A Composite Study of the Tropical Cyclone Outflow Layer

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Motivation

Studies of the tropical cyclone (TC) outflow layer structure have been previously conducted with sparse spatial and temporal data. With the European Centre for Medium-Range Weather Forecasts (ECMWF) ERA-Interim Reanalysis, there is data at every time and point at the reanalysis resolution. Thus, it is now possible to generate composites of the TC outflow layer over a large sampling of storms. Using a balanced vortex approach, the typical secondary circulation response to eddy momentum and heat fluxes can be understood as well. Understanding the structure of TC outflow can hopefully aid in further understanding the outflow's role, if any, in hurricane structure, propagation, and intensification.

A Brief History

Sparse Spatial Data[5,6,7,8] : balloon soundings, rawinsondes, & radiosondes | (1950s & 1960s)
Improved Spatial Density[1,3] : tracing cirrus cloud fragments in satellite imagery | (Early 1970s)
Early Composites[2,4] : a few storms, thousands of rawinsondes, & radiosondes | (Late 1970s & 1980s)
Observations & Models[9,10] : rawinsonde & satellite vs. ECMWF analyses | (1989 & 1990)

Data & Resolution

Source: ECMWF ERA-Interim Reanalysis
Temporal Resolution: 4x Daily, 36 years (1979-2014)
Horizontal Resolution: 0.7° x 0.7° latitude & longitude
Vertical Resolution: 37 pressure levels

Cylindrical Grid Interpolated Resolution
Radial: every 100 km, from 100 km to 2000 km
Vertical: every 25 mb, from 1000 mb to 50 mb

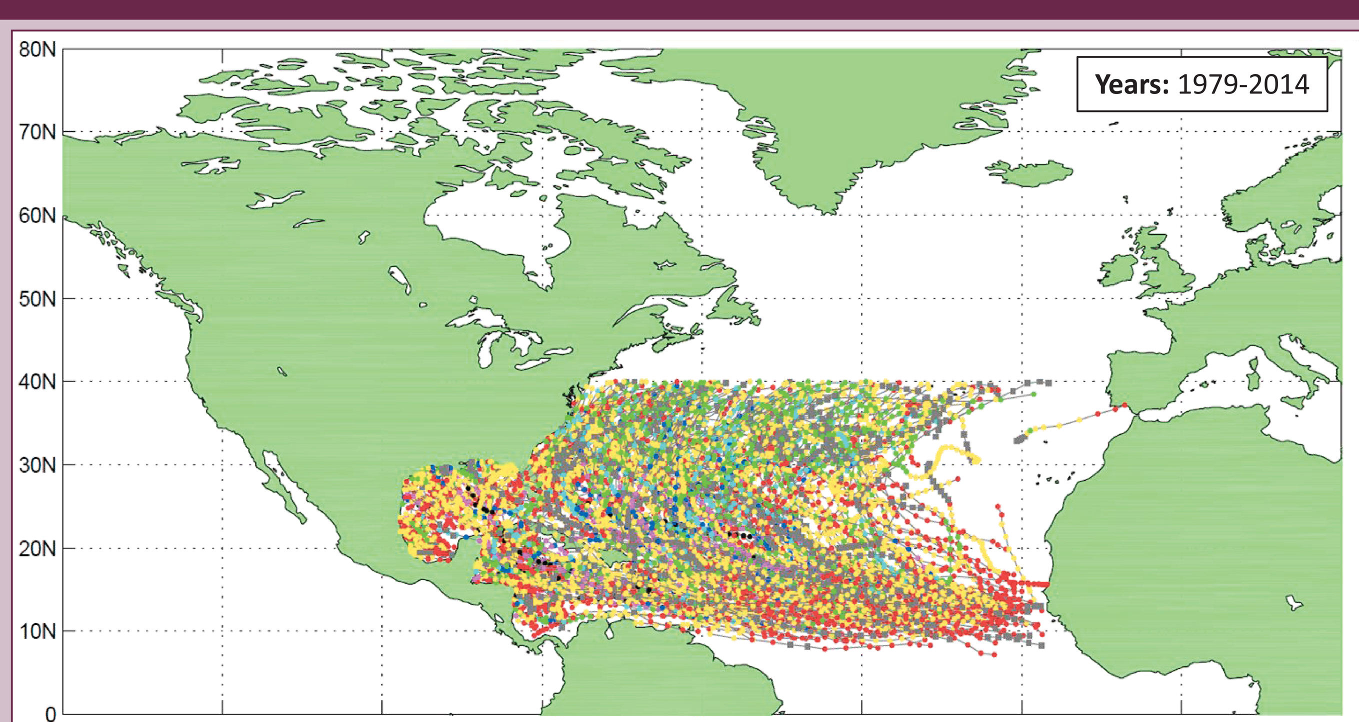
Eliassen's Balanced Vortex Interpolated Resolution
Radial: every 25 km, from 0 km to 2000 km
Vertical: every 25 mb, from 1000 mb to 50 mb

Variables

Name	Units	Formula
Divergence	$10^{-5}s^{-1}$	$\frac{\partial \bar{v}_r}{\partial r} + \frac{\bar{v}_r}{r}$
Eddy Heat Source	$Kday^{-1}$	$-\frac{1}{r}\frac{\partial}{\partial r}\overline{\theta' v_r'} - \frac{\partial}{\partial p}\overline{\theta'\omega'}$
Eddy Momentum Source	$ms^{-1}day^{-1}$	$-\frac{1}{r^2}\frac{\partial}{\partial r}r^2\overline{v'_r v_\lambda'} - \frac{\partial}{\partial p}\overline{\omega' v_\lambda'} - \overline{f' v_r'}$
Inertial Stability	s^{-2}	$\frac{1}{r^3}\frac{\partial \bar{M}^2}{\partial r}$
Potential Temperature	K	θ
Radial Wind	ms^{-1}	$\bar{v}_r$
Relative Vorticity	$10^{-5}s^{-1}$	$\frac{\partial \bar{v}_\lambda}{\partial r} + \frac{\bar{v}_\lambda}{r}$
Tangential Wind	ms^{-1}	$\bar{v}_\lambda$

Tab. 1: The eight variables listed above are illustrated in the composites to the right. Additional variables were also derived including: momentum fluxes, heat fluxes, and vertical velocity.

Subset of HURDAT2 ATL Basin Tracks



TD | TS | Cat. 1 | Cat. 2 | Cat. 3 | Cat. 4 | Cat.5 | ET | Other

TC center times have been removed to eliminate significant structural changes where center:
1: Moved poleward of 40 N | **2:** Made landfall for > 6 h | **3:** Underwent an extra-tropical transition

Number of TC Centers
Removed & Remaining
TD: 915, 2922
TS: 1009, 3820
Cats. 1 & 2: 568, 2025
Cats. 3-5: 73 , 740

Fig. 1: Subsetted TC center times from NOAA's National Hurricane Center's 2nd Generation Hurricane Database (HURDAT2) based on three filters over a 36 year period.

Eliassen's Balanced Vortex Model

Purpose: To determine how the secondary circulation is impacted by eddy heating and momentum forcings
Diagnostic, Elliptical Equation: frictionless, adiabatic, axisymmetric, hydrostatic, gradient-wind balanced

Full Eq. :

$$A\psi_{pp} + 2B\psi_{rp} + C\psi_{rr} - \frac{4B}{r}\psi_p - \left[\frac{1-\kappa}{p}B + \frac{C}{r}\right]\psi_r = r\frac{\partial}{\partial p}\left[\left(\frac{2\overline{v_\lambda}}{r} + f\right)\left(\frac{\partial \overline{v_\lambda}}{\partial t}\right)_{eddy}\right] + \frac{r\pi R}{p}\frac{\partial}{\partial r}\left(\frac{\partial \bar{\theta}}{\partial t}\right)_{eddy}$$

LHS Terms :

Inertial Stability: $$A = \left(f + \frac{2\overline{v_\lambda}}{r}\right)\left(f + \frac{\partial \overline{v_\lambda}}{\partial r} + \frac{\overline{v_\lambda}}{r}\right)$$

Baroclinicity: $$B = -\left(f + \frac{2\overline{v_\lambda}}{r}\right)\left(\frac{\partial \overline{v_\lambda}}{\partial p}\right)$$

Static Stability: $$C = -\frac{R\pi}{p}\frac{\partial \bar{\theta}}{\partial p}$$

RHS Terms :

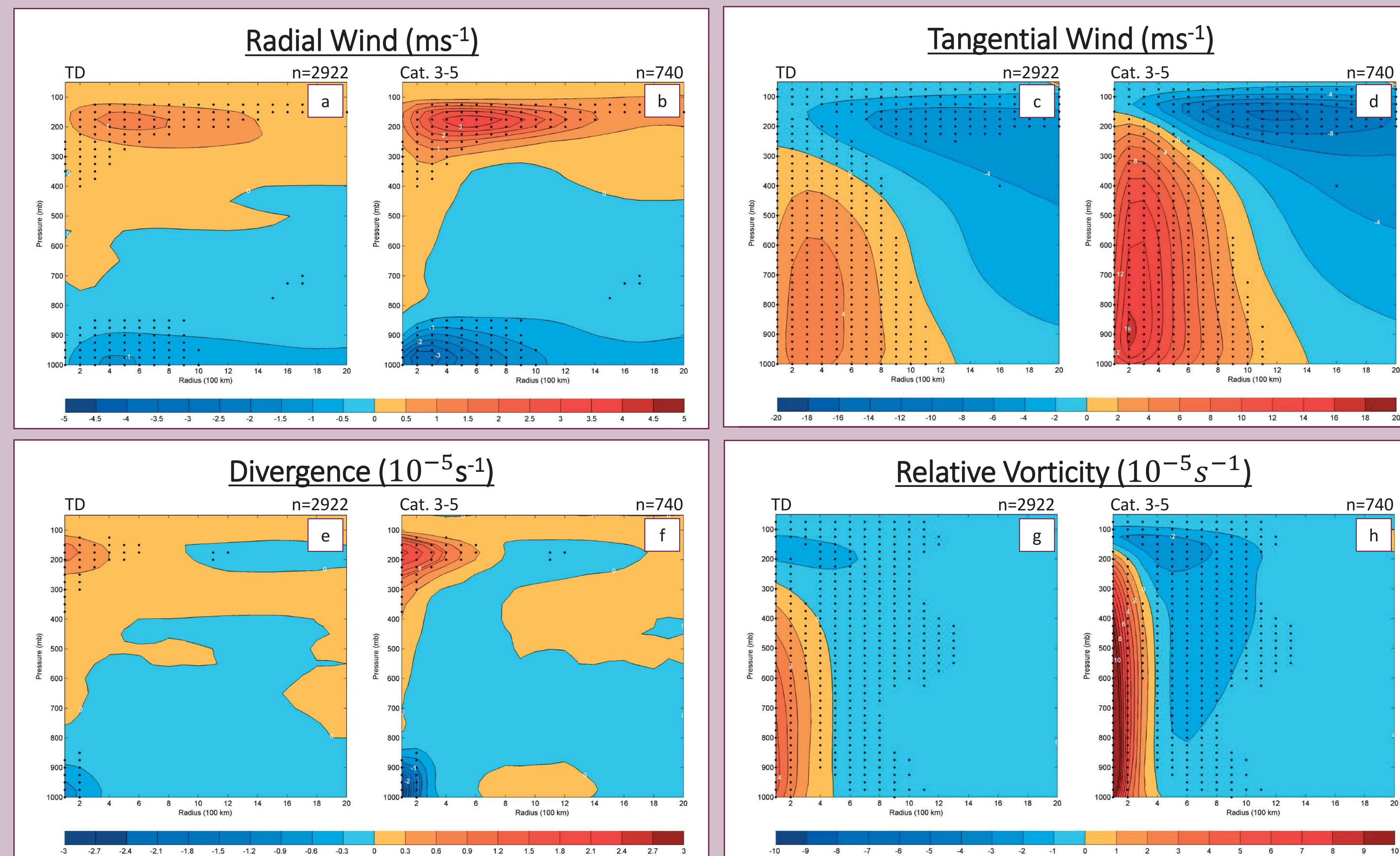
Eddy Momentum Source: $$\left(\frac{\partial \overline{v_\lambda}}{\partial t}\right)_{eddy} = \underbrace{-\frac{1}{r^2}\frac{\partial}{\partial r}r^2\overline{v'_r v_\lambda'}}_{\text{Horizontal Mom. Flux Convergence}} \underbrace{- \frac{\partial}{\partial p}\overline{\omega' v_\lambda'}}_{\text{Vertical Mom. Flux Convergence}} \underbrace{- \overline{f' v_r'}}_{\text{Coriolis Torque}}$$

Eddy Heat Source: $$\left(\frac{\partial \bar{\theta}}{\partial t}\right)_{eddy} = \underbrace{-\frac{1}{r}\frac{\partial}{\partial r}\overline{\theta' v_r'}}_{\text{Horizontal Heat Flux Convergence}} \underbrace{- \frac{\partial}{\partial p}\overline{\theta'\omega'}}_{\text{Vertical Heat Flux Convergence}}$$

Nondim. Pressure: $$\pi = \left(\frac{p}{p_0}\right)^{\left(\frac{R}{c_p}\right)}$$

The linearity of the equation means impacts can be assessed as:
1) a single forcing
2) multiple forcings combined through summation

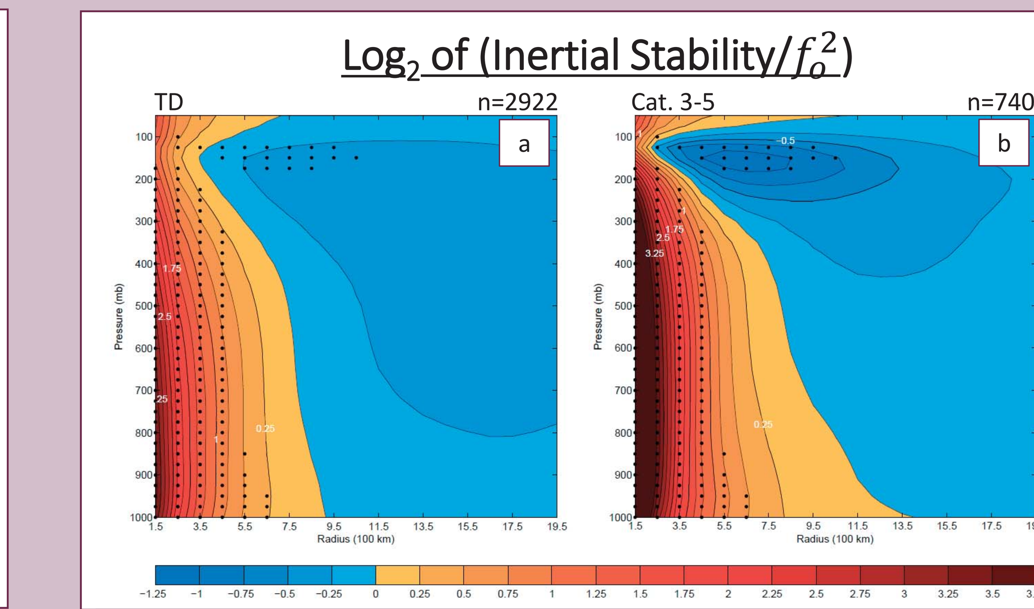
Composites of Weakest & Strongest Categories



Radial Wind: strengthens, max moves radially outward with intensity due to weaker inertial stability in stronger storms → outflow max remains at same pressure level – Why?
Tangential Wind: magnitude becomes larger with intensity → anticyclone max shifts upward and radially inward with increasing intensity – Why?
Divergence: magnitude becomes larger with intensity and covers a larger area → max at same pressure level like radial wind, since derived from the radial wind field
Relative Vorticity: stronger storms have stronger negative relative vorticity → values < 0 indicate areas of negative relative vorticity, synonymous with weak inertial stability

Fig. 2: Shown are composites with corresponding sample sizes (n) of radial wind (a, b), tangential wind (c, d), divergence (e, f) and relative vorticity (g, h). See **FIG. GUIDE** below for details on figure interpretation.

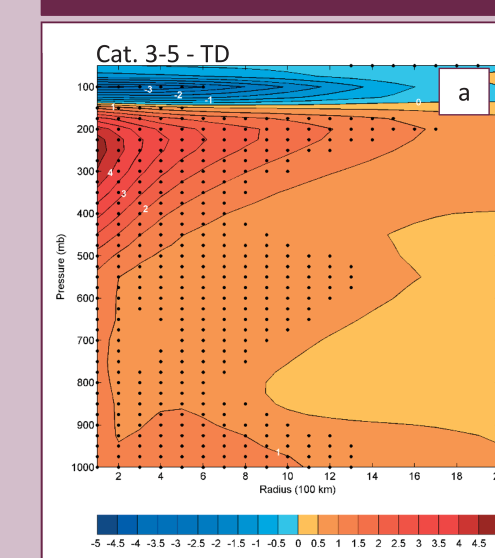
Outflow Layer Stability



Inertial Stability: with increasing intensity, inertial stability becomes weaker, more concentrated in the upper troposphere → values < 0 indicate weak inertial stability

Fig. 3: Shown are composites with corresponding sample sizes (n) of the $\log_2$ of inertial stability/f_0^2. See **FIG. GUIDE** below for details on figure interpretation.

Composite Differences



Potential Temperature (K)

Potential temperature: temperature increases with intensity at the inner radii, indicating a stronger, warm core system → stronger storms have a higher tropopause as indicated by lower temperatures above the warm core

Fig. 4: Shown is the difference field of potential temperature (a). Differences are taken as strongest minus weakest, or Cat. 3-5 - TD. See **FIG. GUIDE** below for details on figure interpretation.

Bal. Vortex Forcings

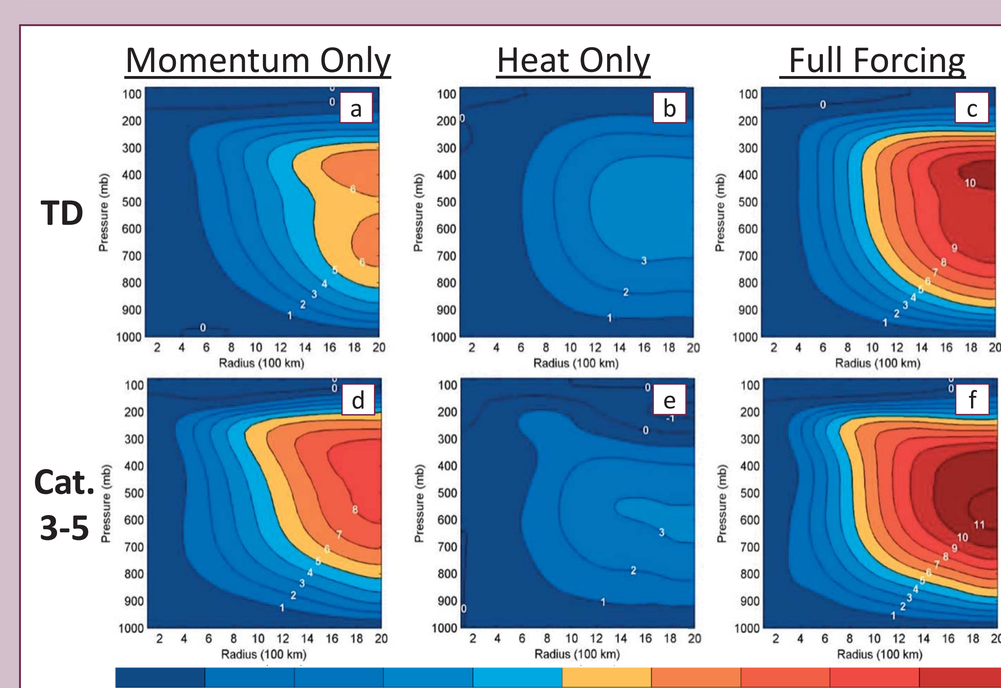
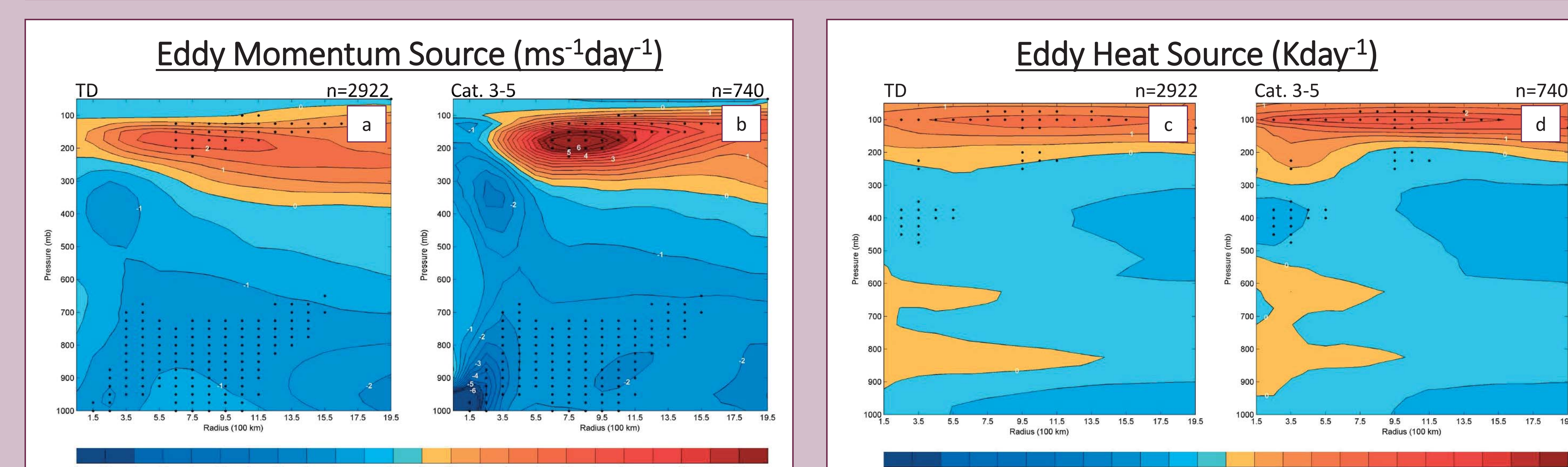


Fig. 5: Momentum only (a,d), heat only (b,e), and full (c,f) balanced vortex solutions for the TD (a,b,c) and Cat. 3-5 (d,e,f) composites. Momentum Only + Heat Only = Full Forcing

Composites of Balanced Vortex RHS Terms



Eddy Momentum Source: maximum increases with intensity → max at same pressure level regardless of intensity – Why?
Eddy Heat Source: upper tropospheric & outer radii maxima increase with intensity → eddies warm stratosphere above and cool the troposphere within the TC to restore balance

Fig. 6: Shown are composites with corresponding sample sizes (n) of eddy momentum source (a, b) and eddy heat source (c, d). See **FIG. GUIDE** below for details on figure interpretation.

Fig. Guide

Filled, Colored Contours: values of the listed variable | **White Numbers:** values of the filled contours
Overlaying Black Dots: differences between composites are statistically significant at the 99% confidence level, as determined by bootstrap testing

Further Stratifications Performed

Pre- vs. Post- Hurricane Intensity: for TDs & TSs
Non-Intensifying vs. Intensifying Storms: for TDs & TSs
Latitudinal Effects: stratified by tropics (0° – 20° N) & midlatitudes (20° – 40° N)

Future Work

Diurnal Cycle: will stratify radius-time plots of radial outflow by time of day
Intensity Changes: will composite radius-time plots before & after rapid intensification
Stratifications: will determine whether to further stratify the subset

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