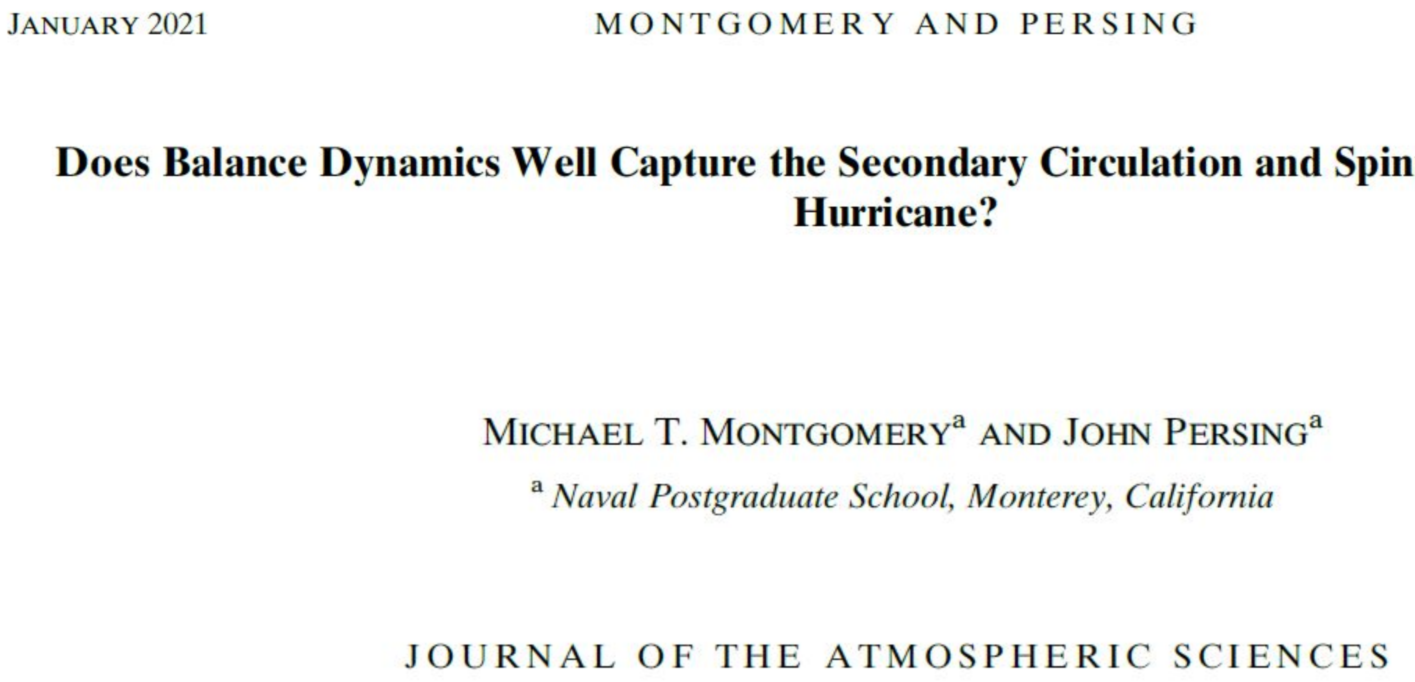


JANUARY 2021 MONTGOMERY AND PERSING

Does Balance Dynamics Well Capture the Secondary Circulation and Spinup of a Simulated Hurricane?

MICHAEL T. MONTGOMERY[a] AND JOHN PERSING[a]
[a] *Naval Postgraduate School, Monterey, California*

JOURNAL OF THE ATMOSPHERIC SCIENCES

vs Heng et al. (2017 & 2018)

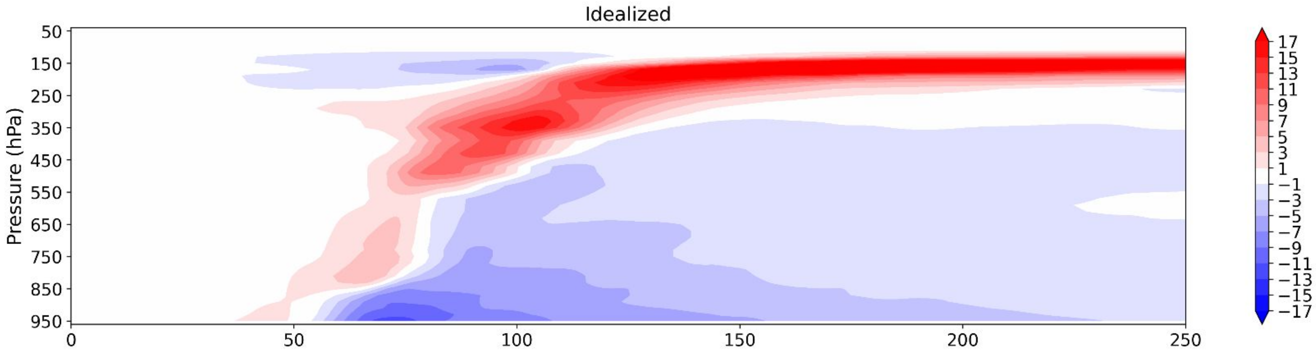
Introduction

- The rotating-convection paradigms need a modest elevation of surface enthalpy fluxes to sustain the deep convection for spinup in the low to middle moist tropical environment. Convection amplifies the vorticity by stretching and tilting process.

- Some abbreviations:
  - BL: boundary layer
  - AAM: absolute angular momentum
  - RMW: Radius of maximum wind
  - FD: Finite difference

Introduction

- The nonlinear BL dynamics in the spinup of a hurricane vortex in important:
    1. The cross-isobaric low-level inflow transports higher AAM from environment to eyewall but is dissipated by friction.
    2. The inflow is decelerated as it approach the RMW because of the centrifugal force.
    3. The inflow ascends in the eyewall and transports AAM to spinup the tangential wind.
    4. The higher AAM produces larger centrifugal force and outflow in eyewall above BL.
    5. TC spinup if the spinup process overcome the spindown process.



Introduction

- Assumptions in the Eliassen (balance) model:
  - Axisymmetric TCs
  - Hydrostatic balance
  - Gradient wind balance

Thermal wind balance

Montgomery

Nonlinear BL dynamics is an essential element of the spinup of the tangential wind, especially in the vortex attains hurricane strength.

Heng

Axisymmetric balanced model is sufficient for explaining the spinup of real or simulated hurricanes (nonlinear, unbalanced, and asymmetric eddy process are secondary to spinup).

Introduction

- Montgomery: The domestic surface inflow was weaker than the simulated surface inflow.
- Heng→Montgomery: The surface inflow was underestimated because the 1st order FD was used at the lower boundary. The tangential wind tendency $\frac{\partial v}{\partial t}$ was also underestimated.
- Montgomery: Update the FD to 2nd order.

Introduction

- Montgomery→Heng: They used the azimuthal averaged tangential wind of the simulation, which did not solve the thermal wind equation, in the Eliassen model. The solutions can not be regard as strict balanced solutions (were contaminate by imbalance singal).

- Montgomery→Heng: $\frac{\partial v}{\partial t}$ was spinup in inner-core at BL in their results, whereas it was spindown in our results.

- The paper consider the strict balanced solutions. Whether the balance model can capture the results (BL inflow and $\frac{\partial v}{\partial t}$)caused from the BL friction imbalance in TC intensification.

The remaining outline

The full-physics simulations

↓

Simulation summary

↓

The Eliassen model in brief

↓

Results

↓

Summary and conclusions

The full-physics simulations

Cloud Model 1 (CM1)

- Three-dimensional simulation
- Inner domain: $\Delta x = \Delta y = 3\ km$, 405 x 405 km
- Outer domain: 2880 x 2880 km
- Vertical layer:

(EX-1)	(EX-2)	(EX-3)
$\Delta z = 500\ m$	Stretched Grid	$\Delta z = 250\ m$
$\mathrm{z} = 250,$ $750,$ $\ldots, (\mathrm{m})$	$\mathrm{z} = 25, 90, 184,$ $308, 461, 644,$ $856, \ldots, (\mathrm{m})$	

- 50 vertical layers (height) (EX-1 & EX-2)

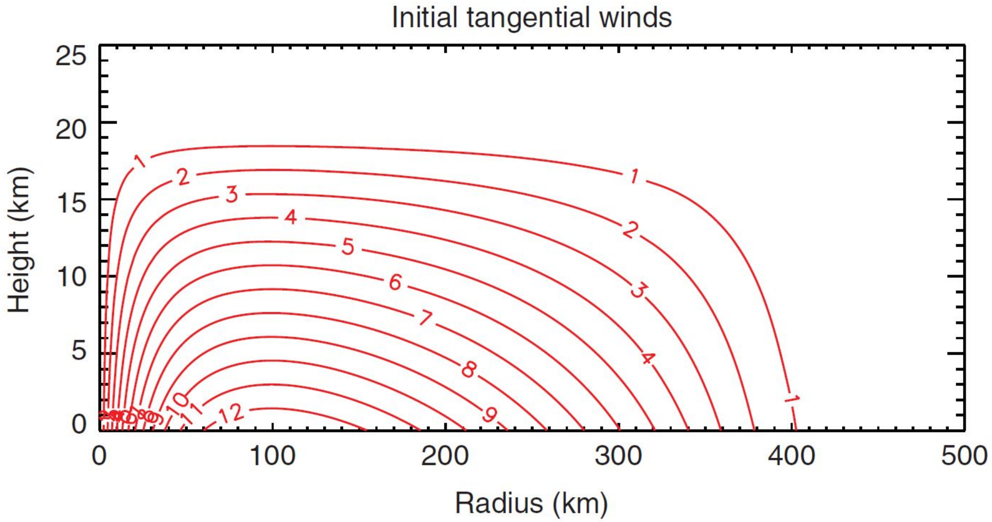
The full-physics simulations

Cloud Model 1 (CM1)

- I.C.: cloud free, circular vortex, thermal wind balance, no environment wind
- Environment: near-moist-neutral sounding (Rotunno and Emanuel 1987)
- Constant $F = 5 \times 10^{-5}\ (s^{-1})$
- Constant $SST = 26.15\ °C$

- Longwave radiati
- Simplified rainfal
- Bulk aerodynami nt surface drag coefficient $C_D = 2.5$
- Subgrid turbulen xing length: 50 m)

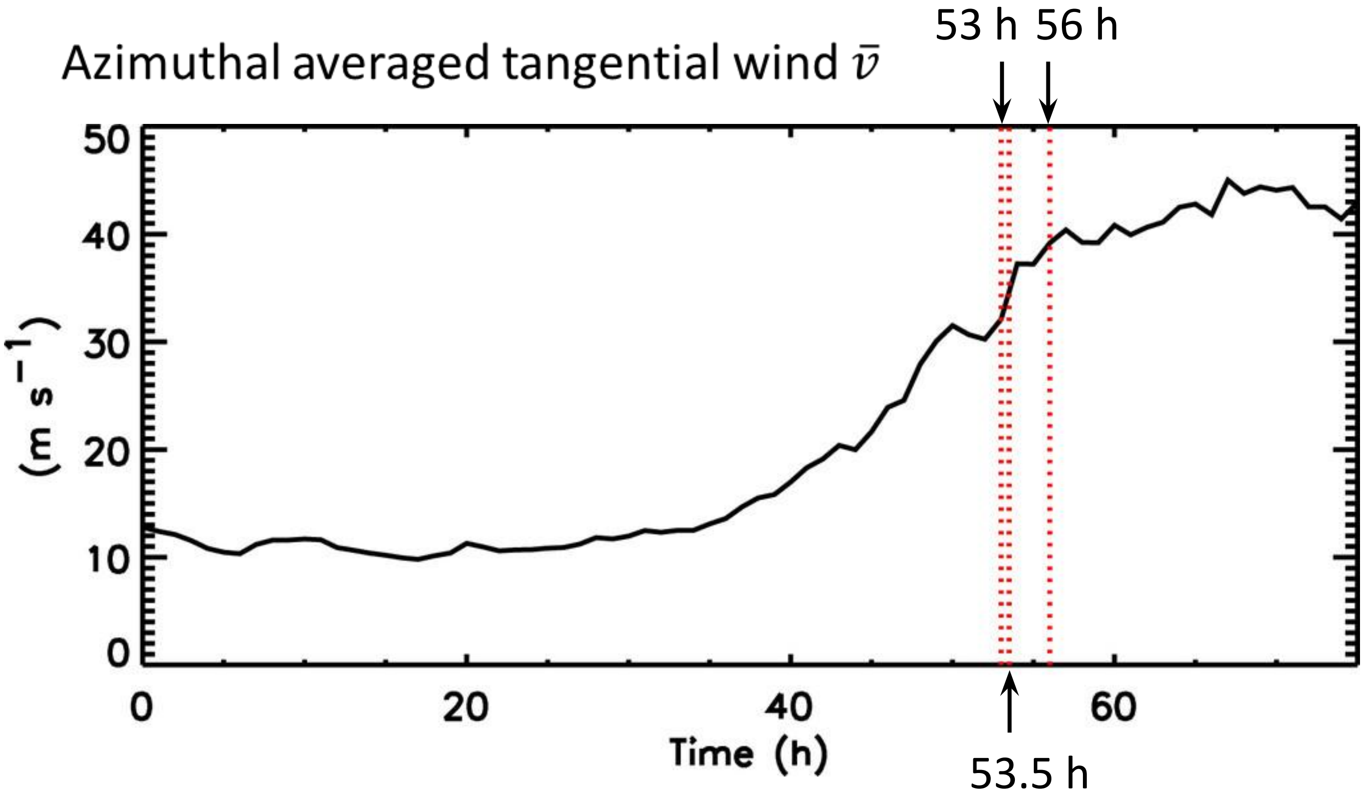
(Constant sea-to-air r



Simulations Overview

EX-1

Azimuthal averaged tangential wind $\bar{v}$



Intensity: max $\bar{v}$

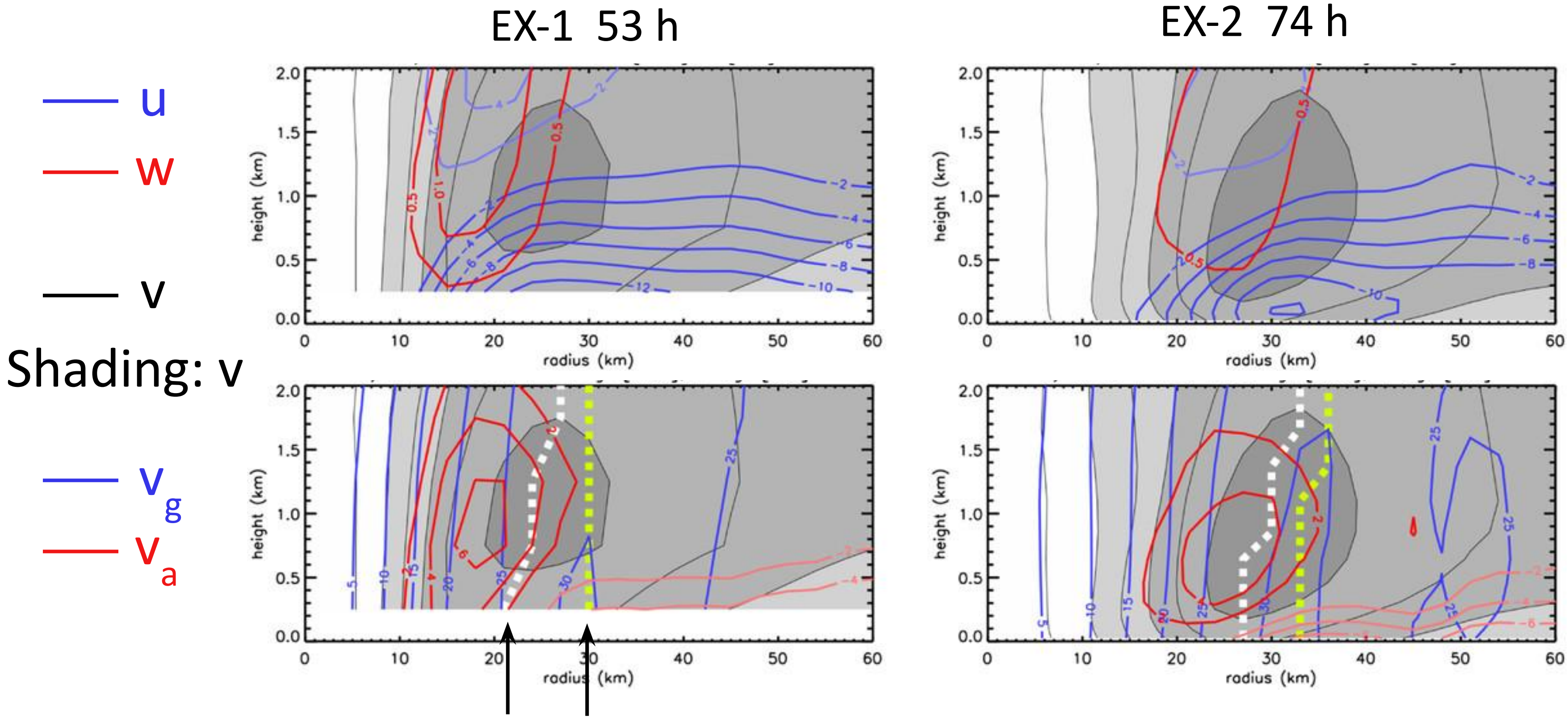
Intensification rate: $\frac{\partial \bar{v}}{\partial t}$

Height of max $\bar{v}$: 750 m

Max $\frac{\partial v}{\partial t}$: 5 m/s/hr

Simulations Overview

EX-1 and EX-2



EX-1 53 h

EX-2 74 h

— u

— w

— v

Shading: v

— v_g

— v_a

RMW of v

RMW of v_g

Max low-level inflow was at RMW.

RMW of v was inner than RMW of v_g, and v_a was inside the strong v.

The Eliassen model in brief

Physical meaning

For a slow evolution of an axisymmetric vortex

Forcing: tangential momentum (tangential momentum equation),
diabatic heating (heat equation)

Hydrostatic balance
Gradient wind balance

Thermal wind balance

Thermal wind balance:

$$\frac{\partial}{\partial r} log\chi + \frac{C}{g}\frac{\partial}{\partial z} log\chi = -\frac{\xi}{g}\frac{\partial v}{\partial z} \qquad C = \frac{v^2}{r} + fv \qquad \chi = \frac{1}{\theta_v}$$

Eliassen equation:

The forcing try to drive the vortex away from thermal wind balance. The secondary circulation try to keep the vortex in thermal wind balanced during the vortex evolving.

The Eliassen model in brief

Equations

$$\frac{\partial}{\partial r}\left(\bar{A}\frac{\partial\psi}{\partial r}+\frac{1}{2}\bar{B}\frac{\partial\psi}{\partial z}\right)+\frac{\partial}{\partial z}\left(\frac{1}{2}\bar{B}\frac{\partial\psi}{\partial r}+\bar{C}\frac{\partial\psi}{\partial r}\right)=\dot{\Theta}$$

$$\bar{A}=-g\frac{\partial\chi}{\partial z}=\left(\frac{\chi}{\rho r}\right)N^2$$

$$\bar{B}=-\frac{2}{\rho r}\left(\chi\xi\frac{\partial v}{\partial z}+C\frac{\partial\chi}{\partial z}\right)$$

$$\bar{C}=\frac{1}{\rho r}\left[\xi(\zeta+f)\chi+C\frac{\partial\chi}{\partial r}\right]=\frac{\chi}{\rho r}I_g^2$$

Forcing: $$\dot{\Theta}=\mathrm{g}\frac{\partial}{\partial r}(\chi^2\dot{\theta})+\frac{\partial}{\partial z}(C\chi^2\dot{\theta})+\frac{\partial}{\partial z}(\chi\xi\dot{V})$$

The Eliassen model in brief

Forcing

$$\frac{\partial}{\partial r}\left(\bar{A}\frac{\partial \psi}{\partial r} + \frac{1}{2}\bar{B}\frac{\partial \psi}{\partial z}\right) + \frac{\partial}{\partial z}\left(\frac{1}{2}\bar{B}\frac{\partial \psi}{\partial r} + \bar{C}\frac{\partial \psi}{\partial r}\right) = \dot{\Theta}$$

Forcing: $$\dot{\Theta} = \mathrm{g}\frac{\partial}{\partial r}(\chi^2\dot{\theta}) + \frac{\partial}{\partial z}(C\chi^2\dot{\theta}) + \frac{\partial}{\partial z}(\chi\xi\dot{V})$$

Diabatic heating ($\dot{\theta}$):

$$\dot{\theta}(r,z) = \frac{\partial\theta}{\partial \mathrm{t}} + u\frac{\partial\theta}{\partial \mathrm{r}} + w\frac{\partial\theta}{\partial \mathrm{z}}$$

Resolved eddy advection
Latent heating
Radiation

Tangential momentum($\dot{V}$):

$$\dot{V}(r,z) = \frac{\partial v}{\partial \mathrm{t}} + u(\zeta + f) + w\frac{\partial v}{\partial \mathrm{z}}$$

Resolved eddy advection
Surface frictional stress
Subgrid-scale stress

(2-min simulation output)

The Eliassen model in brief

Regularization

$$\frac{\partial}{\partial r}\left(\bar{A}\frac{\partial\psi}{\partial r}+\frac{1}{2}\bar{B}\frac{\partial\psi}{\partial z}\right)+\frac{\partial}{\partial z}\left(\frac{1}{2}\bar{B}\frac{\partial\psi}{\partial r}+\bar{C}\frac{\partial\psi}{\partial r}\right)=\dot{\Theta}$$

Elliptic equation when $\bar{A}\bar{C}-\bar{B}^2>0$,
otherwise symmetrically unstable

If $\bar{A}<0$, reset $\bar{A}$ to a small positive value,
If $\bar{C}<0$, reset $\bar{C}$ to $-0.001\bar{C}$
If the remaining points where $\bar{A}\bar{C}-\bar{B}^2<0$, set $\bar{B}$ to zero.

The Eliassen model in brief

Experiments

Simth-balance Solution (S1):
Take v from the simulation.
Solve ρ, p, θ in thermal wind balance.

Holton-balance Solution (H1):
Take ρ, p, θ from the simulation.
Solve v_g. $\left(\frac{v_g^2}{r} + f v_g = \frac{1}{\rho}\frac{\partial p}{\partial r}\right)$ ($v_g = 0$ if complex number are encountered)
Solve ρ, p, θ in thermal wind balance.

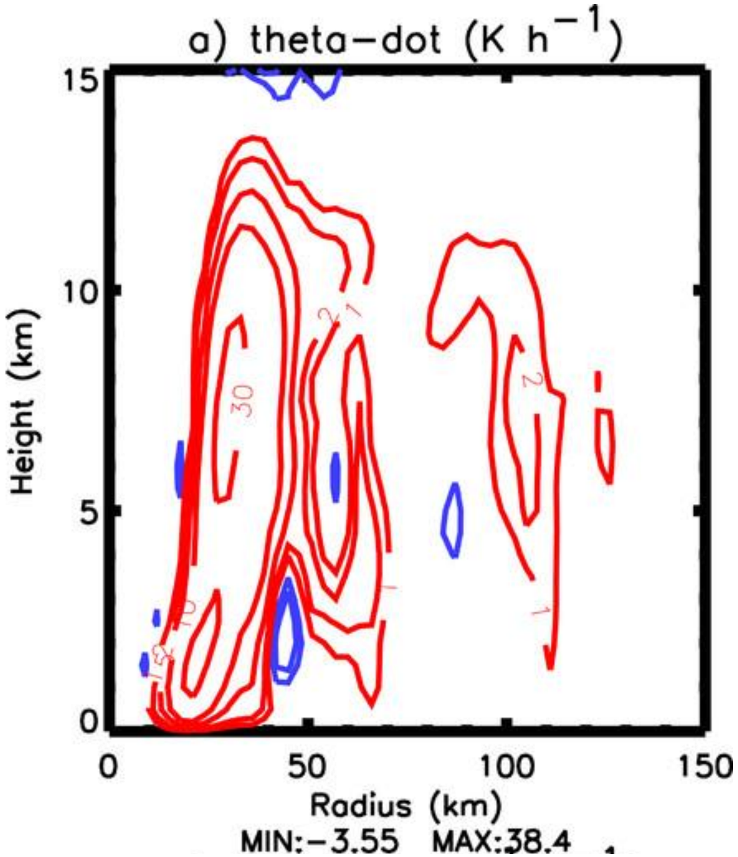
Pseudobalance Solution (P1):
Take v, ρ, p, θ from the simulation.
(Not in thermal wind balance)

Results

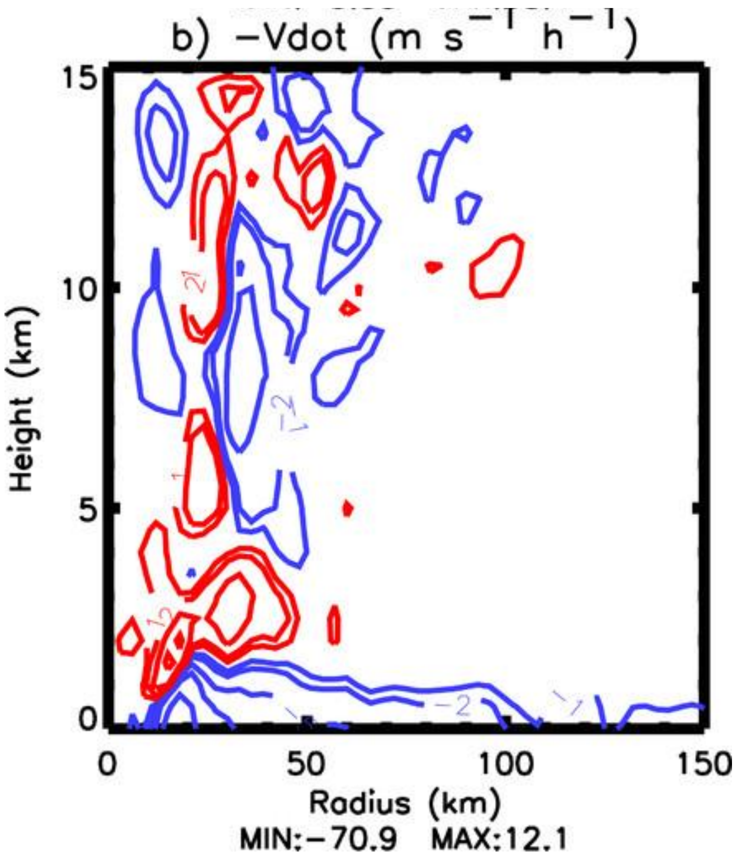
The forcing profiles

53.3~53.7 h
average

— <0
— >0



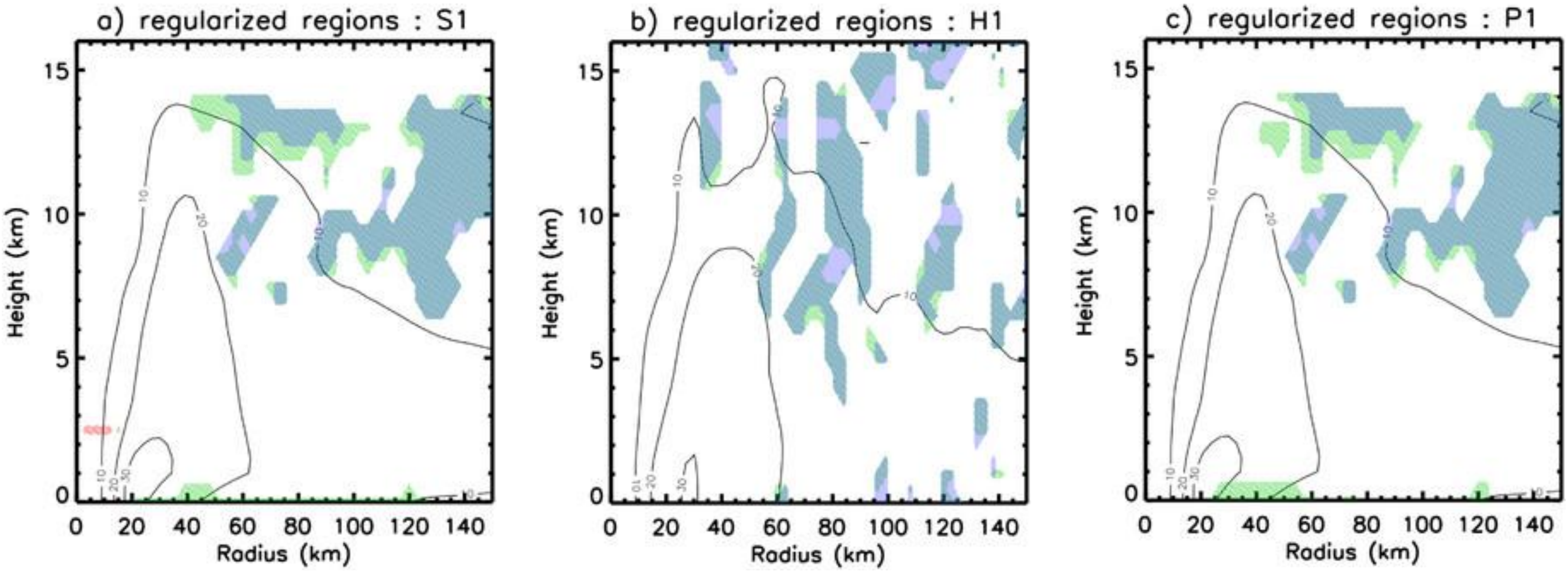
Diabatic heating



Tangential momentum

Results

Regularization region



— v 🟥 $\bar{A} < 0$ 🟩 $\bar{B} < 0$ 🟦 $\bar{C} < 0$

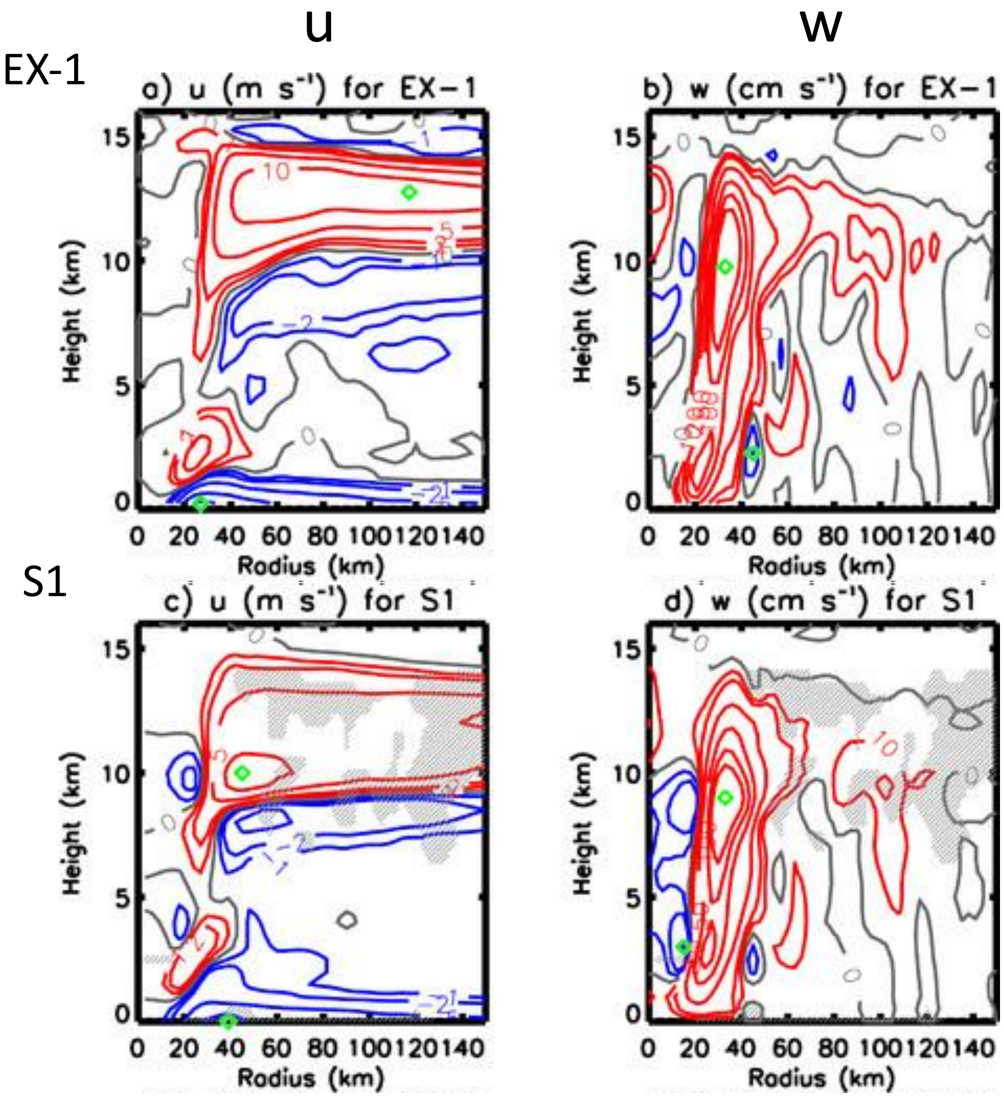
Results

Secondary Circulation

Both:
Low- and mid-level inflow
Upper-level outflow
Eyewall updraft

S1:
Smaller and thicker low-level inflow
Max inflow: -10.60 m/s at 39 km
Max outflow: 13.78 m/s

EX-1:
Max inflow: -16.07 m/s at 27 km
Max outflow: 14.01 m/s



— <0 — >0 — =0

▨ Regularization

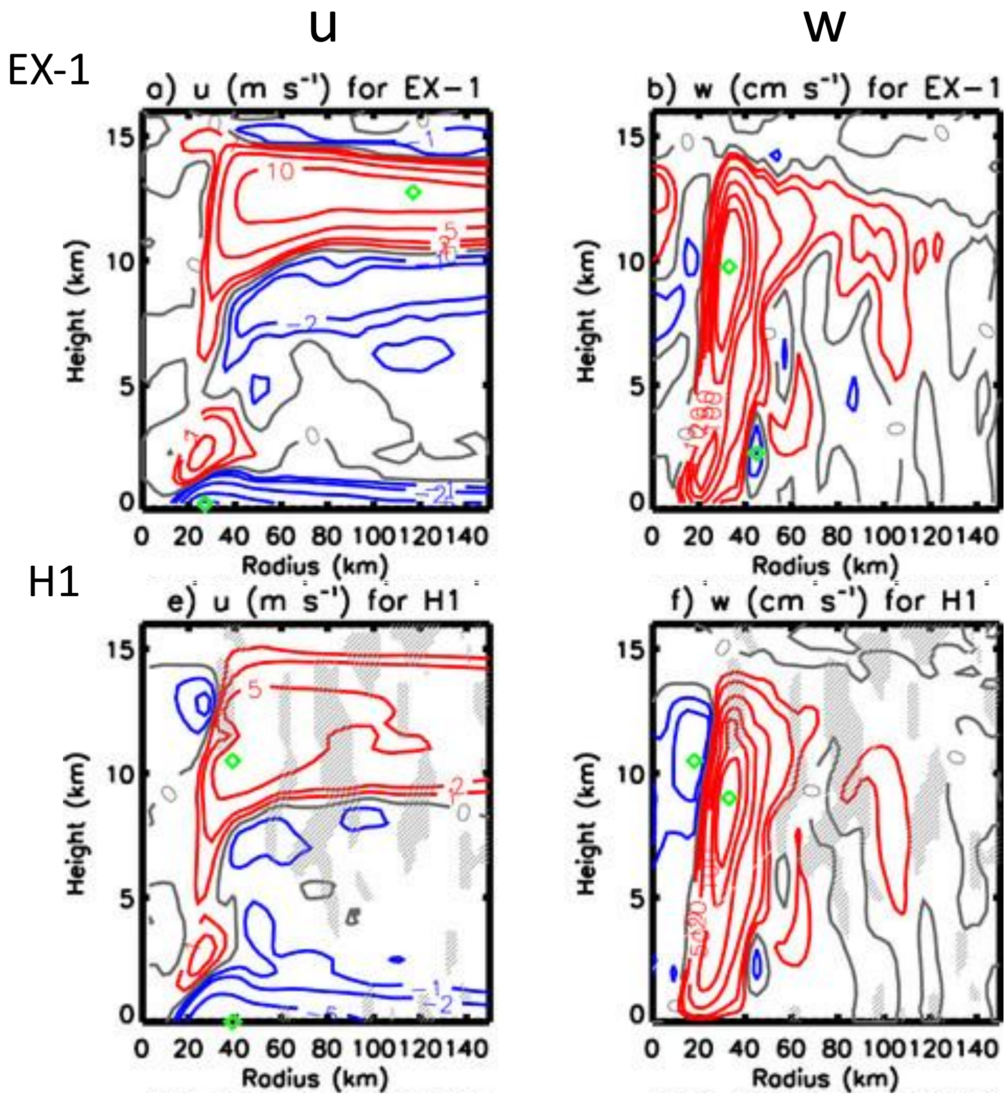
Results

Secondary Circulation

Both:
Low- and mid-level inflow
Upper-level outflow
Eyewall updraft

H1:
Smaller and thicker low-level inflow
Max inflow: -8.85 m/s at 36 km
Max outflow: 9.88 m/s

EX-1:
Max inflow: -16.07 m/s at 27 km
Max outflow: 14.01 m/s



a) u (m s^{-1}) for EX-1

b) w (cm s^{-1}) for EX-1

e) u (m s^{-1}) for H1

f) w (cm s^{-1}) for H1

— <0 — >0 — =0

■ Regularization

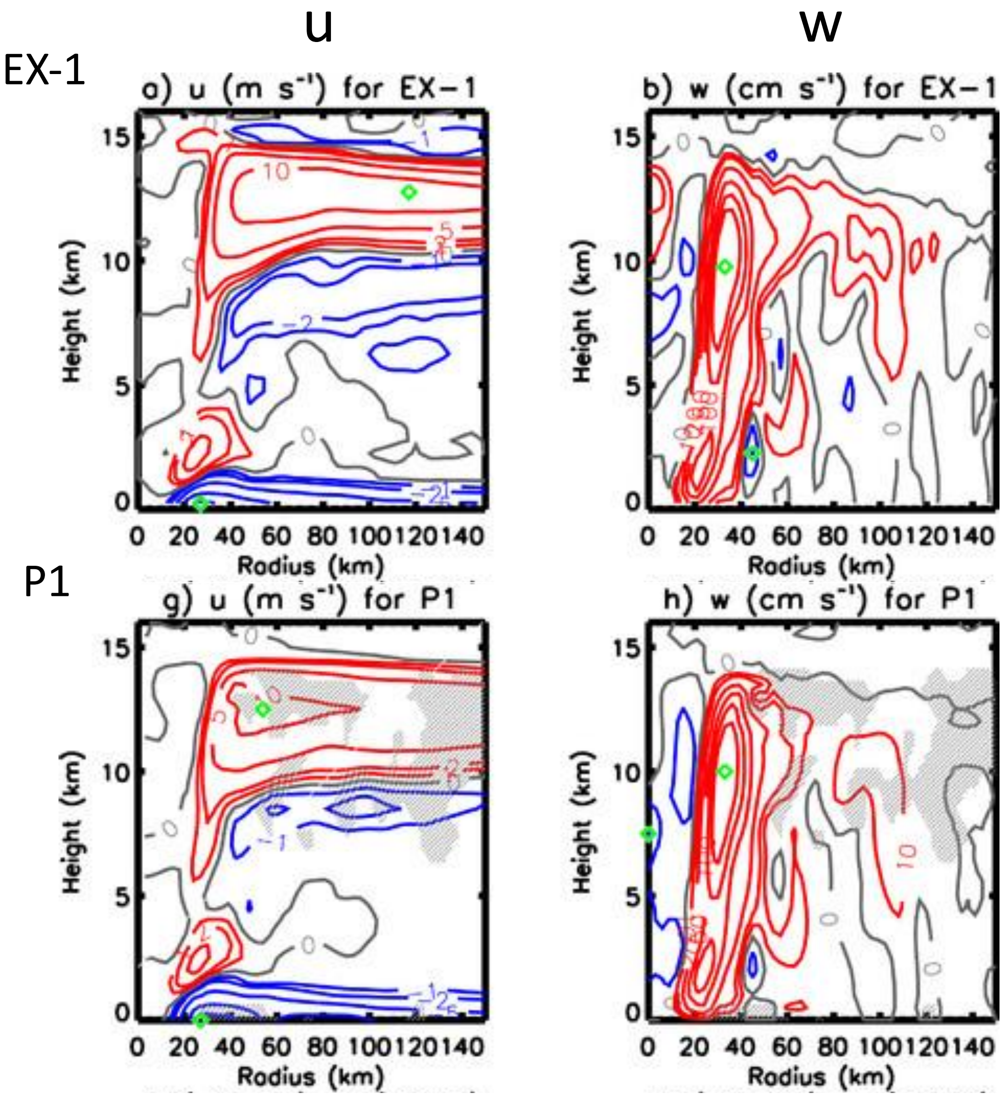
Results

Secondary Circulation

Both:
Low- and mid-level inflow
Upper-level outflow
Eyewall updraft

P1:
Max inflow: -15.39 m/s at 27 km
Max outflow: 13.21 m/s

EX-1:
Max inflow: -16.07 m/s at 27 km
Max outflow: 14.01 m/s



— <0 — >0 — =0

▨ Regularization

Results

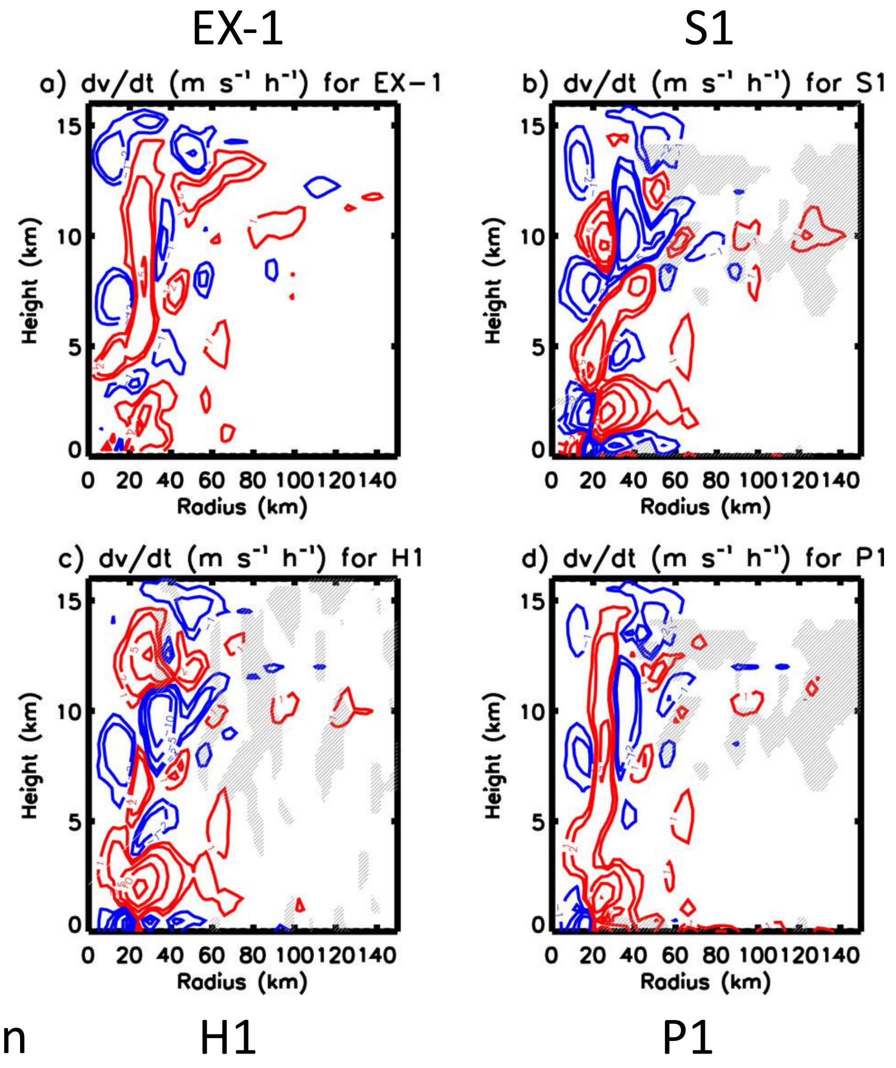
Tangential wind tendency

$$\frac{\partial v}{\partial t} = -u(\zeta + f) - w\frac{\partial v}{\partial z} - \dot{V}$$

$$\frac{\partial v}{\partial t}$$

EX-1 & P1:
Spinup at BL
Spinup at RMW
Spinup at eyewall

S1 & H1:
Spindown at BL
Spinup outside RMW



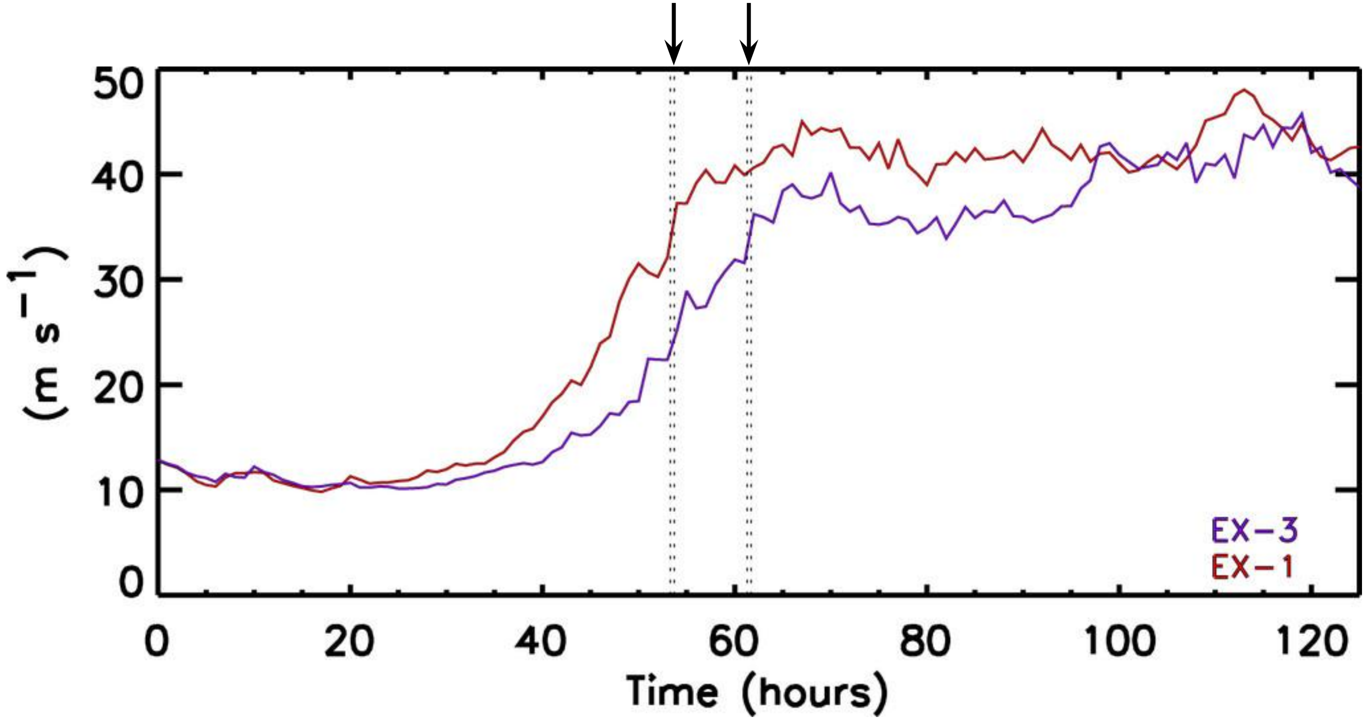
—— <0 —— >0 ▨ Regularization

Simulations Overview

EX-3

53.3 - 53.7 h

61.3 - 61.7 h



Azimuthal averaged tangential wind $\bar{v}$

EX-3 $\Delta z = 250\ m$

EX-1 $\Delta z = 500\ m$

Results

Secondary Circulation

Both:

Low- and mid-level inflow

Upper-level outflow

Eyewall updraft

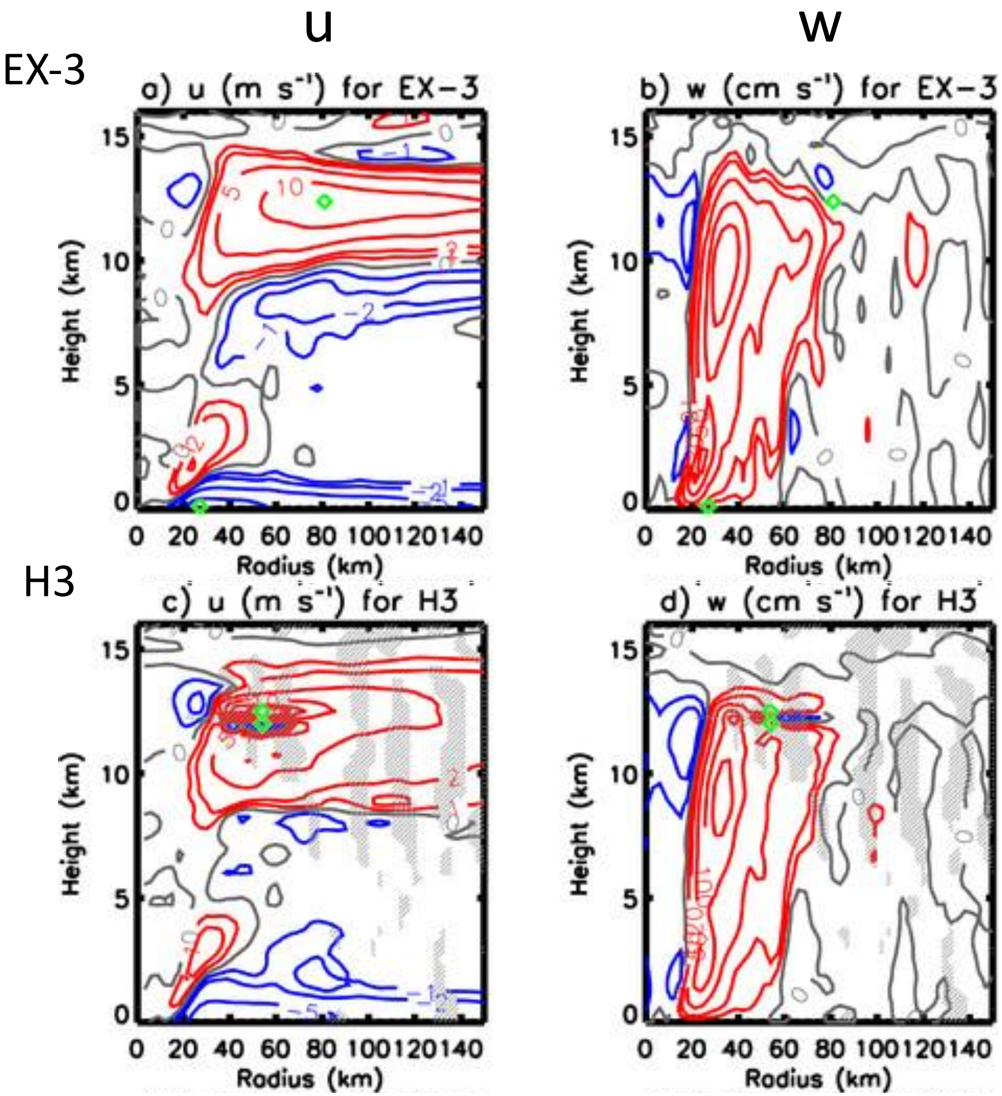
H3:

Smaller and thicker low-level inflow

Max inflow: -8.40 m/s at 45 km

EX-3:

Max inflow: -13.24 m/s at 24 km



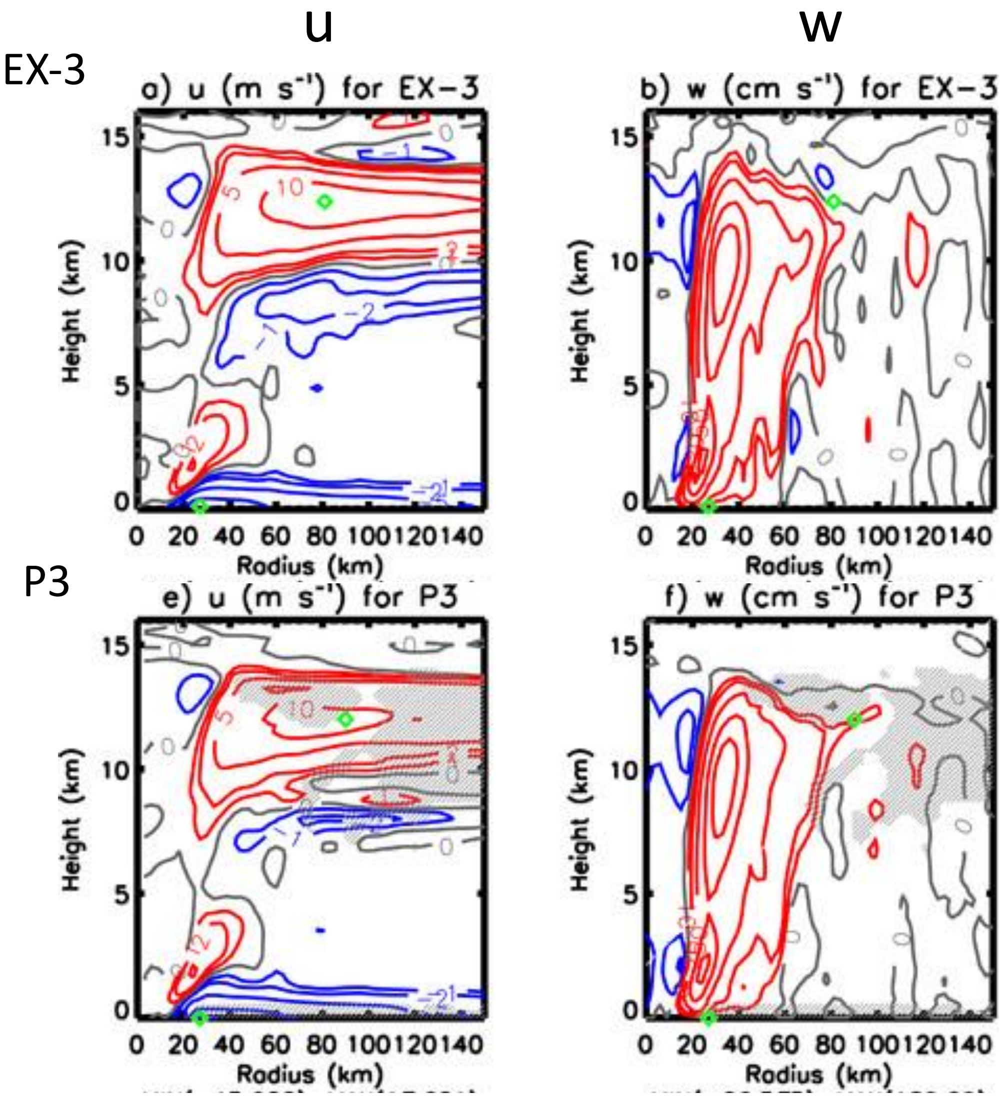
— <0 — >0 — =0

▨ Regularization

Results

Secondary Circulation

Both:
Low- and mid-level inflow
Upper-level outflow
Eyewall updraft



— <0 — >0 — =0

▨ Regularization

Results

Tangential wind tendency

$$\frac{\partial v}{\partial t} = -u(\zeta + f) - w\frac{\partial v}{\partial z} - \dot{V}$$

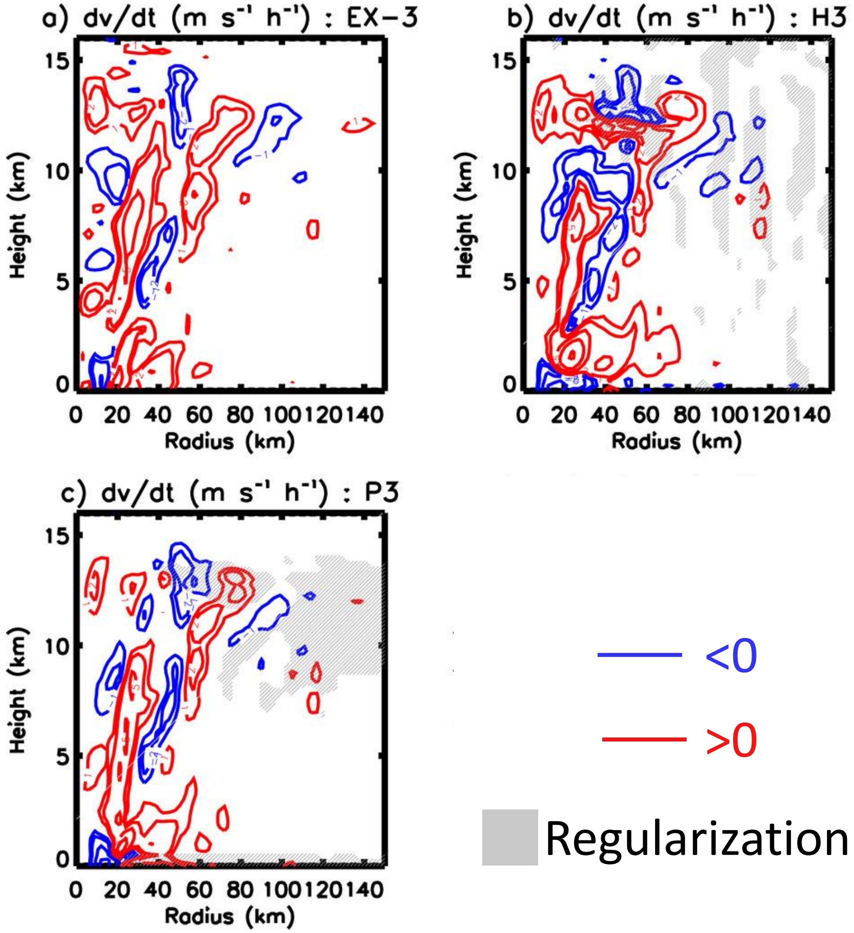
EX-3 & P3:
Spinup at BL
Spinup at RMW
Spinup at eyewall

H3:
Spindown at BL
Spinup outside RMW

$$\frac{\partial v}{\partial t}$$

EX-3

H3



P3

Results

Time variation of solutions

- - - v

— $\bar{v}$

— S1

— EX-1

Diagnose from 53 h to 56 h
2 min diagnostic interval
24 min averaged inputs

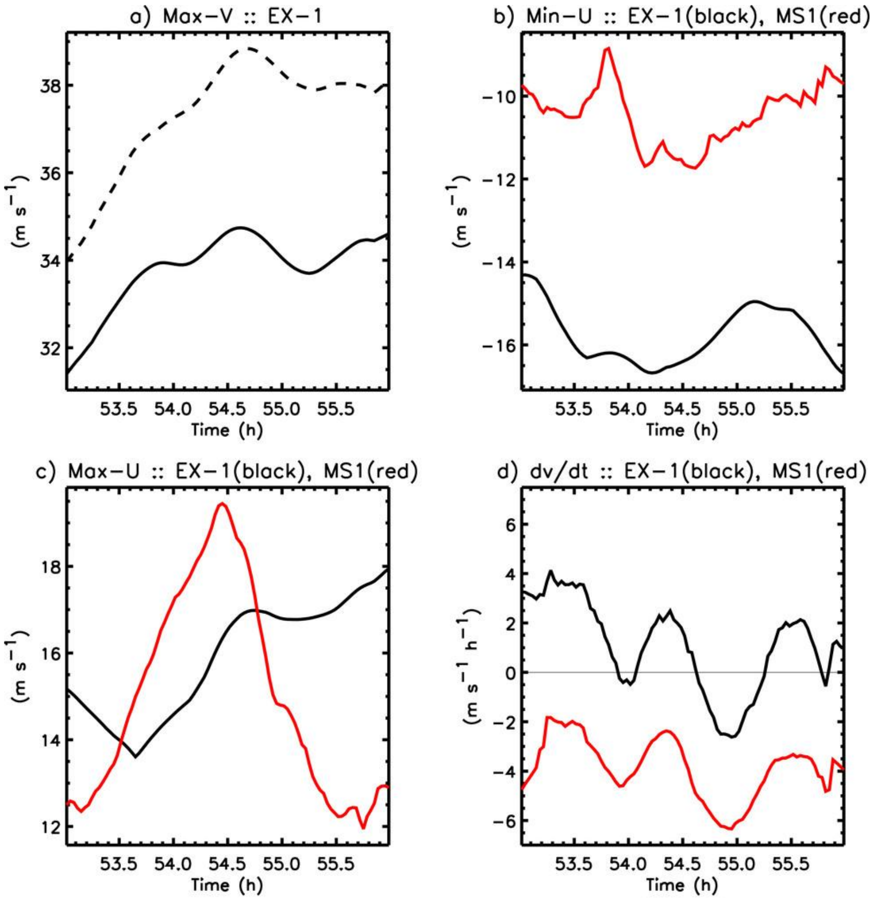
S1 underestimates peak inflow.

No relations to the peak outflow.

S1 underestimates $\frac{\partial v}{\partial t}$, but can capture the trend.

Max v

Peak inflow



Peak outflow

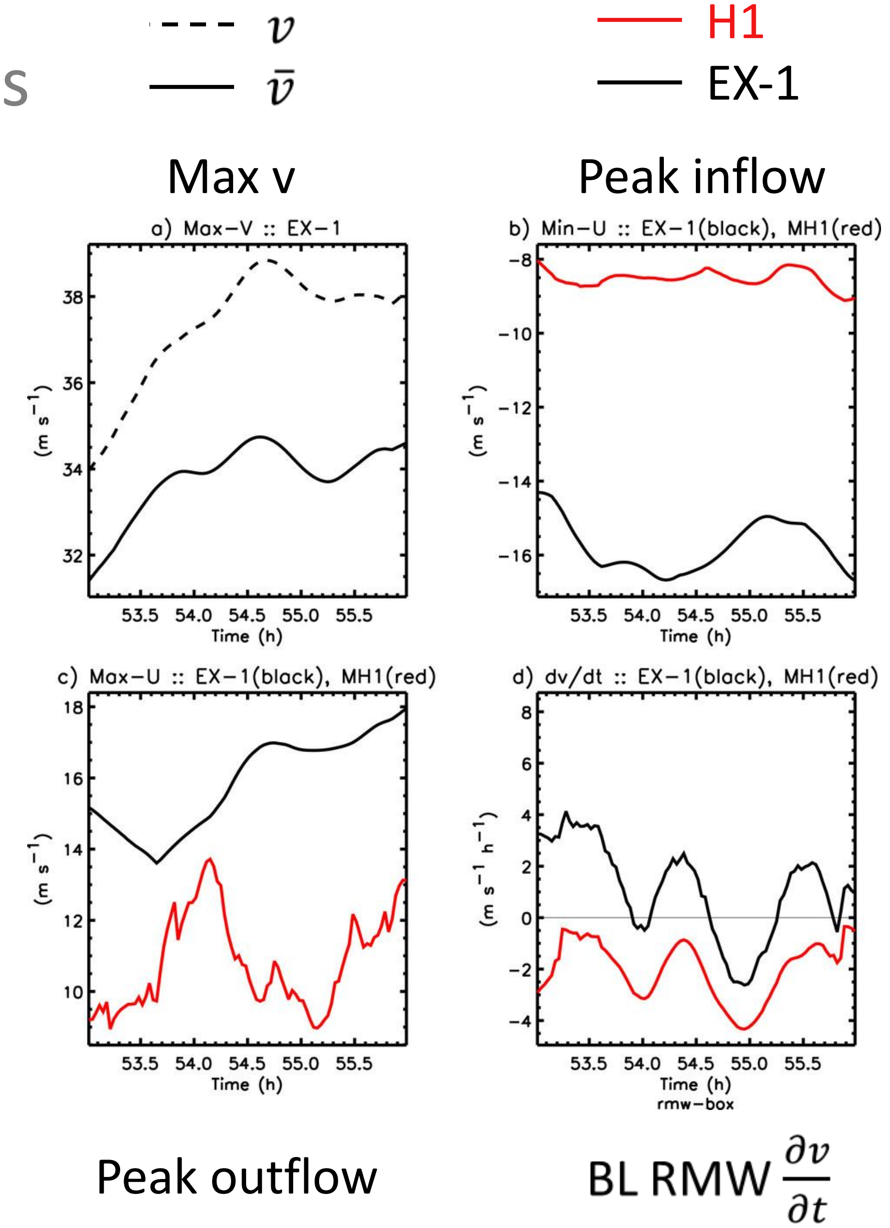
BL RMW $\frac{\partial v}{\partial t}$

Results

Time variation of solutions

H1 underestimates peak inflow, peak outflow, and $\frac{\partial v}{\partial t}$.

H1 can capture the $\frac{\partial v}{\partial t}$ trend.



- - - v

— $\bar{v}$

— H1

— EX-1

Max v

Peak inflow

Peak outflow

BL RMW $\frac{\partial v}{\partial t}$

Results

Time variation of solutions

Diagnose from 53 h to 56 h
2 min diagnostic interval
24 min averaged inputs

P1 can capture the trend of peak inflow, but has discontinuity because of regularization.

P1 outflow has inverse relation to EX-1 outflow.

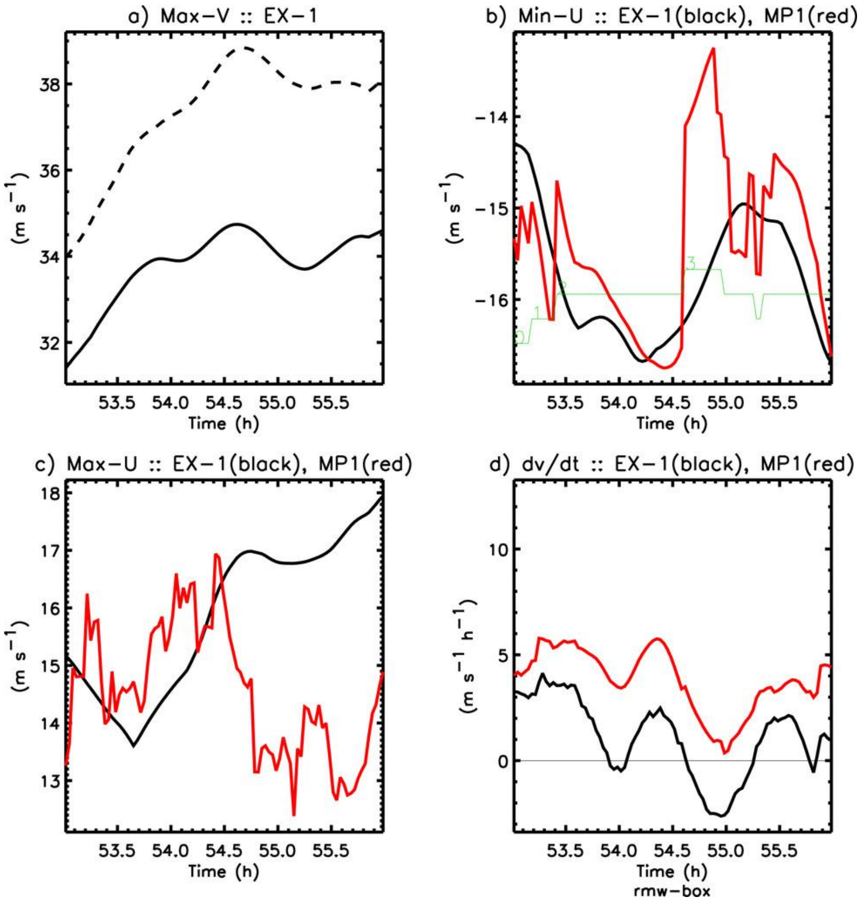
P1 overestimate $\frac{\partial v}{\partial t}$, but can capture the variations.

- - - v
— $\bar{v}$

— P1
— EX-1
— Regularizaiton points

Max v

Peak inflow



Peak outflow

BL RMW $\frac{\partial v}{\partial t}$

Summary

This study examined a claim by Heng et al. (2017) that “balanced dynamics can well capture the secondary circulation in the full-physics model simulation in the inner-core region in BL.”

The azimuthal averaged tangential momentum and diabatic heating from the simulation were used to force Eliassen balanced model under strict balance conditions.

Features in balance solutions:

1. Underestimate the peak inflow in BL → spindown
2. Over predict the radial location of peak inflow
3. Overestimate the thickness of inflow → spinup
4. Inaccurately represent the structure of upper-layer outflow layer

Unbalanced and nonlinear BL dynamics

Inertial instability and regularization

Summary

The azimuthal averaged of the model output used in Eliassen model is the result of a pseudobalance solution because of not in thermal wind balance.

In the long-time diagnoses, Eliassen model predicts spindown in the inner-core region in the BL, but predicts spinup above the BL. The pseudobalance solutions over predict spinup in the BL.

The Eliassen balanced model cannot capture the characteristics of TCs during intensification. The nonlinear BL spinup mechanism is necessary.