How do localized, sub-vortex-scale events within a hurricane contribute to a vortex-scale rapid intensity changes?

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HFIP Bi-weekly Teleconference
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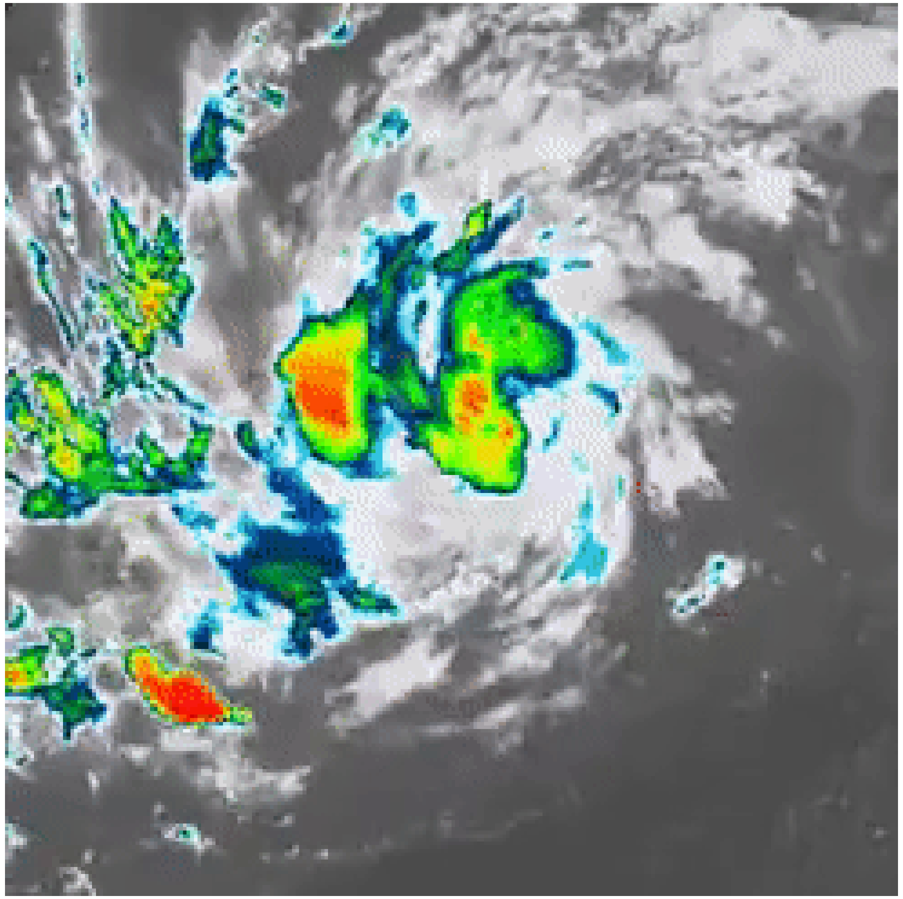
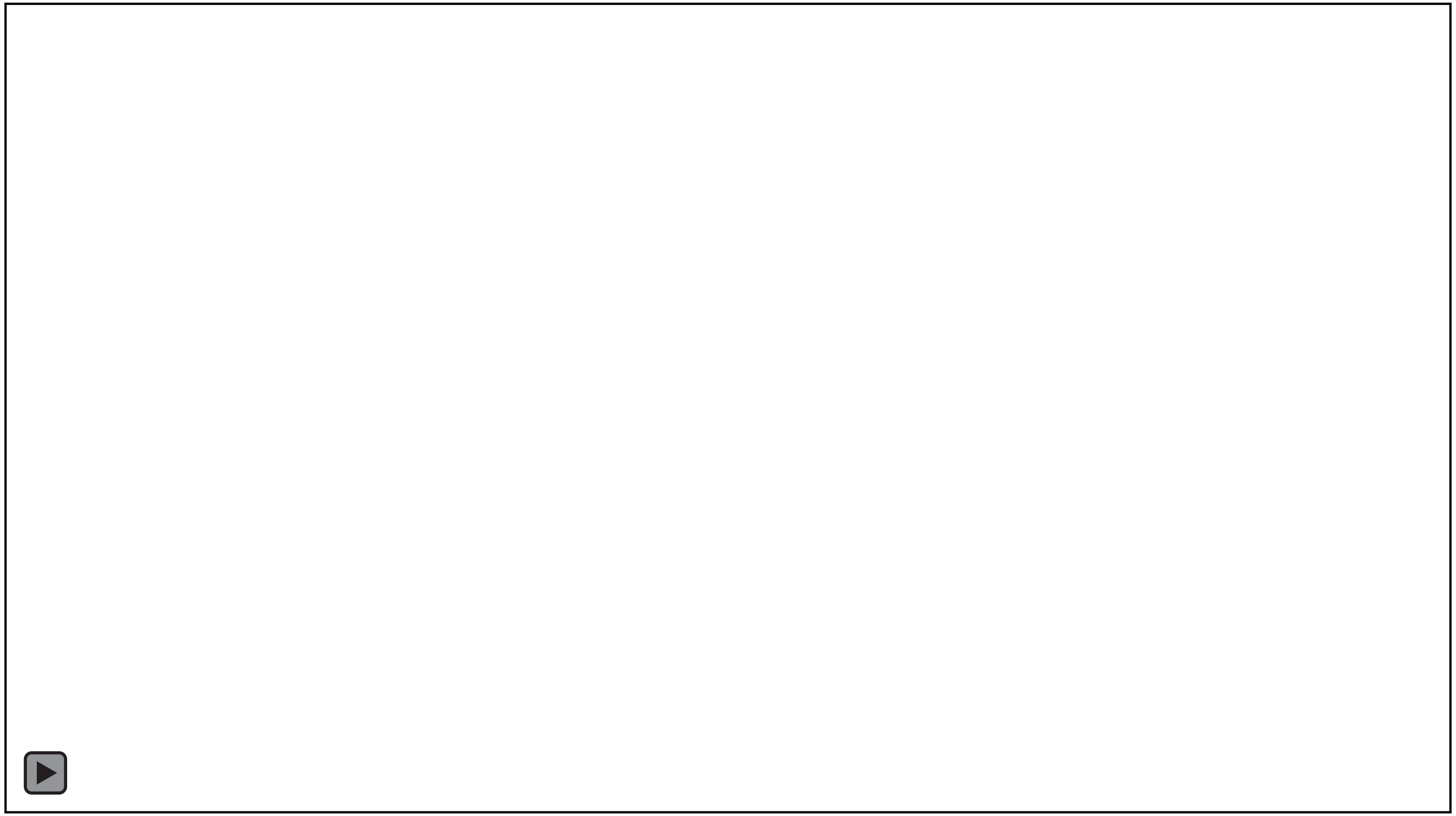


Hurricane Intensity: A Multi-scale problem



The evolution of Hurricane Dorian. Courtesy: NOAA GOES

Rapid Intensity Changes*: A nightmare for forecasters & emergency response teams

Cyclone Phailin triggers India's biggest evacuation operation in 23 years

All India | Press Trust of India | Updated: October 12, 2013 21:58 IST

NDTV

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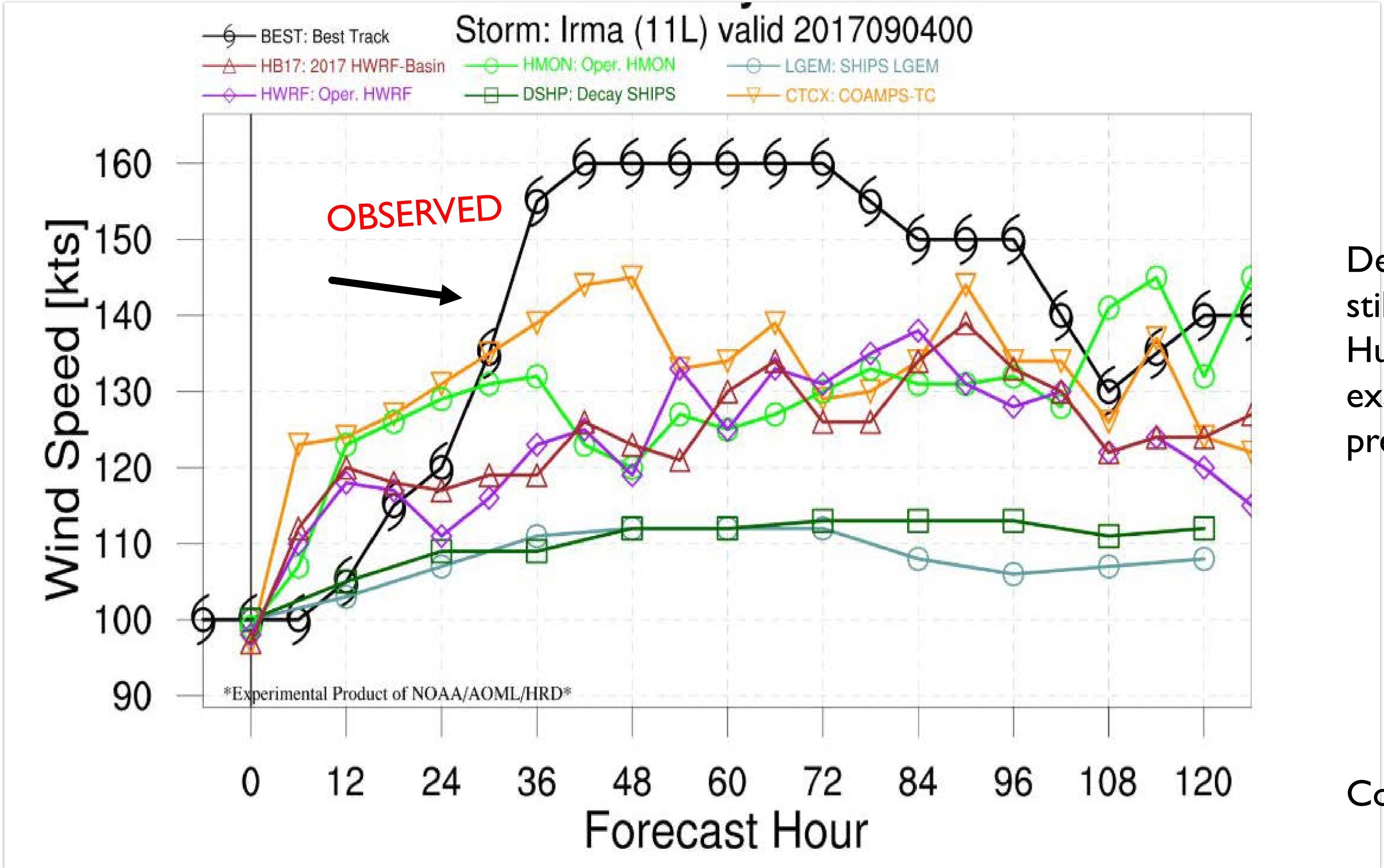
A rapid intensity change is defined as an intensity change of 30 knots or higher in a span of 24 hours

HFIP goal: Improved rapid intensity forecasts

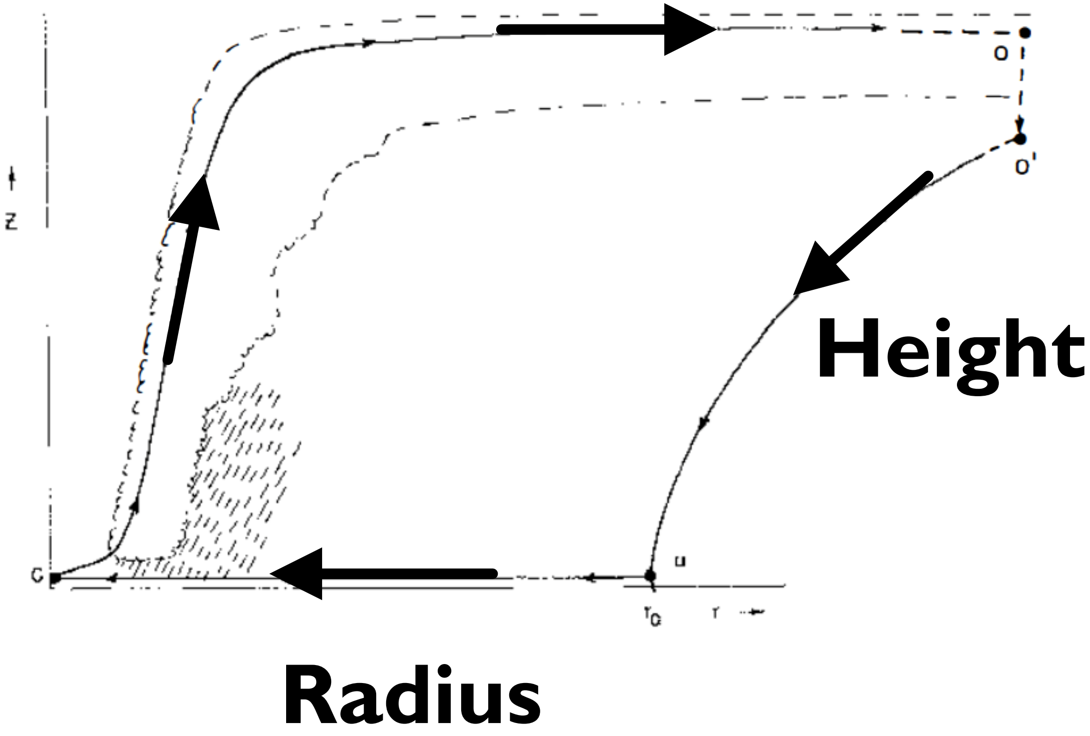


Despite advances, there's still work to be done. Hurricane Irma is a recent example where models failed to predict the RI

Courtesy: Gus Alaka

Early TC Models: Axisymmetric circulation + transverse circulation

Secondary circulation (In-up-out)

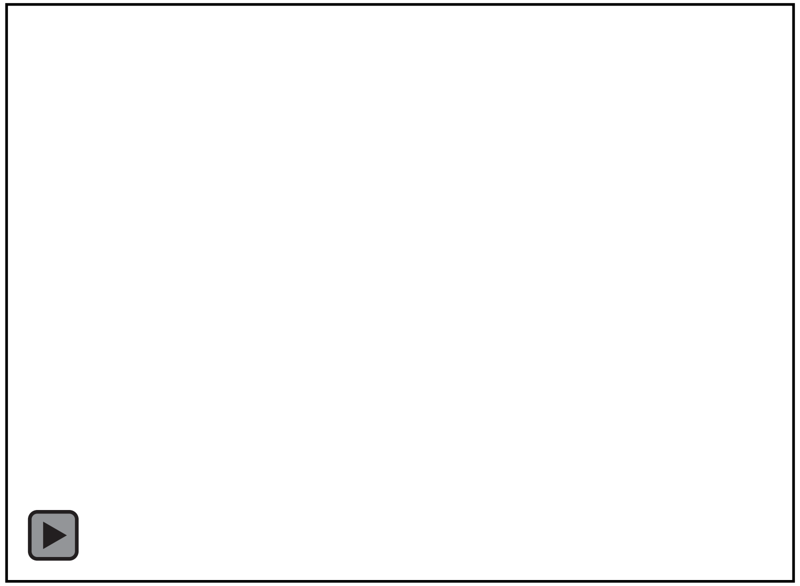


Courtesy: Emanuel (1991)

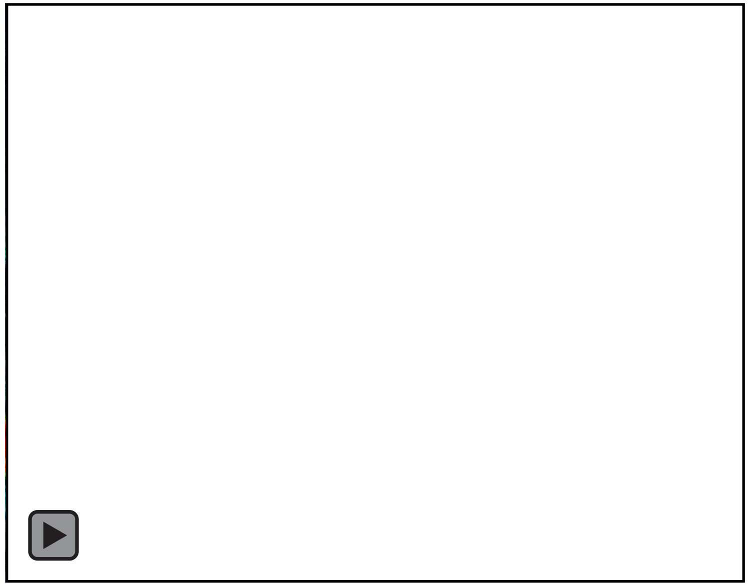
However, observations revealed multiple asymmetric features in addition to the symmetric circulation

GOES-16

These asymmetries manifest at multiple spatial and temporal scales



Super Typhoon Yutu (2018)



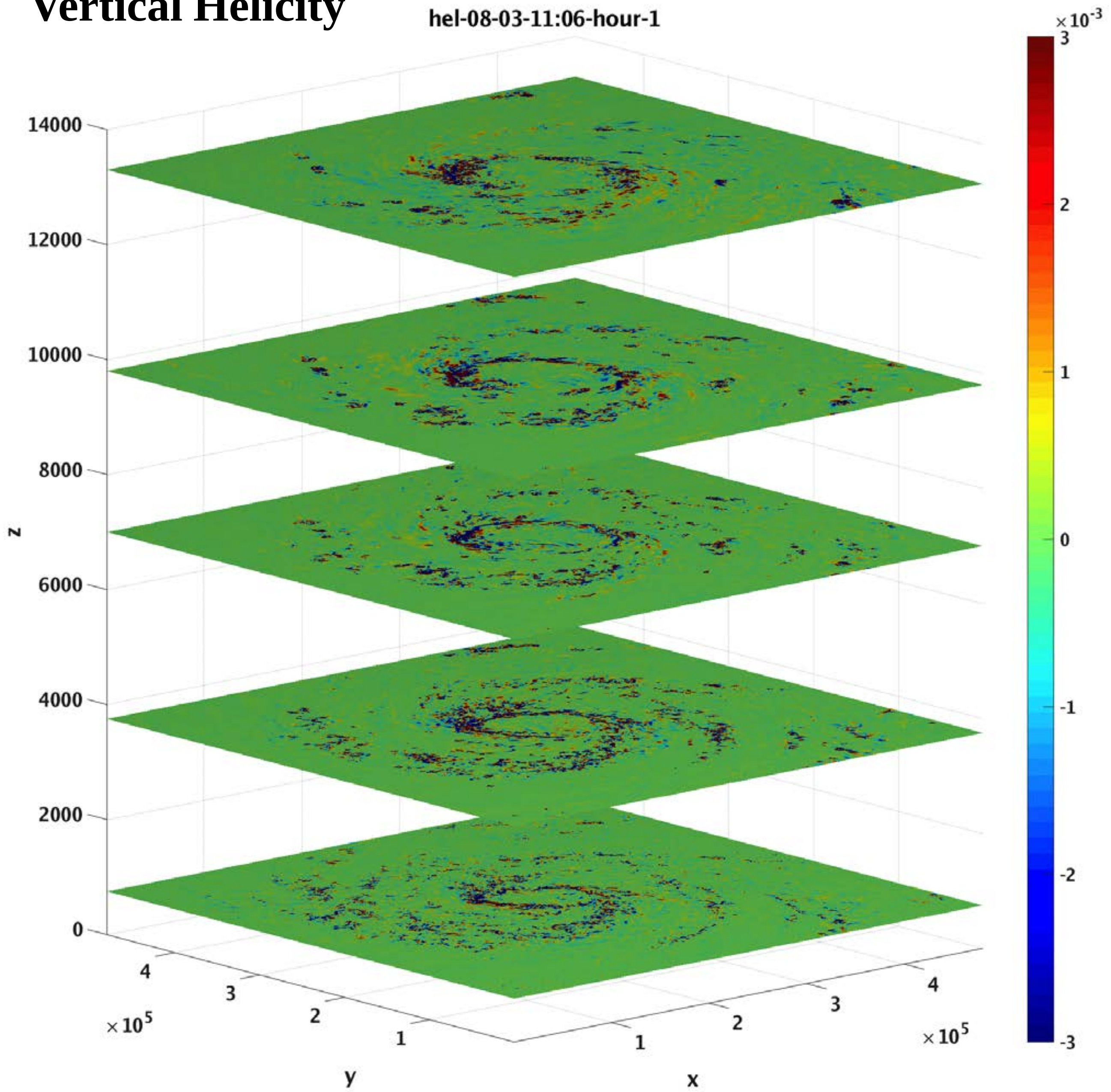
Hurricane Willa (2018)

Examples: Vortical Hot towers, rain bands, collection of eddies and waves

Sample observational references: Hendricks and Montgomery (2006), Marks et al. (2008), Molinari and Vollaro (2008), Houze et al. (2008), Guimond et al. (2010), Several idealized as well as non-idealized numerical simulations have reproduced these localized events

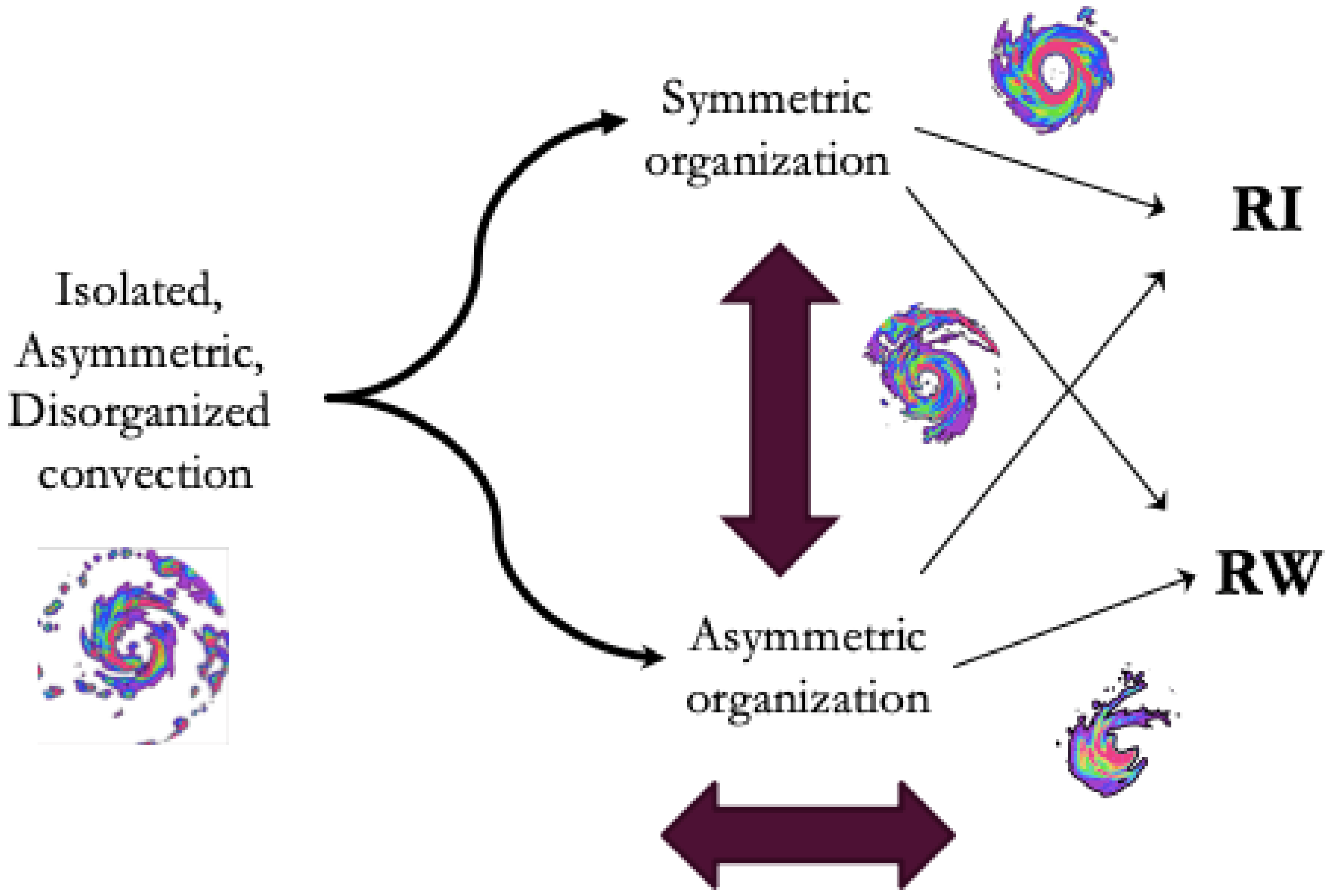
For example: Hendricks et al. (2004),
Nolan et al. (2007), Guimond et al. (2010)
Gopalakrishnan et al. (2011)
Persing et al. (2013),

Vertical Helicity

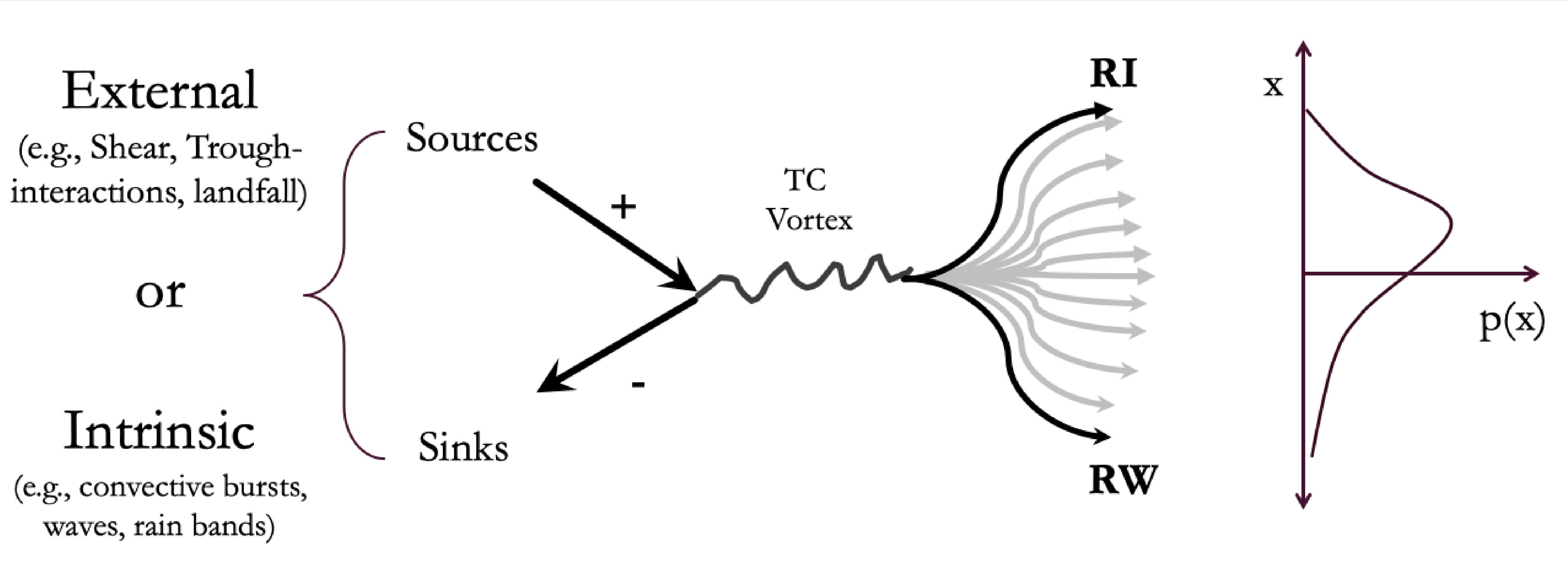


Computed from the Hurricane Nature Run (Nolan et al. 2013)

However, the precise nature of the influence of the organization of asymmetries on TC intensity change remains an enigma!



Spectrum of possible intensity pathways for a tropical cyclone vortex



Bhalachandran et al. (2019) Earth and Space Science

RI: Rapid Intensification; RW: Rapid Weakening

Why care about localized events?

- The growth/decay of these asymmetries is strongly linked to the intensification or weakening of the TC vortex.
- We are currently at a stage where we have invested heavily on high-resolution models that simulate such events
- Scope for improvement of the grid-scale and sub-grid-scale cumulus/microphysics and diffusion schemes in hurricane forecasting models
- Growth and organization are deeply interlinked – Pathway to organization is observable using the high-resolution satellite observations

Talk Objectives

- Detail the challenges and our recent progress regarding the influence of localized events toward vortex-scale rapid intensity changes
- Differentiate between the energetics stand-point and the dynamics/thermodynamics stand points

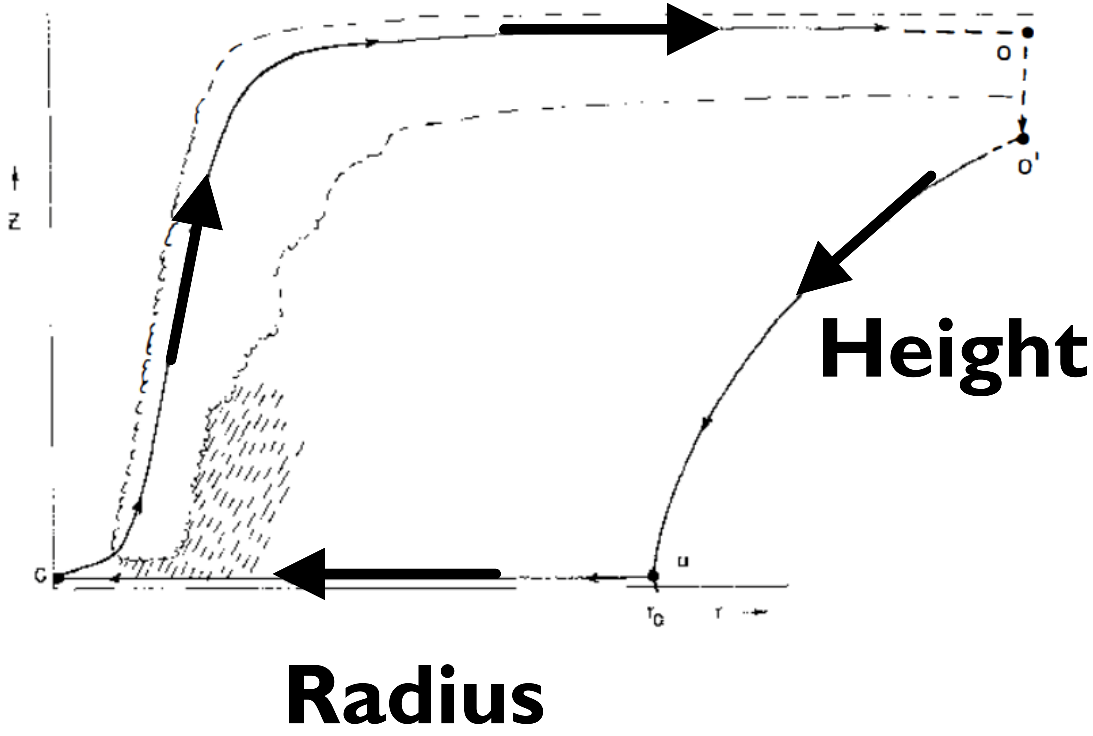
Levels of sophistication in understanding hurricane energetics

1. Axisymmetric energetics
2. Reynolds averaging-based energetics (Mean – eddy partitioning)
3. Fourier-based multi-scale energetics
4. Space-aware energetics in five dimensions :

Ph.D. work

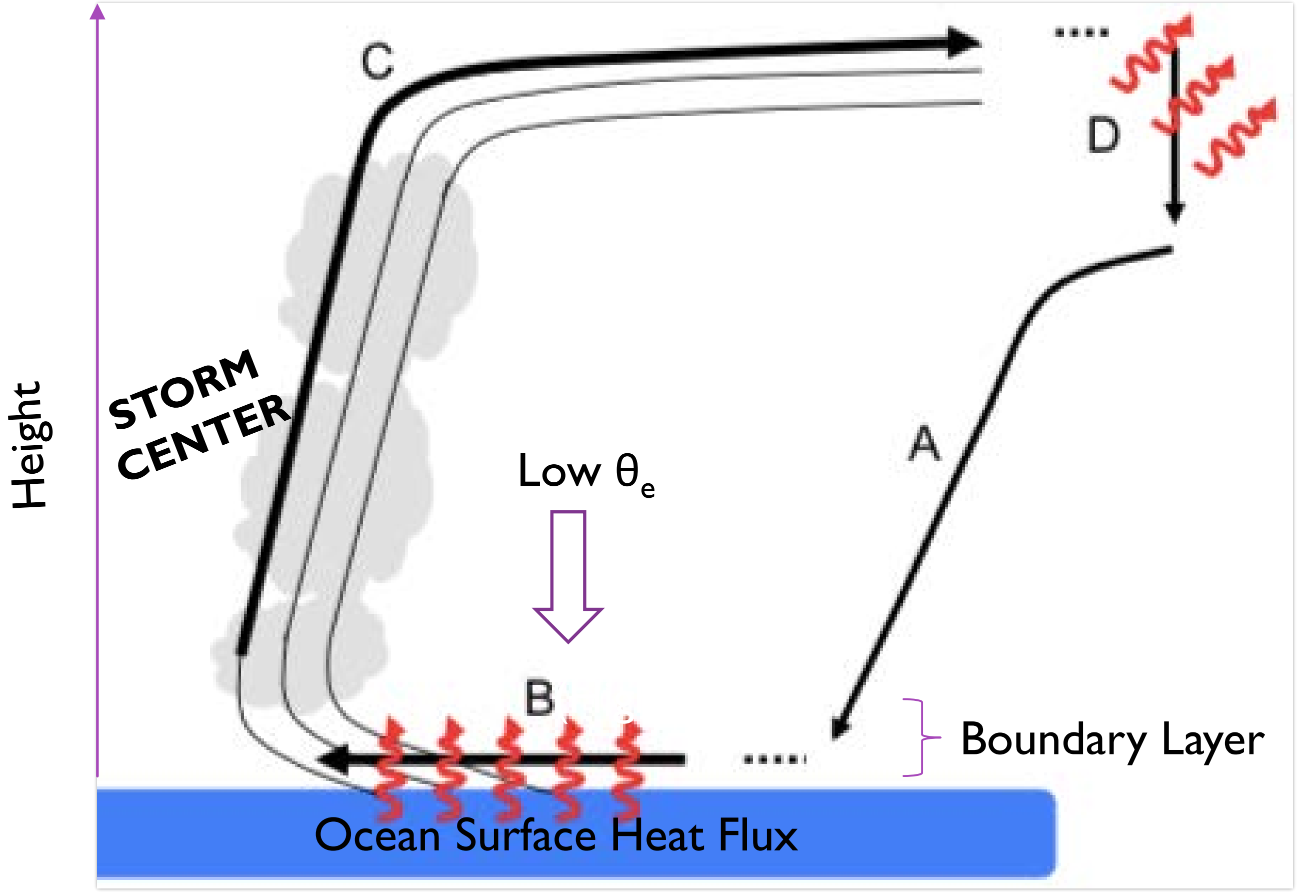
Present work

Level 1: Axisymmetric Energetics



Courtesy: Emanuel (1991)

Level 1: Axisymmetric Energetics



- The energy cycle of a TC is analogous to a heat engine (Emanuel 1986, 1991).
- Frustration of the energy cycle (reduction in work done) results in the decrease of intensity and vice-versa.
- Azimuthally average perspectives for the weakening of the TC due to low- θ_e intrusion – Riemer et al. (2010, 2013); Tang and Emanuel (2010,2012)

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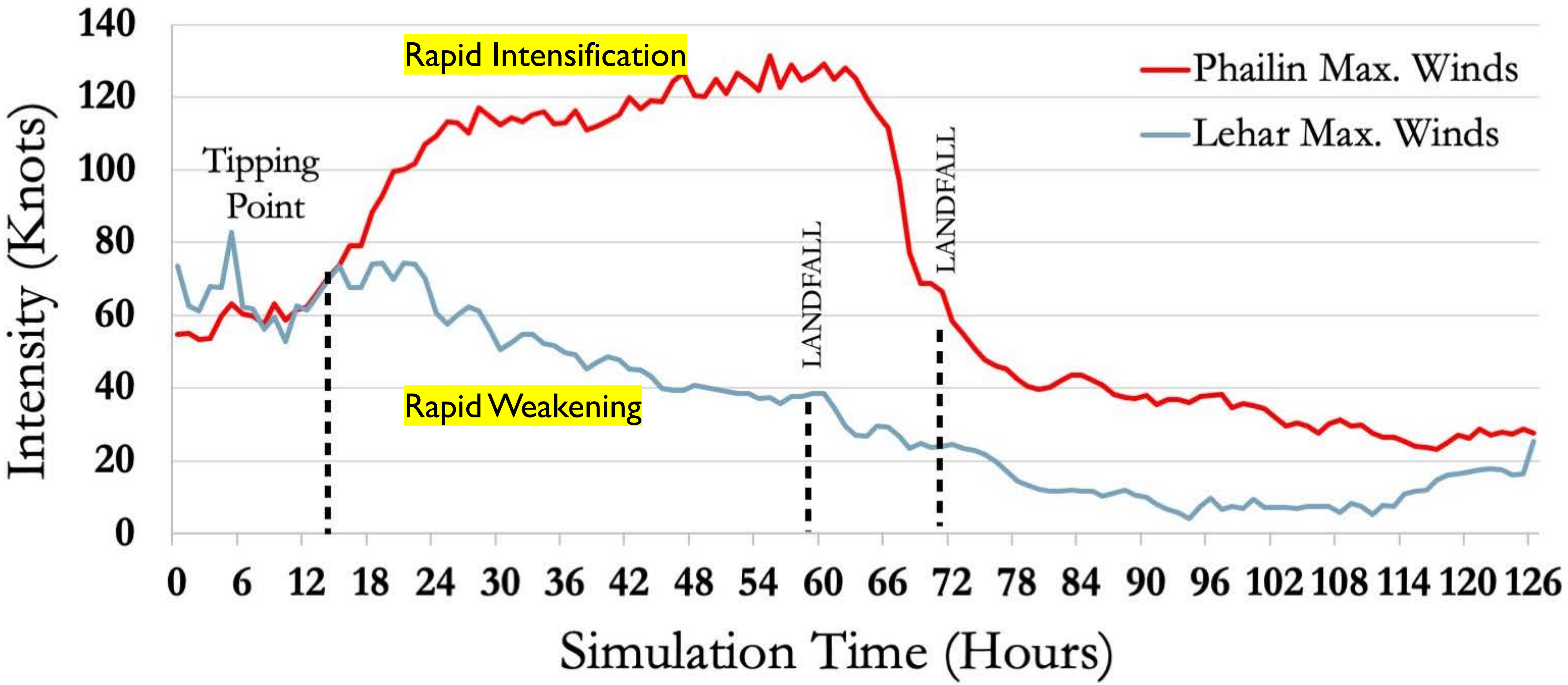
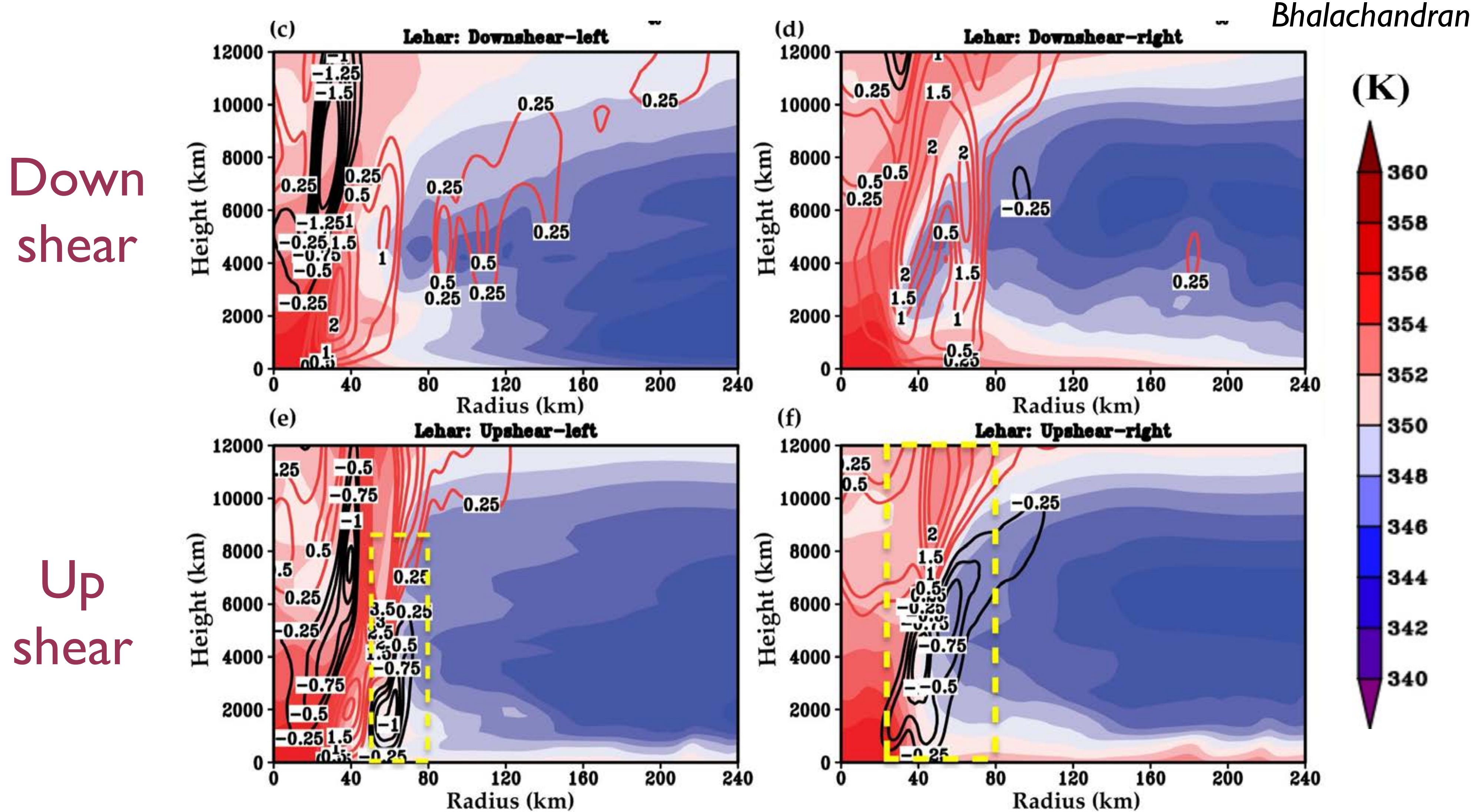
Case studies: HWRF simulations of two Bay of Bengal Tropical Cyclones

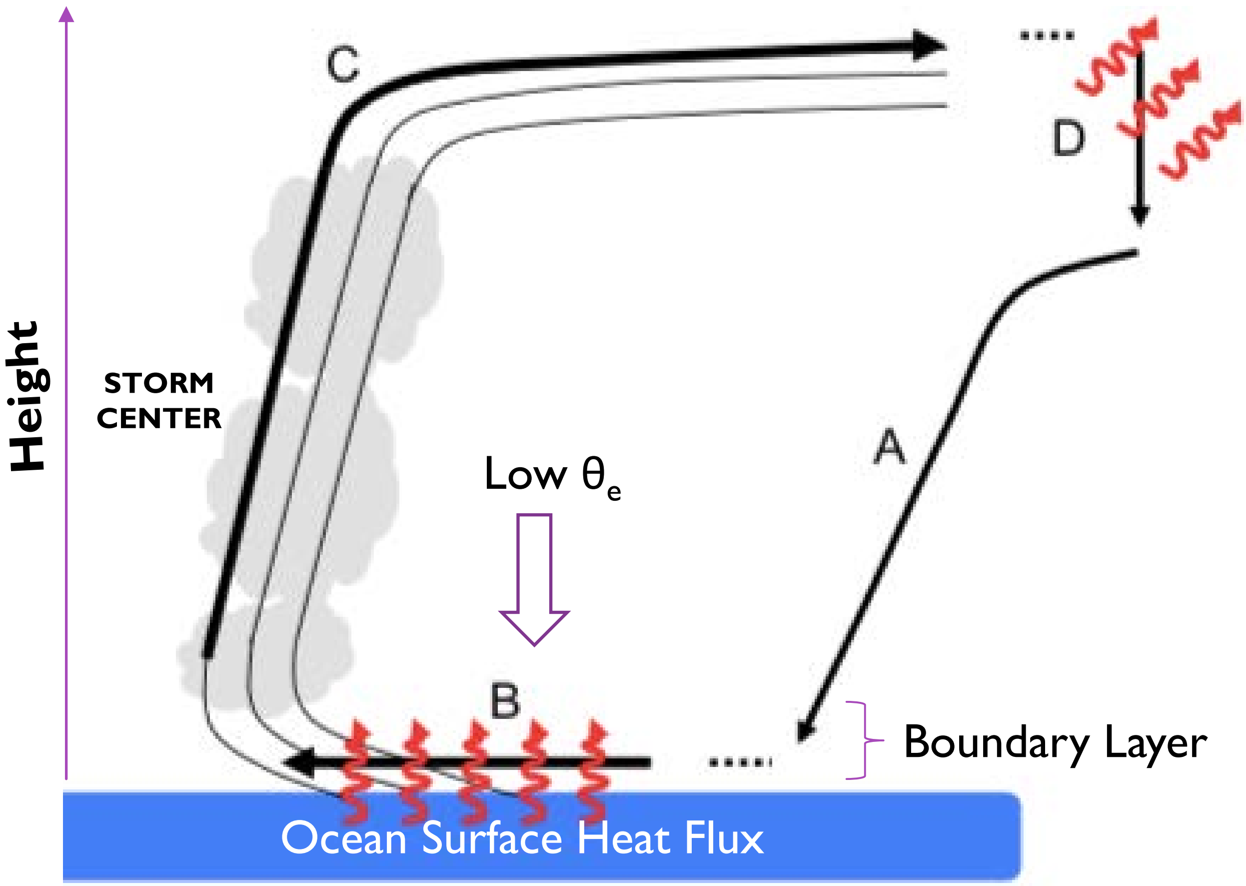


Level 2: Azimuthally asymmetric energetics (Case study: Lehar)

Bhalachandran et al. (2019) Sci. Rep.

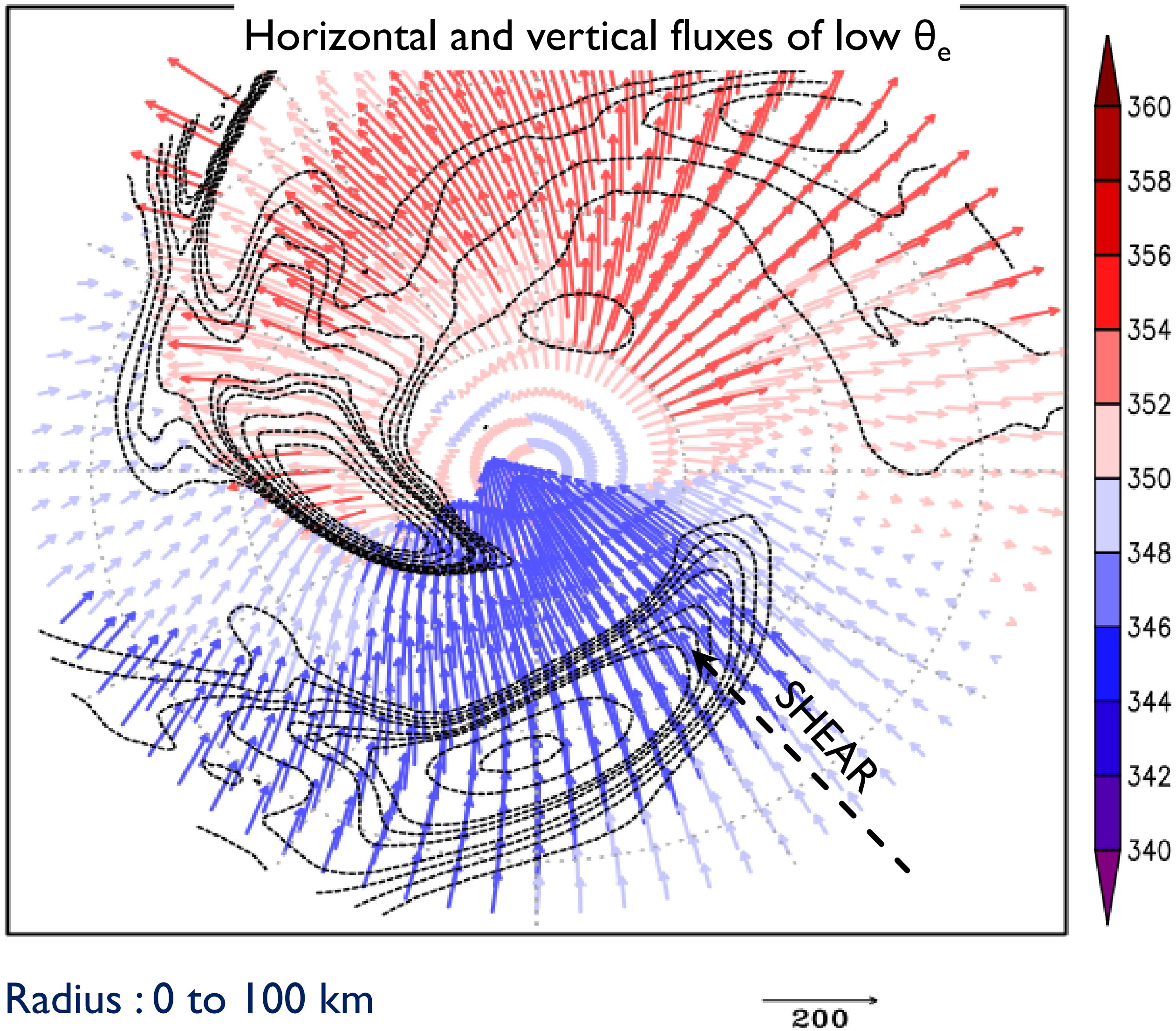


The juxtaposition between the horizontal and vertical fluxes creates a pathway for the low θ_e air to intrude into the vortex



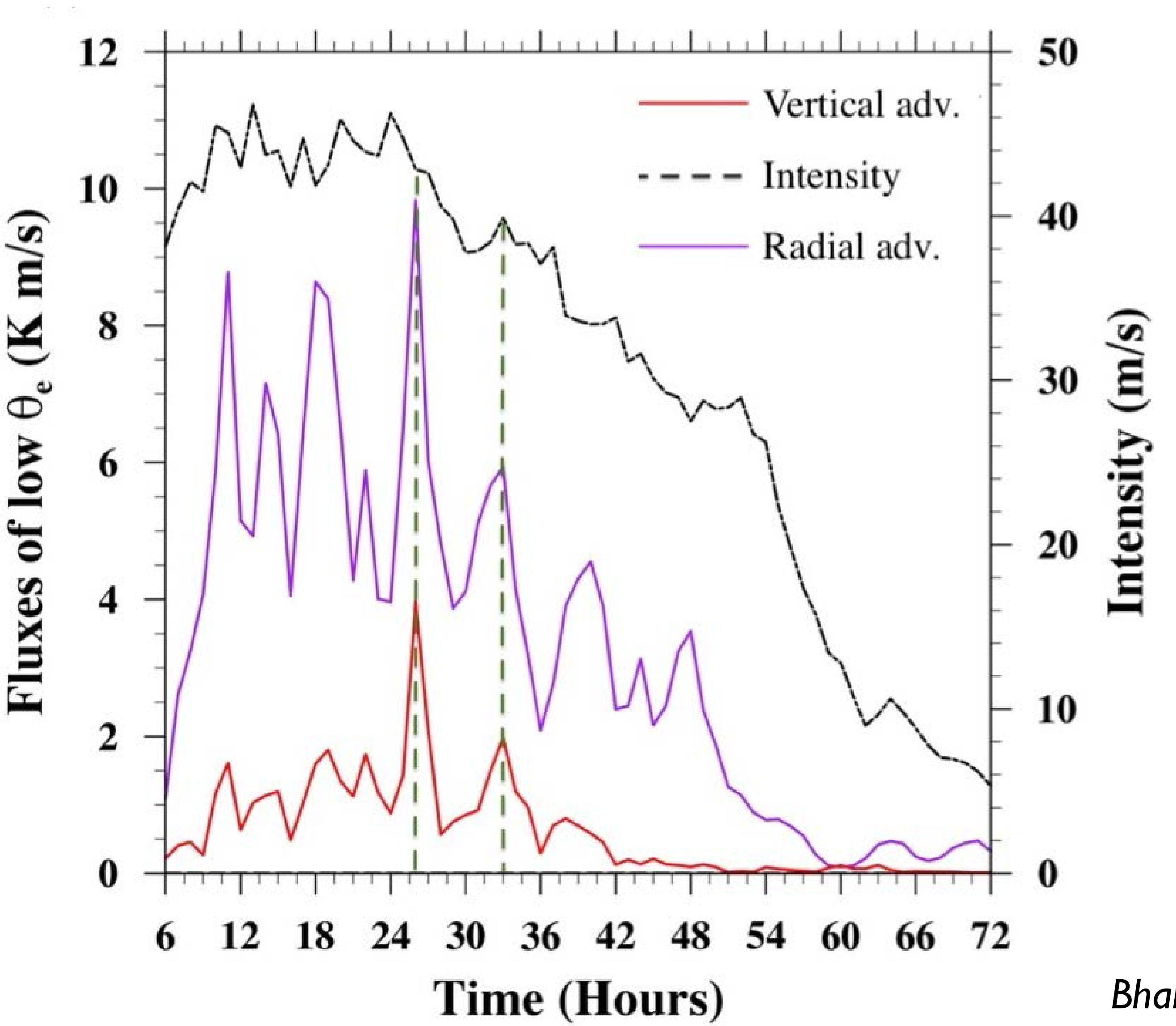
Radius*Bhalachandran et al. (2019) Sci. Rep.*

Lehar: 27 hours



Radius : 0 to 100 km

Synchronization in the phasing and amplitude: Diagnostic for rapid intensity change detection



Bhalachandran et al. (2019) Sci. Rep.

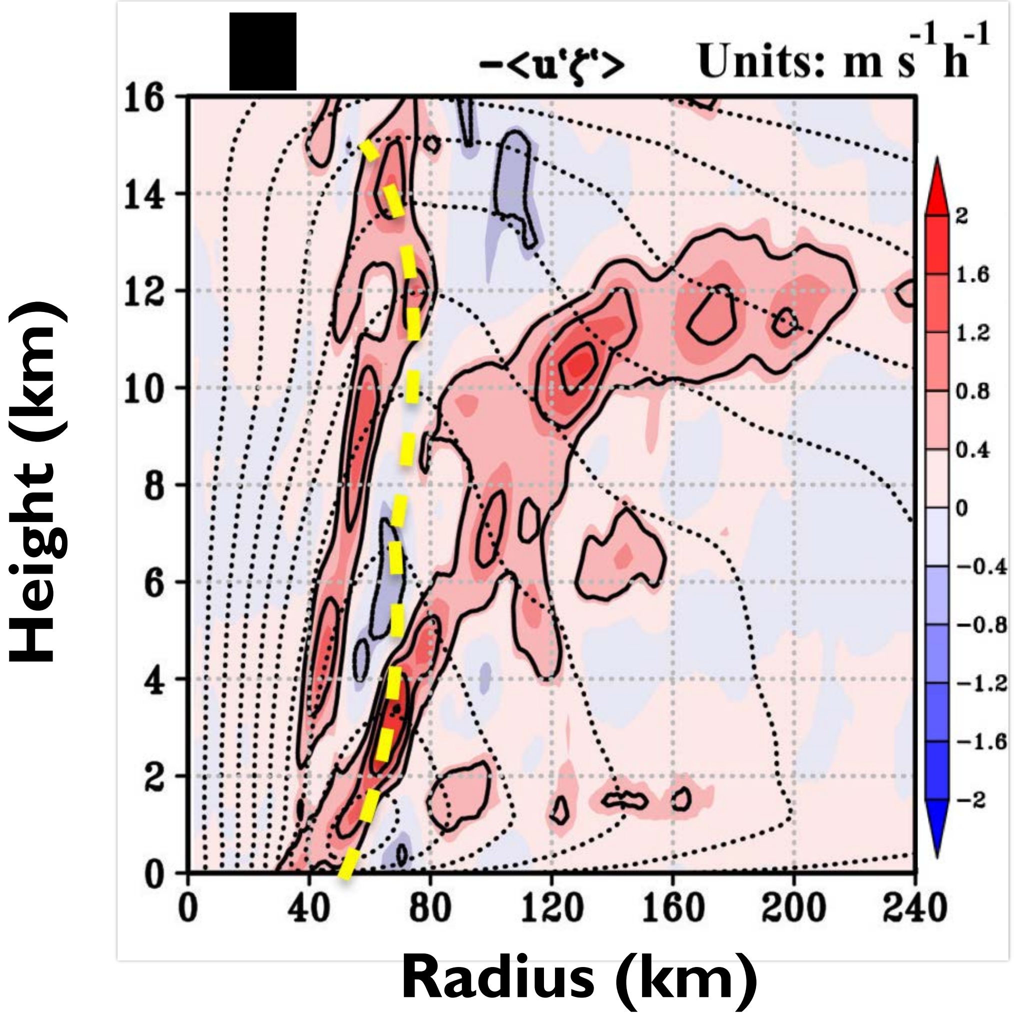
Level 2: Azimuthally asymmetric energetics (Dynamic perspective)

PRIMARY CIRCULATION — IN/OUT — UP/DOWN — IN/OUT

$$\frac{\partial \langle v \rangle}{\partial t} = -\langle u \rangle \left(f + \zeta \right) - \langle w \rangle \frac{\partial \langle v \rangle}{\partial z} - \langle u' \zeta' \rangle$$

$$\underbrace{-\left\langle w' \frac{\partial v'}{\partial z} \right\rangle}_{\text{UP/DOWN}} + \text{Residual terms}$$

PHAILIN: Eddy radial fluxes of vorticity can positively contribute to spin-up by radially advecting positive vorticity inward. Effective through the depth of the vortex!



$$\oint_C \mathbf{V}\cdot d\mathbf{s} = \iint_A \zeta \, dA$$

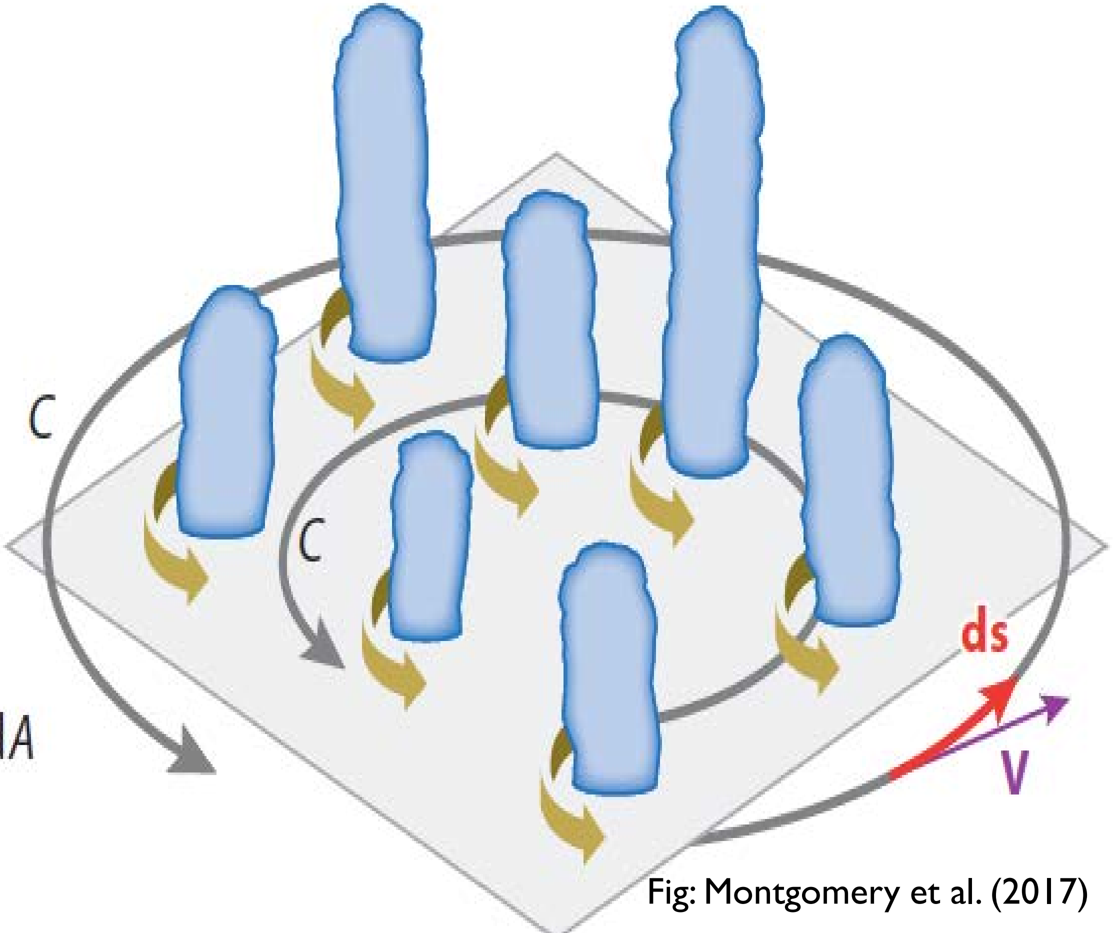
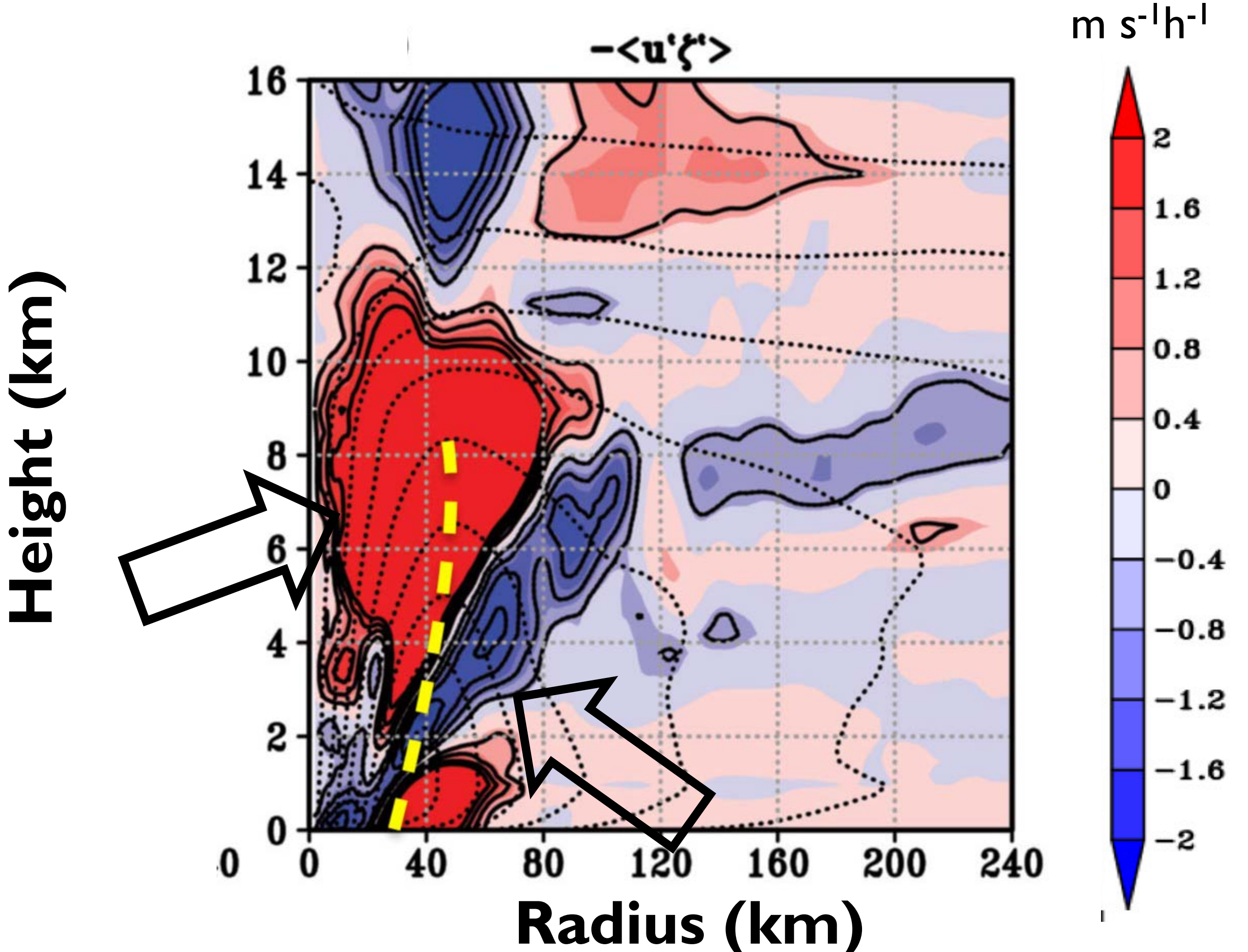


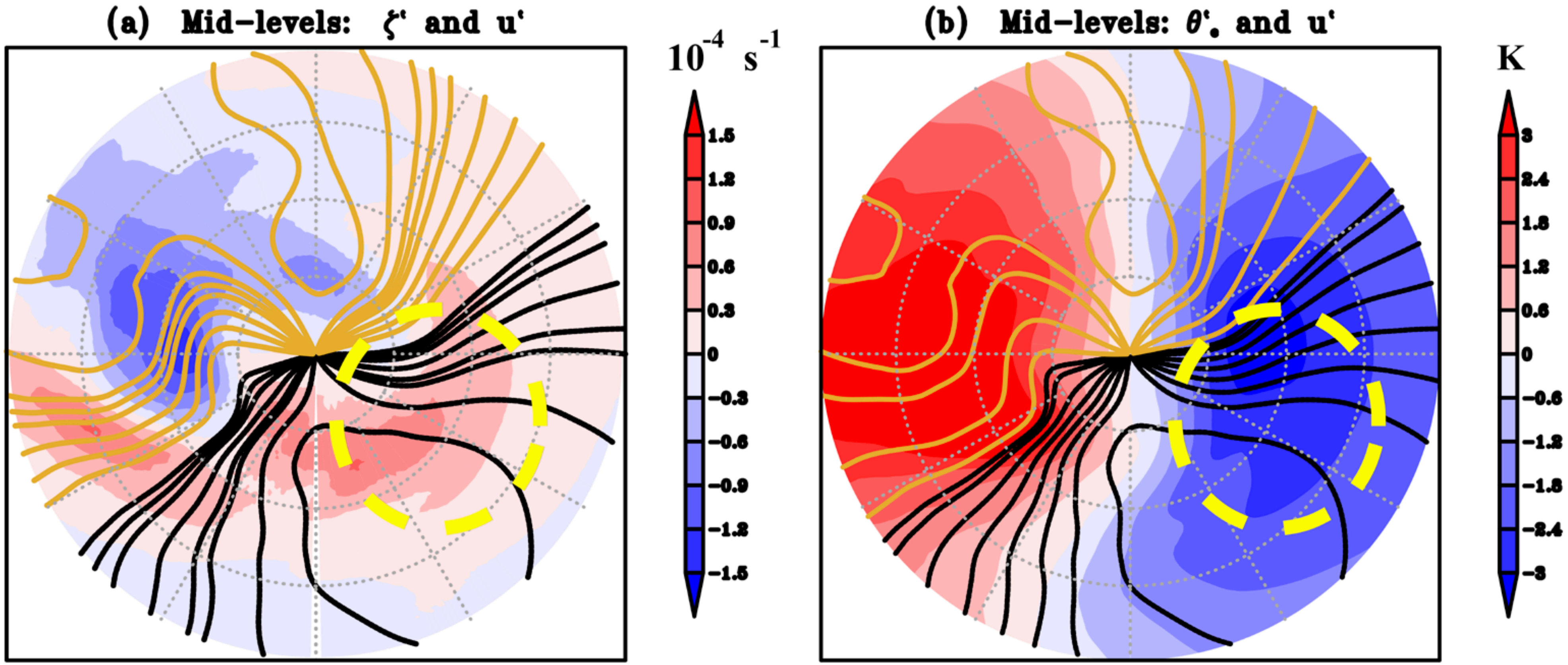
Fig: Montgomery et al. (2017)

LEHAR: Eddy radial vorticity flux is *positive* during *weakening*



Bhalachandran et al. (2019) JAS.

While a region might be dynamically favorable, rapid weakening can still occur if the thermodynamic variables are unfavorable



Radius : 0 to 200 km;
Time-averaged
between
t = 24 to t = 36
(initial period of RW)

Bhalachandran et al. (2019) JAS.

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Present work

Level 3: Fourier-based energetics framework

EDDY (scale)

Mean - Eddy

Eddy – Eddy, Cross-scale

Potential to Kinetic, In-scale

$$\frac{\partial K_n}{\partial t} = \langle K_o \rightarrow K_n \rangle + \langle K_{n,m} \rightarrow K_k \rangle + \langle P_n \rightarrow K_n \rangle + \langle F_n \rightarrow K_n \rangle$$

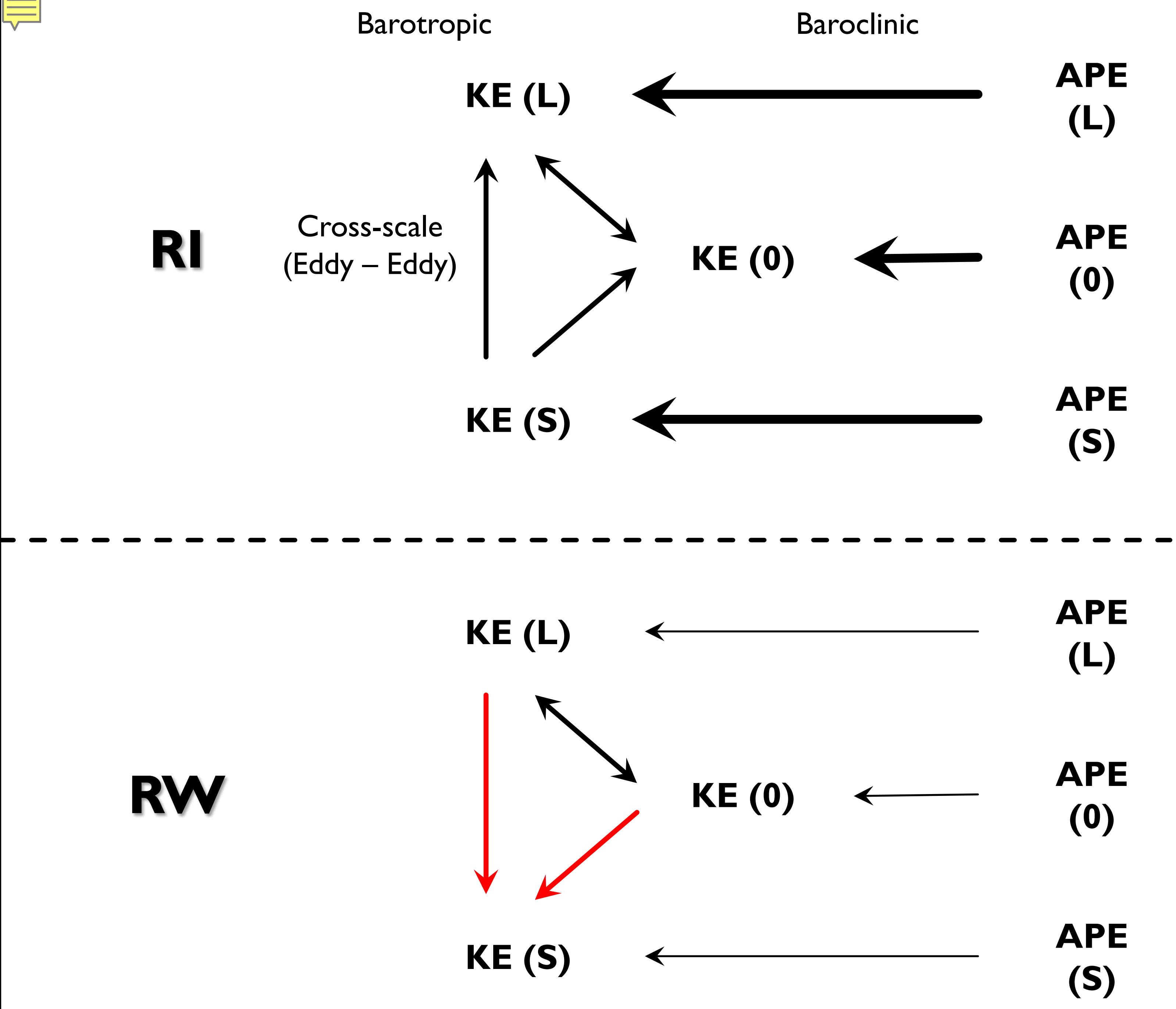
$$\frac{\partial K_0}{\partial t} = -\sum_n \langle K_0 \rightarrow K_n \rangle + \langle P_0 \rightarrow K_0 \rangle + \langle F_0 \rightarrow K_0 \rangle$$

MEAN

Mean - Eddy

K : Kinetic Energy
n : Wavenumber

Bhalachandran et al. (JAS, 2019); Krishnamurti et al. (2013)



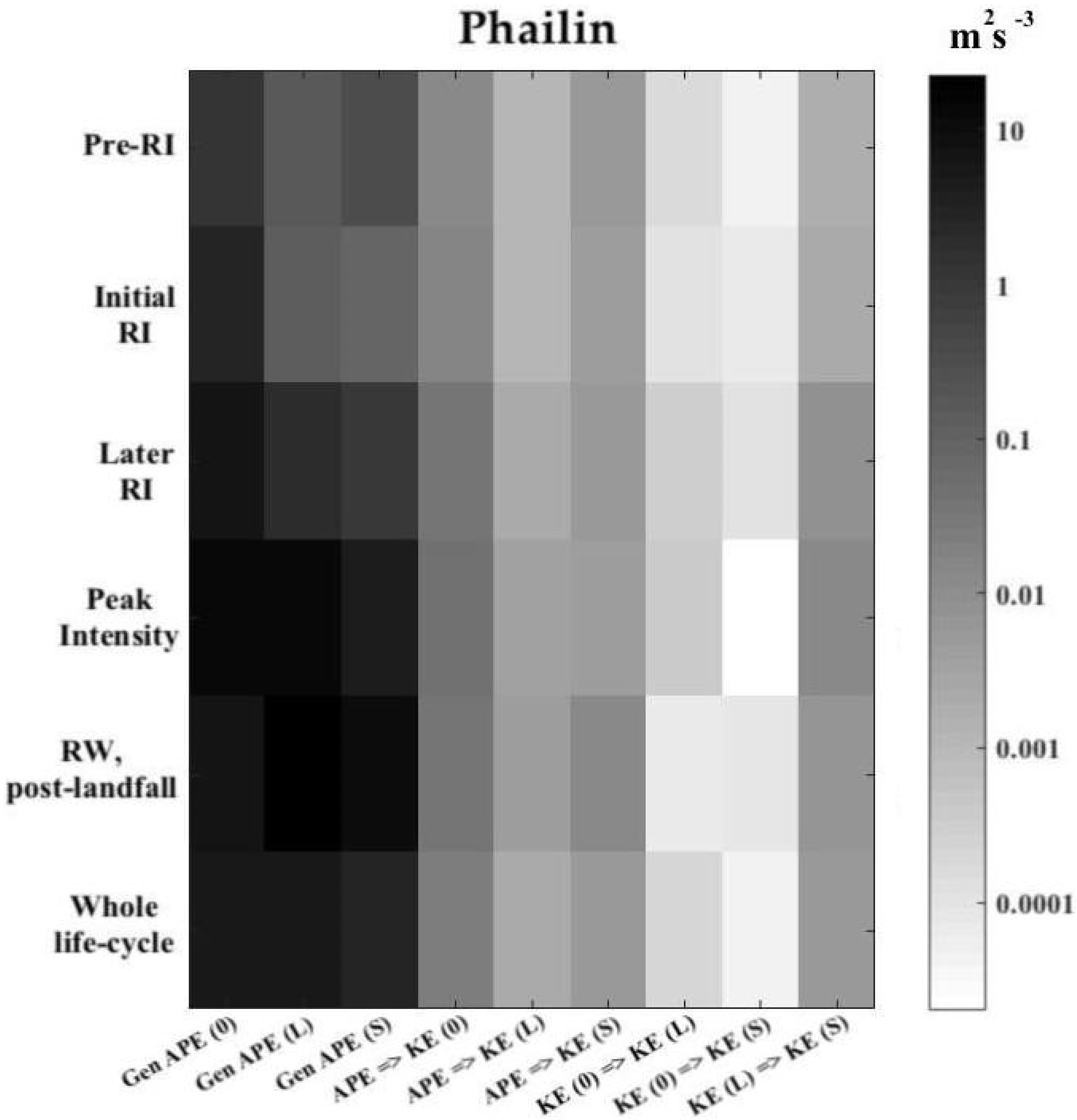
1. APE to KE conversion is higher during RI than RW
2. Unique direction of transfer between mean to eddy and small-scales and between the multi-scale eddies.

Bhalachandran et al. 2019. JAS

Order of magnitude analysis reveals that the most important energy pathways are the baroclinic In-scale transfer from PE to KE and the cascades Across eddies of multiple length-scales.

Not important for system-scale transitions: Individual mean-eddy transactions

Bhalachandran et al. 2019. JAS



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Potential to kinetic energy (n)

Kinetic energy (mean) to eddy

Kinetic energy (eddy) to eddy

Cascades

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   Cascades that are *local* in space (and scale)

Potential to kinetic energy (n)

Kinetic energy (mean) to eddy

Kinetic energy (eddy) to eddy

Cascades

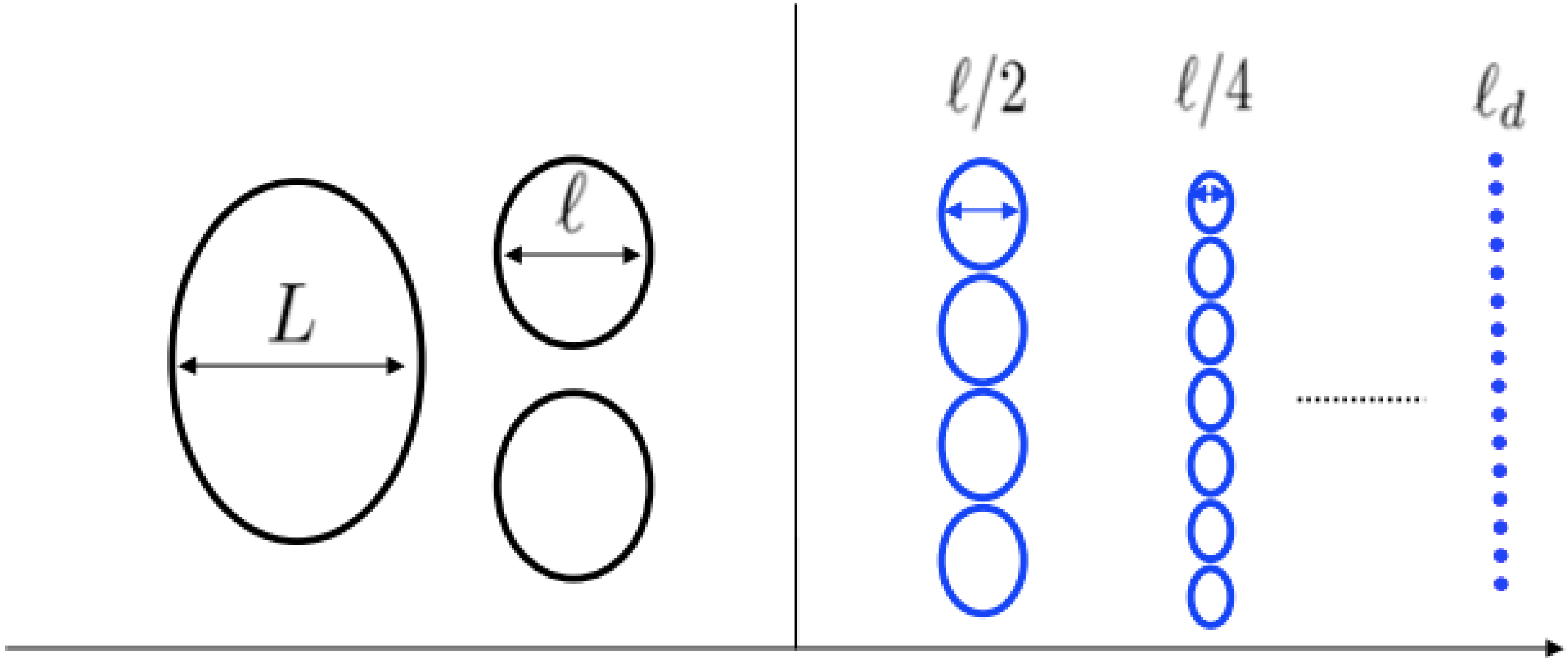
Way forward: Energy cascades in five dimensions

Evolution of kinetic energy iso-surfaces at different filter widths

Cardesa et al. (2017) Science.

Beyond Fourier: A definition of cascade based on filtering

L < l < l_d



Aluie et al. 2018

l is the filter width that sets a threshold such that all the scales above l are retained and all scales below it are filtered out

Beyond Fourier: A definition of cascade based on filtering

$$u = \widetilde{u} + u'$$

where $\widetilde{u}$ represents the filtered component and u' represents the sub-filtered components. The filtered field $\widetilde{u}$ may be written as:

$$\widetilde{u}_i(x,y,z,t,\sigma) = \int_{x_1}^{x_2} \int_{y_1}^{y_2} \int_{z_1}^{z_2} u(x',y',z',t) \quad e^{-\frac{(x-x')^2}{2\sigma_x^2} + \frac{(y-y')^2}{2\sigma_y^2} + \frac{(z-z')^2}{2\sigma_z^2}} \; dx' \, dy' \, dz'$$

Beyond Fourier: A definition of cascade based on filtering

$$\Pi(x, y, z, t, \sigma) = -\rho\left[\widetilde{u_i u_j} - \widetilde{u}_i \widetilde{u}_j\right] \frac{\partial \widetilde{u}_i}{\partial x_j}\, dxdydz$$

Kinetic Energy Transfer from sub-filter scales to filtered-scales

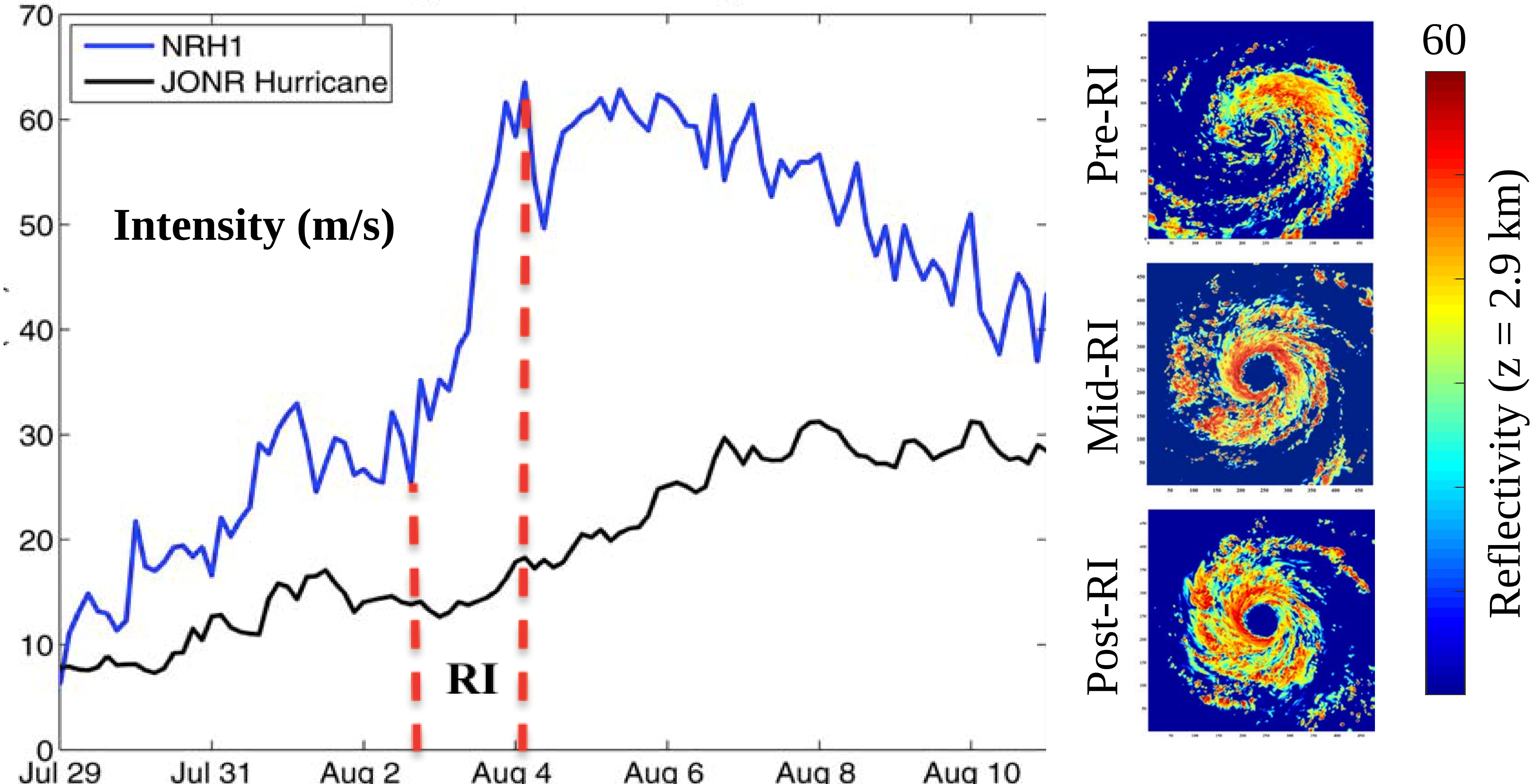
Stress tensor

Strain rate

Positive value: Downscale transfer of KE

Negative value: Upscale transfer of KE

Hurricane Nature Run (Nolan et al. 2013) serves as our numerical case study



Sample result of spatially-explicit energy cascades

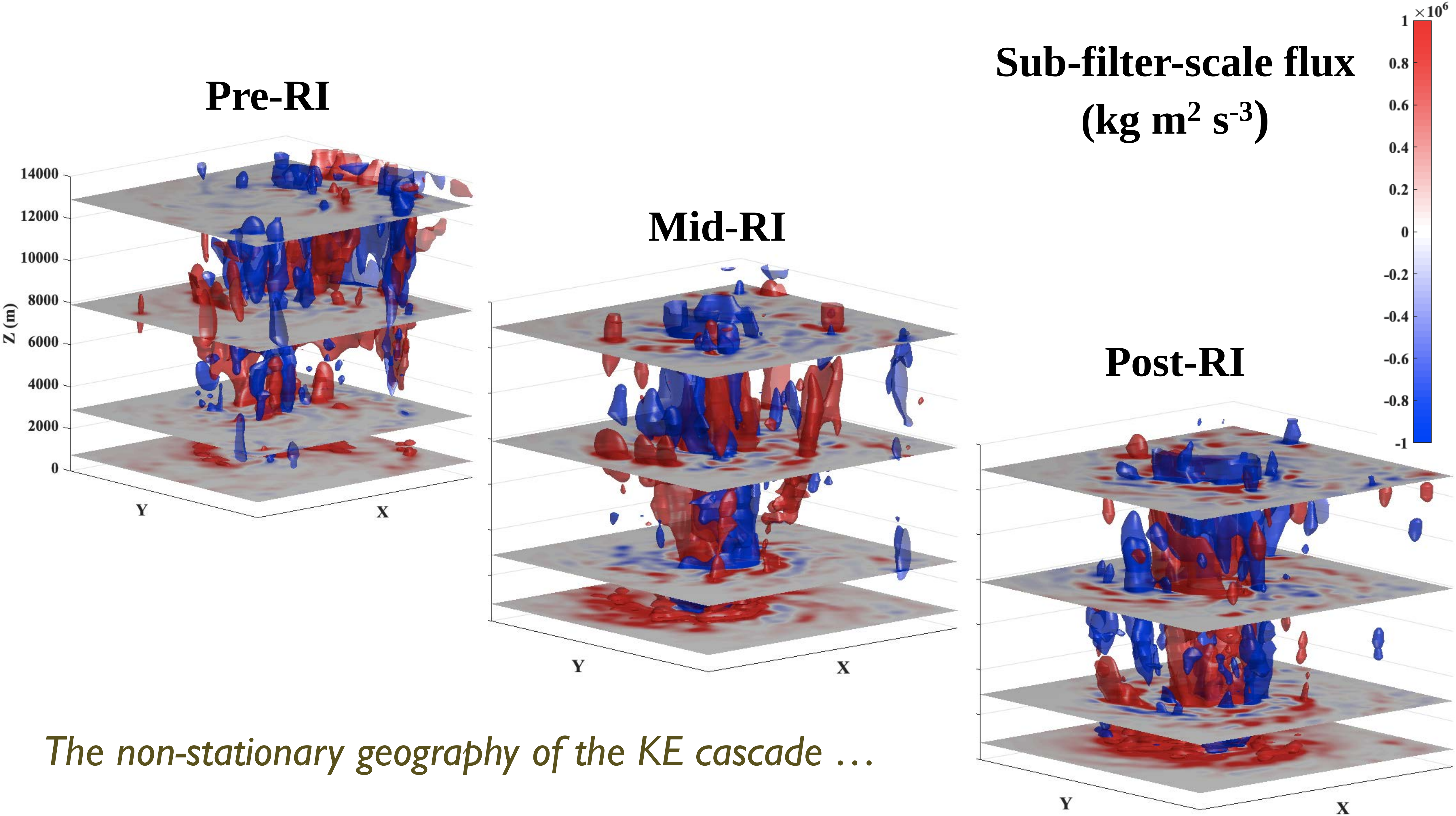
Kinetic Energy Transfer from sub-filter scales to filtered-scales

Positive value: Downscale transfer of KE

Negative value: Upscale transfer of KE

Further results will be presented at the 34th AMS Conference on Hurricanes and Tropical Meteorology

9D.6 Coherent structures in energy cascades during hurricane rapid intensity changes
__Saiprasanth Bhalachandran__, Stanford University, Stanford, CA; and Morgan O'Neill



The non-stationary geography of the KE cascade …

SUMMARY: New ways to think about the influence of localized events in the context of rapid intensity changes

1. Axisymmetric energetics
2. Reynolds averaging-based energetics: u = <u> + u'
3. Fourier-based multi-scale energetics
4. Space-aware energetics in five dimensions :
   Cascades that are *local* in space (and scale)

In the pipeline …

1. Does the classical picture of KE cascade from turbulence literature apply to a hurricane vortex?
2. Identify the spatially coherent phenomena within a hurricane vortex responsible for energy transfer that is local in space and scale
3. What energetic scales directly correspond with *intensity* changes?

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