The structure and dynamics of tropopause polar vortices

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Introduction and background
- What are tropopause polar vortices (TPVs)?
- Observations of TPVs

Methods
- PV diagnostics
- Real-time Modeling System

Results
- Composite TPV structure
- Idealized simulations

Summary
What are tropopause polar vortices?

*Tropopause polar vortices* (TPVs) are:

- *Vortices* isolated from the jet stream, occurring primarily in *polar* regions.
- Based on the *tropopause*.
- Cold-core structures.
What are tropopause polar vortices?

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*Vortices* are defined here by:

- Closed contours of a materially conserved field.
  - Fluid properties are contained within the closed contours.

Potential temperature on the dynamic tropopause

"Dynamic" tropopause = 2 PVU surface

= \(2 \times 10^{-6} \text{ K kg}^{-1} \text{ s}^{-1} \text{ m}^2\)
Observations of TPVs

Tropopause potential temperature

Radiosonde Observation

University of Wyoming
PV Diagnostics

Vortex intensity is measured here using Ertel’s potential vorticity (EPV) theorem (Pedlosky 1998):

\[
\frac{D \Pi}{D t} = \frac{D}{D t} \left( \frac{1}{\rho} \vec{\omega}_a \cdot \nabla \theta \right) = \frac{\vec{\omega}_a}{\rho} \cdot \nabla \frac{D \theta}{D t} + \frac{\nabla \theta}{\rho} \cdot \left( \nabla \times \frac{\vec{F}}{\rho} \right).
\]

→ Changes in vortex intensity arise from diabatic or frictional processes.

→ When friction is negligible, changes in vortex intensity are equivalent to changes in closed contours of \( \theta \).

To conceptualize, the effect on vortex intensity by diabatic processes in the direction of the vertical vorticity vector is:

\[
\frac{D \Pi}{D t} \simeq \zeta_a \frac{\partial}{\partial z} \frac{D \theta}{D t} = \zeta_a \frac{\partial}{\partial z} \left( \dot{\theta}_{\text{radiation}} + \dot{\theta}_{\text{latent heating}} + \dot{\theta}_{\text{convection}} + \dot{\theta}_{\text{pbl}} + \dot{\theta}_{\text{mix}} \right).
\]
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\frac{D\Pi}{Dt} \approx \zeta_a \frac{\partial}{\partial z} \frac{D\theta}{Dt} \approx \zeta_a \frac{\partial}{\partial z} \left( \dot{\theta}_{\text{radiation}} + \dot{\theta}_{\text{latent heating}} \right)
\]

near the tropopause.
Radiation vs. Latent heating
Radiation vs. Latent heating

Latent heating large

$D_\theta/Dt$

$D_\pi/Dt$
Radiation vs. Latent heating

Latent heating large

\[ D_\theta/Dt \quad D_\pi/Dt \quad D_\pi/Dt |_{\text{sum}} \]
Radiation vs. Latent heating

Latent heating small

Latent heating large

$D_\theta/Dt$

$D_\pi/Dt$

$D_\pi/Dt|_{\text{sum}}$
TPV case study, November 2005

GFS tropopause analyses:
Track along tropopause

Tropopause potential temperature
at center of vortex
GFS tropopause analyses:
Track along tropopause

Tropopause potential temperature
at center of vortex

Model time vs. height

TPV case study, November 2005
TPV case study, November 2005

GFS tropopause analyses:
Track along tropopause

Model time vs. height
EPV tendency due to:
All diabatic effects

Tropopause potential temperature
at center of vortex

Radiation
Area weighted regions of tropopause cyclone growth
TPV Growth

Area weighted regions of tropopause cyclone growth
TPV Growth

Area weighted regions of tropopause cyclone growth

Weather Research and Forecasting (WRF) Model:

- Advanced Research dynamical core (ARW) Version 2.2.1 and WRF Preprocessing System (WPS) Version 2.2
- $120 \times 120$ horizontal, 31 vertical grid points
- $\Delta x = \Delta y = 20\text{km}$, $\Delta t = 120$ seconds
- WSM 5-class microphysics, RRTM longwave radiation, Goddard shortwave radiation, Kain-Fritsch cumulus, YSU planetary boundary layer scheme
Composite soundings

Vortex core
composite sounding

Number of samples = 327
Composite soundings

Vortex core composite sounding

Vortex core - Background

Number of samples = 327
Composite cross section section anomalies

Anomalies = vortex core - background

EPV

Temperature

Relative humidity

Tangential wind

West ←→ East
Composite cross section anomalies

Anomalies = vortex core - background

\[ \dot{\theta}_{\text{radiation}} \]

Temperature

West ↔ East
Composite cross section anomalies

\[
\frac{\partial \Pi}{\partial t} | \text{radiation} \nabla \frac{\partial \Pi}{\partial t} | \text{latent heating}
\]

West ←→ East
Idealized model simulations

Idealized experiments/WRF model:

- Initialization: 3DVPAS ("Three-Dimensional Vortex Perturbation Analysis and Simulation") (See Nolan and Montgomery 2002).
- Composite wind cross section, temperature sounding $\Rightarrow$ axisymmetric vortex in hydrostatic and gradient wind balance $\Rightarrow$ interpolate to WRF grid
- $120 \times 120 \times 61$ grid points, $\Delta x = \Delta y = 24$ km, $\Delta t = 120$ seconds.
- RRTM LW radiation, WSM 5-class microphysics, no other physics.
- Relative humidity fixed to 60% in troposphere.
Idealized model simulations

Does longwave (LW) radiational cooling alone intensify vortex?

Experiment 1: LW radiation only

\[ \dot{\theta}_{\text{radiation}} \quad \frac{D \Pi}{Dt} |_{\text{radiation}} \]

Cross Section

Time vs. vortex amplitude

Amplitude = \( \theta_{\text{last closed contour}} - \theta_{\text{core}} \) (on tropopause)
Idealized model simulations

Does latent heating (LH) offset radiational intensification?

Experiment 2: LW + LH

Time vs. vortex amplitude

Amplitude = \( \theta_{\text{last closed contour}} - \theta_{\text{core}} \)
(on tropopause)
Idealized model simulations

Does latent heating offset radiational intensification?

Experiment 2: LW + LH

\[ \frac{D\Pi}{Dt} |_{\text{radiation}} \]

\[ \frac{D\Pi}{Dt} |_{\text{latent heating}} \]

Time vs. height

<table>
<thead>
<tr>
<th>Pressure - Pres. tropopause (Pa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time (hours)</td>
</tr>
<tr>
<td>20 40 60 80 100</td>
</tr>
</tbody>
</table>

Time vs. vortex amplitude

<table>
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<tr>
<th>Amplitude (Kelvin)</th>
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<tr>
<td>Time (hours)</td>
</tr>
<tr>
<td>0 20 40 60 80 100 120</td>
</tr>
</tbody>
</table>

Amplitude = \[ \theta_{\text{last closed contour}} - \theta_{\text{core}} \] (on tropopause)
Idealized model simulations

Does latent heating offset radiational intensification?

Experiment 3: Warm temperatures by 30°C

\[ \frac{D\Pi}{Dt} \mid \text{radiation} \]

\[ \frac{D\Pi}{Dt} \mid \text{latent heating} \]

Amplitude = \( \theta_{\text{last closed contour}} - \theta_{\text{core}} \)
(on tropopause)
Summary

- Cyclonic TPV composites in the region where cyclone growth is most frequent show:
  - Temperature anomalies of +5K in lower stratosphere, -8K in middle troposphere lead to an enhancement of radiational heating gradient leaving a positive EPV tendency inside the vortex core.

- Intensification mechanisms are examined in isolation with idealized experiments, suggesting so far:
  - Longwave radiation tends to intensify the vortex.
  - Latent heating could act to intensify at low temperatures, but weaken at warm temperatures.

- Questions:
  - Is there a certain temperature for which latent heating can dominate over radiational cooling?
  - Will the changing Arctic environment change TPV characteristics?