The Influence of Diabatic Heating on the Development of Two North American Jet Superposition Events

Andrew C. Winters
Department of Atmospheric and Oceanic Sciences (ATOC)
University of Colorado Boulder

2019 AGU Fall Meeting
San Francisco, CA
10 December 2019

This work was funded by an NSF-PRF (AGS-1624316)
Jet Superposition Conceptual Model

1a) Remote production of a cyclonic PV anomaly

Winters and Martin (2017)
Jet Superposition Conceptual Model

1a) Remote production of a cyclonic PV anomaly

Polar cyclonic PV anomalies:
Characterize a dynamical environment conducive to midlatitude cyclogenesis.

Winters and Martin (2017)
Jet Superposition Conceptual Model

1a) Remote production of a cyclonic PV anomaly

1b) Remote production of an anticyclonic PV anomaly

Winters and Martin (2017)
Jet Superposition Conceptual Model

Tropical anticyclonic PV anomalies:
Characterize a thermodynamic environment that features weak upper-tropospheric static stability.

Winters and Martin (2017)
Jet Superposition Conceptual Model

1a) Remote production of a cyclonic PV anomaly

1b) Remote production of an anticyclonic PV anomaly

Winters and Martin (2017)
Jet Superposition Conceptual Model

1a) Remote production of a cyclonic PV anomaly

1b) Remote production of an anticyclonic PV anomaly

Winters and Martin (2017)
Jet Superposition Conceptual Model

1a) Remote production of a cyclonic PV anomaly

2) Both PV anomalies are advected towards middle latitudes

1b) Remote production of an anticyclonic PV anomaly

Winters and Martin (2017)
Jet Superposition Conceptual Model

1a) Remote production of a cyclonic PV anomaly

2) Both PV anomalies are advected towards middle latitudes

1b) Remote production of an anticyclonic PV anomaly

SUPERPOSED

Winters and Martin (2017)
Jet Superposition Conceptual Model

1a) Remote production of a cyclonic PV anomaly

2) Both PV anomalies are advected towards middle latitudes

1b) Remote production of an anticyclonic PV anomaly

2-PVU Contour
Potential Temp.
Wind Speed

Winters and Martin (2017)
The processes that facilitate jet superposition vary based on the location at which the polar and subtropical jets superpose.

1a) Remote production of a cyclonic PV anomaly

2) Both PV anomalies are advected towards middle latitude

1b) Remote production of an anticyclonic PV anomaly

Winters and Martin (2017)
During polar dominant events, diabatic processes do not directly contribute to the formation of a steep, tropopause wall

Winters et al., in revision
During subtropical dominant events, diabatic processes directly contribute to the formation of a steep, tropopause wall.

Winters et al., in revision
Jet Superposition Conceptual Model

If latent heating is omitted during subtropical dominant events, do the polar and subtropical jets still superpose?
Recent Subtropical Dominant Jet Superposition Events
The December 2013 case featured:

- A tornado outbreak in the southeastern U.S.
- Up to 1 in. of total ice accumulation near Toronto, ON
- Maximum jet wind speeds in excess of 110 m s\(^{-1}\)
The February 2019 case featured:
• Up to 1 foot of snow accumulation in the northern Plains
• An Atlantic cyclone with a central pressure below 944 hPa
• Maximum jet wind speeds in excess of 110 m s\(^{-1}\)
Recent Subtropical Dominant Superpositions

1200 UTC 22 December 2013

0600 UTC 20 February 2019

Mean Sea Level Pressure

500-hPa Ascent (Pa s⁻¹)
WRF Simulations:
December 2013 Case
WRF Simulations

- 2 single-domain simulations ("FULL", "NOLH")
- WRF Version 3.9.1 (Skamarock et al. 2008)
- 6-day run time initialized at 0000 UTC 19 December 2013
- 90-second timestep
- 30-km horizontal resolution + 50 vertical levels (model top=50 hPa)
- Initial and boundary conditions provided by the GFS Analysis
- Thompson microphysics
- Kain-Fritsch cumulus parameterization
- MYJ PBL scheme
- RRTMG radiation scheme
- Noah land-surface model
- **No latent heating from microphysics in “NOLH” simulation**
WRF Simulations

1200 UTC 22 December 2013

“FULL”

“NOLH”

- Maximum 250-hPa wind speed is ~40 m s\(^{-1}\) weaker in “NOLH”
- Surface cyclone over the southern Great Lakes is weaker and located farther west in “NOLH”
The “FULL” simulation features a stronger lower-tropospheric temperature gradient than the “NOLH” simulation.
The “FULL” simulation features a stronger lower-tropospheric temperature gradient than the “NOLH” simulation.

The “FULL” simulation features larger geopotential heights and stronger flow curvature within the eastern North American ridge.
In the absence of latent heating, do the polar and subtropical jets become superposed?
• In the absence of latent heating, do the polar and subtropical jets become superposed?
WRF Simulations

1200 UTC 22 December 2013

“FULL”

“NOLH”

2 PVU – “FULL”

2 PVU – “NOLH”

Potential Temp.
The polar and subtropical jets do not superpose in the “NOLH” simulation.
WRF Simulations

1200 UTC 22 December 2013

- The slope of the dynamic tropopause is markedly shallower in the “NOLH” simulation

(Wind Speed (m s⁻¹))
Strong negative PV advection by the ageostrophic wind is diagnosed at the level of the dynamic tropopause on the western flank of the upper-tropospheric ridge in the “FULL” simulation.
WRF Simulations

0600 UTC 22 December 2013

“FULL”: 250-hPa PV Advection by Nondiv. Age. Wind

“NOLH”: 250-hPa PV Advection by Nondiv. Age. Wind

- Negative PV advection by the nondivergent component of the ageostrophic wind accounts for a large fraction of the PV advection by the full ageostrophic wind in the ”FULL” simulation.
WRF Simulations

0600 UTC 22 December 2013

“FULL”: 250-hPa PV Advection by Div. Age. Wind

“NOLH”: 250-hPa PV Advection by Div. Age. Wind

- 2 PVU
- 250-hPa Wind Speed

[Map showing PV advection and wind speed]
WRF Simulations

0600 UTC 22 December 2013

“FULL”: 250-hPa PV Advection by Div. Age. Wind

“NOLH”: 250-hPa PV Advection by Div. Age. Wind

PV Advection (10^{-4} PVU s^{-1})

- 2 PVU
- 250-hPa Wind Speed
• Negative PV advection by the divergent component of the ageostrophic wind is substantial on the western flank of the upper-tropospheric ridge in the “FULL” simulation.
Summary

• Latent heating plays an important role during the development of “subtropical dominant” jet superposition events.

• The omission of latent heating during a WRF simulation (“NOLH”) of a subtropical dominant jet superposition event from December 2013 results in a double-jet structure.

• The presence of strong negative PV advection by the ageostrophic wind at the level of the dynamic tropopause facilitates the formation of a jet superposition in the “FULL” simulation.

• The results from this study have important implications for the subsequent evolution of the downstream large-scale flow pattern over the North Atlantic.
Summary

• Latent heating plays an important role during the development of “subtropical dominant” jet superposition events

• The omission of latent heating during a WRF simulation (“NOLH”) of a subtropical dominant jet superposition event from December 2013 results in a double-jet structure

• The presence of strong negative PV advection by the ageostrophic wind at the level of the dynamic tropopause facilitates the formation of a jet superposition in the “FULL” simulation

• The results from this study have important implications for the subsequent evolution of the downstream large-scale flow pattern over the North Atlantic

Questions: andrew.c.winters@colorado.edu
Supplementary Slides
References


February 2019 Case
February 2019 Case

0600 UTC 20 February 2019

“FULL”

“NOLH”

- Maximum 250-hPa wind speed is ~10–20 m s\(^{-1}\) weaker in “NOLH”
- Surface cyclone over the North Atlantic is ~40 hPa weaker in “NOLH”
WRF Simulations

1200 UTC 22 December 2013

“FULL” – 250-hPa Nondivergent Age. Wind

“A substantial fraction of the difference in jet wind speeds between the two simulations can be attributed to the nondivergent component of the ageostrophic wind

“NOLH”: 250-hPa Nondivergent Age. Wind

250-hPa Height: “FULL”

250-hPa Height: “NOLH”
WRF Simulations

1200 UTC 22 December 2013

• The difference in the slope of the tropopause between the two simulations is due to marked differences in negative PV advection by the ageostrophic wind at the level of the dynamic tropopause
Composite Characteristics
Jet Superposition Event Characteristics

- All events (N=326)
- Polar dominant (N=80)
- Subtropical dominant (N=129)
- Hybrid events (N=117)

Number of Cases

- November: 40
- December: 30
- January: 20
- February: 10
- March: 20

Graph showing the number of cases for each month with different categories.
Jet Superposition Event Composites

Legend:
- **L** Surface Cyclone
- **H** Surface Anticyclone
- 300-hPa Geo. Warm-air Advection
- 300-hPa Geo. Cold-air Advection
- Precipitable Water Anomalies
- 250-hPa Jet Streak
- Polar Cyclonic PV Anomaly
- Tropical Anticyclonic PV Anomaly
- Direction of Moisture Transport
- Movement of Polar Cyclonic PV Anomaly
- Movement of Tropical Anticyclonic PV Anomaly
Downstream Consequences

North Atlantic Oscillation: 5 Days After Jet Superposition

- All events (N=326)
- Polar dominant (N=80)
- Subtropical dominant (N=129)
- Hybrid events (N=117)

<table>
<thead>
<tr>
<th>Condition</th>
<th>NAO Δ</th>
<th>Ave. Polar Dominant NAO Δ</th>
<th>Ave. Subtropical Dominant NAO Δ</th>
<th>Ave. Hybrid NAO Δ</th>
</tr>
</thead>
<tbody>
<tr>
<td>NAO Index &gt; 0.5</td>
<td>+0.11</td>
<td>+0.15</td>
<td>+0.13</td>
<td>+0.07</td>
</tr>
<tr>
<td>NAO Index &lt; -0.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Neutral</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Background Material
Background

Mean Meridional Cross-Section of $\theta$

- **Polar Tropopause**
- **Subtropical Tropopause**
- **Tropical Tropopause**
- **Polar Frontal Zone**

Modified from Defant and Taba (1957)
Maps of tropopause pressure help to identify the location of the jets.

While each jet occupies its own climatological latitude band, substantial meanders are common.

Occasionally, the latitudinal separation between the jets can vanish resulting in a vertical jet superposition.

Modified from Defant and Taba (1957)
The pole-to-equator baroclinicity is combined into a much narrower zone of contrast in the vicinity of a jet superposition. Intensified frontal structure is often attended by a strengthening of the superposed jet’s transverse circulation.
Background

Christenson et al. (2017) highlight three locations that experience the greatest frequency of jet superpositions:

1) Western Pacific

2) North America

3) Northern Africa

Climatological frequency of Northern Hemisphere jet superposition events per cold season (Nov–Mar) 1960–2010

Christenson et al. (2017)
Jet Superpositions and High-Impact Weather

Jet superpositions can be an element of high-impact weather events

1–3 May 2010 Nashville Flood
- Jet superposition enhanced the poleward moisture transport via its ageostrophic circulation (Winters and Martin 2014; 2016).

18–20 December 2009 Mid-Atlantic Blizzard
- Jet superposition was associated with a rapidly deepening East Coast cyclone (Winters and Martin 2016; 2017).

26 October 2010: Explosive Cyclogenesis Event
- Jet superposition over the West Pacific preceded the development of an intense Midwest U.S. cyclone.

25–28 April 2011 Tornado Outbreak
- Jet superposition occurred over the West Pacific prior to the outbreak (Knupp et al. 2014; Christenson and Martin 2012).
Ageostrophic Transverse Jet Circulations

Traditional four-quadrant model

Geo. cold-air advection (CAA) along the jet axis promotes **subsidence** through the jet core

Geo. warm-air advection (WAA) along the jet axis promotes **ascent** through the jet core

Lang and Martin (2012)
Insight into how the tropopause can be restructured from a PV perspective can be found by consulting Wandishin et al. (2000)

Two processes can account for "foldogenesis":

1) **Differential vertical motions** can vertically steepen the tropopause.

2) **Convergence or a vertical shear** can produce a differential horizontal advection of the tropopause surface.

These same mechanisms are also likely to play an important role in superpositions.
Jet Identification
1. Determined the mean position of the 2-PVU contour on the 320-K and 350-K surfaces at each analysis time in the CFSR.

2. Compared the position of the jet superposition centroid at the start of each event against the climatological position of the 2-PVU contour.

• Polar Dominant
1. Determined the mean position of the 2-PVU contour on the 320-K and 350-K surfaces at each analysis time in the CFSR.

2. Compared the position of the jet superposition centroid at the start of each event against the climatological position of the 2-PVU contour.

- Polar Dominant
- Subtropical Dominant
1. Determined the mean position of the 2-PVU contour on the 320-K and 350-K surfaces at each analysis time in the CFSR.

2. Compared the position of the jet superposition centroid at the start of each event against the climatological position of the 2-PVU contour.

- Polar Dominant
- Subtropical Dominant
- Hybrid
Isolated grid points over North America in the CFSR (Saha et al. 2014) characterized by polar and subtropical jets during Nov–Mar 1979–2010.

Jet Superposition Event Identification

0000 UTC 27 April 2010

250-hPa wind speed

Isotachs
Potential Temp.
1,2,3-PVU contours

Winters and Martin (2014, 2016, 2017); Christenson et al. (2017); Handlos and Martin (2016)
Isolated grid points over North America in the CFSR (Saha et al. 2014) characterized by polar and subtropical jets during Nov–Mar 1979–2010.

Jet Superposition Event Identification

0000 UTC 27 April 2010

Isotachs
Potential Temp.
1,2,3-PVU contours

Strong horizontal PV gradient within the 1–3-PVU channel in the 315–330-K isentropic layer

Winters and Martin (2014, 2016, 2017); Christenson et al. (2017); Handlos and Martin (2016)
Jet Superposition Event Identification

Isolated grid points over North America in the CFSR (Saha et al. 2014) characterized by polar and subtropical jets during Nov–Mar 1979–2010.

0000 UTC 27 April 2010

Integrated 400–100-hPa wind speed must exceed 30 m s\(^{-1}\)

Isotachs
Potential Temp.
1,2,3-PVU contours

Winters and Martin (2014, 2016, 2017); Christenson et al. (2017); Handlos and Martin (2016)
Jet Superposition Event Identification

Isolated grid points over North America in the CFSR (Saha et al. 2014) characterized by polar and subtropical jets during Nov–Mar 1979–2010.
Isolated grid points over North America in the CFSR (Saha et al. 2014) characterized by polar and subtropical jets during Nov–Mar 1979–2010.

Jet Superposition Event Identification

0000 UTC 27 April 2010

250-hPa wind speed

Strong horizontal PV gradient within the 1–3-PVU channel in the 340–355-K isentropic layer

Isotachs Potential Temp. 1,2,3-PVU contours

Winters and Martin (2014, 2016, 2017); Christenson et al. (2017); Handlos and Martin (2016)
Jet Superposition Event Identification

Isolated grid points over North America in the CFSR (Saha et al. 2014) characterized by polar and subtropical jets during Nov–Mar 1979–2010.

250-hPa wind speed

Isotachs
Potential Temp.
1,2,3-PVU contours

Integrated 400–100-hPa wind speed must exceed 30 m s⁻¹

Winters and Martin (2014, 2016, 2017); Christenson et al. (2017); Handlos and Martin (2016)
Jet Superposition Event Identification

Isolated grid points over North America in the CFSR (Saha et al. 2014) characterized by polar and subtropical jets during Nov–Mar 1979–2010.

250-hPa wind speed

Isotachs
Potential Temp.
1,2,3-PVU contours

Winters and Martin (2014, 2016, 2017); Christenson et al. (2017); Handlos and Martin (2016)
Jet Superposition Event Identification

Isolated grid points over North America in the CFSR (Saha et al. 2014) characterized by a jet superposition during Nov–Mar 1979–2010.

0000 UTC 24 October 2010

Isotachs
Potential Temp.
1,2,3-PVU contours

Winters and Martin (2014, 2016, 2017); Christenson et al. (2017); Handlos and Martin (2016)
Jet Superposition Event Identification

0000 UTC 24 October 2010

Isolated grid points over North America in the CFSR (Saha et al. 2014) characterized by a jet superposition during Nov–Mar 1979–2010.

Criteria for both the polar and subtropical jets satisfied within the same grid column

Isotachs
Potential Temp.
1,2,3-PVU contours

Winters and Martin (2014, 2016, 2017); Christenson et al. (2017); Handlos and Martin (2016)
Jet Superposition Event Identification

Isolated grid points over North America in the CFSR (Saha et al. 2014) characterized by a jet superposition during Nov–Mar 1979–2010.

0000 UTC 24 October 2010

Criteria for both the polar and subtropical jets satisfied within the same grid column

250-hPa wind speed

Isotachs
Potential Temp.
1,2,3-PVU contours

Winters and Martin (2014, 2016, 2017); Christenson et al. (2017); Handlos and Martin (2016)
Figure 2. (a) Cold season average of zonally averaged $\Delta y$ (km) for 5-K isentropic layers ranging from 300–305 to 365–370 K. The 315–330- and 340–355-K layers are highlighted in light gray shading. (b) The average frequency of occurrence of grid points with a maximum wind speed value within the 5-K isentropic layers along the abscissa per cold season. The 315–330- and 340–355-K layers are shaded in blue and red, respectively.
Jet Superposition Event Identification

90th percentile for superposition grid points at a time: 18 grid points
Jet Superposition Event Identification

Calculated the centroid of each jet superposition based on all valid grid points at a particular analysis time.

To calculate the centroid, there must exist a group of 18 superposition grid points, of which no superposition grid point is >1000 km away from another superposition grid point.

---

Sample Jet Superposition Centroid Calculation

- Green 'X': Used for calculation
- Red 'X': Not used for calculation
- Yellow circle: Jet superposition centroid

Distances marked as 'd >1000 km' indicate points not used for calculation.