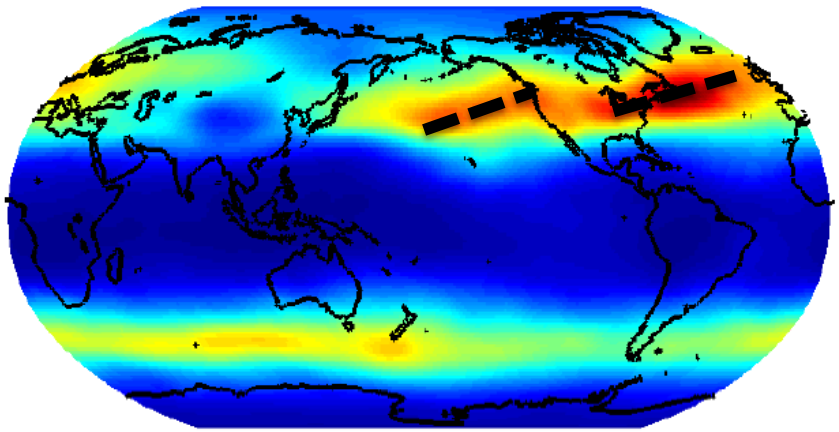
The poleward tilt of storm tracks

from a PV tendency analysis of cyclone tracking composites

Talia Tamarin and Yohai Kaspi
Weizmann Institute of Science
Les Houches, France, March 2015

Storm Tracks

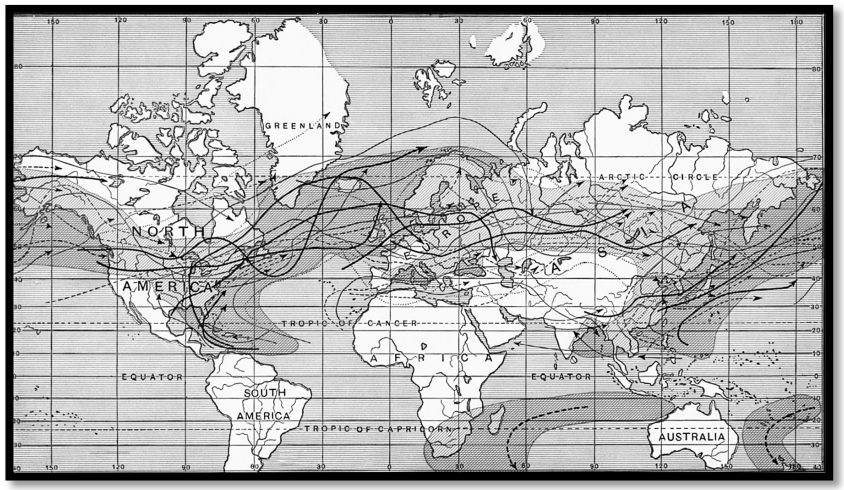
1nd definition: Regions of enhanced 'eddy activity'



$$EKE = \frac{1}{2}\left(\overline{u'^2} + \overline{v'^2}\right)$$

Filtered 3-10 days Kinetic energy, based on (NCEP) reanalysis averaged over the years 1981-2010 during Northern Hemisphere winter (DJF)

2st definition: high density cyclone track



Storm frequency distribution. The stippling denotes high storm frequency, while arrows indicate individual storms. *Reproduced from Hinman (1888)*

Storm Tracks

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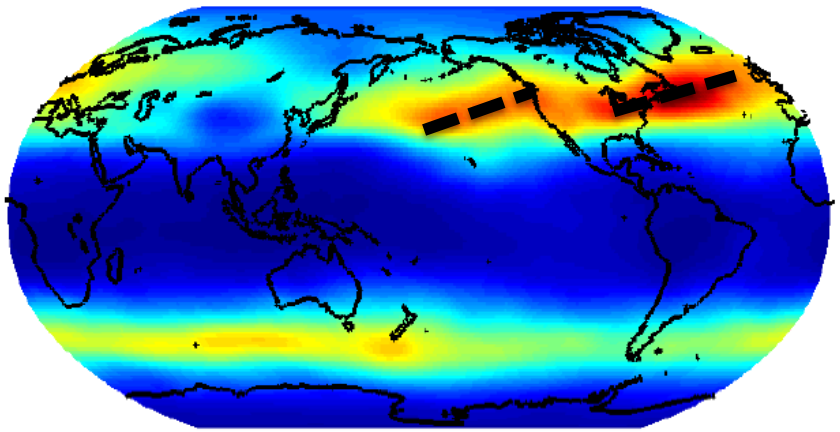

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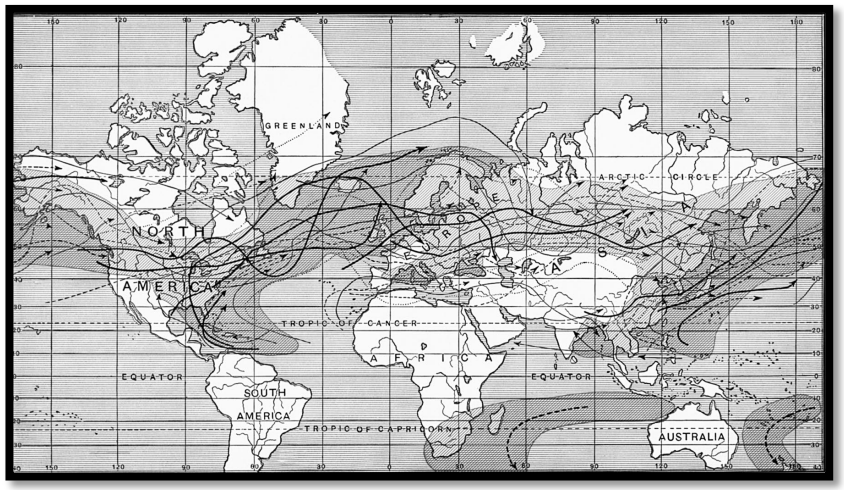


Key questions:

- What controls the poleward tilt of storm tracks?
- Is there a fundamental dynamical mechanism?
- What is the role of latent heat release (LHR) in the poleward deflection?

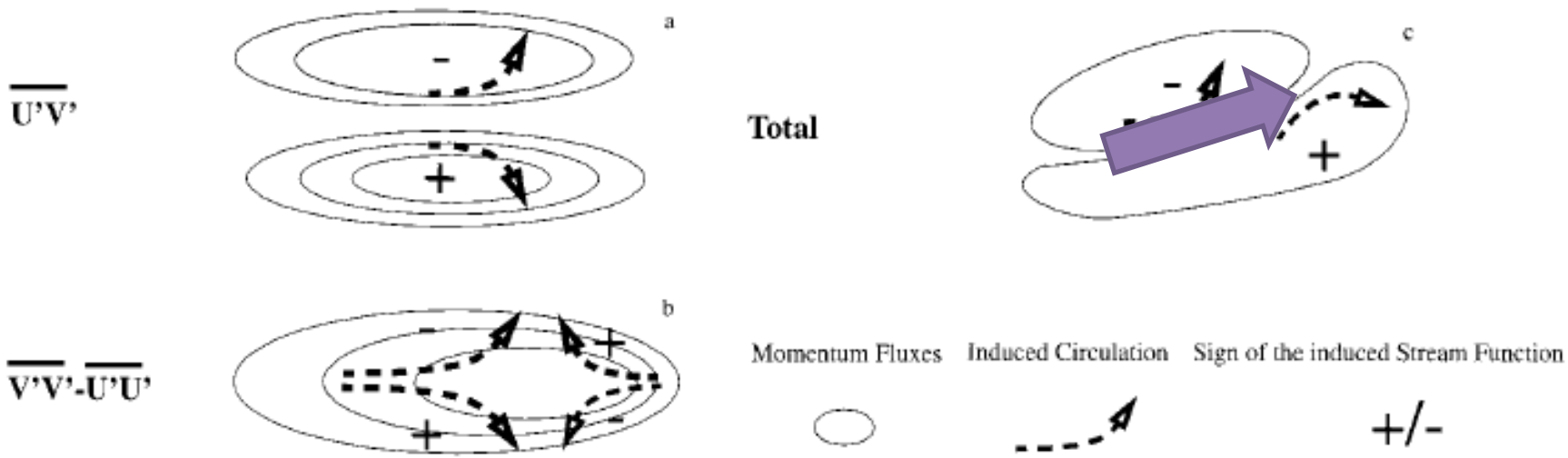
From a time-mean balance perspective:

Poleward Deflection of Storm Tracks

ISIDORO ORLANSKI

Geophysical Fluid Dynamics Laboratory/NOAA, Princeton University, Princeton, New Jersey

(Manuscript received 20 February 1997, in final form 18 November 1997)



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- **Shows a consistent balance at equilibrium, however, does not give information about cause and effect**

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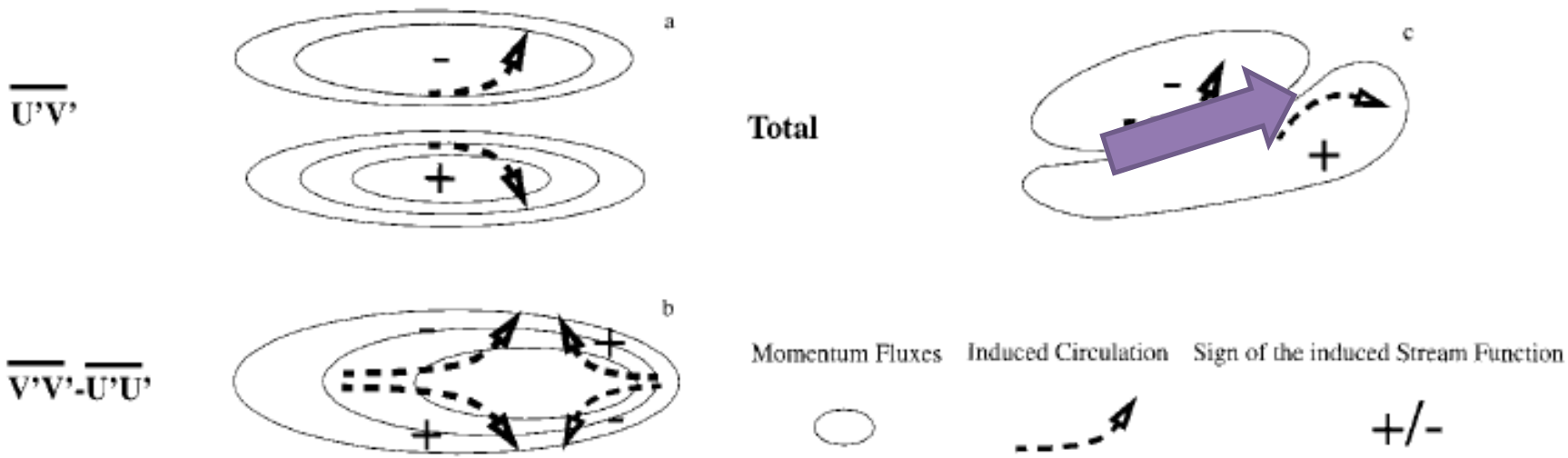

- **Eddy momentum fluxes tend to force a tilted mean flow**
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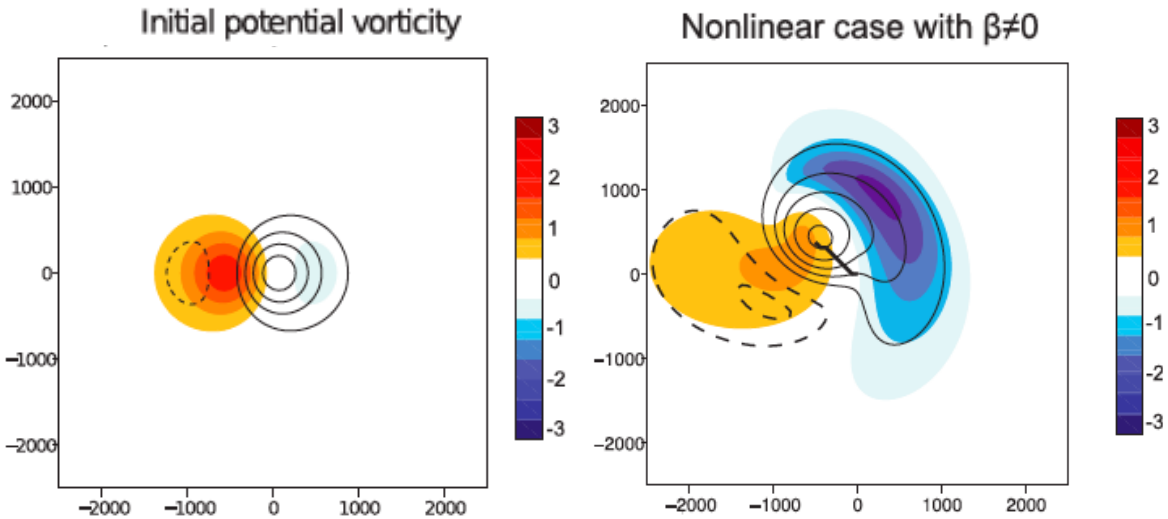
From a single- storm perspective:

A possible mechanism for the poleward propagation-

nonlinear advection by the upper level PV



Oruba et al. (2012) and Oruba et al. (2013), Rivière et al. (2012)

Idealized baroclinic 2-layer model shows a poleward motion of the lower PV due to the upper level PV

Our methods to approach the problem

To study the propagation from a "single storm perspective", we combine an idealized moist GCM with a storm tracking algorithm

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- Does not include: Orography, clouds, chemistry, sea-ice etc.

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- moist dynamics (e.g. Frierson 2007, O'Gorman & Schneider 2008)
- Does not include: Orography, clouds, chemistry, sea-ice etc.

- Tracks separately cyclones and anticyclones
- Identifies mobile features in the pressure or vorticity field that last for more than 2 days
- Follows them Lagrangially

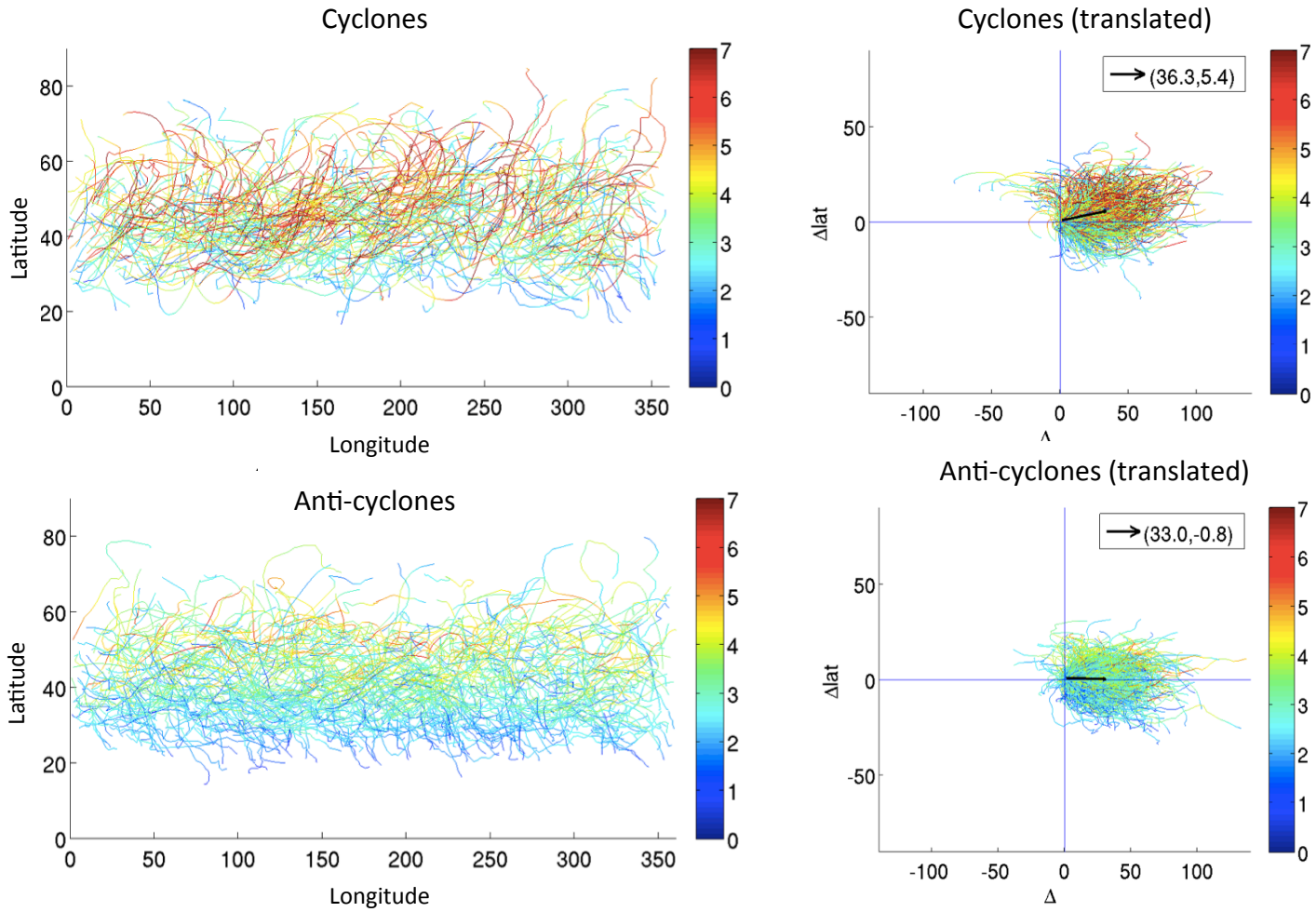
("TRACK" by Kevin Hodges)

make the problem simpler-
consider first a zonally symmetric model

Cyclone and anticyclone tracks

Cyclones

Anti-cyclones



- **Averaged cyclone propagate ~5.4° (poleward),**
- **Averaged anti- cyclones propagate ~-0.8° (equatorward)**

Cyclone and anticyclone tracks

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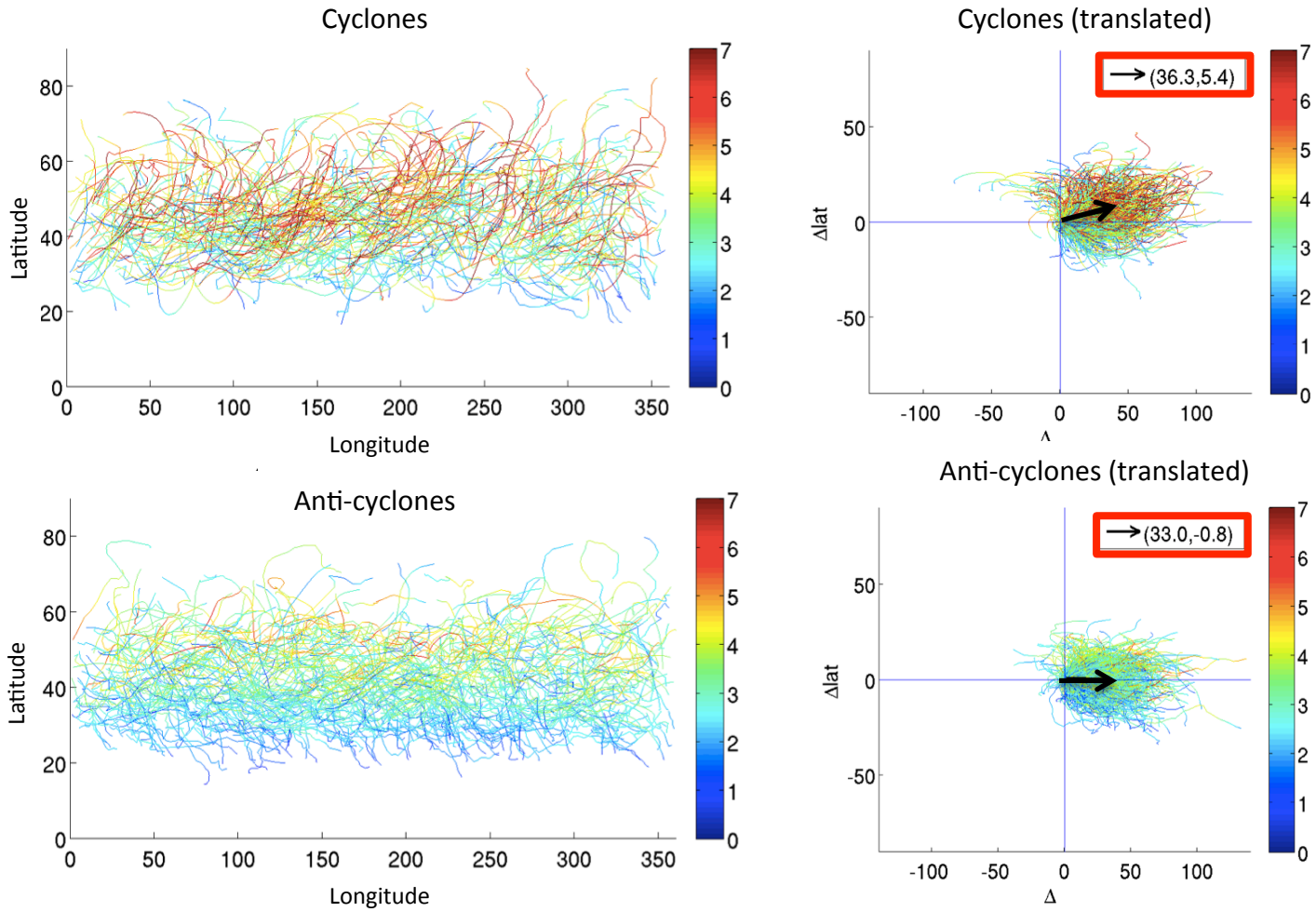
Anti-cyclones



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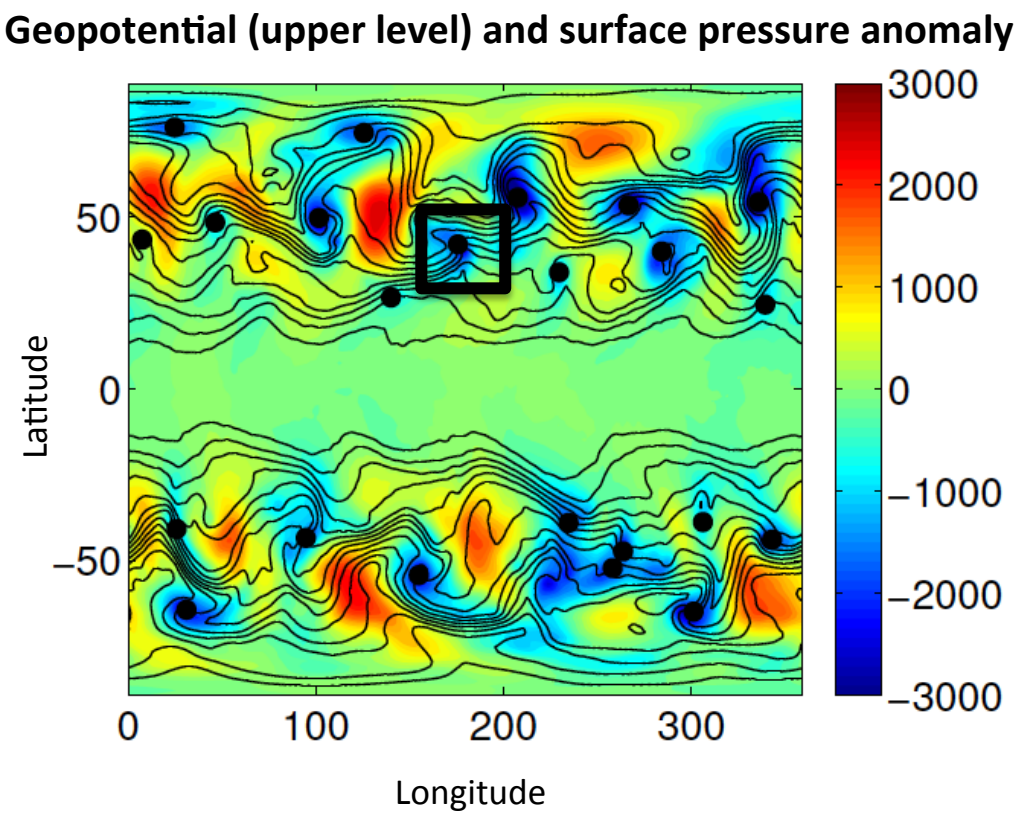
Cyclone tracking composites

- Around each cyclone identified, take a box sized 40°×30° around its center
- Average fields Lagrangially in the box during the growth stage of the cyclone, and sum over all cyclones

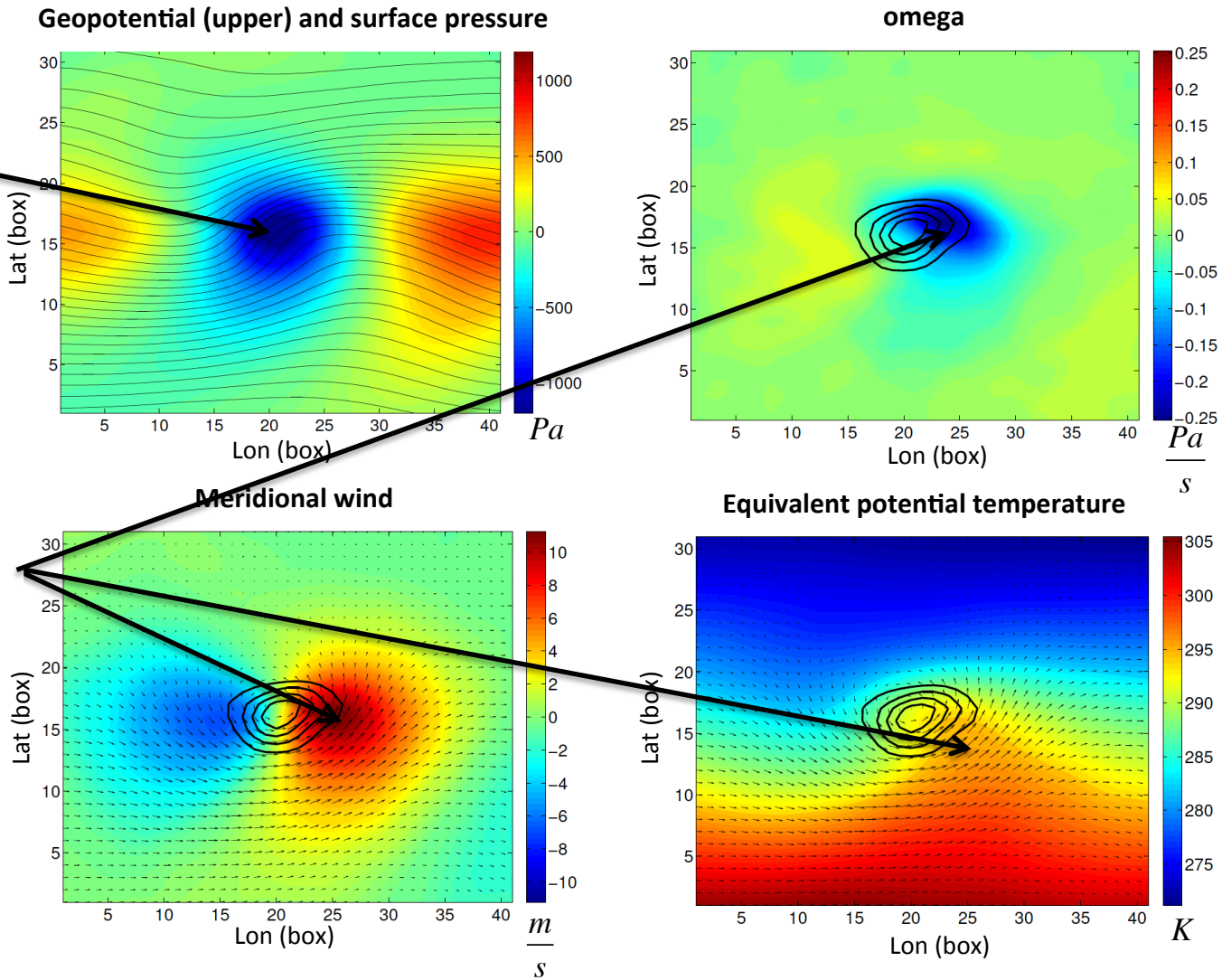
Snapshot from the simulation:



Cyclone tracking composites

Baroclinic structure- *westward tilt with height!*

Strong upward and poleward flow of warm and moist air (the warm conveyer belt)

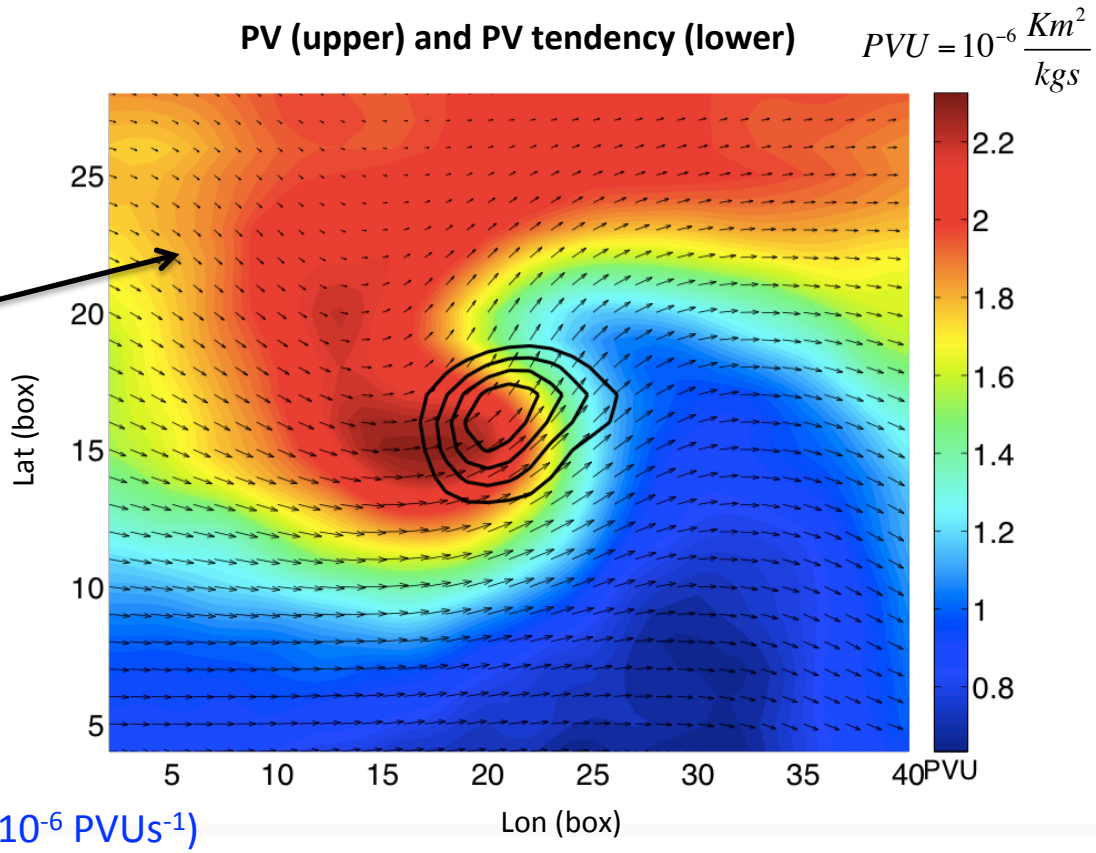


Captures the main characteristics of extratropical cyclones

Composites of upper PV and lower PV tendency $\frac{\partial q}{\partial t}$

$$q = -g\left(f + \zeta\right)\frac{\partial \theta}{\partial p}$$

Upper level winds



Colored contours= Upper level PV

Surface PV

Negative surface PV tendency ($-4 \cdot 10^{-6}$ $PVUs^{-1}$)

Positive surface PV tendency ($4 \cdot 10^{-6}$ $PVUs^{-1}$)

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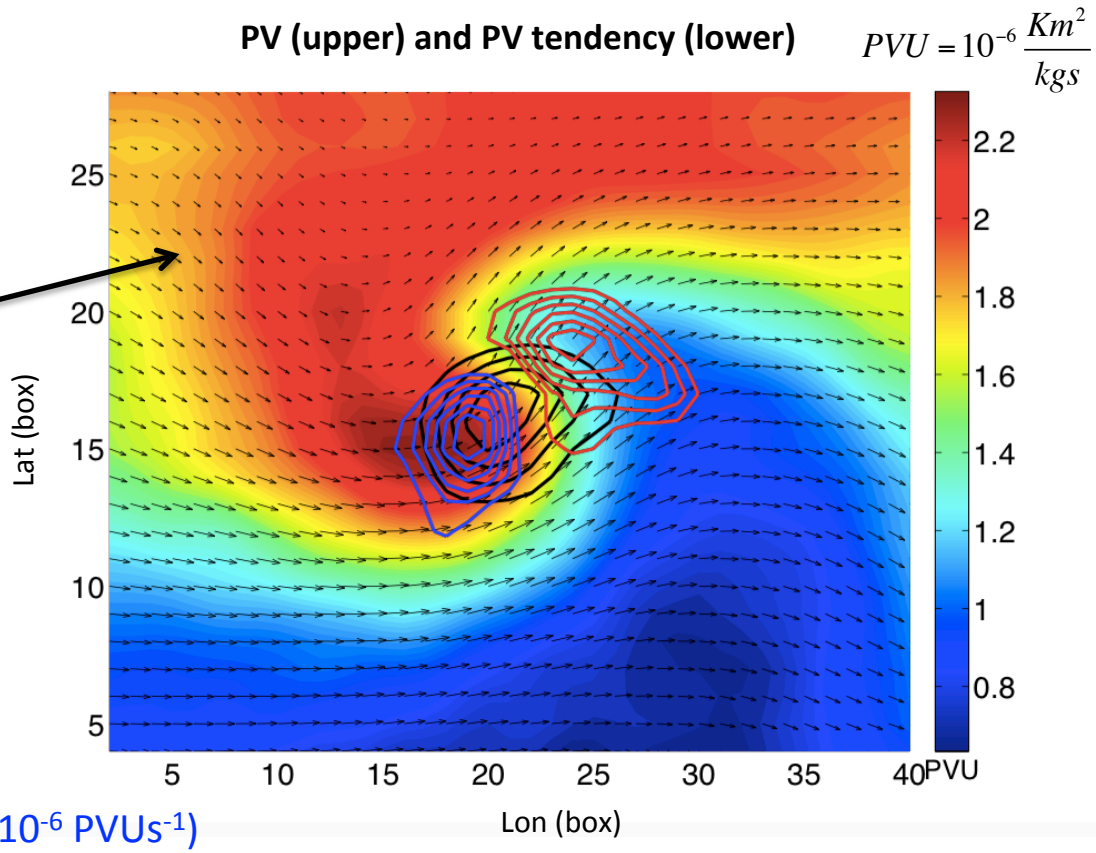


Colored contours= Upper level PV

Surface PV

Negative surface PV tendency ($-4 \cdot 10^{-6}$ $PVUs^{-1}$)

Positive surface PV tendency ($4 \cdot 10^{-6}$ $PVUs^{-1}$)

- Positive PV tendency in the northeastern side of the surface PV
- Strong indication for upper level advection

PV tendency analysis

Decompose $q = \bar{q} + q'$ and plug into into $\frac{dq}{dt} = Q$

$$Q = -g\left(f\hat{k} + \nabla \times u\right) \cdot \nabla\left(\frac{\partial \theta}{\partial t}\right)$$

Diabatic heating

The perturbation PV tendency equation-

$$\frac{\partial q'}{\partial t} \approx -\bar{U}\frac{\partial q'}{\partial x} - v'\frac{\partial \bar{q}}{\partial y} - u'\frac{\partial q'}{\partial x} - v'\frac{\partial q'}{\partial y} - w'\frac{\partial q'}{\partial z} + Q$$

PV tendency

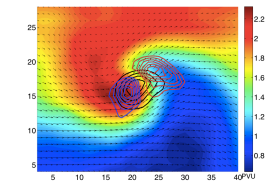
Advection of pert. by mean flow

Advection of mean flow by pert.

Nonlinear zonal advection

Nonlinear meridional advection

Vertical advection term



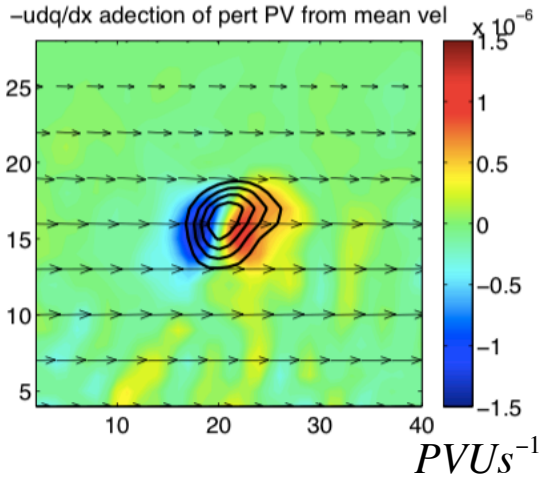
Linear terms

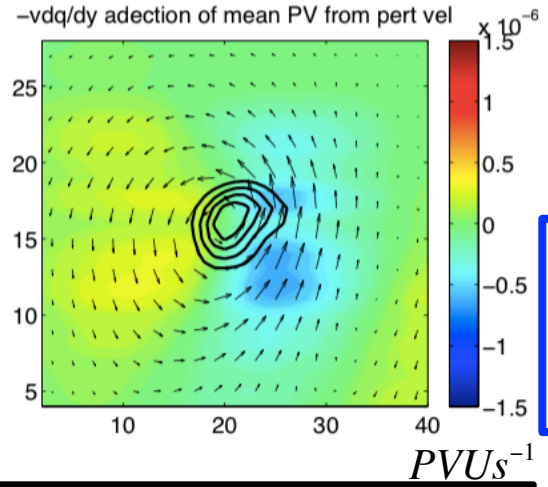
Nonlinear terms

PV tendency analysis

$$-\bar{U}\frac{\partial q'}{\partial x}$$

Advection of pert. by mean flow



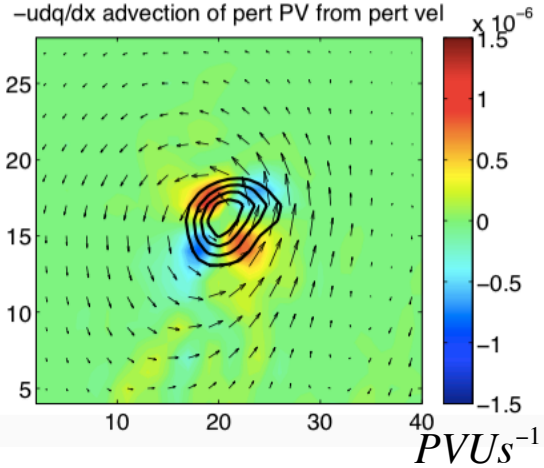


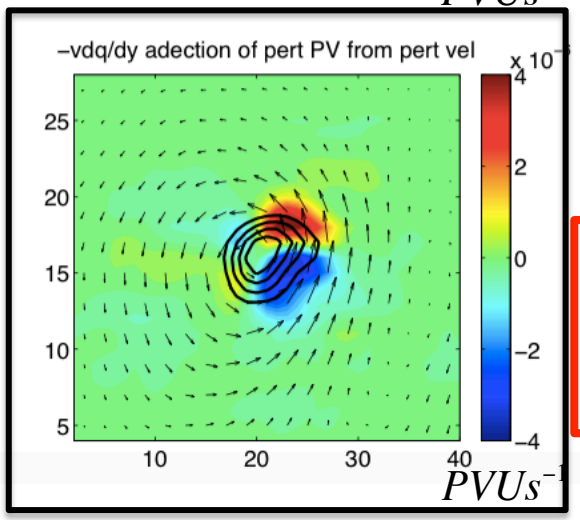
$$-v'\frac{\partial \bar{q}}{\partial y}$$

Advection of mean flow by pert.

$$-u'\frac{\partial q'}{\partial x}$$

Nonlinear zonal advection





$$-v'\frac{\partial q'}{\partial y}$$

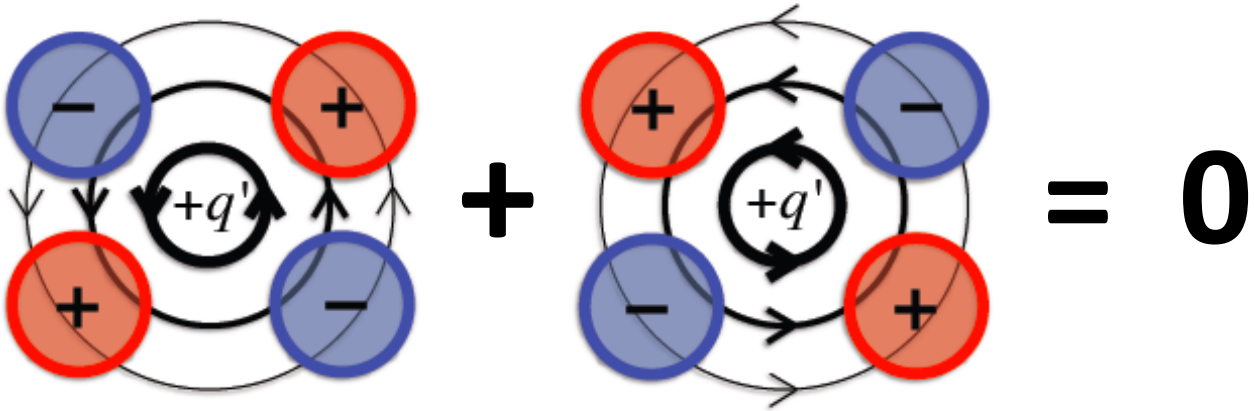
Nonlinear meridional advection

Meridional nonlinear advection is dominant

Nonlinear advection terms for an axisymmetric PV

Meridional self advection

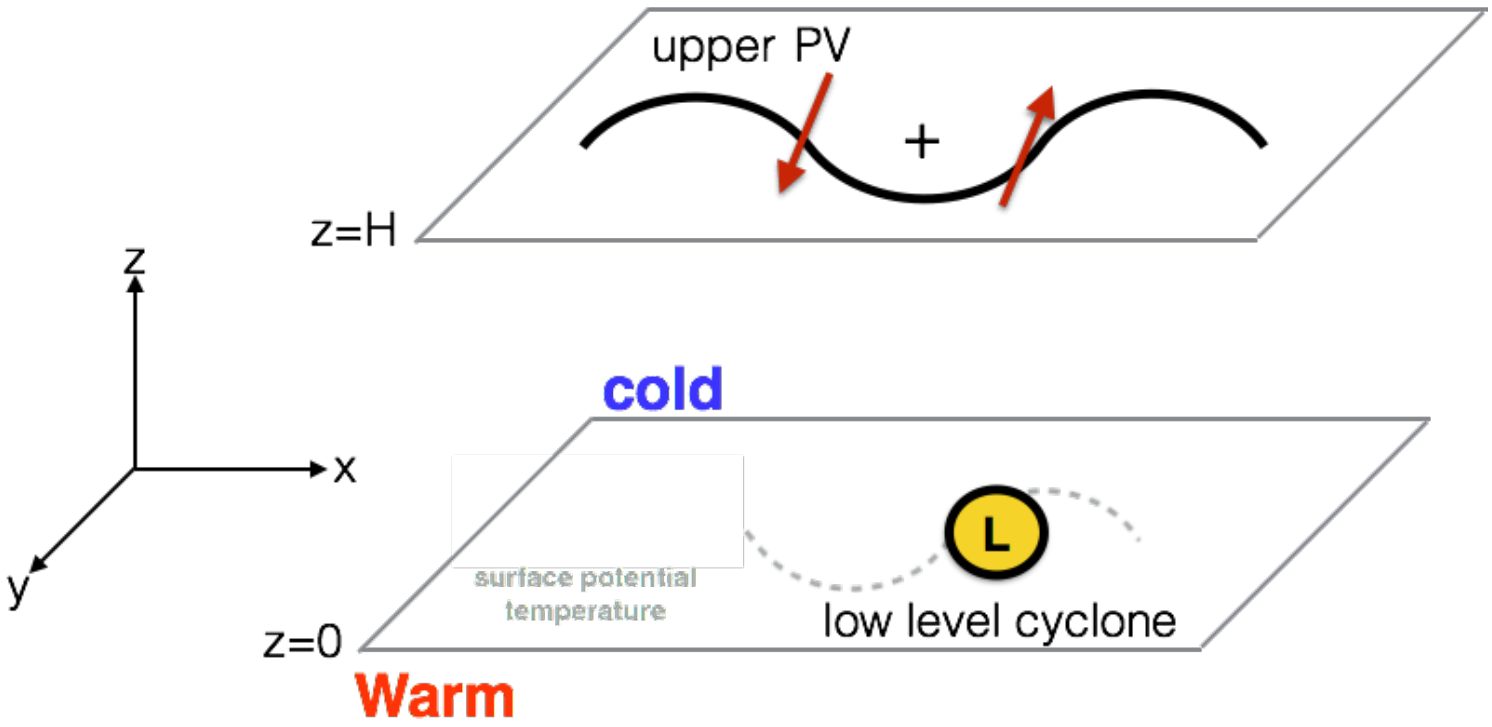
Zonal self advection



Nonlinear advection of axisymmetric PV should be zero!
(in analogy to a point vortex that cannot move itself)

- Implies that the upper level PV may be responsible for the poleward tendency in the meridional advection term

The role of upper level PV in the poleward propagation of the surface cyclone-



(based on ideas from Hoskins et al. 1985)

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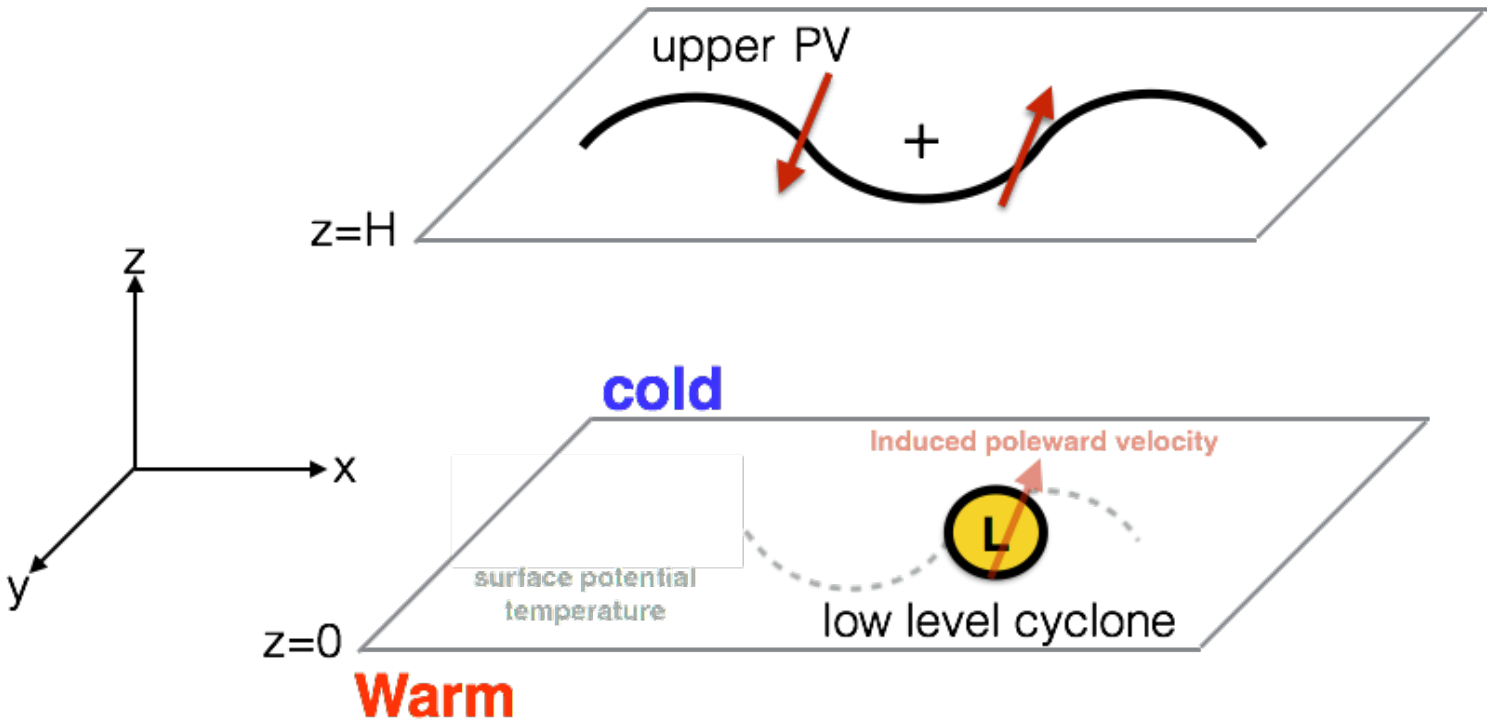

- Westward tilt with height results in a nonlinear poleward advection of the lower PV anomaly by upper level PV.

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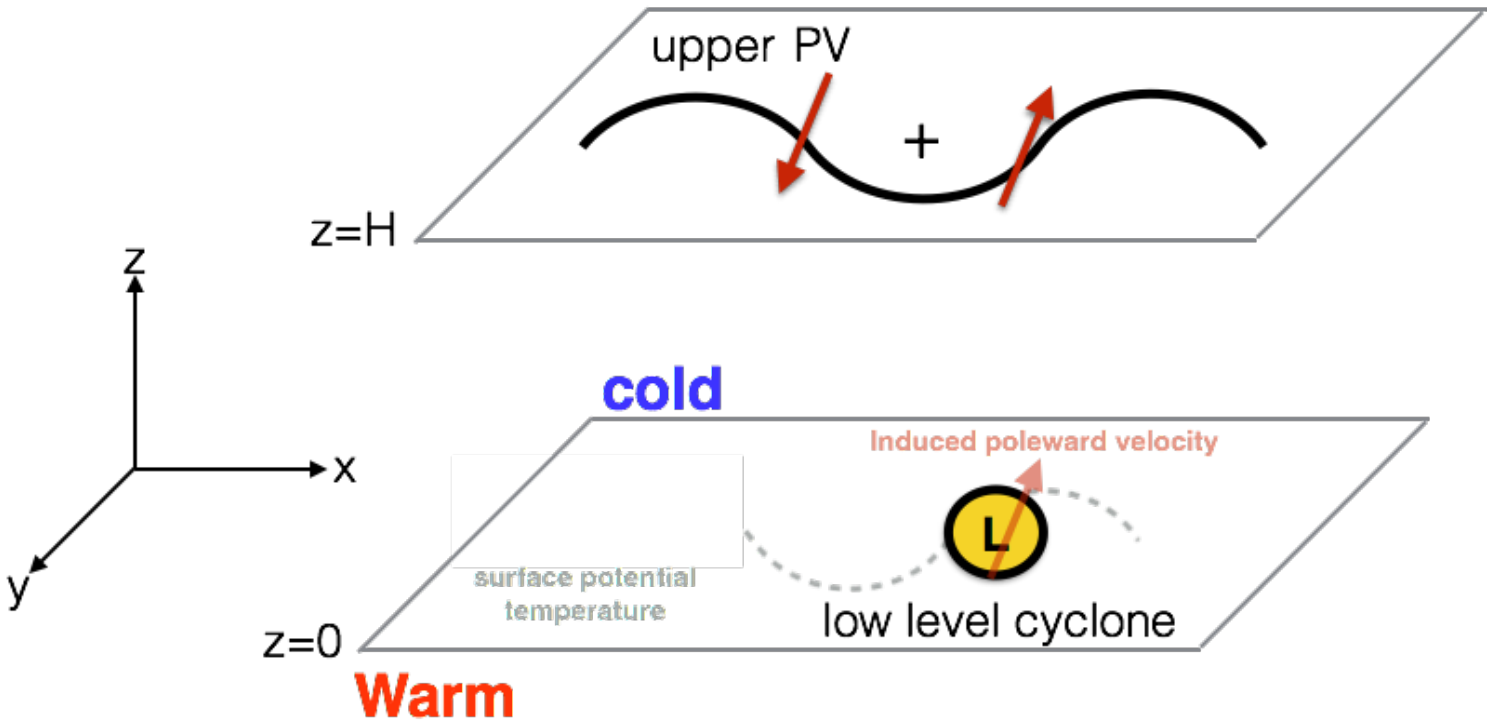


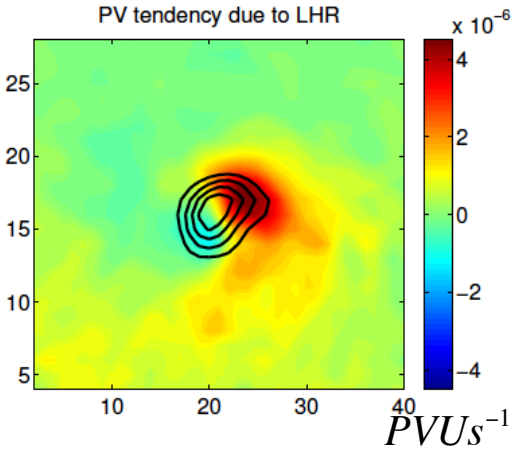
- Westward tilt with height results in a nonlinear poleward advection of the lower PV anomaly by upper level PV.
- To prove and quantify it, need PV inversion- to find the induced velocity from upper PV (work in progress)

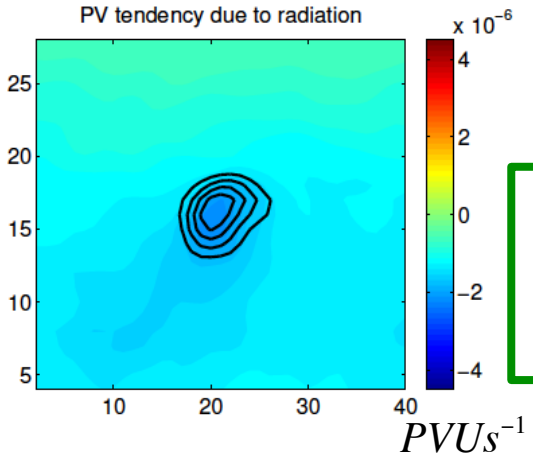
(based on ideas from Hoskins et al. 1985)

PV tendency analysis-cont.

Q_{LHR}

Diabatic term associated with LHR



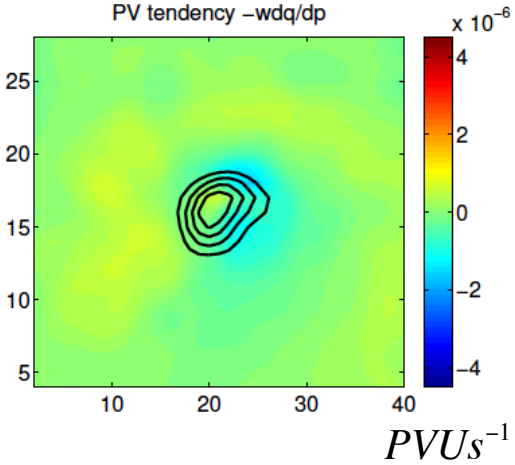


Q_{rad}

Diabatic heating Associated with radiation

$$-w'\frac{\partial q'}{\partial z}$$

Vertical advection term



PV tendency analysis-cont.

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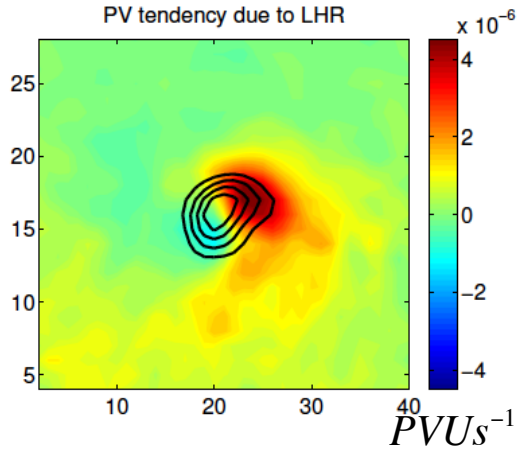

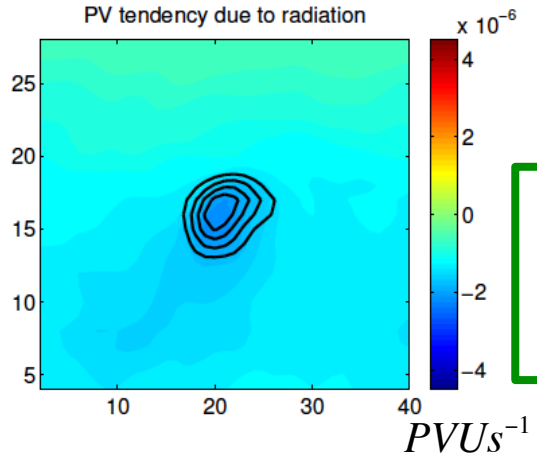

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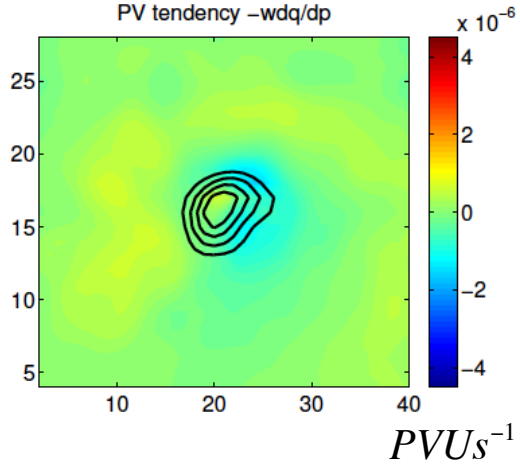
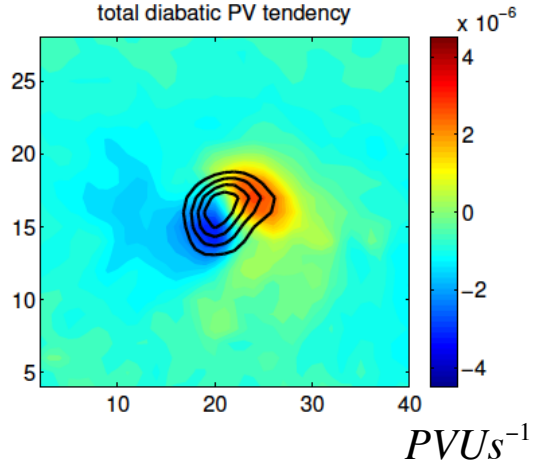
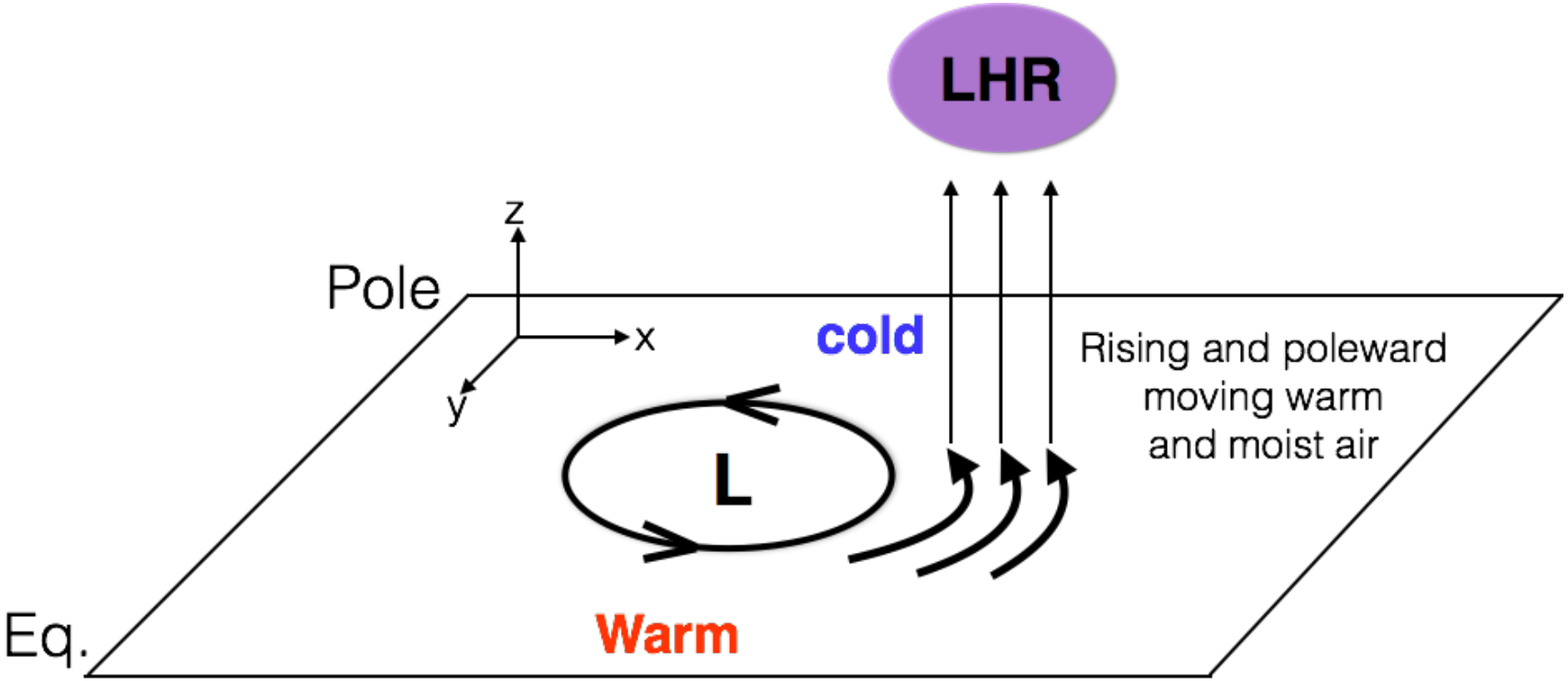




Sum of diabatic terms

LHR is responsible for the positive PV tendency on northeastern side of the cyclone

The role of latent heat release (LHR)

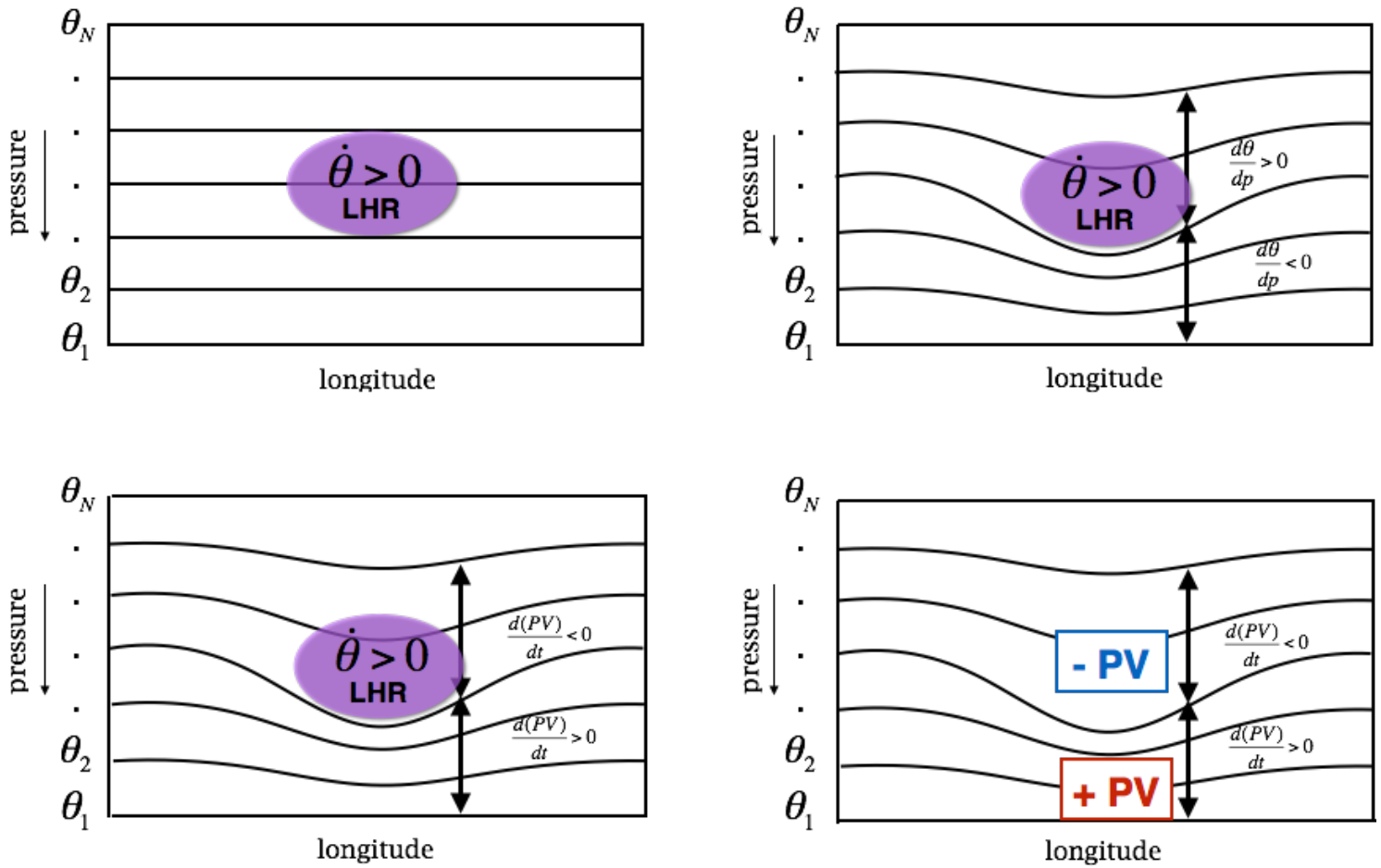


LHR is maximized in the northeastern side of the cyclone, where warm and moist subtropical air ascents, cools and condenses

The role of latent heat release

$$\frac{dq}{dt} = -g(f+\zeta)\frac{\partial \dot{\theta}}{\partial p}$$

$$\theta_1 < \theta_2 < \ldots < \theta_N$$



Stoelinga (1996), Posselt and Martin (2004)

LHR at mid-troposphere results in positive (negative) PV anomaly at lower (upper) levels

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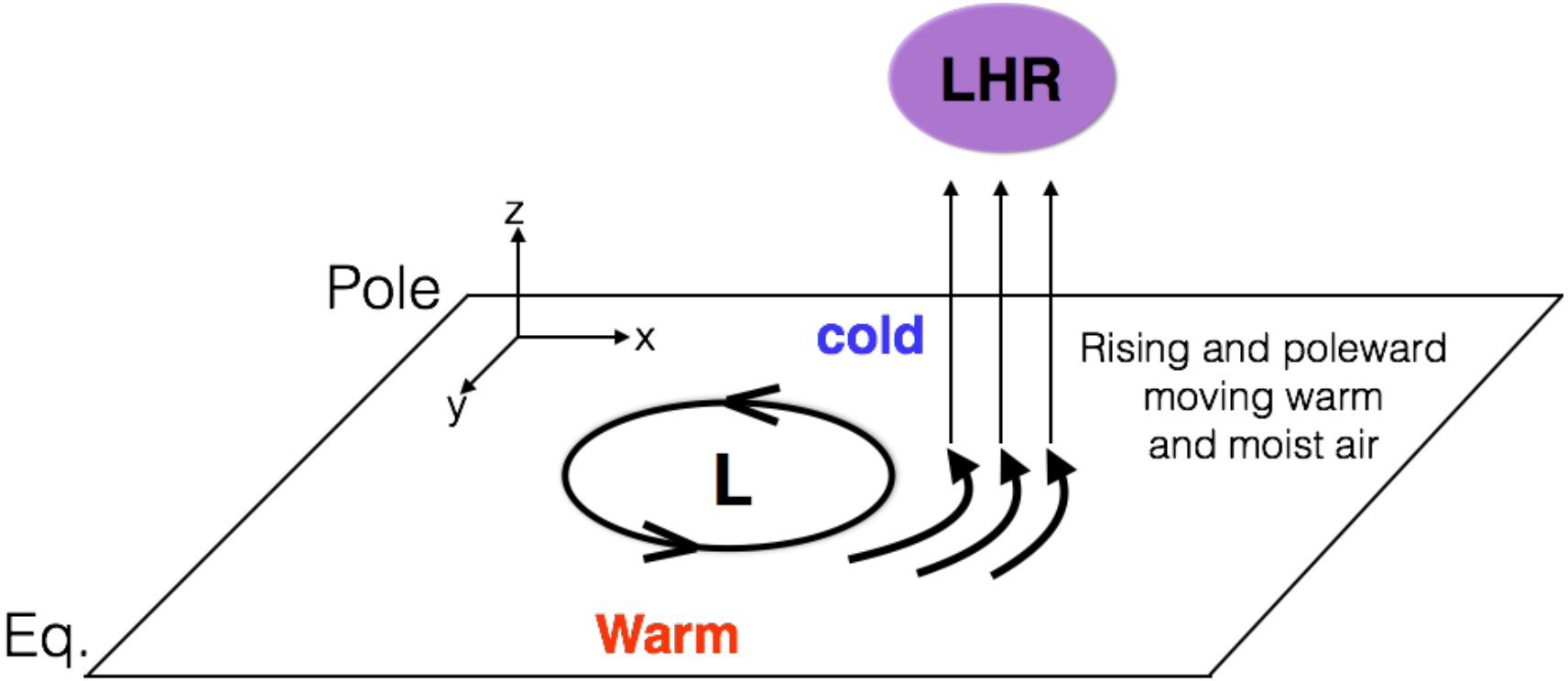

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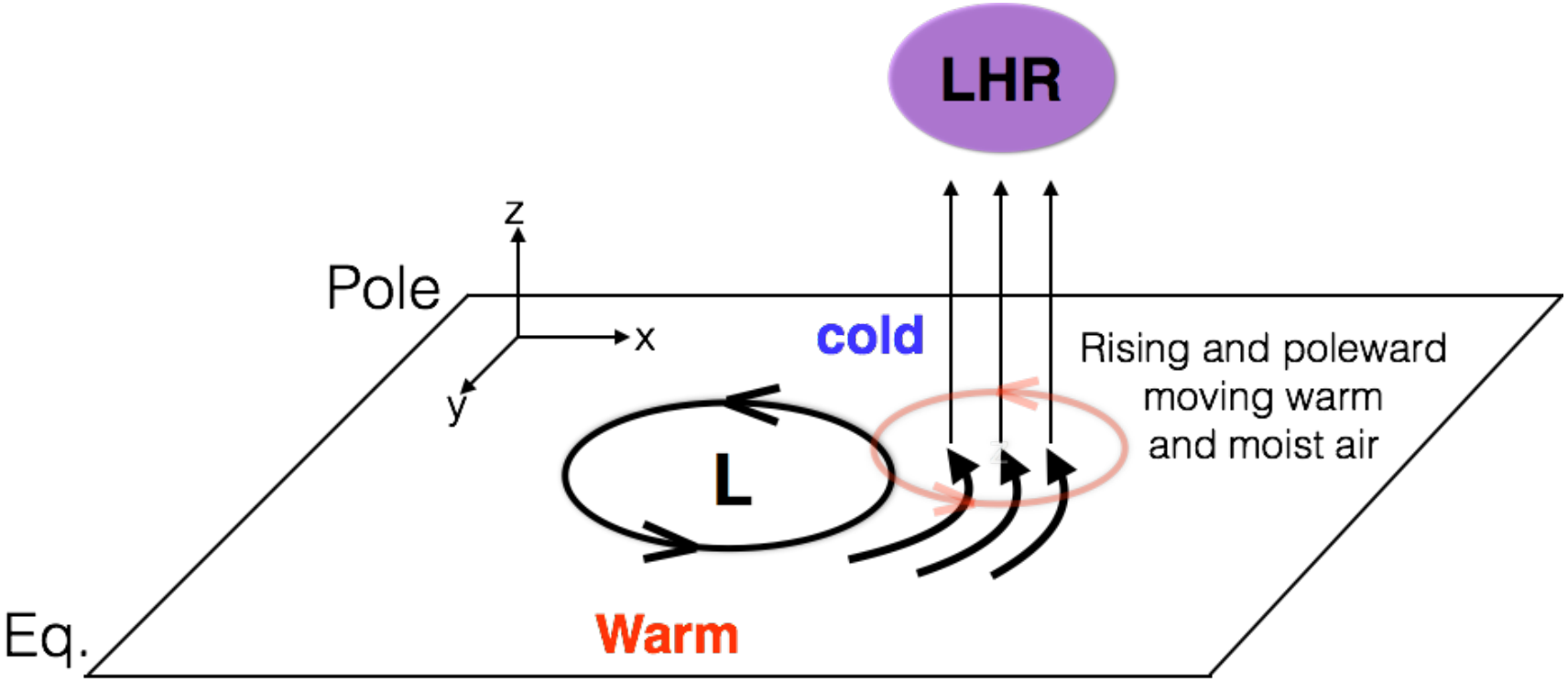

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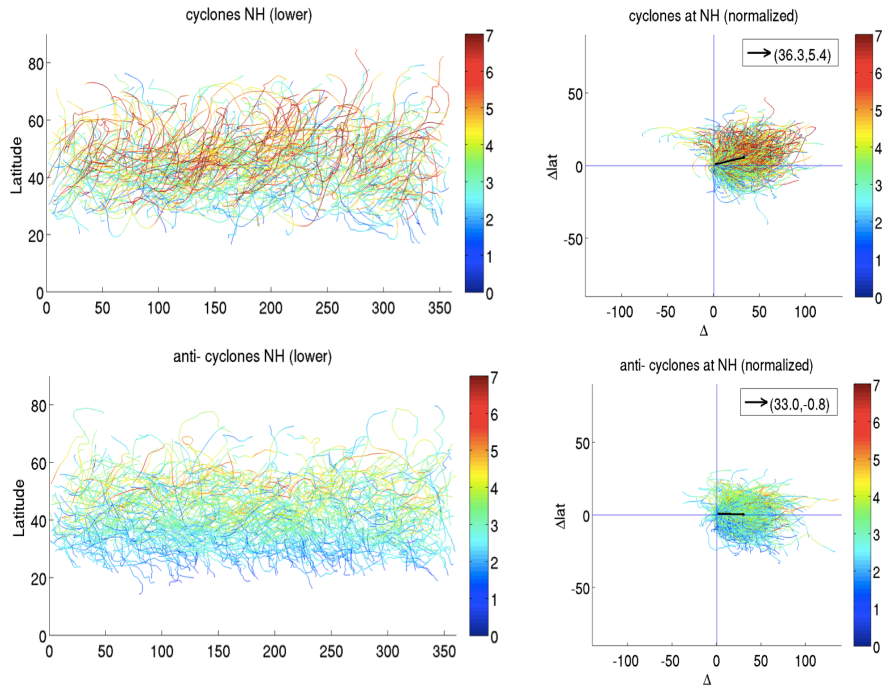
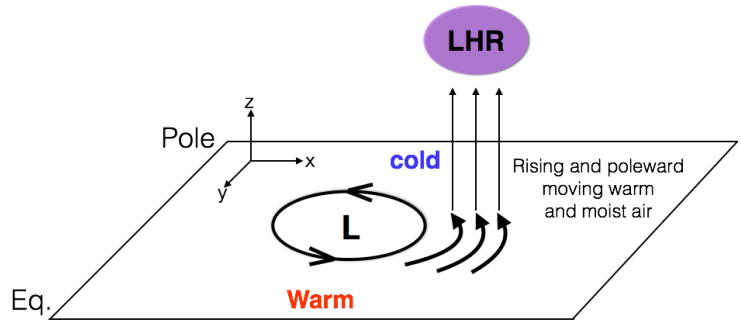
The role of latent heat release (LHR)

Cyclones Vs. Anticyclones





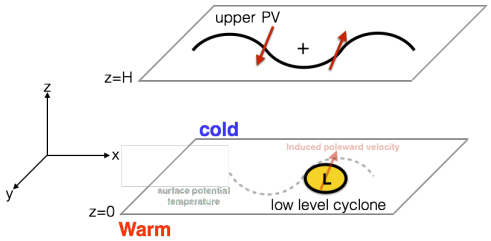
The LHR effect may explain the differences in propagation between cyclones and anticyclones, since the latter is associated with descending air (surface high pressure)

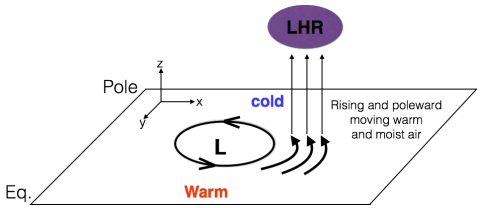
Summary and conclusions

- An average cyclone propagates ~5.4° (poleward), while an averaged anti- cyclones propagate ~-0.8° (equatorward)
- Cyclones composites- positive PV tendency in the northeastern side of the PV anomaly at lower levels, mainly due to meridional nonlinear advection and LHR.

Westward tilt with height results with poleward advection of the lower PV anomaly by upper level PV

LHR is maximized on the northeastern side of the surface cyclone, where warm and moist are ascents and condenses





- May explain the differences between cyclones and anticyclones
- Next: PV inversion- to quantify the contribution of the upper level PV in the poleward motion of the surface PV

Thank you!

☺