Climate Factors Influencing Hurricane Landfall

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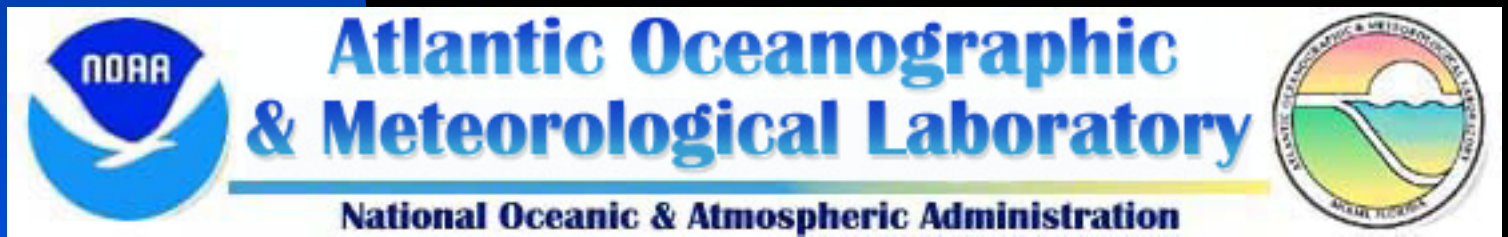
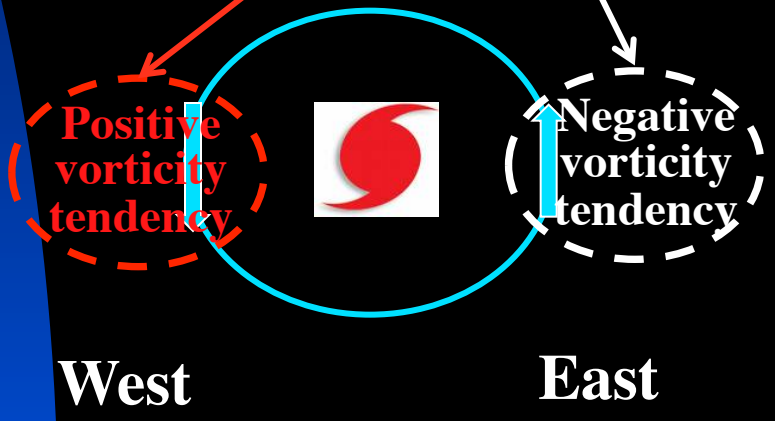


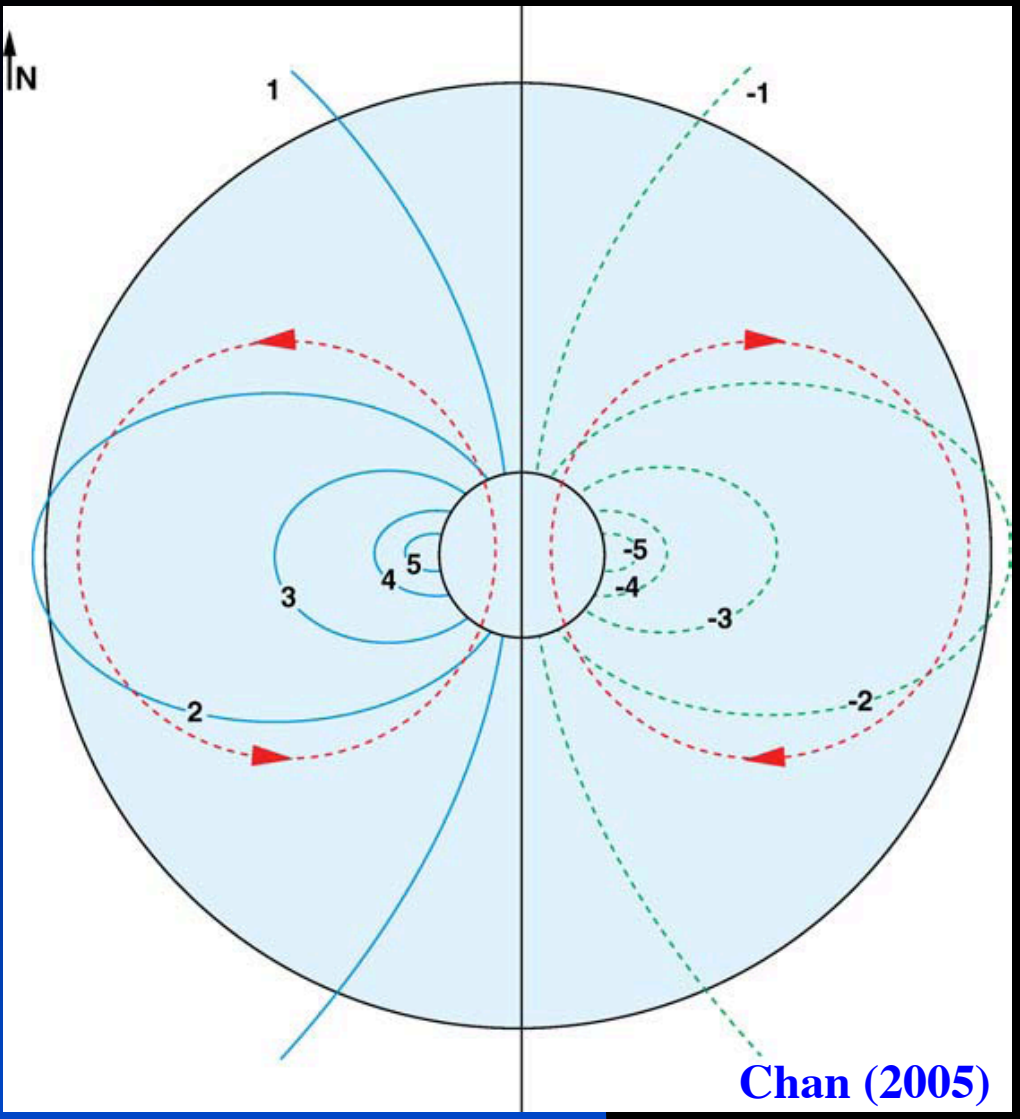
Why do TCs (hurricanes) move northwestward in N. H.?

- Linear beta drift.
- Environmental steering flow.

$$\frac{\partial \zeta}{\partial t} = -\vec{V} \bullet \nabla \zeta - \beta V$$



Why do TCs (hurricanes) move northwestward in N. H.?



- Due to the β-effect, positive (negative) vorticity tendency is generated in the west (east).
- This sets up a "secondary circulation" (red color) that tends to advect TC poleward.
- Combined result is to drive TC northwestward.

TC Steering Flow

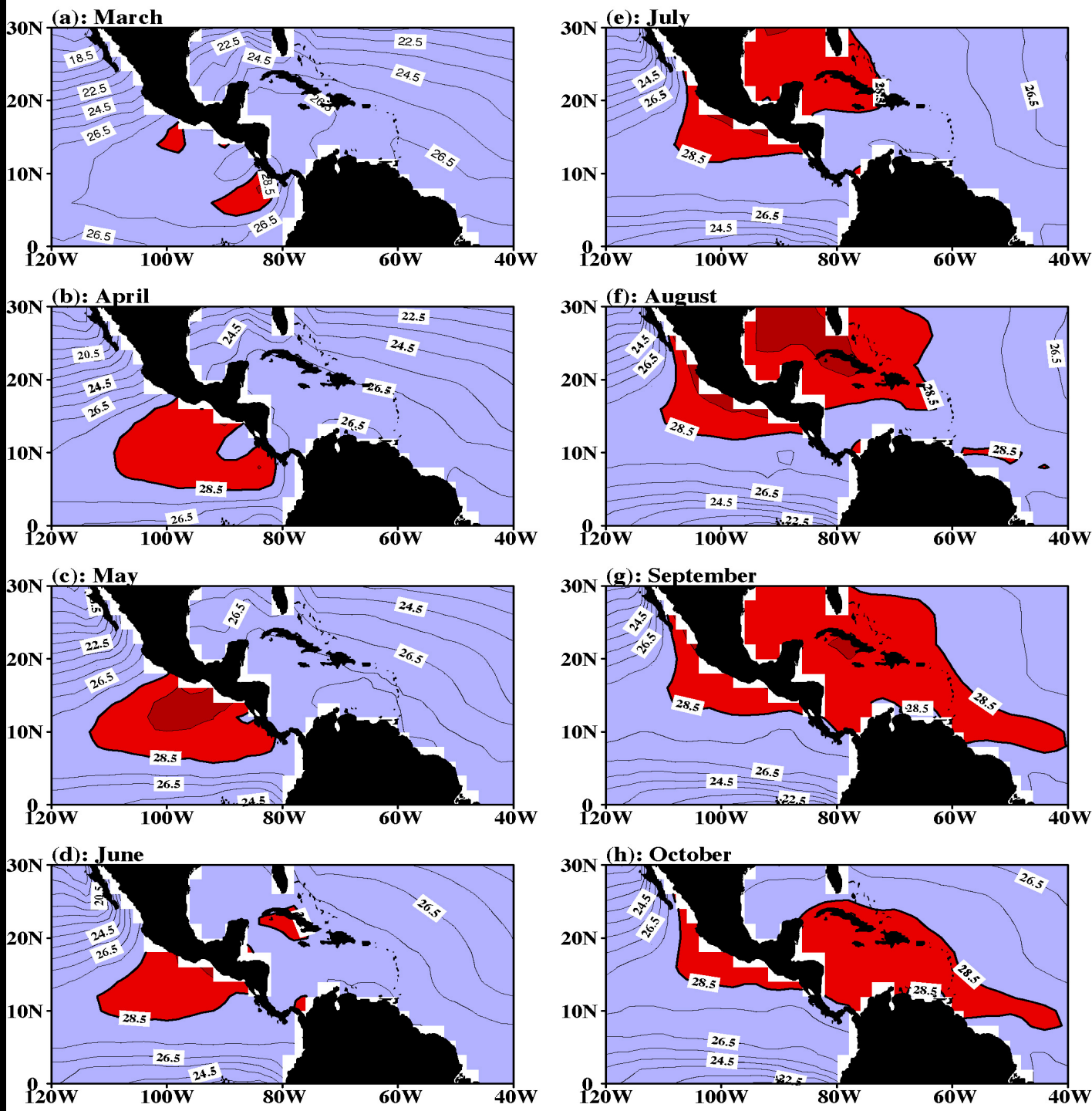
North Atlantic subtropical high (NASH) plays an important role for the TC track; but what controls the NASH?

Analogy: The movement of a TC is like a leaf being steered by the currents in the stream, except that for a TC the stream has no set boundaries.

Wang & Enfield (2001, *GRL*) named the Western Hemisphere warm pool (WHWP)

SST ≥ 28.5°C

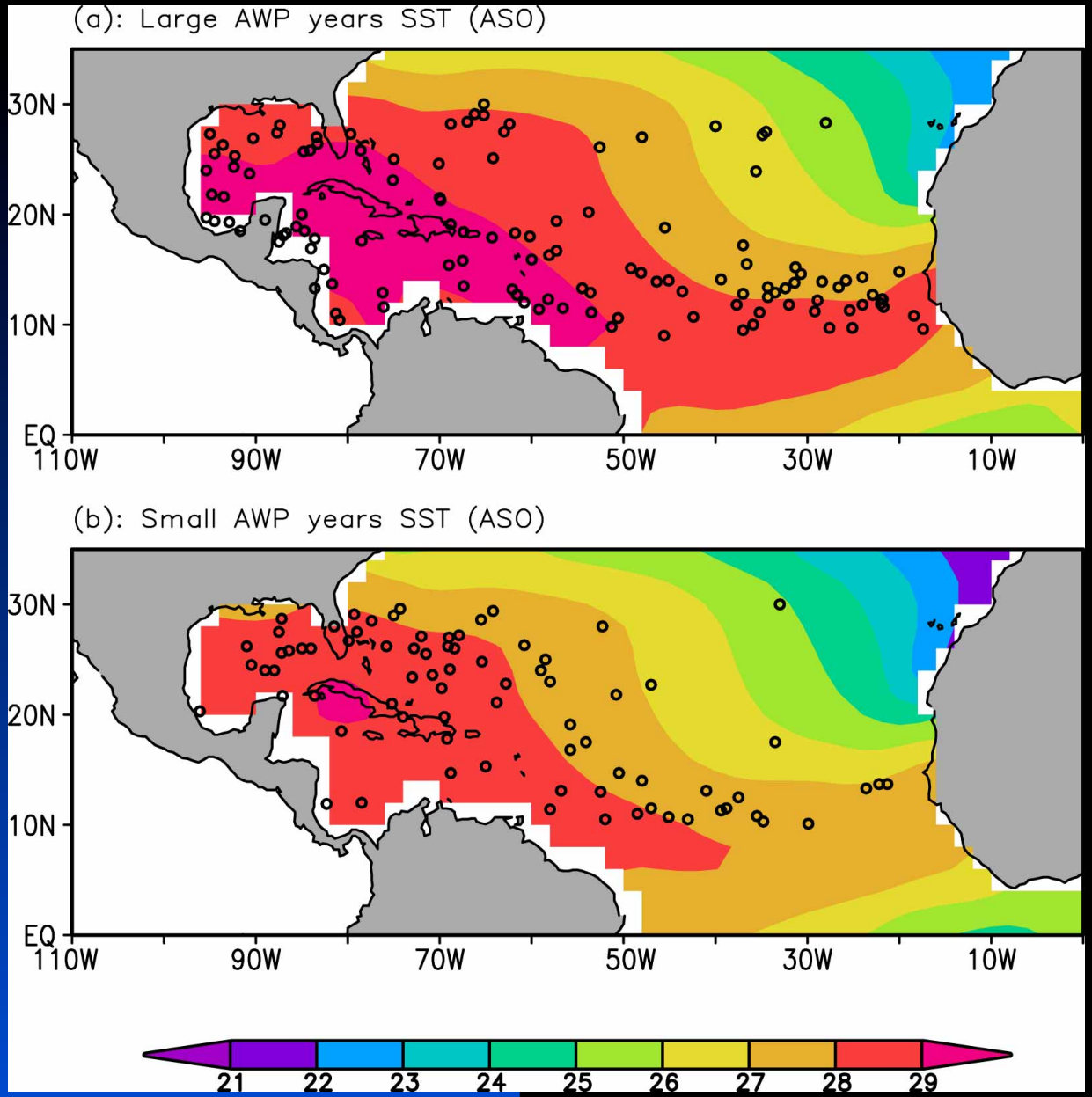
We focus on the Atlantic side of WHWP (AWP).



Impact of the AWP on the TC track via two ways:

- AWP variability changes the TC genesis location and then the TC track.
- AWP variability induces the changes of atmospheric circulation pattern to influence the TC track.

AWP-related shift of the TC genesis location



Large AWPs (126 TCs)

- **Large AWPs increase the number of TCs.**
- **More TCs form east of 40°W in large AWP years, which decreases landfall possibility.**

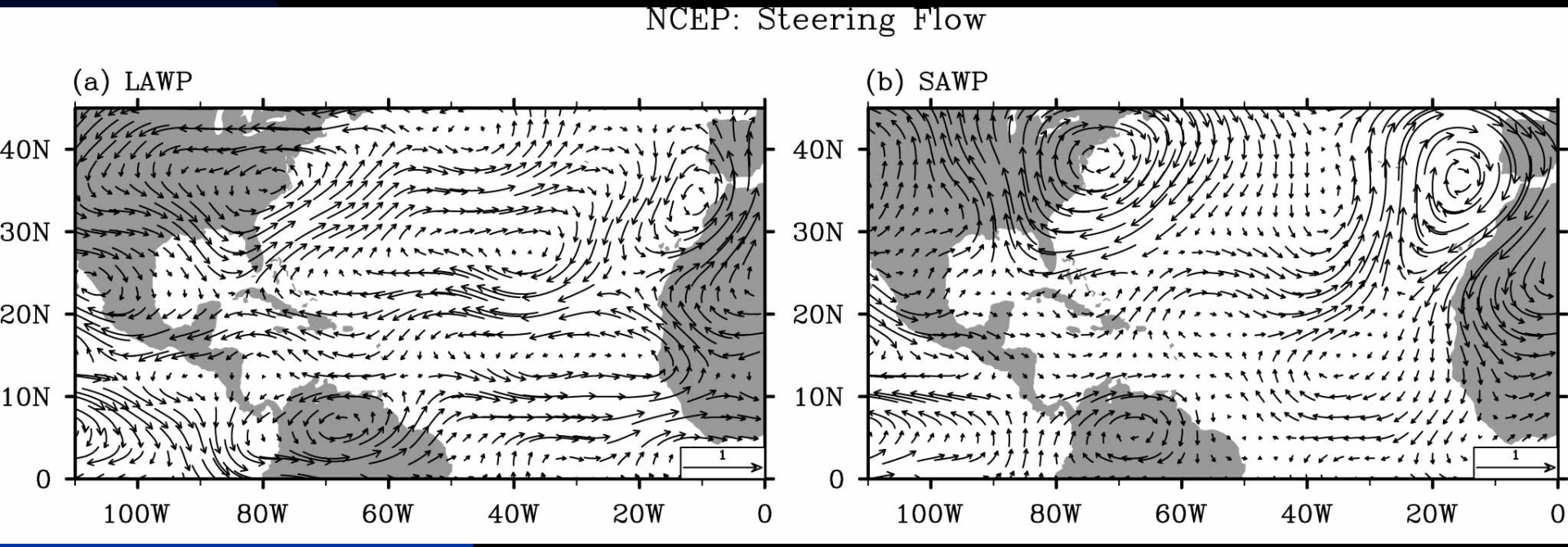
Small AWPs (79 TCs)

Hurricanes formed in the MDR during 1970-2009

	Hurricanes	Landfalling Hurricanes	Ratio
10 Large AWPs	31	7	0.23
10 Small AWPs	13	5	0.38

- Large AWPs increase the number of hurricanes in the MDR (main development region).
- Large AWPs decrease the ratio of U. S. landfalling hurricanes by 40%.

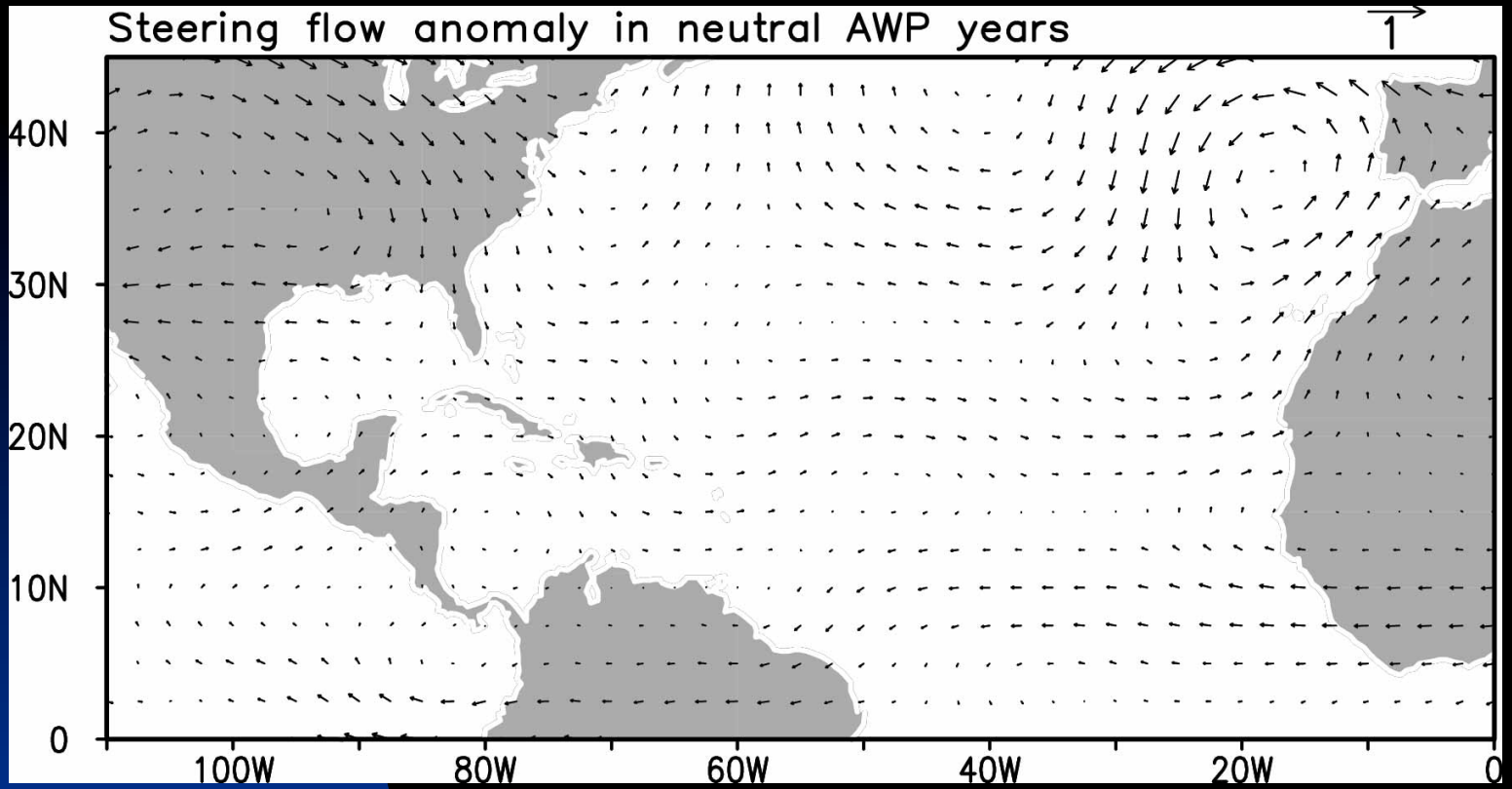
The observed TC steering flow and AWP variability (1970-2009): The AWP-induced eastward/northeastward flow anomalies steer TCs away from the U. S.



10 large AWP years

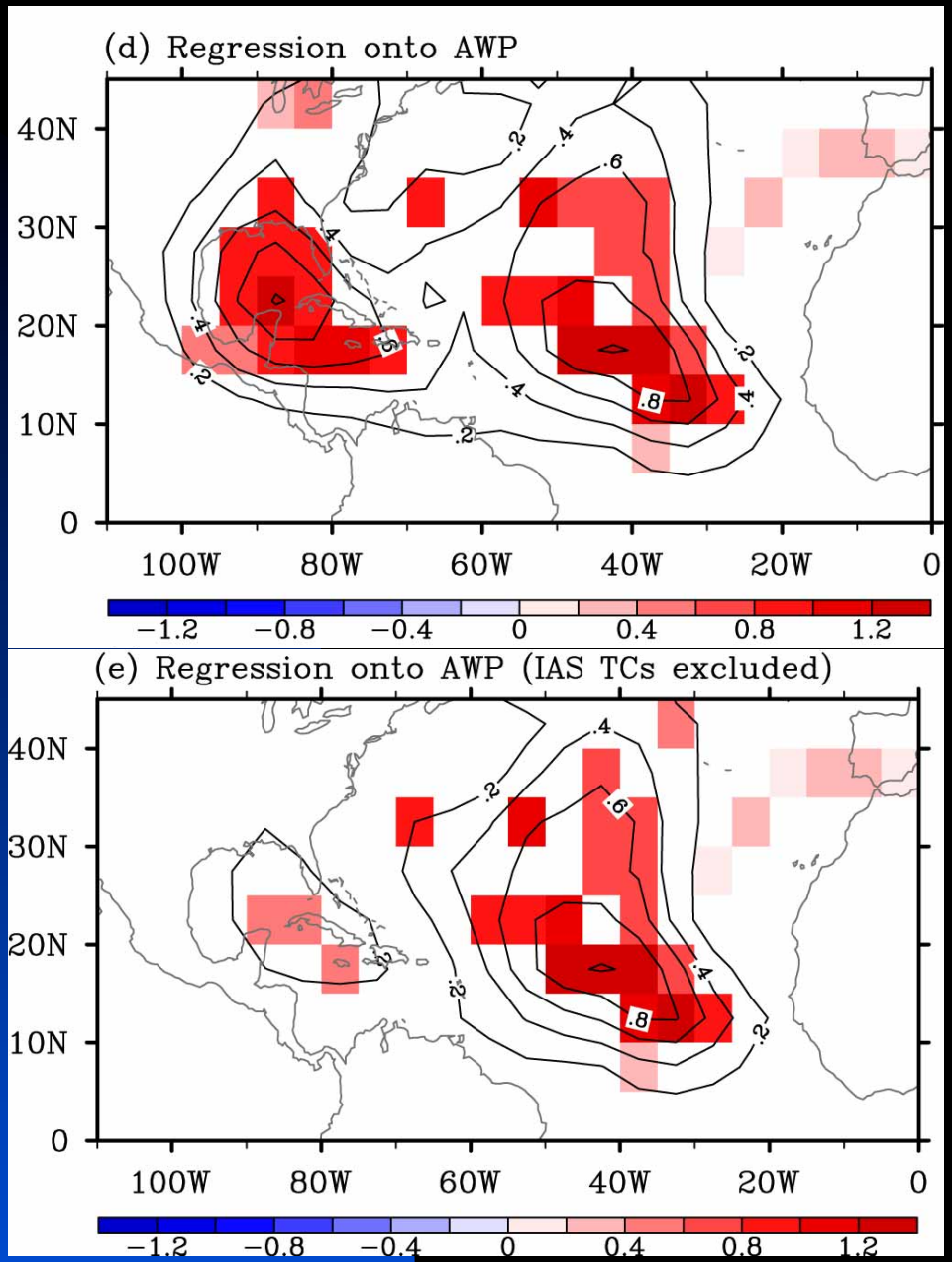
10 small AWP years

The TC steering flow is defined as an integrated flow from 850-hPa to 200-hPa.



The TC steering flow anomalies in neutral AWP years are very small in comparison with large/small AWP years, indicating that AWP variability plays a key role for the TC steering flow change.

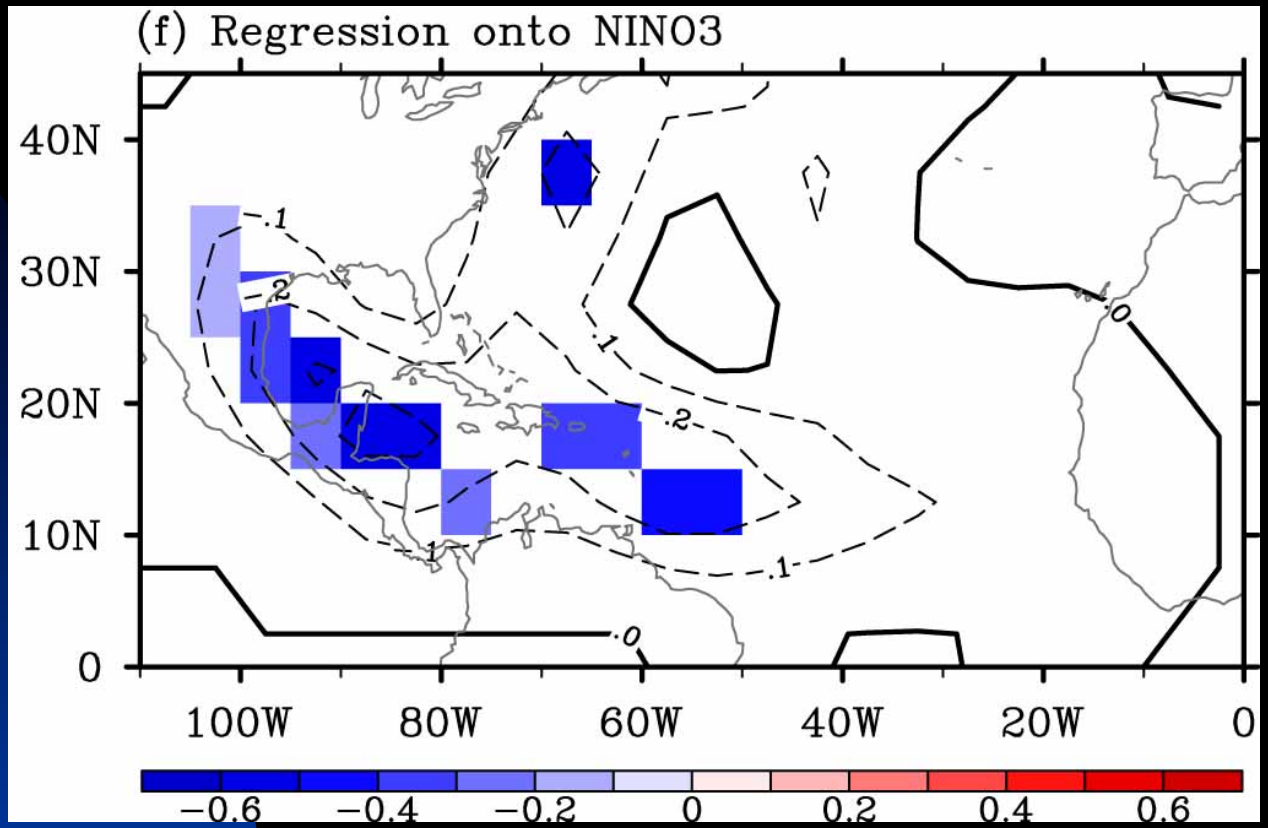
Impact of the AWP on the TC track



- Regression is positive everywhere, consistent with that a large (small) AWP increases (decreases) TC activity overall (Wang et al. 2006, *JC*).
- Two maxima.
- Orientation is in a south-to-north direction far away from the U. S., indicating a northward track.

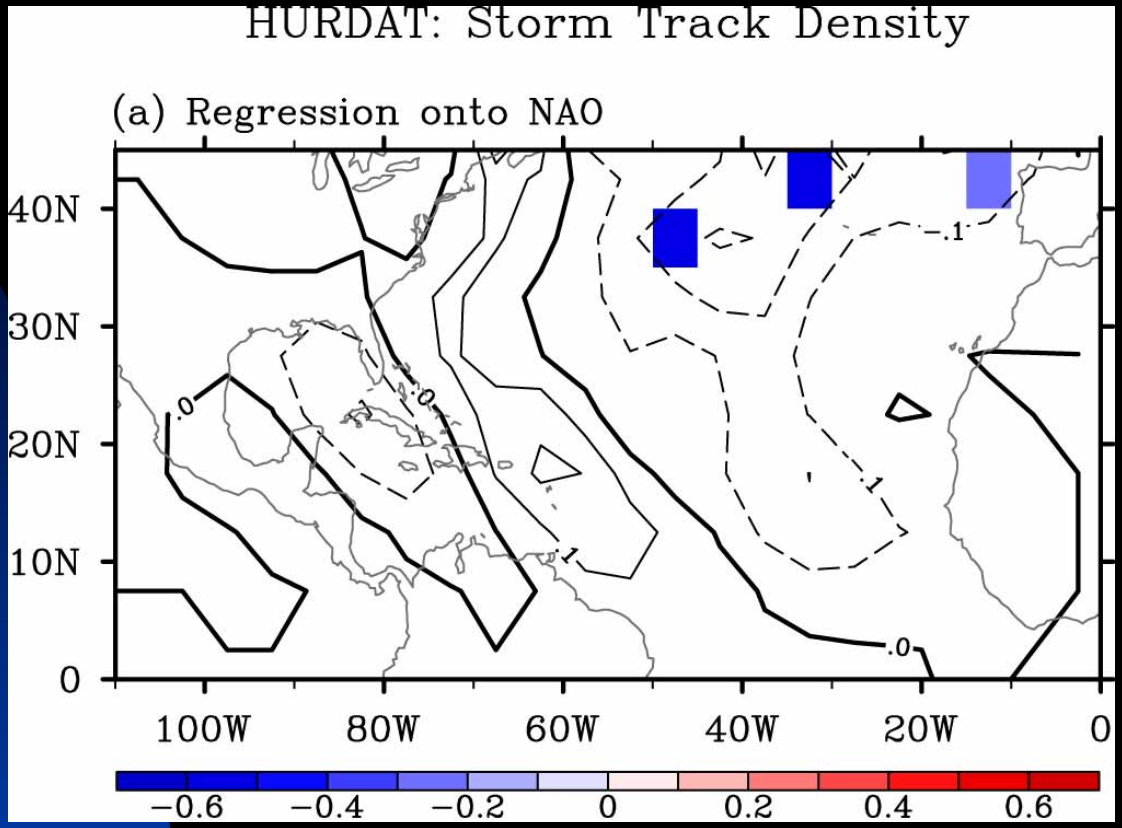
Exclude TCs that form locally in the Intra-Americas Sea (IAS; (normally during early and late season)

Impact of ENSO on the TC track



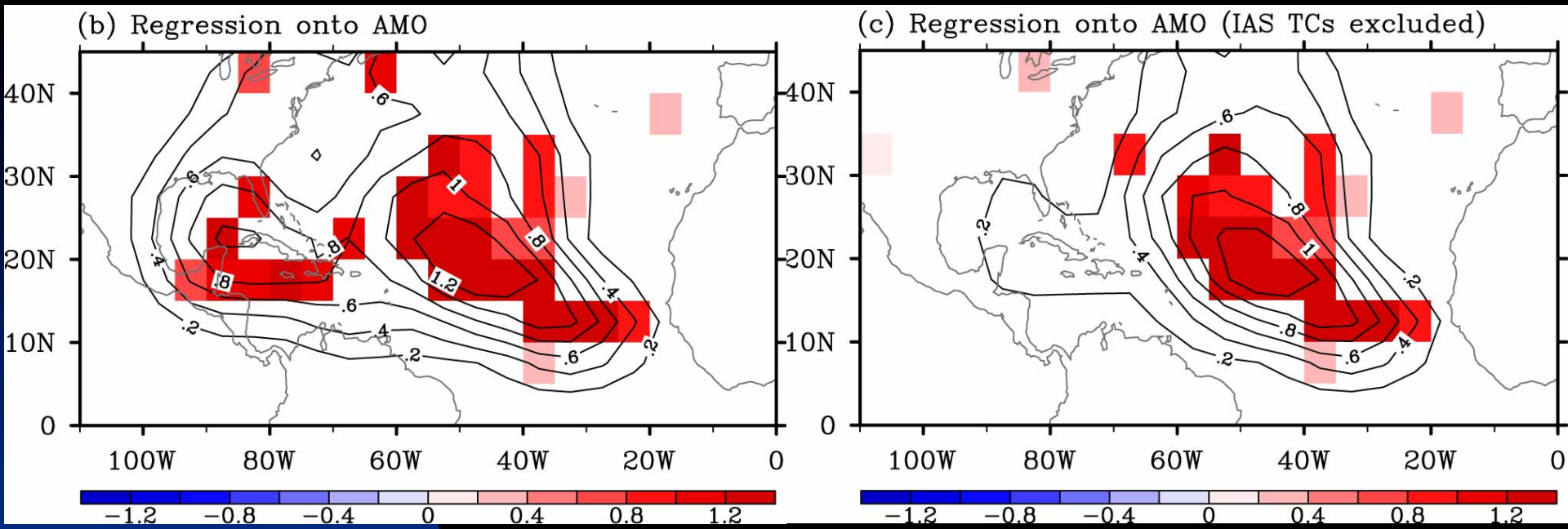
La Niña (El Niño) tends to enhance (suppress) the possibility for a TC to make landfall in Central America, Caribbean Islands and the southeastern U. S.

Impact of the NAO on the TC Track



The regression is not statistically significant.

Impact of the AMO on the TC Track

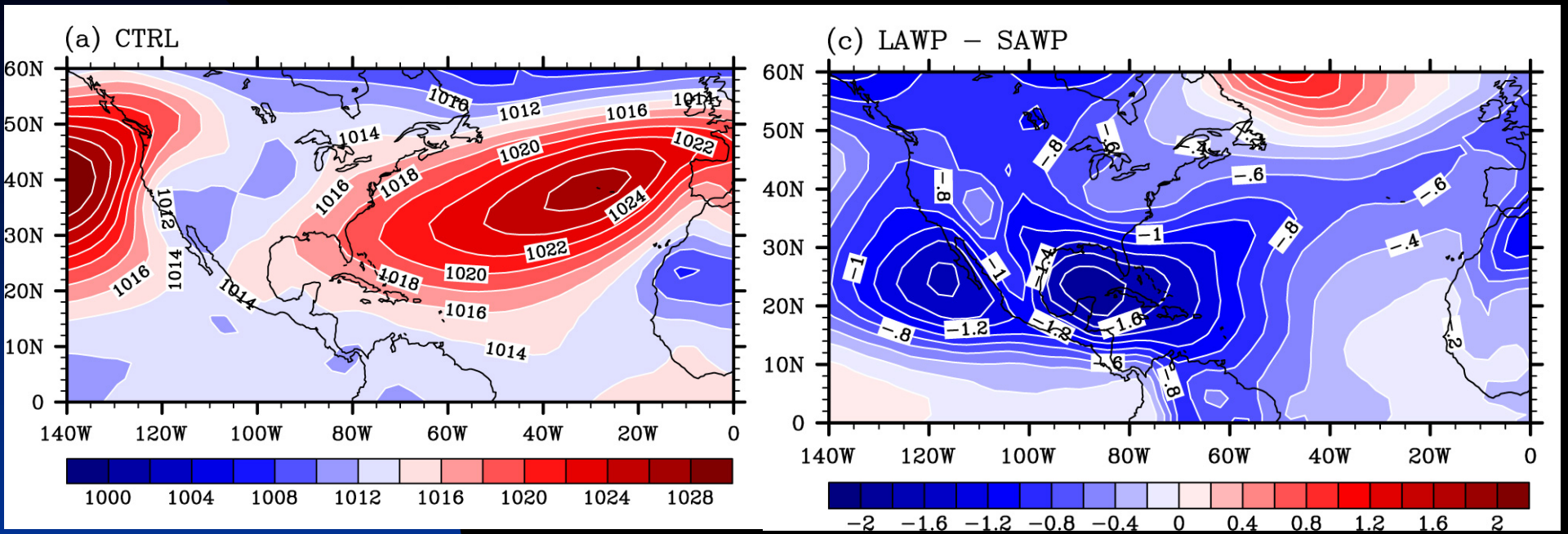


Exclude TCs that form in the IAS

The patterns are similar to those by the AWP, indicating that influence of the AMO operates via the AWP-induced mechanisms, which is consistent with Wang et al. (2008, *G*^{3}).

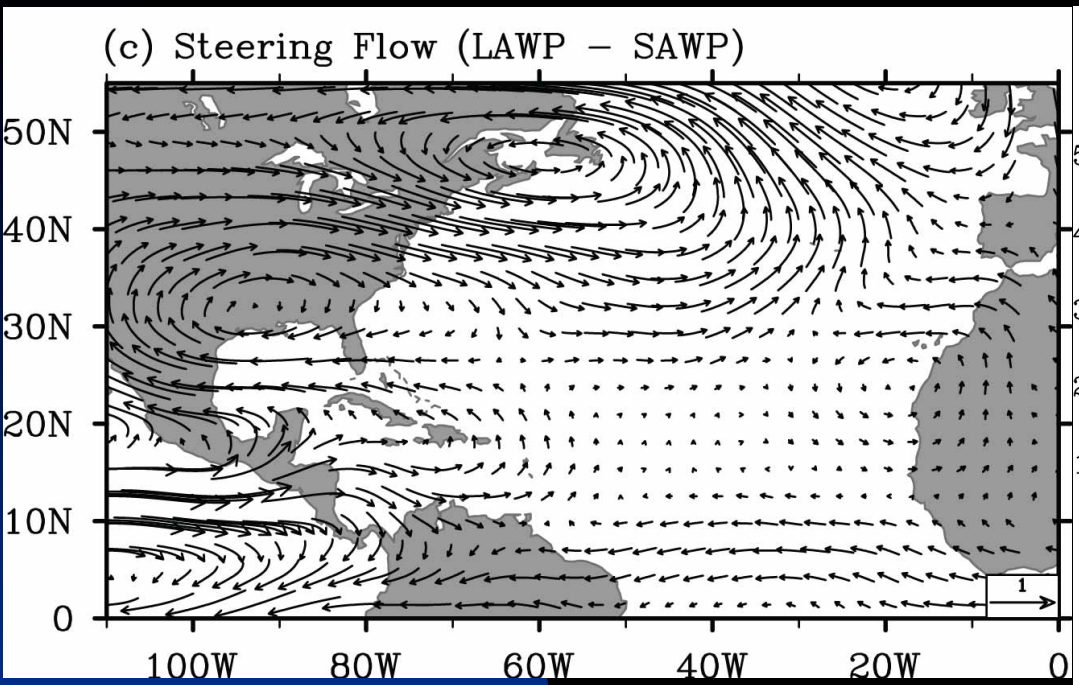
Impact of the AWP on the NASH: AGCM runs

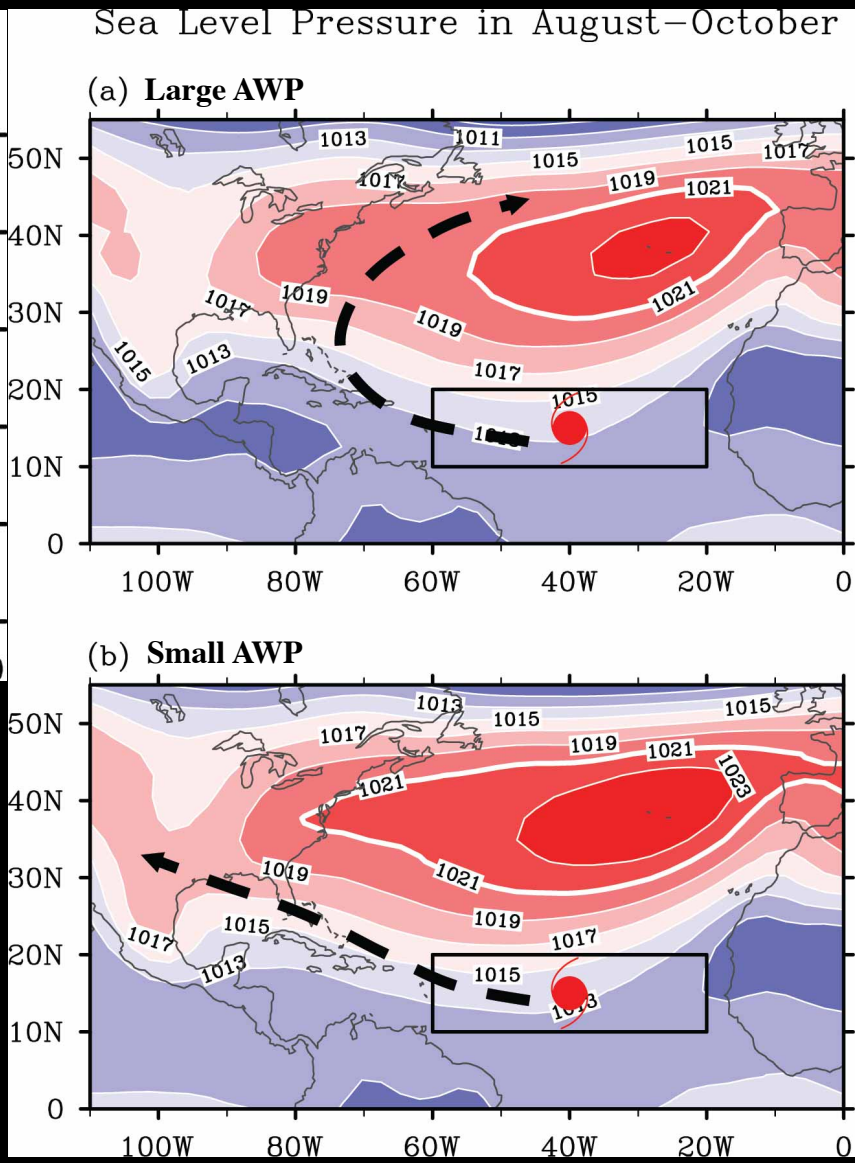
SLP response to AWP variability in JJA



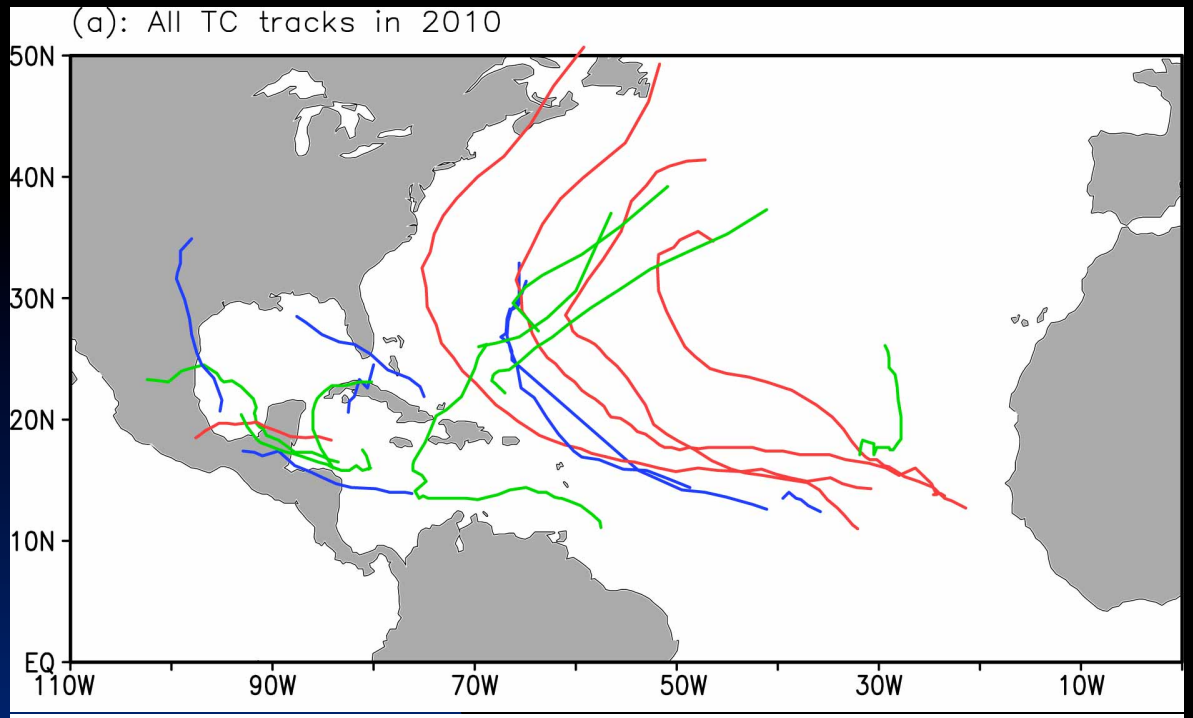
The large AWP weakens the NASH (especially at its southwestern edge) and pushes the NASH northeastward.

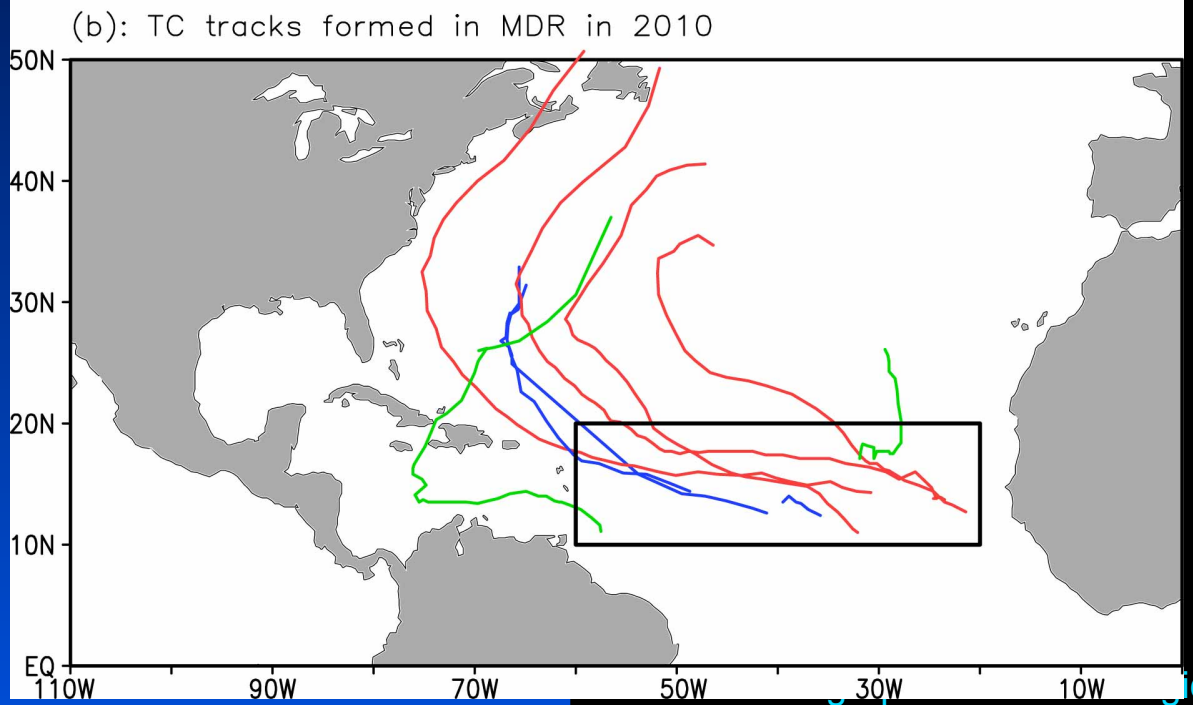
AWP-induced TC steering flow & NASH: AGCM results





Consistent with the observed TC steering flow patterns associated with AWP variability.

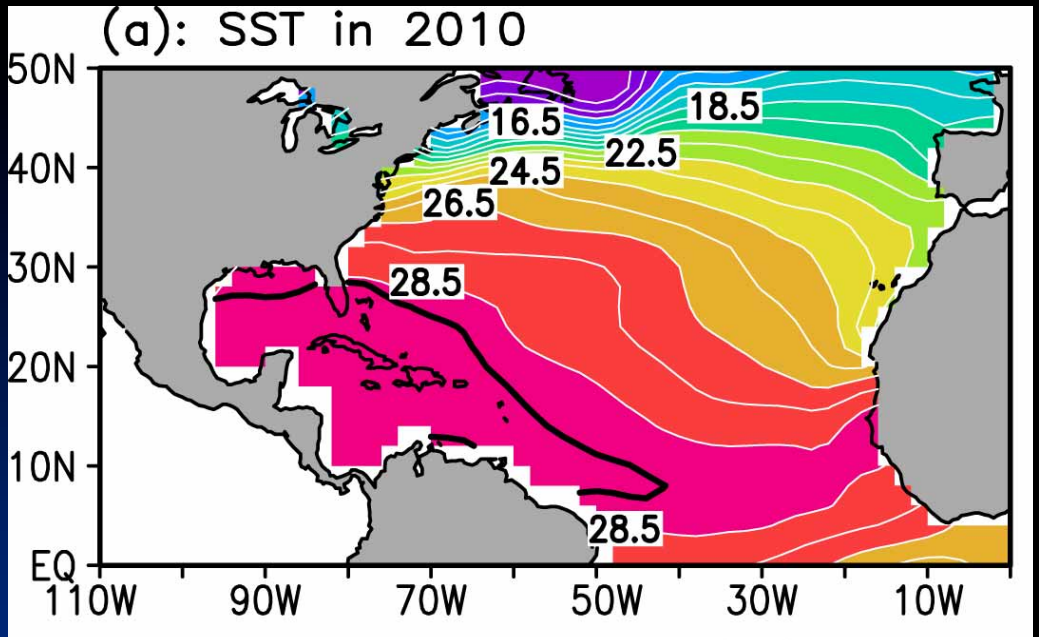




All TCs in 2010: 19 storms, 12 hurricanes.

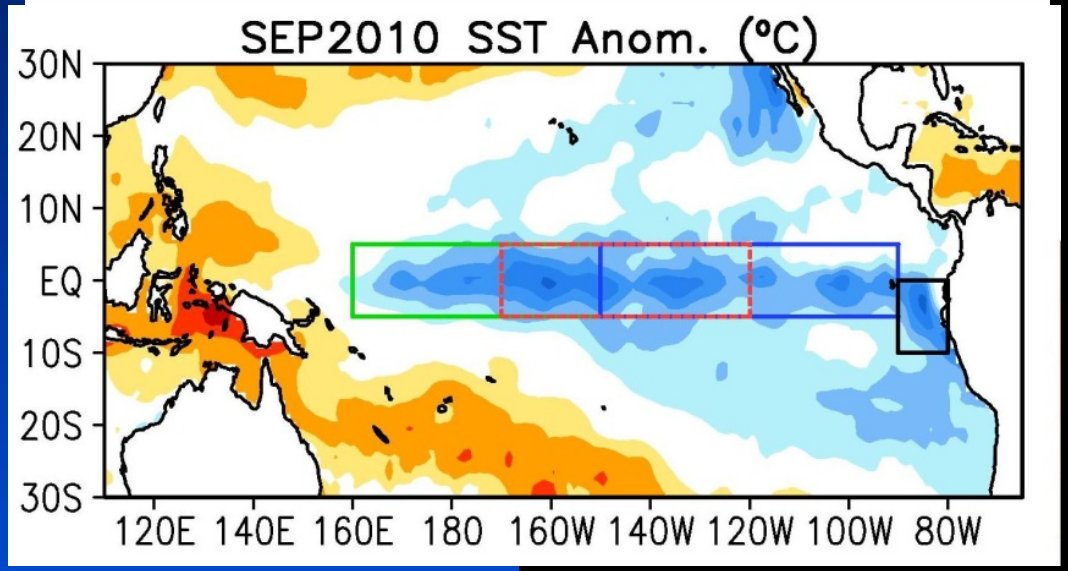
All TCs in 2010 that formed in the main development region (MDR). No hurricanes made landfall. Why???

2010: Extremely large AWP and La Niña Event



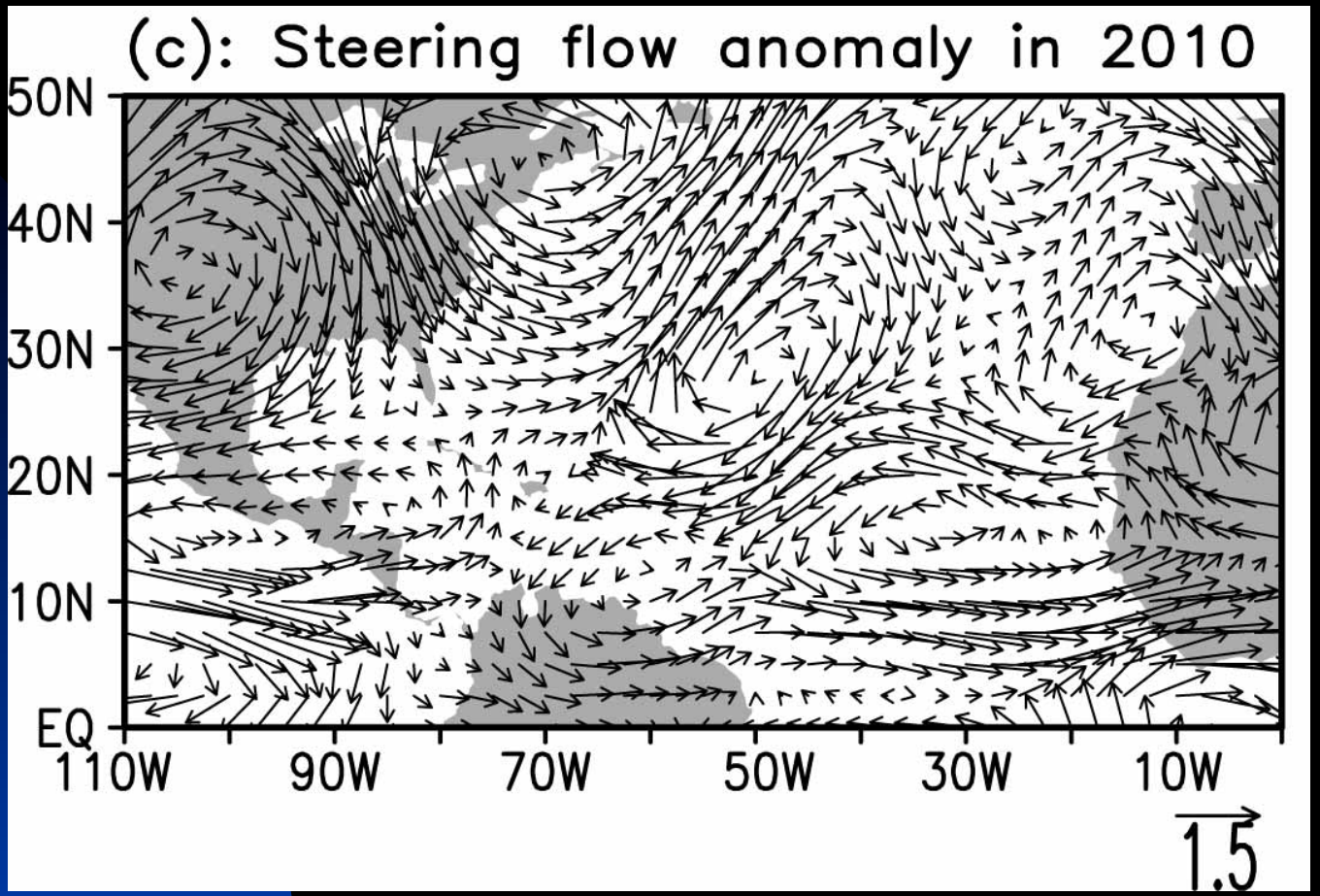
A warm Atlantic

- Both increase the TC number.
- Large AWP is unfavorable for landfall activity.
- La Niña is favorable for landfall activity.



A cold Pacific

The TC Steering Flow in ASO of 2010



An extremely large AWP in 2010 shrinks the NASH and induces the eastward and northeastward steering flow anomalies which steered hurricanes away from the U. S.

Summary

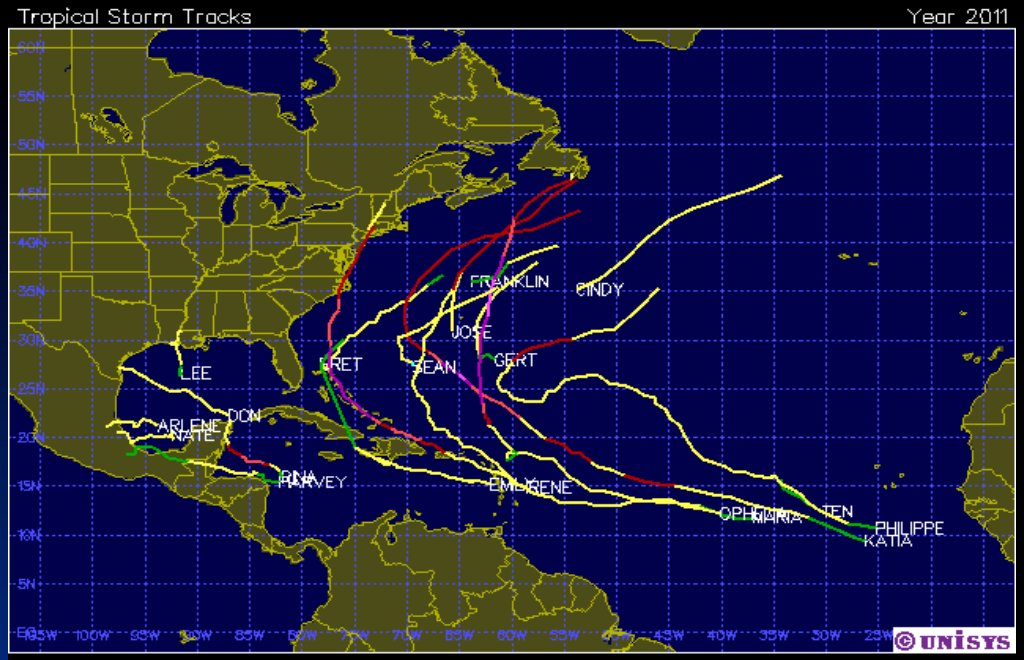
- A large (small) AWP and a La Niña (El Niño) event increase (decrease) the number of Atlantic hurricanes.

- A large (small) AWP is unfavorable (favorable) for hurricanes to make landfall in the U. S. The mechanisms are due to (1) the shift of TC genesis location & (2) the change of TC steering flow.

- A La Niña (El Niño) event is favorable (unfavorable) for hurricanes to make landfall in Central America, Caribbean Islands and the southeast U. S.

- The effect of large AWP in 2010 overwhelmed that of La Niña: No hurricanes made landfall in the U. S.

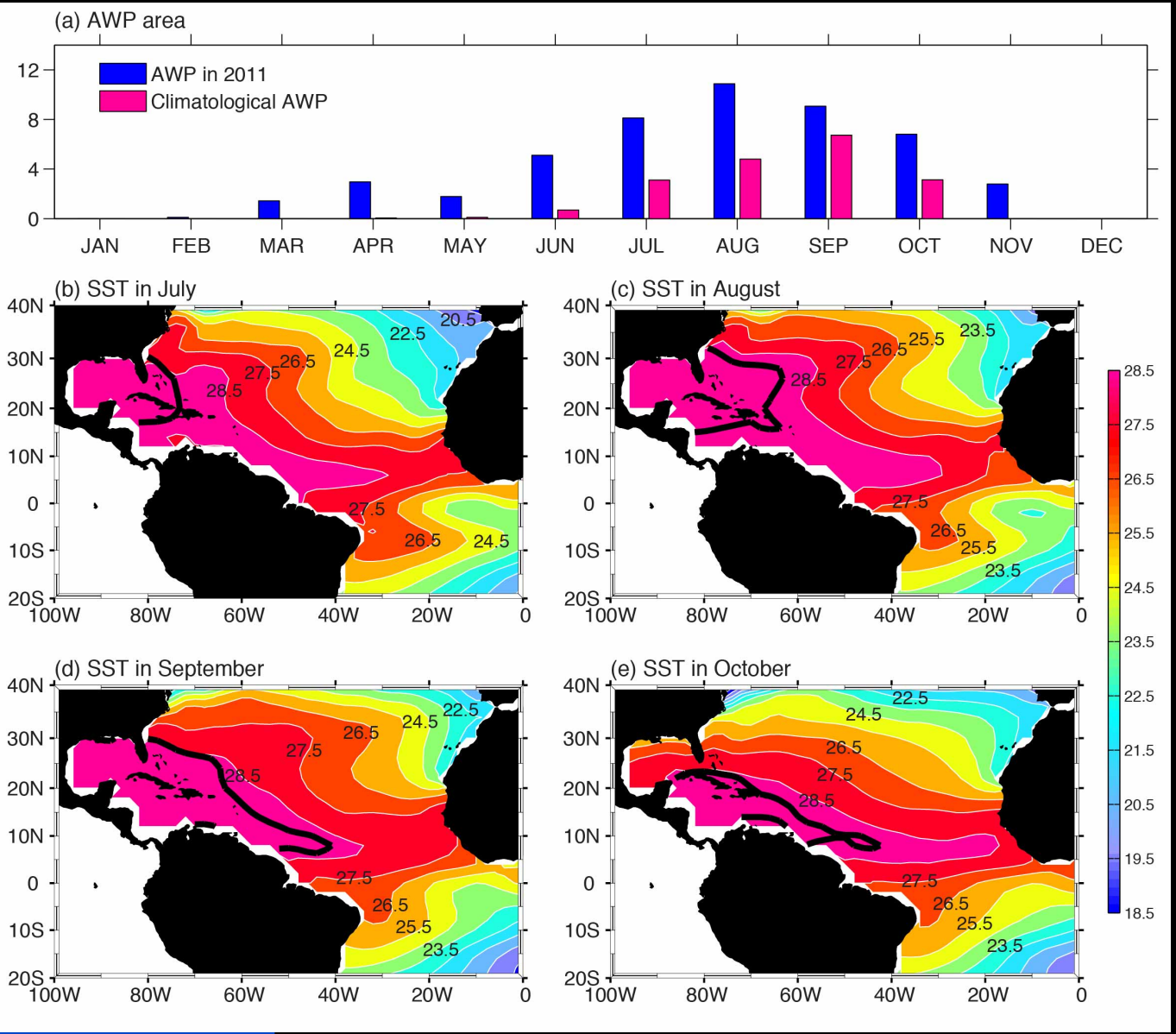
NOAA Predicts an Active Atlantic Hurricane Season in 2011



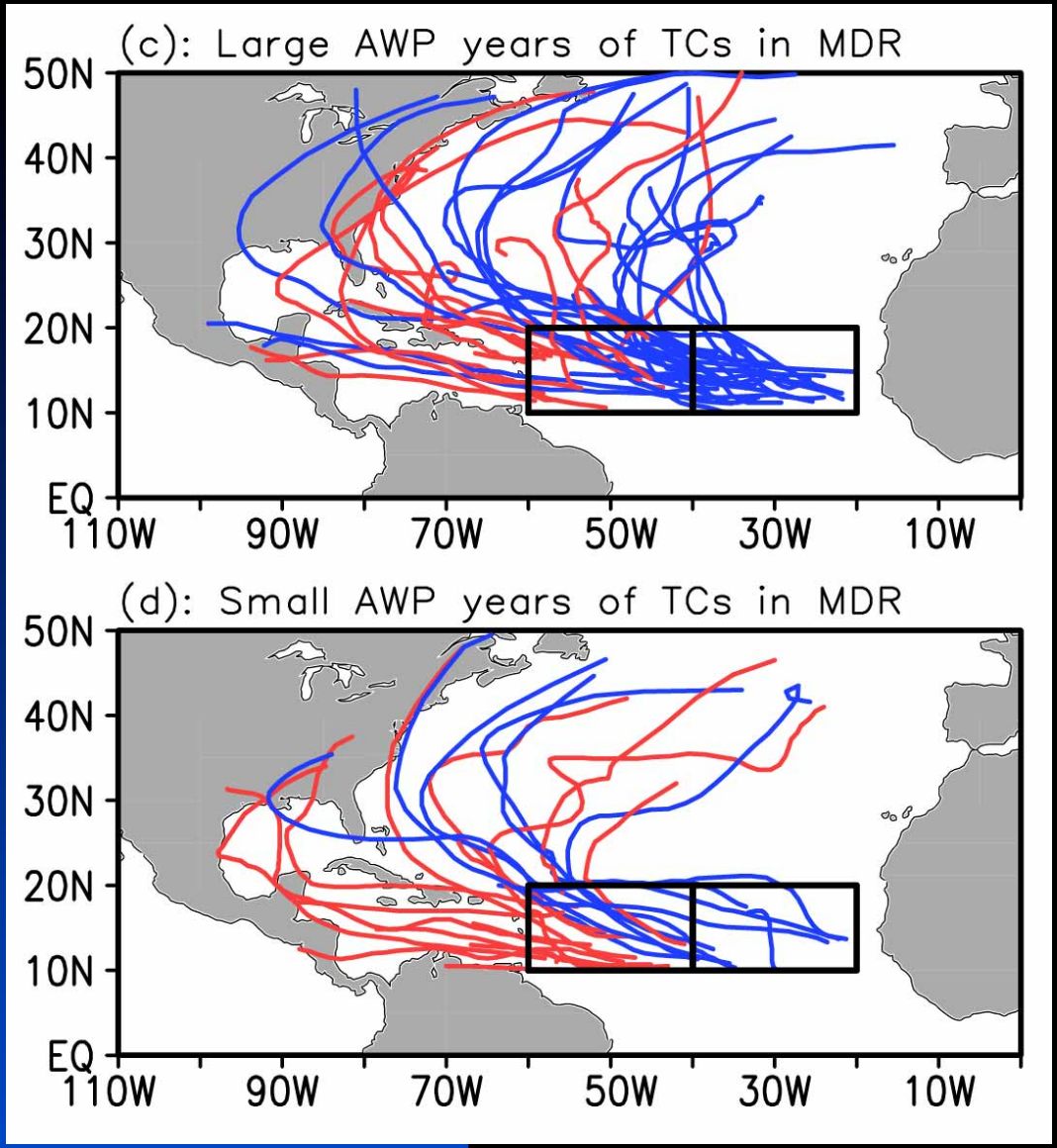
- **19 tropical storms, 7 hurricanes and 4 major hurricanes (category 3, 4) formed in the North Atlantic Ocean.**
- **The NOAA's Atlantic Hurricane outlook verified well.**

	Normal	May 19	Aug. 4	*Observed*
Named storms	**11**	**12-18**	**14-19**	**19**
Hurricanes	**6**	**6-10**	**7-10**	**7**
Major hurricanes	**2**	**3-6**	**3-5**	**4**
ACE (% median)	**100**	**105-200**	**135-215**	**121**

The AWP in 2011 is large



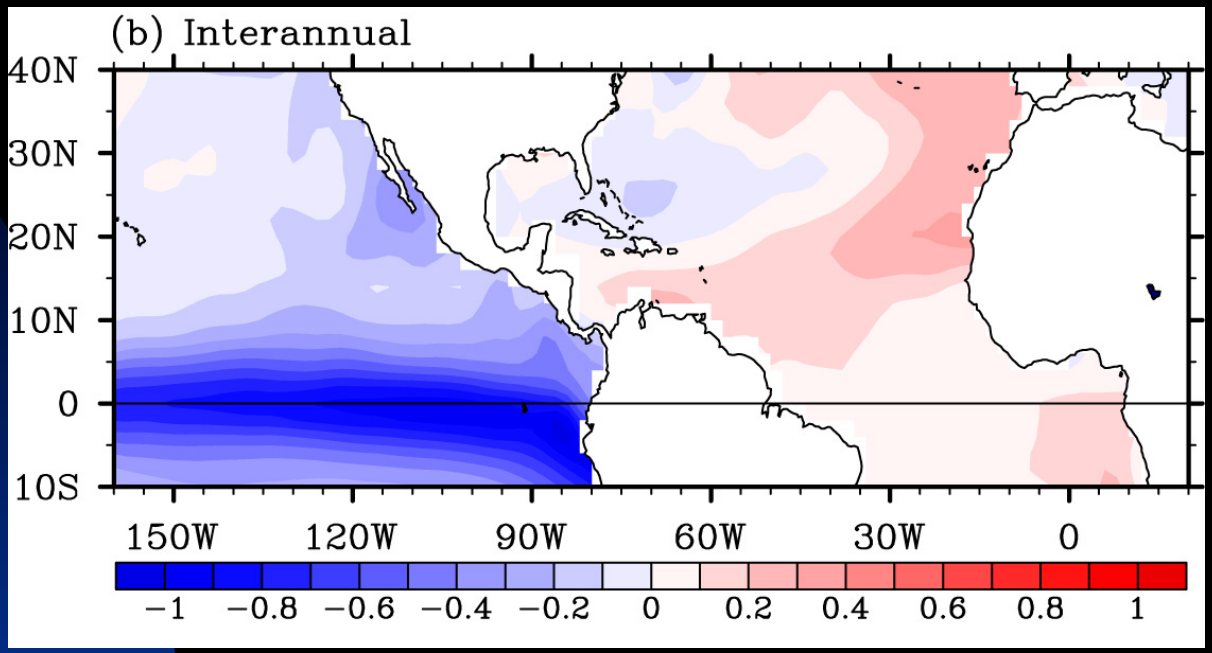
TCs formed further eastward are less likely to make landfall in U. S.



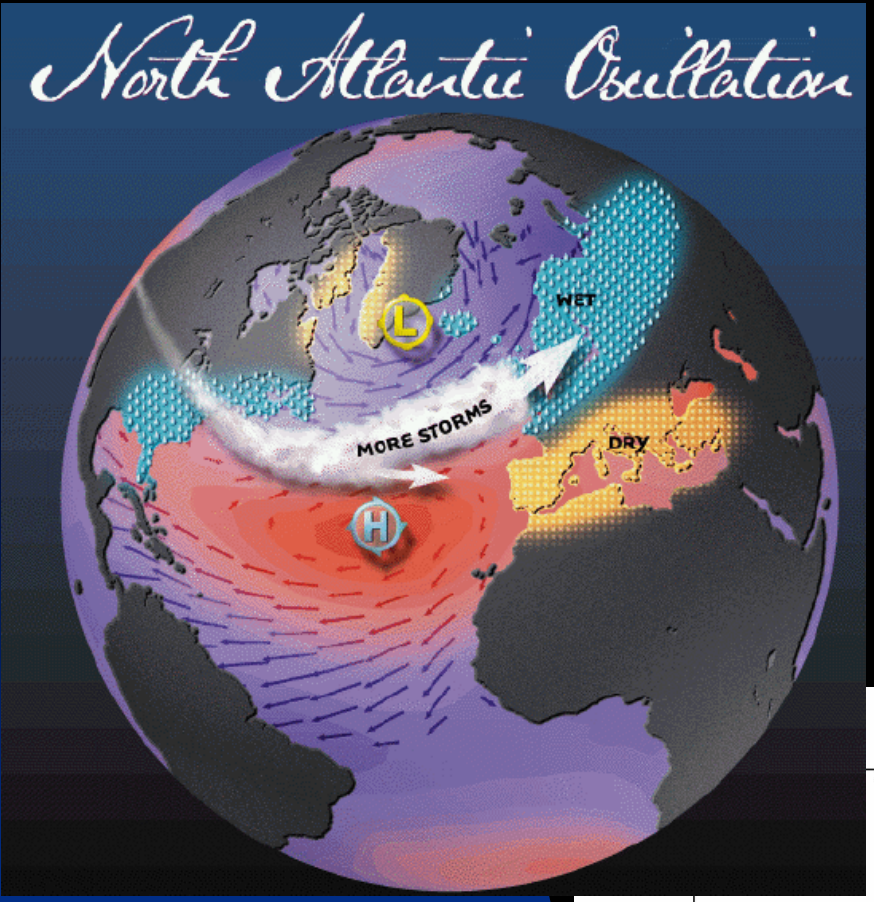
The ratios of U. S. landfalling TCs in the east and west of 40°W are 13.2% and 29.0%, respectively.

ENSO and Atlantic Hurricanes

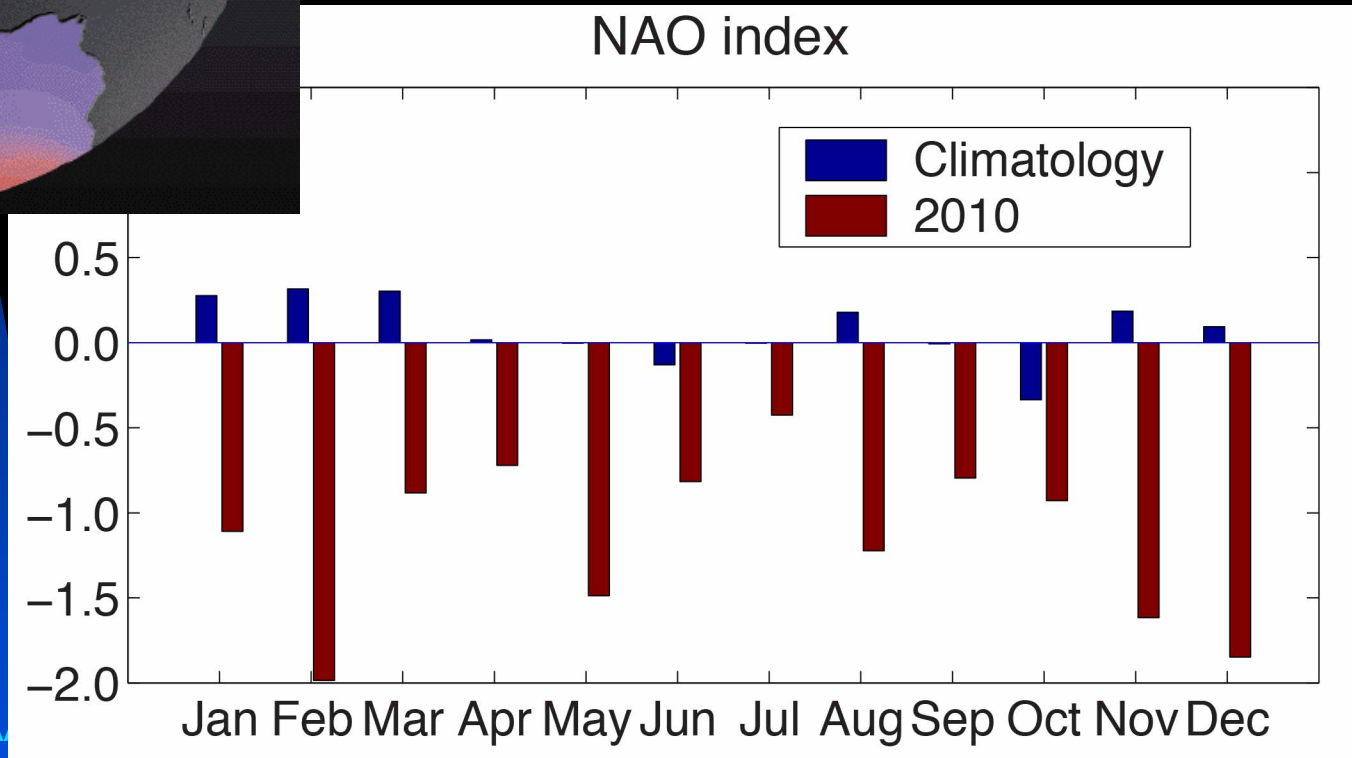
Regression of SST (Jun-Nov) onto North Atlantic ACE



- **La Niña-like pattern.**
- **La Niña (El Niño) increases (decreases) Atlantic hurricane activity.**
- **But what about the TC track?**

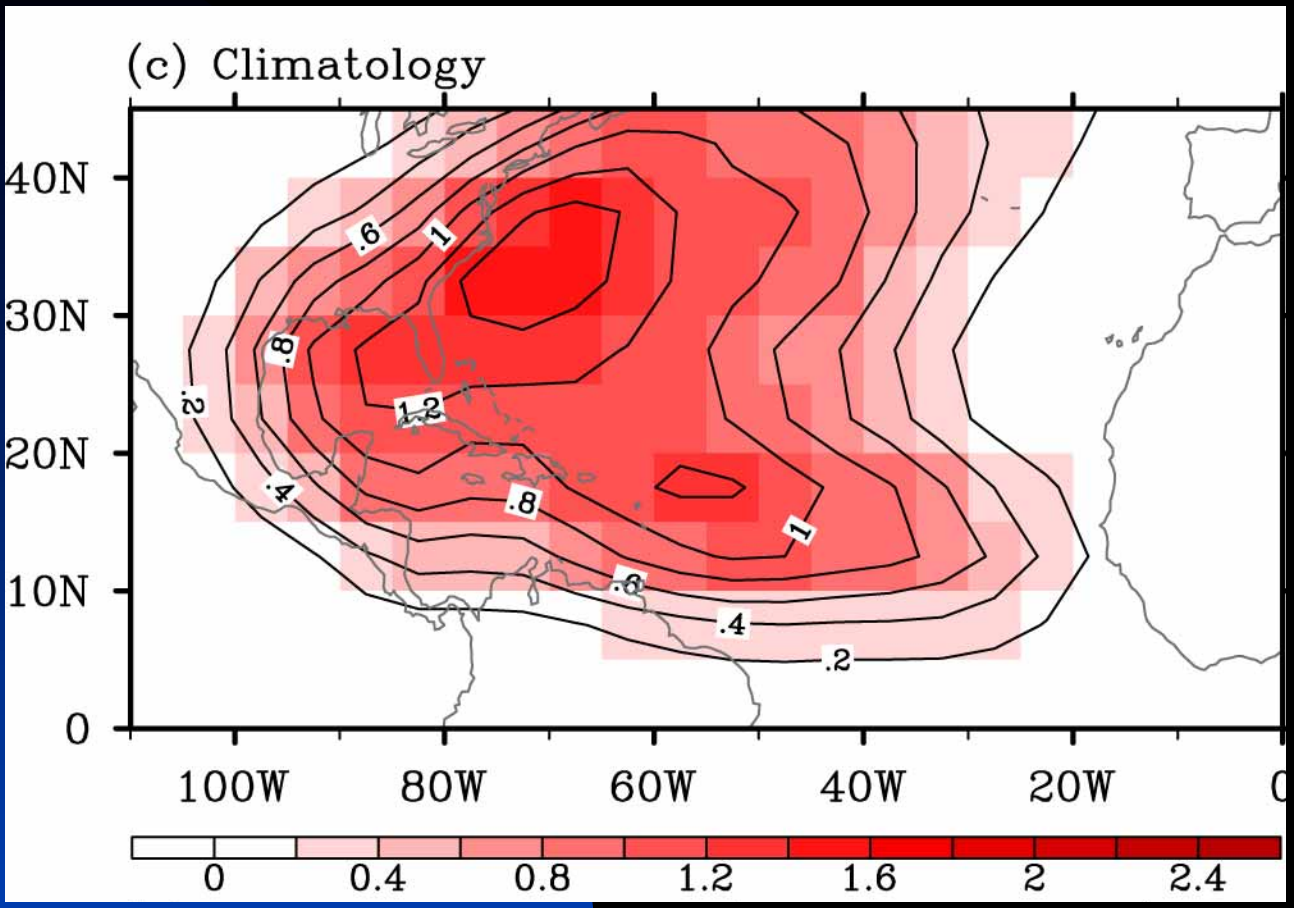


North Atlantic Oscillation (NAO)



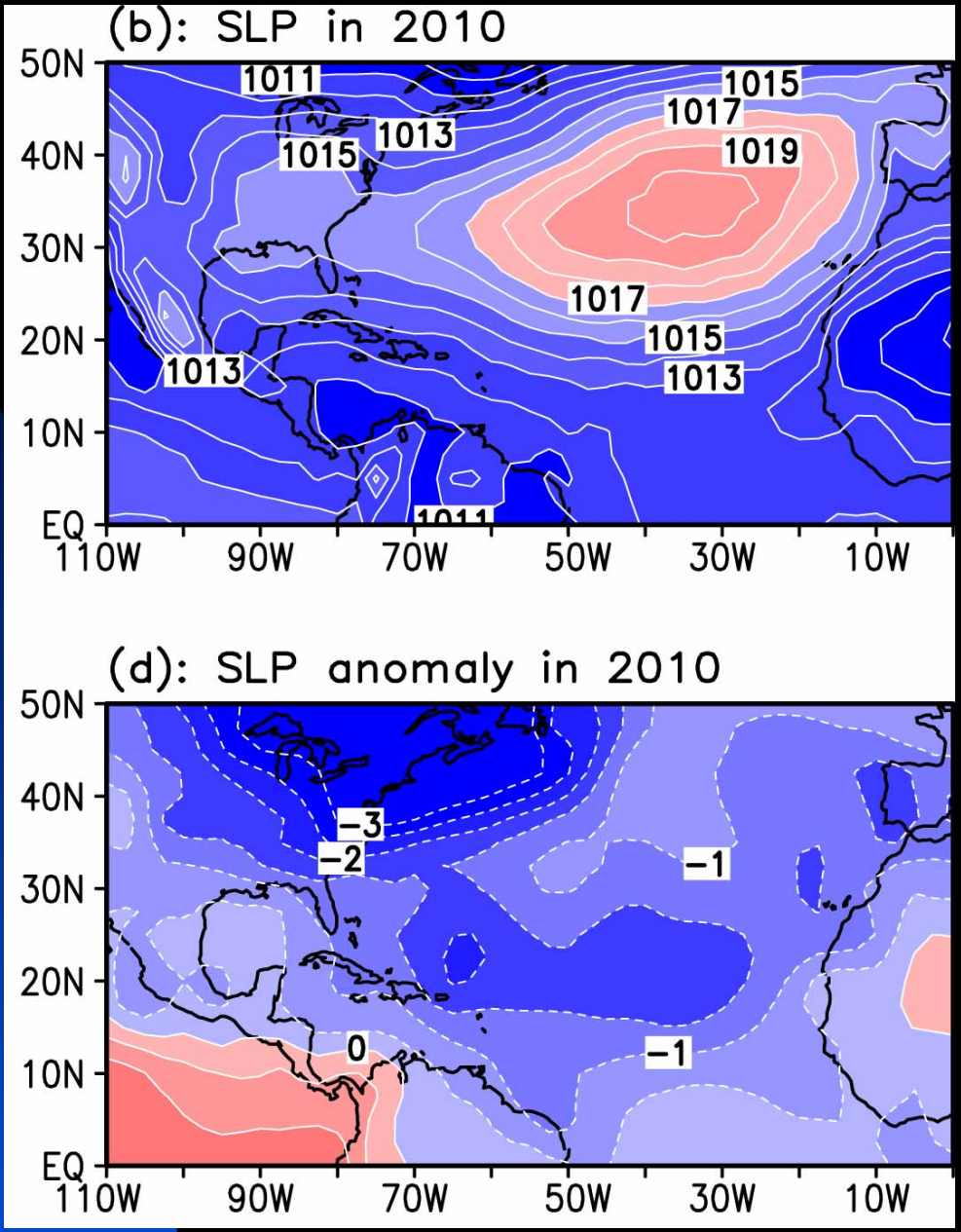
NOA

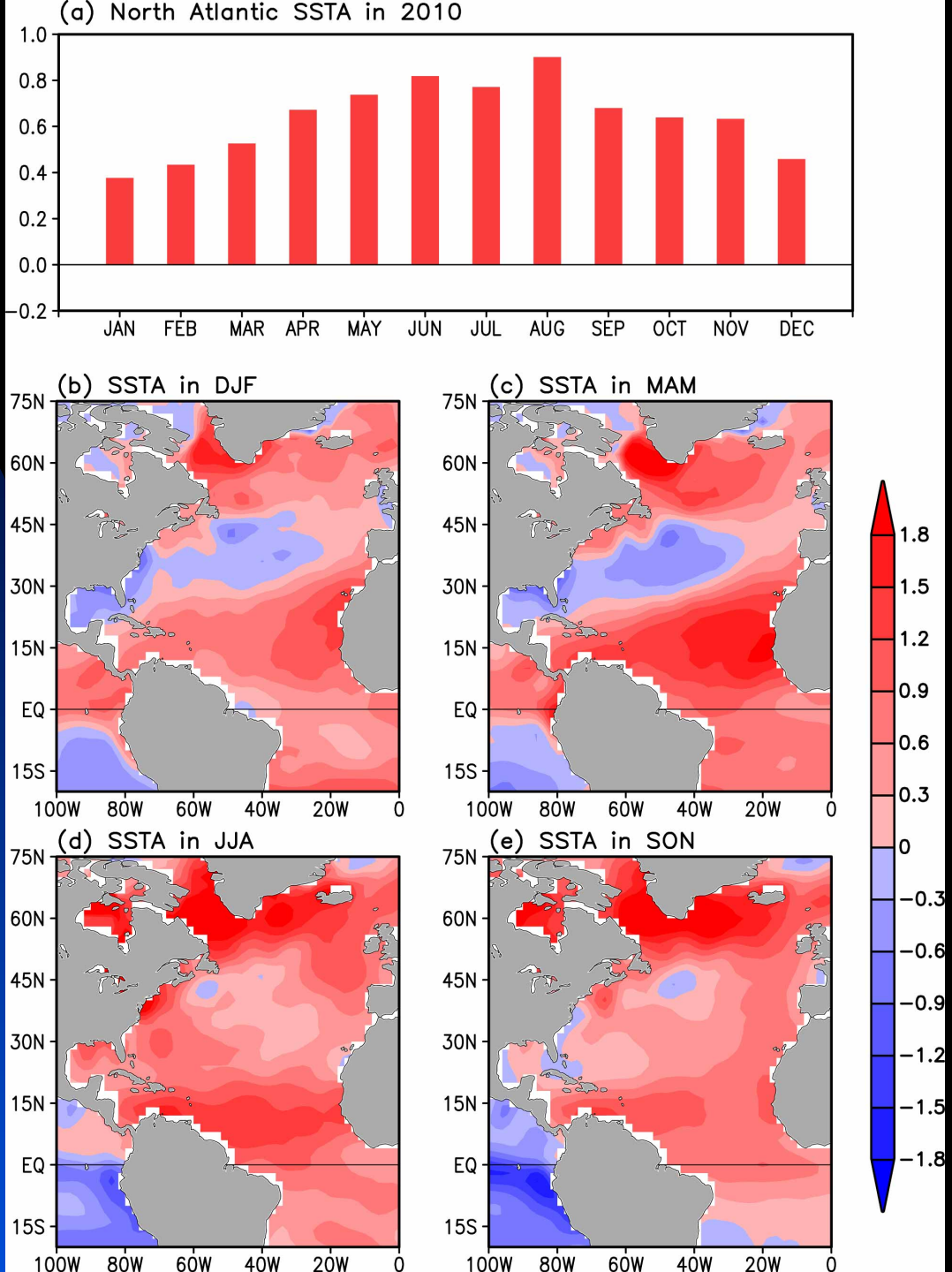
Observed climatology of TC track density during ASO (1970-2009)

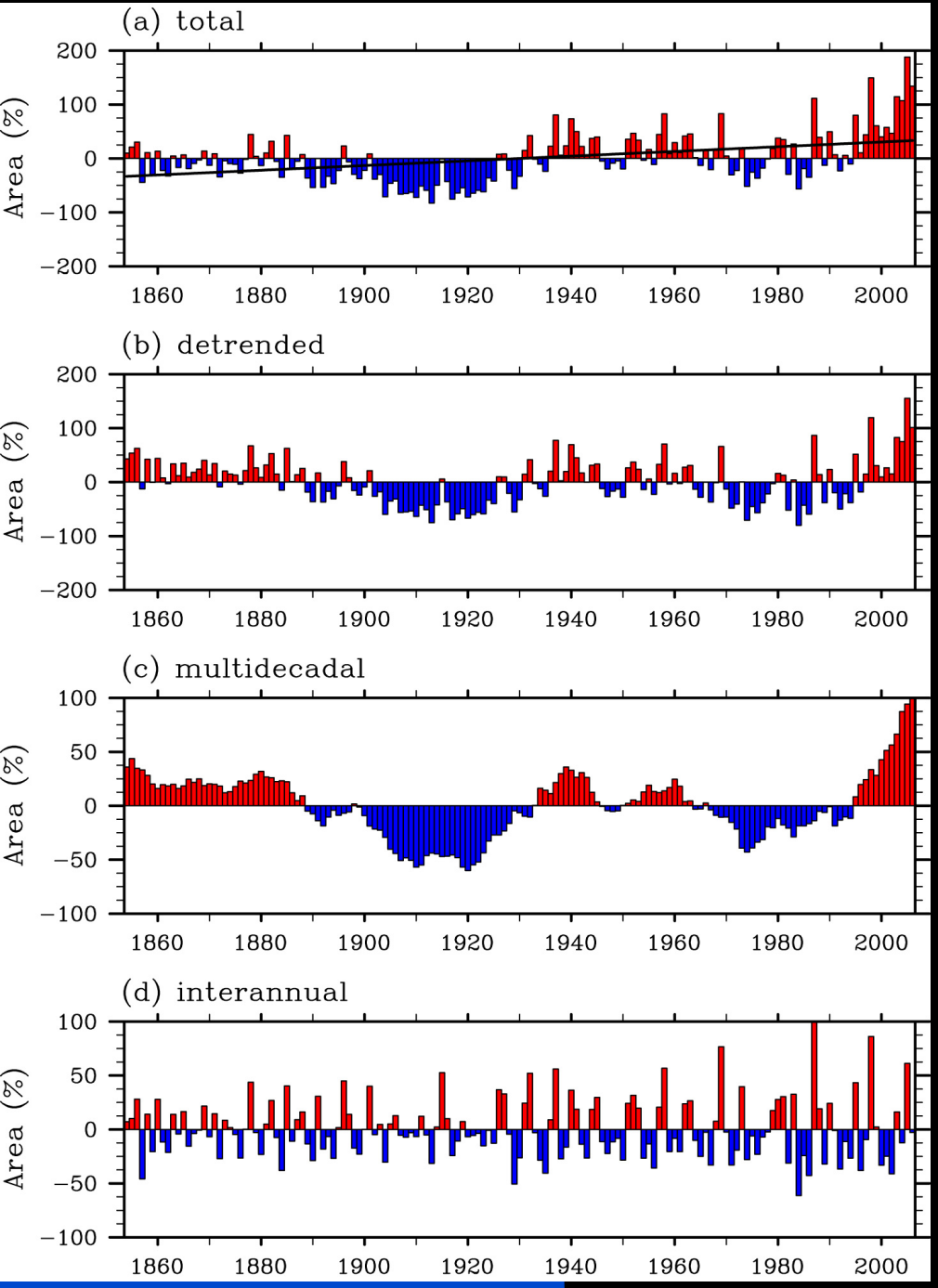


Maximum TC density is located in the western subtropical NA, reflecting that most of TCs move northwestward.

North Atlantic subtropical high (NASH) in 2010




(a) North Atlantic SSTA in 2010
1.0
0.8
0.6
0.4
0.2
0.0
−0.2
JAN
FEB
MAR
APR
MAY
JUN
JUL
AUG
SEP
OCT
NOV
DEC
(b) SSTA in DJF
(c) SSTA in MAM
(d) SSTA in JJA
(e) SSTA in SON
75N
60N
45N
30N
15N
EQ
15S
100W
80W
60W
40W
20W
0
1.8
1.5
1.2
0.9
0.6
0.3
0
−0.3
−0.6
−0.9
−1.2
−1.5
−1.8

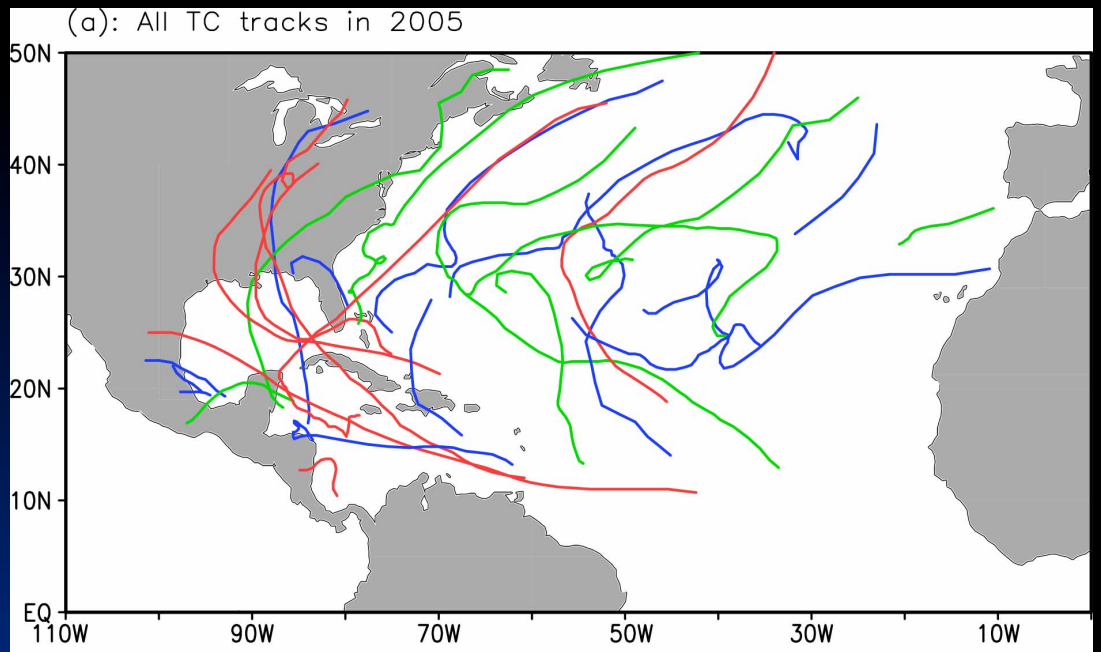


AWP (SST ≥ 28.5°C) area anomaly indices during June-November

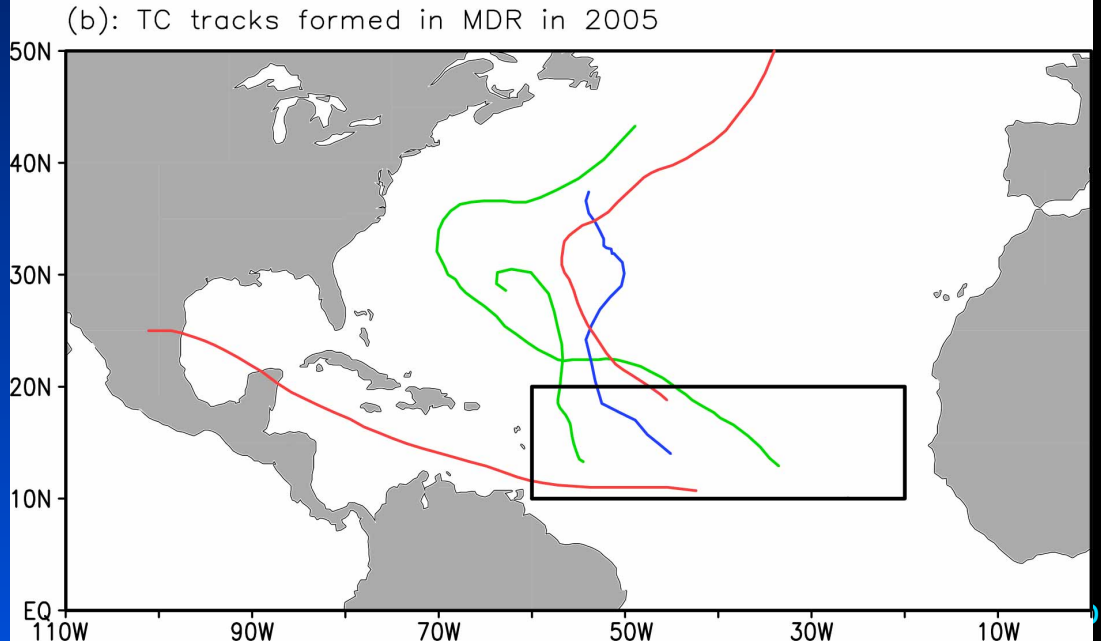
In additional to seasonal cycle, AWP also shows interannual, multidecadal, and linear warming trend variations.

Wang et al. (2008, G^3)

Is the 2005 Hurricane Season an Outlier?

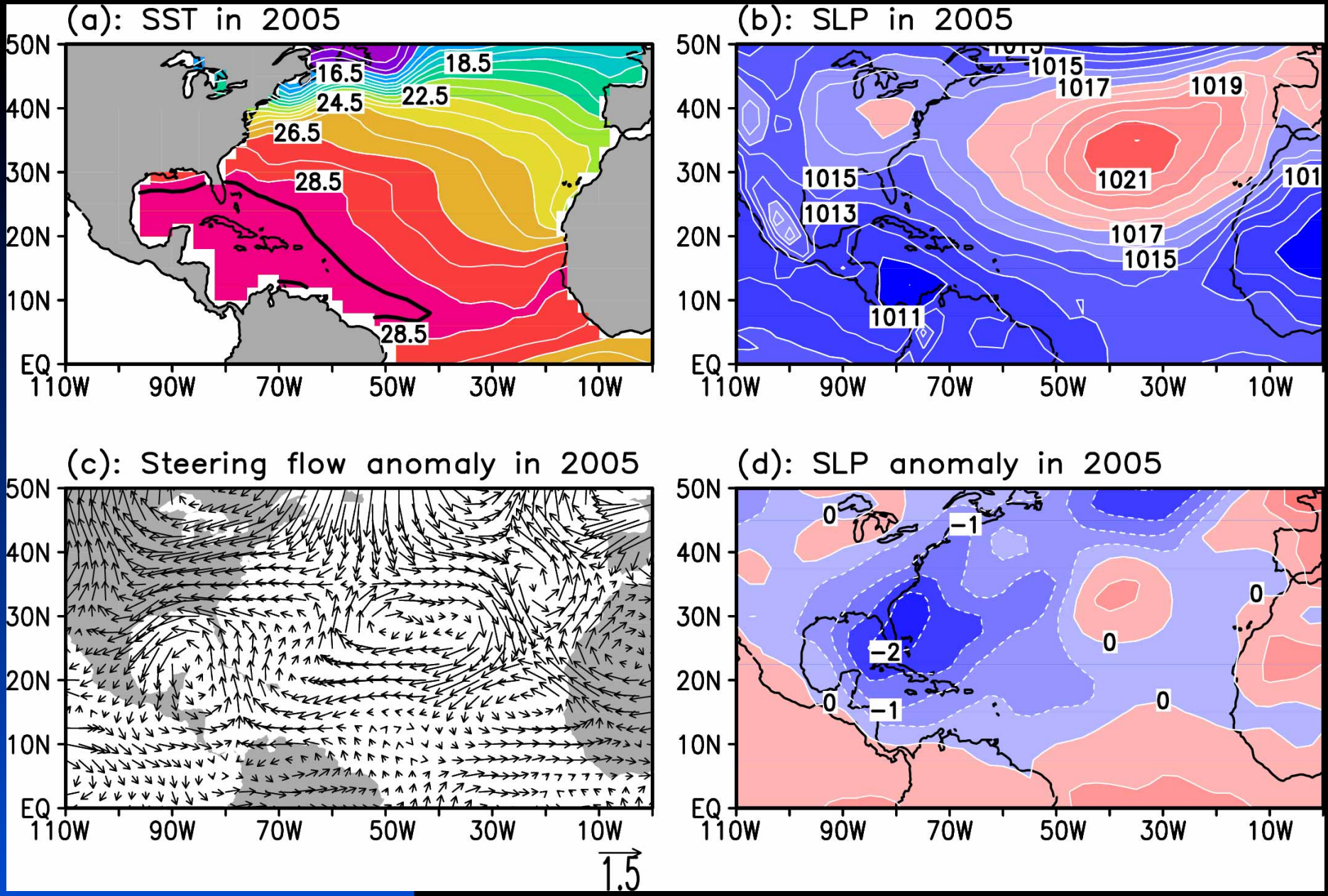


All TCs in 2005: 28 storms, 15 hurricanes (5 made landfall in the U. S.).



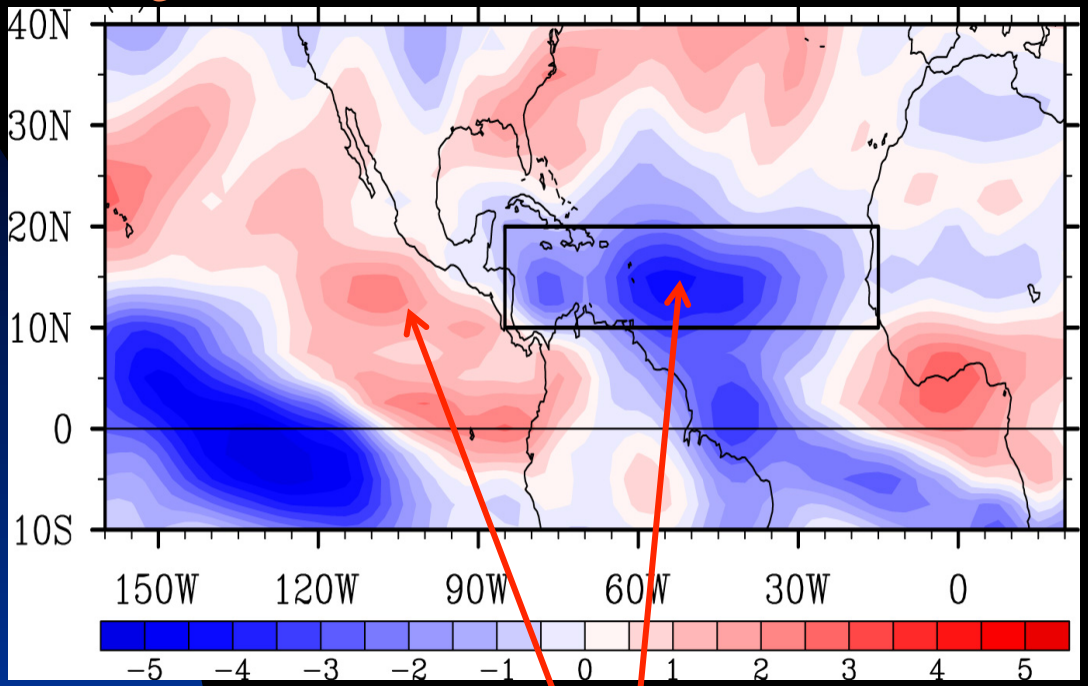
Hurricanes in 2005 that formed in the MDR.

Conditions during the 2005 Hurricane Season



AWP variability can induce the opposite vertical wind shear (VWS) in North Atlantic (NA) and eastern North Pacific (ENP).

Regression of VWS (Jun-Nov) onto AWP index



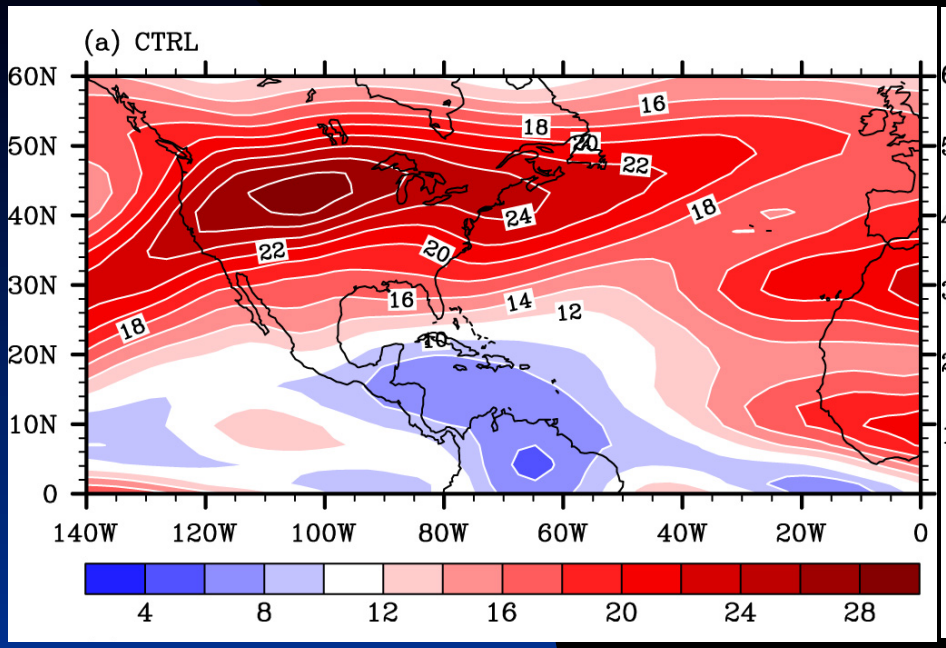
Opposite VWS in NA and ENP

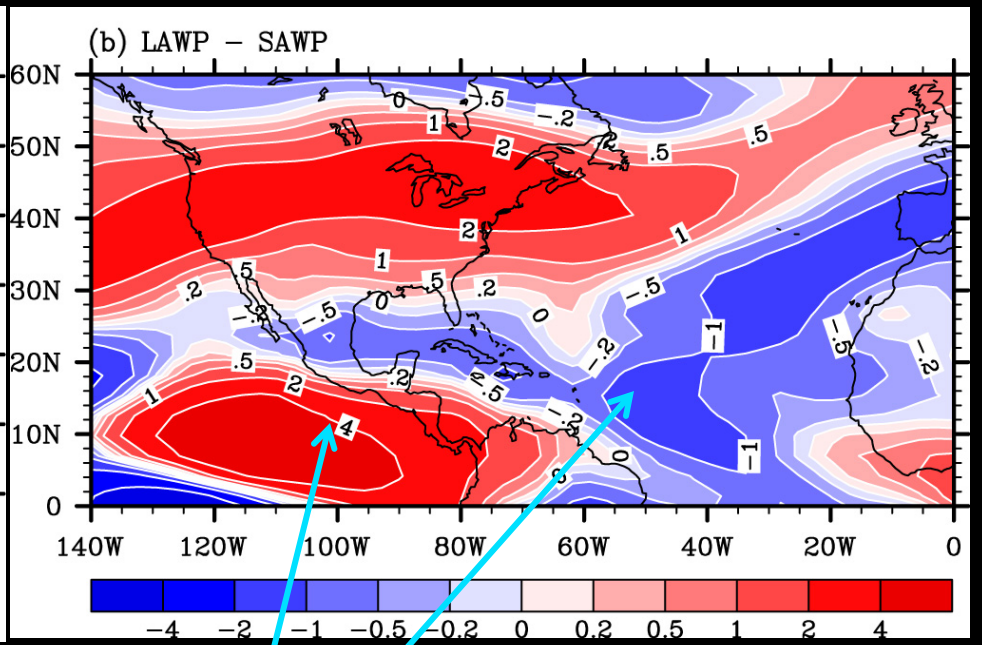
Large (small) AWPs => Low (high) shear in NA => More (less) NA TCs.

Large (small) AWPs => High (low) shear in ENP => Less (more) ENP TCs.

Impact of AWP on Hurricanes via Wind Shear: AGCM Runs

Vertical Wind Shear (VWS): $VWS = \sqrt{(U_{200} - U_{850})^2 + (V_{200} - V_{850})^2}$

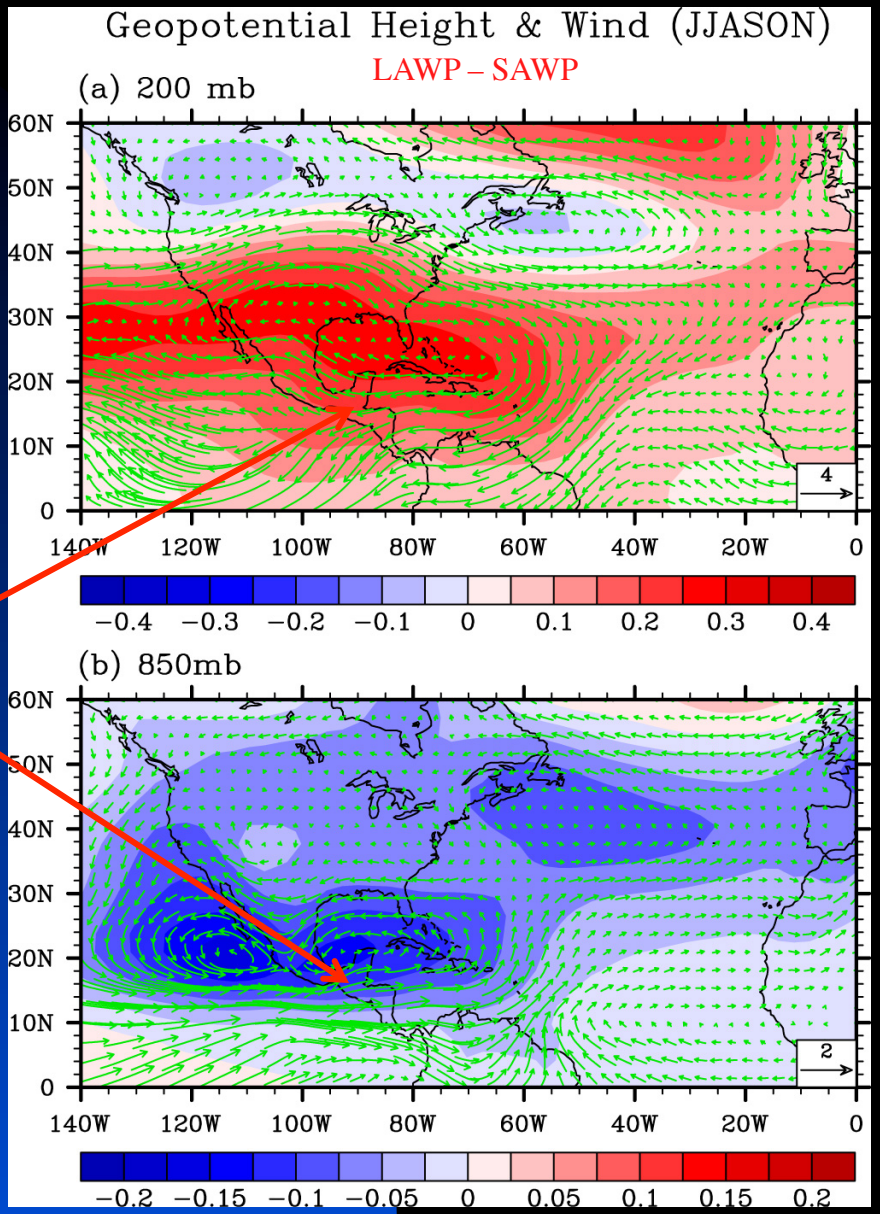




Wang et al. (2008, *JC*)

AWP reduces lower-level easterly flow and upper-level westerly flow, resulting in a reduction of VWS in the NA MDR that favors Atlantic hurricanes. The opposite result occurs in the ENP. This is why NA and ENP TCs vary out-of-phase (Wang & Lee 2009, *GRL*).

How/Why does AWP reduce (enhance) VWS in the NA (ENP) MDR?



Gill's (1980) physics: Baroclinic response to an AWP heating.

Wind anomalies cross Central America

Anomalous anticyclone at 200-mb

Anomalous cyclone at 850-mb

Wang et al. (2008, *JC*)