Tropical cyclone outflow and warm core structure as revealed by HS3 & TCI dropsonde data

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TCI telecon
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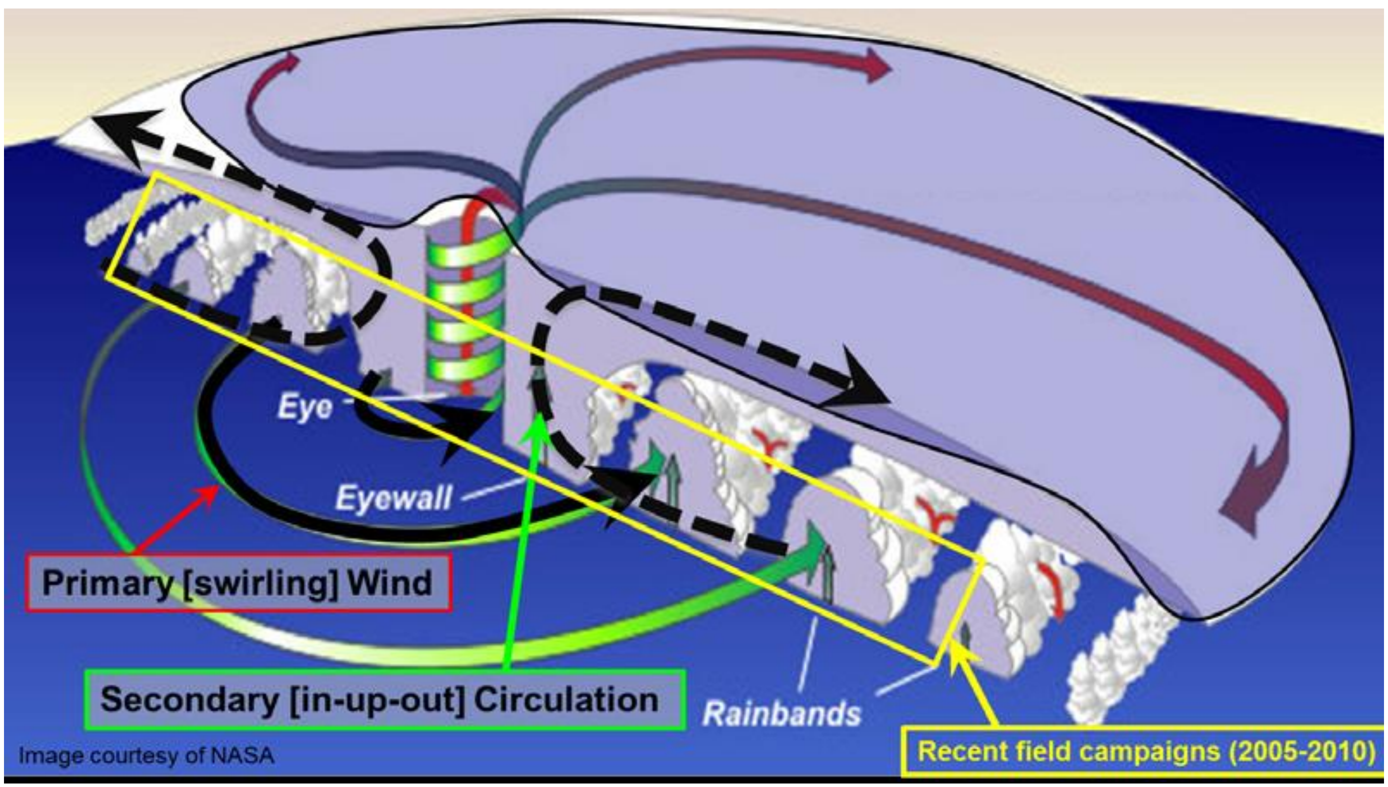
- High Performance Computing (HPC) time from the Navy Defense Resource Center (DSRC) at Stennis, MS

Background

- Until recently, single ER-2 flight investigating Hurricane Erin (2001) only direct dropsonde observations of tropical cyclone (TC) outflow layer (Halverson et al. 2006)
- Air Force C-130s, NOAA P-3s, much lower ~700 hPa
- NOAA G-IV ~150 hPa still misses some outflow; generally avoids TC core



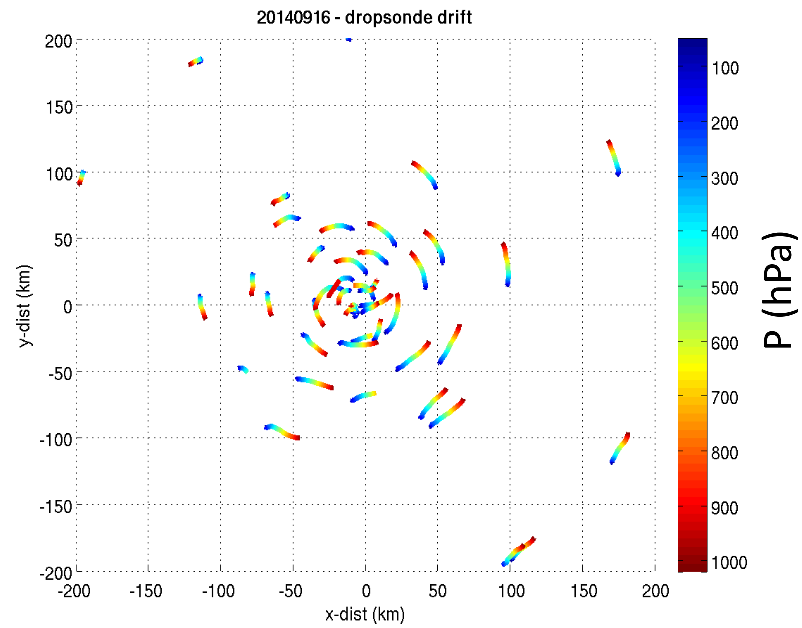
The NASA Hurricane and Severe Storm Sentinel (HS3)

- 2012-2014 in the Atlantic
- Primary goal: observe TC formation & intensity change, interaction between large-scale environment & internal dynamics (Braun et al. 2016)
- Aircraft: Global Hawk AV-6
  - 18-24 h flight time
  - Release at or above 100 mb
  - Sample both:
    - inner-core & environment
    - outflow & *outflow roots*, or region above TC core in which outflow originates
- Research missions flown: 22 (16 included here)

Date (1st dropsonde)	System Name	Classification	Intensity (kt)	Δ Intensity (kt)
2012-09-11	Nadine	TD	30	0
2012-09-14	Nadine	H	70	+10
2012-09-19	Nadine	TS	50	0
2012-09-22	Nadine	TS	45	+5
2012-09-26	Nadine	TS	50	+5
2013-08-29	Gabrielle	Pre-genesis	< 25	0
2013-09-04	Gabrielle	TD	30	0
2013-09-07	Gabrielle	Disturbance	25	0
2013-09-16	Humberto	TS	35	-5
2014-08-26	Cristobal	H	70	+5
2014-08-29	Cristobal	H	70	-10
2014-09-02	Dolly	TS	40	-5
2014-09-12	Edouard	TS	35	+5
2014-09-14	Edouard	H	80	+15
2014-09-16	Edouard	H	85	-20
2014-09-18	Edouard	H	65	-10

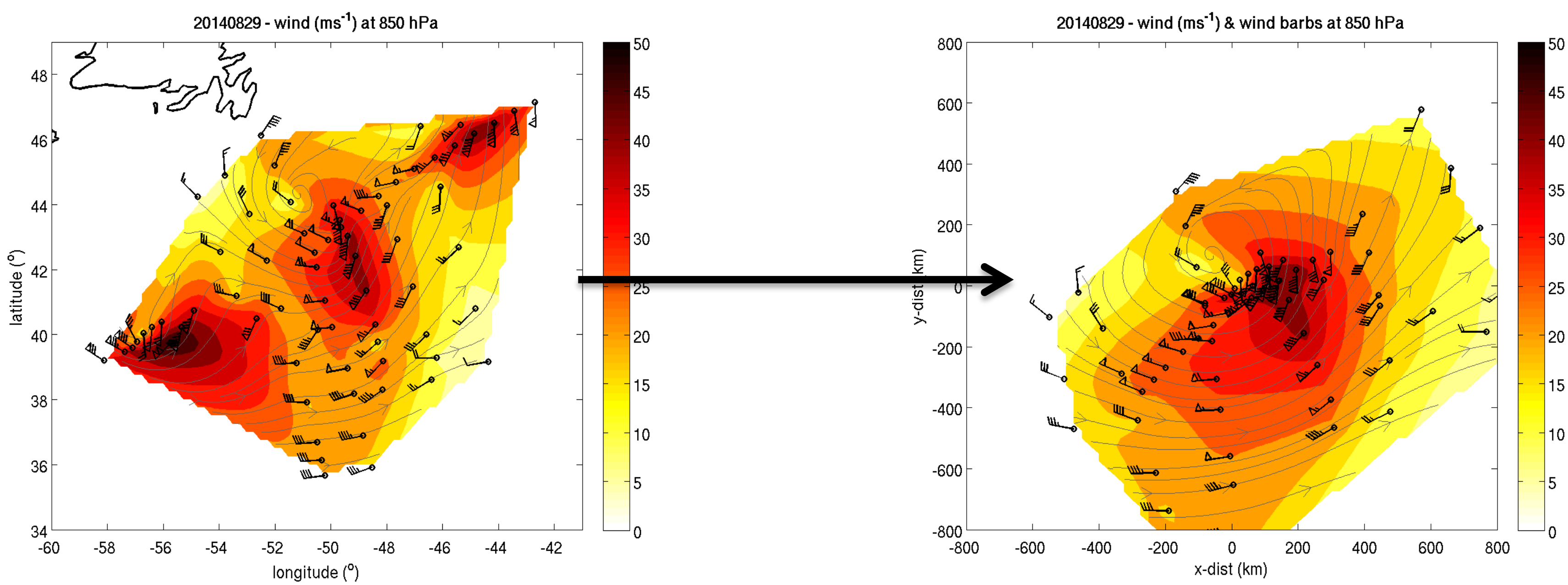
Methodology

- Drop locations computed in storm-relative coordinates, linear extrapolation of NHC best track (2 min HRD track when available)
- Dropsonde GPS lat/lon coordinates throughout fall used to account for “drift” (advection)
- Data from each dropsonde interpolated to P(hPa) every 5 mb
- Data then interpolated to 25-km x/y grid via triangulation-based natural neighbor interpolation (compromise between linear & cubic)



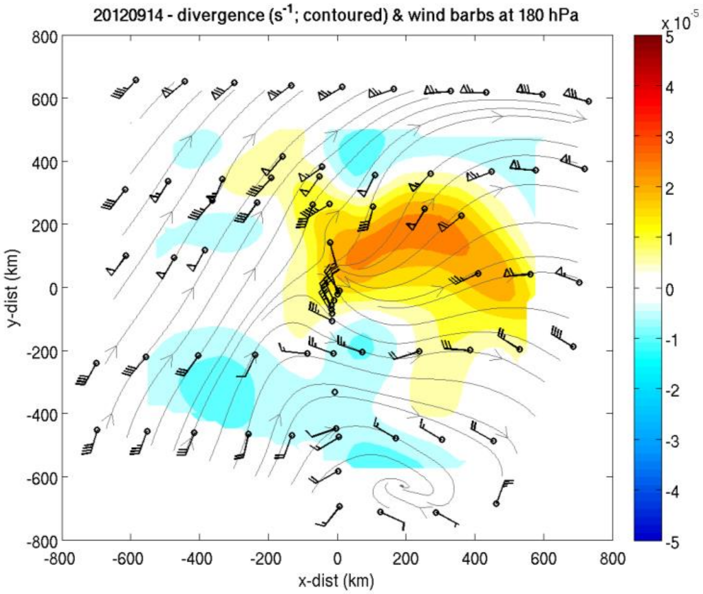
“Dropsonde drift” from release point to surface for H Edouard on 2014-09-16

H Cristobal, 850 hPa winds: Earth-relative (left) vs storm-relative (right)

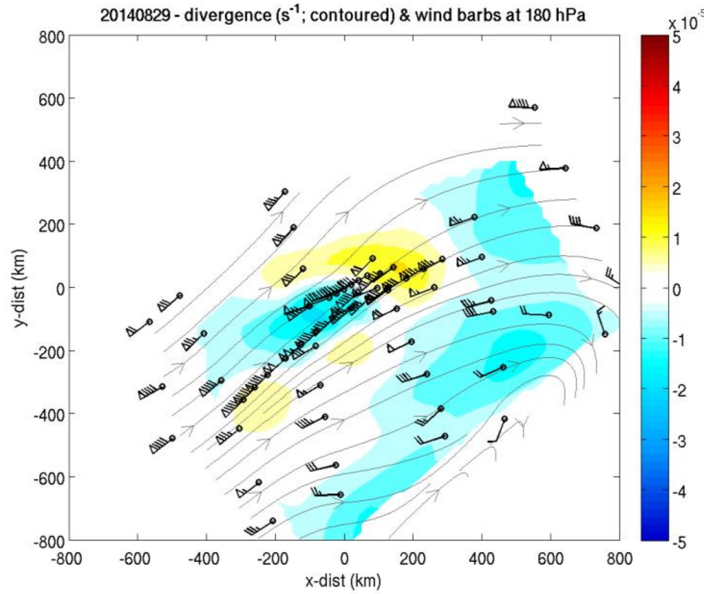


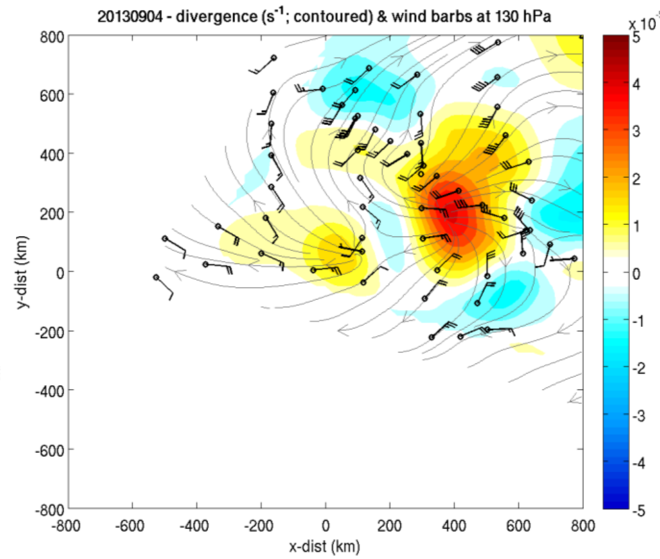
Association between strength of UL divergence and intensity trend

TS Nadine 70kt, strengthening

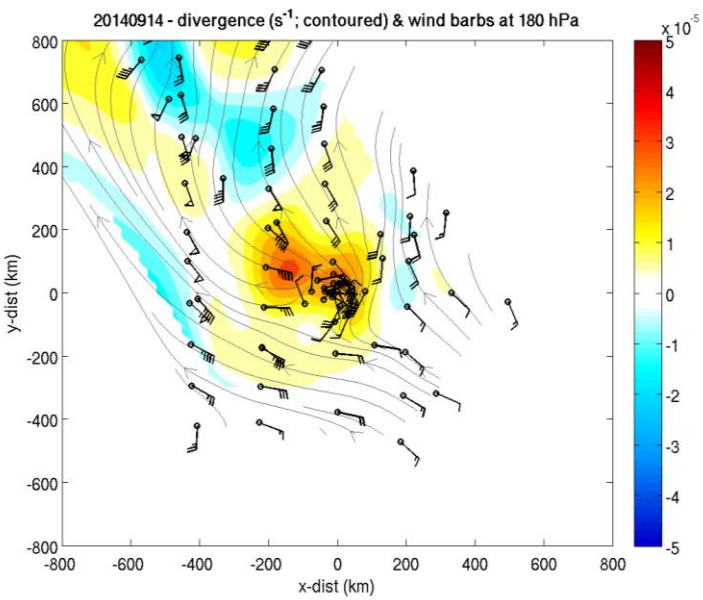


H Cristobal 70kt, weakening

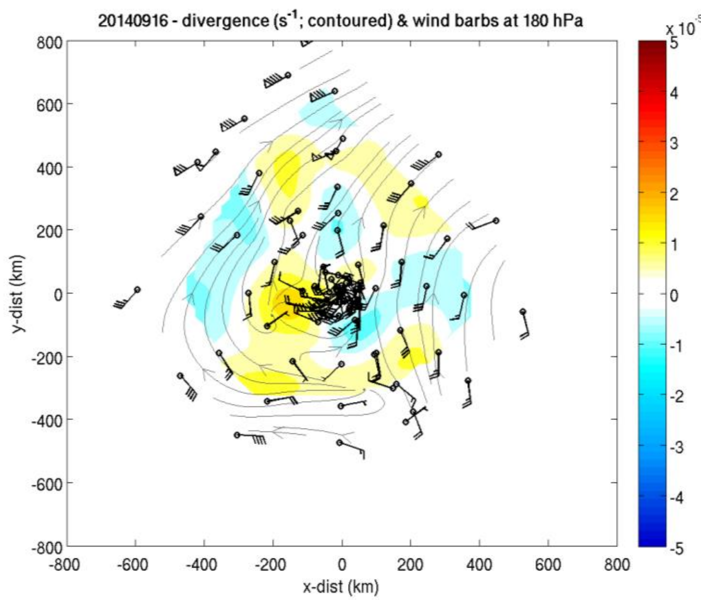




H Edouard 80kt, strengthening

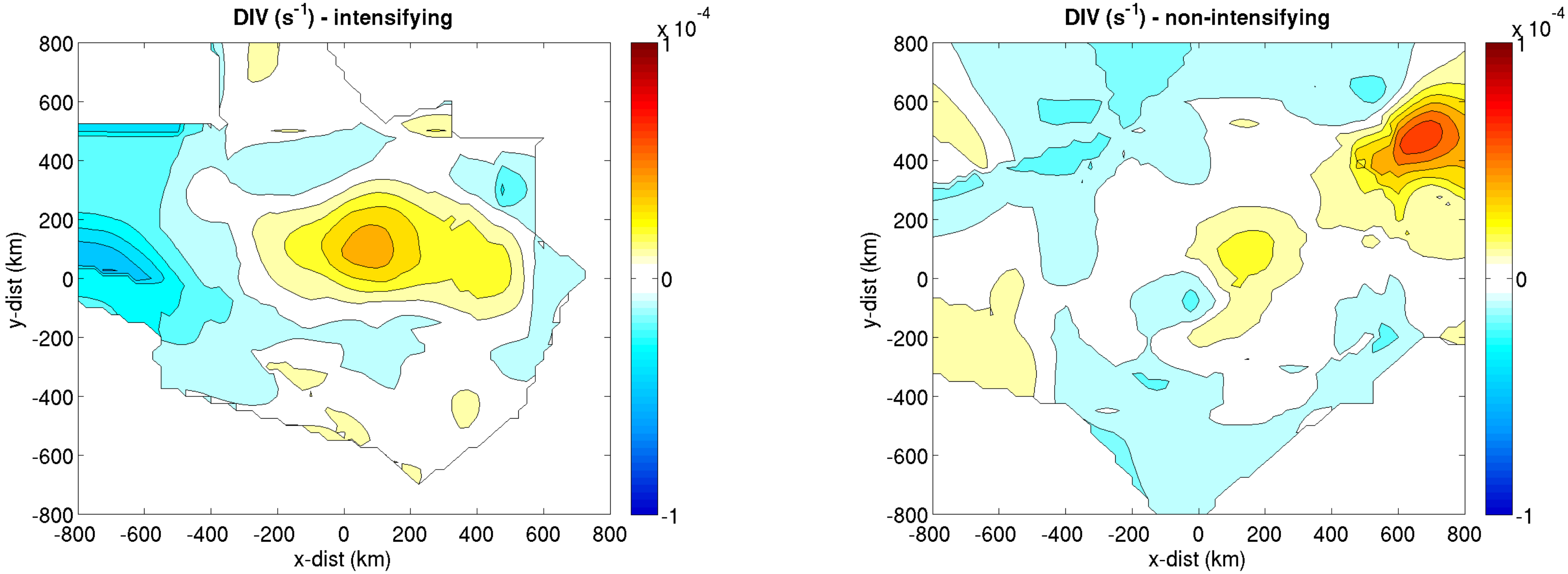


H Edouard 85kt, weakening

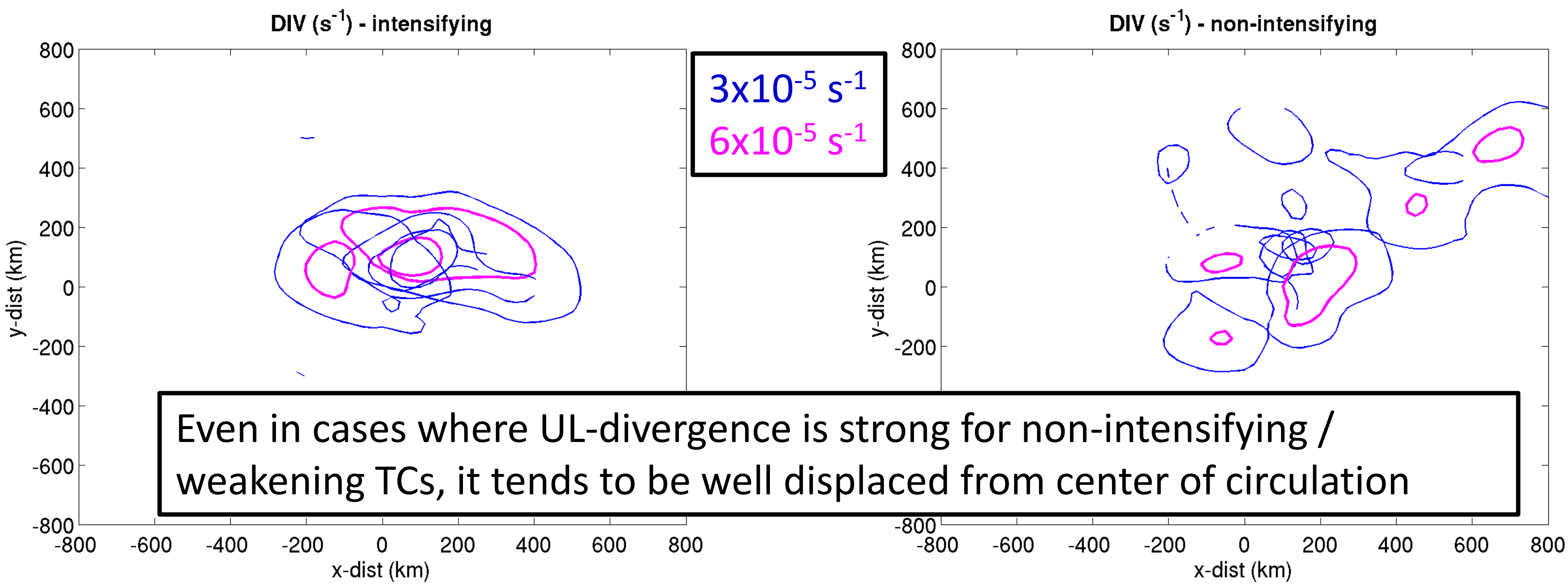


Does not always work: non-intensifying 30 kt Gabrielle

Mean divergence - all cases averaged



Contour each case individually, then composite the contours

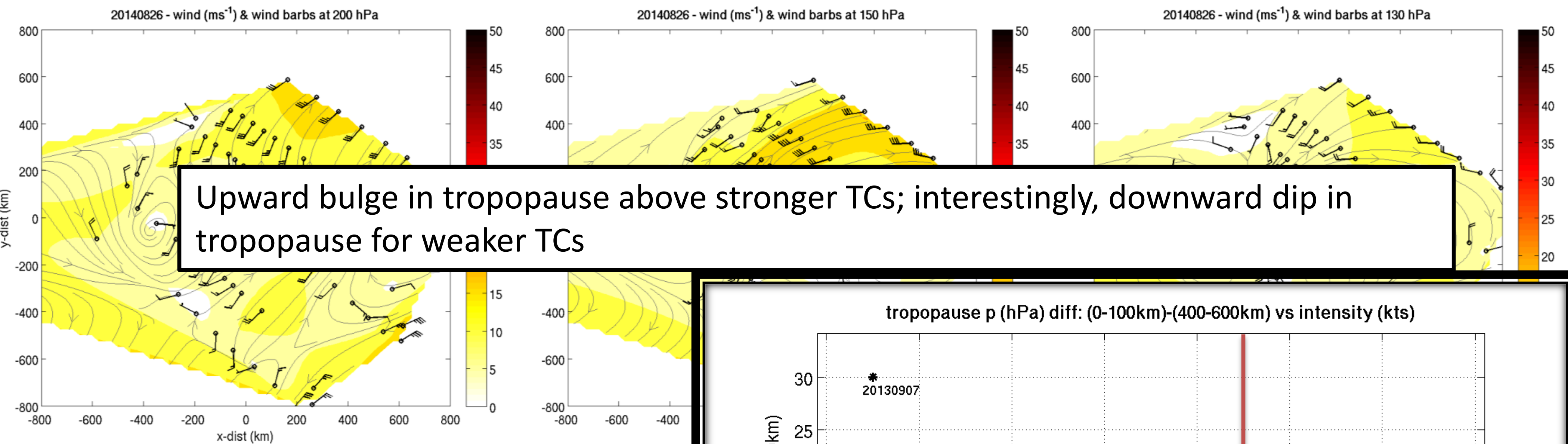


Even in cases where UL-divergence is strong for non-intensifying / weakening TCs, it tends to be well displaced from center of circulation

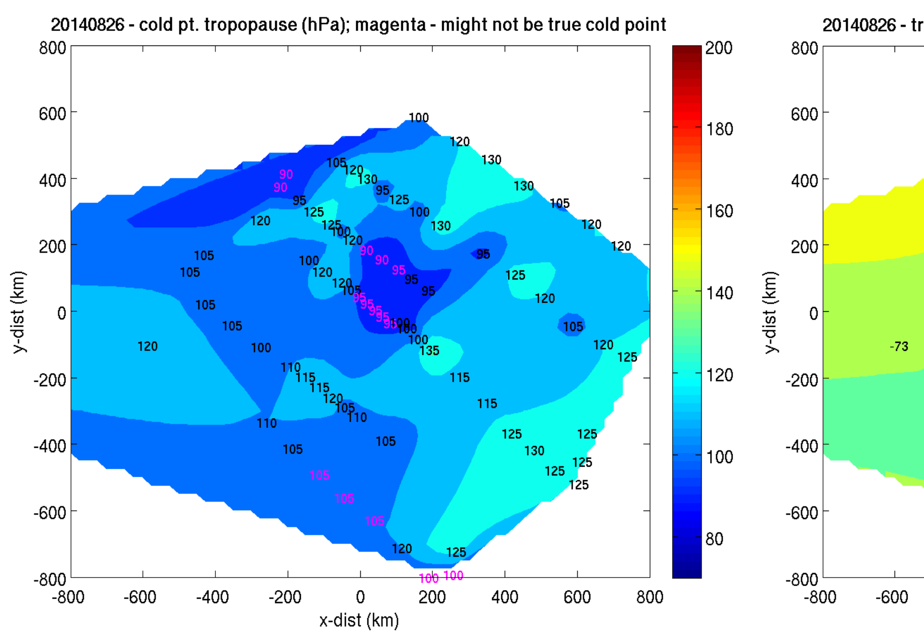
H Cristobal (2014) – dual outflow channels

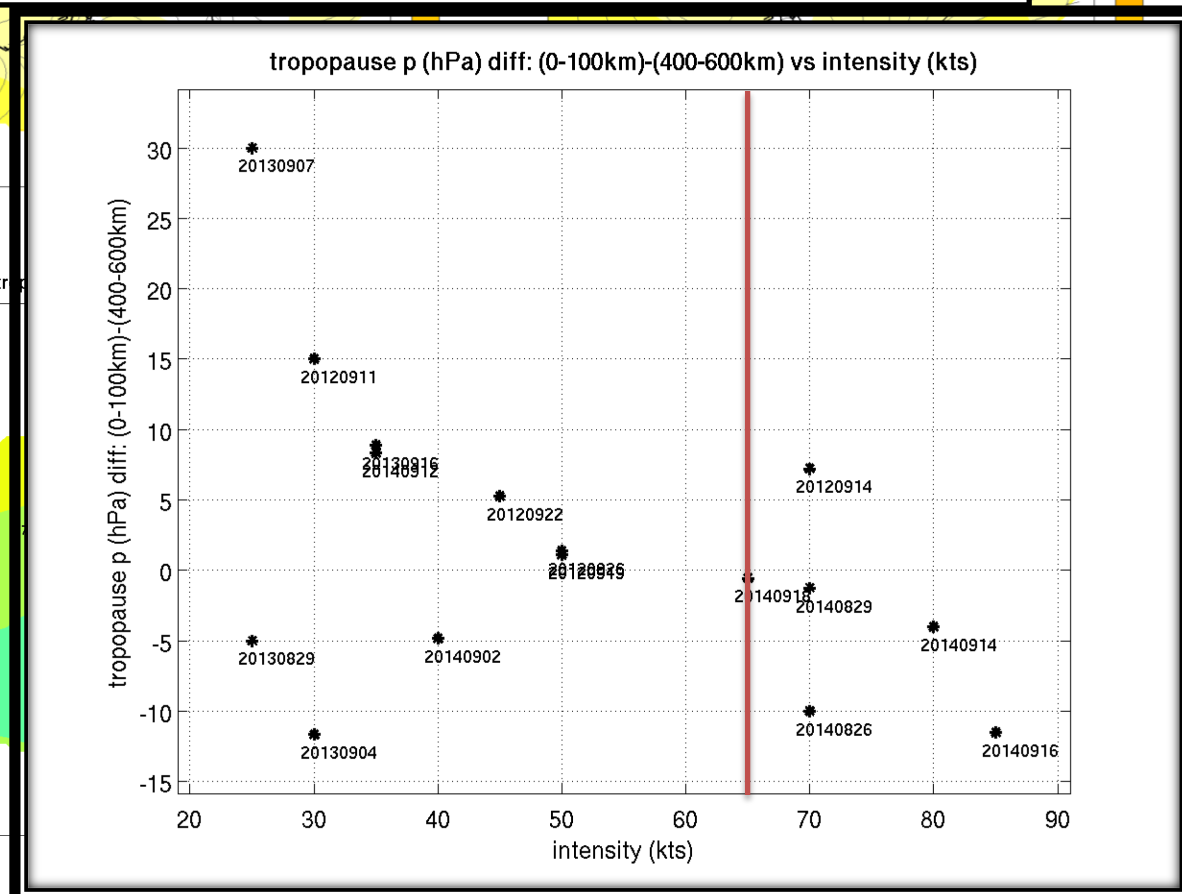
… but minimal intensification

Maximum S outflow occurs higher levels than max N outflow, consistent with Merrill and Velden (1996). Related to slope in tropopause p/T?



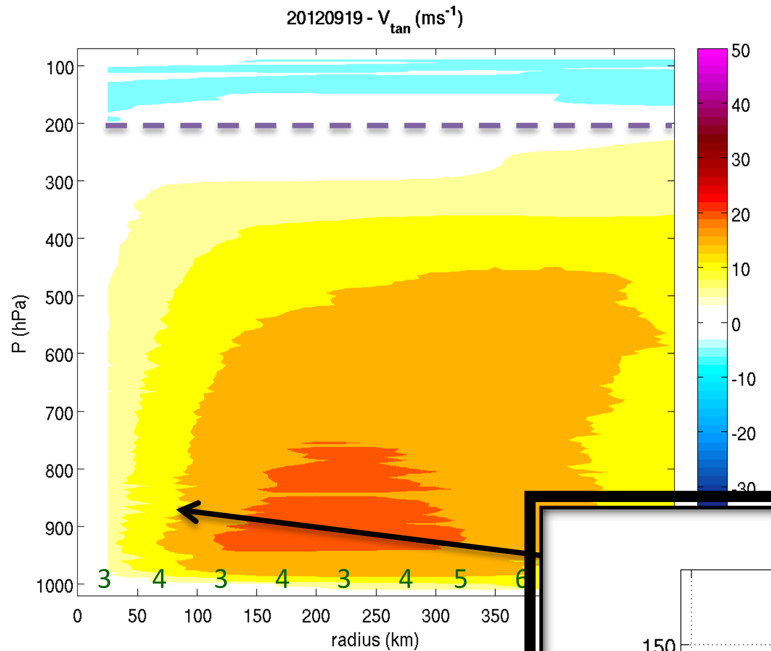
Upward bulge in tropopause above stronger TCs; interestingly, downward dip in tropopause for weaker TCs



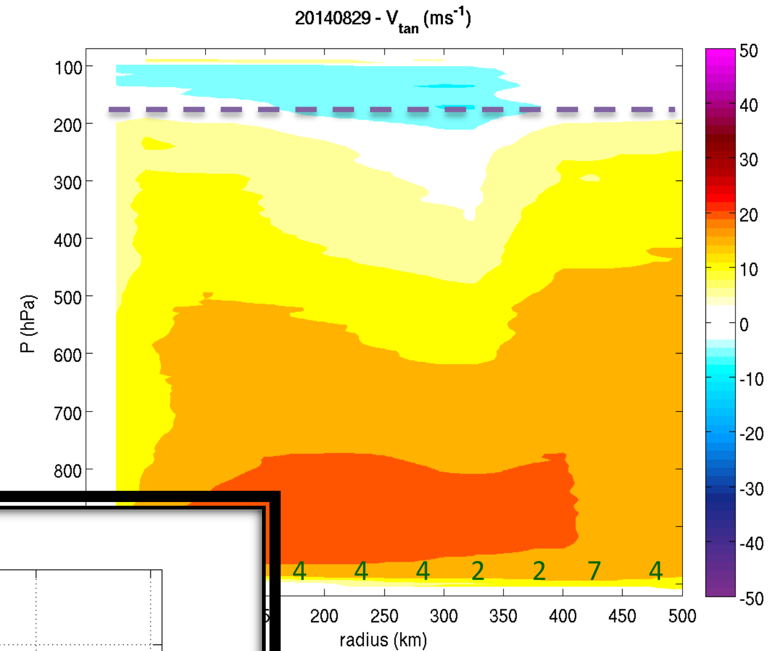


Azimuthal avg V_{tan} – 4 select cases

50 kt TS Nadine (2012)

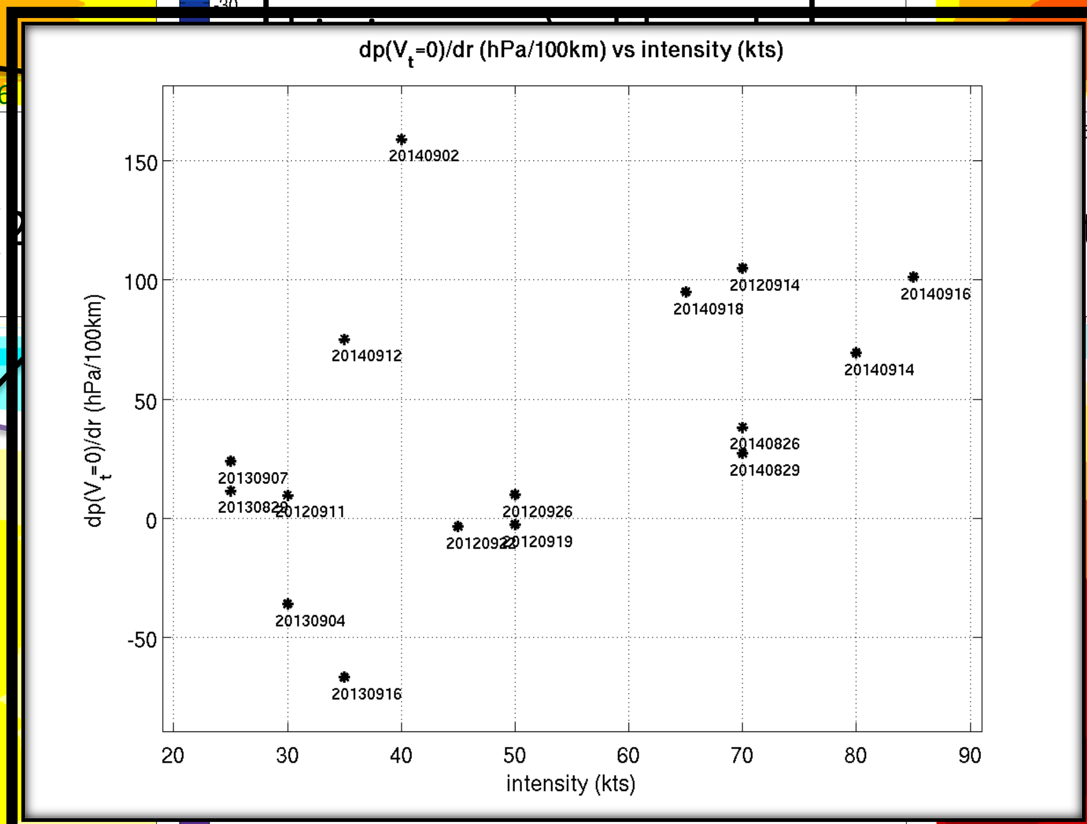


70 kt H Cristobal (2014)

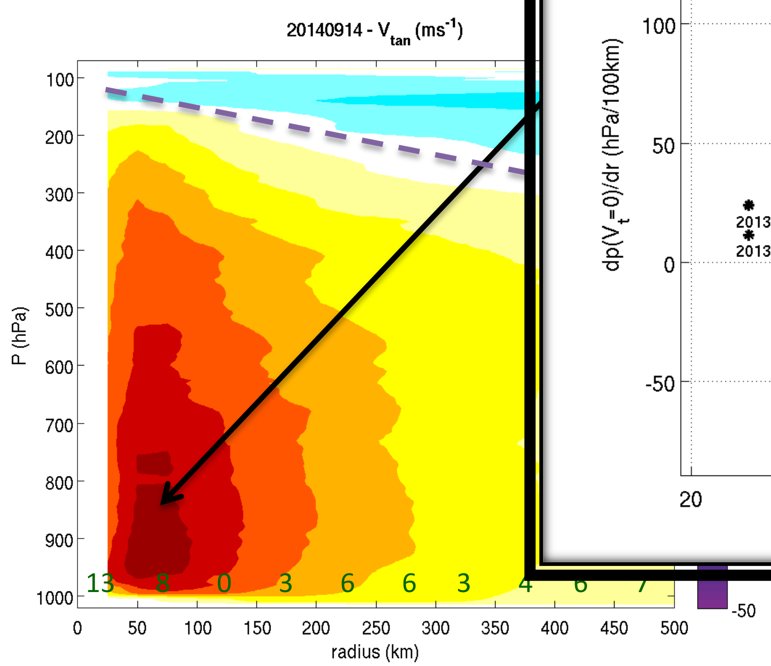


Outward slope of Vtan=0 line, or $\frac{\partial p(V_{tan}=0)}{\partial r}$, greater for stronger TCs

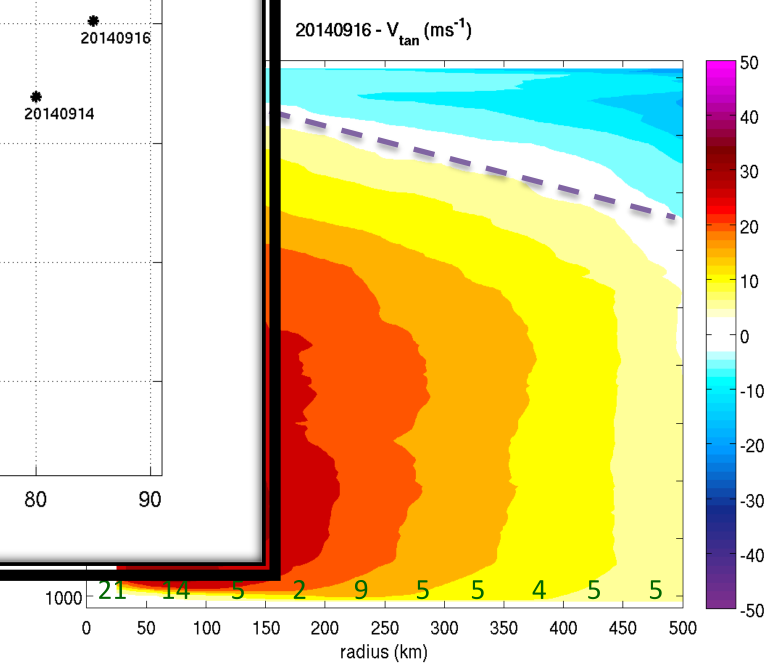
(#drops in each 50-km



80 kt H Edouard (2

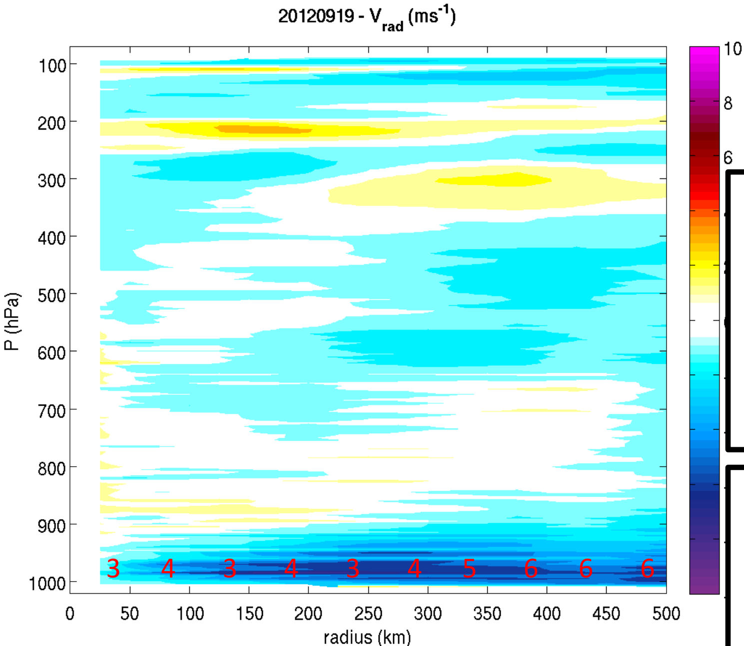


H Edouard (2014)

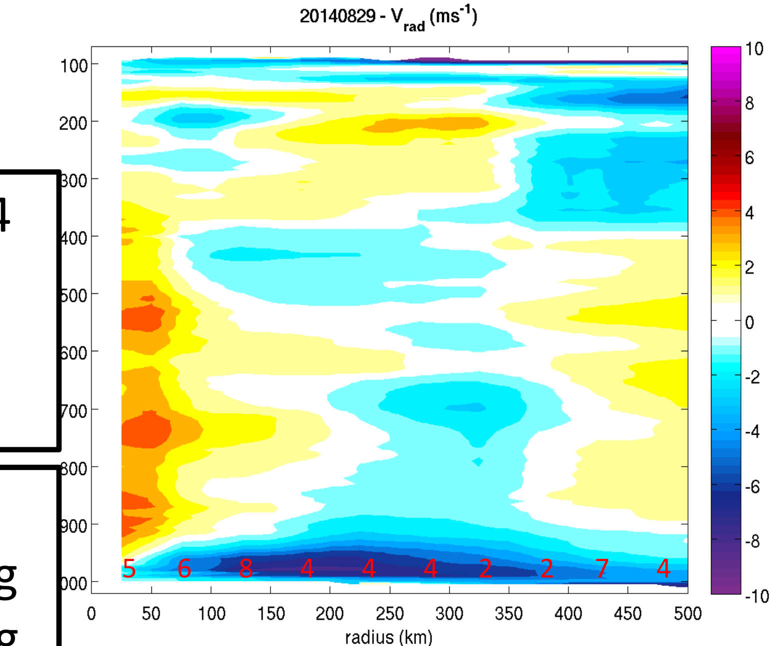


Azimuthal avg V_{rad} – 4 select cases

50 kt TS Nadine (2012)



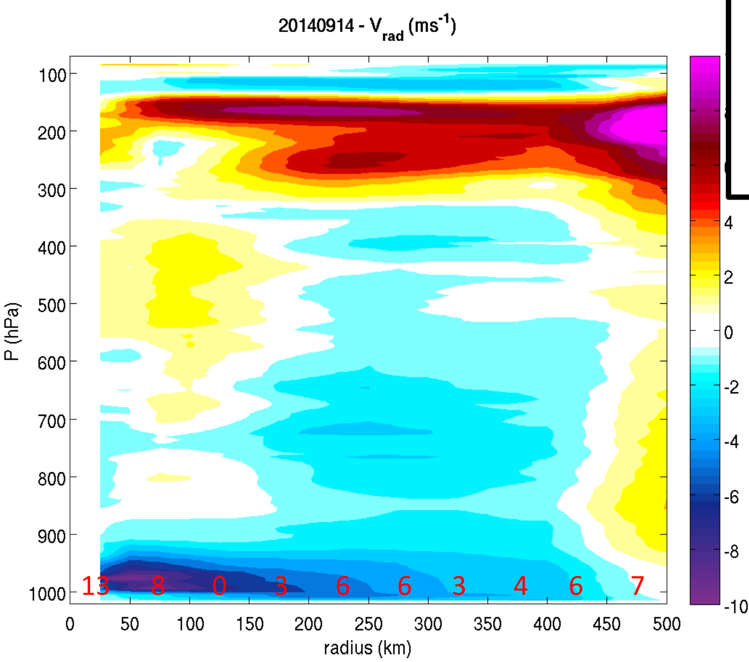
70 kt H Cristobal (2014)



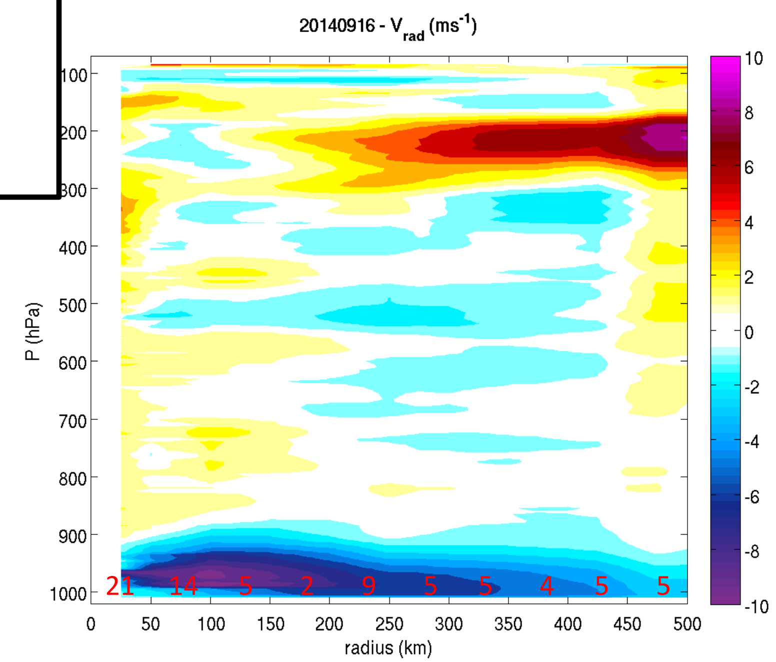
Inflow well defined for all 4 cases, but outflow weak & poorly defined for 2 top cases

Stronger outflow for Edouard during intensifying (lower left) than weakening (lower right) stage, despite stronger intensity during weakening stage; is this a common theme?

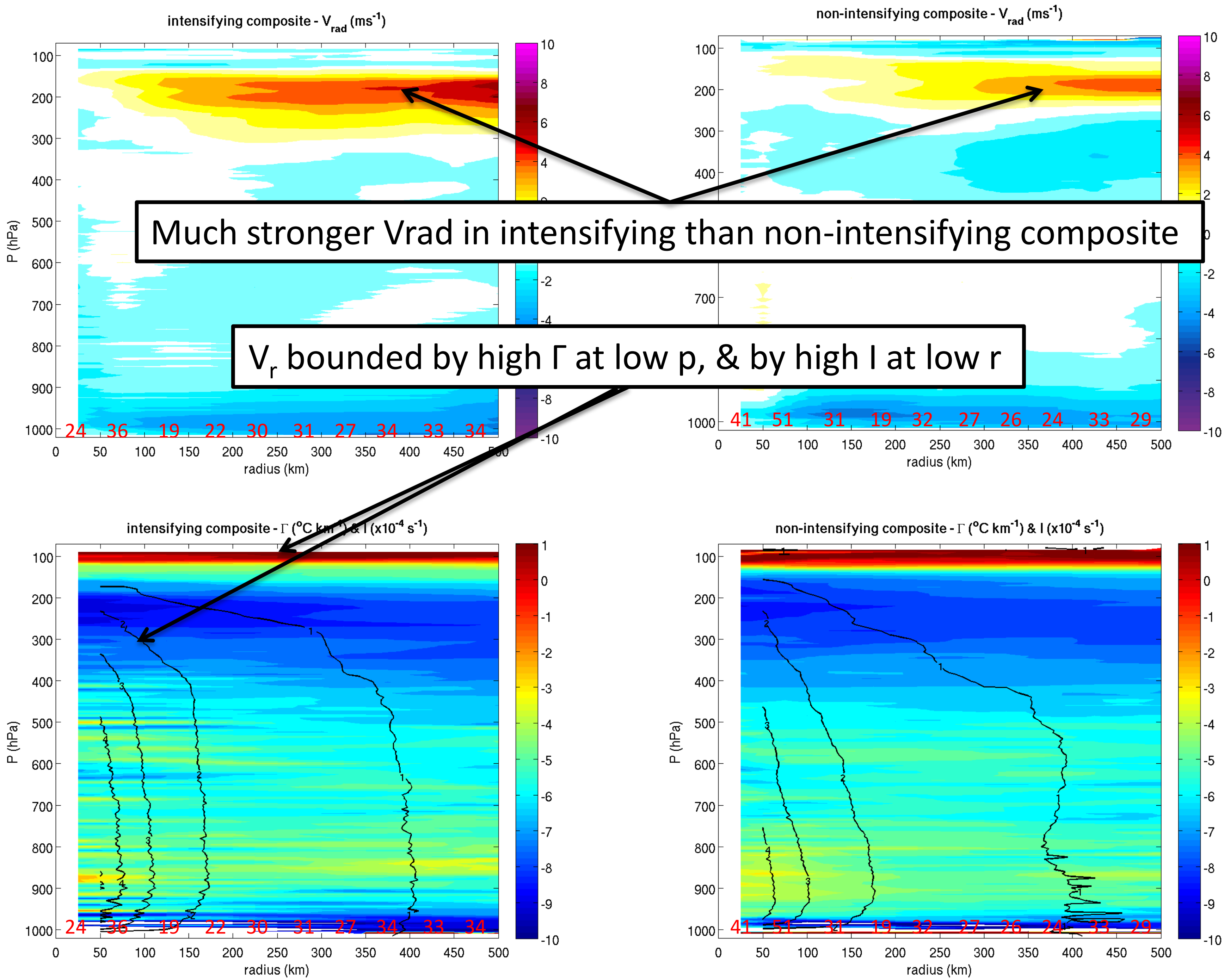
80 kt H Edouard (2014)



85 kt H Edouard (2014)

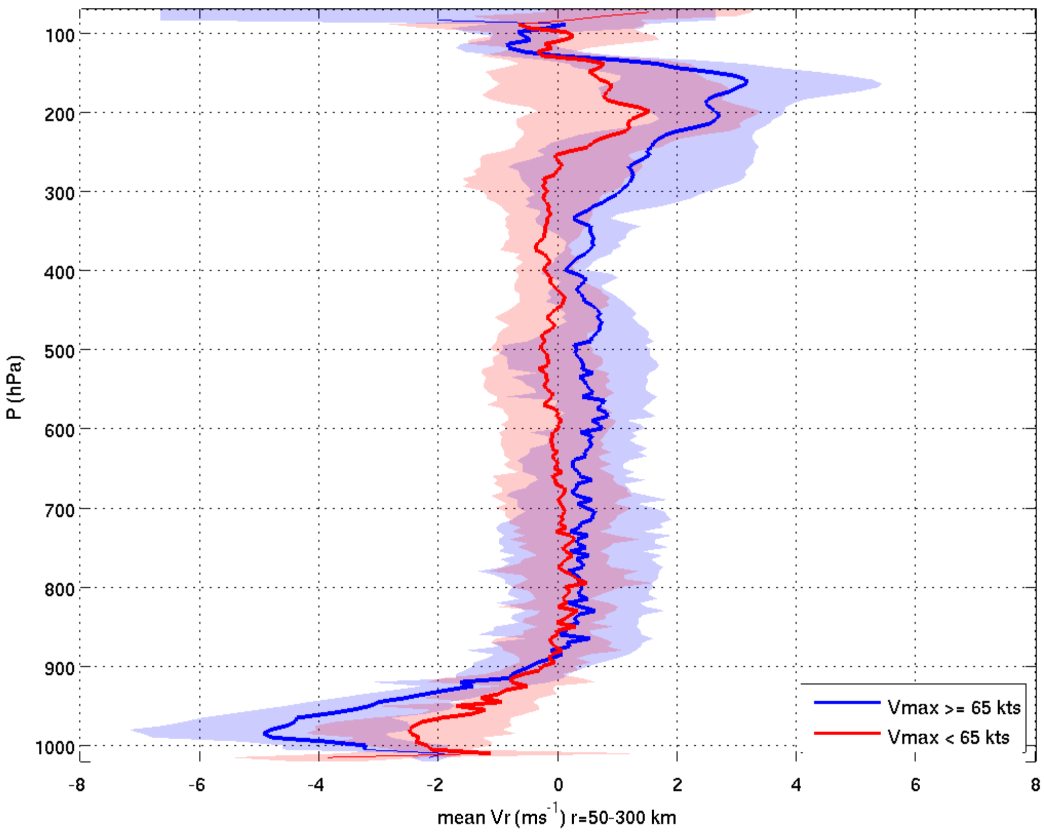


Intensifying vs non-intensifying composites

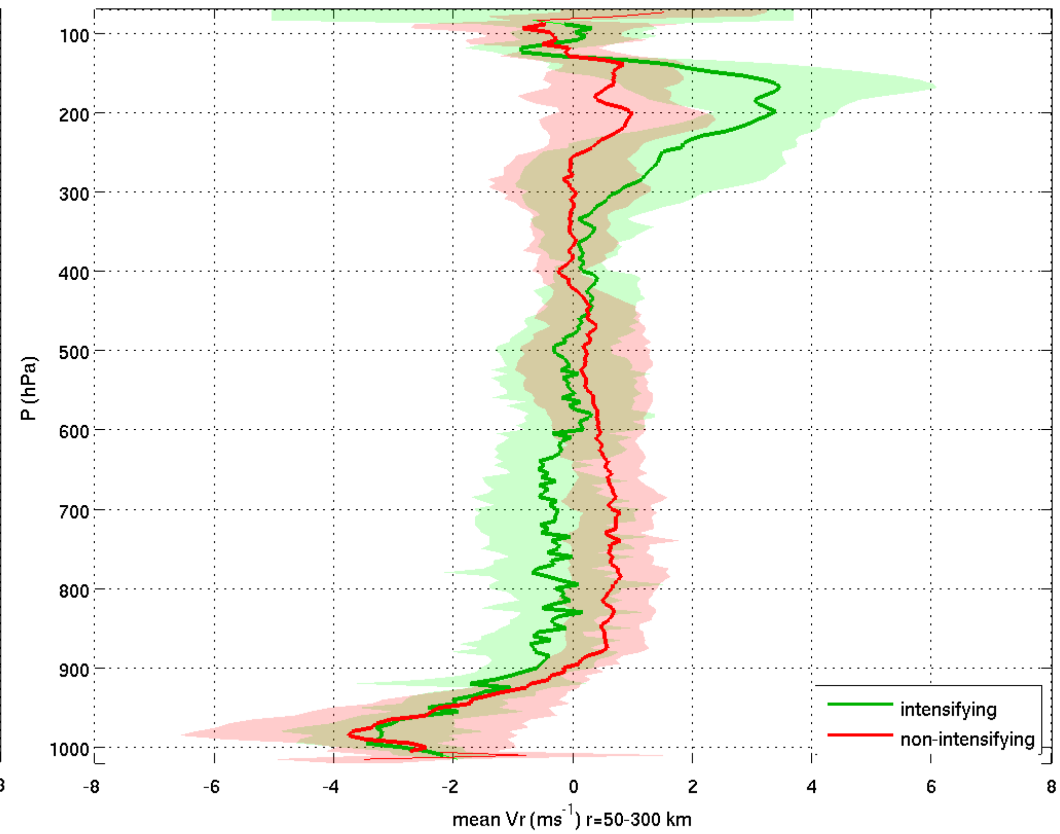


Vertical profiles of r=50-300 km mean radial wind & 1σ shading

Hurricanes vs TDs/TSs



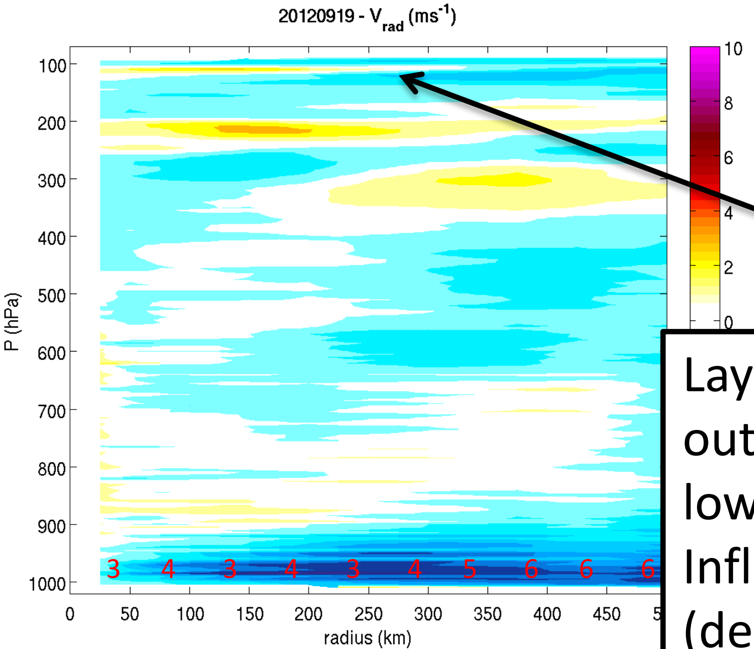
Intensifying vs weakening TCs



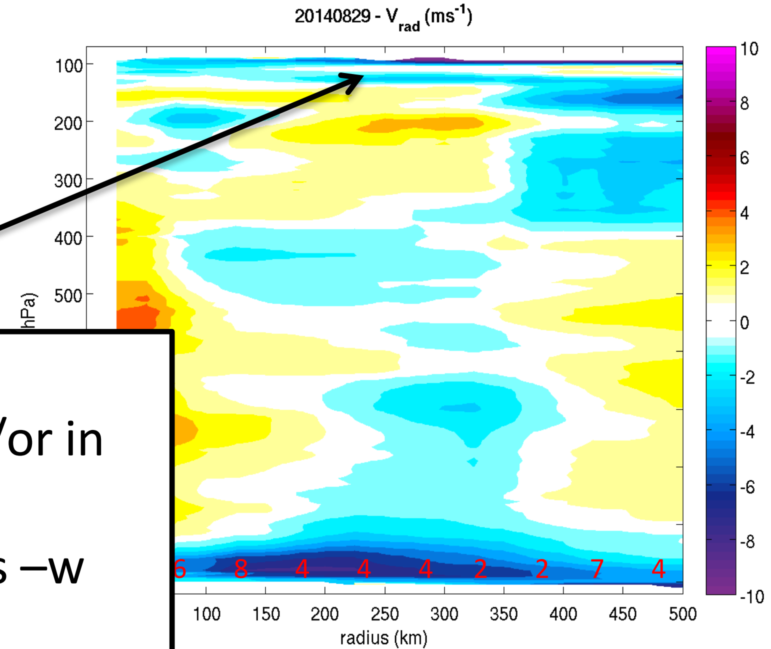
On average, there is a greater difference between hurricanes and TDs/TSs in terms of LL-inflow, but greater difference between intensifying and non-intensifying TCs in terms of UL-outflow, with less overlap of 1σ region

Azimuthal avg V_{rad} – 4 select cases

50 kt TS Nadine (2012)

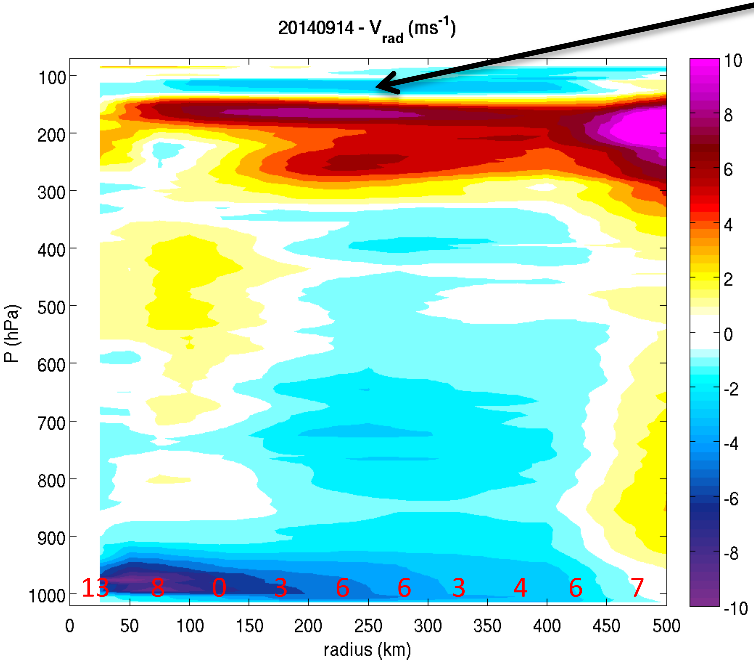


70 kt H Cristobal (2014)



Layer of 1-3 m/s inflow above outflow near tropopause and/or in lower stratosphere
Inflow above outflow suggests –w (descent) above eye

80 kt H Edouard (2014)



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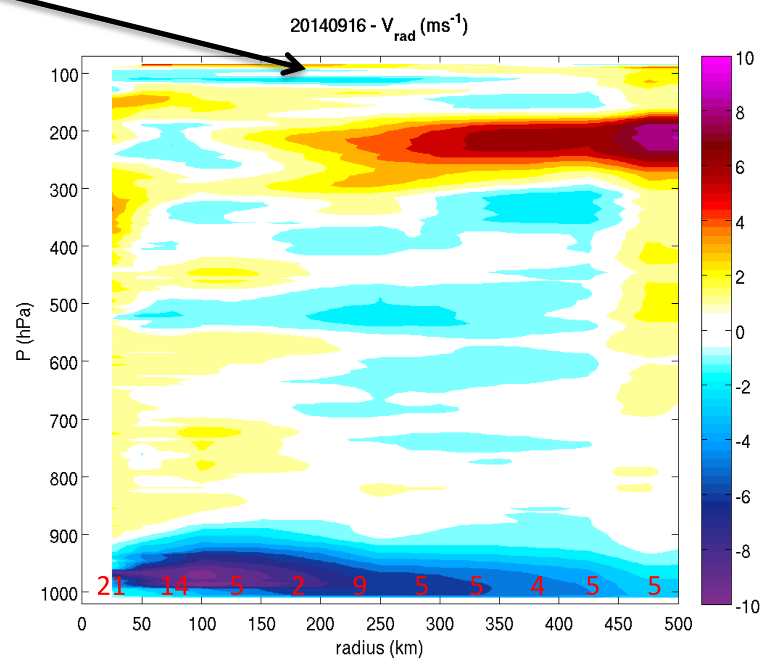
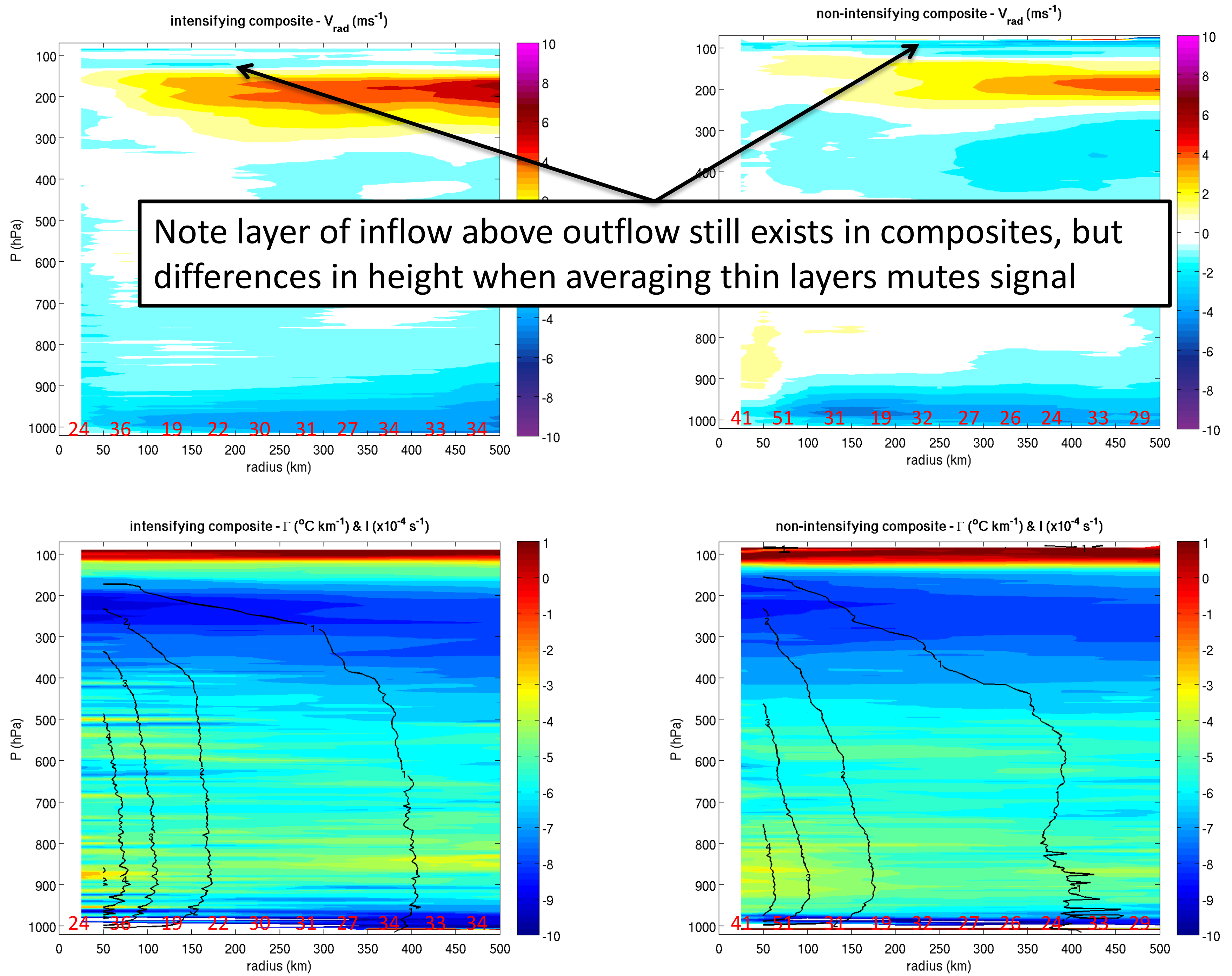
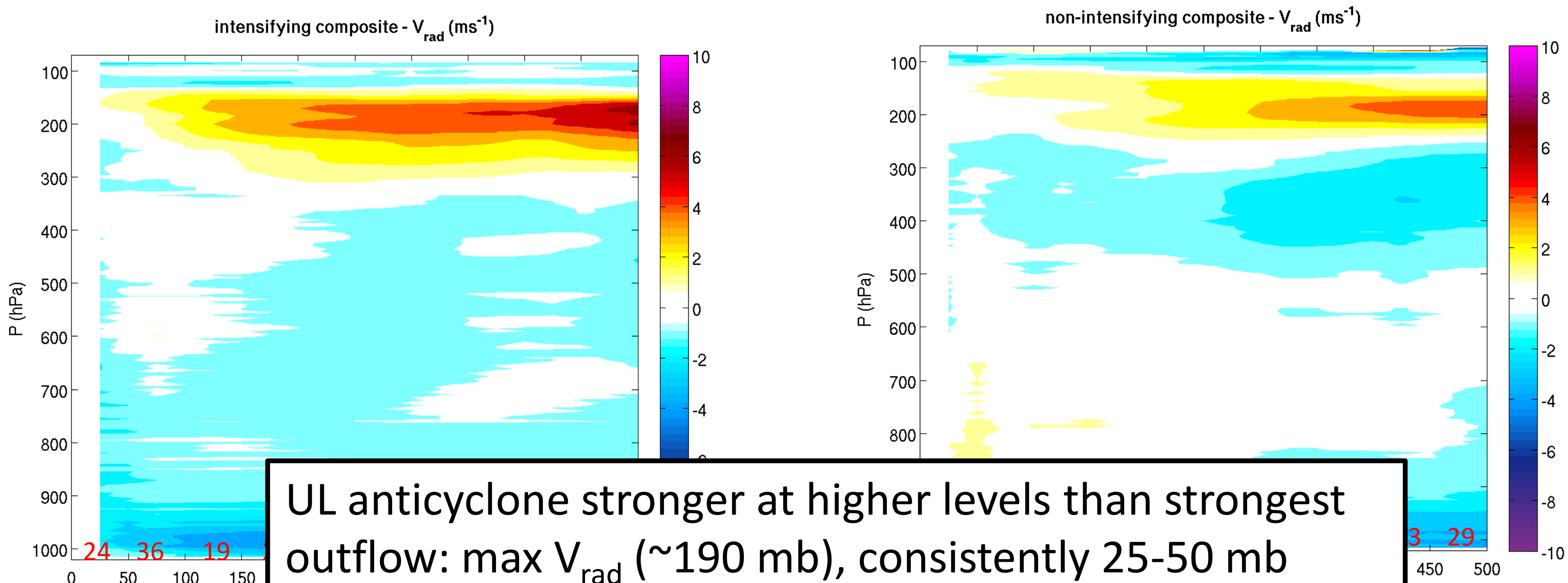


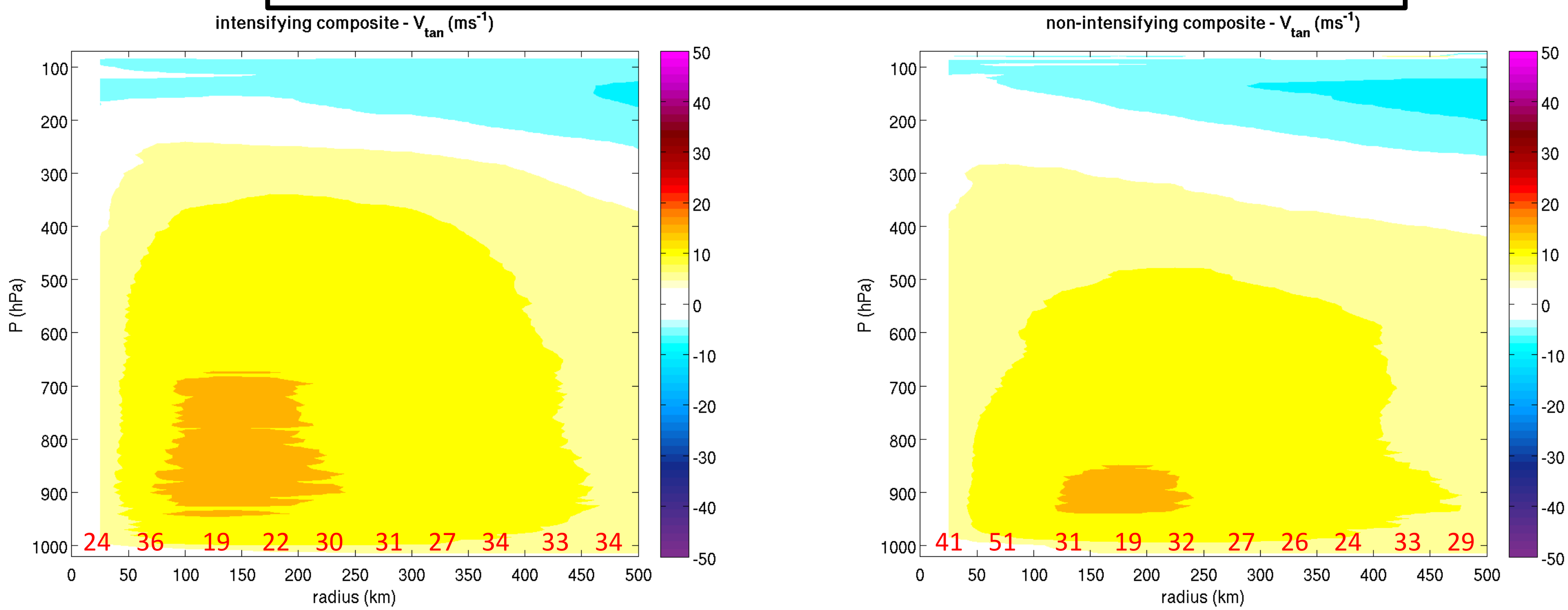
Intensifying vs non-intensifying composites



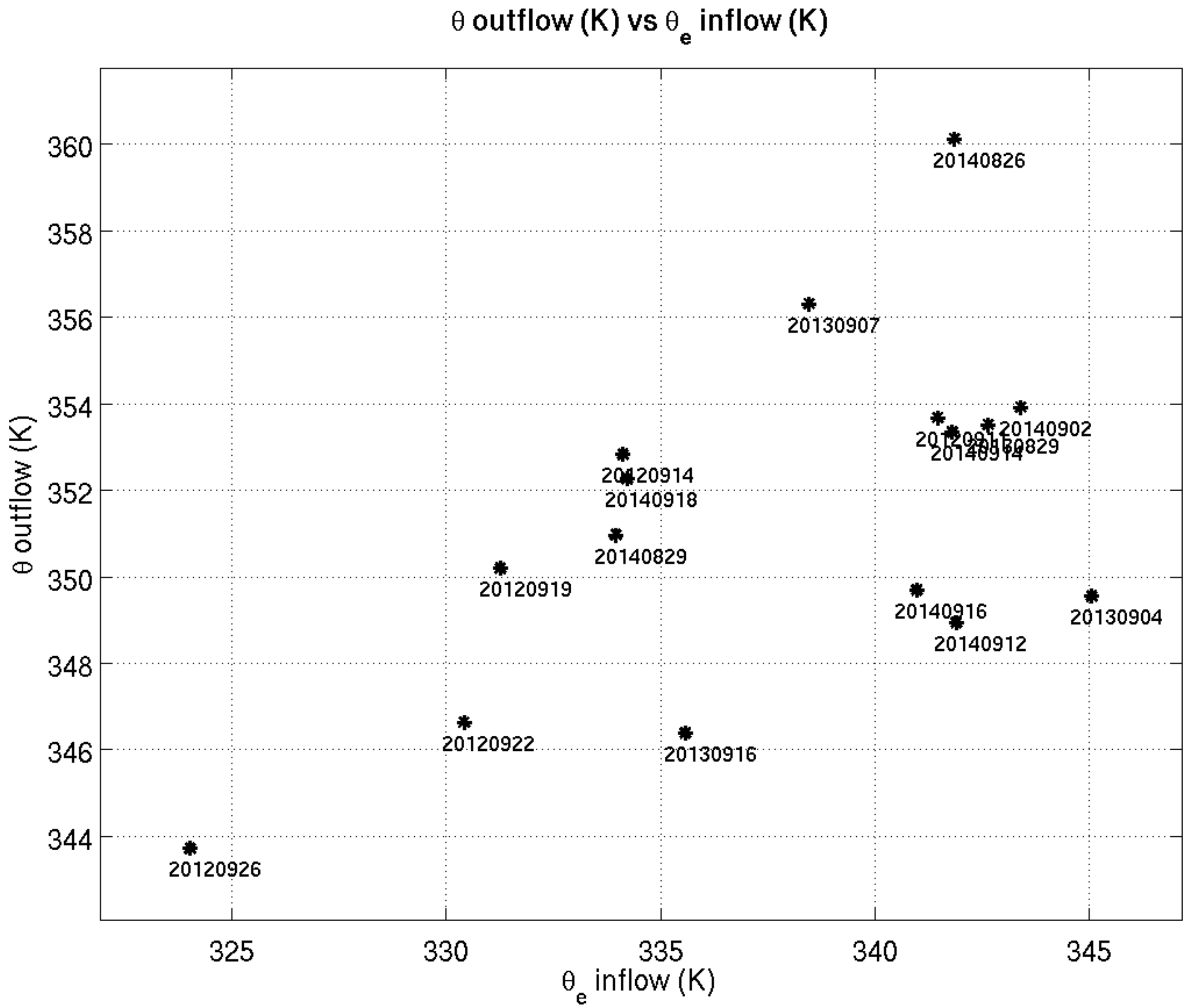
Intensifying vs non-intensifying composites



UL anticyclone stronger at higher levels than strongest outflow: max V_{rad} (~190 mb), consistently 25-50 mb lower than min V_{tan} (~160 mb)



100-500km mean θe_inflow vs θoutflow

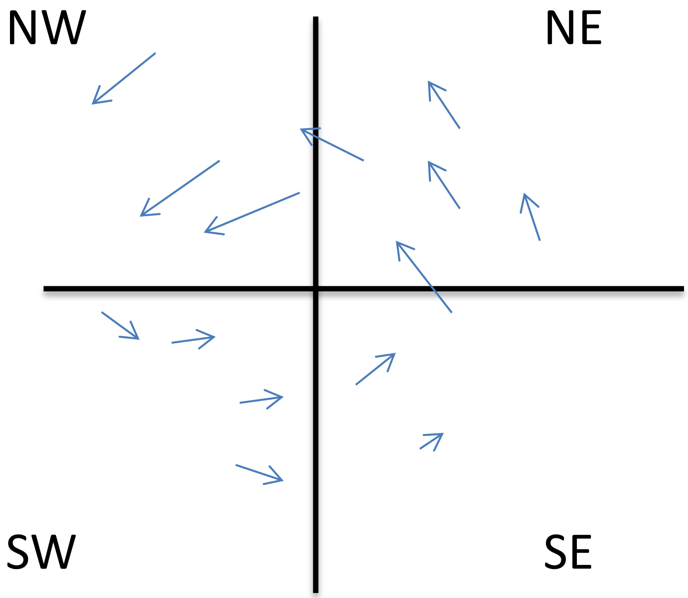


Greater SSTs & more low-level moisture → greater θe in the PBL → stronger TC → higher outflow

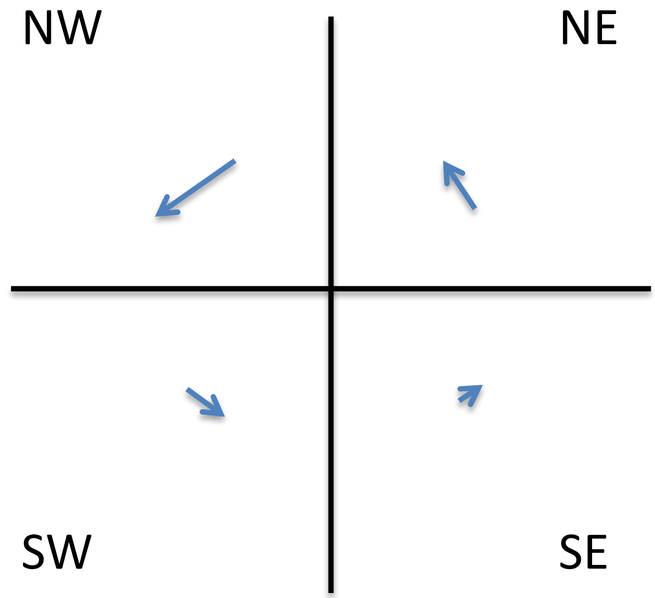
θe seems low for given θ, but max θe achieved

Vertical wind shear "*S*" (computed vs 850hPa reference level)

e.g. Davis and Ahijevych (2012)



Decompose wind vectors into quadrants



Compute average wind vector in each quad

Average all 4 quads to get $\begin{bmatrix} \overline{u(p)} \\ \overline{v(p)} \end{bmatrix}$

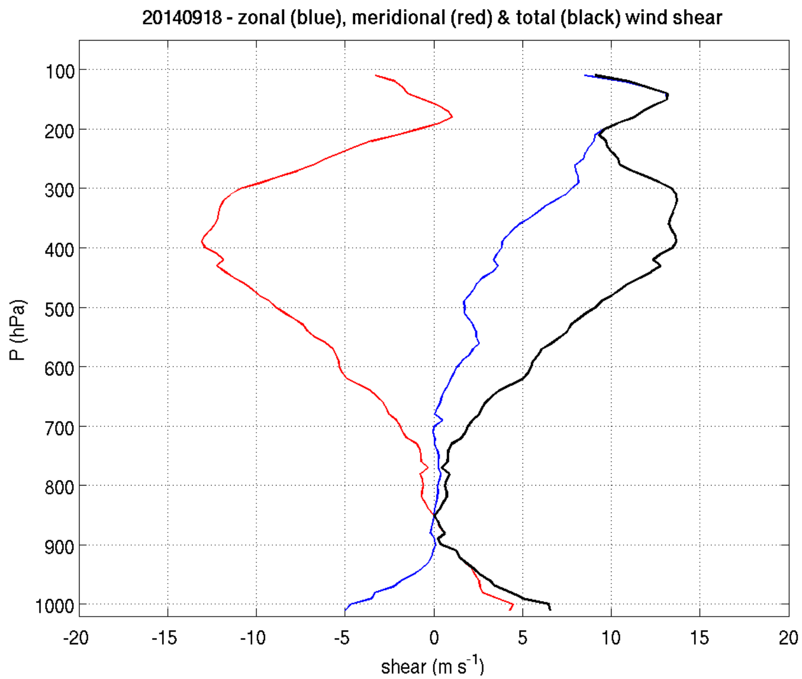
$$u_{shear} = \overline{u(p)} - u_{850}$$

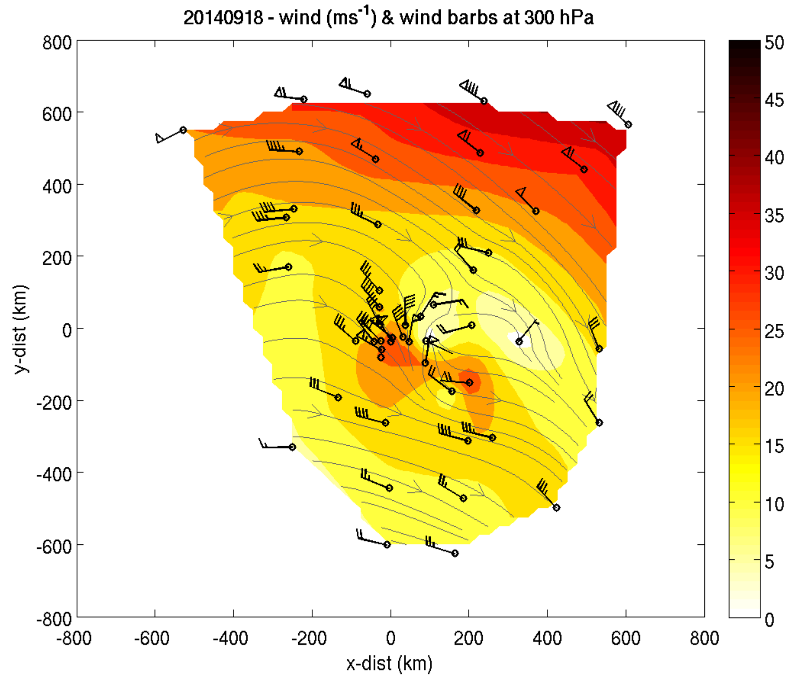
$$v_{shear} = \overline{v(p)} - v_{850}$$

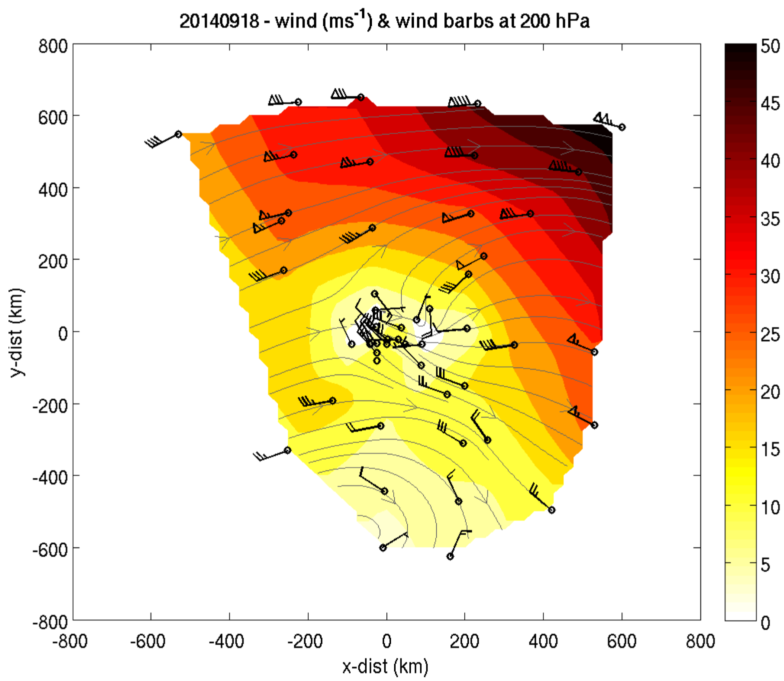
$$S = \sqrt{{u_{shear}}^2 + {v_{shear}}^2}$$

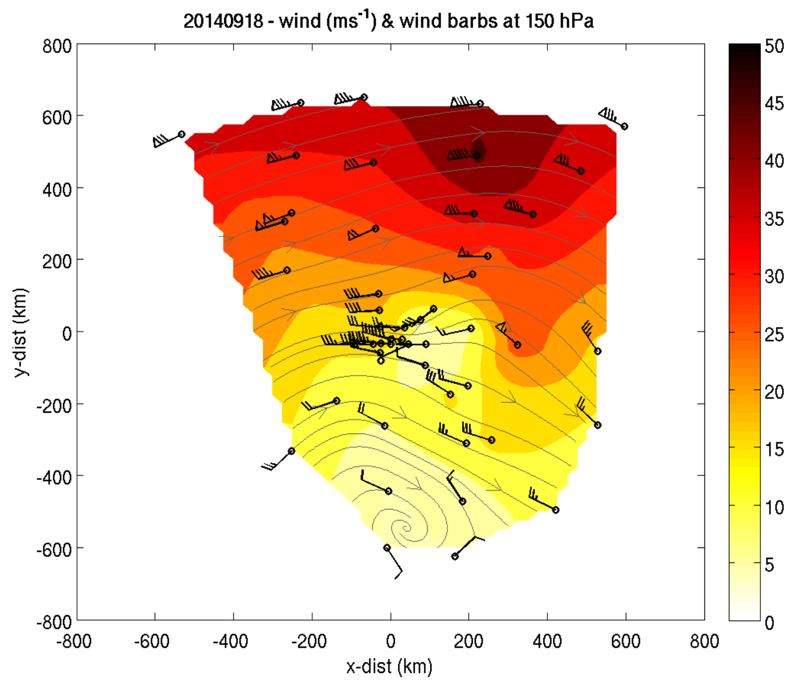
Vertical wind shear (computed vs 850 mb reference level)

Greatest outflow occurs ~200 mb, also level of loacl min in shear
Is lower shear promoting outflow, or outflow “resisting” the shear?

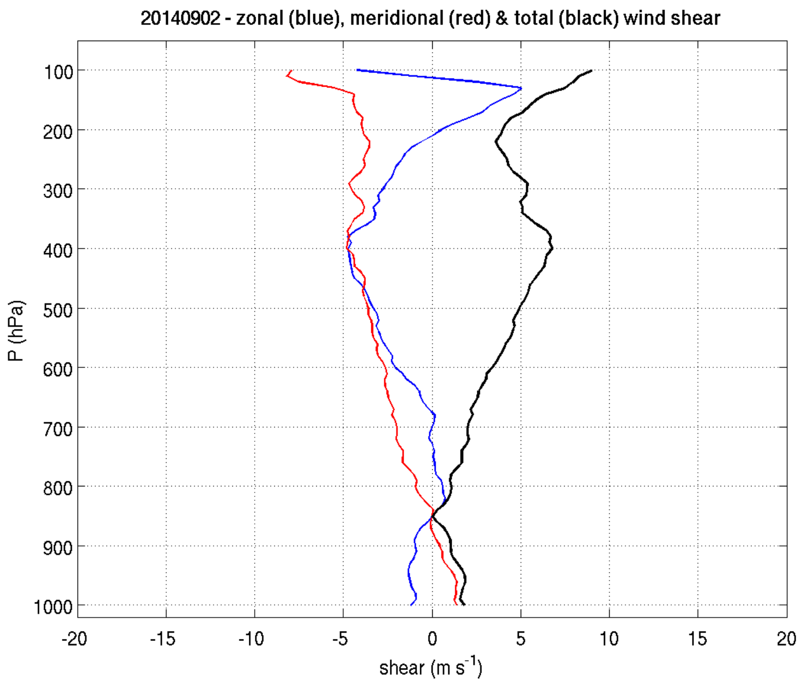




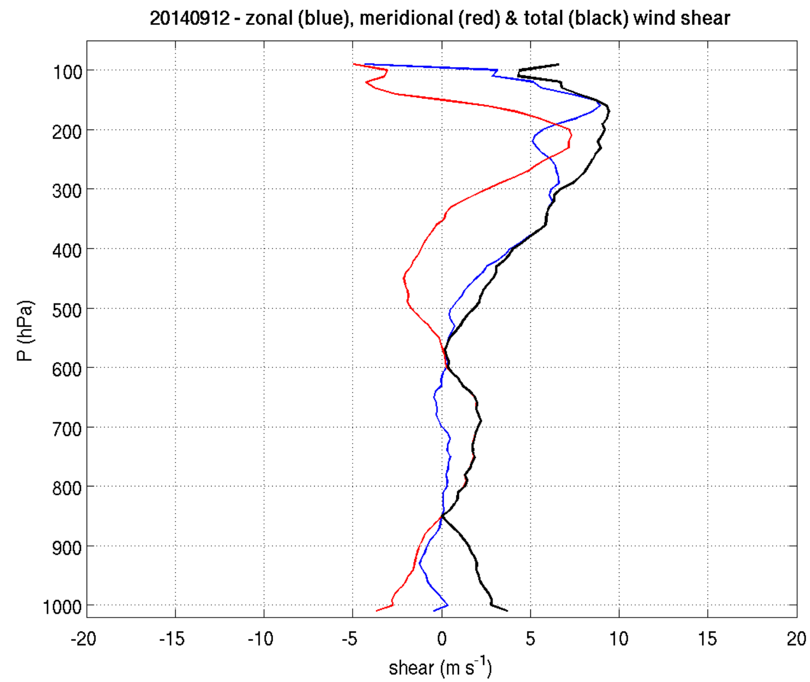


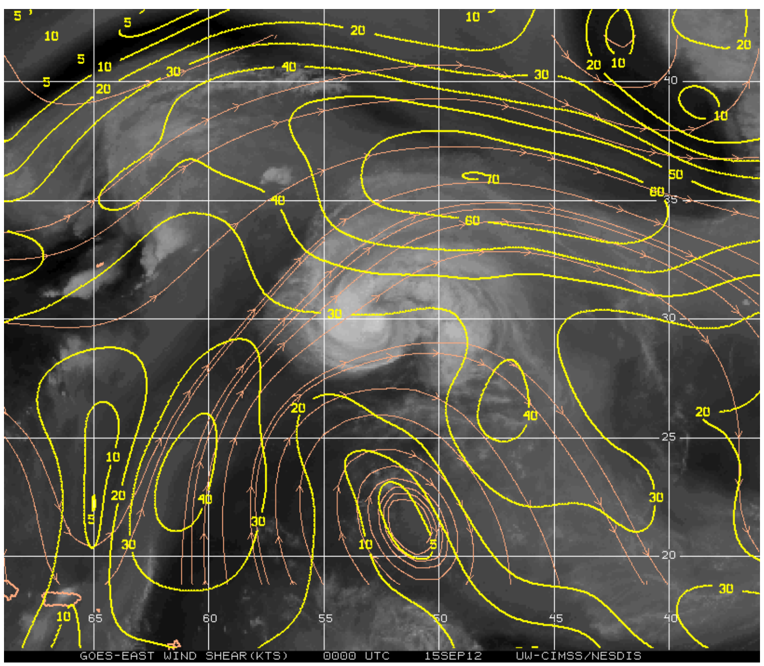


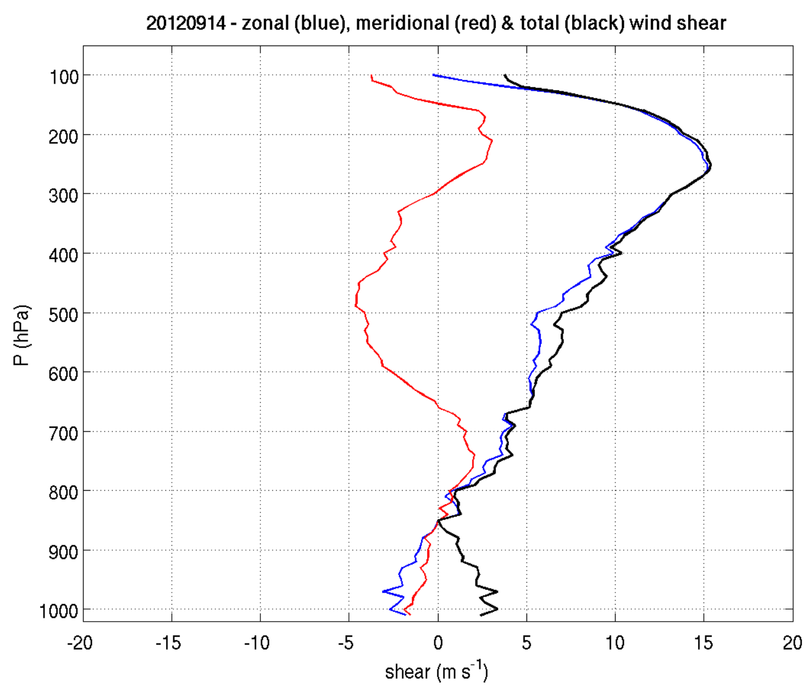
TS Dolly (2014): here 850-200 mb shear weak, but 850-400 mb shear great. TC weakens.



H Edouard (2014): here 850-200hPa shear greater, but mid-level shear weak. TC strengthens.



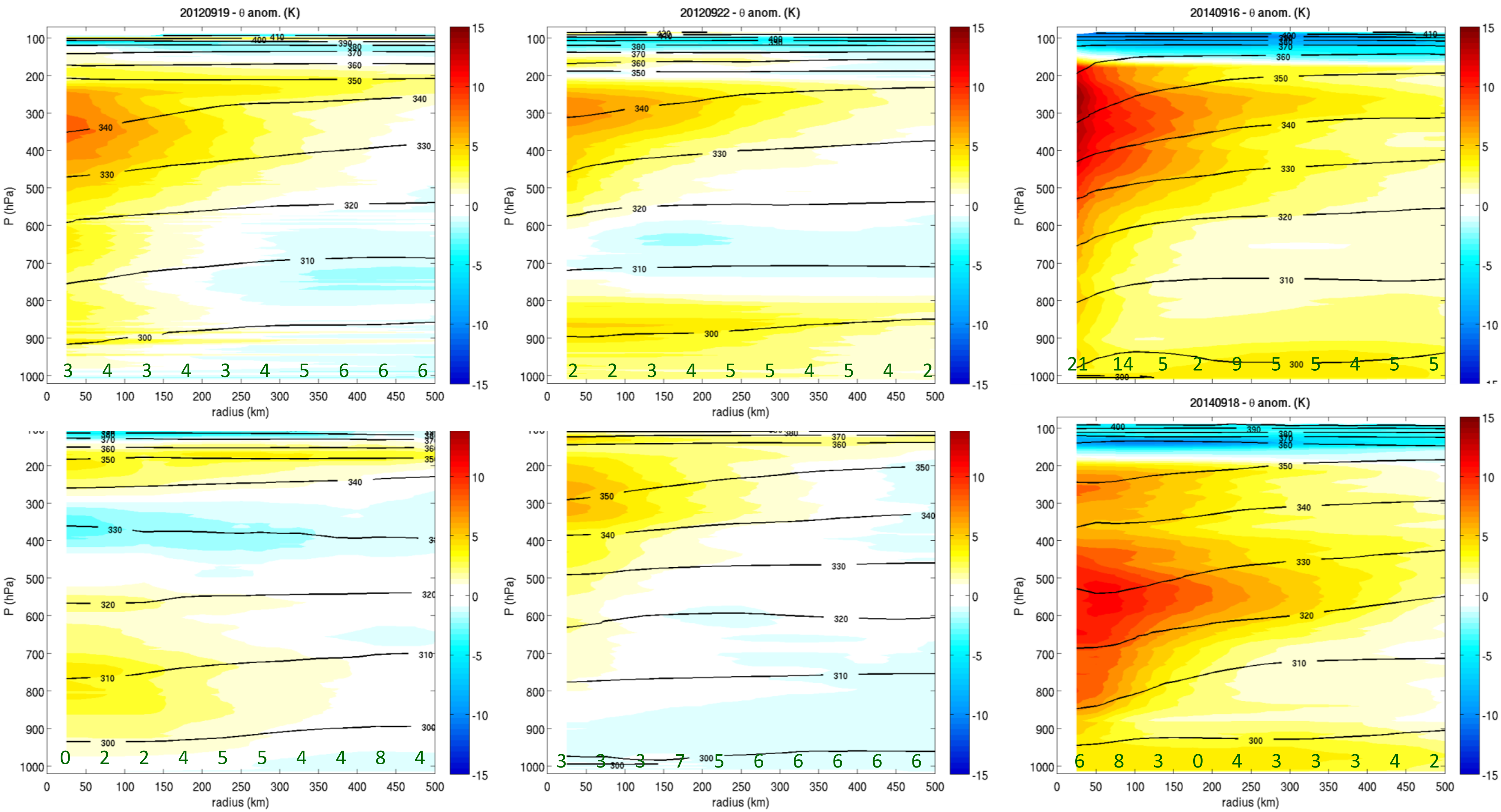




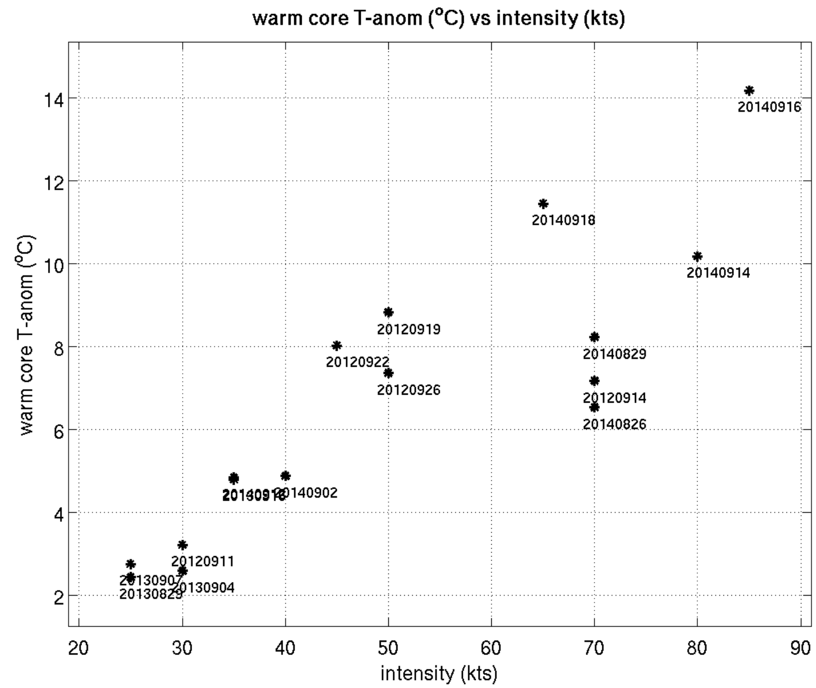
CIMSS deep-layer shear analyses suggest SW'erly shear over Nadine on 2012-09-15. Dropsonde data consistent, suggesting SW'erly 850-200mb shear. However, most mid-level shear NW'erly, more consistent with convection initiating SE of storm center

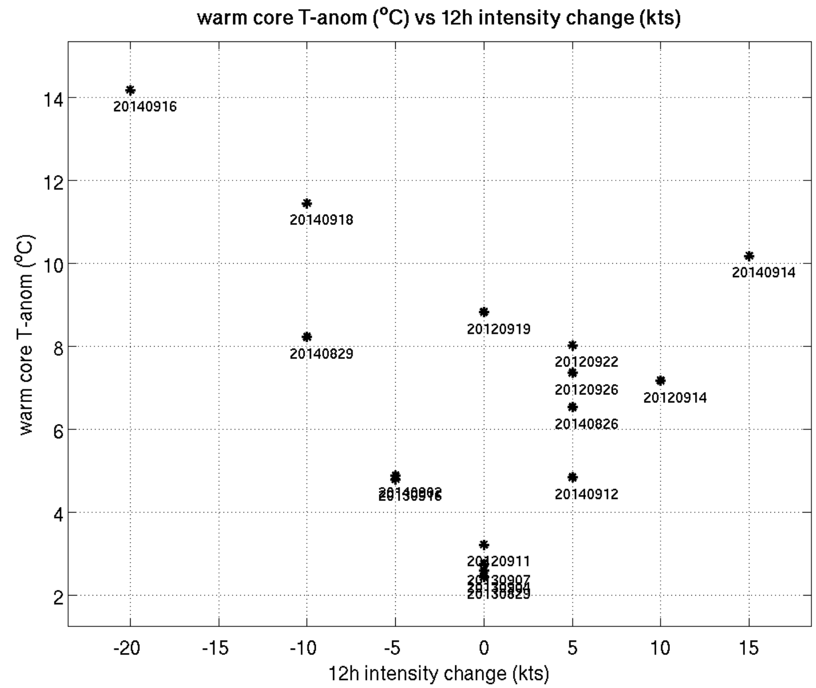
Variability in height and strength of warm core, as well as existence of single or multiple warm cores

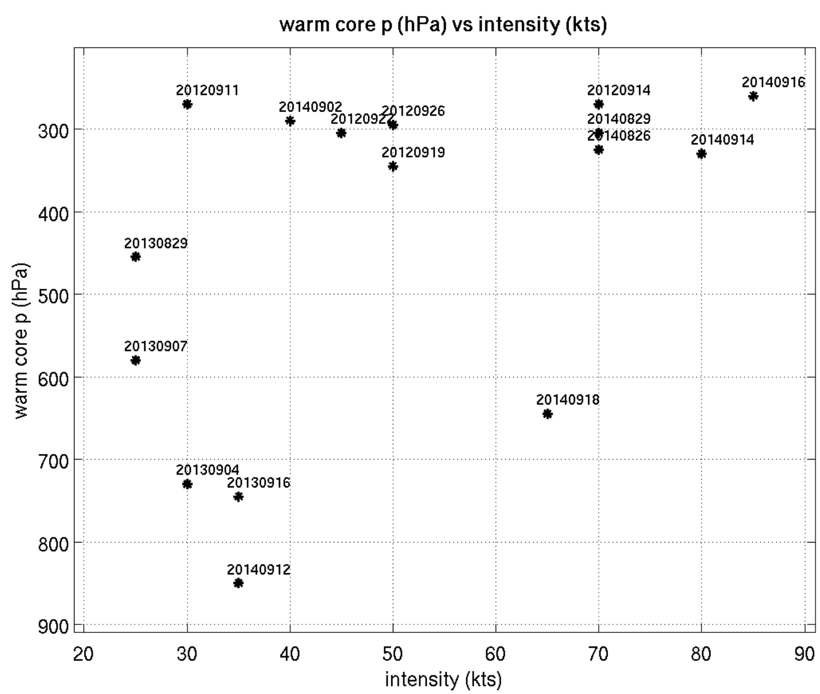
$$\theta'(r,p) = \theta(r,p) - \bar{\theta}_{r>500km}(p)$$

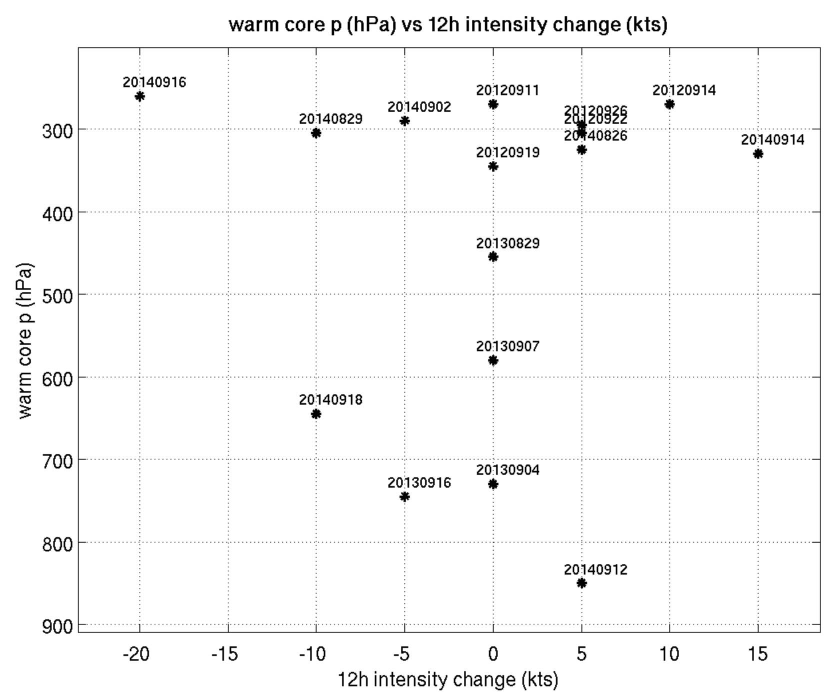


Warm core – overall statistics

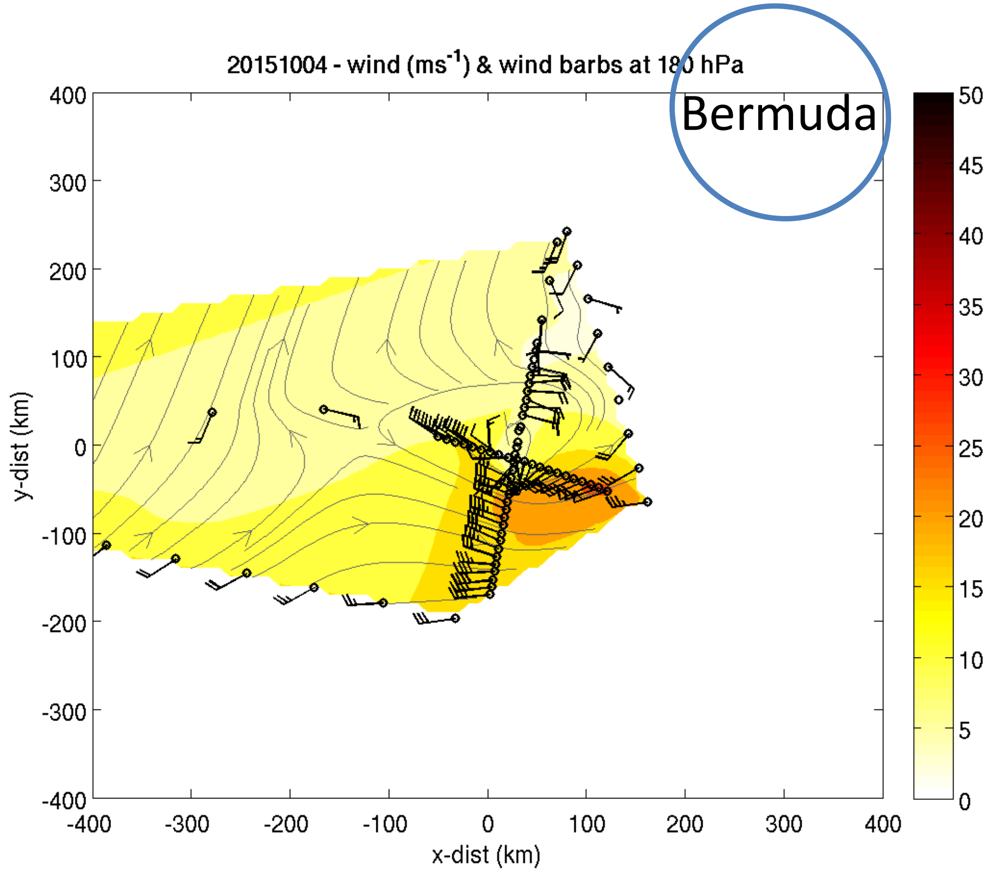


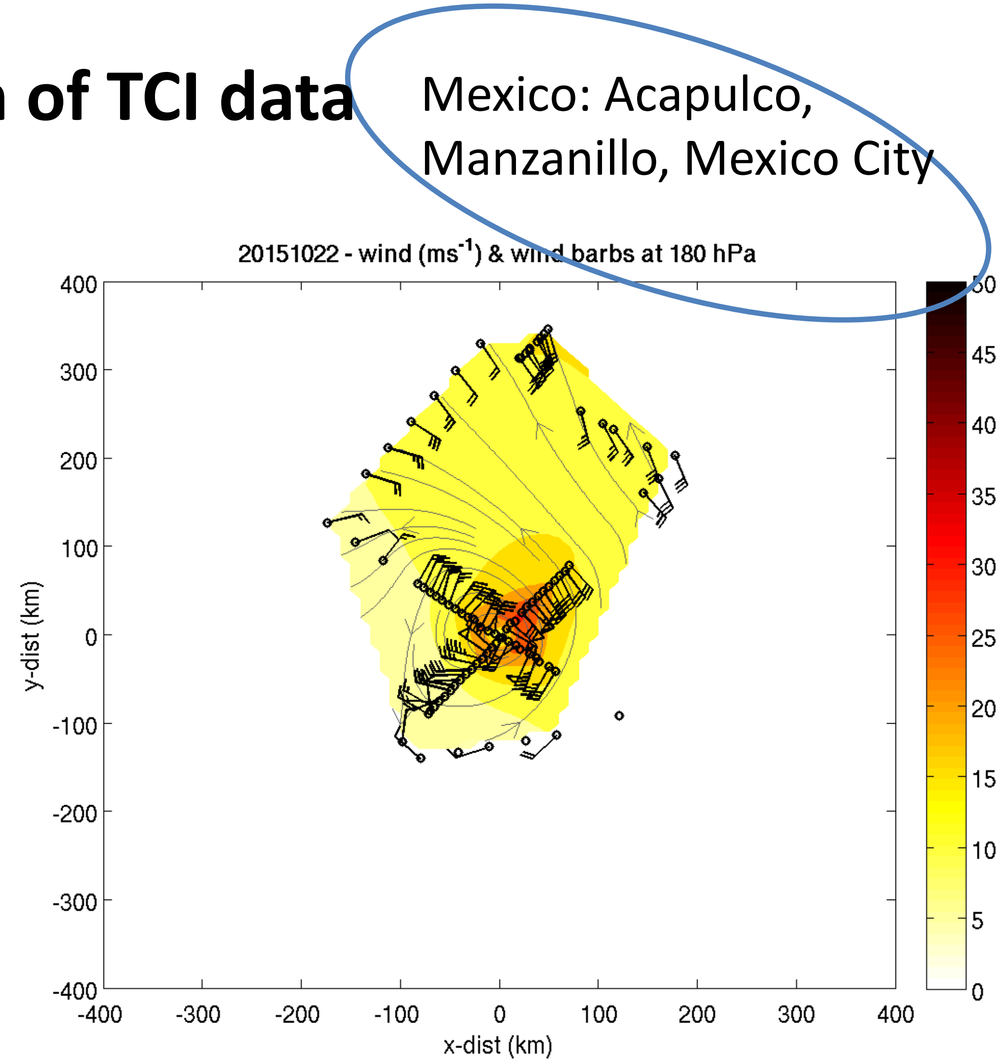






Future inclusion of TCI data





- Great coverage of inner core and outflow roots
- In order to get full outflow structure, will want to supplement with radiosondes & other aircraft observations
- 4d-var experiments with COAMPS-TC

Summary

- Stronger UL DIV & V_{rad} for strengthening vs weakening TCs, especially from 180-150 mb with less difference at or below 200 mb. Stronger TCs not necessarily associated with greater UL DIV or V_{rad} than weaker TCs. However, intense UL DIV no guarantee of strengthening system
- Level of max V_{rad} (~190 mb), consistently 25-50 mb lower than min V_{tan} (~160 mb), some disconnect between UL anticyclone and outflow
- Only one case of dual outflow channels (Cristobal 2014), associated with modest 5 kts intensification. S outflow stronger at higher levels than N outflow, with S outflow in region of colder but not higher tropopause. Over all cases, tropopause bulges slightly upward above core for stronger TCs
- Outflow roots region where $+V_r$ originates above TC coincides from r=50-200km, 300-150 hPa associated with low I (~ $1\text{-}2 \times 10^{-4}\ s^{-1}$)
- Location of deep convection relative to the vortex center more consistent with mid-level shear vector than 850-200 hPa shear. Also, a few instances of stronger shear "undercutting" the outflow
- Strong relationship: warm core ΔT & intensity, little or no relationship: warm core ΔT & Δintensity, height of warm core with either