Assessing the sensitivity of the tropical cyclone secondary circulation to perturbed outflow via idealized COAMPS-TC simulations

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Background

- Observational data have suggested structural differences in the outflow of intensifying versus non-intensifying tropical cyclones (TCs), with stronger radial outflow in intensifying systems and more curved anticyclonic flow in non-intensifying systems (Merrill 1988)
- Multiple outflow channels, with one often to the north and one to the south, can develop in intensifying TCs; the outflow also may thicken in the vertical to a greater θ range during intensification (Merrill and Velden 1996)
- Idealized modeling results suggest that a zonal jet to the north of the TC may enhance outflow by generating a minimum in inertial stability, allowing the TC to intensify beyond what it otherwise would (Rappin et al. 2011)

3D structure of the mature tropical cyclone (TC)

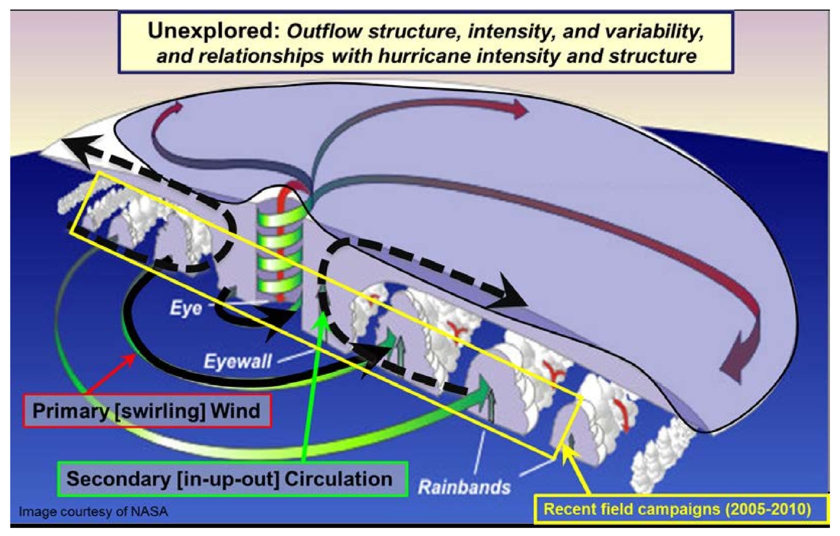


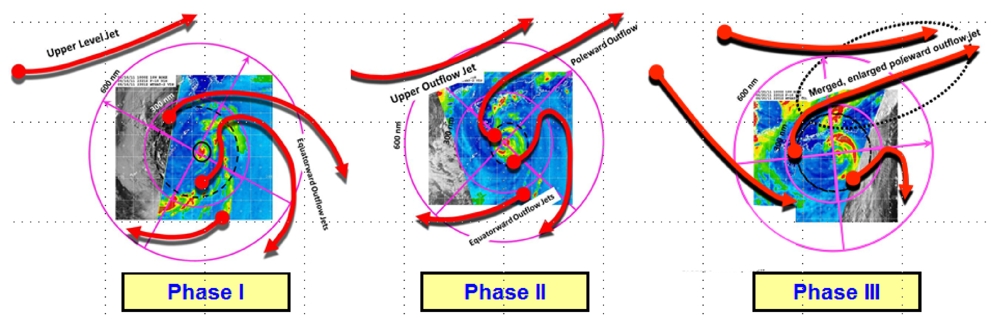
Image courtesy NASA + modifications by NRL

Conventional train of thought: all else equal, stronger primary circulation associated with stronger inflow / secondary circulation, which drives stronger outflow

Key Questions

- How does TC outflow couple with inner-core convection and what is its relationship to intensity changes?
- What is the relationship between the upper-level outflow and the low-level wind field?
- How does TC outflow interact with larger scale features?
- Seek to investigate these questions via idealized TC simulations using COAMPS

Interaction between TC and an approaching jet



Conversely, stronger outflow (synoptically-enhanced) should result in a stronger TC

Methodology

Model Configuration

- COAMPS-TC v4
- 5km res, 801x801 grid points (4005x4005 km)
- 40 vertical levels
- No cumulus parameterization
- Periodic in x, wall boundaries in y
- Modified Mellor-Yamada PBL scheme
- Radiation off
- *f*-plane / β-plane
- Fixed SST – 28.0 °C
- θ (K) and q (g/kg) from Dunion (2011) MT sounding
- u = 0 or -3 ms^{-1} geostrophic wind
- Initialized with Rankine vortex: rmw = 90 km, $V_t \rightarrow 0$ at 240 km

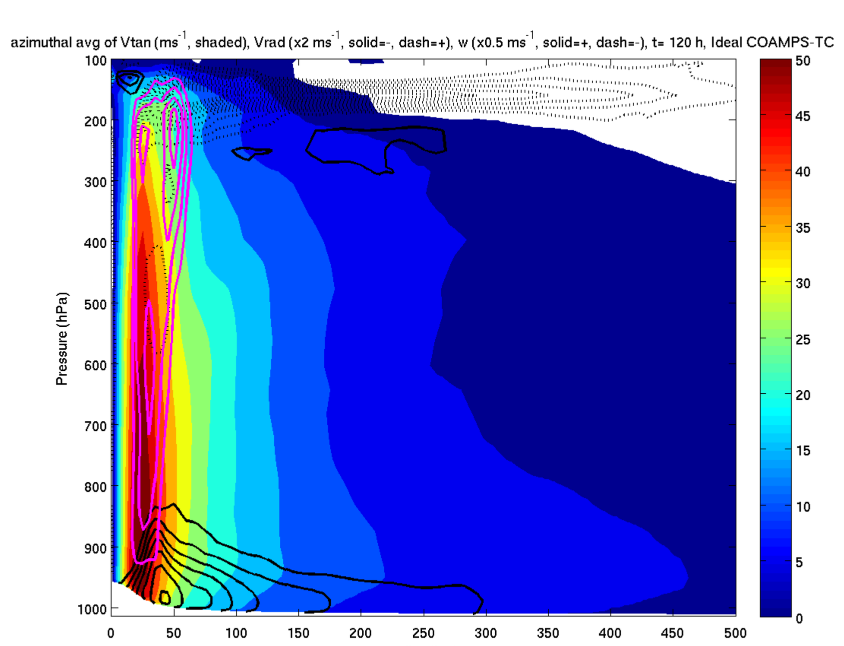
Inertial stability:

$$I = \sqrt{\left(f + \frac{2v_t}{r}\right)(f + \zeta)}$$

where $\zeta = \frac{1}{r}\frac{\partial (r v_t)}{\partial r}$

Goal: explore sensitivity of TC intensity and structure to enhancing outflow:

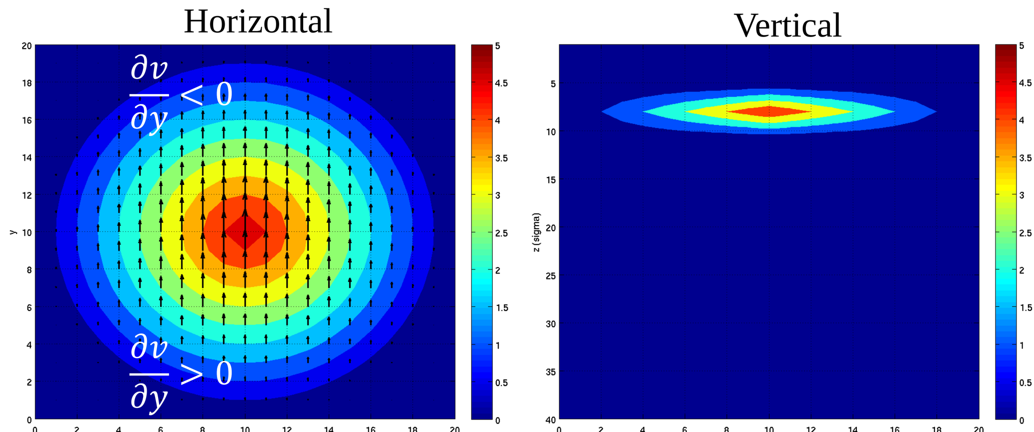
- *Directly* via enhancing v_r and thereby divergence in the outflow region (~300-100mb)
- *Indirectly* by decreasing v_t in the outflow region, thereby decreasing *I* and creating an environment more favorable for outflow expansion



Azimuthal average cross section of tangential wind (v_t shaded), radial inflow/outflow (v_r solid/dashed black contours in 2 ms^{-1} increments), and vertical velocity (w; magenta contours in 0.5 ms^{-1} increments)

Perturbing the outflow:

Technique 1: Direct perturbation of radial wind in outflow region



Added as a tendency to the RHS of the u/v momentum equations

Since $\nabla_H = \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y}$ we increase divergence by introducing $+\frac{\partial v}{\partial y}$ north of the TC (or $+\frac{\partial u}{\partial x}$ east of the TC)

Perform large set of perturbed simulations, varying:

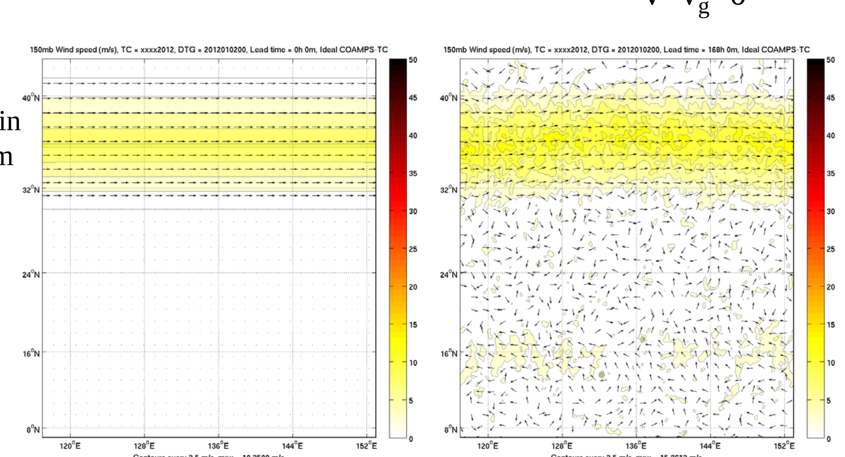
- Initial location of perturbation in x and y
- Radius of perturbation from 300 to 1100 km
- V(24h) from 10 ms^{-1} to 30 ms^{-1}
- Vertical maximum from σ=8 (~158 mb) to σ=11 (~249 mb)
- Timing at which perturbation is turned on and off

Technique 2: Add in zonal jet

From u and v momentum equations: $\frac{\partial u}{\partial t} \sim f(v - v_g)$ $\quad \frac{\partial v}{\partial t} \sim f(u - u_g)$

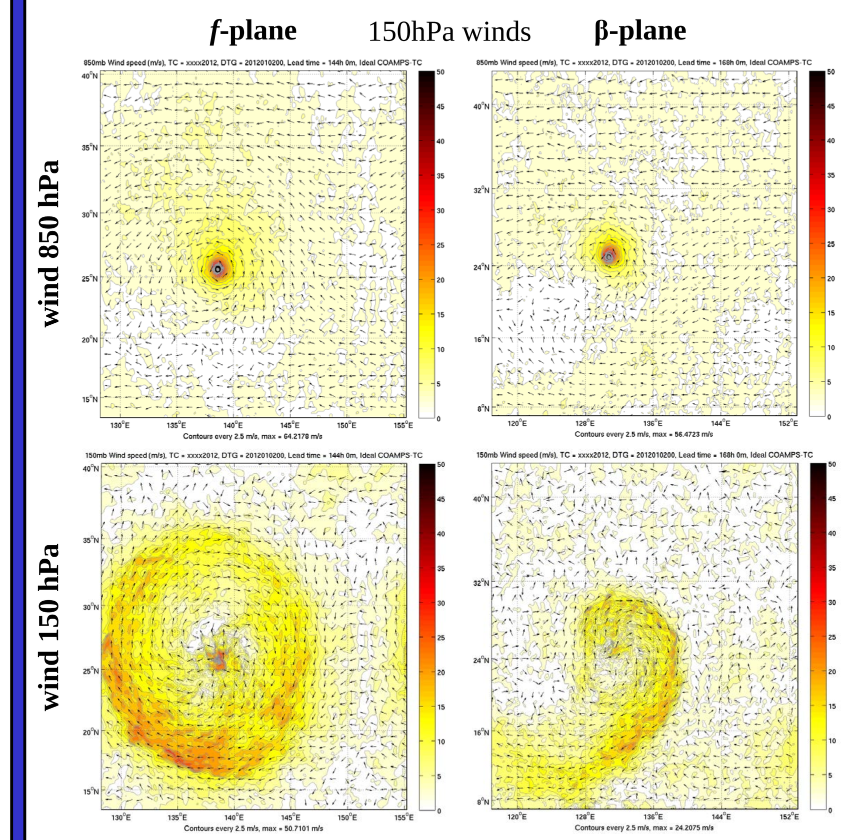
At t=0 we let $u(y)=u_g(y)$ and $v=v_g=0$

Jet extends in vertical from ~500-100 hPa, strongest at 300 hPa decaying linearly above and below



Jet remains relatively steady-state through 168h, although convection that develops in the moderately-unstable Dunion (2011) MT sounding generates some "noise"

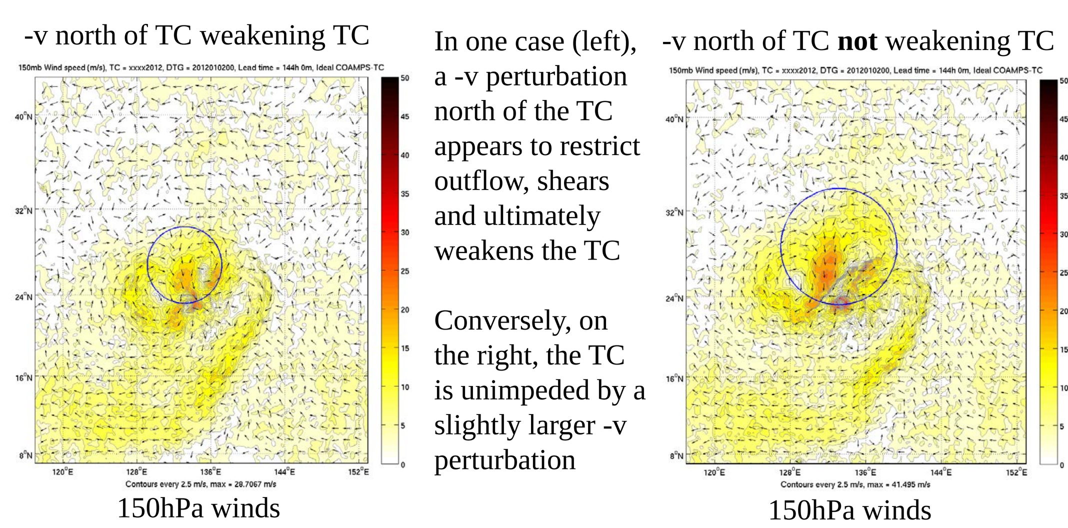
f-plane vs B-plane



In absence of local minima in I^2, outflow expands outward to Rossby radius of deformation, which is inversely proportional to *f* (Merrill 1988a,b)

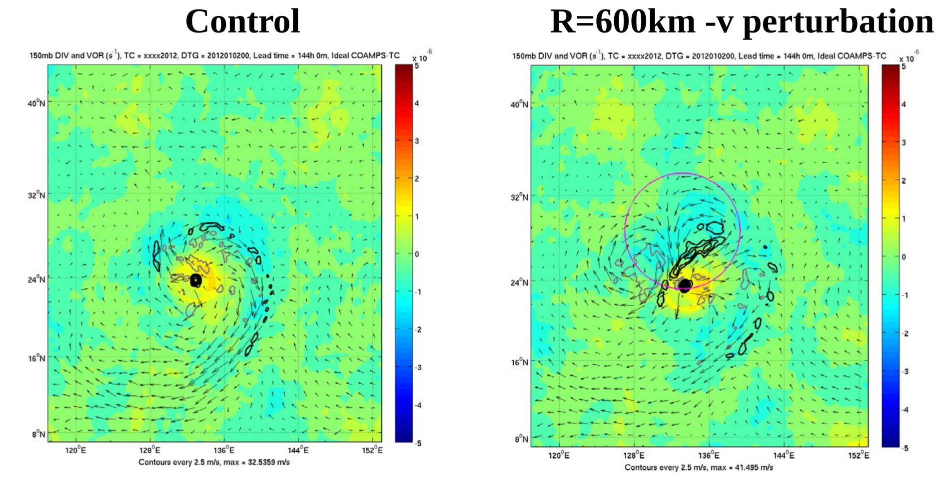
The effect this has on the structure of the outflow is perhaps under-appreciated in the idealized modeling community

The reverse hypothesis: does a –v perturbation weaken the secondary circulation?



In one case (left), a -v perturbation north of the TC appears to restrict outflow, shears and ultimately weakens the TC

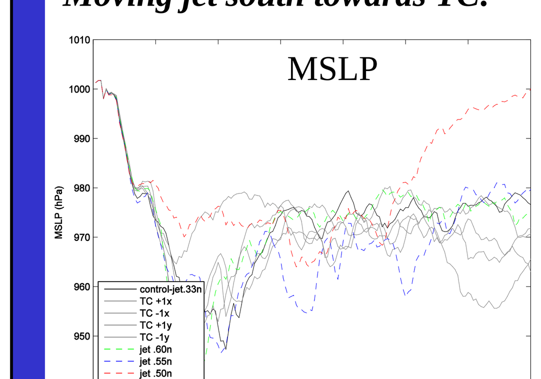
Conversely, on the right, the TC is unimpeded by a slightly larger -v perturbation

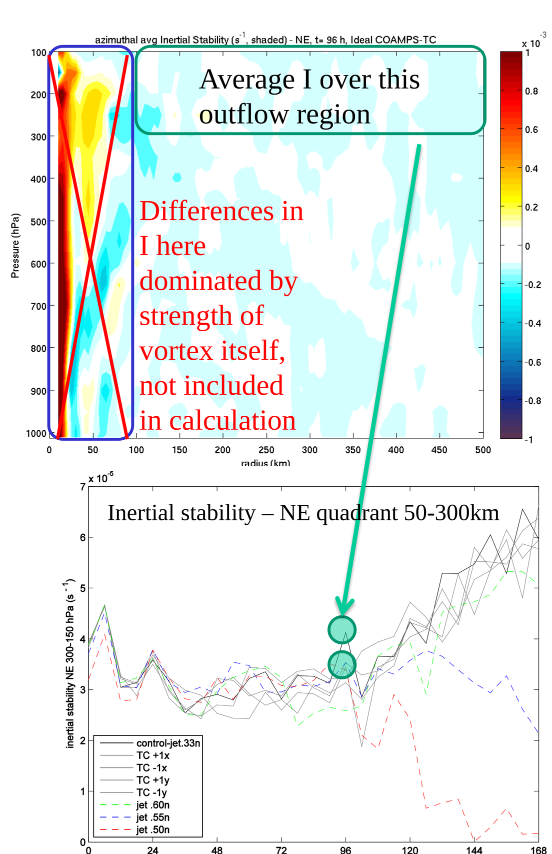


150hPa divergence (shaded) and relative vorticity (contoured)

In the case of the strengthened TC, DIV clearly decreases to the N with respect to control, but increased DIV to the S and E sufficiently compensate

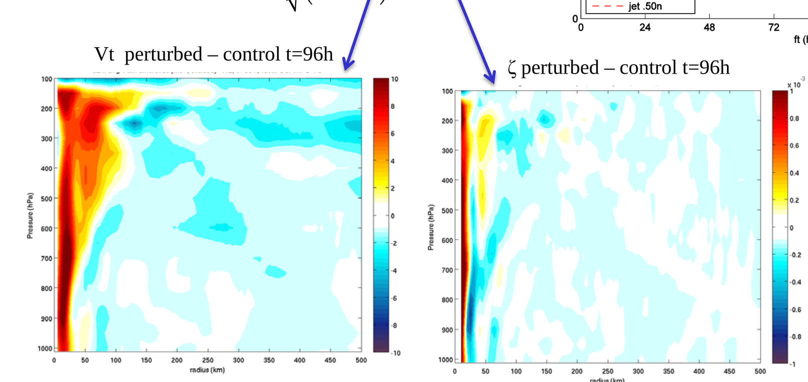
Moving jet south towards TC:





Reduction in I^2 does not consistently correspond with run stronger than control at the expected time (72-120h)

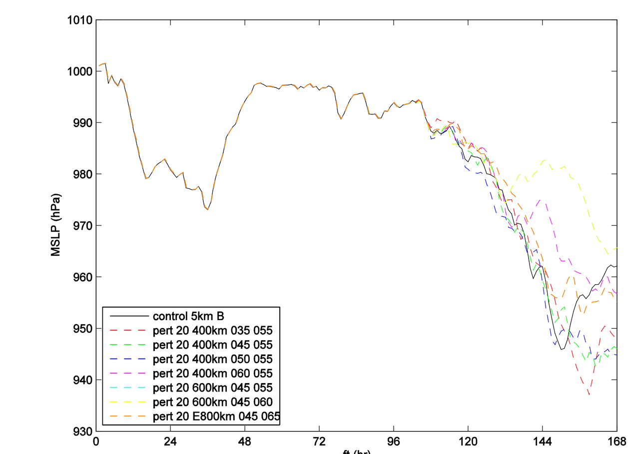
$$I = \sqrt{\left(f + \frac{2v_t}{r}\right)(f + \zeta)}$$



While the zonal jet reduces v_t the effect becomes small with increasing radius from the center of the vortex (recall that I^2 always computed in vortex-relative framework)

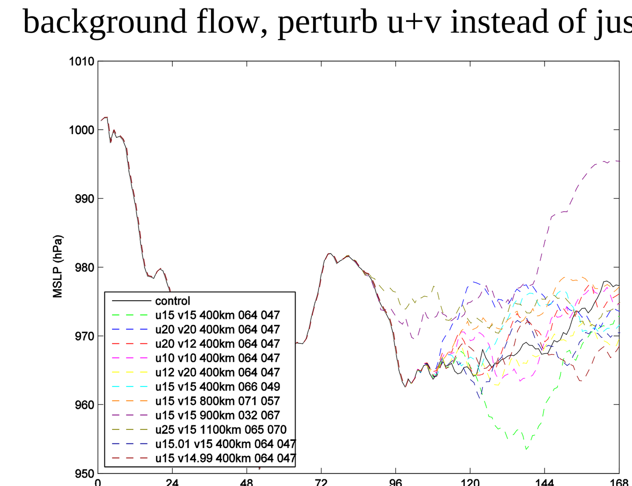
Results from perturbing outflow wind tendency

TC MSLP from simulations with 3 m/s easterly flow: turn on perturbation at 96h, turn off at 144h

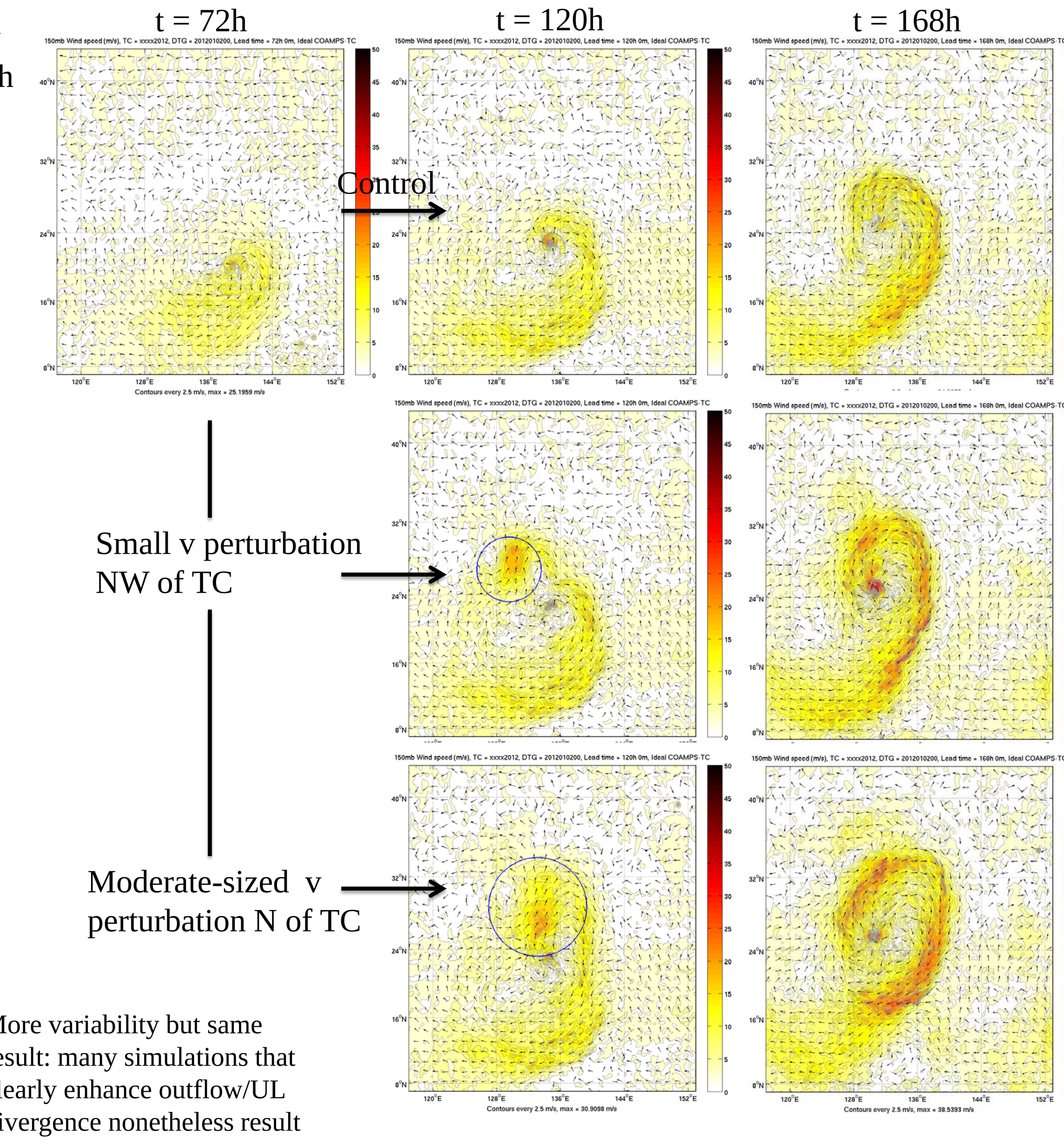


All of these simulations were expected to strengthen the TC relative to the control, but many weaken the TC and the runs that DO strengthen the TC the difference is negligible until after the perturbation is shut off

TC MSLP for simulations with no background flow, perturb u+v instead of just v

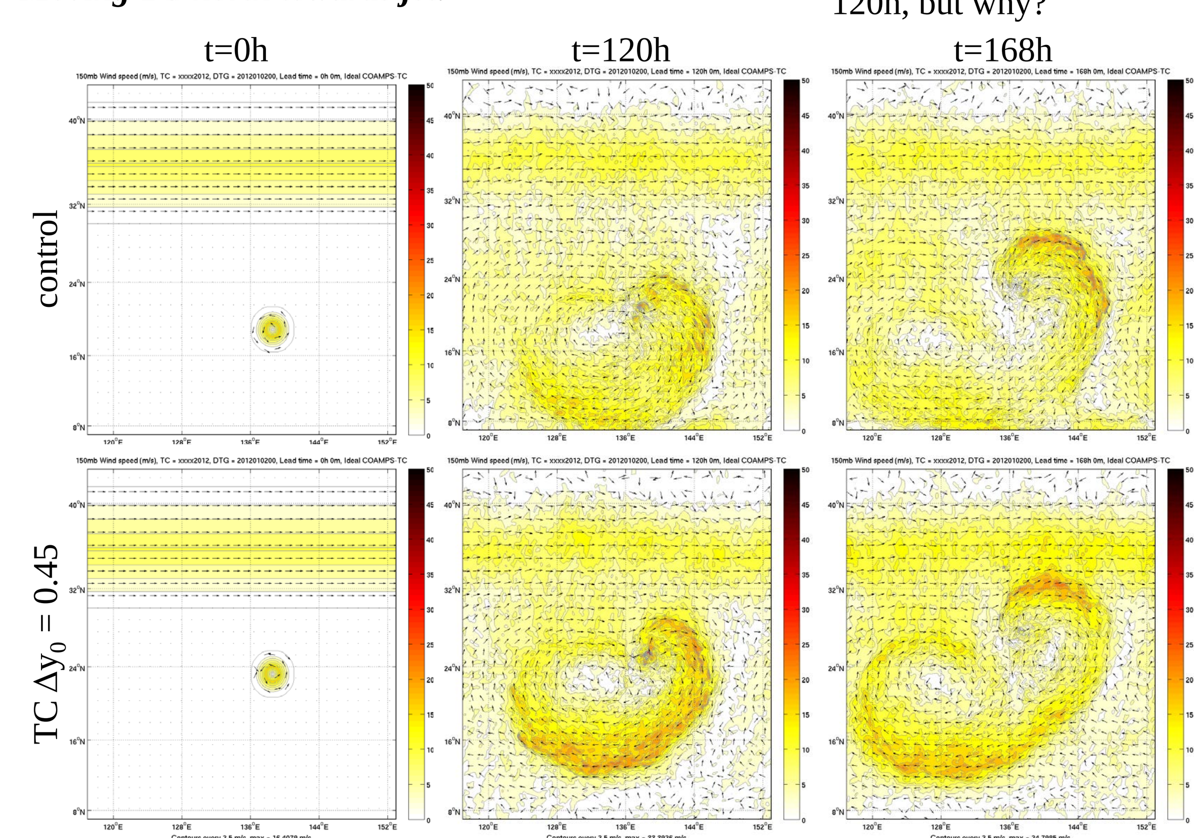


More variability but same result: many simulations that clearly enhance outflow/UL divergence nonetheless result in a weaker TC than the control

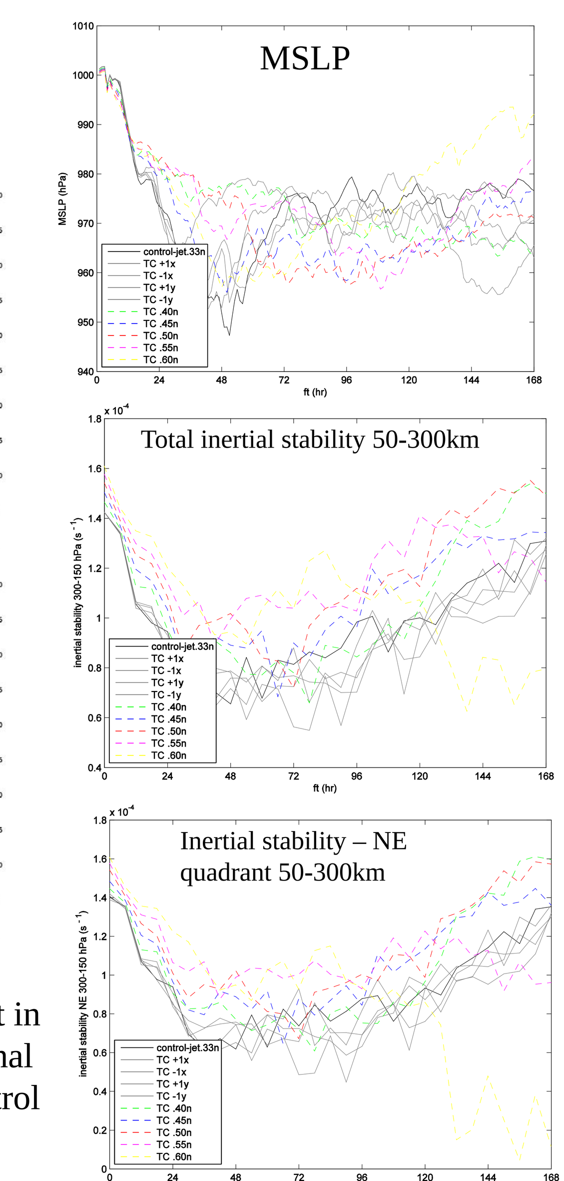


Results from TC/jet interaction

Moving TC north towards jet:

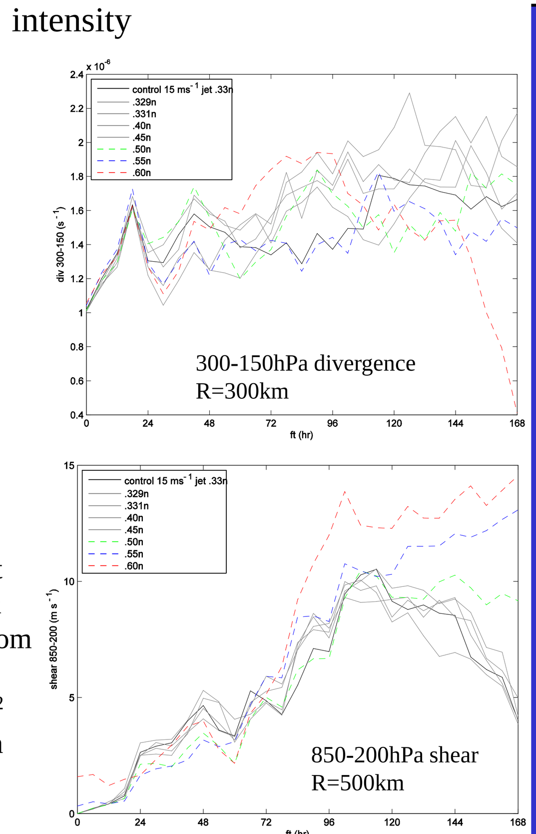


A few runs stronger than the control(s) from 72-120h, but why?



Some reduction in I^2 in NE quadrant in like runs relative to the total azimuthal average, but I^2 still greater than control due to increased *f*

For an "ideal" TC/trough interaction, divergence increases while shear does not; however, here we have more of the opposite occurring, which is likely producing conflicting signals in TC intensity



Summary:

- We have examined sensitivity of TC intensity and structure to perturbed outflow. Outflow is perturbed more directly via adding a v_r tendency, and less directly by introducing $-v_t$ via a zonal jet to reduce inertial stability
- While intensity and structure have been found to be sensitive to these perturbations, they appear to be of comparable or lesser magnitude vs stochastic fluctuations in TC intensity
- TC intensity and structure are highly sensitive to the complex combination of shear, divergence and inertial stability, all of which vary with changes in upper-level flow

Future Work:

- Combine moisture perturbations (enhancing latent heat release) with wind perturbations to see if dynamic + thermodynamic enhancement has greater effect on TC intensity than either factor alone
- Perturb P instead of V to see if a stronger pressure gradient -> sub-geostrophic winds -> outflow deflecting away from TC

Acknowledgements

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