Antecedent Environments Conducive to North American Polar/Subtropical Jet Superposition Events

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Superposition represents the “merger” of two separate, rapidly-moving air streams
Background

Modified from Defant and Taba (1957)

**Mean Meridional Cross-Section of \( \theta \)**

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

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Maps of tropopause pressure help to identify the location of the jets.

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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.
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
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1) Western Pacific
2) North America
3) Northern Africa
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).

Moore et al. (2012)
Jet Superpositions and High-Impact Weather

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• Jet superposition over the West Pacific preceded the development of an intense Midwest U.S. cyclone.
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How do these structures develop?
Jet Superposition Conceptual Model

1a) Remote production of a cyclonic PV anomaly

Winters and Martin (2017)
Jet Superposition Conceptual Model

Polar cyclonic PV anomalies:

1) Often referred to as coherent tropopause disturbances (Pyle et al. 2004) or tropopause polar vortices (Cavallo and Hakim 2010).
2) Typify 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)
1) Typify a thermodynamic environment characterized by weak upper-tropospheric static stability.

2) Atmospheric rivers often form within the poleward-directed branch of their circulation.
Jet Superposition Conceptual Model

1a) Remote production of a cyclonic PV anomaly

1b) Remote production of an anticyclonic PV anomaly

2) Both PV anomalies are advected towards middle latitudes

Winters and Martin (2017)
Jet Superposition Conceptual Model

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Jet Superposition Conceptual Model

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2) Both PV anomalies are advected towards middle latitudes

The relative importance of these PV anomalies is highly variable between jet superposition events

Winters and Martin (2017)
Jet Superposition Conceptual Model

**GOAL:** To determine the characteristic types of interaction that exist between upper-tropospheric PV anomalies during jet superposition events

1a) Remote production of a cyclonic PV anomaly

1b) Remote production of an anticyclonic PV anomaly

2) Both PV anomalies are advected towards middle latitudes

Winters and Martin (2017)
Jet Superposition Event Identification and Classification
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.

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

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

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

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Jet Superposition Event Identification

0000 UTC 27 April 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

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

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

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Potential Temp.
1,2,3-PVU contours

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0000 UTC 24 October 2010

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Potential Temp.
1,2,3-PVU contours

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

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Potential Temp.
1,2,3-PVU contours

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2. Retained analysis times that rank in the top 10% in terms the number of grid points characterized by a jet superposition.

3. Filtered retained analysis times to group together jet superpositions that are < 30 h and < 1500 km apart.
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.
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Jet Superposition Event Classification

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

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.

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• Polar Dominant
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- 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
Climatological Characteristics of Jet Superposition Events
Jet Superposition Event Characteristics

Number of Cases

- All events (N=326)
- Polar dominant (N=80)
- Subtropical dominant (N=129)
- Hybrid events (N=117)
Jet Superposition Event Characteristics

Number of Cases

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Bar chart showing the number of cases for each month from November to March.
Jet Superposition Event Characteristics

Number of Cases

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- Polar dominant (N=80)
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Jet Superposition Event Characteristics

Frequency of Polar Dominant Jet Superposition Events

Legend

- Avg. Location of Superposition

N = 80

Number of events
Jet Superposition Event Characteristics

Frequency of Hybrid Jet Superposition Events

N = 117

Legend

- Avg. Location of Superposition
Frequency of Subtropical Dominant Jet Superposition Events

Legend

- Avg. Location of Superposition

Number of events

N = 129
Jet Superposition Event Characteristics

Frequency of Subtropical Dominant Jet Superposition Events

N = 129

West: N = 53

East: N = 76

Legend

Avg. Location of Superposition
Jet Superposition Event Composites:

Polar Dominant vs. East Subtropical Dominant
Polar Dominant Jet Superposition Events

2 Days Prior to Jet Superposition

N=80
Polar Dominant Jet Superposition Events

1 Day Prior to Jet Superposition

N=80
Polar Dominant Jet Superposition Events

0 Days Prior to Jet Superposition

Average Location of Superposition

N=80
Polar Dominant Jet Superposition Events

0 Days Prior to Jet Superposition

Average Location of Superposition

N=80
Polar Dominant Jet Superposition Events

0 Days Prior to Jet Superposition

Average Location of Superposition

N=80
Polar Dominant Jet Superposition Events

12 Hours Prior to Jet Superposition

Legend
- 1.5-, 2-, 3-PVU
- $\theta$
- + pert. PV
- – pert. PV

$\omega$ wind speed
Polar Dominant Jet Superposition Events

12 Hours Prior to Jet Superposition

Strong cyclonic PV anomaly poleward of the developing jet superposition

Legend
- 1.5-,2-, 3-PVU
- $\theta$
- + pert. PV
- – pert. PV

Wind into page
Wind out of page
Polar Dominant Jet Superposition Events

**12 Hours Prior to Jet Superposition**

Subsidence directly beneath and poleward of the jet core

Legend

- 1.5-, 2-, 3-PVU
- \( \theta \)
- + pert. PV
- – pert. PV
Polar Dominant Jet Superposition Events

12 Hours Prior to Jet Superposition

Subsidence acts to steepen the tropopause

Legend

- 1.5-, 2-, 3-PVU
- θ
- + PV adv.
- − PV adv.
Polar Dominant Jet Superposition Events

0 Hours Prior to Jet Superposition

Subsidence acts to steepen the tropopause
**Polar Dominant Jet Superposition Events**

**0 Hours Prior to Jet Superposition**

- **Cyclonic PV anomaly intensifies poleward of the jet superposition**

**Legend**
- **1.5-, 2-, 3-PVU**
- **θ**
- **+ pert. PV**
- **– pert. PV**

**Wind**
- ✖️ Wind into page
- 🔍 Wind out of page
E. Subtropical Dominant Jet Superposition Events

2 Days Prior to Jet Superposition

N=76
E. Subtropical Dominant Jet Superposition Events

1 Day Prior to Jet Superposition

N=76
E. Subtropical Dominant Jet Superposition Events

250-hPa Jet, Geo. Height, & Geo. Height Anom., & 300-hPa Geo. Temp Adv.

0 Days Prior to Jet Superposition

Average

Location of Superposition

N=76
E. Subtropical Dominant Jet Superposition Events

0 Days Prior to Jet Superposition

Average

Location of Superposition

N=76
E. Subtropical Dominant Jet Superposition Events

12 Hours Prior to Jet Superposition
E. Subtropical Dominant Jet Superposition Events

12 Hours Prior to Jet Superposition

Juxtaposition of cyclonic and anticyclonic PV anomalies near the tropopause.

Legend
- 1.5-, 2-, 3-PVU
- $\theta$
- + pert. PV
- – pert. PV

Wind into page
Wind out of page
E. Subtropical Dominant Jet Superposition Events

12 Hours Prior to Jet Superposition

Ascent directly beneath the jet core

Legend
- 1.5-, 2-, 3-PVU
- $\theta$
- + pert. PV
- – pert. PV

$\omega$ wind speed

C C'

Legend
- 1.5-, 2-, 3-PVU
- $\theta$
- + pert. PV
- – pert. PV

C C'

Ascent directly beneath the jet core
E. Subtropical Dominant Jet Superposition Events

12 Hours Prior to Jet Superposition

Ascent and the diabatic destruction of PV act to steepen the tropopause

Legend
- 1.5-, 2-, 3-PVU
- \( \theta \)
- + PV adv.
- - PV adv.
E. Subtropical Dominant Jet Superposition Events

Subsidence develops beneath the jet core and acts to further steepen the tropopause.
E. Subtropical Dominant Jet Superposition Events

The intensification of both PV anomalies is associated with an acceleration of jet wind speeds.
Jet Superposition Event Composites

- MSLP Anomaly < $-1\sigma$
- 300-hPa Geo. CAA
- OLR Anomaly < $-10$ W m$^{-2}$
- Prcp. Water Anomaly > 10 mm

Polar Dominant
- E. Subtropical Dominant
Jet Superposition Event Composites

Surface cyclogenesis and precipitation processes lead superposition
Jet Superposition Event Composites

Surface cyclogenesis and precipitation processes coincide with superposition
Jet Superposition Event Composites

Forcing for QG descent peaks at the time of superposition for both event types
The Consistent Role of Descent

Descent within the jet-entrance region is a common element among the jet superposition event composites.
The Consistent Role of Descent

The consistent role of descent motivates further investigation of the dynamical structures responsible for the observed descent.
The Consistent Role of Descent

The descent characterizing each jet superposition event composite is examined further by isolating quasi-geostrophic (QG) PV anomalies in the vicinity of the jet superposition.
The Consistent Role of Descent

Polar Dominant Events

East Subtropical Dominant Events

Polar Cyclonic QGPV Anomalies

Avg. Location of Superposition
The Consistent Role of Descent

Polar Dominant Events

East Subtropical Dominant Events

- Polar Cyclonic QGPV Anomalies
- Tropical Anticyclonic QGPV Anomalies

Avg. Location of Superposition
The Consistent Role of Descent

Polar Dominant Events

East Subtropical Dominant Events

- Polar Cyclonic QGPV Anomalies
- Tropical Anticyclonic QGPV Anomalies

Avg. Location of Superposition

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
The Consistent Role of Descent

Polar Dominant Events

East Subtropical Dominant Events

0 h  250 hPa

0 h  300 hPa

- Polar Cyclonic QGPV Anomalies
- Tropical Anticyclonic QGPV Anomalies
- Residual Upper-Tropospheric QGPV Anomalies

Avg. Location of Superposition
The Consistent Role of Descent

Polar Dominant Events

East Subtropical Dominant Events

- Polar Cyclonic QGPV Anomalies
- Tropical Anticyclonic QGPV Anomalies
- Residual Upper-Tropospheric QGPV Anomalies
- Lower-Tropospheric QGPV Anomalies
- Avg. Location of Superposition
Each category of QGPV anomalies ($q'$) is inverted to determine its associated geopotential ($\phi'$) field:

\[ q' = \frac{1}{f_0} \nabla^2 \phi' + f_0 \frac{\partial}{\partial p} \left( \frac{1}{\sigma_r} \frac{\partial \phi'}{\partial p} \right) \quad \text{where} \quad f_0 = \text{Reference Coriolis Parameter} \]
\[ \sigma_r = \text{Static Stability of the U.S. Std. Atm.} \]
The Consistent Role of Descent

Each category of QGPV anomalies ($q'$) is inverted to determine its associated geopotential ($\phi'$) field:

$$ q' = \frac{1}{f_0} \nabla^2 \phi' + f_0 \frac{\partial}{\partial p} \left( \frac{1}{\sigma_r} \frac{\partial \phi'}{\partial p} \right) $$

where $f_0 = \text{Reference Coriolis Parameter}$

$\sigma_r = \text{Static Stability of the U.S. Std. Atm.}$

The geopotential fields and the composite temperature ($T$) field are used to determine the QG vertical motion ($\omega$) associated with each category of QGPV:

$$ \sigma_r \nabla^2 \omega + f_0^2 \frac{\partial^2 \omega}{\partial p^2} = -2 \nabla \cdot \mathbf{Q} $$

where

$$ \mathbf{V}_g' = -\left(1/f_0\right)\left(\hat{k} \times \nabla \phi'\right) $$

$$ \mathbf{Q} = -\frac{R}{p} \left[ \left( \frac{\partial \mathbf{V}_g'}{\partial x} \cdot \nabla T \right), \left( \frac{\partial \mathbf{V}_g'}{\partial y} \cdot \nabla T \right) \right] $$
The Consistent Role of Descent

Polar Dominant Events

East Subtropical Dominant Events

0 h

500 hPa

0 h

500 hPa

Polar Cyclonic QGPV Anomalies
Tropical Anticyclonic QGPV Anomalies
Residual Upper-Tropospheric QGPV Anomalies
Lower-Tropospheric QGPV Anomalies
Avg. Location of Superposition
The Consistent Role of Descent

Descent is primarily associated with polar cyclonic QGPV anomalies.
The Consistent Role of Descent

Polar cyclonic QGPV anomalies play a critical role during jet superpositions.
Summary

1a) Remote production of a cyclonic PV anomaly

1b) Remote production of an anticyclonic PV anomaly

Polar Dominant Events:
Summary

**Polar Dominant Events:**

1) Anticyclonic wave breaking event amplifies the flow over North America
2) QG descent beneath the jet core facilitates jet superposition
3) Downstream precipitation slows the propagation of the upper-level trough
1a) Remote production of a cyclonic PV anomaly

1b) Remote production of an anticyclonic PV anomaly

East Subtropical Dominant Events:
Summary

East Subtropical Dominant Events:
1) Antecedent precipitation and southerly flow amplify ridge over eastern North America
2) Arrival of upper-level trough is associated with geostrophic CAA at the time of jet superposition
3) QG descent beneath the jet core completes jet superposition
Future Work

• Examine the impact that each type of jet superposition event has on the evolution of the downstream large-scale flow pattern.

• Decipher the relationship between each type of jet superposition and the development of high-impact weather.

• Utilize numerical simulations of jet superposition events to examine the sensitivity of jet superposition to diabatic processes.

• Examine the frequency and characteristics of jet superposition events within future climate scenarios.

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Supplementary Slides
References


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.

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Sample Jet Superposition Centroid Calculation

- Used for calculation
- Not used for calculation
- Jet superposition centroid

\[ d > 1000 \text{ km} \]
Jet Superposition Event Identification

Frequency of East Subtropical Dominant Jet Superposition Events

Legend

- Centroid of all events
- Composite movement of superposition

N = 76
Jet Superposition Event Identification

Frequency of West Subtropical Dominant Jet Superposition Events

N = 53

Legend
- Centroid of all events
- Composite movement of superposition
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)

### All Events
ΔNAO
+0.11

### Ave. Polar Dominant ΔNAO
+0.15

### Ave. Subtropical Dominant ΔNAO
+0.13

### Ave. Hybrid ΔNAO
+0.07
Polar Dominant Jet Superposition Events

3 Days Prior to Jet Superposition

N=80
E. Subtropical Dominant Jet Superposition Events

3 Days Prior to Jet Superposition

N=76
Jet Superposition Conceptual Model

Dynamic Tropopause Potential Temperature

Pyle et al. (2004)
Jet Superposition Conceptual Model

Dynamic Tropopause
Potential Temperature
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.
FIG. 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.