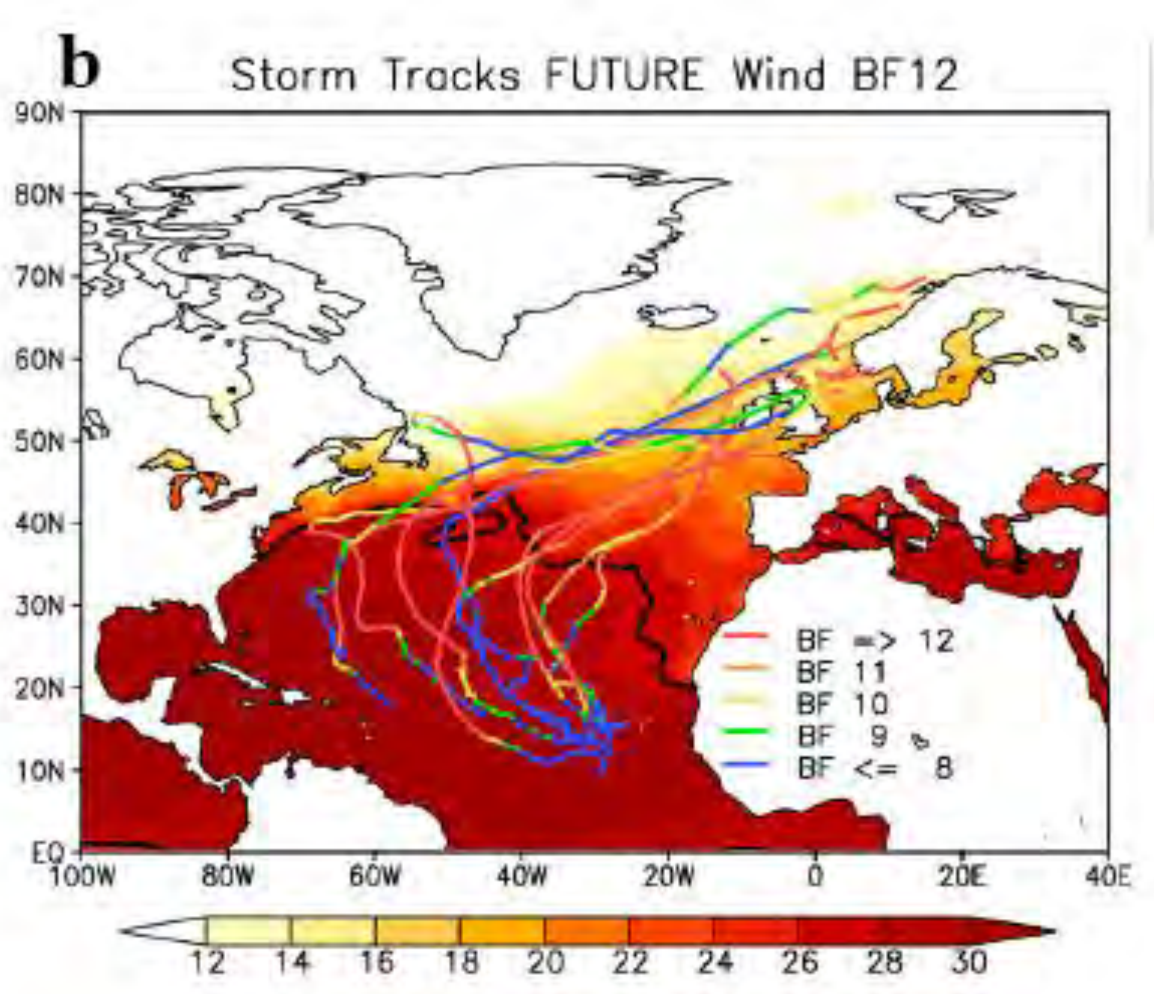
Motivation II: a changing risk from TCs





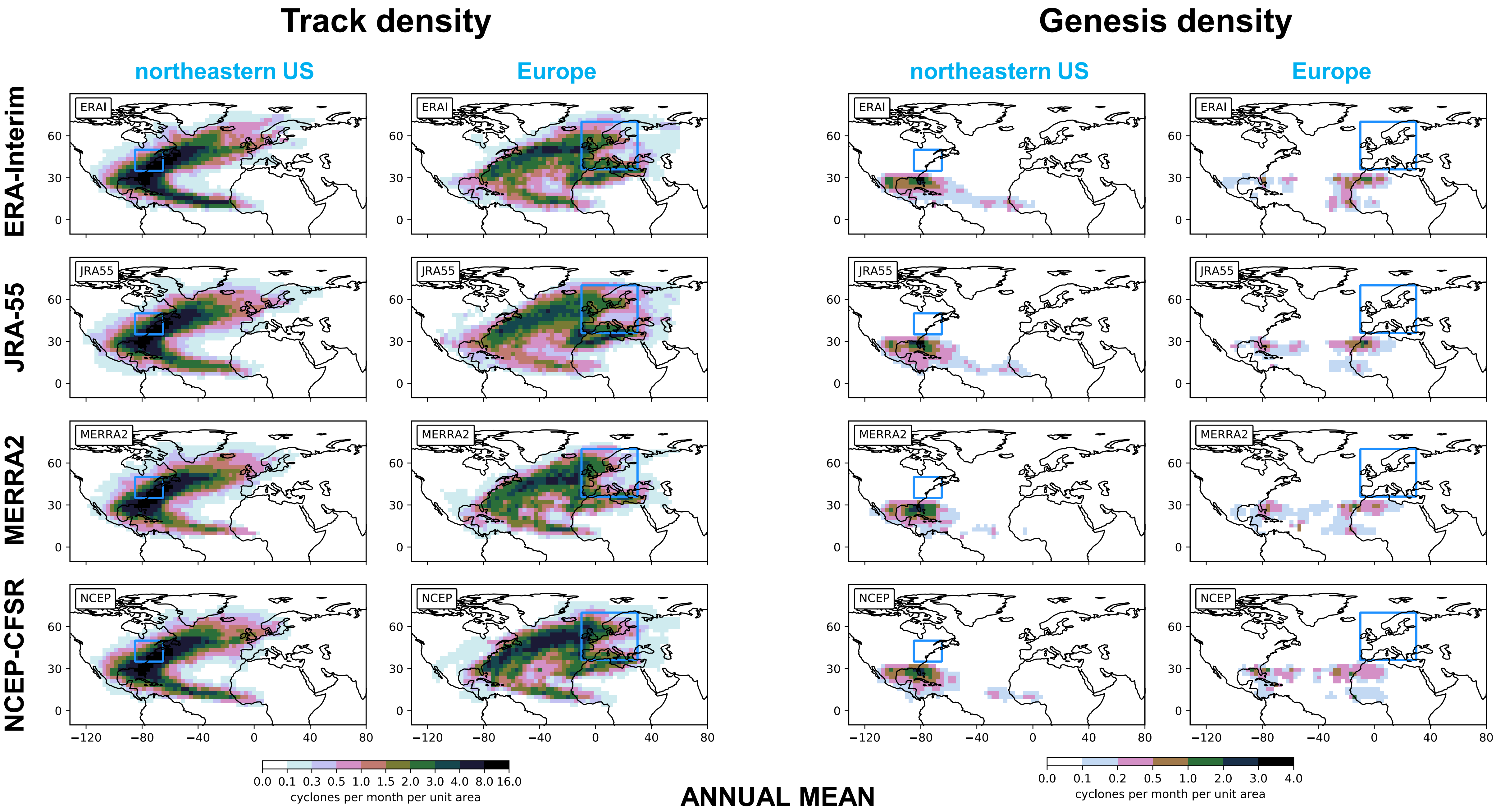


Total storms: 17

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

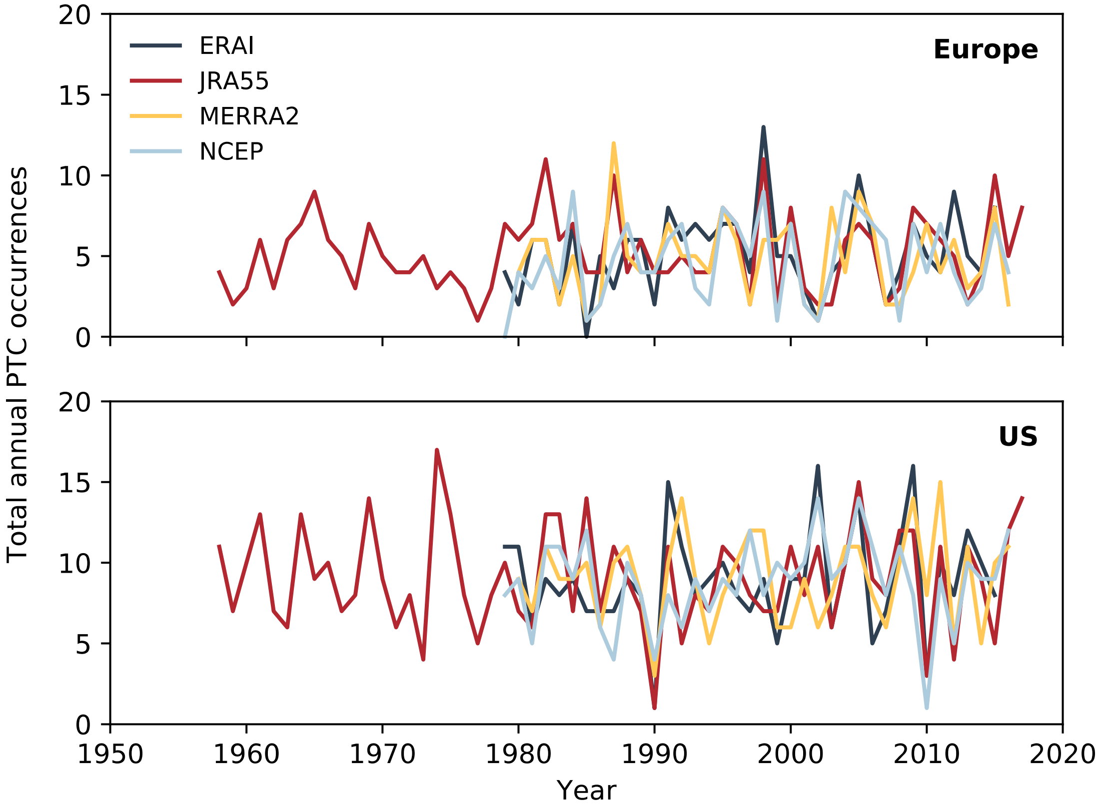
Accumulated Cyclone Energy (ACE) index = 226

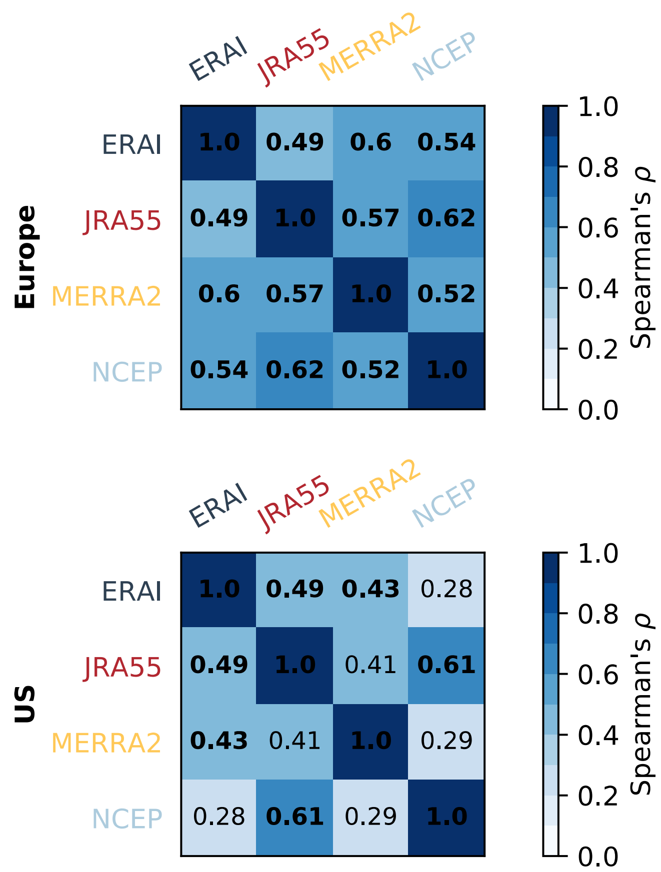
Thanks to Jo Camp



Alex Baker, GRL 2019 in prep.

Historical variability of North Atlantic post-tropical cyclones



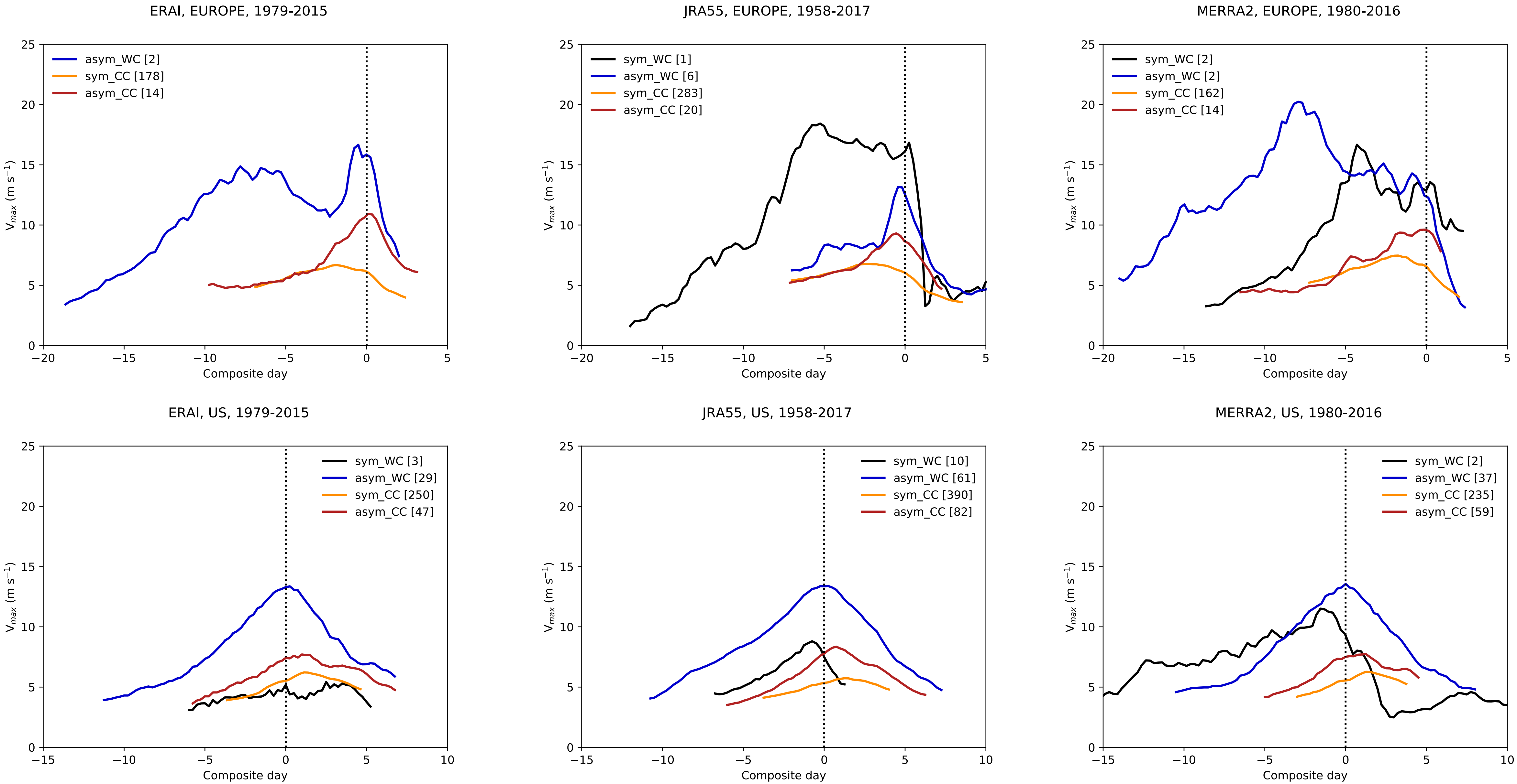


***bold = significant at 99% level**

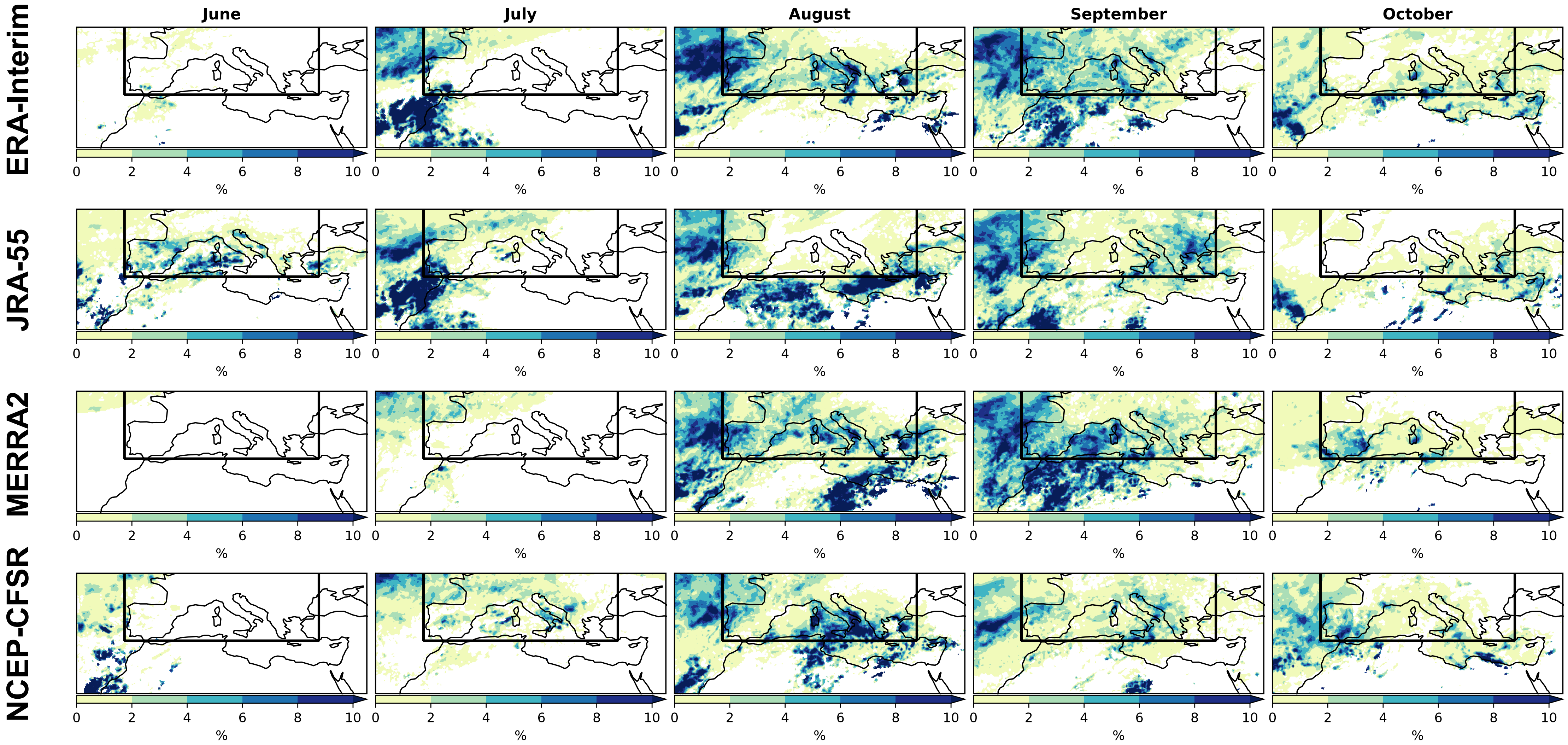
Alex Baker, GRL 2019 in prep.

Alex Baker, GRL 2019 in prep.

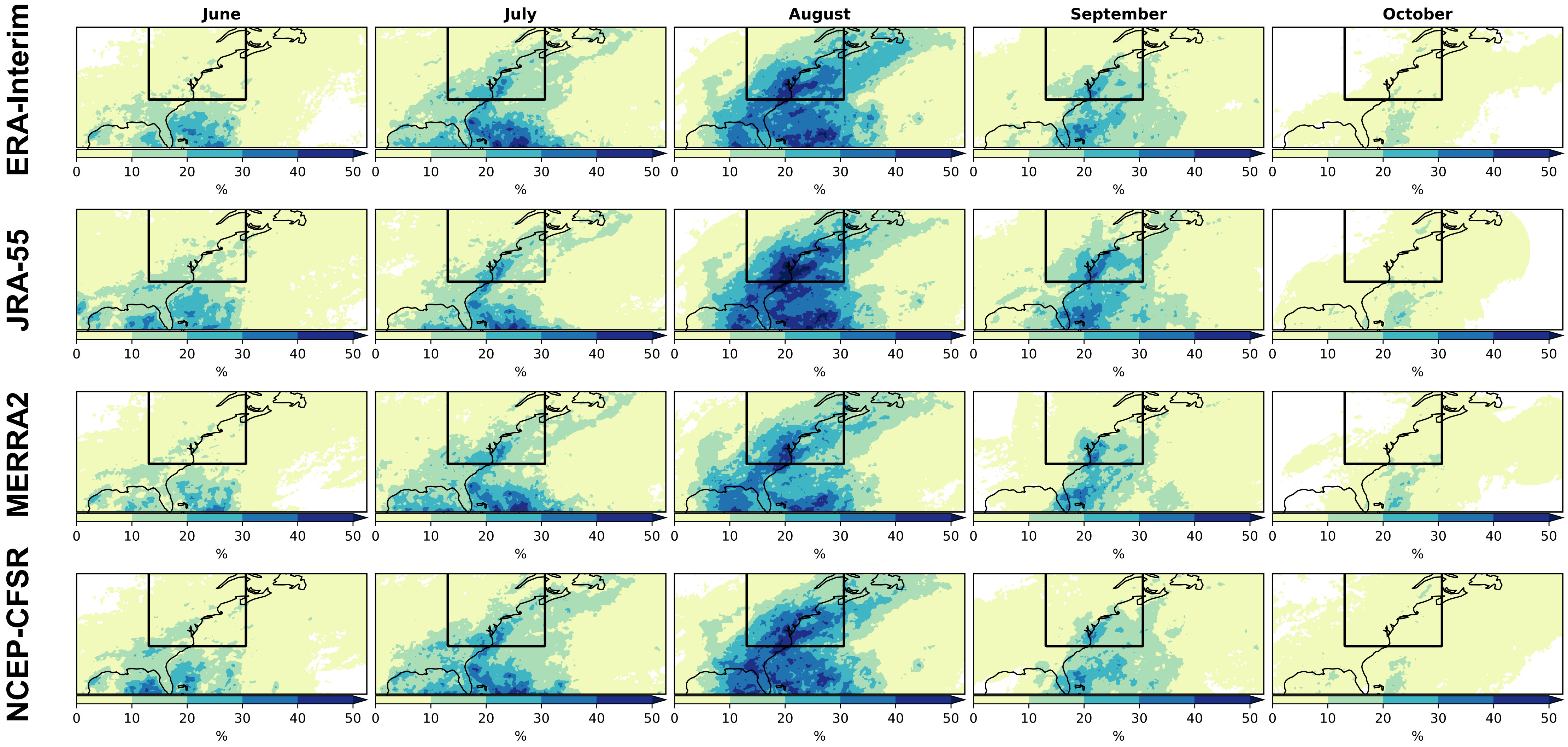
Composite post-tropical cyclone lifecycles



Post-tropical cyclone-associated precipitation – Europe



Post-tropical cyclone-associated precipitation – northeast US



TRMM
Tropical Rainfall Measuring Mission

Summary

- 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)
  - In this context it is extremely important that we are working as a community, under **an agreed protocol, HighResMIP**. Progress in understanding from that decision. <u>However</u>:
    - 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.

University of Reading
National Centre for Atmospheric Science
NATURAL ENVIRONMENT RESEARCH COUNCIL
Met Office
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HRCM and TC research: who is doing what?

Topic	Sub-topic	People
Storm tracks, variability		M Roberts, K Hodges
TCs simulation	Role of resolution Role of Stochastic Phyisics	M Roberts, PL Vidale PL Vidale, K Hodges, M Robersts, ECMWF group
Post-Tropical Cyclones		A Baker
TC-centred hydrological cycle		B Vanniere
TC energetics		B Harris
Decadal Variability		P Loizou
Impacts	Climatologies of precipitation(and mositure transports) caused by TCs	L Guo, A Franco Diaz

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