An Examination of Tropical Cyclone Evolution Using Curvature Vorticity and Shear Vorticity

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Outline

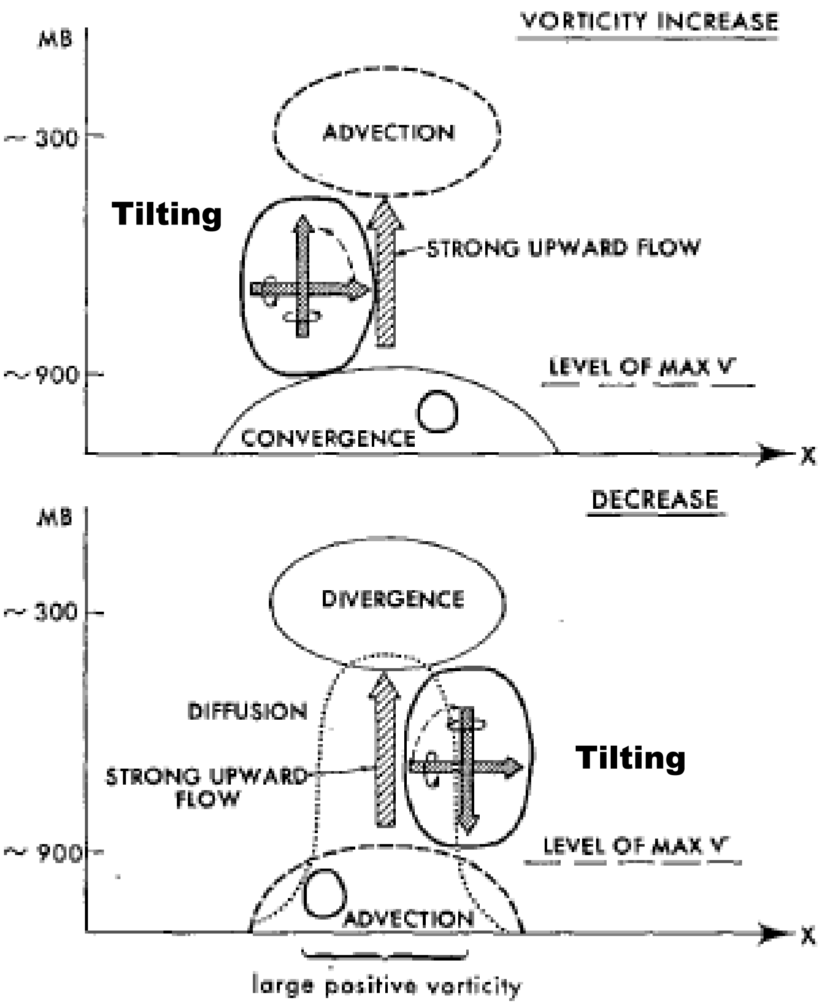
- Motivation
- Previous Work
- Background
- Methodology
- Budget Studies of Tropical Cyclone Ivan (2004)
    - Curvature Vorticity Budget
    - Shear Vorticity Budget
- Statistical Evaluation of Shear to Curvature Vorticity Exchanges for HWRF Tropical Cyclone Hindcasts
- Conclusions

Motivation

- Tropical cyclones (TCs) cause extreme social and financial burdens
- Operational track forecasts have improved over the last several decades, but intensity forecasts have not seen similar gains (Franklin, 2008)
- Recent work has uncovered important aspects of TC dynamics including Vortex Rossby waves (Montgomery and Kallenbach, 1997) and eyewall mesovortices (Schubert et al., 1999) that possibly have implications for predicting TC intensity fluctuations
- Much remains to be discovered to improve the understanding of TCs
- Given the link between intensity change and vortex efficiency as seen in previous research (Schubert and Hack, 1982), it would be natural to study curvature vorticity and shear vorticity given its relationship with vortex efficiency
- The following study attempts to provide insight into the issue of TC intensity changes using curvature vorticity and shear vorticity

Previous Work

TC Vorticity Budget Studies



Summary of relevant tendencies from earliest budget studies (Kurihara, 1975).

- No budget studies have been done for TCs using shear vorticity or curvature vorticity
- Budget studies are common approach to study of dynamics in the atmosphere
- Yanai (1961) emphasized importance of low level stretching and the vertical advection of low level vorticity for genesis and intensification
- Yamasaki (1968) and Kurihara (1975) confirmed these results, but also stated that the tilting of vorticity plays an important role at the surface in generating vorticity at inner radii, while friction creates vorticity at outer radii

Curvature Vorticity and Shear Vorticity Studies

- Curvature vorticity and shear vorticity are important for describing the curvature of the flow

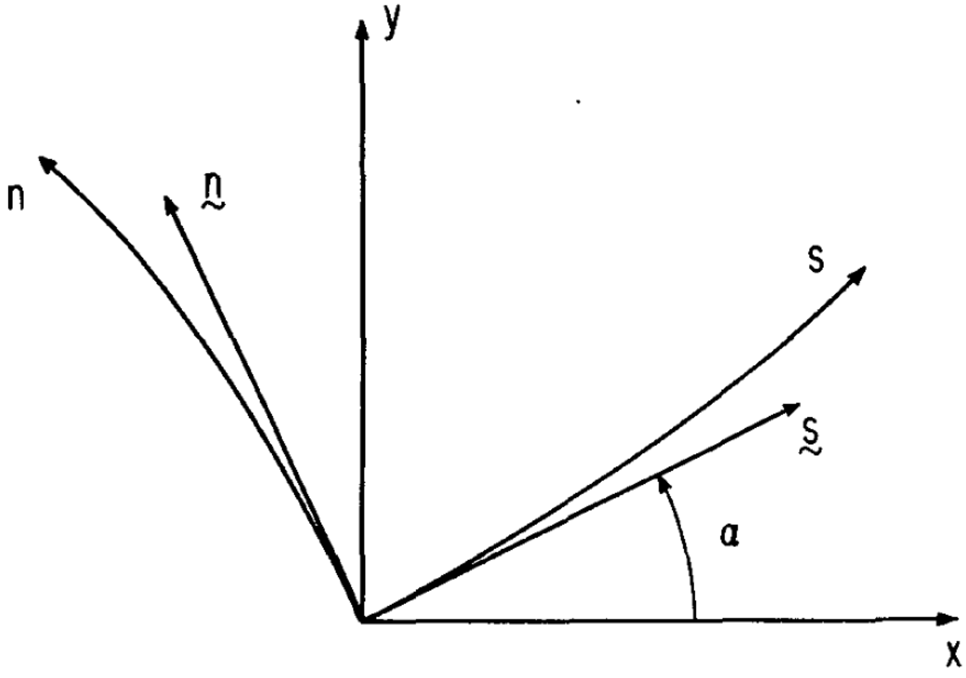
- Pichler and Steinacker (1987) determined that the stretching of vorticity followed by the conversion of vorticity from shear to curvature was important for orographically induced cyclogenesis

- Bell and Keyser (1993) presented a case study showing the importance of shear potential vorticity to curvature potential vorticity exchanges in transforming a diffluent trough to a cutoff low

Background

Natural Coordinate System

- Flow following coordinate system consisting of s-axis and n-axis
- s-axis is tangent to the velocity vector at a given point
- n-axis is 90° counterclockwise with respective to the s-axis
- Orientation of coordinate axis defined with respect to Cartesian coordinate system with angle α representing the angle between the s-axis and x-axis



Schematic of natural coordinate system (Bell and Keyser, 1993)

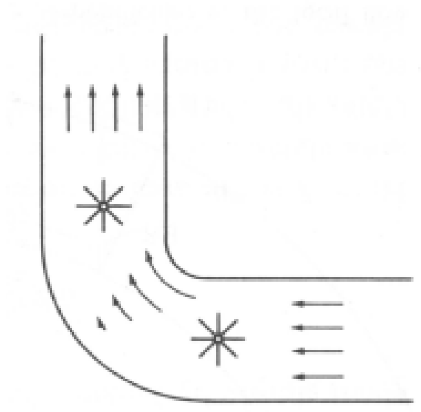
Dynamics Review

- Absolute vorticity comprised of three components:

$$\xi = f + \zeta = f + \zeta_c + \zeta_s$$

- Curvature vorticity: rotation caused by the directional turning of the flow

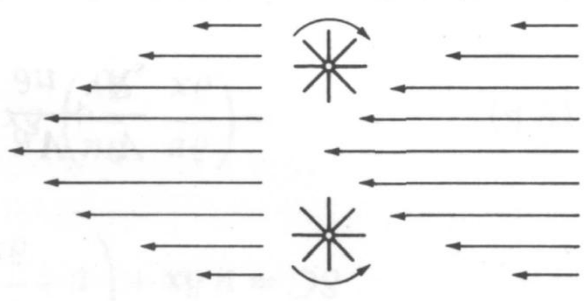
$$\zeta_c = \frac{V}{R_s}$$



Example of shear vorticity and curvature vorticity (Holton, 1992)

- Shear vorticity: rotation due to change in wind speed normal to the flow

$$\zeta_s = -\frac{\delta V}{\delta n}$$



Example of shear vorticity (Holton, 1992)

Shear and Curvature Vorticity Tendency Equations

- Curvature and shear vorticity tendency equations as given in Bell and Keyser (1993)
- Terms boxed in red are shear to curvature vorticity conversion term

Curvature Vorticity Tendency Equation:

$$\frac{\partial \zeta_c}{\partial t} = \boxed{-\frac{\delta V}{\delta s}\frac{d\alpha}{dt} - \frac{\delta}{\delta n}\left(\frac{\delta \phi}{\delta s}\right)} - V\frac{\delta \zeta_c}{\delta s} - V\frac{\delta f}{\delta s} - \omega\frac{\partial \zeta_c}{\partial p} - (\zeta_c + f)\nabla \cdot V - V\frac{\delta \omega}{\delta s}\frac{\partial \alpha}{\partial p} + F_{\zeta_c}$$

(1) (2) (3) (4) (5) (6) (7) (8)

Shear Vorticity Tendency Equation:

$$\frac{\partial \zeta_s}{\partial t} = \boxed{\frac{\delta V}{\delta s}\frac{d\alpha}{dt} + \frac{\delta}{\delta n}\left(\frac{\delta \phi}{\delta s}\right)} - V\frac{\delta \zeta_s}{\delta s} - \omega\frac{\partial \zeta_s}{\partial p} - (\zeta_s)\nabla \cdot V + \frac{\delta \omega}{\delta n}\frac{\partial V}{\partial p} + F_{\zeta_s}$$

(1) (2) (3) (4) (5) (6) (7)

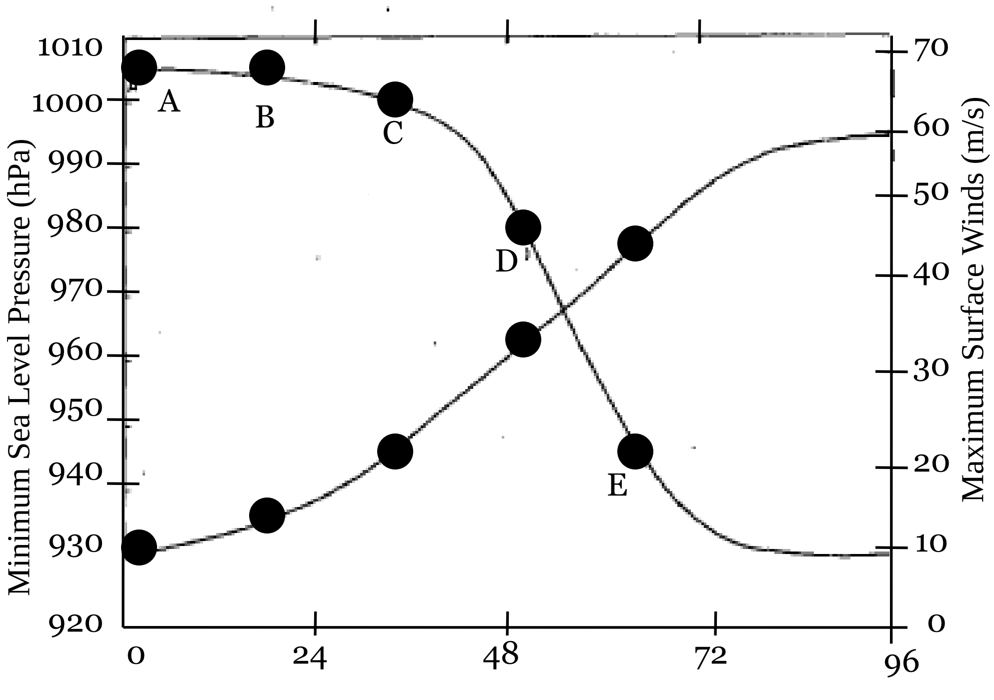
Vorticity and the Efficiency of TC Heating

- Vortex efficiency defined by Schubert and Hack (1982) as:

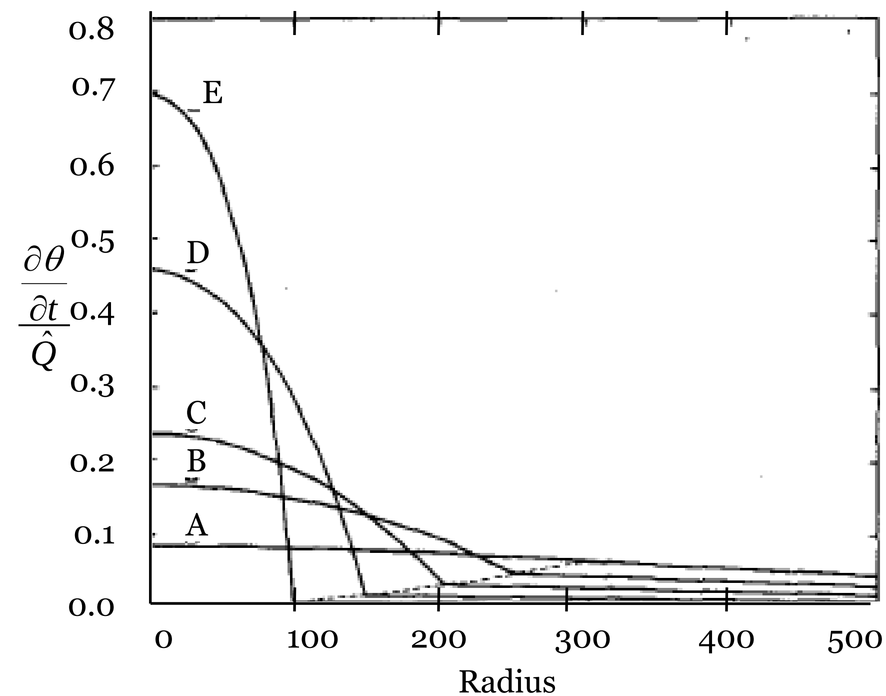
$$\frac{\partial \theta}{\partial t} / \hat{Q}$$

- Vortex efficiency is dependent on the inertial stability:

$$\eta^2 = [f + \frac{V_\theta}{R} + \frac{\partial V_\theta}{\partial R}][f + \frac{2V_\theta}{R}]$$

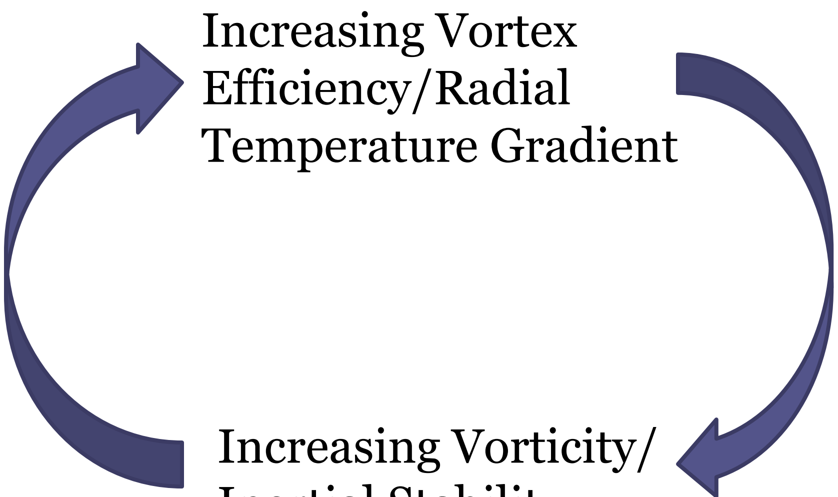


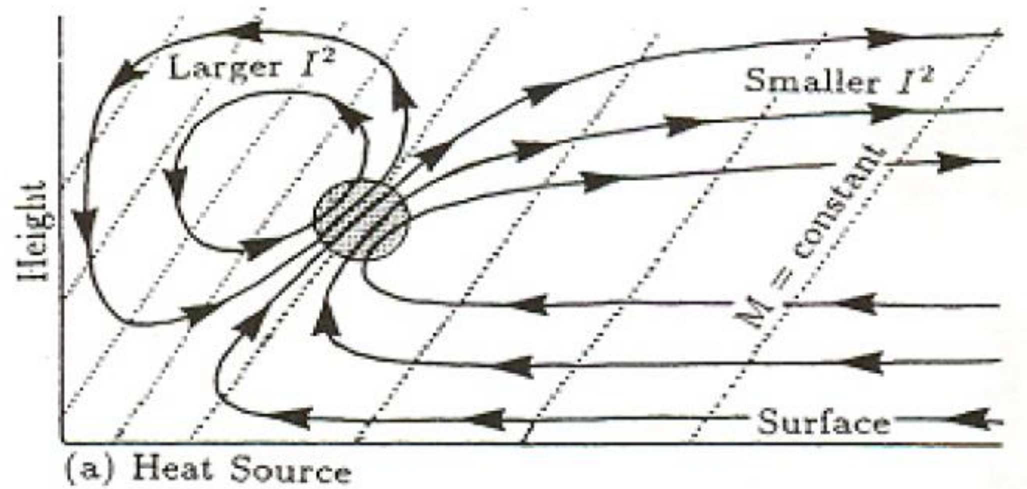
Typical TC development time for minimum sea level pressure and maximum surface winds (Schubert and Hack , 1982)



Efficiency of heating for radii for storms of different intensities (Schubert and Hack , 1982)

Vorticity and the Efficiency of Tropical Cyclone Heating





Secondary circulation induced by heat source placed inwards of RMW (Elsberry, 1995)

- For balanced vortex, inertial stability becomes:

$$\eta^2 = [f + \zeta_s + \zeta_c][f + 2\zeta_c] \quad \text{where} \quad \zeta_c = \frac{V_\theta}{R} \quad \text{and} \quad \zeta_s = \frac{\partial V_\theta}{\partial R}$$

- Increasing curvature or shear vorticity yields increased inertial stability
- For vorticity conversions, only increasing curvature and decreasing shear will lead to increased inertial stability

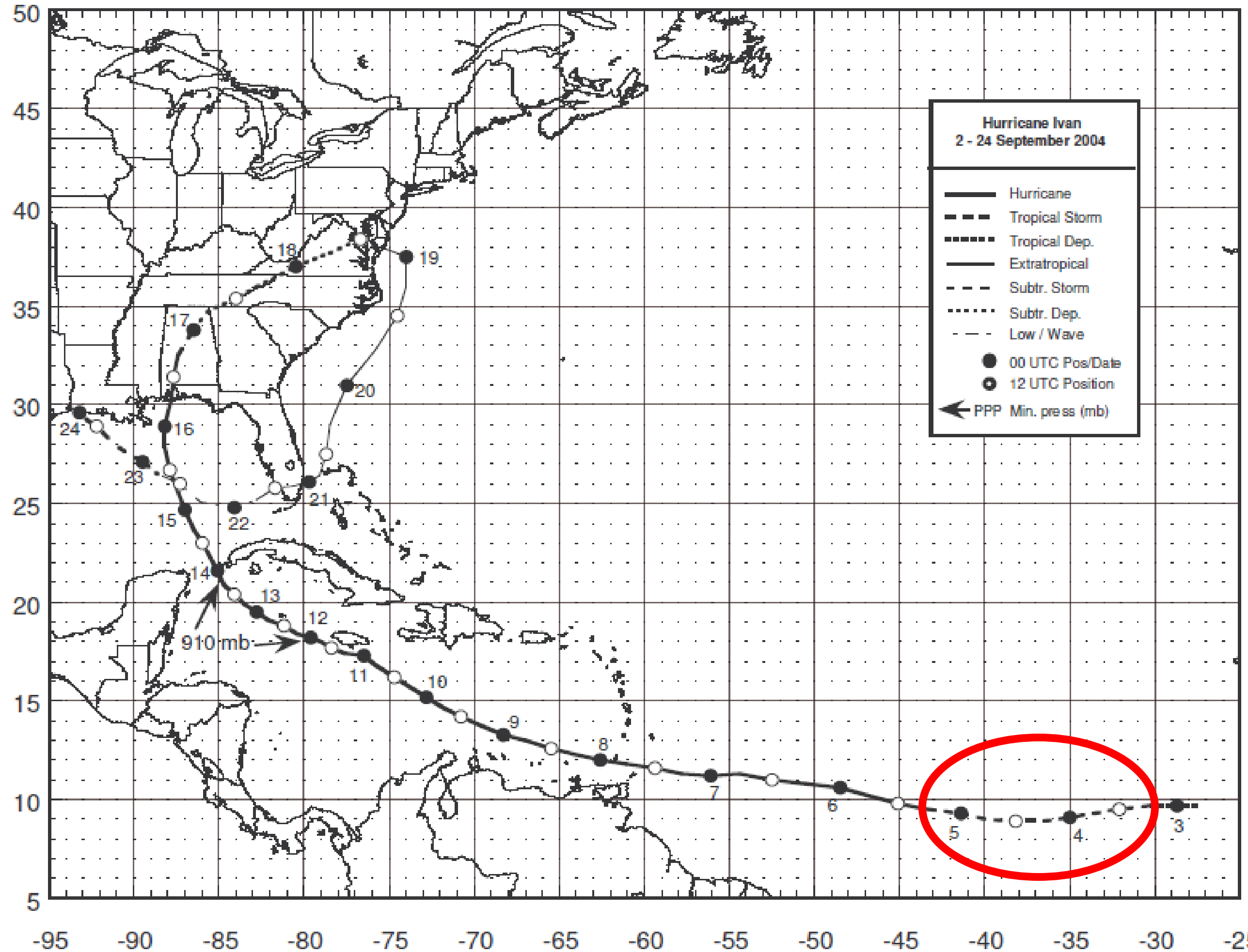
Questions to be Answered…

- What is the spatial distribution of each term in the curvature vorticity and shear vorticity tendency equations?
- What are the mechanisms responsible for forcing each term?
- Which tendency terms are important in each budget equation?
- Is there any relation between the tendency terms and intensity changes?

Methodology

Storm History for TC Ivan

- TC Ivan (2004) simulated using MM5
- Simulation covers strengthening from tropical storm to weak hurricane
- Simulation conducted over 48 hour period from 0600 UTC September 3 – 0600 UTC September 5 2004



Track of TC Ivan (2004) as given in the best track (Stewart, 2004)

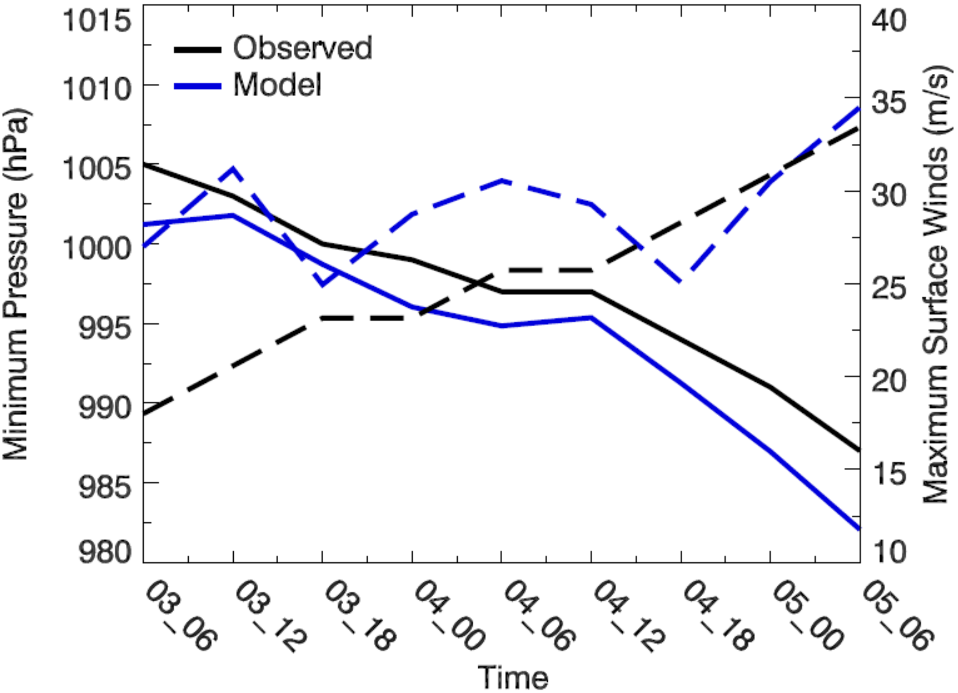
MM5 Simulation Methodology

- Series of one way nests with horizontal resolutions of 36, 12, and 4 km with 43 sigma levels
- Initial and boundary conditions from NCEP 1° x 1° FNL Analysis used for coarsest domain
- Physics options:
  - Explicit convective scheme in 4 km domain and Kain-Fritsch convective parameterization in 12 and 36 km domains
  - Blackadar planetary boundary layer scheme (Blackadar 1979)
  - Cloud-radiation scheme (Dudhia et al., 2004)
  - Goddard microphysics explicit moisture scheme (Tao et al. 1989)
  - Five-layer soil model (Dudhia, 1996)
- Data was outputted hourly and interpolated onto uniform grid
- Center of storm defined using methodology similar to Braun (2002)

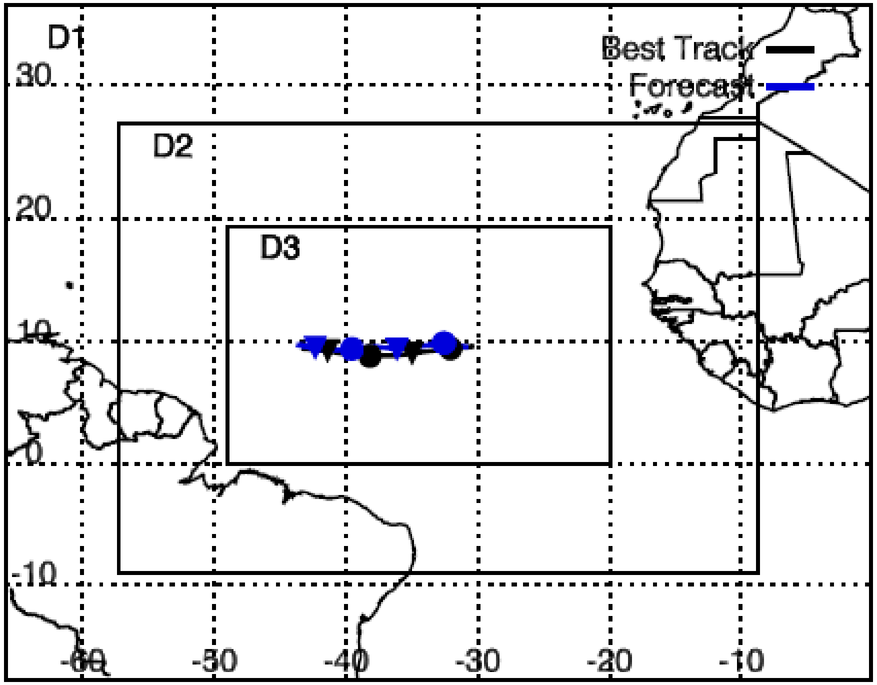
Simulation Verification

- Minimum sea level pressure verifies well, but maximum surface winds do not

- Track corresponds well with MM5 simulation moving slightly faster



Comparison of maximum surface winds and minimum sea level pressure of TC Ivan (2004) from best track and MM5 simulation



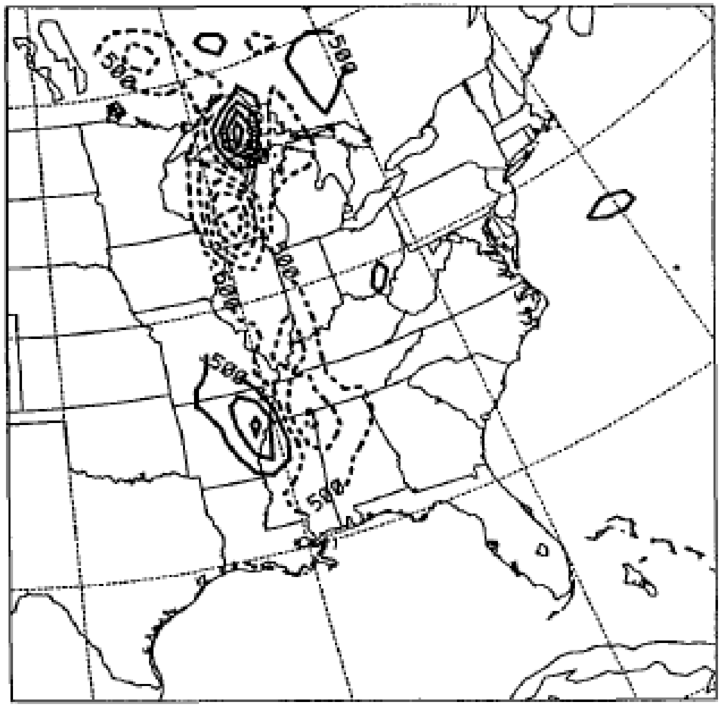
Track of TC Ivan (2004) in best track (black) and MM5 simulation (blue)

Vorticity Budget Calculation Methodology

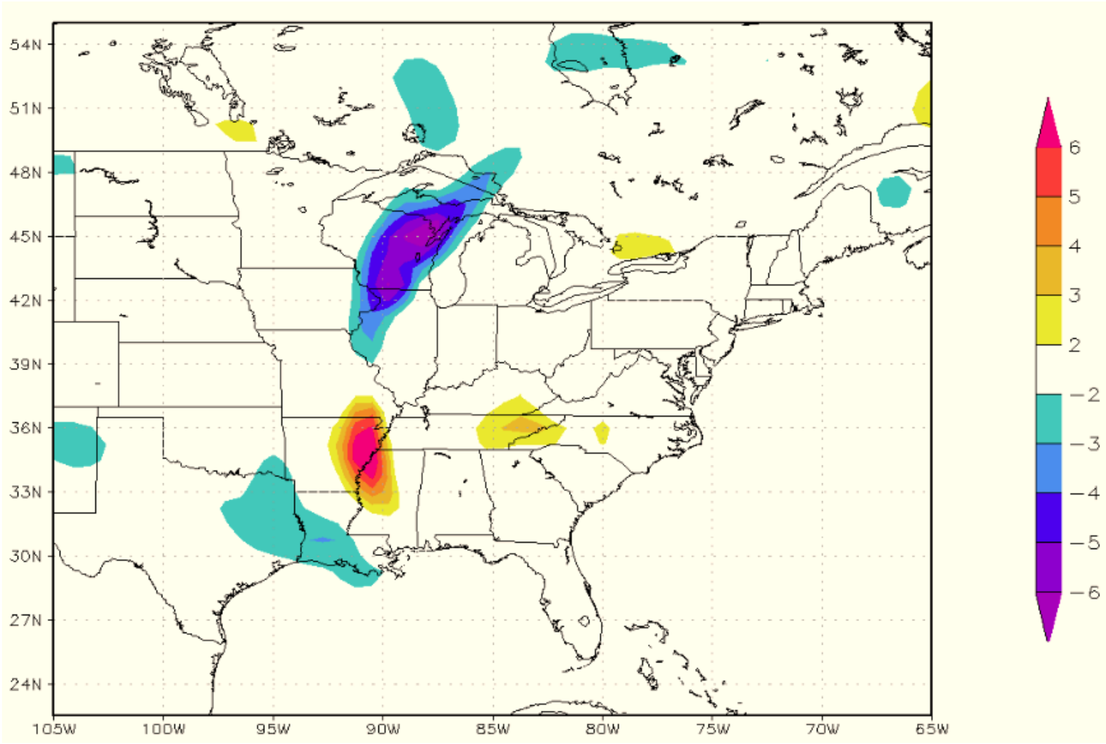
- Calculations performed using equations given in Bell and Keyser (1993) using MM5 data
- Computations performed on innermost domain with first six hours disregarded
- Divergence adjustment performed using method of O'Brien (1970)
- Vertical velocities recalculated from corrected divergence using isobaric continuity equation
- Error reduction performed on each vorticity tendency budget to reduce residuals
- Budgets are computed in an Earth relative reference frame

Confirmation of Results

- Computations involving case study from Bell and Keyser (1993) show results are similar
- Bell and Keyser use PV while calculations in this case done for vorticity using North American Regional Reanalysis (NARR) interpolated to 315 K isentropic surface and to a horizontal resolution of 0.75°



Shear to curvature potential vorticity conversion term (PVU / (6 hr)$^{-1}$) from Bell and Keyser (2003) at 315 K on 0600 UTC September 19 1986

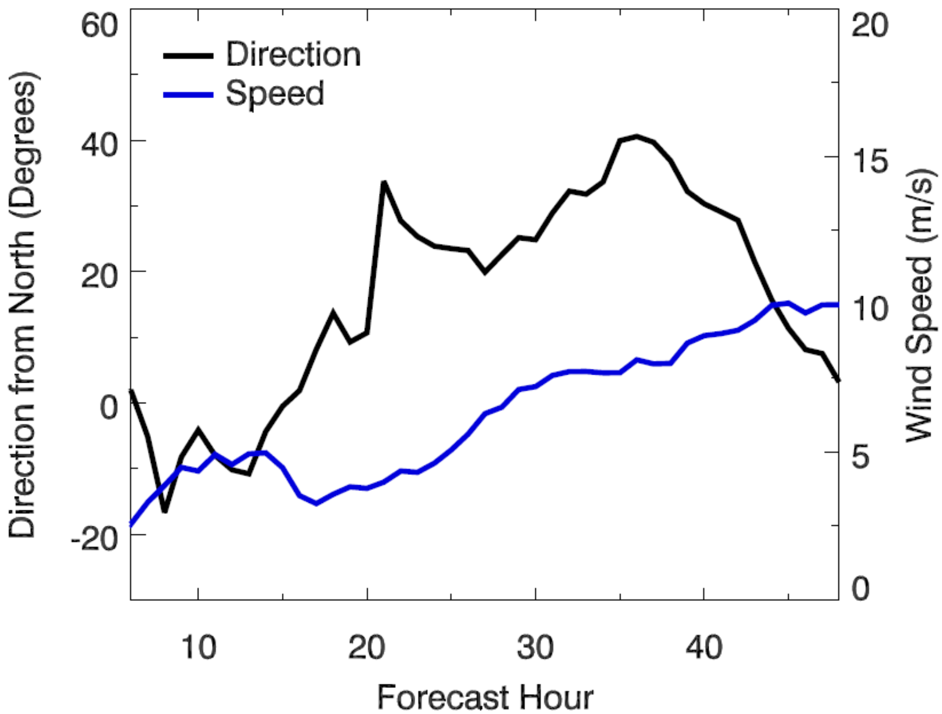


Shear to curvature vorticity conversion (10^{-9} s^{-2}) calculated from NARR interpolated to 315 K on 0600 UTC September 19 1986

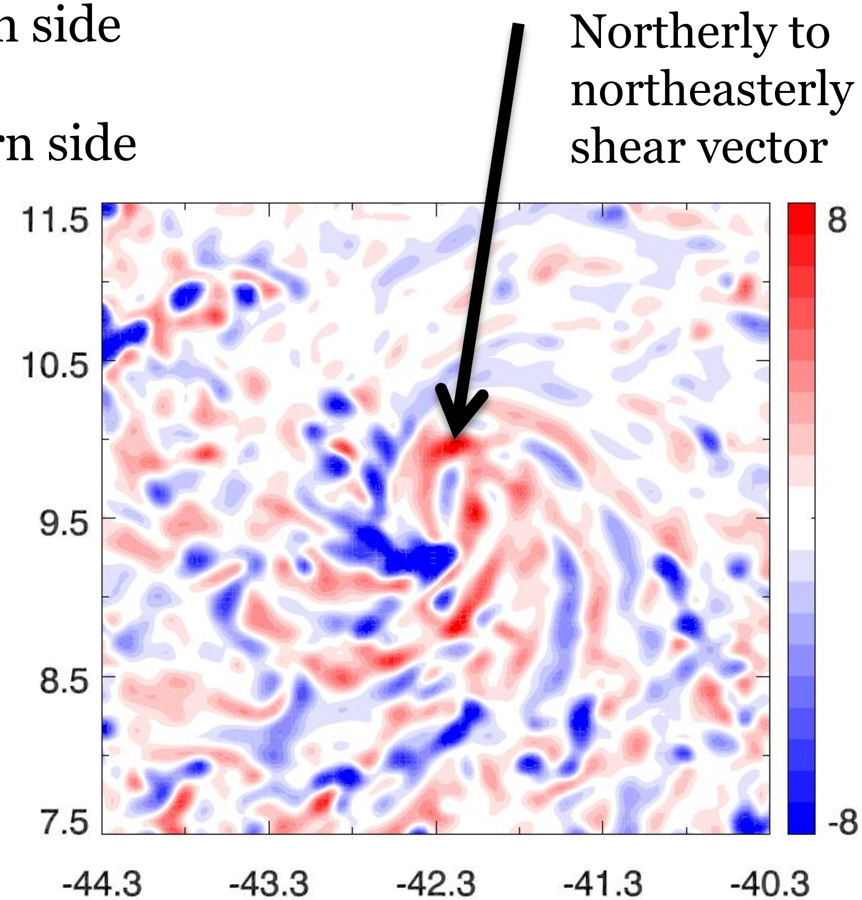
Budgets for TC Ivan (2004)

Impact of Environmental Flow Upon the TC

- Northerly to northeasterly shear throughout simulation with weak to moderate wind speed
- Inner maximum is southern/southeastern side
- Outer maximum is southern/southwestern side



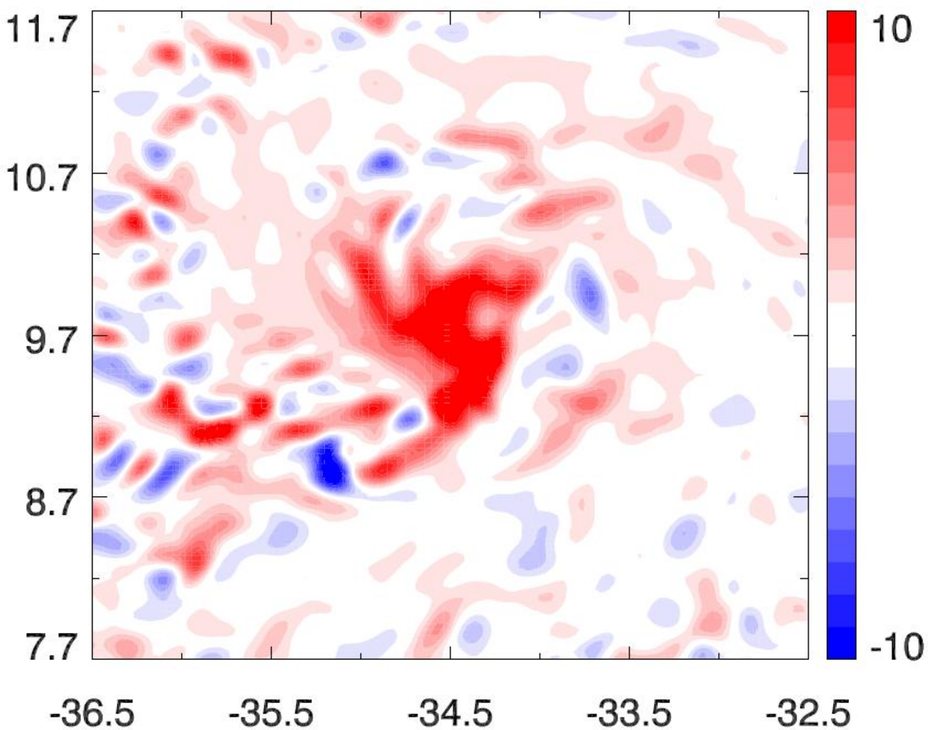
Time series of vertical shear vector direction and magnitude



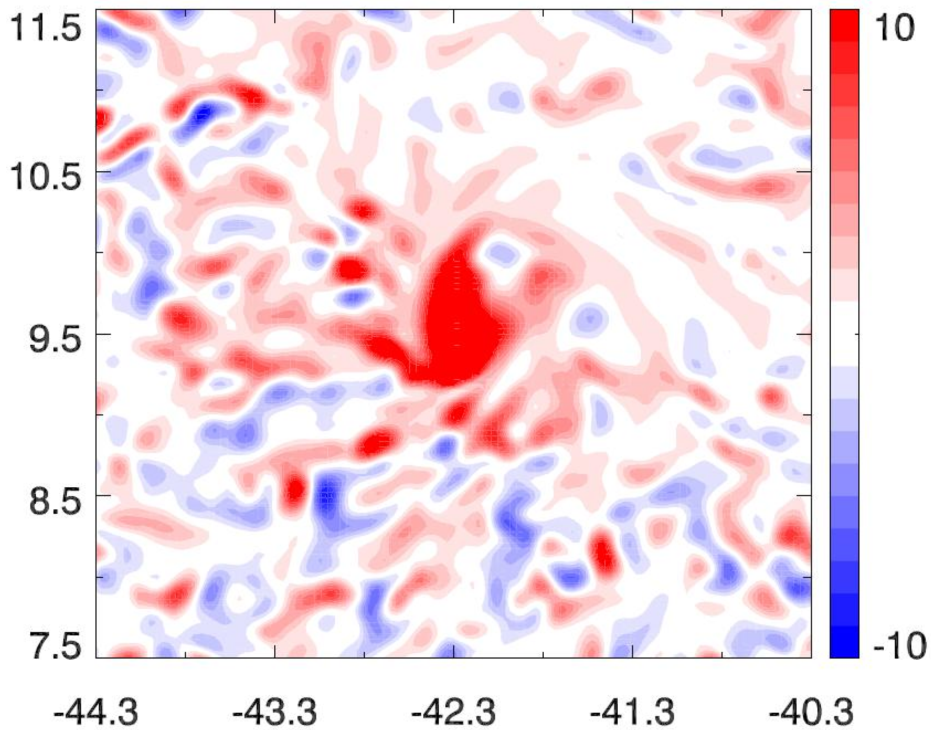
900 hPa divergence (10^{-4} s^{-1}) at simulation hour 42

Relative Vorticity

- Relative vorticity maximum becomes smaller and more symmetric with time
- Relative vorticity is sum of curvature vorticity and shear vorticity



Plan view of relative vorticity for simulation hour 12 at 900 hPa



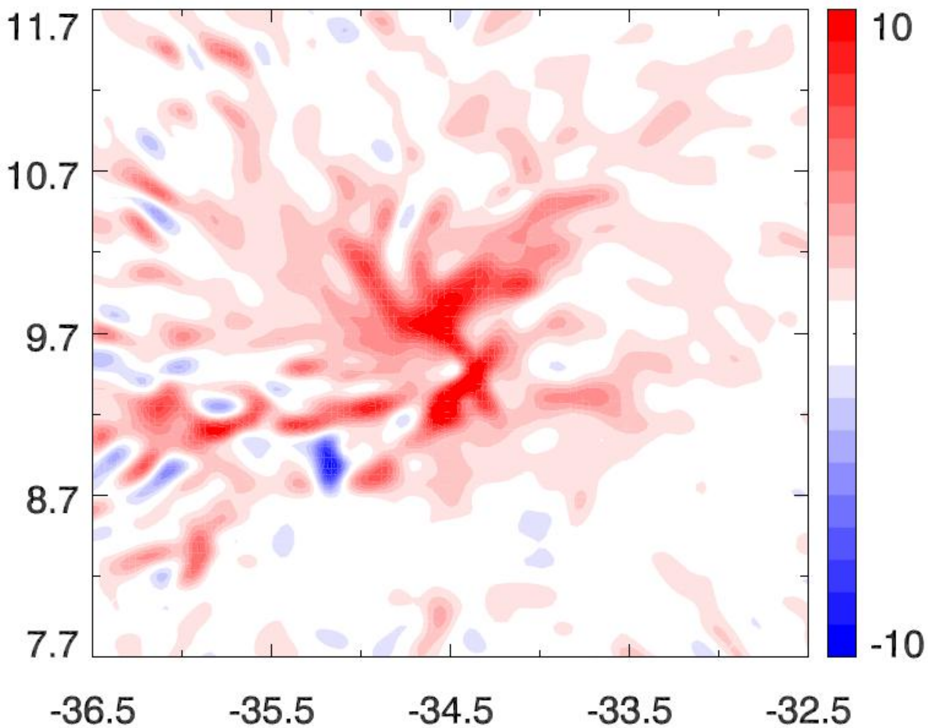
Plan view of relative vorticity for simulation hour 42 at 900 hPa

Curvature Vorticity Budgets

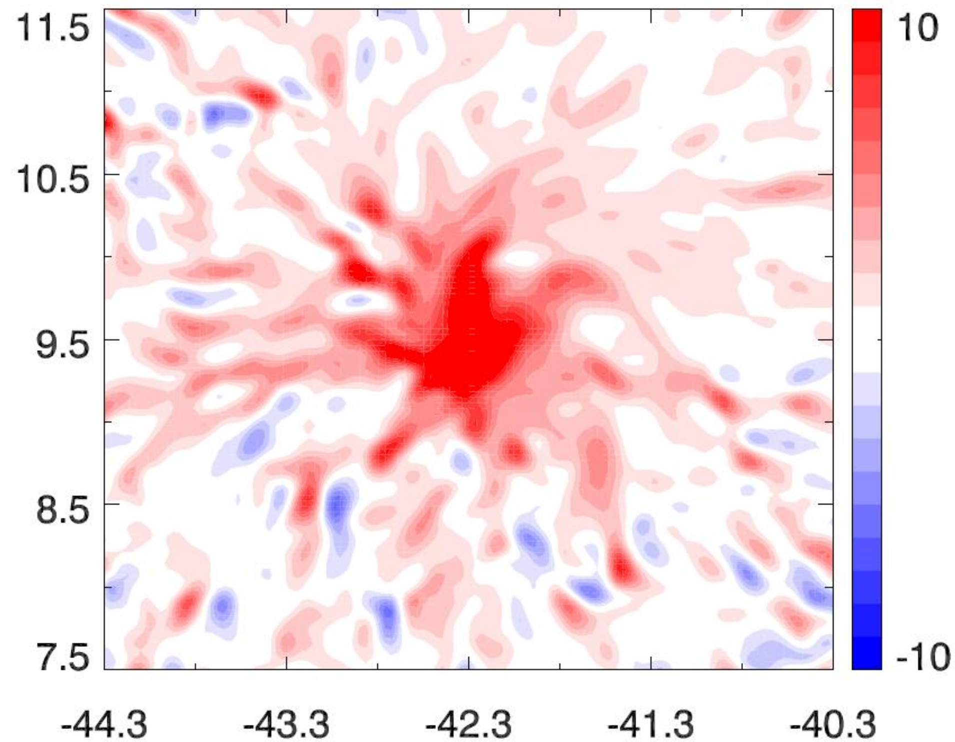
Curvature Vorticity

- Curvature vorticity maxima becomes more symmetric and concentrated over time indicating smaller radius of flows

$$V \frac{\delta \alpha}{\delta s}$$



Plan view of curvature vorticity for simulation hour 12 at 900 hPa

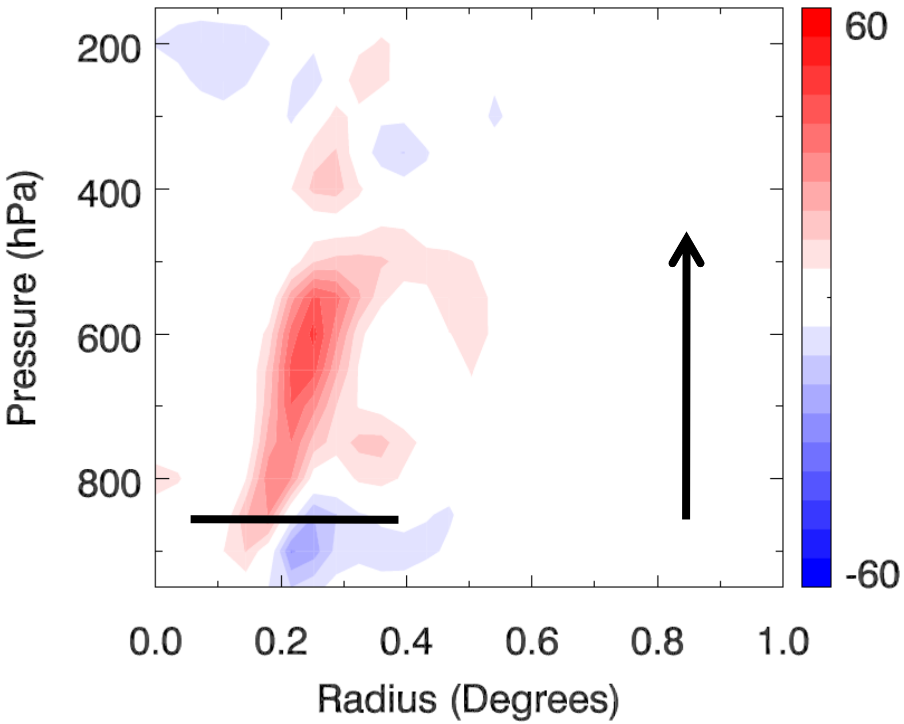


Plan view of curvature vorticity for simulation hour 42 at 900 hPa

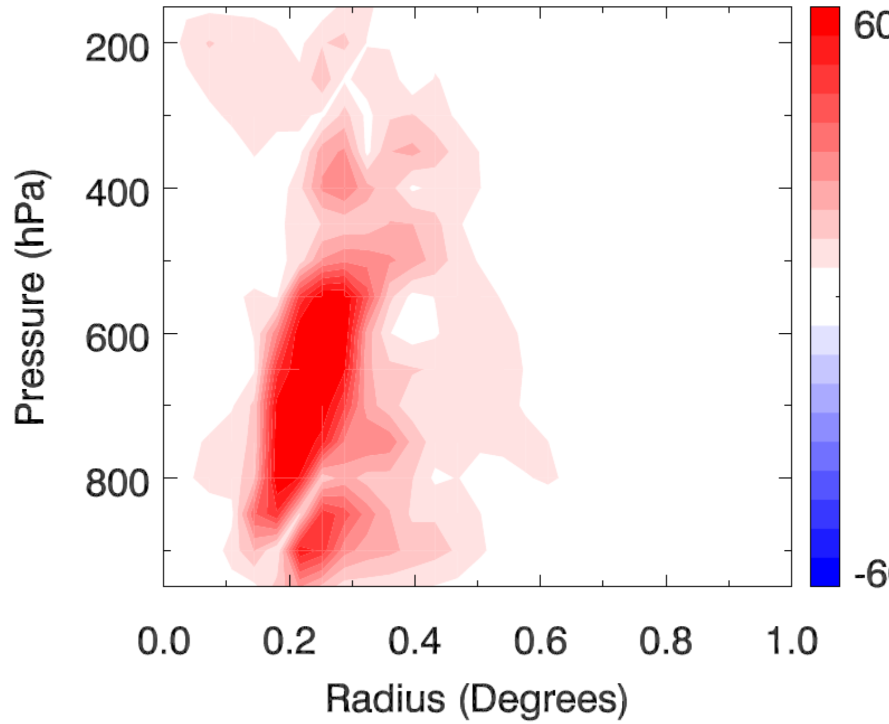
Vertical Advection of Curvature Vorticity

- Negative tendency consistently found on South and West part of TC
- Negative tendencies found at low levels associated with upgradient advection of curvature vorticity
- Positive tendencies associated downgradient advection of curvature vorticity

$$-\omega \frac{\partial \zeta_c}{\partial p}$$



Vertical cross section of wavenumber 0 from spectral analysis at simulation hour 42

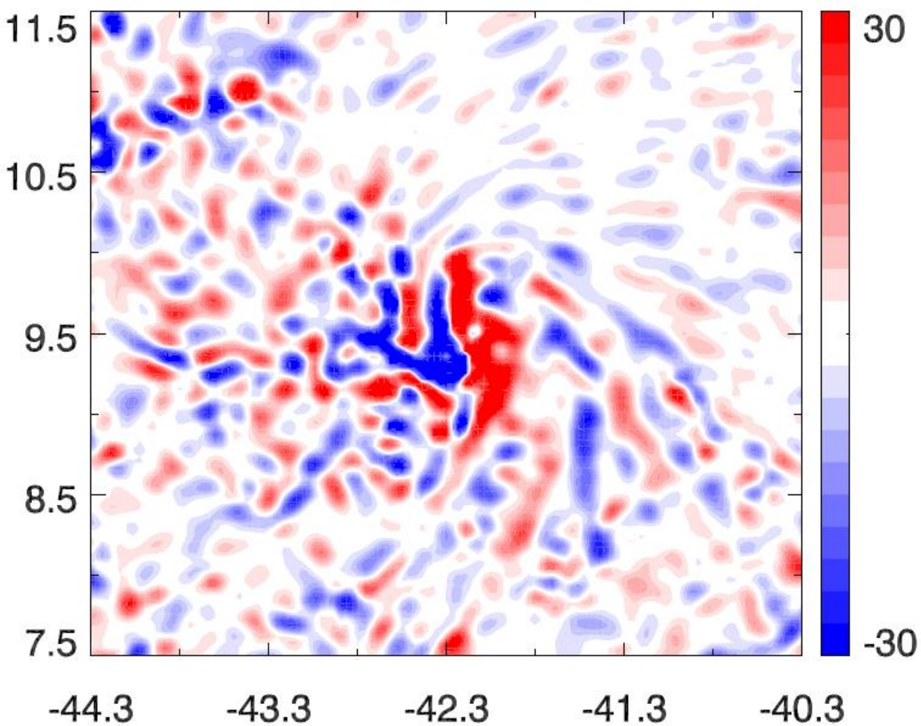


Vertical cross section of wavenumber 1 from spectral analysis at simulation hour 42

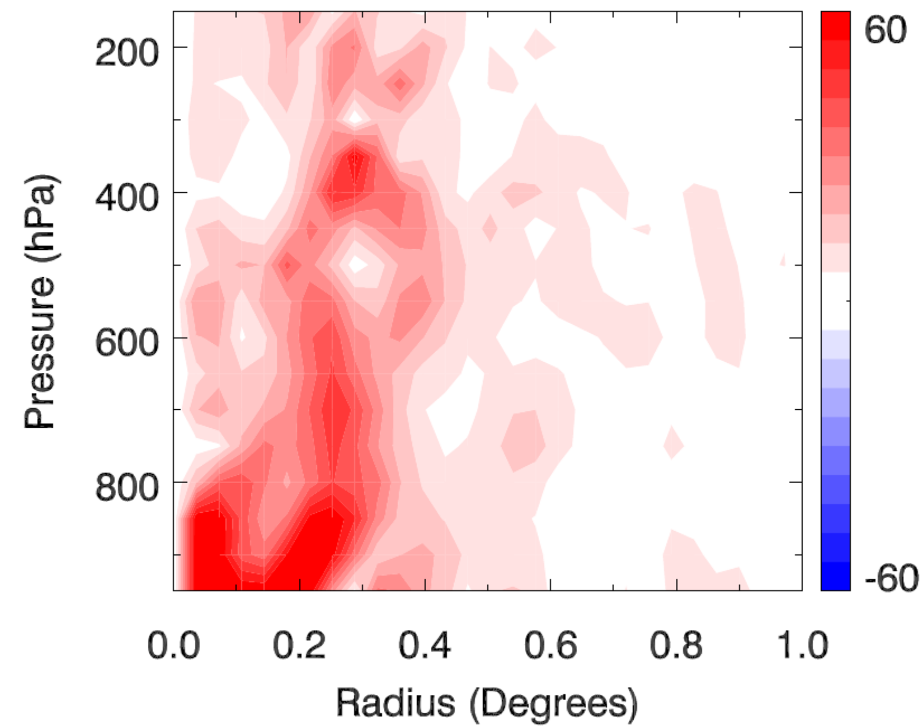
Shear to Curvature Vorticity Conversion Term

- Dipole in vorticity tendency term at low levels
- Banded nature of conversions on eastern half of TC
- Net negative contribution at small radii at later hours in simulation

$$-\frac{\delta V}{\delta s}\frac{d\alpha}{dt}-\frac{\delta}{\delta n}\left(\frac{\delta \phi}{\delta s}\right)$$



Plan view of vertical advection of curvature vorticity four hour 42 at 900 hPa

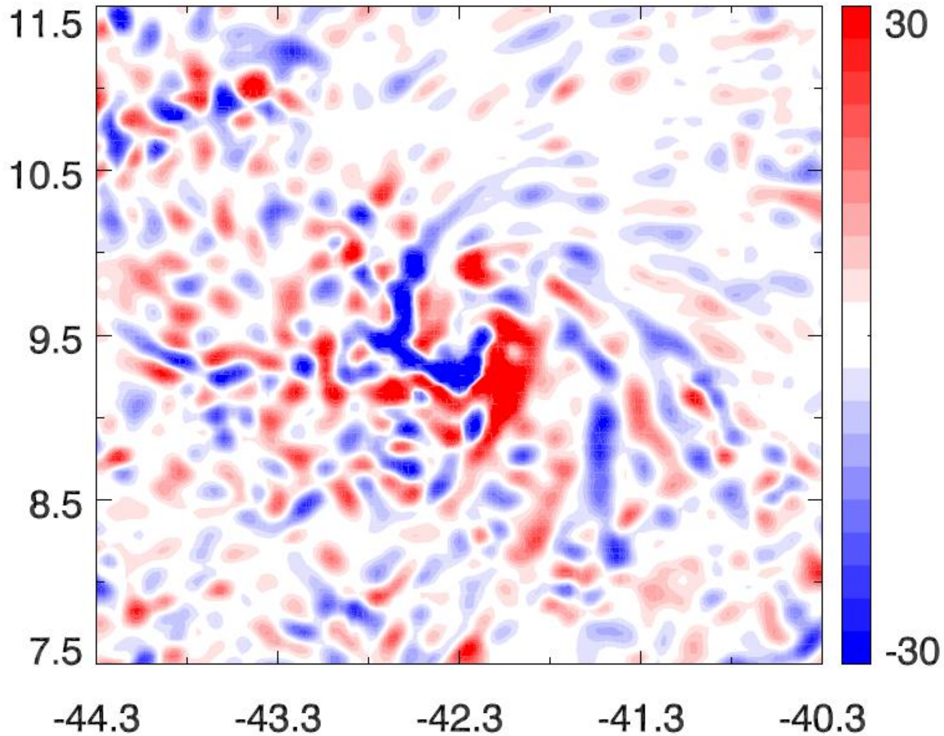


Vertical cross section of wavenumber 1 from spectral analysis at simulation hour 42

Shear to Curvature Vorticity Conversion Term 2

- Conversion term 2 is more dominant of terms spatially
- Influenced by diffluence induced vertical shear

$$-\frac{\delta}{\delta n}\left(\frac{\delta \phi}{\delta s}\right)$$



900 hPa shear to curvature vorticity conversion term 2 at simulation hour 42 (10^{-8} s^{-2})

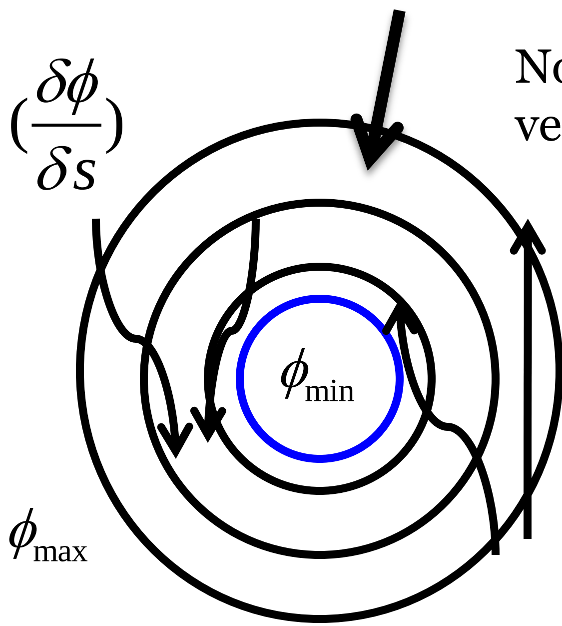
Shear to Curvature Vorticity Conversion Term 2 Mechanism

- As a reasonable approximation consider a symmetric TC with geopotential minimum at center and maximum pressure gradient force at radius of maximum winds
- Assume vertical shear induces diffluence on right side of TC, confluence on left side of TC
- On right side of vortex , diffluence leads to positive conversion
- On left side of vortex, confluence leads to negative conversion

$$-\frac{\delta}{\delta n}\left(\frac{\delta \phi}{\delta s}\right)$$

Northerly to northeasterly vertical wind shear

$$\frac{\delta \phi_{inner}}{\delta s} > \frac{\delta \phi_{outer}}{\delta s}$$

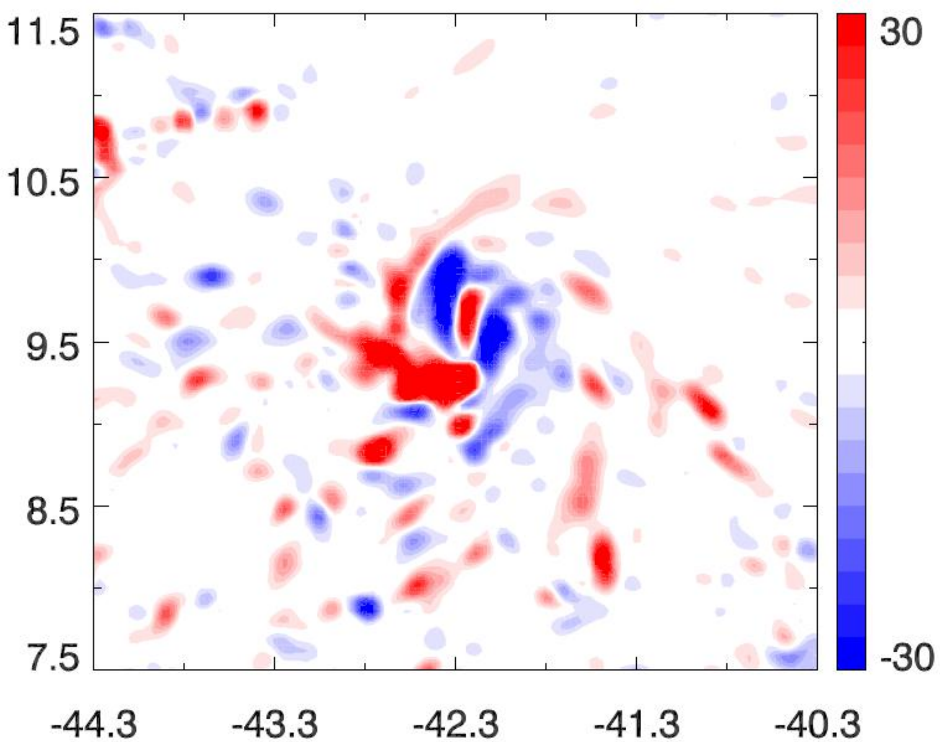


$$\frac{\delta \phi_{inner}}{\delta s} < \frac{\delta \phi_{outer}}{\delta s}$$

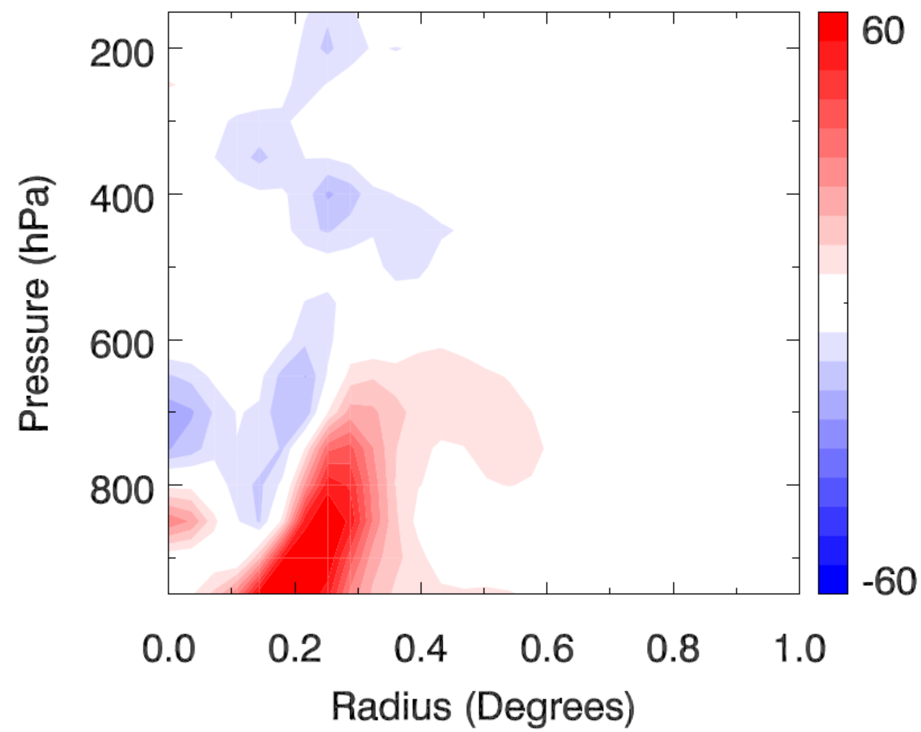
Stretching of Absolute Curvature Vorticity

- Stretching of curvature vorticity follows that of divergence field
- Small negative tendencies associated with divergence found at inner radii and aloft
- Positive tendencies due to surface convergence

$$-(\zeta_c + f)\nabla \cdot V$$



Plan view of stretching of curvature vorticity for hour 42 at 900 hPa

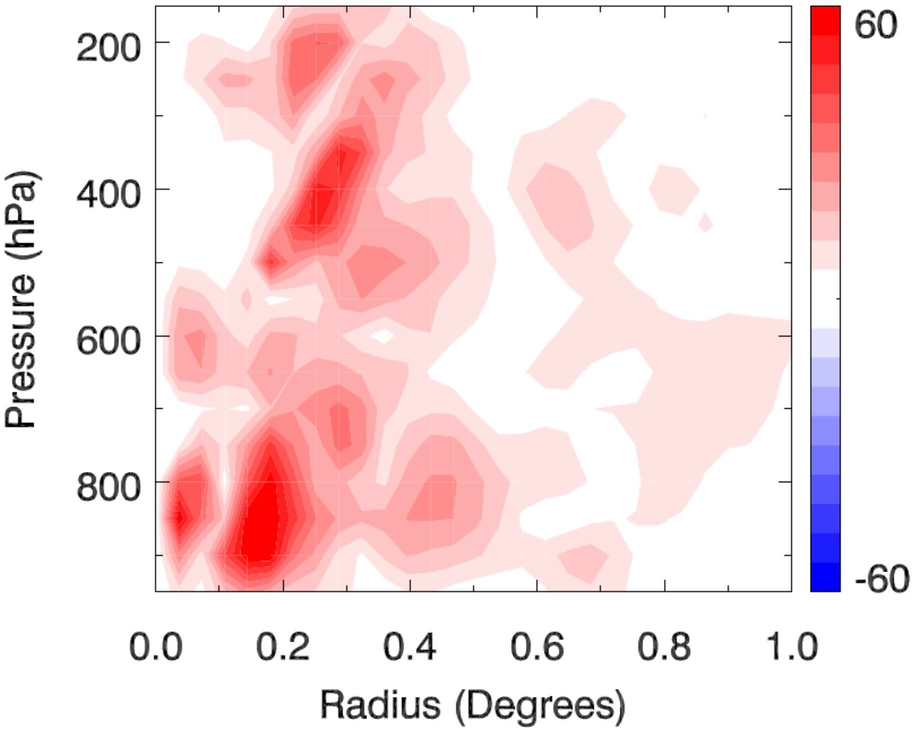


Vertical cross section of wavenumber 0 from spectral analysis at simulation hour 42

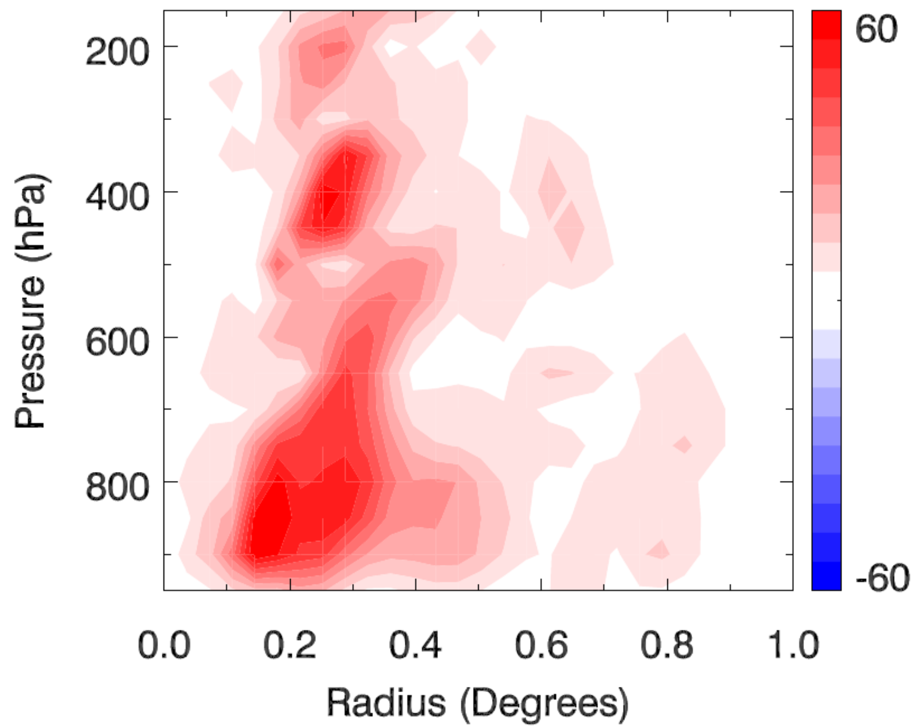
Tilting of Curvature Vorticity

- Tendencies limited to western side of vortex due to along flow gradient of vertical motion with predominantly positive values
- Temporally inconsistent net contribution on scale of mean
- Large asymmetries throughout vertical

$$-V \frac{\delta \omega}{\delta s} \frac{\partial \alpha}{\partial p}$$



Vertical cross section of wavenumber 1 from spectral analysis at simulation hour 42



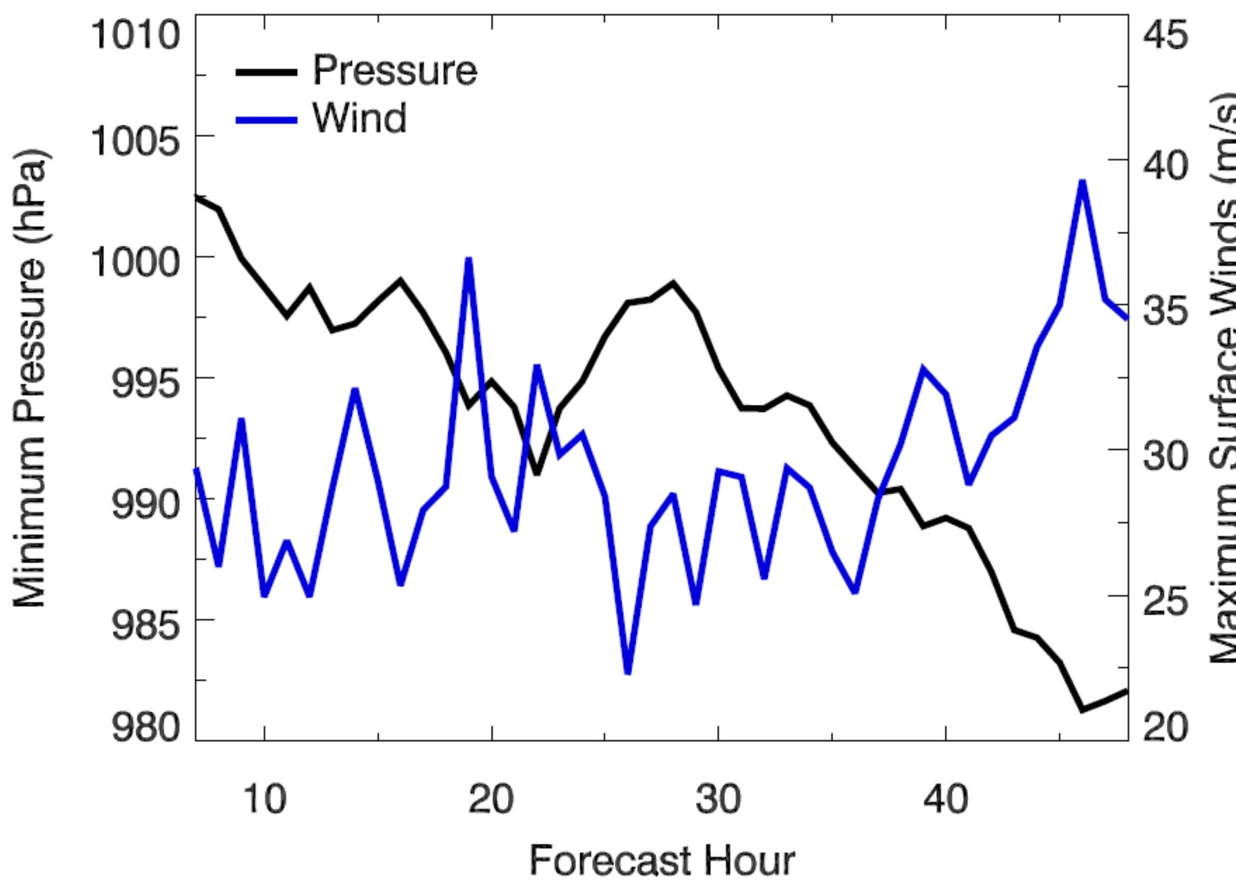
Vertical cross section of wavenumber 2 from spectral analysis at simulation hour 42

Summary of Results

- Each of the terms examined was shown to have distinct asymmetries throughout the domain
- Difficulties exist in trying to estimate the net contribution of each term and making an intercomparison of terms
- Layer averages of areal averages of terms and their magnitudes are used to relate terms to each other
- Only results for the lowest layer, extending from 950 – 750 hPa, are shown

Hourly Time Series of Intensity

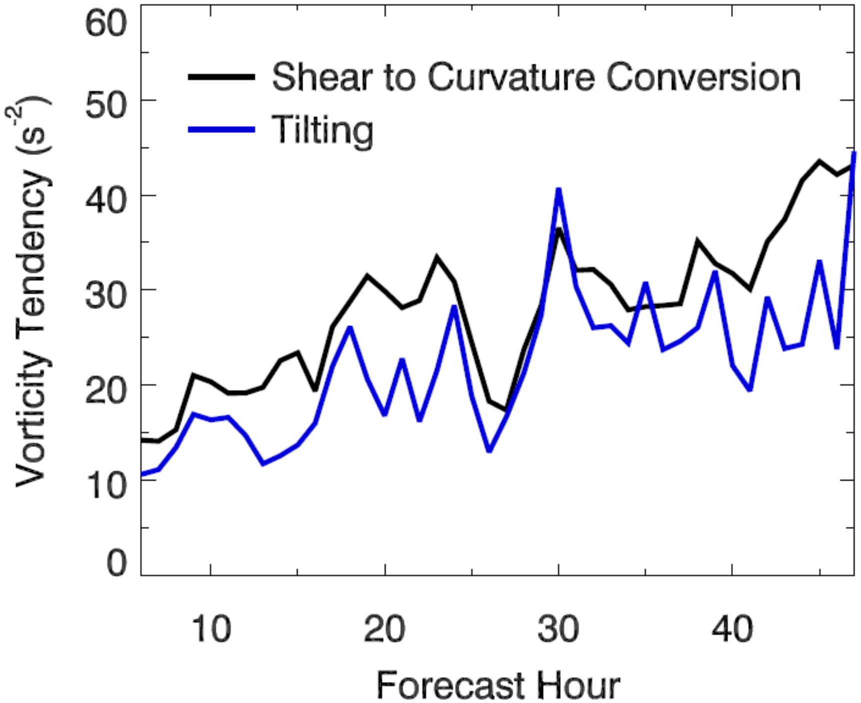
- Storm goes through three periods of intensity change



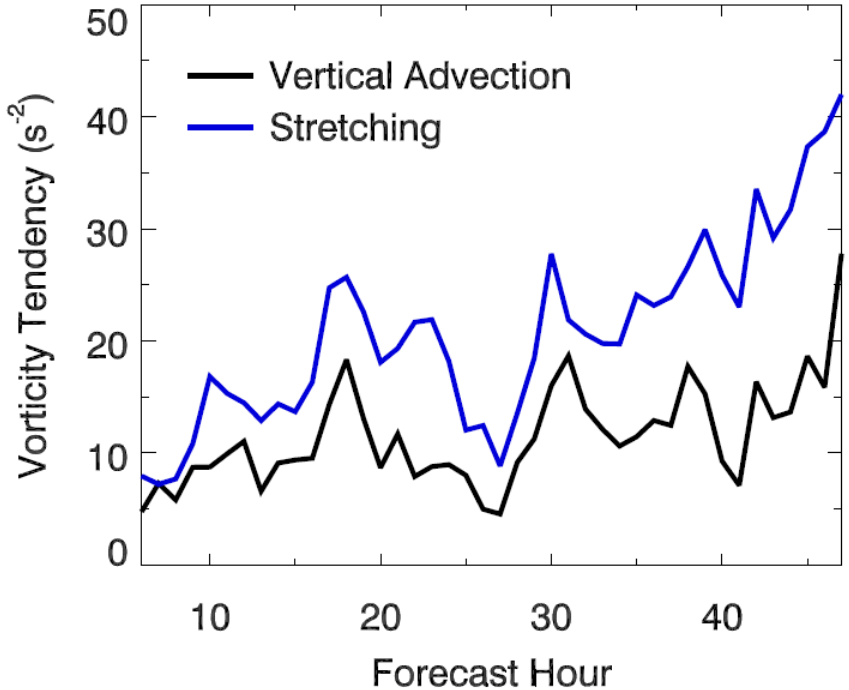
Hourly Time Series of Minimum Sea Level Pressure and 10 m Maximum Surface Wind

Intercomparison of Terms

- Magnitude of all terms increases throughout simulation
- Vorticity conversion term generally has largest magnitude
- Stretching term becomes relatively more important during second stage of intensification



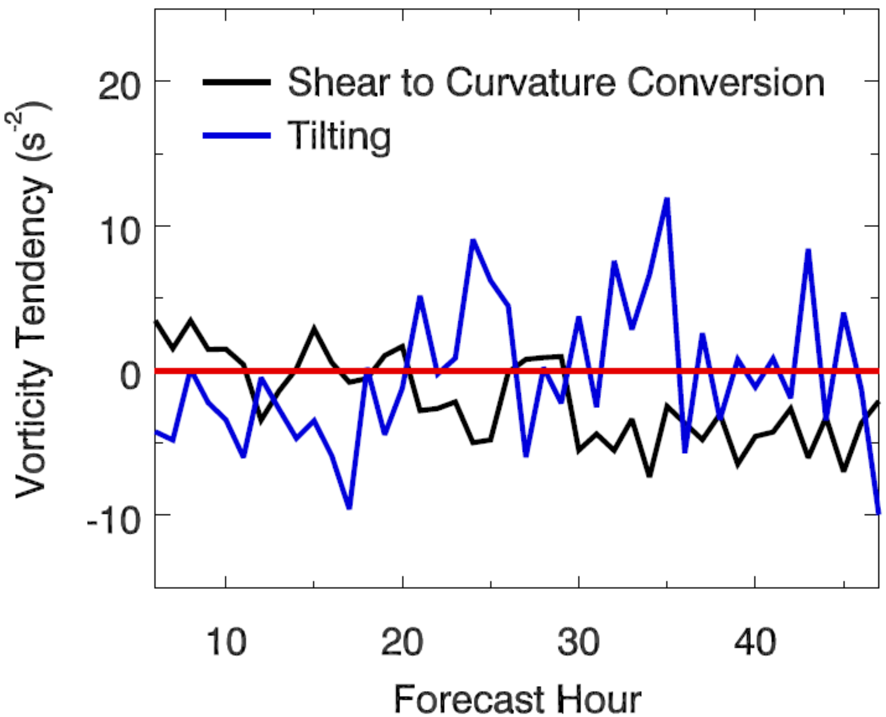
Layer average magnitude of shear to curvature vorticity conversion and tilting terms ($10^{-8}\ s^{-2}$)



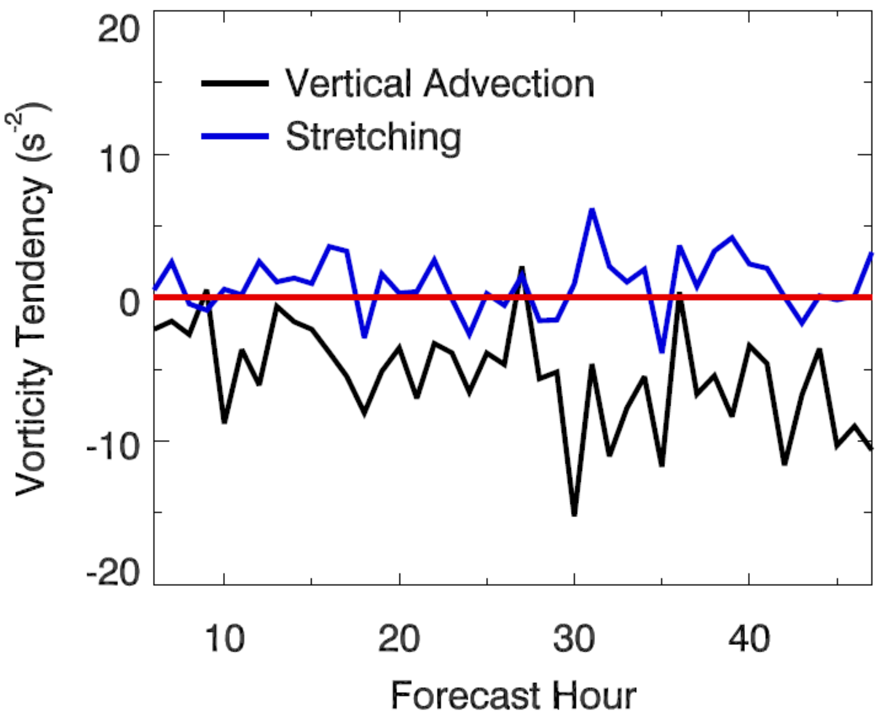
Layer average magnitude of vertical advection and stretching terms ($10^{-8}\ s^{-2}$)

Intercomparison of Terms

- Average magnitude of vorticity conversion term is negative in second half of simulation
- Vertical advection has strong negative contribution and stretching has net positive tendency



Layer average of shear to curvature conversion term and tilting term ($10^{-8}\ s^{-2}$)

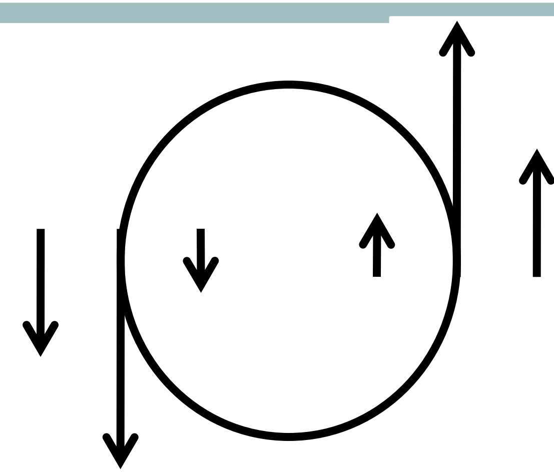


Layer average of vertical advection term and stretching term ($10^{-8}\ s^{-2}$)

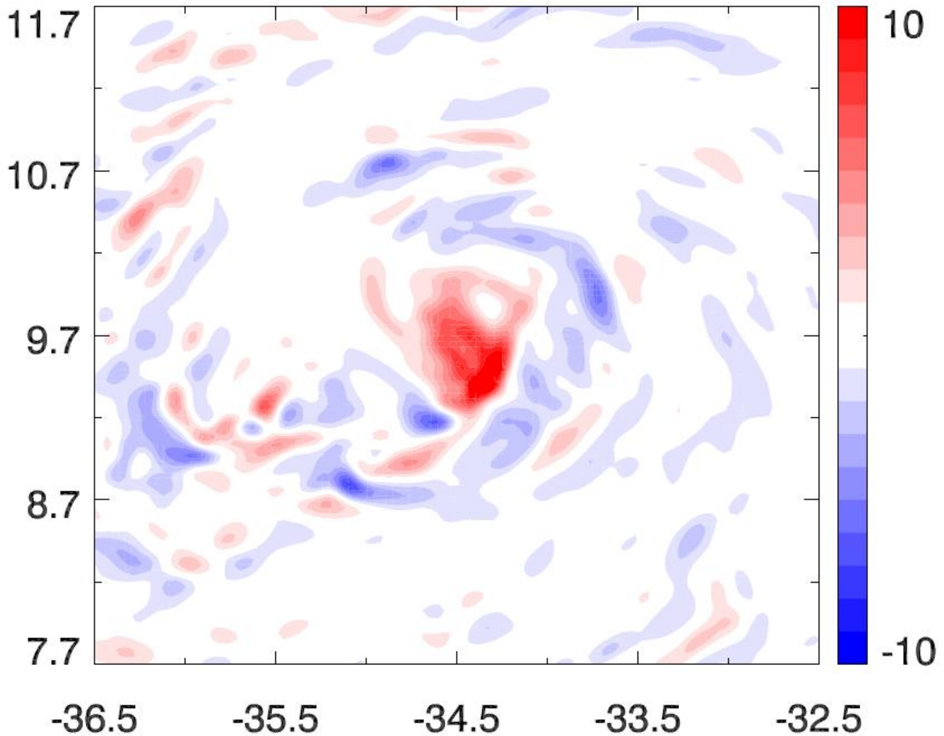
Shear Vorticity Budgets

Shear Vorticity

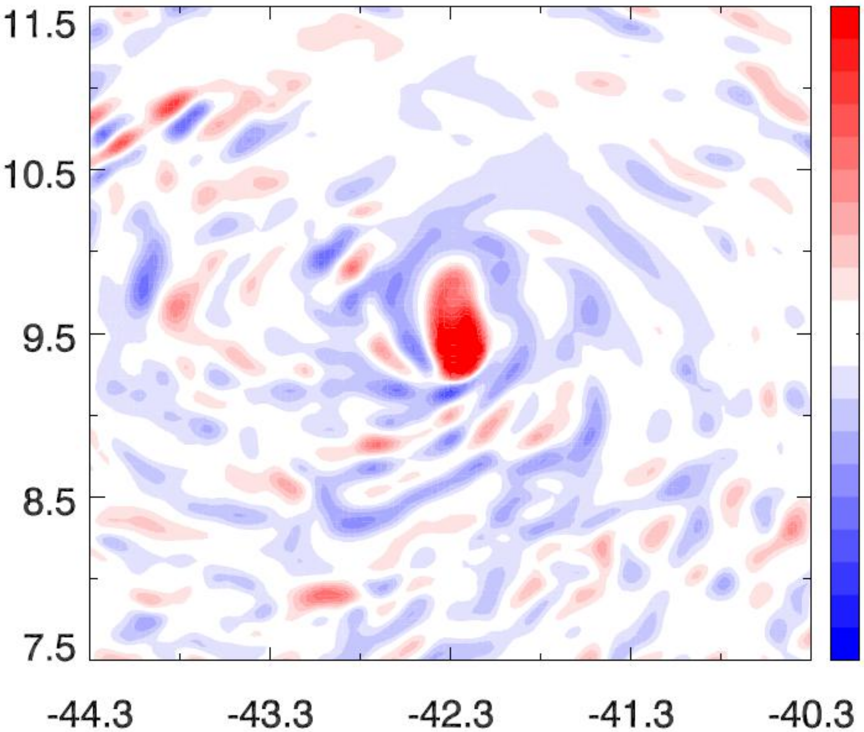
- Cyclonic shear vorticity maxima at center inwards of RMW
- Anticyclonic shear vorticity outwards of RMW
- Cyclonic vorticity maximum will expand and weaken with height



$$-\frac{\delta V}{\delta n}$$



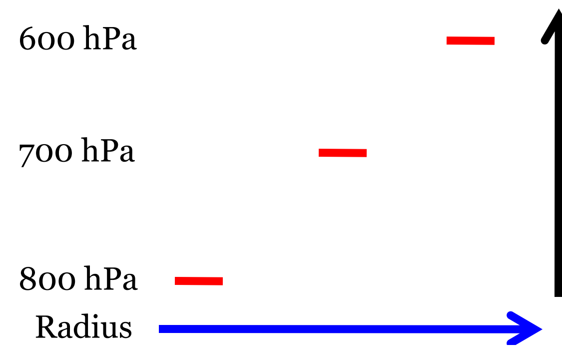
Plan view of shear vorticity for simulation hour 12 at 900 hPa



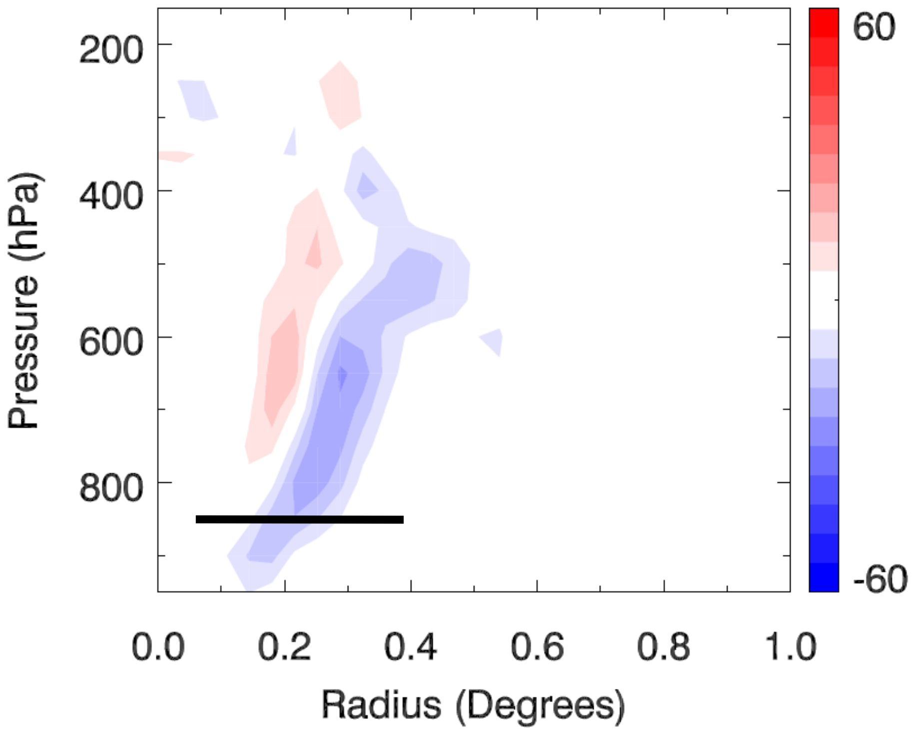
Plan view of shear vorticity for simulation hour 42 at 900 hPa

Vertical Advection of Shear Vorticity

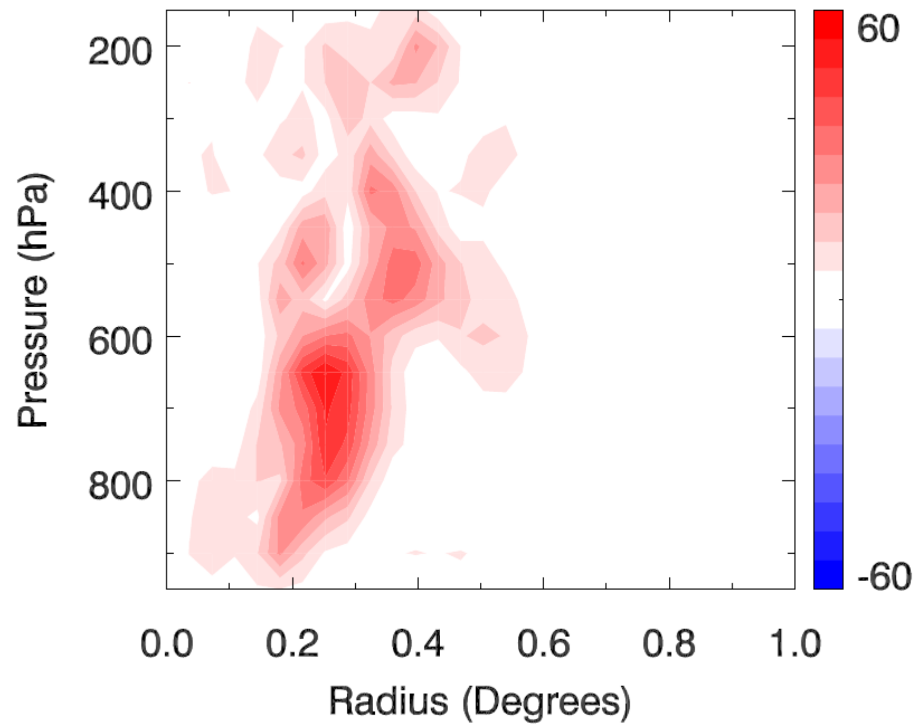
- Negative tendency found on South/West part of TC
- Negative tendencies found at low levels due to upgradient fluxes at small radii
- Presence of positive tendencies inwards and negative tendencies outwards due to expansion of RMW with height



$$-\omega \frac{\partial \zeta_s}{\partial p}$$



Vertical cross section of wavenumber 0 from spectral analysis at simulation hour 42

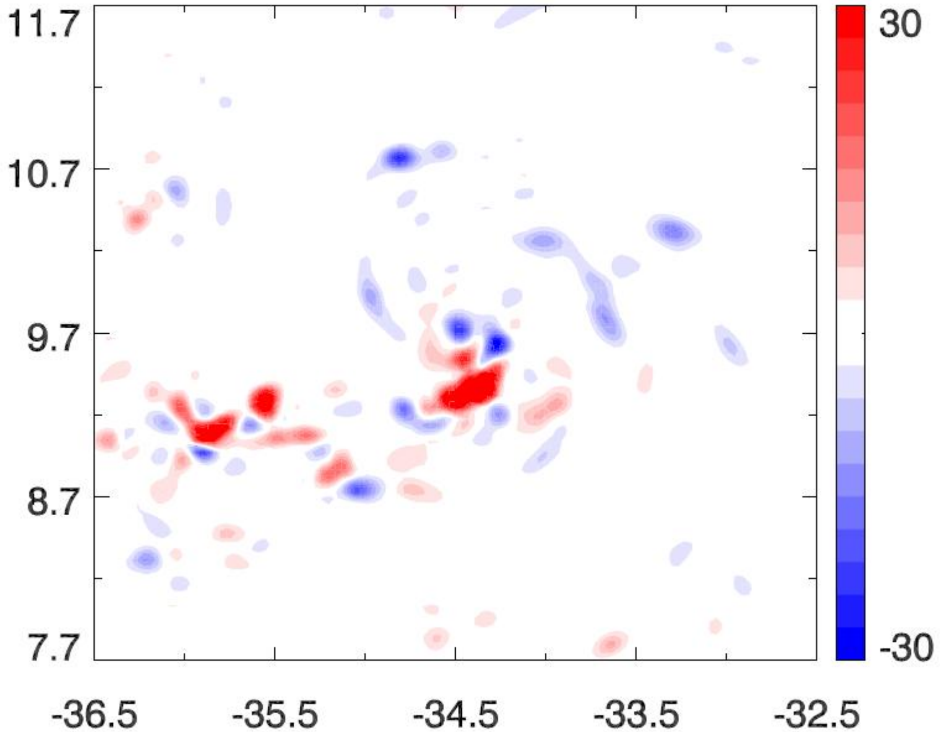


Vertical cross section of wavenumber 1 from spectral analysis at simulation hour 42

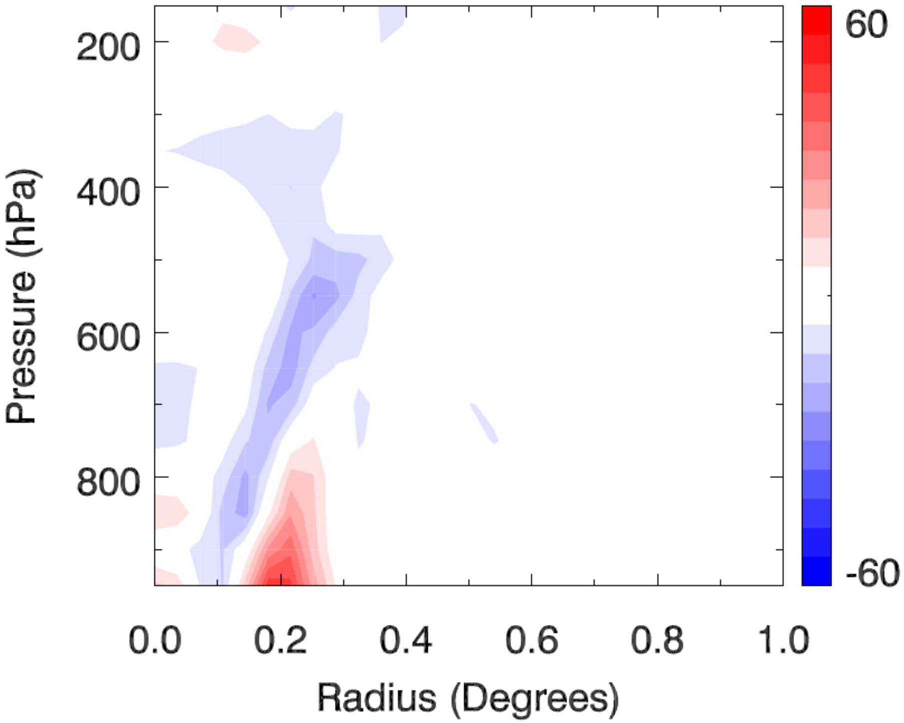
Stretching of Shear Vorticity

$$-(\zeta_s)\nabla \cdot V$$

- Positive stretching tendencies at low level with surface convergence
- Negative tendencies aloft with compensating divergence
- Negative tendencies inwards with divergence at inner radii with nascent eye



Plan view of stretching of shear vorticity for hour 12 at 900 hPa

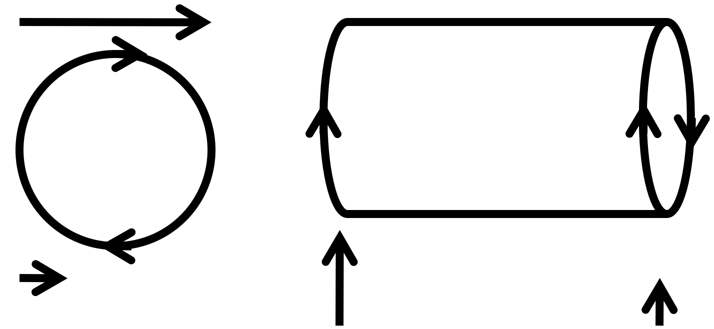


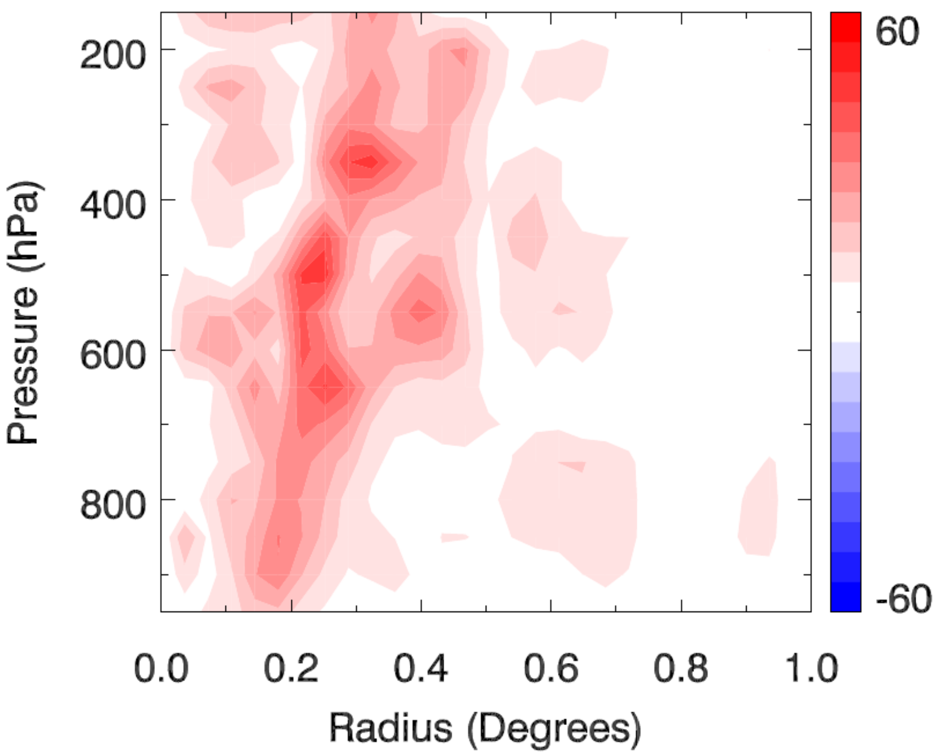
Vertical cross section of wavenumber 0 from spectral analysis at simulation hour 42

Tilting of Shear Vorticity

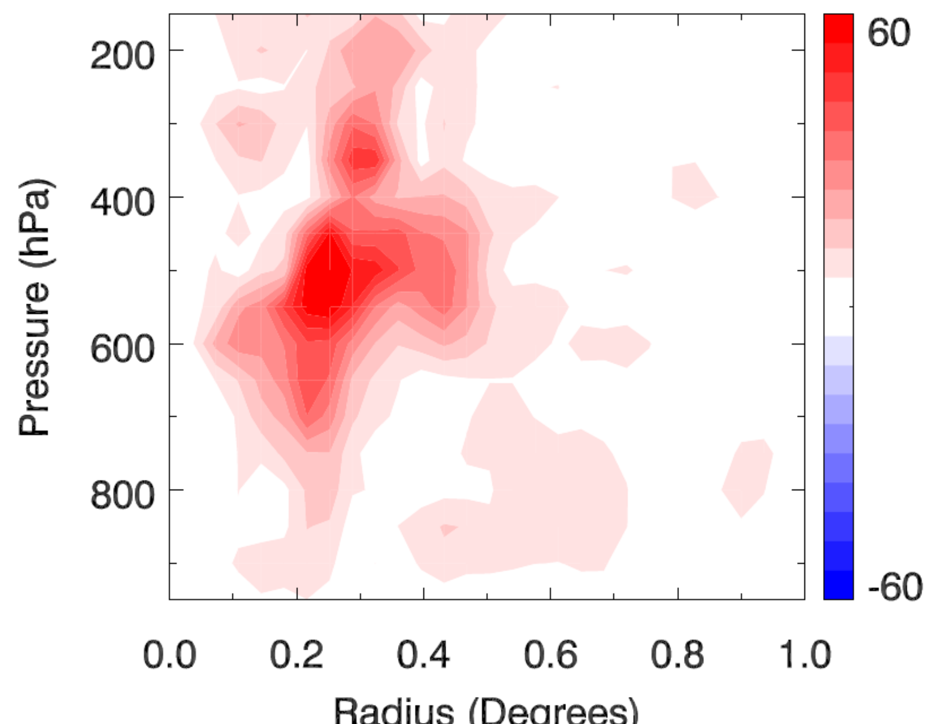
$$\frac{\delta\omega}{\delta n}\frac{\partial V}{\partial p}$$

- Confined near center due to flow normal gradients of vertical motion with positive values to South of storm and negative values radially outwards
- Temporally inconsistent contribution on scale of mean
- Wavenumbers 1 and 2 maximized at mid-to-upper levels





Vertical cross section of wavenumber 1 from spectral analysis at simulation hour 42



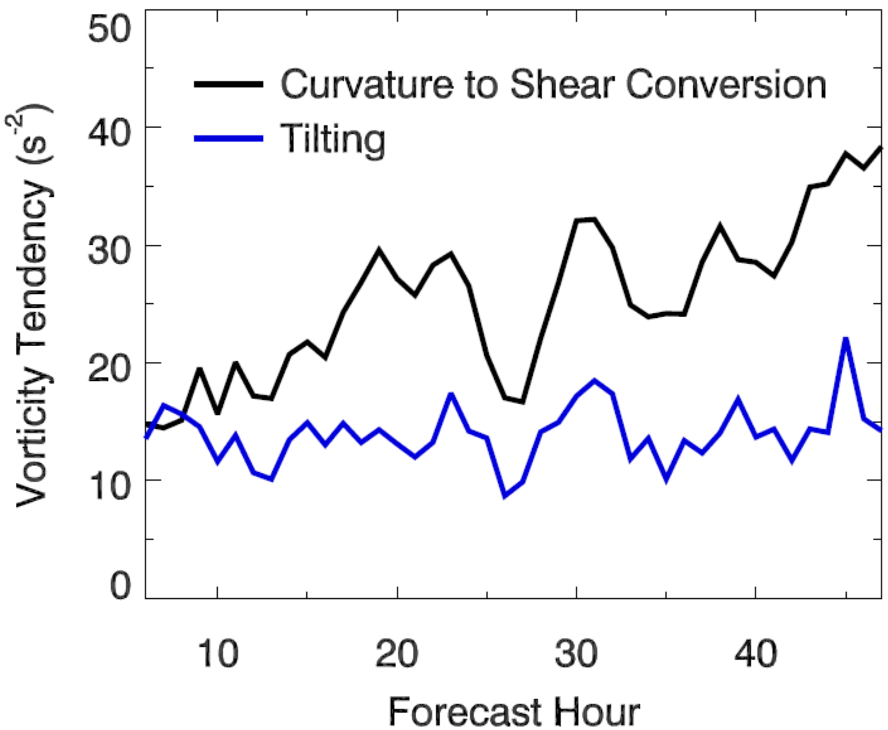
Vertical cross section of wavenumber 2 from spectral analysis at simulation hour 42

Summary of Results

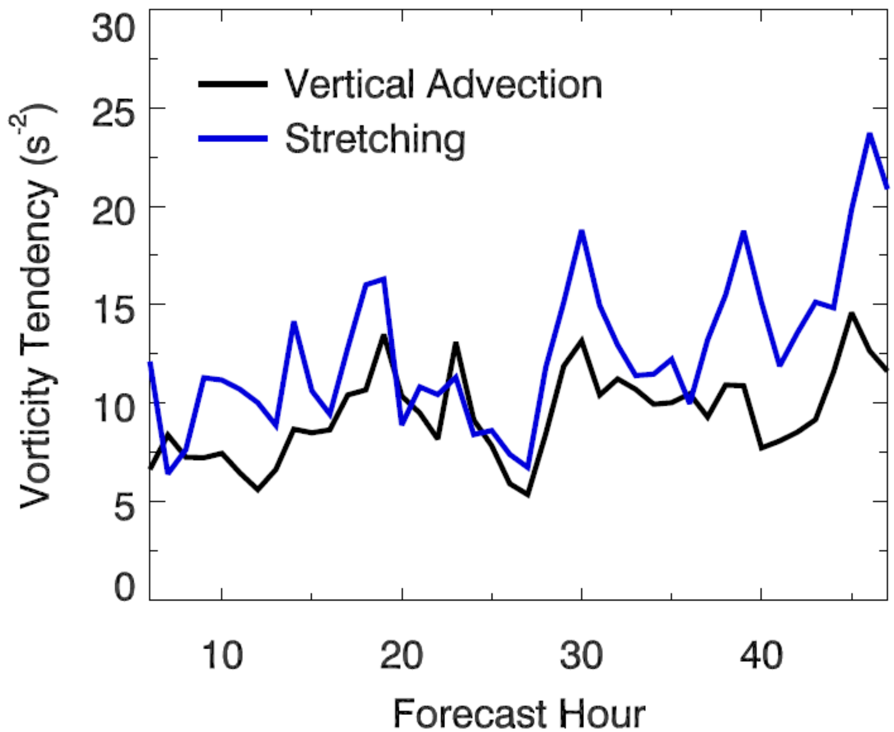
- Once again the terms are shown to have asymmetries throughout the domain making it difficult to relate tendency terms to each other
- For purposes of comparison, layer averages of areal averages of the terms and their magnitudes are computed
- Only results in the lowest layer, 750 – 950 hPa, will be shown

Intercomparison of Terms

- Curvature to shear vorticity tendency has strongest magnitude
- Stretching has large magnitude increase during latter portion of simulation



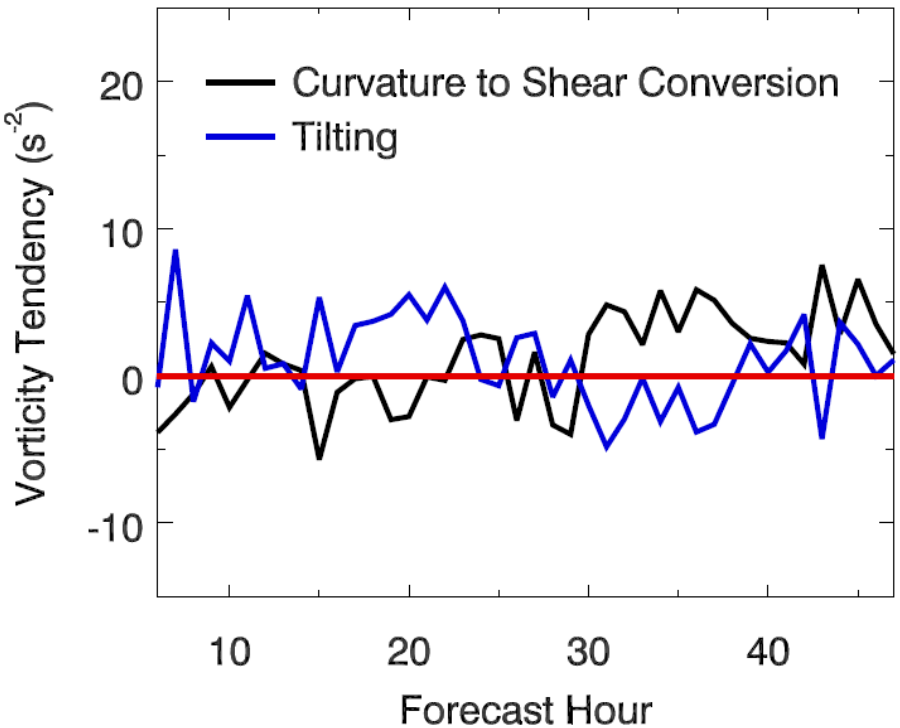
Layer average magnitude of curvature to shear vorticity conversion and tilting terms (10^{-8} s^{-2})



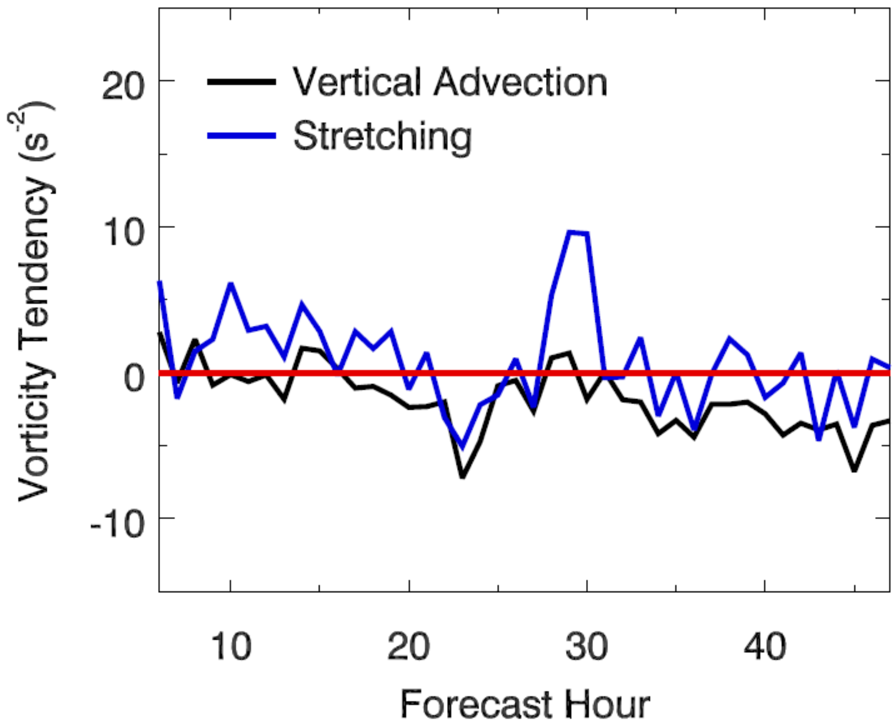
Layer average magnitude of vertical advection and stretching term (10^{-8} s^{-2})

Intercomparison of Terms

- Curvature to shear vorticity conversion becomes predominantly negative prior to second half of simulation
- Vertical advection negative throughout simulation



Layer average of curvature to shear vorticity conversion and tilting term (10^{-8} s^{-2})



Layer average of vertical advection and stretching term (10^{-8} s^{-2})

Correlation with Intensity Change

- Strong correlation between layer averages of vorticity tendency terms and hourly intensity change (minimum sea level pressure) in either equation not present

- Correlation coefficients computed for layer average magnitudes:
  1. Show weak relationships (range from 0.24 to 0.41) that do not change significantly throughout vertical
  2. Upper level has lowest correlation coefficient values

- Correlation coefficients computed for layer average values:
  1. Values are slightly larger and have much wider range than for layer average magnitudes
  2. Little consistency between coefficients from level to level
  3. Range is from 0.52 (stretching of curvature vorticity in lowest layer) to -0.01 (shear to curvature vorticity conversion term at upper levels)
  4. Existence of positive correlation coefficients at lower levels needs further investigation

Conclusions

Conclusions

- Case study of TC Ivan (2004) simulated used in curvature vorticity and shear vorticity budget study
- All terms showed asymmetries due to vertical wind shear
- For relevant curvature vorticity tendency terms:
  1. Vertical advection contains negative values at surface and positive values above level of maximum vorticity due to reversal of vertical vorticity gradient
  2. Shear to curvature vorticity conversion term yields dipole at low levels with a net negative contribution at later hours in the simulation due to divergence induced by vertical shear
  3. Stretching of vorticity contains positive tendencies at surface at outer radii associated with convergence and negative tendencies aloft and at inner radii due to divergence.
  4. Tilting tendencies limited to western side of TC with significant asymmetries in vertical

Conclusions

- For relevant shear vorticity tendency terms:
  1. Vertical advection of vorticity associated with negative values at the surface and both negative and positive values above level of maximum vorticity due to reversal of vertical vorticity gradient and expansion of RMW
  2. Stretching term yields patterns similar to the corresponding curvature vorticity tendency term
  3. Tilting of vorticity contains tendencies limited to the vortex center with significant asymmetries in the vertical especially at mid-levels

- For both the shear and curvature vorticity tendency equations, layer averages of magnitudes of terms showed shear to curvature vorticity conversion term with largest average magnitude in all layers with the tilting term also being important at mid-to-upper levels

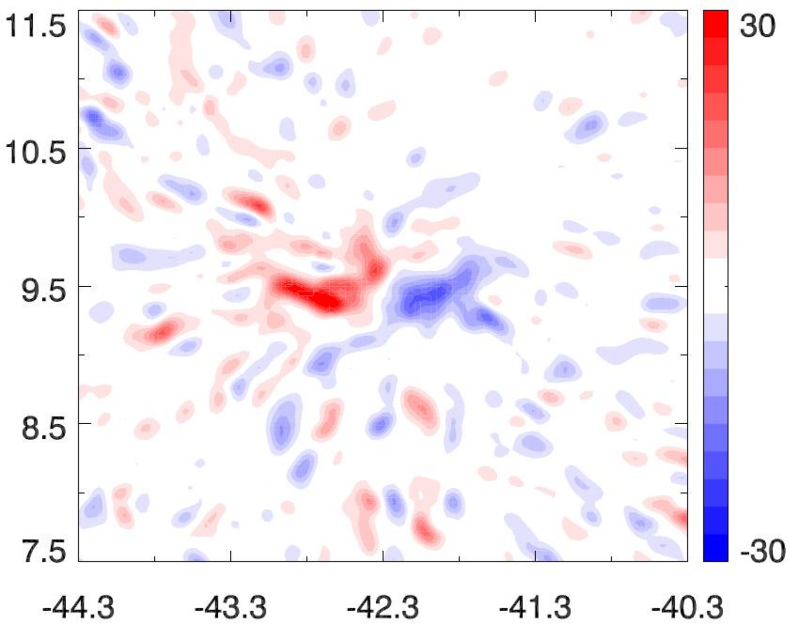
Conclusions

- Layer averages of curvature tendency equation show net conversion of curvature vorticity into shear vorticity, negative vertical advection tendencies, and positive stretching tendencies
- Layer averages of shear vorticity tendency equation show net conversion of curvature vorticity into shear vorticity and negative vertical advection tendencies at low levels
- Correlation of layer averages with intensity change show only weak relationships with either minimum sea level pressure or maximum surface wind speed
- The low correlation values may be attributed to layers chosen for averaging

Future Work

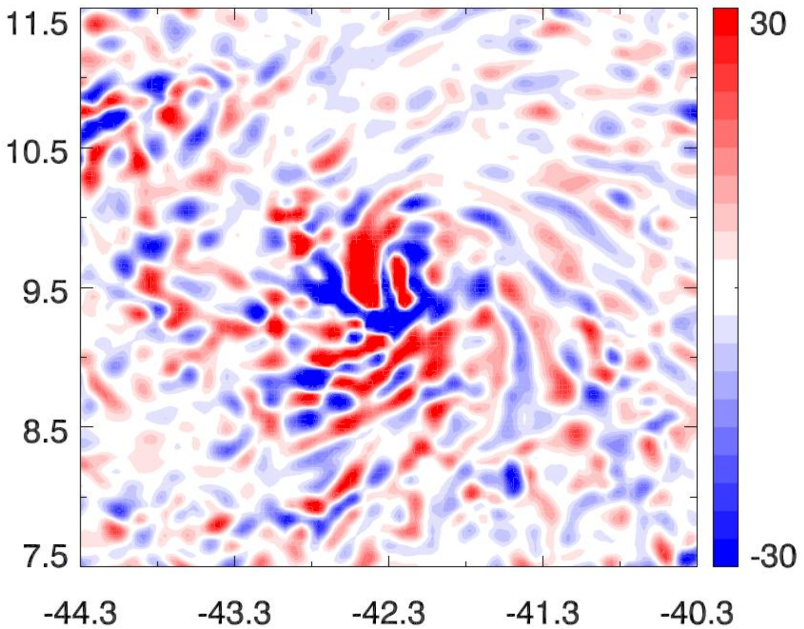
1. Correct derivation of curvature vorticity tendency equations and shear vorticity tendency equations as given in Viúdez and Haney (1996) needs to be used.

2. Computations should be done in a storm relative reference frame rather than an Earth relative frame.



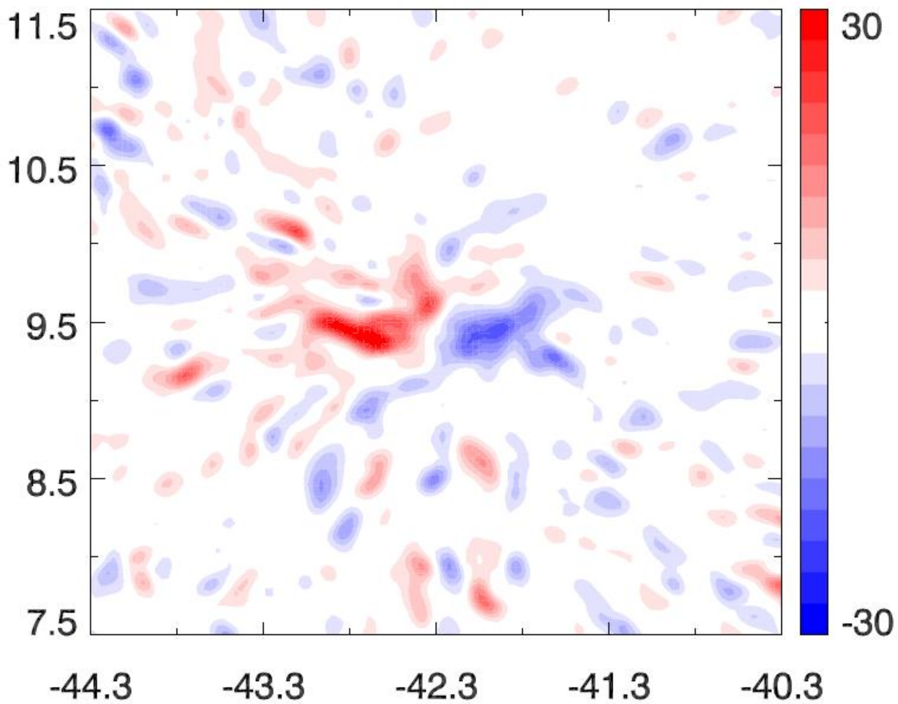
Left: eulerian curvature vorticity time tendency

Right: Horizonal advection of shear vorticity

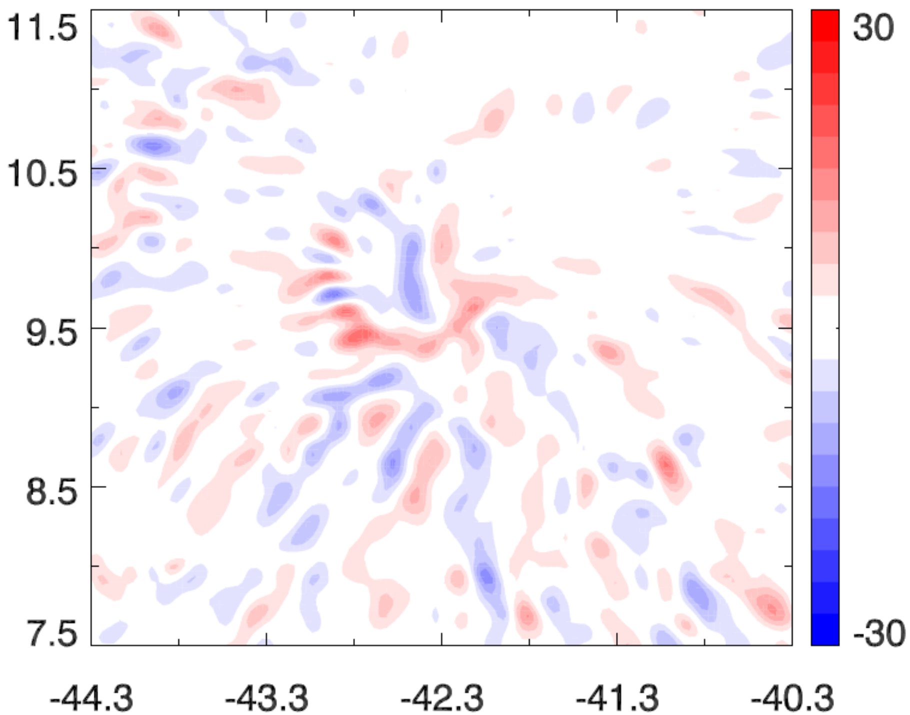


Storm Relative Versus Earth Relative

- Comparison of storm relative versus Earth relative computations for TC Ivan (2004) dramatically impacts Eulerian time tendency and horizontal advection terms



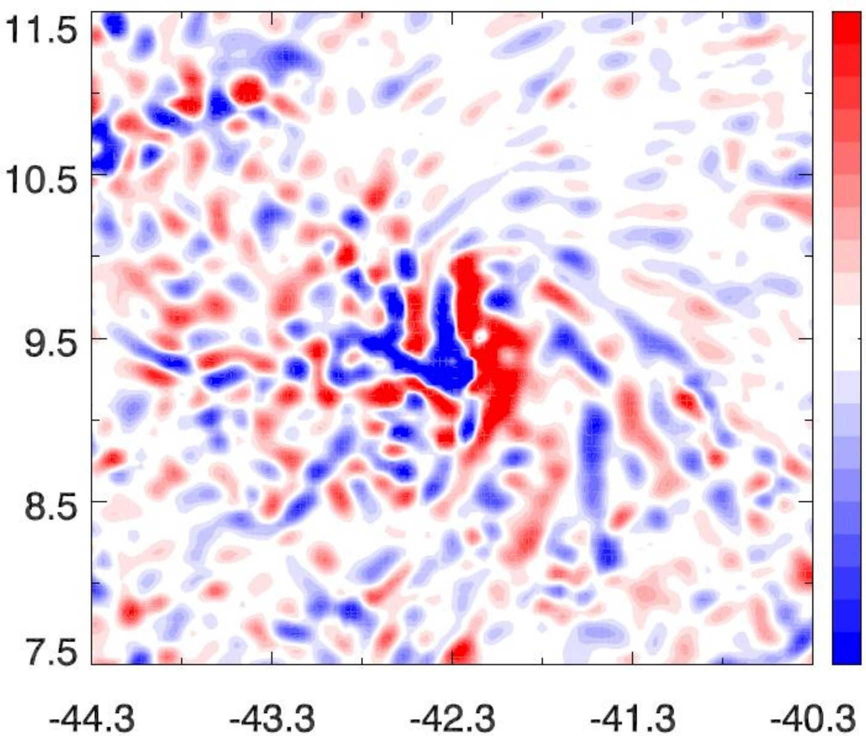
Earth relative Eulerian time tendency of curvature vorticity (10^{-8} s^{-2})



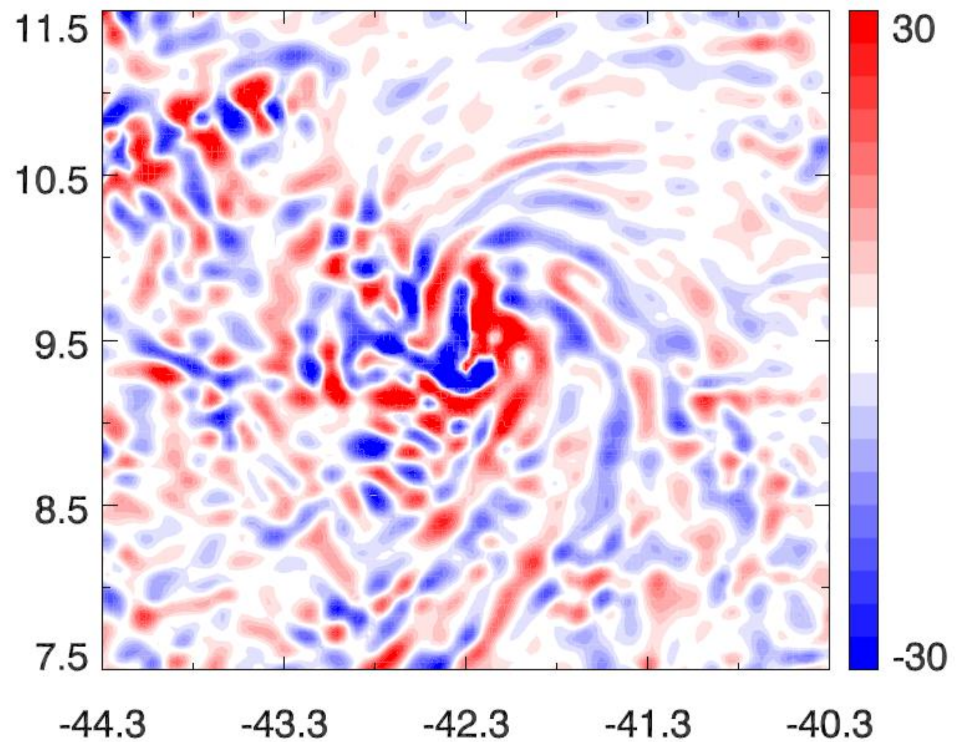
Storm relative Eulerian time tendency of curvature vorticity (10^{-8} s^{-2})

Storm Relative Versus Earth Relative

- Comparison does not yield substantial difference between other terms such as shear to curvature vorticity conversion term and stretching term



Earth relative shear to curvature vorticity conversion term ($10^{-8}\ s^{-2}$)



Storm relative shear to curvature vorticity conversion term ($10^{-8}\ s^{-2}$)

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