Comparison of Vertical Velocity Profiles between Tropical Cyclones and Polar Lows

T. Connor Nelson

Atmospheric Sciences Research Center

University at Albany, State University of New York

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Motivation for Work

- Strength and location of convection in cyclones is crucial for understanding intensity change
  - Especially tropical cyclones (TCs)
  - Intensity change: Strengthening of the low-level horizontal wind or relative vorticity
- Results from the Tropical Cyclone Intensity (TCI) Experiment…

Tropical Cyclone Intensity (TCI) Experiment

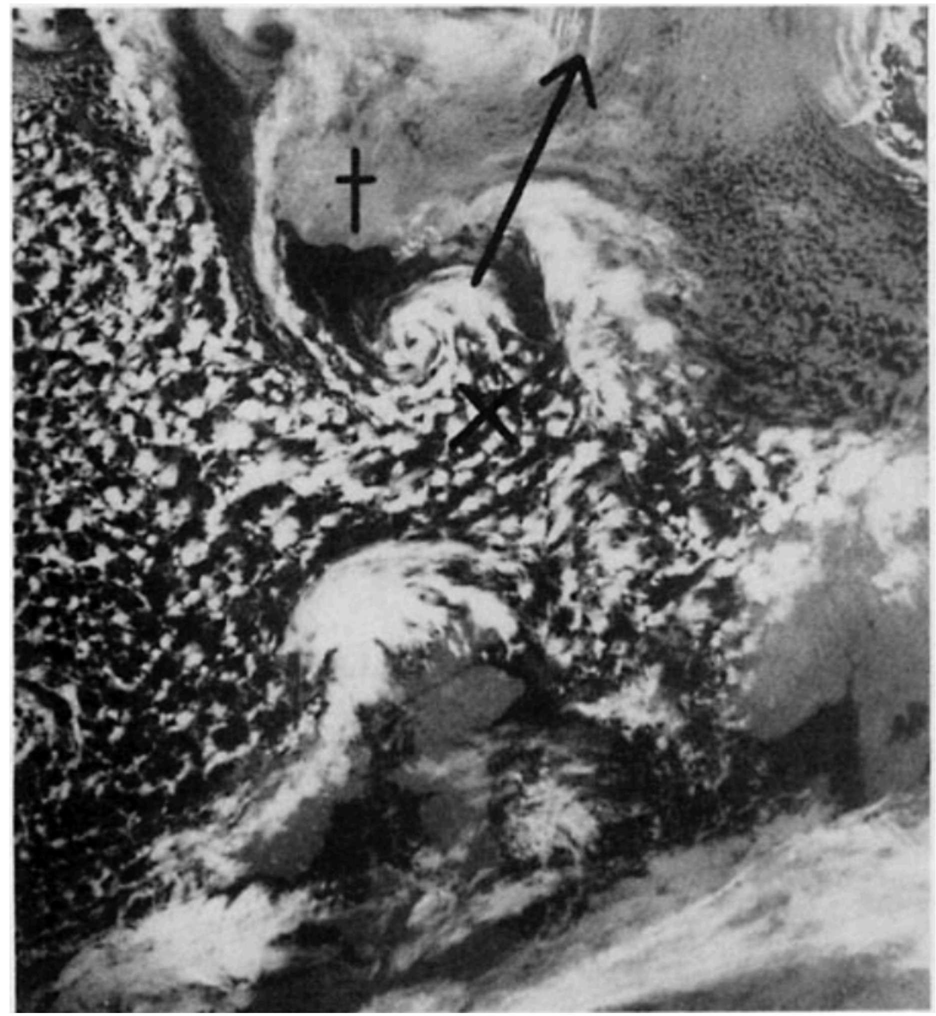
- Goal: Improve prediction of tropical cyclone (TC) intensity and structural changes
  - Specifically, focusing on the role of the TC outflow
  - Look at cases of rapid intensification (RI) and rapid decay (RD)
- Launched 784 eXpendable Digital Dropsondes (XDDs) into TCs:
  - Erika (30 August), Marty (27 – 28 October), Joaquin (2 – 5 October), and Patricia (20 – 23 October)

1. Introduction

Definitions…

- **Polar Low:**
  - Intense maritime cyclone
  - Forms poleward of the Polar Jet
  - Horizontal scale 10's to 100's km (AMS Glossary)
  - Low-level warm core
  - Surface winds approach gale force
    - 15 – 30 m s^{-1}

(Douglas et al. 1991; Montgomery and Farrell 1992; Moore and Haar 2003, Rasmussen and Turner 2003)



Rasmussen 1981

Definitions…

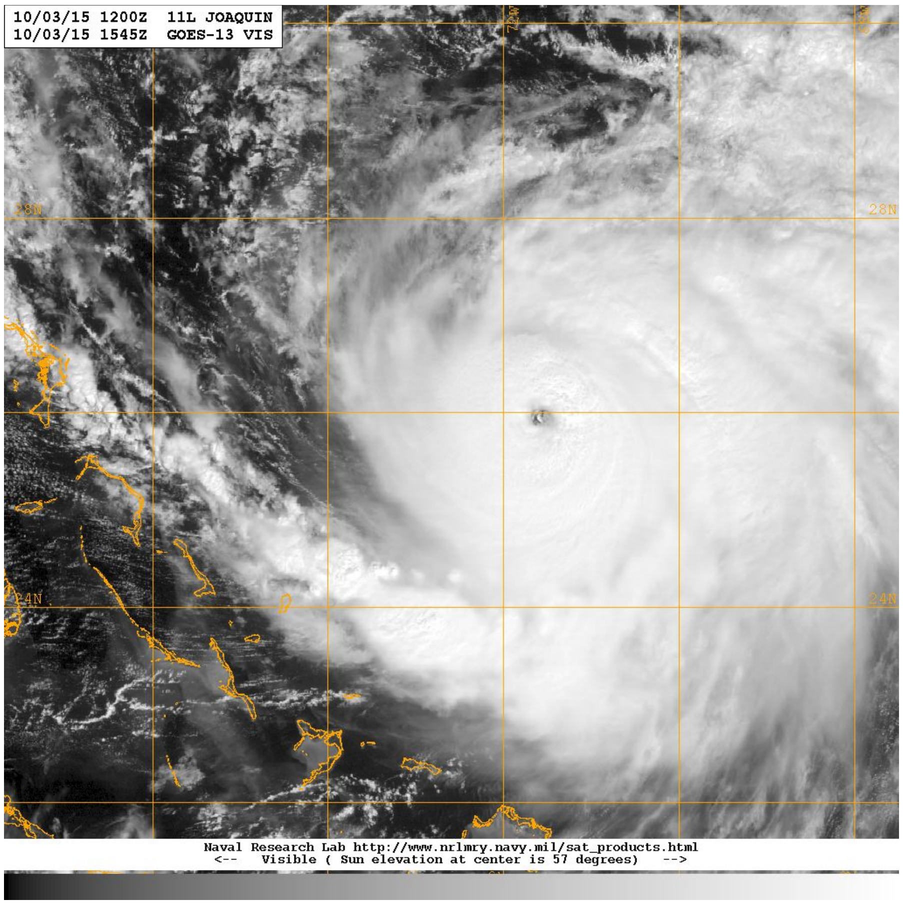


Image courtesy of the Naval Research Laboratory archives at http://www.nrlmry.navy.mil/TC.html

- **Tropical Cyclone:**
  - Intense maritime cyclone
  - Forms over tropics/ subtropics
  - Horizontal scale (500 – 1000 km)
  - Warm-core, non-frontal
  - Organized deep convection
  - Closed surface wind circulation
    - 17 – 70 m s^{-1}

(Adapted from National Hurricane Center 2016)

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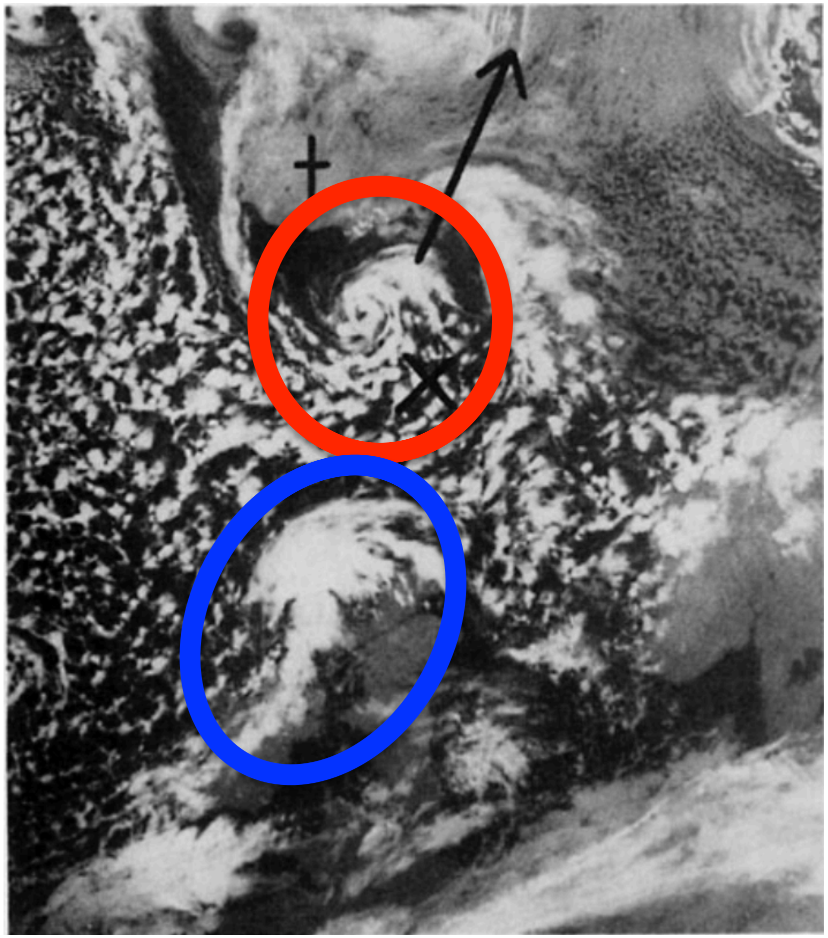
(Adapted from National Hurricane Center 2016)

Because of their similarities in appearance and structure, Emanuel and Rotunno (1989) called a subclass of Polar Lows ‘Arctic Hurricanes’.

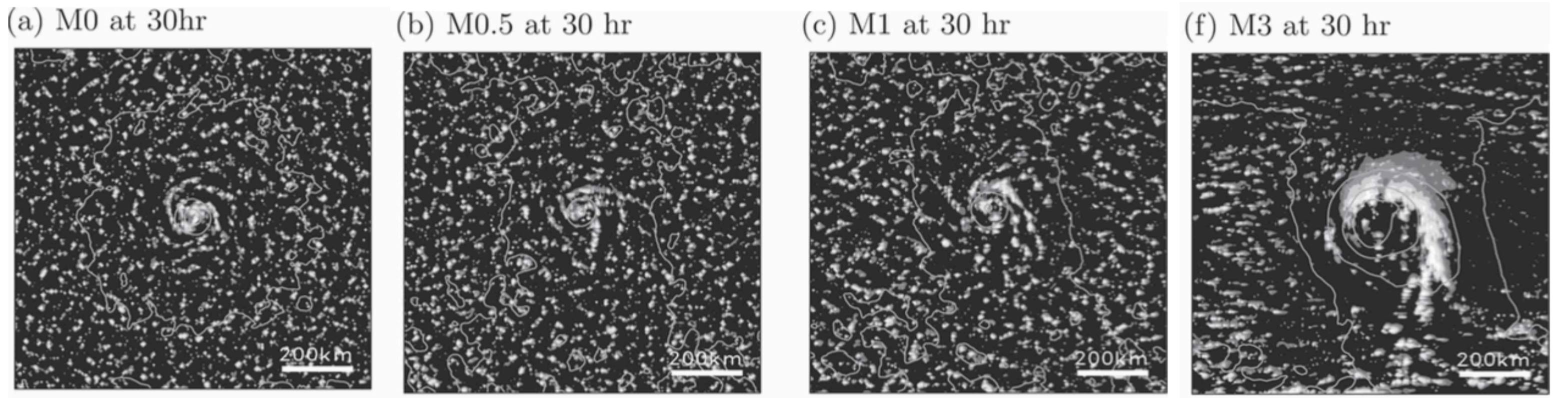
Two Main Archetypes for Polar Lows

- **'Arctic hurricane' (AH):** tight circulation, well defined eye, convective "rainbands"
- **Classic 'comma cloud':** circulation with extending primary convective band



Adapted from Rasmussen 1981. His Fig.6

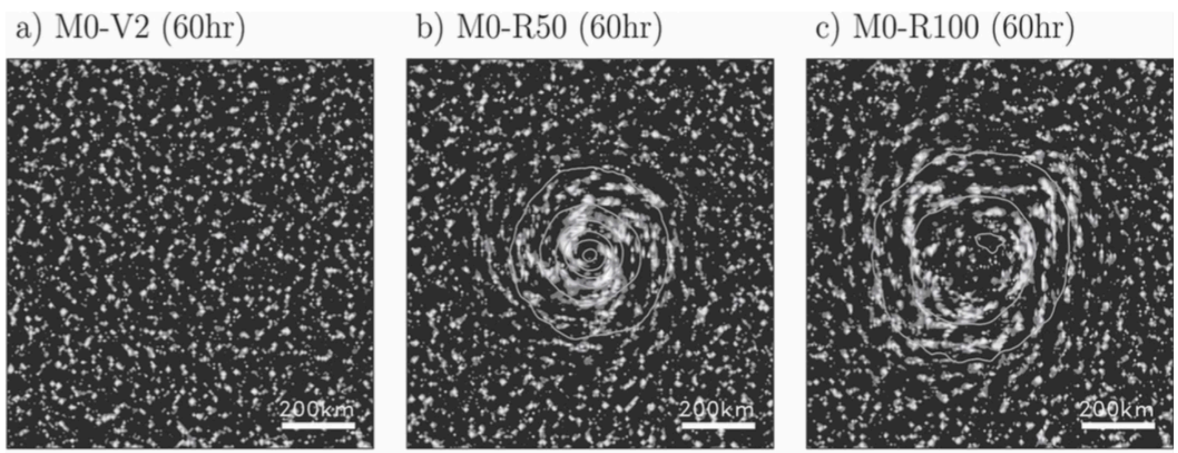
Can I choose a flavor?



Baroclinicity (Shear)

R_o=20km

V_o=7 m s^{-1}



Vertically integrated total condensed water (g kg^{-1}) and SLP (~3 hPa)

RMW

Adapted from Yanase and Niino 2007

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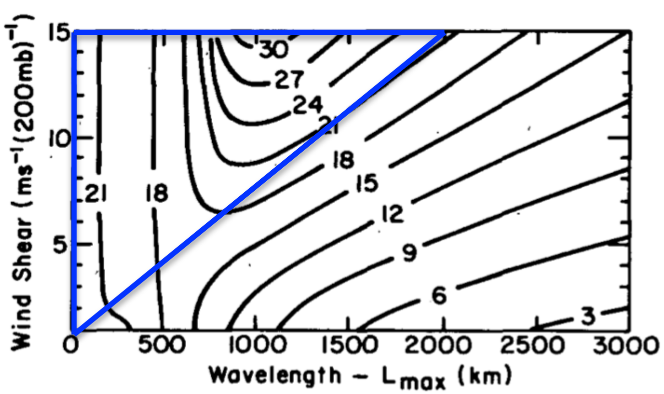


FIG. 7. Maximum growth rate (10^{-6} s^{-1}) plotted as a function of wind shear in the 700–900 mb layer and wavelength for the BCD/CISK mode with $\hat{r}_8$ = 0.7.

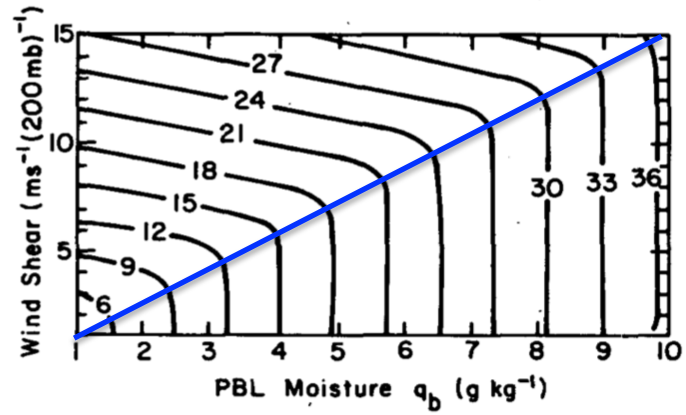


FIG. 9. Maximum growth rate (10^{-6} s^{-1}) plotted as a function of wind shear in the 700–900 mb layer and PBL moisture for the BCD/CISK mode.

Adapted from Sardie and Warner (1983)

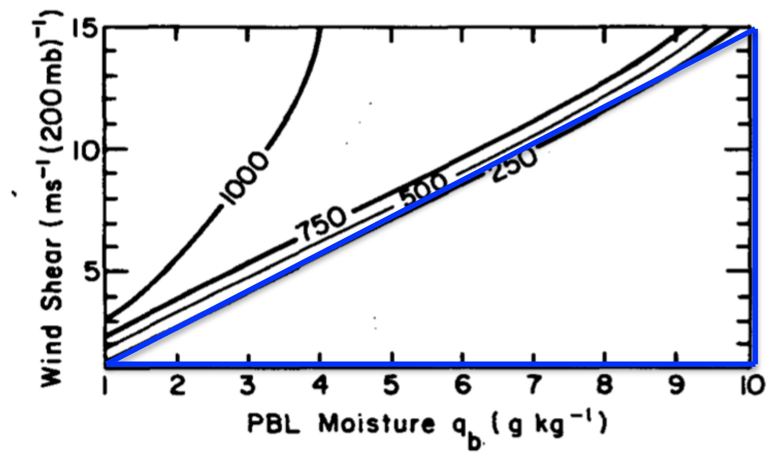
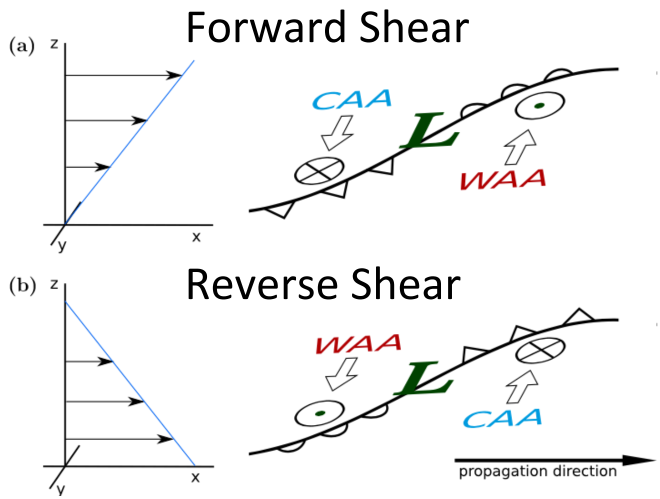
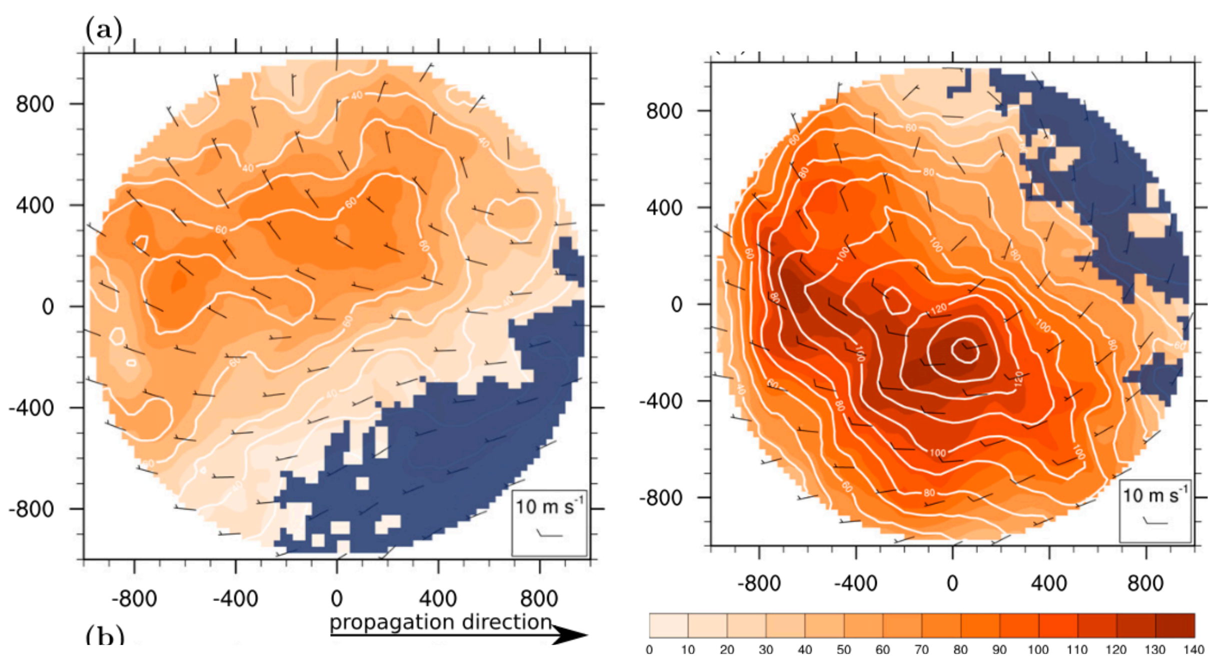


FIG. 8. Wavelength of maximum growth rate (km) plotted as a function of wind shear in the 700–900 mb layer and PBL moisture for the BCD/CISK mode.

Can I choose a flavor?





Adapted from Terpstra et al. (2016)

FIG. 10. Composites in the rotated frame of the surface sensible heat flux (W m^{-2}; shading), latent heat flux (W m^{-2}; solid lines), and wind at 10 m (wind barbs) for (a) forward and (b) reverse shear conditions. Areas with less than 75% of ocean are masked. Values on the axes indicate the distance (km) from the genesis location.

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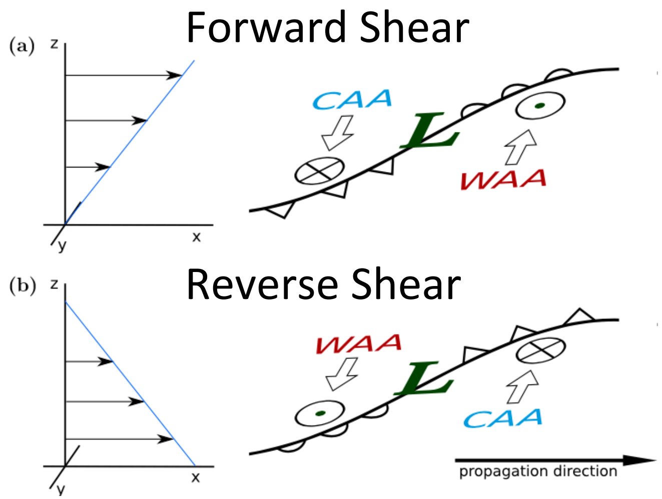
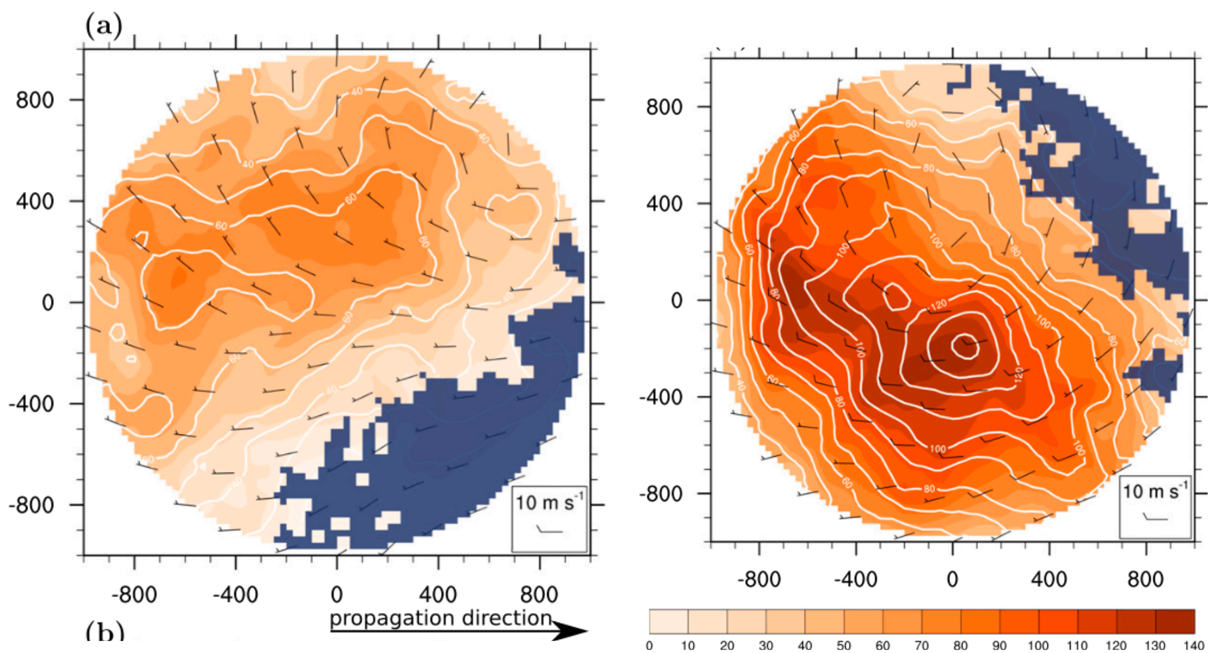


- Because of their warm core nature, PLs will generally be reverse shear
- Reverse shear environments will have enhanced surface heat flux
    - Better for convection!!!!!!



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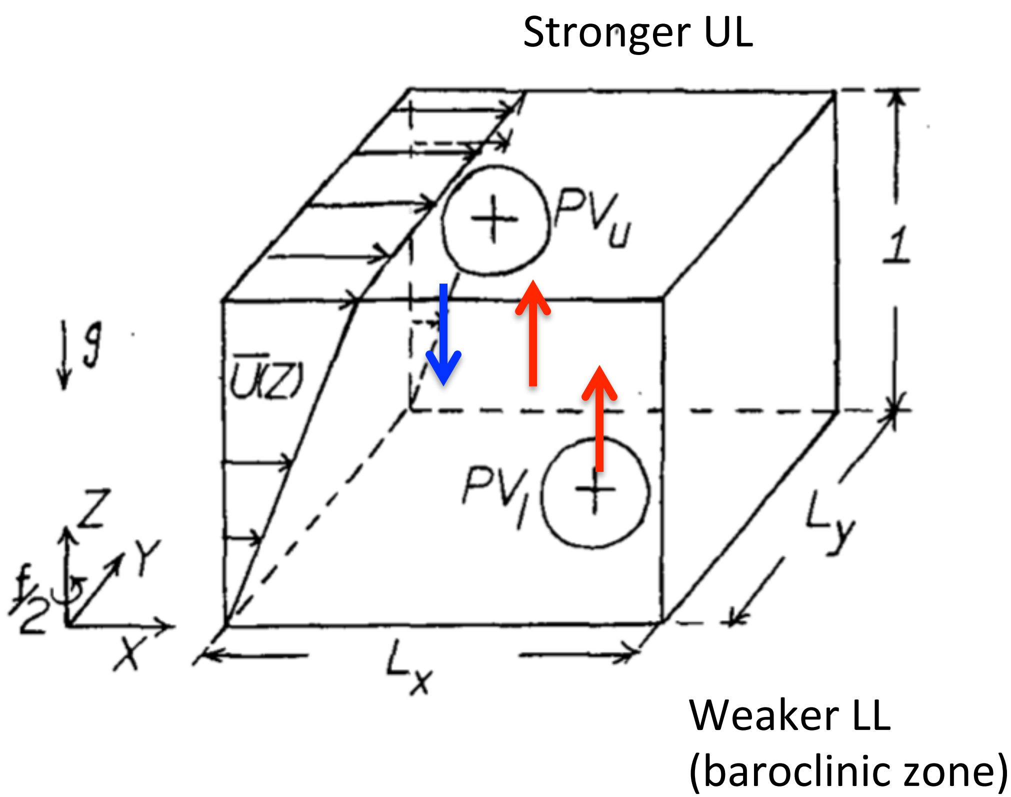
Upper Level PV Interaction and Vertical Velocity



Adapted from Montgomery and Farrell (1992)

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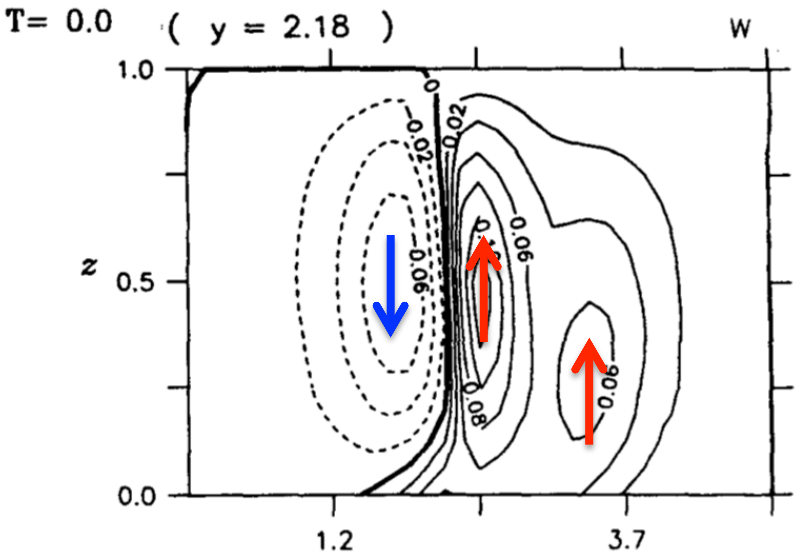
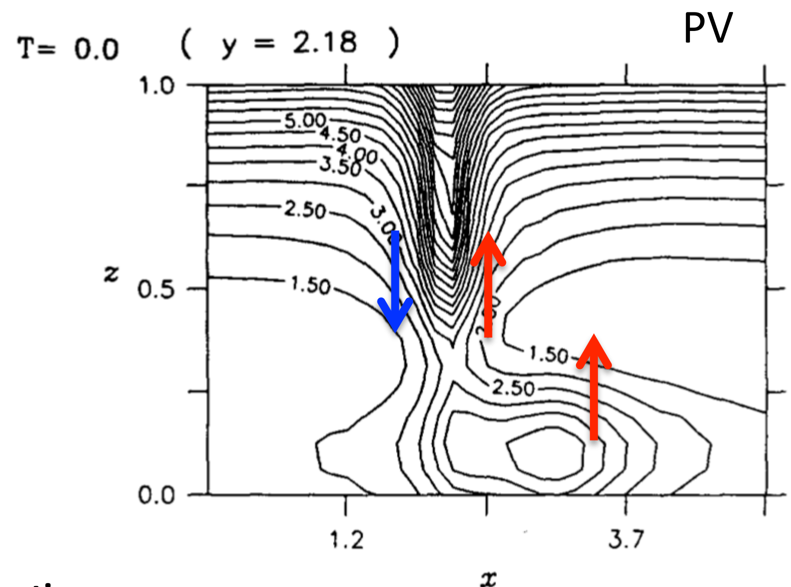


Stronger UL

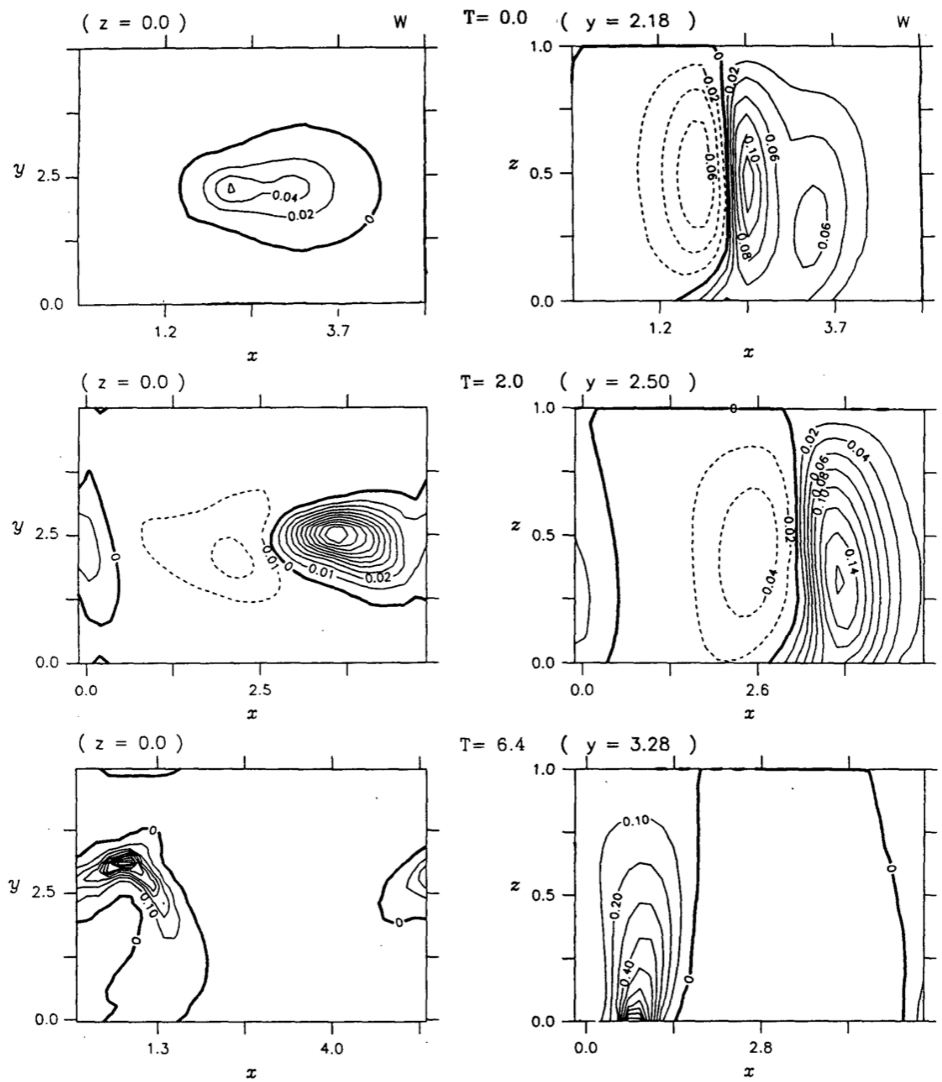


***Y Cross-sections through the maximum absolute vorticity**

Weaker LL (baroclinic zone)

Adapted from Montgomery and Farrell (1992)

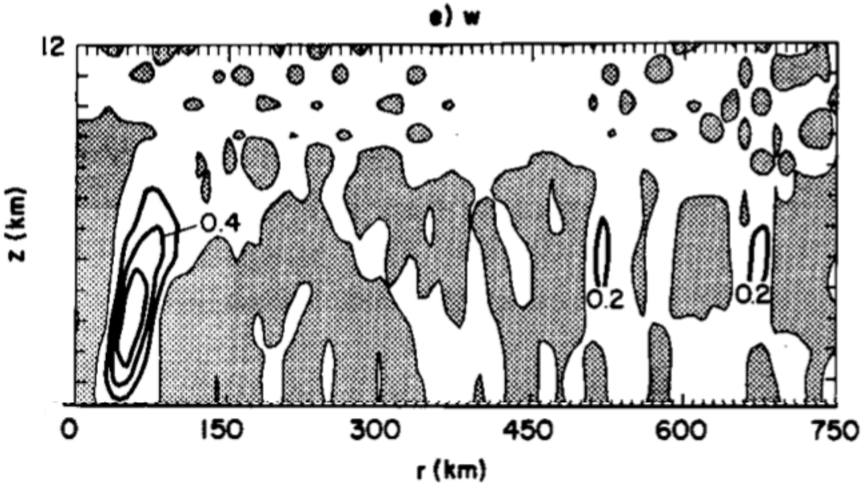
Interlocked PV Non. Dimensional Vertical Velocity

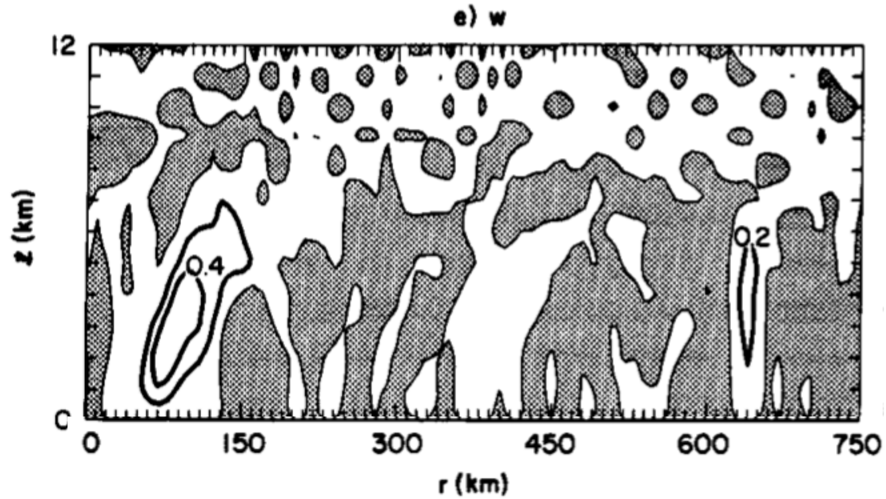


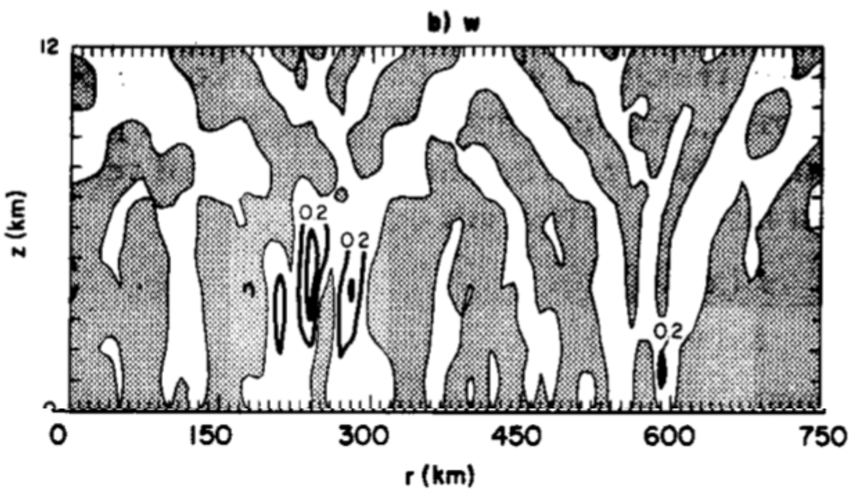
- Cross-sections through maximum absolute vorticity at Z= 0.0
- Initially, strongest updraft and downdraft is in the mid-levels
- Over, time the couplet descends to the surface
- In low static stability, to maintain strong ascent it is required to maintain TWB
  - Vortex stretching
  - Generation of surface PV

Adapted from Montgomery and Farrell (1992)

Presence of an upper-level trough…







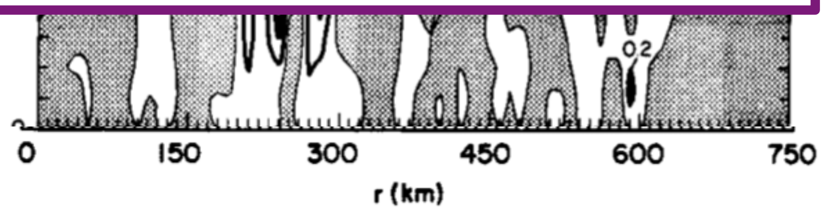
- Used an axisymmetric TC-Carnot Cycle model
  - Goal: Show that enthalpy differences can drive AHs
- Ran experiments of different low-level soundings, presence of an upper-level trough, and strength and location of RMW

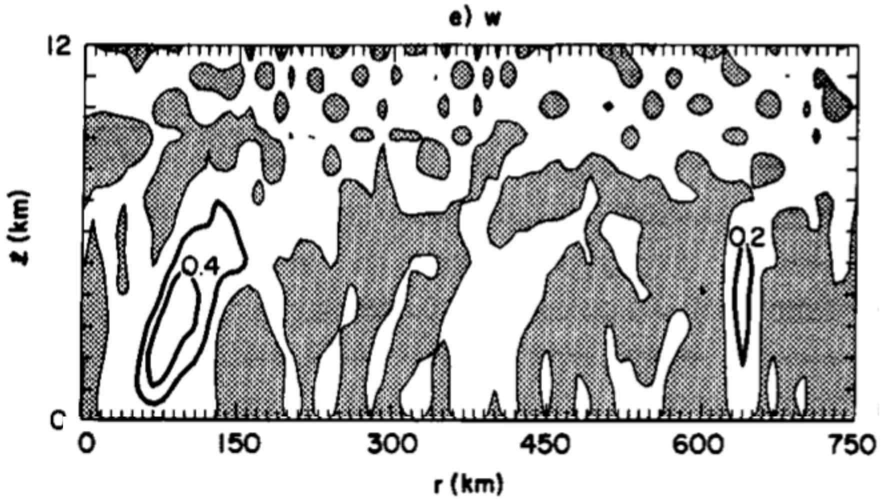
Adapted from Emanuel and Rotunno (1988)

Presence of an upper-level trough…

Experiment	r_{max} (km)	V_s (ms^{-1})	r_m (km)	V_m (ms^{-1})	Sounding
A	50	10		0	WM
B	50	10		0	HD
C	50	10		0	CD
D	50	5		0	WM
E	50	2		0	WM
F	100	10		0	WM
G	100	5		0	WM
H	50	10	500	20	WM
I	100	10	500	20	WM
J	50	5	500	20	WM

r_{max} ≡ radius of maximum surface winds.
V_s ≡ maximum surface winds.
r_m ≡ radius of maximum winds at tropopause.
V_m ≡ maximum winds at tropopause.





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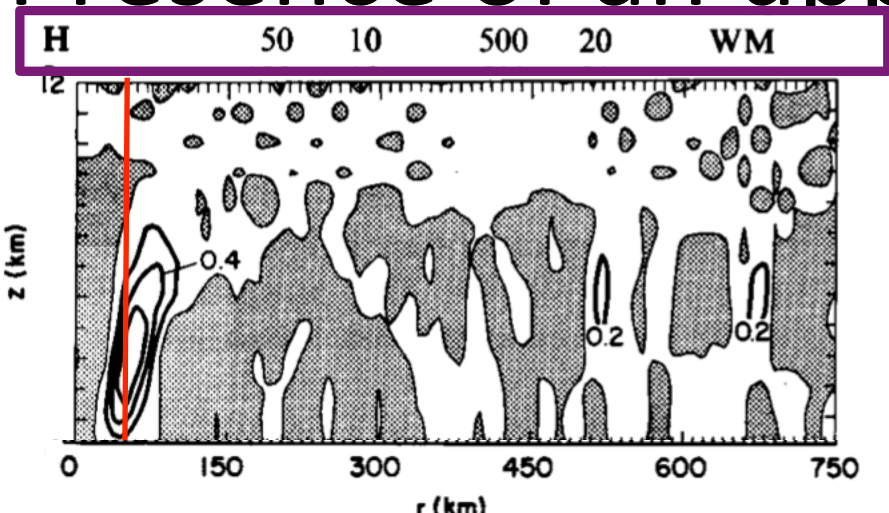

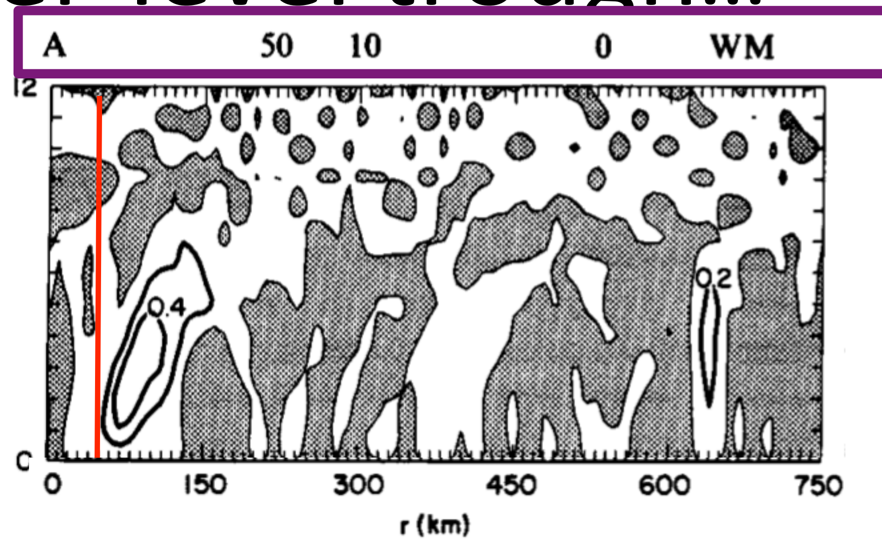

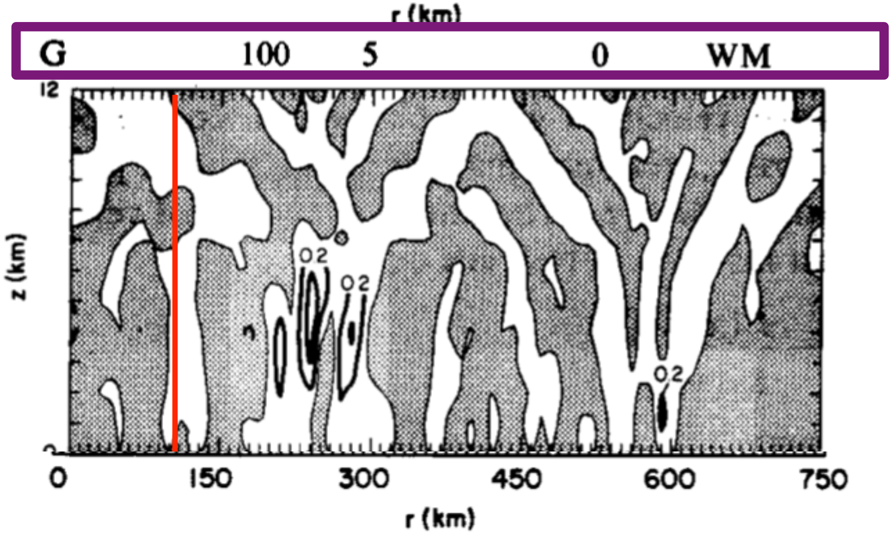

- Contours of 0.2 m s^{-1}
- Strongest updrafts are in Run H with an upper level trough
  - 0.6 m s^{-1}
  - Updraft core tilts outward
  - Part of updraft is inside the RMW!!!

Adapted from Emanuel and Rotunno (1988)

Role of Convection in TCs

- Updraft and downdraft strength is weak [near-zero] (Black et al. 1996)
  - However, abnormally strong updrafts [> 10 m s^{-1}] can occur (Jorgensen et al. 1985; Black et al. 1994, 1996, 2002; Aberson et al. 2006; Marks et al. 2008; Heymsfield et al. 2010)
    - Mainly tied to the eyewall rather than rainband regions (Jorgensen et al. 1985; Black et al. 1996; Stern and Aberson 2006; Aberson et al. 2006; Guimond et al. 2010)
- The strength and number of updrafts inside the radius of maximum wind (RMW) correlates well with intensity change (e.g., Rogers et al. 2012)
  - Linked to intensification of low-level winds after RMW contraction (Stern et al. 2015)
  - Occur with eyewall vorticies that draw entropy rich air from eye into eyewall (Persing and Montgomery 2003; Aberson et al. 2008)

Role of Convection in TCs

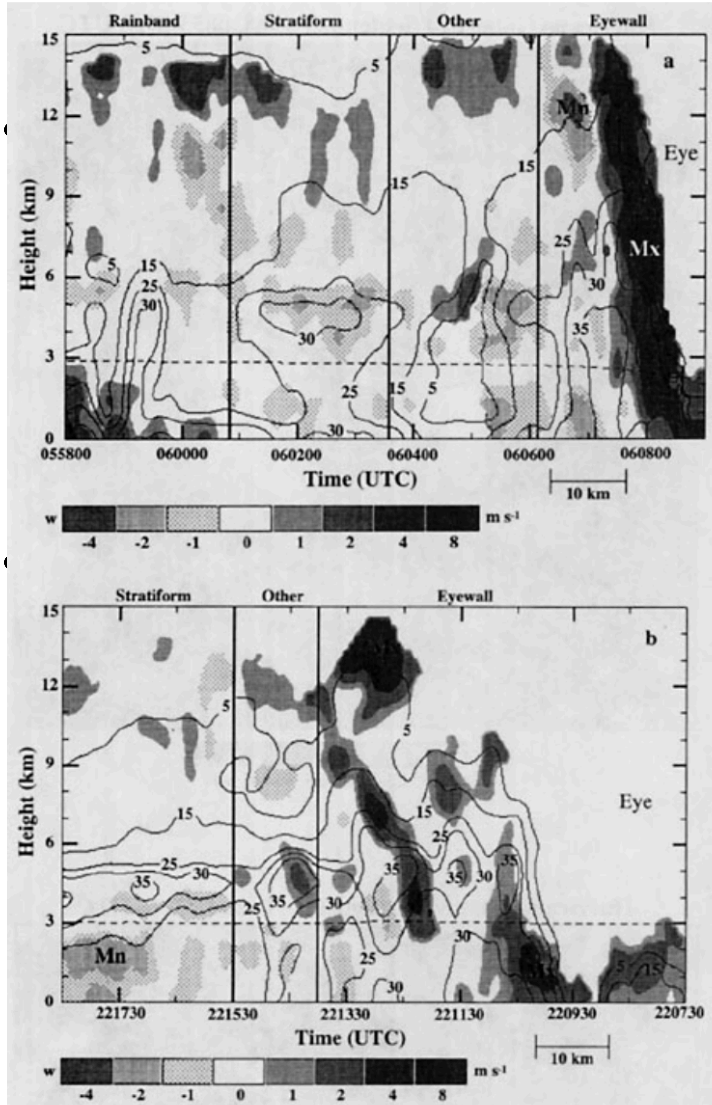

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FIG. 3. Vertical profiles of reflectivity (contoured in dBZ) and *w* (shaded contours) for (a) an inbound leg into the center of Hurricane Gilbert on 14 September 1988 and (b) an outbound leg from the center of Hurricane Gustav on 29 August 1990. The data has been smoothed, which reduces the magnitudes of the data extrema. The locations of the minimum *w* of -7 m s^{-1} and the maximum *w* of 15 m s^{-1} for Gilbert and the minimum *w* of -3 m s^{-1} and the maximum *w* of 7 m s^{-1} for Gustav are shown by *Mn* and *Mx*, respectively. The domain is 80 km in the horizontal by 15 km in the vertical. The bold vertical lines are the locations of the vertical partitioning between the regions indicated at the top. Horizontal dashed lines are the aircraft altitudes where flight-level *w* has been interpolated across the range delay in the Doppler data. The horizontal distance scale and the scale for *w* are shown at the bottom of (a) and (b).

tgomery 2003; Aberson et al. 2008)

Black et al. (1996)

Problem Statement

- Despite past research comparing TCs and AHs thermodynamically, little study has been done to compare the convective environments of the two
  - TCs tend to have weaker vertical velocities than most mid-latitude cyclones (Jorgensen et al. 1985; Black et al. 1996; Heymsfield et al. 2010), but this doesn't cover PLs or AHs
  - Independent studies of PLs have shown that the strength of vertical velocities tends to be near-zero (Emanuel and Rotunno 1989; Douglas et al. 1995; Yanase and Niino 2007)
    - Strongest updrafts on order of 1 − 3 m s^{-1}

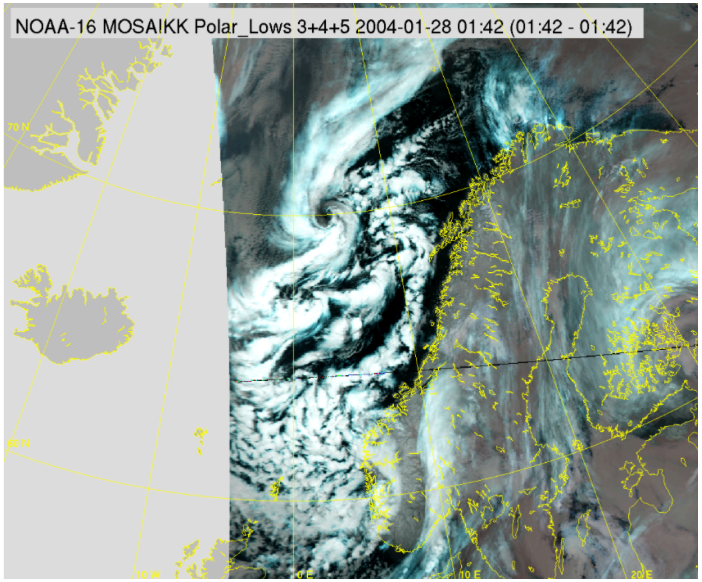
Hypothesis

- The bulk strength of vertical velocities in PLs agrees well with findings for TCs
- **Hypothesis:** Vertical velocity profiles and frequencies of vertical velocity strength below the tropopause would be comparable between AHs and TCs
  - PLs tend to have lower tropopause heights (e.g., Douglas et al 1991)
- **Goal:** Compare and contrast the strength and location of convection in TCs and AHs
  - Compute contoured frequency diagrams of vertical velocity similar to Nelson et al. (2017) for TCs and AHs

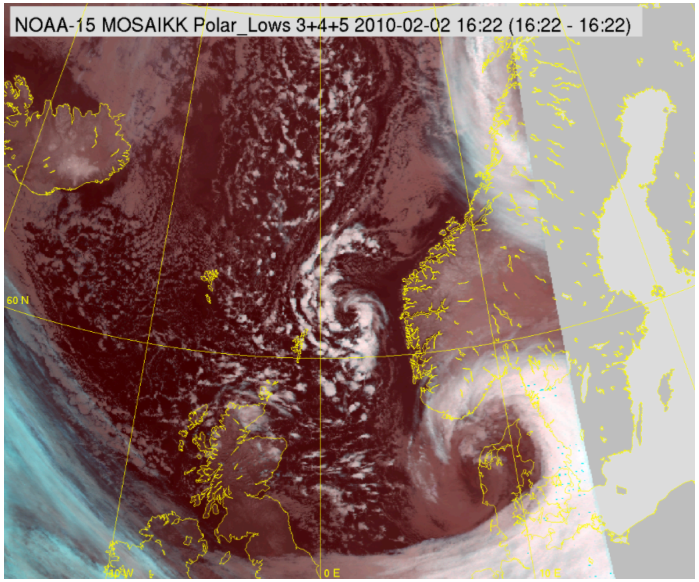
2. Data and Methods

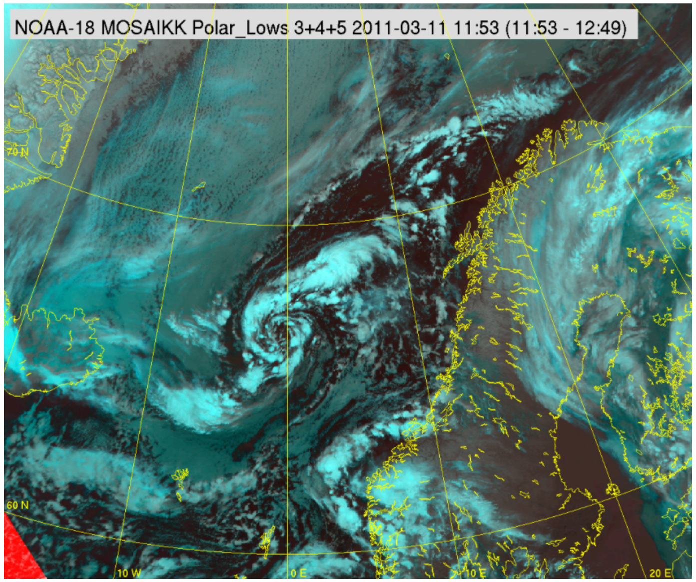
The data…

- Use storm-centered data from the six-hourly ERA-Interim reanalysis (ERA-I, Dee et al. 2011)
  - Three AHs
    - Sea Surface Temperature and Altimeter Synergy for Improved Forecasting of Polar Lows (STARS) project dataset (Noer et al. 2011)
  - Three TCs
    - 2015 Tropical Cyclone Intensity (TCI) experiment → Nelson et al. (2017) study
- AH cases were only considered if their satellite imagery resembled a TC (i.e., had a well defined eye, rainbands, etc.)



- Top-left: PL 28 occurred 27 January 2004 1000 UTC – 28 January 2004 1300 UTC
- Bottom-left: PL 110 occurred 02 February 2010 1600 UTC – 02 February 2010 2100 UTC
- Bottom-right: PL 134 occurred 11 March 2011 0600 UTC – 12 March 2011 1000 UTC

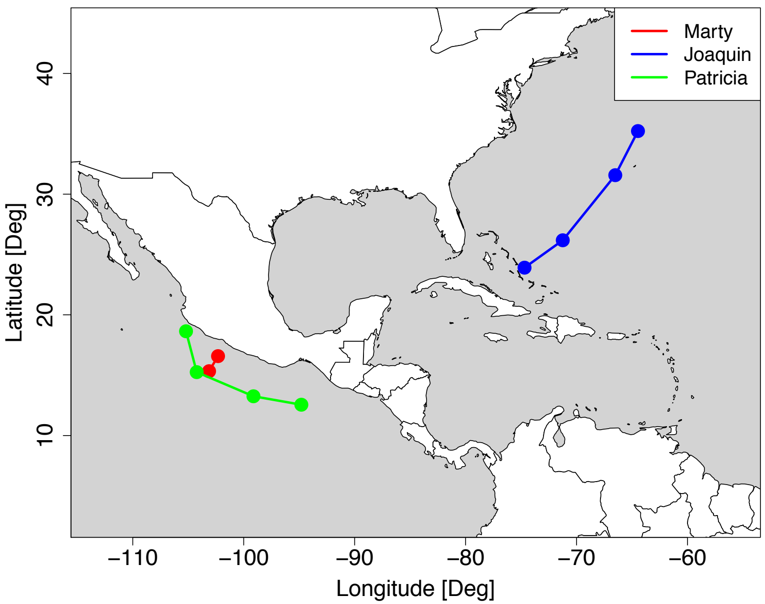




Images courtesy of the STARS Data Set Image Data Base at http://polarlow.met.no/STARS-DAT/browser/view_stars-dat.php

Fig. 1

(a)


Marty
Joaquin
Patricia
Latitude [Deg]
Longitude [Deg]
10
20
30
40
−110
−100
−90
−80
−70
−60

(b)

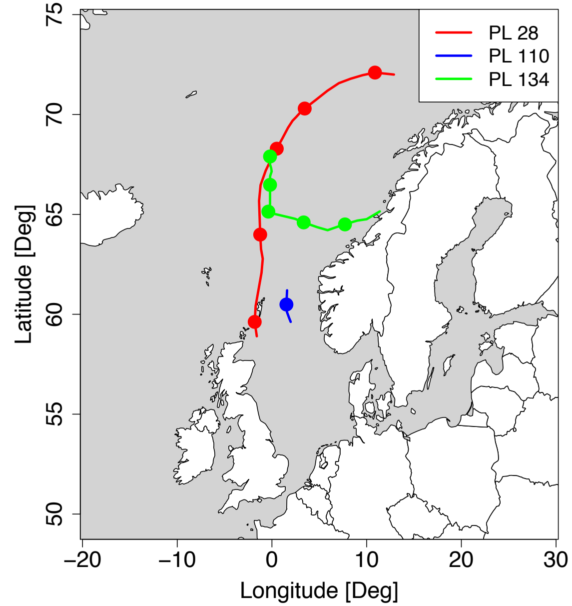

PL 28
PL 110
PL 134
Latitude [Deg]
Longitude [Deg]
50
55
60
65
70
75
−20
−10
0
10
20
30

Fig. 1

(a) (b)

Table 1 List of ERA-I analysis times and dates for each TC used in this study. Provided is the cyclone name, date, time (UTC) and numerical assignment 1 – 10 for ERA-I analysis time.

Cyclone Name	**Date**	**Time**	**ERA-I Analysis Time**
Marty	27 Sept. 2015	18	1
Marty	28 Sept. 2015	18	2
Joaquin	02 Oct. 2015	18	3
Joaquin	03 Oct. 2015	18	4
Joaquin	04 Oct. 2015	18	5
Joaquin	05 Oct. 2015	18	6
Patricia	20 Oct. 2015	18	7
Patricia	21 Oct. 2015	18	8
Patricia	22 Oct. 2015	18	9
Patricia	23 Oct. 2015	18	10

Fig. 1

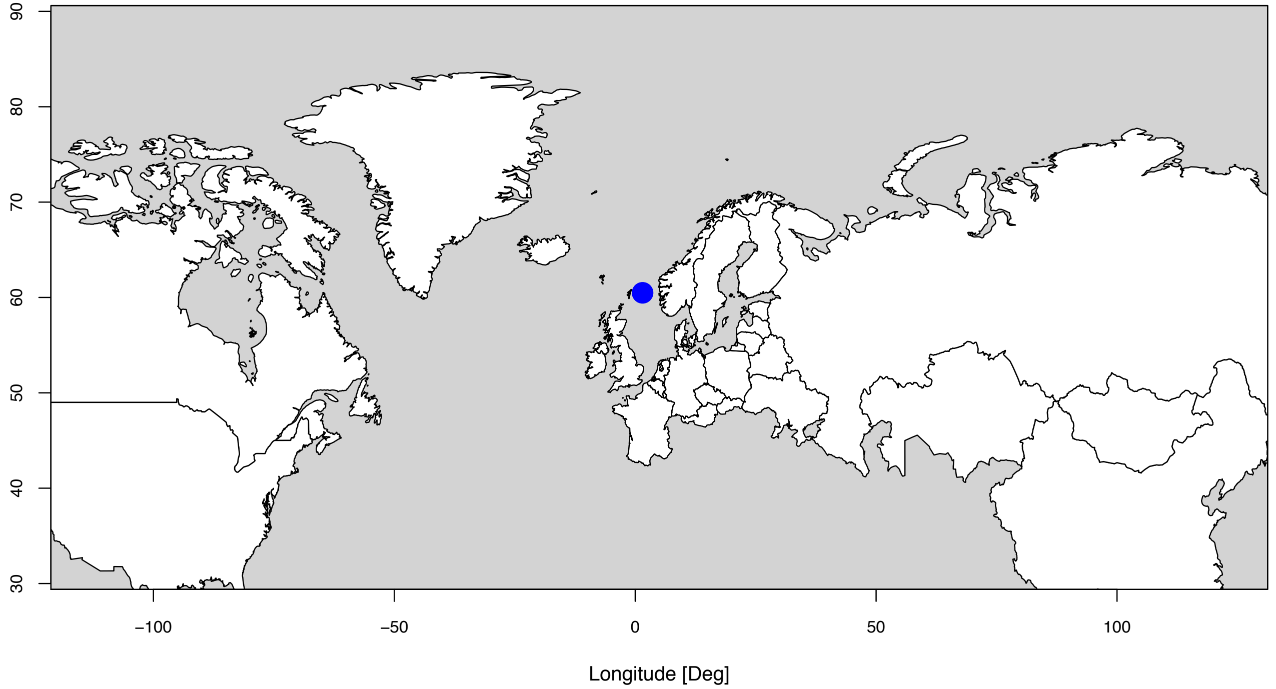
(a) (b)

Table 2 Same as Table 1, except for AHs and numerical assignments of 1 – 11.

Cyclone Name	Date	Time	ERA-I Analysis Time
PL 134	11 March 2011	06	1
PL 134	11 March 2011	12	2
PL 134	11 March 2011	18	3
PL 134	12 March 2011	00	4
PL 134	12 March 2011	06	5
PL 110	02 Feb. 2010	18	6
PL 28	27 Jan. 2004	12	7
PL 28	27 Jan. 2004	18	8
PL 28	28 Jan. 2004	00	9
PL 28	28 Jan. 2004	06	10
PL 28	28 Jan. 2004	12	11

The methods…

- Use storm-centered data from the six-hourly ECMWF Reanalysis – Interim (ERA-I, Dee et al. 2011)



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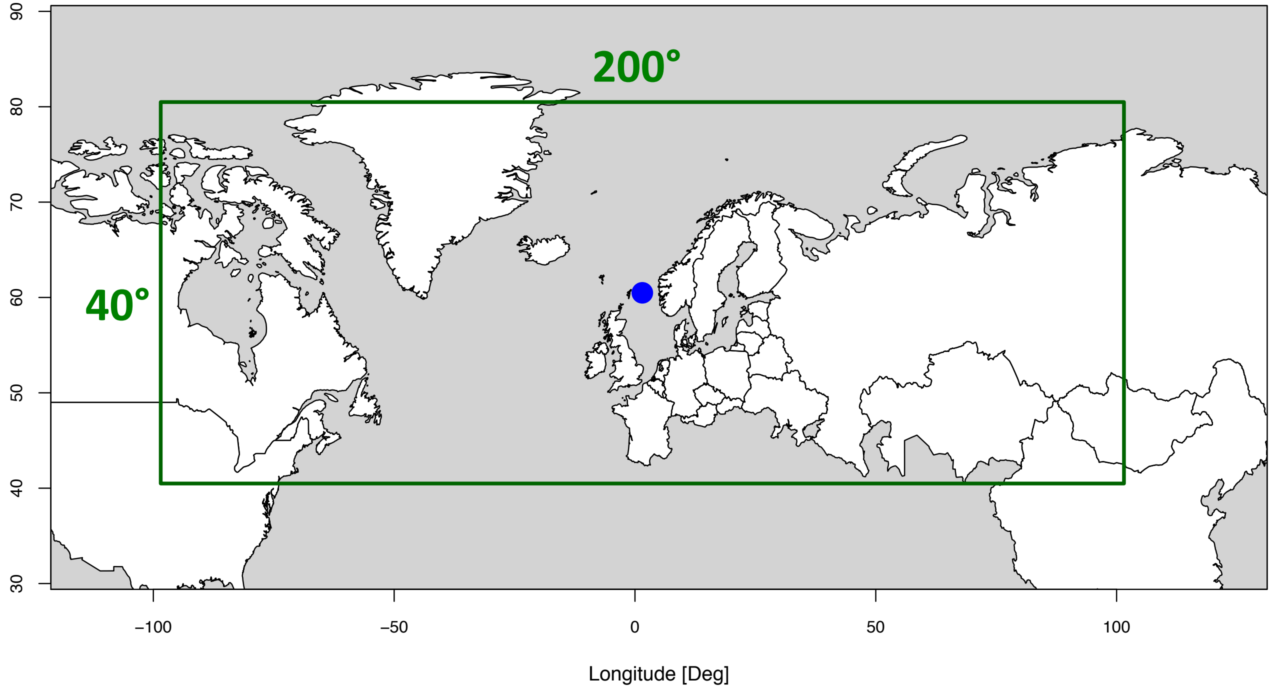

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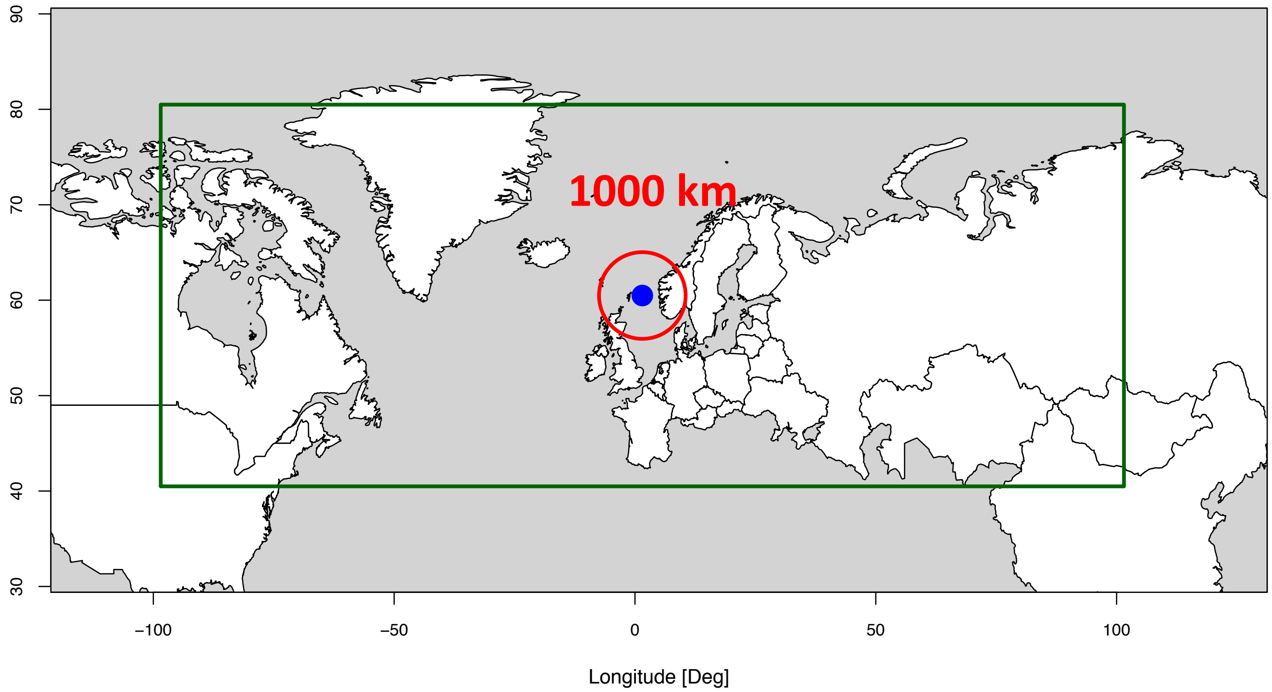

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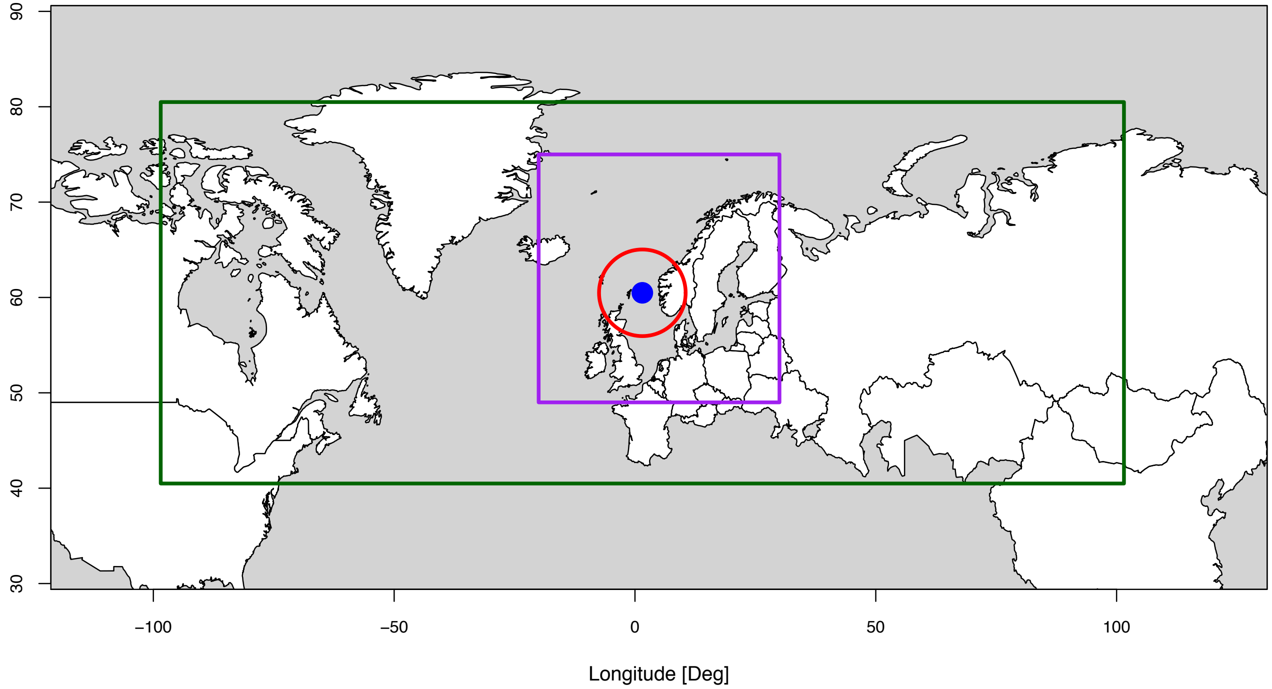
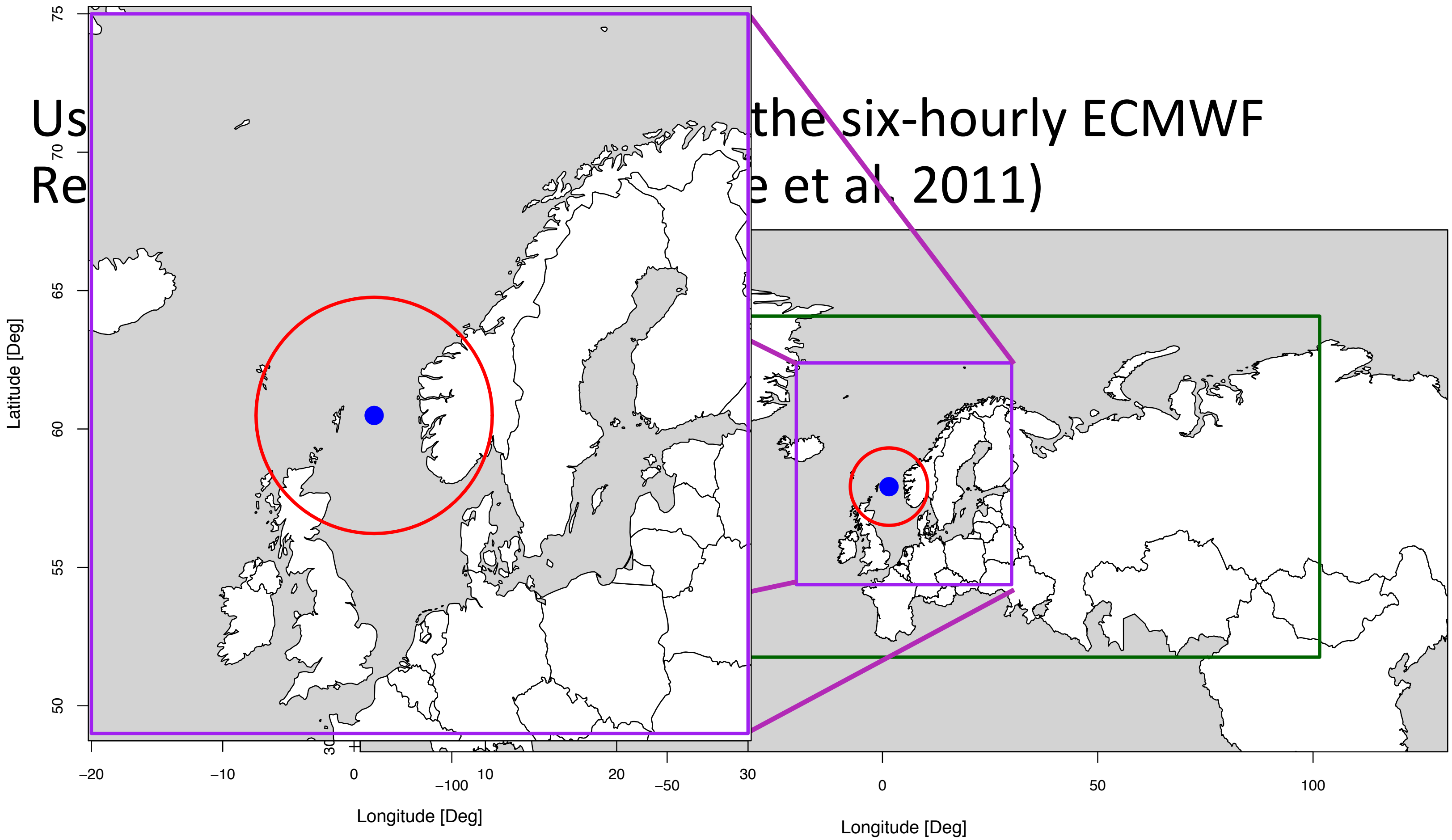


The methods…

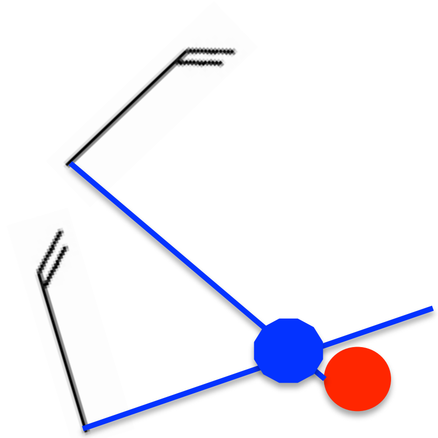
- Us… the six-hourly ECMWF Re… e et al. 2011)



Obtaining the "true" center

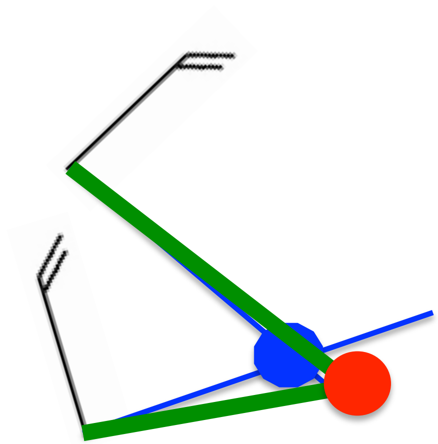
- Initial cyclone centers obtained from the STARS (AHs) and National Hurricane Center Best-track (TCs) datasets
  - Cyclone centers corrected using a zero-wind center algorithm following a power law weighting scheme similar to Nelson et al. (2017)
  - U and V wind components were storm motion corrected
    - Storm motion calculated using centered differencing and Lat/Lon locations

Obtaining the “true” center



- Red dot is the initial cyclone center position from either the NHC Best-Track data or STARS dataset
- Use a pair of wind observations (Obs. 1 and Obs. 2)
- Blue lines are orthogonal to wind barbs
- Blue dot is intersection

Obtaining the "true" center

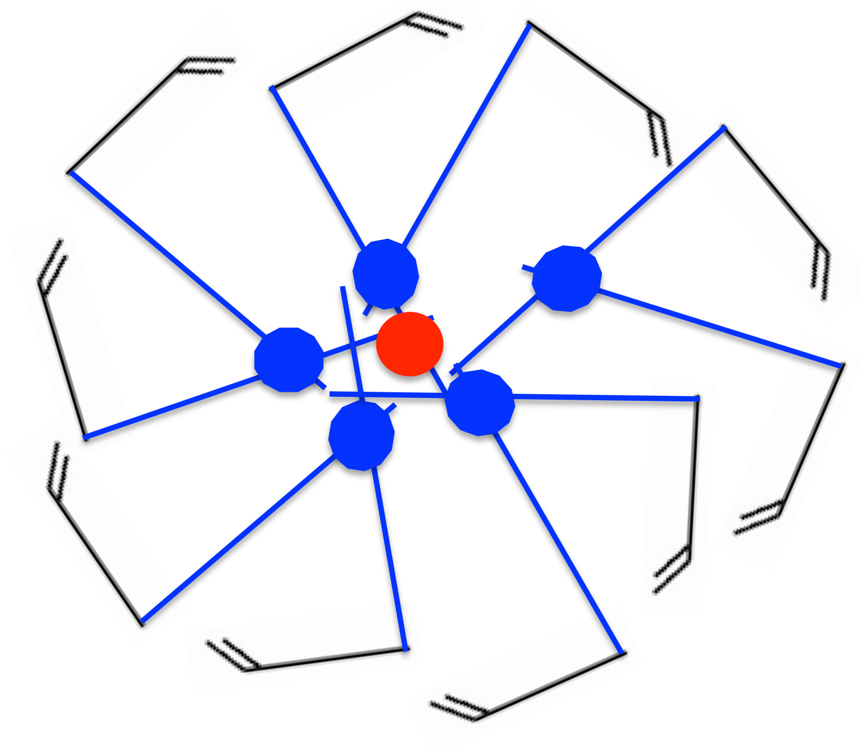


- The weighting function is:

$$W = \frac{V_t}{(d^2)}$$

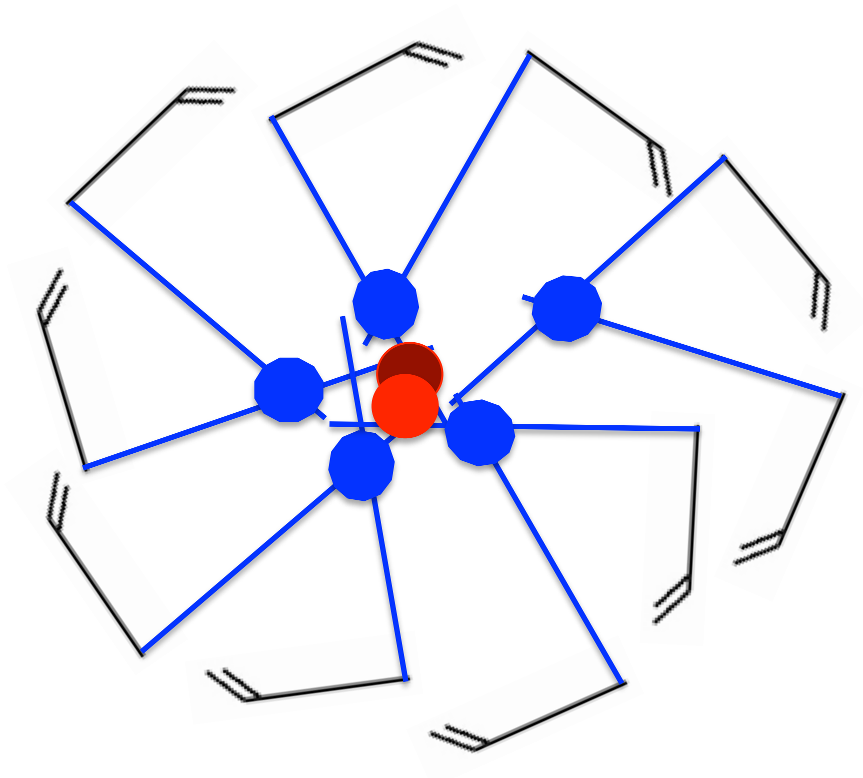
(weighting shown in green)

Obtaining the "true" center



- Given many observations, a MEAN wind corrected cyclone center can be obtained

Obtaining the "true" center



- Once a new center is obtained, the algorithm will re-run until a solution converges within 0.001°
  - Must do this within 100 iterations

Obtaining the "true" center

- Altitude was taken to be the geopotential height assuming a layer mean temperature
- For the TCs, restricted to be below an altitude of 13.5 km and within a 1000 km radius of the initial center
- For the AHs, restricted to be below an altitude of 1 km and within a 300 km radius of the initial center

Obtaining the RMW

- RMW calculated by:
  - Bilinear interpolation to increase "resolution" (~12 to 40)
  - Looked at the top 10 horizontal wind speed data points below 2 km and within 100 km
- Restrict data by removing all data outside of an RMW normalized radius (R*) of 10R* and above an altitude of 13.5 km

Calculating shear

- For TCs, used the 850-200 hPa shear magnitude and direction:
  - TCs → SHIPS dataset
- For AHs, used the 900-600 hPa shear magnitude and direction:
  - AHs → Computed from the ERA-I data at the cyclone center
  - AHs are much more shallow features!!!
    - Here, height of the tropopause was the mean height estimated from the temperature profiles

Calculating/Evaluating vertical velocity profiles…

- Compute vertical velocity from the approximation:

$$\omega \approx -\rho g w$$

- Contoured frequency diagrams (CFDs) by altitude, tropopause normalized altitude (A*), R*, and shear-relative (SR) azimuth were computed
- Evaluate convection strength based upon percentile thresholds: 97.5% (moderate), 99.2% (strong), and 99.5% (extreme)

The analysis…

- Compare the CFD plots for ERA-I TCs to the Nelson et al. (2017) study
  - Gauge the ability of ERA-I to accurately represent the observed convective environments of cyclones
- Compare the CFD plots for ERA-I TCs to ERA-I AHs
- Look at the net vertical motion (mean vertical motion) inside and outside the RMW
- Use composite planar and cross-sectional plots of vertical velocity and temperature to examine the ‘mean’ convective environments

The Nelson et al. (2017) study

- Examined the convective environment in three of the TCs
  - Marty, Joaquin, and Patricia (590 XDDs)
- Derived vertical velocity using dropsonde fall speed and density correction

$$w = V - V_f$$

$$V = F_o \sqrt{\frac{\rho_o}{\rho}}$$

$$\rho = \frac{p}{(R_d T_v)}$$

Fig. 10

APPENDIX: Nelson et al. (2017)

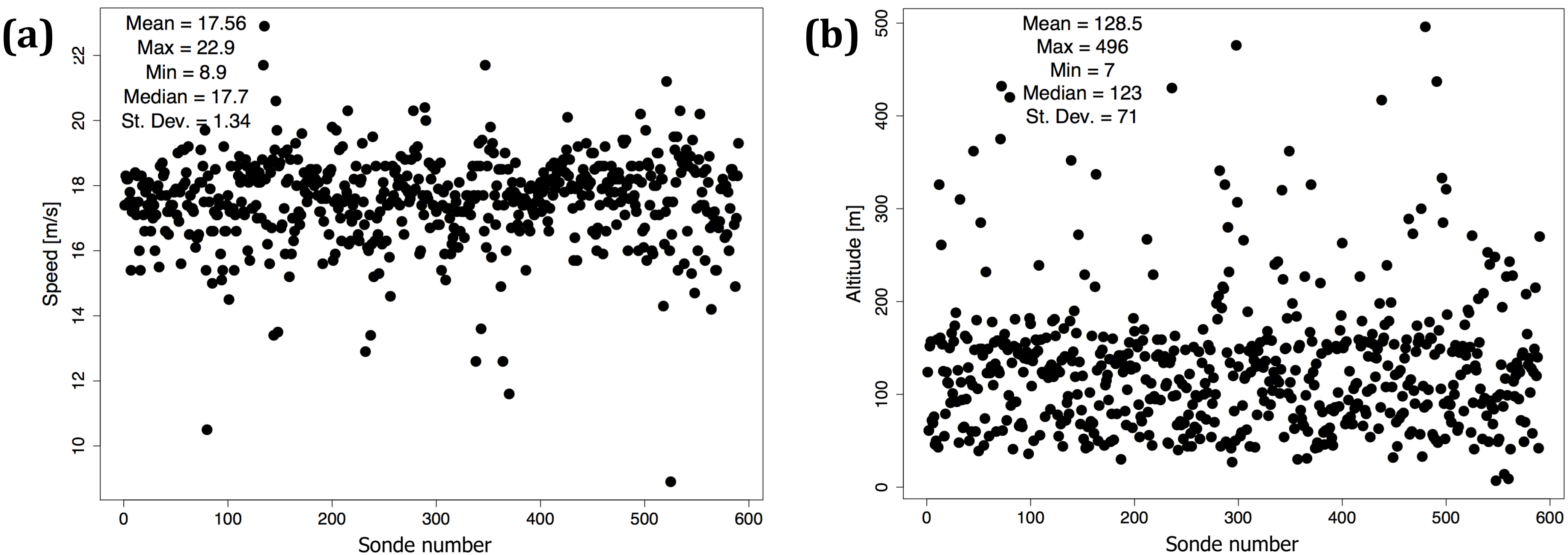


Fig. 11

APPENDIX: Nelson et al. (2017)

- Most sondes made it below 5000 m, many made it below 500 m
- NO correlation between surface fall speed and altitude
- Most within 1 St. Dev.