The effect of clouds, radiation and turbulence on upper-level PV

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Introduction

- Intensification of extratropical cyclones
  e.g., Davis and Emanuel (1991, MWR); Stoelinga (1996, MWR); Binder et al. (2016, JAS)
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- Evolution of surface fronts
  e.g., Lackmann (2002; MWR); Forbes and Clark (2003, QJRMS); Crezee et al. (2017; JAS)
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- **Modification of tropopause structure**
  
  e.g., Zierl and Wirth (1997, JGR); Pomroy and Thorpe (2000, MWR); Chagnon et al. (2013, QJRMS); Saffin et al. (2017, JGR)
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**How do individual physical processes modify potential vorticity near the tropopause?**
**Methods: Diabatic PV modification**

\[
PVR = \frac{D}{Dt} PV = \frac{1}{\rho} \left( \eta \cdot \nabla \dot{\theta} + \nabla \times F \cdot \nabla \theta \right)
\]

Direct diabatic PV modification

Potential vorticity (PV)

\[
PV = \frac{1}{\rho} \eta \cdot \nabla \theta
\]

- **tendencies of**
- **temperature & momentum**
- **vorticity**
- **gradient of potential temperature**
Methods: Diabatic PV modification

\[ \text{PVR} = \frac{D}{Dt} \text{PV} = \frac{1}{\rho} \left( \eta \cdot \nabla \dot{\theta} + \nabla \times F \cdot \nabla \theta \right) \]

Potential vorticity (PV)

\[ \text{PV} = \frac{1}{\rho} \eta \cdot \nabla \theta \]

Direct diabatic PV modification

e.g., Wernli and Davies (1997, QJRMS)
**Methods: Diabatic PV modification**

Direct diabatic PV modification

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PVR = \frac{D}{Dt} PV = \frac{1}{\rho} \left( \eta \cdot \nabla \hat{\theta} + \nabla \times F \cdot \nabla \theta \right)
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tendencies of temperature & momentum

Potential vorticity (PV)

\[
PV = \frac{1}{\rho} \eta \cdot \nabla \theta
\]

---

In NWP, parametrized diabatic processes affect dynamics, e.g.:

- Cloud latent heating/cooling
- Radiative transfer
- Turbulent mixing

---

e.g., Forster and Wirth (2000, JGR)
Methods: Diabatic PV modification

\[
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\]

Direct diabatic PV modification

Potential vorticity (PV)

\[
\text{PV} = \frac{1}{\rho} \eta \cdot \nabla \theta
\]

techniques of temperature & momentum

\[\begin{align*}
\text{Cloud latent heating/cooling} \\
\text{Radiative transfer} \\
\text{Turbulent mixing}
\end{align*}\]

\[\begin{align*}
\dot{\theta}_{\text{rad}} & \uparrow \downarrow \\
\dot{\theta}_{\text{cloud}} & \quad \quad \quad \text{Tropopause} \\
\end{align*}\]

e.g., Forster and Wirth (2000, JGR)
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tendencies of temperature & momentum

Direct diabatic PV modification

Potential vorticity (PV)

\[
PV = \frac{1}{\rho} \eta \cdot \nabla \theta
\]

vorticity

gradient of potential temperature

e.g., Shapiro (1976, MWR)
Methods: Diabatic PV modification

\[ \text{PVR} = \frac{D}{Dt} \text{PV} = \frac{1}{\rho} \left( \eta \cdot \nabla \dot{\theta} + \nabla \times F \cdot \nabla \theta \right) \]

Potential vorticity (PV)

\[ \text{PV} = \frac{1}{\rho} \eta \cdot \nabla \theta \]

Direct diabatic PV modification

Lagrangian accumulated PV along trajectories:
following Crezee et al. (2017, JAS)

\[ \text{APV}(x(t_0), t) = \int_t^{t_0} \text{PVR}(x(\tau), \tau) \, d\tau \] \rightarrow for each parametrized process

Reverse domain filling: Backward trajectories from each grid point
\rightarrow 3D-field of APV
Methods: Model simulations

Simulations with the global model of the ECMWF

- Horizontal resolution ~16 km
- Output of all instantaneous temperature & momentum tendencies from parametrized physics
Methods: Model simulations

Simulations with the global model of the ECMWF

- Horizontal resolution ~16 km
- Output of all instantaneous temperature & momentum tendencies from parametrized physics

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<th>Physical tendencies:</th>
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<td>Large-scale cloud</td>
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<td>Moist convection</td>
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<td>Long-/short-wave radiation</td>
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<td>Vertical diffusion and gravity wave drag</td>
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→ complete physical budget
Methods: Model simulations

Simulations with the global model of the ECMWF

- Horizontal resolution ~16 km
- Output of all instantaneous temperature & momentum tendencies from parametrized physics

> One case study simulation

> Three monthly simulations (DJF)

Physical tendencies:
- Large-scale cloud
- Moist convection
- Long-/short-wave radiation
- Vertical diffusion and gravity wave drag

> Complete physical budget
I. Near-tropopause PV modification: Case study

Spreitzer et al. (2019, JAS)
I. Near-tropopause PV modification: Case study

Spreitzer et al. (2019, JAS)
I. Near-tropopause PV modification: Case study

24-h total accumulated PV

Vertical cross section

PV decrease

PV increase

Isentropes
2 PVU
Wind speed (40, 55, 70 m s⁻¹)
I. Near-tropopause PV modification: Case study

24-h accumulated PV
I. Near-tropopause PV modification: Case study

24-h accumulated PV

Total

Clouds + convection

APV [PVU (24 h)^{-1}]
I. Near-tropopause PV modification: Case study

24-h accumulated PV

[Images of maps showing Total, Clouds + convection, and Radiation]
I. Near-tropopause PV modification: Case study

24-h accumulated PV

Total

Clouds + convection

Turbulence

Radiation

APV

[ PVU (24 h) ]

Pressure [hPa]

Pressure [hPa]

-30°W -20°W -10°W 0°W 10°

-30°W -20°W -10°W 0°W 10°
I. Near-tropopause PV modification: Case study

24-h accumulated PV

Total

Clouds + convection

Turbulence

Radiation
I. Near-tropopause PV modification: Case study

24-h accumulated PV
I. Near-tropopause PV modification: Case study

24-h accumulated PV

Total Clouds + convection Radiation

Vertical PV dipole

Consistent with Chagnon et al. (2013, QJRMS); Chagnon and Gray (2015, MWR)
I. Near-tropopause PV modification: Case study

24-h accumulated PV

Total

Clouds + convection

Warm conveyor belt outflow

APV [PVU (24 h)^{-1}]

-2.5
-1.5
-0.5
0.0
0.5
1.5
2.5
I. Near-tropopause PV modification: Case study

24-h accumulated PV

Total

Clouds + convection

Turbulence

Radiation

APV [PVU (24 h)^{-1}]
I. Near-tropopause PV modification: Case study

24-h accumulated PV

- **Total**
- **Clouds + convection**
- **Turbulence**
- **Radiation**

APV (PVU (24 h)^{-1})

Pressure [hPa]

-30°W  -20°W  -10°W  0°W  10°W
I. Near-tropopause PV modification: Case study

24-h accumulated PV
I. Near-tropopause PV modification: Case study

24-h accumulated PV

Turbulent mixing in shear zone

Isentropes

Wind speed

Turbulence
I. Near-tropopause PV modification: Case study

24-h accumulated PV

Turbulent mixing in shear zone

Isentropes
2 PVU
Wind speed
Low Richardson number
I. Near-tropopause PV modification: Case study

24-h accumulated PV

Turbulent mixing in shear zone

- Isentropes
- 2 PVU
- Wind speed
- Low Richardson number

Inst. PV tendency [PVU h^{-1}]
I. Near-tropopause PV modification: Case study

24-h accumulated PV

Turbulent mixing in shear zone

Evolution along trajectories

Total PV change

Turbulent mixing

- Isentropes
- 2 PVU
- Wind speed
- Low Richardson number

Inst. PV tendency \[\text{[PVU h}^{-1}\]\n
Evolution along trajectories
I. Near-tropopause PV modification: Case study

24-h accumulated PV

Turbulent mixing in shear zone

PV anomalies
cf. observational studies by
Staley (1960, JM)
Shapiro (1976, MWR)
I. Near-tropopause PV modification: Case study

24-h accumulated PV

Total

Turbulence

Turbulent mixing in shear zone

Isentropes

2 PVU

Wind speed

Low Richardson number

Inst. PV tendency [PVU h$^{-1}$]

-0.20 -0.15 -0.10 -0.05 0.05 0.10 0.15 0.20

PV anomalies
cf. observational studies by
Staley (1960, JM)
Shapiro (1976, MWR)
II. Systematic analysis: Jet streaks

- Three monthly simulations
- Identification of jet streaks
- Composite cross sections across jet streaks
II. Systematic analysis: Jet streaks

Composite cross section across jet streaks

Accumulated PV:

Turbulence

Cloud + Convection

Radiation

[Color scale with PVU (24 h)⁻¹ intervals]
II. Systematic analysis: Vertical profiles

- Three monthly simulations
- Identification of ridge/trough area
- Tropopause-relative vertical composites of accumulated PV (similar to Saffin et al. (2017; JGR))
II. Systematic analysis: Vertical profiles

Composite vertical profiles of accumulated PV

Troughs: PV dipole → tropopause sharpening
Consistent with
Chagnon et al. (2013, QJRMS);
Chagnon and Gray (2015, MWR); Saffin et al. (2017; JGR)
II. Systematic analysis: Vertical profiles

Composite vertical profiles
of accumulated PV

Troughs: PV dipole → tropopause sharpening
Consistent with
Chagnon et al. (2013, QJRMS);
Chagnon and Gray (2015, MWR); Saffin et al. (2017; JGR)

Ridges:
Turbulent PV erosion in lower stratosphere
→ weaker vert. PV gradient
Contradicting Saffin et al. (2017; JGR)
II. Systematic analysis: Vertical profiles

**Composite vertical profiles of accumulated PV: Residual**

- Troughs
- Ridges

PV budget not closed: \( \Delta PV = APV + RES \)

Large Residual → partly due to non-conservation of PV by the model

Consistent with Saffin et al. (2017; JGR)
II. Systematic analysis: Isentropic profiles

- Three monthly simulations
- Identification of waveguide on isentropes (2 PVU)
- Average isentropic profiles of APV

![Graph showing accumulated PV through isentropic distance from 2 PVU](image)

- Large-scale cloud
- Convection
- Radiation
- Turbulence
II. Systematic analysis: Isentropic profiles

- Three monthly simulations
- Identification of waveguide on isentropes (2 PVU)
- Isentropic profiles of APV

“WCB” outflow near the waveguide

Cloud outflow region: Cloud-diabatic heating of $> 5$ K in 24 h
“WCB” outflow near the waveguide

Figure 4.9: (a) Frequency of occurrence of cloud outflow and negative PV as a function of distance from the tropopause. (b) Contribution of individual processes to the PV budget at grid points with negative PV within 200 km of the waveguide. The percentages below each process indicate how often it was the dominant one. Medians are shown as orange lines, boxes indicate the interquartile range and whiskers show the 5th to 95th percentile. (c) PV distribution in cloud outflow regions (orange) and at all grid points (blue). (d) like (c) but for PV$_{APV}$ls$_{APV}$conv. Boxes in (c) and (d) indicate the interquartile range, medians are shown as horizontal black lines, means as green crosses. The whiskers show the range between the 5th and 95th percentile. Outliers are shown as coloured dots. Note that in (d) some values are outside the displayed range. The position of the boxes is slightly shifted along the x-axes such that the blue (orange) box is to the left (right) of the corresponding x-value.

Distance from tropopause

Cloud outflow grid points
All other grid points

Cloud outflow: Cloud-diabatic heating of > 5 K in 24 h

“WCB” outflow near the waveguide

Significantly lower PV in cloud outflow regions >> caused by direct cloud PV modification

Cloud outflow: Cloud-diabatic heating of > 5 K in 24 h
Summary

- Lagrangian PV-tendency diagnostics: PV budget and process attribution
  - >> Case study
  - >> Systematic analysis:
    - Mesoscale PV anomalies near jet streaks
    - Turbulent mixing in ridges relevant for vertical PV structure
    - PV dipole in troughs (clouds and radiation)
    - Direct PV modification due to clouds enhances negative PV anomaly in WCB outflows
Thank you