Lessons from simulating tropical cyclones in climate models

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Reference:

Review paper:

- S.J. Camargo & A.A. Wing, 2015. Tropical cyclones in climate models, WIREs Climate Change, early online, doi: 10.1002/wcc373

Main challenge:

- Climate model simulations: low horizontal resolution – computationally compatible with long simulations, multiple future scenarios and multiple ensemble members.
- Tropical cyclones: accurate simulation necessary to run models with high horizontal resolution.
- Simulation of TCs in climate models a difficult task.

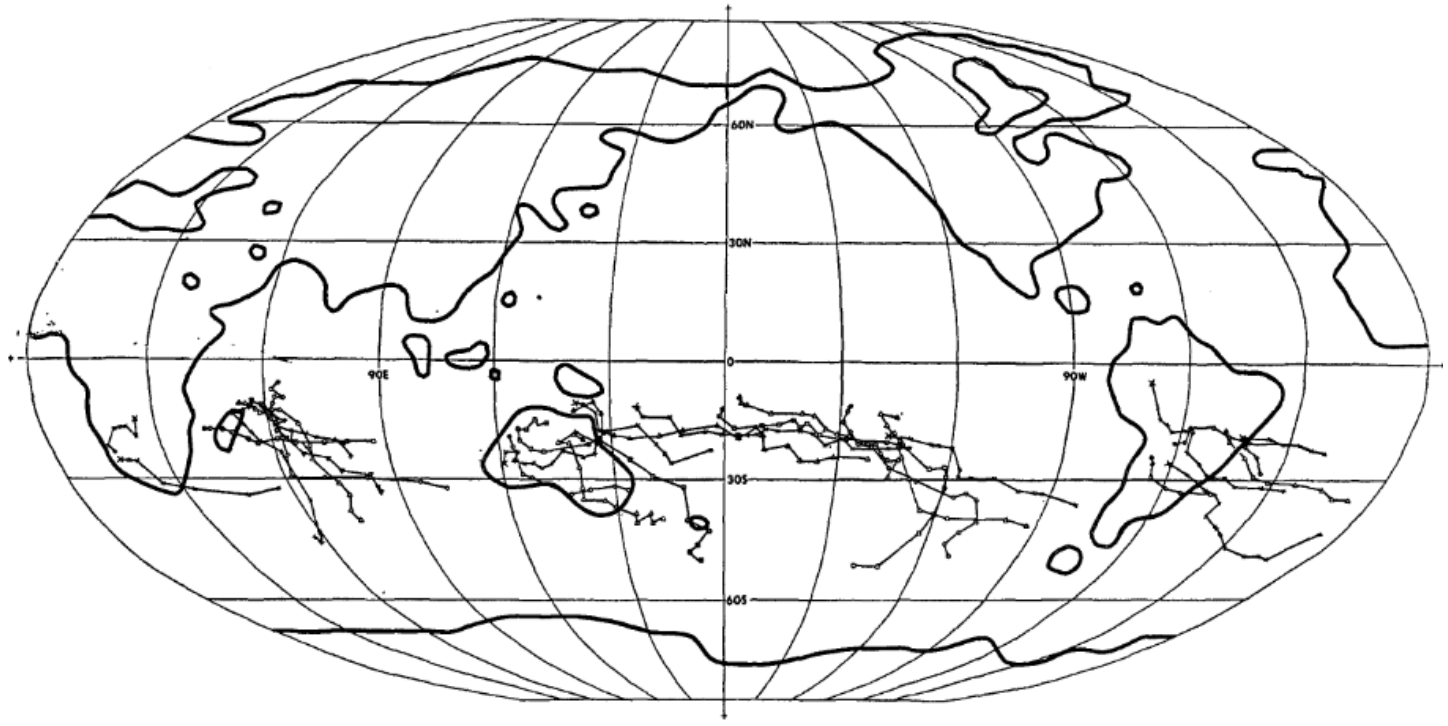
Historical perspective I

- Since 1970s: climate models produce disturbances similar to Tropical Cyclones (TCs)
- Location, seasonality, tracks, lifetime: "compatible" with observations

Historical Perspective II:

1st paper discussing tropical cyclones in climate models:
Manabe, Holloway and Stone, JAS 1970

- Cyclonic vortices in observed TC regions
- Low-resolution model: 417 km (Equator) to 655 km (Poles)



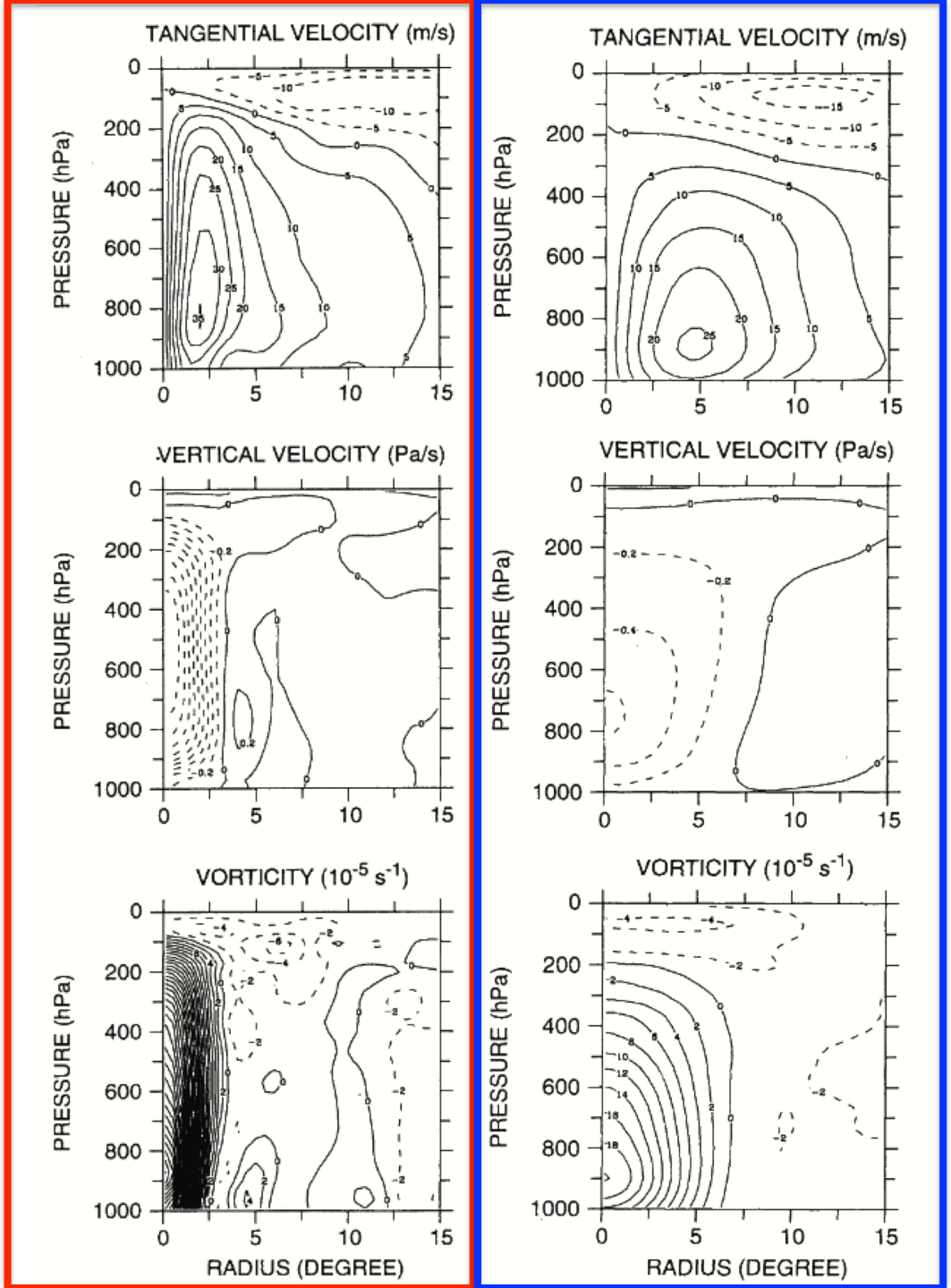
Manabe et al., J. Atmos. Sci., 1970

Historical Perspective III

- Structure somewhat similar to observed TCs
- Vortices with low pressure values, heavy precipitation, strong convergence near the surface and divergence in the upper troposphere
- Formation with warm over warm sea surface temperatures (SSTs)
- Main biases: large size and weak intensity – due to low horizontal resolution

Historical Perspective IV:

- Bengtsson, Böttger & Kanamitsu, Tellus A, 1982: TCs in the ECMWF model (1 year) – sensitivity to SST.
- 1980s: substantial progress in forecasting individual storms. Necessary requirements:
  - Horizontal high-resolution
  - Surface layer fluxes with adequate resolution
  - Parametrizations of boundary layer, cumulus convection, radiative processes



Improvements with increasing model resolution

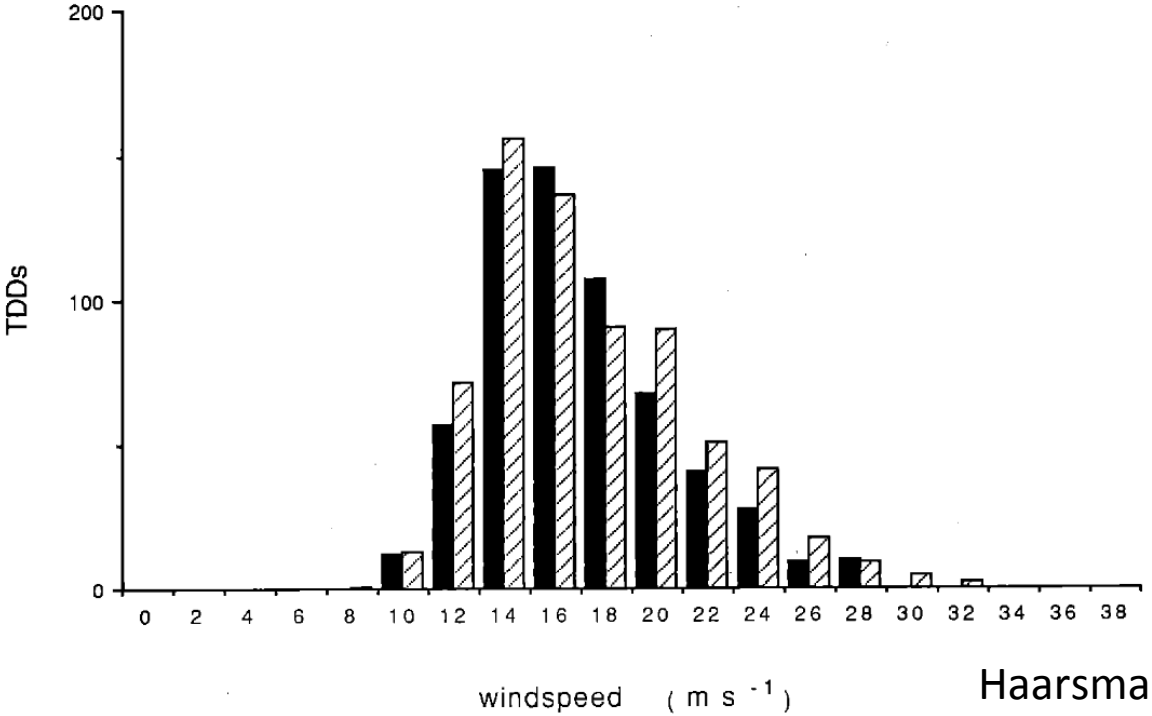
Bengtsson et al. 1995

Historical Perspective V: Climate Change & Tropical Cyclones

- First study - Broccoli & Manabe (1990): simulations with 2xCO_2 vs. control:
  - TC like storms tracked in both models
  - Results were inconclusive, depending on cloud treatment.
- Launch of a new way of studying the interaction of TCs and climate change

Historical Perspective VI

- First studies analyzing the impact of climate change on tropical cyclone activity in the 1990s (Broccoli & Manabe, 1990; Haarsma et al. 1993; Bengtsson et al. 1996).
- Double CO_2 vs. control

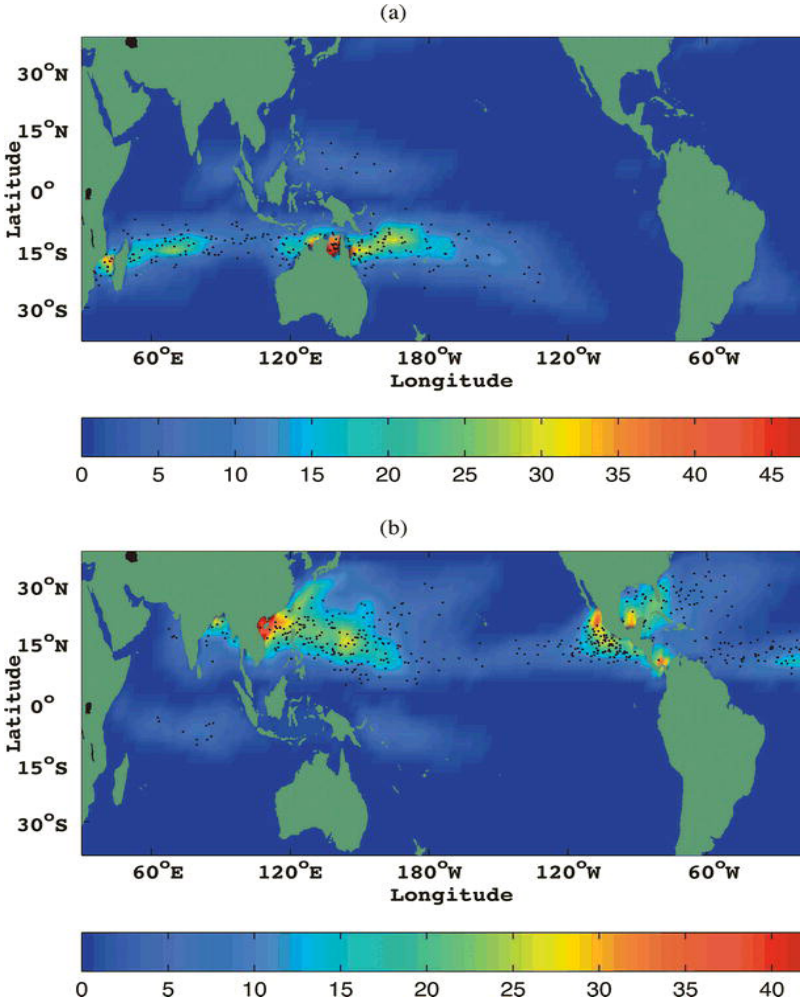


Haarsma et al., Clim. Dyn., 1993

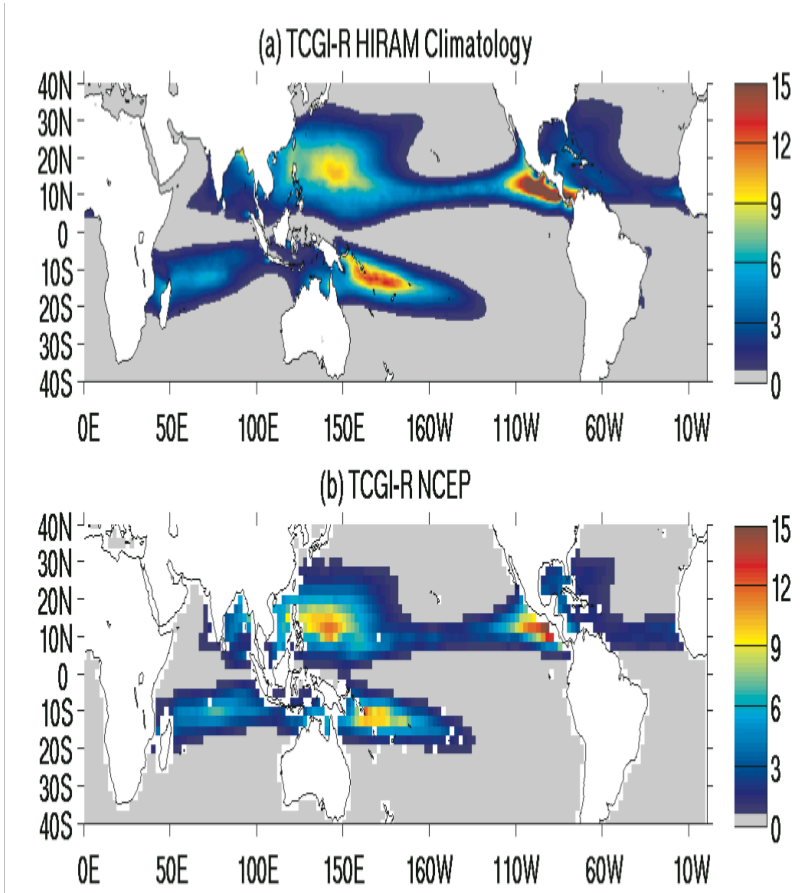
Alternative approaches

- Genesis indices applied to climate models
- Dynamical Downscaling
- Statistical-dynamical downscaling
- Statistical-dynamical forecasts

Genesis Indices

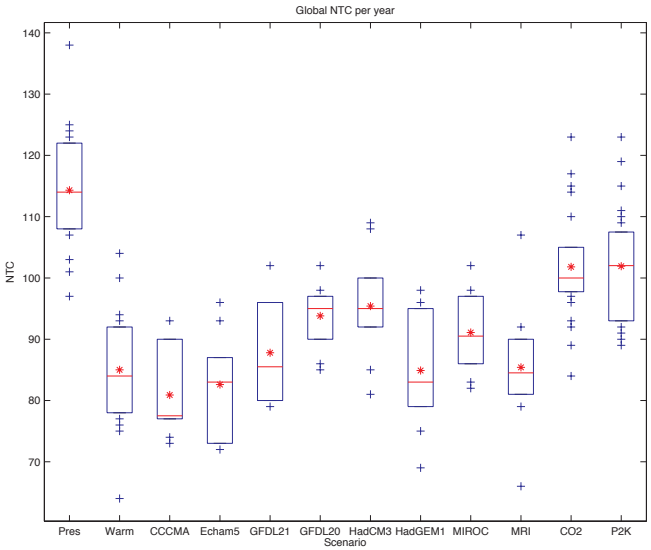


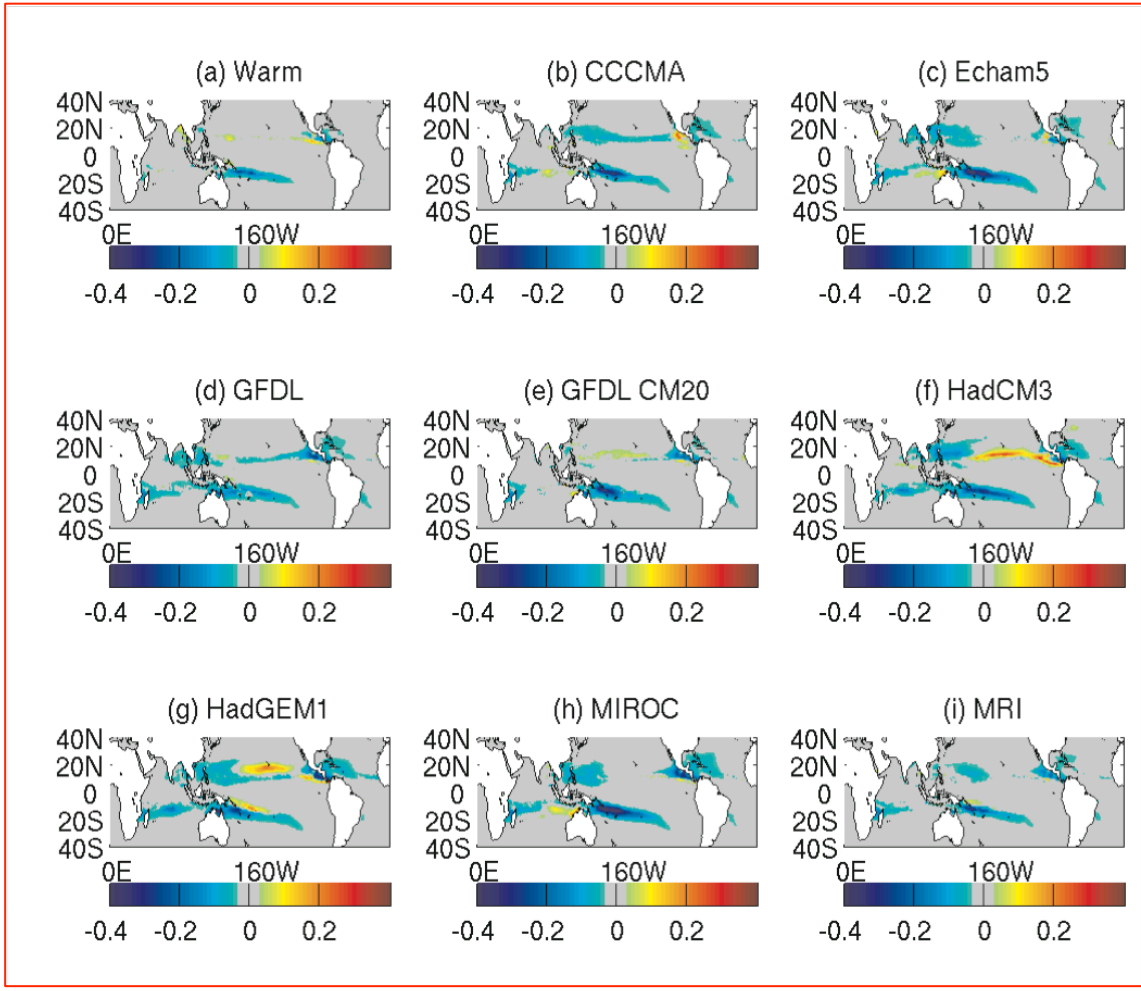
Emanuel & Nolan GPI
Camargo et al. 2007



Tippett et al. 2011 TCGI
Camargo et al. 2014

Genesis Indices & Climate Change





Camargo et al. 2014

Synthetic tracks – large-scale environment from climate models

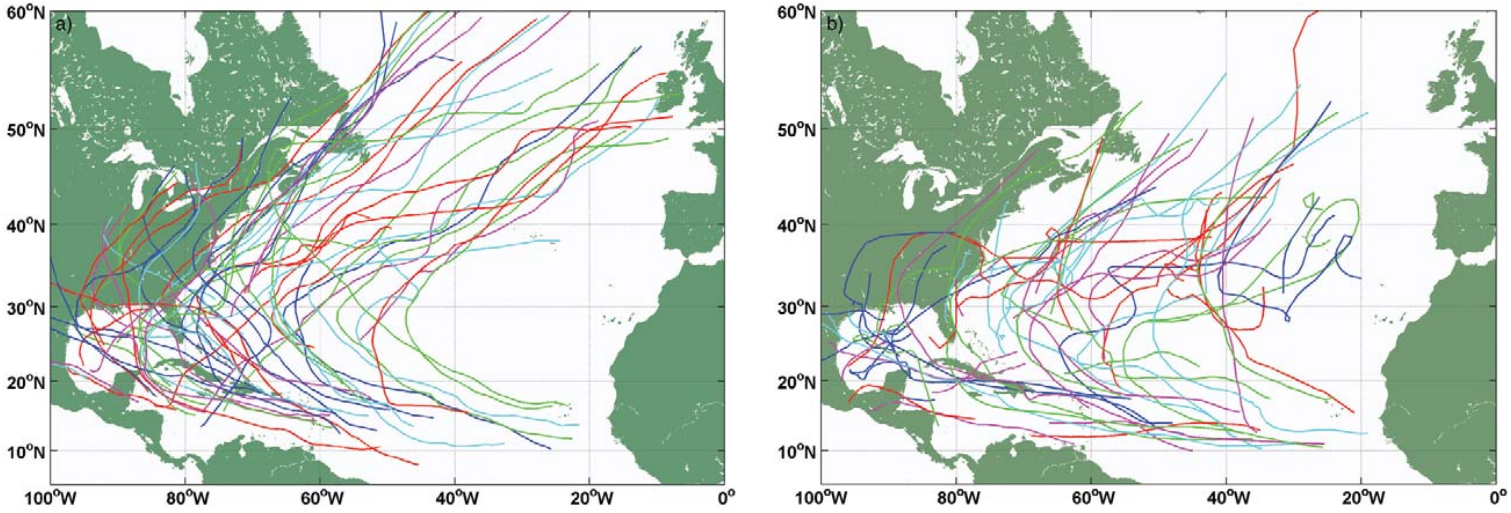
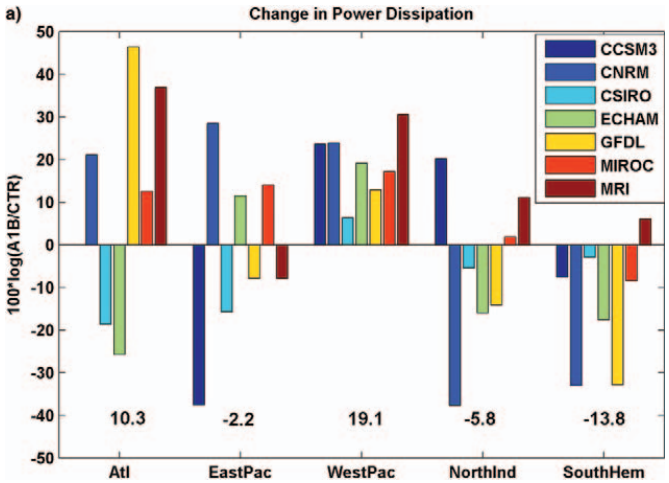
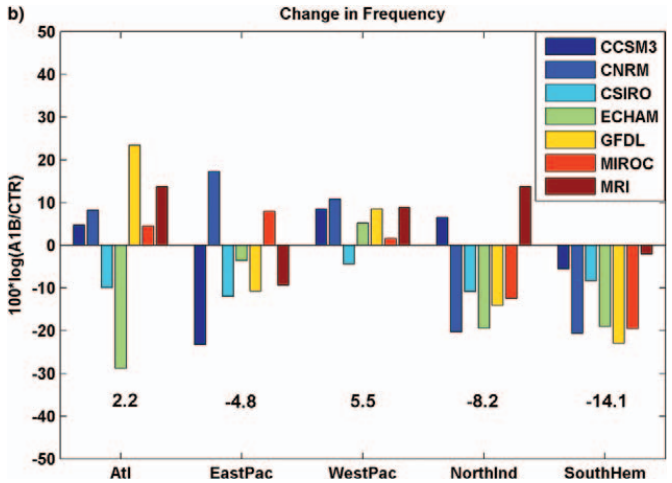


FIG. A1. Sixty random tracks from (a) the Markov chain method, and (b) HURDAT data.

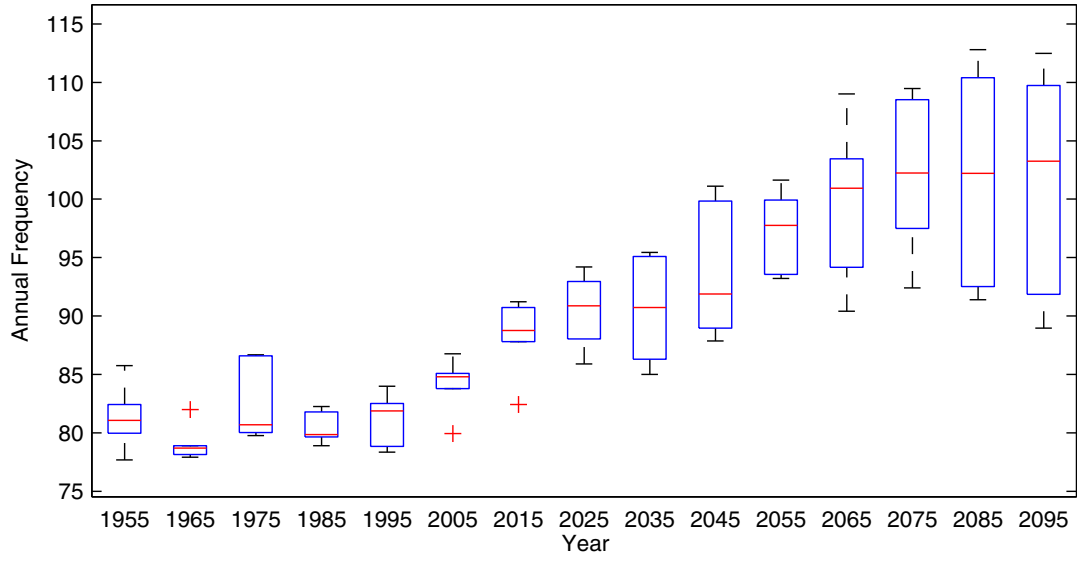
Emanuel 2006

Statistical-Dynamical Downscaling



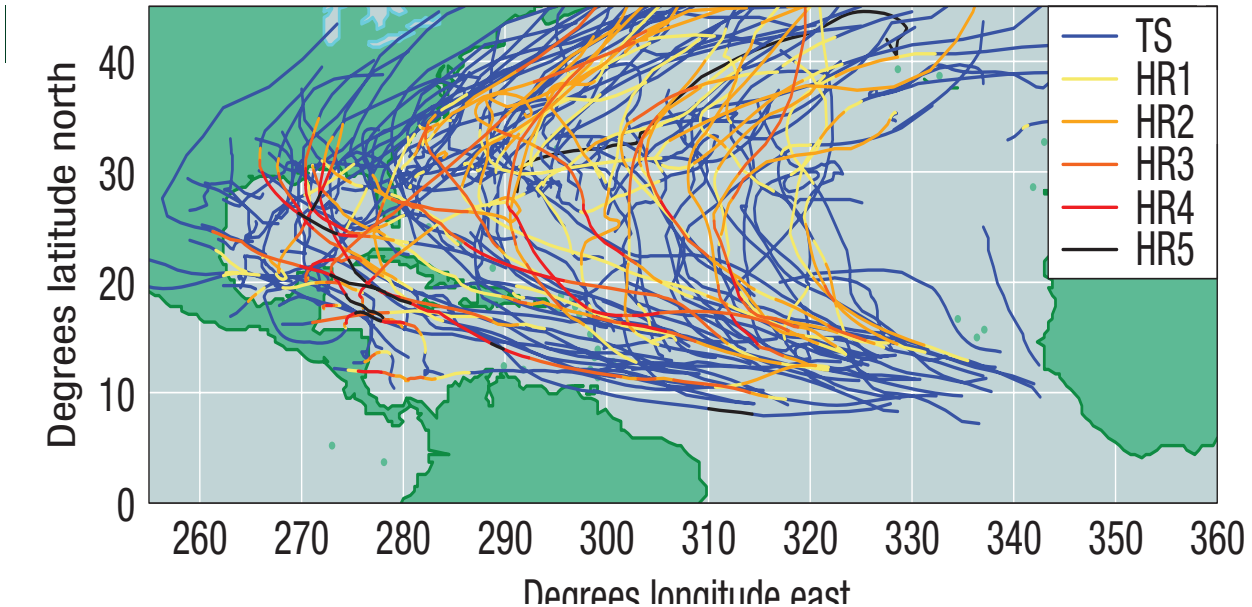


Emanuel, BAMS 2008



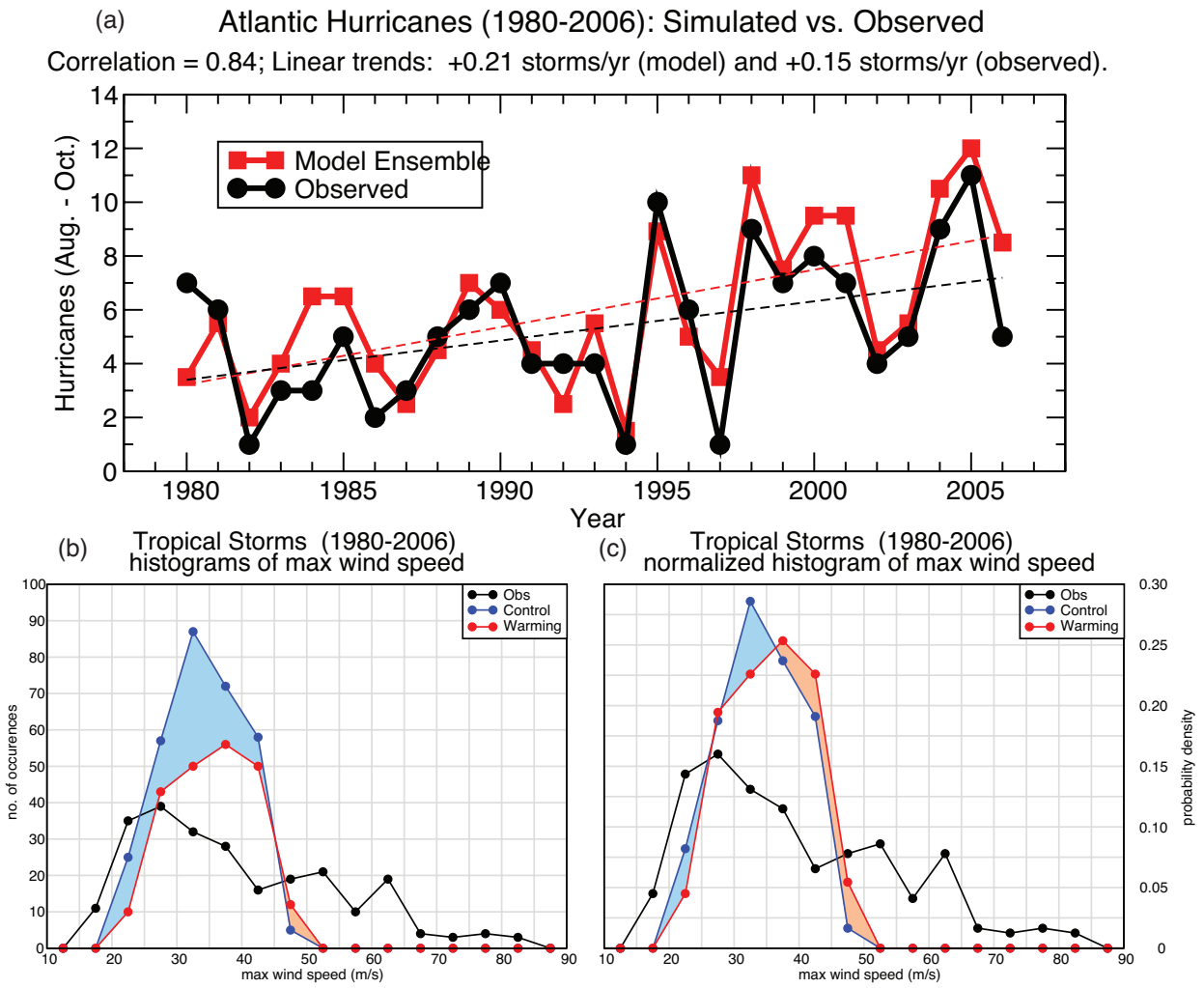
Emanuel, PNAS 2013

Regional Climate Model



Knutson et al., Nature, 2008

Significant progress in TC simulation in climate models



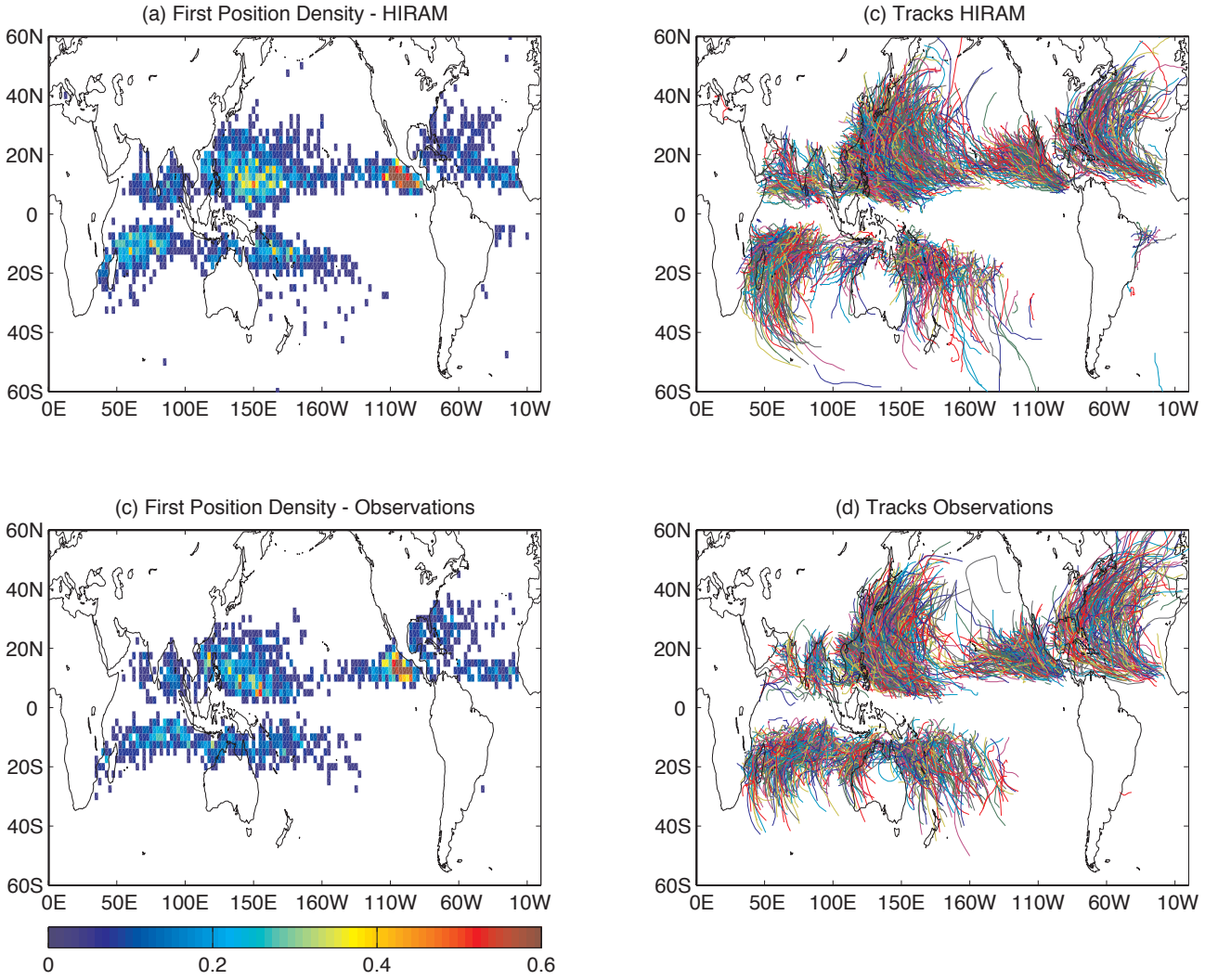
Knutson et al. 2008

CURRENT CLIMATE MODELS TROPICAL CYCLONE ACTIVITY

Current Climate models

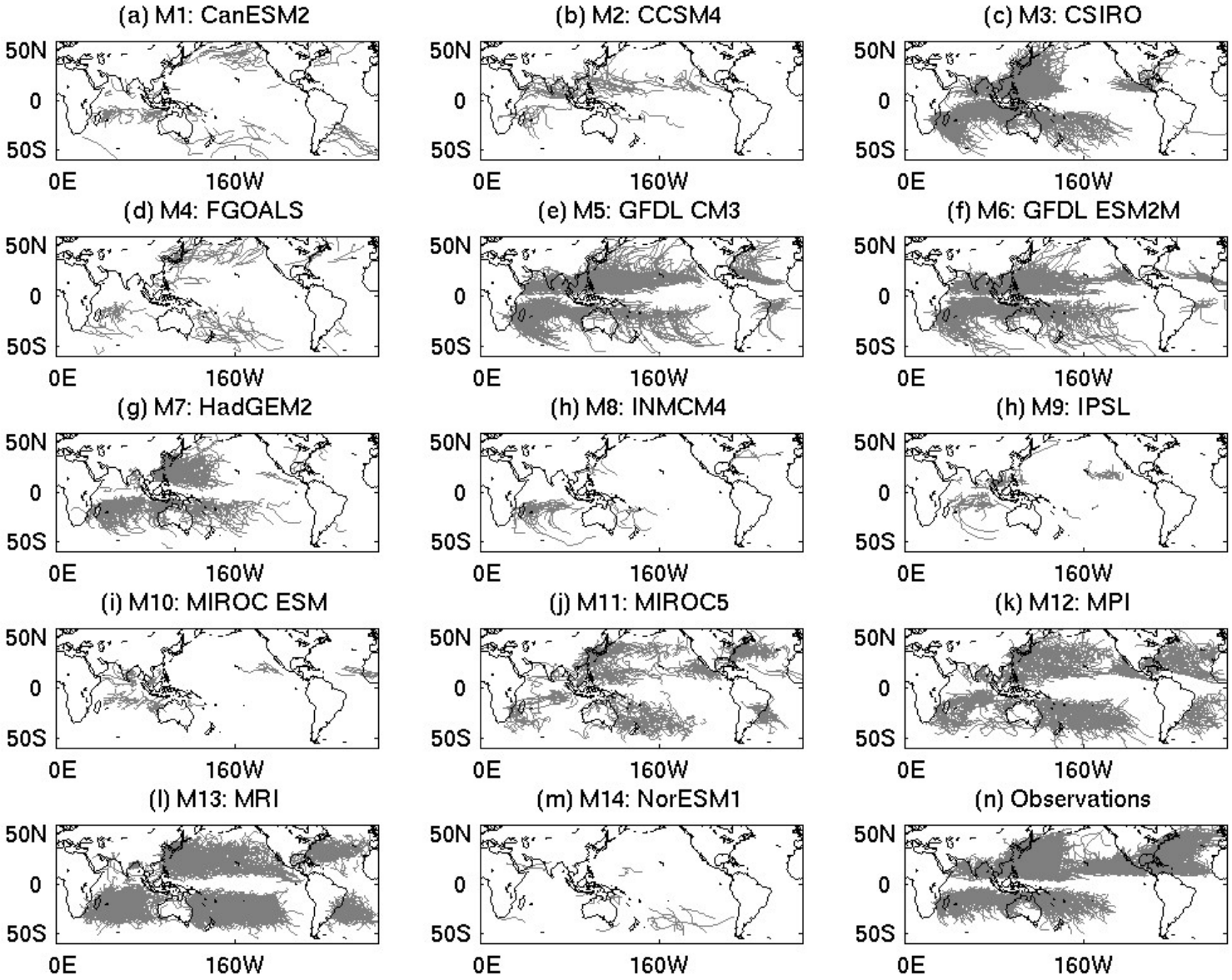
- TC activity: part of the diagnostics of climate models, as resolution increases.
- Analysis of TC activity in various time-scales: from sub-seasonal, including seasonal towards decadal and longer (climate change).
- TC forecasts and projections are part of seamless predictions approach.

TC Climatology



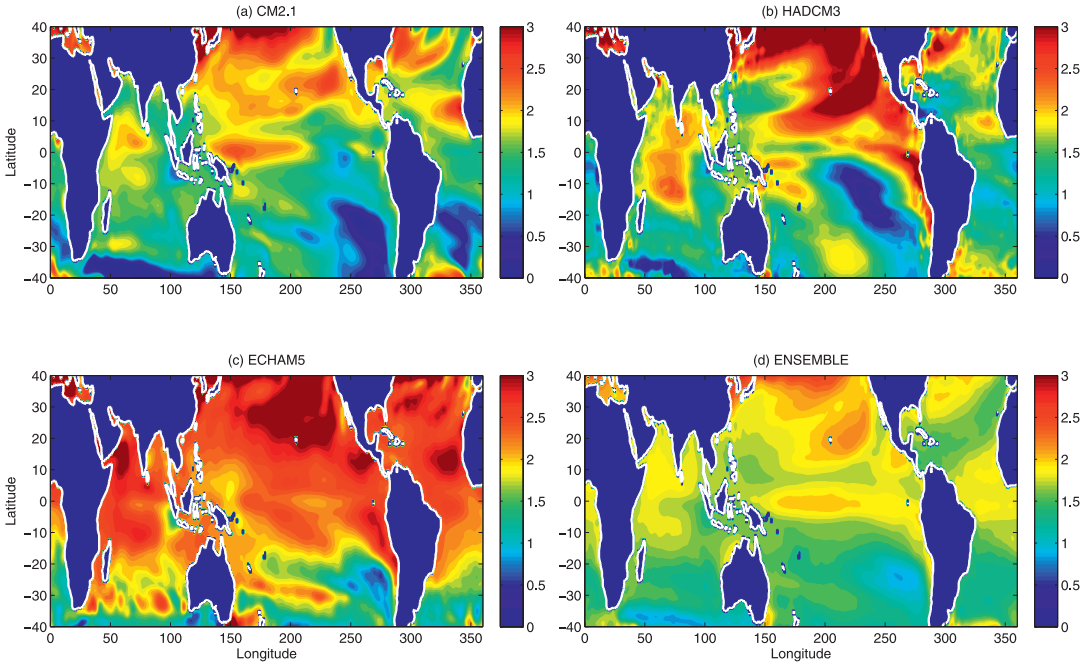
Camargo et al., J. Clim., 2014

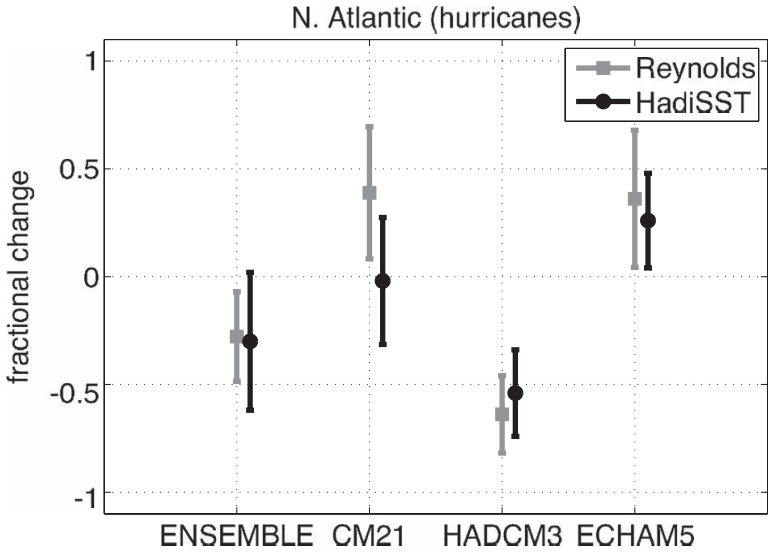
TCs in the CMIP5 models

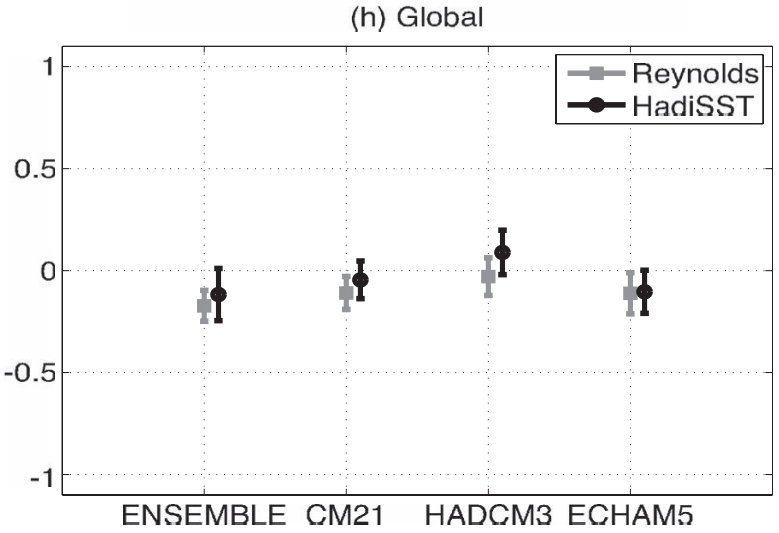


Camargo, J. Clim., 2013

“Downscaling”: SST anomalies

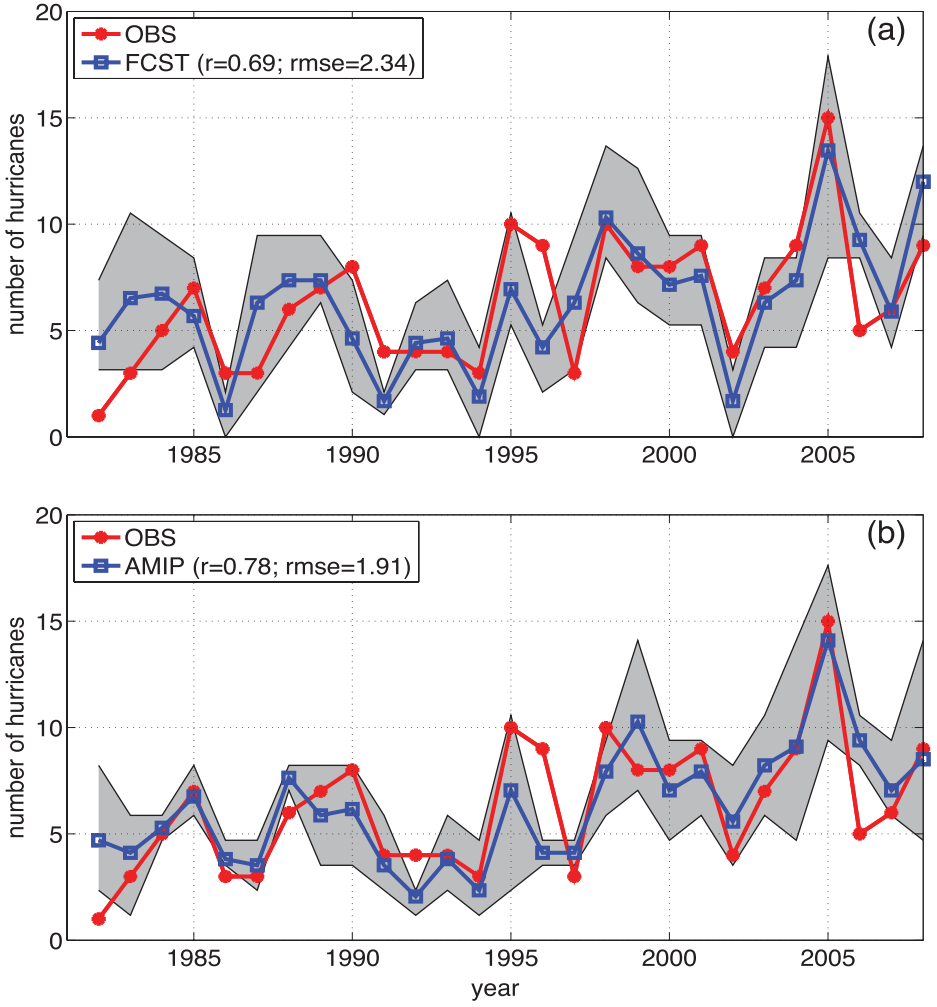






Zhao et al., J. Clim., 2009

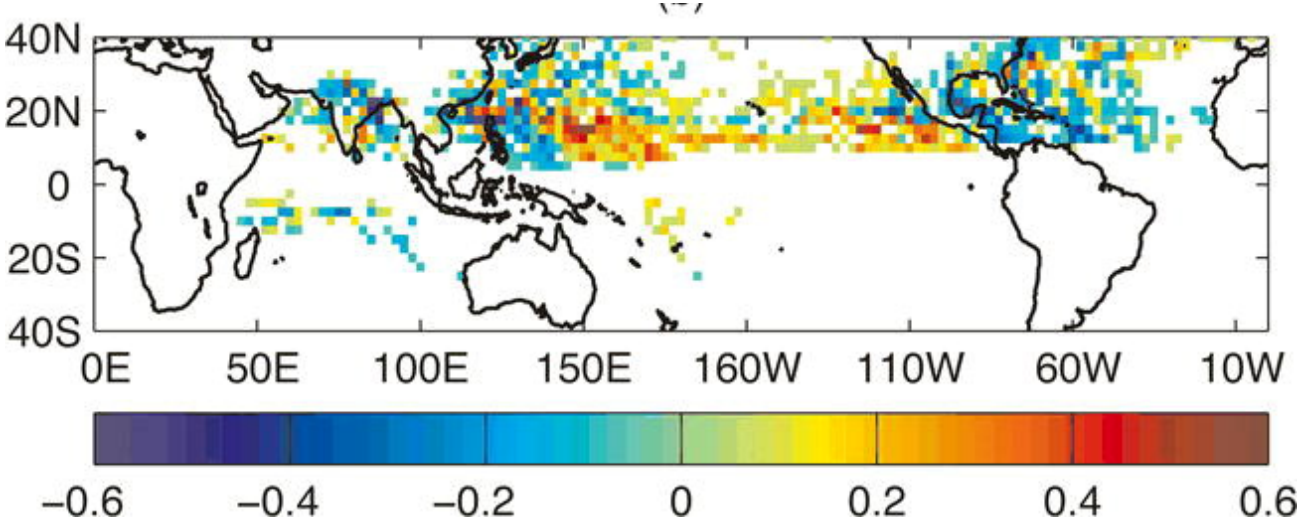
Atlantic Hurricane Interannual Variability



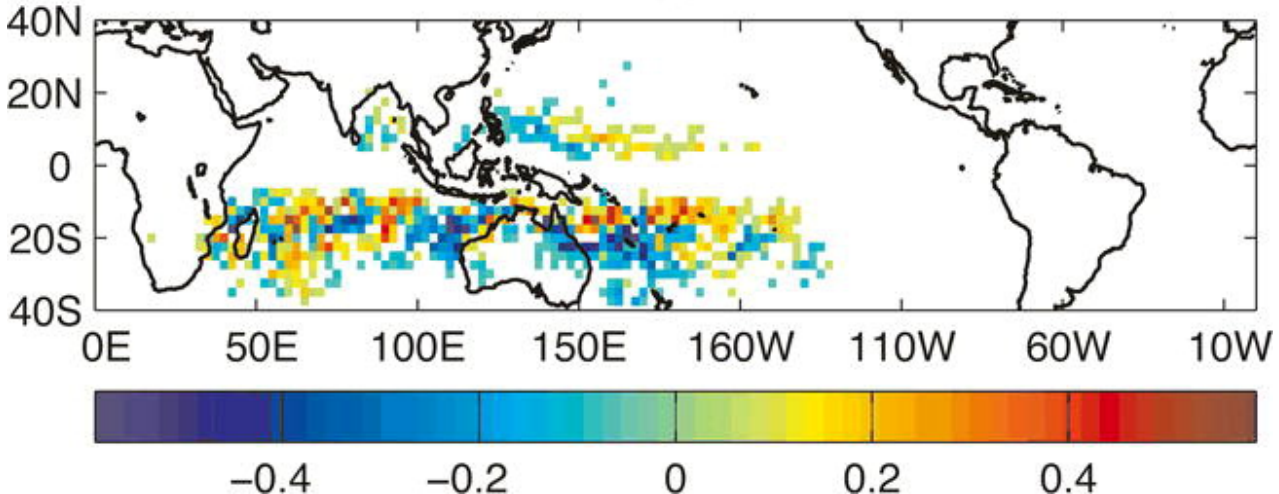
Zhao et al., Mon. Wea. Rev., 2010

Tropical Cyclones and ENSO

Track Density ASO difference: El Niño & La Niña



Track Density JFM difference: El Niño & La Niña



Camargo et al. 2007

Can climate models reproduce the TC-ENSO modulation?

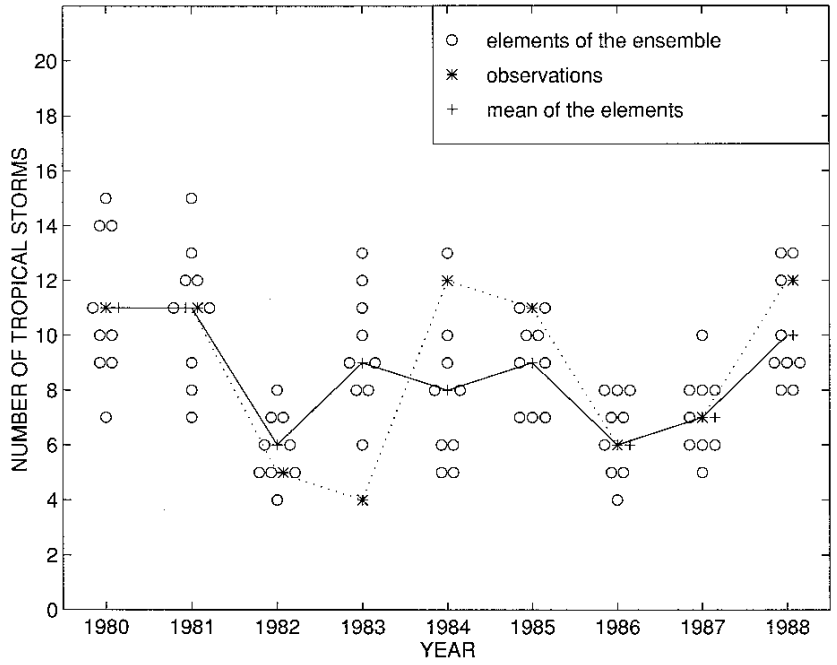
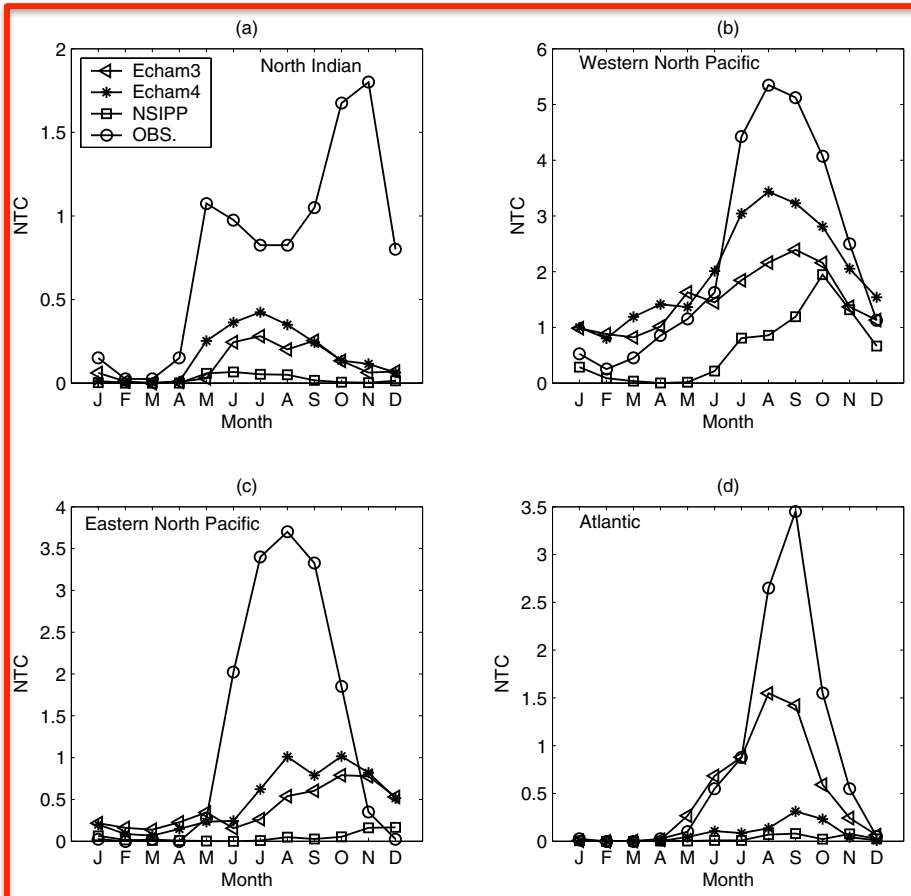


TABLE 2. Linear correlation for each ocean basin between observations and the mean of the 9-member ensemble.

	Total	WNA	ENP	WNP	NI	SI	AUS	SP
Correlation	0.41	0.56	0.545	0.66	−0.63	−0.66	0.57	−0.775
Significance	0.69	0.89	0.88	0.945	0.93	0.93	0.87	0.977

Vitart et al. 1997



Basin	Model	JJASON
WNP	ECHAM3	0.36
WNP	ECHAM4	0.26
ENP	ECHAM4	**0.42**
ATL	ECHAM3	**0.53**
ATL	ECHAM4	**0.52**
ATL	NSIPP	**0.38**

Basin	Model	NDJFMA
SI	ECHAM4	0.21
AUS	ECHAM4	**0.41**
SP	ECHAM3	**0.72**
SP	ECHAM4	**0.52**
SP	NSIPP	**0.62**

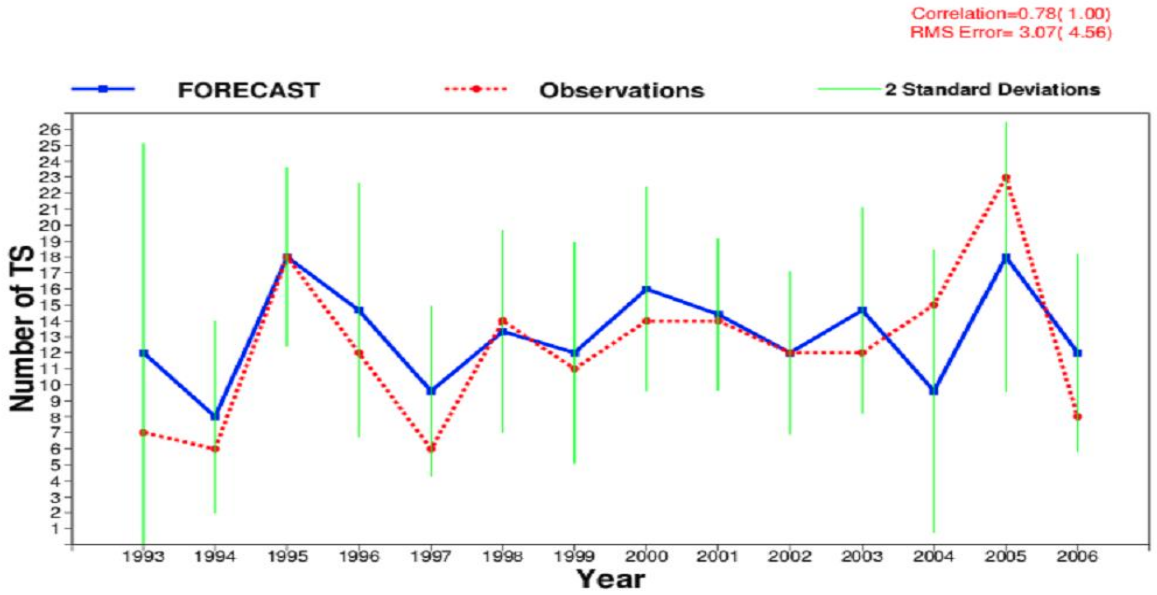
Camargo et al. 2005

Dynamical Seasonal TC Forecasts

- First forecasts - statistical: Nicholls (Australia), Gray (Atlantic).
- First seasonal dynamical forecast of TC activity developed in the early 2000s: ECMWF, IRI, based on the modulation of TC activity by ENSO.
- Currently, many groups produce dynamical seasonal TC forecasts: ECMWF, FSU, MetOffice, GFDL, with good skill, especially in the Atlantic.

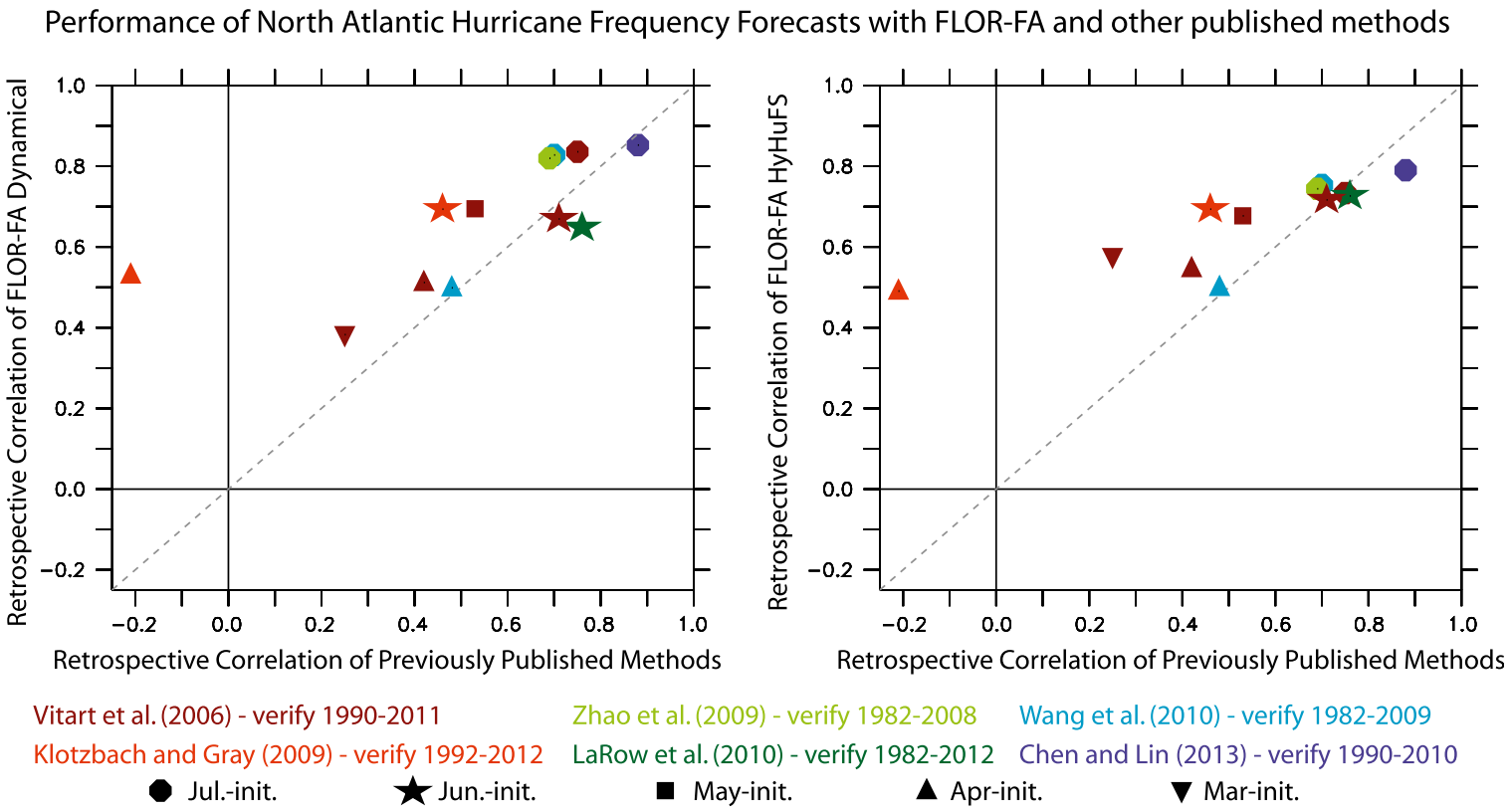
TC seasonal forecasts:

- Currently, the TC dynamical seasonal forecasts have good skill, especially in the Atlantic:



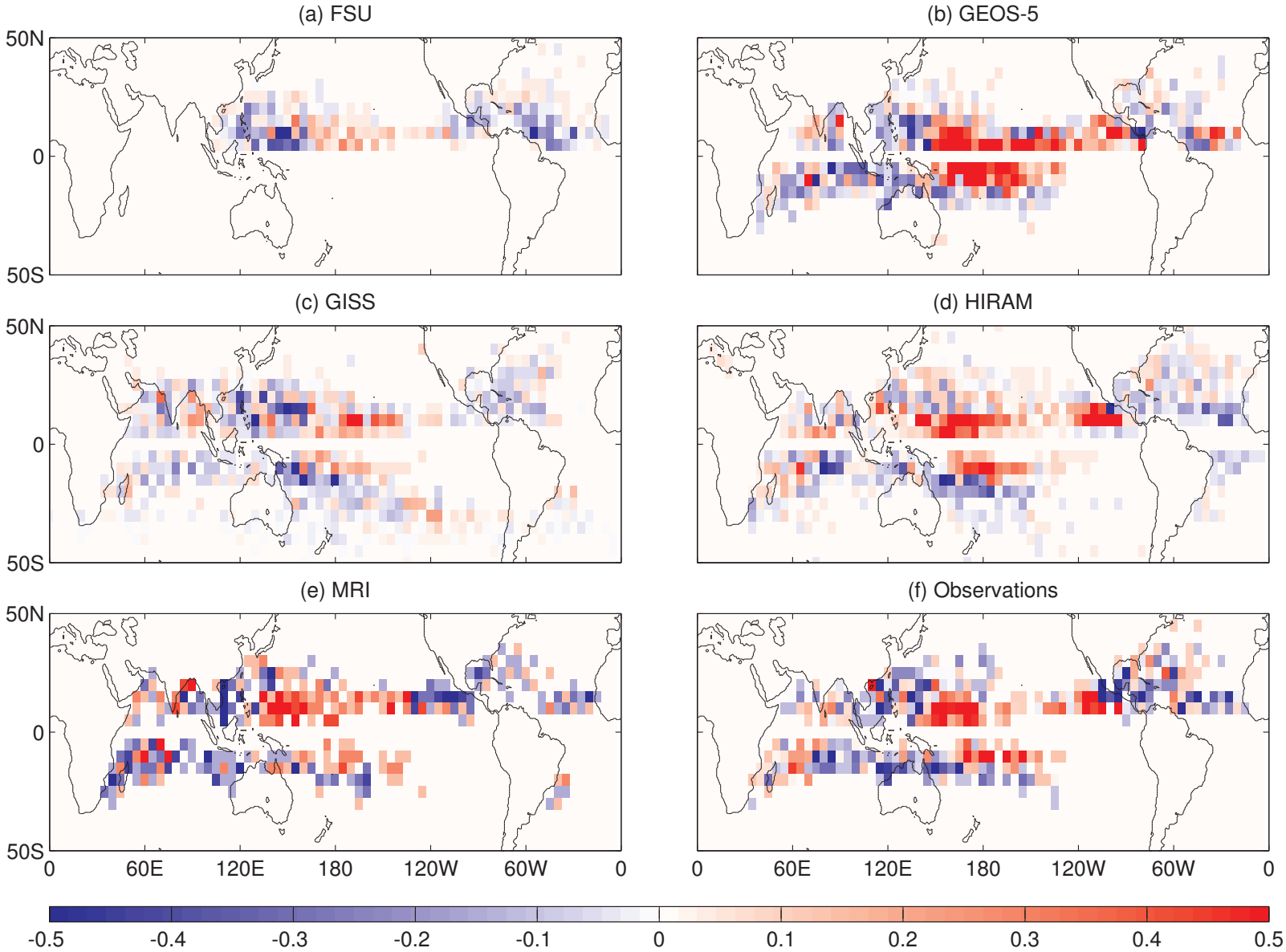
Vitart et al. 2007

Skill of Current Atlantic TC Forecasts



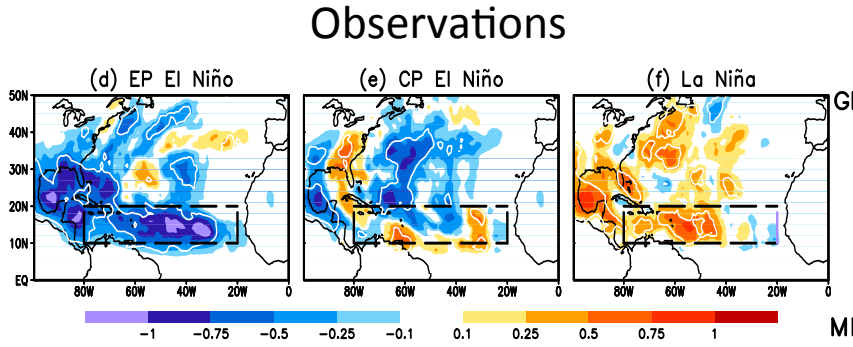
Vecchi et al., J. Climate, 2014

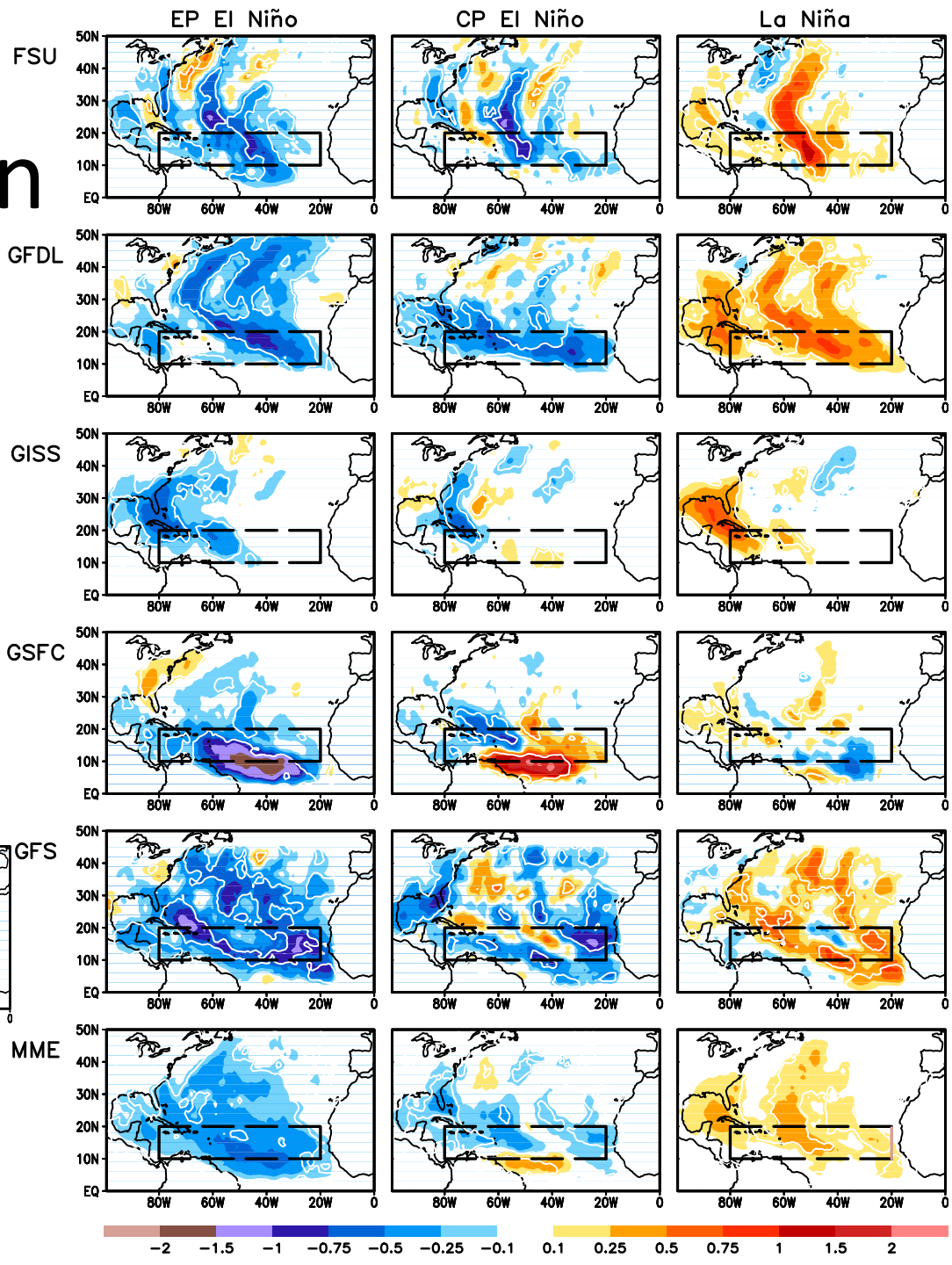
TCs & ENSO


(a) FSU
(b) GEOS-5
(c) GISS
(d) HIRAM
(e) MRI
(f) Observations
50N
0
50S
0
60E
120E
180
120W
60W
0
-0.5
-0.4
-0.3
-0.2
-0.1
0
0.1
0.2
0.3
0.4
0.5

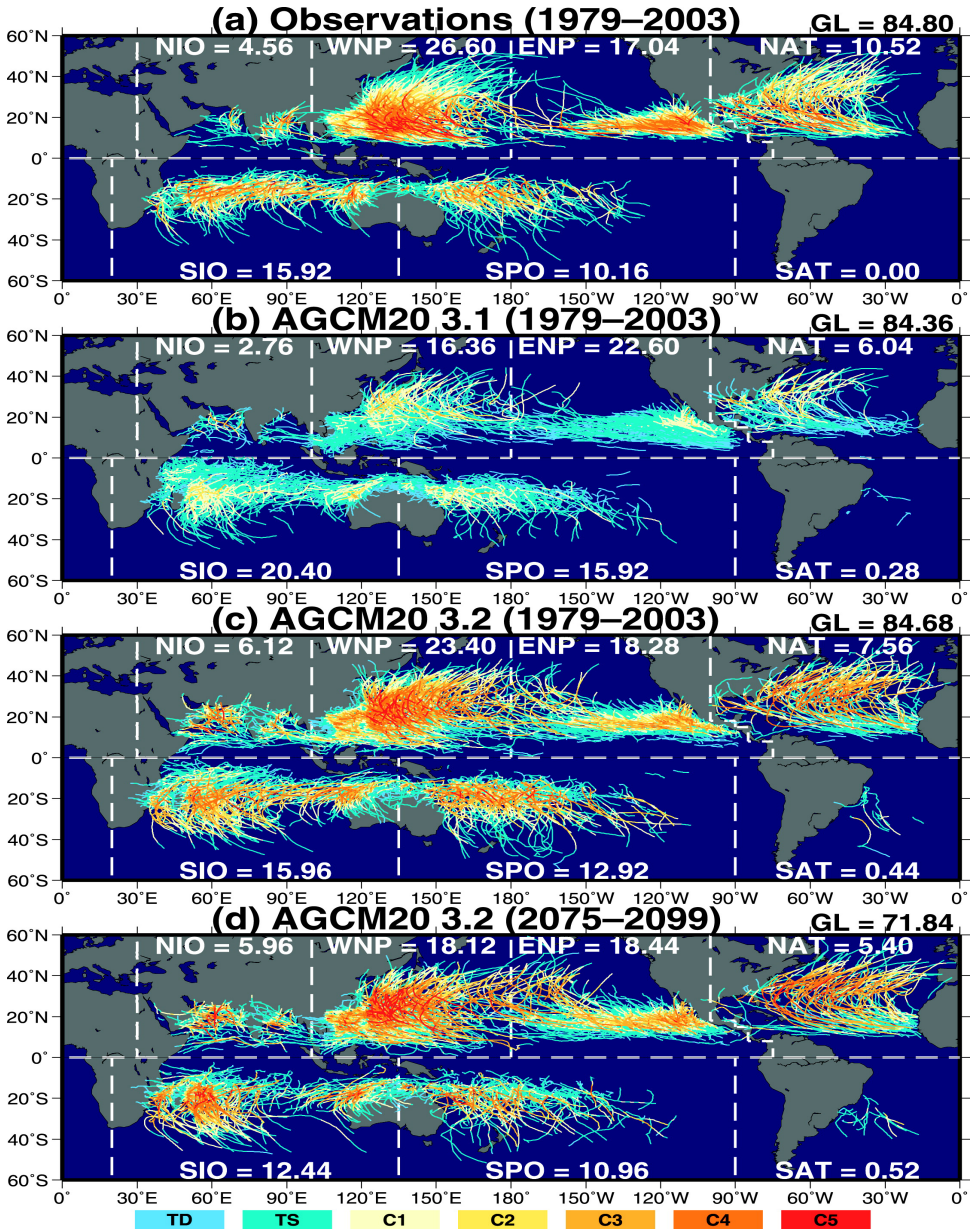
Central vs Eastern Pacific El Niño impacts on Atlantic TCs

Wang et al., J. Climate 2014



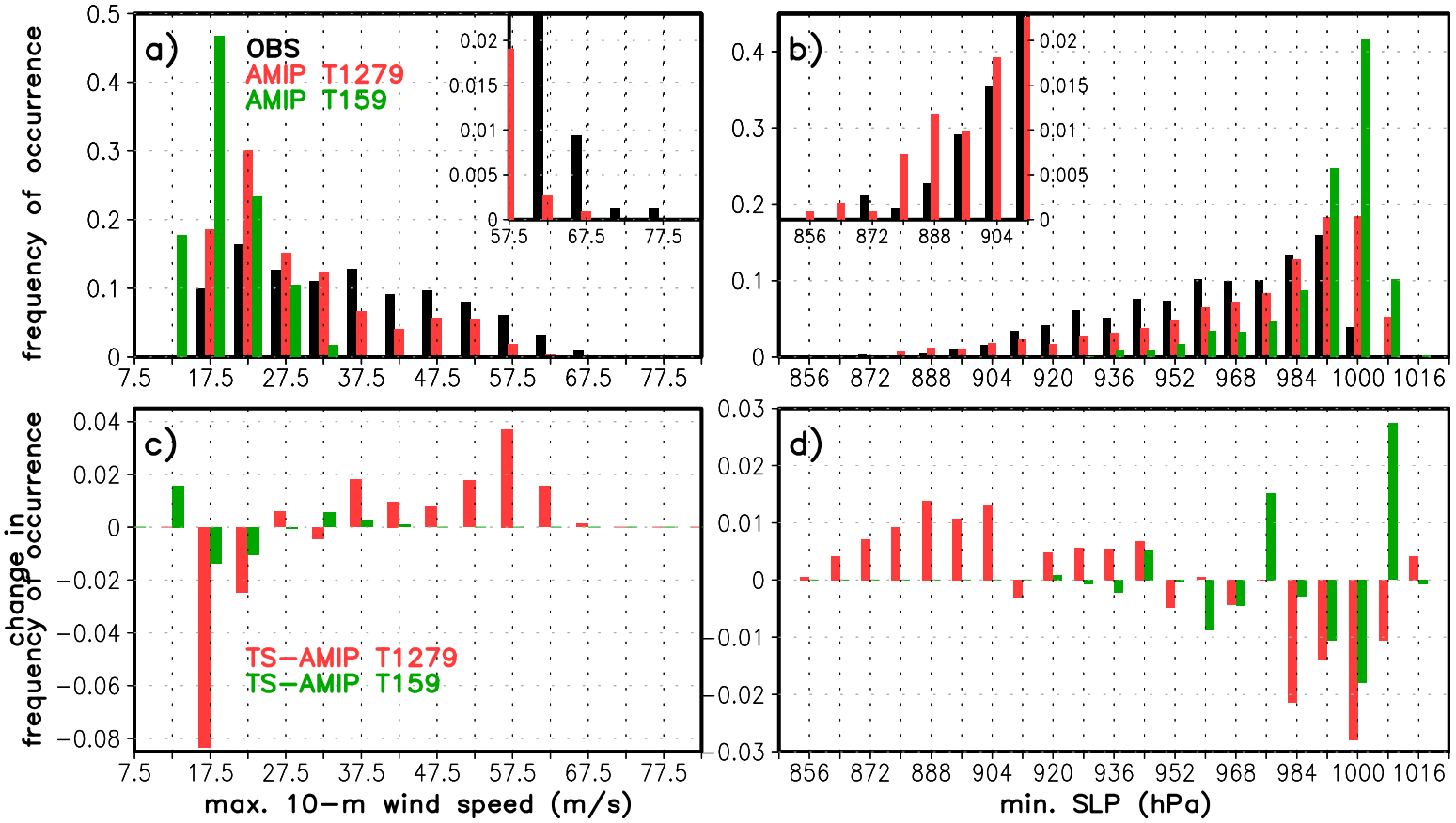


Simulation of intense storms



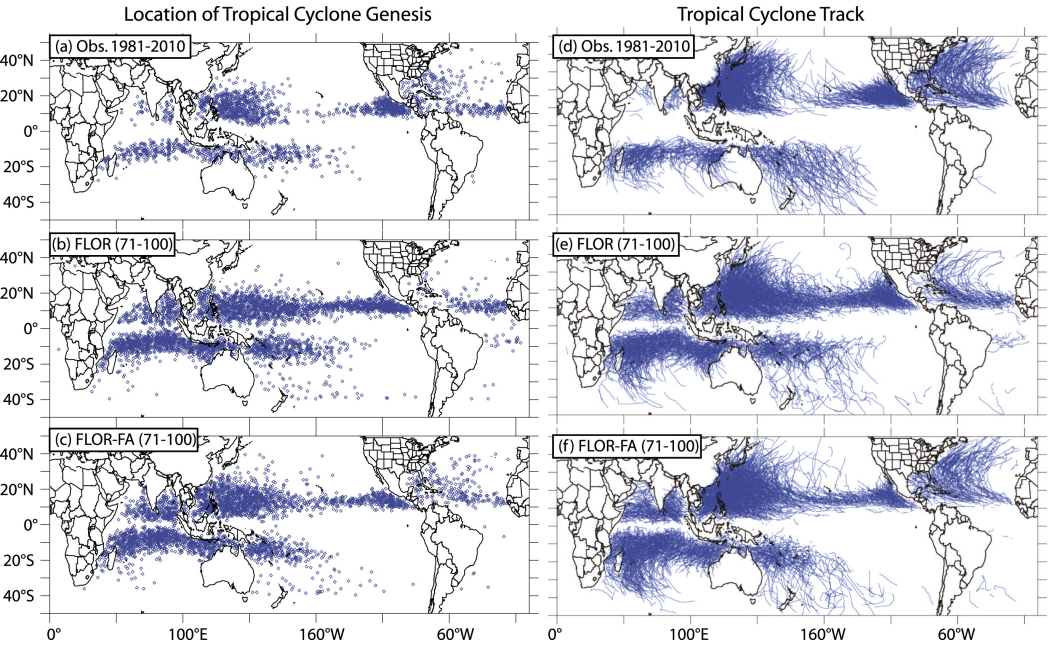
Murakami et al. 2012

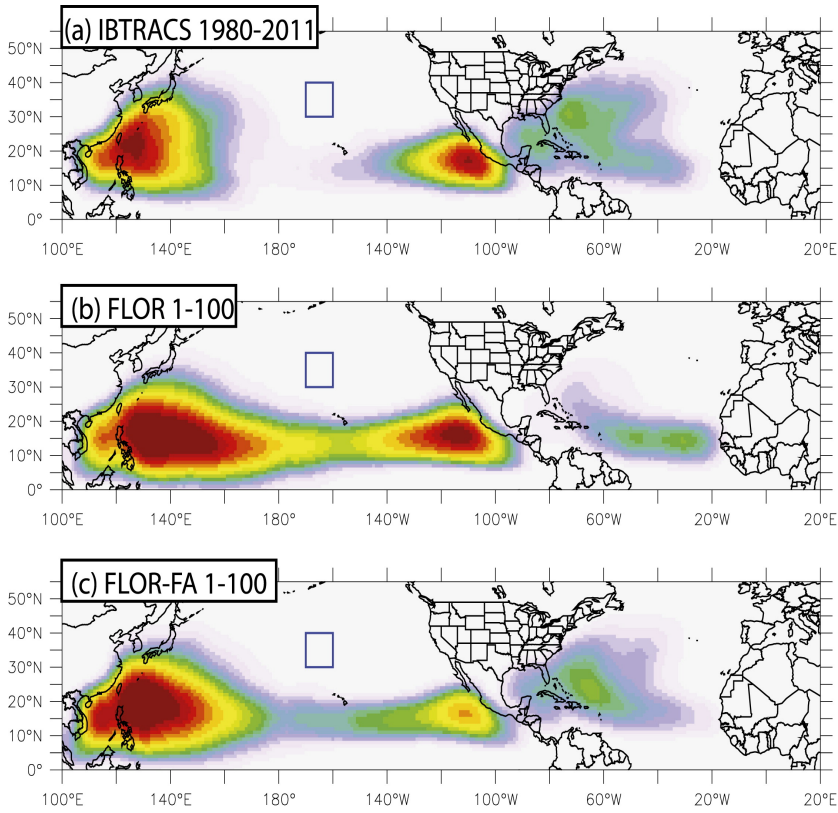
TC intensity



Manganello et al. J. Clim., 2014

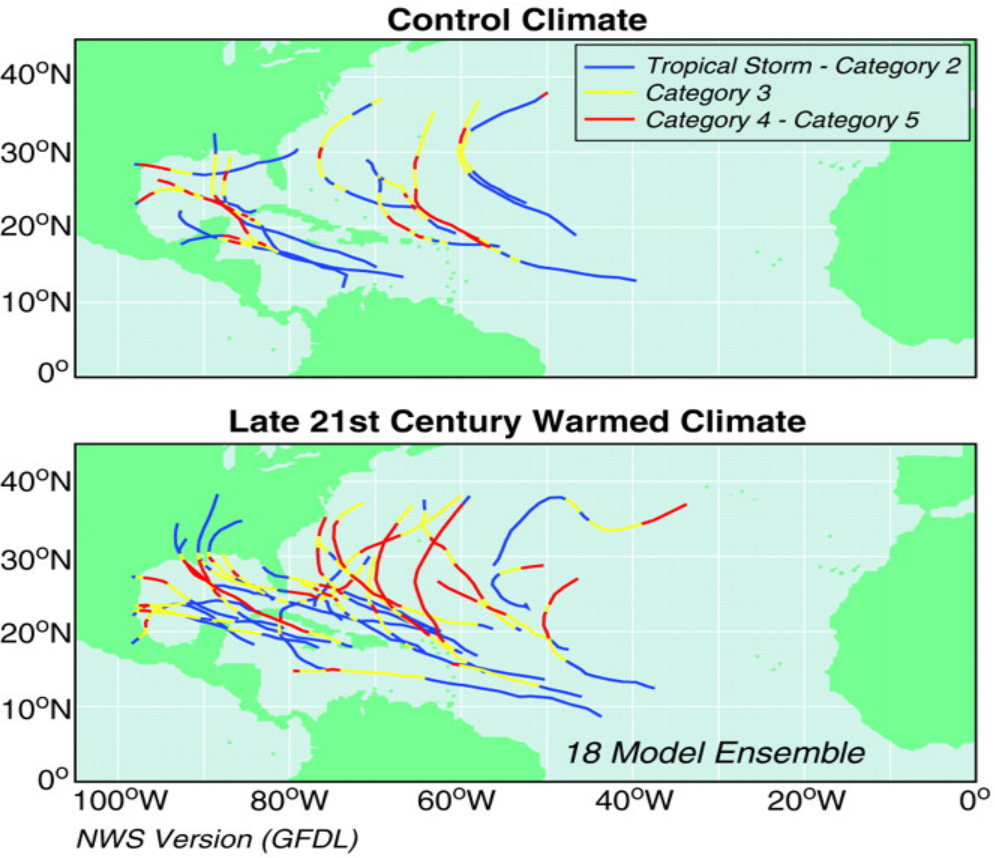
Current state-of-the-art: FLOR coupled model

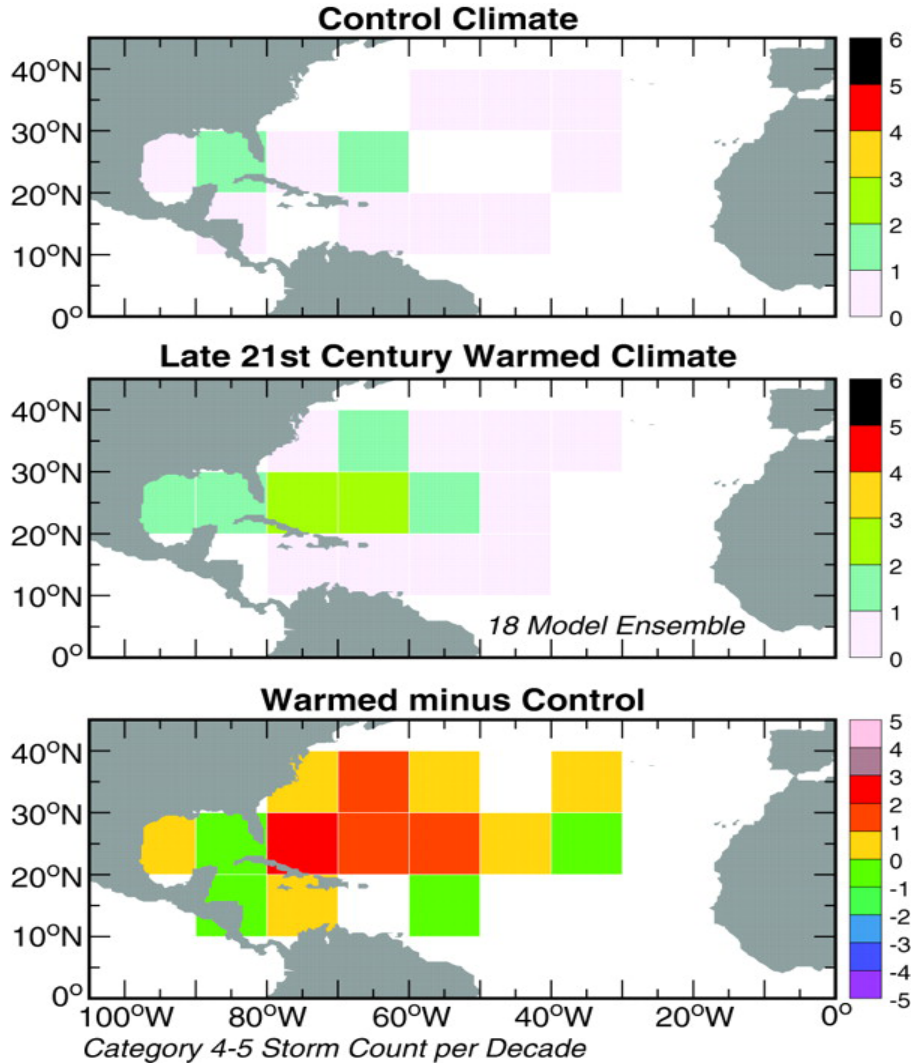




Vecchi et al. 2014

Downscaling: simulation of the most intense storms

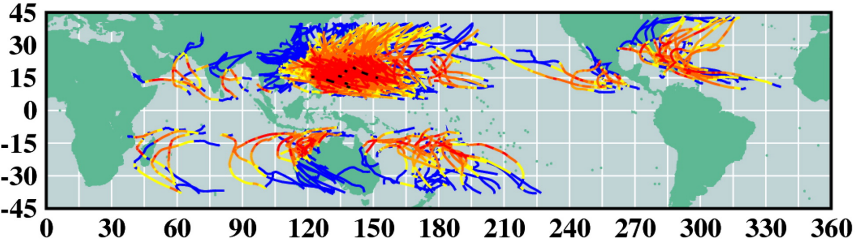




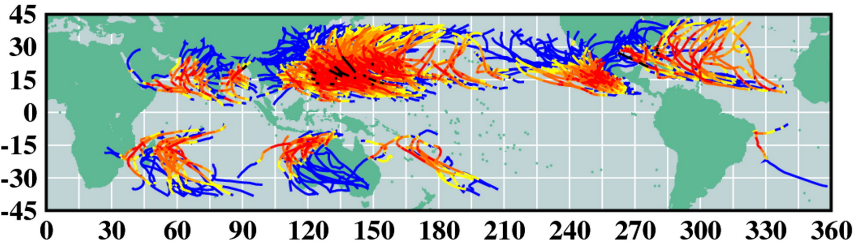
Bender et al. 2010

Projections I

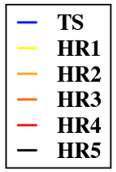
a) Present Day Simulation: 244 Cat 4-5 storms

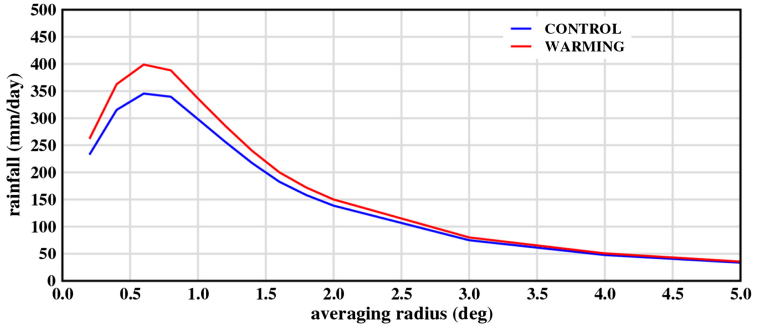


b) RCP4.5 Late 21st Century: 313 Cat 4-5 storms

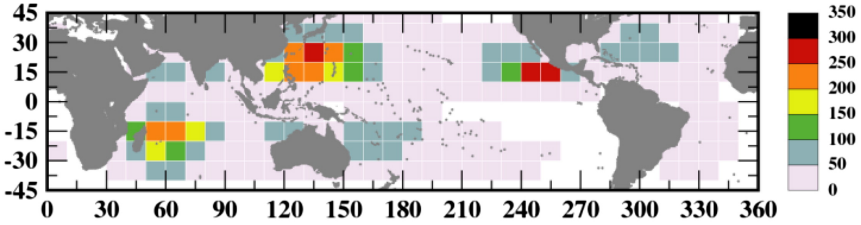


Storm Category

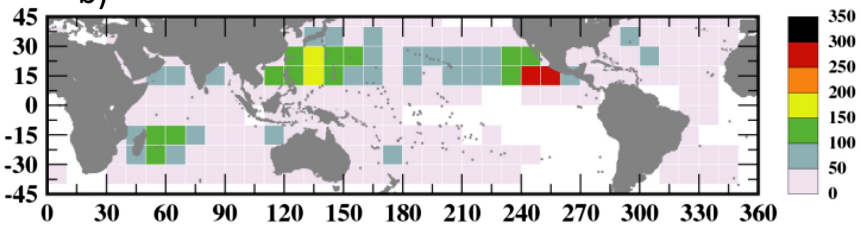




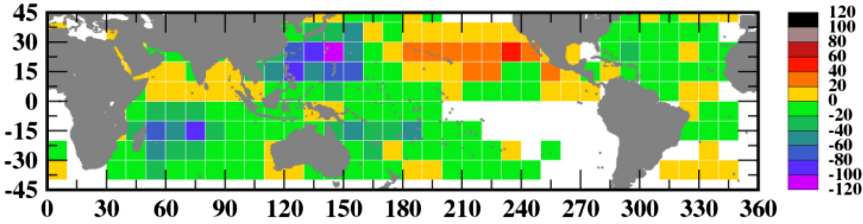
a) Present-day simulation



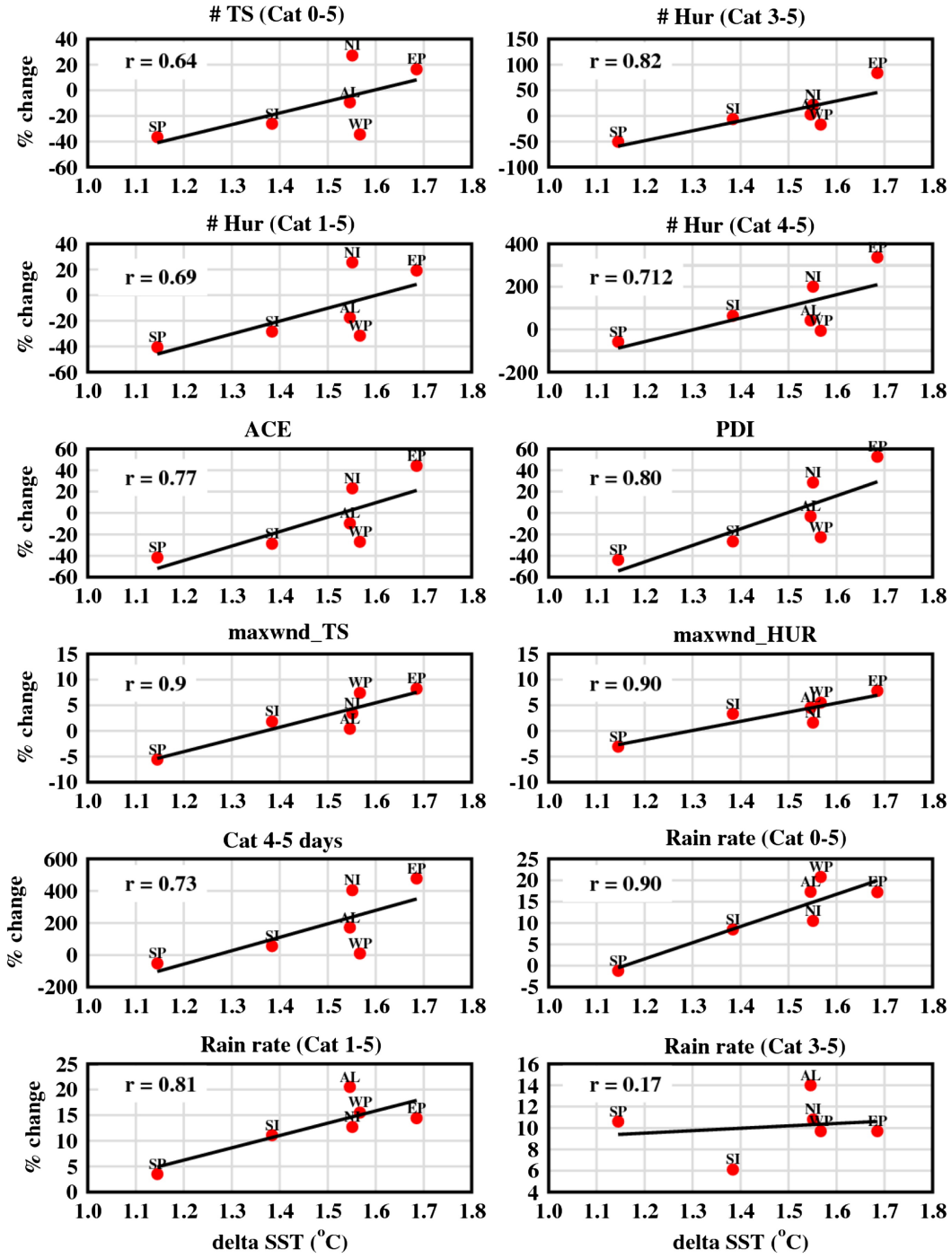
b) RCP4.5 Late 21st Century Projection



c) Late 21st century minus present-day



Knutson et al. 2015

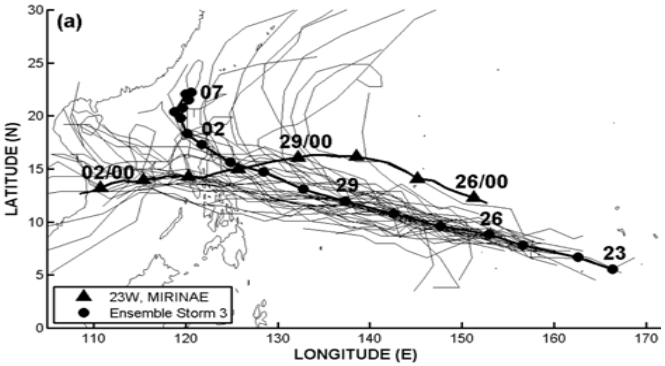


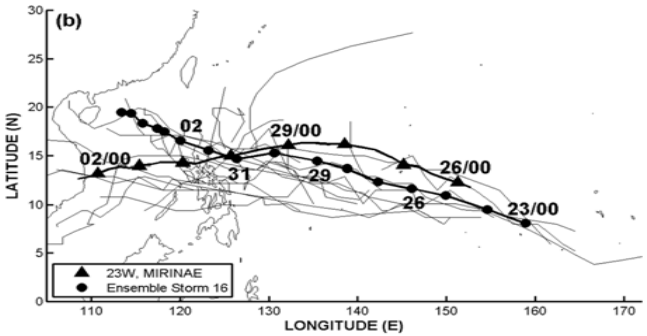
Projections II

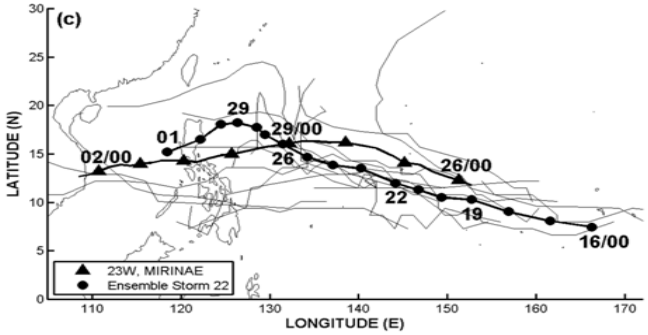
Knutson et al. 2015

A few successful forecasts

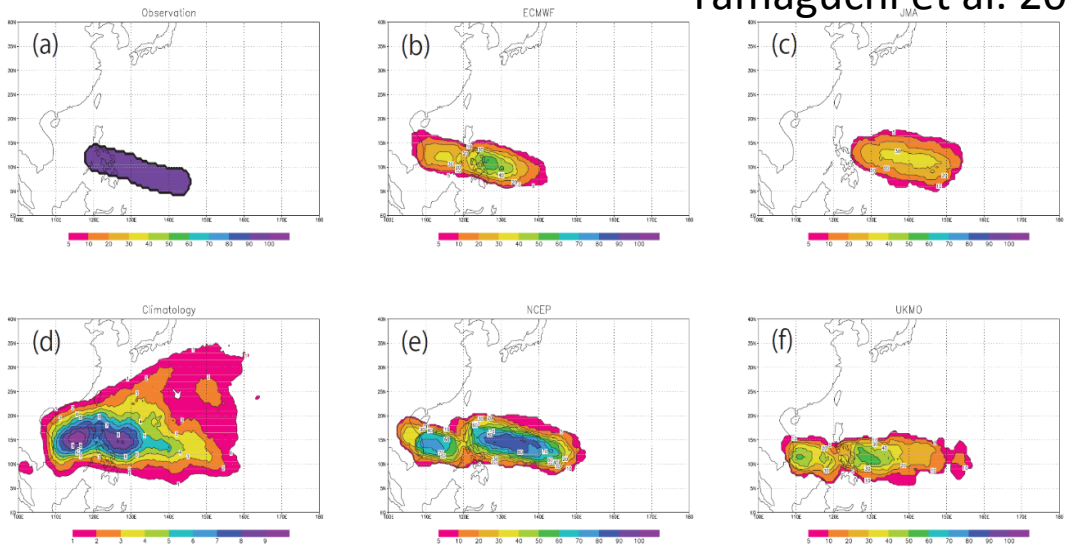
Yamaguchi et al. 2015

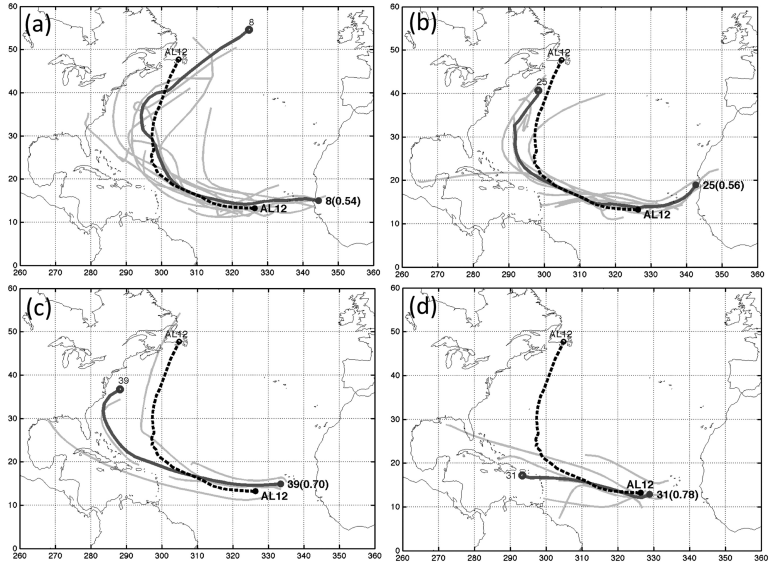






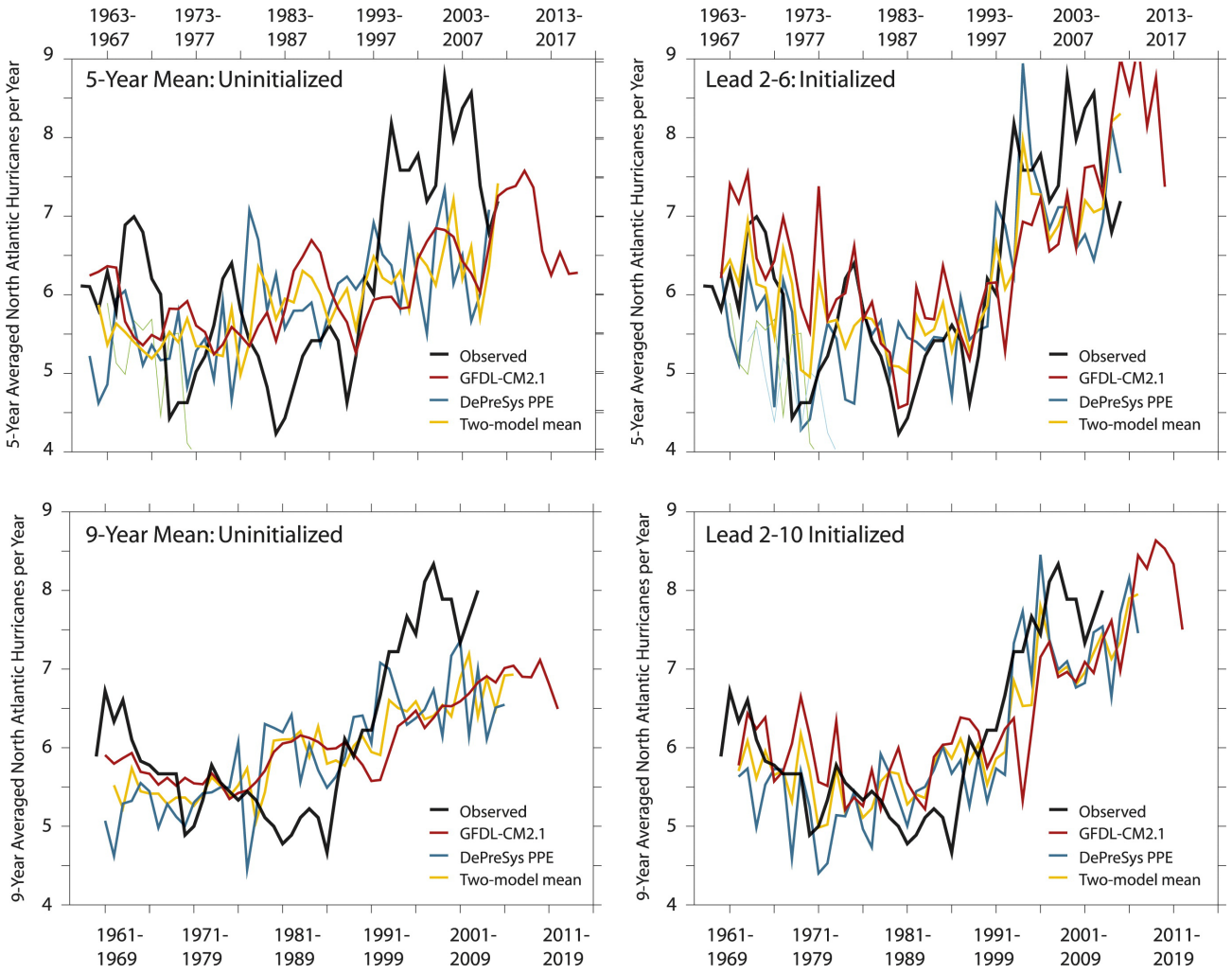
Elsberry et al. 2011





Elsberry et al. 2014

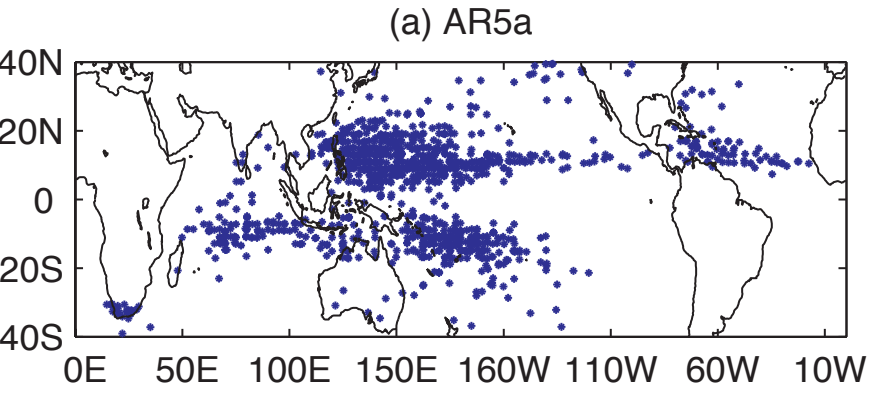
Potential for Decadal TC predictions

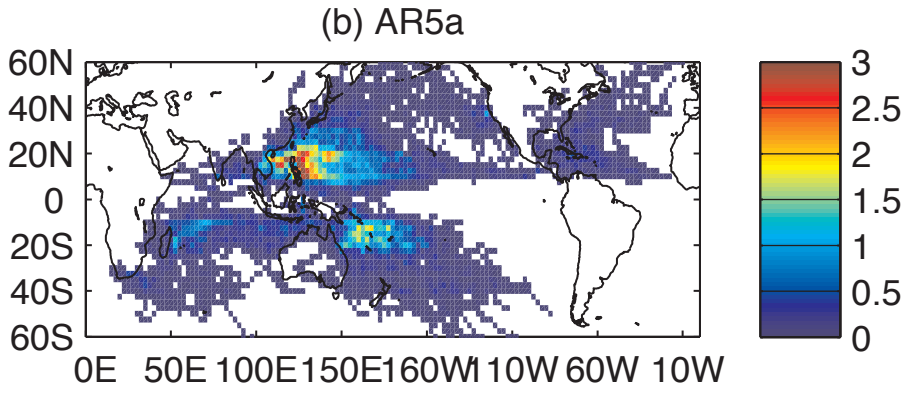


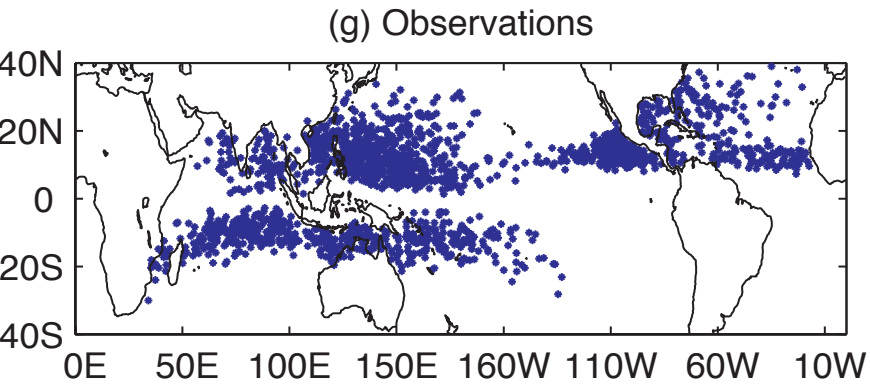
Vecchi et al., J. Clim., 2013

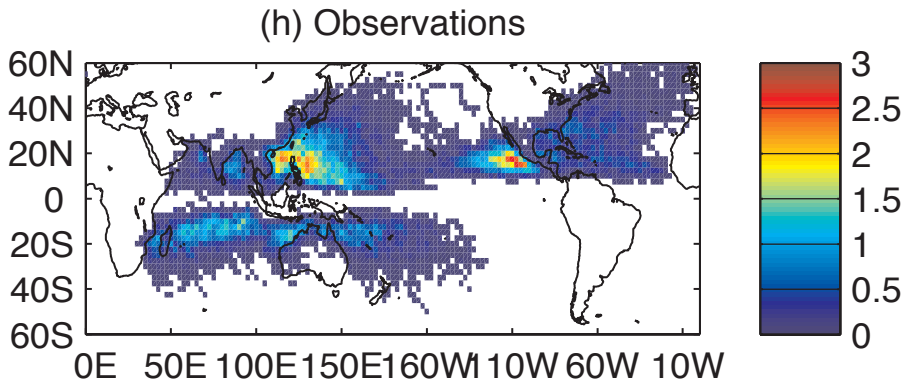
Models' sensitivities and biases

Tropical Cyclones – GISS Model E2









Kim et al., J. Climate 2012

US CLIVAR Hurricanes and CLIMATE Working Group

Objectives:

- An improved understanding of interannual variability, and trends, in tropical cyclone activity from the beginning of the 20th century to the present.
- Quantifying changes in the characteristics of tropical cyclones under a warming climate

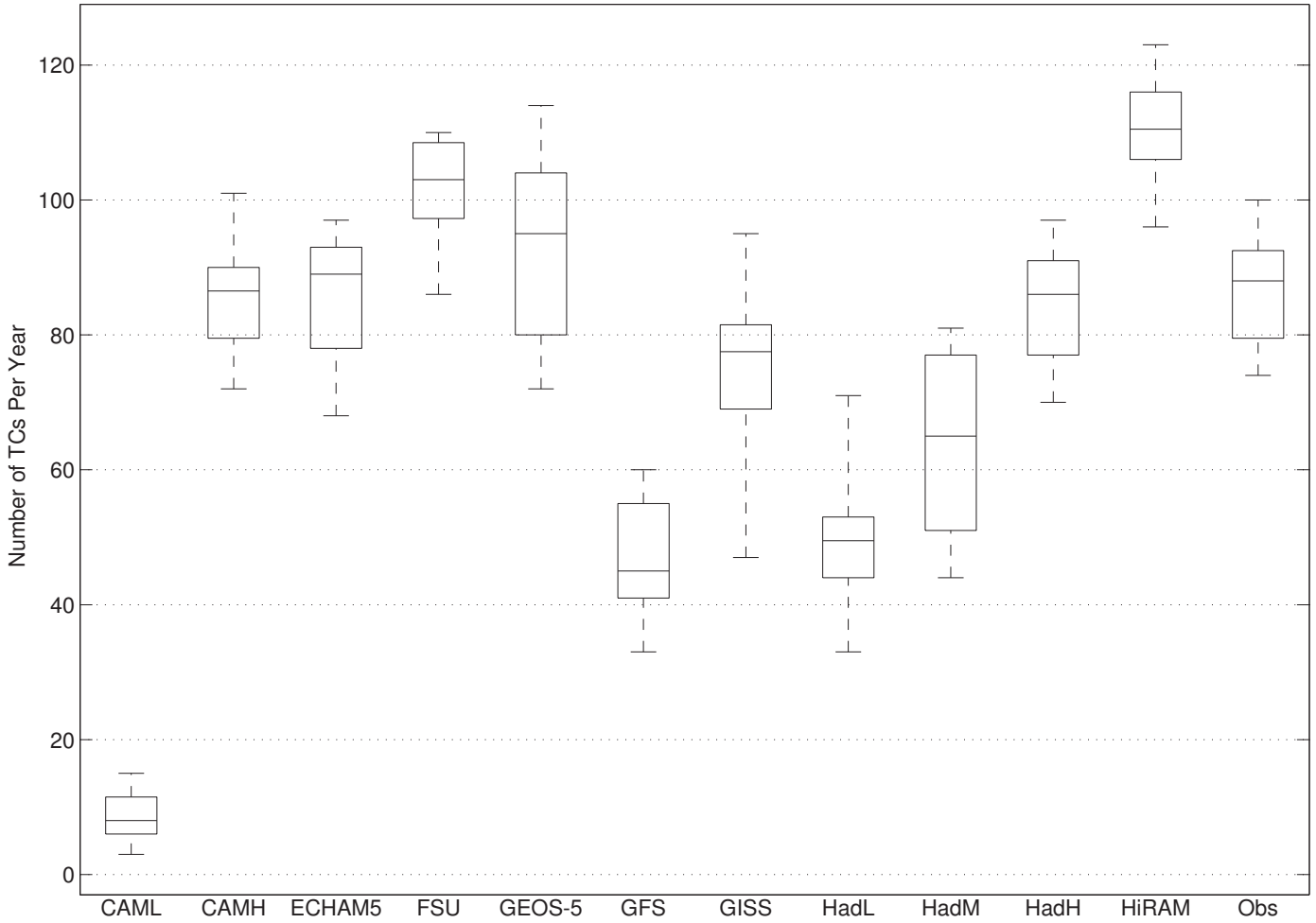
Simulations:

- Climatology
- Climatology plus 2K
- Climatology + $2CO_2$
- Climatology plus 2K + $2CO_2$
- Interannual

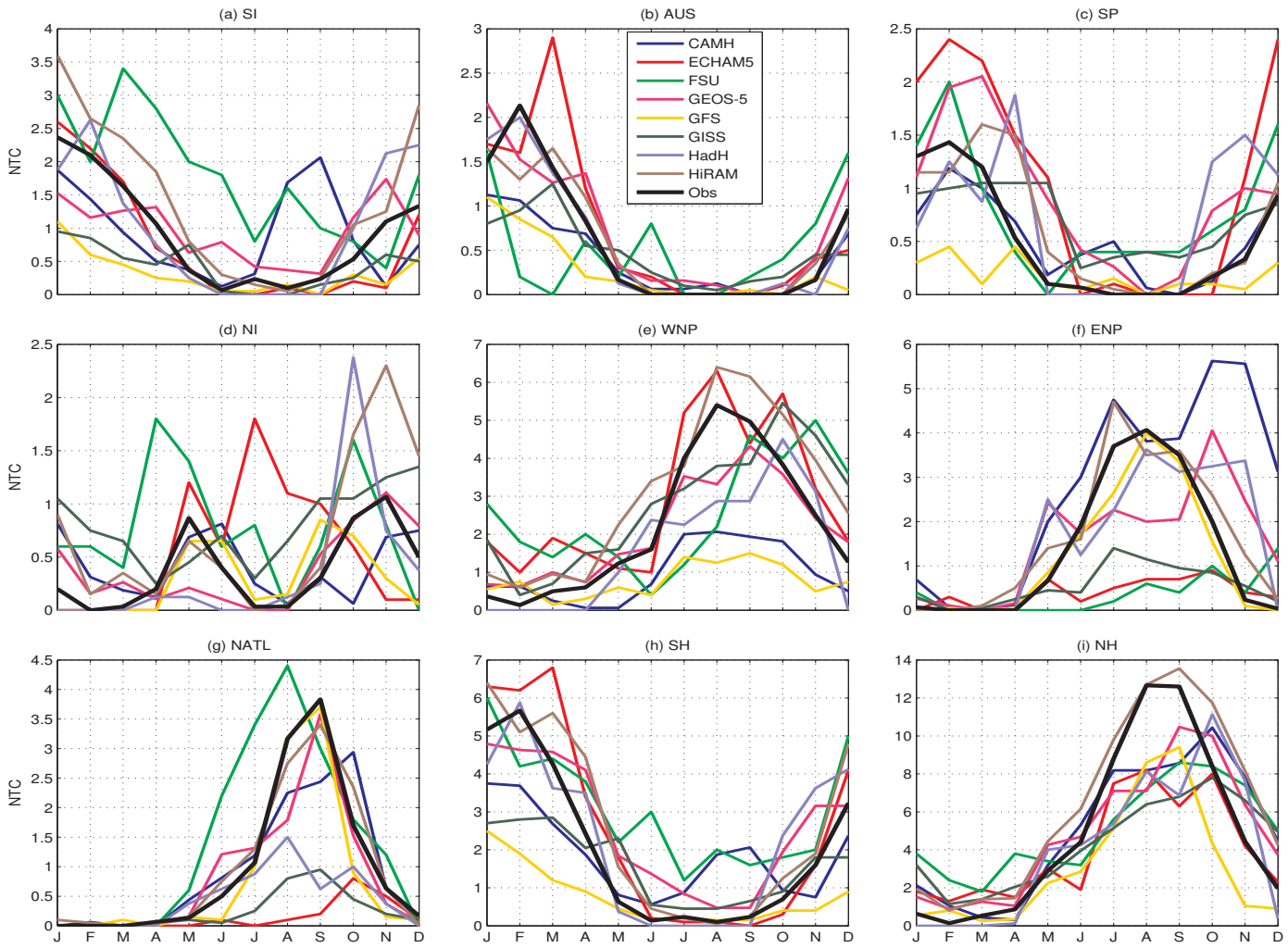
HWG Multi-model comparison

Shaevitz et al. JAMES 2014

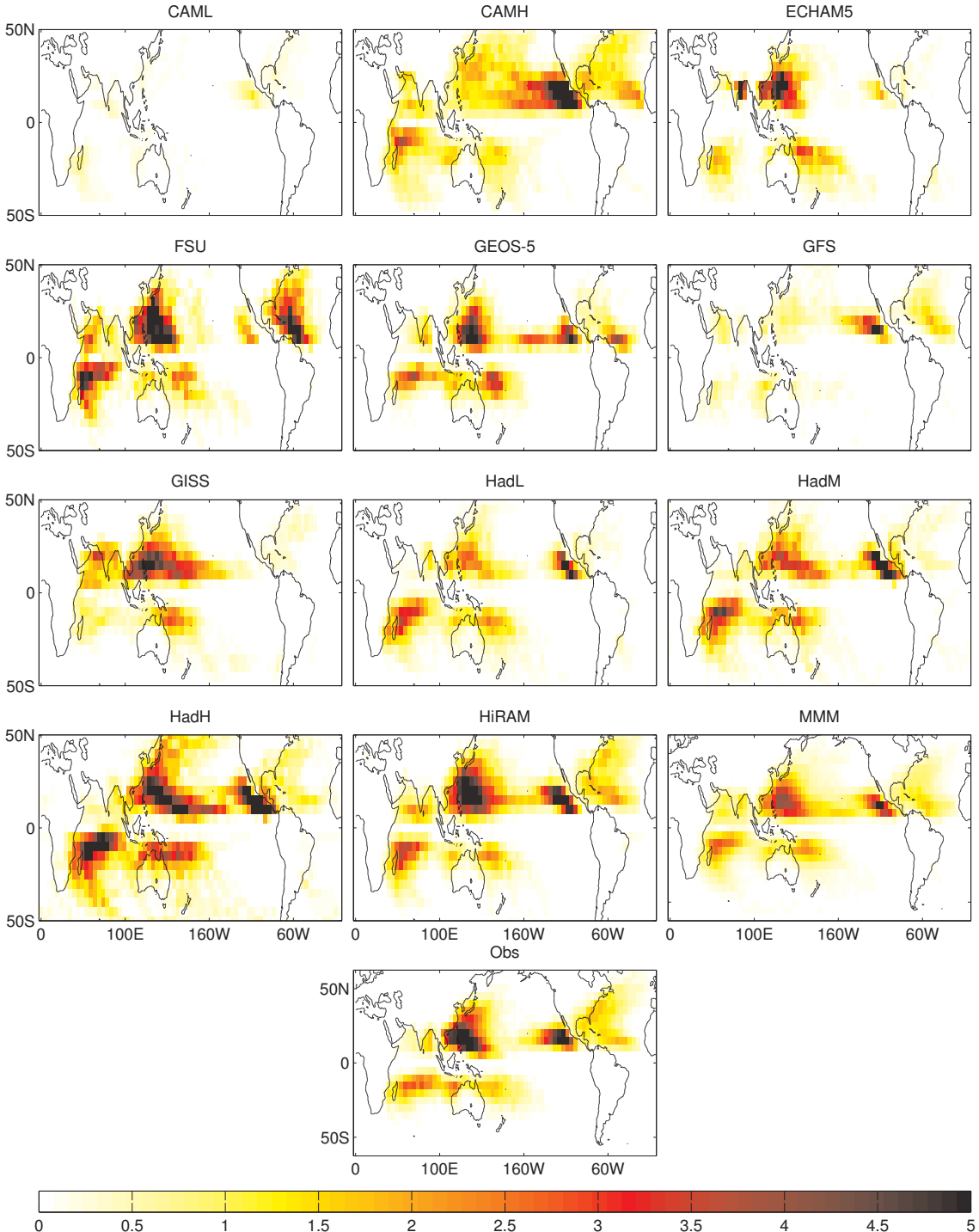
NTC Globe



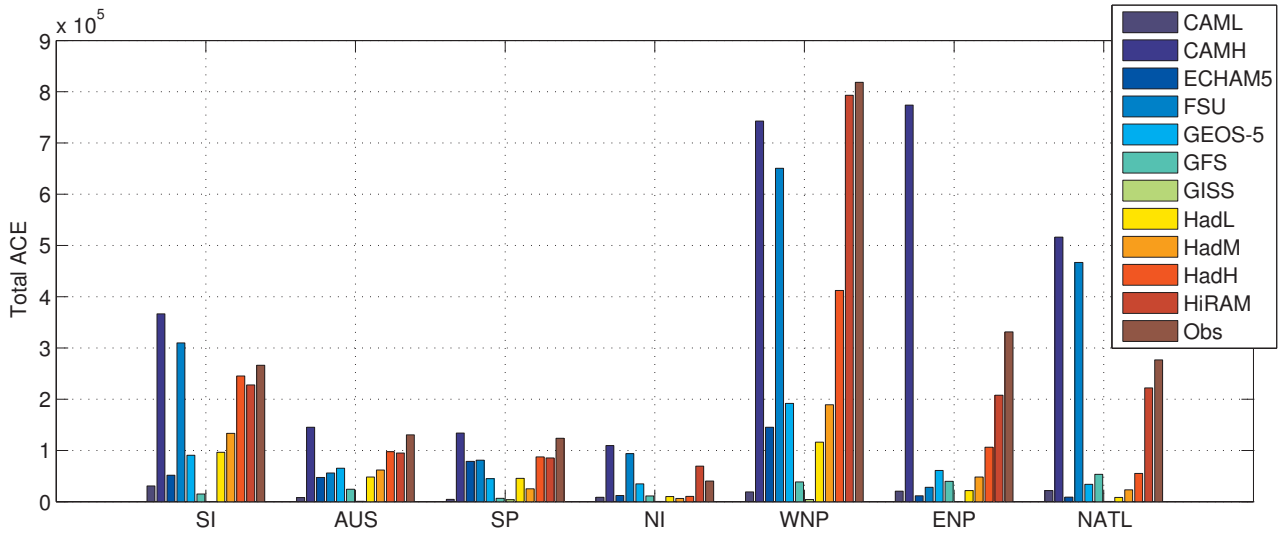
NTC - Annual Cycle Basins

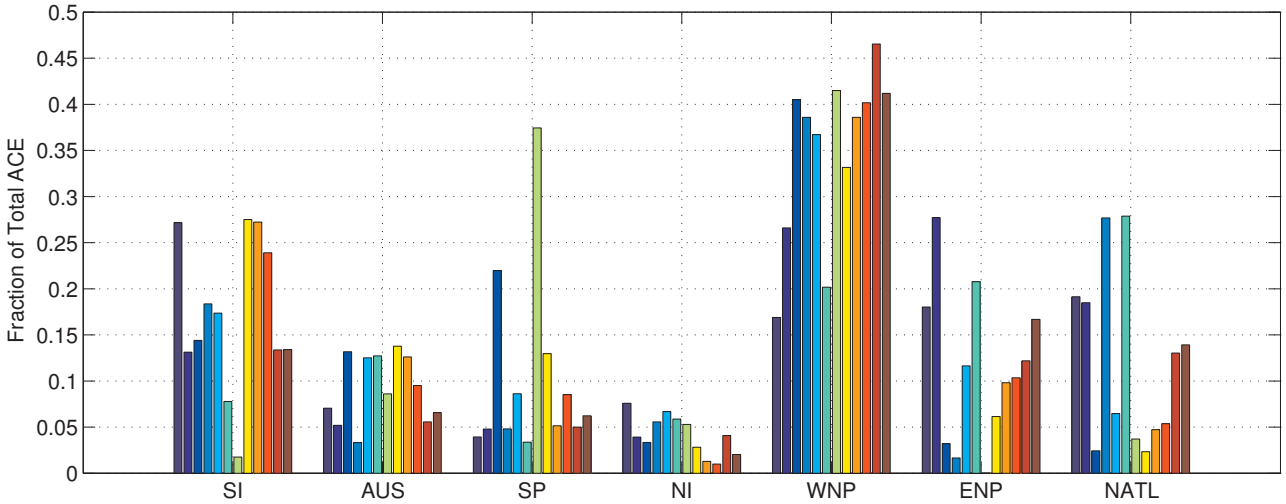


Track Density

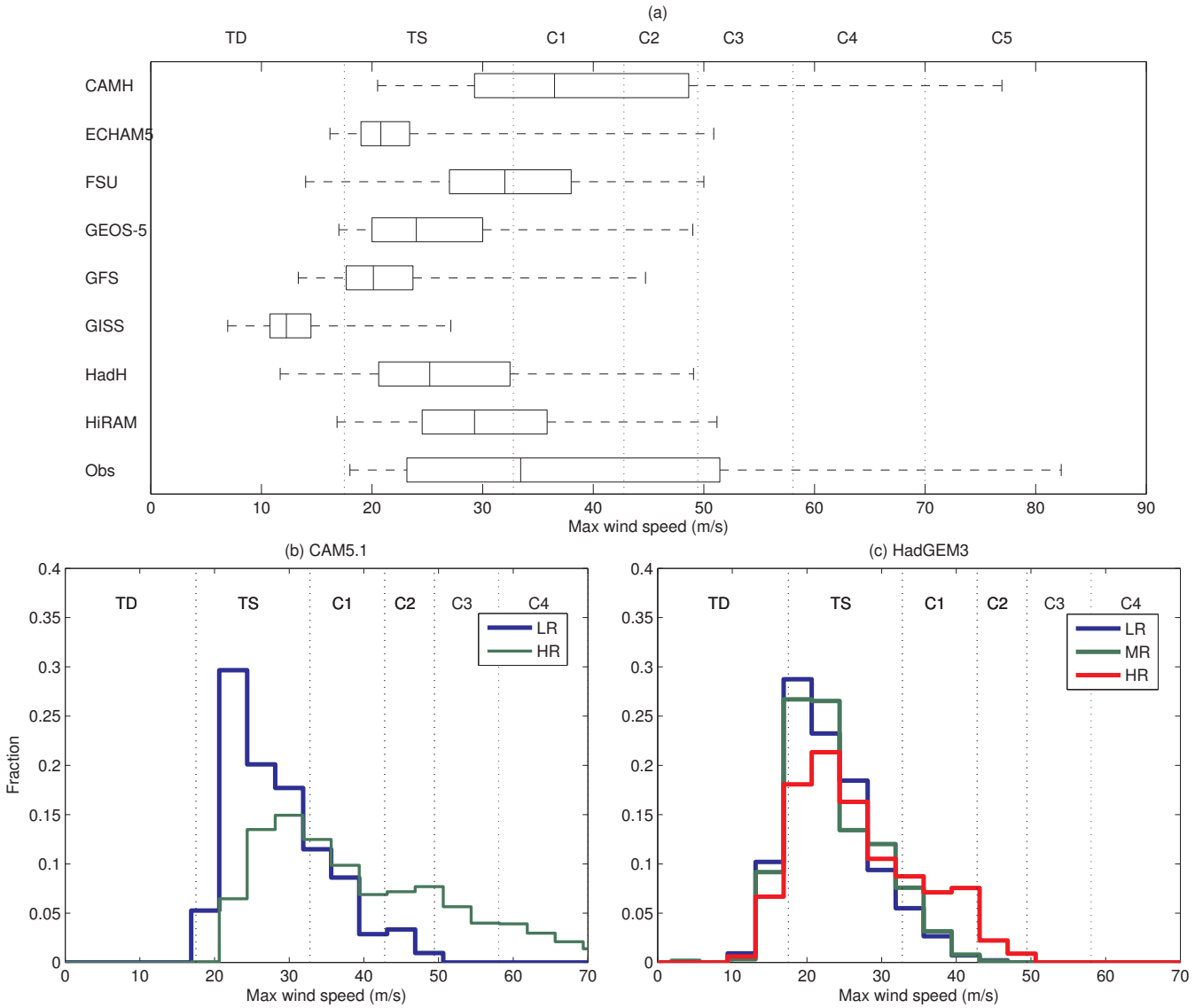


ACE

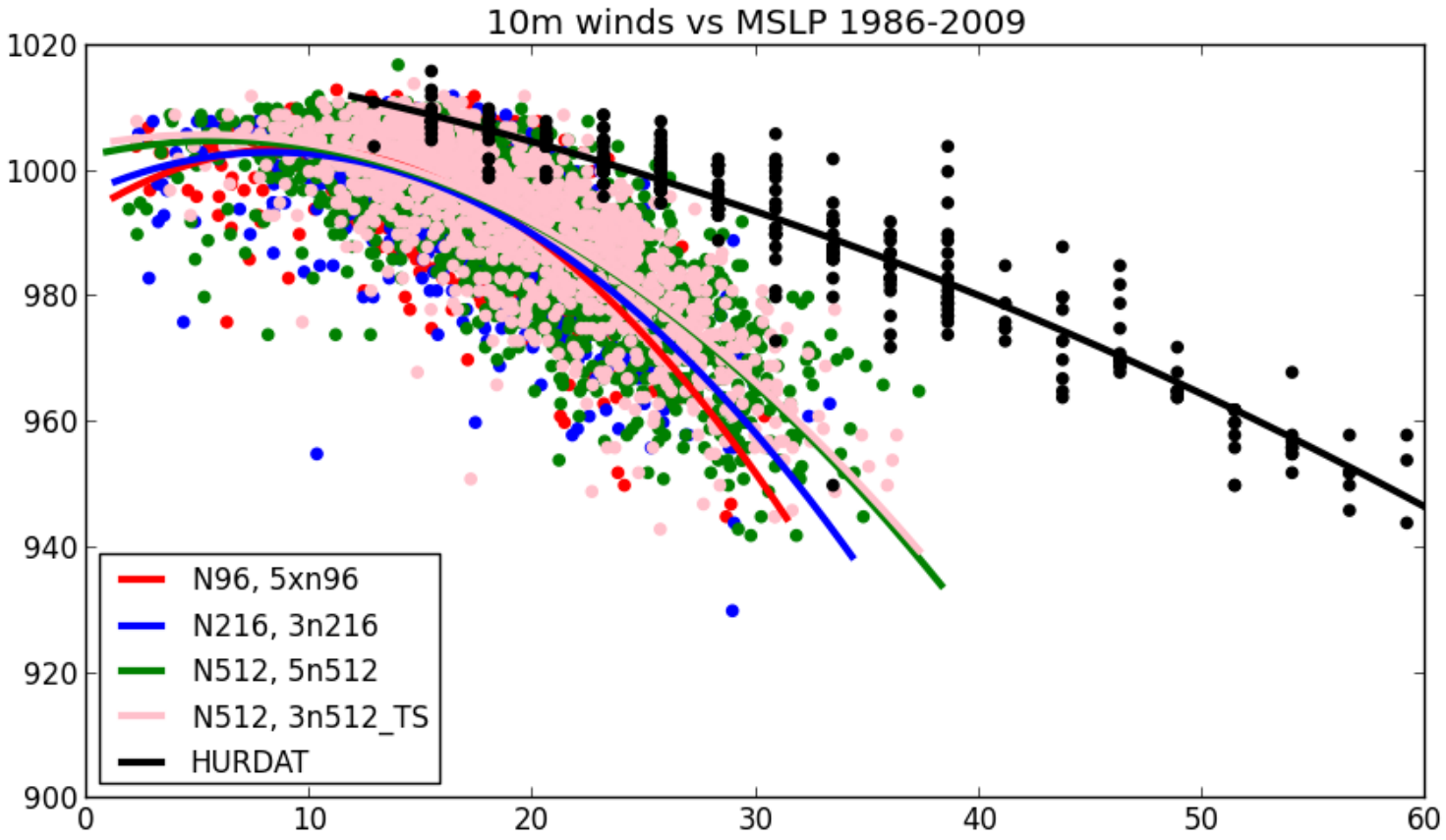

x 10^5
Total ACE
0
1
2
3
4
5
6
7
8
9
SI
AUS
SP
NI
WNP
ENP
NATL
CAML
CAMH
ECHAM5
FSU
GEOS-5
GFS
GISS
HadL
HadM
HadH
HiRAM
Obs


Fraction of Total ACE
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45
0.5
SI
AUS
SP
NI
WNP
ENP
NATL

Intensity

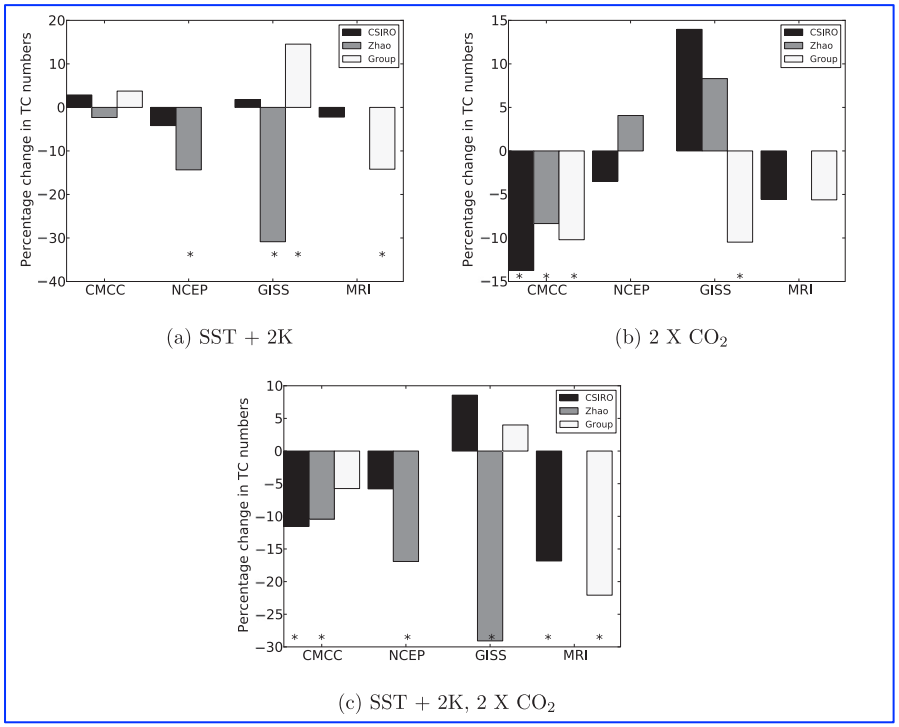

(a)
TD
TS
C1
C2
C3
C4
C5
CAMH
ECHAM5
FSU
GEOS-5
GFS
GISS
HadH
HiRAM
Obs
0
10
20
30
40
50
60
70
80
90
Max wind speed (m/s)
(b) CAM5.1
(c) HadGEM3
Fraction
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
LR
MR
HR
Max wind speed (m/s)

TC intensity vs model resolution



Roberts et al. J. Clim. 2015

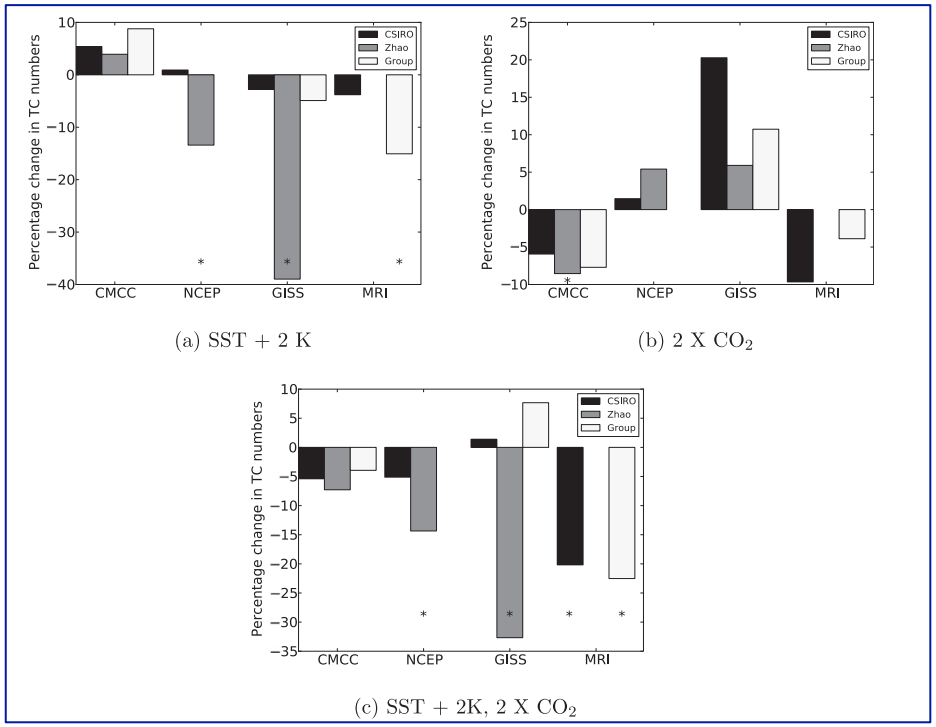
Sensitivity to tracking scheme



(a) SST + 2K

(b) 2 X CO_2

(c) SST + 2K, 2 X CO_2



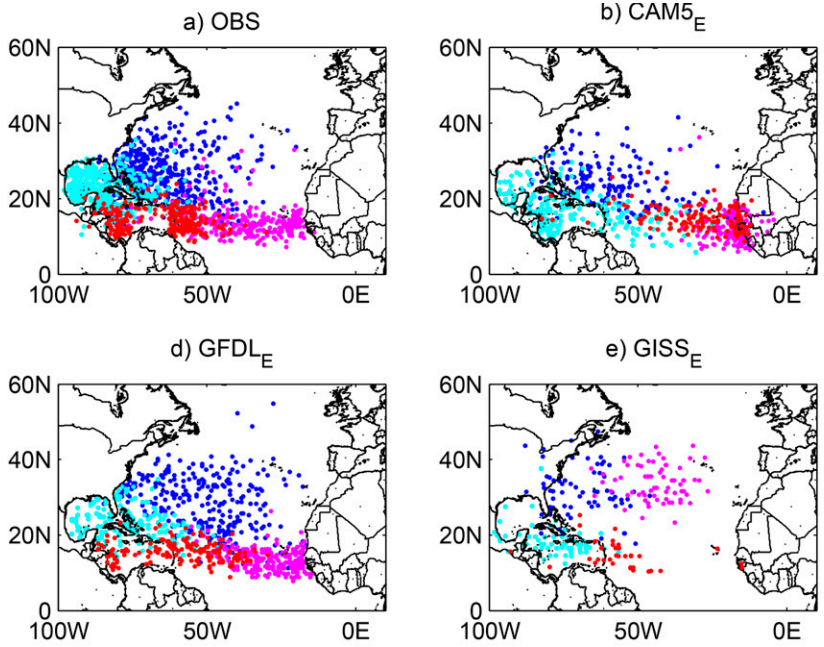
(a) SST + 2 K

(b) 2 X CO_2

(c) SST + 2K, 2 X CO_2

Figures from Horn et al. J. Climate, 2014

Cluster analysis of Atlantic TC tracks



Daloz et al. J. Climate, 2015

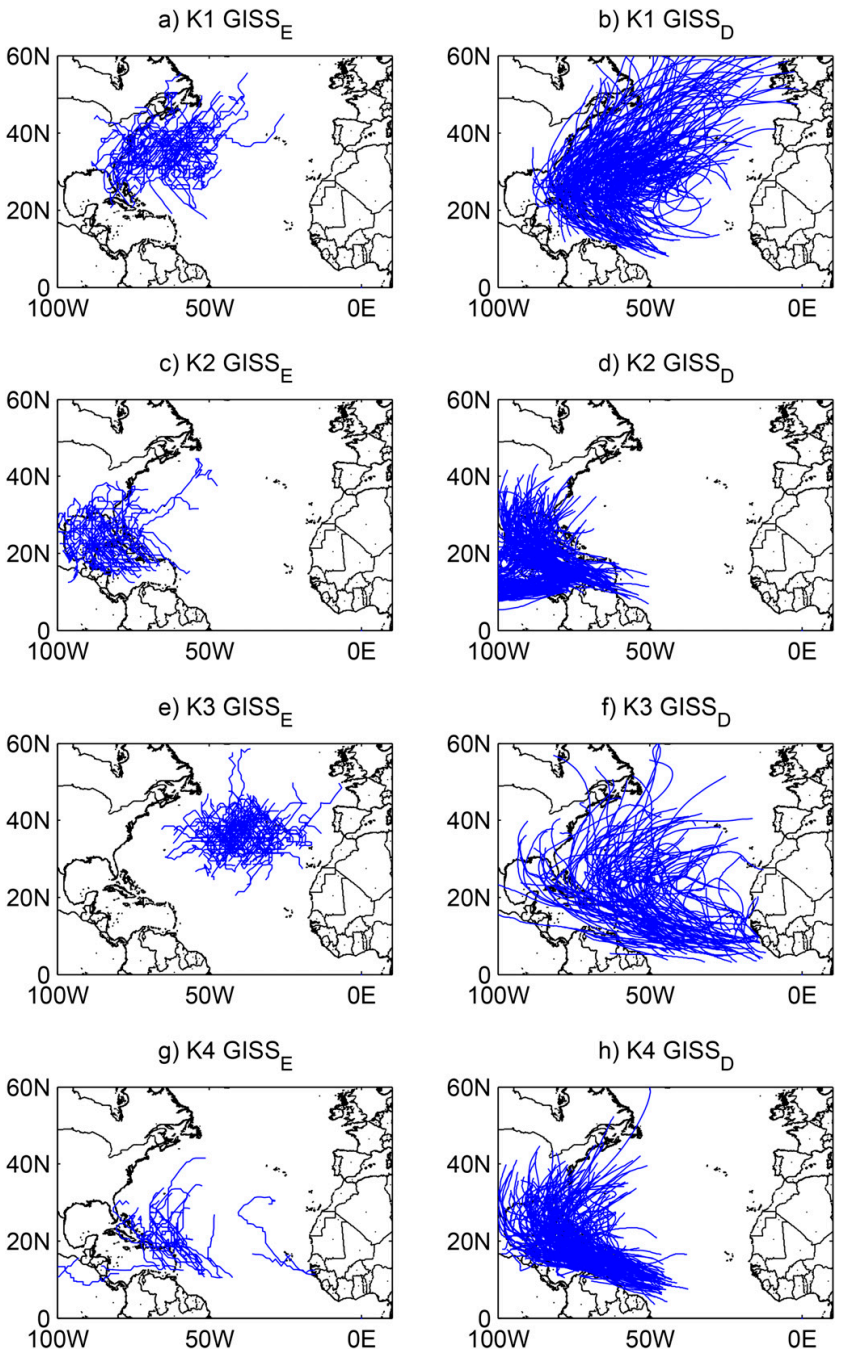


FIG. 6. As in Fig. 5, but for GISS_E and GISS_D.

Issues

- Model sensitivity to parametrizations, e.g. convection scheme
- Model biases
- Results depend on model TC definition – not uniform
- Similar resolution models: TC climatology (intensity, frequency) can be very different

Conclusions

- In the last few years there has been a huge progress in the research of TCs in climate models.
- The HWG working is the first effort of a multi-model comparison on this topic.
- There is a large sensitivity on model resolution and physics in climate models' ability to simulate TCs.
- A large range of research topics is now possible with the improvement in the ability of climate models in simulating TCs.

Perspective

- Remarkable progress
- Seamless predictions
- Ability to further improve:
  - Simulation of disturbances need to be improved (e.g. MJO, easterly waves, equatorial waves)
  - Modeling improvement: convection, dynamical cores
  - ENSO spring barrier
  - Reliable SST projections