The poleward tilt of storm tracks
from a PV tendency analysis
of cyclone tracking composites

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Storm Tracks

1\textsuperscript{nd} definition: Regions of enhanced ‘eddy activity’

\[ EKE = \frac{1}{2}(u'^2 + v'^2) \]

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

2\textsuperscript{st} 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

1\textsuperscript{st} definition: Regions of enhanced ‘eddy activity’

2\textsuperscript{nd} definition: high density cyclone track

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?

\[ EKE = \frac{1}{2} \left( u'^2 + v'^2 \right) \]
From a time-mean balance perspective:

- Eddy momentum fluxes tend to force a tilted mean flow
- Shows a consistent balance at equilibrium, however, does not give information about cause and effect
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From a single-storm perspective:

A possible mechanism for the poleward propagation-nonlinear advection by the upper level PV

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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- Idealized aqua-planet GCM (FMS GFDL)
- moist dynamics (e.g. Frierson 2007, O’Gorman & Schneider 2008)
- Does not include: Orography, clouds, chemistry, sea-ice etc.
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- Idealized aqua-planet GCM (FMS GFDL)
- 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

- Averaged cyclone propagate \(\sim 5.4^\circ\) (poleward),
- Averaged anti-cyclones propagate \(\sim -0.8^\circ\) (equatorward)
Cyclone and anticyclone tracks

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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 $\frac{\partial q}{\partial t}$

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

Colored contours = Upper level PV

- Surface PV
- Negative surface PV tendency ($-4 \times 10^{-6}$ PVUs$^{-1}$)
- Positive surface PV tendency ($4 \times 10^{-6}$ PVUs$^{-1}$)
Composites of upper PV and lower PV tendency \( \frac{\partial q}{\partial t} \)

\[ q = -g(f + \zeta) \frac{\partial \theta}{\partial p} \]

Upper level winds

Colored contours= Upper level PV
- Surface PV
- Negative surface PV tendency (-4•10^{-6} PVUs^{-1})
- Positive surface PV tendency (4•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 \( \frac{dq}{dt} = Q \)

The perturbation PV tendency equation-

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

Linear terms:
- Advection of pert. by mean flow
- Advection of mean flow by pert.

Nonlinear terms:
- Nonlinear zonal advection
- Nonlinear meridional advection

Vertical advection term

Diabatic heating

\[ Q = -g \left( f \hat{k} + \nabla \times u \right) \cdot \nabla \left( \frac{\partial \theta}{\partial t} \right) \]
PV tendency analysis

\[-\bar{U} \frac{\partial q'}{\partial x}\]

Advection of pert. by mean flow

\[-u' \frac{\partial q'}{\partial x}\]

Nonlinear zonal advection

\[-v' \frac{\partial \bar{q}}{\partial y}\]

Advection of mean flow by pert.

\[-v' \frac{\partial q'}{\partial y}\]

Nonlinear meridional advection

Meridional nonlinear advection is dominant
Nonlinear advection terms for an axisymmetric PV

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

- 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

\[ -w' \frac{\partial q'}{\partial z} \]

Vertical advection term

\[ Q_{rad} \]

Diabatic heating Associated with radiation
PV tendency analysis-cont.

\[ Q_{LHR} \]
Diabatic term associated with LHR

\[ -w^t \frac{\partial q^t}{\partial z} \]
Vertical advection term

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

\[ \frac{dq}{dt} = -g(f + \zeta) \frac{\partial \hat{\theta}}{\partial p} \]

\[ \theta_1 < \theta_2 < \ldots < \theta_N \]

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

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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.

- 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!