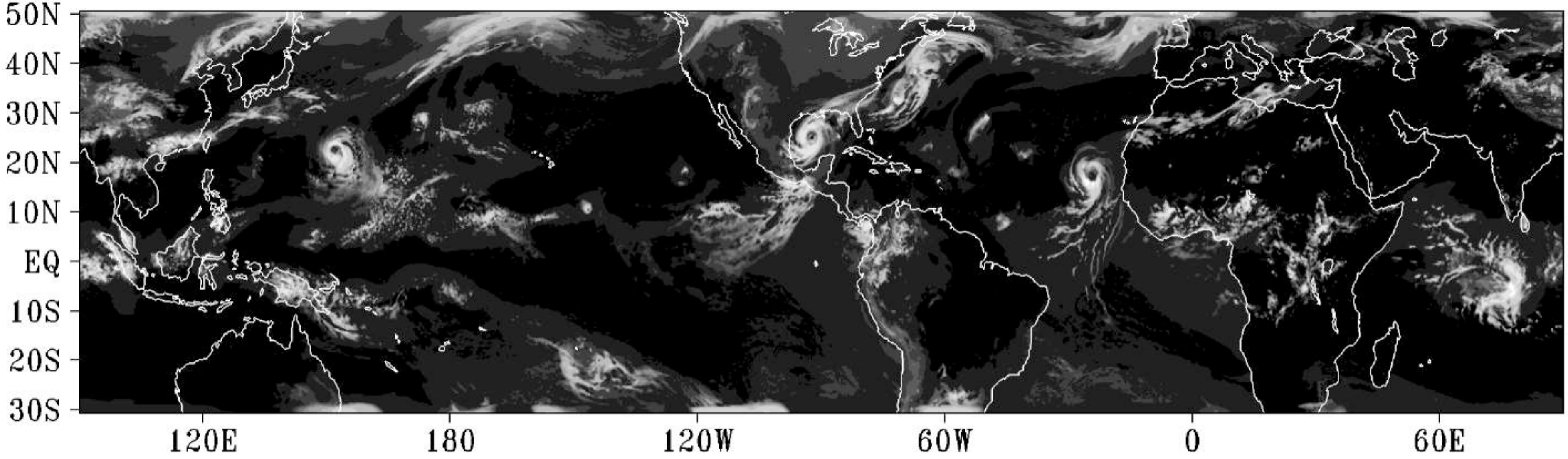
Oceanic and Atmospheric Sources of Tropical Cyclone Predictability



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Research Scientist
Lawrence Berkeley National Laboratory

with Ping Chang, R. Saravanan (Texas A&M)
Michael Wehner, and Dáithí Stone (LBL)

Improving seasonal – climate TC prediction

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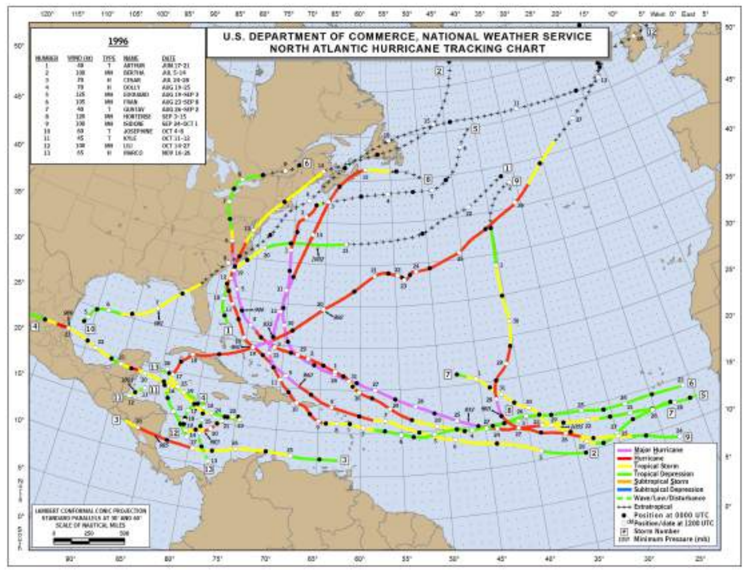

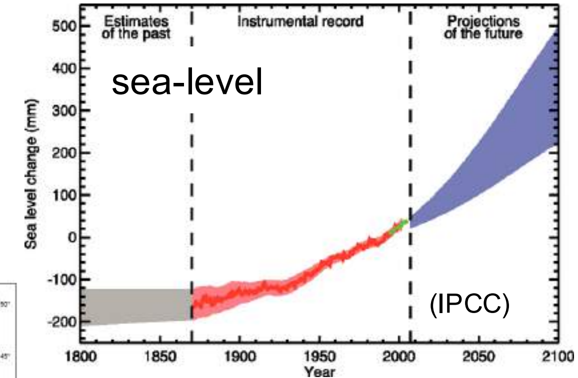

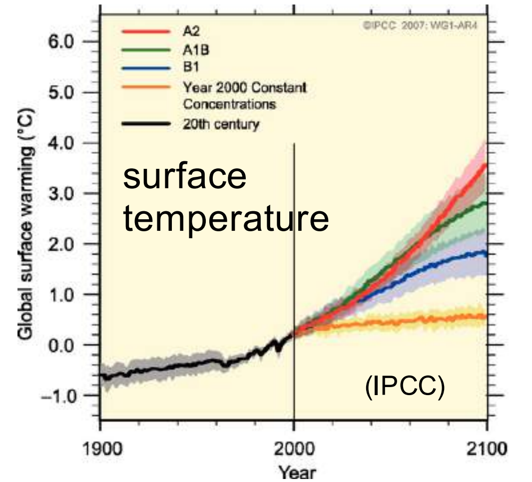

Individual TCs — TC seasons — Centennial TC activity

- tropical easterly waves
- local ocean heat content

- basin-scale sea-surface temperature and atmospheric circulation patterns

- greenhouse gas emissions
- sea-level rise

Outline

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- Are Atlantic tropical cyclones limited by tropical wave activity?

- Influence of the location/magnitude of El Niño on TC seasons
- Compensating and constructive influences of Atlantic and Pacific SST on TCs
- An ENSO-like teleconnection between Atlantic SST and East Pacific TCs

- *Preview*: Anthropogenic influence on “worst-case scenario” TCs

Individual TCs — TC seasons — Centennial TC activity

Ingredients for tropical cyclones

1) system of organized convection to provide a "seed"
   - Atlantic: tropical easterly wave

2) warm ocean temperatures at surface to ~100 m depth

3) unstable atmosphere with moist mid-troposphere

4) weak tropospheric vertical wind shear

[Avila 1991; Landsea 1993; Tuleya and Kurihara 1981; Elsner et al. 2000; Frank and Ritchie 2001; Wong and Chan 2004; Gray 1979; Lin et al. 2013; Gray 1968]

Are Atlantic TCs limited by tropical easterly wave activity?

Patricola, Saravanan, and Chang (2017) *In prep.*

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Motivation

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- African easterly waves (AEWs) and Atlantic TCs are strongly linked on synoptic timescale
  - 85% of major Atlantic hurricanes originate from AEWs
- Relationship on interannual – climate timescales unclear

<u>Other TC genesis mechanisms:</u>

- **ITCZ wave instability**, observed in Atlantic
- **Self-aggregation of convection**, in radiative-convective equilibrium simulations
- **Disturbances from monsoon trough**, observed in NW Pacific, where 10-25% of typhoons form from tropical waves

➢ Are changes in AEWs a source of uncertainty in projections of future Atlantic TC activity?

[Landsea et al. 1993; Russell et al. 2017; Belanger et al. 2010; Thorncroft and Hodges, 2001; Hopsch et al. 2007; Belanger et al. 2014; Agee, 1972; Held and Zhao, 2008; Khairoutdino and Emanuel, 2013; Frank, 1988; Ritchie, 1995; Lander, 1994; Chen et al., 2004; Chen et al., 2008]

Regional climate model simulations

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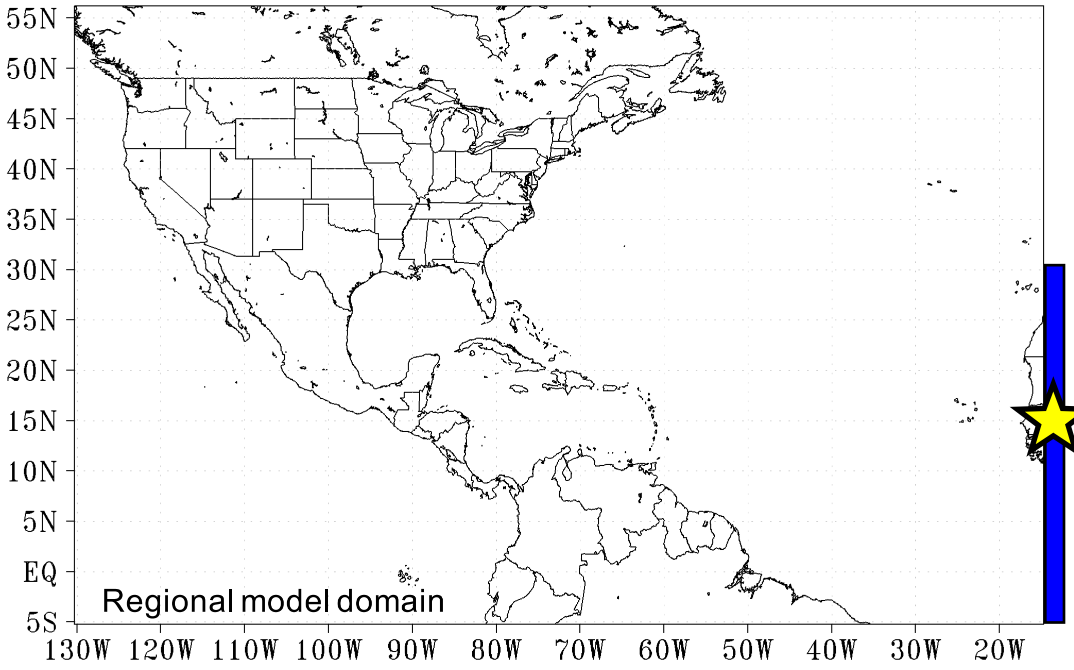
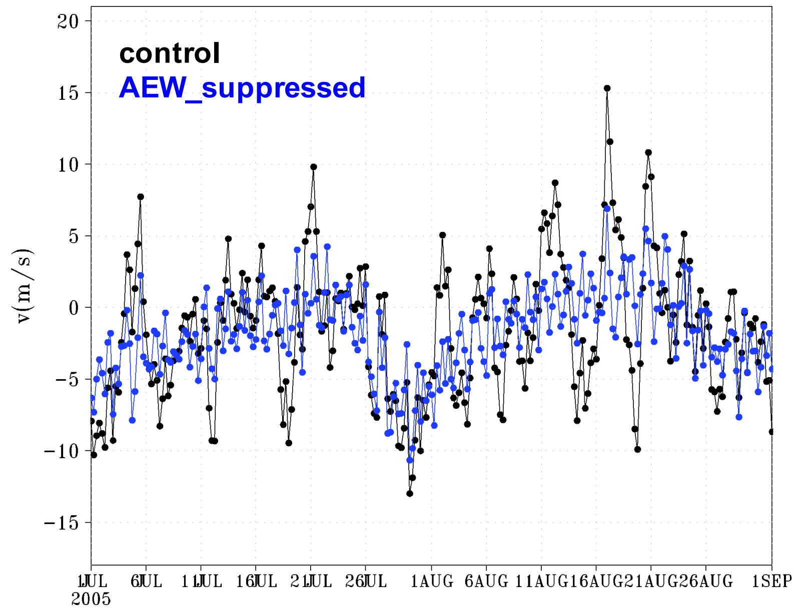
<u>Weather Research and Forecasting Model (WRF)</u>

- 27 km resolution
- SST: daily NOAA-OI V2; LBCs: 6-hourly NCEP CFSR
- 10 ensemble members (1 Jun -1 Dec 2005)
- AEWs contributed to 75% of Atlantic TC genesis in 2005 [Beven et al. 2008]

- **Control: 2005**
- **AEW_suppressed: 2-10 day variability removed from eastern LBC (5°S-30°N) w/ Lanczos filter**



Regional model domain



Time series of meridional wind (m/s) at 700mb, 15N, and 15W from the eastern LBC of control (black) and AEW_suppressed (blue) simulations

Seasonal Atlantic TC response to AEW suppression

	control	AEW suppressed	% change	p-value
Number of TCs/season	19.5	20.2	+4%	0.64
Number of TC days/season	105	117	+11%	0.17

Conclusions: Suppression of AEWs produces no significant change in simulated seasonal Atlantic TC number, suggesting

- AEW variability minimally influences interannual-climate variations in Atlantic TC number
  - Supported by synthetic TC track model, which reproduces interannual TC activity without AEW variability input (Emanuel 2008; Emanuel 2010)
- Although TCs readily generate from AEWs, in the absence of AEWs TCs will generate by other mechanisms

Influence of location/magnitude of El Niño on TC seasons

Patricola, Chang, and Saravanan (2016) *Nature Geoscience*

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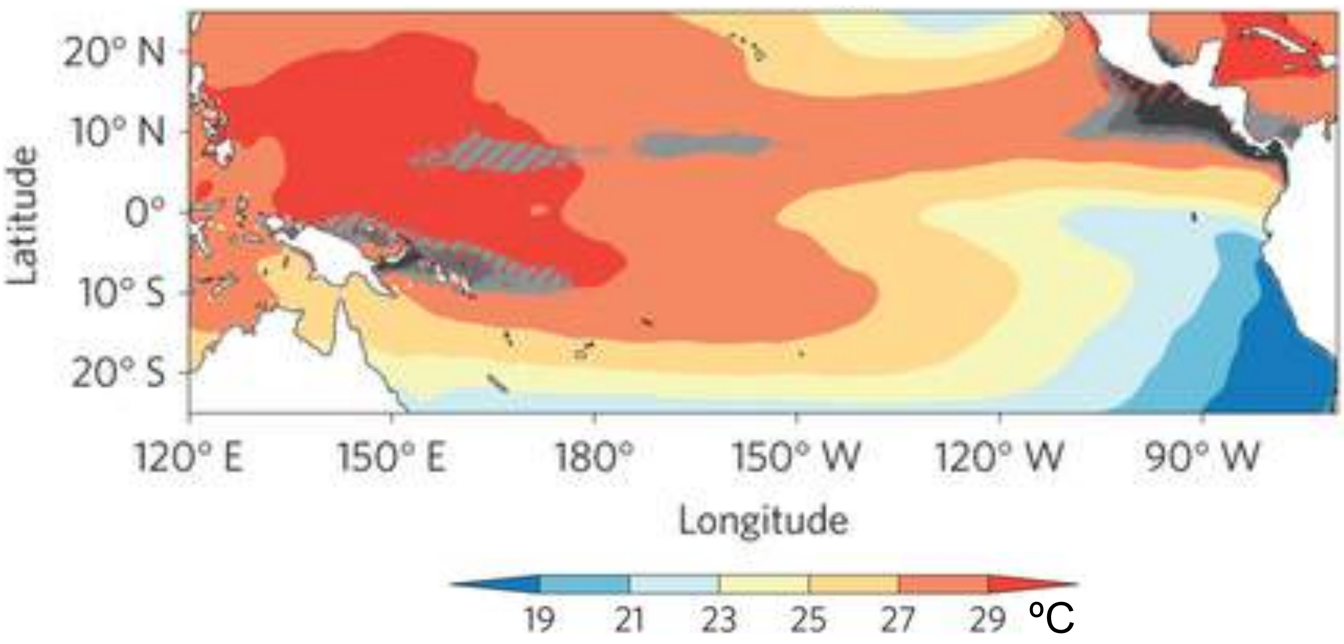
Tropical Pacific warm pool and cold tongue

SST: Aug-Oct climatology

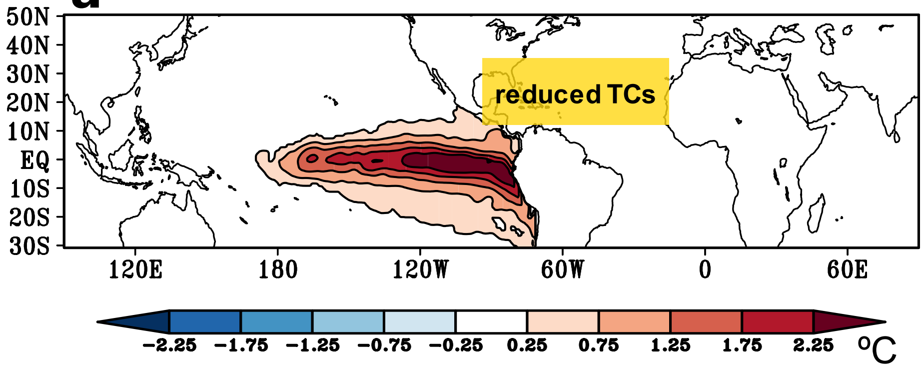


El Niño and Atlantic TC activity

El Niño is one major source of seasonal tropical cyclone predictability.

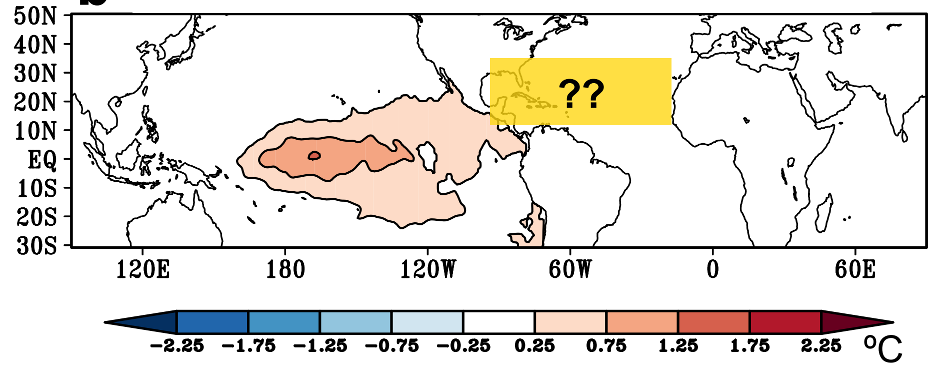
<u>Location-dependent “flavors” of El Niño:</u>

a **East Pacific/ Cold Tongue**



suppresses Atlantic TCs via dynamical teleconnections: increased vertical wind shear

b **Central Pacific/ Warm Pool**



influence on TCs has not been understood

[Arkin 1982; Gray 1984; Goldenberg and Shapiro 1996; Bove et al. 1998; Pielke and Landsea 1999; Tang and Neelin 2004; Smith et al. 2007]

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Motivation

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How does the location and magnitude of SST warming during El Niño impact Atlantic tropical cyclone activity, and through what mechanisms?

Observations:

Since 1980's Warm Pool El Niño has been

- more frequent
- more intense

Future projections:

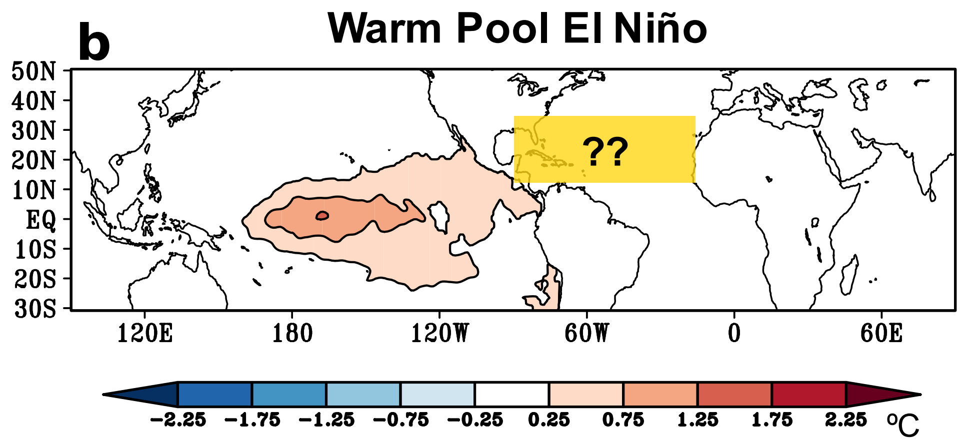
- more frequent / intense Warm Pool El Niño

[Ashok et al. 2007; Kug et al. 2009; Lee and McPhaden 2010; Yeh et al. 2009; Kim and Yu 2012]

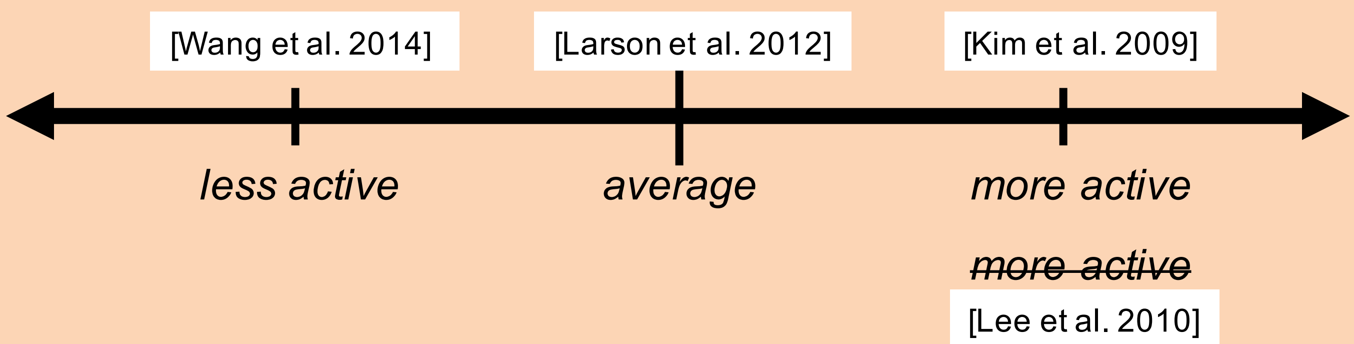
Observations: Warm Pool El Niño and Atlantic TCs

Warm Pool El Niño's influence on Atlantic TCs is unclear.

- observational record is short
- complicated by Atlantic SST variability



Atlantic TC activity:



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Tropical Channel Model Simulations

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Weather Research and Forecasting Model (WRF)

- global tropics-extratropics
- 27 km horizontal resolution
- 22 ensemble members
- SST: monthly HadISST
- lateral boundary conditions: 6-hourly NCEP-II (1989 or 1996)

Simulation	SST
Climatology	1950-2011 monthly climatology
Cold Tongue El Niño	Monthly climatology + CT Niño forcing
Warm Pool El Niño	Monthly climatology + WP Niño forcing
Doubled Warm Pool El Niño	Monthly climatology + 2x WP Niño forcing

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Flavors of El Niño

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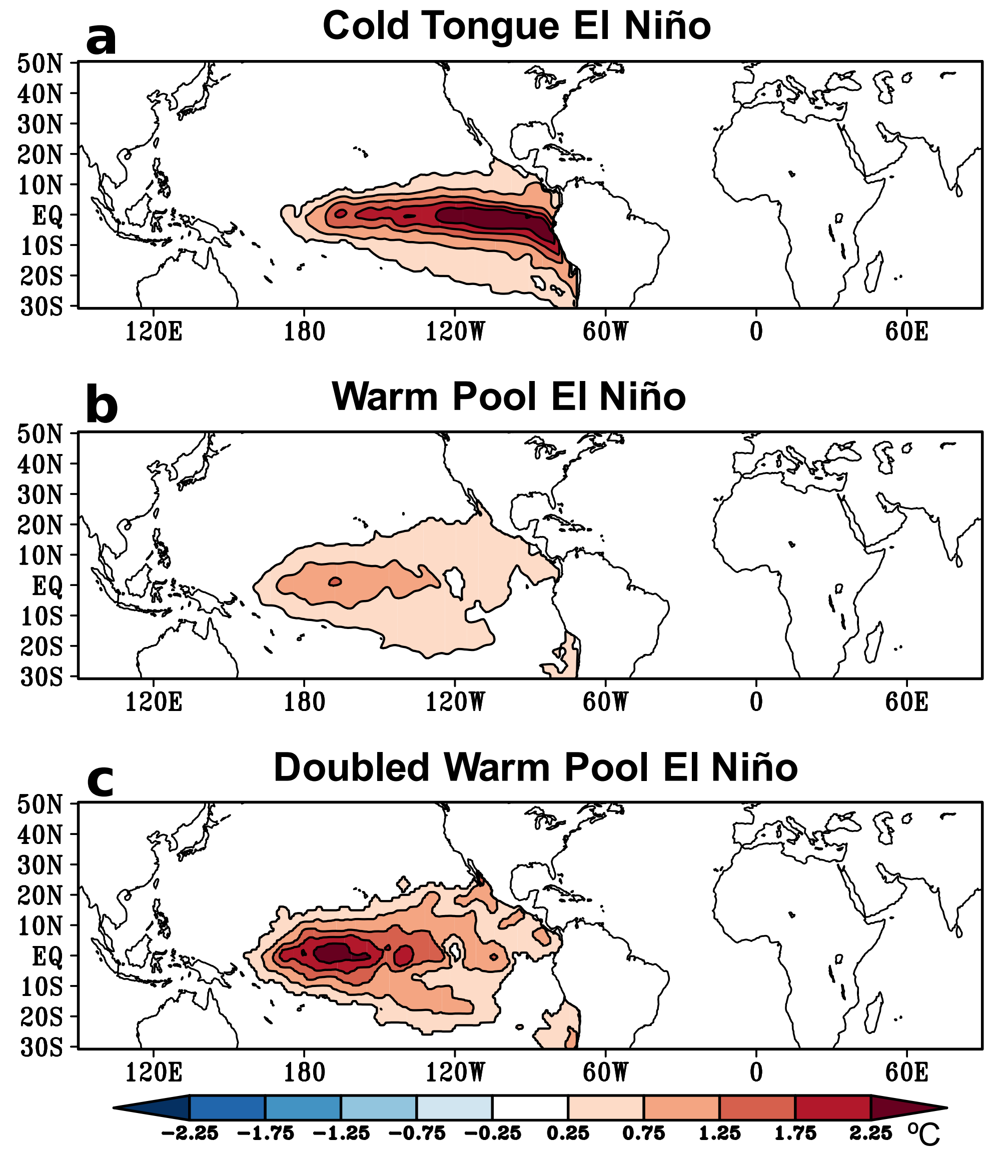
Strongest 10%

Aug-Oct Niño 3 index from 1950-2011, where significant

Strongest 10%

Aug-Oct Niño 4 index (excludes CT events)

Doubling of strongest 10% WP events



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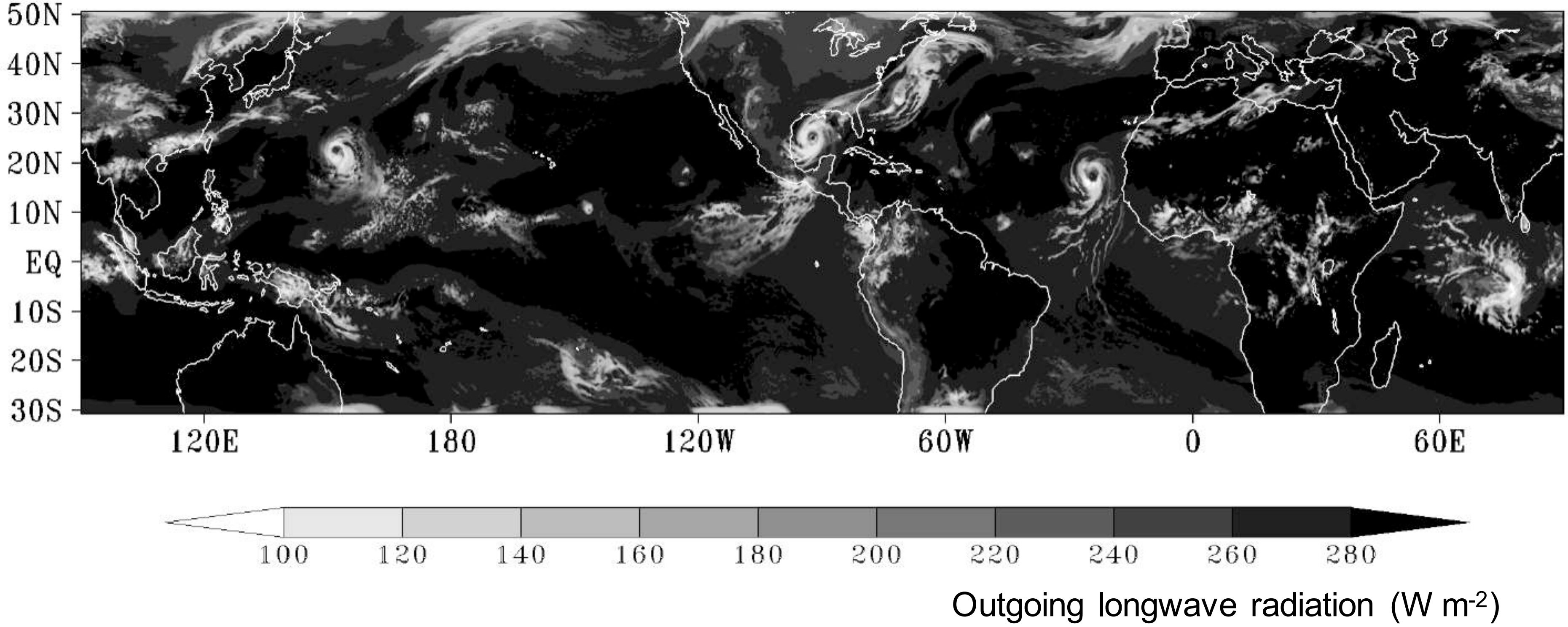
TCs in the tropical channel model



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TC track density

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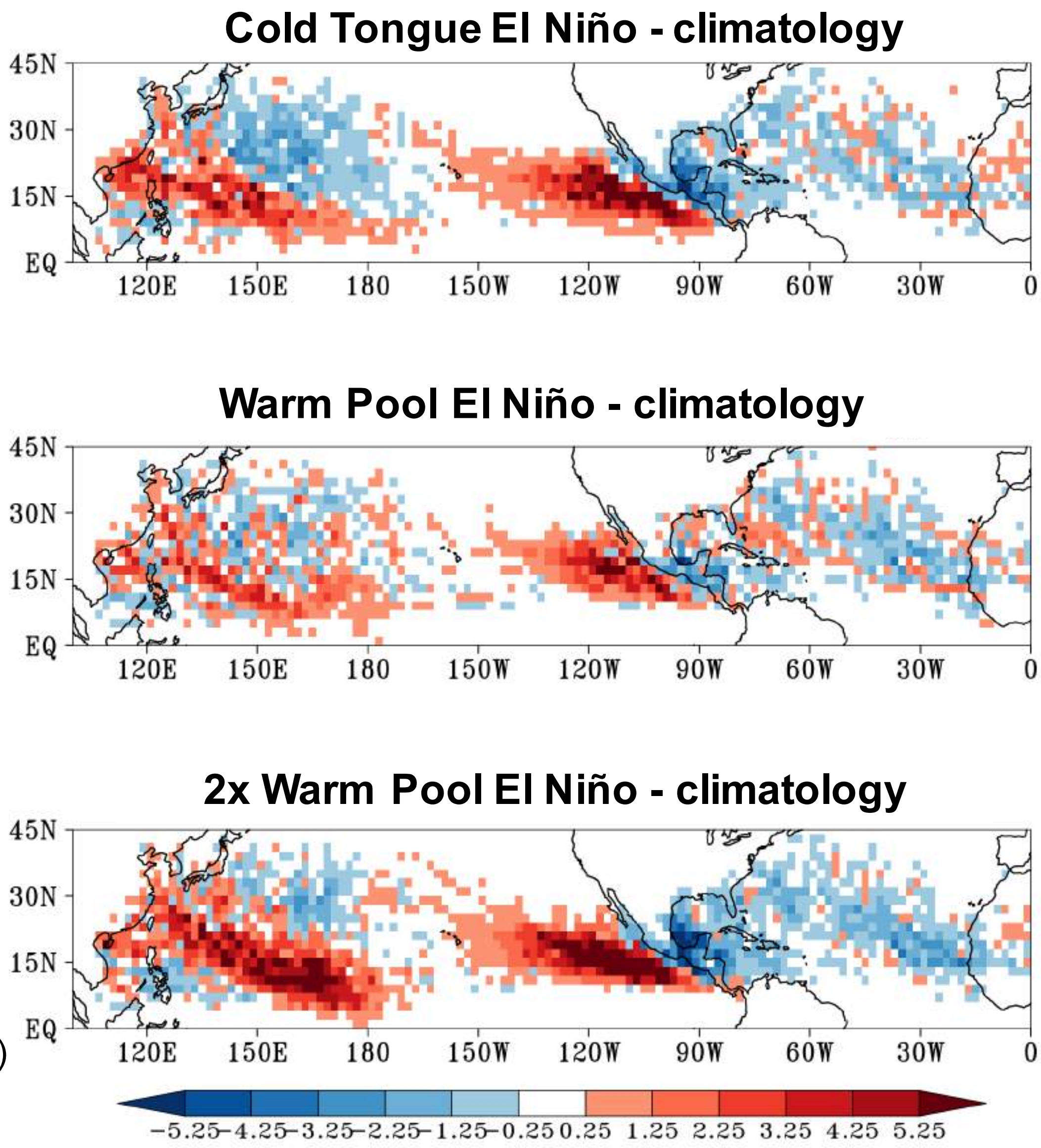
Stay tuned for the Western North Pacific:
Patricola, Camargo, et al., *In prep*



TC track density (number of TCs day^{-1} per 10 seasons) calculated over 2° x 2° boxes at a frequency of 6-hours during 1 Jun – 1 Dec

Quantifying tropical cyclone activity

<u>Accumulated cyclone energy (ACE)</u>

$$ACE = 10^{-4} \Sigma v^2_{max}$$ (unit: 10^4 knots^2)

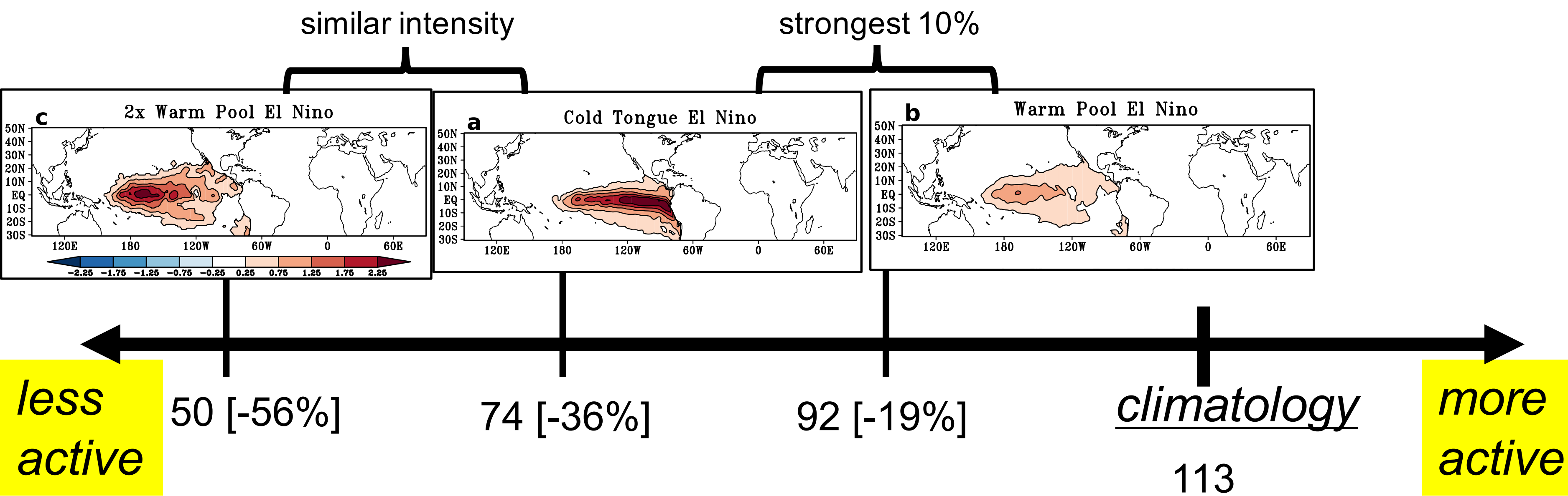
v_{max} = 6-hourly maximum sustained wind speed (knots)

- accounts for storm strength, number, and duration

[Bell et al. 2000]

Atlantic tropical cyclone activity

ACE: seasonal (Jun-Nov) ensemble mean (10^4 knots^2)



Warming near the warm pool is more effective at suppressing Atlantic TC activity than warming of the cold tongue.

Percent change from climatology in brackets. All changes are significant (5% level).

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East Pacific tropical cyclone activity

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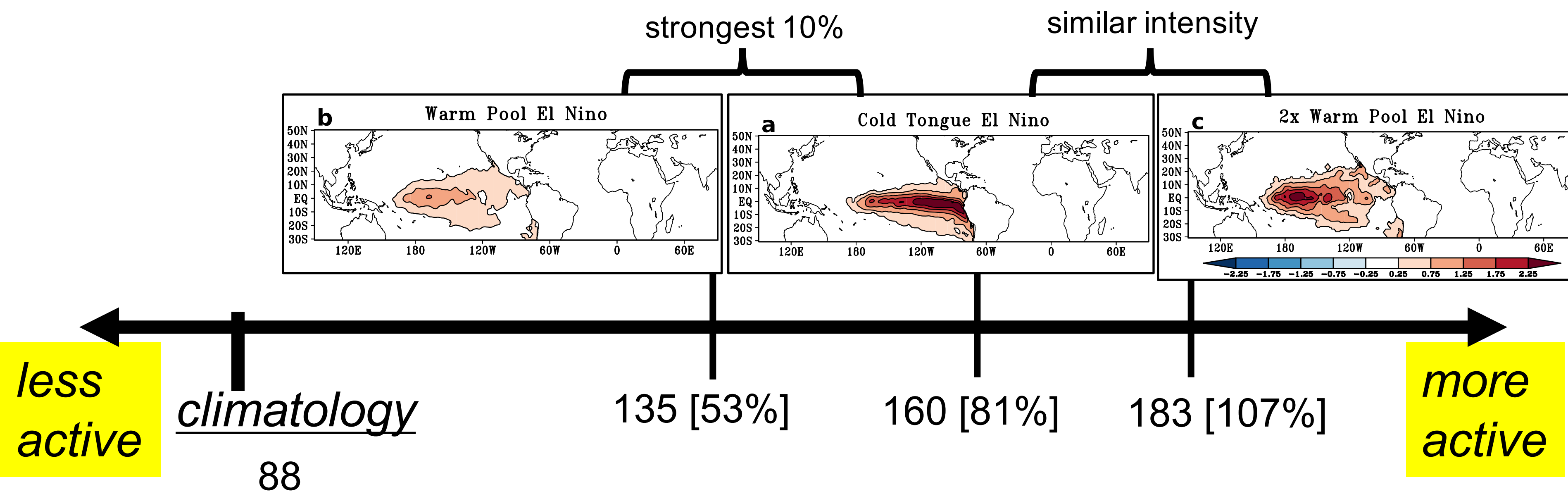
ACE: seasonal (Jun-Nov) ensemble mean (10^4 knots^2)



Warming near the warm pool is more effective at enhancing East Pacific TC activity than warming of the cold tongue.

Percent change from climatology in brackets. All changes are significant (5% level).

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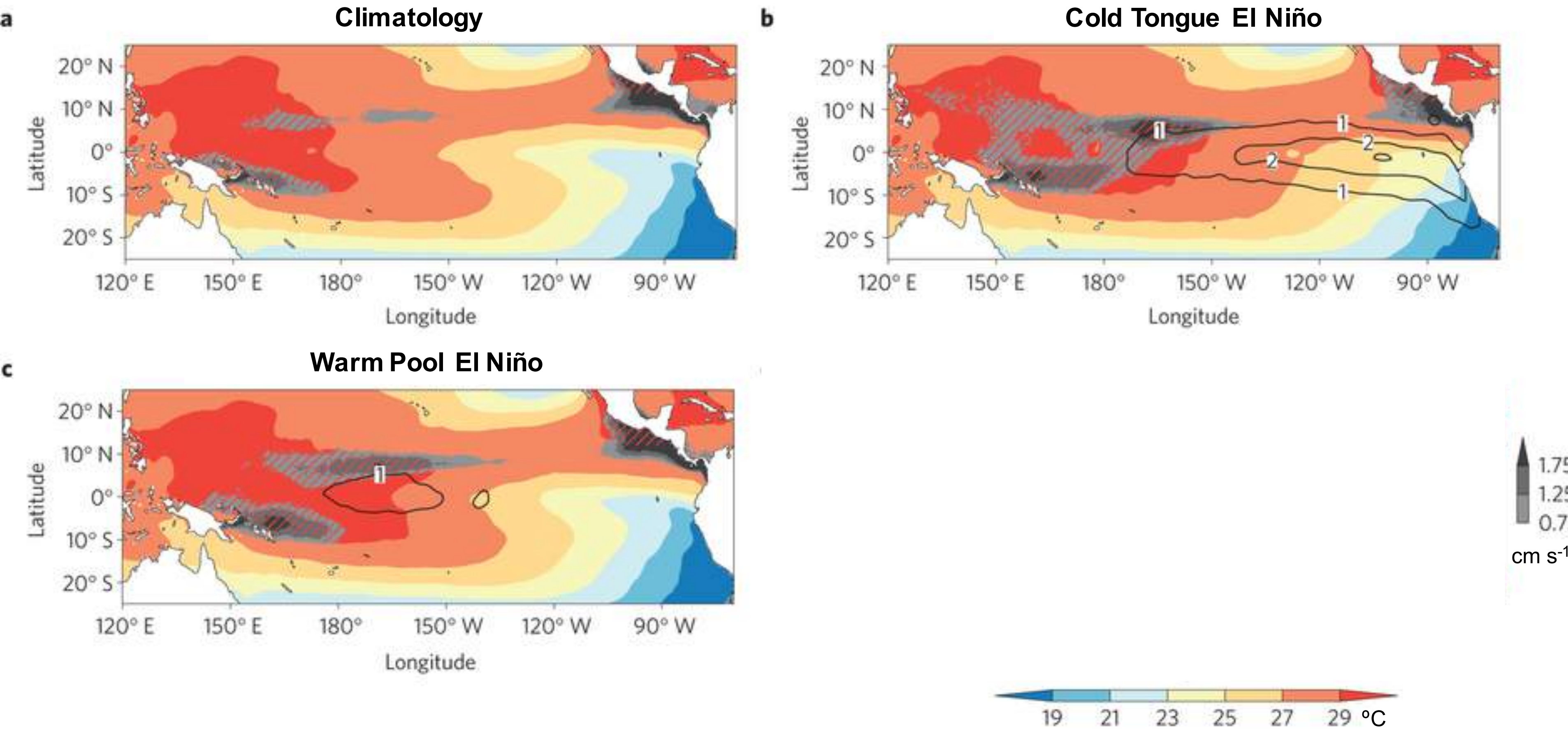
SST thresholds for deep convection

Simulated deep convection and prescribed SST and SST anomalies

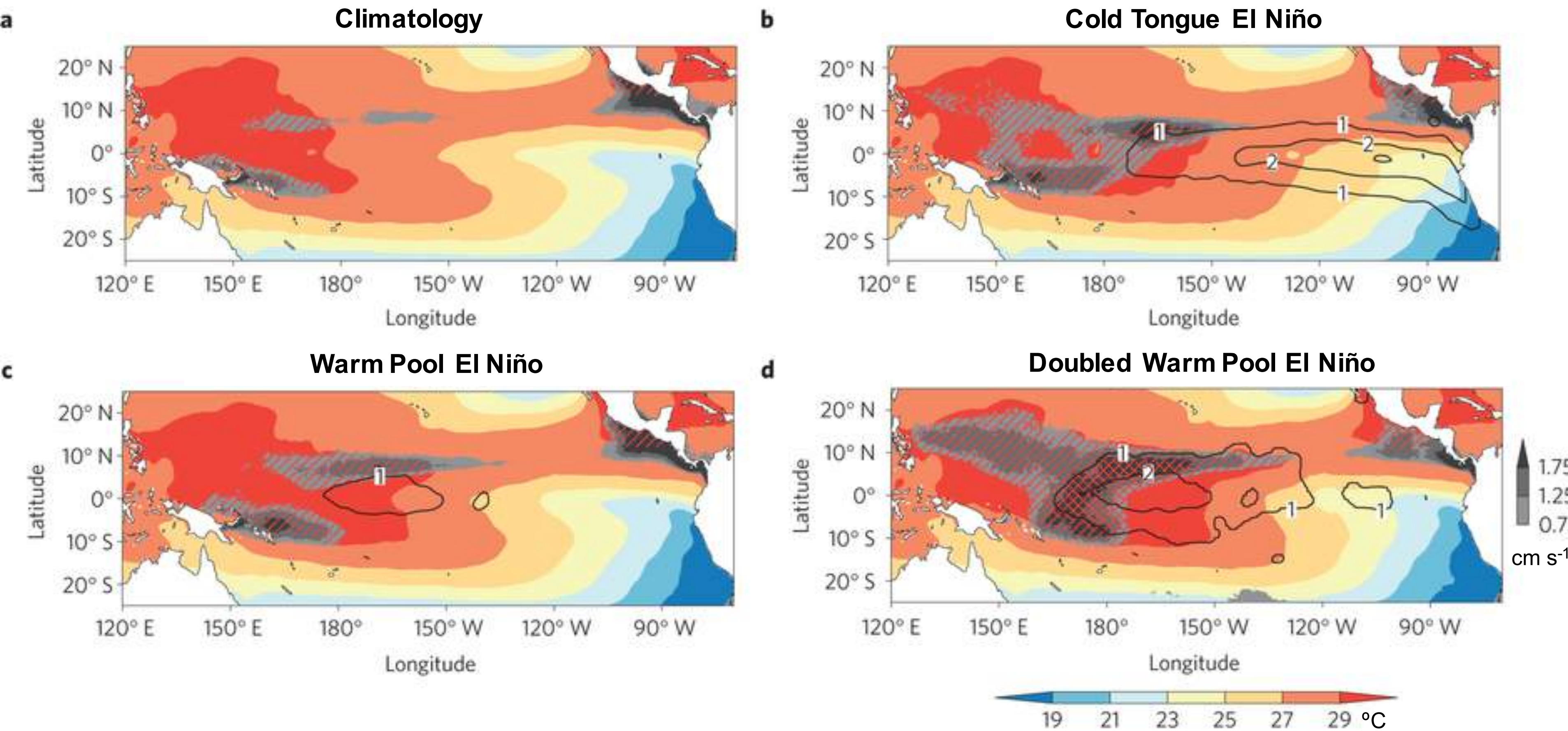


Aug-Oct ensemble mean SST (color), SST anomaly (contour), and vertical velocity at 500 hPa over ocean (grey; only > 0.75 cm s^{-1}). Single and double red hatching denote SST values between 29-30ºC and exceeding 30ºC, respectively.

SST thresholds for deep convection

Less warming is required over the central vs. eastern Pacific to satisfy the SST threshold for deep convection.

Simulated deep convection and prescribed SST and SST anomalies



Aug-Oct ensemble mean SST (color), SST anomaly (contour), and vertical velocity at 500 hPa over ocean (grey; only > 0.75 cm s^{-1}). Single and double red hatching denote SST values between 29-30ºC and exceeding 30ºC, respectively.

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Walker Circulation

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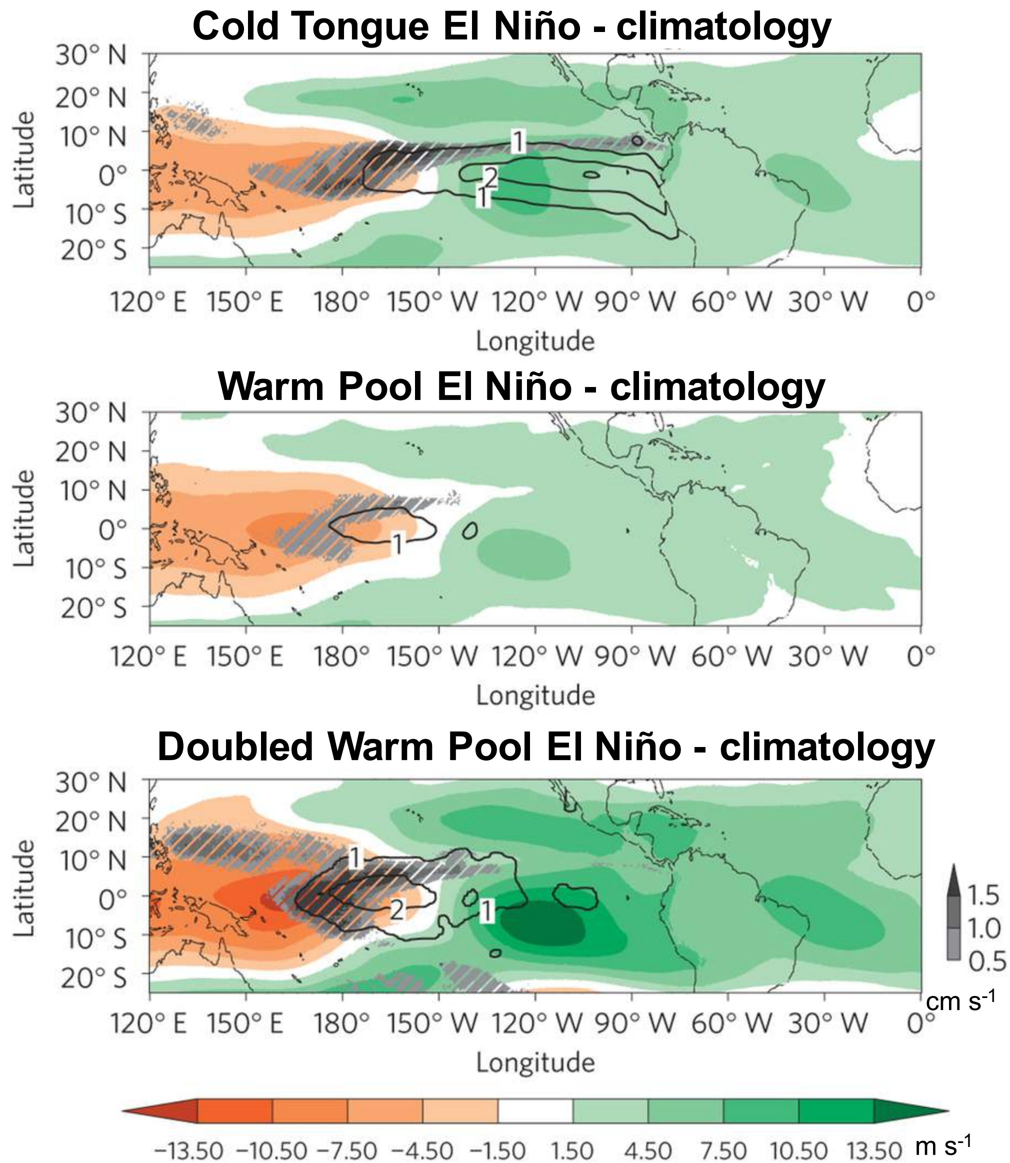
Upper level wind response leads to increased vertical wind shear in tropical Atlantic.



Aug-Oct ensemble mean zonal wind at 200 hPa (color), vertical velocity at 500 hPa over ocean (grey; only > 0.5 cm s^{-1}), and SST anomaly (ºC; contour)

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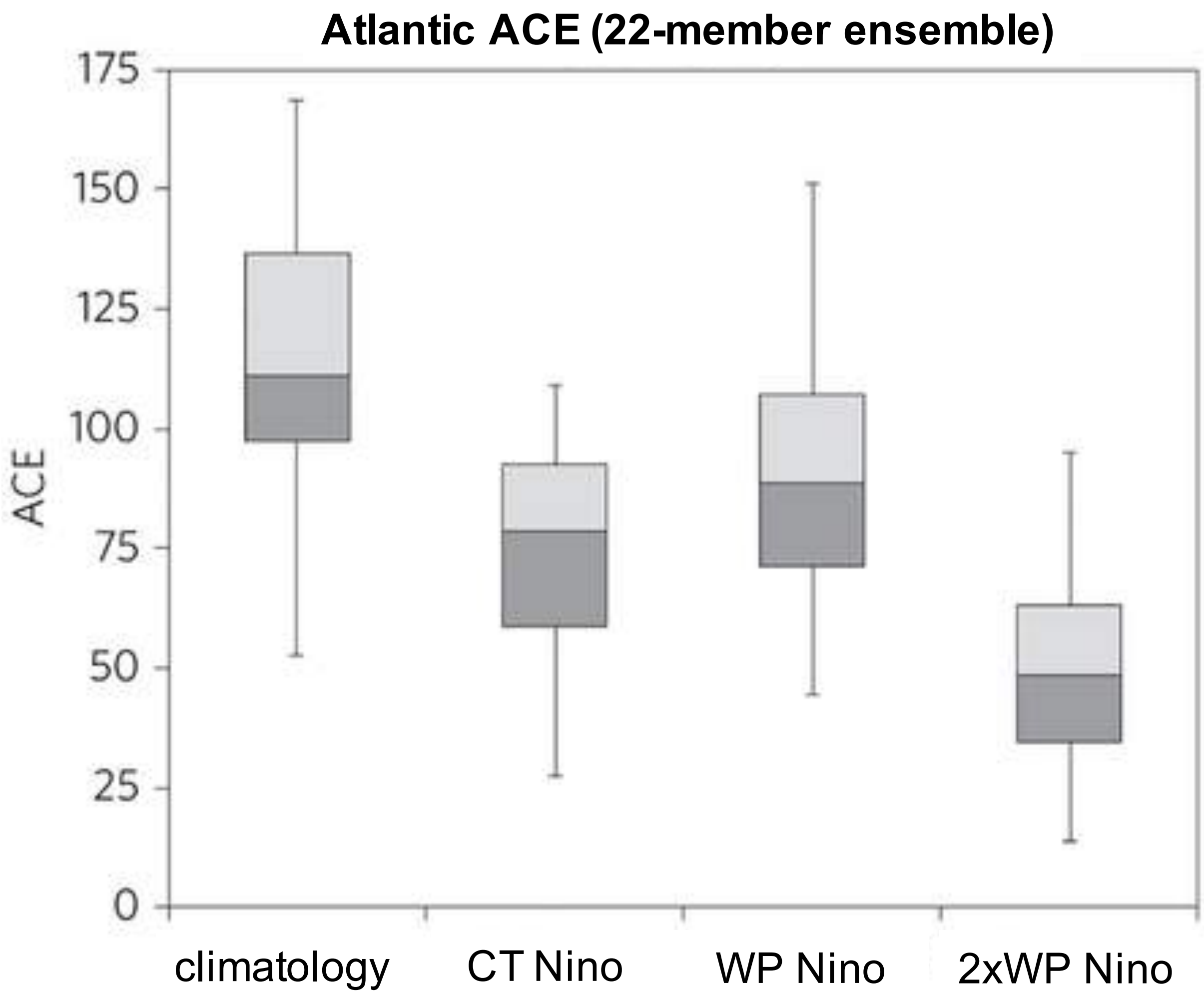
Internal atmospheric variability



- Internal atmospheric variability and small sample size can explain different results in obs.

Summary

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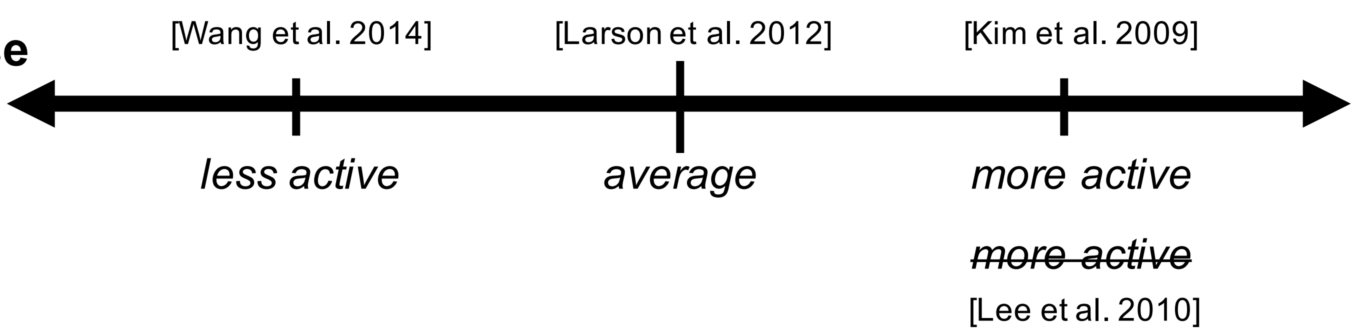
- Both El Niño flavors suppress Atlantic / enhance East and West Pacific TC activity
- SST warming near the warm pool is more effective than warming of the cold tongue at doing so….
- …because less warming is required in the central vs. eastern Pacific to satisfy the SST threshold* for deep convection.
  - *Thresholds vary in time and depend on global SST. [Williams and Pierrehumbert 2009; Johnson and Xie 2010]

Atlantic TC response to WP El Nino:



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Atlantic and Pacific Ocean controls on Atlantic TCs

Patricola, Saravanan, and Chang (2014) *Journal of Climate*

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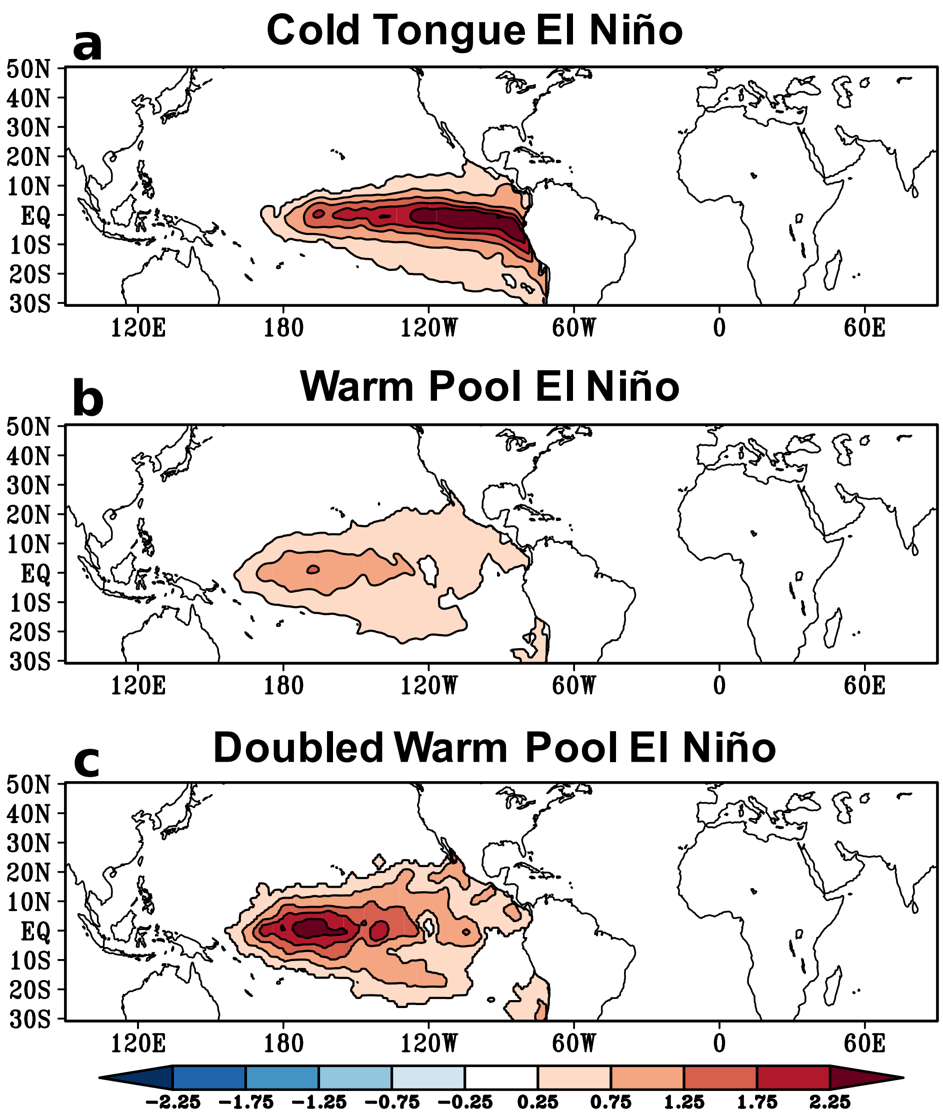
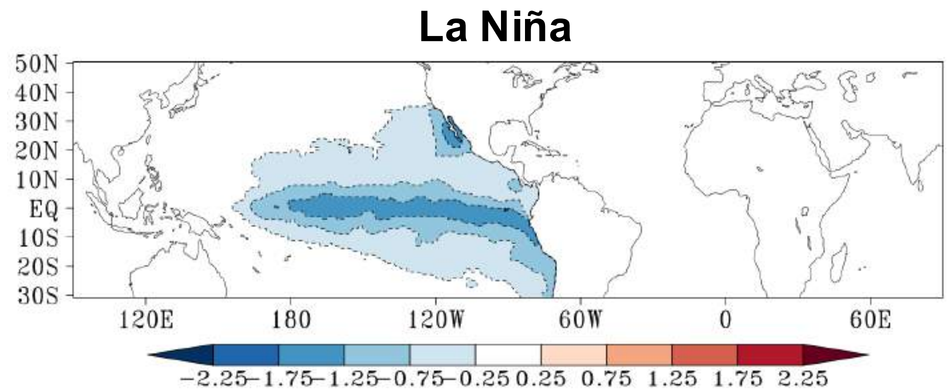
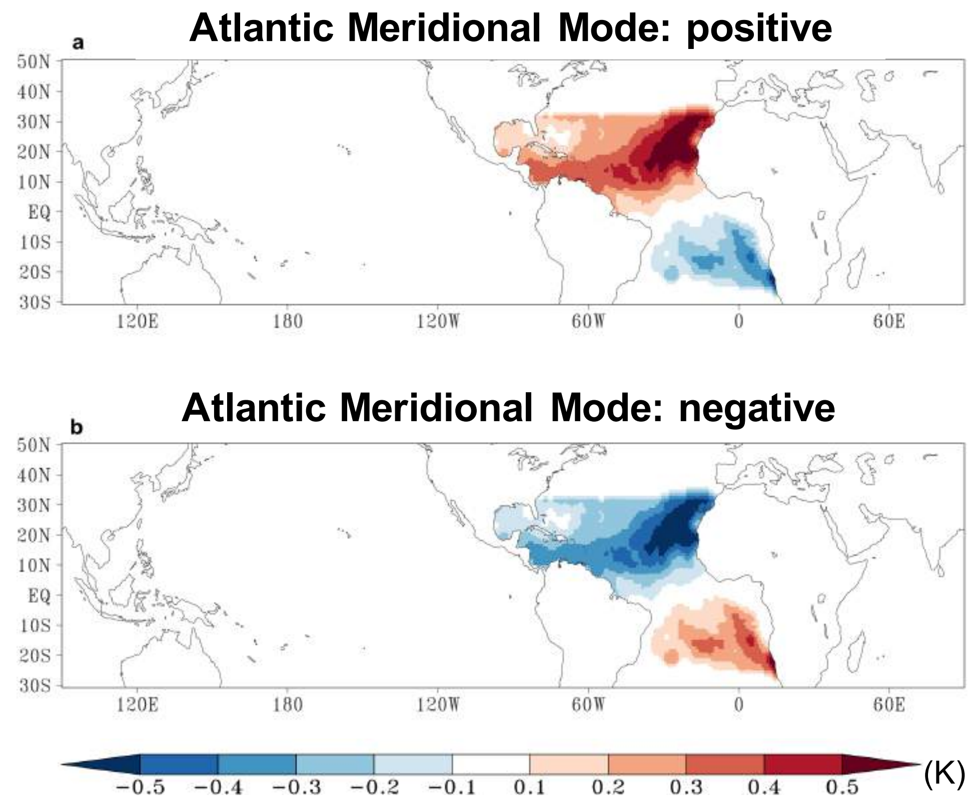
Oceanic sources of TC predictability







Influence of AMM and ENSO on Hurricane Seasons

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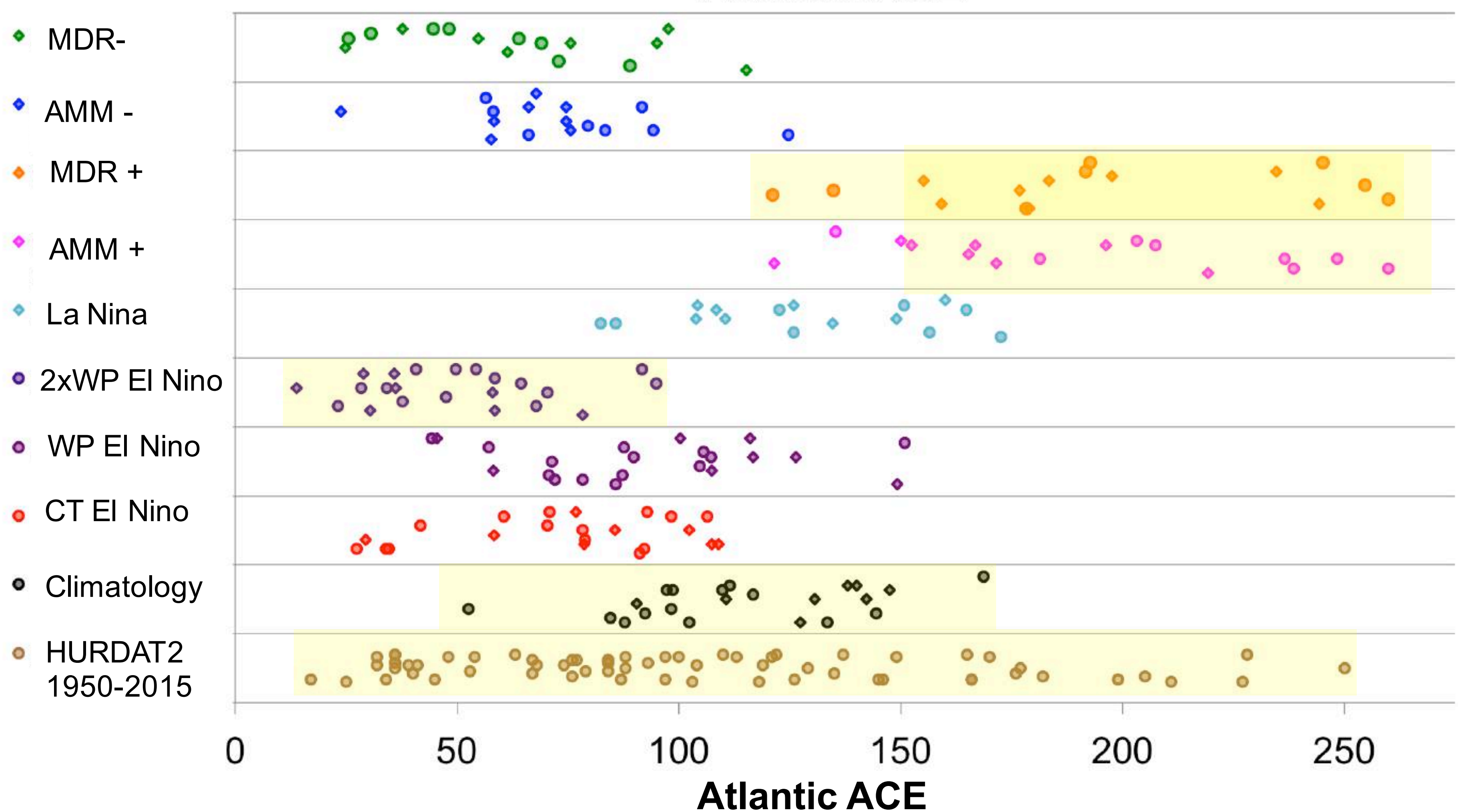
- Tails of seasonal distribution related to interannual SST, rather than internal atmospheric variability
- Uncertainty in seasonal TC forecast is greater for an active vs. inactive season



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Question

How does concurrent Pacific and Atlantic SST variability influence hurricane seasons?

Motivation:

- Many studies investigate individual, but not combined, roles of Pacific or Atlantic SST variability on Atlantic TC activity
- Improve prediction for extreme hurricane seasons unlike those on record

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Observed response in Atlantic TCs to ENSO and AMM

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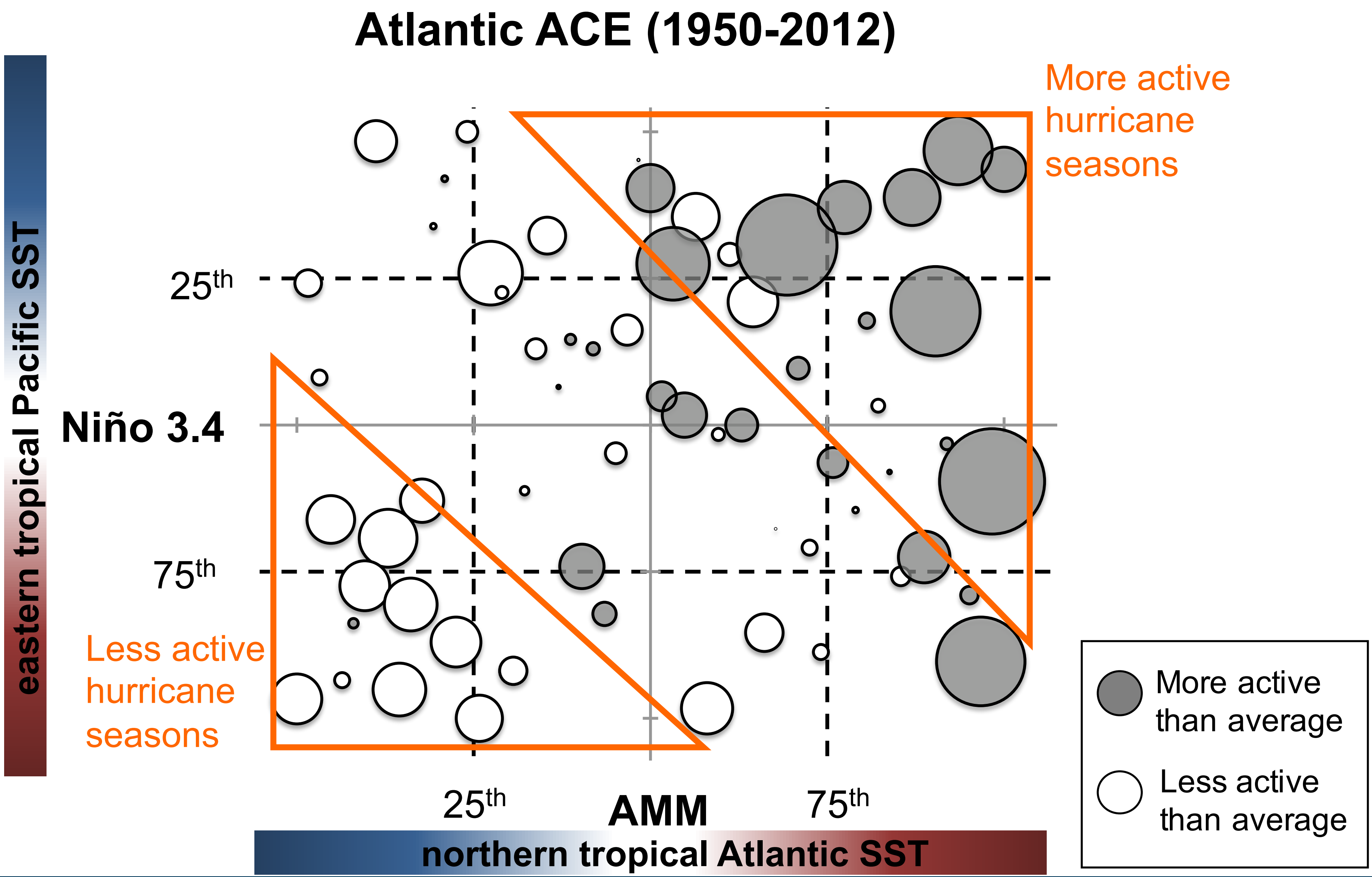

Observed response in Atlantic TCs to ENSO and AMM

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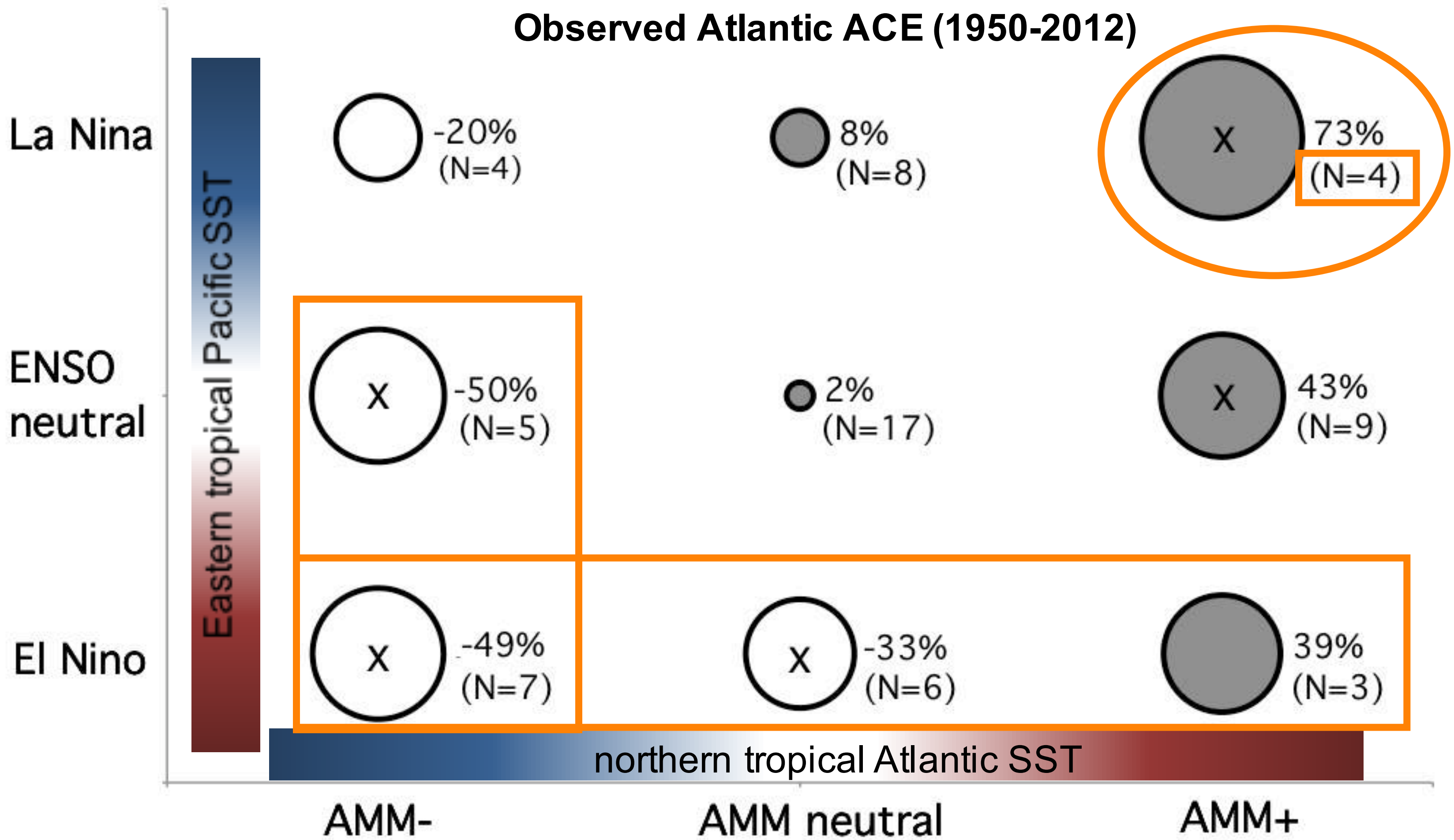
- Lower limit of Atlantic TC activity does not require both unfavorable ENSO and AMM conditions
- ENSO and AMM phases that individually produce opposing influences on Atlantic TCs together compensate
- Positive AMM and La Nina together work constructively to support the most active TC seasons on average



Average deviation from 1950-2012 mean in seasonal Atlantic ACE (%) from HURDAT2 for composites according to Aug-Oct AMM and Niño 3.4 indices

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Summary

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- AMM and ENSO exert constructive and compensating influences on Atlantic TC activity
  - Supported by observations and regional climate model simulations
- Active hurricane seasons are related to interannual SST, not internal atmospheric variability
- Strong concurrent AMM and La Nina lead to extremely active Atlantic hurricane seasons

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An ENSO-like teleconnection: Atlantic SST and East Pacific TCs

Patricola, Saravanan, and Chang (2017) *GRL*

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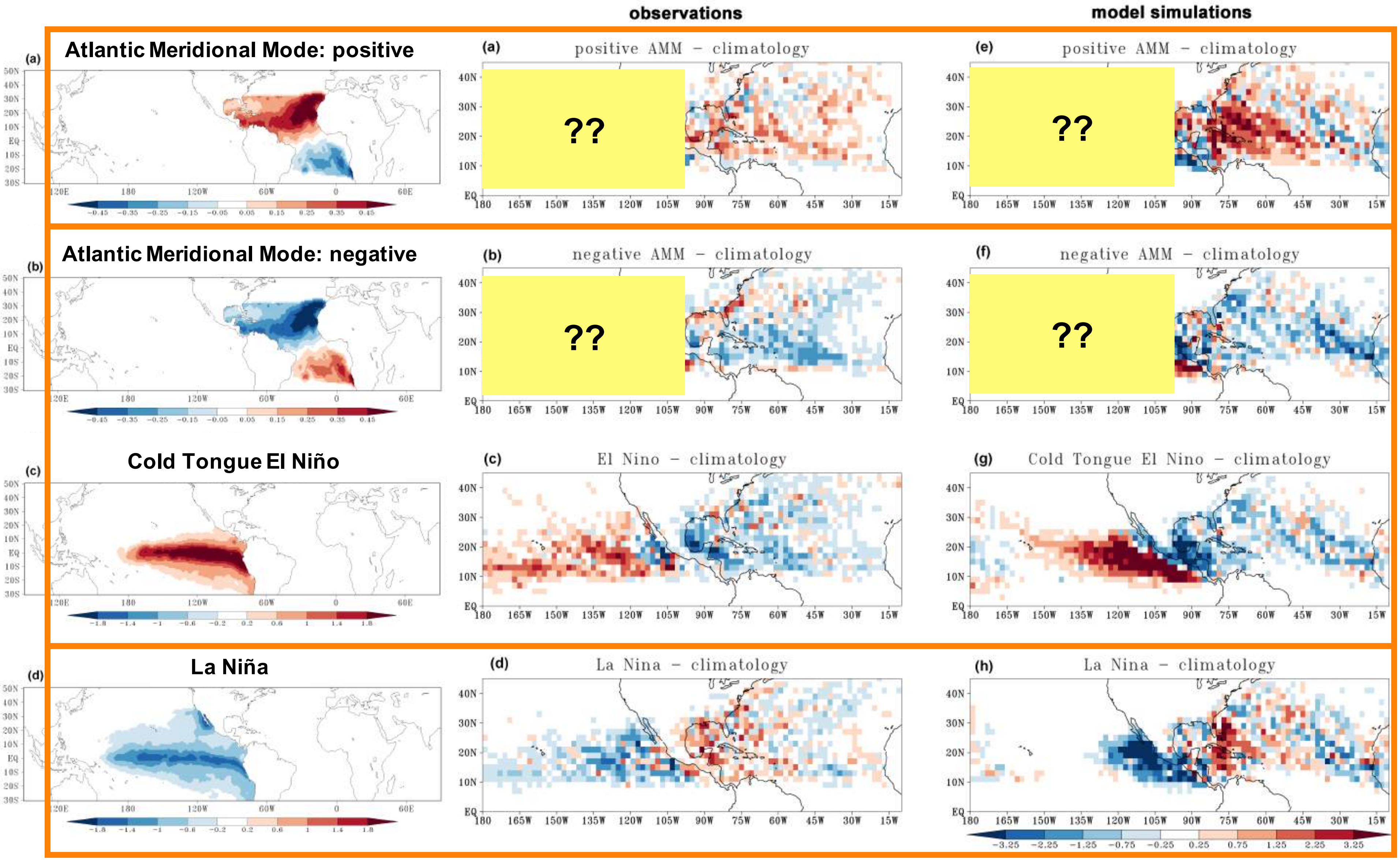
ENSO, AMM, and TC track density



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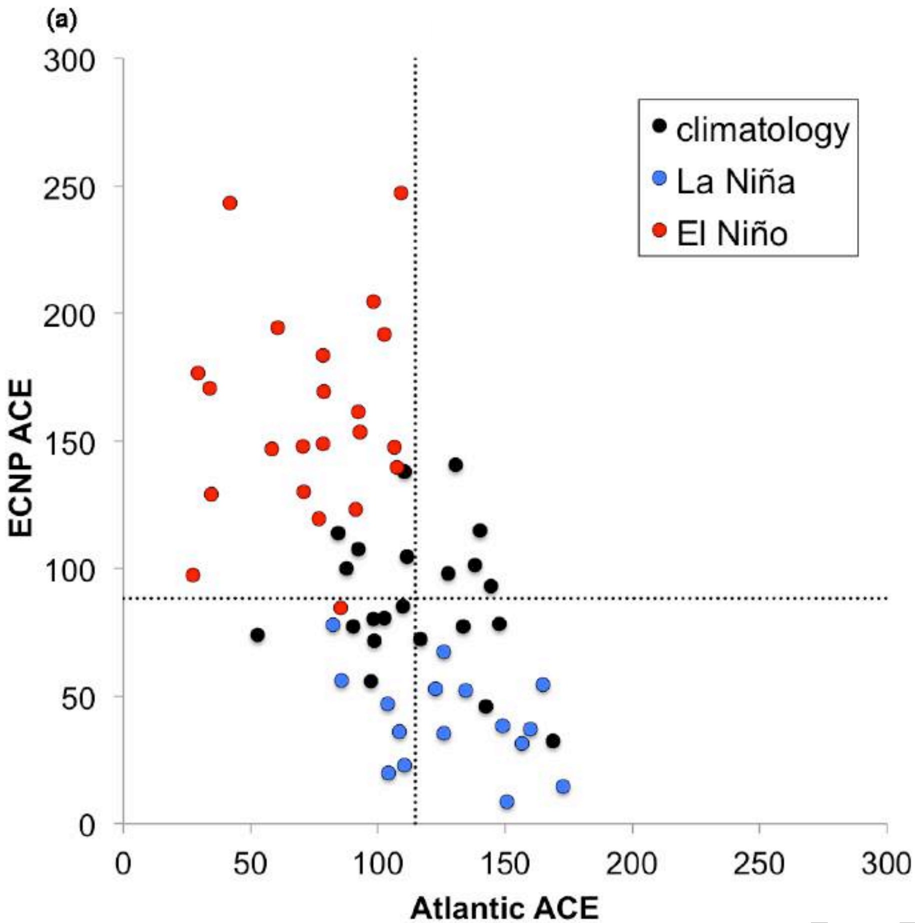
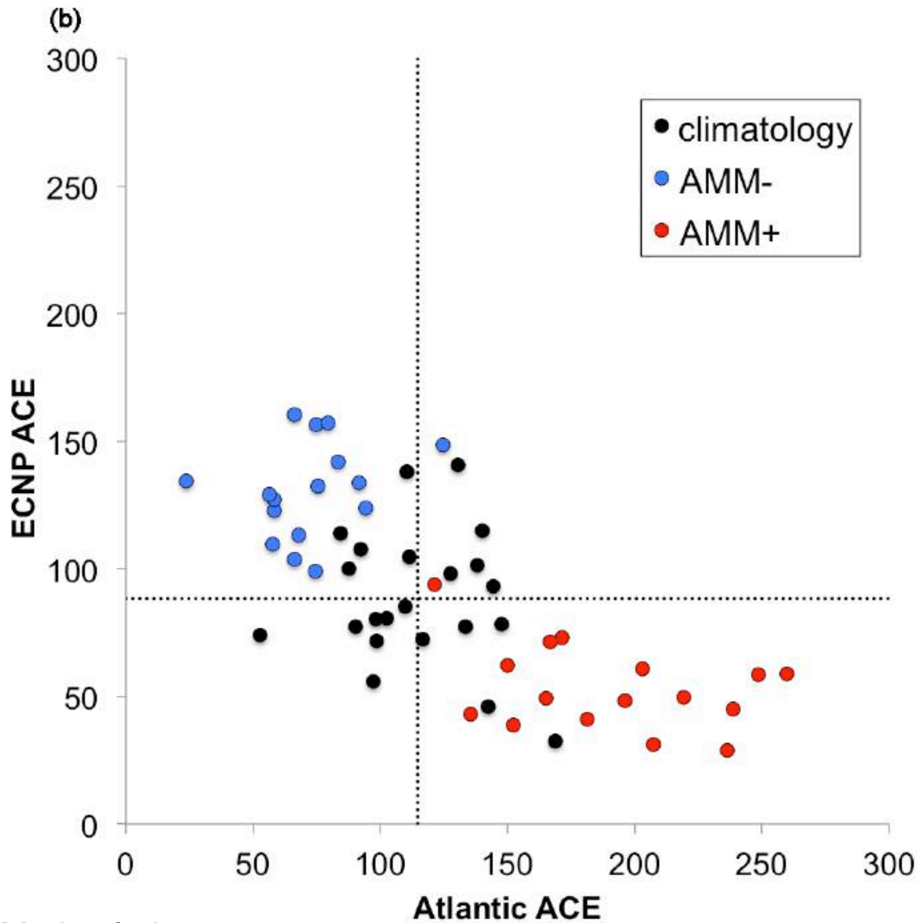
Seasonal TC / SST relationships

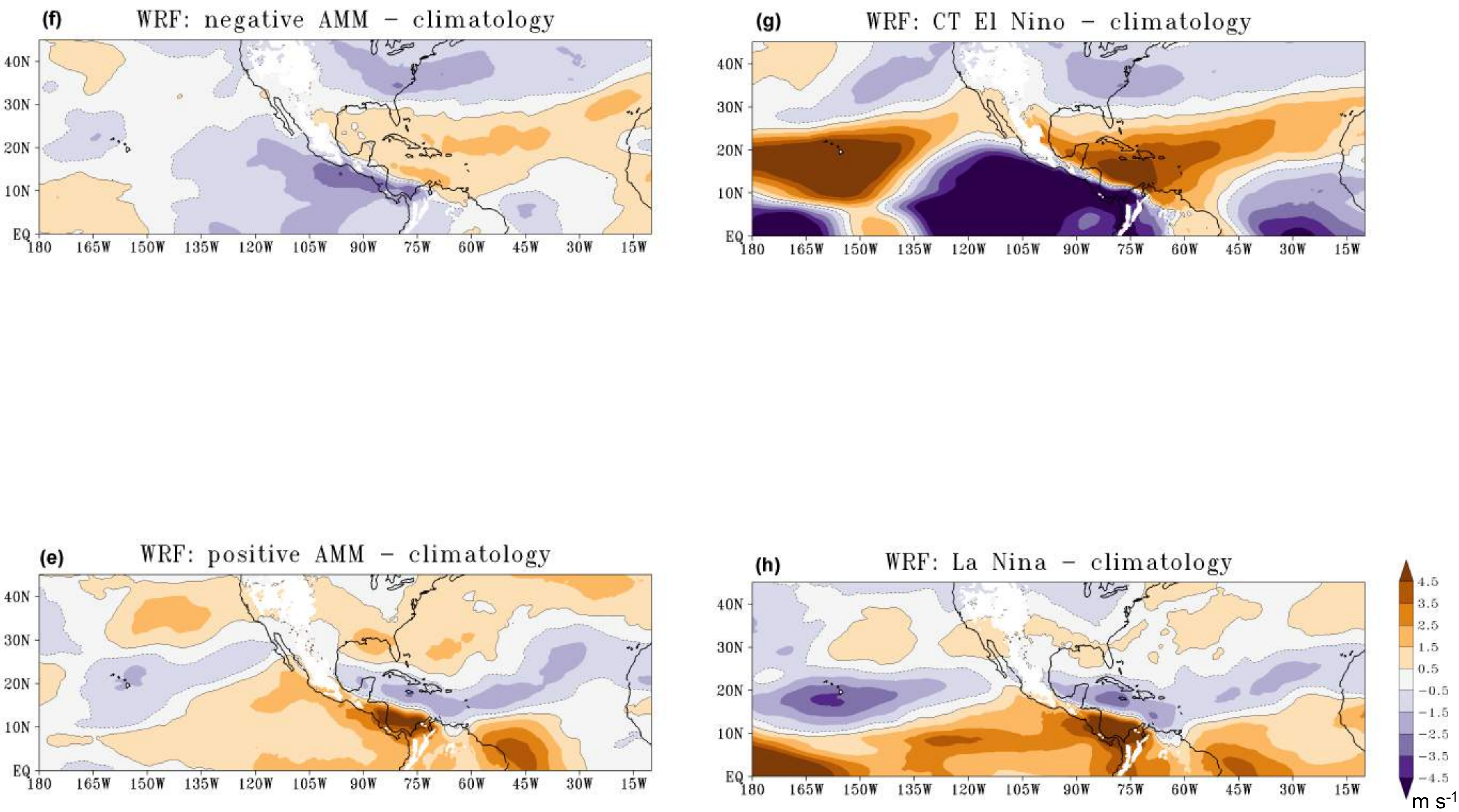
- Anti-correlation in Atlantic and East-central Pacific TC seasons associated with Atlantic Meridional Mode and ENSO





From TCM simulations

Teleconnection mechanism: vertical wind shear



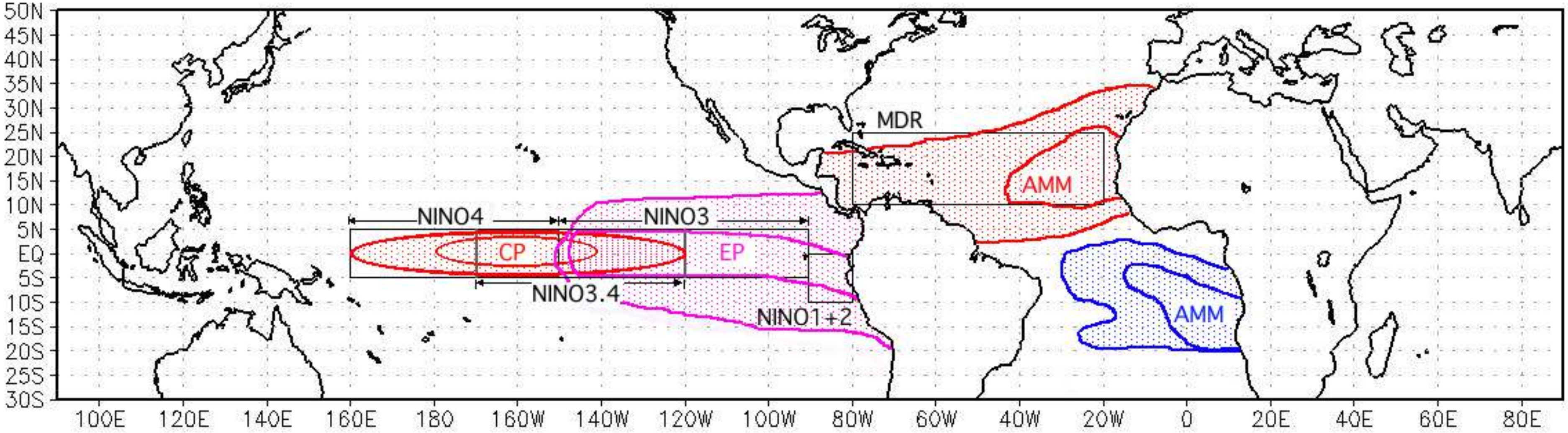
Summary

- Discovered a teleconnection between tropical Atlantic SST and seasonal East Pacific TC activity
  - Positive AMM suppresses East Pacific TC activity, and vice versa

- Physical mechanism is in many ways analogous to the Walker Circulation response associated with ENSO-Atlantic TC teleconnection

Implications

- Future TC projections require knowledge of location and intensity of El Niño, and the joint distribution of Atlantic and Pacific SSTs
- Climatological mean SST changes are insufficient.



Preview:

Anthropogenic Influences on TC Intensity and Rainfall

Patricola, Wehner, and Stone (2017) *In prep.*

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Question

Investigate "worst-case scenario" TC events using convection-resolving climate model experiments:

- How would intensity and rainfall change if TCs like actual destructive events happened in a warmer world?
  - 13 TCs, representing all ocean basins, under multiple emissions scenarios

Fairly robust TC intensification under RCP4.5+

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Maximum 10-m wind speed (kt)

Basin	TC	RCP45	RCP60	RCP85
Atlantic	Andrew			
	Bob	-6.1		
	Floyd	11.2	13.5	
	Gilbert	18.0	18.6	28.8
	Ike	12.8	14.1	18.0
	Katrina	6.0	8.5	13.8
	Matthew	10.6	11.1	15.8
Eastern Pacific	Iniki			
NW Pacific	Haiyan	6.7		12.3
	Morakot			
	Songda	10.4	5.5	
South Pacific	Yasi	11.2	13.7	18.9
SW Indian	Gafilo	8.6	8.8	16.8

Minimum sea-level pressure (hPa)

Basin	TC	RCP45	RCP60	RCP85
Atlantic	Andrew			
	Bob	3.1	1.7	7.8
	Floyd	-12.3	-14.9	
	Gilbert	-17.6	-15.2	-20.8
	Ike	-15.2	-17.6	-21.7
	Katrina	-7.7	-7.6	-8.7
	Matthew	-12.5	-12.8	-17.0
Eastern Pacific	Iniki			-7.2
NW Pacific	Haiyan	-12.0	-11.9	-20.6
	Morakot			
	Songda	-12.1	-4.7	
South Pacific	Yasi	-9.9	-11.7	-17.7
SW Indian	Gafilo	-15.4	-12.5	-24.6

Ensemble mean changes:
White = no significant change (5% level)
Grey = large deviation in TC track from actual
Red = more intense
Blue = less intense

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Acknowledgements

- **National Science Foundation**
  - Award: AGS-1347808
- **U.S. Department of Energy**
  - Office of Science, Office of Biological and Environmental Research, Climate and Environmental Sciences Division, Regional & Global Climate Modeling Program (Award Number DE-AC02-05CH11231)

- Supercomputing resources provided by:
  - **Texas Advanced Computing Center (TACC)**
    - at the University of Texas at Austin, in conjunction with the Extreme Science and Engineering Discovery Environment (XSEDE), which is supported by National Science Foundation grant ACI-1053575
  - **Texas A&M Supercomputing Center**
  - **National Energy Research Scientific Computing Center (NERSC)**
    - A DOE Office of Science User Facility supported by the Office of Science of the U.S. Department of Energy (Contract No. DE-AC02-05CH11231)

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Extras

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Anthropogenic Influences on TC Intensity and Rainfall

Patricola, Wehner, and Stone (2017) *In prep.*

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Motivation

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How has climate change *so far* influenced tropical cyclone activity?

- No detectable trend in TC number
- Trends in TC intensity inconclusive

How is climate change expected to influence *future* TC activity?

- No consensus on global frequency
- Global models and theory suggest increase in intense TCs

[Landsea et al. 2006; Landsea et al. 2010; Vecchi and Knutson 2008; Emanuel 2005; Webster et al. 2005; Klotzbach 2006; Kossin et al. 2007; Broccoli and Manabe 1990; Haarsma et al. 1993; Sugi et al. 2002; Bengtsson et al. 2007; Gualdi et al. 2008; Knutson et al 2010; Emanuel 2013; Emanuel 1987; Knutson and Tuleya 2004; Bender et al. 2010; Hill and Lackmann 2011; Knutson et al. 2013; Lin and Chan 2015]

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Motivation

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Compensating influences of increasing greenhouse gas concentrations on TCs

- SST warming: intensify TCs
  - Ocean subsurface: may be dampening effect (Huang, Lin, et al. 2015)
- Greater warming of upper-troposphere: weaken TCs
- Tropopause cooling: strengthen maximum potential intensity
- Vertical wind shear changes: uncertain

Additional challenges:

- Observation quality issues
- Difficult for global models to represent extremely intense TCs
- Climate simulations rely on convective parameterization

CASCADE

Questions

Investigate "worst-case scenario" TC events using convection-resolving climate model experiments:

1) How did climate change (so far) influence Hurricane Katrina?

2) If a hurricane like Katrina occurred in the future, how would intensity and rainfall change?

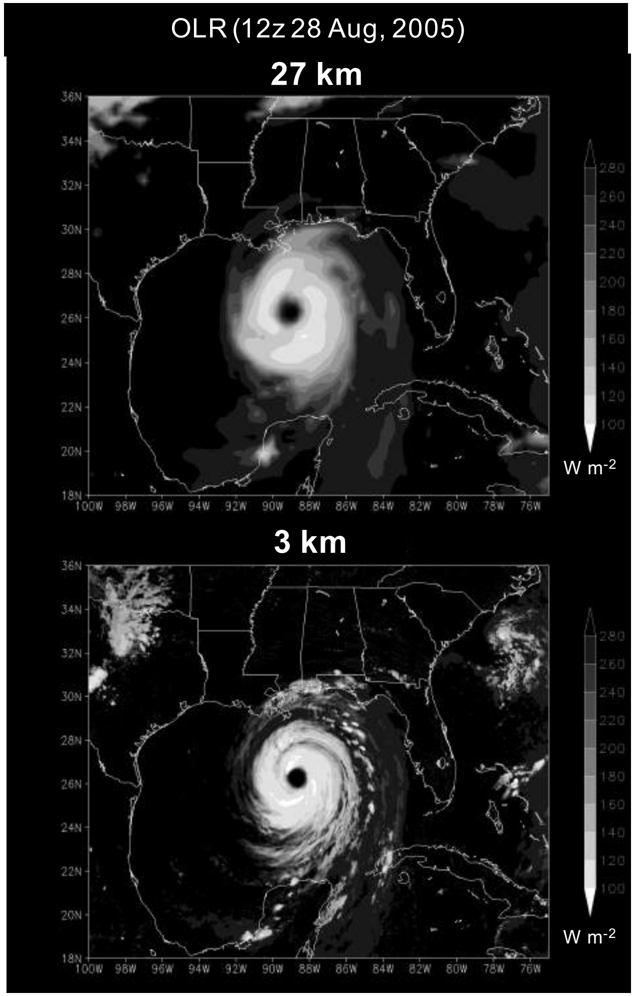
3) What is the uncertainty due to convective parameterization?

4) How would intensity and rainfall change if TCs like actual destructive events happened in a warmer world?
    - 15 TCs, representing all ocean basins, under multiple emissions scenarios

Regional climate model simulations: Katrina

Weather Research and Forecasting (WRF) Model

- Lateral boundary conditions: 6-hourly NCEP CFSR
- SST: 0.25º daily NOAA-OI
- 00z 27 August – 00z 31 August, 2005
- 10 member ensemble



Resolution	Cumulus parameterization
27 km	Kain-Fritsch
9 km	Kain-Fritsch
9 km	none
3 km	none

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Regional climate model simulations

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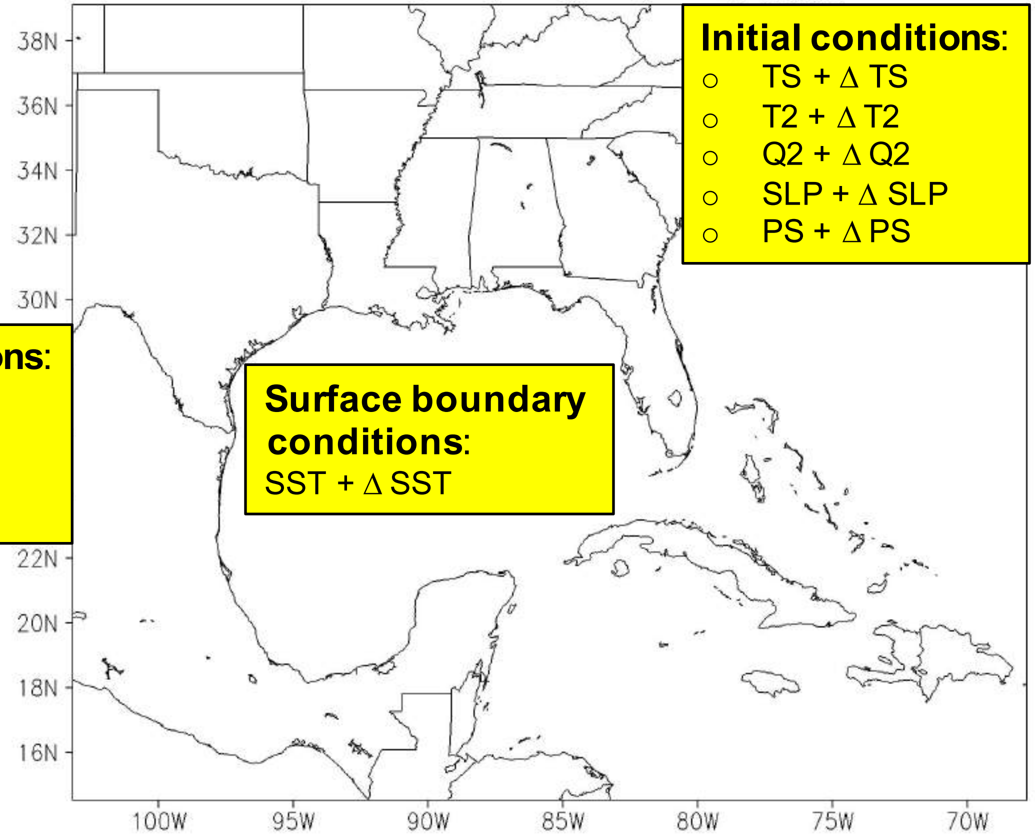
Experiments

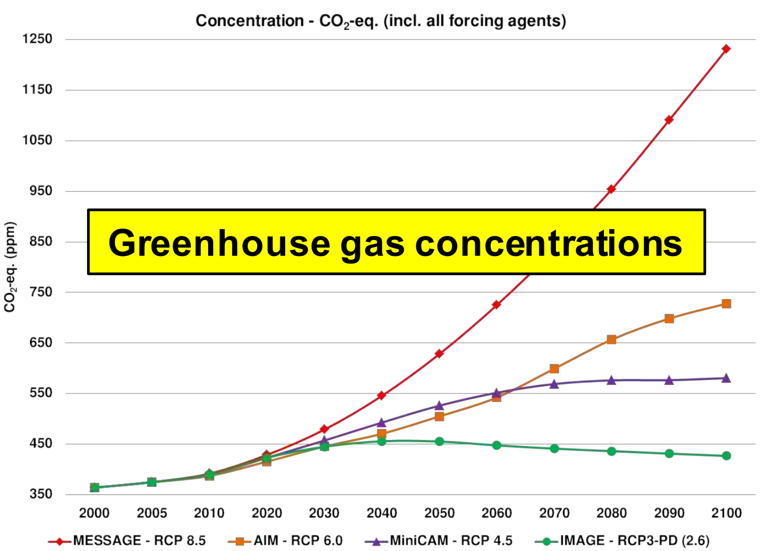
- **actual** (2005 hindcast)
- **natural** (preindustrial, CAM)
- **RCP8.5** (2081-2100, CCSM4)

Lateral boundary conditions:
- T + Δ T
- RH + Δ RH
- Z + Δ Z
- ~~U + ΔU; V + ΔV~~

Initial conditions:
- TS + Δ TS
- T2 + Δ T2
- Q2 + Δ Q2
- SLP + Δ SLP
- PS + Δ PS

Surface boundary conditions:
SST + Δ SST





Greenhouse gas concentrations

Hindcast methodology for conditional event attribution:
Pall, P., C.M. Patricola, M.F. Wehner, D.A. Stone, C. Paciorek, and W.D. Collins (2017) Diagnosing conditional anthropogenic contributions to heavy Colorado rainfall in September 2013. *Weather and Climate Extremes*

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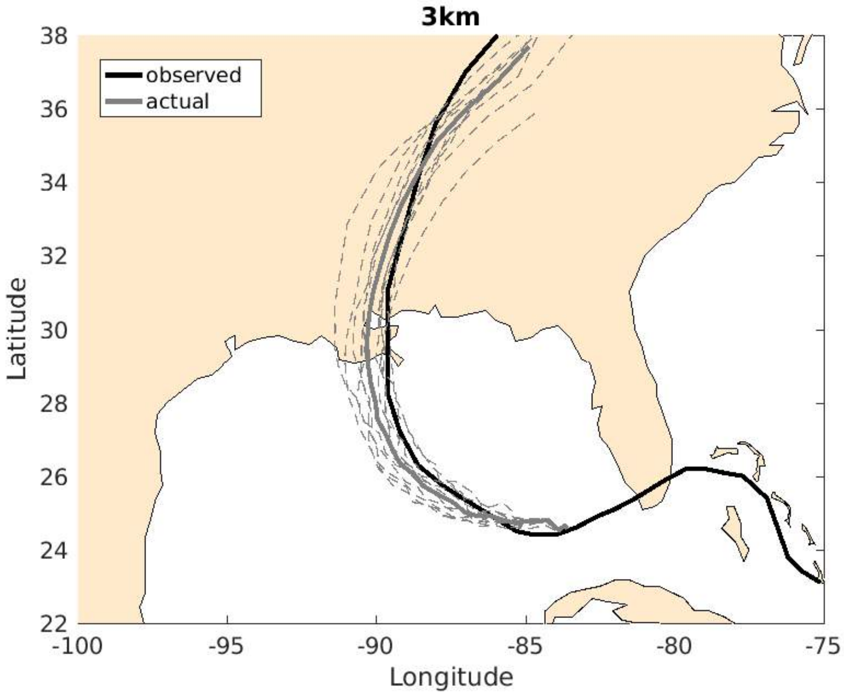
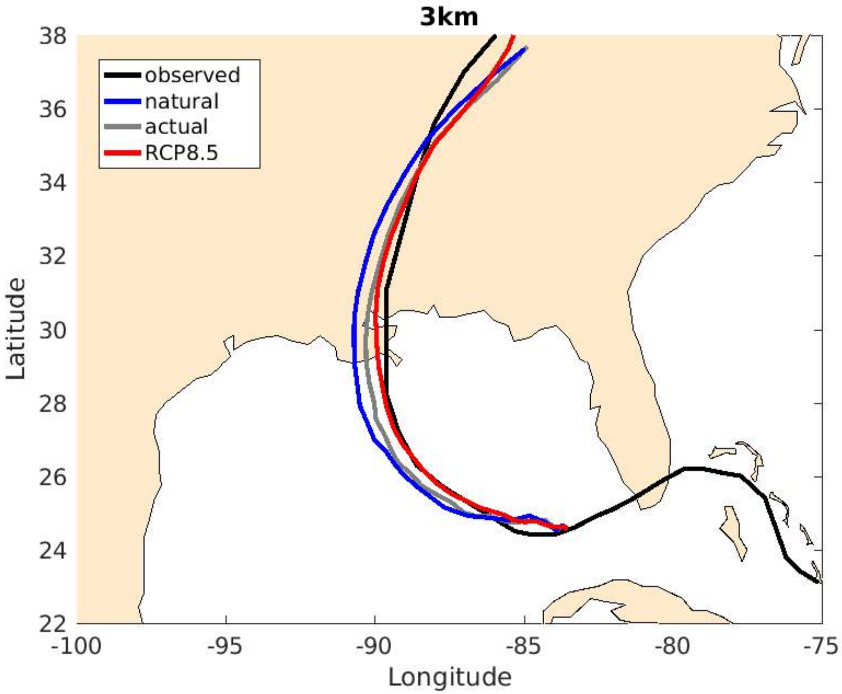
Hurricane Katrina tracks



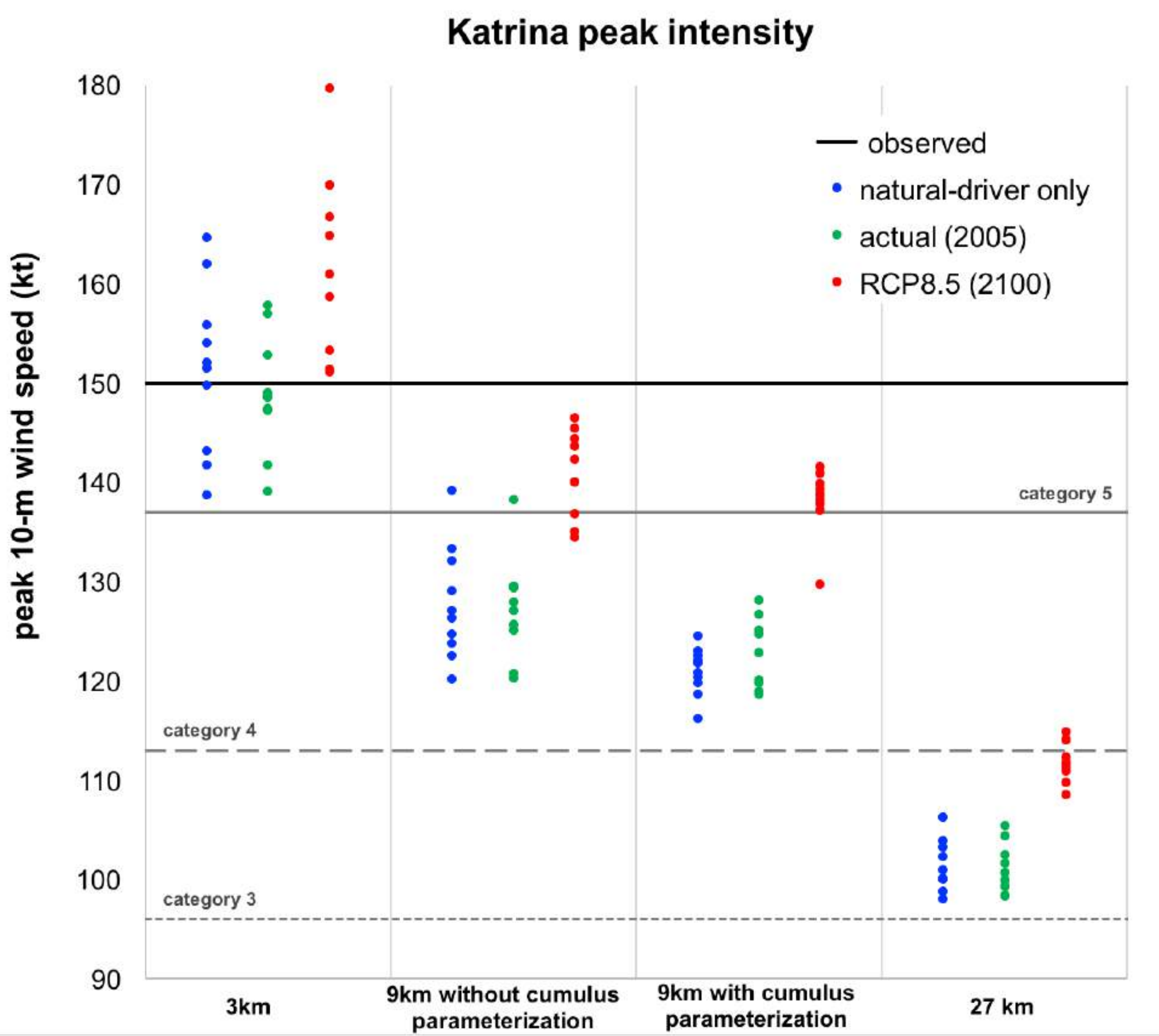
TC tracks in the 10-member ensemble "actual" hindcast deviate little from observations.



"natural" and "RCP8.5" TC tracks deviate little from "actual" hindcast

- Methodology is suitable for understanding anthropogenic influences on Hurricane Katrina.

Maximum 10-m wind speed



- Climate change (so far) had no significant influence on Katrina's simulated intensity.
- Katrina is expected to significantly intensify at the end of the century under RCP8.5.
- Use of convective parameterization has no influence on the sign of the intensity response.

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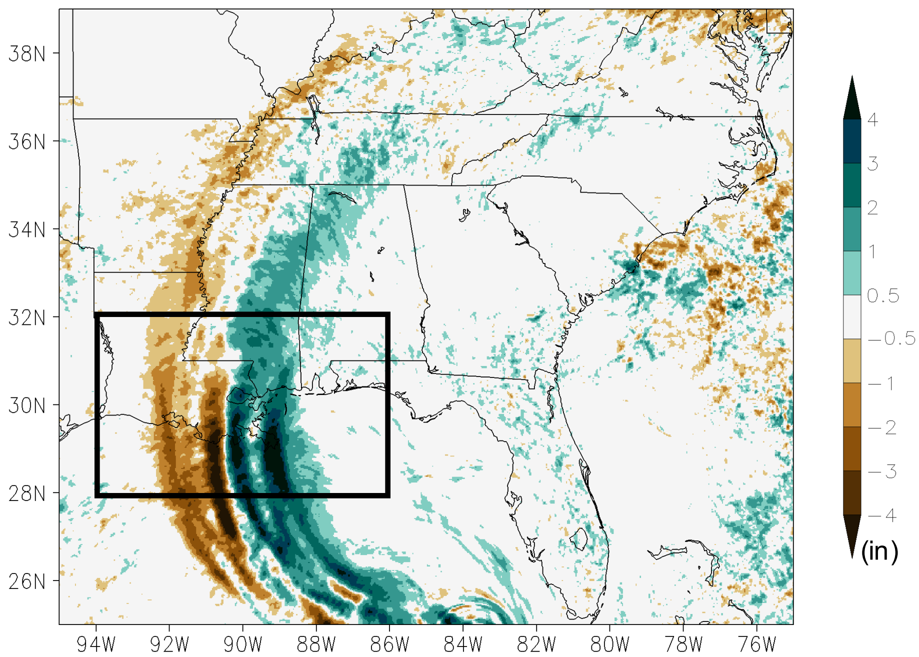
Precipitation

BERKELEY LAB

actual – natural
Accumulated precipitation (00z 27 Aug – 00z 31 Aug)



- Small track deviations impact spatial distribution of rainfall → quantify area-averages

	natural → actual	actual → RCP8.5	natural → RCP8.5
3 km	**6.6%**	**6.4%**	**13.9%**
9 km no CU	4.1%	**7.0%**	**11.6%**
9 km CU	3.9%	3.2%	**7.3%**
27 km	**4.4%**	**7.0%**	**11.7%**

Ensemble mean changes, bold where significant at 15% level

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Regional climate model simulations

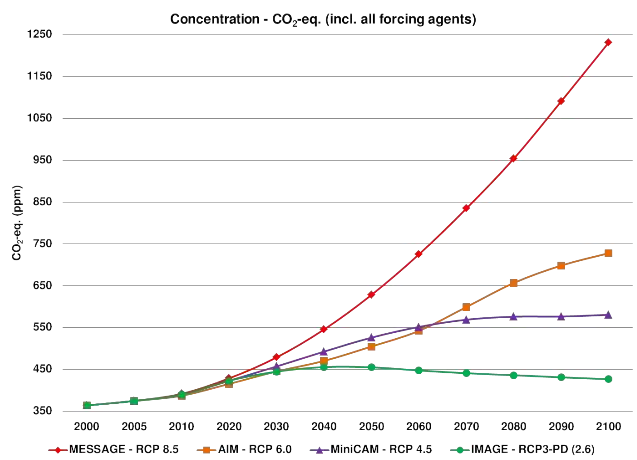
BERKELEY LAB

Weather Research and Forecasting (WRF) Model

- 10 member ensemble
- 4.5 km resolution (no cumulus param.)
- 44 levels in the vertical; model top at 20 hPa

Experiments

- actual
- RCP4.5 (CCSM4 2081-2100)
- RCP6.0
- RCP8.5



13 of 15 candidate events

Basin	TC	Landfall
Atlantic	Andrew	Florida, Gulf of Mexico
	Bob	New England
	Floyd	US east coast
	Gilbert	Mexico
	Ike	Texas, Caribbean
	Katrina	Gulf of Mexico
	Matthew	Caribbean
Eastern Pacific	Iniki	Hawaii
NW Pacific	Haiyan	Philippines
	Morakot	Taiwan
	~~Saomai~~	China
	Songda	Japan
South Pacific	Yasi	Australia
North Indian	~~Odisha~~	India
SW Indian	Gafilo	Madagascar

Complicated by Fujiwhara → (Saomai)

Numerical instability (Tibetan Plateau) → (Odisha)

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Fairly robust TC intensification under RCP4.5+

Maximum 10-m wind speed (kt)

Basin	TC	RCP45	RCP60	RCP85
Atlantic	**Andrew**			
	Bob	-6.1		
	Floyd	11.2	13.5	
	Gilbert	18.0	18.6	28.8
	Ike	12.8	14.1	18.0
	Katrina	6.0	8.5	13.8
	Matthew	10.6	11.1	15.8
Eastern Pacific	**Iniki**			
NW Pacific	**Haiyan**	6.7		12.3
	Morakot			
	Songda	10.4	5.5	
South Pacific	**Yasi**	11.2	13.7	18.9
SW Indian	**Gafilo**	8.6	8.8	16.8

Minimum sea-level pressure (hPa)

Basin	TC	RCP45	RCP60	RCP85
Atlantic	**Andrew**			
	Bob	3.1	1.7	7.8
	Floyd	-12.3	-14.9	
	Gilbert	-17.6	-15.2	-20.8
	Ike	-15.2	-17.6	-21.7
	Katrina	-7.7	-7.6	-8.7
	Matthew	-12.5	-12.8	-17.0
Eastern Pacific	**Iniki**			-7.2
NW Pacific	**Haiyan**	-12.0	-11.9	-20.6
	Morakot			
	Songda	-12.1	-4.7	
South Pacific	**Yasi**	-9.9	-11.7	-17.7
SW Indian	**Gafilo**	-15.4	-12.5	-24.6

<u>Ensemble mean changes:</u>
White = no significant change (5% level)
Grey = large deviation in TC track from actual
Red = more intense
Blue = less intense

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Summary

- Climate change to date:
  - no significant influence on Katrina's simulated intensity
  - significantly enhanced rainfall (at 3 km resolution)

- Use of convective parameterization has no influence on the sign of Katrina's intensity response
  - ➢ Provides support for global model projections

Strong support for robust future intensification of extreme TC events globally

- 9 of 13 TCs significantly intensify under RCP4.5+

- TCs that did not significantly intensify were relatively weak in the "actual" simulation (owing to being weak in reality, or to model bias)

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