# Intensity Variations of Subtropical Potential Vorticity Streamers:

## Impact on the Environment of the Subtropical Atlantic and Tropical Cyclone Activity

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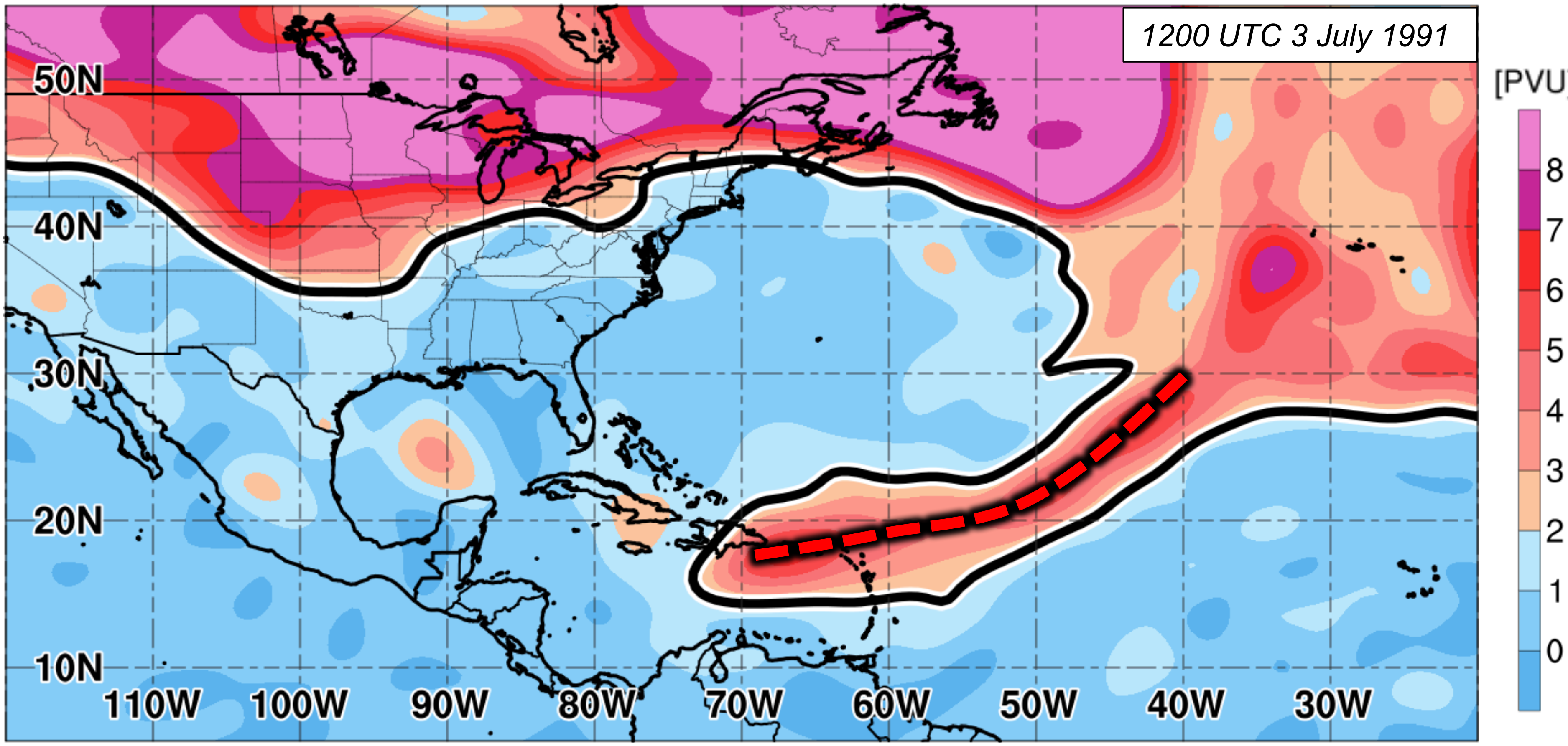
# What are PV Streamers

- Potential vorticity (PV) streamers are elongated filaments of high PV air
  - Correspond to positively tilted upper-tropospheric troughs

350-K PV (shaded, PVU), 2-PVU contour (black line)



# Motivation

## A tale of two PV streamers

- Tale 1: August 2005
  - ❖ PV streamer draped across subtropical Atlantic basin
  - ❖ Small width and weak intensity in Bahamas
  - ❖ A developing system in the Bahamas (Katrina) easily overcomes PV streamer induced shear

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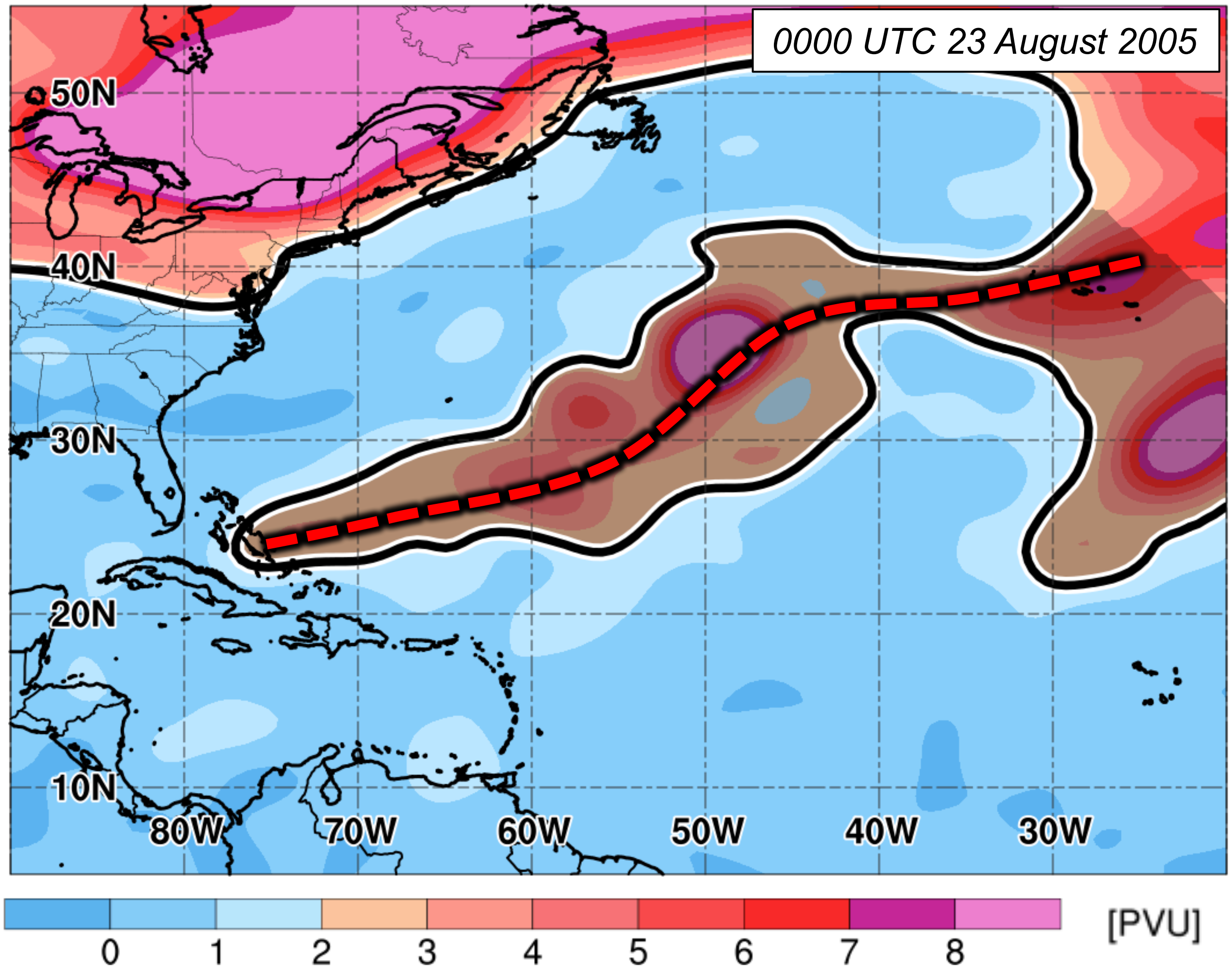

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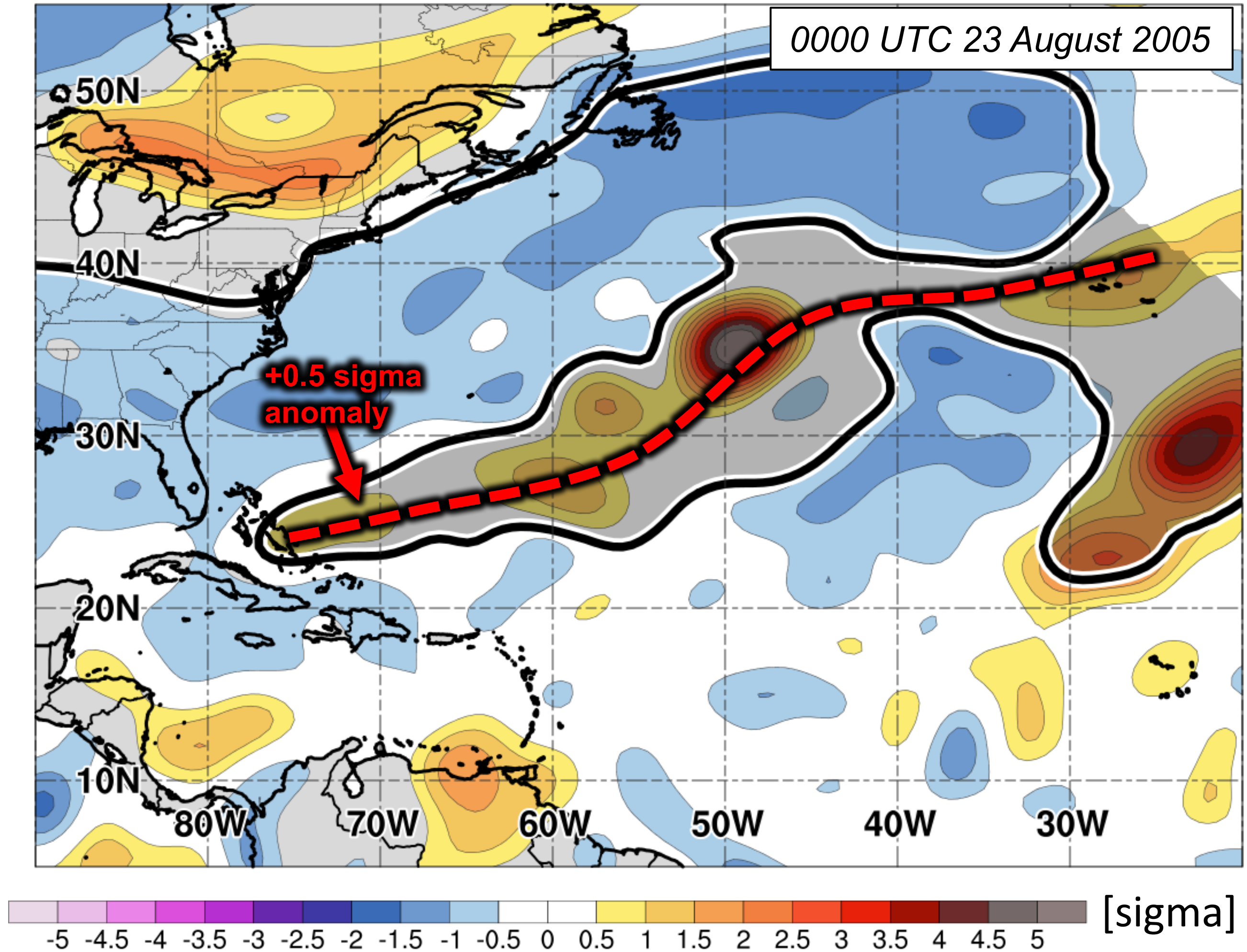
350-K PV standardized intensity (shaded, sigma), 2-PVU contour (black line)



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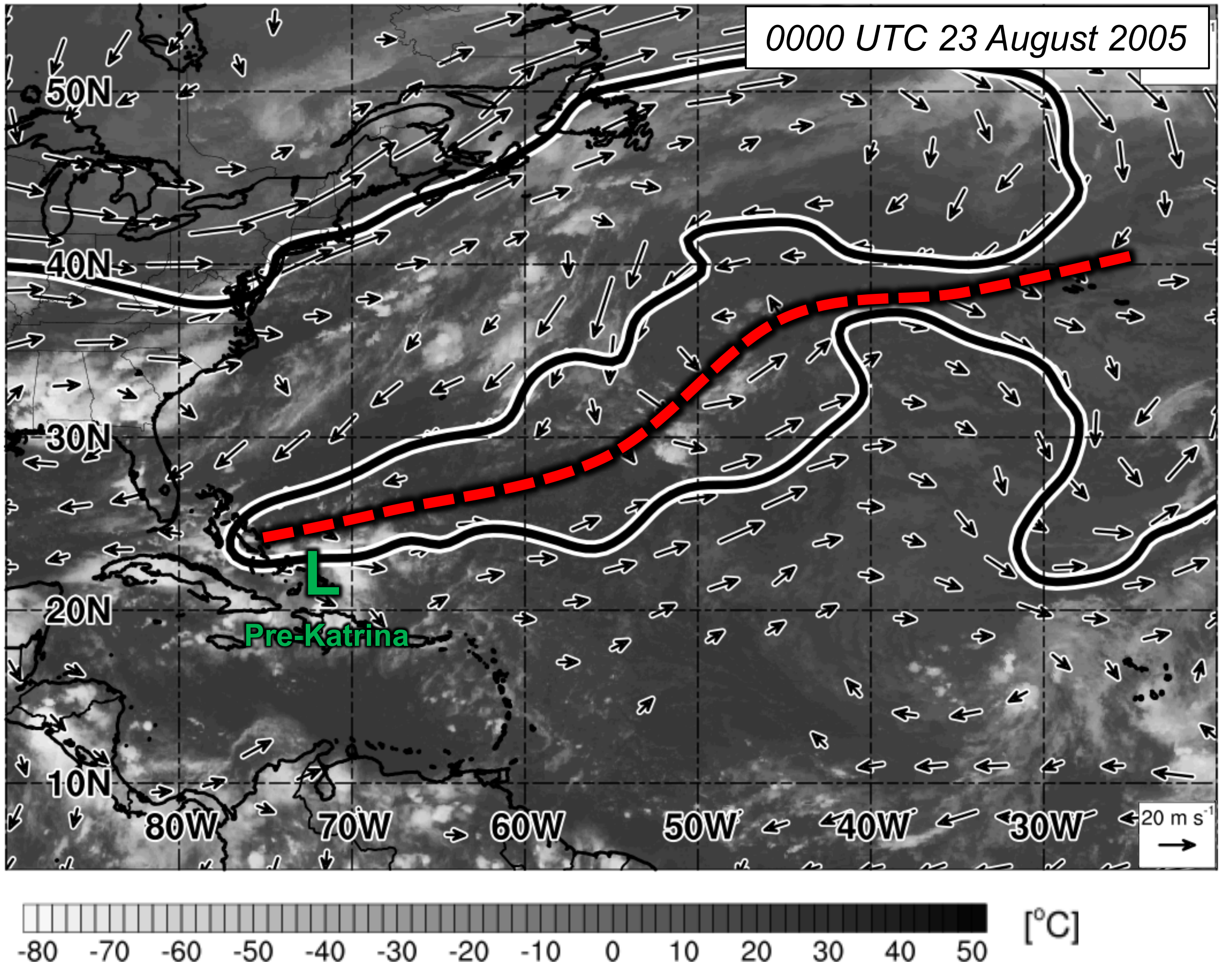
200–850-hPa vertical wind shear (vectors, m s$^{-1}$), 2-PVU contour (black line)



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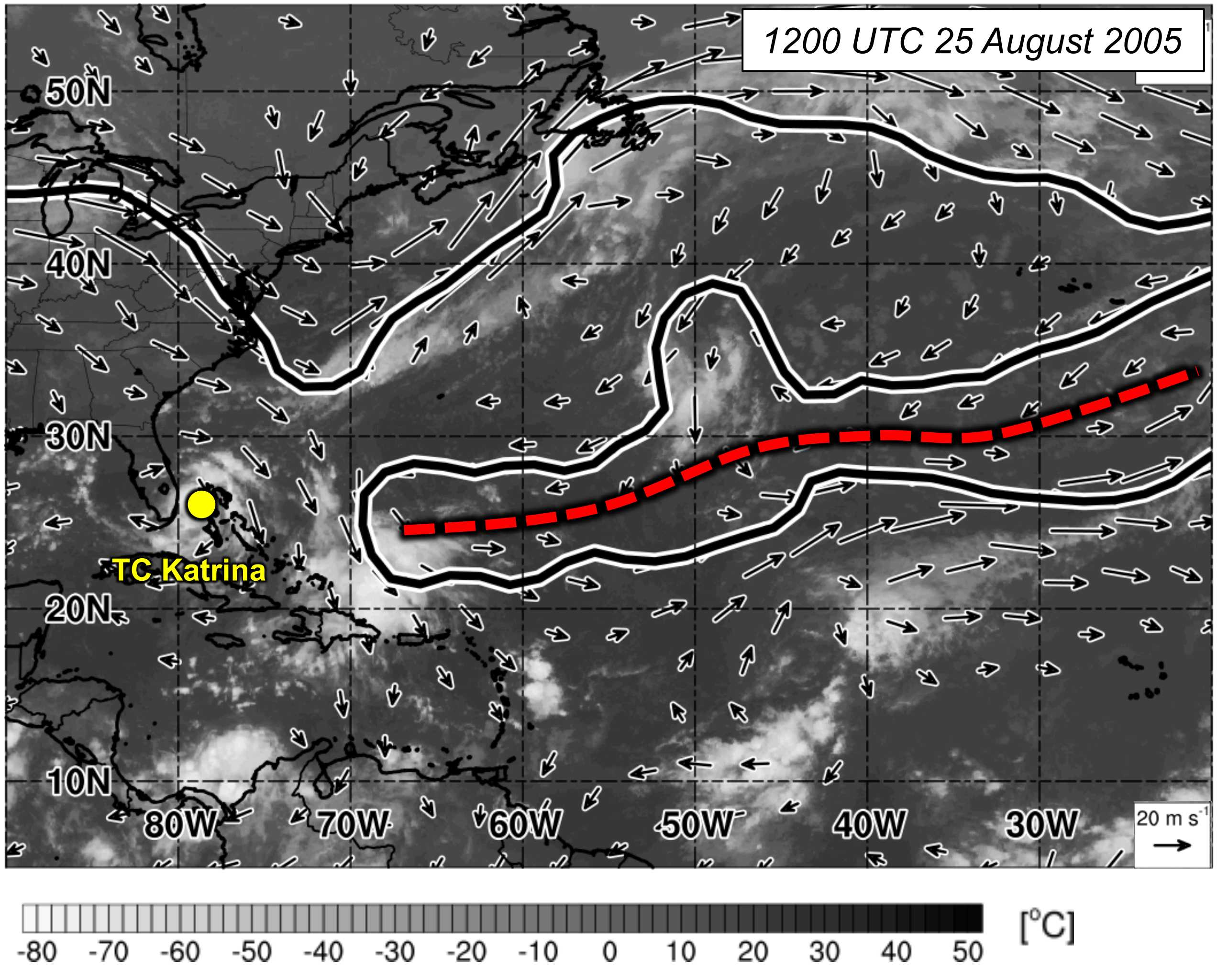

# Motivation

## A tale of two PV streamers

- Tale 2: September 2013
  - PV streamer over the eastern Atlantic
  - Large width and strong intensity in central Atlantic
  - The PV streamer negatively interacted with TC Humberto due to high vertical wind shear and dry mid-latitude air

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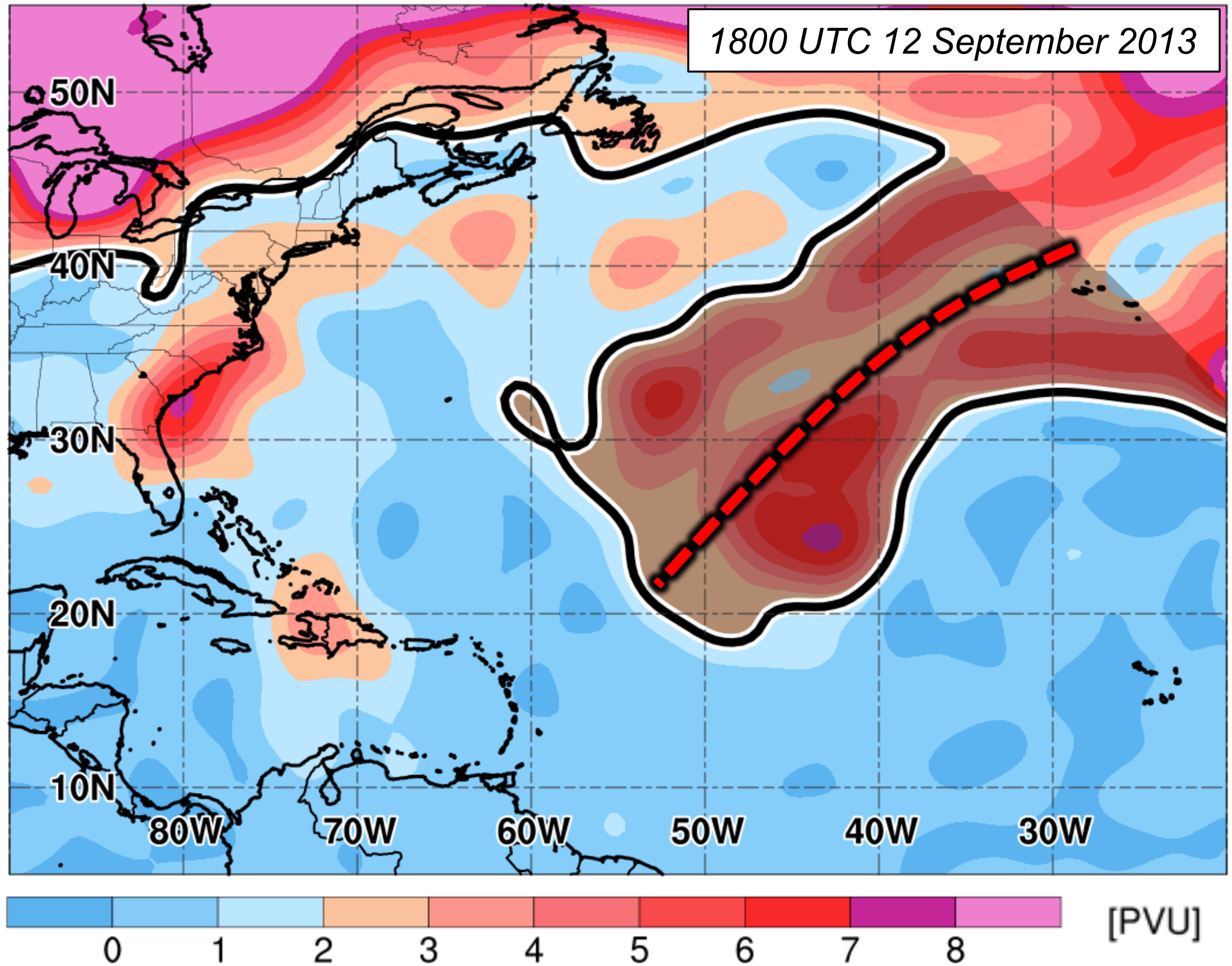

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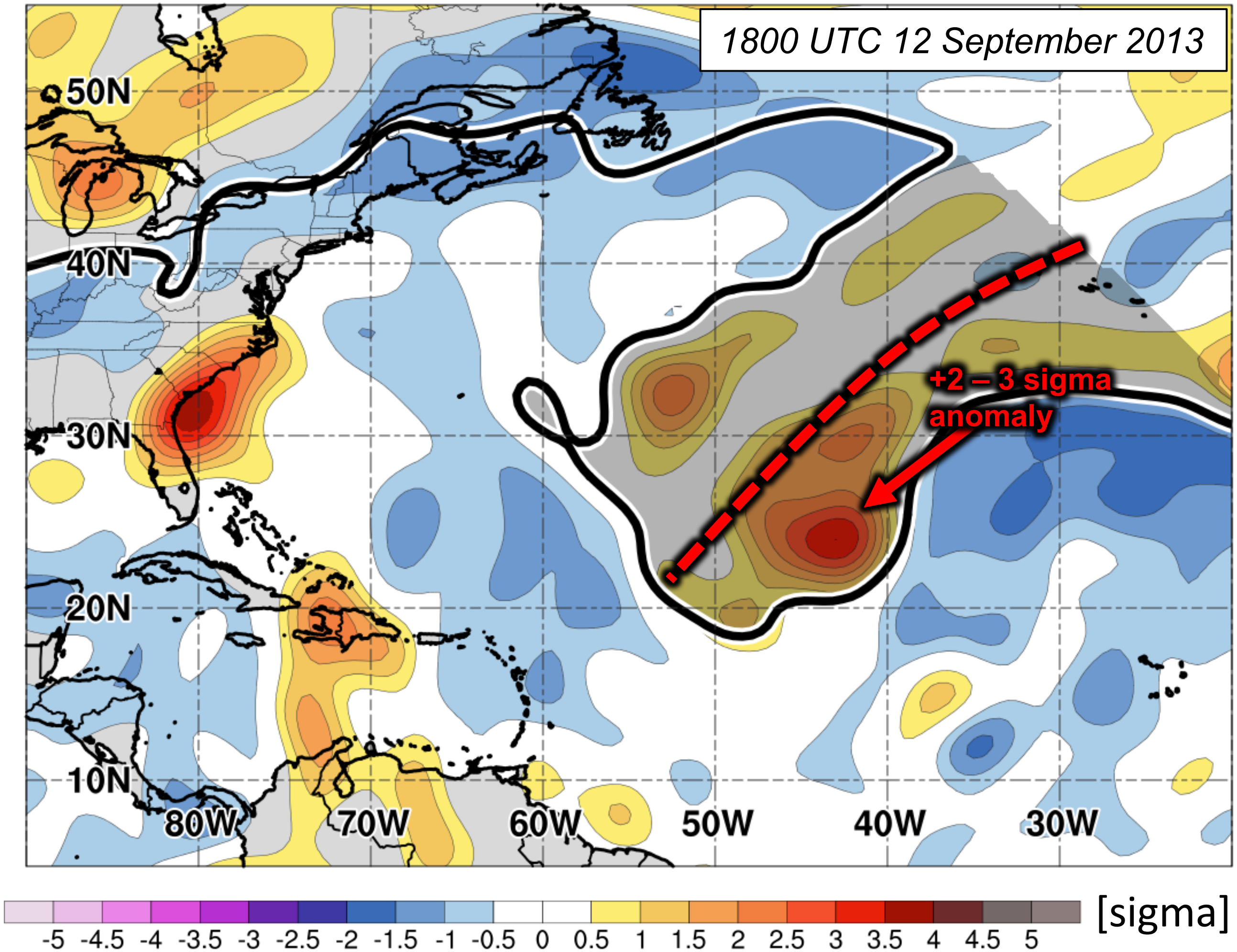

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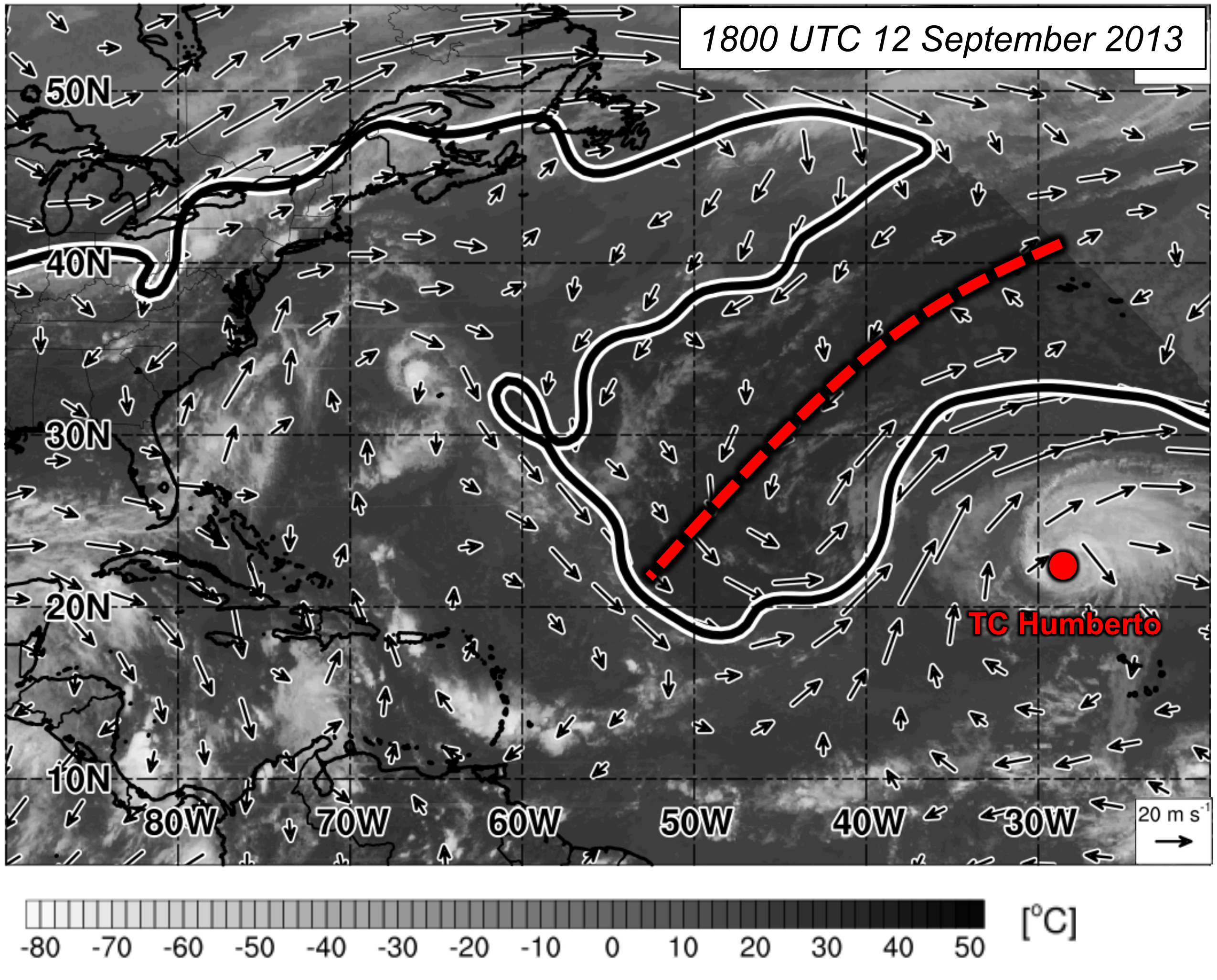

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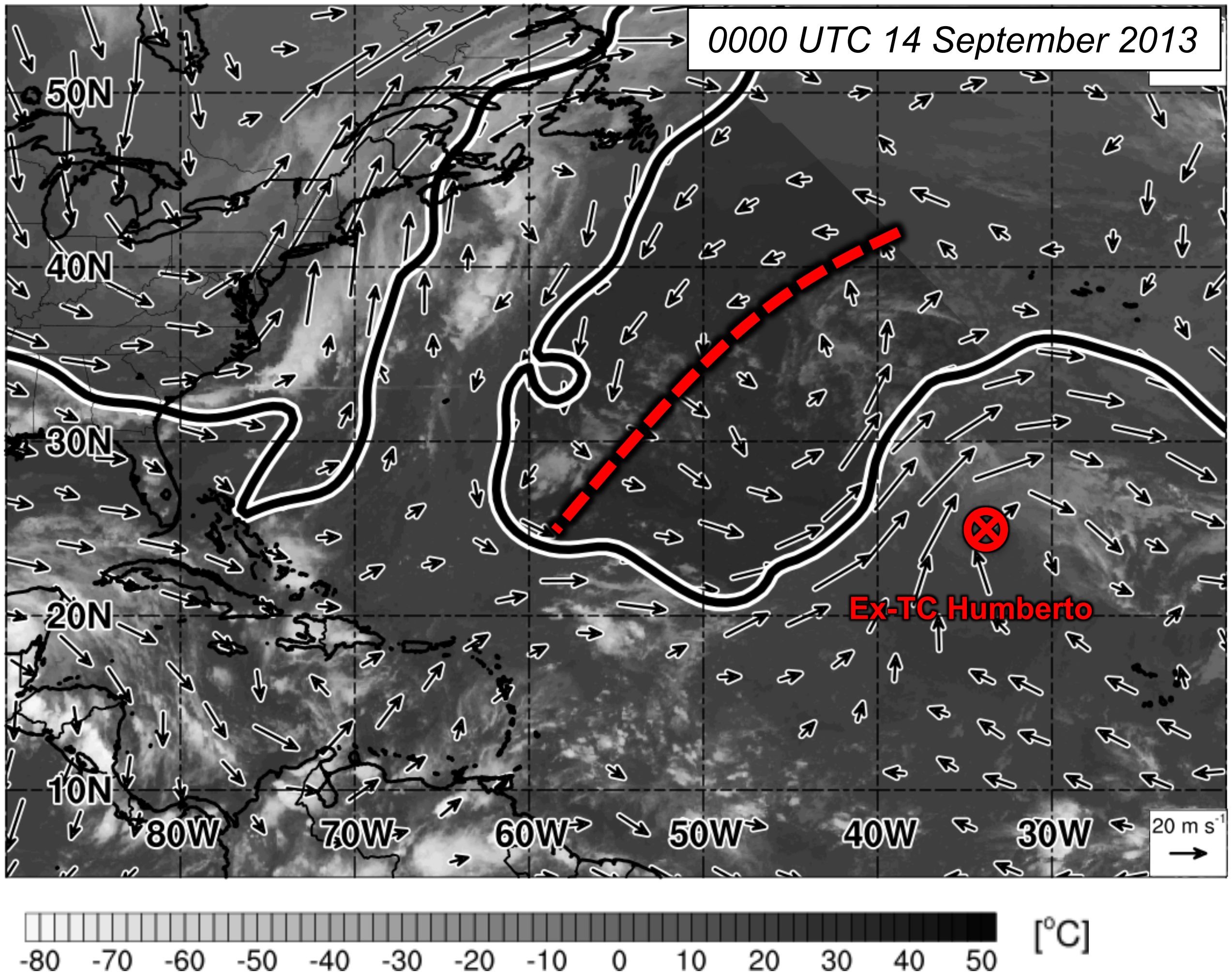
These cases illustrate how different PV streamers alter the environment of TCs in their vicinity

200–850-hPa vertical wind shear (vectors, m s$^{-1}$), 2-PVU contour (black line)



# Outline

- Introduction
  - Motivation
  - Literature review of PV Streamers
- Methodology
  - Identification of PV Streamers
  - Unique characteristics associated with each PV streamer
- Results
  - Climatological characteristics of PV streamers
  - Relationship with TC activity
  - Comparing composite PV streamers of different intensity

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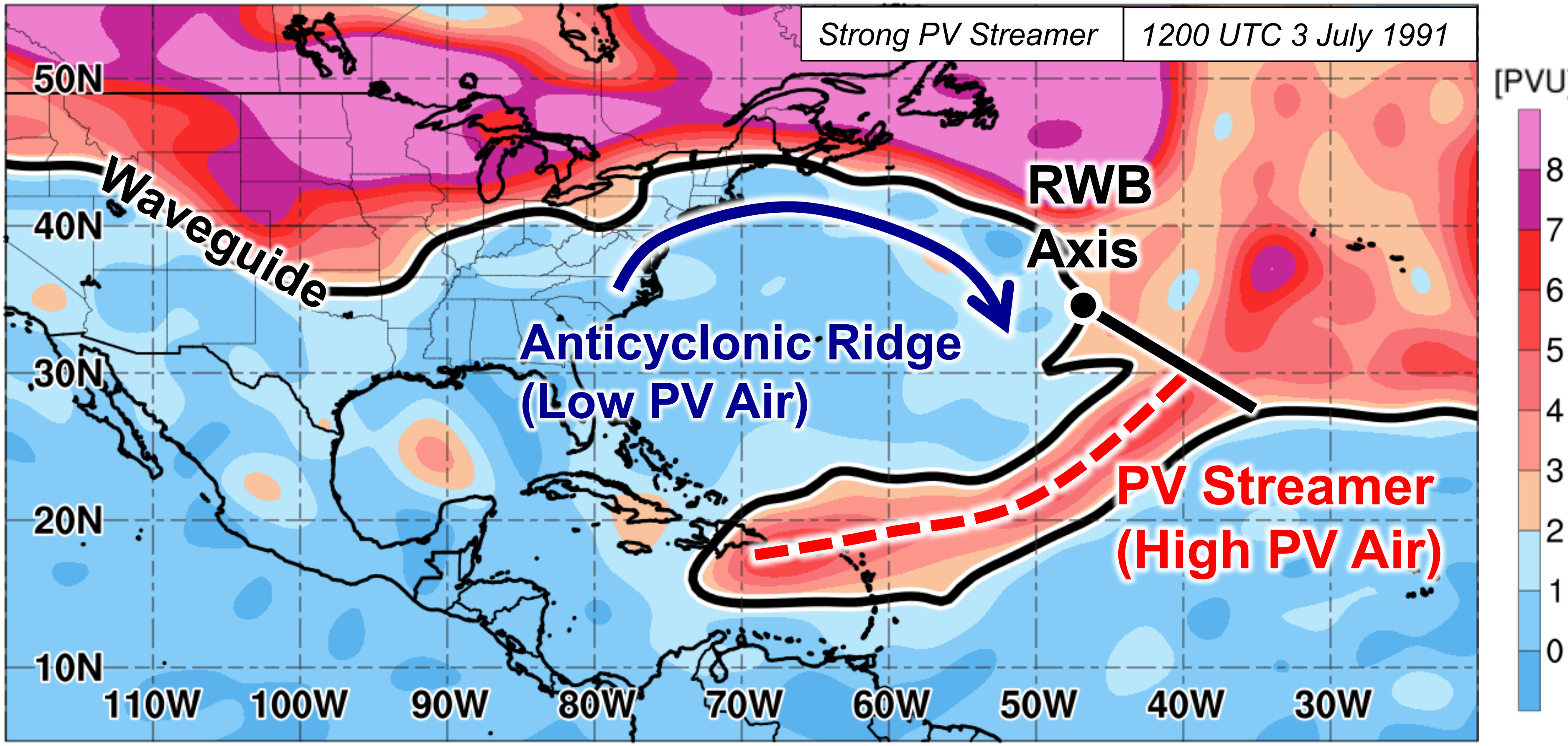
# Literature Review

# Literature Review

- Potential vorticity (PV) streamers are elongated filaments of high PV air
  - Occur in tandem with Rossby wave breaking (RWB)
  - Occur in the subtropical Atlantic with anticyclonic RWB (AWB)
  - Often Impact tropical cyclone (TC) activity in the Atlantic basin (McTaggart-Cowan et al. 2013, Galarneau et al. 2015)

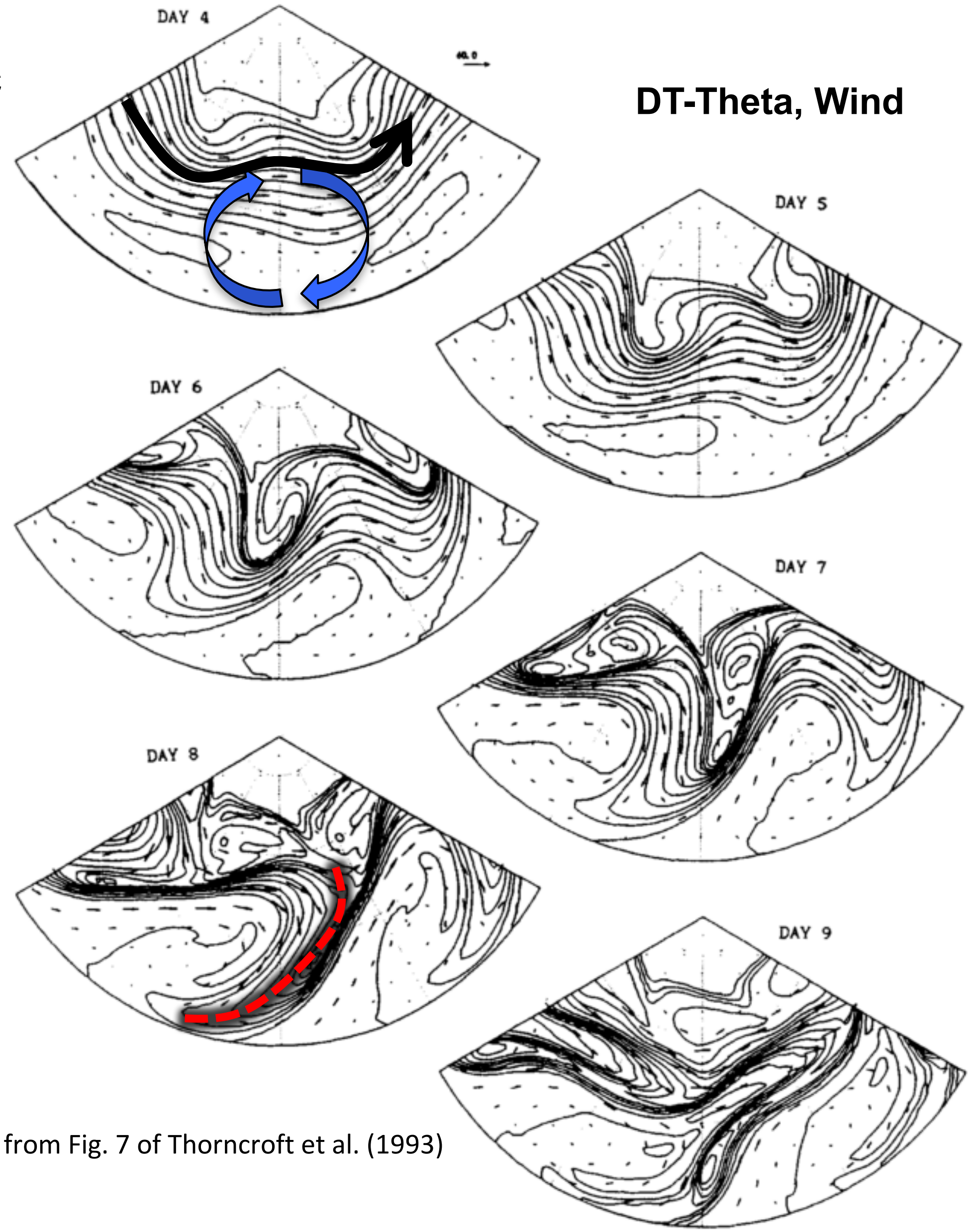
350-K PV (shaded, PVU), 2-PVU contour (black line)



# Literature Review: Rossby Wave Breaking

- RWB Manifests as two characteristic baroclinic wave lifecycles
  - ✧ Anticyclonic Wave Breaking (LC1, AWB)
  - ✧ Cyclonic Wave Breaking (LC2, CWB)
- Anticyclonic meridional shear found equatorward of the waveguide
  - ✧ Thin positively tilted PV streamer
- Cyclonic meridional shear found poleward of the waveguide
  - ✧ Thick negatively tilted PV streamer

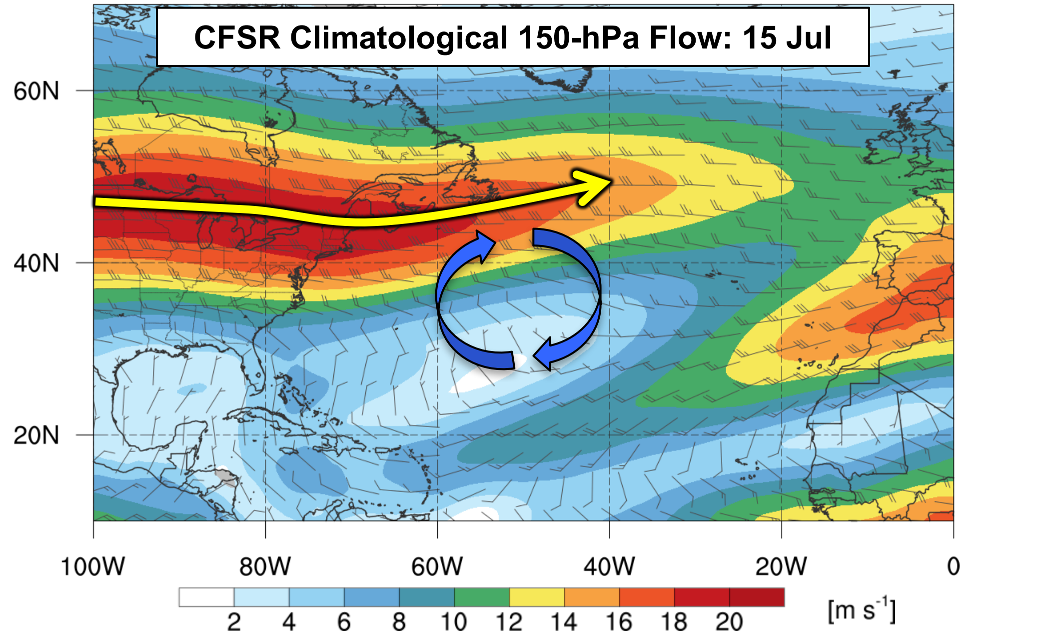
This study emphasizes the AWB pathway of occurrence

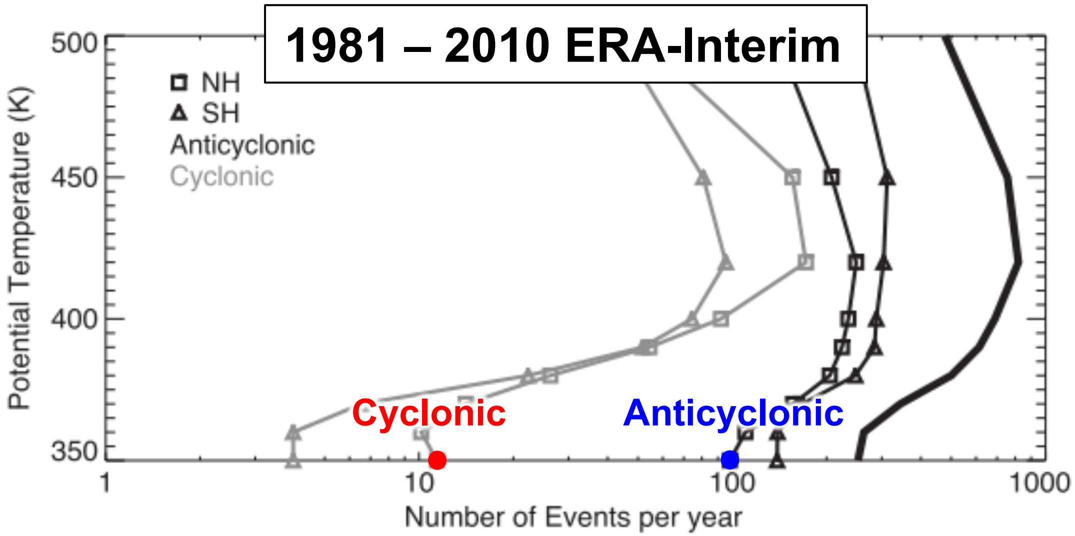



Adapted from Fig. 7 of Thorncroft et al. (1993)

# Literature Review: RWB Frequency

- Anticyclonic RWB is much more common in subtropical latitudes
  - ✧ Equatorward of waveguide, background barotropic meridional shear is anticyclonic
- Results in primarily positively oriented PV streamers in low latitudes

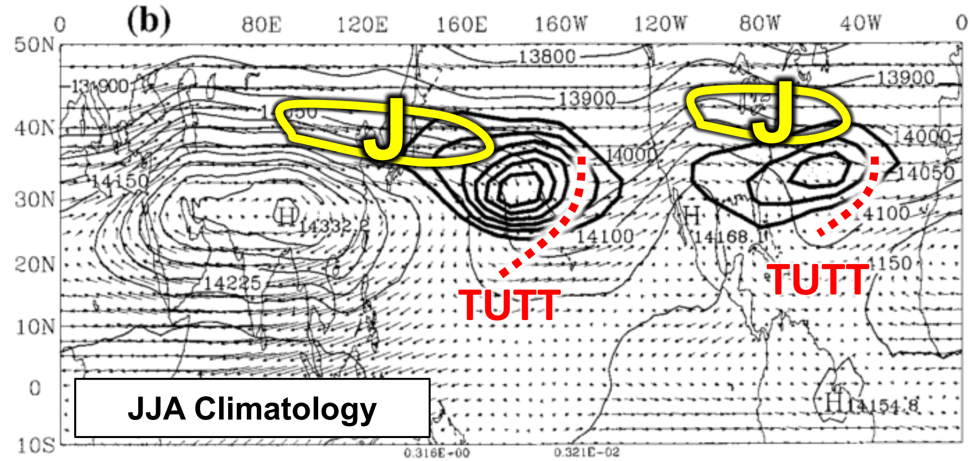


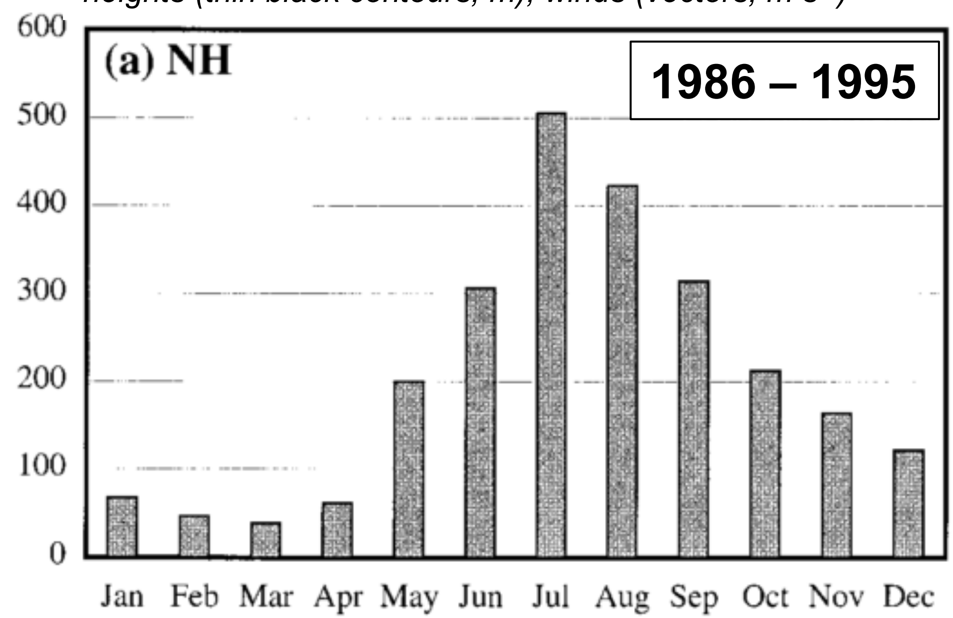

Adapted from Figs. 5 of Homeyer and Bowman (2013)

# Literature Review: RWB Frequency

- RWB is favored over oceanic basins near jet exit regions
- RWB frequency peaks in the warm season when the time-mean flow along the waveguide is the weakest
- A weaker waveguide allows more perturbations in flow to become significant relative to the time mean flow (Holton 2004).



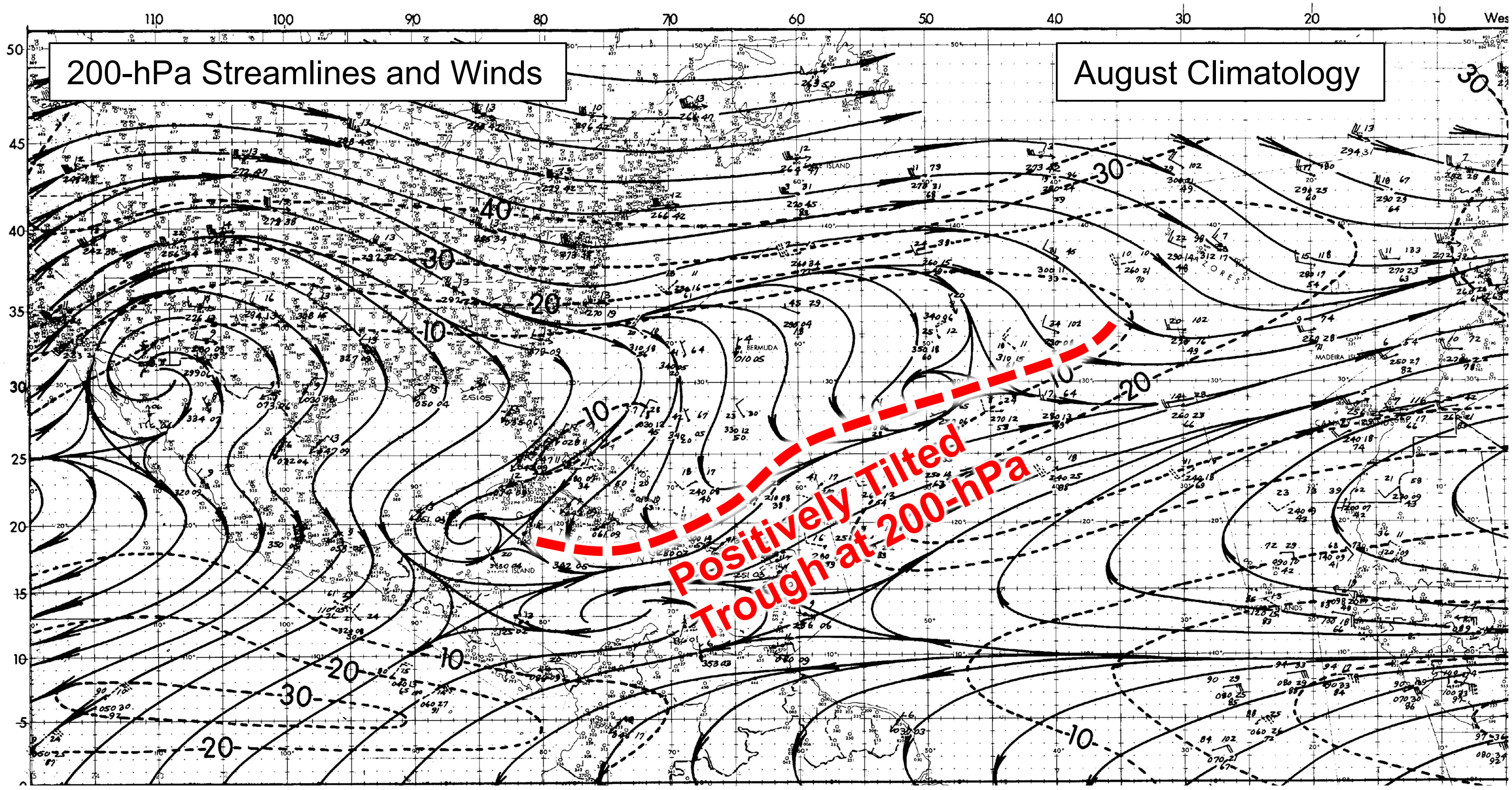

*RWB frequency (thick black contours), 150-hPa geopotential heights (thin black contours, m), winds (vectors, m s$^{-1}$)*




Adapted from Figs. 3a and 4b of Postel and Hitchman (1999)

# Literature Review: RWB Linkage to TUTTs

- Tropical Upper-Tropospheric Trough (TUTT) are located in both the subtropical NPAC and NATL basins (Sadler 1975, 1976)
  - Also called Mid Ocean Troughs (MOTs) in the time mean
- The dynamical component of the TUTT/MOT has been described in literature as PV streamers (Postel and Hitchman 1999; McTaggart Cowan et al. 2013)




Adapted from Sadler (1975)

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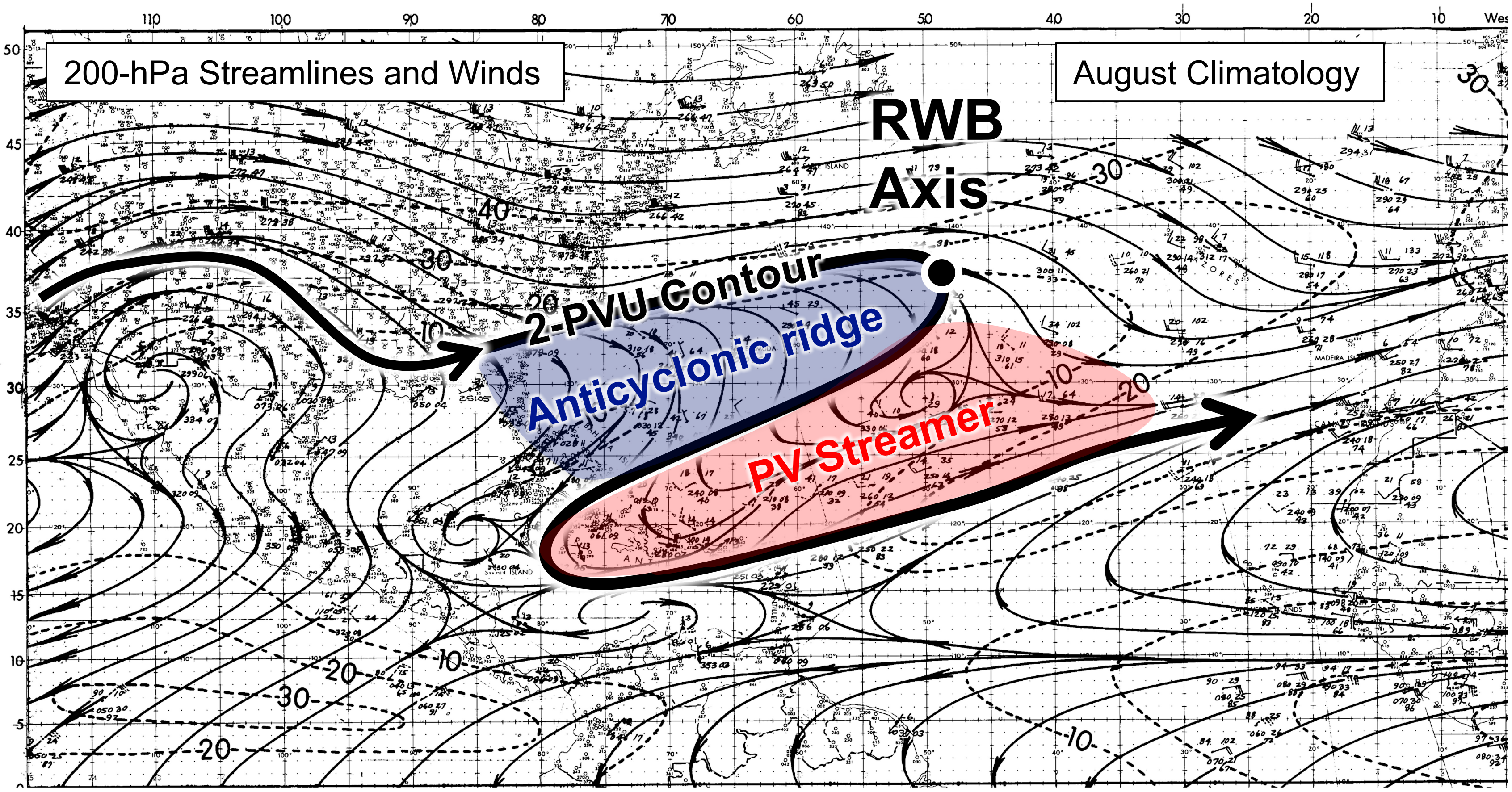


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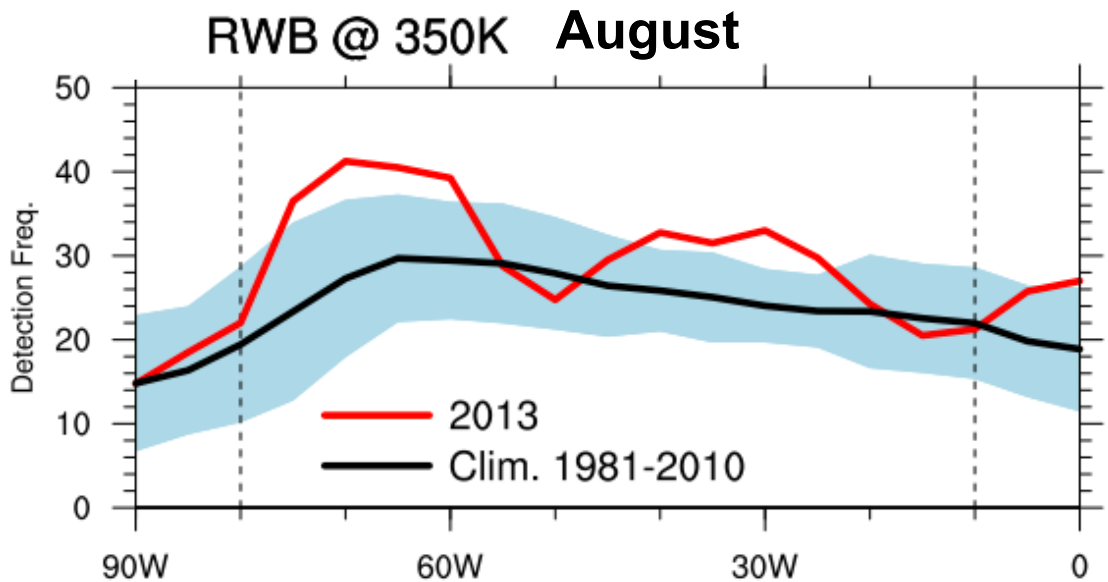
# Literature Review: RWB Impact on TC Activity

- Recent research by Zhang et al. (2016) on the frequency of RWB in the Atlantic basin has revealed a significant negative correlation with tropical cyclone (TC) activity in August.

| | HurrN | TSN | ACE |
|---|---|---|---|
| RWBFreq | **-0.47** | **−0.39** | **−0.49** |
| MDR | **0.43** | **0.54** | **0.47** |
| RSST | **0.50** | **0.57** | **0.50** |
| Niño-3.4 | **-0.35** | −0.26 | **−0.34** |
| SahelR | **0.34** | 0.30 | 0.30 |
| HC1 | **-0.45** | **−0.36** | **−0.41** |
| NAO/CPC | -0.19 | −0.23 | −0.02 |
| NAO/Jones | -0.21 | −0.19 | −0.26 |




*Adapted from Table 1 and Fig. 5a in Zhang et al. (2016)*

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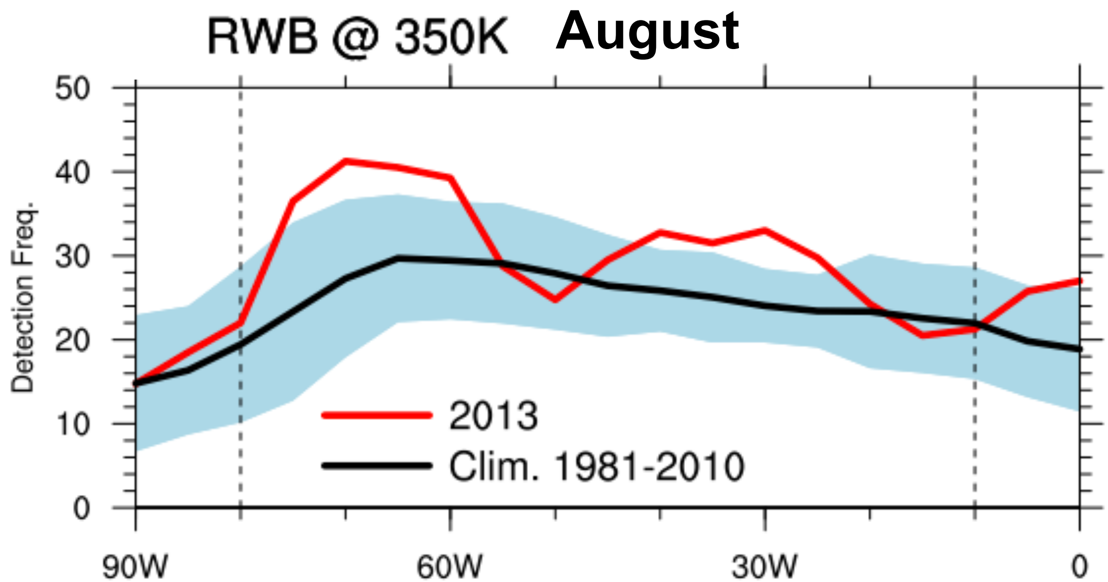
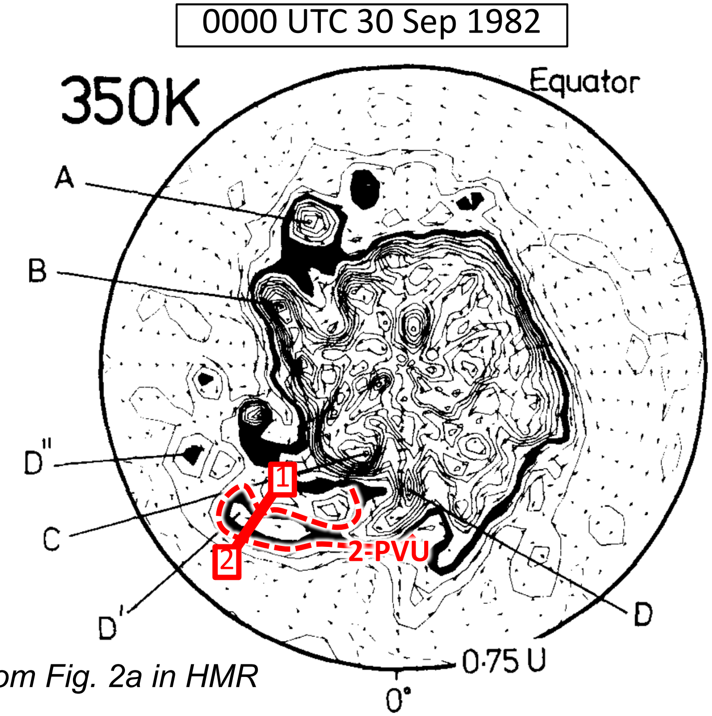



*Adapted from Table 1 and Fig. 5a in Zhang et al. (2016)*

However, not all RWB events are created equal!

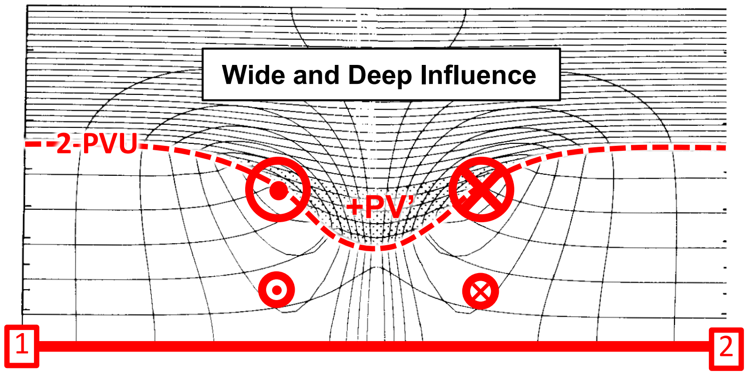
# Literature Review: PV Streamer Intensity

- PV streamer intensity impacts its ability to affect the troposphere below
  - ✧ Stronger intensity and larger size enable deeper and wider pertubation flow associated with the PV streamer
  - ✧ Impacts vertical wind shear, nearby tropospheric static stability, and moisture anomalies
  - ✧ Static stability of the troposphere affects size and intensity of pertubation flow



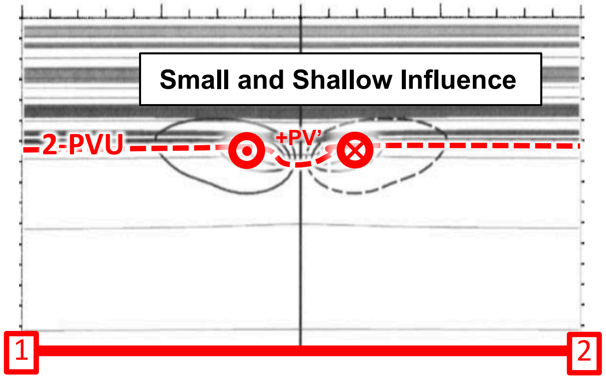

*Adapted from Fig. 2a in HMR*

## Strong PV Streamer




*Adapted from Fig. 15a of HMR*

## Weak PV Streamer

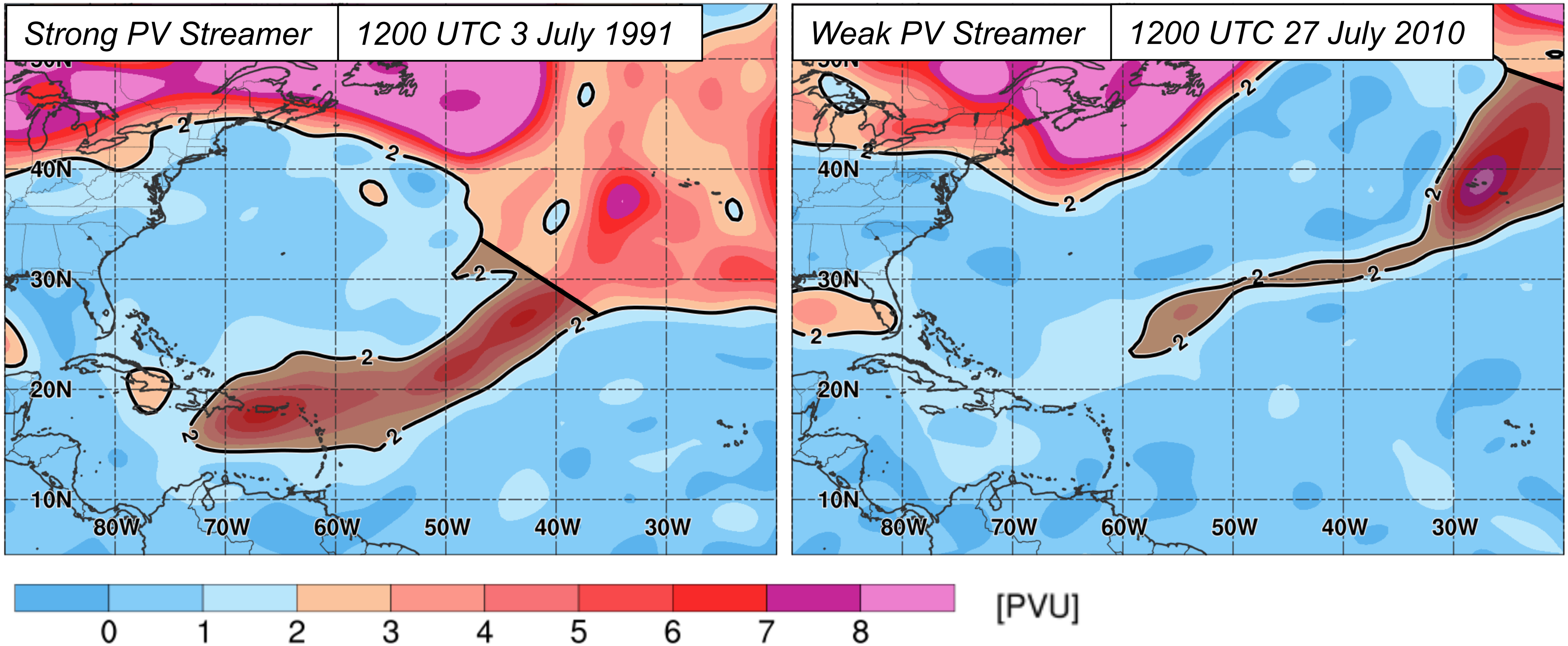



*Adapted from Fig. 1 of Juckes and Smith (2000)*

# Literature Review: PV Streamer Intensity

- We hypothesize that in addition to RWB frequency, the size and intensity of the PV streamers they produce may significantly alter seasonal TC Activity
  - Different sizes and intensities may modify important variables for TC intensity
    - Vertical Wind Shear (VWS)
    - Moisture (PW)

350-K PV (shaded, PVU), 2-PVU contour (black line)



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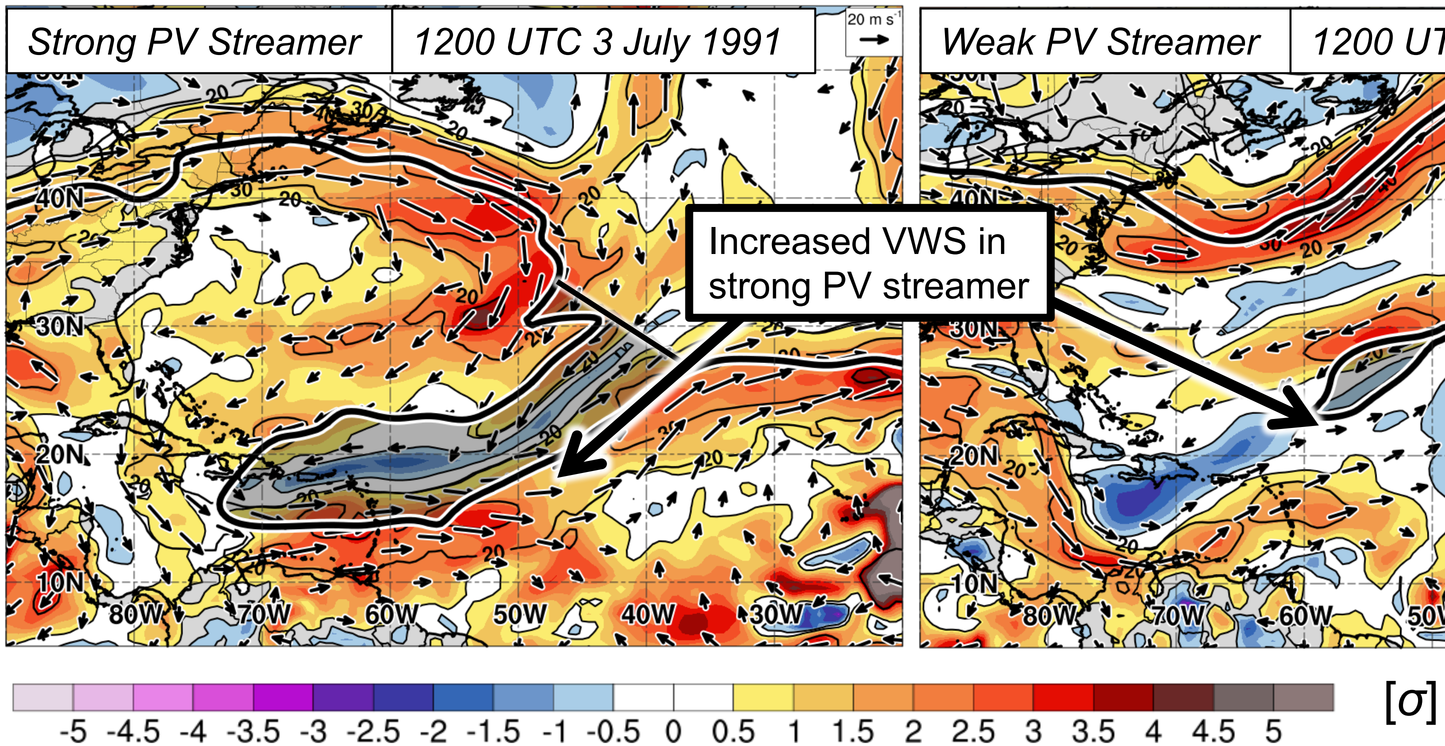
200–850-hPa Vertical Wind Shear Magnitude (black contours, m s$^{-1}$), Direction (vectors), Normalized Anomaly (shaded, $\sigma$)



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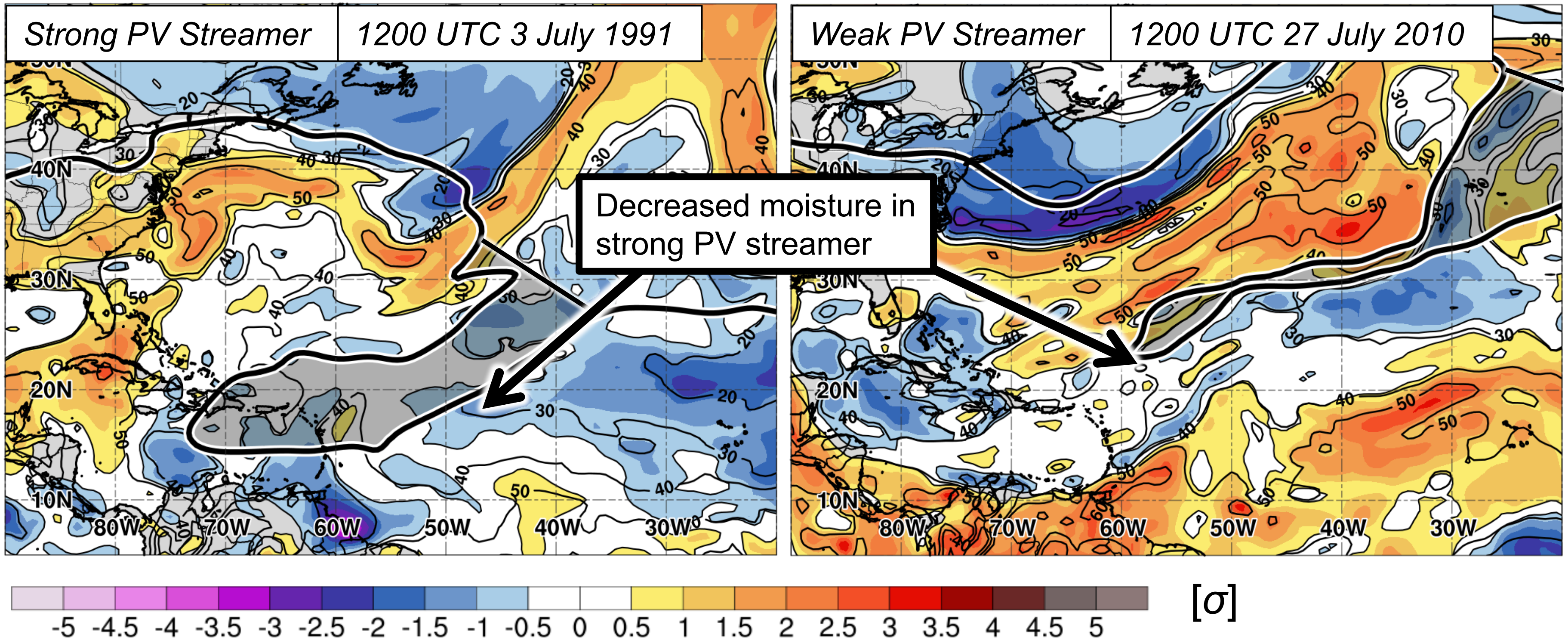
Precipitable Water (black contours, mm), and Normalized Anomaly (shaded, σ)



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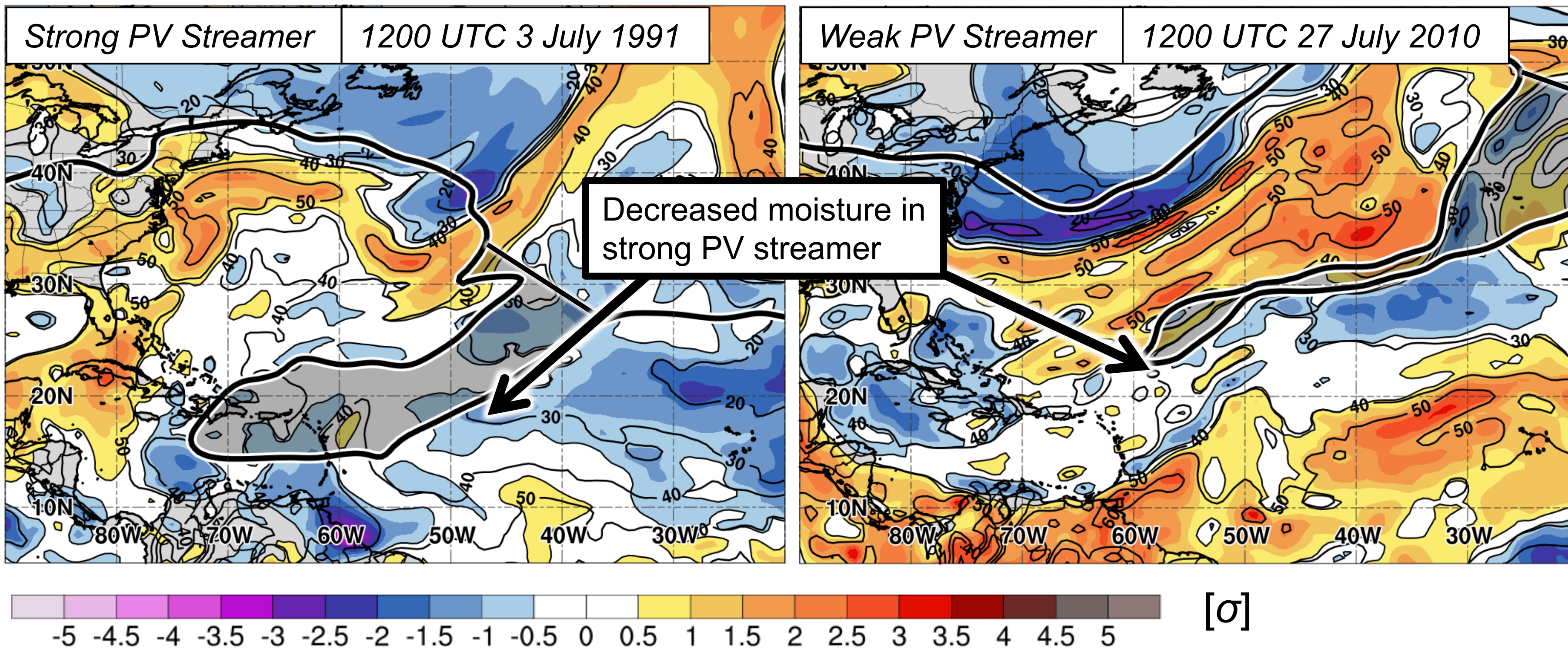



We will investigate this hypothesis by composing a climatology that will quantify the size and intensity variations of PV streamers

# Methodology:
## PV Streamer Identification

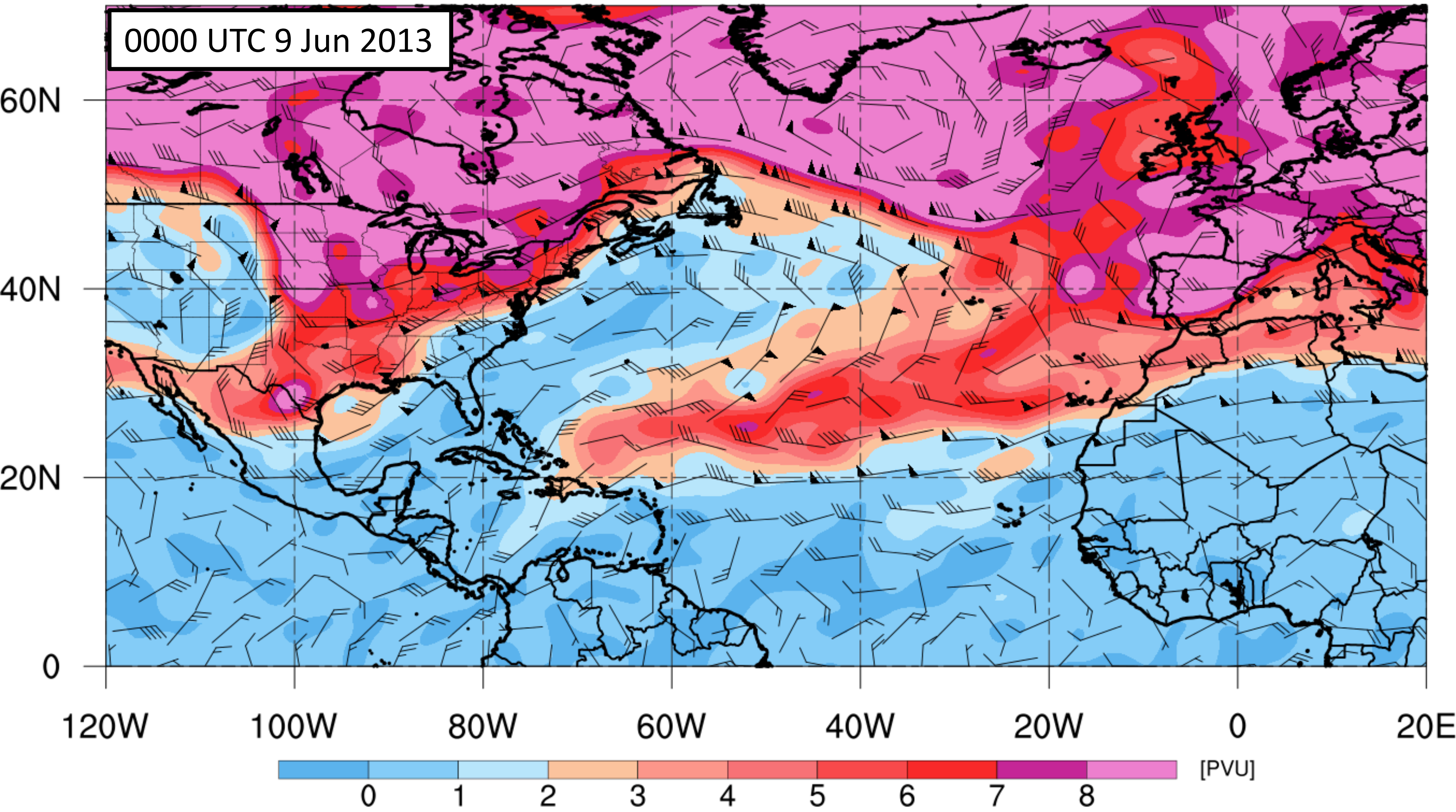
# Methodology: PV Streamer Identification

- PV streamers are identified from June–November 1979–2015 using the 0.5$^{o}$ NCEP CFSR (Saha et al. 2010).
- A new PV streamer algorithm is created that combines previous methodologies
  - Postel and Hitchman (1999)
    - ✧ Identifies locations where RWB occurs (meridional gradient reversal in PV)
  - Wernli and Sprenger (2007)
    - ✧ Identifies elongated filaments of high PV air using width and perimeter of PV streamer
- Identification of PV streamers occurs on a isentropic surface that approximates the location of the subtropical tropopause
  - 350-K surface using the 2-PVU contour as the dynamical tropopause

# Methodology: PV Streamer Identification

- Identify 2-PVU contour on 350-K surface

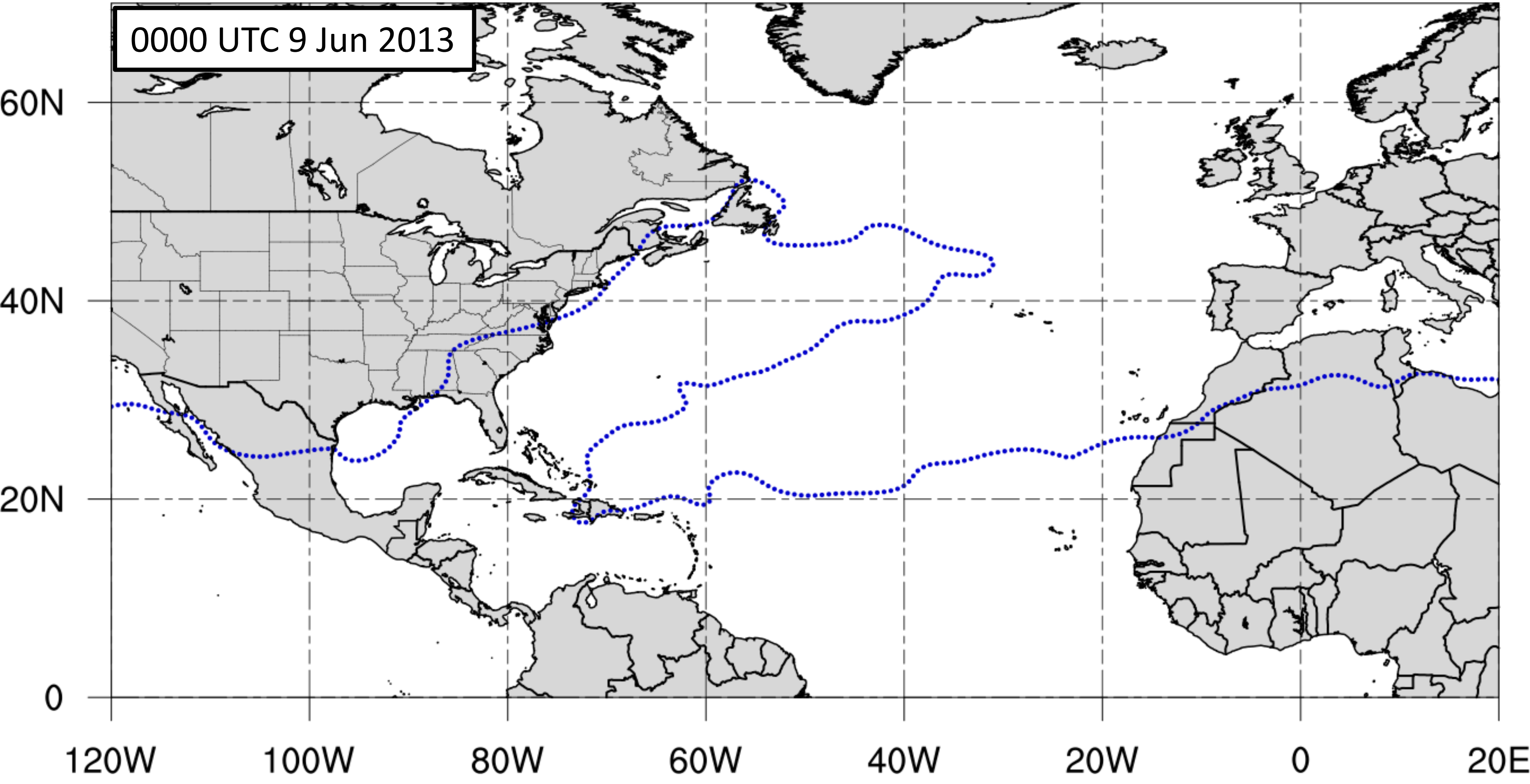
350-K PV (shaded, PVU), and winds (barbs, kt)



# Methodology: PV Streamer Identification

- Identify 2-PVU contour on 350-K surface

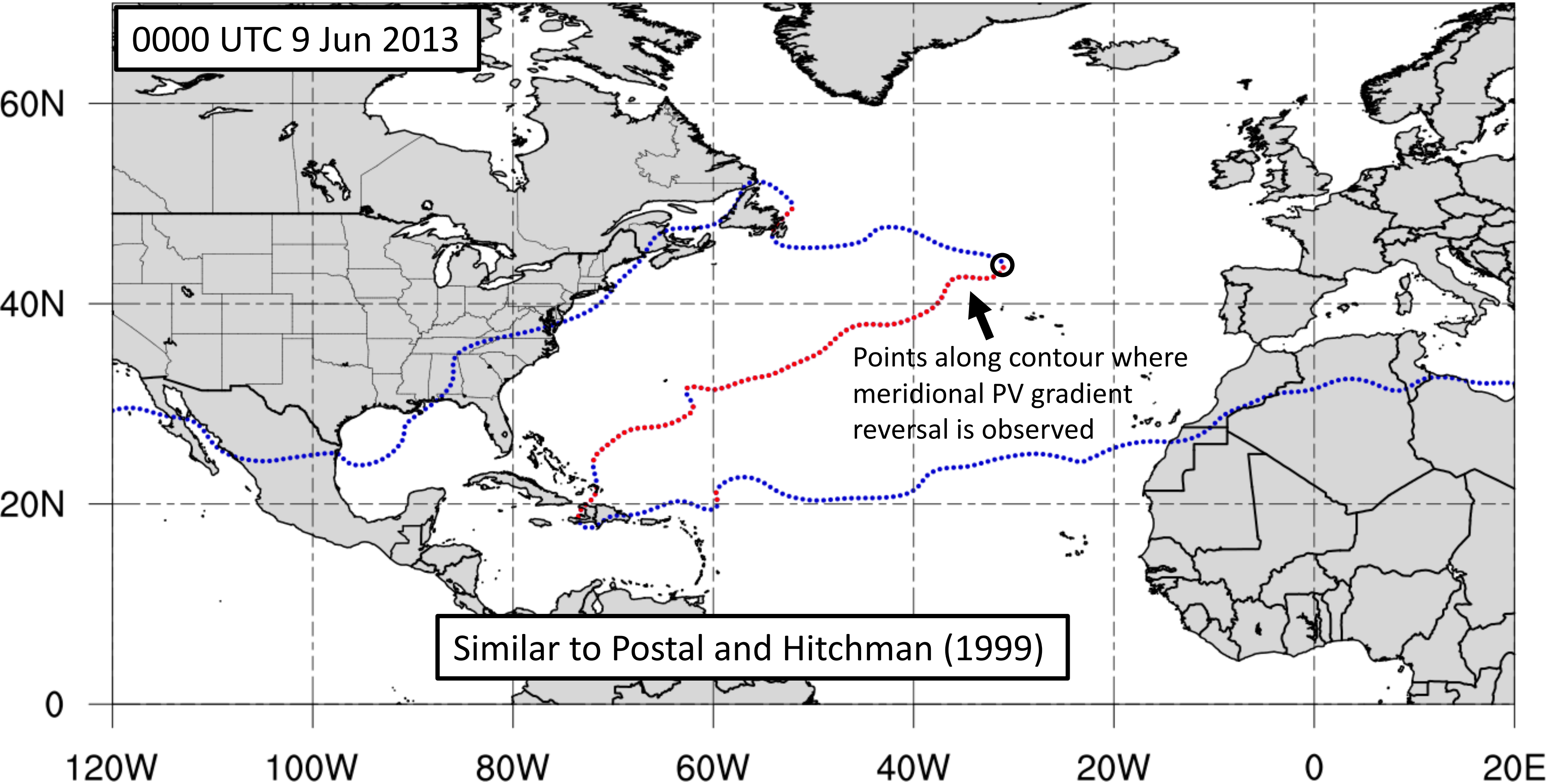
2-PVU contour on 350-K surface (blue contour)



# Methodology: PV Streamer Identification

- Identify all points along contour where meridional PV gradient reversal is observed
  - First point along meridional reversal chosen as starting point of PV streamer

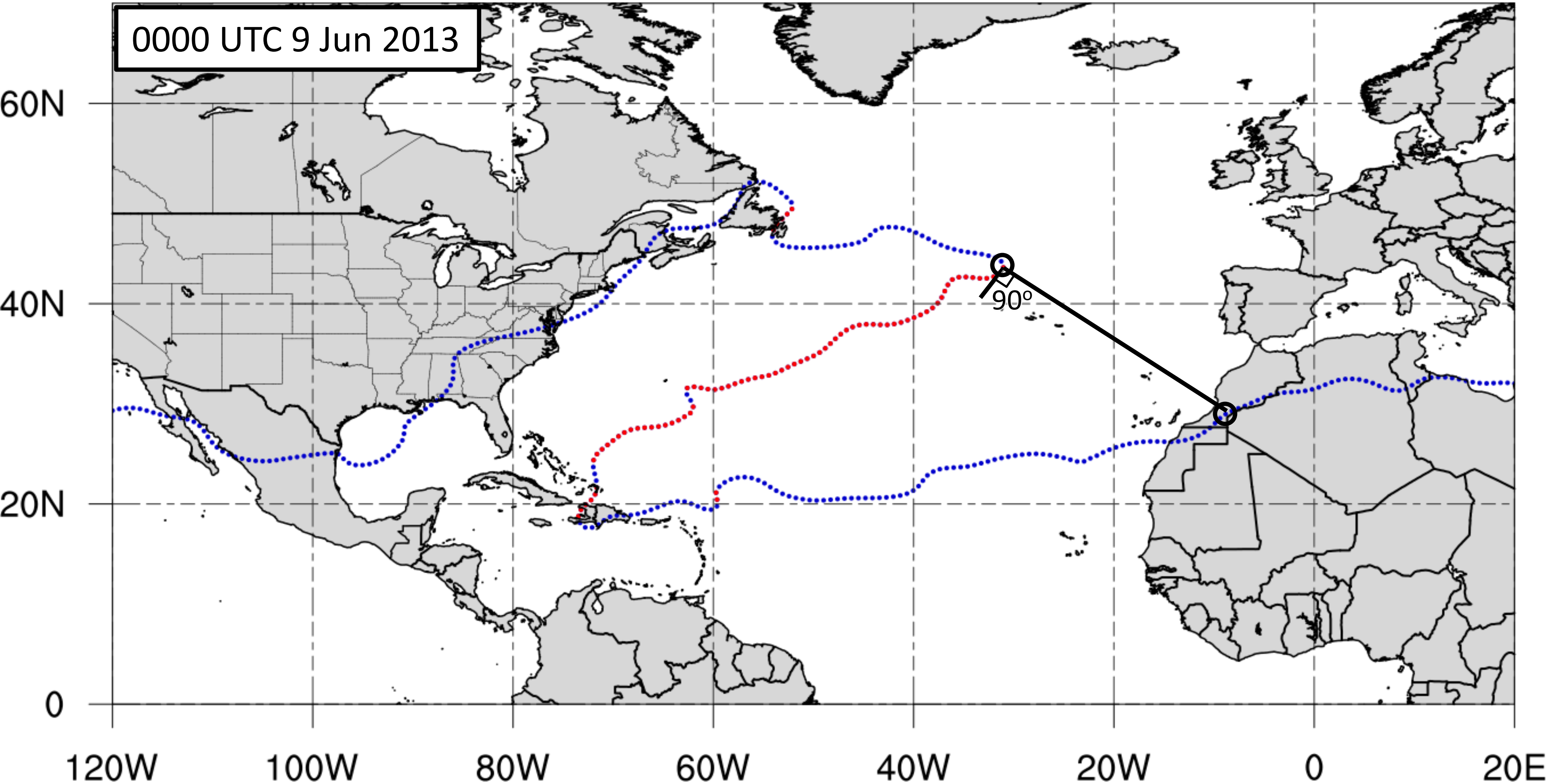
2-PVU contour on 350-K surface (blue contour), regions with meridional PV gradient reversal (red contour)



# Methodology: PV Streamer Identification

- Line drawn orthogonal to line made by first few points of PV reversal
- Line ends when line crosses 2-PVU contour downstream

2-PVU contour on 350-K surface (blue contour), regions with meridional PV gradient reversal (red contour)



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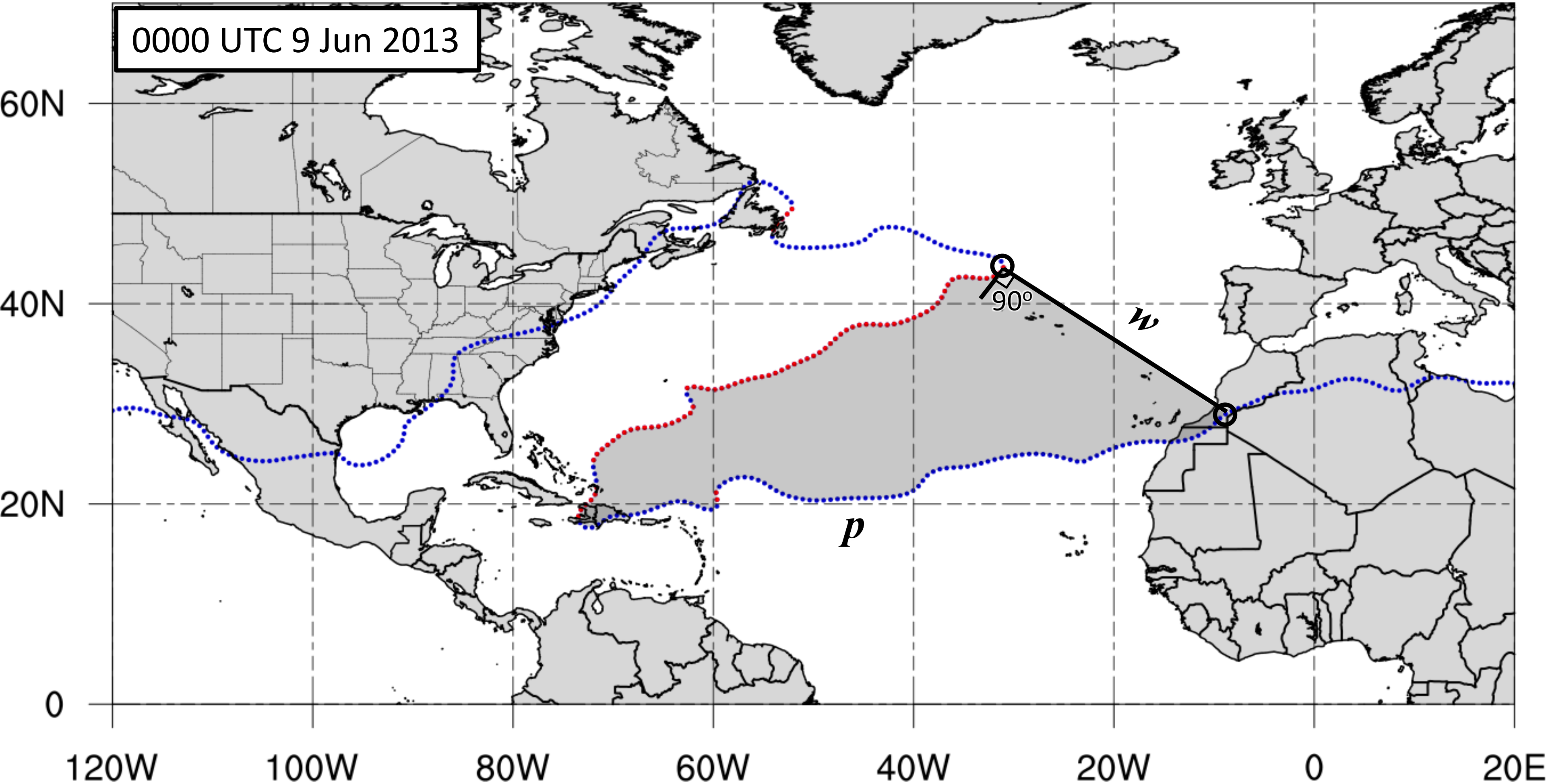
PV streamer area (black shading), *w* (width between two points), *p* (along contour perimeter between two points)

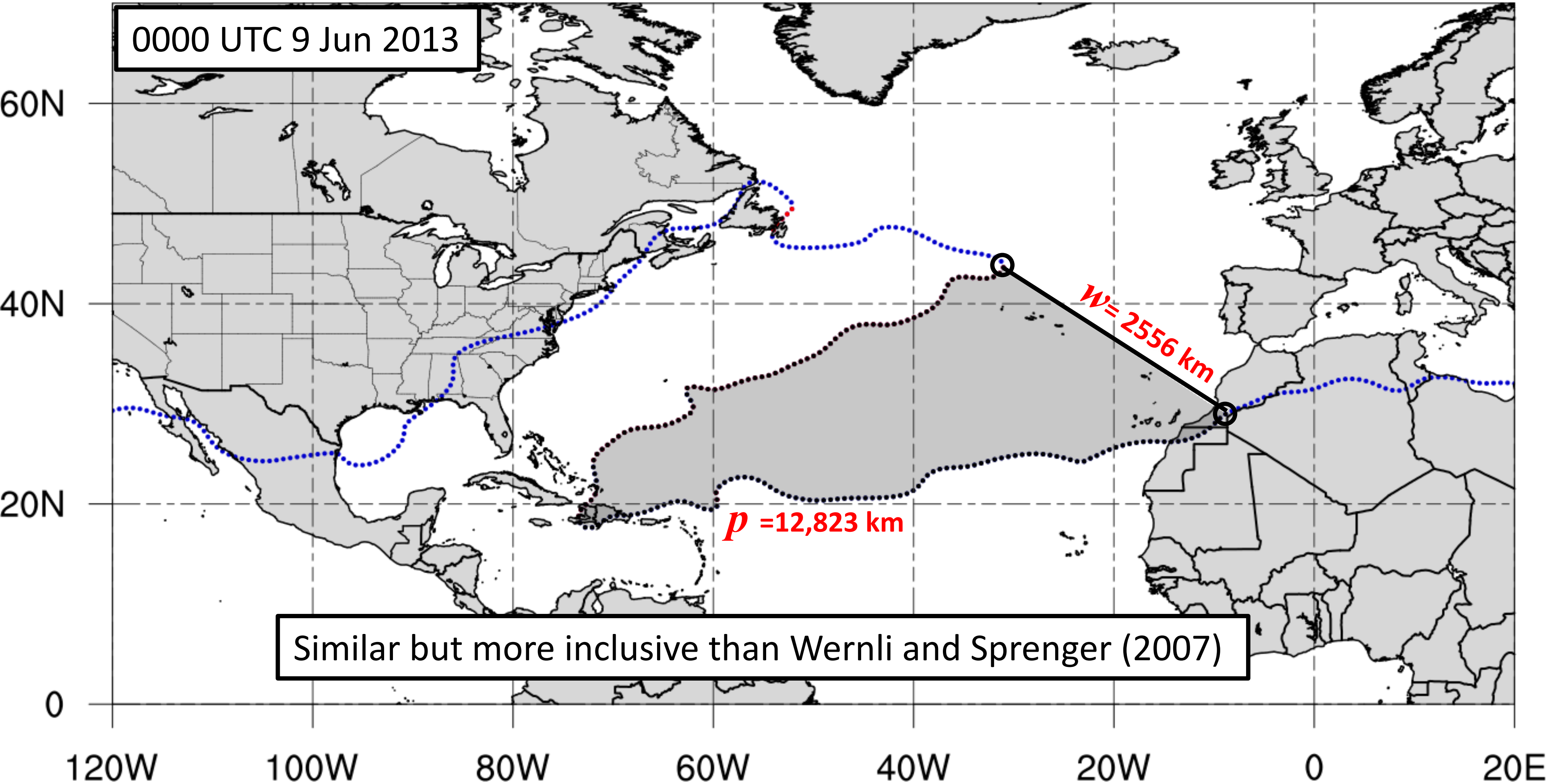


# Methodology: PV Streamer Identification

- Check if PV streamer candidate is large and elongated enough

**Threshold Values: *p* must be 3 times > than *w* and *p* > 3000 km**

PV streamer area (black shading), *w* (width between two points), *p* (along contour perimeter between two points)

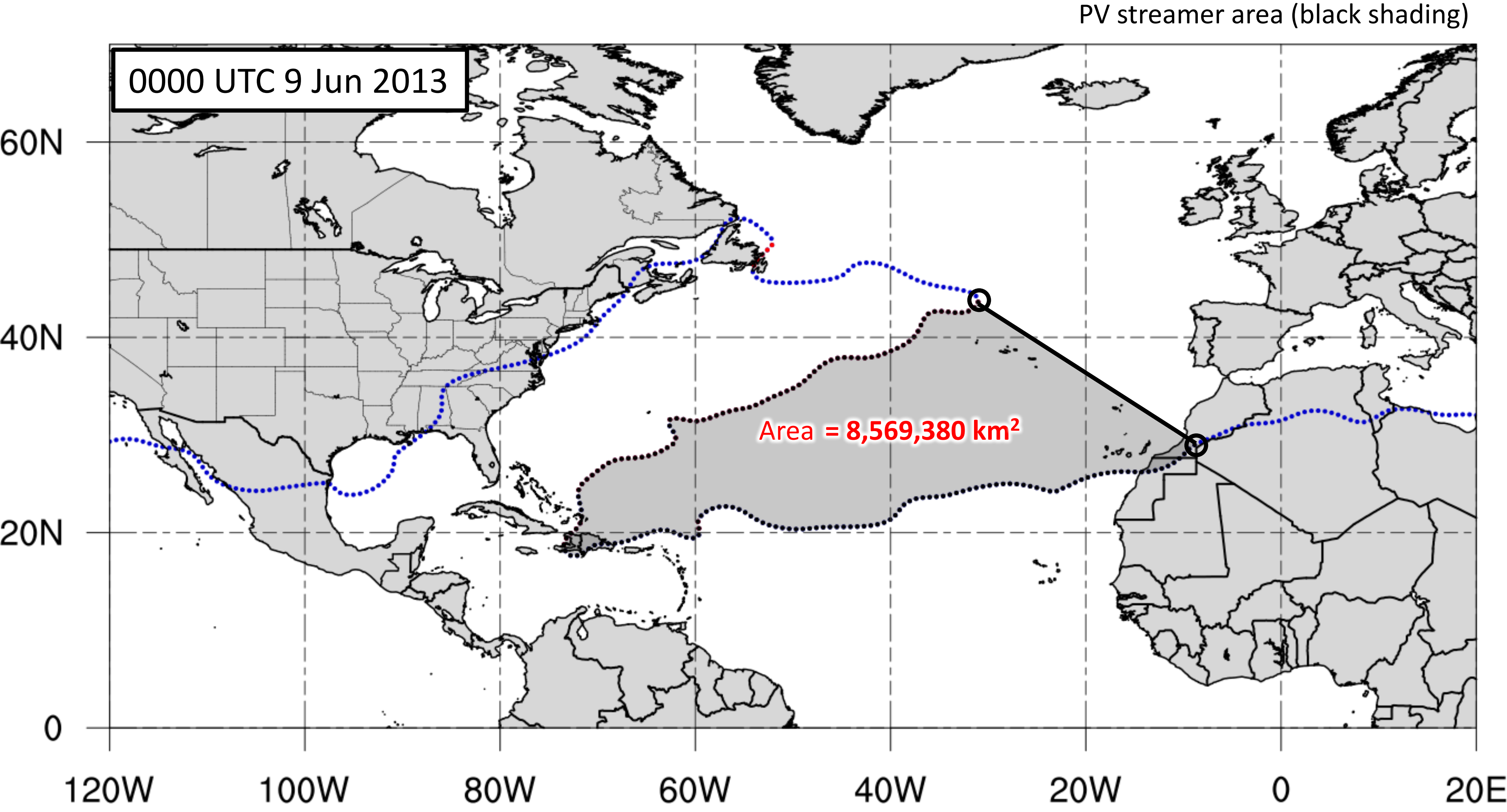


# Methodology:

## Unique PV Streamer Variables

# Methodology: PV Streamer Variables

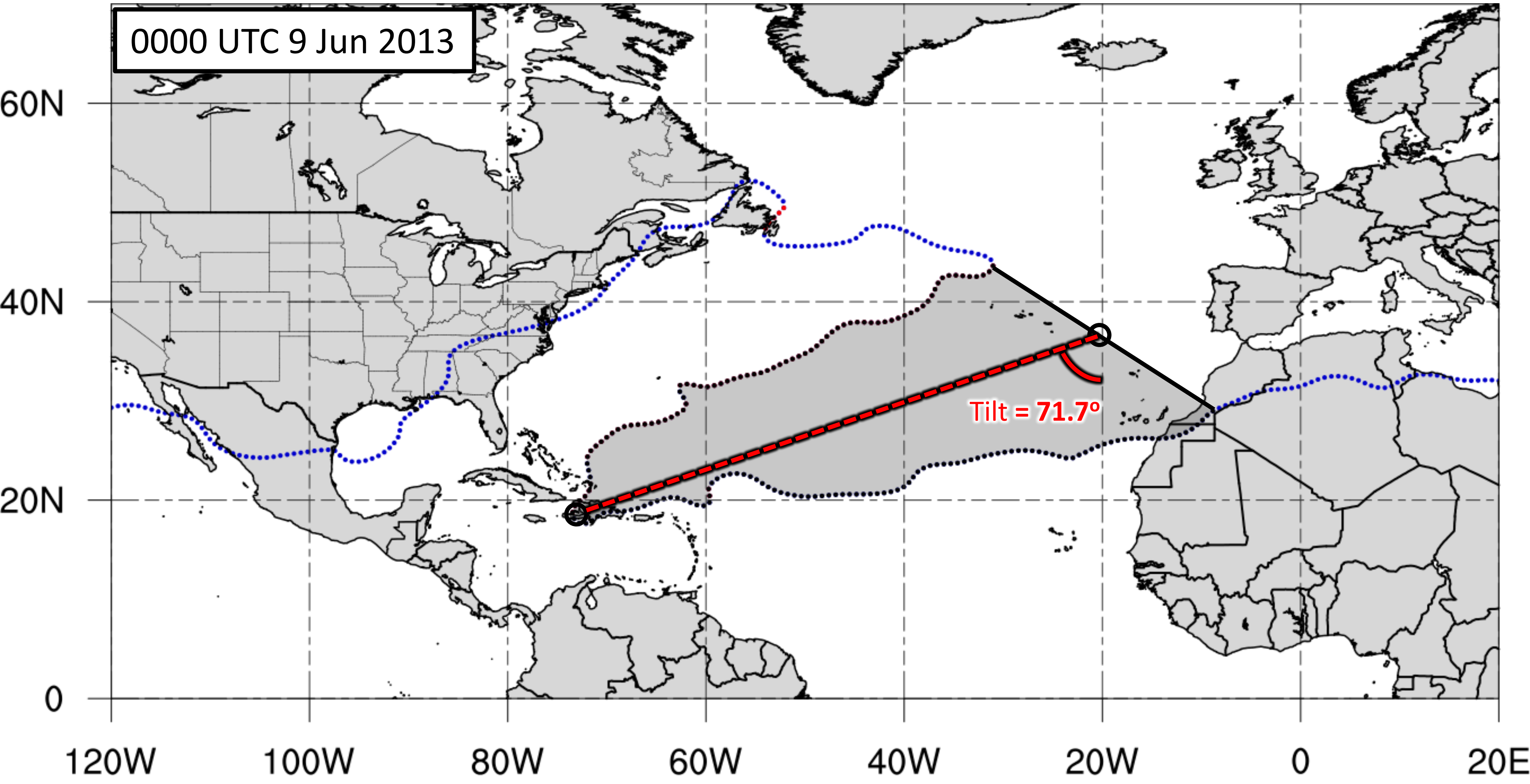
- **PV streamer Area**
  - An closed polygon allows us to calculate the area of the PV streamer



# Methodology: PV Streamer Variables

- **PV streamer Tilt**
  - First obtain midpoint between the start & end of PV streamer
  - Find furthest location from midpoint along PV streamer perimeter
  - Determine angle of line relative to N–S meridian

PV streamer area (black shading)



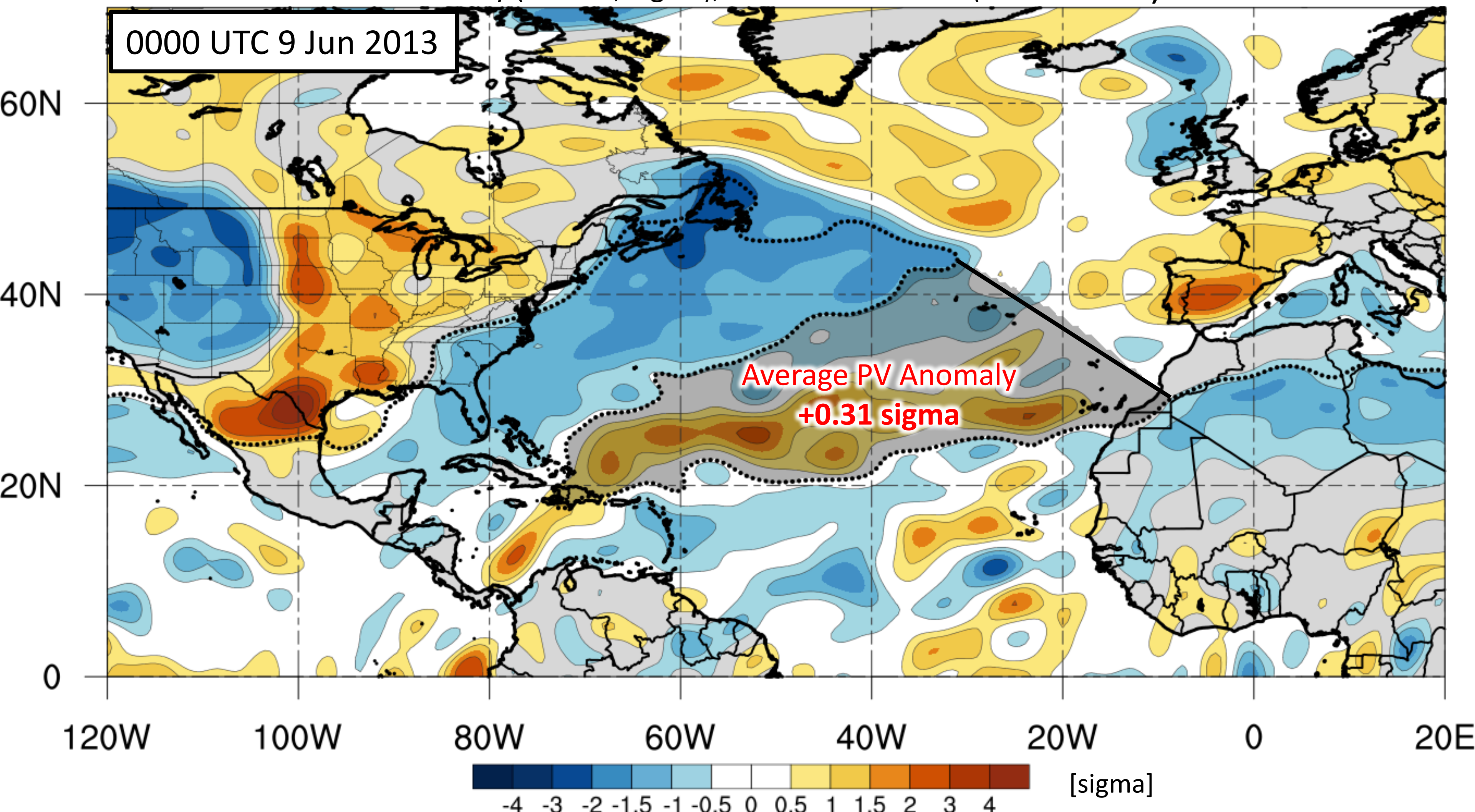
# Methodology: PV Streamer Variables

- **PV streamer Intensity**
  - Calculated as a standardized anomaly

$$PV_{std\_anom} = (PV - PV_{mean}) / PV_{sd}$$

Mean and Standard Deviations are derived from a 1979-2009 CFSR climatology

350-K Standardized PV Anomaly (shaded, Sigma), and 2-PVU contour (black contour)



# Results: PV Streamer Climatology

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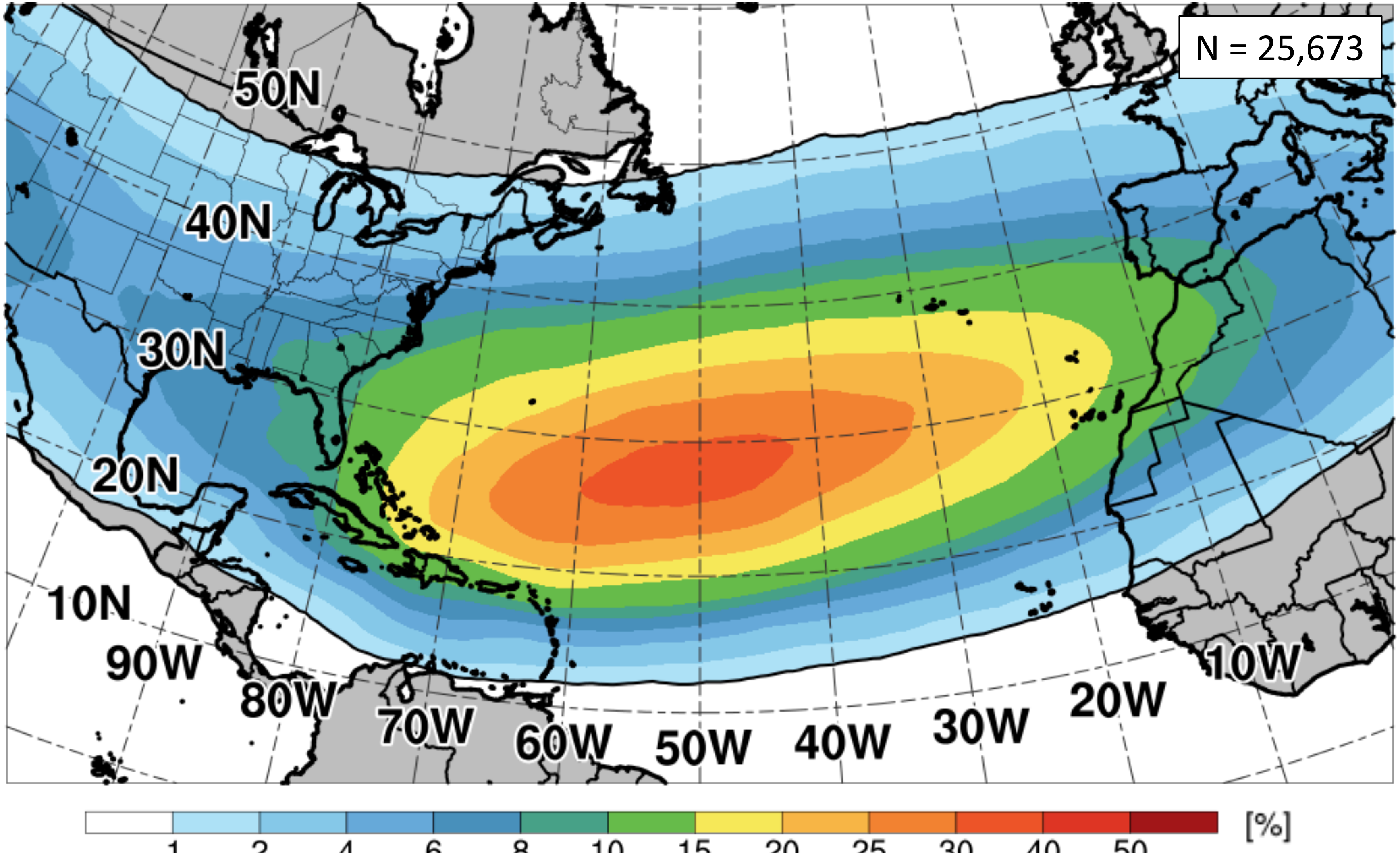
- PV streamer frequency in the North Atlantic
  - 1 Jun–30 Nov
    - Occurrence maximized on equatorward side of jet
    - Corresponds to climatological position of Mid-Ocean trough (i.e., TUTT)

Probability PV streamer is observed on any particular day (shading, %)



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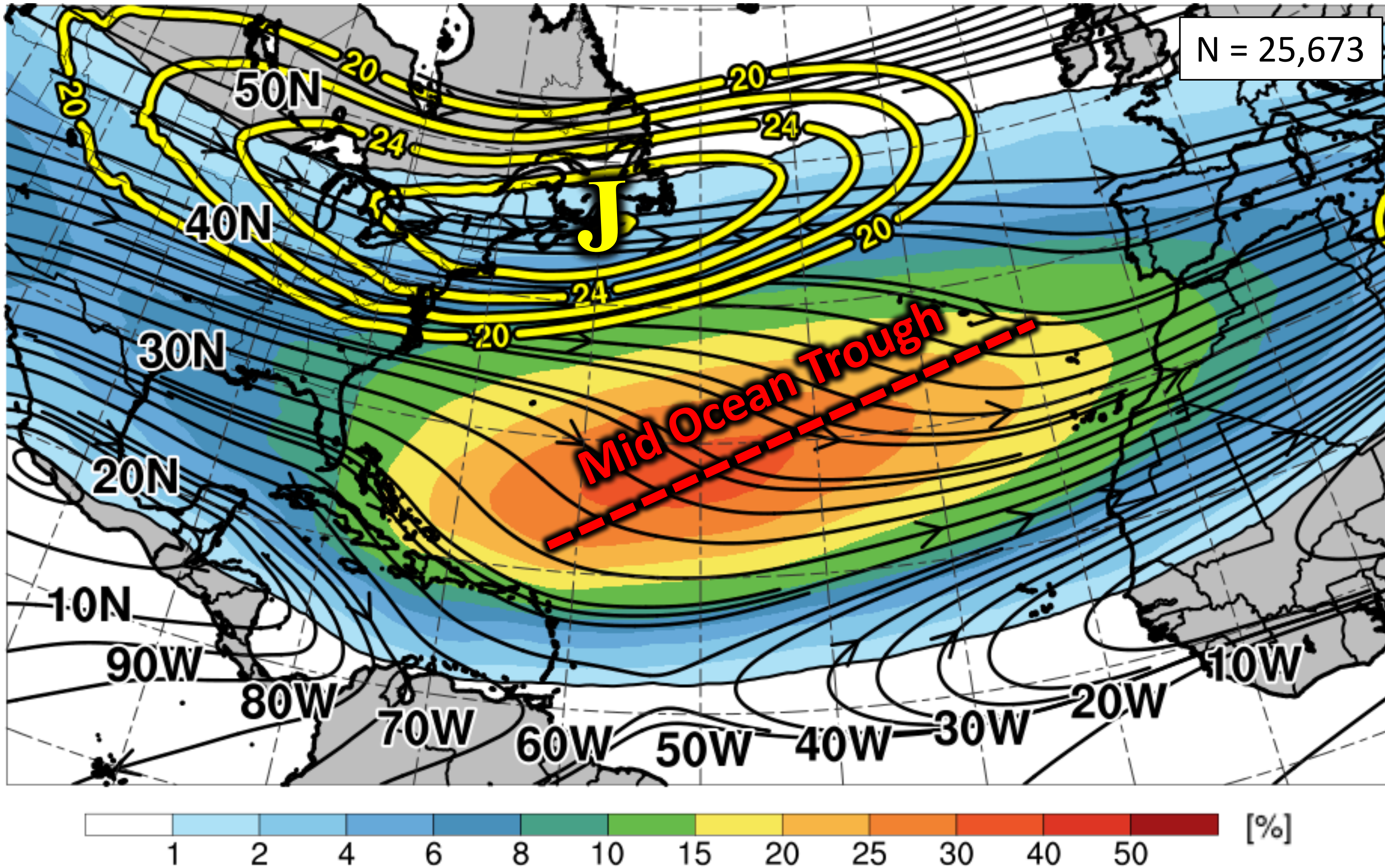
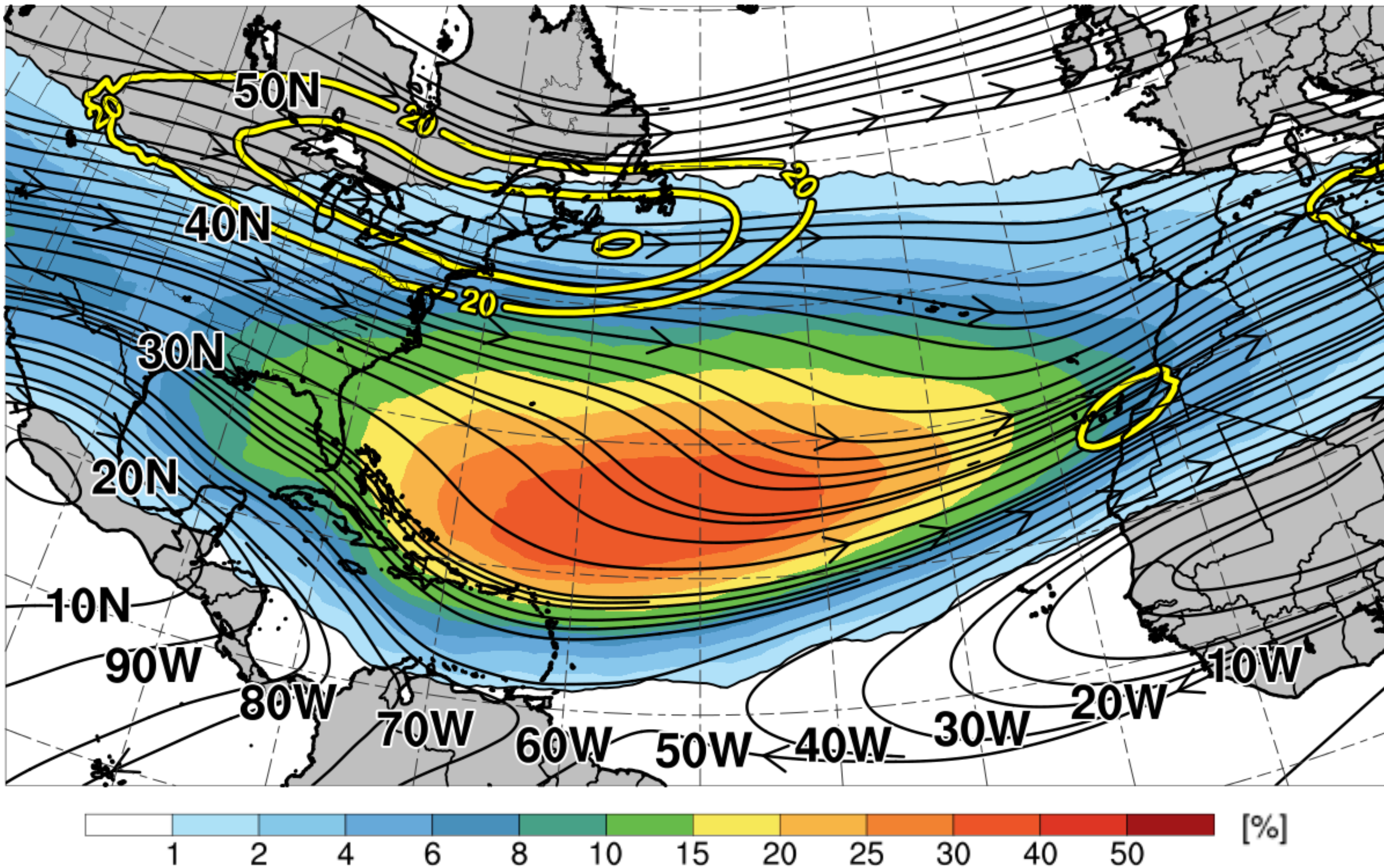


# Results: Month by Month

# Results: PV Streamer Climatology – June

- PV Streamer occurrence shifts over TC season
  - Westerlies dominate Atlantic basin at beginning of TC season

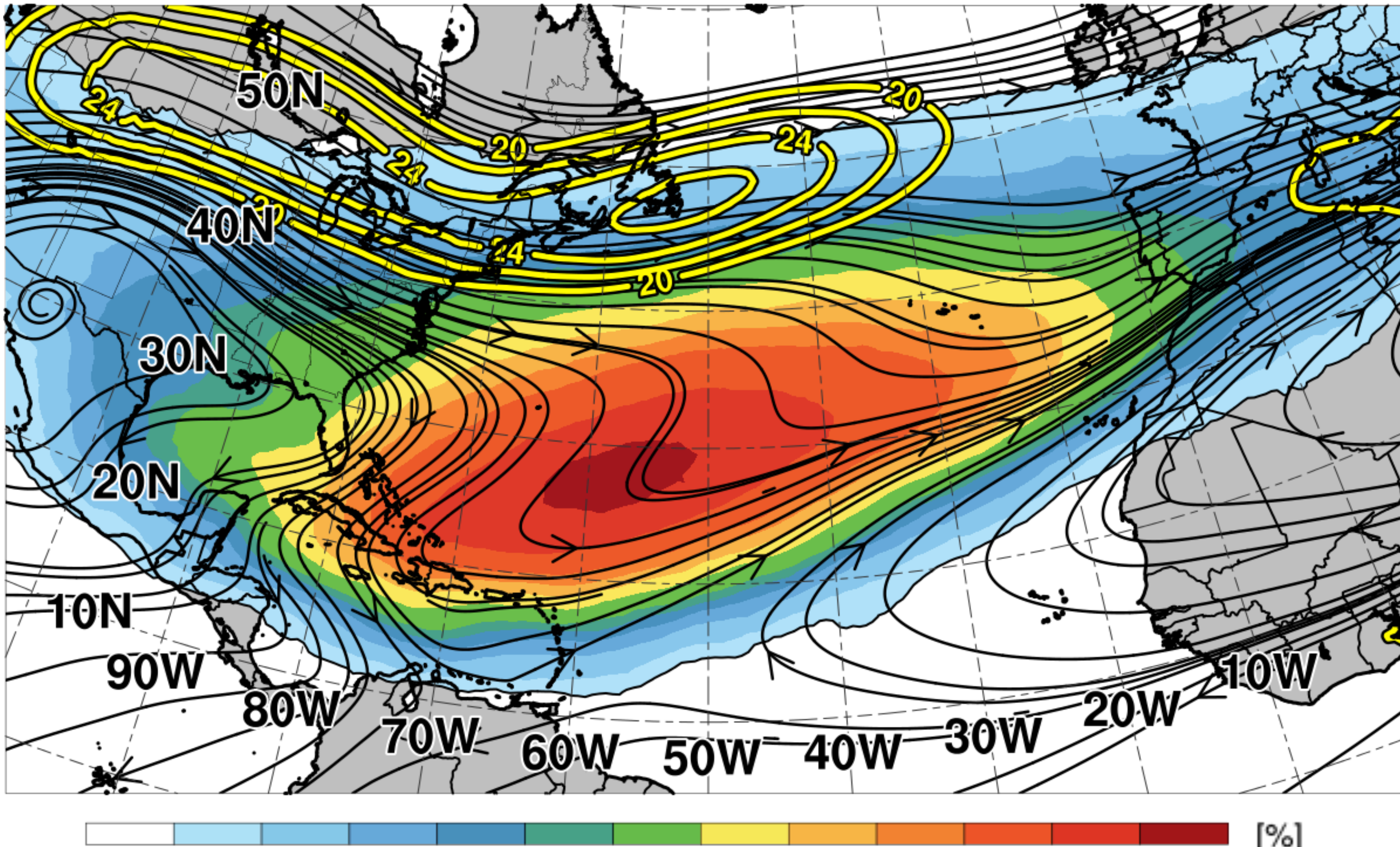
Probability PV streamer is observed on any particular day (shading, %), 200-hPa winds (yellow contours, m s$^{-1}$) and streamlines (black lines)



# Results: PV Streamer Climatology – July

- PV Streamer occurrence shifts over course of season
  - ➢ Max frequency at 60°W with increased frequency over Caribbean

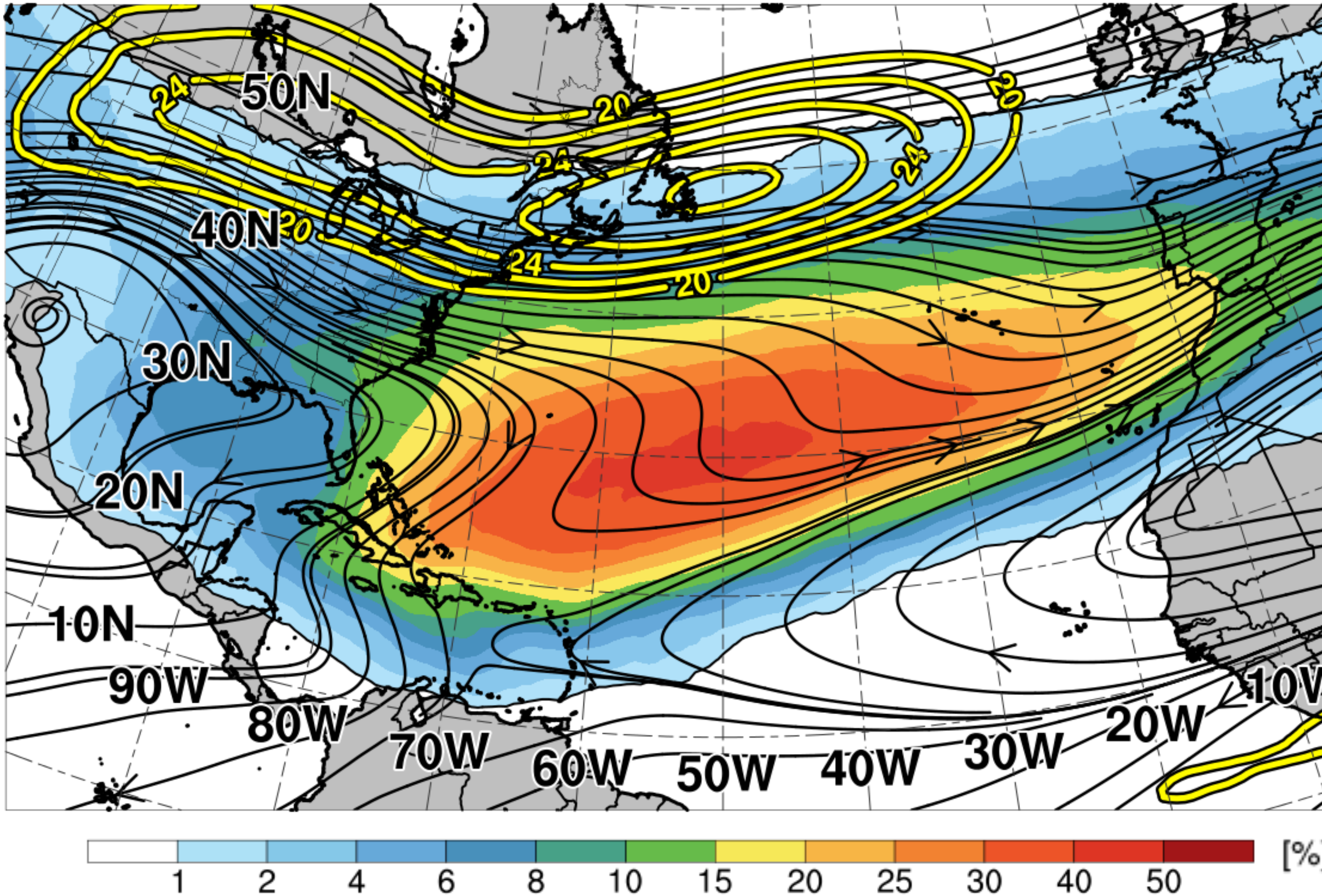
Probability PV streamer is observed on any particular day (shading, %), 200-hPa winds (yellow contours, m $s^{-1}$) and streamlines (black lines)



# Results: PV Streamer Climatology – August

- PV Streamer occurrence shifts over course of season
  - Subtle shift north and west away from Caribbean

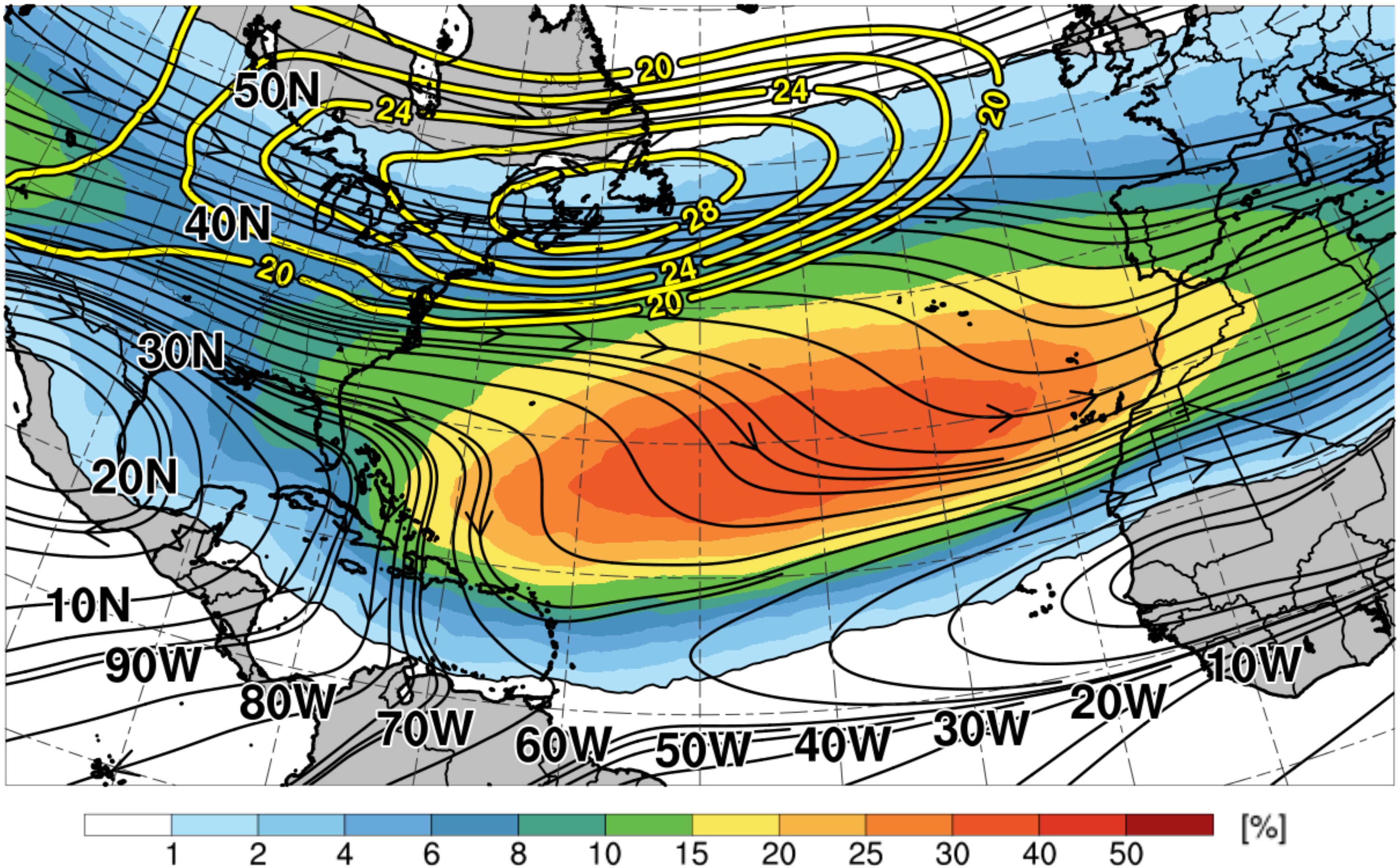
Probability PV streamer is observed on any particular day (shading, %), 200-hPa winds (yellow contours, m s$^{-1}$) and streamlines (black lines)



# Results: PV Streamer Climatology – September

- PV Streamer occurrence shifts over course of season
  - More distinct shift in maxima towards eastern subtropical Atlantic

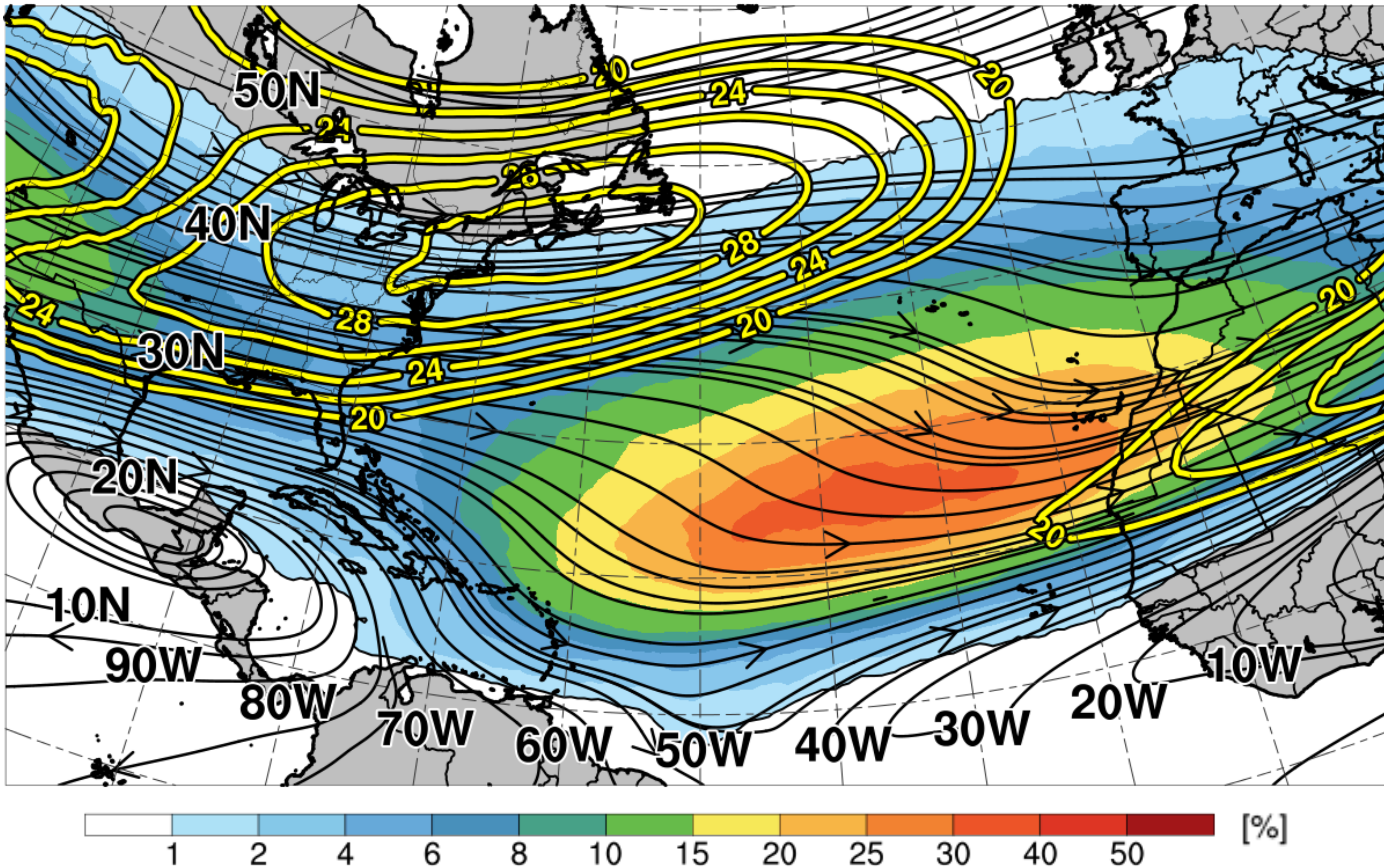
Probability PV streamer is observed on any particular day (shading, %), 200-hPa winds (yellow contours, m $s^{-1}$) and streamlines (black lines)



# Results: PV Streamer Climatology – October

- PV Streamer occurrence shifts over course of season
  - Continued shift increases 200-hPa westerlies in eastern Atlantic

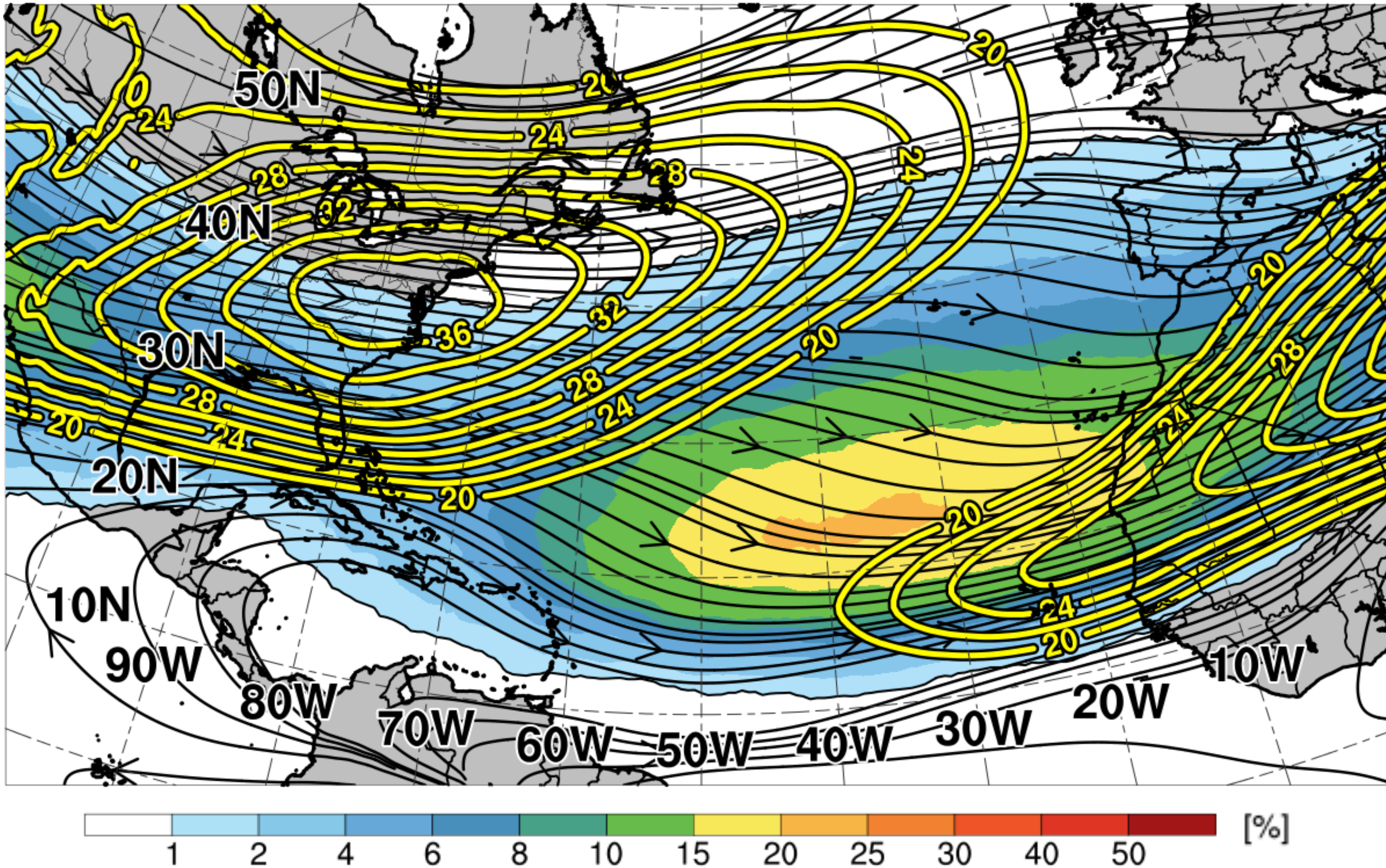
Probability PV streamer is observed on any particular day (shading, %), 200-hPa winds (yellow contours, m s$^{-1}$) and streamlines (black lines)



# Results: PV Streamer Climatology – November

- PV Streamer occurrence shifts over course of season
  - Westerlies dominate Atlantic basin at end of TC season again

Probability PV streamer is observed on any particular day (shading, %), 200-hPa winds (yellow contours, m s$^{-1}$) and streamlines (black lines)



# Results: Year to Year Variability

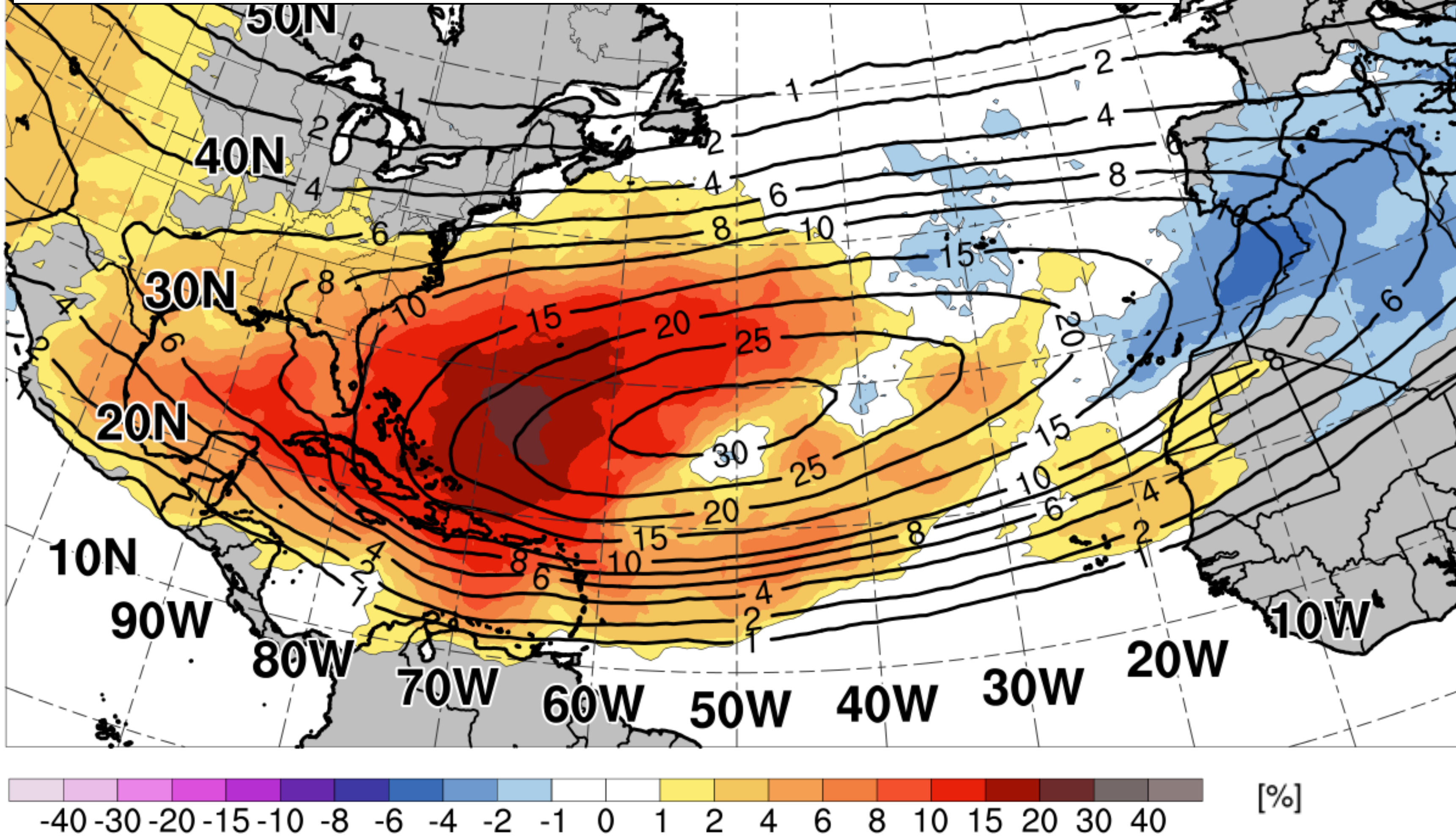
# Results: PV Streamer Variability – 1994

- PV streamer activity can vary greatly from season to season

Accumulated Cyclone Energy (ACE): 32.0 x $10^4$ $kt^2$ **Inactive Hurricane Season**

PV streamer frequency anomaly for given season (shaded, %), Climatological frequency (black contours, %)

Substantial increase in PV streamer frequency in subtropical Atlantic

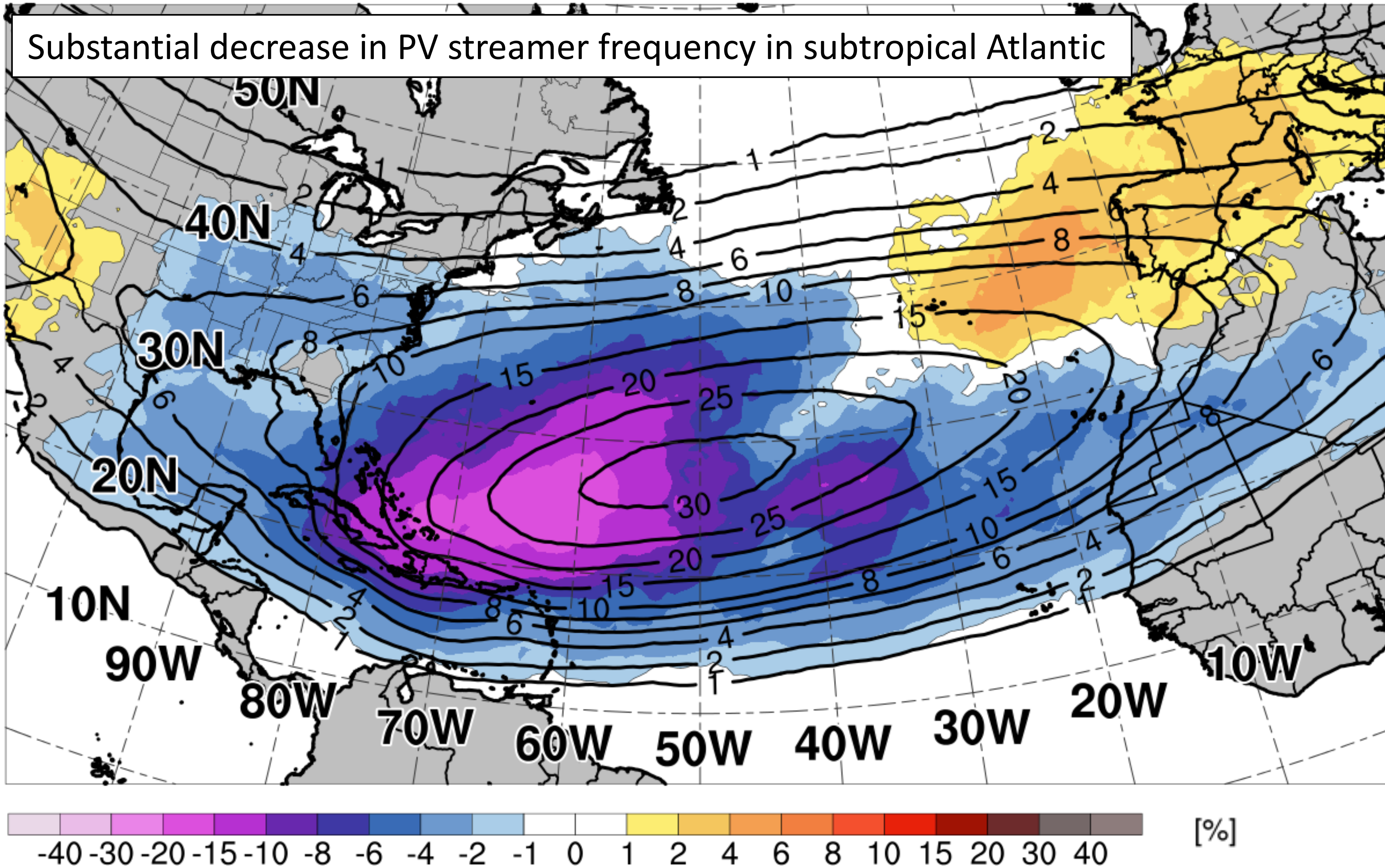


# Results: PV Streamer Variability – 1995

- PV streamer activity can vary greatly from season to season

Accumulated Cyclone Energy (ACE): 227.1 x $10^4$ $kt^2$ **Hyperactive Hurricane Season**

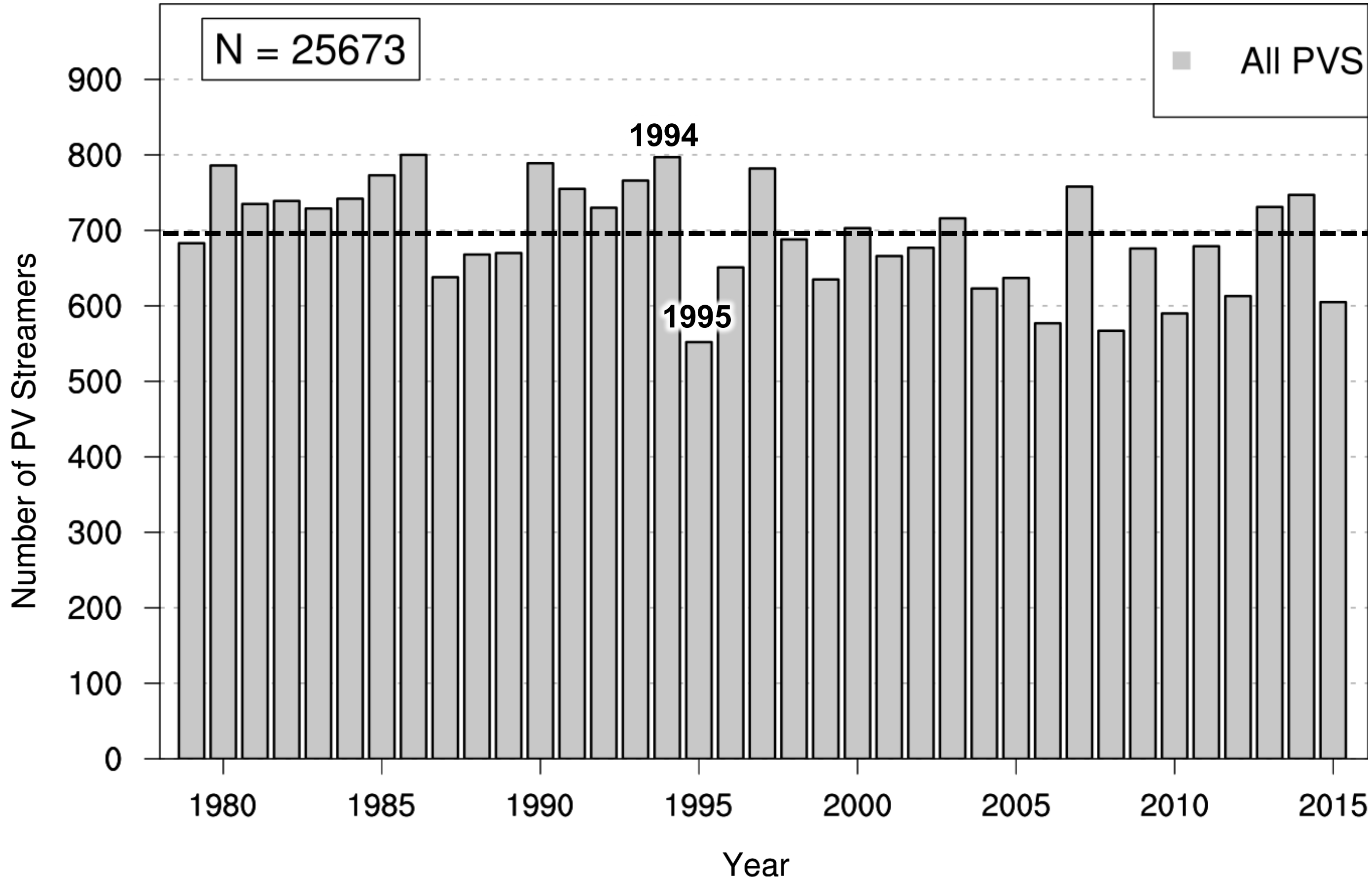
PV streamer frequency anomaly for given season (shaded, %), Climatological frequency (black contours, %)



# Results: PV Streamer Variability 1979–2015

- Interseasonal variability in the number of PV streamers
  - ➢ 1 Jun–30 Nov between 100–10°W
  - ➢ Mean: 694
  - ➢ Stdev: +/- 70

Other variables important other than just number of of PV streamers

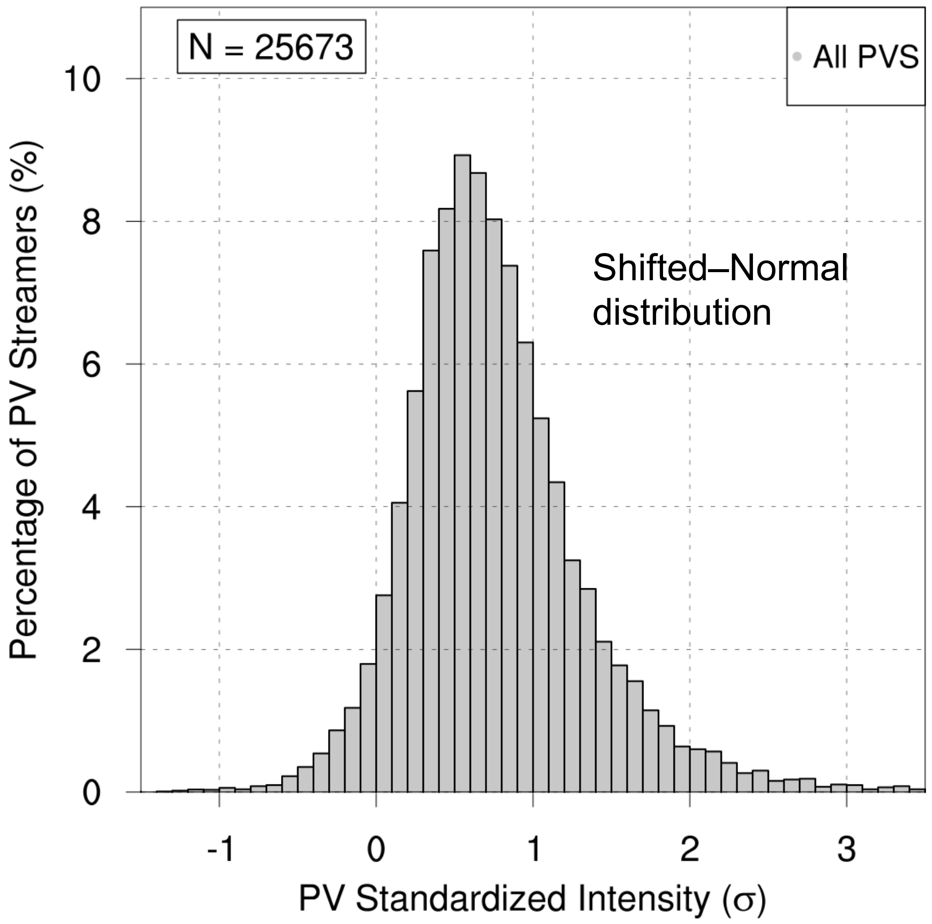



*Yearly Distribution of PV Streamer Count*

# Results: Variability of Intensity and Area

# Results: Variability of PV Streamer Intensity

- Intensity of PV streamers (standardized anomaly)
  - 1 Jun–30 Nov between 100–10$^{o}$W
  - Mean: 0.76 sigma
  - Stdev: +/- 0.57 sigma

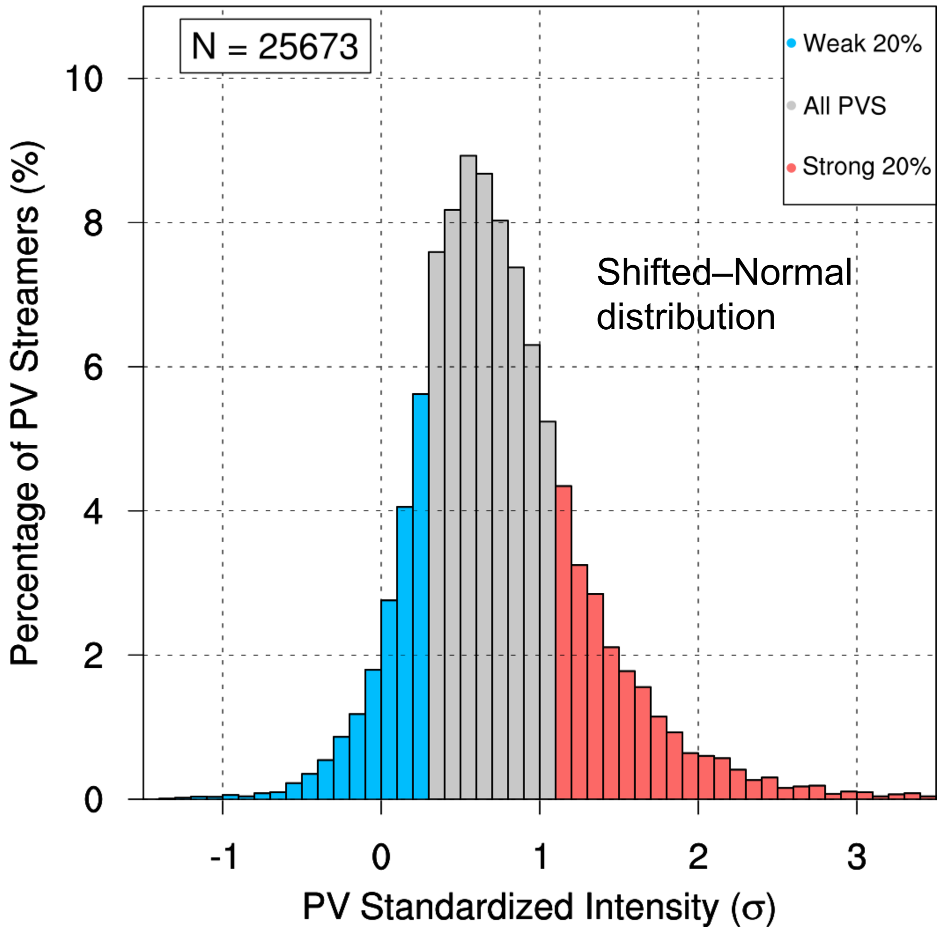



*PDF of PV Streamer Intensity*

# Results: Variability of PV Streamer Intensity

- Intensity of PV streamers (standardized anomaly)
  - 1 Jun–30 Nov between 100–10°W
  - Mean: 0.76 sigma
  - Stdev: +/- 0.57 sigma

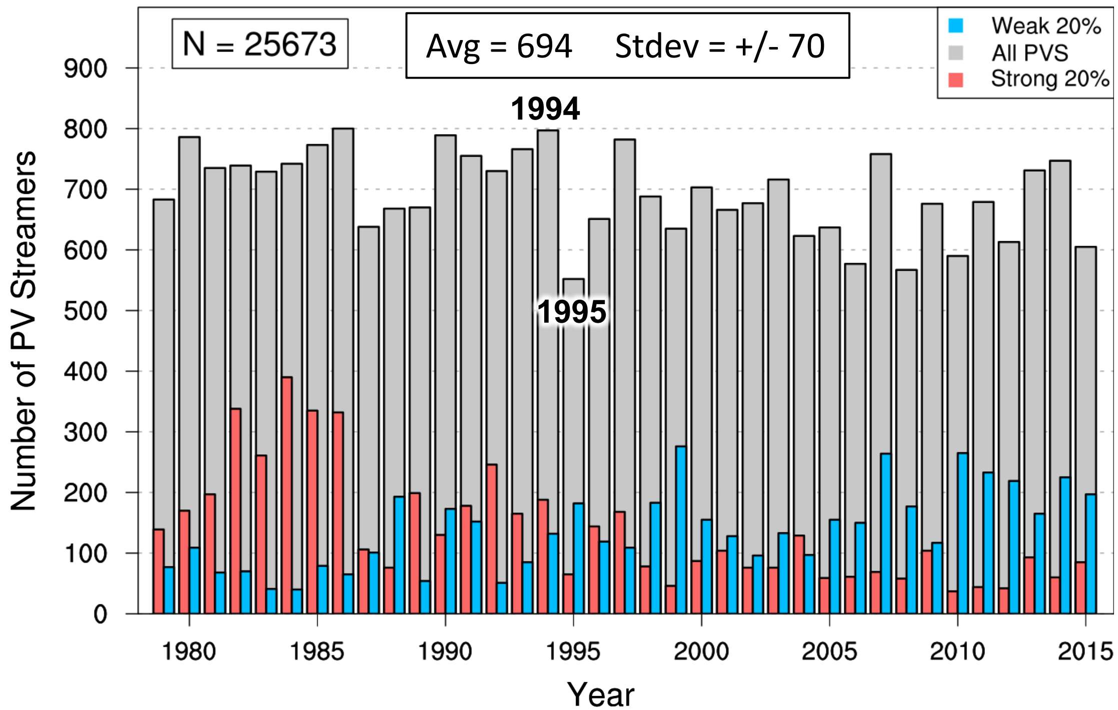
For this study, we emphasize the strongest and weakest 20 percentile of PV streamers

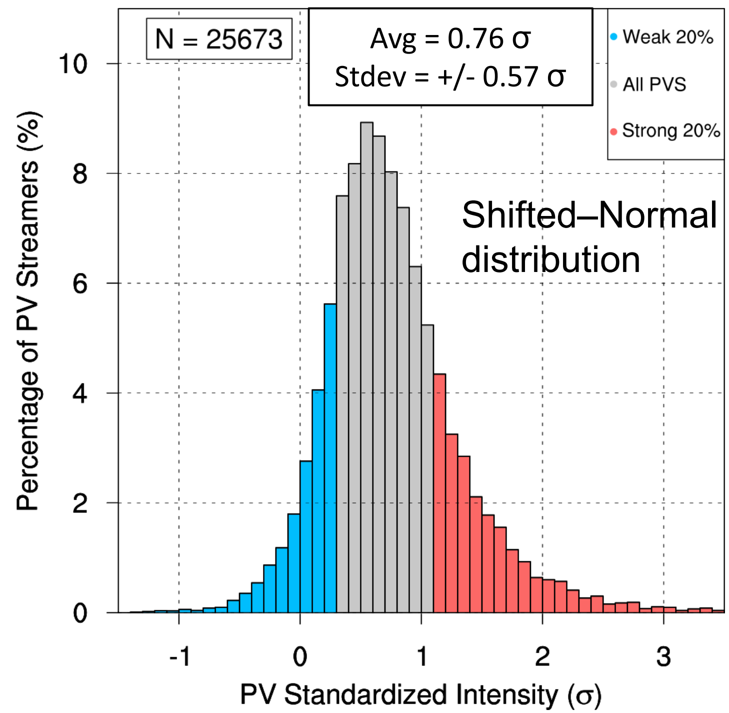



*PDF of PV Streamer Intensity*

# Results: Variability of PV Streamer Intensity

- Interseasonal variability in the number of PV streamers
  - 1 Jun–30 Nov between 100–10°W



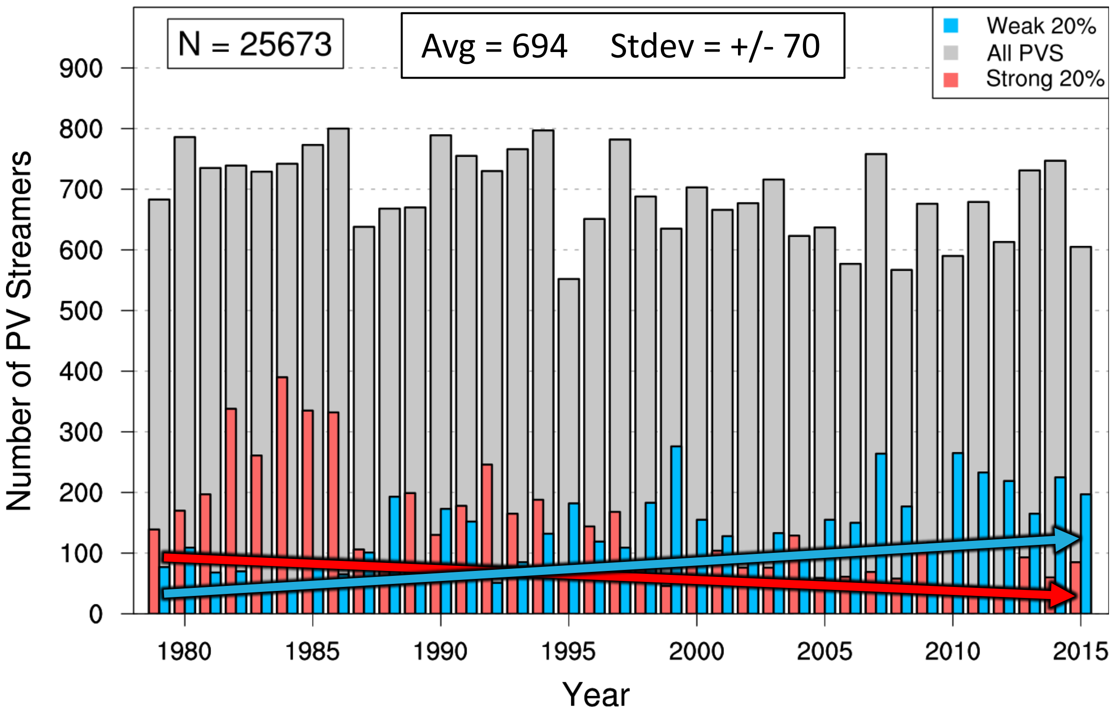



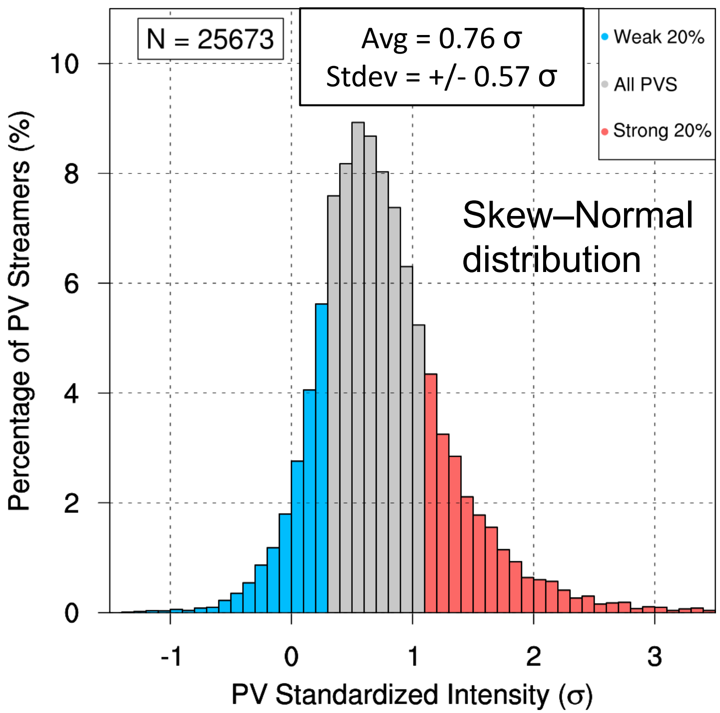

*Yearly Distribution of PV Streamer Count* *PDF of PV Streamer Intensity*

- CFSR depicts a trend towards a decrease in the number of strong PV streamers and increase in the number of weak PV streamers with time
  - Questions remain if this is a real trend or is dataset dependent

# Results: Variability of PV Streamer Intensity

- Interseasonal variability in the number of PV streamers
  - ➢ 1 Jun–30 Nov between 100–10°W




*Yearly Distribution of PV Streamer Count*

*PDF of PV Streamer Intensity*

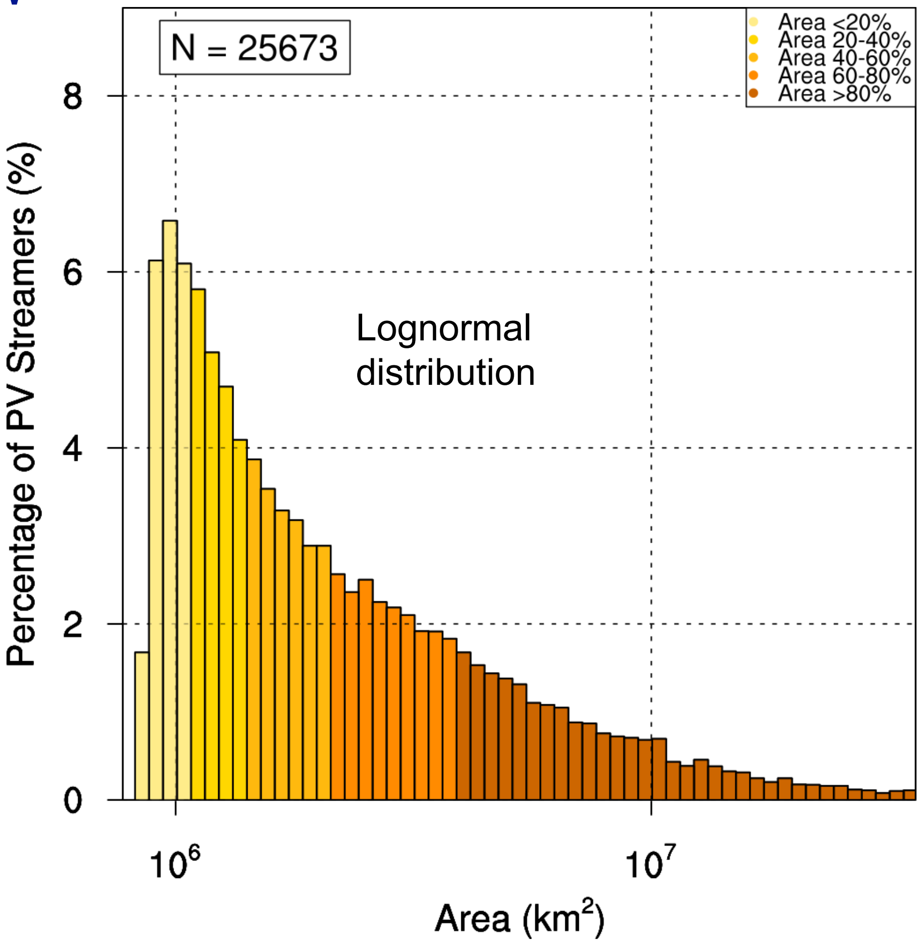
✧ CFSR depicts a trend towards a decrease in the number of strong PV streamers and increase in the number of weak PV streamers with time

✧ Questions remain if this is a real trend or is dataset dependent

# Results: Variability of PV Streamer Area

- Area of PV streamers (raw value)
  - 1 Jun–30 Nov between 100–10ºW
  - Mean: $4.05 \times 10^6$ km$^2$
  - Stdev: +/- $5.24 \times 10^6$ km$^2$

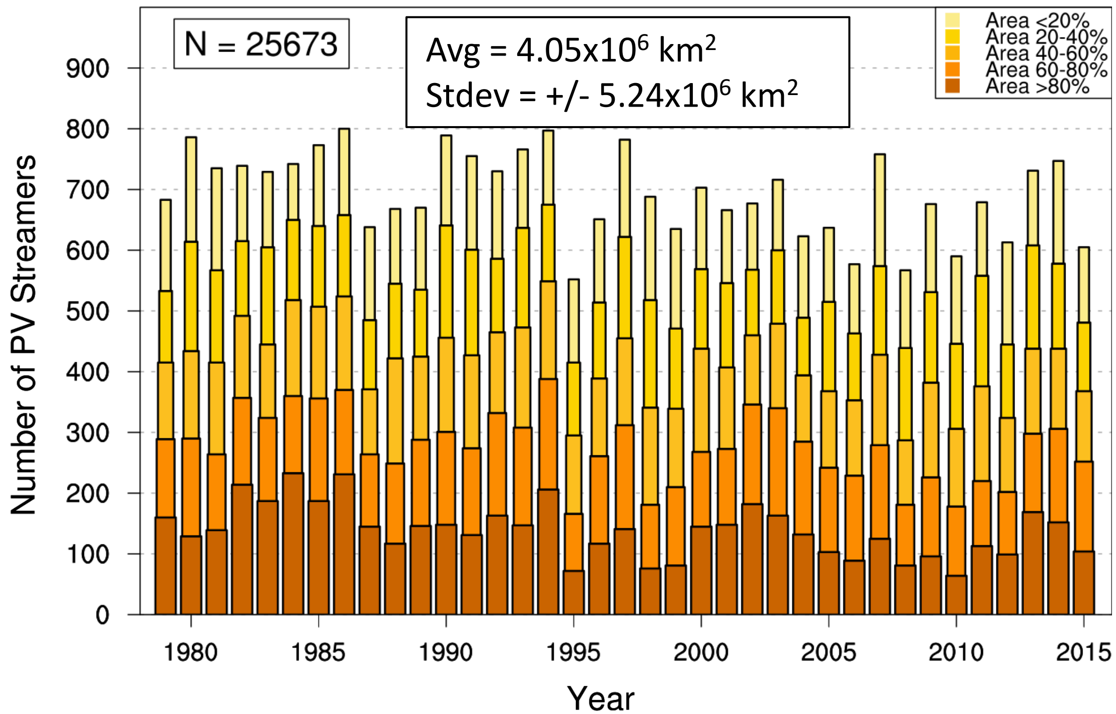
Because of the highly skewed distribution, it is useful to use percentiles when describing area values.

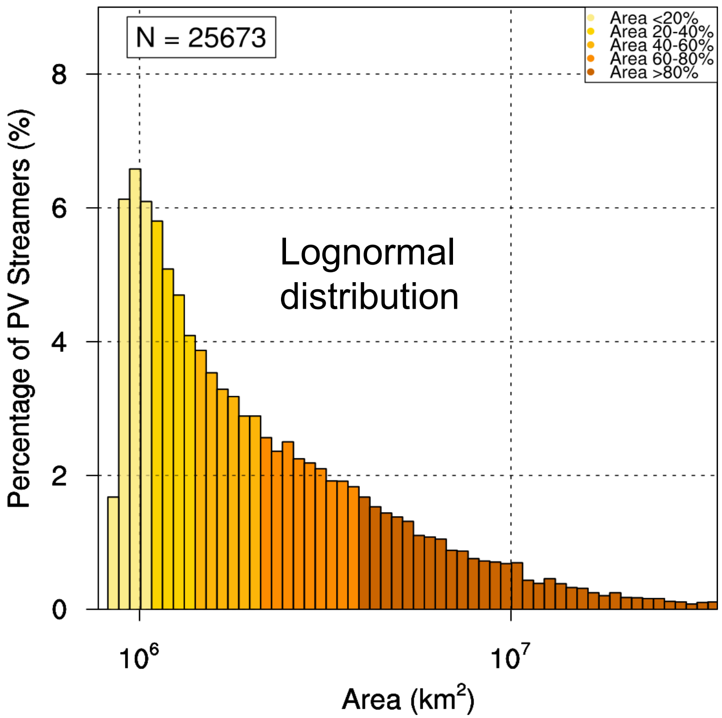



*PDF of PV Streamer Area*

# Results: Variability of PV Streamer Area

- Interseasonal variability in PV streamer area
  - ➢ 1 Jun–30 Nov between 100–10°W




*Yearly Distribution of PV Streamer Count by Area*

*PDF of PV Streamer Area*

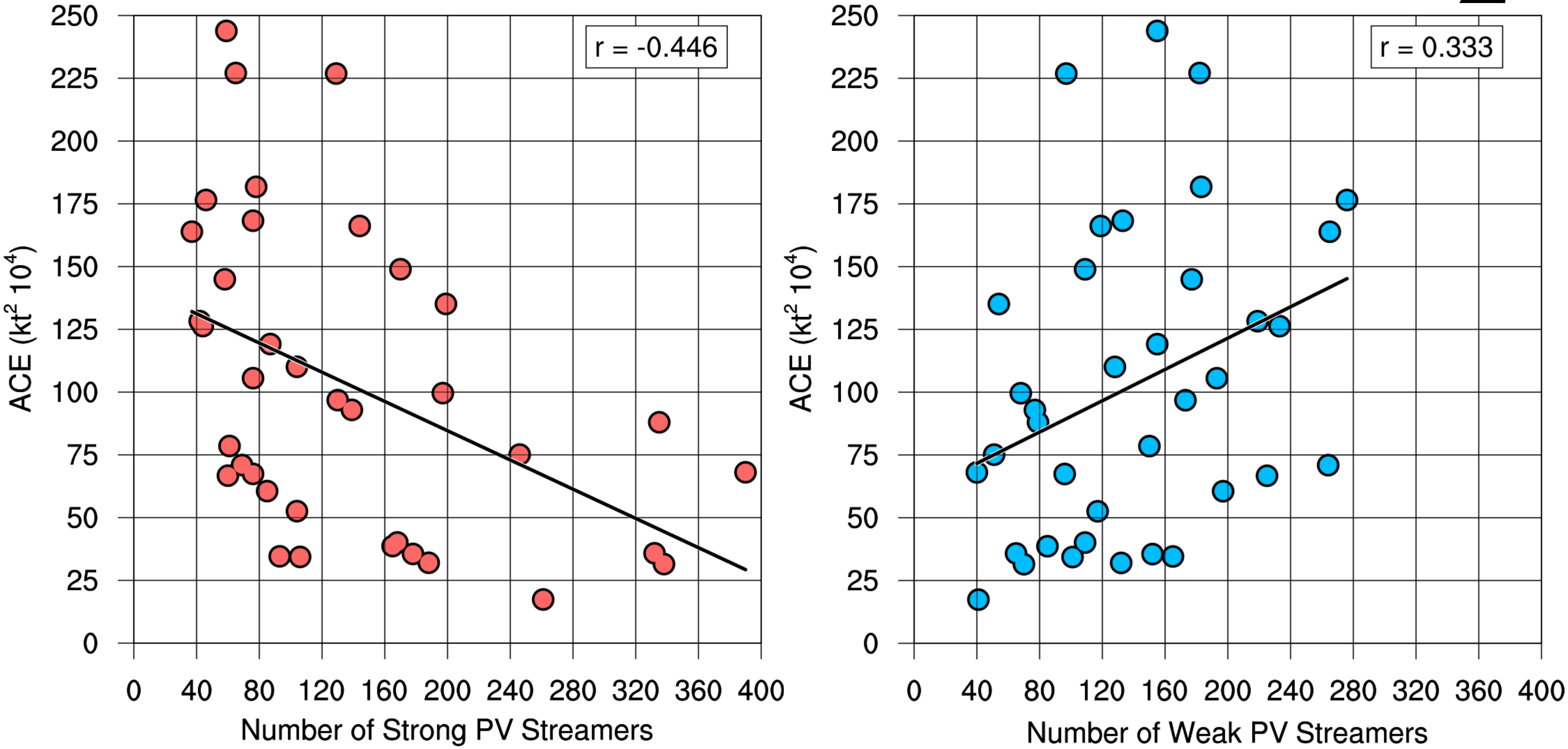
✧ Subtle decreasing trend in the number of large PV streamers with little noticeable trend in the number of small PV streamers

# Results: Relationship to TC Activity

# Results: Relationship to TC Activity – Intensity

- How is TC activity related to differences in PV streamer intensity
  - Seasonal TC activity measured by accumulated cyclone energy (ACE)

$$ACE = 10^{-4} \sum v_{max}^2$$

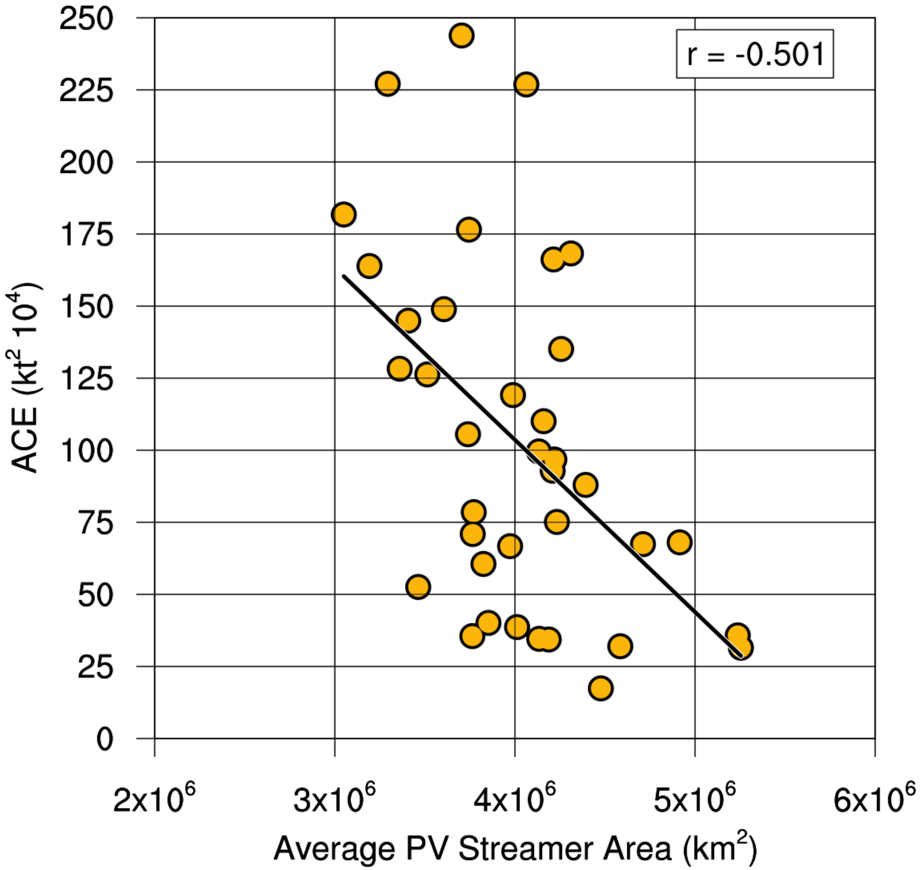



✧ Strong PV streamers are negatively correlated with ACE
✧ Weak PV streamers are positively correlated with ACE

# Results: Relationship to TC Activity – Area

- How is TC activity related to differences in PV streamer area
  - Seasonal TC activity measured by accumulated cyclone energy (ACE)

$$ACE = 10^{-4} \sum v_{max}^2$$




To further illustrate TC activity relationship to PV streamer intensity and area lets compare the most and least active TC seasons (using ACE).

✧ PV streamer area is negatively correlated with ACE

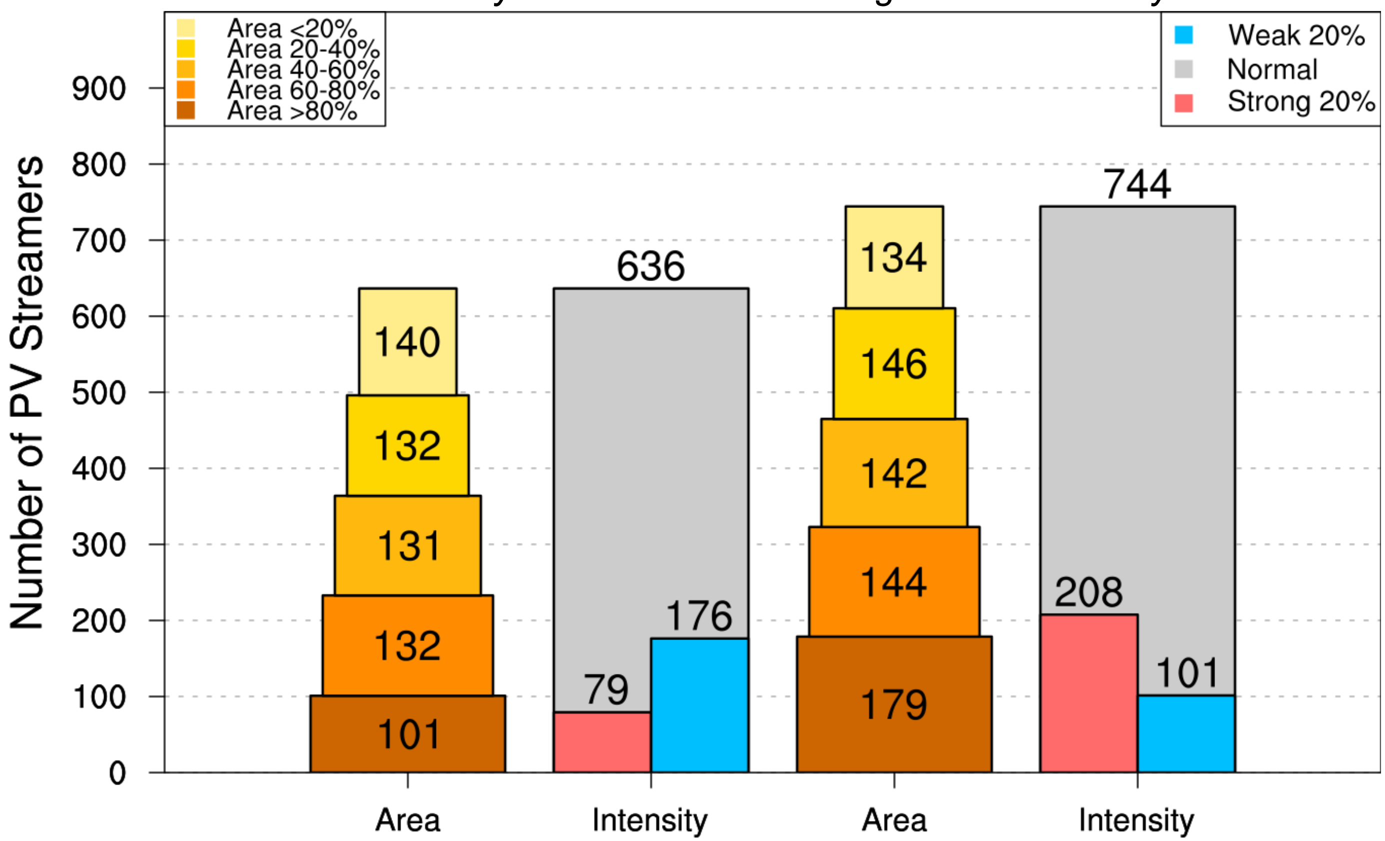
# Results: TC Activity – High vs. Low ACE

- Active TC seasons (High ACE) feature:
  - ✧ Fewer PV streamers (**-14.5%**)
  - ✧ Much Fewer Strong PV streamers (**-62.0%**)
  - ✧ Many More Weak PV streamers (**+74.2%**)
  - ✧ Less Large PV Streamers (**-56.4%**)

Combine these variables into a seasonal index

| **Top 8** High ACE Years | **Bottom 8** Low ACE Years |
|---|---|
| 2005 | 1983 |
| 1995 | 1982 |
| 2004 | 1994 |
| 1998 | 1987 |
| 1999 | 2013 |
| 2003 | 1991 |
| 1996 | 1986 |
| 2010 | 1993 |

*Area and Intensity of PV Streamers in high and low ACE years*



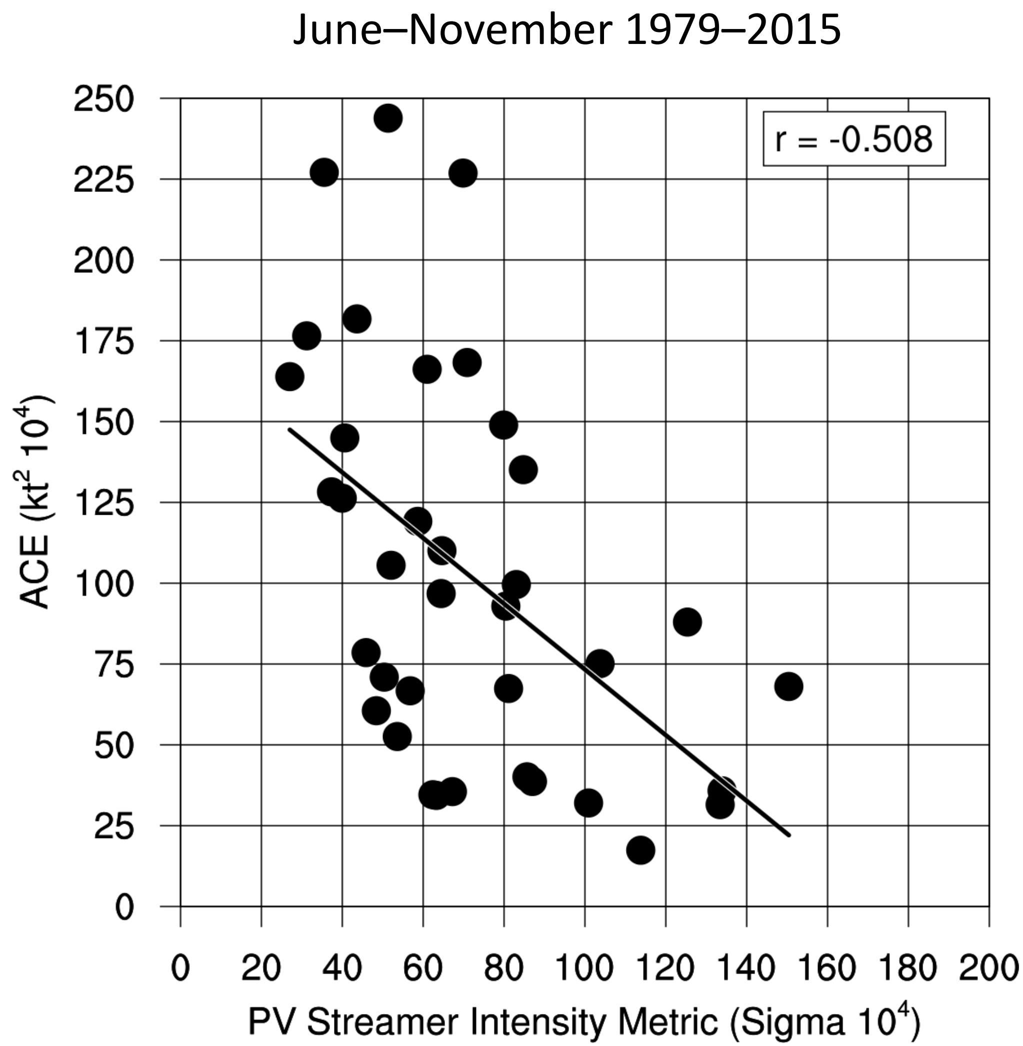

High ACE = 194.3 ($10^4$ kt$^2$) | Low ACE = 32.5 ($10^4$ kt$^2$)

# Results: PV Streamer Intensity Metric vs. ACE

- Putting these variables together over the course of a season
  - **PV Streamer Occurrence**
  - **PV Streamer Area**
  - **PV Streamer Intensity**

$$Seasonal\ Intensity\ Metric = \iint PV_{std\_anom}\, dA dt$$

- Combining these variables produces the highest negative correlation between PV streamer activity and ACE
- Caveats
  - Not a perfectly linear relationship
  - Other factors may be responsible for correlation
    - ENSO
    - SSTA



# Results: PV Streamer Intensity Metric vs. ACE

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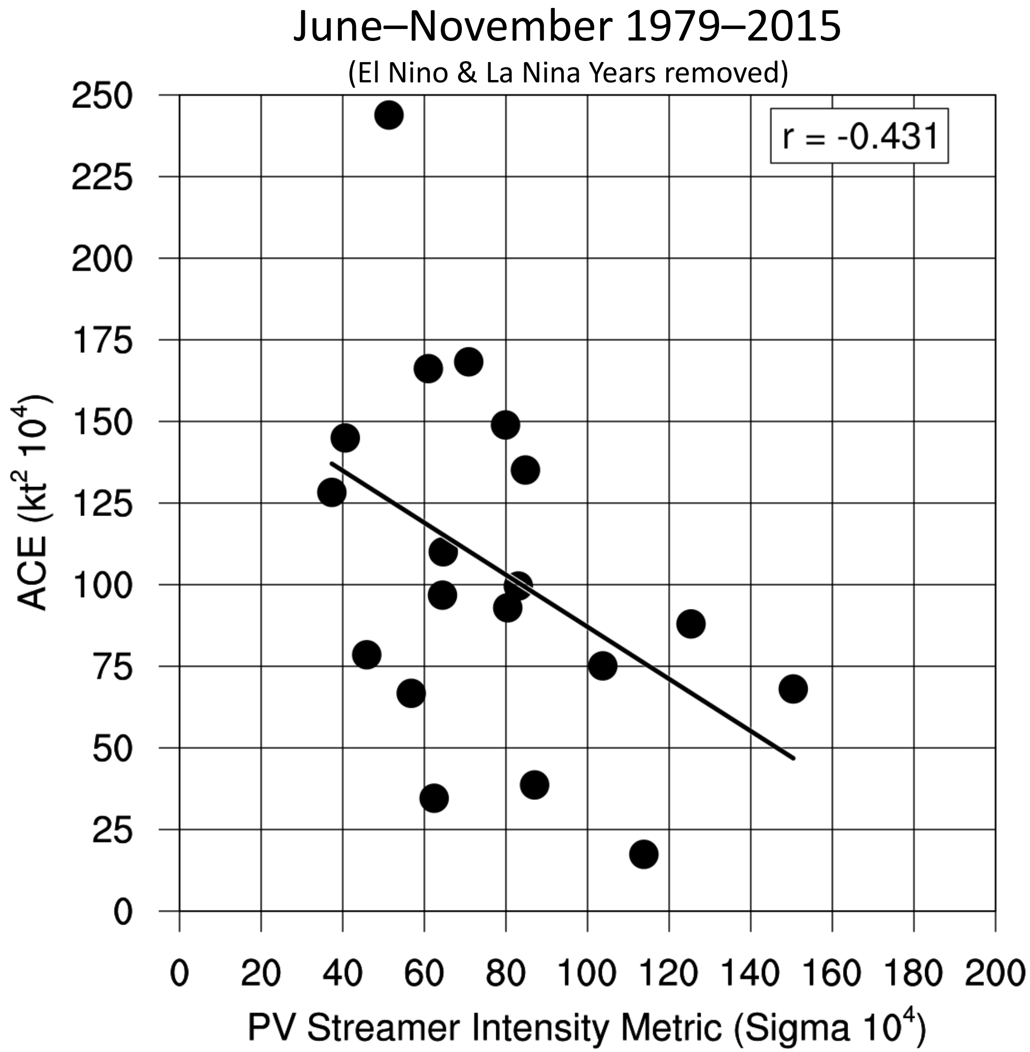
- Combining these variables produces the highest negative correlation between PV streamer activity and ACE
- Caveats
  - Not a perfectly linear relationship
  - Other factors may be responsible for correlation
    - ENSO
    - SSTA

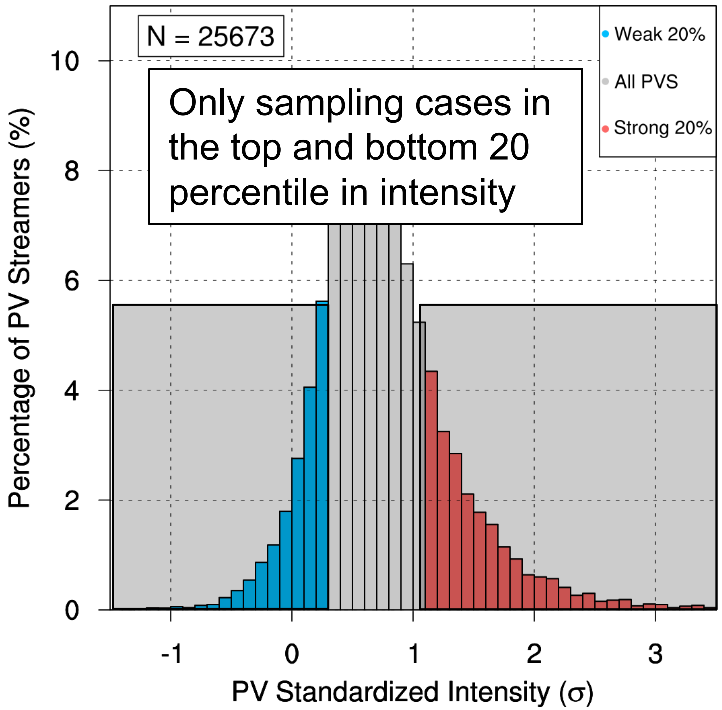
Proven correlation but can we now explain causation?

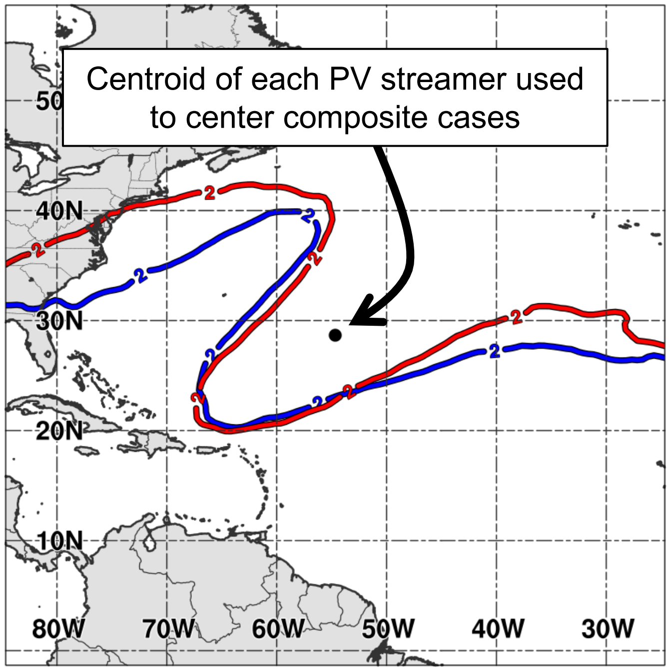


# Results: Composite Differences

# Results: PV Streamer Composite Differences

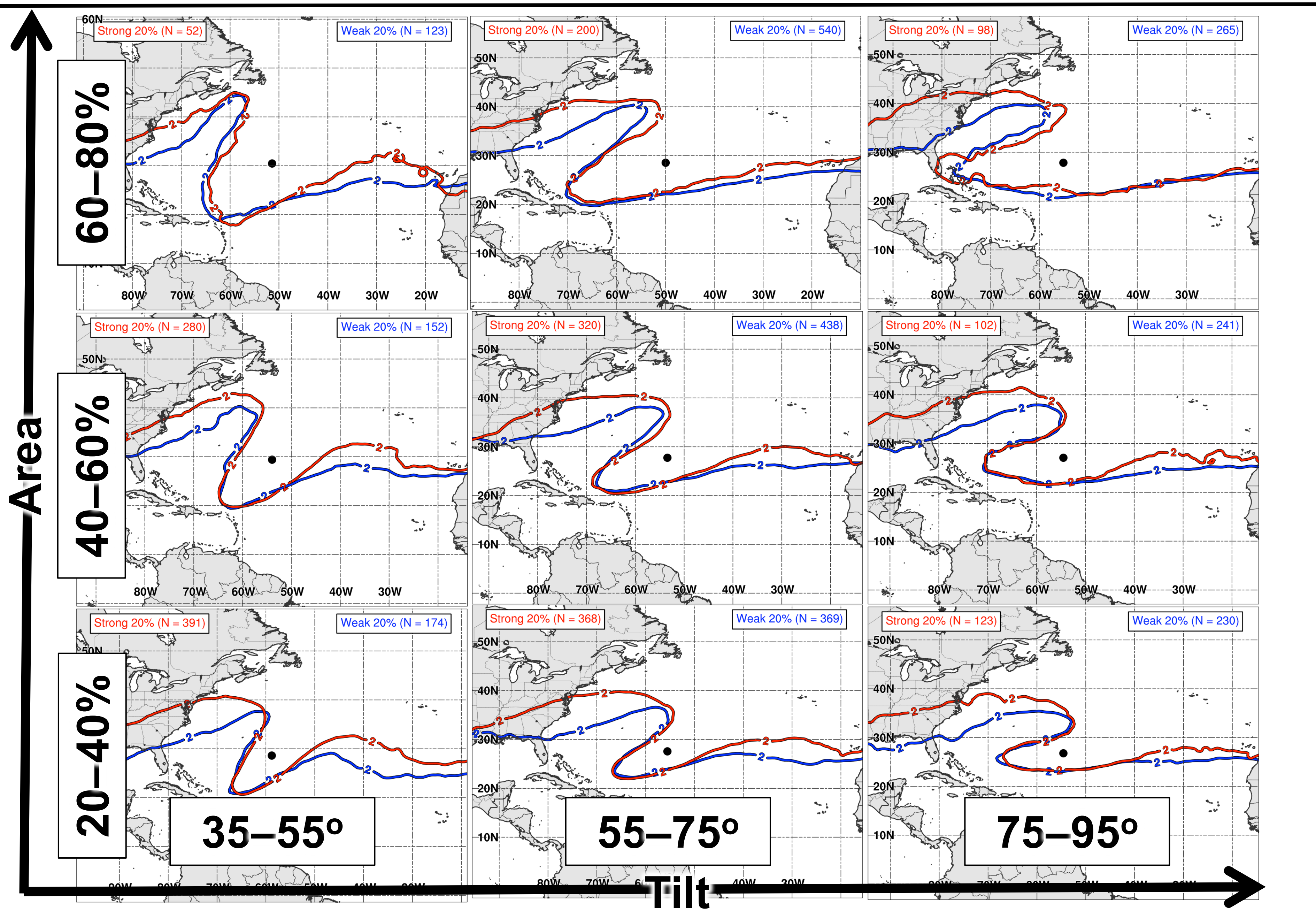
- There are a number of ways to composite PV streamers
  - Similar intensities (using top and bottom 20 percentile categories)
  - Similar areas (using percentile areas)
  - Similar tilts (using tilt degree thresholds)
- Emphasis of this study is on PV streamer intensity differences
  - Compare strong and weak PV streamers using similar areas and tilts
  - A "composite matrix" can be produced by organizing composites by tilt and area



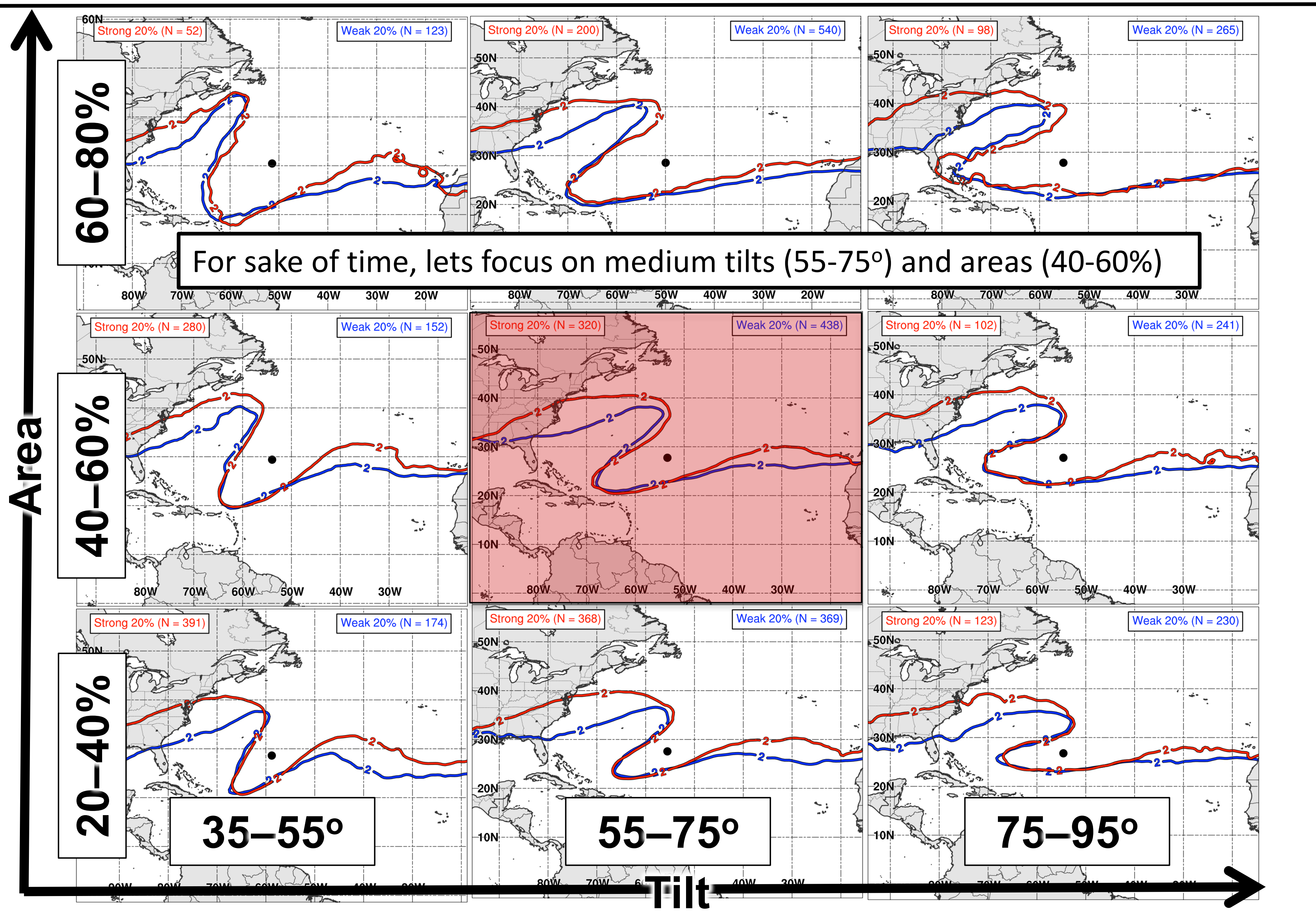




*Average 350-K 2-PVU contour for weak and strong PV streamers (blue and red contours respectively)*

# Results: PV Streamer Composite Differences



# Results: PV Streamer Composite Differences



# Results: PV Streamer Composite Differences

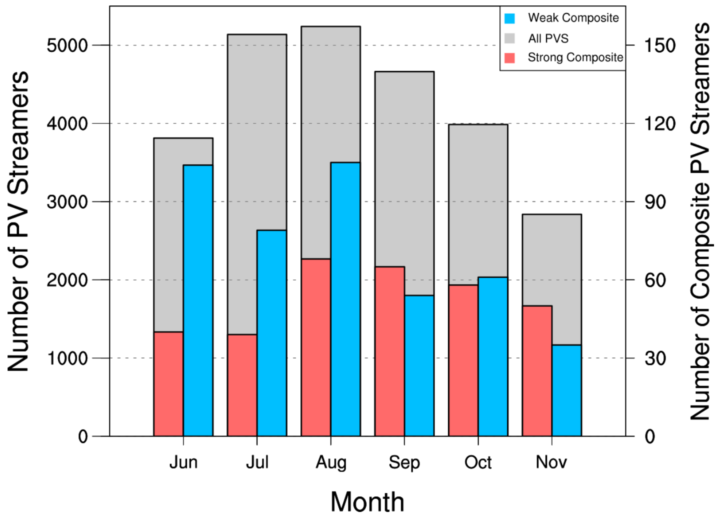
- Composite differences created between strong & weak PV streamers
  - Variable anomalies are normalized to allow for comparison of PV streamers in different locations or different times for each case

$$\Delta x_{strong-weak} = \left\{\frac{\bar{x}_i^{Composite} - \bar{x}_i^{Mean}}{\overline{\sigma x_i}}\right\}_{strong} - \left\{\frac{\bar{x}_i^{Composite} - \bar{x}_i^{Mean}}{\overline{\sigma x_i}}\right\}_{weak}$$

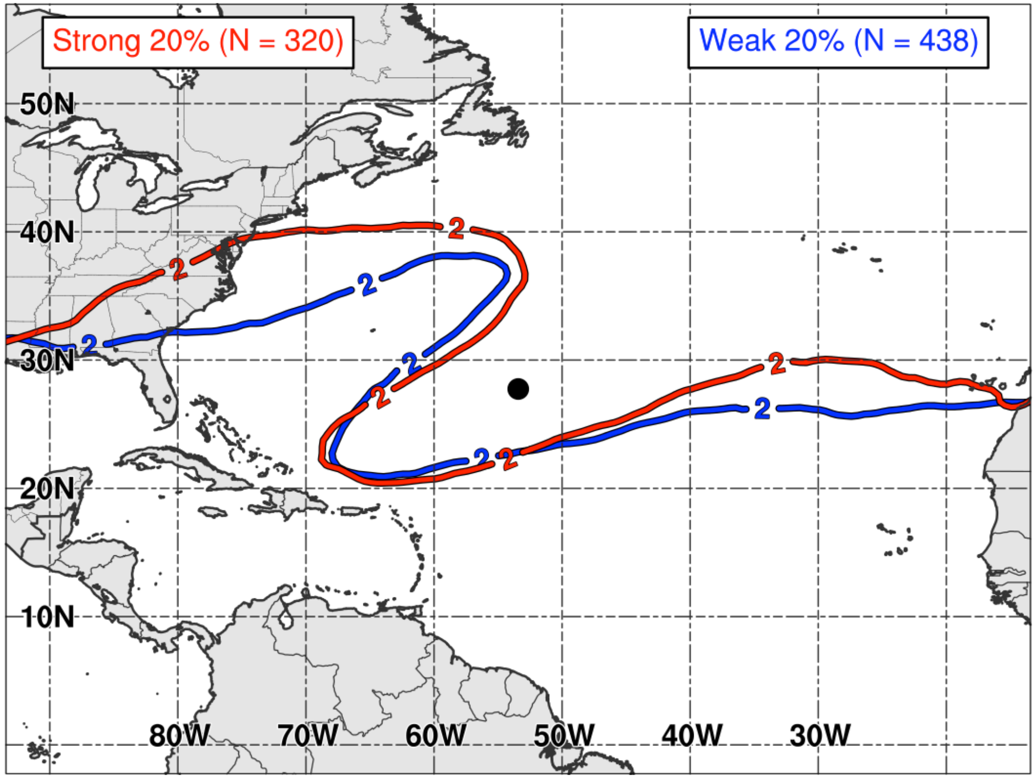
$N_{strong} = 320$

$N_{weak} = 438$

  - Statistical significance will be assessed using bootstrap resampling (useful when comparing different sample sizes)




*Average 350-K 2-PVU contour for weak and strong PV streamers (blue and red contours respectively)*



# Results: Composite Differences - VWS

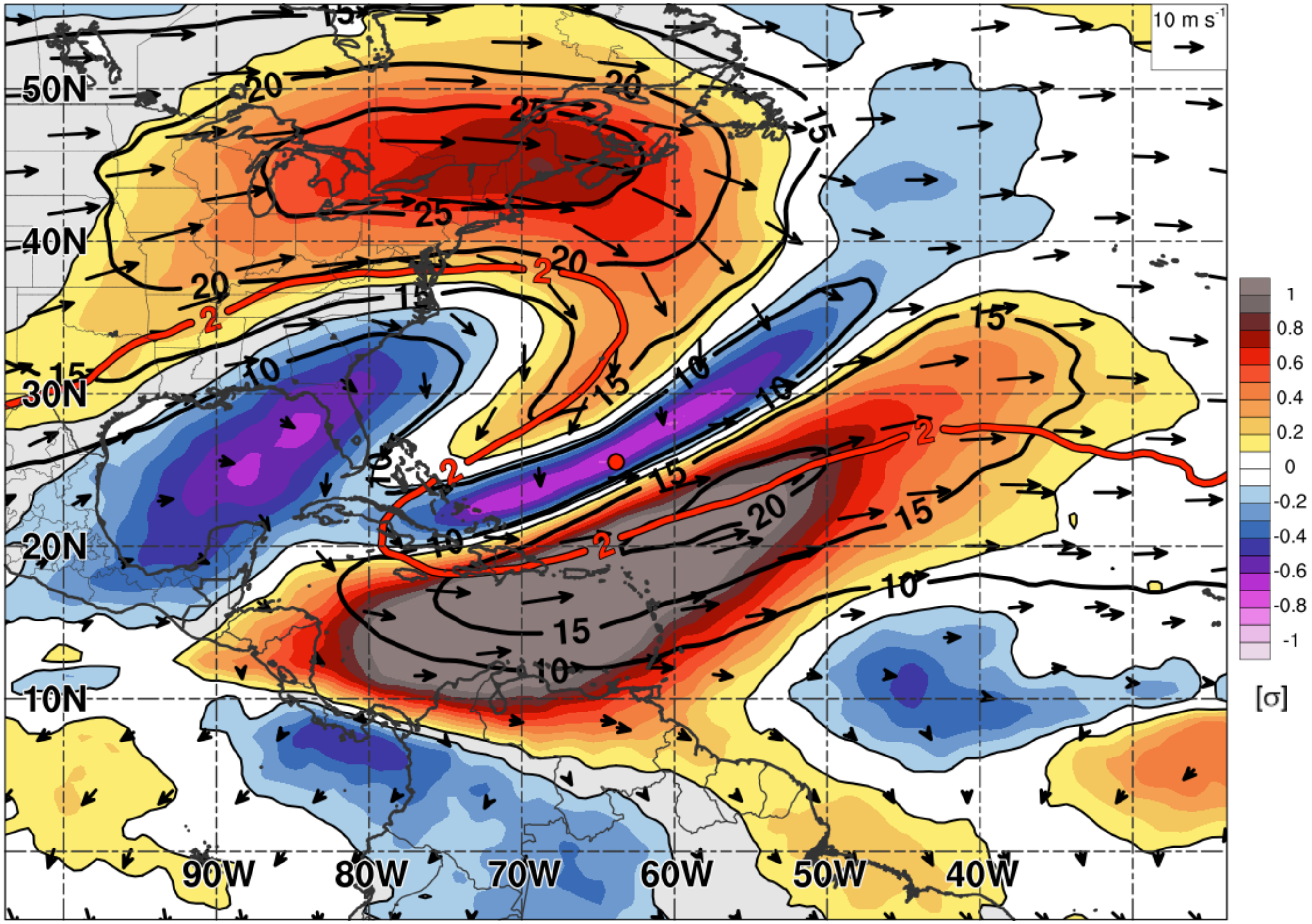
- Vertical Wind Shear (VWS)
  - 200–850-hPa

$$\left\{\frac{\bar{x}_i^{Composite} - \bar{x}_i^{Mean}}{\overline{\sigma x_i}}\right\}_{strong}$$

$N_{strong} = 320$

❖ **Enhanced shear primarily equatorward of strong PV streamer**

**> 1σ**




Normalized VWS Differences (shaded, *σ*), Mean magnitude VWS (black contours, m $s^{-1}$) and direction (vectors), Mean 350-K 2-PVU contour of strong PV streamers (red line)

# Results: Composite Differences - VWS

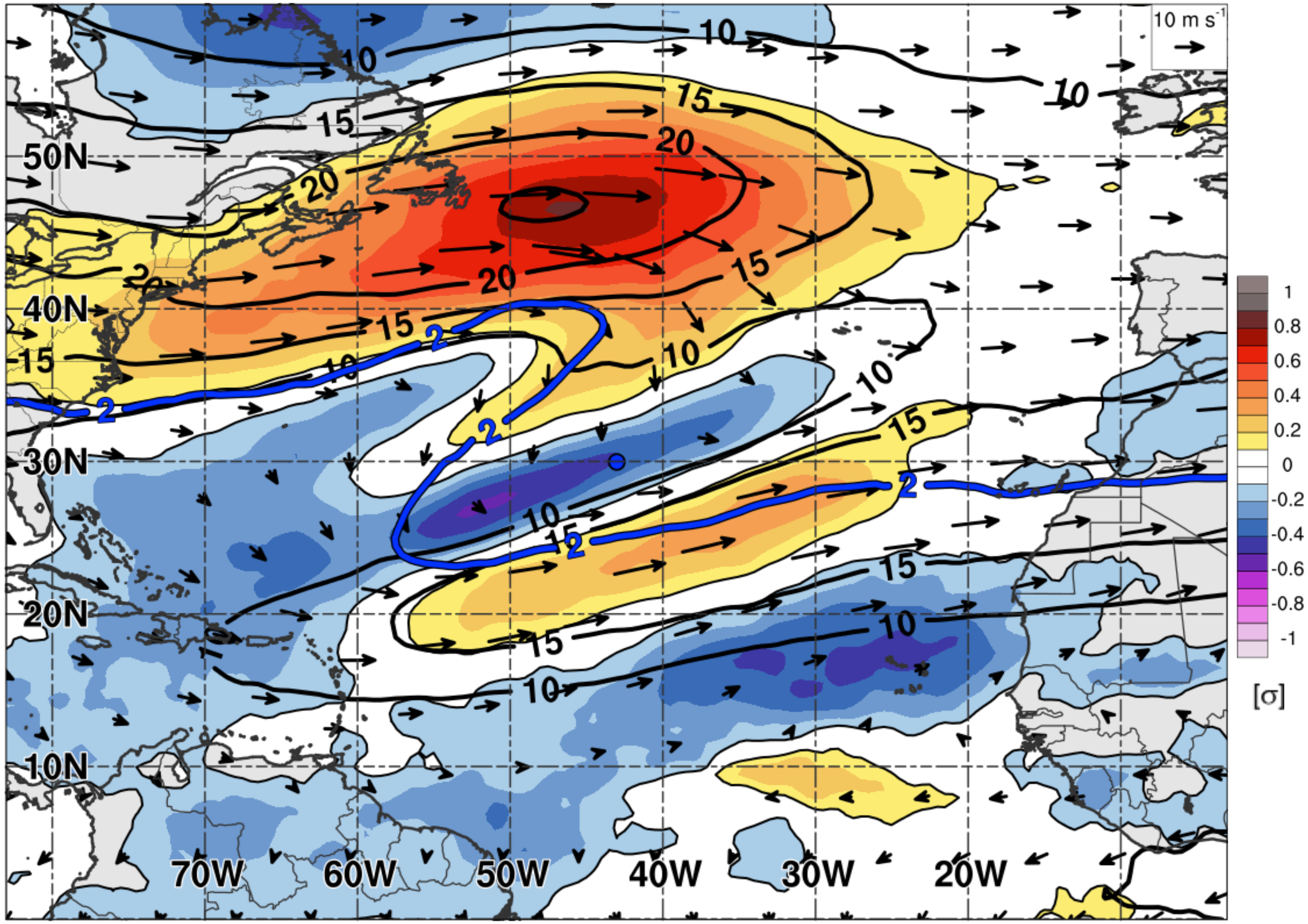
- Vertical Wind Shear (VWS)
  - 200–850-hPa

$$\left\{\frac{\bar{x}_i^{Composite} - \bar{x}_i^{Mean}}{\overline{\sigma x_i}}\right\}_{weak}$$

$N_{weak} = 438$

❖ **Only small corridor of enhanced shear equatorward of PV streamer**

**$< 0.5\sigma$**



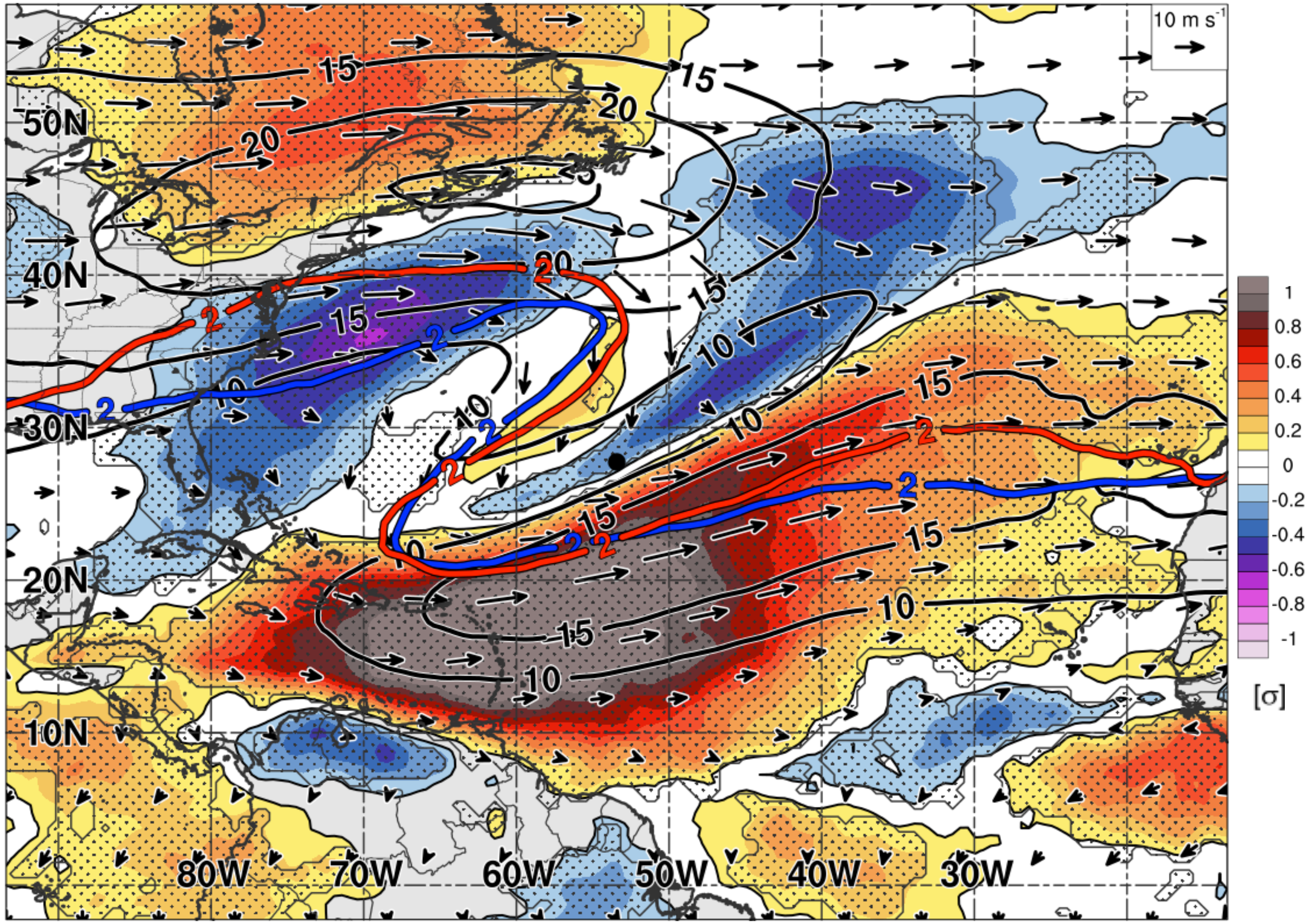

Normalized VWS Differences (shaded, $\sigma$), Mean magnitude VWS (black contours, m $s^{-1}$) and direction (vectors), Mean 350-K 2-PVU contour of weak PV streamers (blue line)

# Results: Composite Differences - VWS

- Vertical Wind Shear (VWS)
  - 200–850-hPa

$\Delta x_{strong-weak}$

❖ **Strong PV streamers have a much larger and more intense corridor of VWS**




Normalized VWS Differences (shaded, $\sigma$), Mean magnitude VWS (black contours, m s$^{-1}$) and direction (vectors), Mean 350-K 2-PVU contour of strong & weak PV streamers (blue and red lines respectively), hatched areas indicate statistical significance to the 99% confidence interval

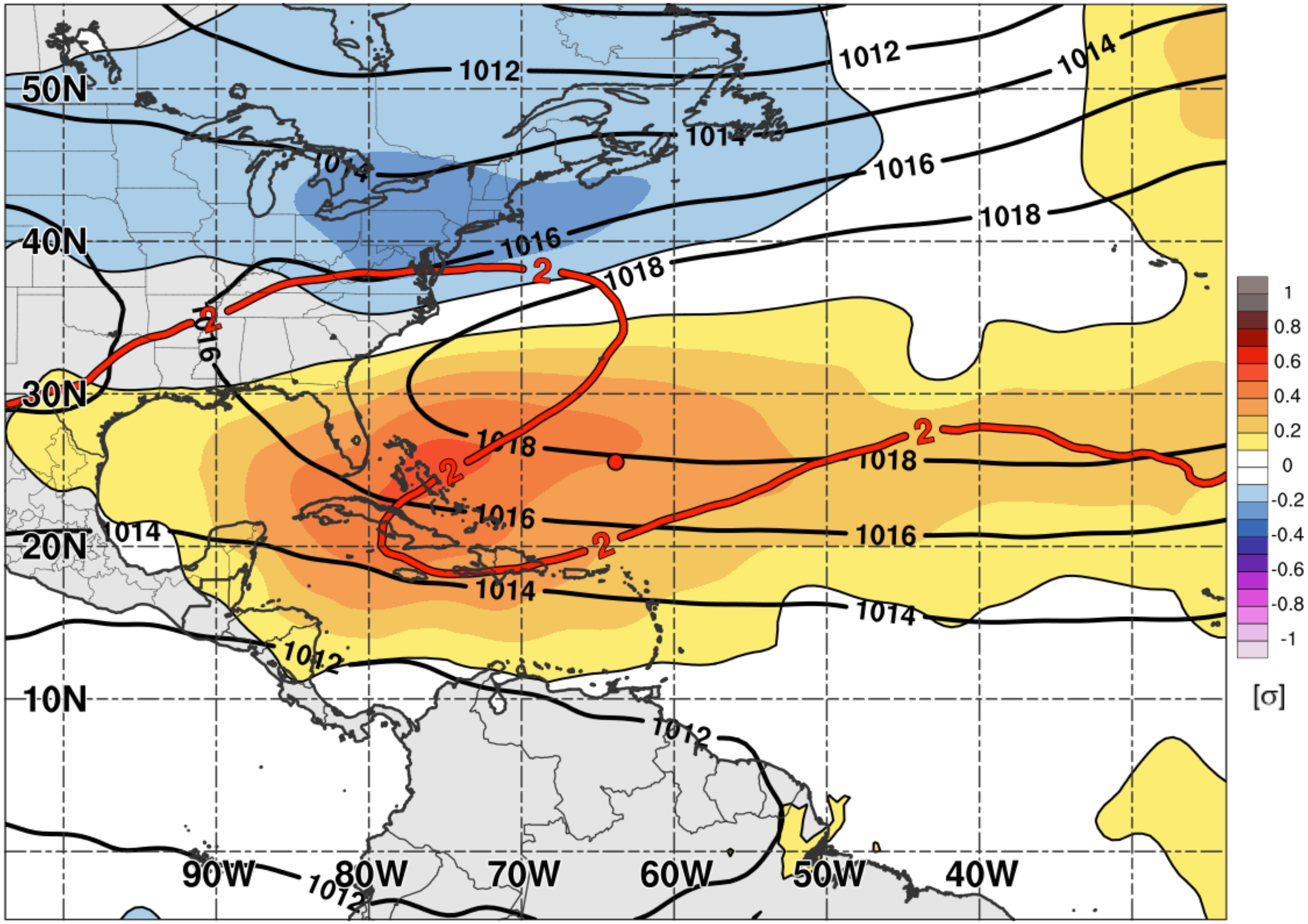
# Results: Composite Differences - SLP

- Sea Level Pressure (SLP)

$$\left\{\frac{\bar{x}_i^{Composite} - \bar{x}_i^{Mean}}{\overline{\sigma x_i}}\right\}_{strong}$$

$N_{strong} = 320$

- Enhanced SLP over strong PV streamer trough axis equatorward of strong PV streamer




Normalized SLP Differences (shaded, σ), Mean magnitude SLP (black contours, hPa)
Mean 350-K 2-PVU contour of strong PV streamers (red line)

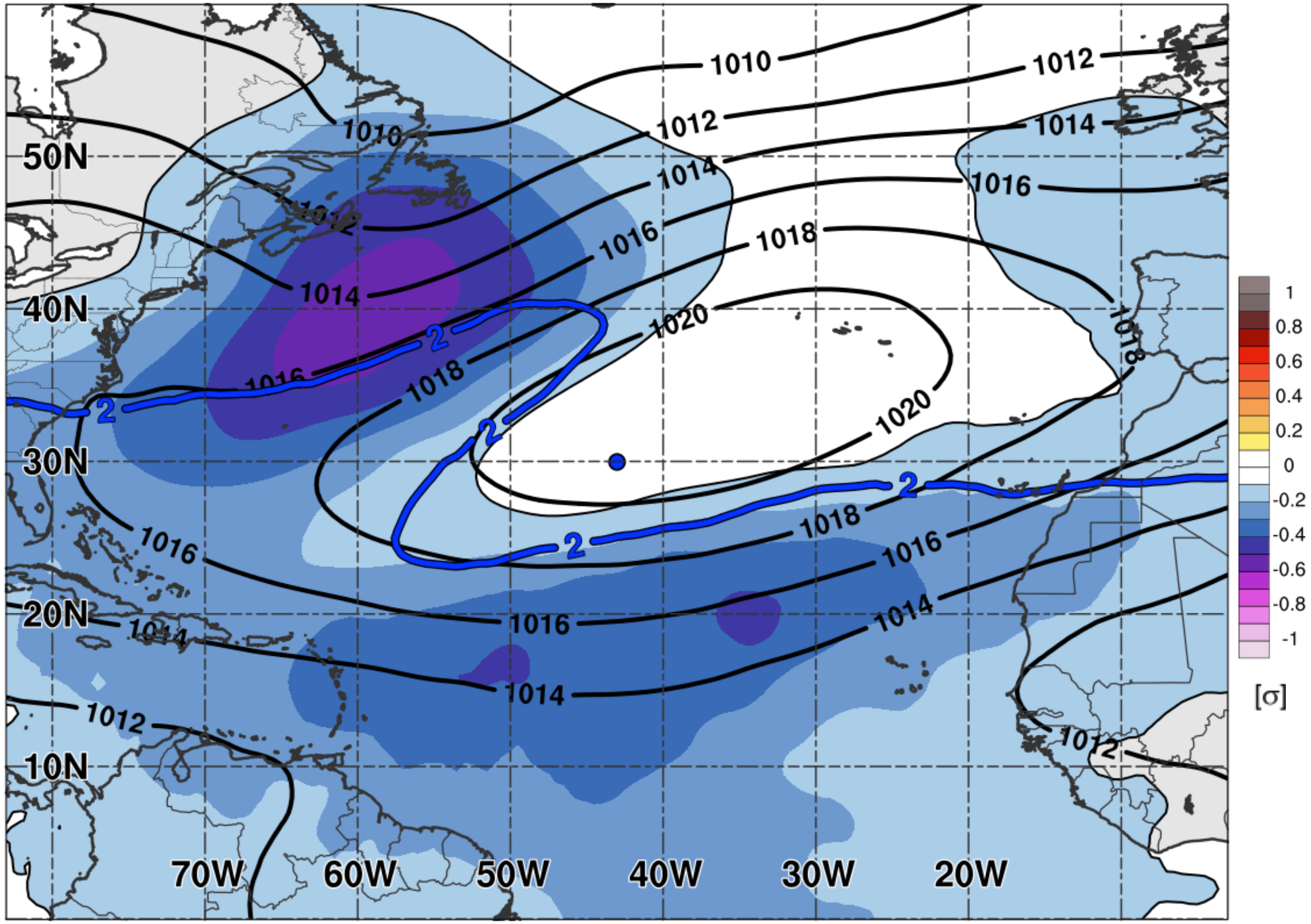
# Results: Composite Differences - SLP

- Sea Level Pressure (SLP)

$$\left\{\frac{\overline{x}_i^{\,Composite} - \overline{x}_i^{\,Mean}}{\overline{\sigma x_i}}\right\}_{weak}$$

$N_{weak} = 438$

- **Reduced SLP surrounding weak PV streamer trough axis**



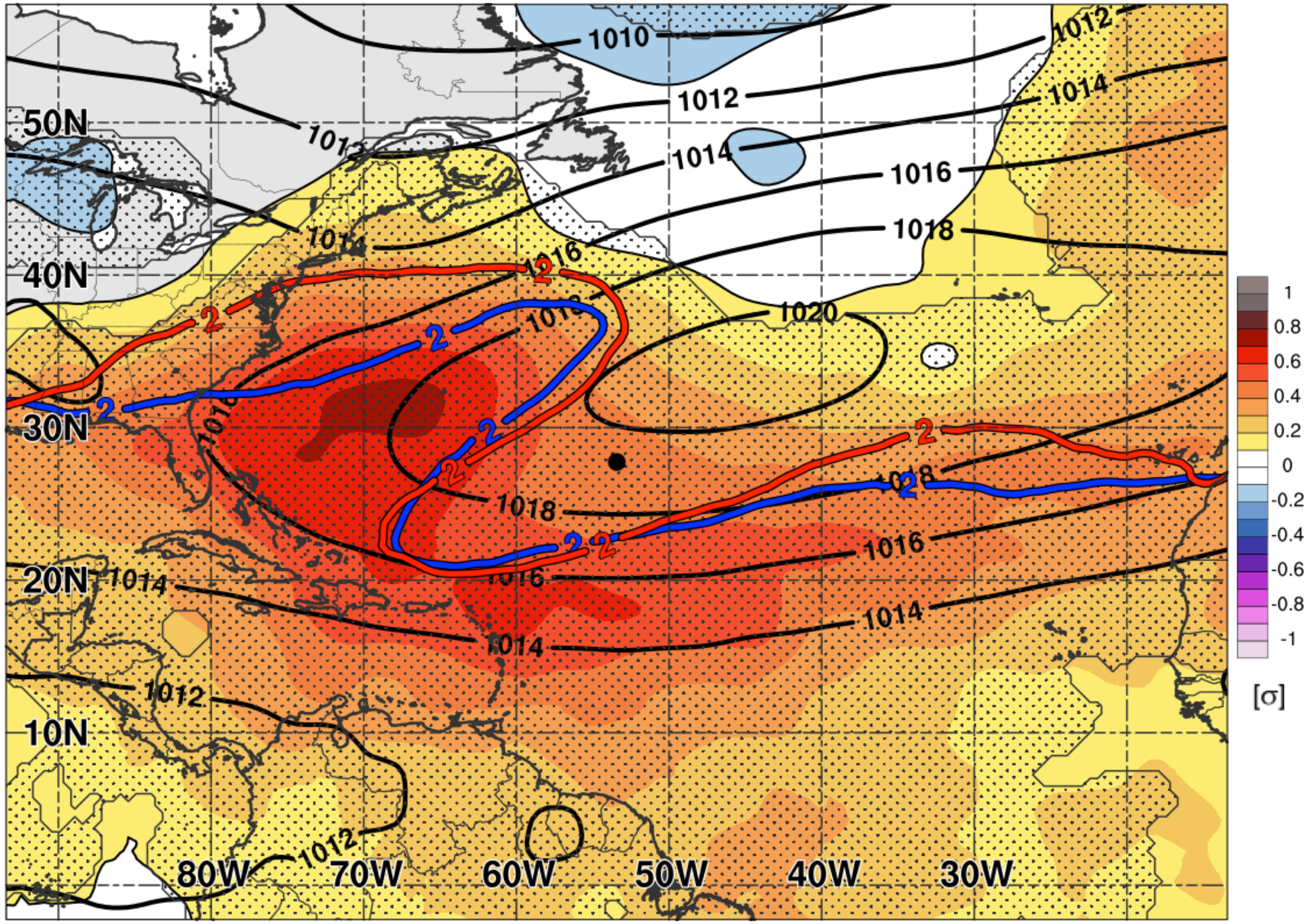

Normalized SLP Differences (shaded, *σ*), Mean magnitude SLP (black contours, hPa) and Mean 350-K 2-PVU contour of weak PV streamers (blue line)

# Results: Composite Differences - SLP

- Sea Level Pressure (SLP)

$\Delta x_{strong-weak}$

❖ **Near basin wide increased in SLP, especially upstream of PV streamer trough axis**




Normalized SLP Differences (shaded, $\sigma$), Mean magnitude SLP (black contours, hPa)
Mean 350-K 2-PVU contour of strong and weak PV streamers (red and blue lines respectively)
hatched areas indicate statistical significance to the 99% confidence interval

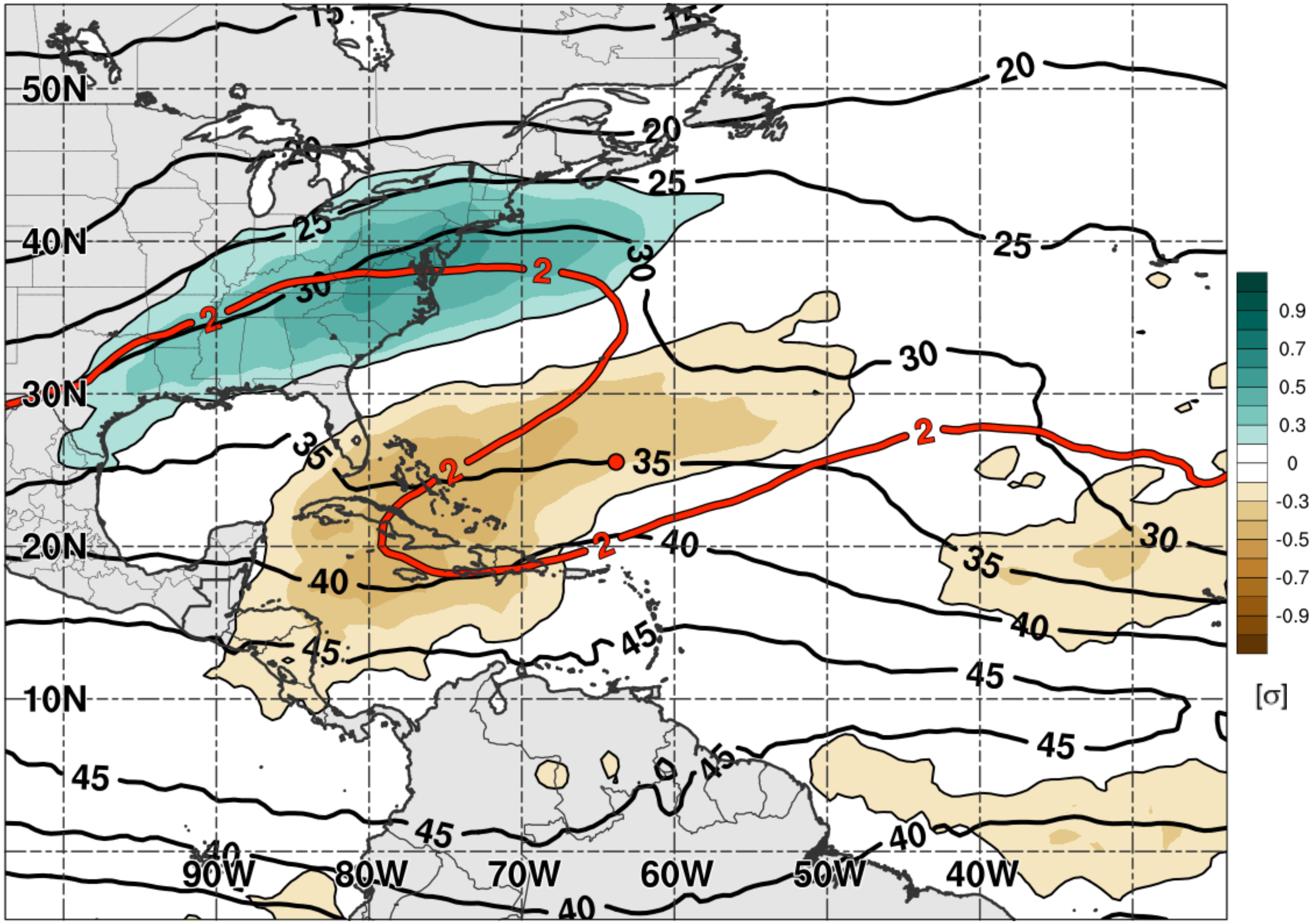
# Results: Composite Differences - PW

- Precipitable Water (PW)

$$\left\{\frac{\bar{x}_i^{Composite} - \bar{x}_i^{Mean}}{\overline{\sigma x_i}}\right\}_{strong}$$

$N_{strong} = 320$

- Couplet of increased moisture upstream with decreased moisture along strong PV streamer trough axis




Normalized PW Differences (shaded, *σ*), Mean magnitude PW (black contours, mm)
Mean 350-K 2-PVU contour of strong PV streamers (red line)

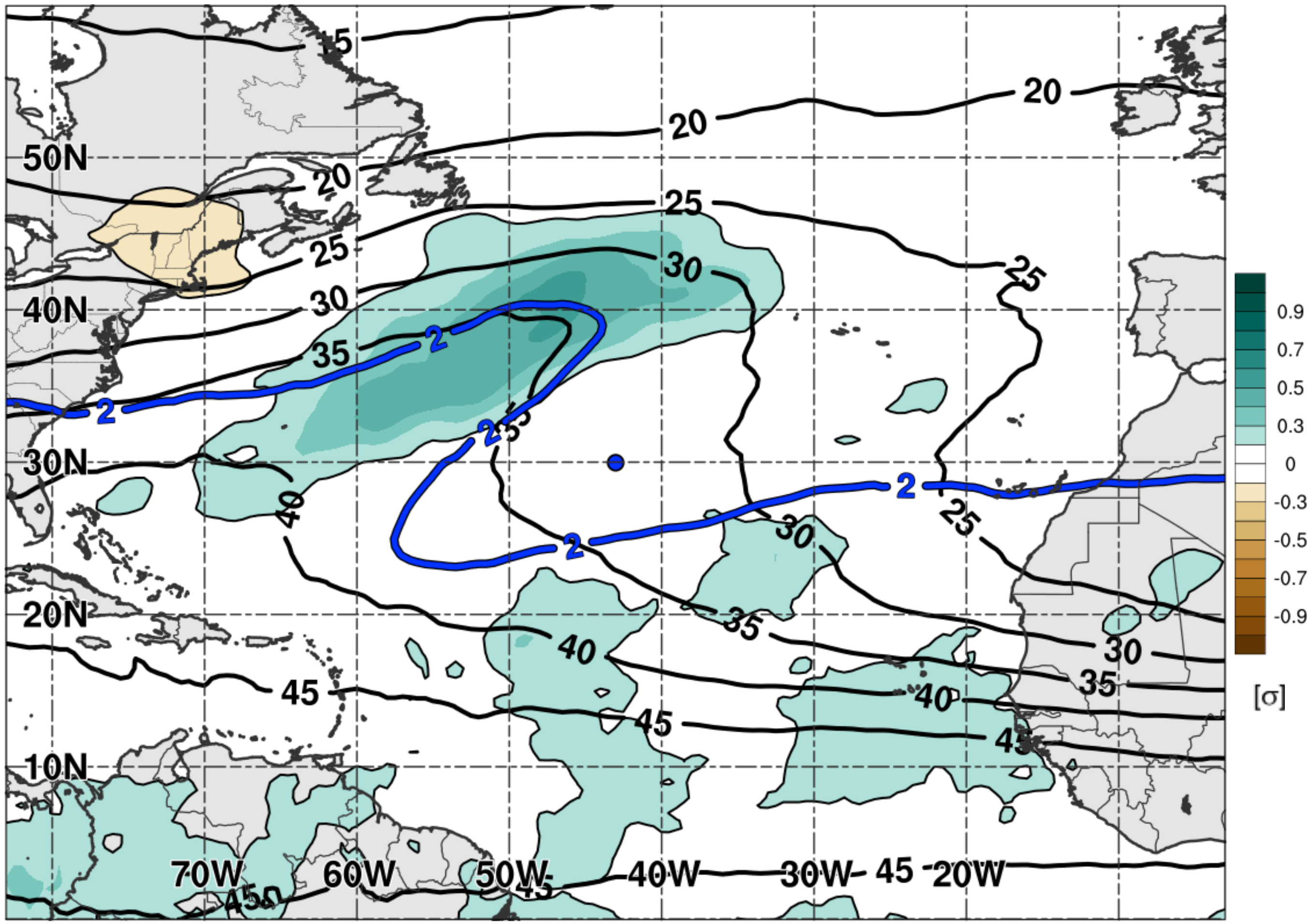
# Results: Composite Differences - PW

- Precipitable Water (PW)

$$\left\{\frac{\bar{x}_i^{Composite} - \bar{x}_i^{Mean}}{\overline{\sigma x_i}}\right\}_{weak}$$

$N_{weak} = 438$

❖ **Only increased moisture upstream of weak PV streamer**



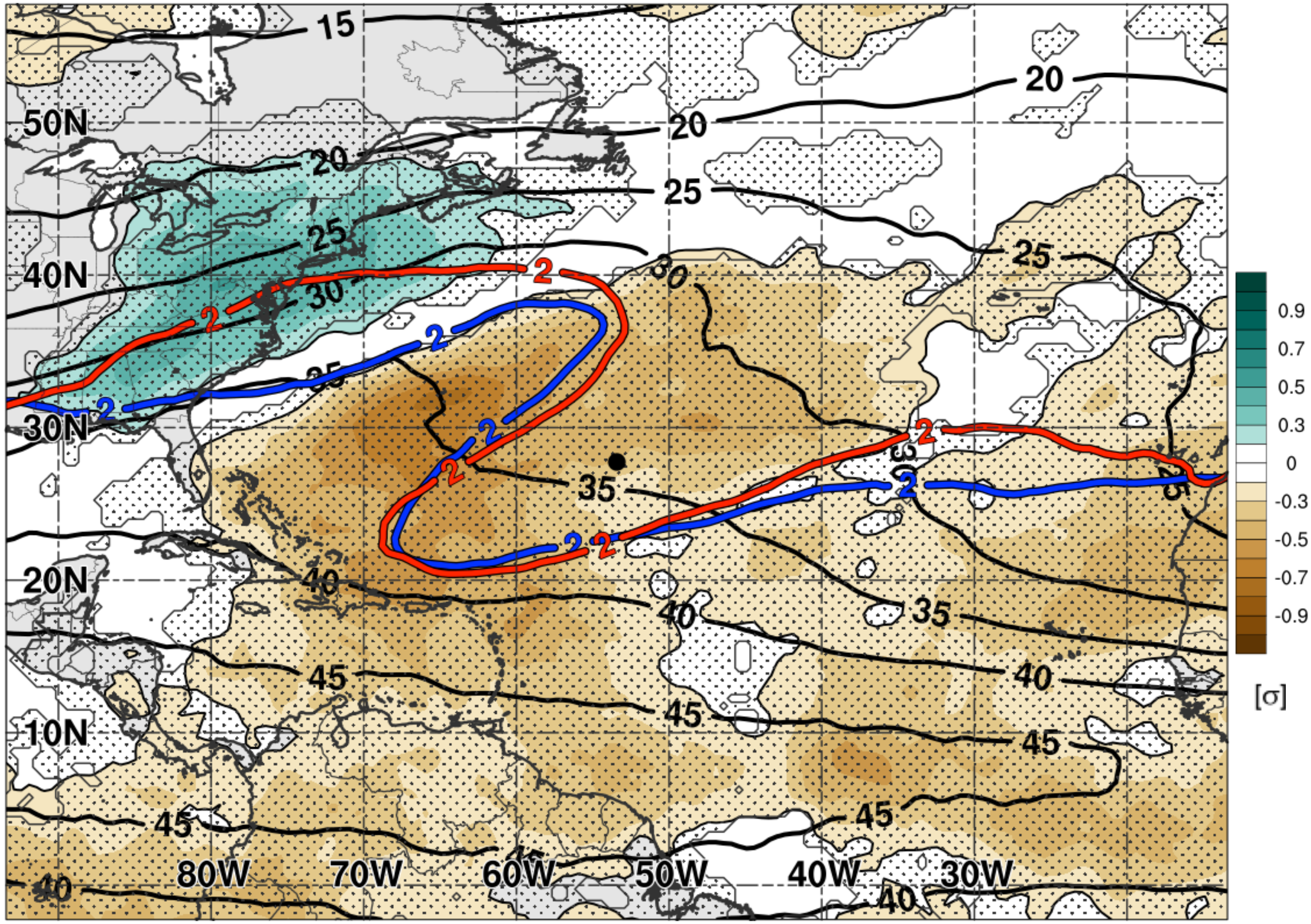

Normalized PW Differences (shaded, σ), Mean magnitude PW (black contours, mm)
Mean 350-K 2-PVU contour weak PV streamers (blue line)

# Results: Composite Differences - PW

- Precipitable Water (PW)

$$\Delta x_{strong-weak}$$

❖ **Large region of negative PW anomalies surrounding PV streamer trough axis**

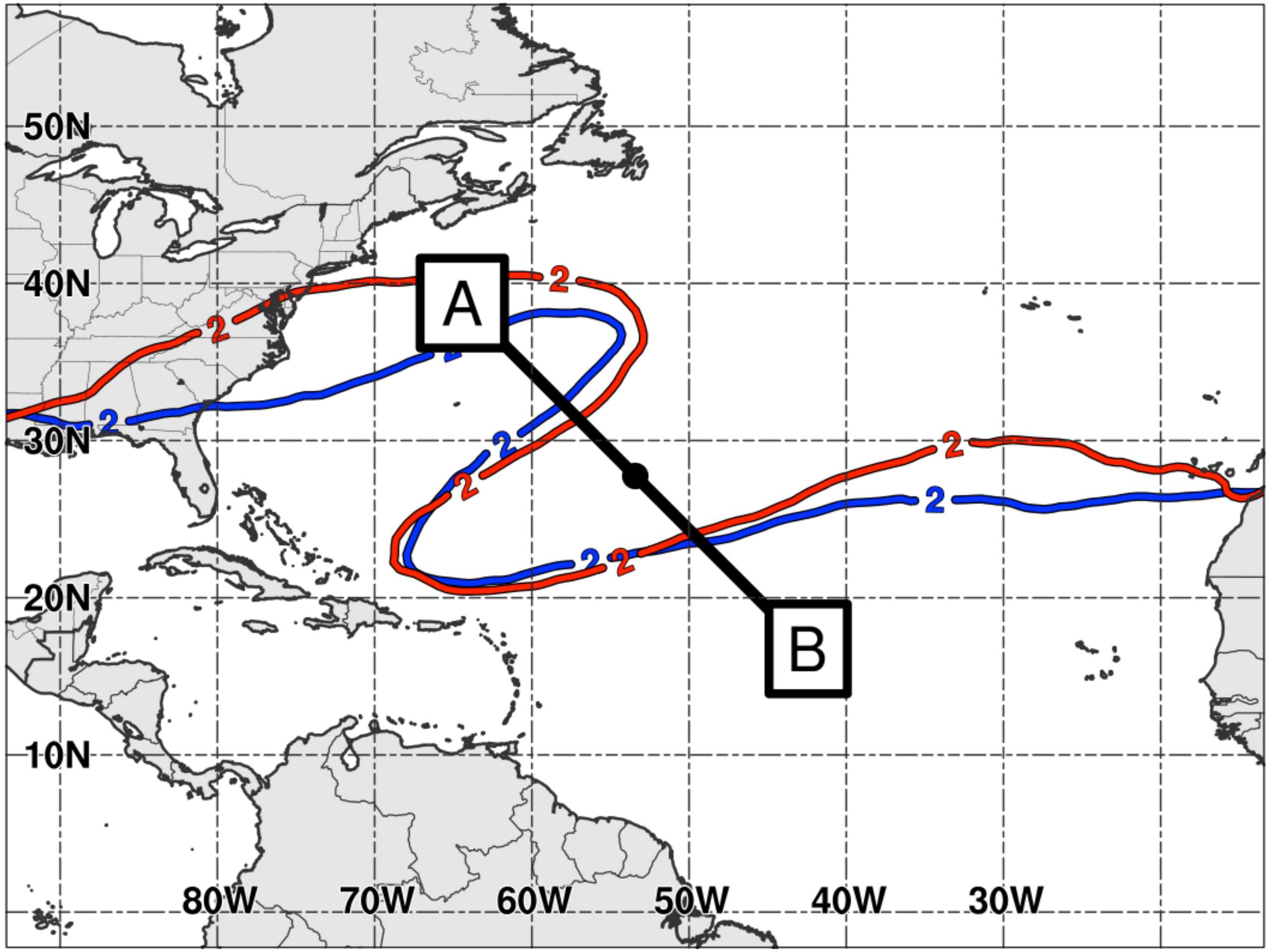



Normalized PW Differences (shaded, *σ*), Mean magnitude PW (black contours, mm)
Mean 350-K 2-PVU contour of strong and weak PV streamers (red and blue lines respectively)
hatched areas indicate statistical significance to the 99% confidence interval

# Results: Composite Differences - PW

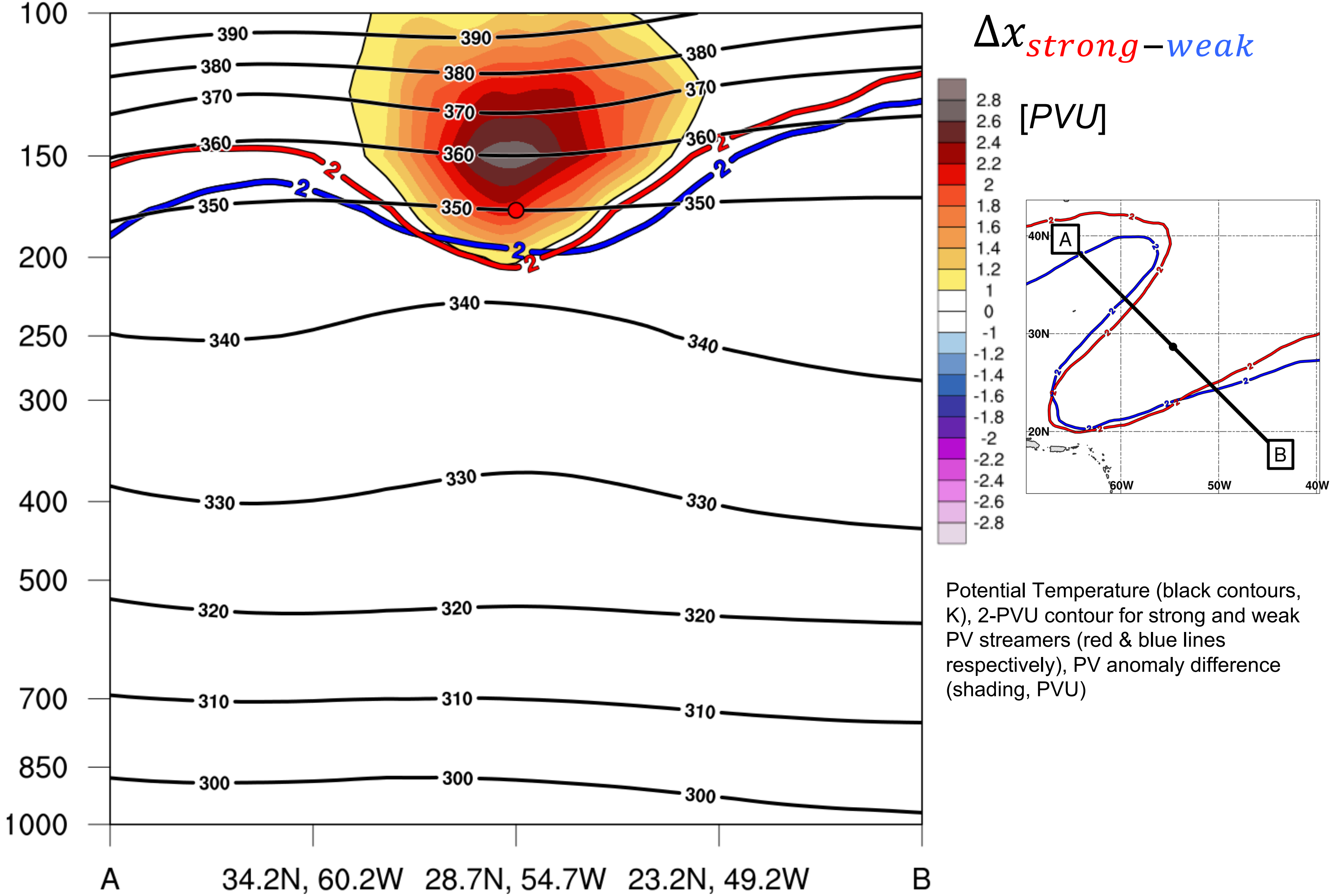
- Lets take a cross-section through the PV streamer trough

$\Delta x_{strong-weak}$



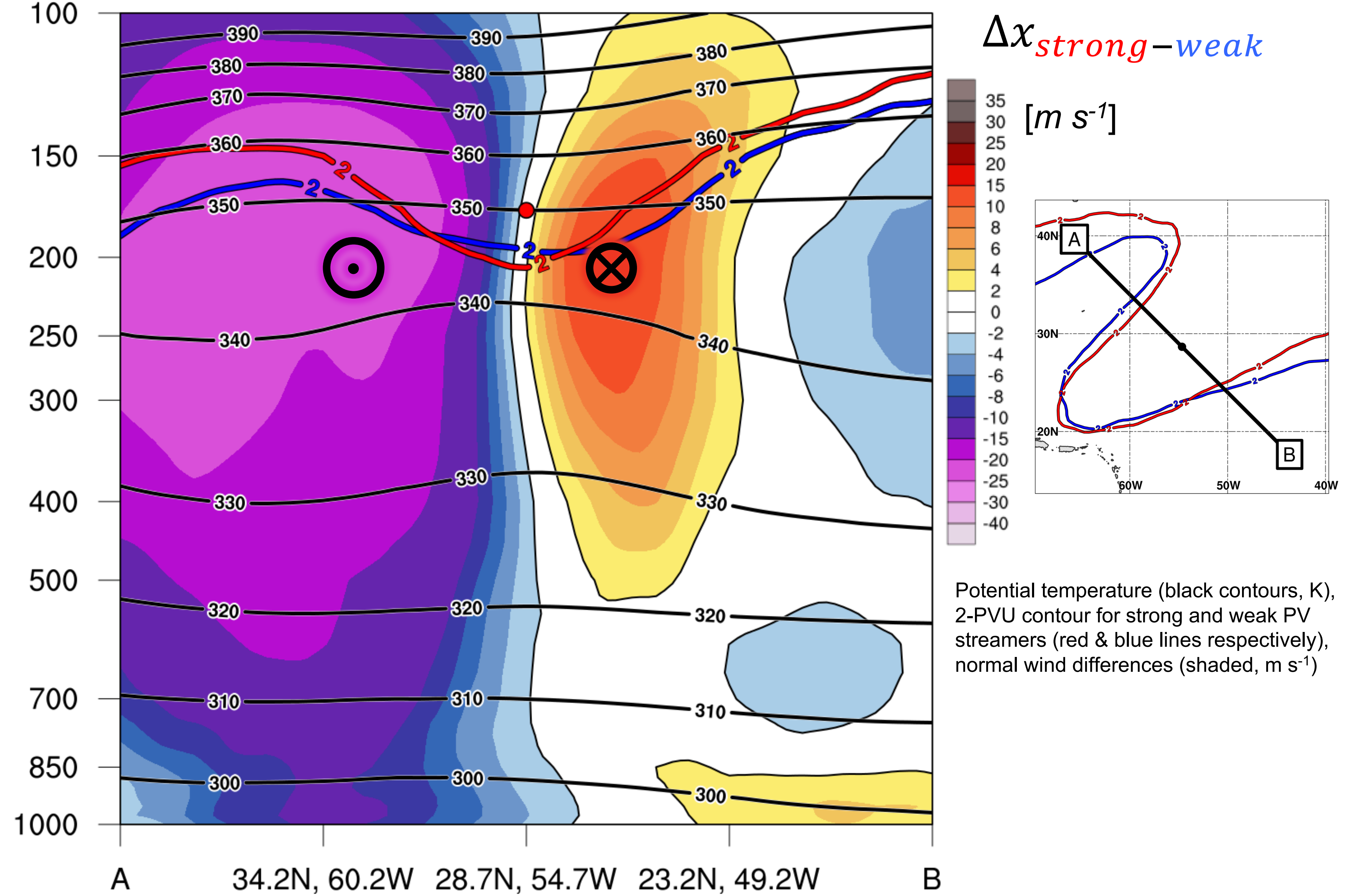

Mean 350-K 2-PVU contour of strong and weak PV streamers (red and blue lines respectively)

# Composite Environment Differences: PV



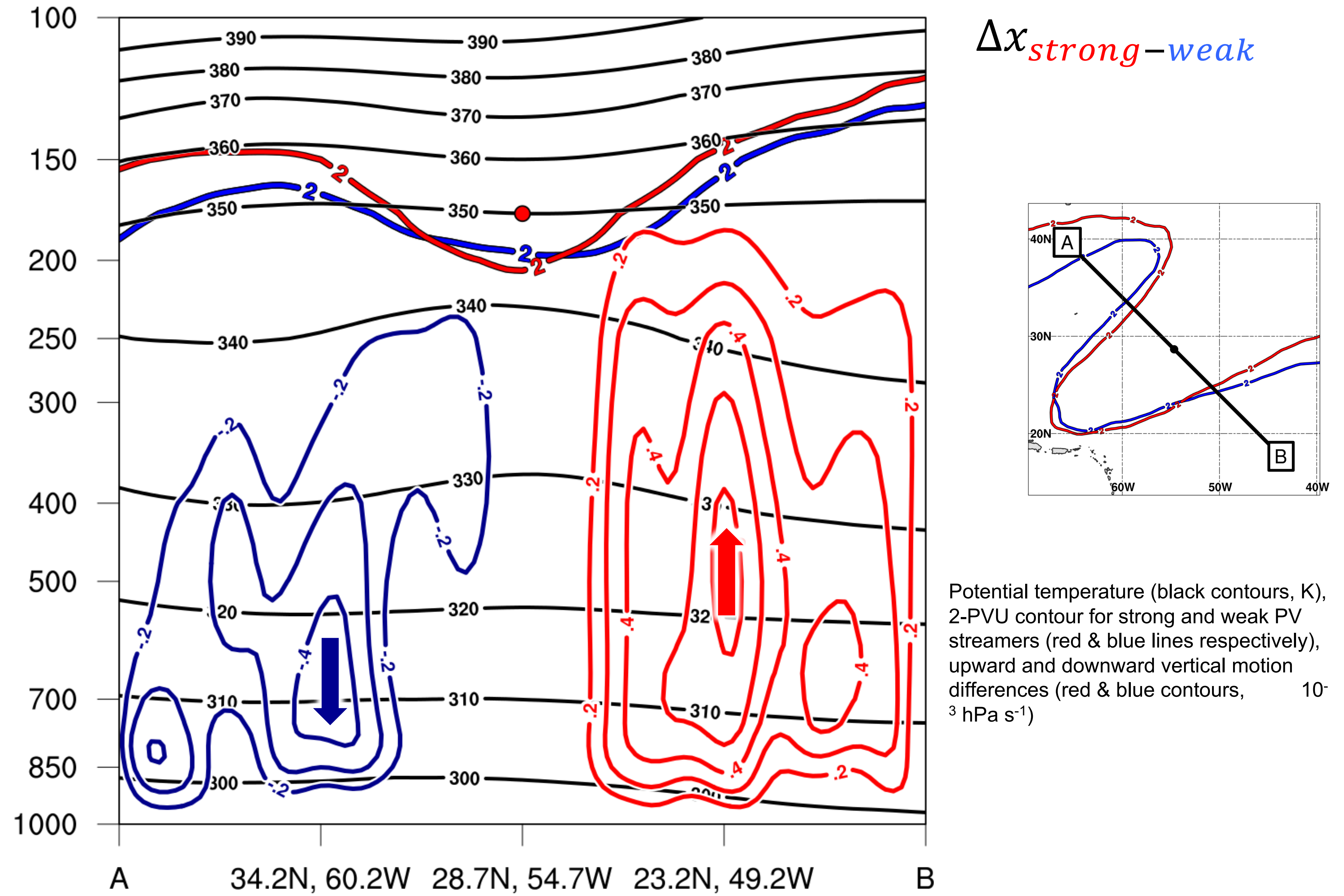

Potential Temperature (black contours, K), 2-PVU contour for strong and weak PV streamers (red & blue lines respectively), PV anomaly difference (shading, PVU)

# Composite Environment Differences: Wind



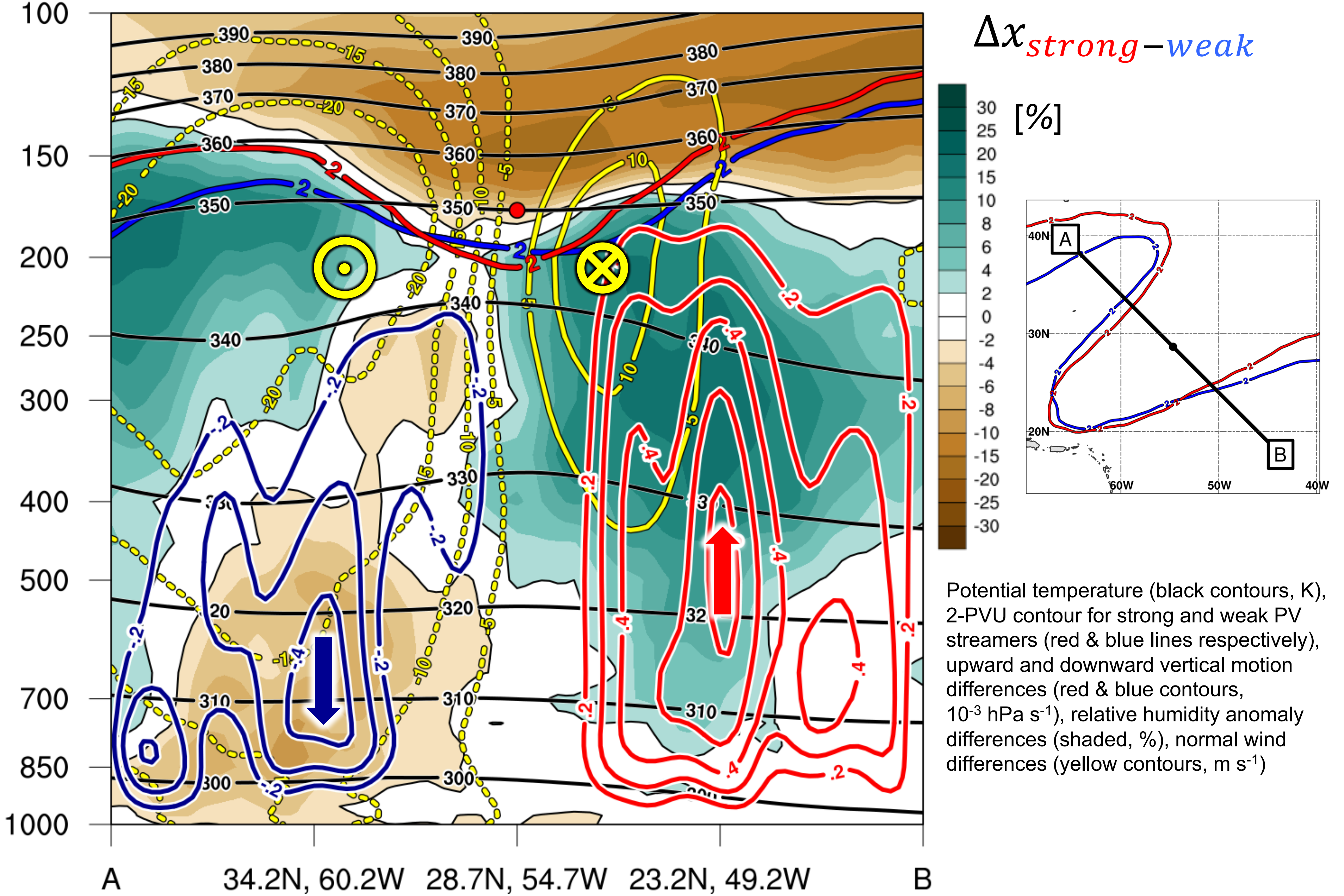

Potential temperature (black contours, K), 2-PVU contour for strong and weak PV streamers (red & blue lines respectively), normal wind differences (shaded, m $s^{-1}$)

# Composite Environment Differences: W




Potential temperature (black contours, K), 2-PVU contour for strong and weak PV streamers (red & blue lines respectively), upward and downward vertical motion differences (red & blue contours, $10^{-3}$ hPa $s^{-1}$)

# Composite Environment Differences: RH




Potential temperature (black contours, K), 2-PVU contour for strong and weak PV streamers (red & blue lines respectively), upward and downward vertical motion differences (red & blue contours, $10^{-3}$ hPa $s^{-1}$), relative humidity anomaly differences (shaded, %), normal wind differences (yellow contours, m $s^{-1}$)

# Concluding Summary

# Concluding Summary: Part 1

- A 1979–2015 climatology of PV streamers on the 350-K surface is created by adapting previous techniques
  - During the TC season (June–November) in Atlantic basin (10-100$^{o}$W)
- PV streamer climatology in the Atlantic basin
  - Highest frequency equatorward of 200-hPa jet
  - Notable shifts occur both from month to month and year to year
  - PV streamers drive the dynamical portion of the TUTT (i.e., MOT) where climatological westerlies occur
- PV streamer intensity and area compared to TC activity
  - Strong and large PV streamers are correlated with lower TC activity
  - Weak PV streamers are correlated with higher TC activity
    - Most obvious differences shown when comparing top and bottom 8 ACE years
  - PV streamer activity metric (combining amount, size, and intensity) exhibits greatest negative correlation with TC activity.

# Concluding Summary: Part 2

- Composite differences of PV streamers
  - An effective comparison needs to compare different intensities that are similar in area and similar in tilt
  - Top and bottom 20 percentile in intensity are compared to 55-75$^{o}$ tilts and 40-60 percentile areas
- Vertical Wind Shear
  - Strong PV streamers have much larger and stronger corridors of shear downstream of their trough axis
- Sea Level Pressure
  - Strong PV streamers have higher SLP in and around their trough axis
- Precipitable Water
  - Strong PV streamers have lower PW in their trough axis, but higher PW upstream of the trough axis in the upstream ridge
- Cross Section
  - Enhanced shear from stronger tropopause based winds of a strong PV anomaly
  - Enhanced anomalies related to stronger vertical motion upstream and downstream of strong PV streamers

# Final Thoughts and Future Work

- Seasonal PV streamer activity represents an important extratropical impact on TC activity
  - While not fully independent of other factors (ENSO, SSTs, AEW activity) it may still add predictability when combined with these well known seasonal prediction factors
- Future Work
  - ➢ Assessing the seasonal predictability of PV streamer activity
  - ➢ Understanding upstream precursors lead to strong vs. weak PV streamers (in progress)
  - ➢ Real time PV streamer identification, including assessment of relevant variables
    - Area, Intensity, Tilt
    - May provide additional clues into how these individual events are likely to influence TCs that occur nearby

**Questions? ppapin@albany.edu**

# Extra Slides

# Results: Reference Websites for more Figures

## Yearly PV Streamers 1979-2015

http://www.atmos.albany.edu/student/ppapin/lb13_img/phd/pvs_year.html

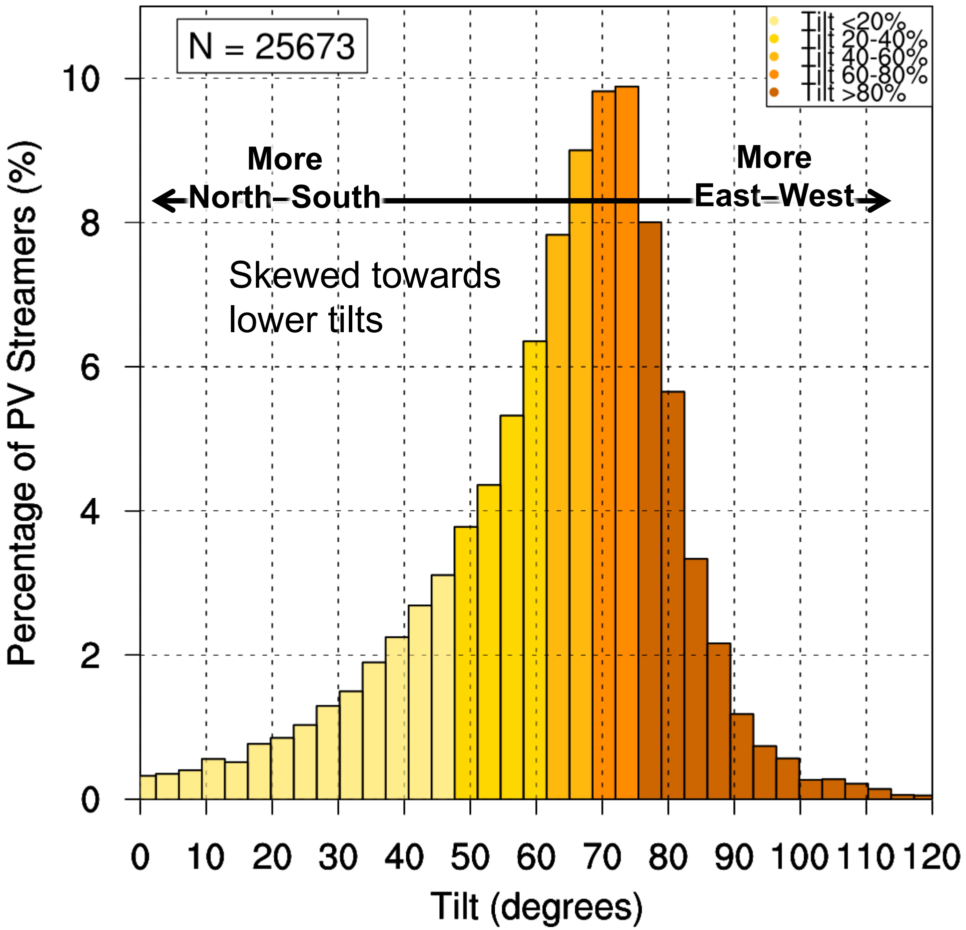
## All Composite Results of PV Streamers

http://www.atmos.albany.edu/student/ppapin/lb13_img/phd/pvs_composite.html

# Results: Variability of PV Streamer Tilt

- Tilt of PV streamers (degree tilt relative to a meridian)
  - ➢ 1 Jun–30 Nov between 100–10°W
  - ➢ Mean: 59.5°
  - ➢ Stdev: +/- 26.1°

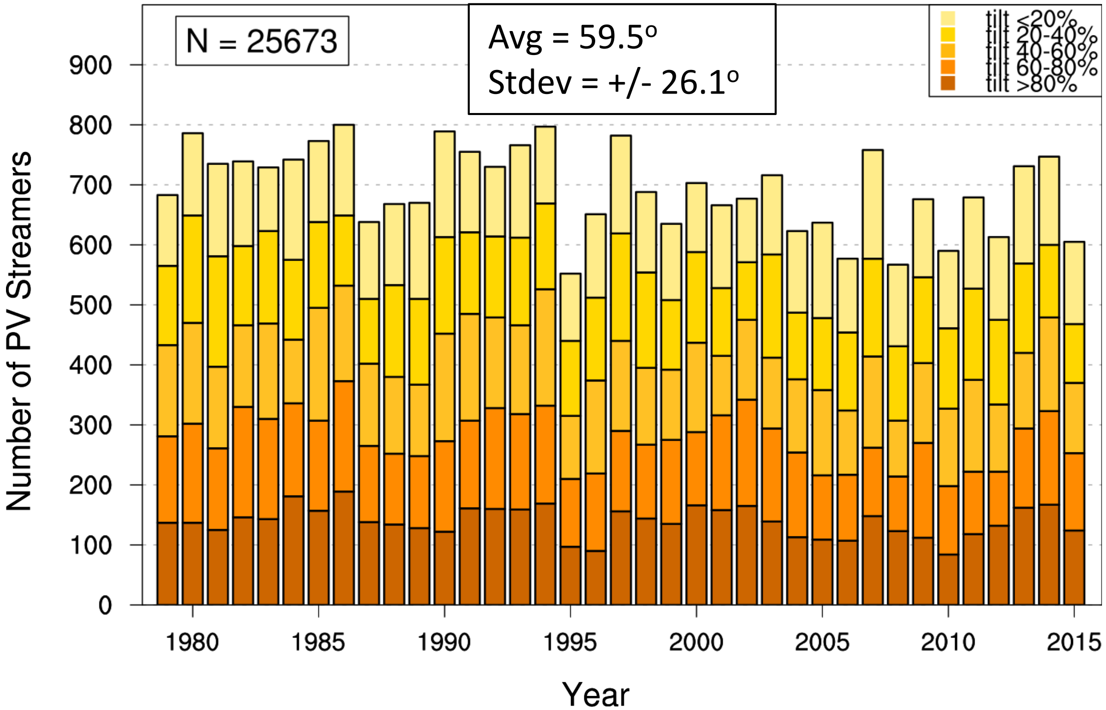
Because of the highly skewed distribution, it is useful to use percentiles when describing tilt values.



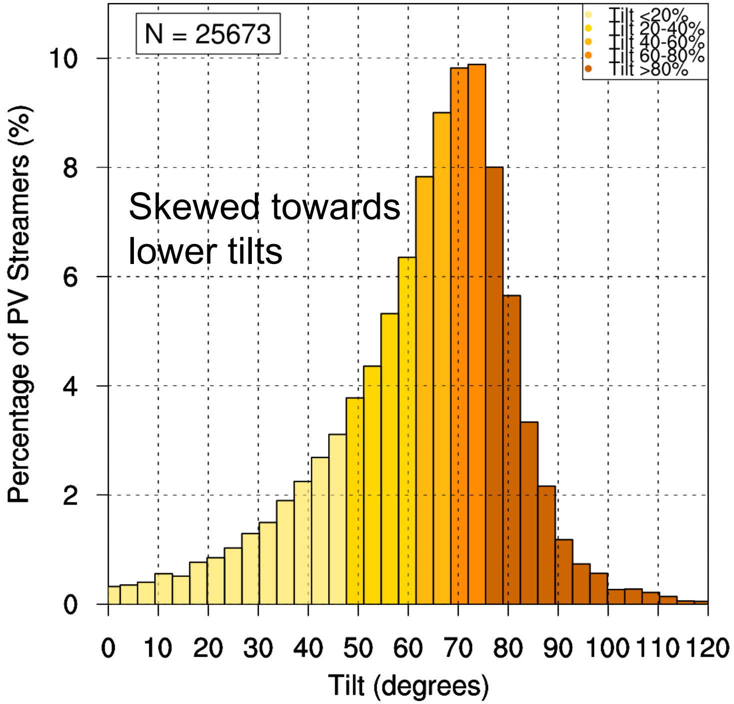

*PDF of PV Streamer Tilt*

# Results: Variability of PV Streamer tilt

- Interseasonal variability in PV streamer area
  - 1 Jun–30 Nov between 100–10°W




*Yearly Distribution of PV Streamer Count by Tilt*

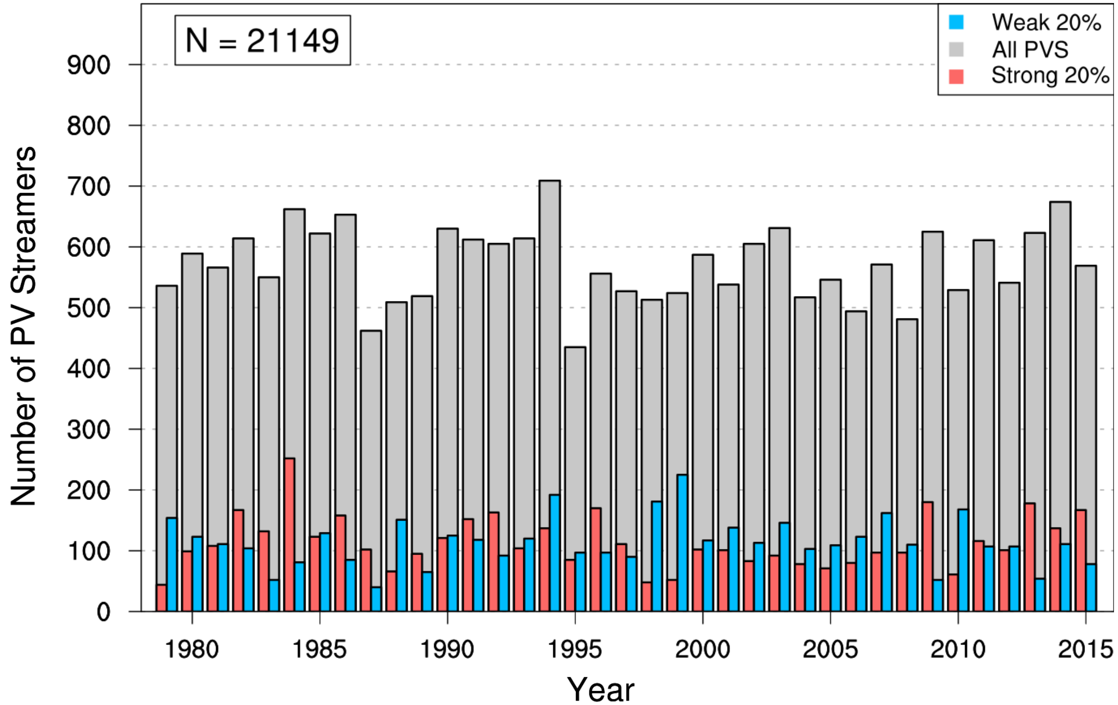


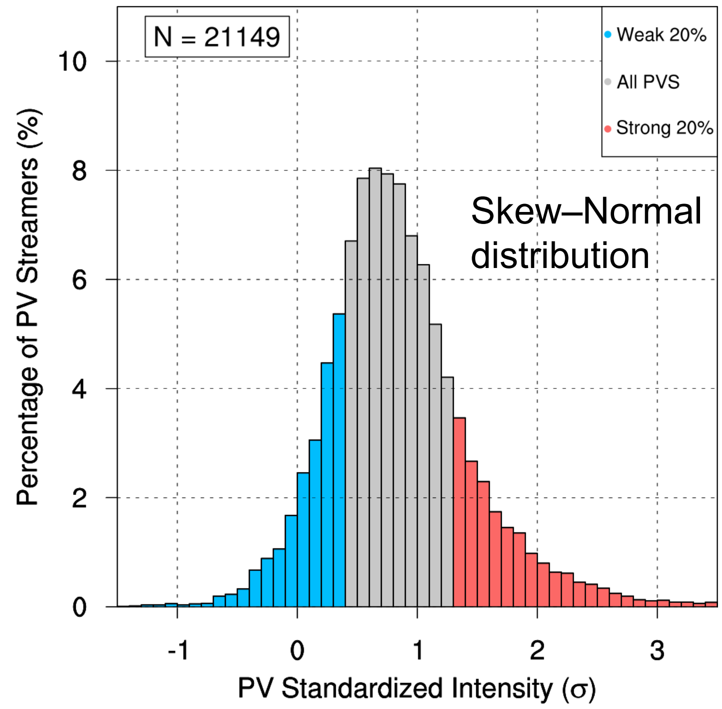

*PDF of PV Streamer Tilt*

✧ No obvious tilt trends over the CFSR period

# ERA Interim: PV Streamer Intensity

- Interseasonal variability in the number of PV streamers
  - 1 Jun–30 Nov between 100–10ºW



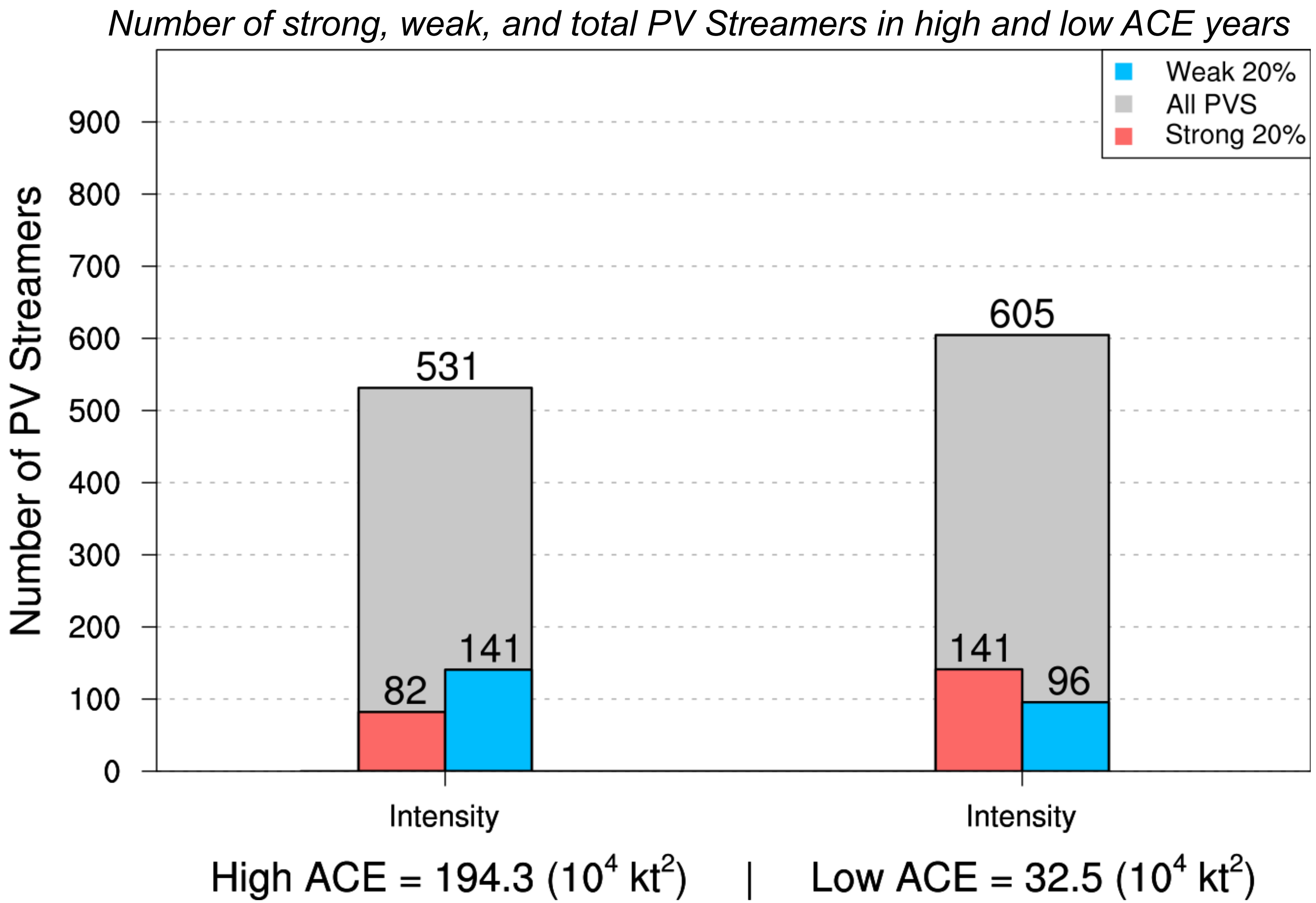

*Yearly Distribution of PV Streamer Count*

*PDF of PV Streamer Intensity*

✧ ERA-Interim does not display the same long-term intensity trends that were observed in the CFSR.

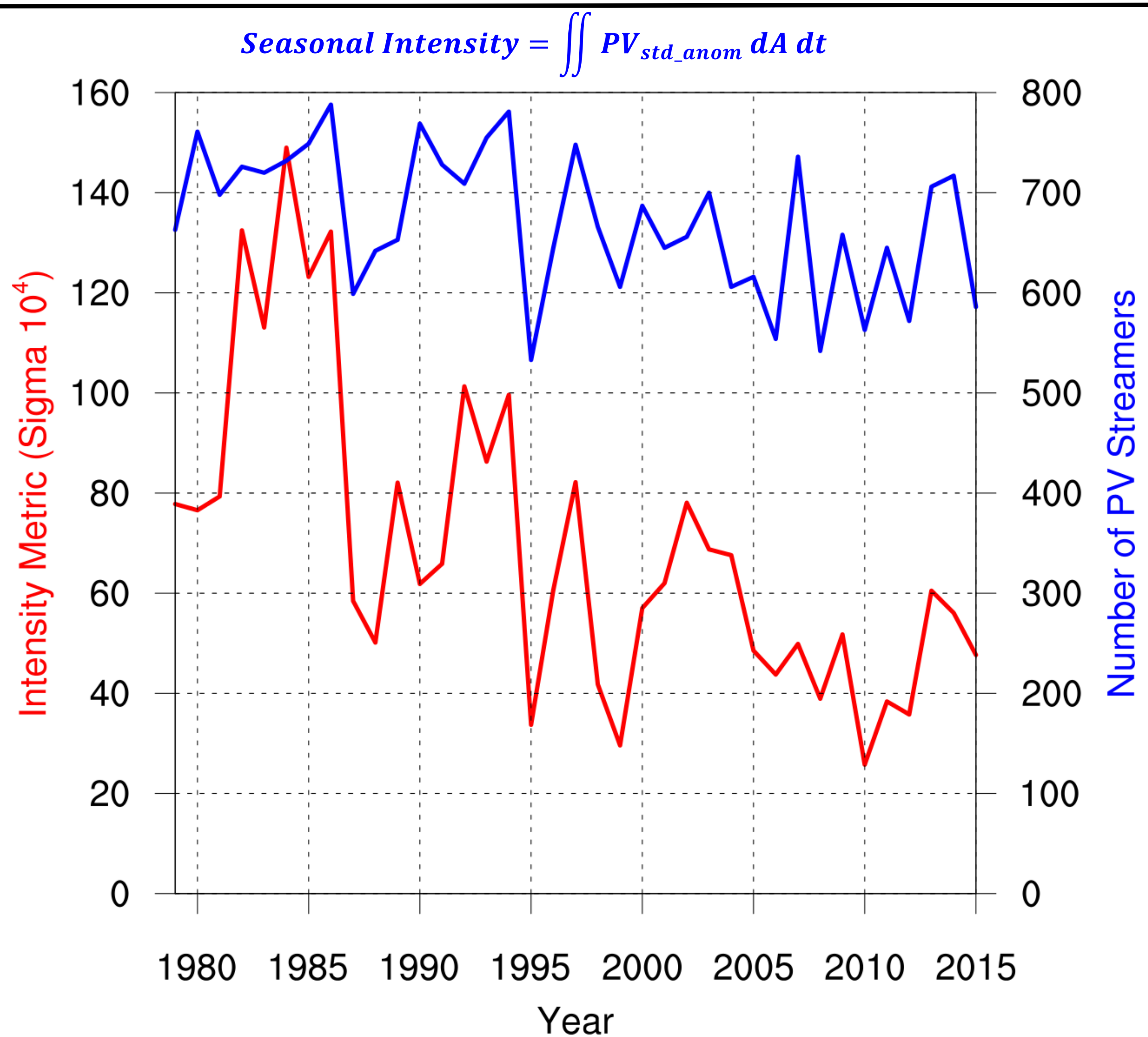
# ERA Interim: High ACE vs. Low ACE

| Top 8 High ACE Years | Bottom 8 Low ACE Years |
|---|---|
| 2005 | 1983 |
| 1995 | 1982 |
| 2004 | 1994 |
| 1998 | 1987 |
| 1999 | 2013 |
| 2003 | 1991 |
| 1996 | 1986 |
| 2010 | 1993 |



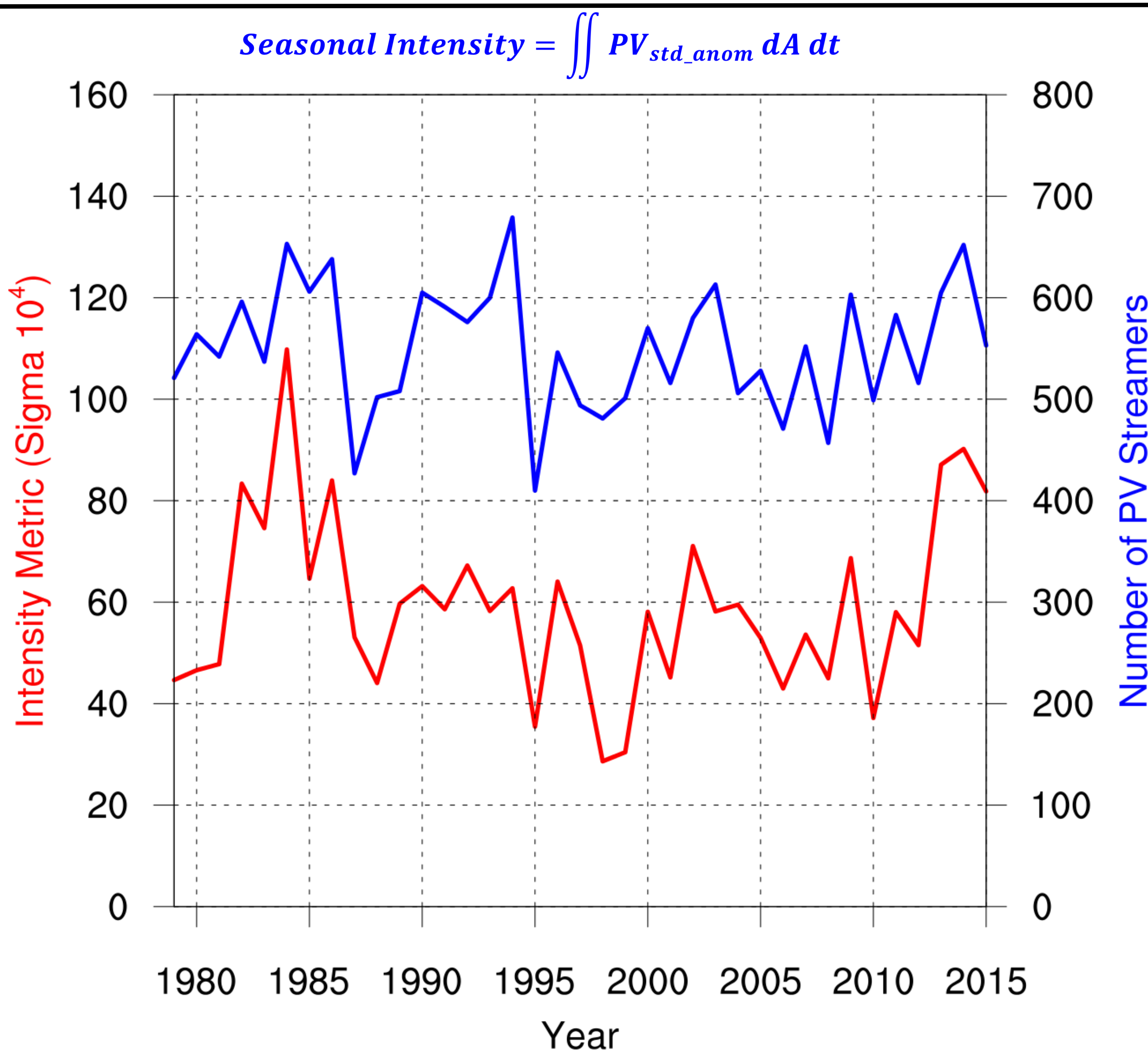
# Time Series: Intensity Metric vs. PVS Count

## CFSR



# Time Series: Intensity Metric vs. PVS Count

## ERAI

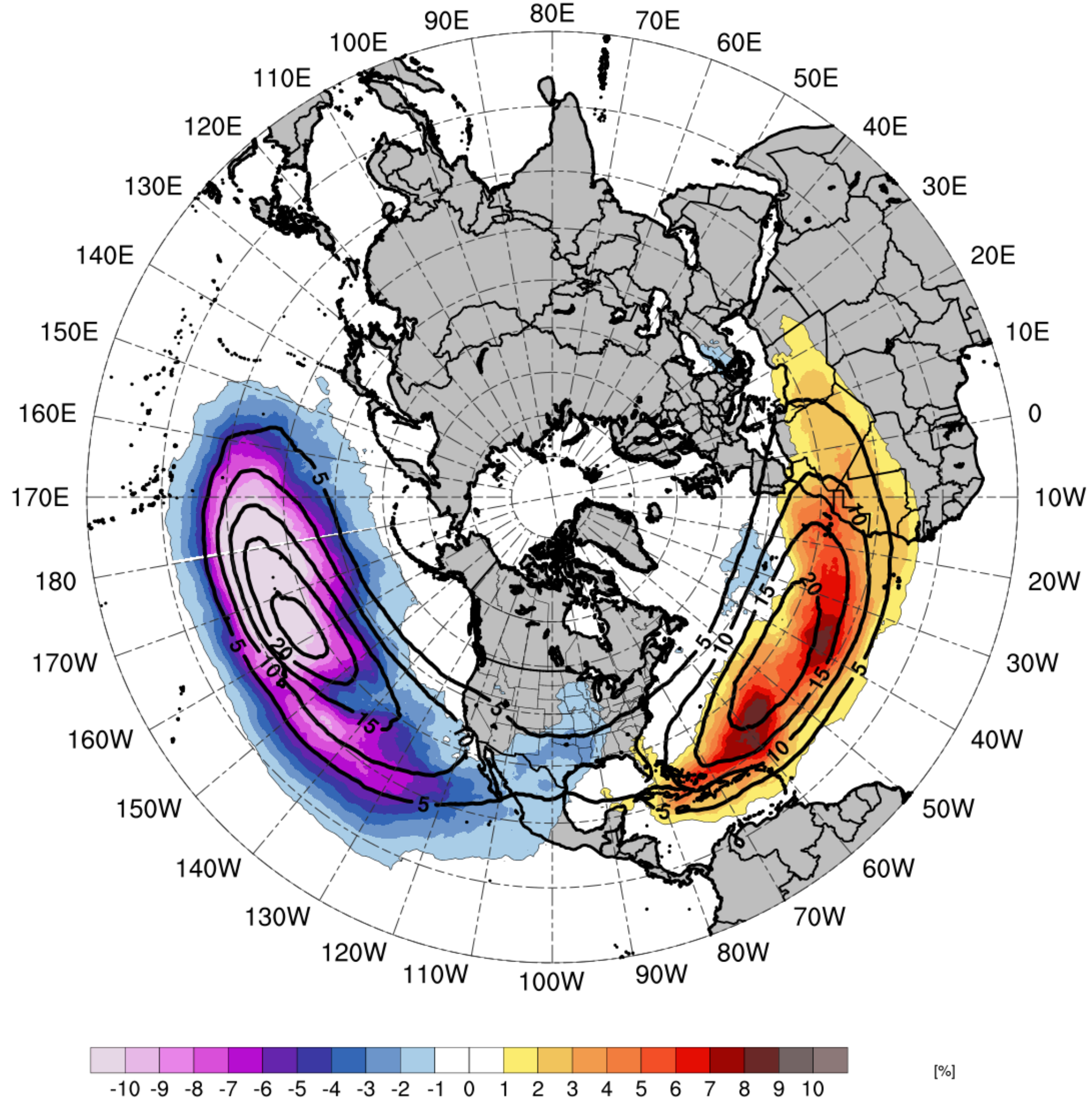


# PV Streamer Frequency Anomalies vs. ENSO

## CFSR

**El Nino – La Nina**

**Percentage change in PV Streamer frequency relative to climatology**

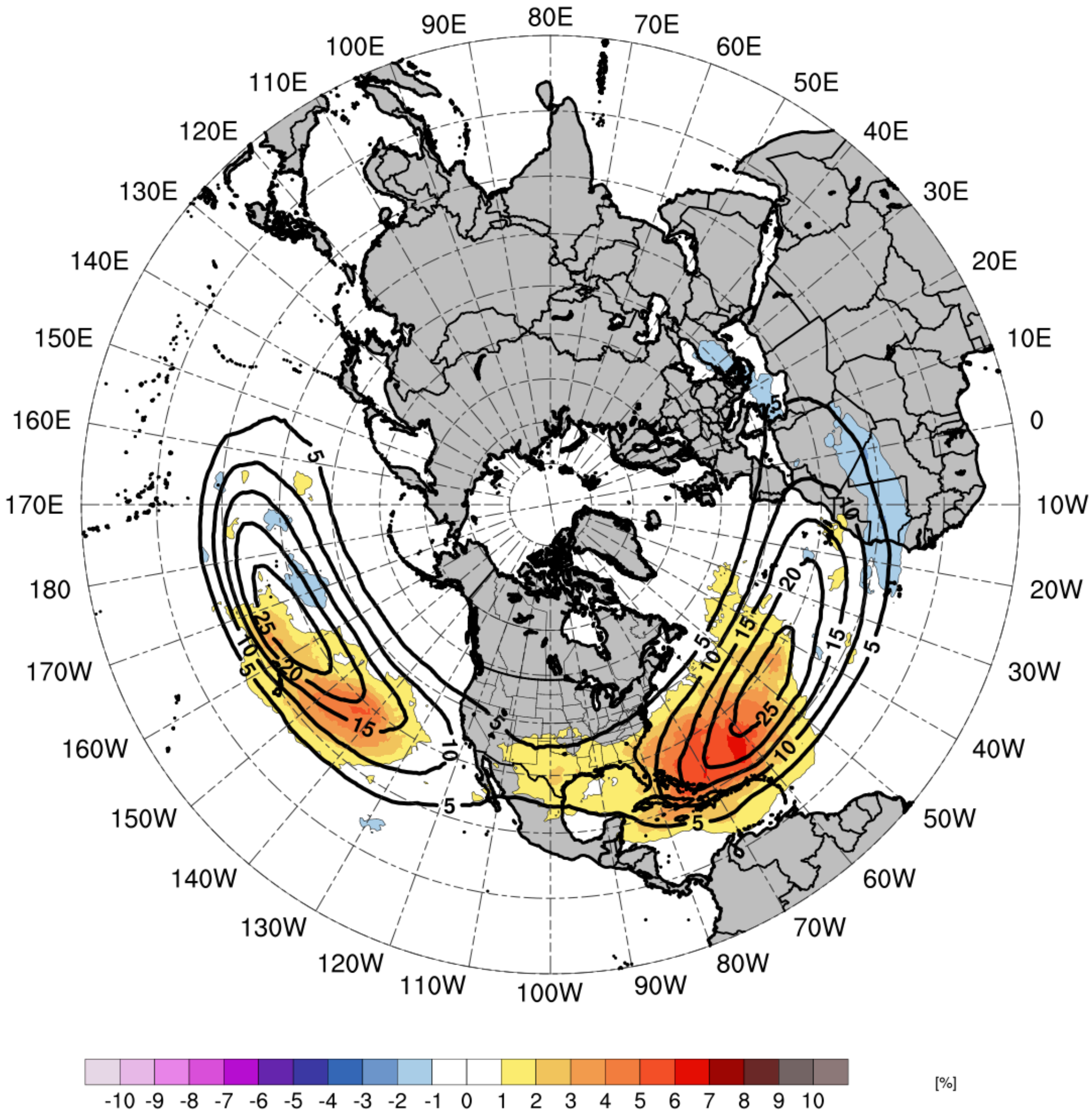


# PV Streamer Frequency Anomalies vs. NAO

## CFSR

**Positive – Negative NAO**

**Percentage change in PV Streamer frequency relative to climatology**

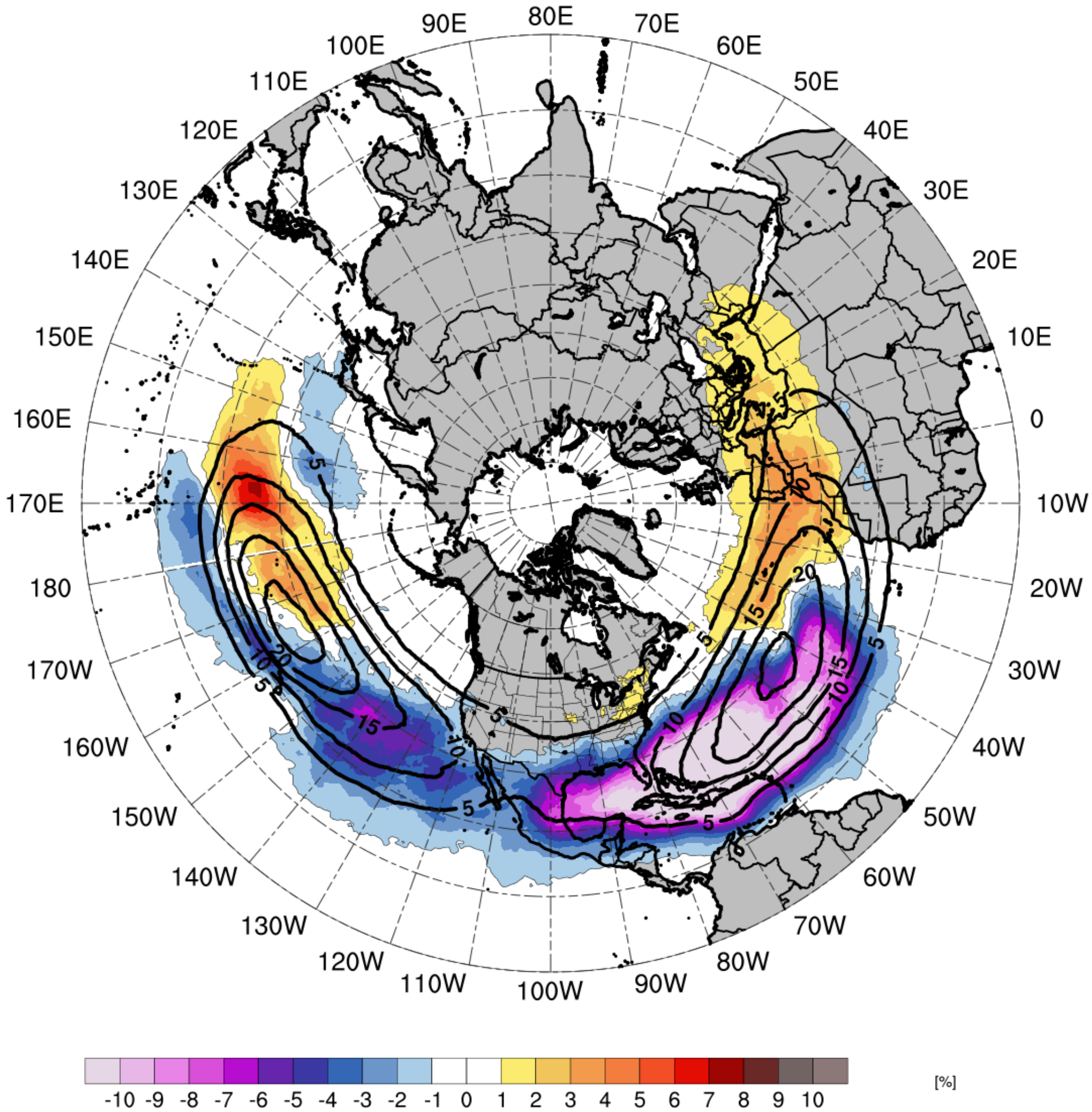


# PV Streamer Frequency Anomalies vs. SSTAs

## CFSR

**Positive – Negative SSTAs**

**Percentage change in PV Streamer frequency relative to climatology**

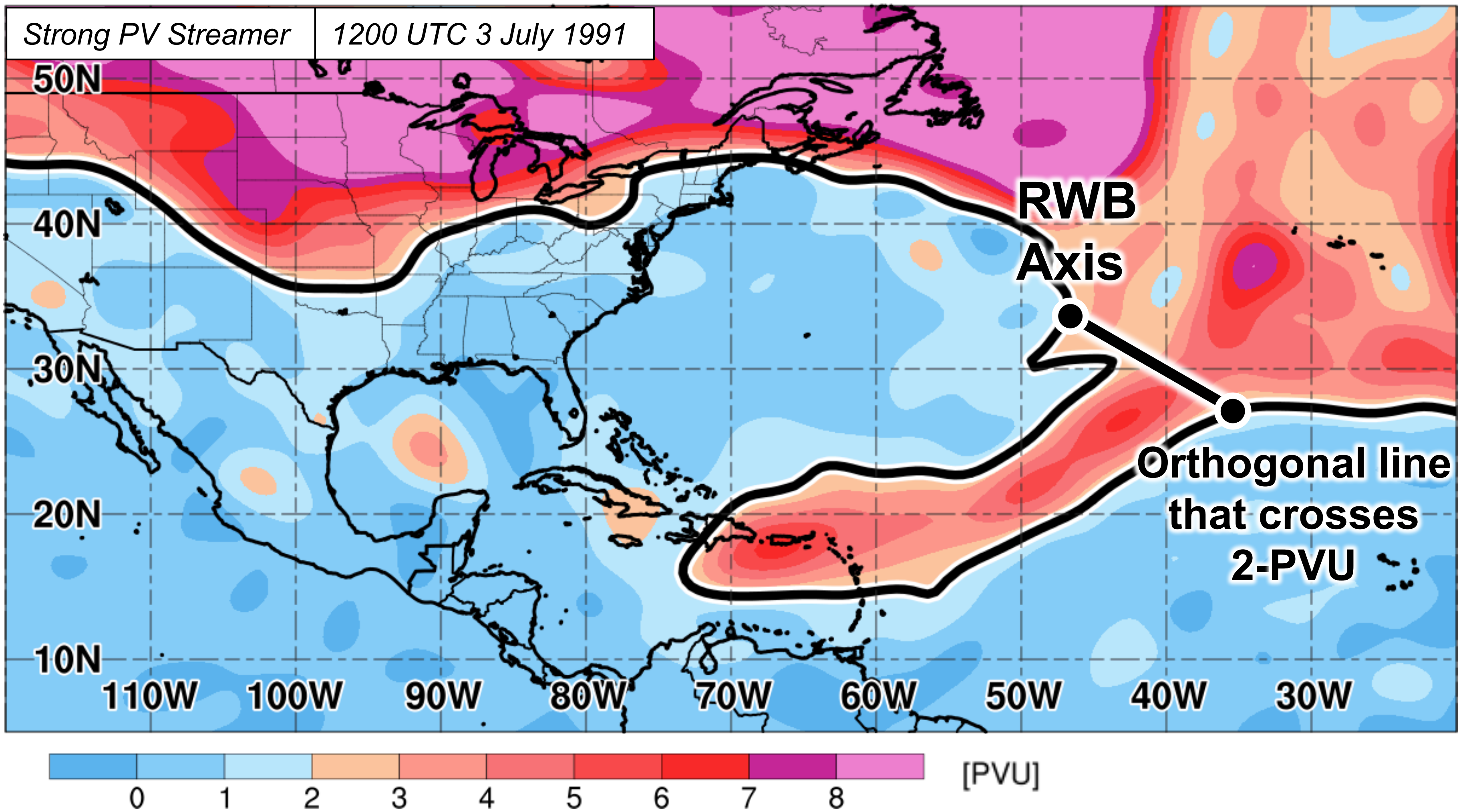


# PV Streamer Identification: Example

Mean and Standard Deviations are derived from a 1979-2009 CFSR climatology

- $PV_{std\_anom} = (PV - PV_{mean}) / PV_{stdev}$

350-K PV (shaded, PVU), and 2-PVU contour (black contour)

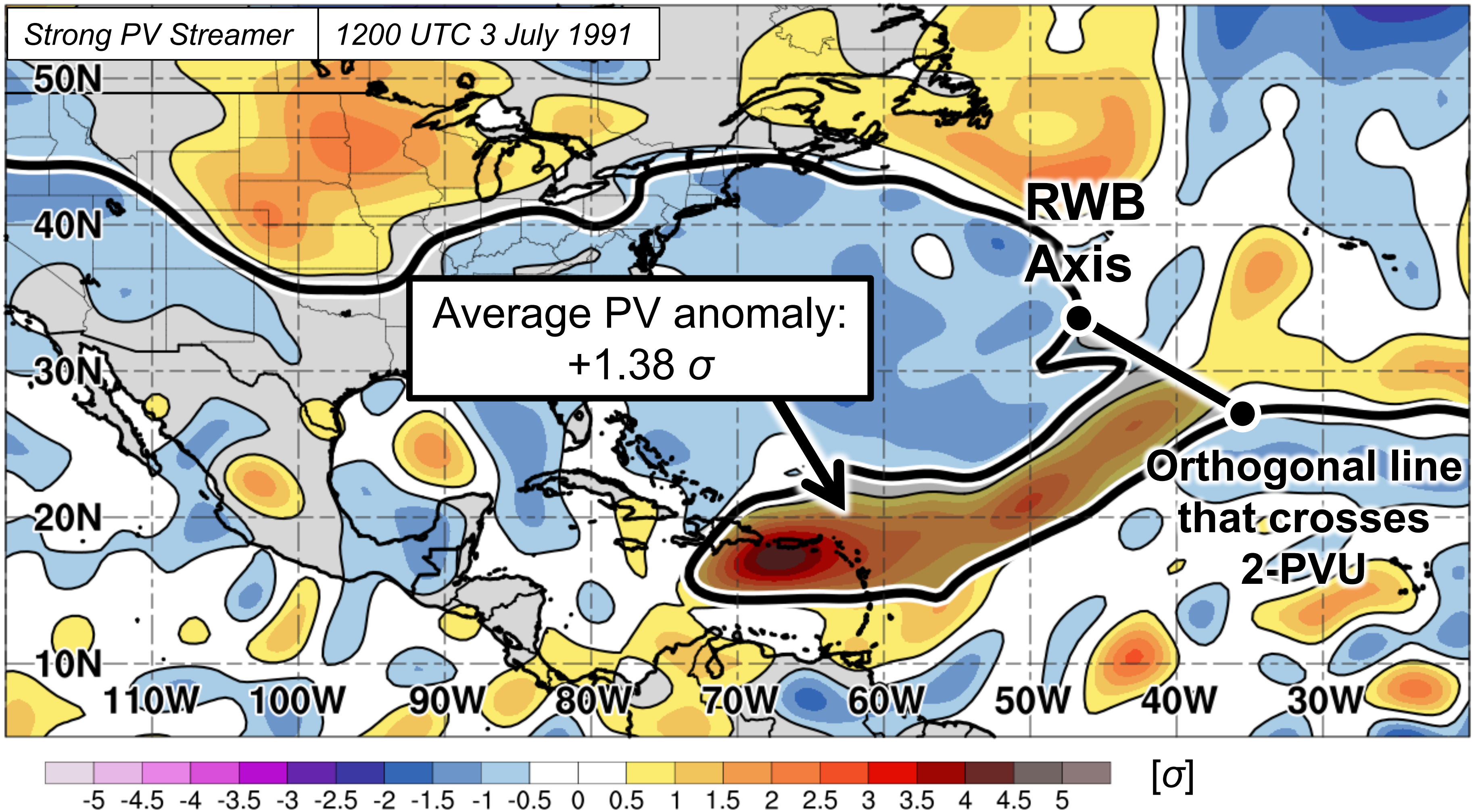


# PV Streamer Identification: Example

Mean and Standard Deviations are derived from a 1979-2009 CFSR climatology

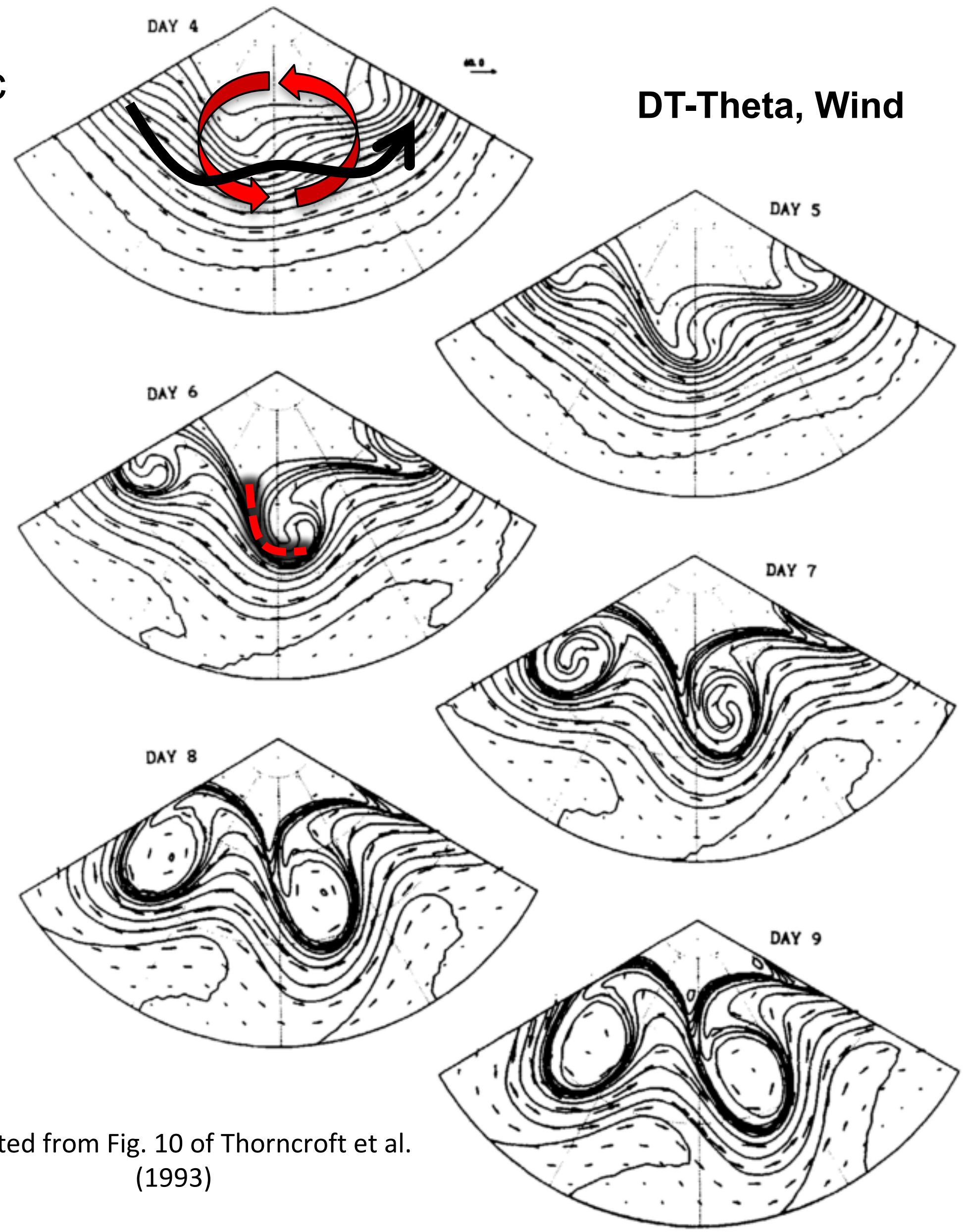
- $PV_{std\_anom} = (PV - PV_{mean}) / PV_{stdev}$

350-K Standardized PV Anomaly (shaded, Sigma), and 2-PVU contour (black contour)



# Literature Review: Rossby Wave Breaking

- RWB Manifests as two characteristic baroclinic wave lifecycles
  - ✧ Anticyclonic Wave Breaking (LC1, AWB)
  - ✧ Cyclonic Wave Breaking (LC2, CWB)
- Anticyclonic meridional shear found equatorward of the waveguide
  - ✧ Thin positively tilted PV streamer
- Cyclonic meridional shear found poleward of the waveguide
  - ✧ Thick negatively tilted PV streamer




Adapted from Fig. 10 of Thorncroft et al. (1993)

# PV Streamer Identification

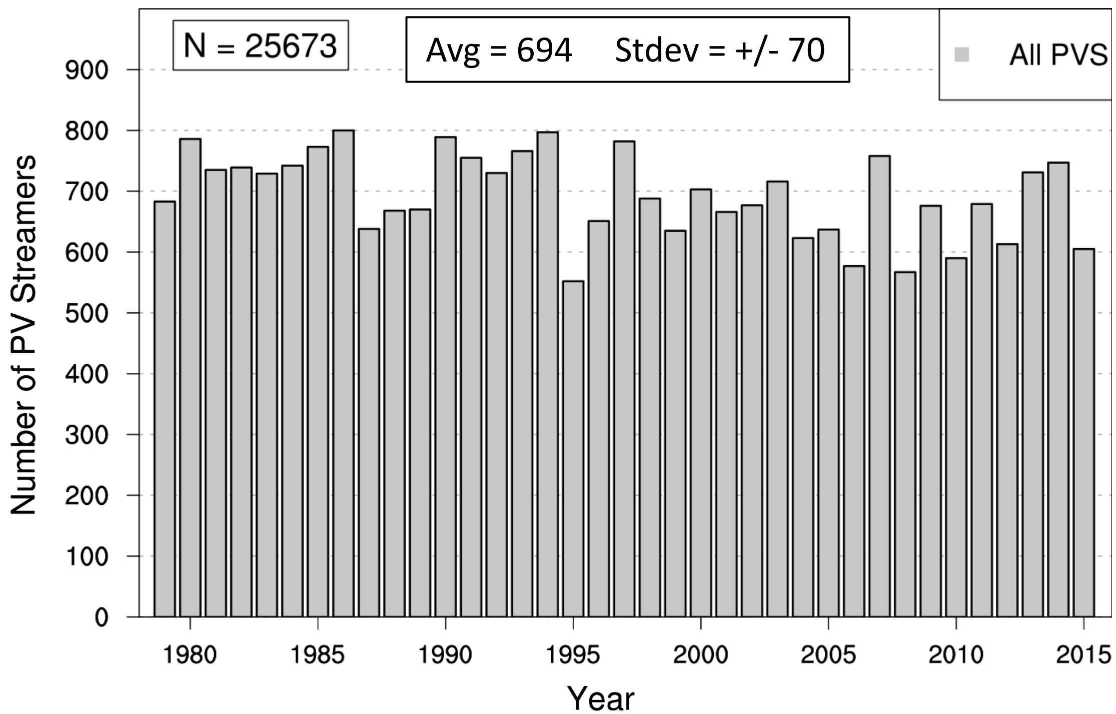
- PV streamers are identified from June–November 1979–2015 using the 0.5° NCEP CFSR (Saha et al. 2010).
- A new PV streamer algorithm is created that combines previous methodologies
  - Postel and Hitchman (1999)
    - ✧ Identifies locations where RWB occurs (meridional gradient reversal in PV)
  - Wernli and Sprenger (2007)
    - ✧ Identifies elongated filaments of high PV air using width and perimeter of PV streamer
- Identification of PV streamers occurs on a isentropic surface that approximates the location of the subtropical tropopause
  - 350-K surface using the 2-PVU contour as the dynamical tropopause
  - PV streamer intensity is calculated as a standardized PV anomaly of the area encompassed by the PV streamer

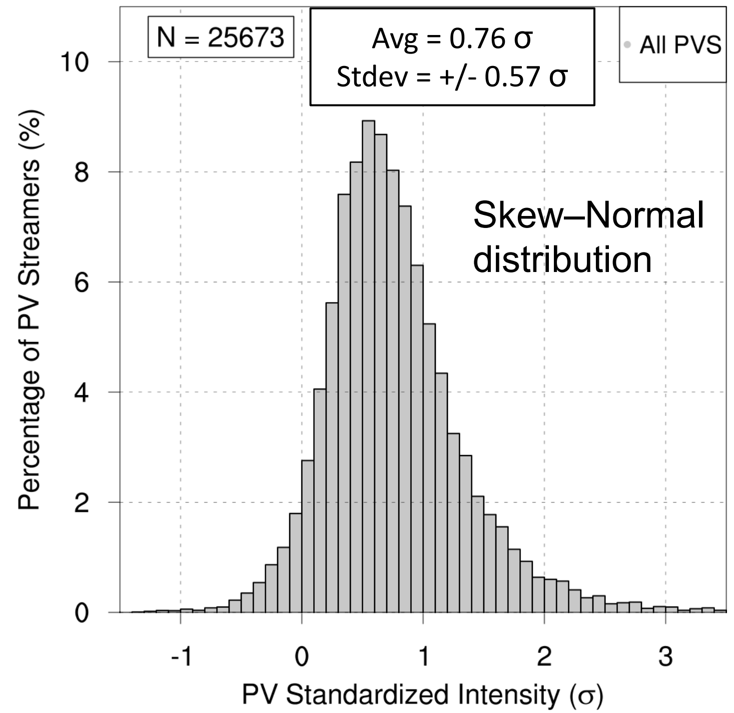
$$PV_{std\_anom} = (PV - PV_{mean}) / PV_{stdev}$$

Mean and Standard Deviations are derived from a 1979-2009 CFSR climatology

# Results: PV Streamer Variability 1979–2015

- Interseasonal variability in the number of PV streamers
  - 1 Jun–30 Nov between 100–10°W



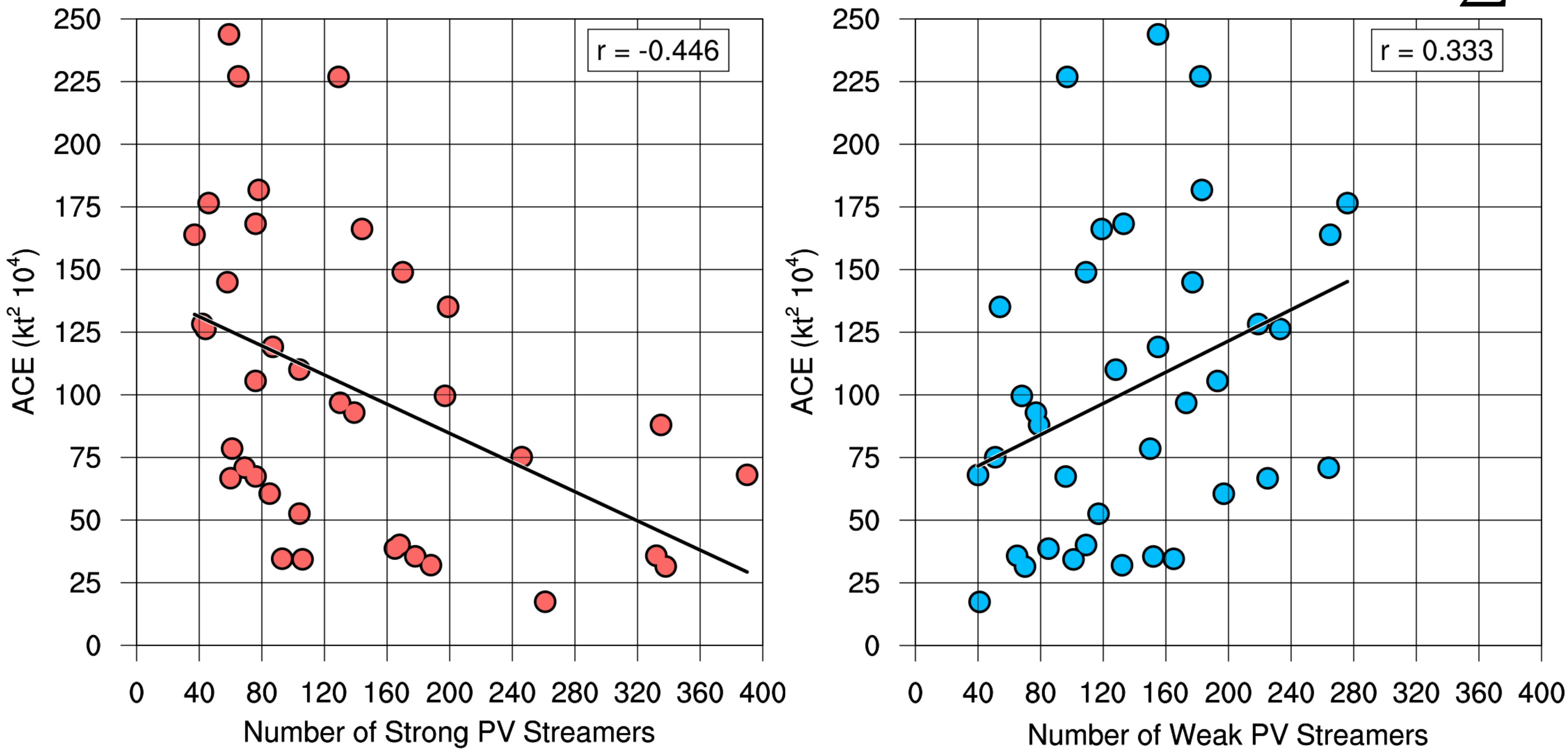

*Yearly Distribution of PV Streamer Count* *PDF of PV Streamer Intensity*

- CFSR depicts a trend towards a decrease in the number of strong PV streamers and increase in the number of weak PV streamers with time
  - Questions remain if this is a real trend or is dataset dependent

# Climatological Results: PV Streamer Intensity

- How TC activity related to differences in PV streamer intensity
  - ➢ Seasonal TC activity measured by accumulated cyclone energy (ACE)

$$ACE = 10^{-4} \sum v_{max}^2$$




✧ Strong PV streamers are negatively correlated with ACE

✧ Weak PV streamers are positively correlated with ACE

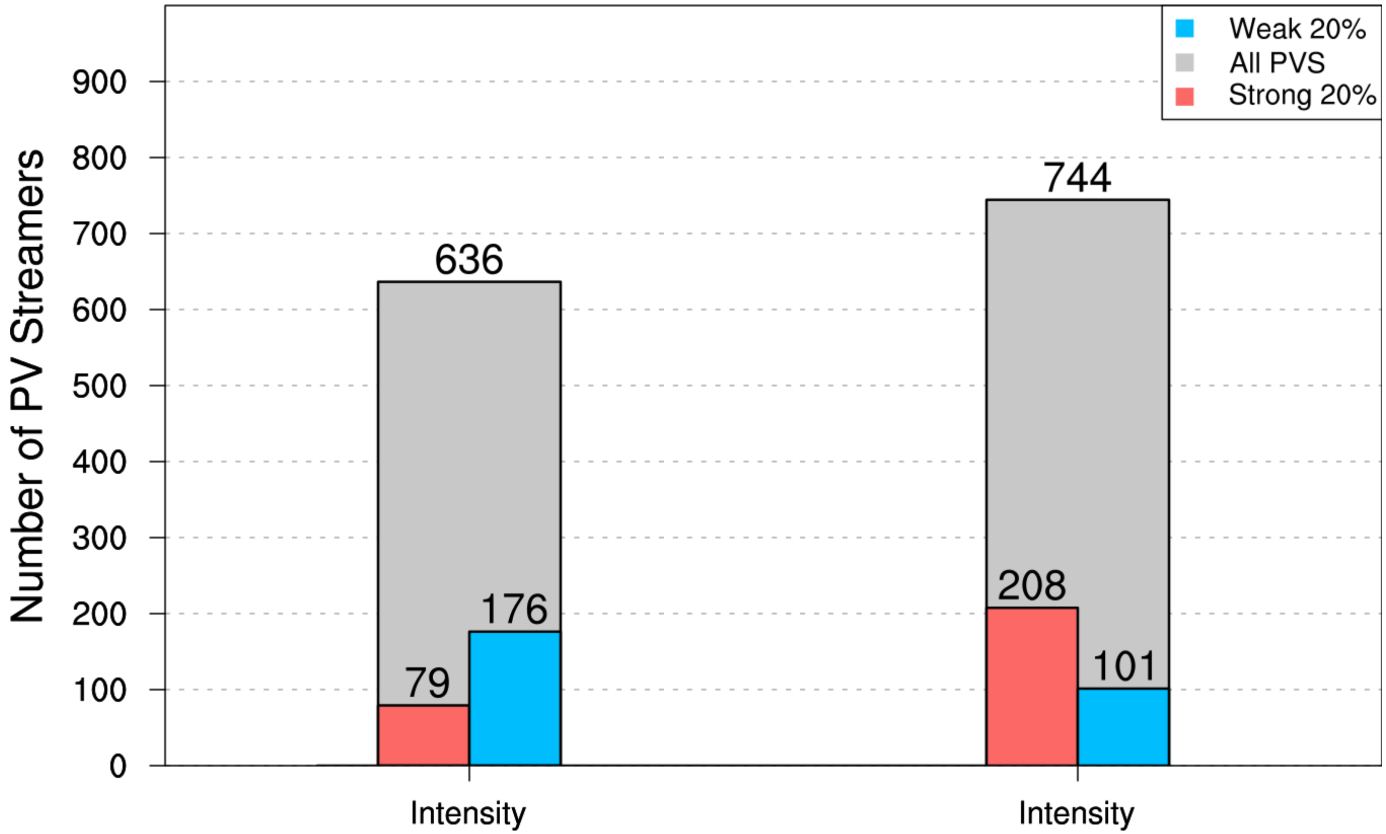
To further illustrate TC activity relationship to PV streamer intensity, lets compare the most and least active TC seasons (using ACE).

# Results: TC Activity – High vs. Low ACE

- Active TC seasons (High ACE) feature:
  - ✧ Fewer PV streamers (**-14.5%**)
  - ✧ Much Fewer Strong PV streamers (**-62.0%**)
  - ✧ Many More Weak PV streamers (**+74.2%**)

| **Top 8** High ACE Years | **Bottom 8** Low ACE Years |
|---|---|
| 2005 | 1983 |
| 1995 | 1982 |
| 2004 | 1994 |
| 1998 | 1987 |
| 1999 | 2013 |
| 2003 | 1991 |
| 1996 | 1986 |
| 2010 | 1993 |

*Number of strong, weak, and total PV Streamers in high and low ACE years*




High ACE = 194.3 ($10^4$ kt$^2$) | Low ACE = 32.5 ($10^4$ kt$^2$)

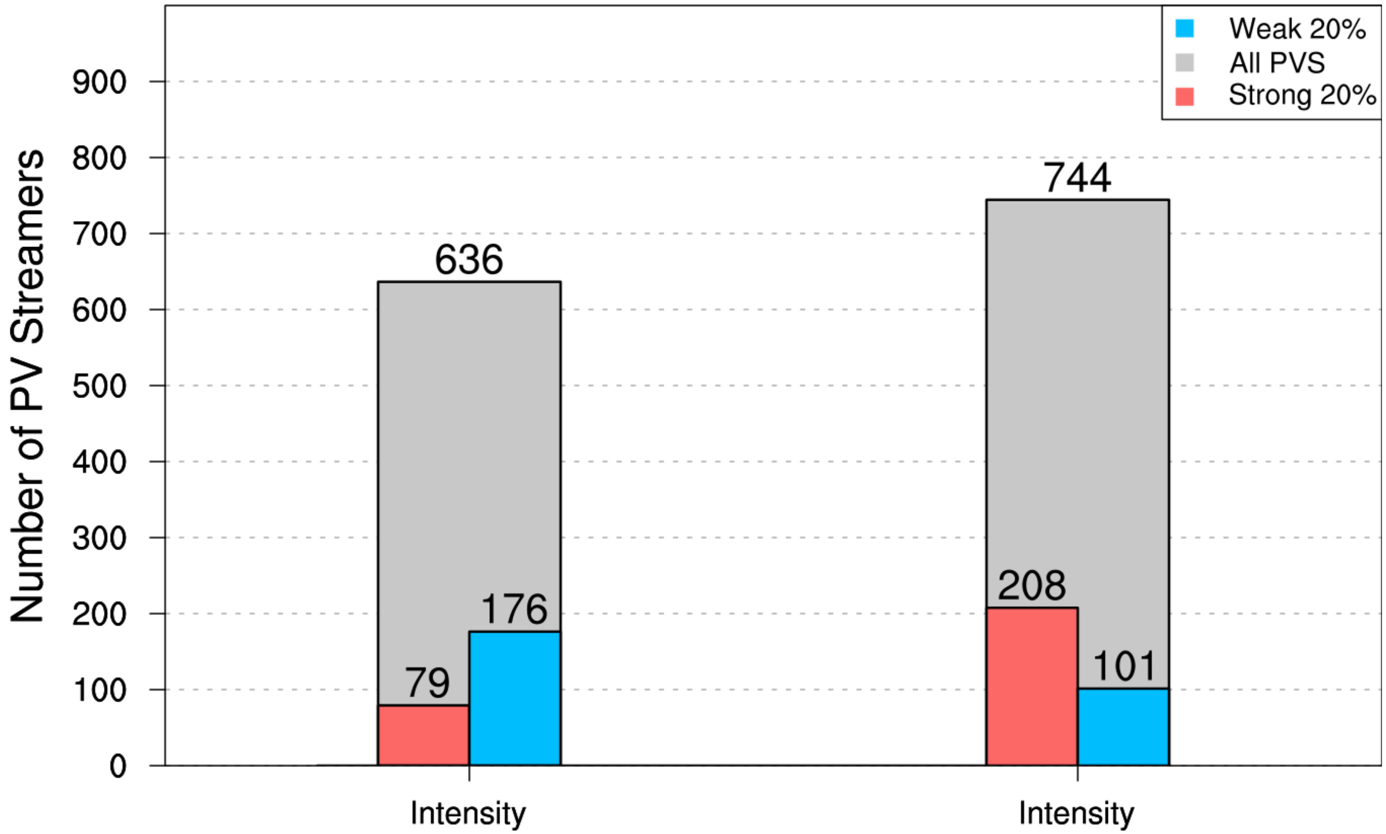
# Climatological Results: High ACE vs. Low ACE

- Active TC seasons (High ACE) feature:
  - ✧ Fewer PV streamers (**-14.5%**)
  - ✧ Much Fewer Strong PV streamers (**-62.0%**)
  - ✧ Many More Weak PV streamers (**+74.2%**)

Why are weak PV streamers more common in high ACE years while strong PV streamers are more common in low ACE years?

| Top 8 High ACE Years | Bottom 8 Low ACE Years |
|---|---|
| 2005 | 1983 |
| 1995 | 1982 |
| 2004 | 1994 |
| 1998 | 1987 |
| 1999 | 2013 |
| 2003 | 1991 |
| 1996 | 1986 |
| 2010 | 1993 |

*Number of strong, weak, and total PV Streamers in high and low ACE years*




High ACE = 194.3 ($10^4$ $kt^2$) | Low ACE = 32.5 ($10^4$ $kt^2$)

# Questions? ppapin@albany.edu

- A 1979–2015 climatology of PV streamers on the 350-K surface is created by adapting previous techniques
  - During the TC season (June–November) in Atlantic basin (10-100$^{o}$W)
- PV streamer climatology in the Atlantic basin
  - Highest frequency equatorward of 200-hPa jet.
  - Contribute to the formation of the time-mean Mid-Ocean trough (i.e., TUTT)
- PV streamer intensity and area compared to TC activity
  - Strong PV streamers are correlated with lower TC activity
  - Weak PV streamers are correlated with higher TC activity
- Composite Differences of strong minus weak PV streamers:
  - Strong PV streamers exhibit larger and more intense VWS corridors
  - Strong PV streamers exhibit drier air upstream of the trough
    - Linked to stronger upstream subsidence and northeasterly flow