Exploring the Relationship between Vortex Misalignment and Tropical Cyclone Intensity Change

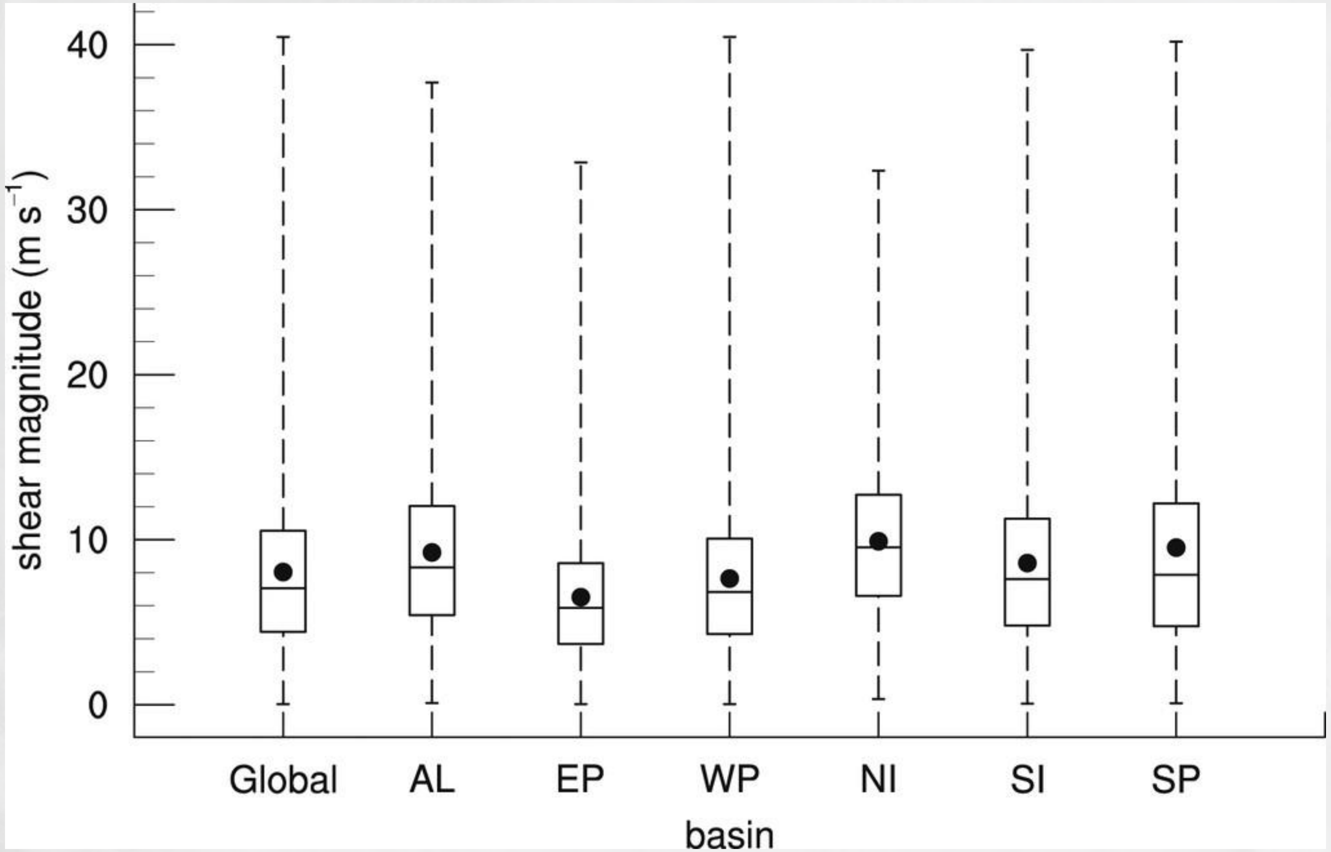
Michael Fischer[1,2], Paul Reasor[2], Robert Rogers[2], Jason Dunion[1,2], Brian Tang[3], Kristen Corbosiero[3], Ryan Torn[3], and Xiaomin Chen[2,4]

[1]University of Miami/CIMAS
[2]NOAA/AOML/Hurricane Research Division
[3]University at Albany
[4]Northern Gulf Institute/Mississippi State University

HFIP Seminar, 12 April 2023

Motivation

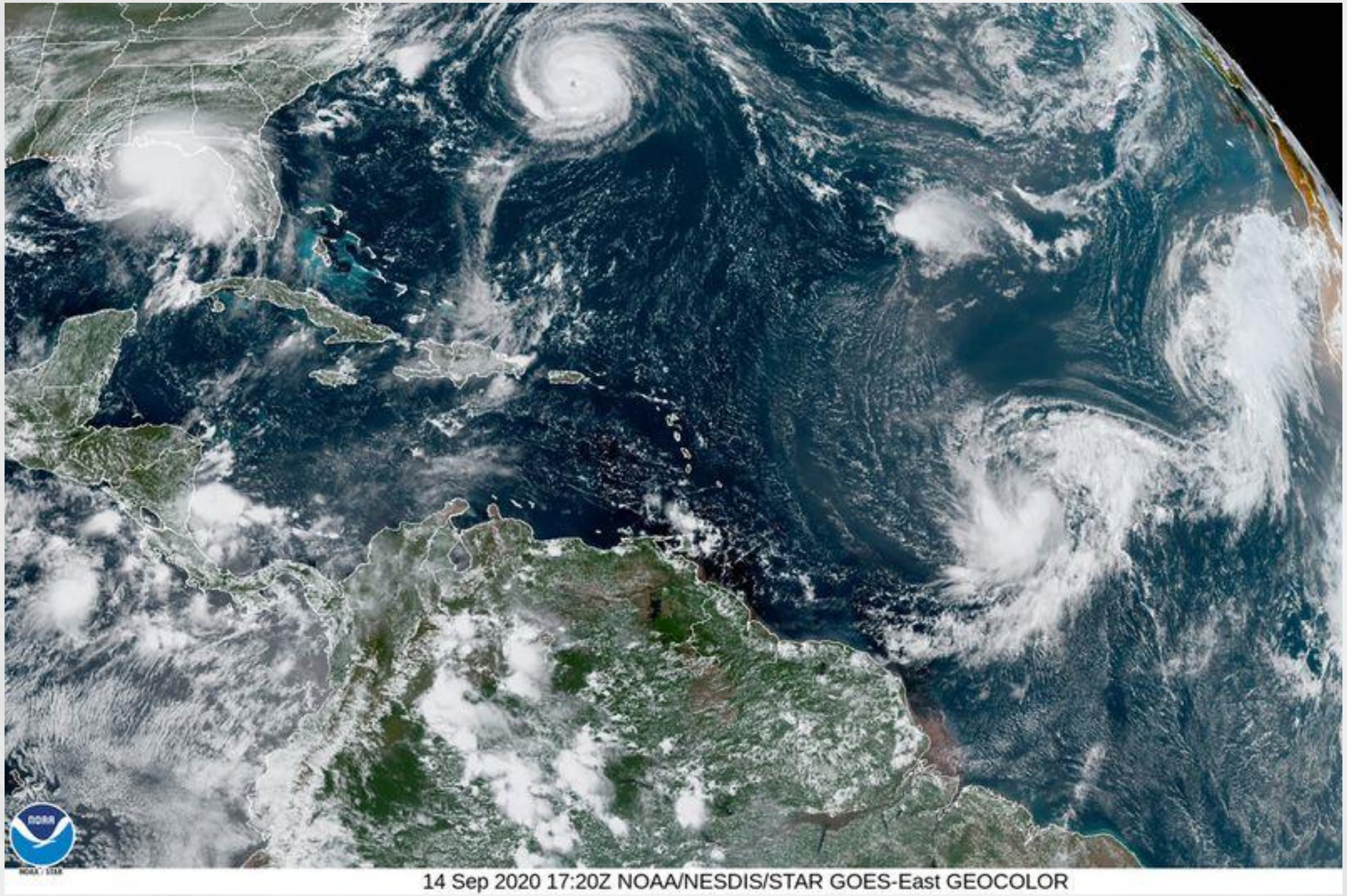
- Nearly all tropical cyclones (TCs) experience some degree of vertical wind shear!



Distribution of 850–200-hPa shear magnitude. Fig. 3 from Rios-Berrios and Torn (2017)

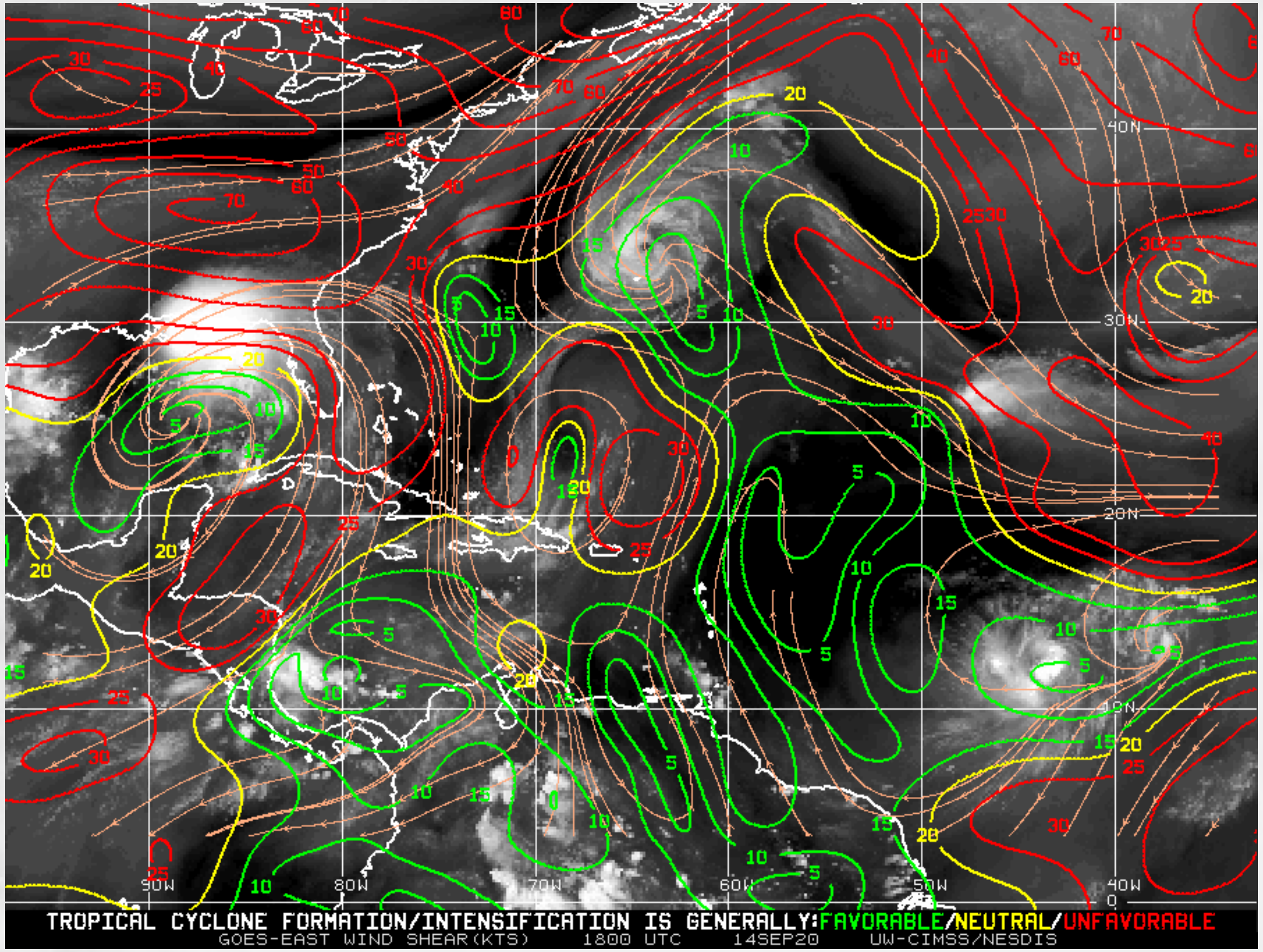
Motivation

- Nearly all tropical cyclones (TCs) experience some degree of vertical wind shear!



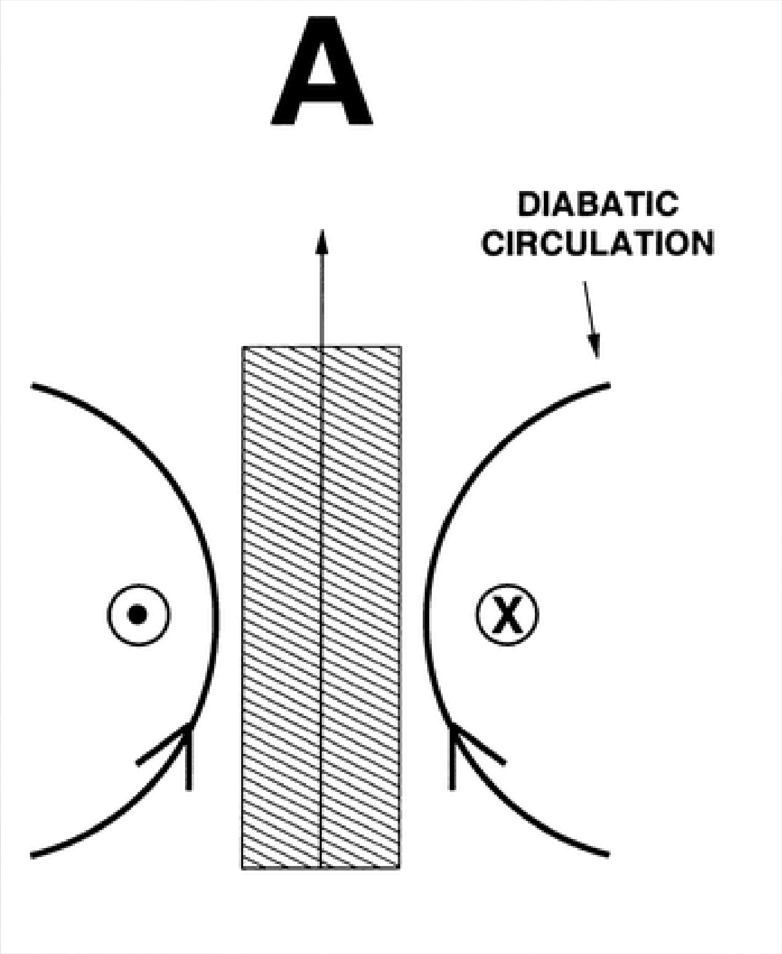
Motivation

- Nearly all tropical cyclones (TCs) experience some degree of vertical wind shear!



What does shear do to a TC vortex?

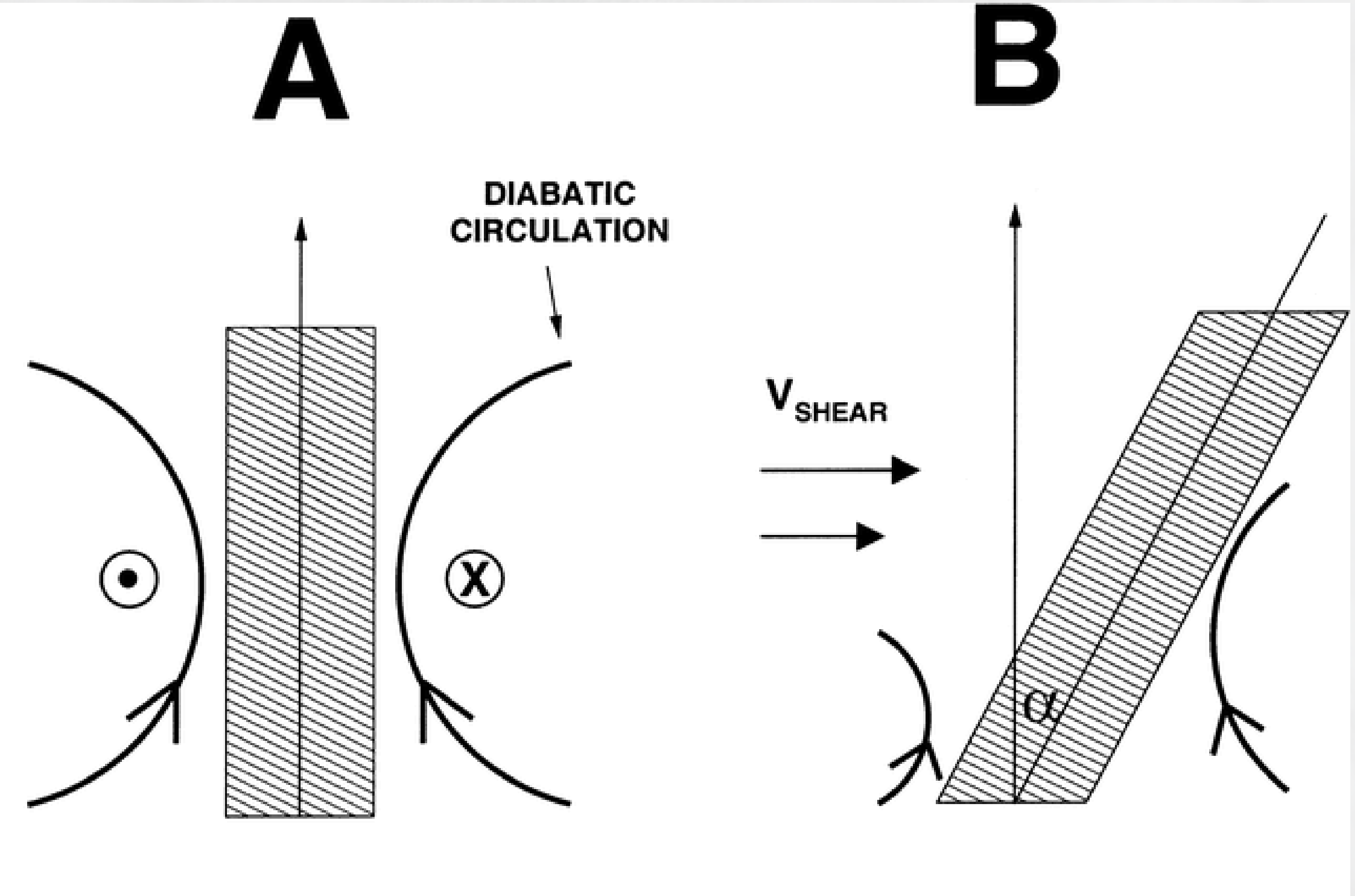
- Shear acts to differentially advect (or tilt) a vortex



Adapted from Reasor et al. (2004)

What does shear do to a TC vortex?

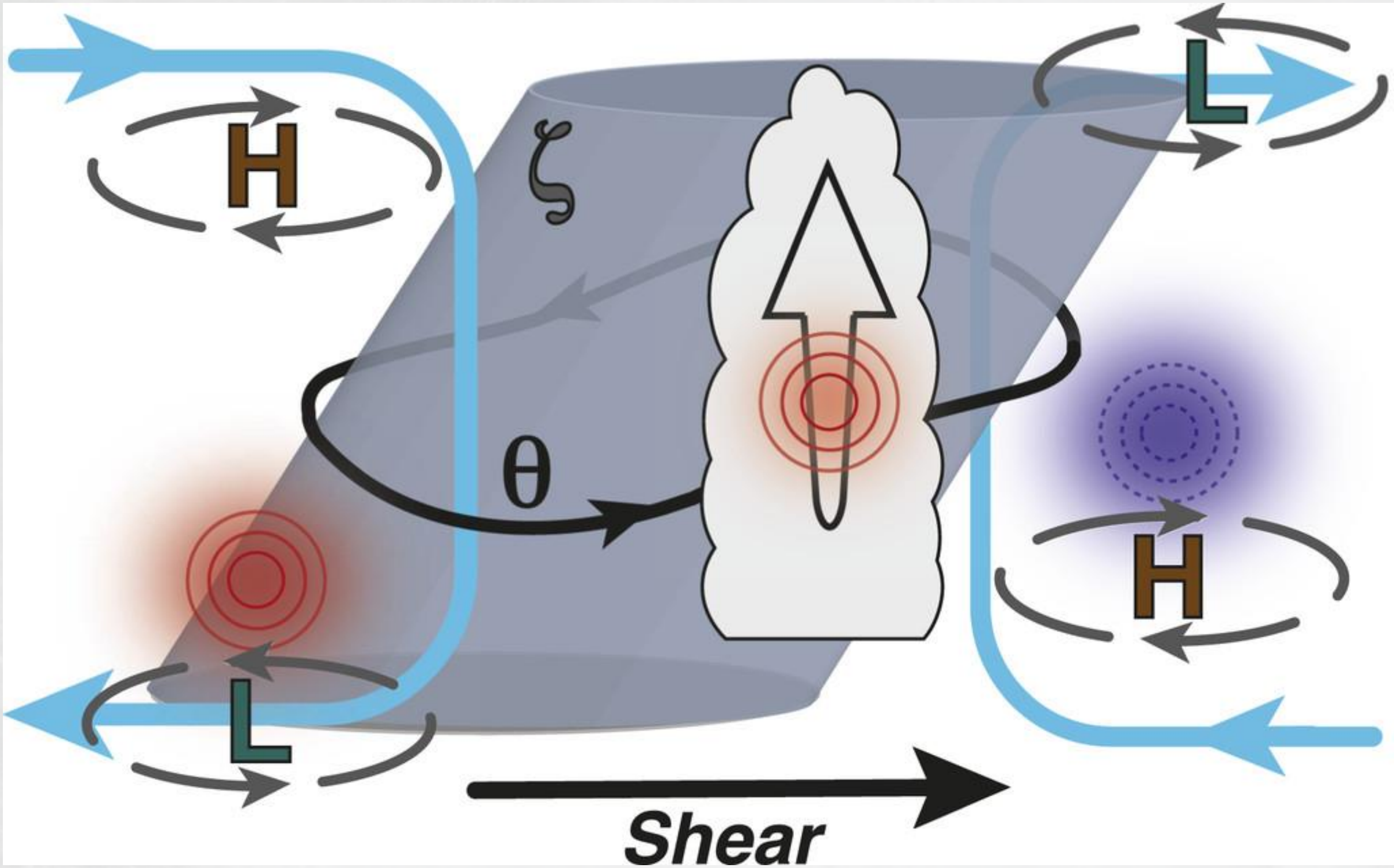
- Shear acts to differentially advect (or tilt) a vortex



Adapted from Reasor et al. (2004)

A tilted vortex is an asymmetric vortex

- Thermal asymmetries exist in a tilted vortex
- To maintain thermal wind balance, vertical velocity asymmetries arise



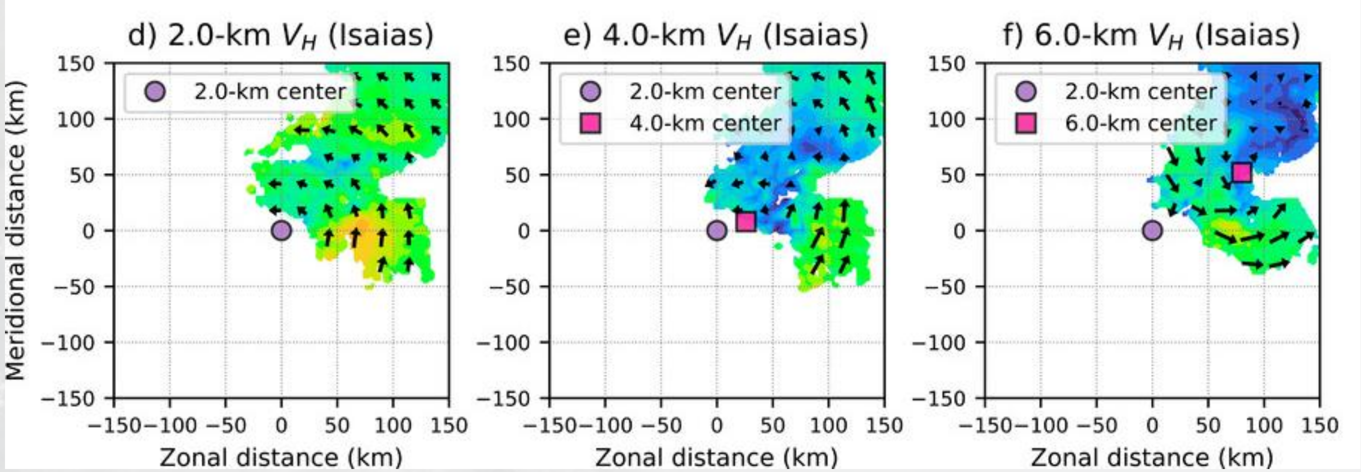
Adapted from Boehm and Bell (2021)

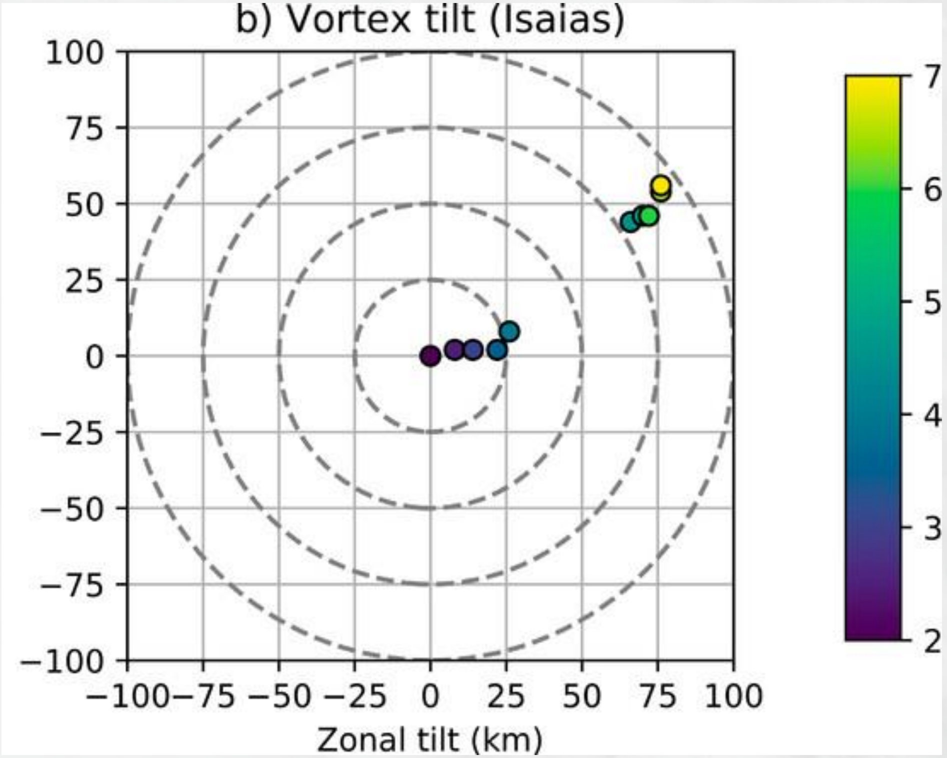
A tilted vortex can be a messy vortex

- In relatively weak TCs, multiple circulations can exist
- A TC may not be accurately characterized by a tilted column of vorticity

Tilt hodograph:

Tail Doppler Radar (TDR) analyses:

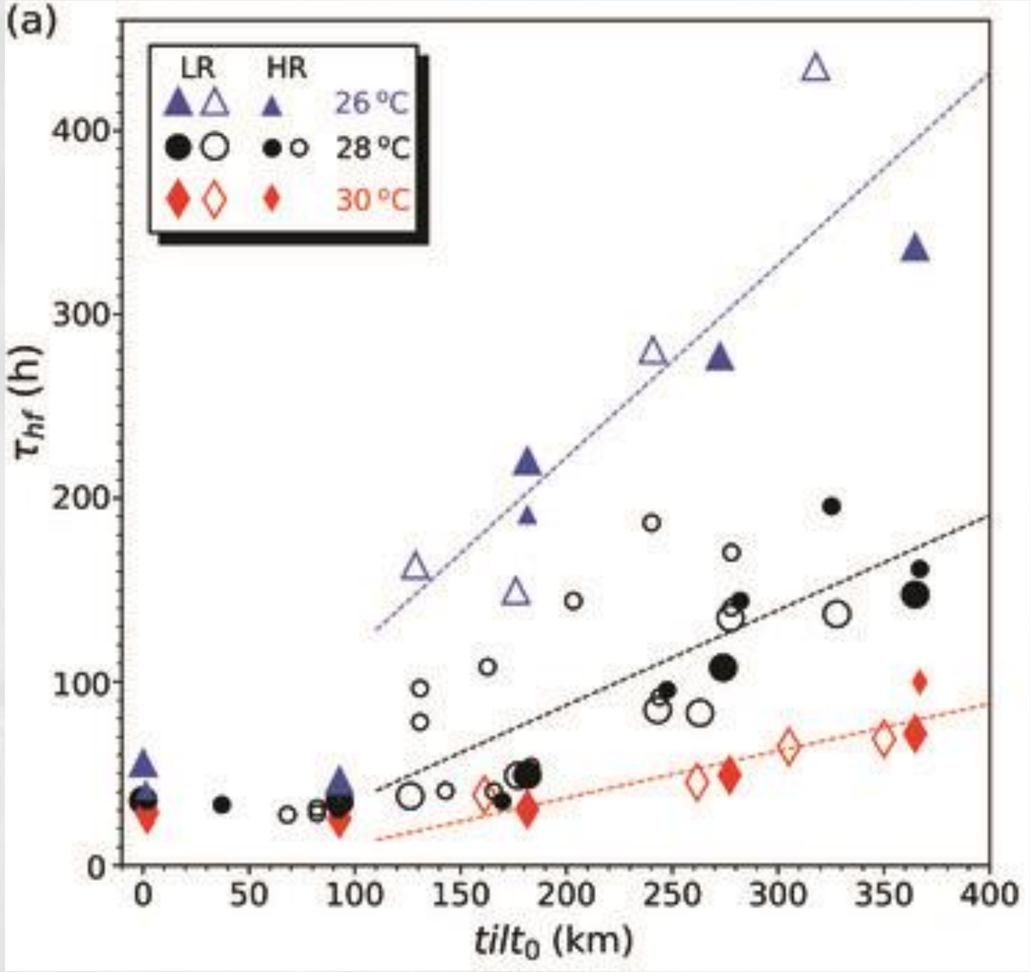




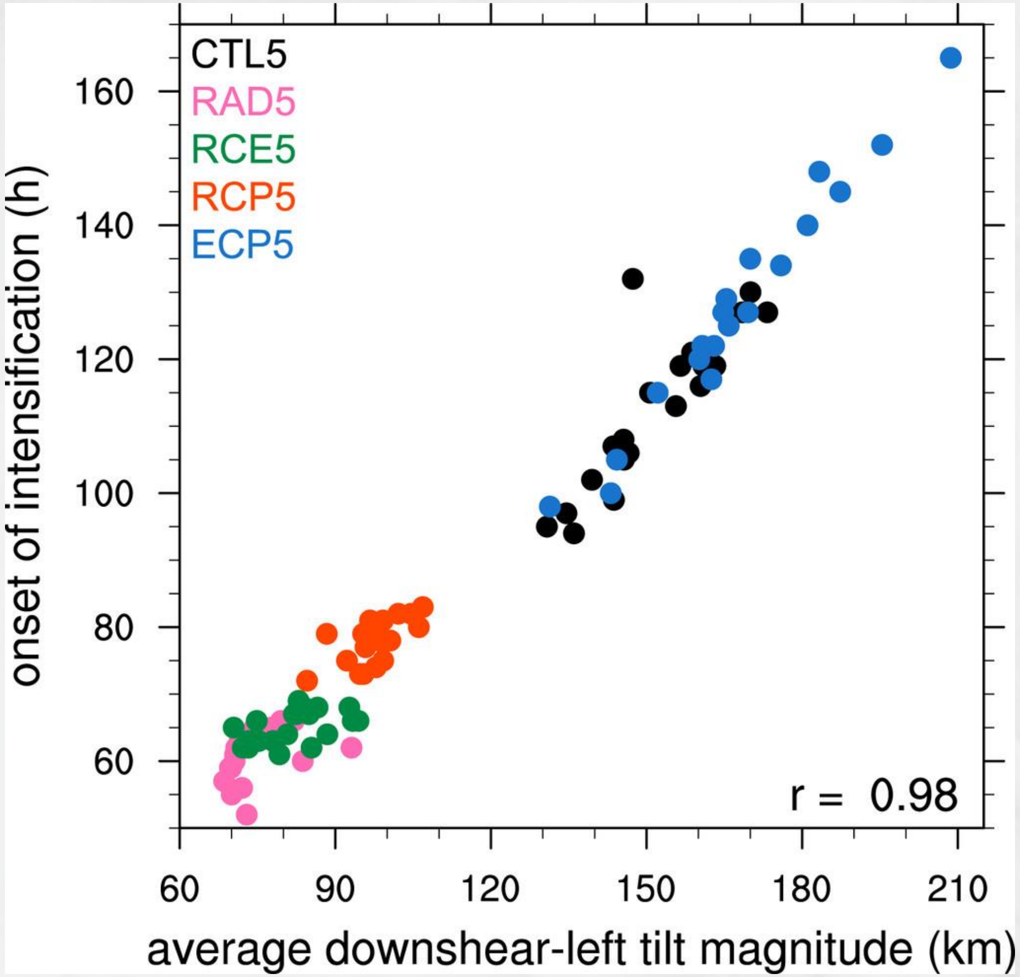
Adapted from Fischer et al. (2022)

How is tilt related to intensity change?

- Modeling studies have shown more tilted vortices delay intensification



Adapted from Schecter (2022)



Adapted from Rios-Berrios (2020)

Is tilt related to intensity change?

- Observations say: Well, we don't really know…

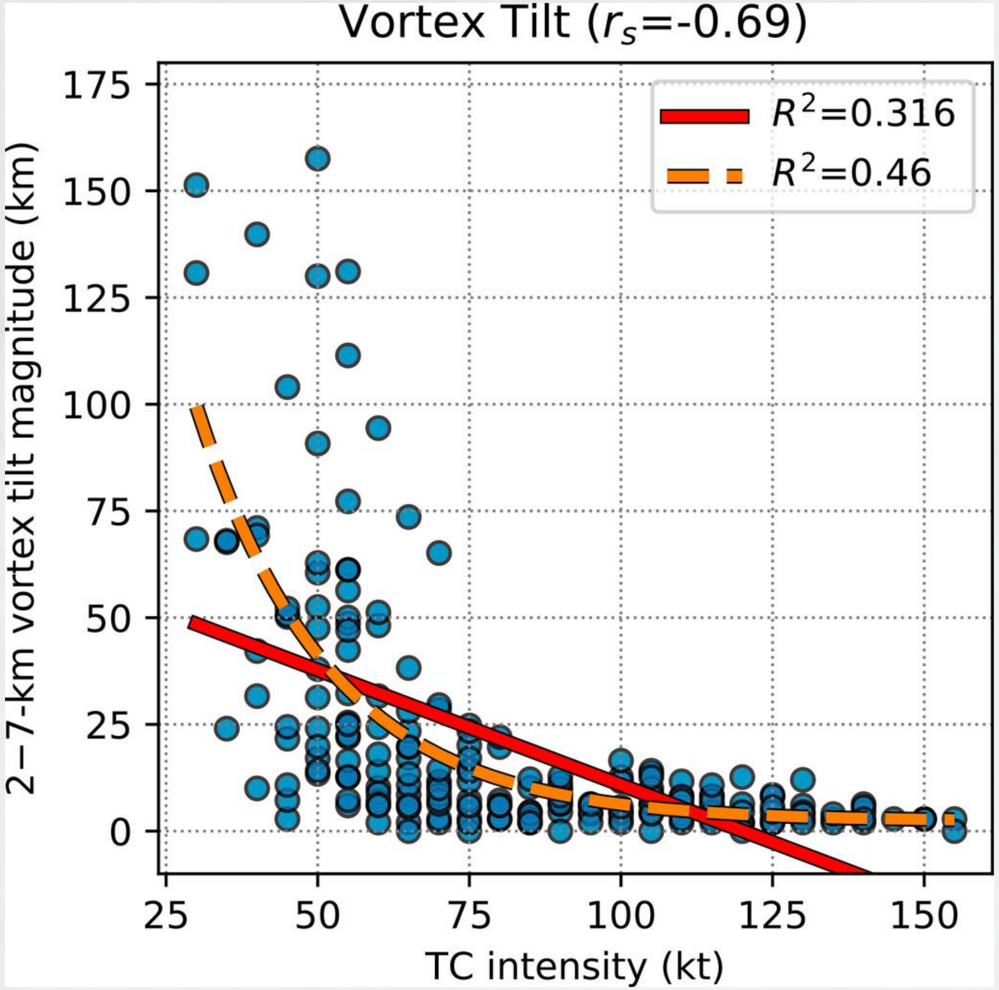


Fig. 9 from Fischer et al. (2022)

Is tilt related to intensity change?

- Observations say: Well, we don't really know…

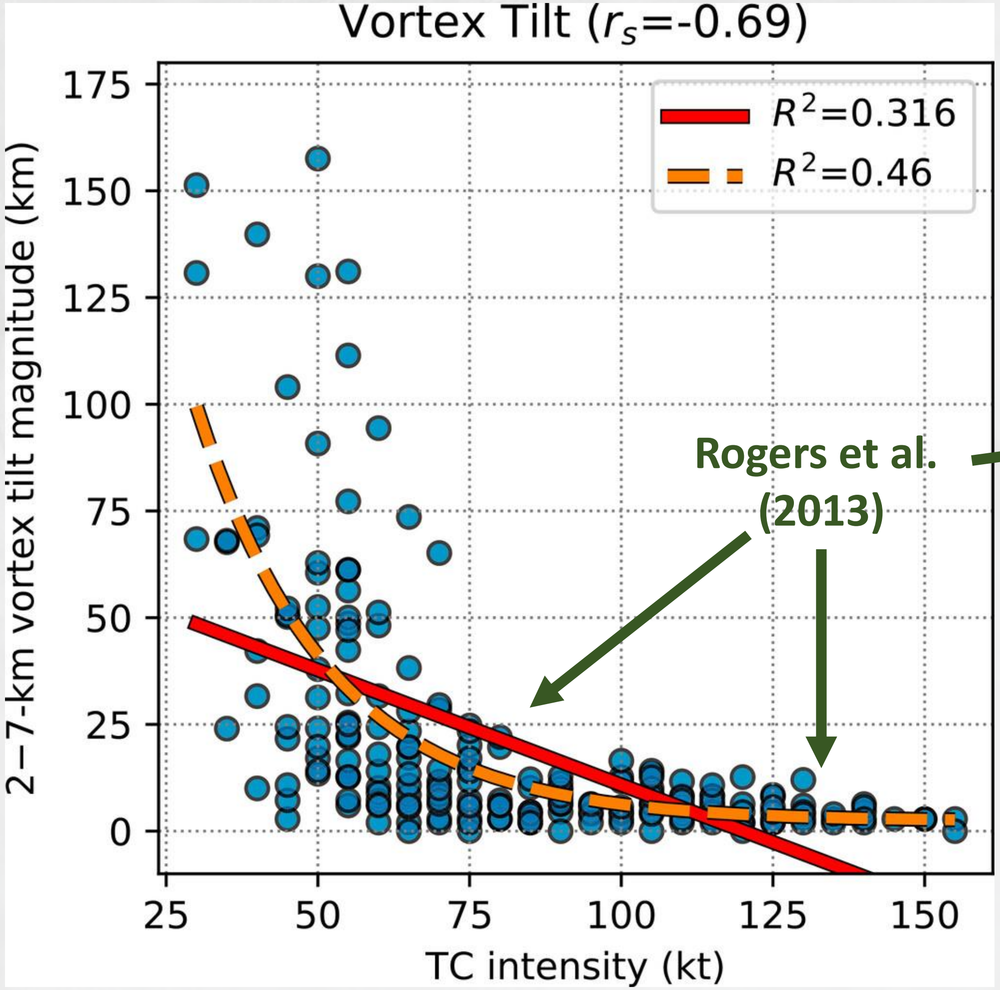
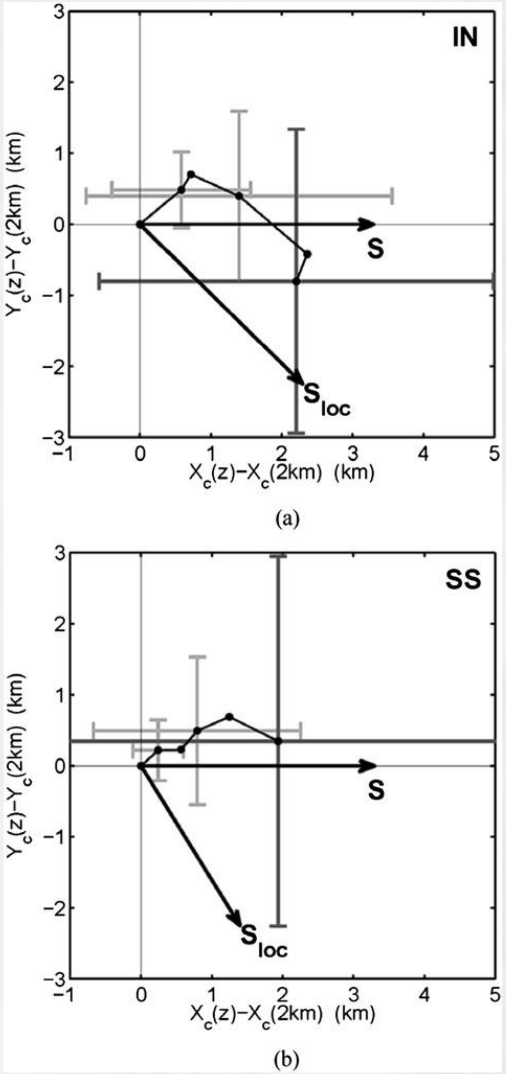


Fig. 9 from Fischer et al. (2022)



Is tilt related to intensity change?

- Observations say: Well, we don't really know…

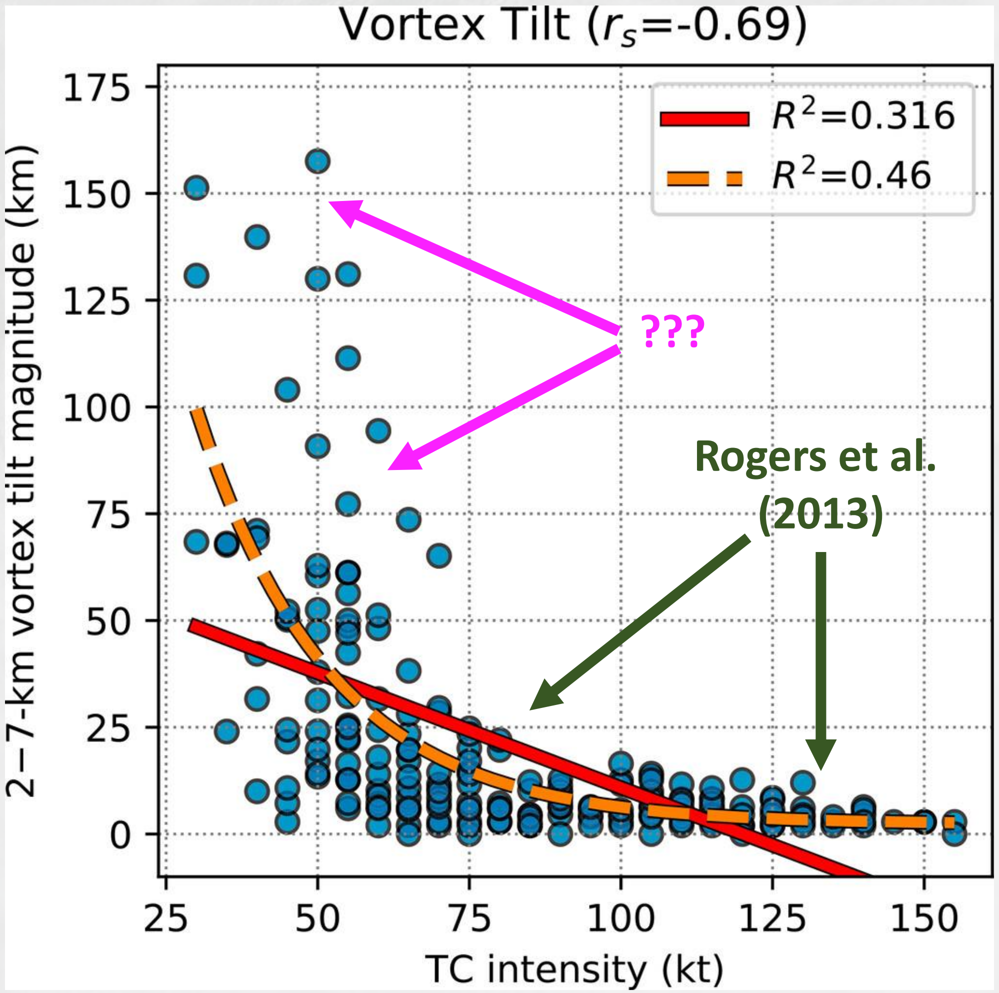


Fig. 9 from Fischer et al. (2022)

Is tilt related to intensity change?

- Observations say: Well, we don't really know…

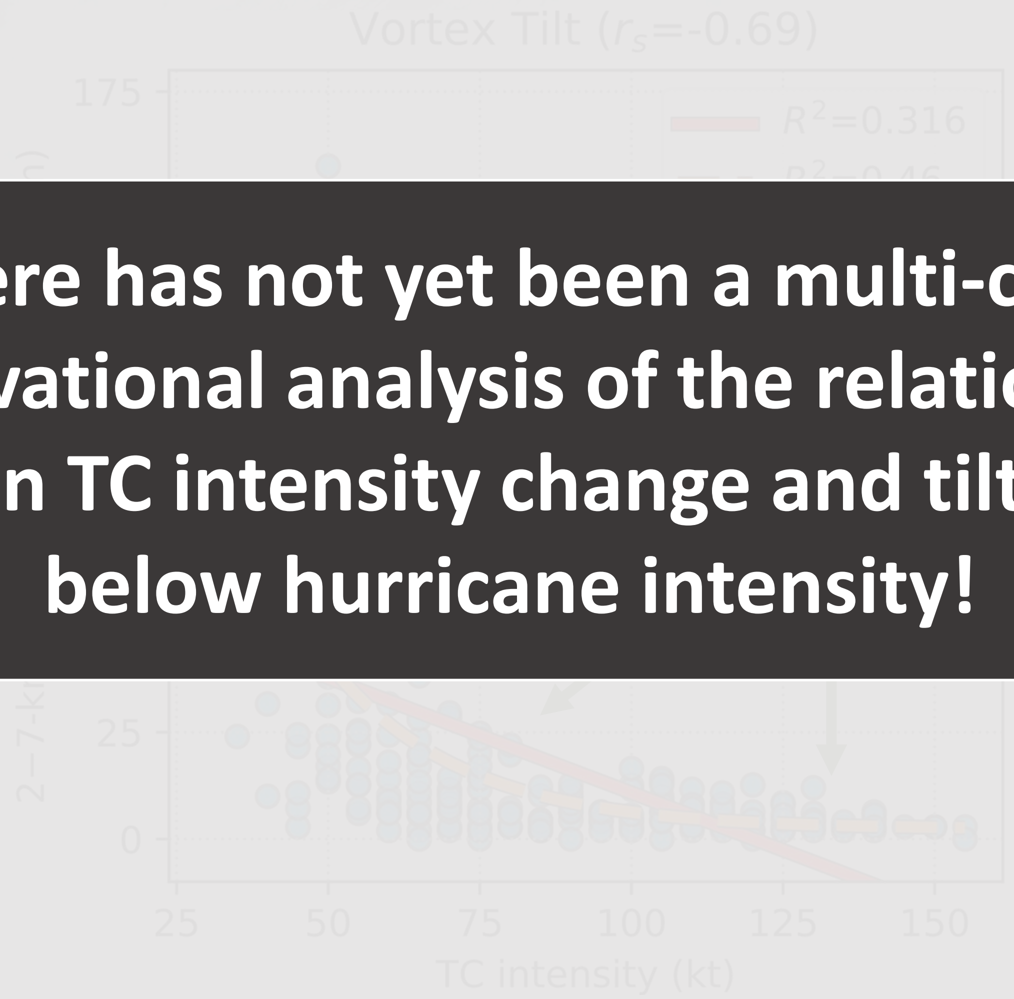


Fig. 9 from Fischer et al. (2022)

There has not yet been a multi-case observational analysis of the relationship between TC intensity change and tilt for TCs below hurricane intensity!

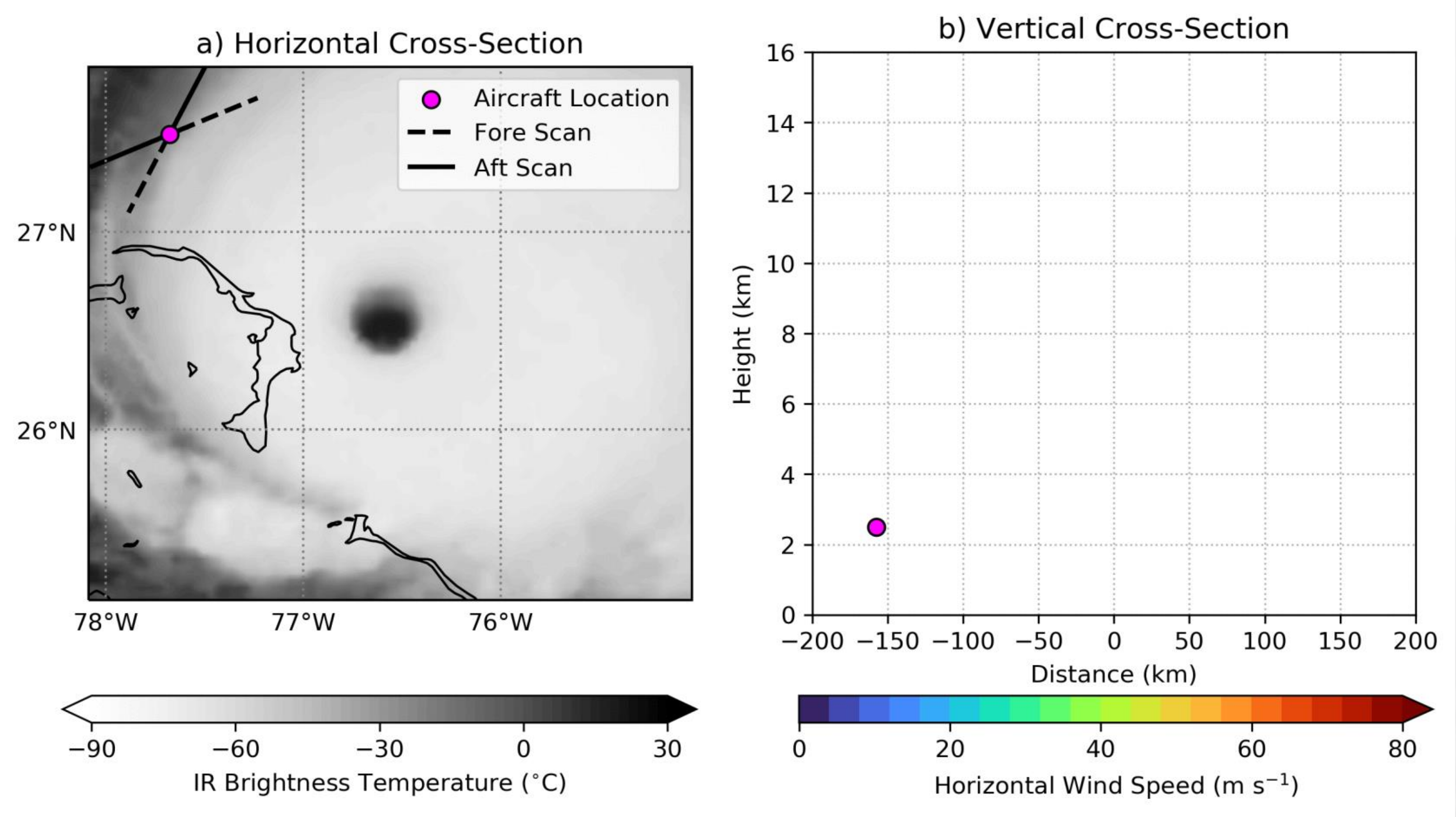
Key research questions

Q1) Is vortex tilt related to TC intensity change in nature?

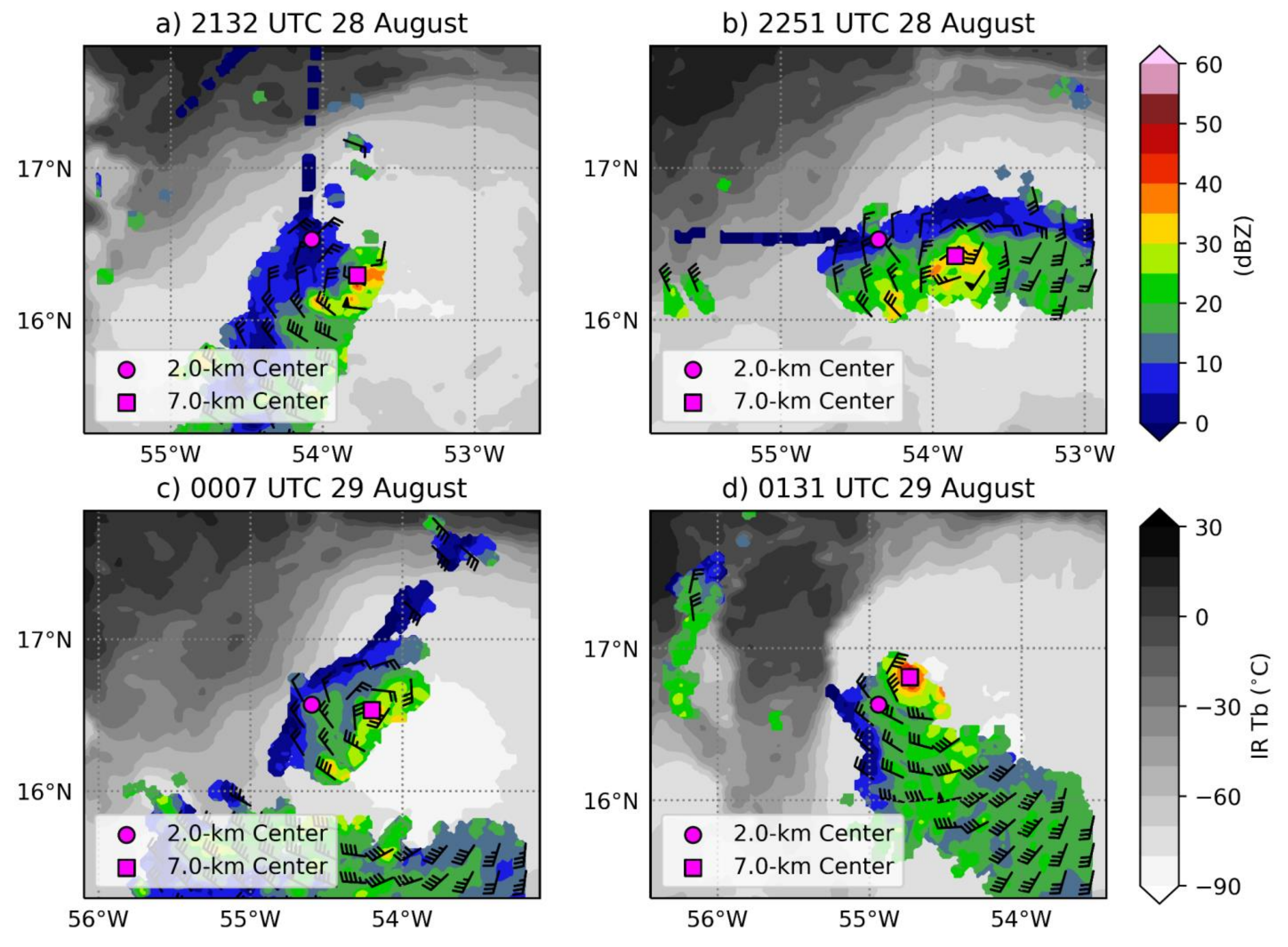
Q2) You'll see later :D

Tools to explore vortex tilt in nature

- Let's use a collection of tail Doppler radar (TDR) observations
- The TDR is an X-band radar onboard NOAA's P3 aircraft
- Can retrieve 3D wind field within ~50 km of flight track if sufficient scatterers



Tools to explore vortex tilt in nature



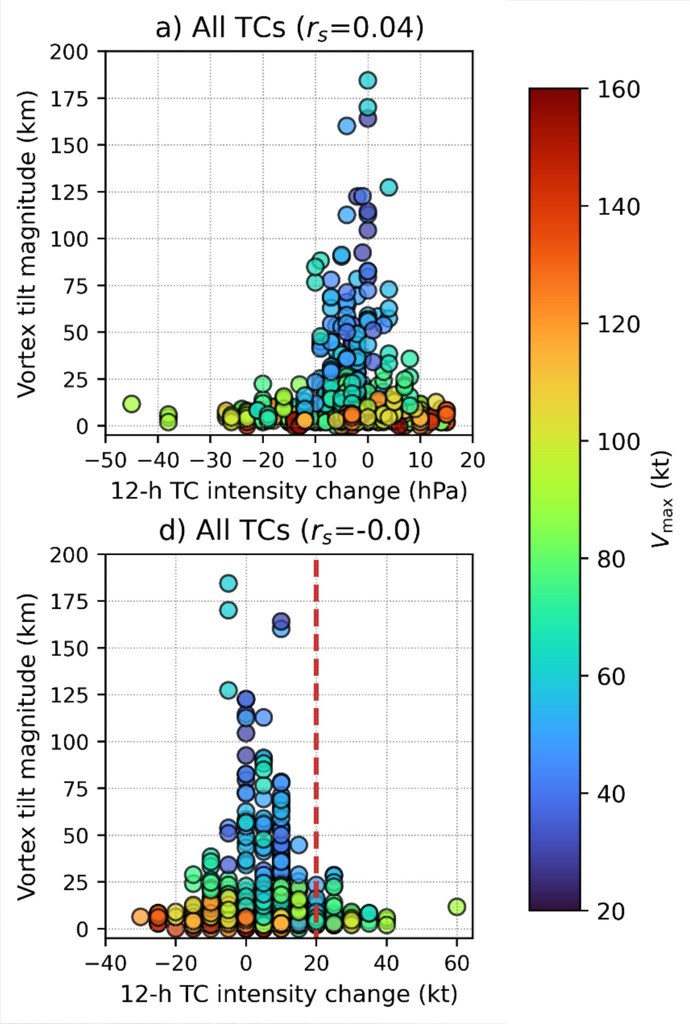
Tropical Storm Earl (2010)

- Use TC-RADAR (Fischer et al. 2022), which contains over 1,000 analyses of TC kinematic and precipitation structure
- Uses a novel center-finding algorithm, which allows for estimates of vortex tilt from individual swaths (seen to the left)
- Includes best-track and SHIPS diagnostics
- Exclude cases that make landfall over the next 12 h or are in very unfavorable thermodynamic environments

Vortex tilt vs. TC intensity change

Changes in MSLP:

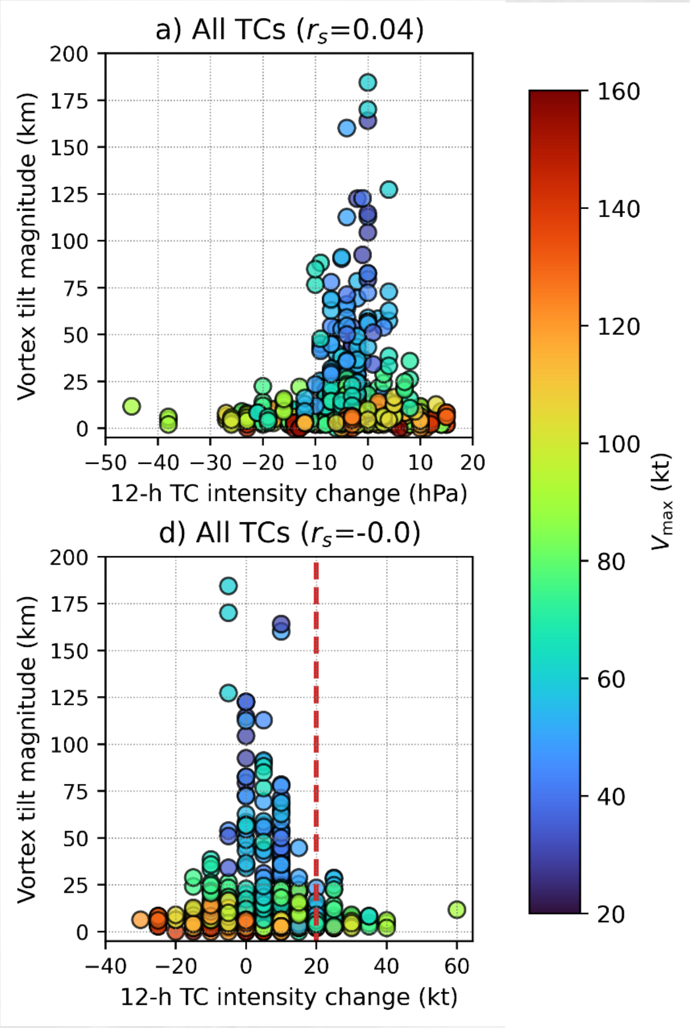
Changes in Vmax:



Vortex tilt vs. TC intensity change

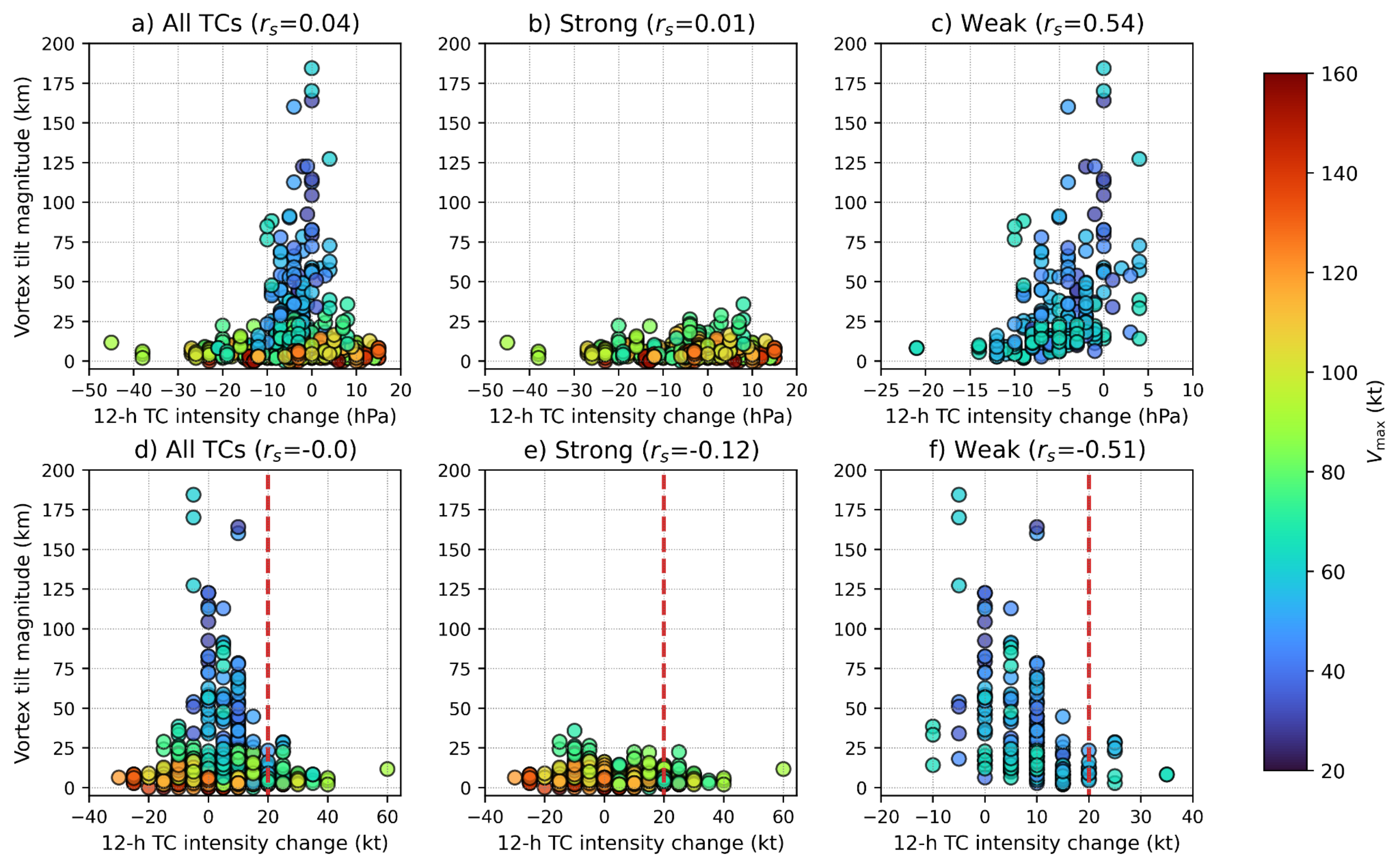
Changes in MSLP:

Changes in Vmax:



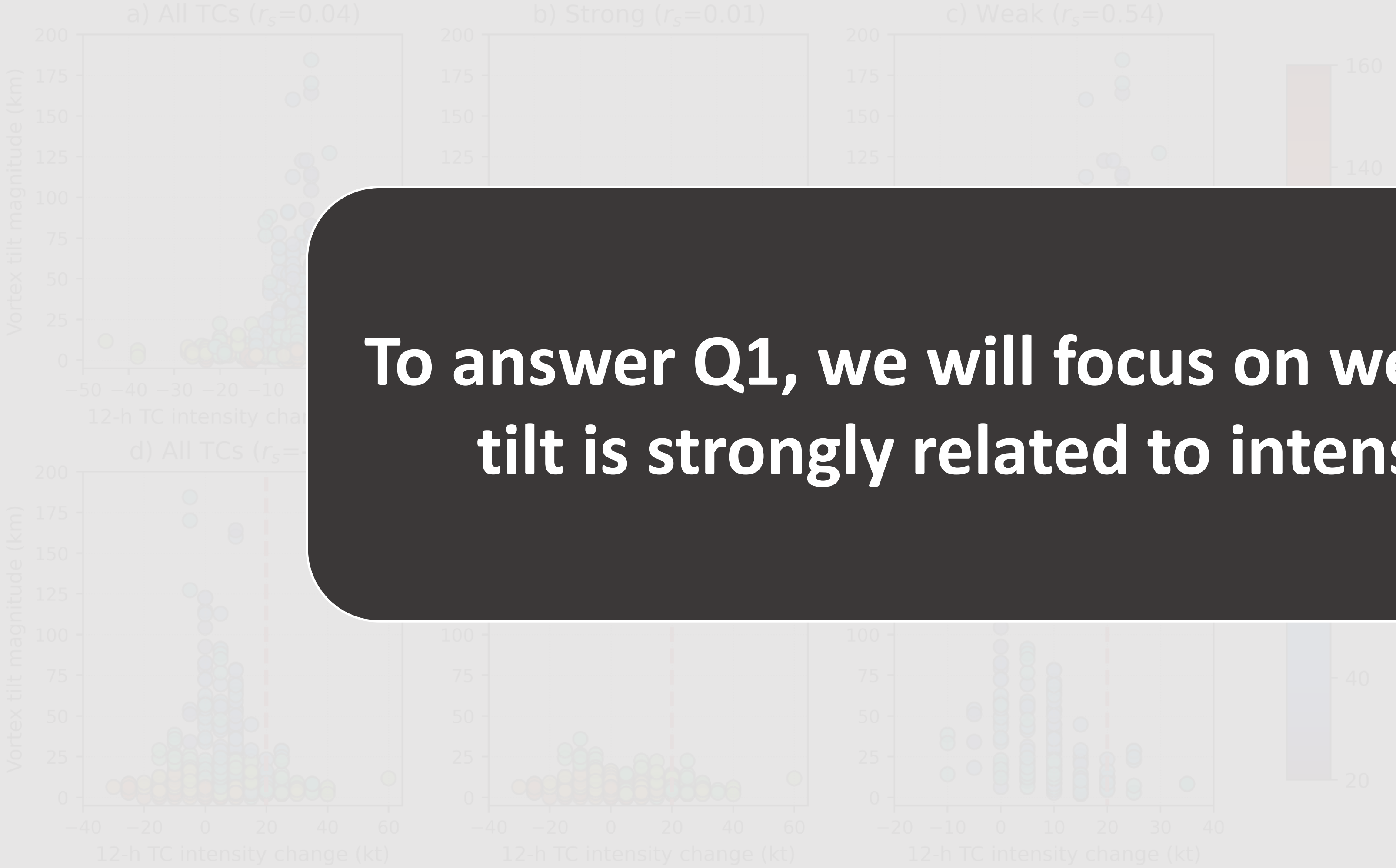
- No signal?
  - We need to look closer!

Vortex tilt vs. TC intensity change



- **The maximum 2–6.5-km tilt magnitude is a strong predictor of intensity change in weak TCs** (Vmax ≤ 65 kt), but not in strong TCs
- RI (12-h ΔVmax ≥ 20 kt; red line) is only observed to occur for relatively aligned vortices

Vortex tilt vs. TC intensity change

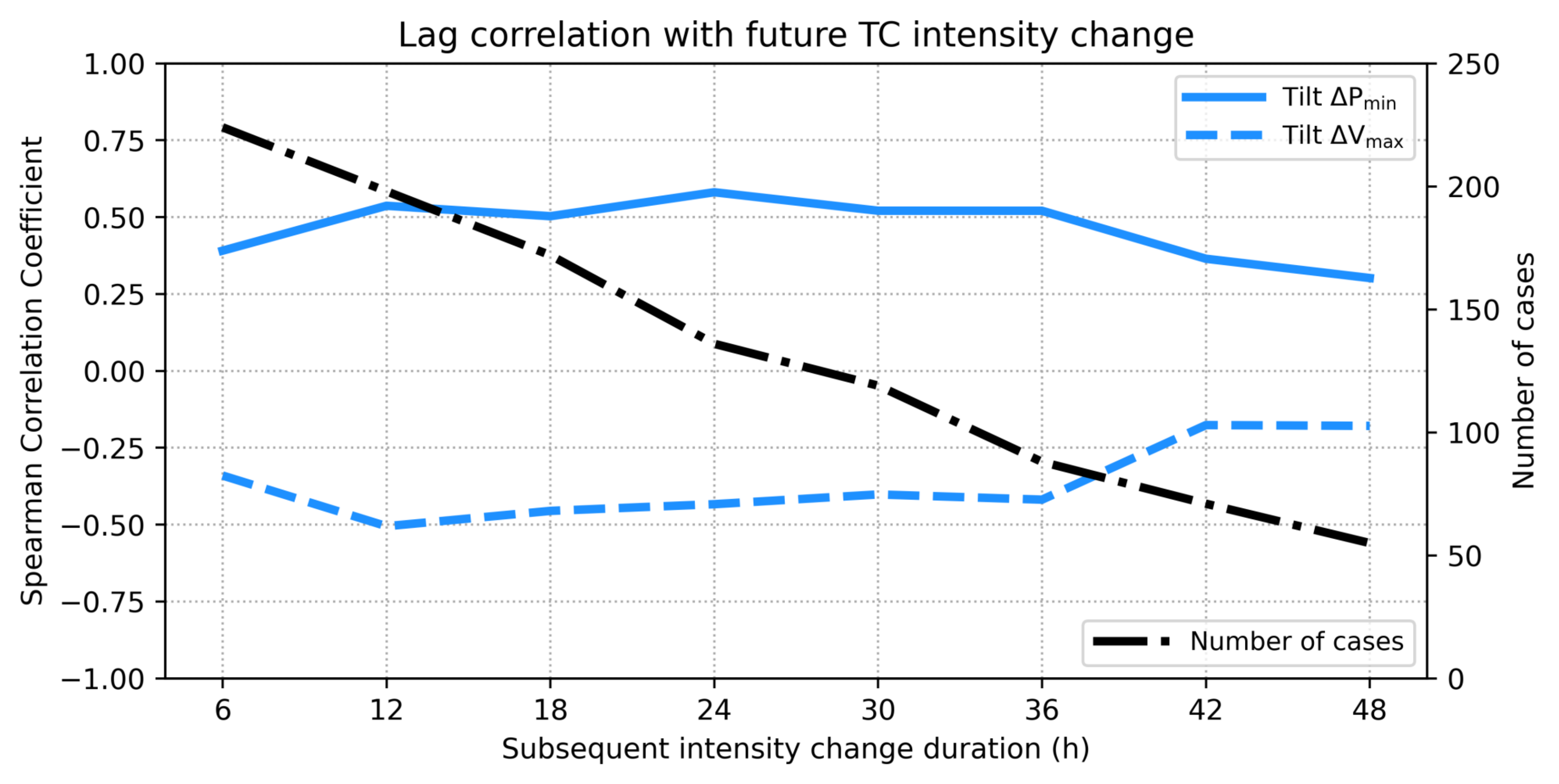


km tilt
predictor of
eak TCs (Vmax
ong TCs

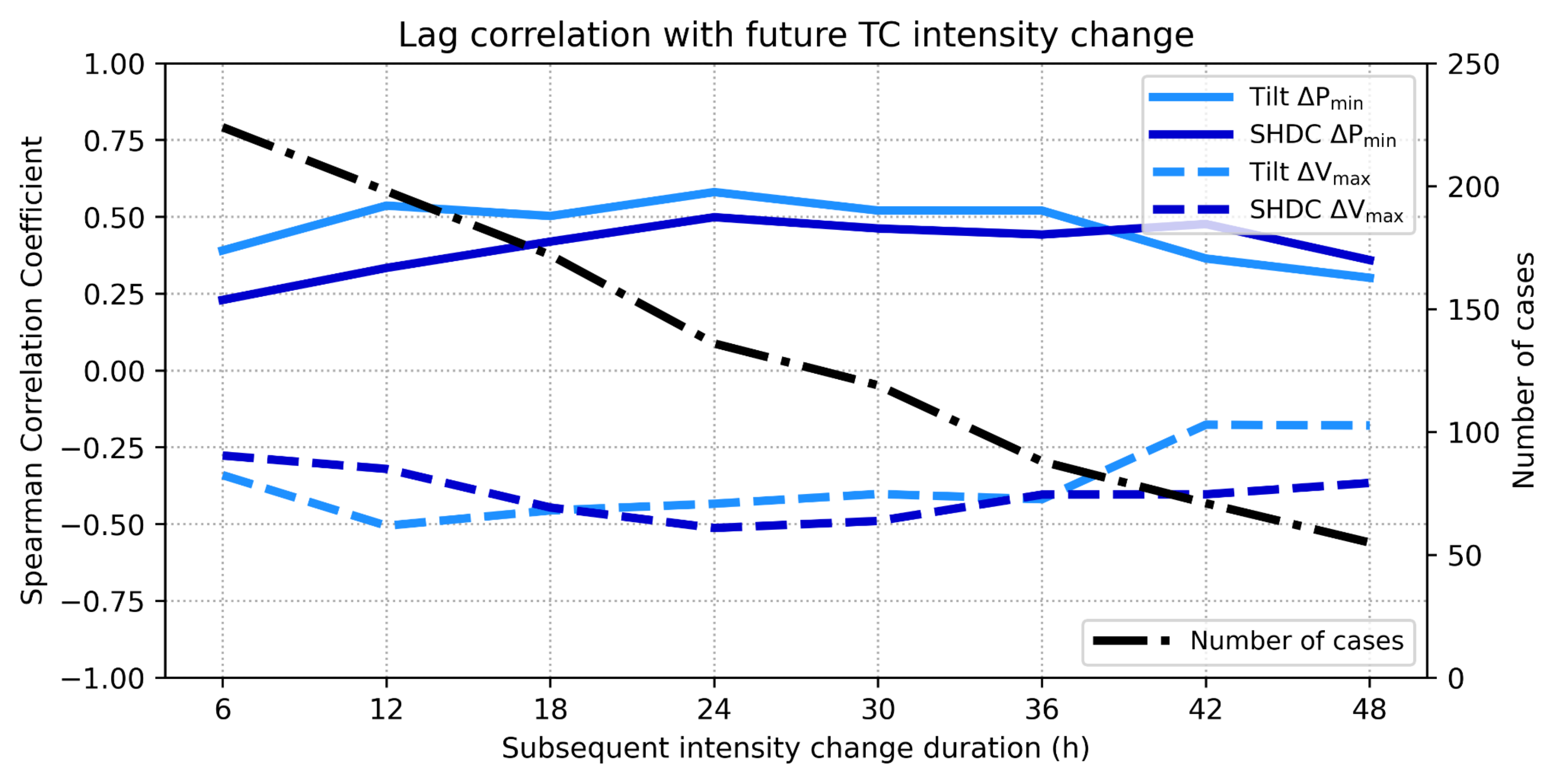
t; red line) is
cur for relatively
aligned vortices

To answer Q1, we will focus on weak TCs, where tilt is strongly related to intensity change

Lag correlation between tilt and intensity change

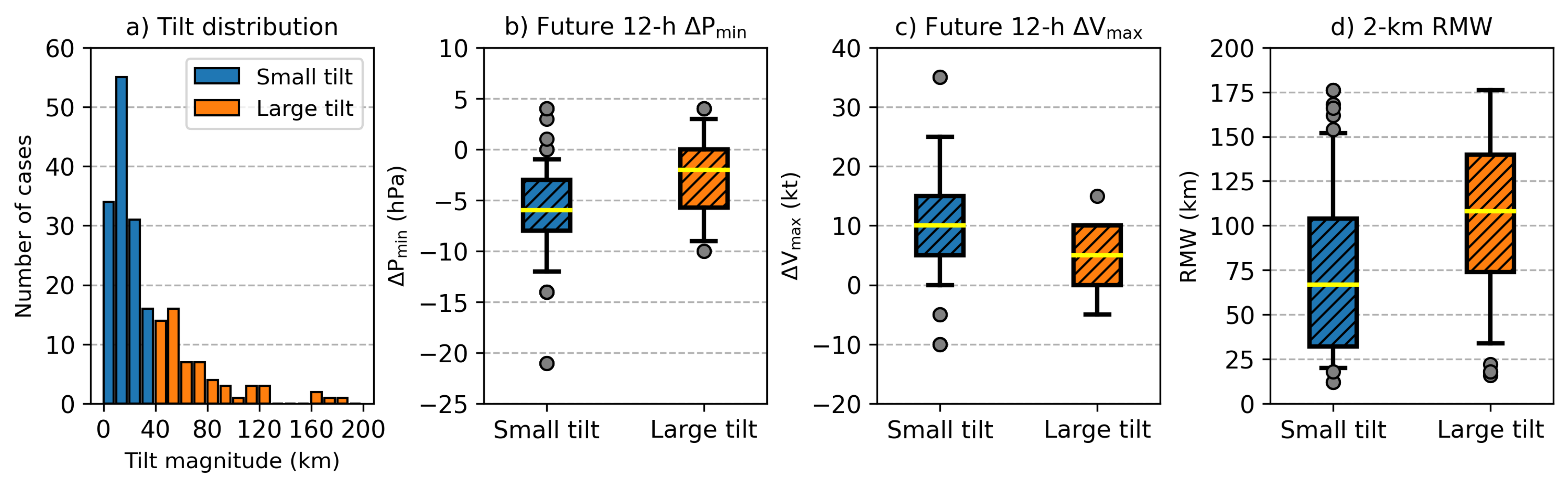


TC intensity change vs. shear and tilt



- Tilt is more strongly correlated to short-term (e.g., 12–36-h) TC intensity change than the SHIPS deep-layer shear magnitude (SHDC)

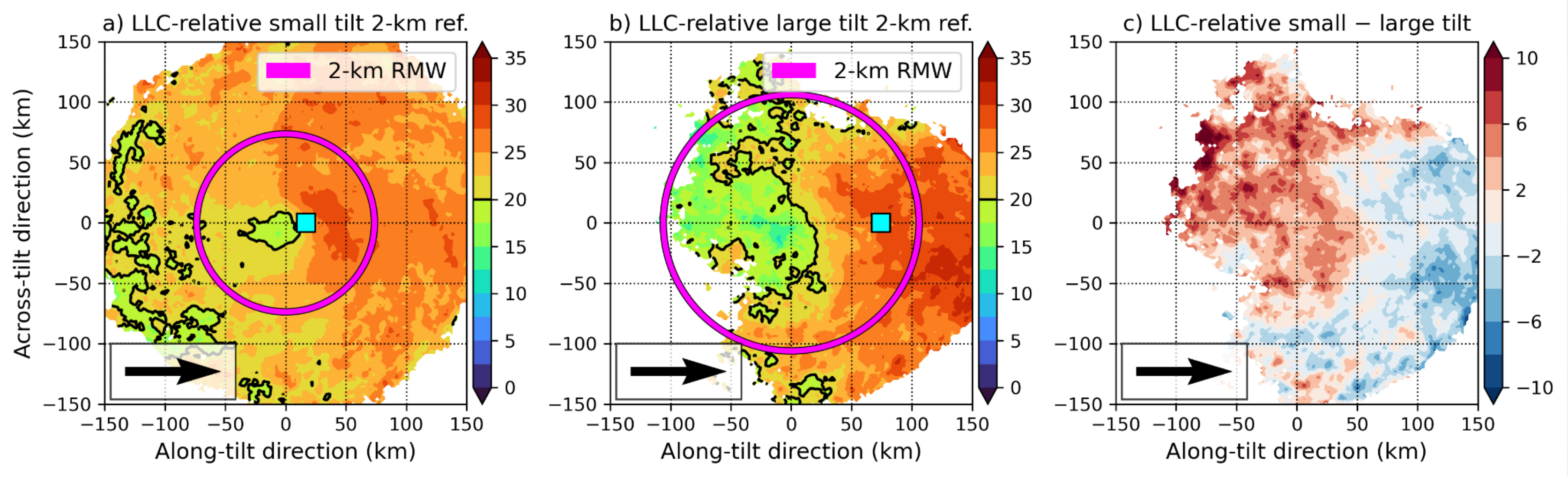
Comparing small-tilt vs. large-tilt TCs



- All weak TCs tend to intensify, but small-tilt TCs intensify at significantly greater rates than their more tilted counterparts

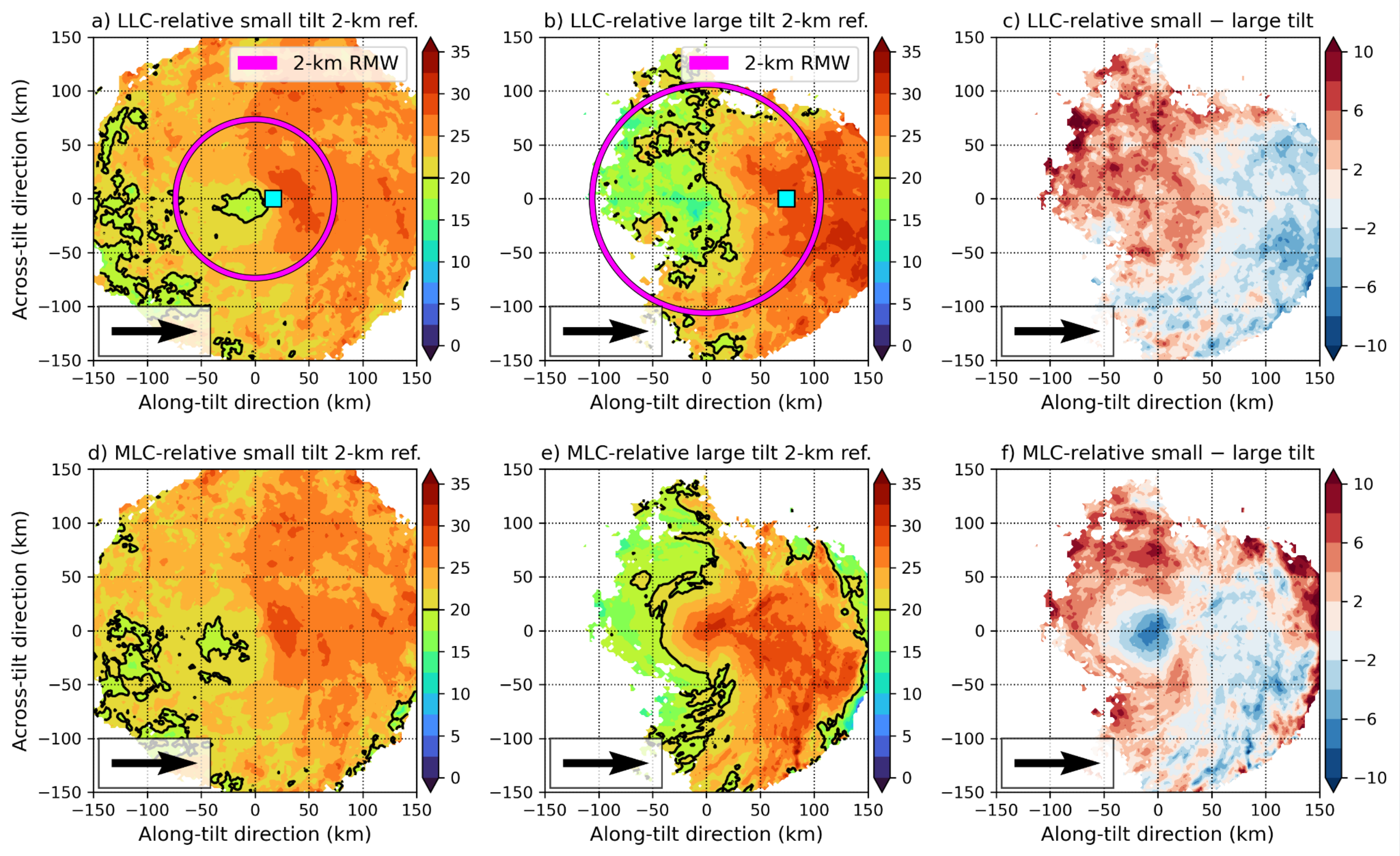
- Small-tilt TCs also have more compact vortices, consistent with idealized simulations in other studies

Tilt-relative reflectivity composites for two tilt groups



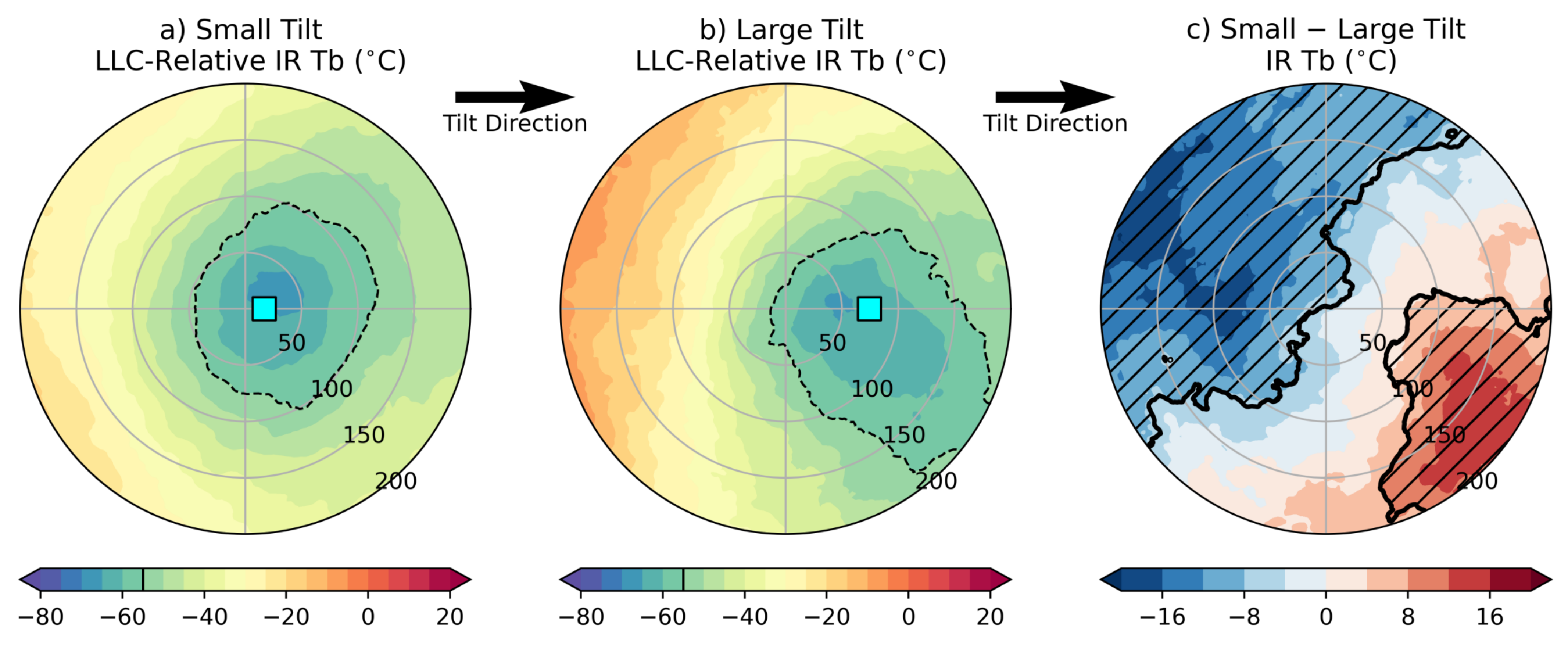
- Small-tilt storms are associated with more symmetric precipitation structures and greater reflectivity near LLC

Tilt-relative reflectivity composites for two tilt groups



- Small-tilt storms are associated with more symmetric precipitation structures and greater reflectivity near LLC
- Interestingly, in large-tilt TCs, reflectivity structure is closely tied to MLC location
- Large-tilt TCs tend to have more vigorous convection

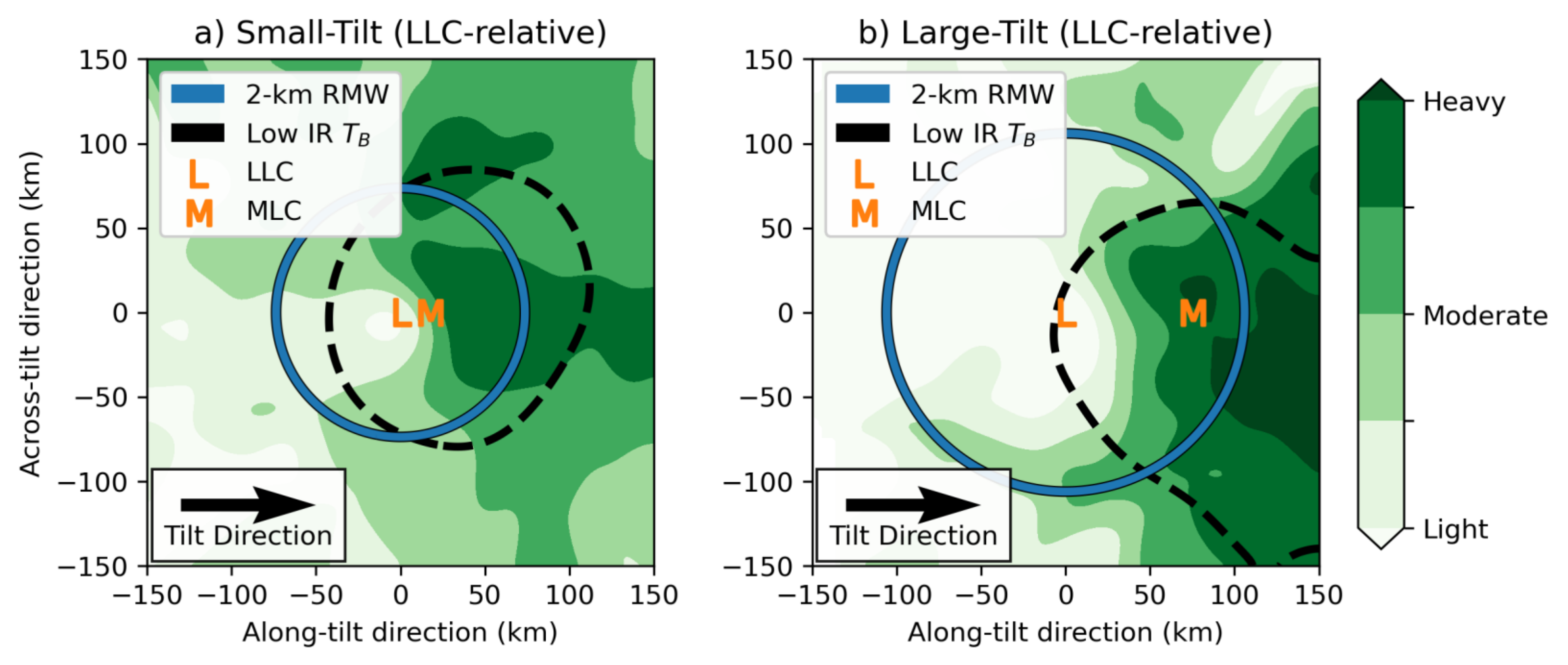
Tilt-relative IR brightness composites for two tilt groups



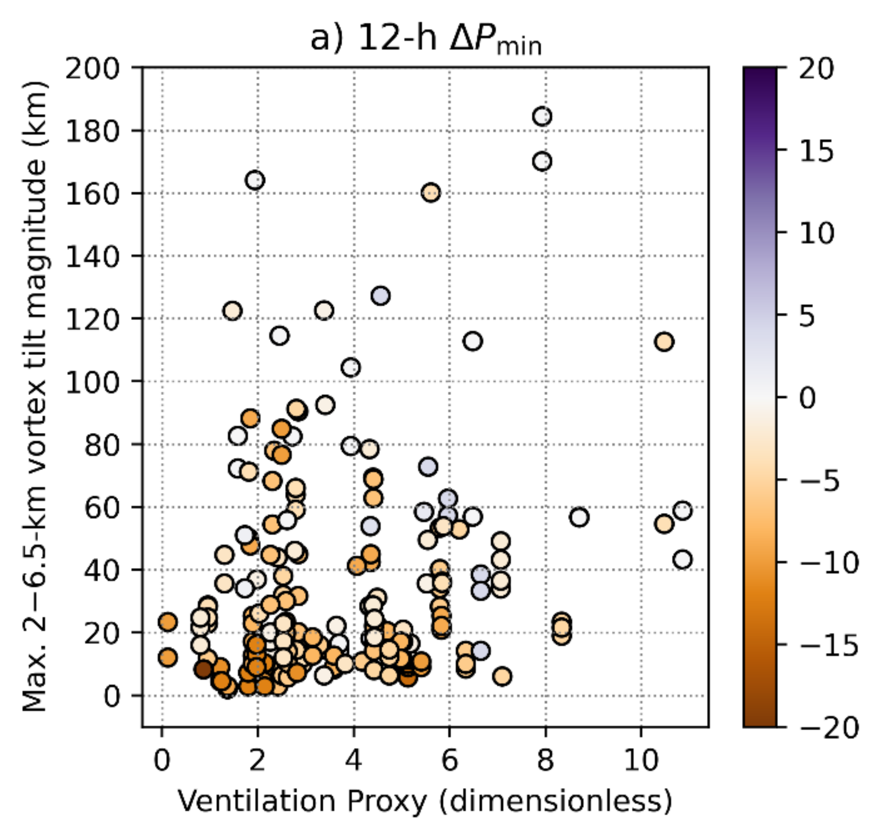
- Composites of infrared brightness temperatures support TDR composites

Q1 Summary

- Q1) Is vortex tilt related to TC intensity change in nature?
  - Yes! But primarily for weak TCs.
  - TCs will smaller tilt magnitudes have a greater areal coverage of precipitation, and more frequent ascent, near the LLC
  - A relatively aligned vortex appears required for RI over next 12 h

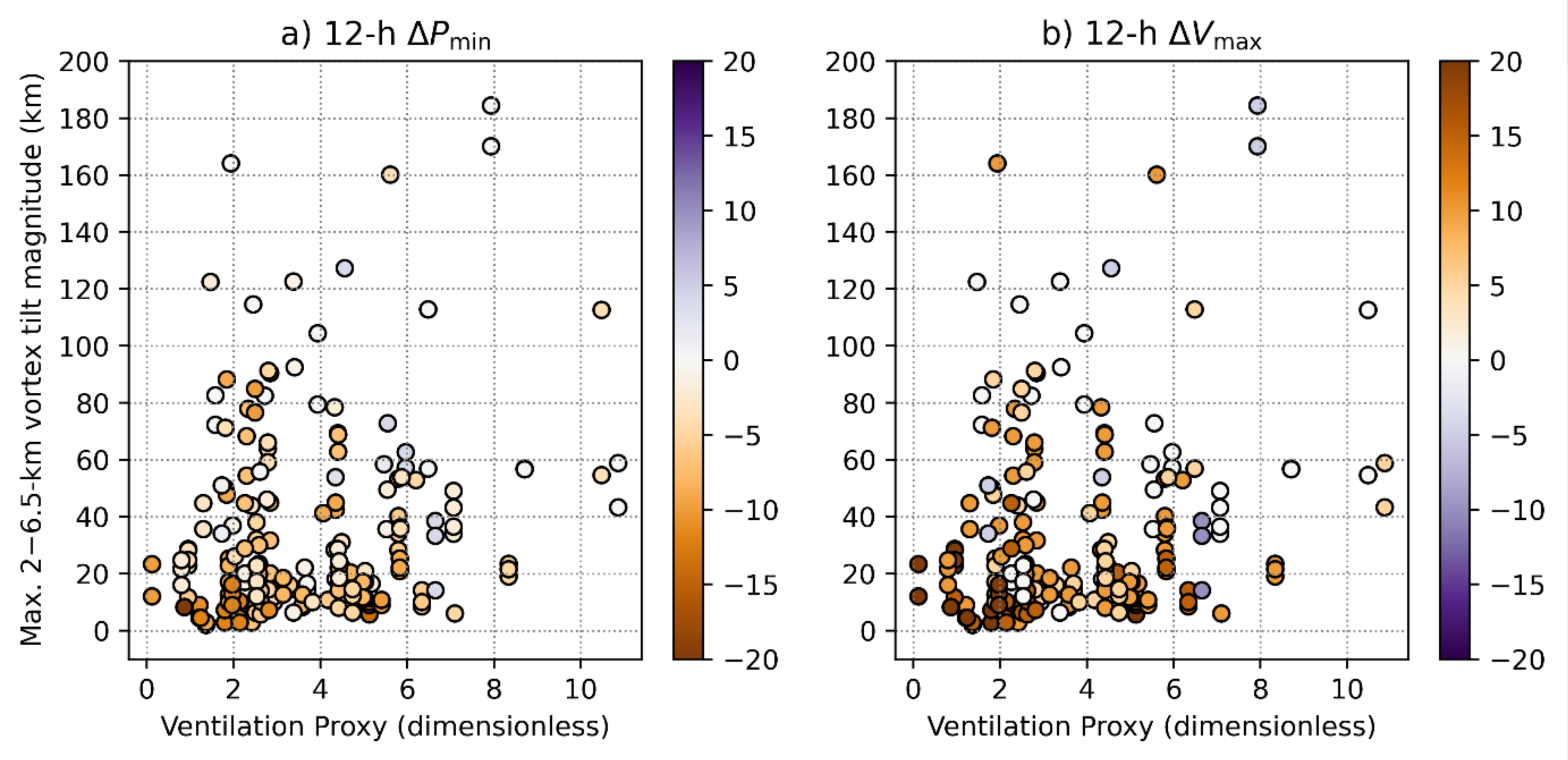


TC intensity change depends on multi-scale processes



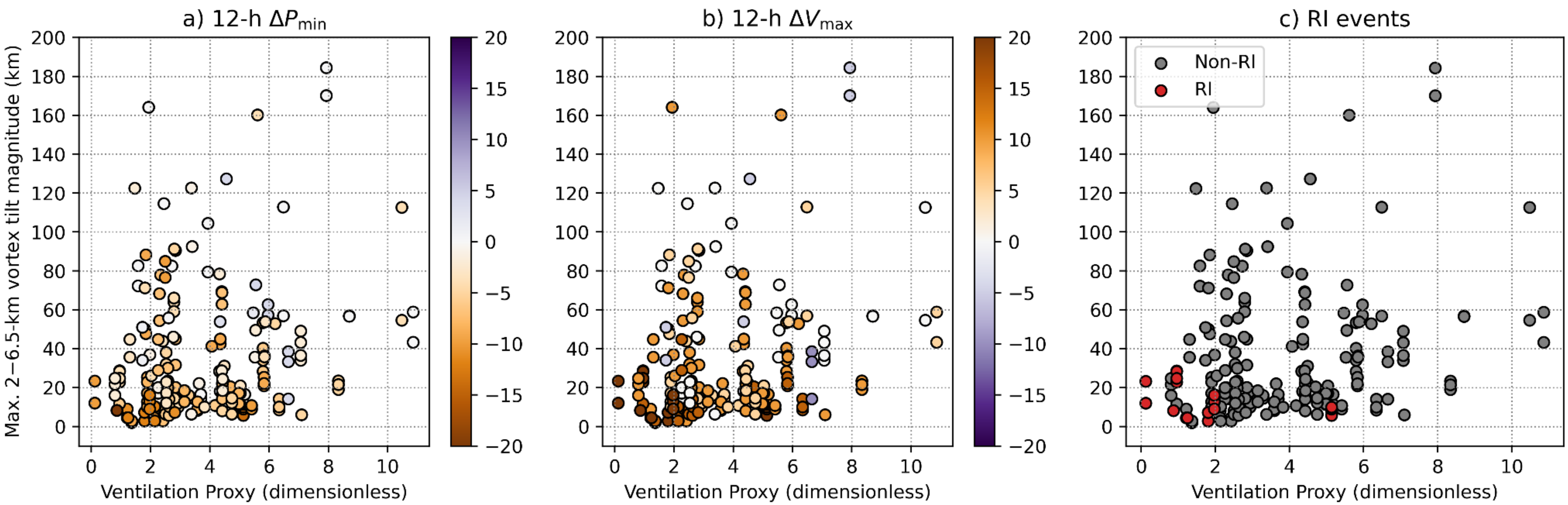
- Ventilation proxy defined as: $\frac{Shear*(100-RHMD)}{MPI}$, similar to the Ventilation Index of Tang and Emanuel (2012), but using existing SHIPS parameters

TC intensity change depends on multi-scale processes



- Ventilation proxy defined as: $\frac{Shear*(100-RHMD)}{MPI}$, similar to the Ventilation Index of Tang and Emanuel (2012), but using existing SHIPS parameters

TC intensity change depends on multi-scale processes



- **RI occurs preferentially in weak TCs when tilt is small and ventilation is low**
- Ventilation proxy defined as: $\frac{Shear*(100-RHMD)}{MPI}$, similar to the Ventilation Index of Tang and Emanuel (2012), but using existing SHIPS parameters

Vortex tilt can influence ventilation

- Idealized modeling studies suggest the TC tilt structure in weak TCs strongly influences the extent of ventilation of the TC warm core
- What happens in non-idealized TCs?

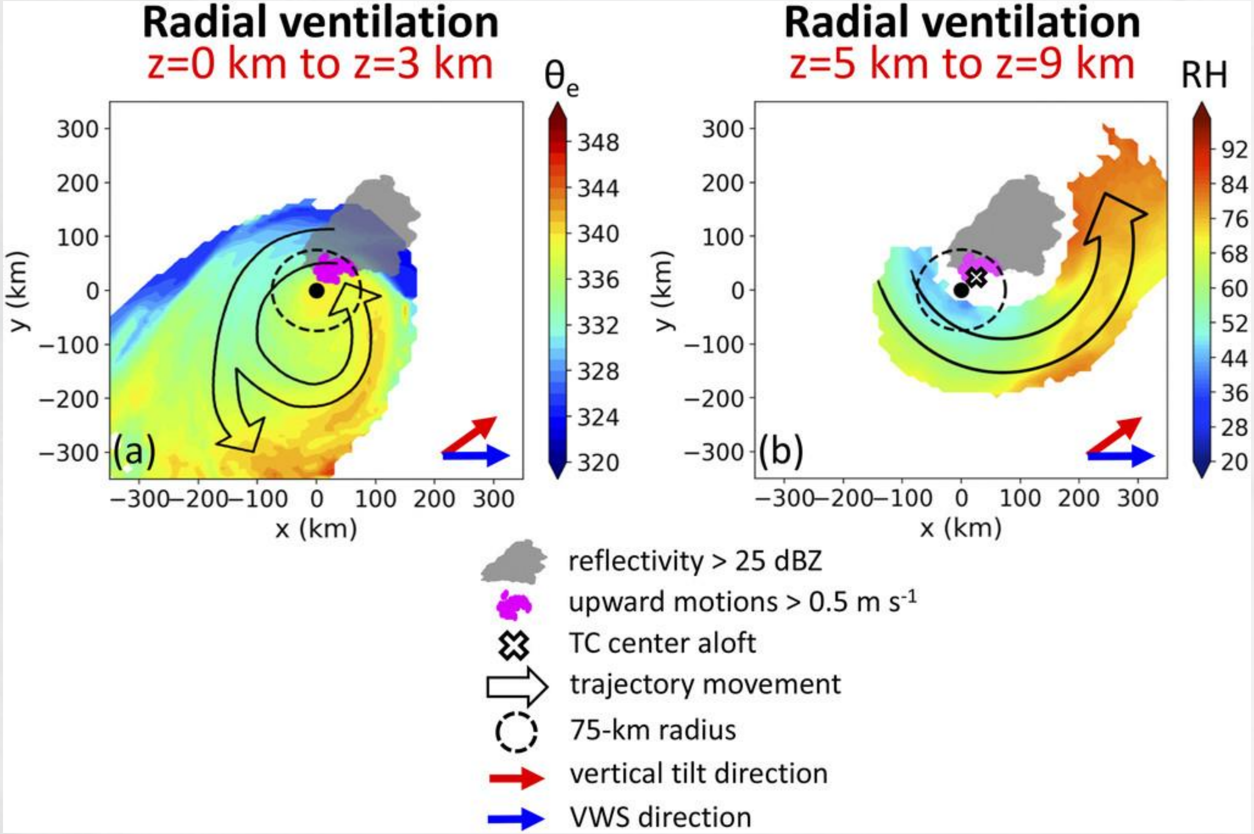


Fig. 13 from Alland et al. (2021b)

Q1 Summary

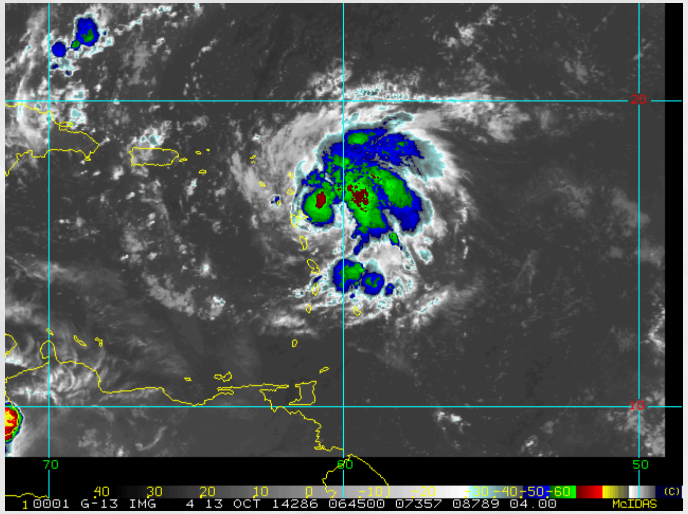
- Q1) Is vortex tilt related to TC intensity change in nature?
    - Yes! But primarily for weak TCs.
    - TCs will smaller tilt magnitudes have a greater areal coverage of

Q2:

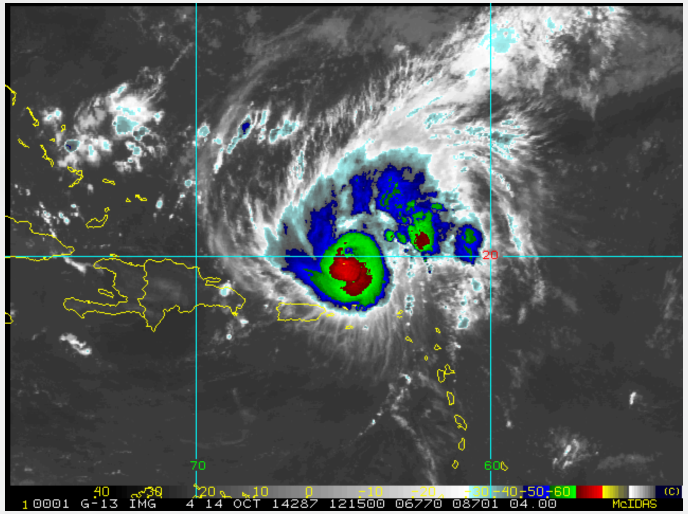
How does tilt influence ventilation and TC intensity change in non-idealized vortices?

Ensemble set-up

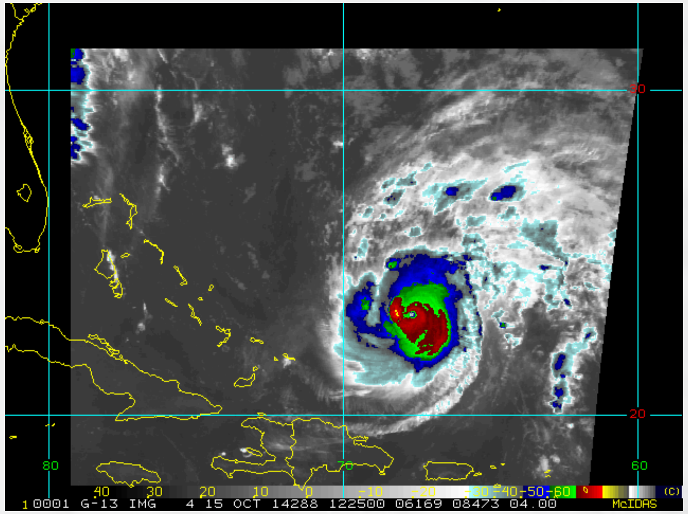
- Examined a 60-member WRF-AHW ensemble of Hurricane Gonzalo (2014)
  - 1.33-km grid spacing for inner nest
  - Only differences between members are perturbations to initial and boundary conditions (e.g., Cavallo et al. 2013)
- Simulations began at 1200 UTC 13 October 2014, near the start of an observed RI event with nearby dry air, and ran for 72 h



12Z 13 October: 65 kt



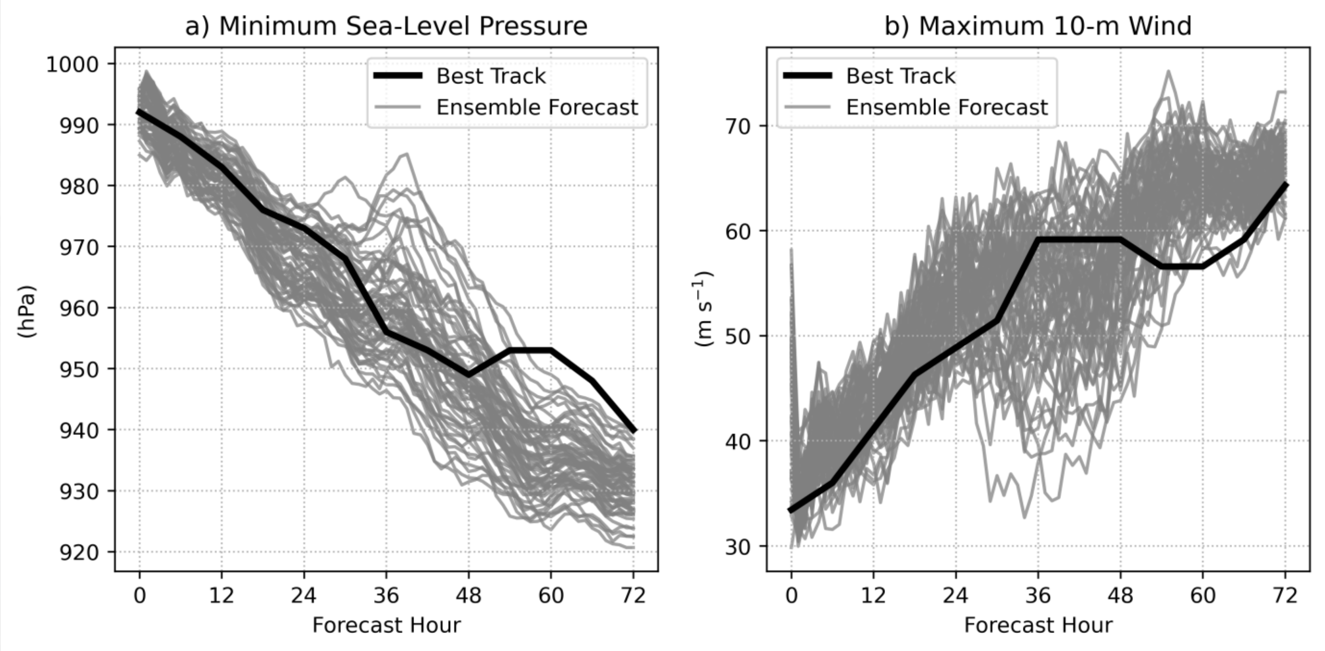
12Z 14 October: 95 kt



12Z 15 October: 115 kt

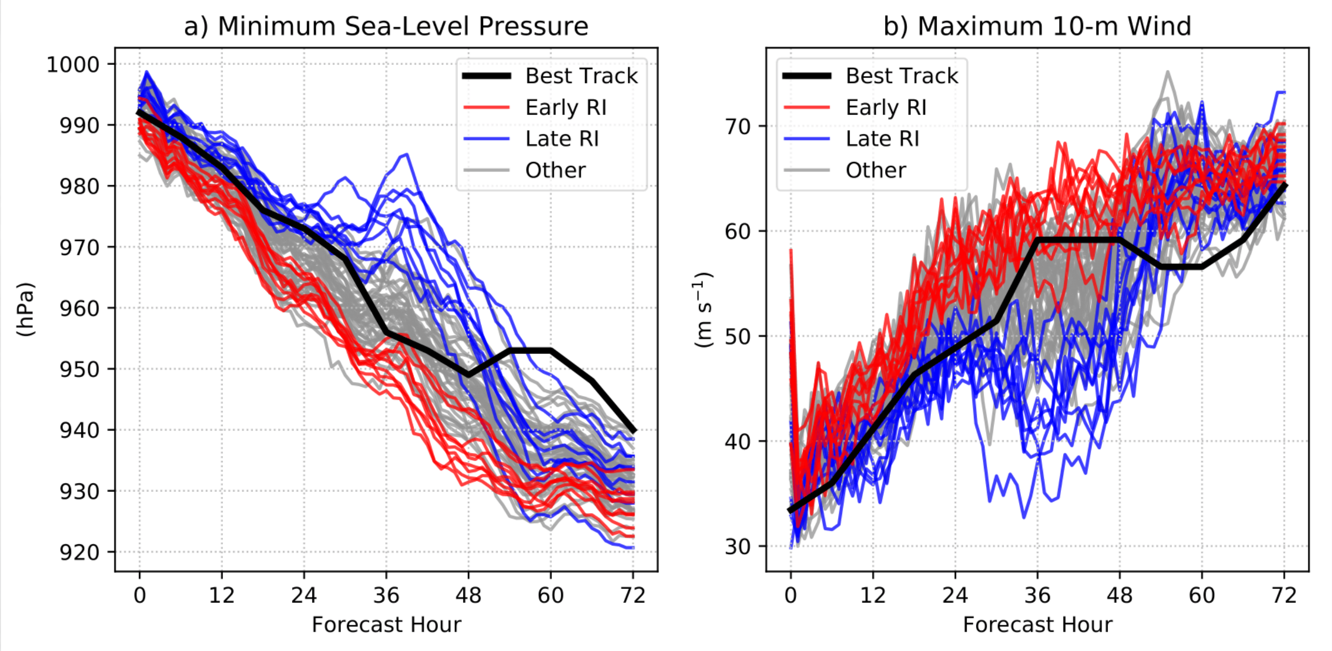
Ensemble set-up

- Examined a 60-member WRF-AHW ensemble of Hurricane Gonzalo (2014)
  - 1.33-km grid spacing for inner nest
  - Only differences between members are perturbations to initial and boundary conditions (e.g., Cavallo et al. 2013)
- Significant intensity spread related to differences in the timing of RI onset



Ensemble set-up

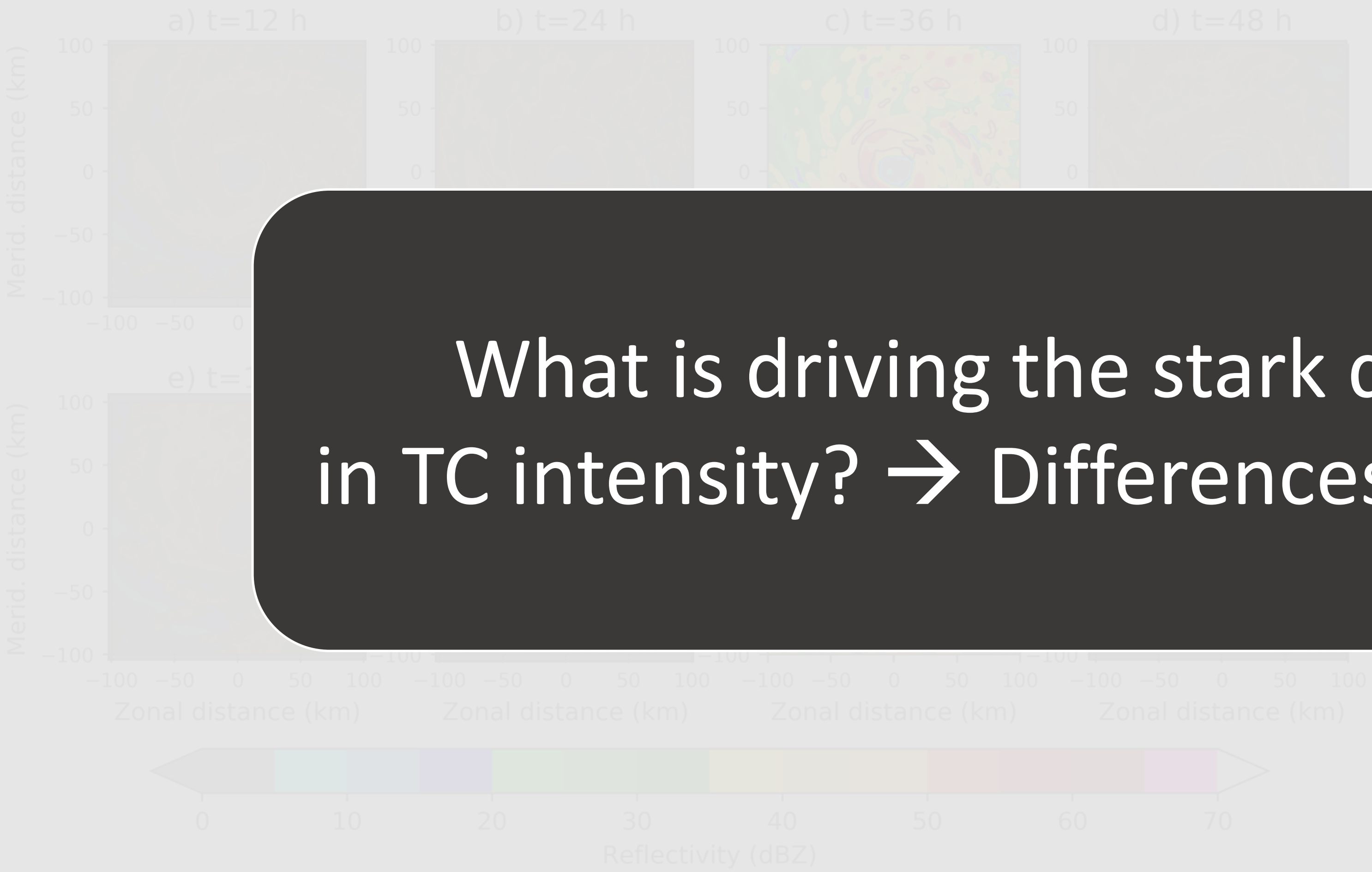
- Examined a 60-member WRF-AHW ensemble of Hurricane Gonzalo (2014)
  - 1.33-km grid spacing for inner nest
  - Only differences between members are perturbations to initial and boundary conditions (e.g., Cavallo et al. 2013)
- Significant intensity spread related to differences in the timing of RI onset
- Focused on two groups of members



Nine strongest members through first 48 h (**Early-RI**)

Nine weakest members through first 48 h (**Late-RI**)

Reflectivity Evolution

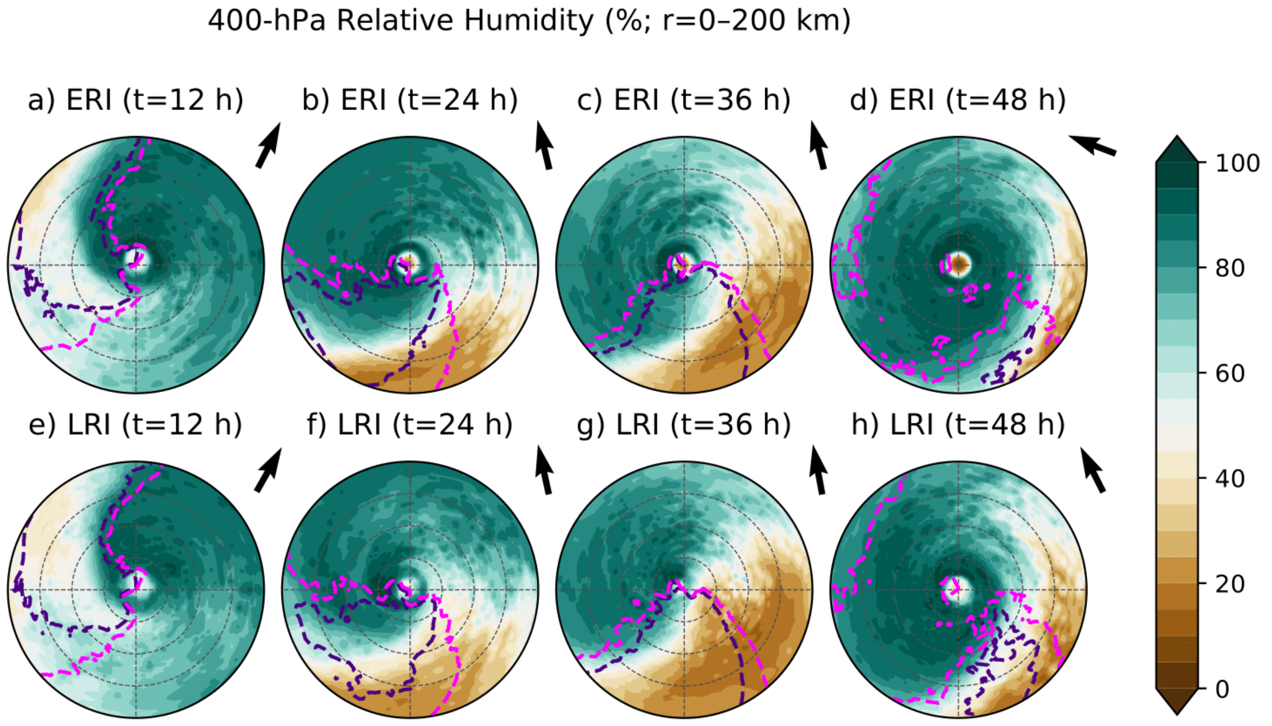


What is driving the stark differences in TC intensity? → Differences in ventilation

- Significant differences in convective structure at t=36!

Evolution of 400-hPa relative humidity

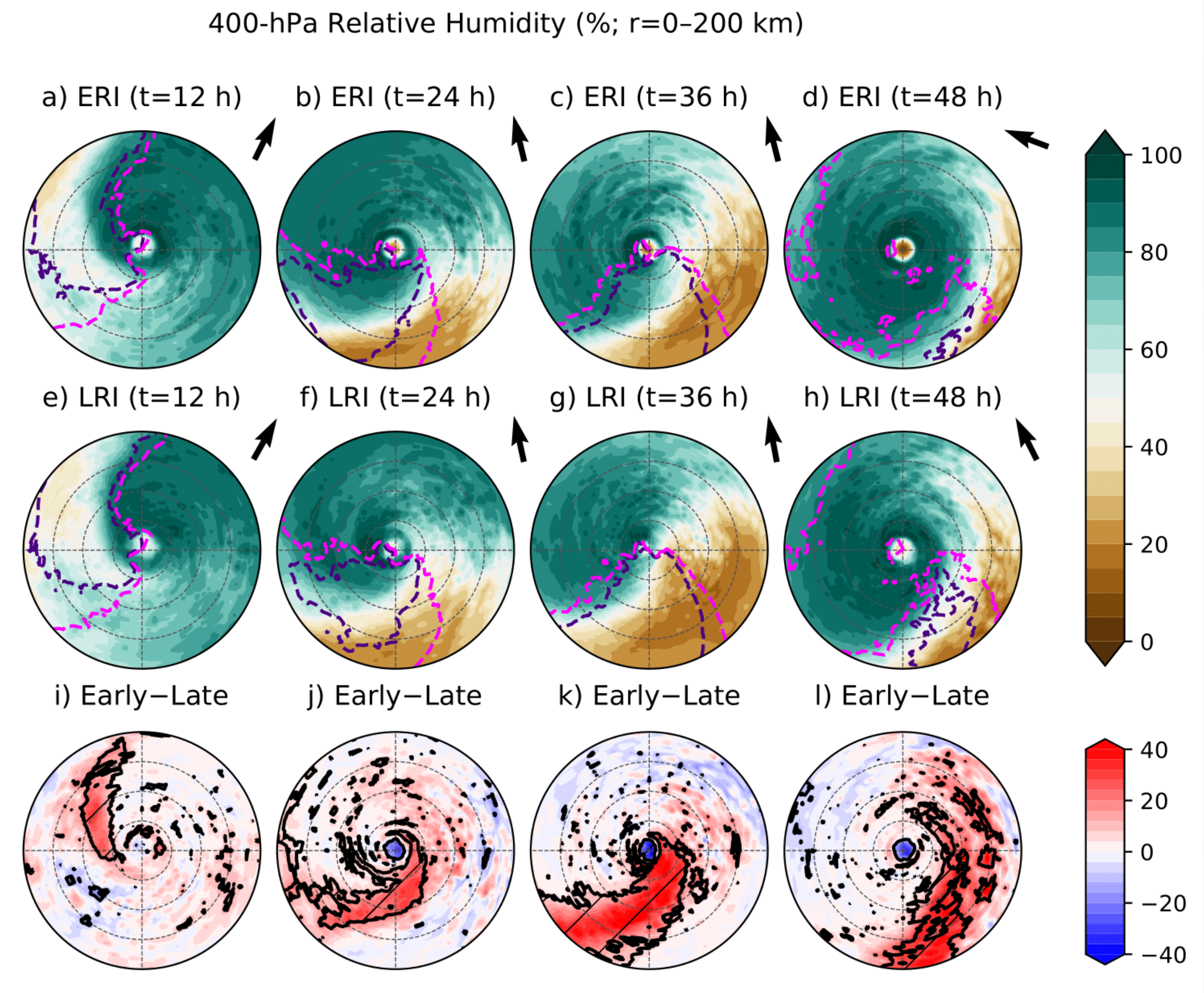
400-hPa Relative Humidity (shaded; %) and inflow (contours):



- Composite mean 400-hPa relative humidity and inflow for **early-RI** (top) and **late-RI** (bottom) members
- Deep-layer shear vectors shown in black

Evolution of 400-hPa relative humidity

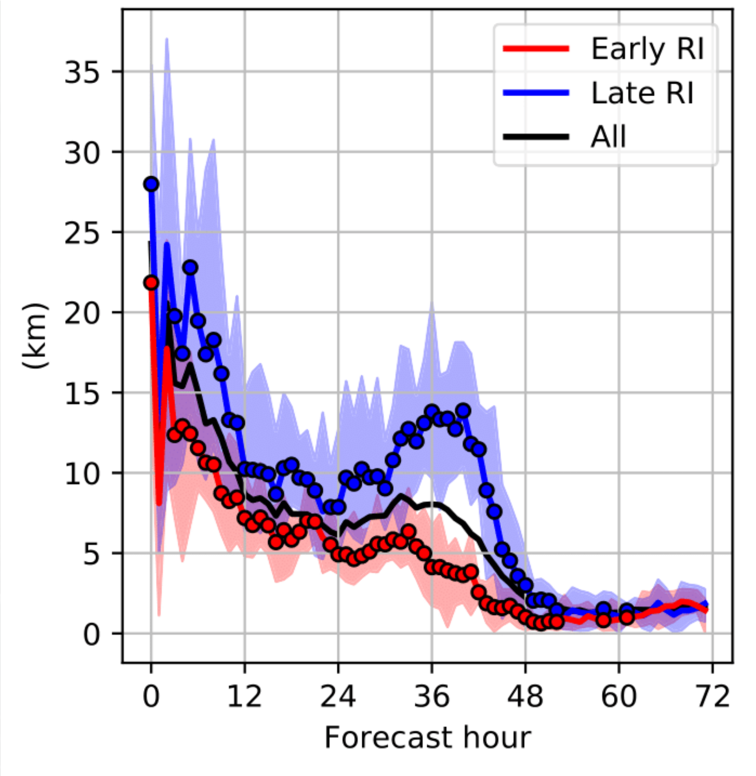
400-hPa Relative Humidity (shaded; %) and inflow (contours):



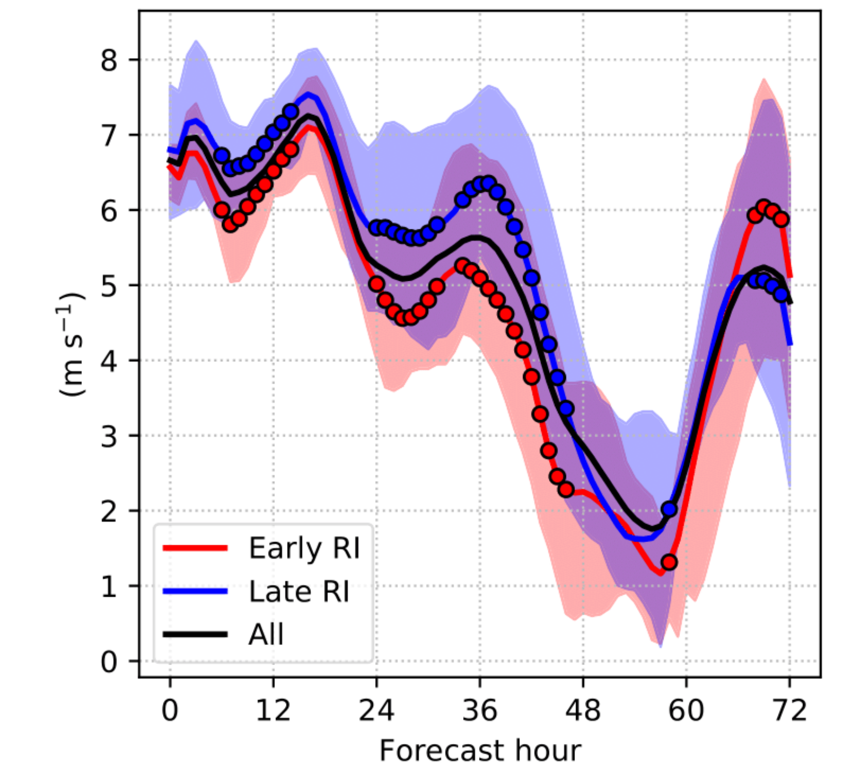
- Composite mean 400-hPa relative humidity and inflow for **early-RI** (top) and **late-RI** (bottom) members
- Deep-layer shear vectors shown in black
- Late-RI members associated with a region of significantly drier mid–upper-tropospheric dry air than early-RI members, especially at the time of greatest TC intensity differences (t=36 h)
- This dry air intrusion overlaps with inflow region, indicating radial ventilation

Vortex Tilt Evolution

Surface–400-hPa Vortex Tilt Magnitude:



Deep-Layer Shear Magnitude:

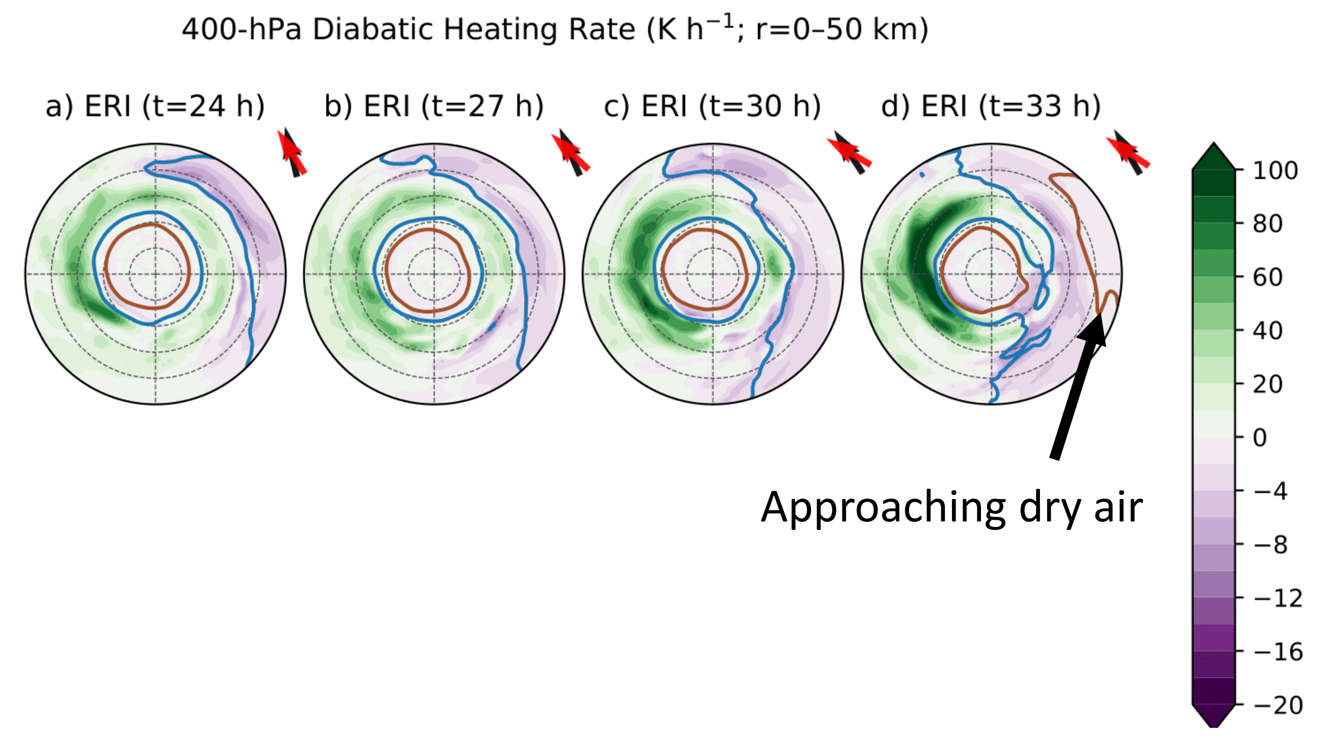


Markers indicate statistical significance at 95% confidence level

- **Early-RI members** are consistently associated with statistically significantly smaller vortex tilt magnitudes than **late-RI members** over first 48 h
- **Late-RI members** exhibit an increase in tilt leading up to t=36 h
- Shear alone doesn't seem to explain differences in tilt, as the shear distributions overlap
- What's going on here?

Relationship between tilt and ventilation

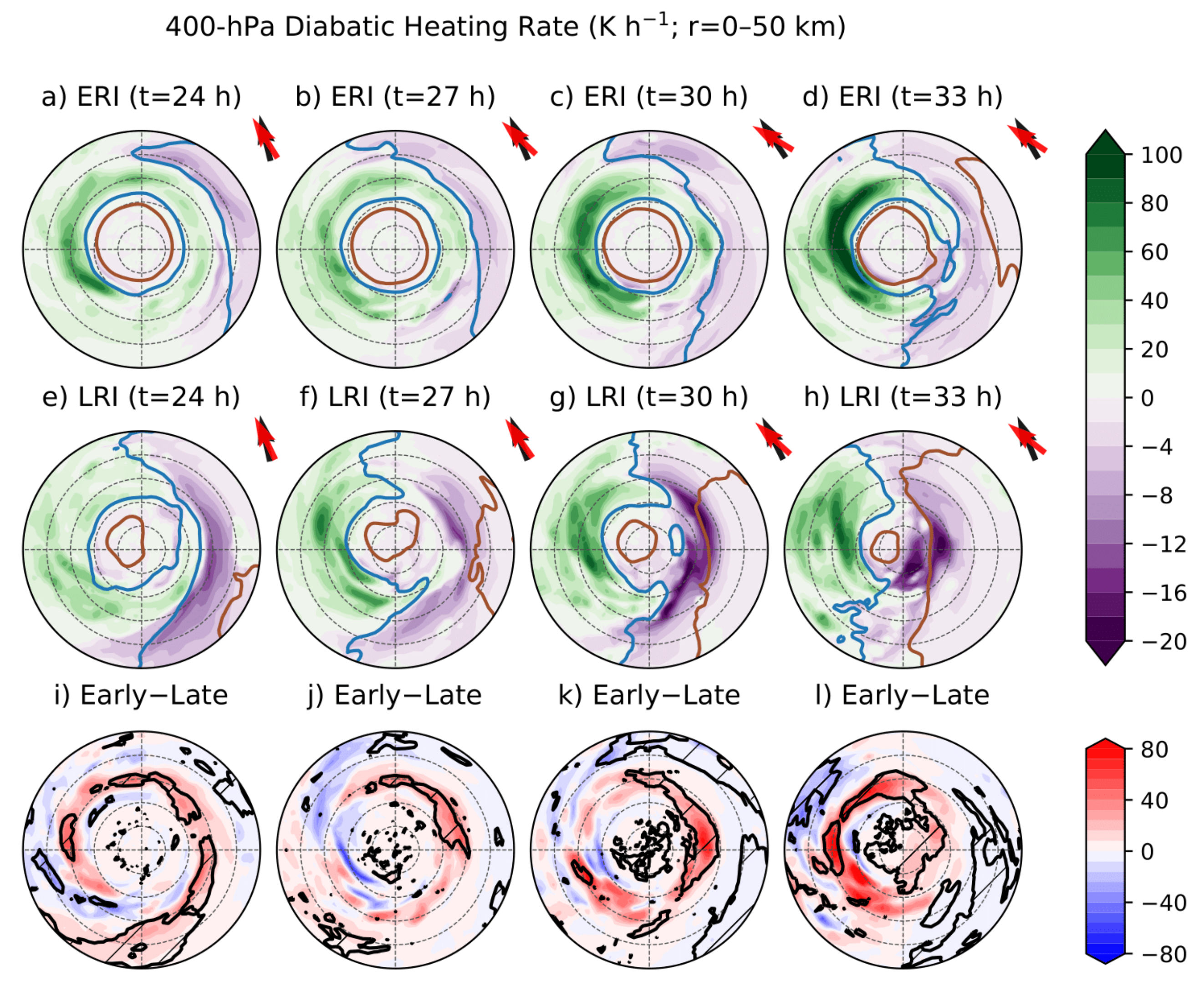
400-hPa Diabatic Heating (shaded; K/h) and RH (contours):



- Composite-mean 400-hPa heating rate and RH (contoured at **75%** and **50%**) for **early-RI** (top) and **late-RI** (bottom)
- Arrows show **shear** and **tilt** directions

Relationship between tilt and ventilation

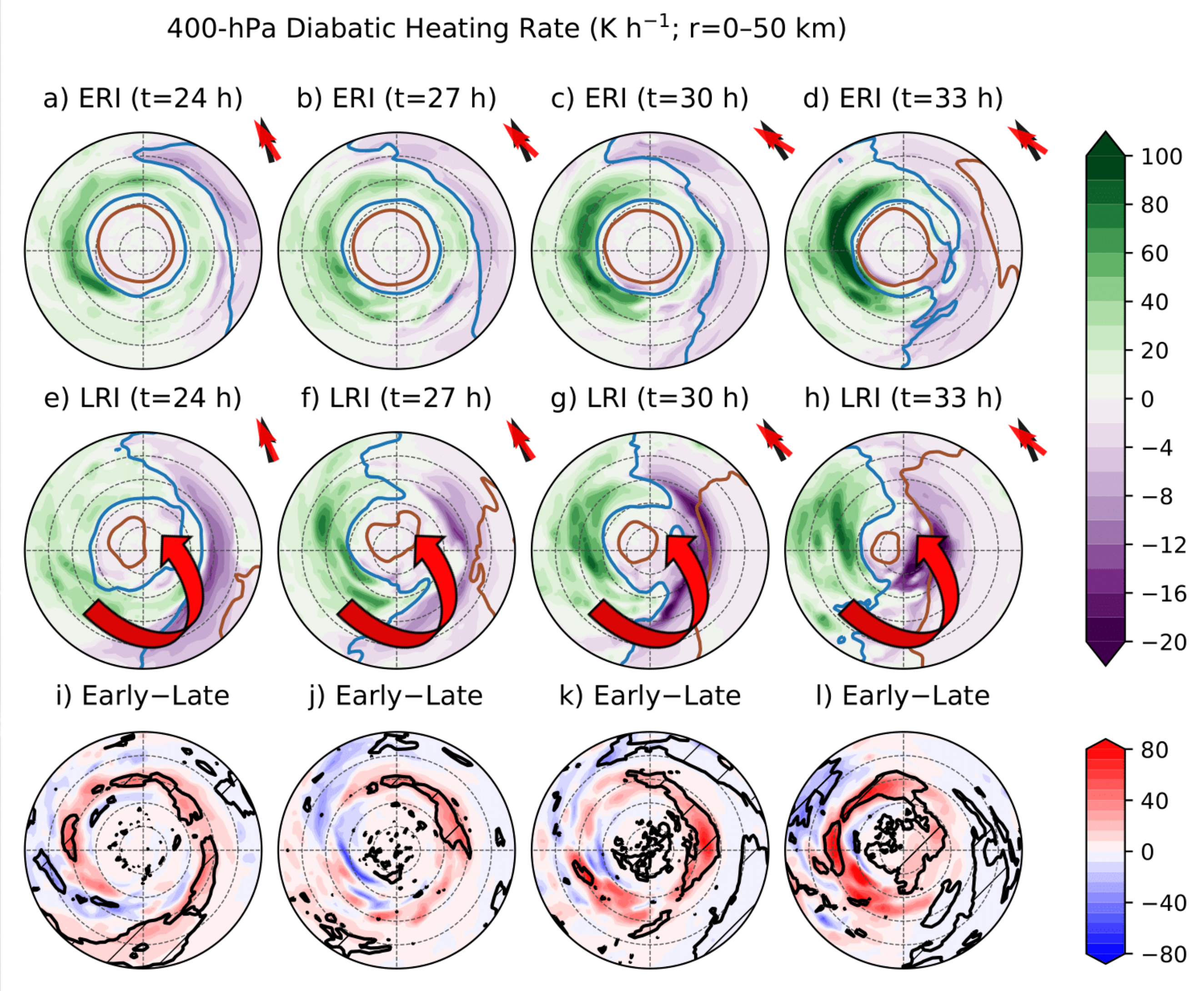
400-hPa Diabatic Heating (shaded; K/h) and RH (contours):



- Composite-mean 400-hPa heating rate and RH (contoured at **75%** and **50%**) for **early-RI** (top) and **late-RI** (bottom)
- Arrows show **shear** and **tilt** directions
- In **late-RI** members, dry air approaches from uptilt regions and significantly reduces diabatic heating in core. Diabatic cooling seen in dry regions
- Leads to a weakening of the vortex and tilt amplifies with time… Part of an unfavorable feedback!

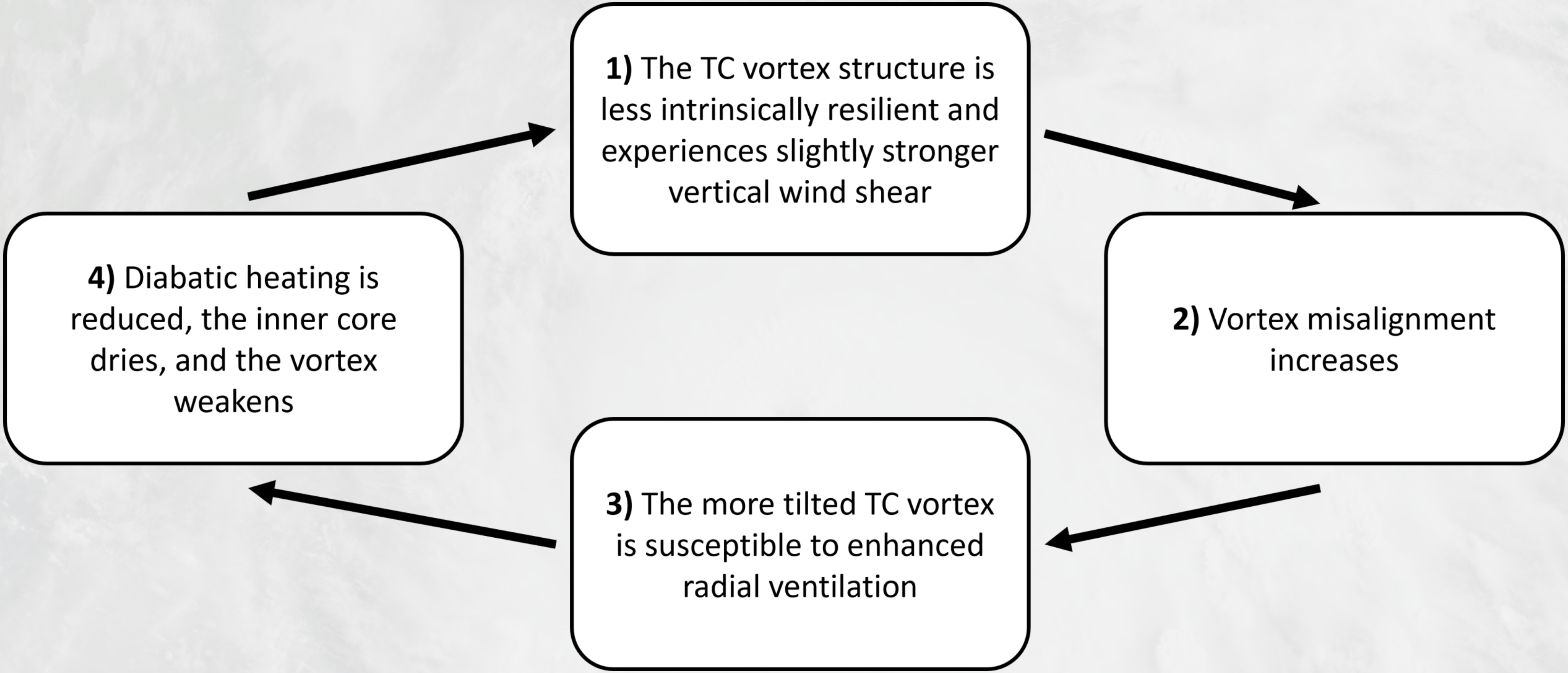
Relationship between tilt and ventilation

400-hPa Diabatic Heating (shaded; K/h) and RH (contours):

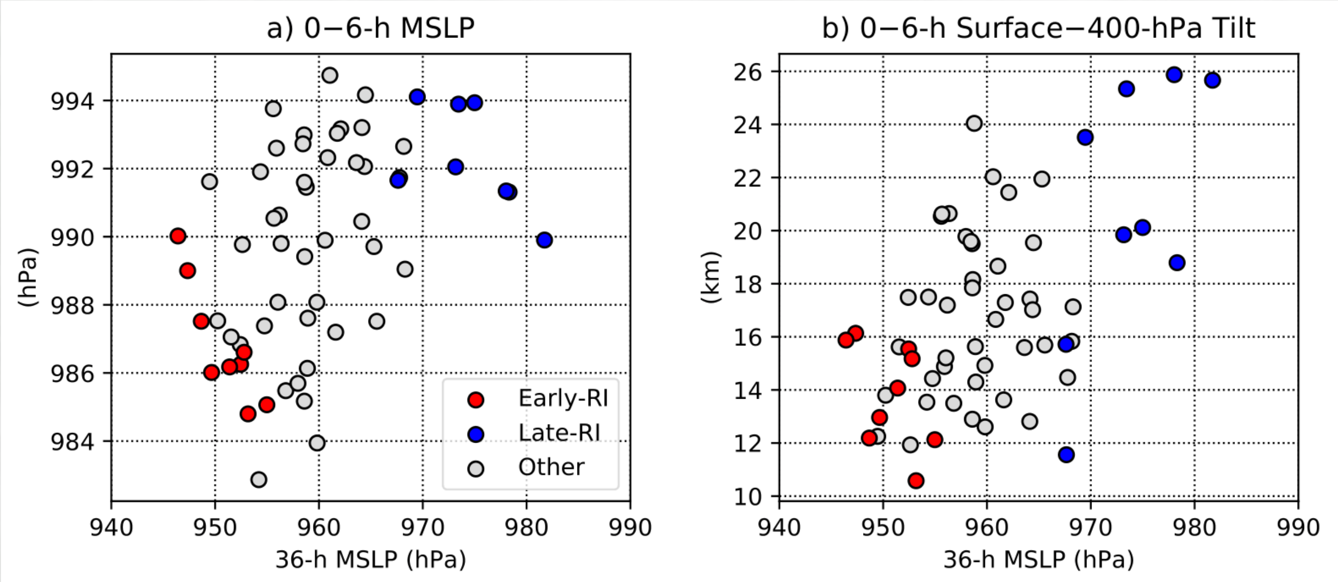


- Composite-mean 400-hPa heating rate and RH (contoured at **75%** and **50%**) for **early-RI** (top) and **late-RI** (bottom)
- Arrows show **shear** and **tilt** directions
- In **late-RI** members, dry air approaches from uptilt regions and significantly reduces diabatic heating in core. Diabatic cooling seen in dry regions
- Leads to a weakening of the vortex and tilt amplifies with time… Part of an unfavorable feedback!

Weakening feedback in late-RI members

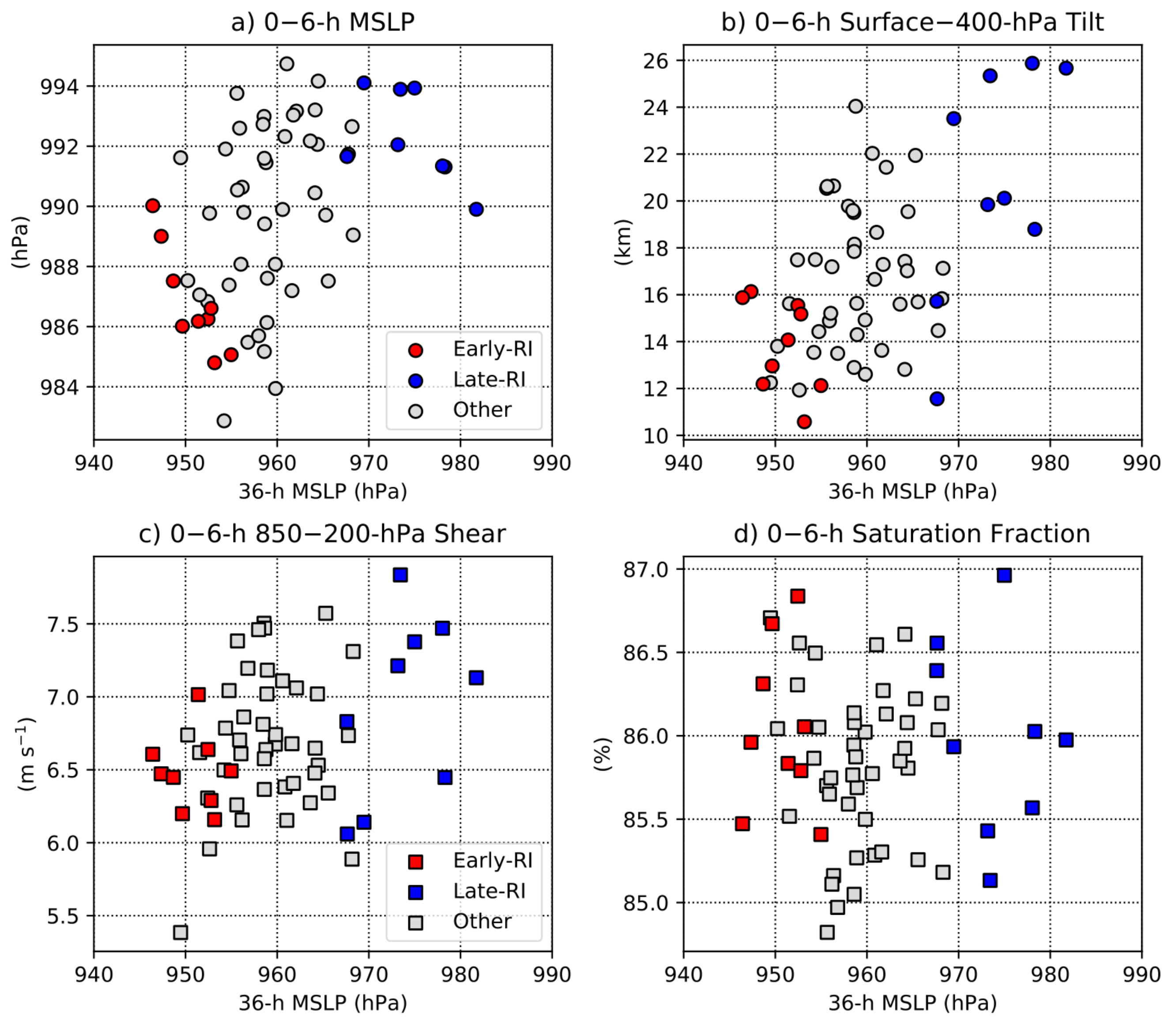


Significance of initial conditions



- Scatterplots of initial value (averaged between t=0–6 h) and 36-h TC intensity (hPa)
- Circle markers indicate sig. differences between **early-RI** and **late-RI** members
- Initial differences in TC intensity and tilt were key

Significance of initial conditions



- Scatterplots of initial value (averaged between t=0–6 h) and 36-h TC intensity (hPa)
- Circle markers indicate sig. differences between **early-RI** and **late-RI** members
- Initial differences in TC intensity and tilt were key
- Interestingly, initial environmental conditions were similar…

Q2 Summary

Q2) How does tilt influence ventilation and TC intensity change in non-idealized vortices?

- Small differences in TC intensity and vortex tilt can quickly amplify with time in environments of moderate shear
- More tilted (less resilient) vortices can provide a pathway for dry air to move directly over the low-level TC center and erode inner core convection, leading to an unfavorable feedback
- To accurately predict TC intensity change, we need to accurately observe, assimilate, and model the multi-scale processes associated with TC intensity change.
  - **Getting the vortex intensity and structure right is important!**

Future work

- Through what processes do misaligned TCs become aligned in nature?
- Do these processes vary depending on the alignment pathway (e.g., vortex precession vs. reformation)?
- Use AI to estimate the vortex tilt structure from satellite observations when aircraft observations are not available

Fischer et al. 2022

Fischer et al. 2023

Extra slides

A tilted vortex can be a messy vortex

- In relatively weak TCs, multiple circulations can exist
- A TC may not be accurately characterized by a tilted column of vorticity

Vorticity (shaded):

Rotational wind (shaded):

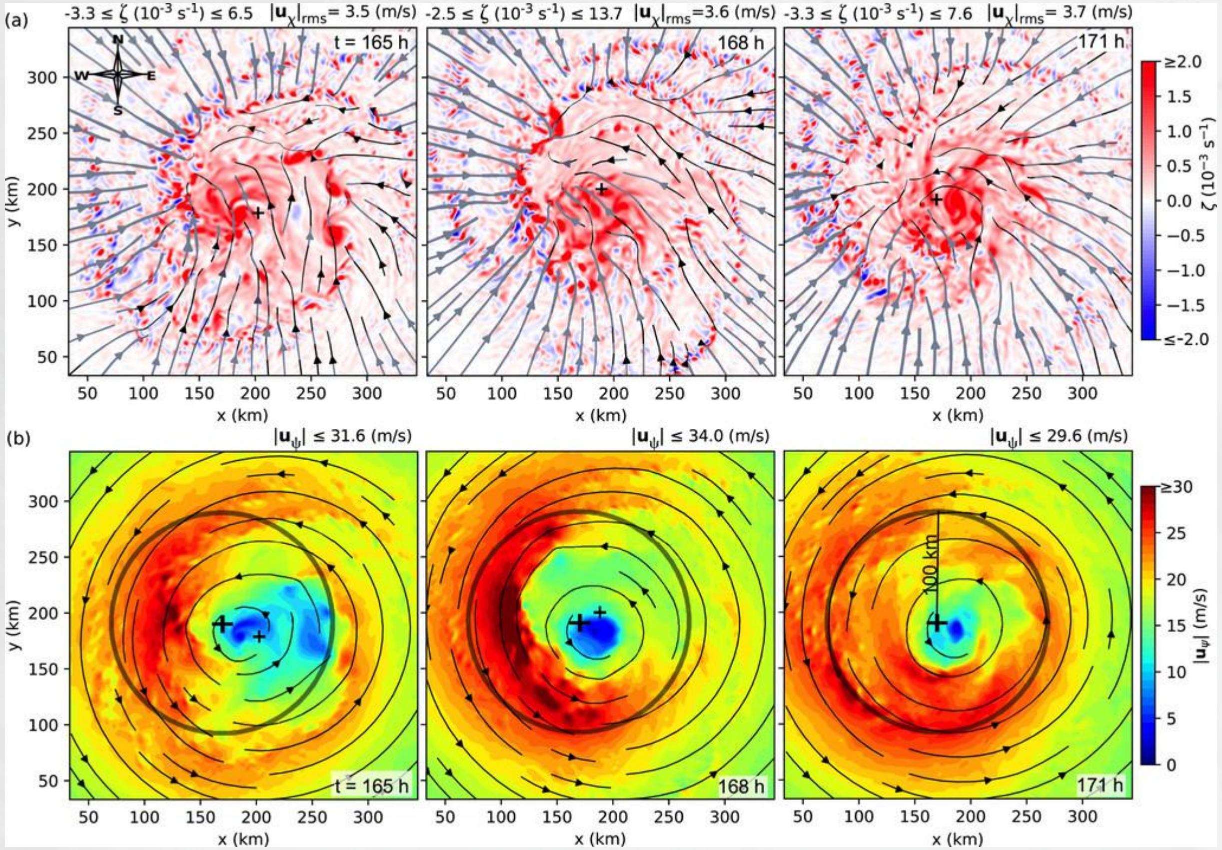
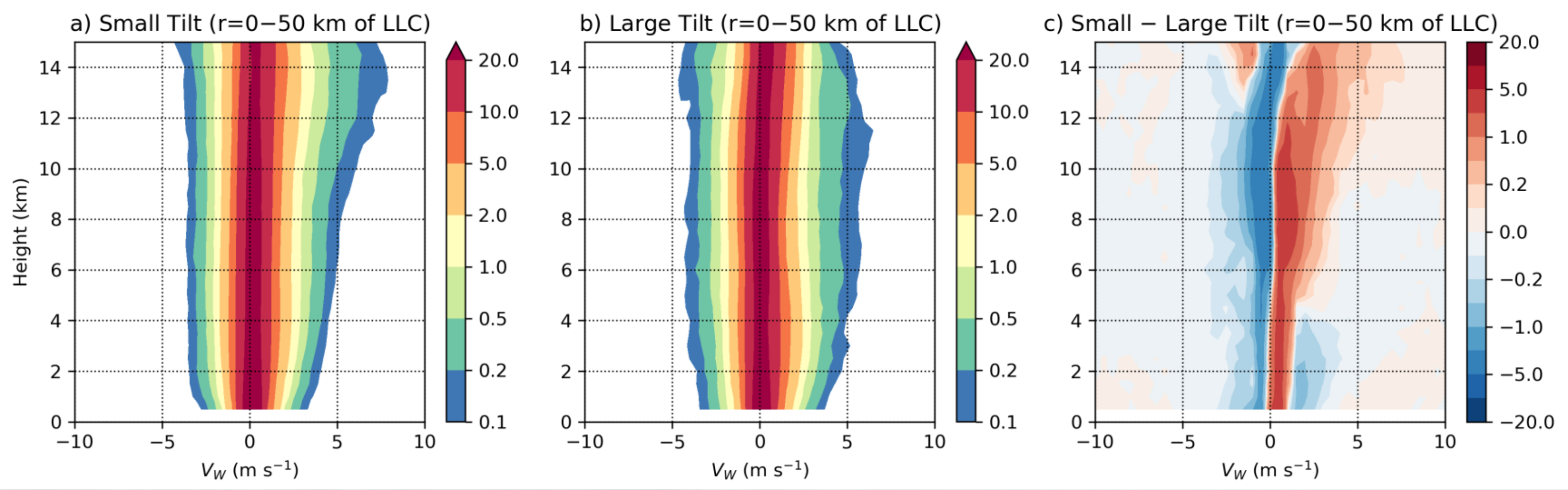


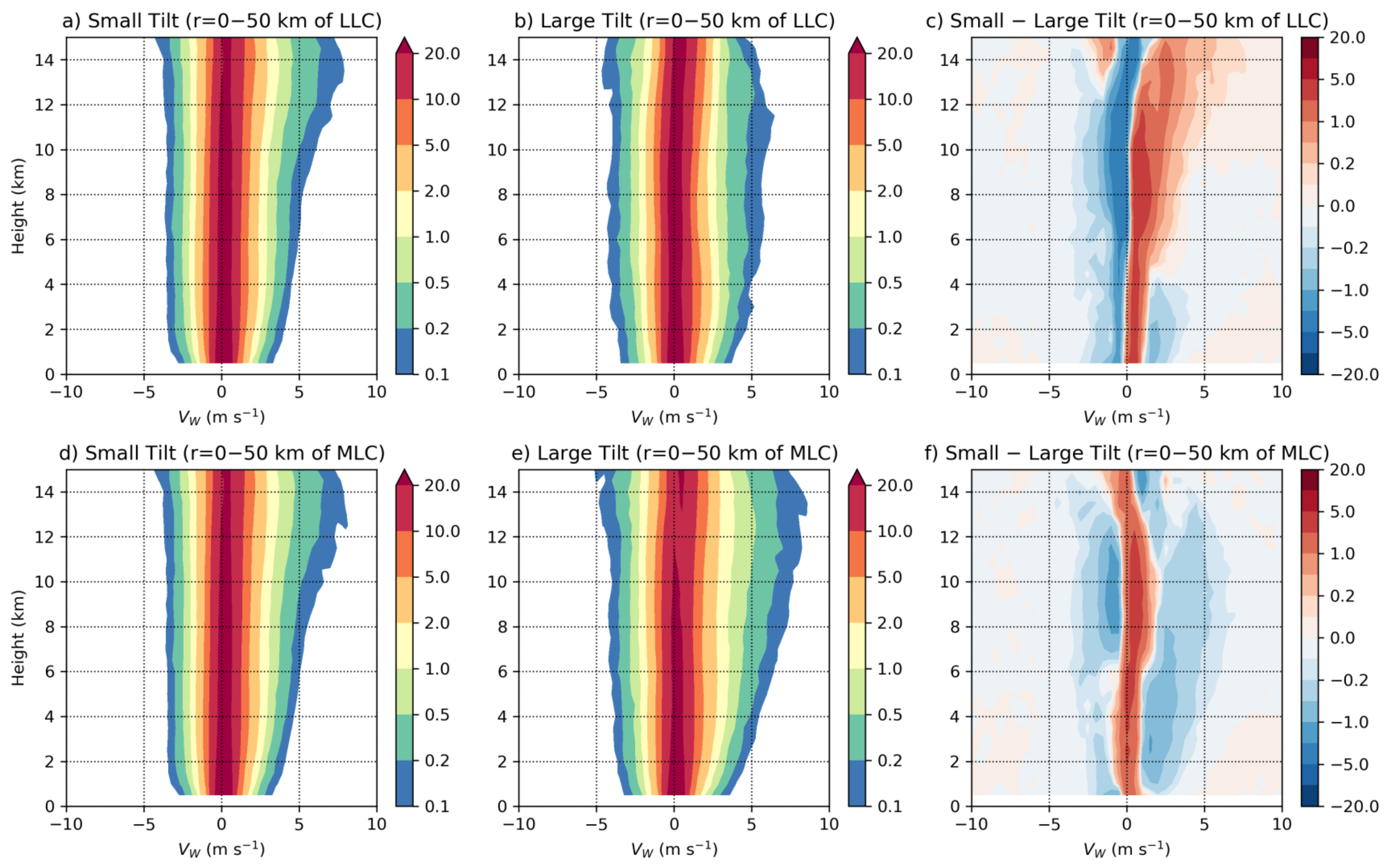
Fig. 22 from Schecter and Menelaou (2020)

Vertical velocity CFADs



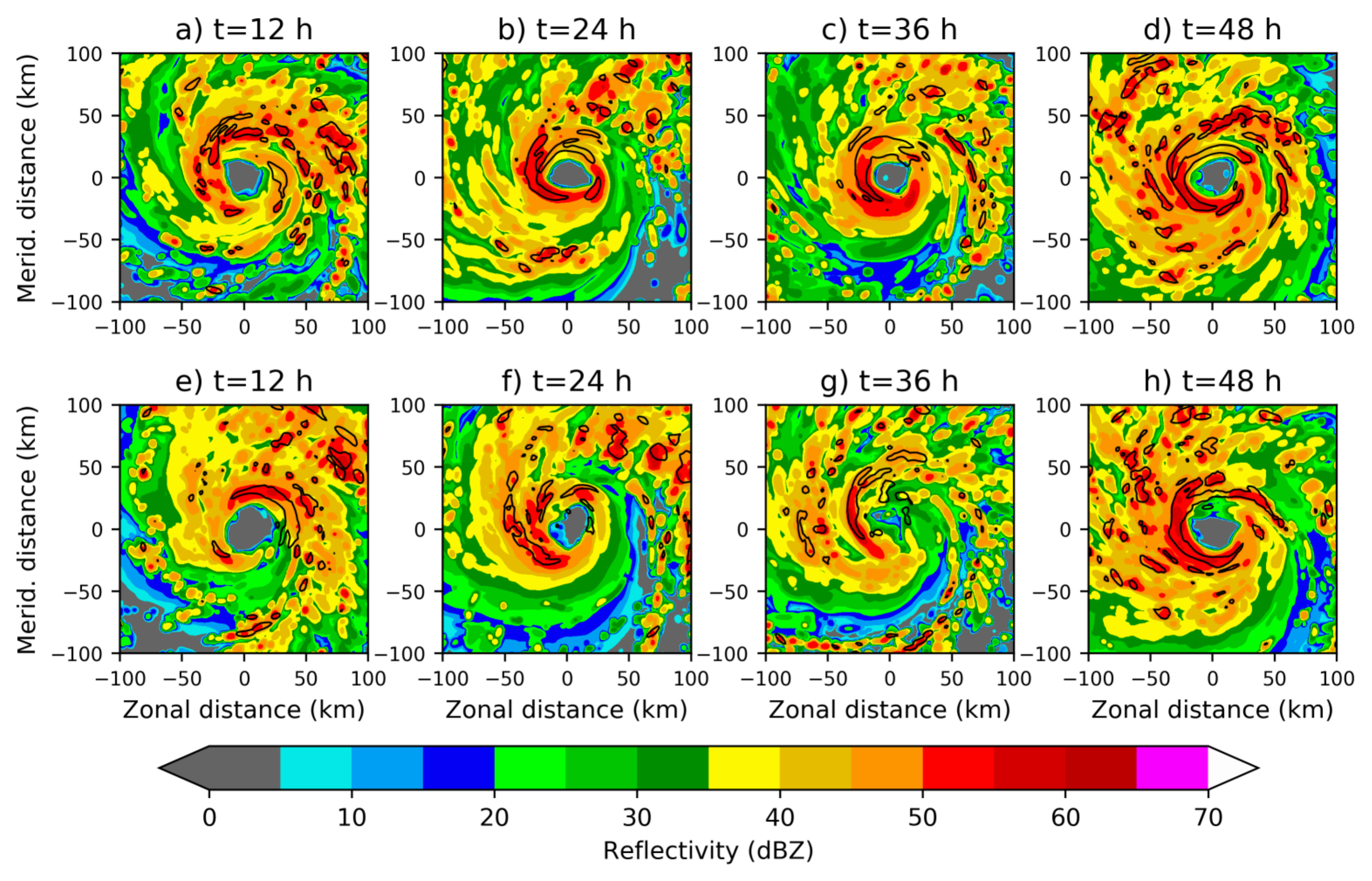
- Small-tilt storms have a greater frequency of ascent near the LLC (within 50 km) than large-tilt storms

Vertical velocity CFADs



- Small-tilt storms have a greater frequency of ascent near the LLC (within 50 km) than large-tilt storms
- Large-tilt TCs have a greater frequency of large ascent (> 1 m/s) near the MLC, indicating more vigorous convection

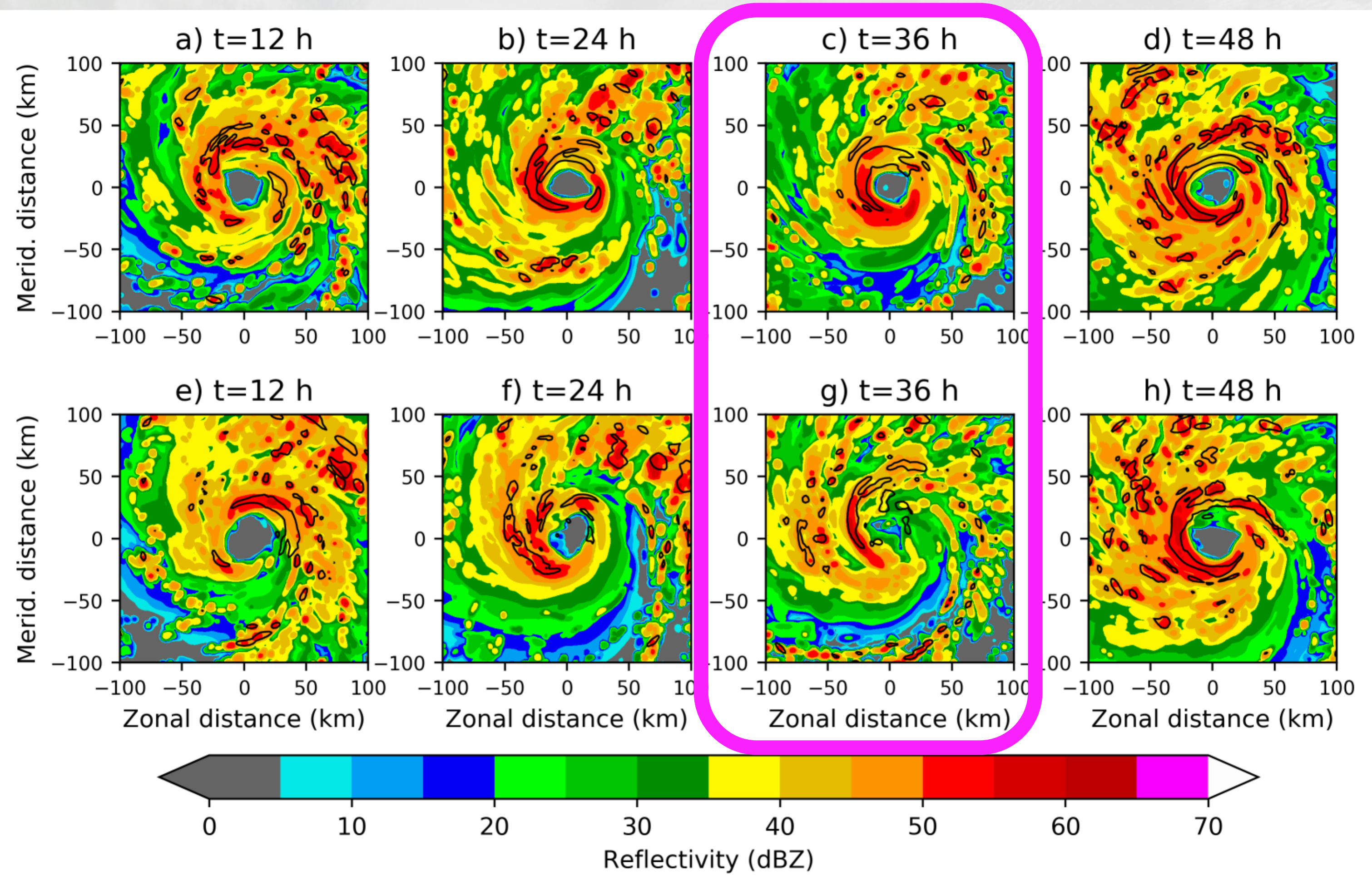
Reflectivity Evolution



Early-RI member

Late-RI member

Reflectivity Evolution

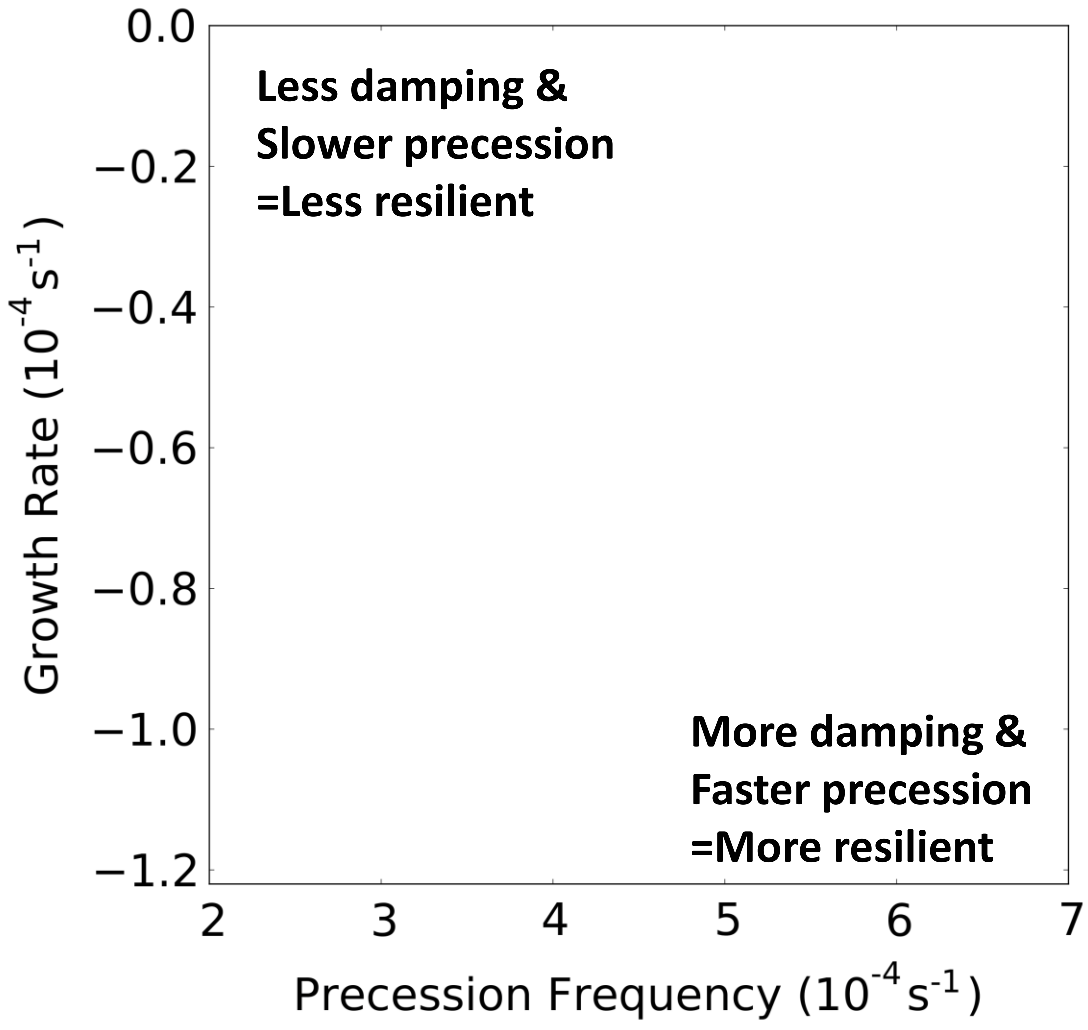


Early-RI member

Late-RI member

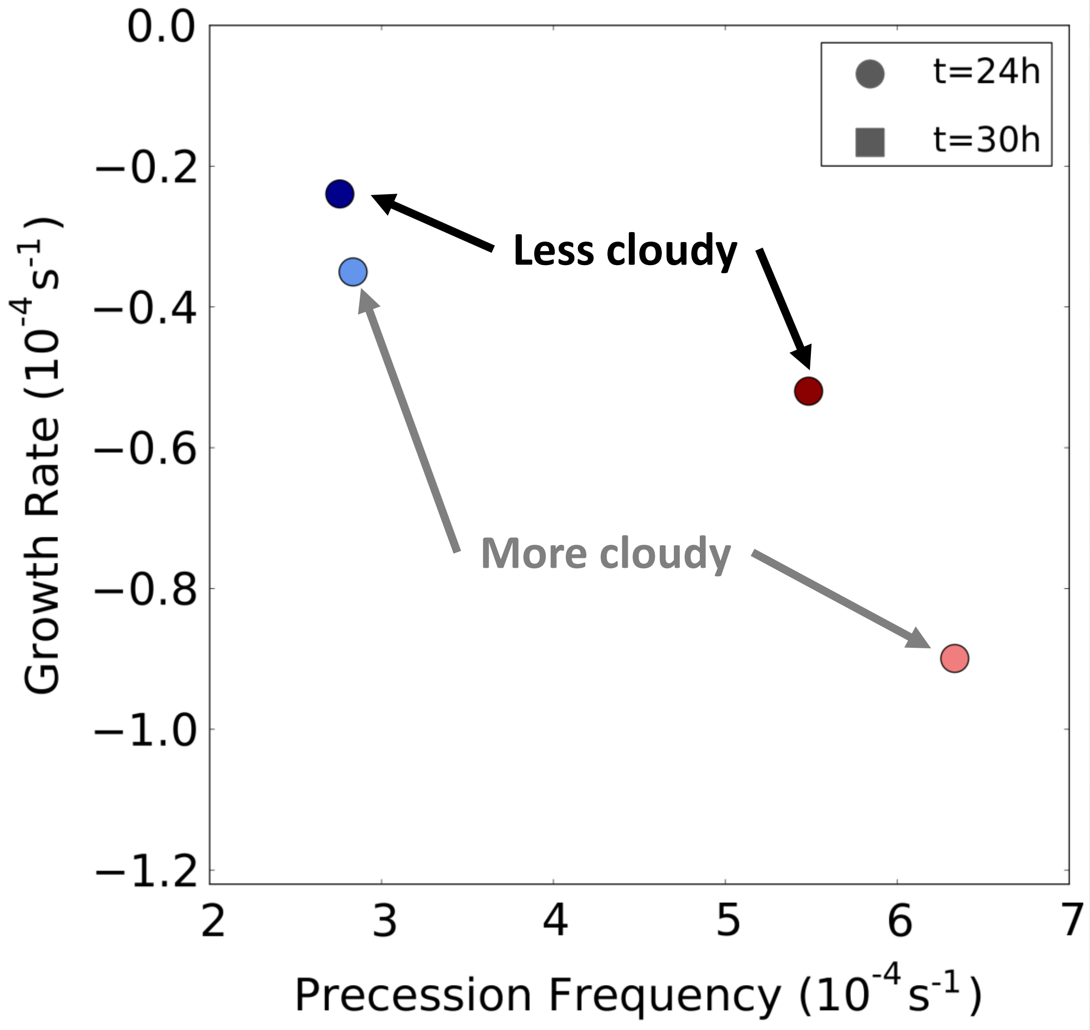
- Significant differences in convective structure at t=36!

Vortex Resilience Analysis



- We performed a vortex resilience analysis on a representative **early-RI** and **late-RI** member (following Schecter 2015; Reasor and Montgomery 2015)
- Linearize equations about barotropic mean vortex state derived from early- and late-RI member
- Shear is set to zero and model is initialized with a quasi-balanced vorticity perturbation, approximating tilt
- “Cloudiness” in eyewall region is parameterized using a reduced static stability (lighter markers = more cloudy)

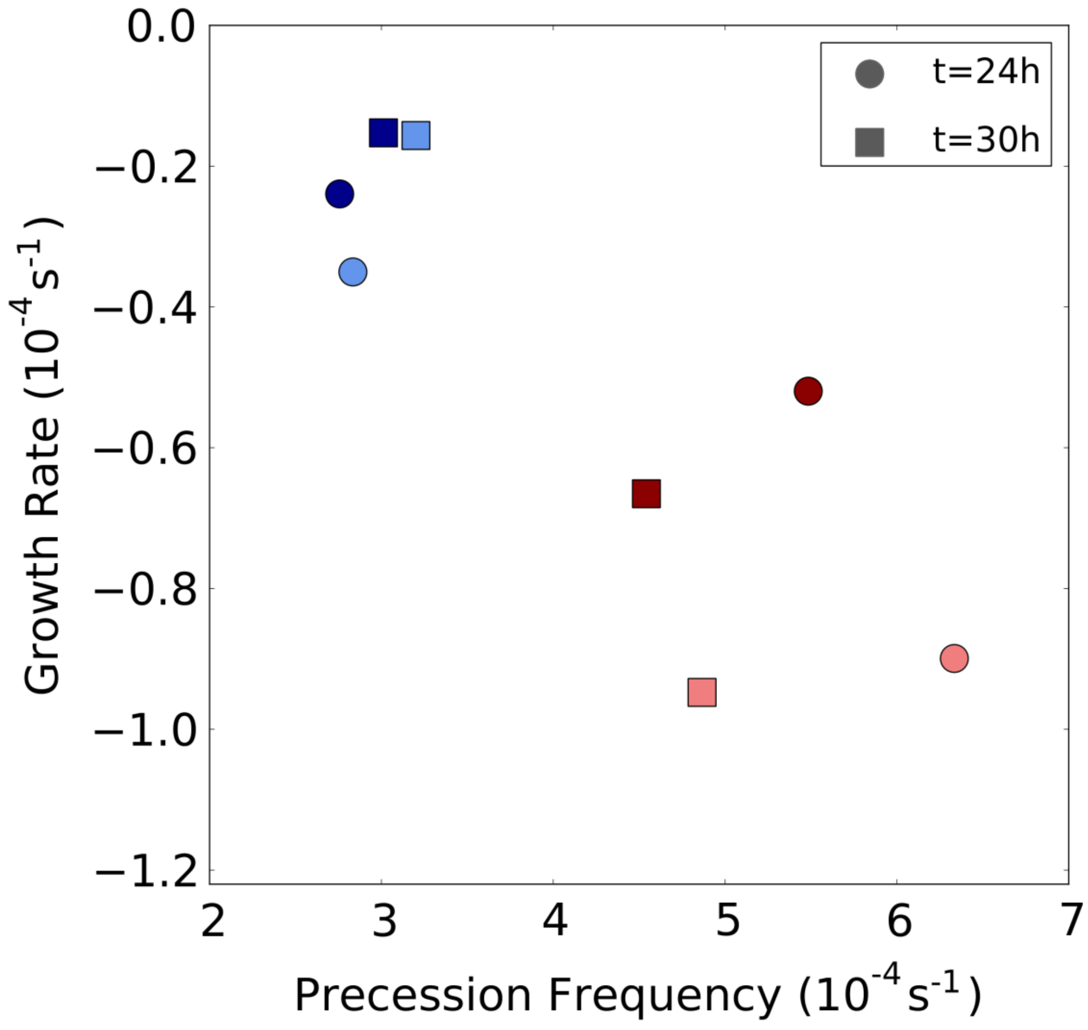
Vortex Resilience Analysis



- We performed a vortex resilience analysis on a representative **early-RI** and **late-RI** member (following Schecter 2015; Reasor and Montgomery 2015)

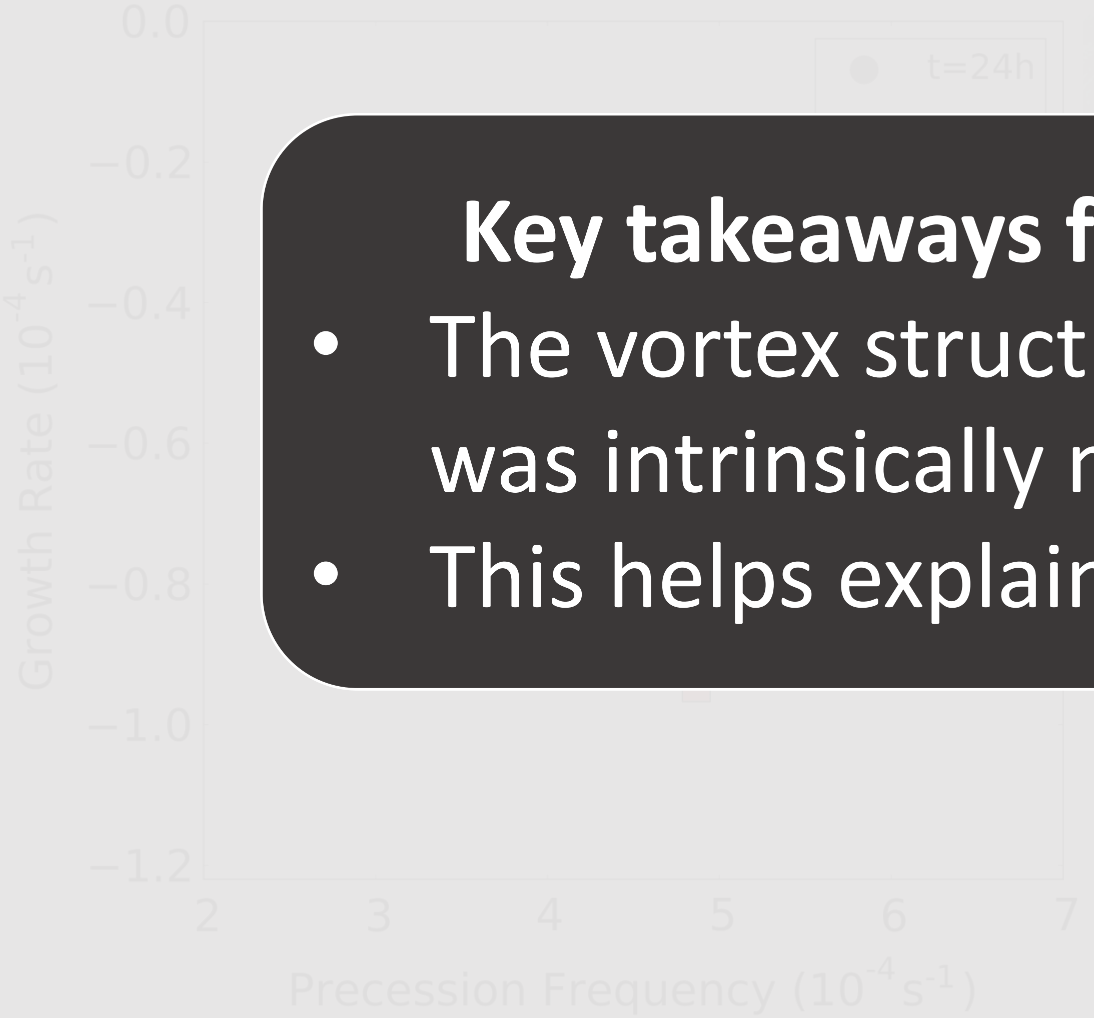
- At t=24 h, when tilt begins to amplify in **late-RI** members:
  - The tilt mode of the **late-RI** vortex precesses a factor of two slower than **early-RI** vortex
  - The **late-RI** vortex is damped at nearly 1/3 the rate of the **early-RI** vortex

Vortex Resilience Analysis



- We performed a vortex resilience analysis on a representative **early-RI** and **late-RI** member (following Schecter 2015; Reasor and Montgomery 2015)
- At t=24 h, when tilt begins to amplify in **late-RI** members:
  - The tilt mode of the **late-RI** vortex precesses a factor of two slower than **early-RI** vortex
  - The **late-RI** vortex is damped at nearly 1/3 the rate of the **early-RI** vortex
- At t=30 h, as the vortex is further ventilated and the vortex structure evolves, the **early-RI** member remains more resilient

Vortex Resilience Analysis



Key takeaways from resilience analysis:

- The vortex structure of the **early-RI** member was intrinsically more resilient!
- This helps explain difference in tilt evolution

- We performed a vortex resilience analysis on a

- At t=30 h, as the vortex is further ventilated and the vortex structure evolves, the early-RI member remains more resilient

Moist Static Energy (MSE) Budget

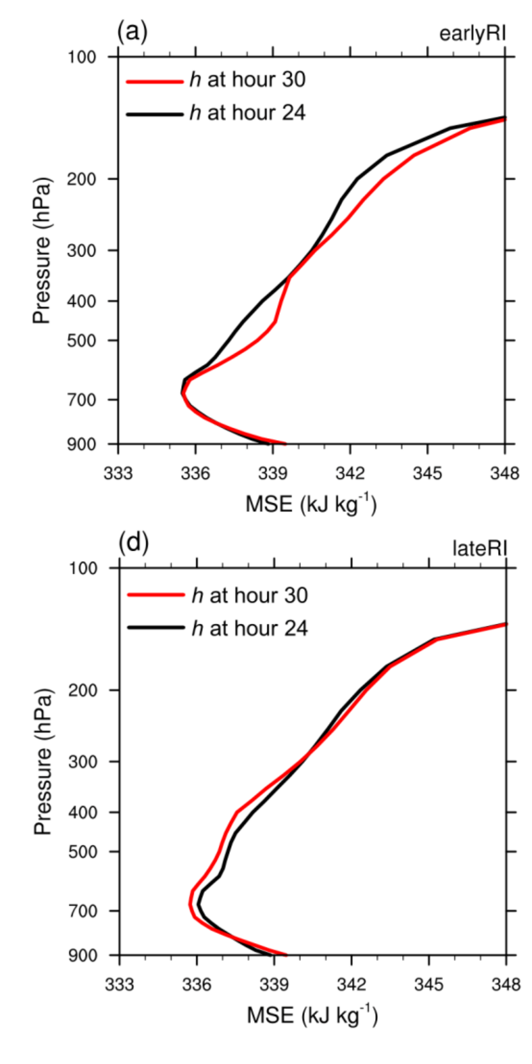
$$\left\langle \frac{\partial(c_p T + L_v q)}{\partial t} \right\rangle = -\langle \boldsymbol{u} \cdot \nabla (c_p T + L_v q) \rangle - \left\langle \omega \frac{\partial h}{\partial p} \right\rangle + SFX + \left\langle c_p \left(\frac{\partial \theta}{\partial t} \right)_R \right\rangle,$$

- MSE provides a desirable framework to examine the impacts of ventilation on TC convective processes as column-integrated MSE approximately conserved under moist adiabatic motions

- Following the methods of Neelin (2007) and Chen et al. (2019), the MSE budget here uses the time tendency of moist enthalpy (Cp*T + Lv*q) as this leads to a better closure of the MSE budget

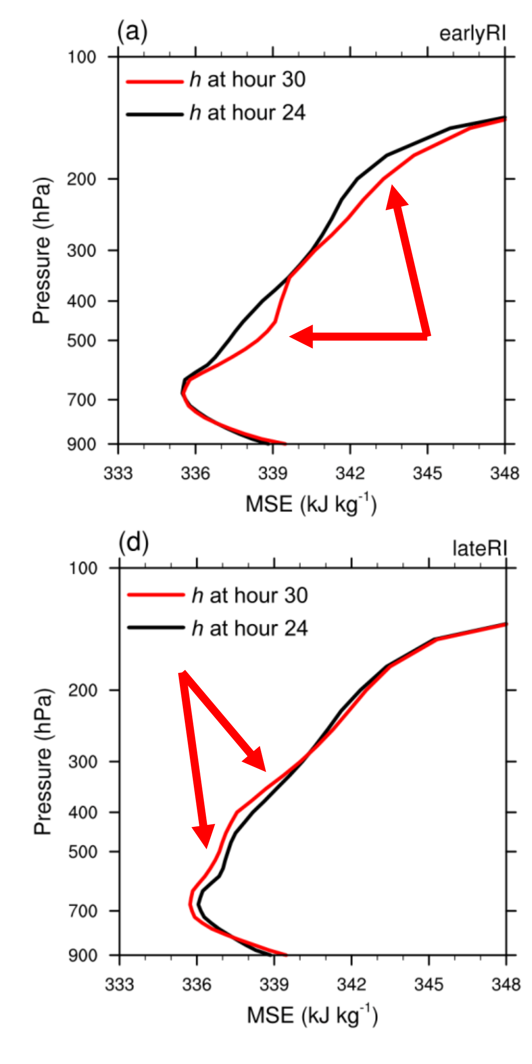
- Computed within a 240x240-km TC-centered box

Moist Static Energy (MSE) Budget



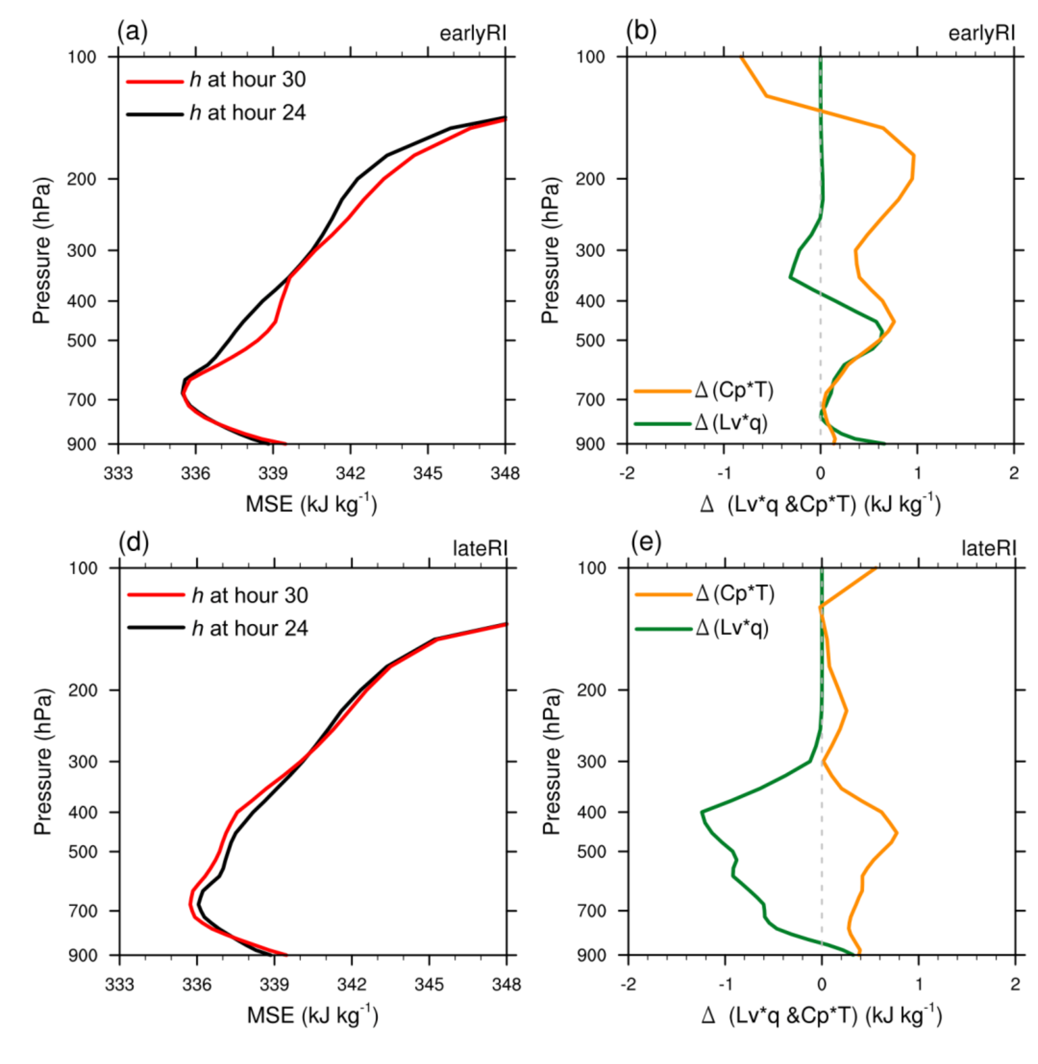
- (a),(d): Vertical profiles of area-averaged MSE (*h*) within a 240x240-km TC-centered box

Moist Static Energy (MSE) Budget



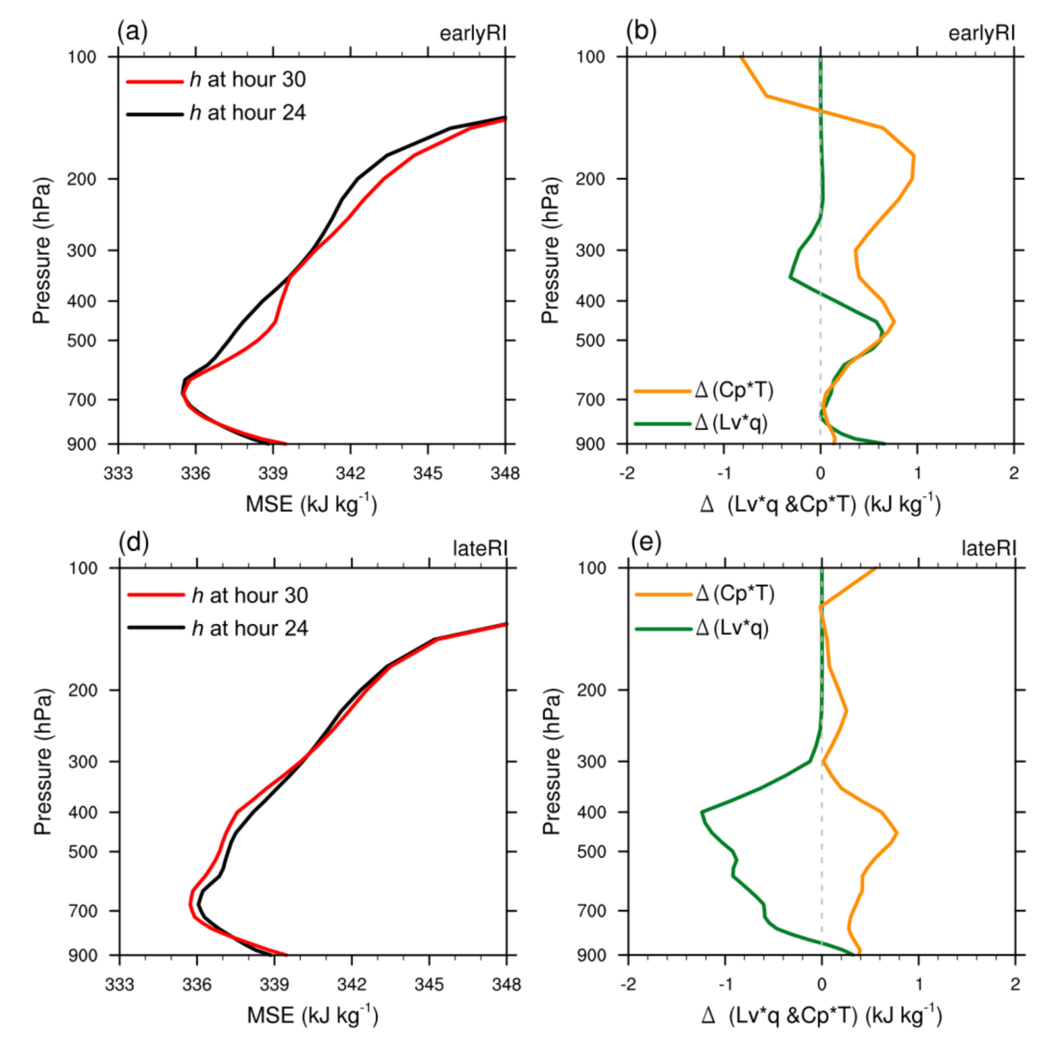
- (a),(d): Vertical profiles of area-averaged MSE (*h*) within a 240x240-km TC-centered box

Moist Static Energy (MSE) Budget



- (a),(d): Vertical profiles of area-averaged MSE (*h*) within a 240x240-km TC-centered box
- (b),(e): Change in internal energy (Cp*T) and latent heat (Lv*q) between forecast hours 24 and 30

Moist Static Energy (MSE) Budget



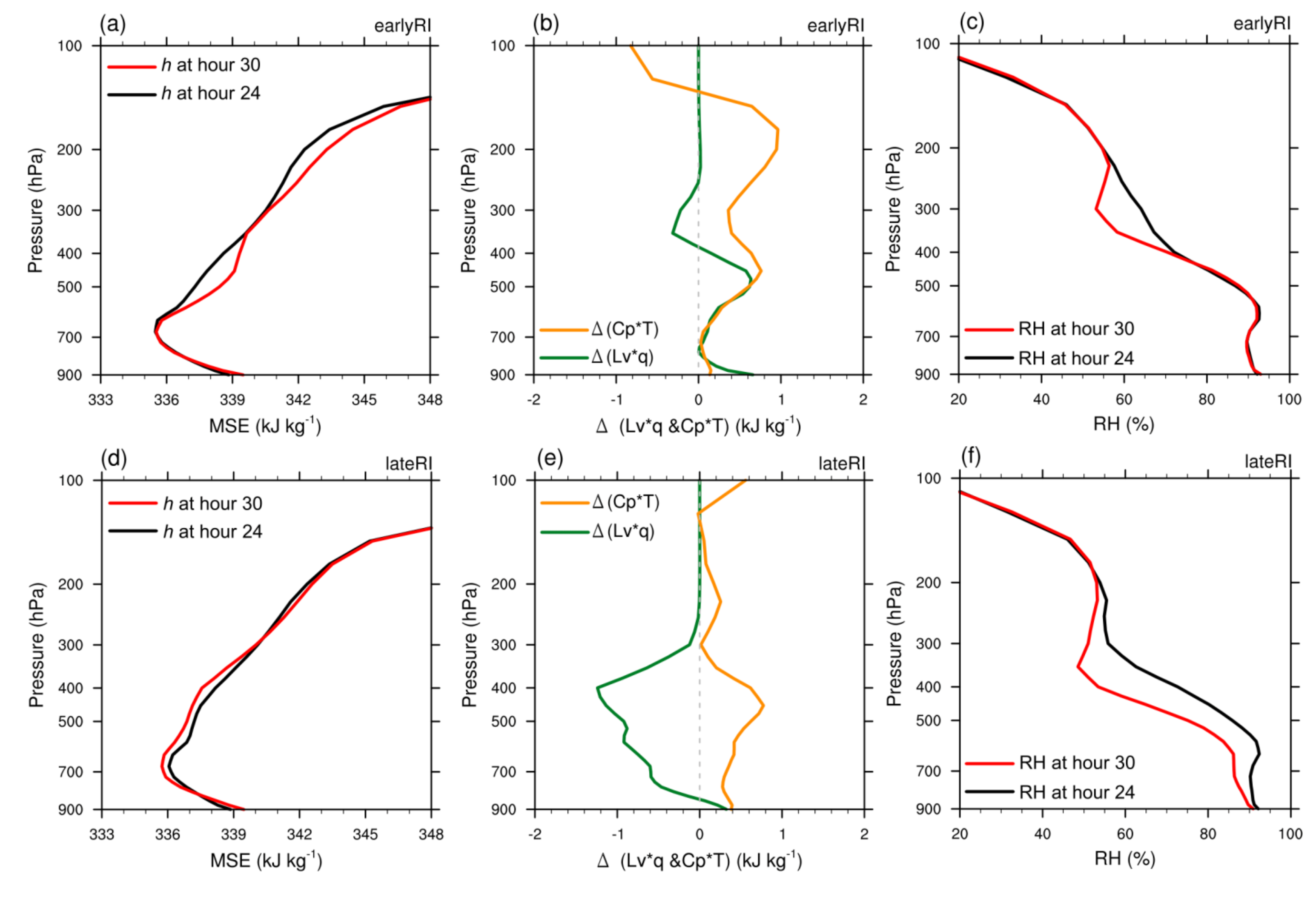
Increase in both Cp*T and Lv*q

Increase in Cp*T
Decrease in Lv*q

Mesoscale subsidence beneath dry air intrusion

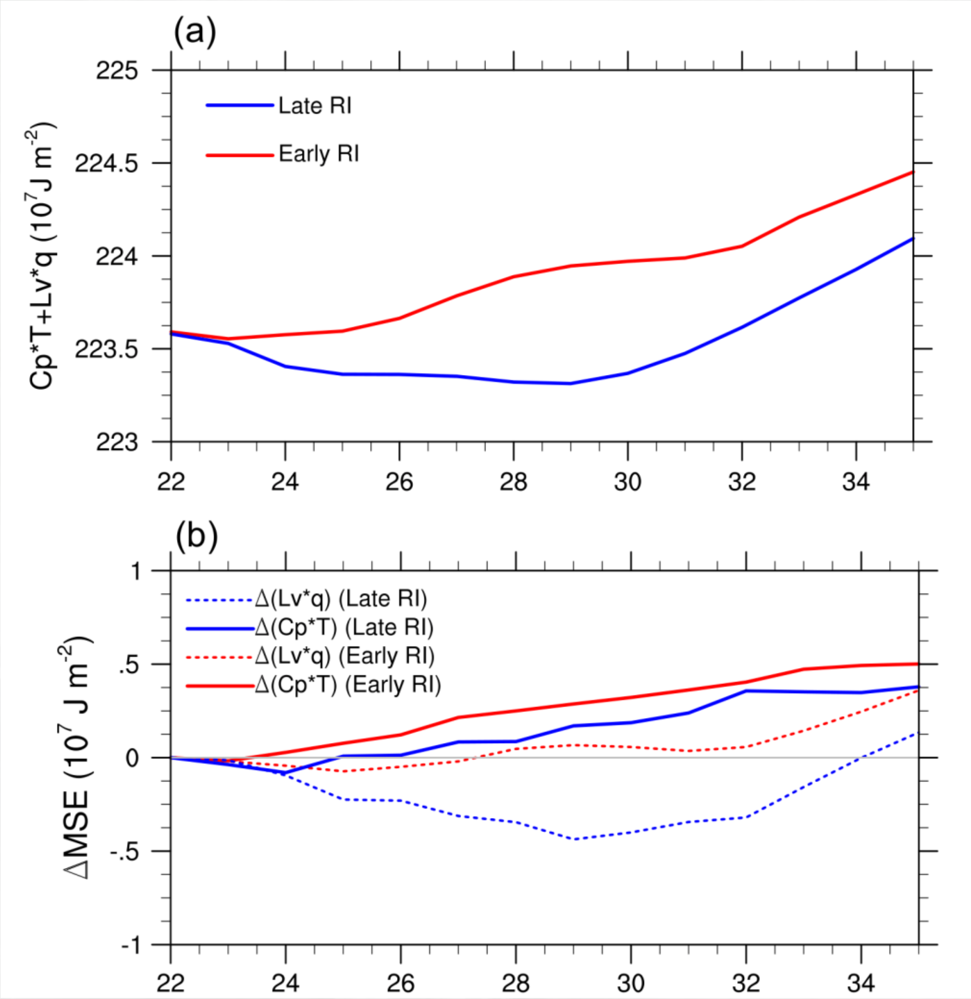
- (a),(d): Vertical profiles of area-averaged MSE (*h*) within a 240x240-km TC-centered box
- (b),(e): Change in internal energy (Cp*T) and latent heat (Lv*q) between forecast hours 24 and 30

Moist Static Energy (MSE) Budget



- (a),(d): Vertical profiles of area-averaged MSE (*h*) within a 240x240-km TC-centered box
- (b),(e): Change in internal energy (Cp*T) and latent heat (Lv*q) between forecast hours 24 and 30
- (c),(f): Change in area-averaged RH between forecast hours 24 and 30
- Evolution in late-RI member is consistent with drying from mesoscale subsidence beneath dry-air intrusion

Moist Static Energy (MSE) Budget

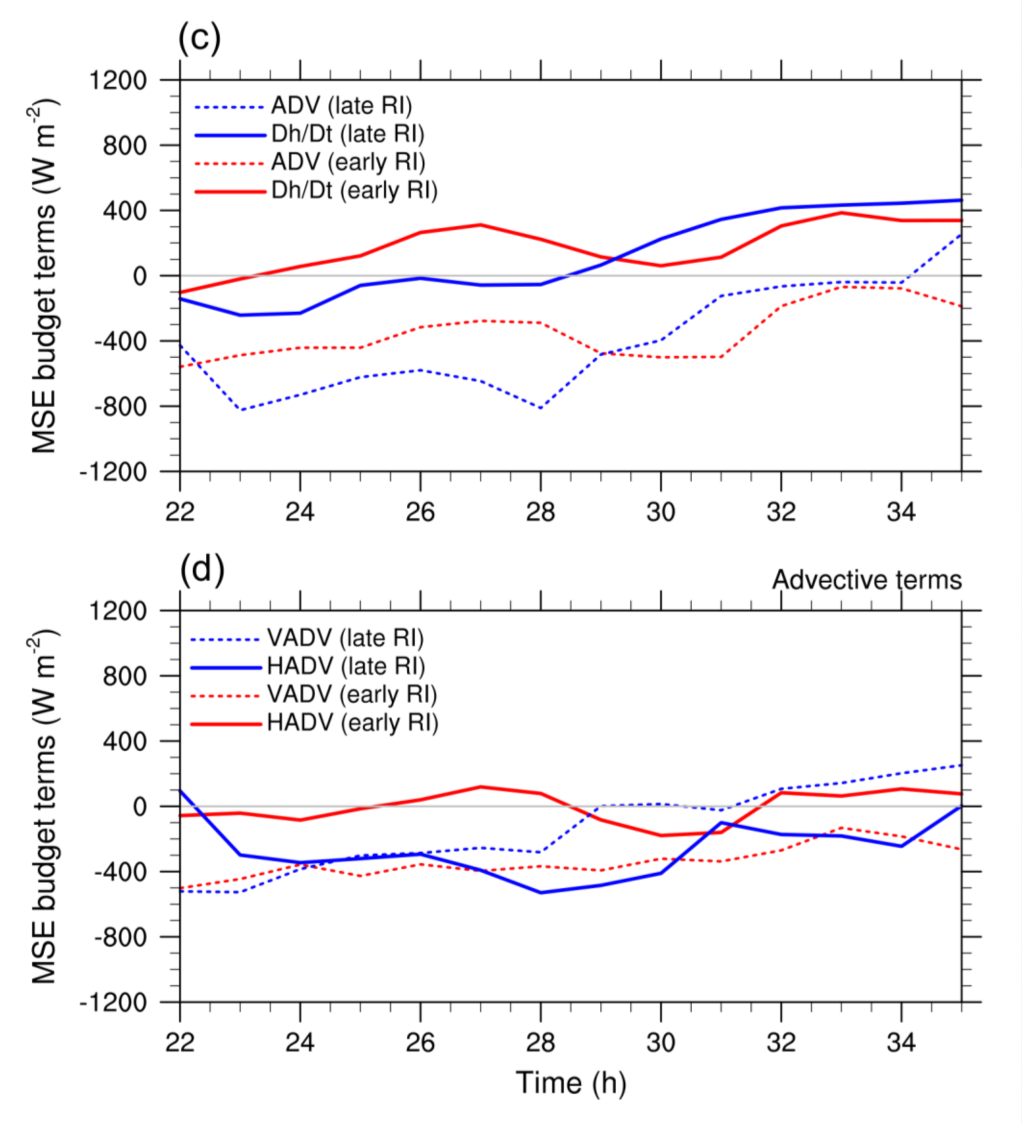


Forecast hour

- **Early-RI** member experiences an increase moist enthalpy, while **late-RI** member experiences a decrease in moist enthalpy (panel a)

- Change in moist enthalpy are primarily driven by changes in latent heat (Lv*q; panel b)
  - Indicates a drying of the column, consistent with mesoscale subsidence

Moist Static Energy (MSE) Budget

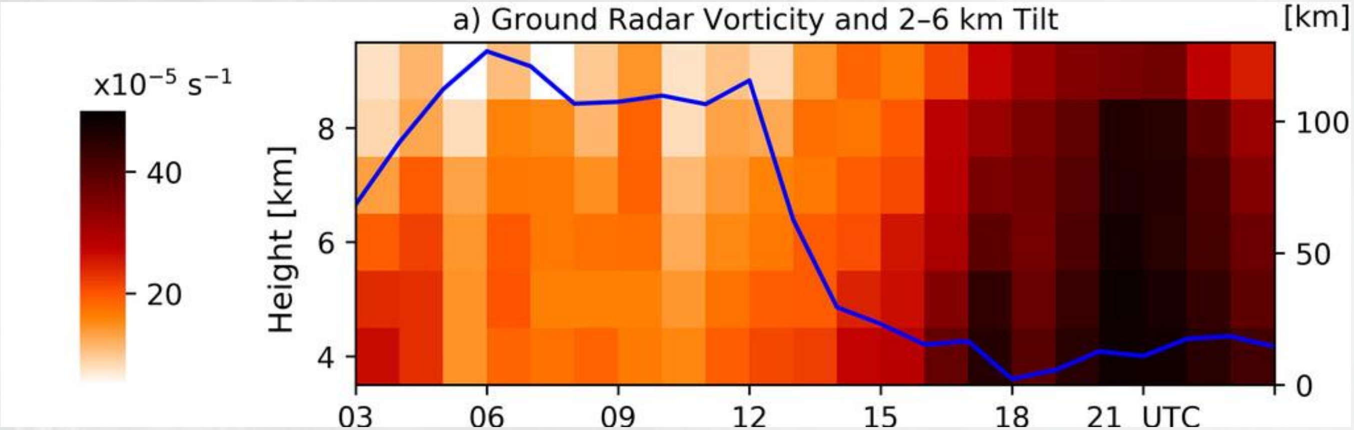


- The time derivative of MSE for both members are shown more clearly in panel c
    - The sum of the MSE advective terms vary in phase with the MSE tendency, indicating the key role of advective processes

- The loss of MSE in the **late-RI** member is primarily driven by horizontal advection (panel d)
    - Consistent with radial ventilation!

Is tilt related to intensity change?

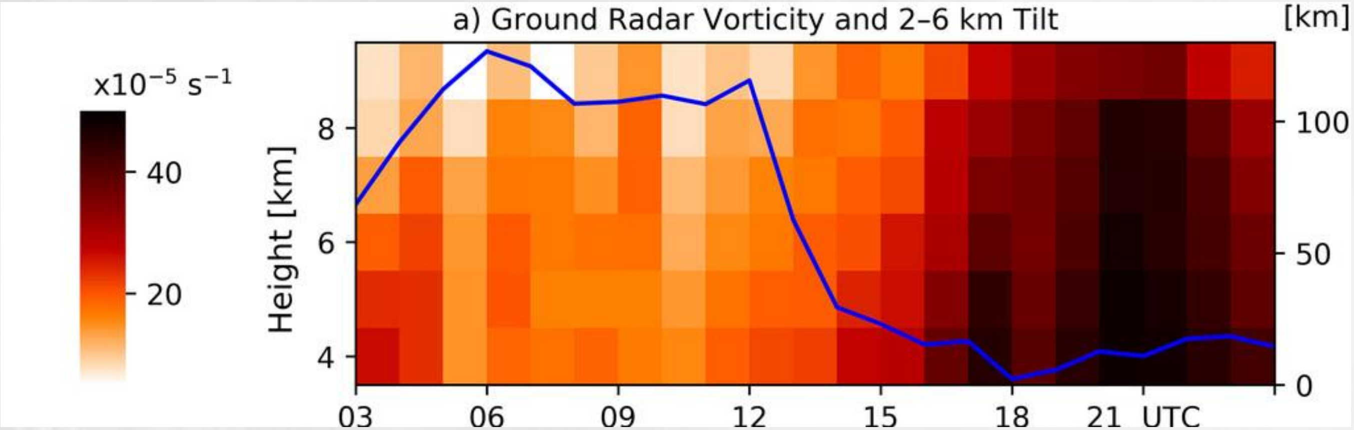
- Observations say: Well, we don't really know…



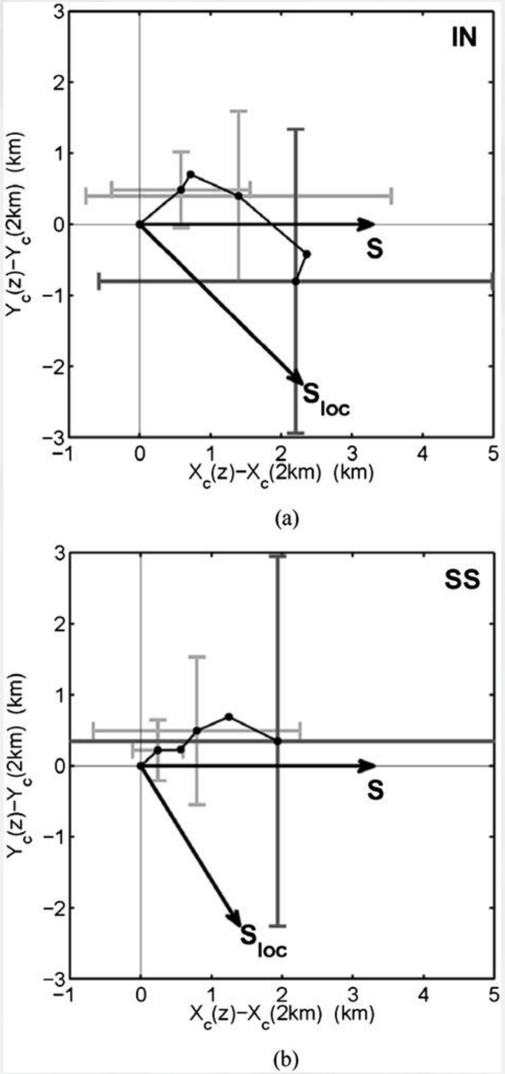
Adapted from Stone et al. (2023);
RI of Hurricane Sally (2020)

Is tilt related to intensity change?

- Observations say: Well, we don't really know…



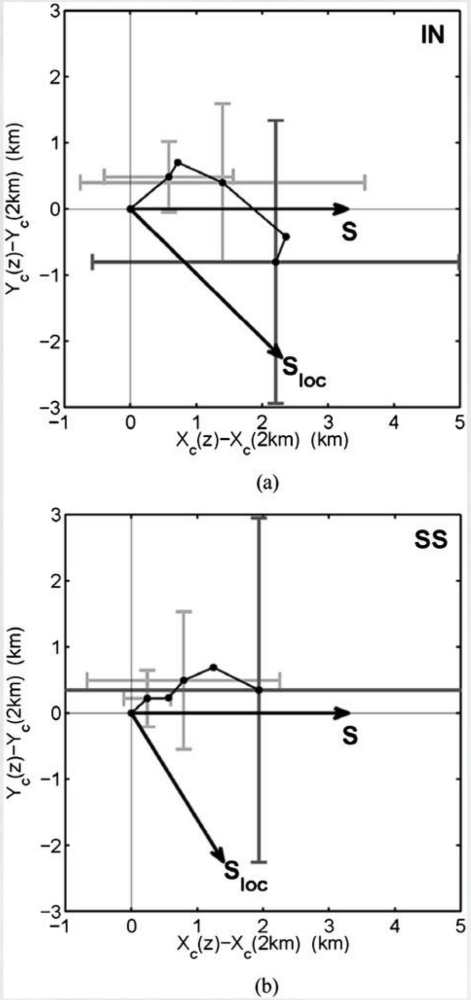
Adapted from Stone et al. (2023);
RI of Hurricane Sally (2020)



Adapted from Rogers et al. (2013)

Is tilt related to intensity change?

- Observations say: Well, we don't really know…



Adapted from Rogers et al. (2013)

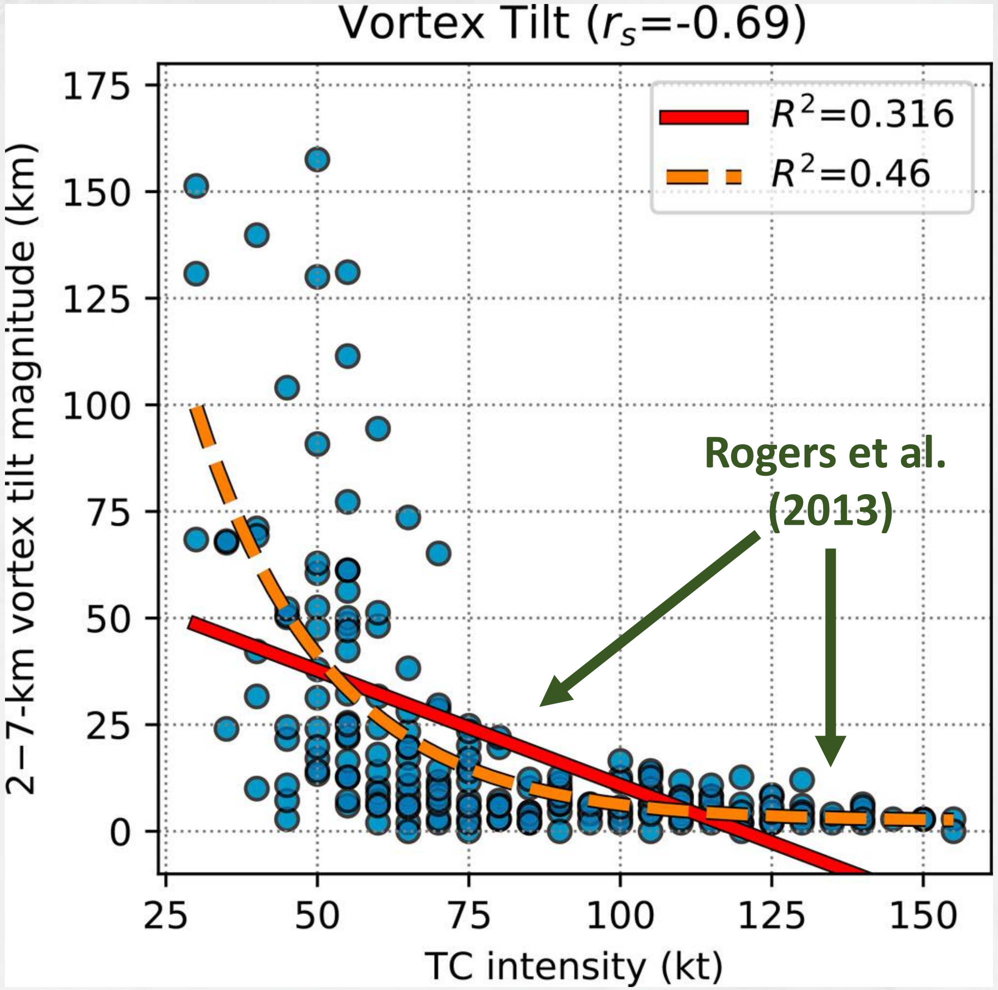
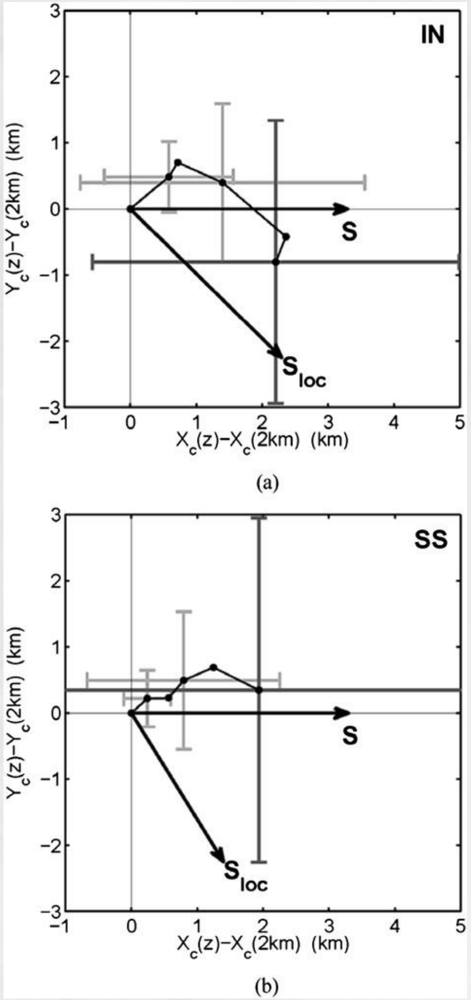


Fig. 9 from Fischer et al. (2022)

Is tilt related to intensity change?

- Observations say: Well, we don't really know…



Adapted from Rogers et al. (2013)

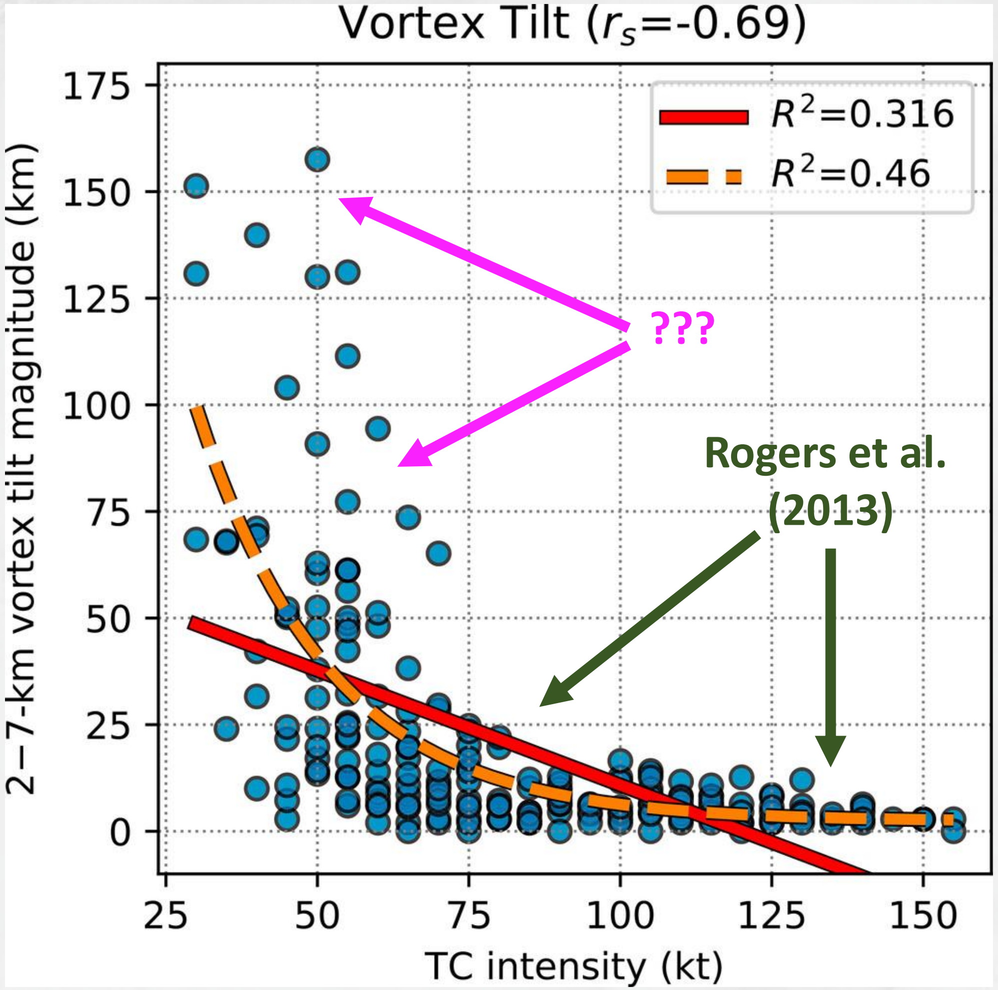


Fig. 9 from Fischer et al. (2022)