Linkages Between the Equatorward Transport of Tropopause Polar Vortices and the Development of Cold Air Outbreaks

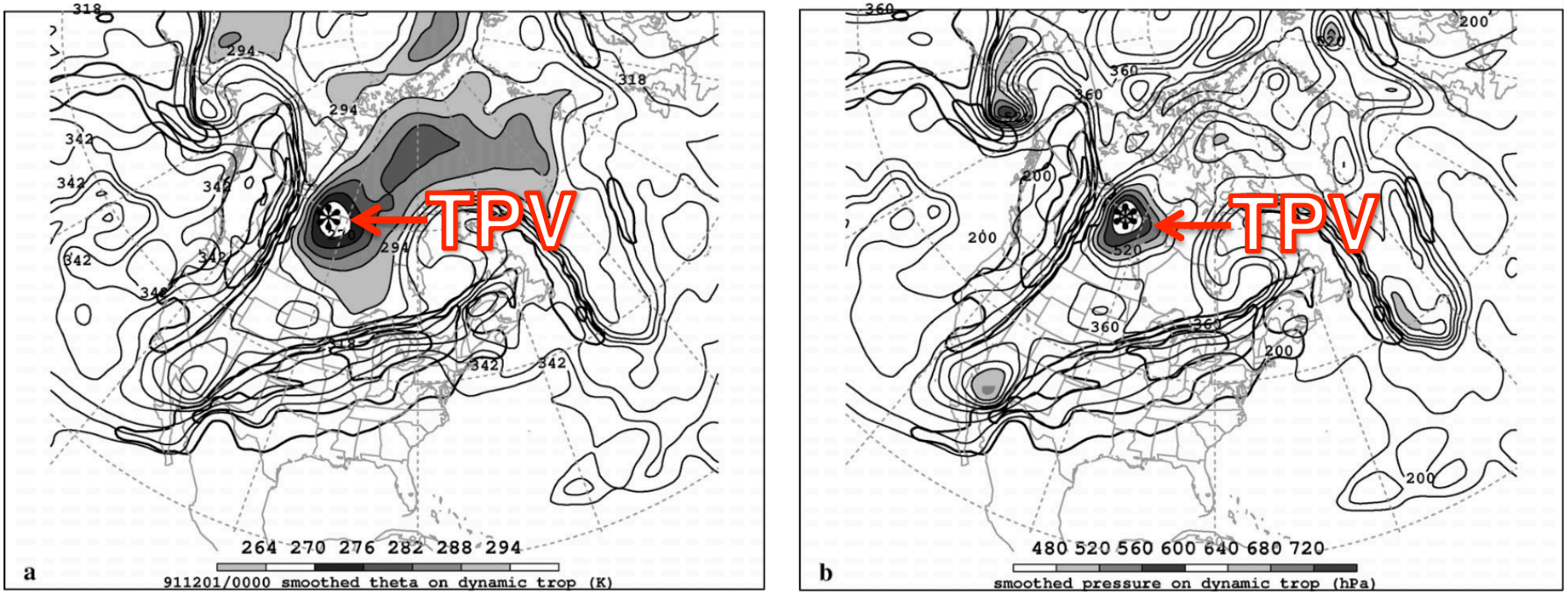
Kevin A. Biernat, Daniel Keyser, and Lance F. Bosart
Department of Atmospheric and Environmental Sciences
University at Albany, SUNY

28th Conference on Weather Analysis and Forecasting
24th Conference on Numerical Weather Prediction
23 January 2017
Seattle, WA

Research support provided by NSF Grant AGS-1355960

What are Tropopause Polar Vortices (TPVs)?

- TPVs are defined as tropopause-based vortices of high-latitude origin and are material features (Pyle et al. 2004; Cavallo and Hakim 2009, 2010)



(left) Dynamic tropopause (DT) wind speed (every 15 m s^{-1} starting at 50 m s^{-1}, thick contours) and DT potential temperature (K, thin contours and shading) on 1.5-PVU surface valid 0000 UTC 1 Dec 1991; **(right)** same as left except DT pressure (hPa, thin contours and shading).
Adapted from Fig. 11 in Pyle et al. (2004).

Motivation

- TPVs may interact with and strengthen midlatitude jet streams, and act as precursors to intense midlatitude cyclones

Motivation

- TPVs may interact with and strengthen midlatitude jet streams, and act as precursors to intense midlatitude cyclones

- Arctic air surges that accompany TPVs as they are transported into middle latitudes may lead to widespread cold air outbreaks (CAOs)

Motivation

- TPVs may interact with and strengthen midlatitude jet streams, and act as precursors to intense midlatitude cyclones

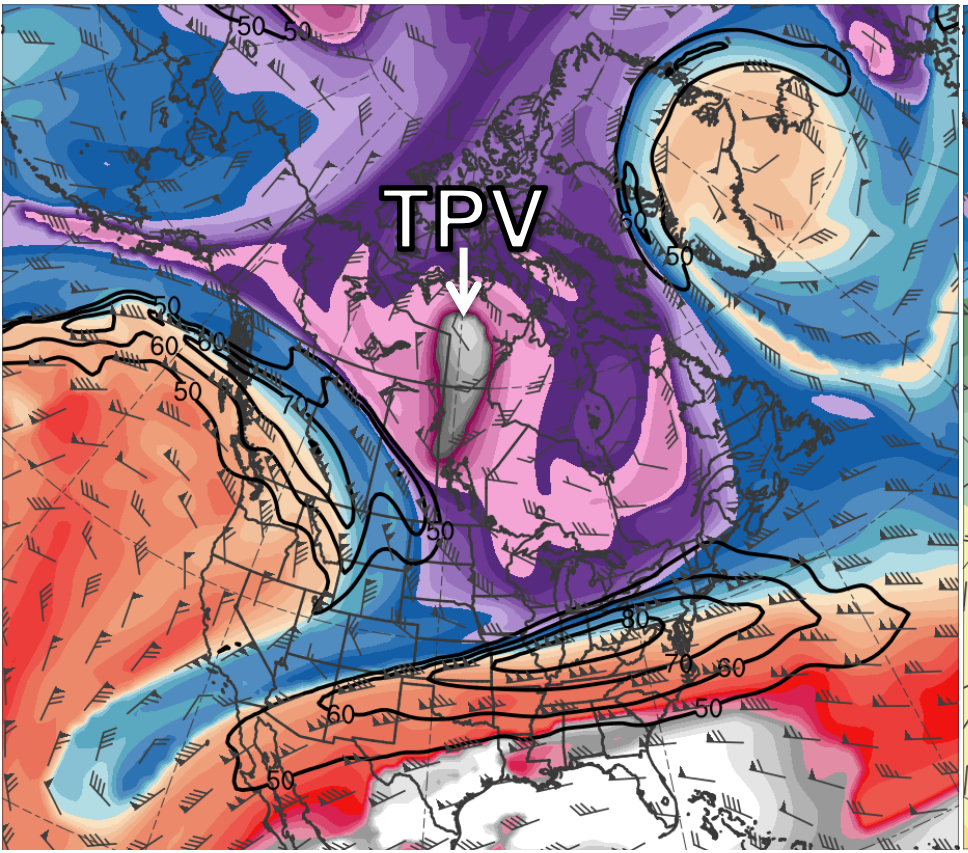
- Arctic air surges that accompany TPVs as they are transported into middle latitudes may lead to widespread cold air outbreaks (CAOs)

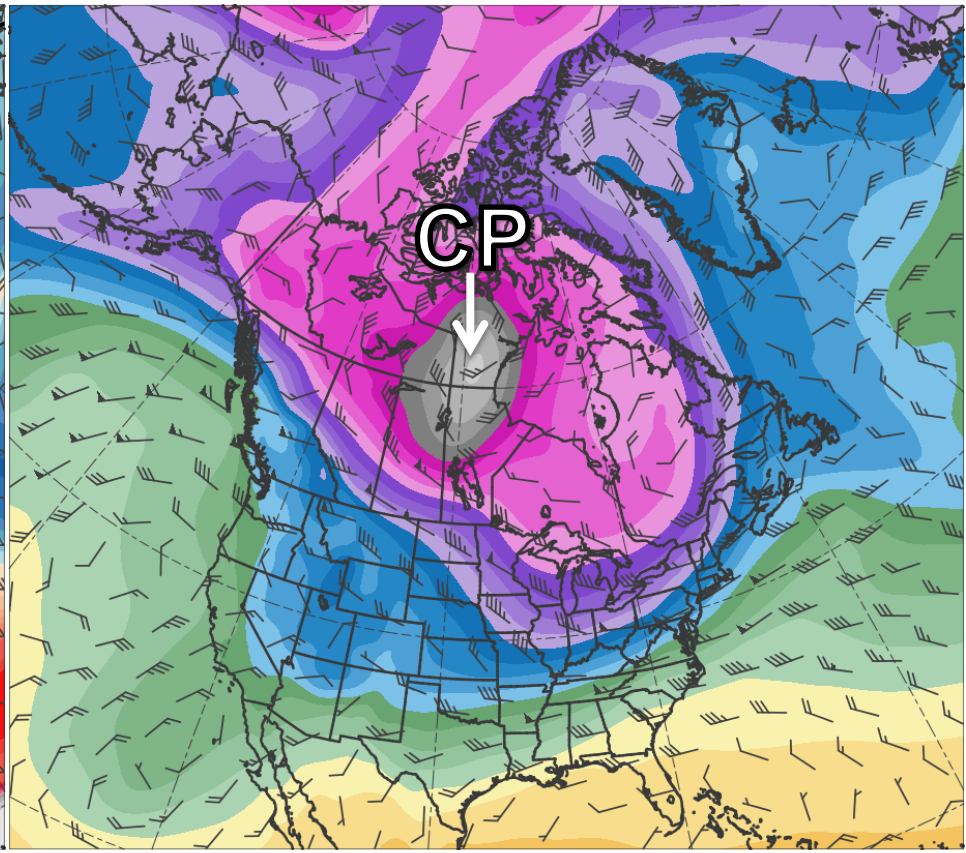
- CAOs may lead to significant socioeconomic impacts, posing a hazard to society, agriculture, and infrastructure

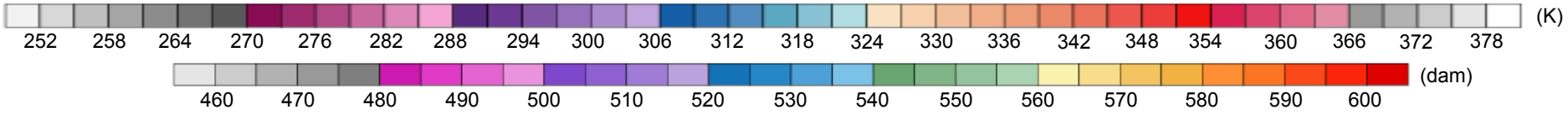
Example: 9–12 Jan 1982 CAO

0000 UTC 8 Jan 1982

Data Source: ERA-Interim







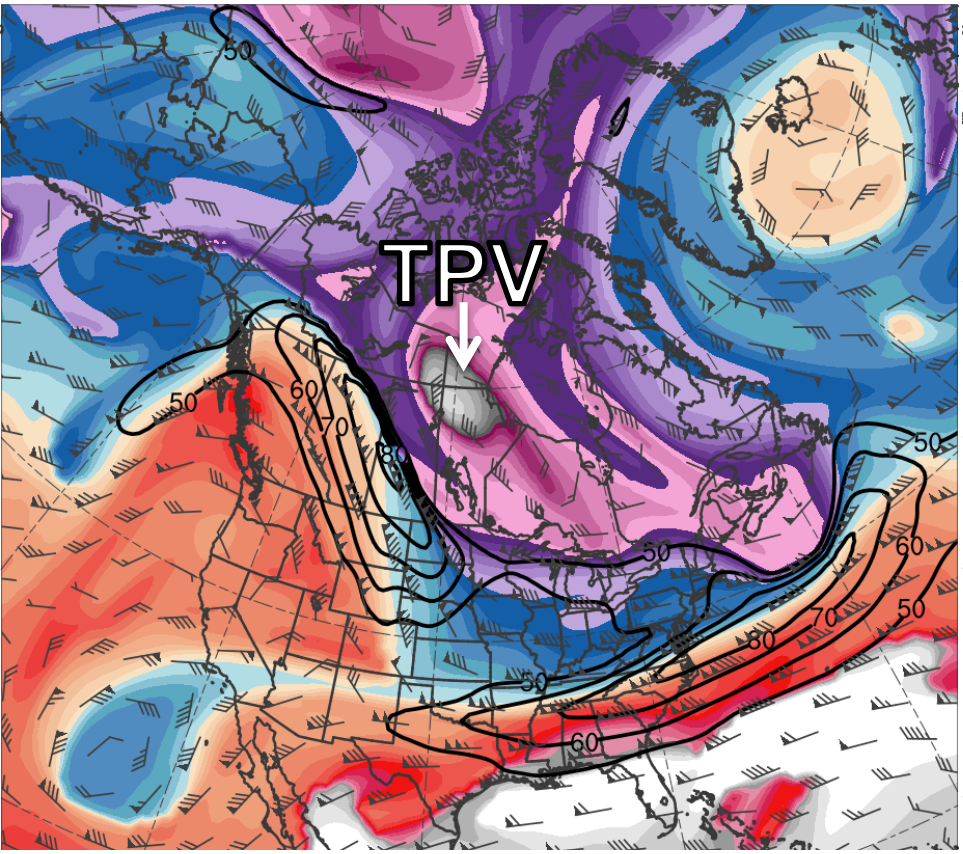
Potential temperature (K, shaded), wind speed (black, every 10 m s^{-1} starting at 50 m s^{-1}), and wind (m s^{-1}, flags and barbs) on 2-PVU surface

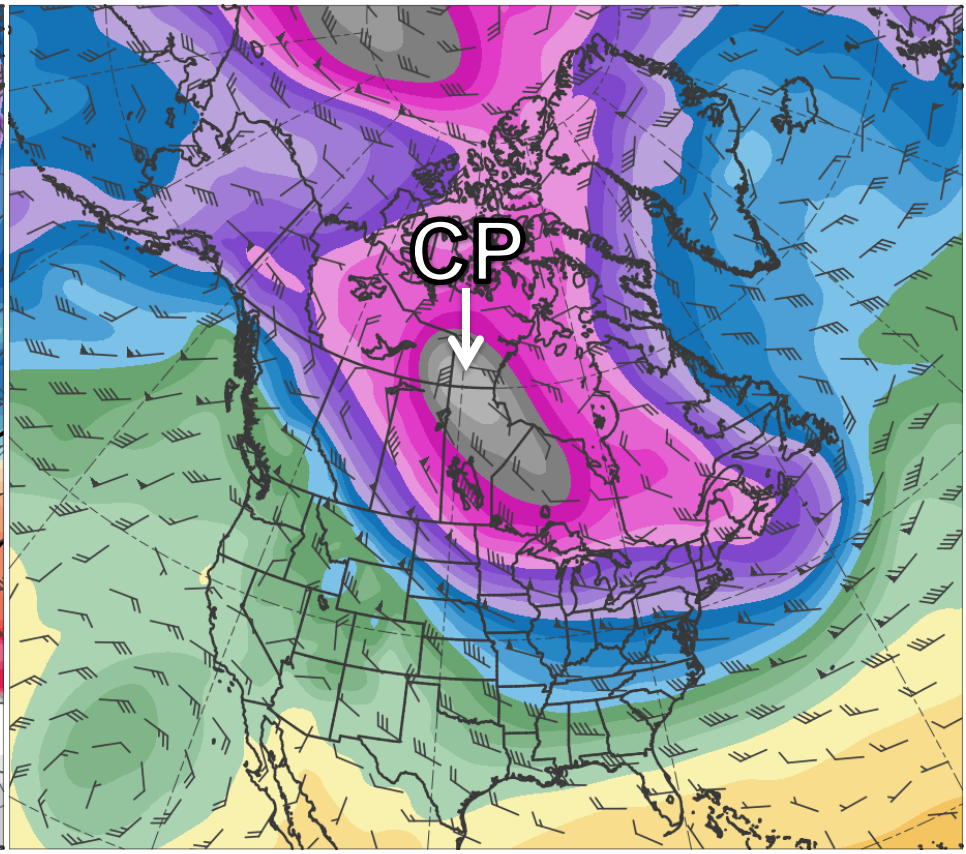
1000–500-hPa thickness (dam, shaded) and 700-hPa wind (m s^{-1}, flags and barbs); CP denotes “cold pool”

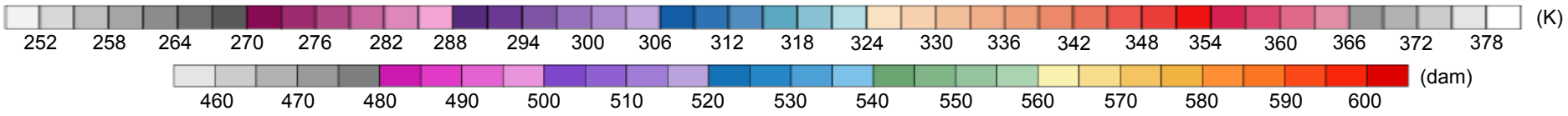
Example: 9–12 Jan 1982 CAO

0000 UTC 9 Jan 1982

Data Source: ERA-Interim







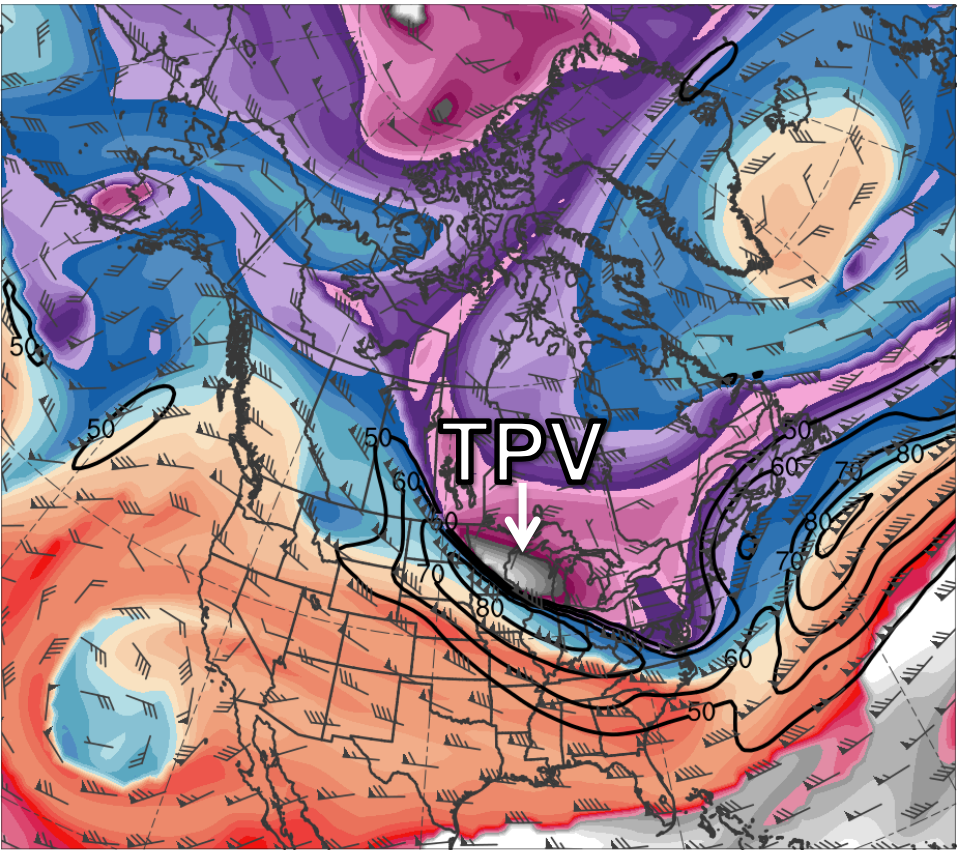
Potential temperature (K, shaded), wind speed (black, every 10 m s^{-1} starting at 50 m s^{-1}), and wind (m s^{-1}, flags and barbs) on 2-PVU surface

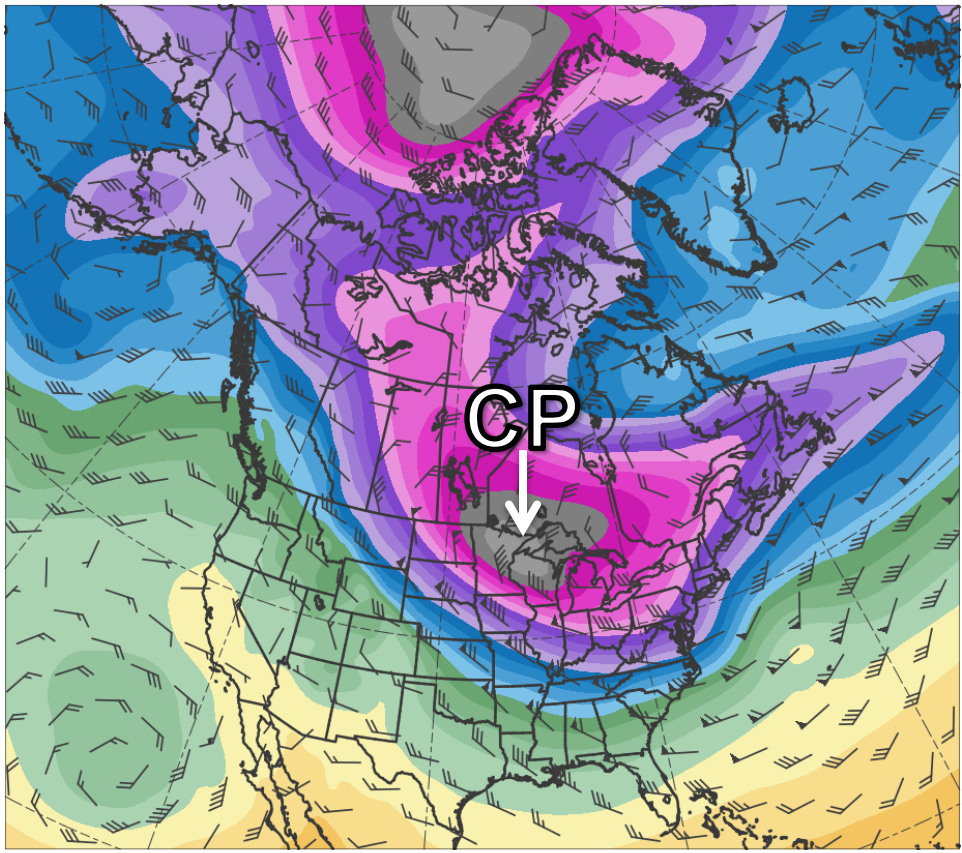
1000–500-hPa thickness (dam, shaded) and 700-hPa wind (m s^{-1}, flags and barbs); CP denotes “cold pool”

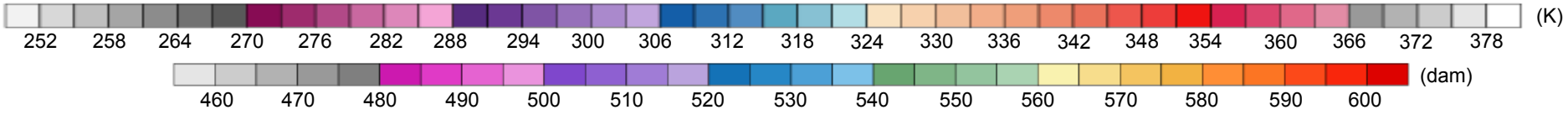
Example: 9–12 Jan 1982 CAO

0000 UTC 10 Jan 1982

Data Source: ERA-Interim







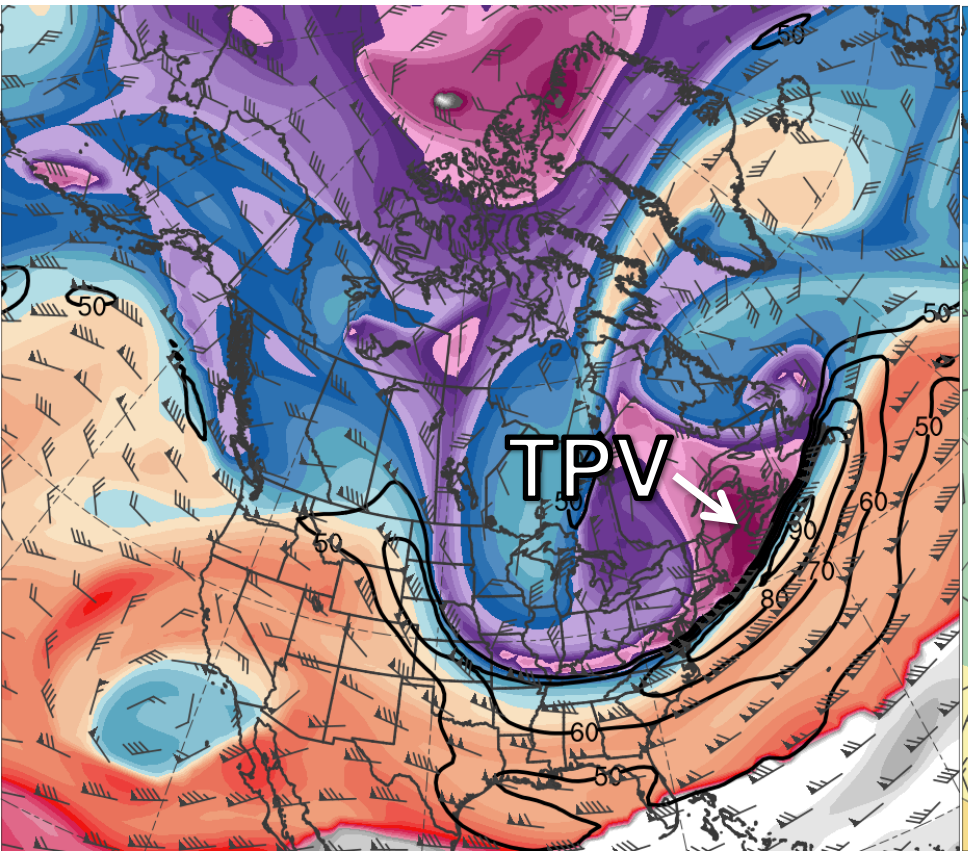
Potential temperature (K, shaded), wind speed (black, every 10 m s^{-1} starting at 50 m s^{-1}), and wind (m s^{-1}, flags and barbs) on 2-PVU surface

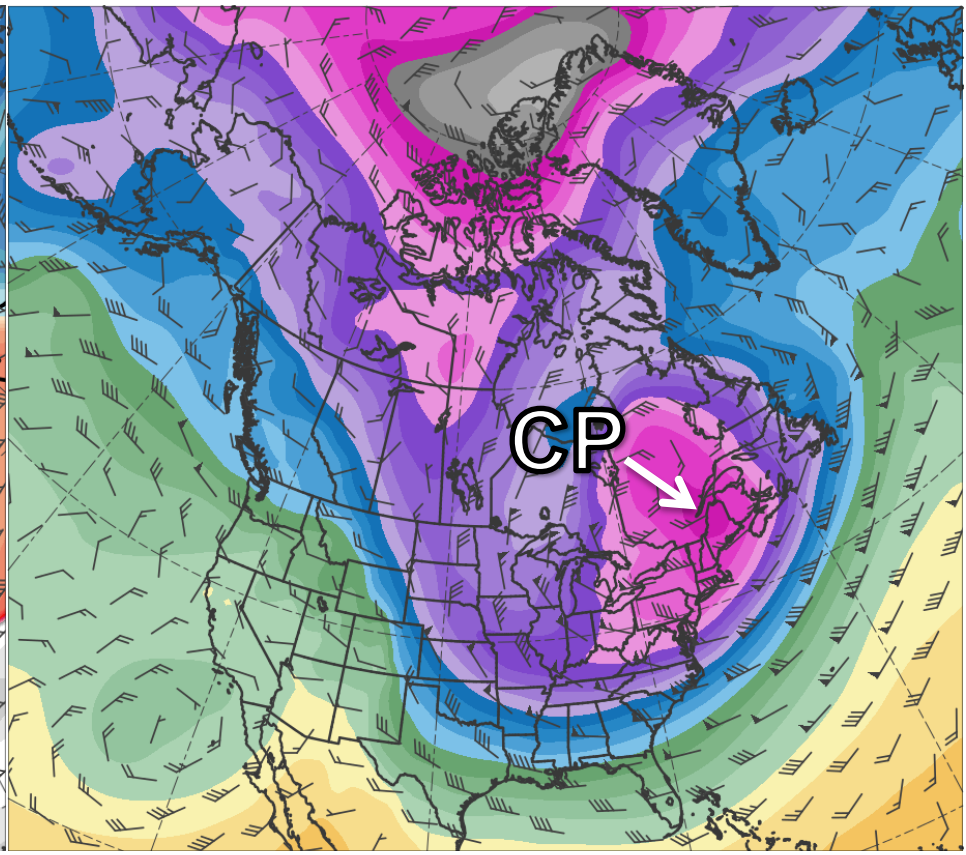
1000–500-hPa thickness (dam, shaded) and 700-hPa wind (m s^{-1}, flags and barbs); CP denotes “cold pool”

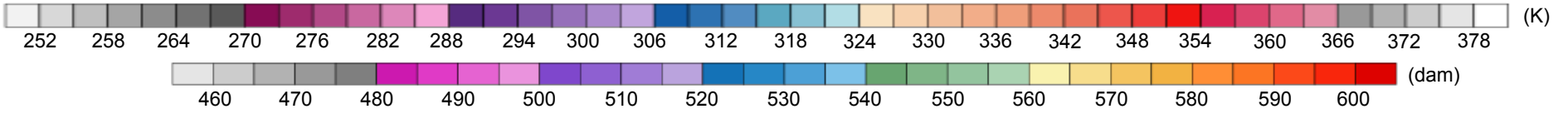
Example: 9–12 Jan 1982 CAO

0000 UTC 11 Jan 1982

Data Source: ERA-Interim







Potential temperature (K, shaded), wind speed (black, every 10 m s^{-1} starting at 50 m s^{-1}), and wind (m s^{-1}, flags and barbs) on 2-PVU surface

1000–500-hPa thickness (dam, shaded) and 700-hPa wind (m s^{-1}, flags and barbs); CP denotes “cold pool”

Outline

- TPV and cold pool tracking
- TPV and cold pool climatologies
- Identification of CAOs
- Identification of CAOs linked to cold pools
- Identification of cold pools associated with TPVs
- Identification of CAOs that are linked to cold pools associated with TPVs
- Conclusions

TPV Tracking

- Data:
  - 0.5° ERA-Interim (Dee et al. 2011)
  - 1979–2015, every 6 h
- Utilized TPV tracking algorithm developed by Nicholas Szapiro and Steven Cavallo to identify and track TPVs
  - Input variables: potential temperature, relative vorticity, and wind on 2-PVU surface
  - Potential temperature minima on 2-PVU surface tracked spatially and temporally to create TPV tracks

Link for Tracking Algorithm: https://github.com/nickszap/tpvTrack

Cold Pool Tracking

- Modified TPV tracking algorithm by changing input variables to identify and track cold pools
  - Input variables: 1000–500-hPa thickness and thermal vorticity, and 700-hPa wind
  - 1000–500-hPa thickness minima tracked spatially and temporally to create cold pool tracks

Filtering TPV and Cold Pool Tracks

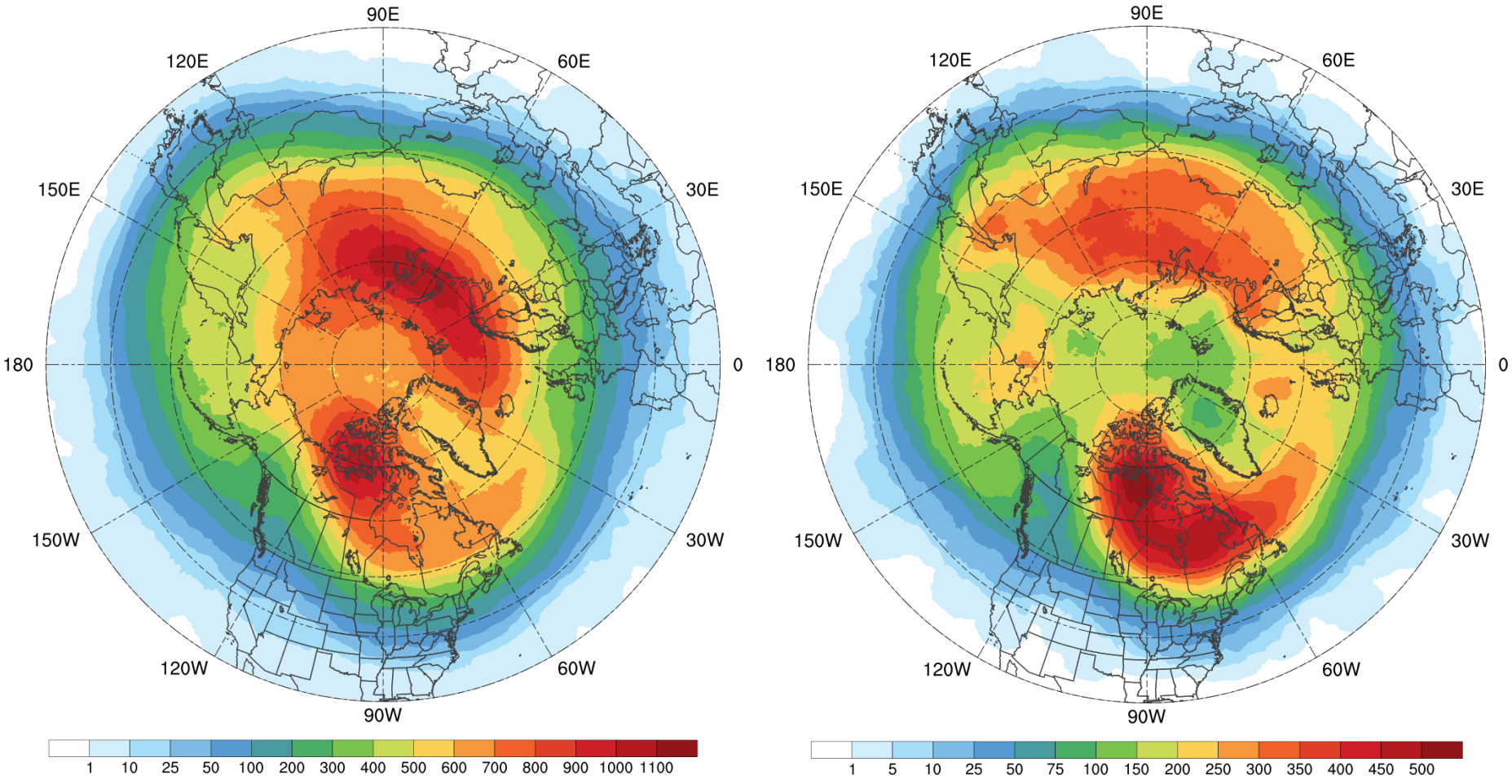
- TPVs must last at least 2 days and spend at least 30% of their lifetimes poleward of 65°N (adapted from criteria of Cavallo and Hakim 2010)

- Cold pools must last at least 2 days and spend at least 6 hours poleward of 65°N

- Focus on TPVs and cold pools transported from high latitudes into middle latitudes over central and eastern North America

  – Require that TPVs and cold pools in high latitudes move equatorward of 55°N between 120°W and 50°W

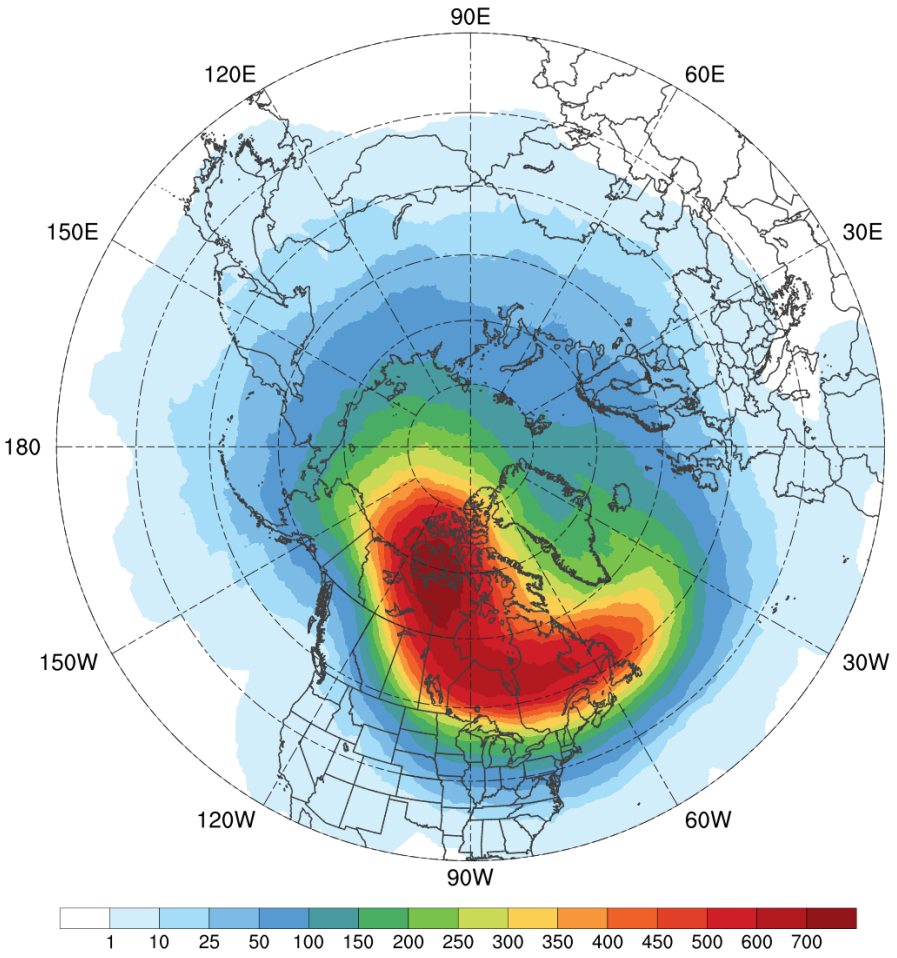
TPV and Cold Pool Track Density



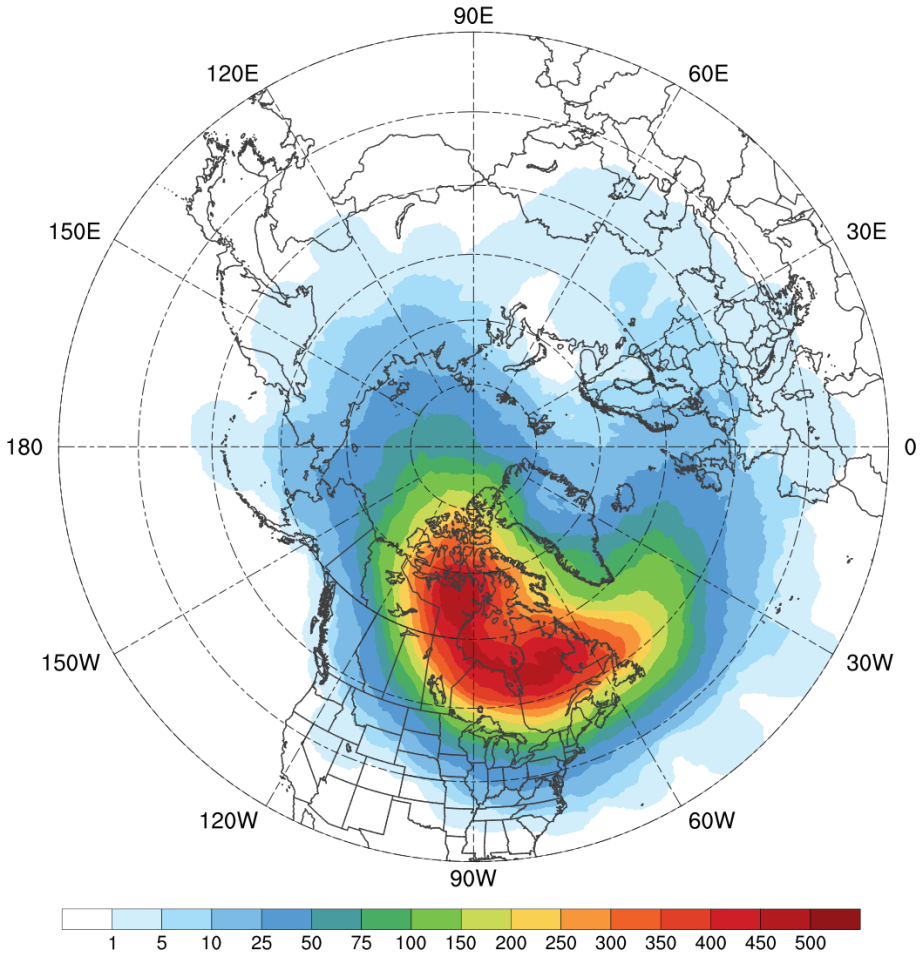
Total number of unique TPVs (left) and cold pools (right) within 500 km of each grid point (using a 0.5° grid) for TPVs and cold pools that move equatorward of 55°N during 1979–2015

TPV and Cold Pool Track Density

TPVs (N = 1262)

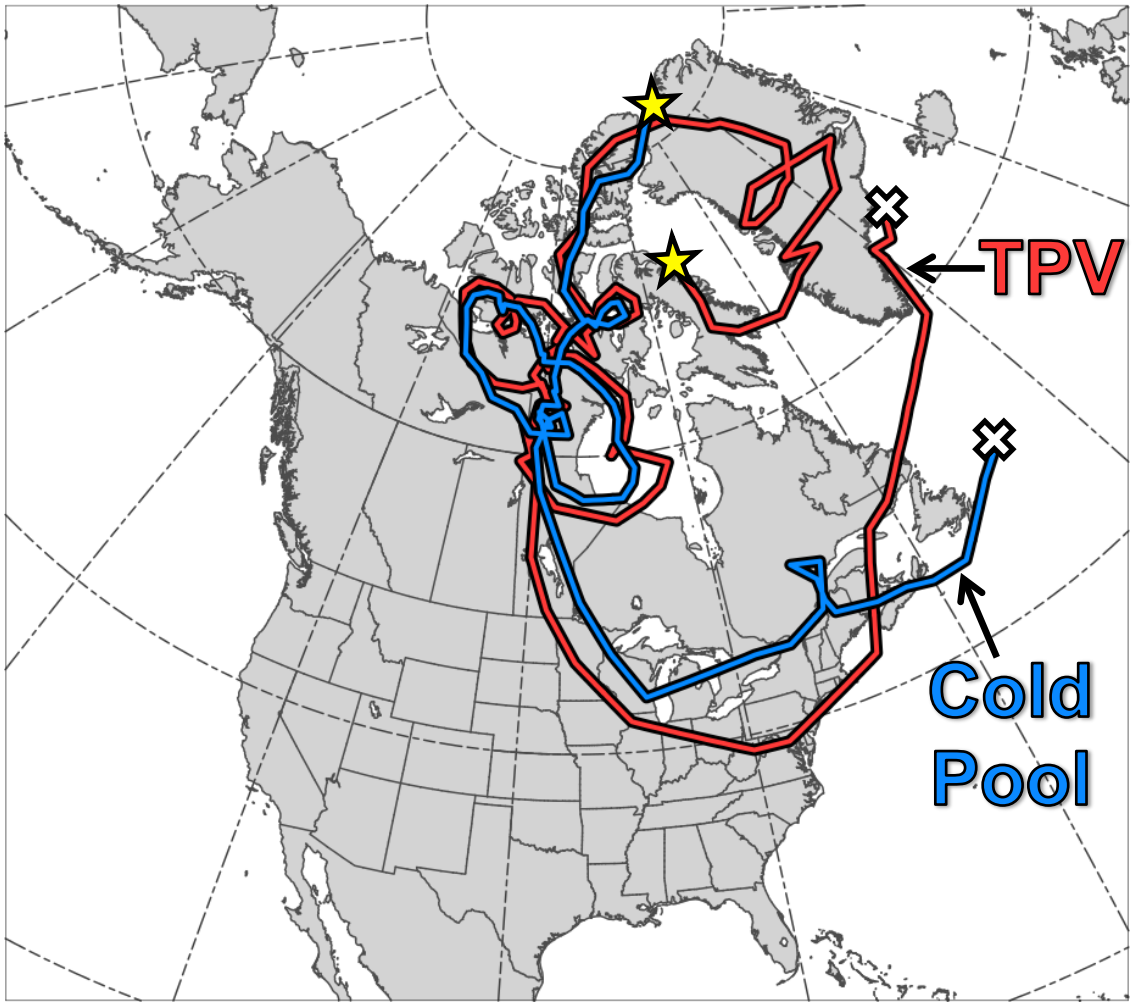


Cold Pools (N = 776)



Total number of unique TPVs (left) and cold pools (right) within 500 km of each grid point (using a 0.5° grid) for TPVs and cold pools that move equatorward of 55°N between 120°W and 50°W during 1979–2015

Tracks for Jan 1982 CAO



- **TPV Track:**
  - **Genesis:** 0600 UTC 15 Dec 1981
  - **Lysis:** 0000 UTC 13 Jan 1982
  - **Lifetime:** ~29 days
- **Cold Pool Track:**
  - **Genesis:** 1800 UTC 20 Dec 1981
  - **Lysis:** 1800 UTC 13 Jan 1982
  - **Lifetime:** ~24 days

Tracks for Jan 1982 CAO

0000 UTC 21 Dec 1981

TPV Cold Pool

- **TPV Track:**
  - **Genesis:** 0600 UTC 15 Dec 1981
  - **Lysis:** 0000 UTC 13 Jan 1982
  - **Lifetime:** ~29 days
- **Cold Pool Track:**
  - **Genesis:** 1800 UTC 20 Dec 1981
  - **Lysis:** 1800 UTC 13 Jan 1982
  - **Lifetime:** ~24 days

Tracks for Jan 1982 CAO

0000 UTC 22 Dec 1981

TPV Cold Pool

- **TPV Track:**
  - **Genesis:** 0600 UTC 15 Dec 1981
  - **Lysis:** 0000 UTC 13 Jan 1982
  - **Lifetime:** ~29 days
- **Cold Pool Track:**
  - **Genesis:** 1800 UTC 20 Dec 1981
  - **Lysis:** 1800 UTC 13 Jan 1982
  - **Lifetime:** ~24 days

Tracks for Jan 1982 CAO

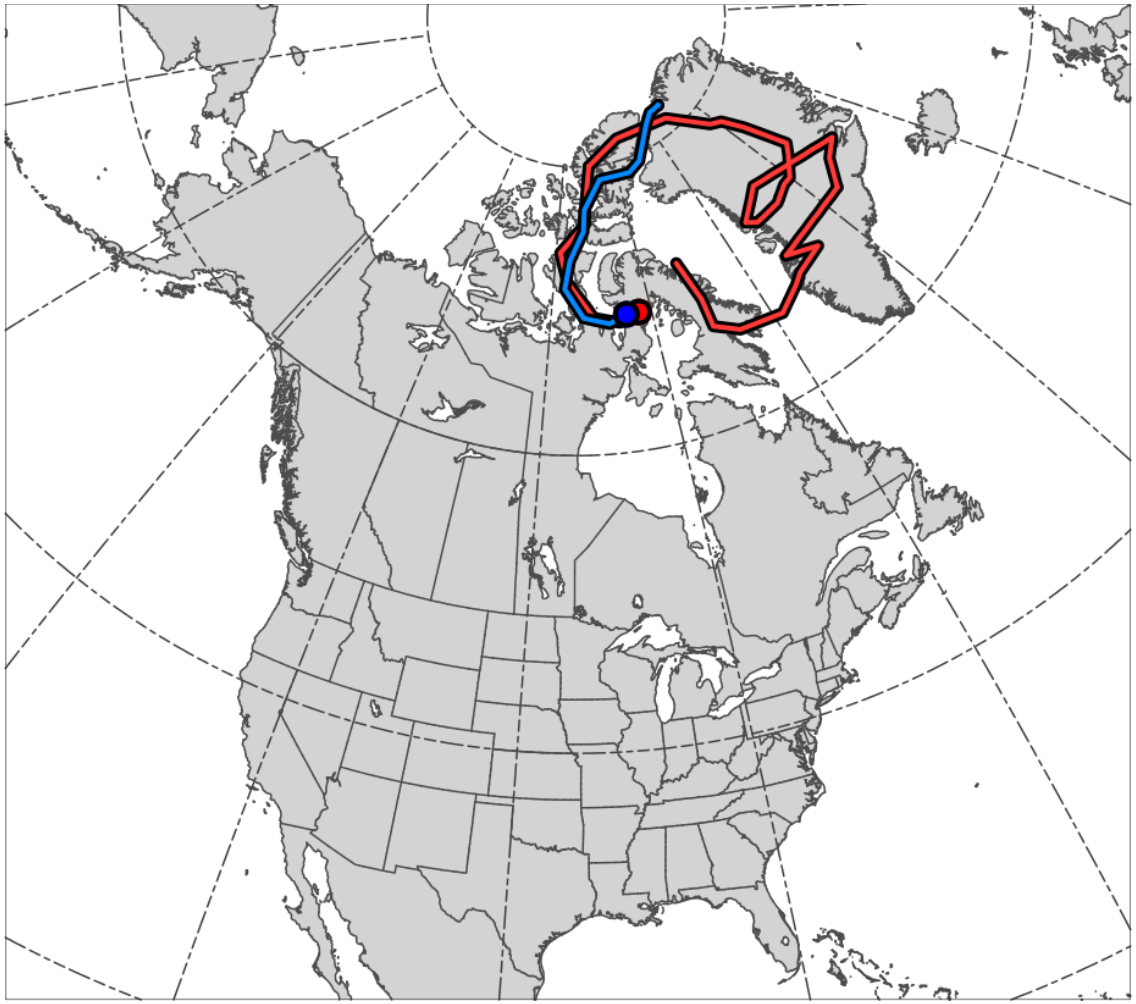
0000 UTC 23 Dec 1981

TPV Cold Pool

- **TPV Track:**
  - **Genesis:** 0600 UTC 15 Dec 1981
  - **Lysis:** 0000 UTC 13 Jan 1982
  - **Lifetime:** ~29 days
- **Cold Pool Track:**
  - **Genesis:** 1800 UTC 20 Dec 1981
  - **Lysis:** 1800 UTC 13 Jan 1982
  - **Lifetime:** ~24 days

Tracks for Jan 1982 CAO

0000 UTC 24 Dec 1981

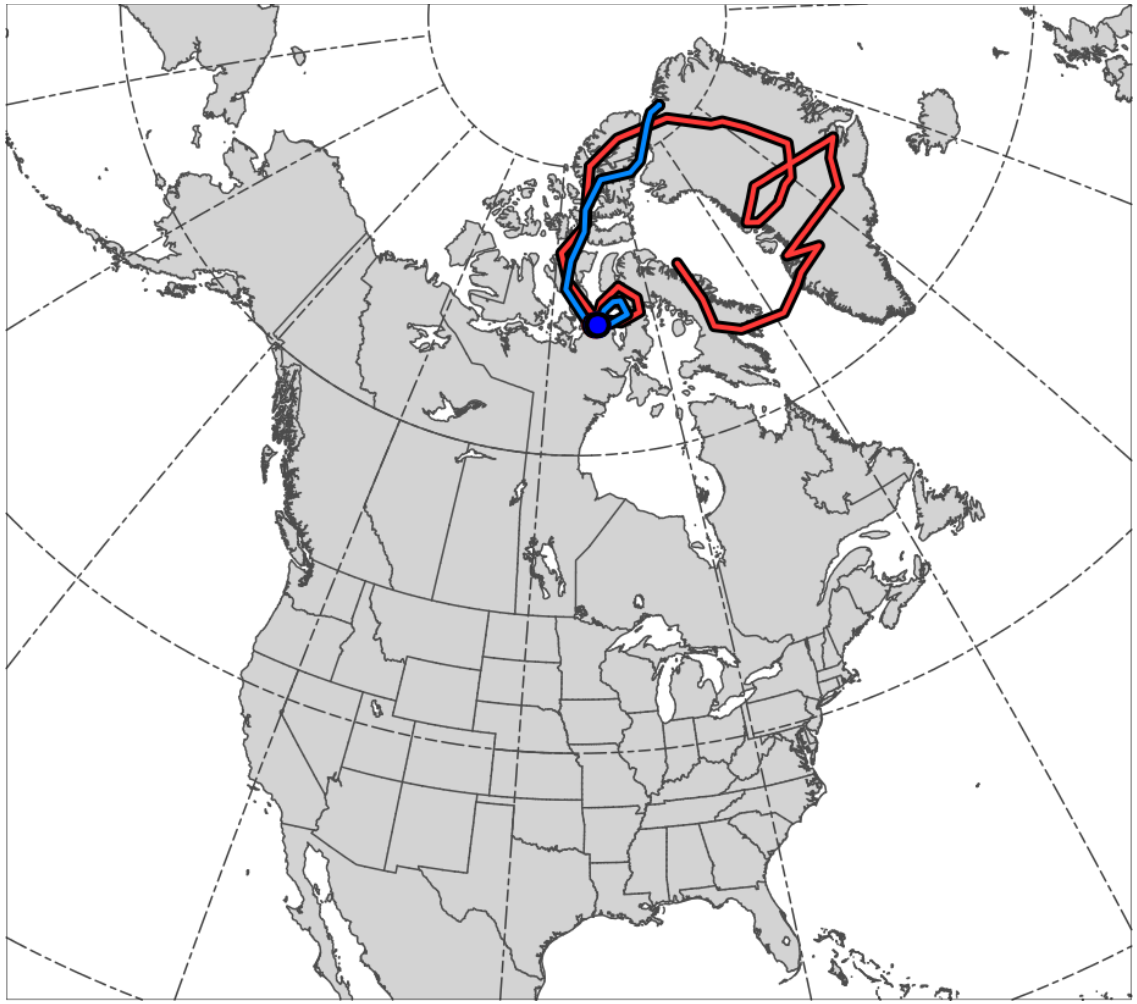


TPV Cold Pool

- **TPV Track:**
  - **Genesis:** 0600 UTC 15 Dec 1981
  - **Lysis:** 0000 UTC 13 Jan 1982
  - **Lifetime:** ~29 days
- **Cold Pool Track:**
  - **Genesis:** 1800 UTC 20 Dec 1981
  - **Lysis:** 1800 UTC 13 Jan 1982
  - **Lifetime:** ~24 days

Tracks for Jan 1982 CAO

0000 UTC 25 Dec 1981

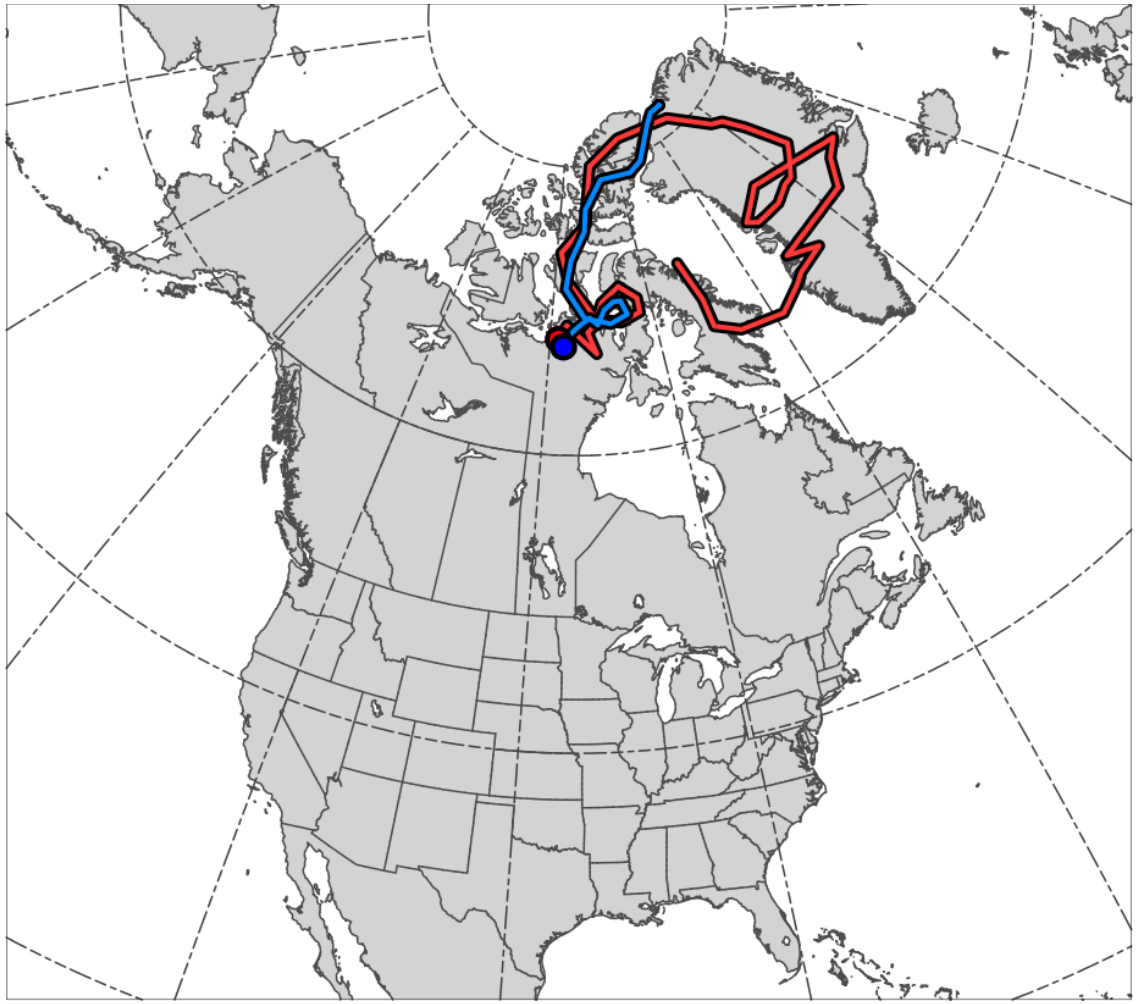


TPV Cold Pool

- **TPV Track:**
  - **Genesis:** 0600 UTC 15 Dec 1981
  - **Lysis:** 0000 UTC 13 Jan 1982
  - **Lifetime:** ~29 days
- **Cold Pool Track:**
  - **Genesis:** 1800 UTC 20 Dec 1981
  - **Lysis:** 1800 UTC 13 Jan 1982
  - **Lifetime:** ~24 days

Tracks for Jan 1982 CAO

0000 UTC 26 Dec 1981

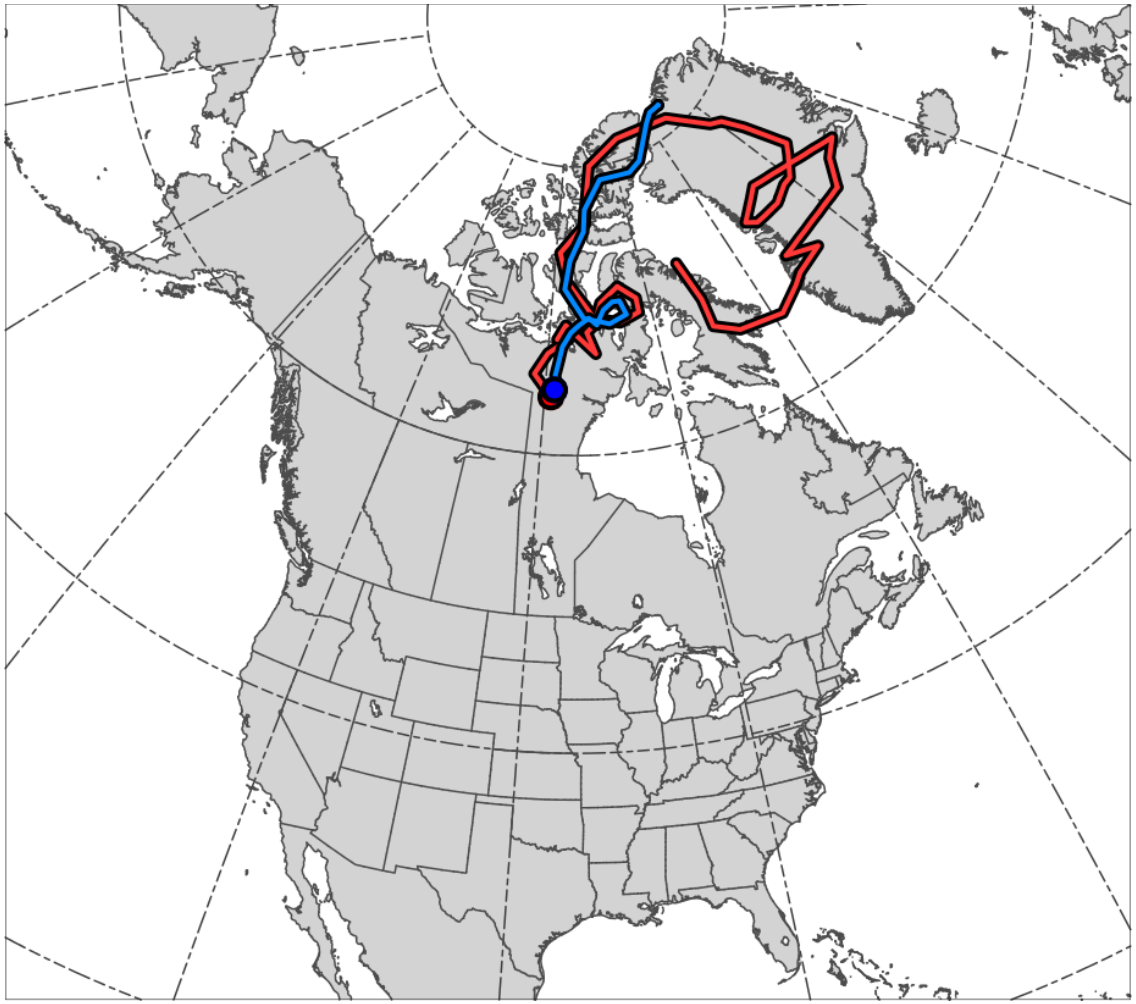


TPV Cold Pool

- **TPV Track:**
  - **Genesis:** 0600 UTC 15 Dec 1981
  - **Lysis:** 0000 UTC 13 Jan 1982
  - **Lifetime:** ~29 days
- **Cold Pool Track:**
  - **Genesis:** 1800 UTC 20 Dec 1981
  - **Lysis:** 1800 UTC 13 Jan 1982
  - **Lifetime:** ~24 days

Tracks for Jan 1982 CAO

0000 UTC 27 Dec 1981

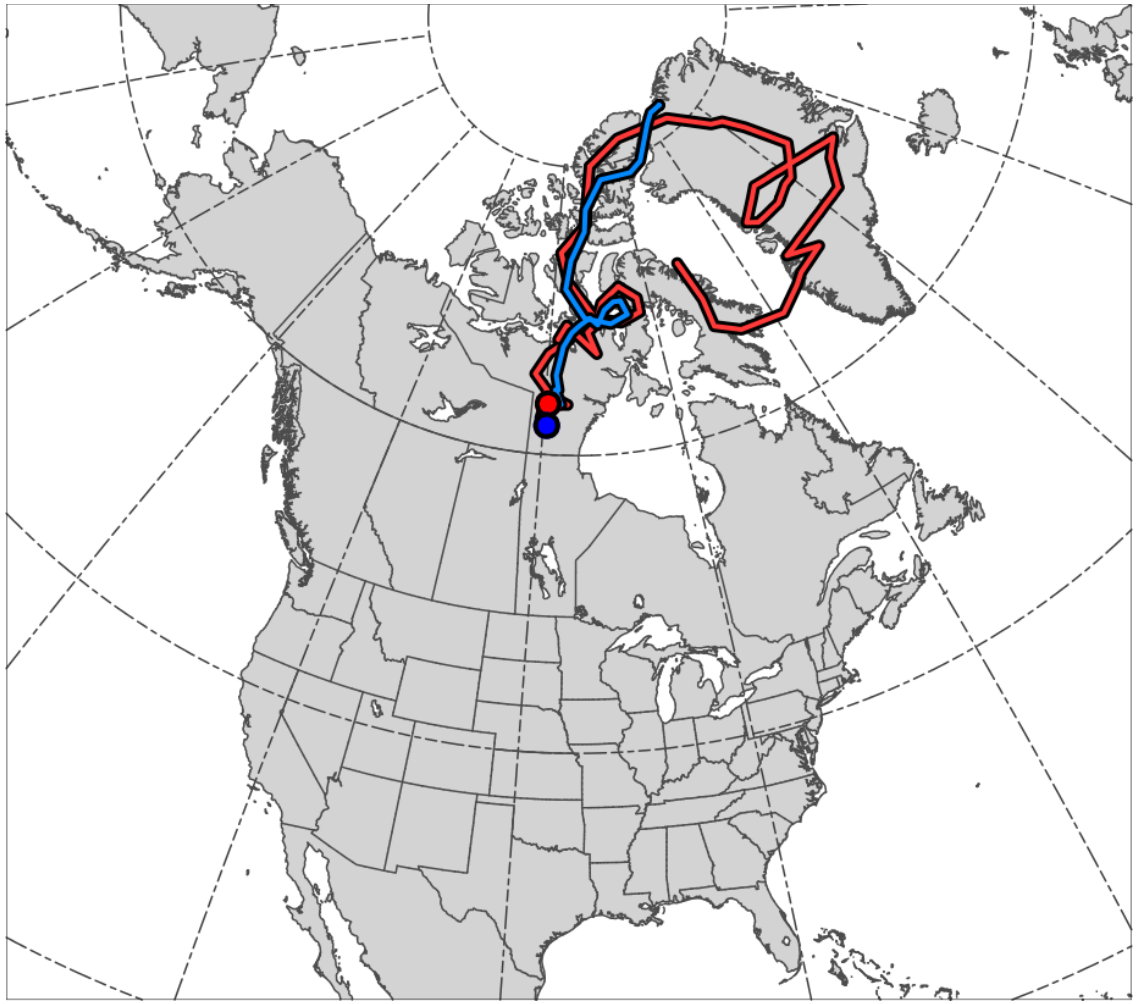


TPV Cold Pool

- **TPV Track:**
  - **Genesis:** 0600 UTC 15 Dec 1981
  - **Lysis:** 0000 UTC 13 Jan 1982
  - **Lifetime:** ~29 days
- **Cold Pool Track:**
  - **Genesis:** 1800 UTC 20 Dec 1981
  - **Lysis:** 1800 UTC 13 Jan 1982
  - **Lifetime:** ~24 days

Tracks for Jan 1982 CAO

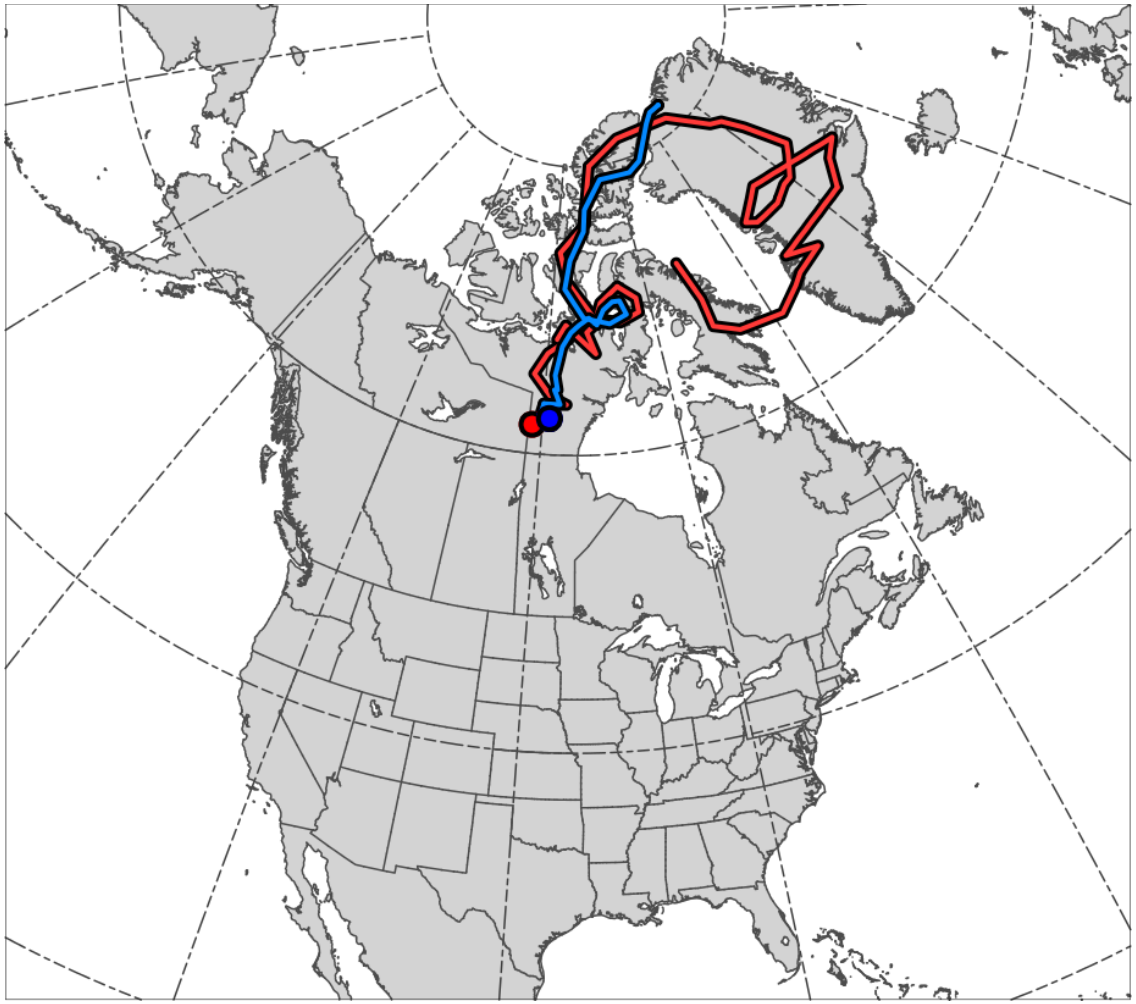
0000 UTC 28 Dec 1981



- **TPV Track:**
  - **Genesis:** 0600 UTC 15 Dec 1981
  - **Lysis:** 0000 UTC 13 Jan 1982
  - **Lifetime:** ~29 days
- **Cold Pool Track:**
  - **Genesis:** 1800 UTC 20 Dec 1981
  - **Lysis:** 1800 UTC 13 Jan 1982
  - **Lifetime:** ~24 days

Tracks for Jan 1982 CAO

0000 UTC 29 Dec 1981

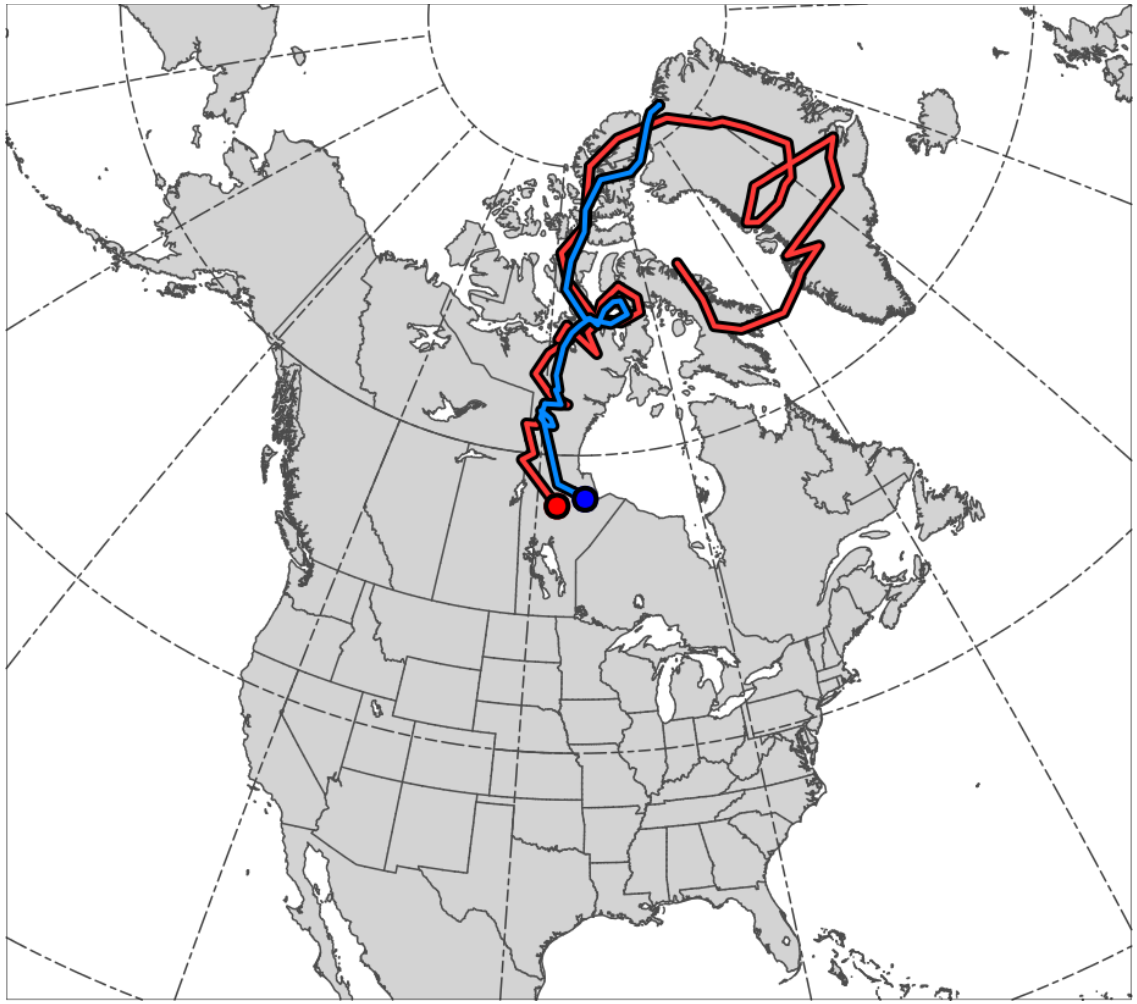


TPV Cold Pool

- **TPV Track:**
  - **Genesis:** 0600 UTC 15 Dec 1981
  - **Lysis:** 0000 UTC 13 Jan 1982
  - **Lifetime:** ~29 days
- **Cold Pool Track:**
  - **Genesis:** 1800 UTC 20 Dec 1981
  - **Lysis:** 1800 UTC 13 Jan 1982
  - **Lifetime:** ~24 days

Tracks for Jan 1982 CAO

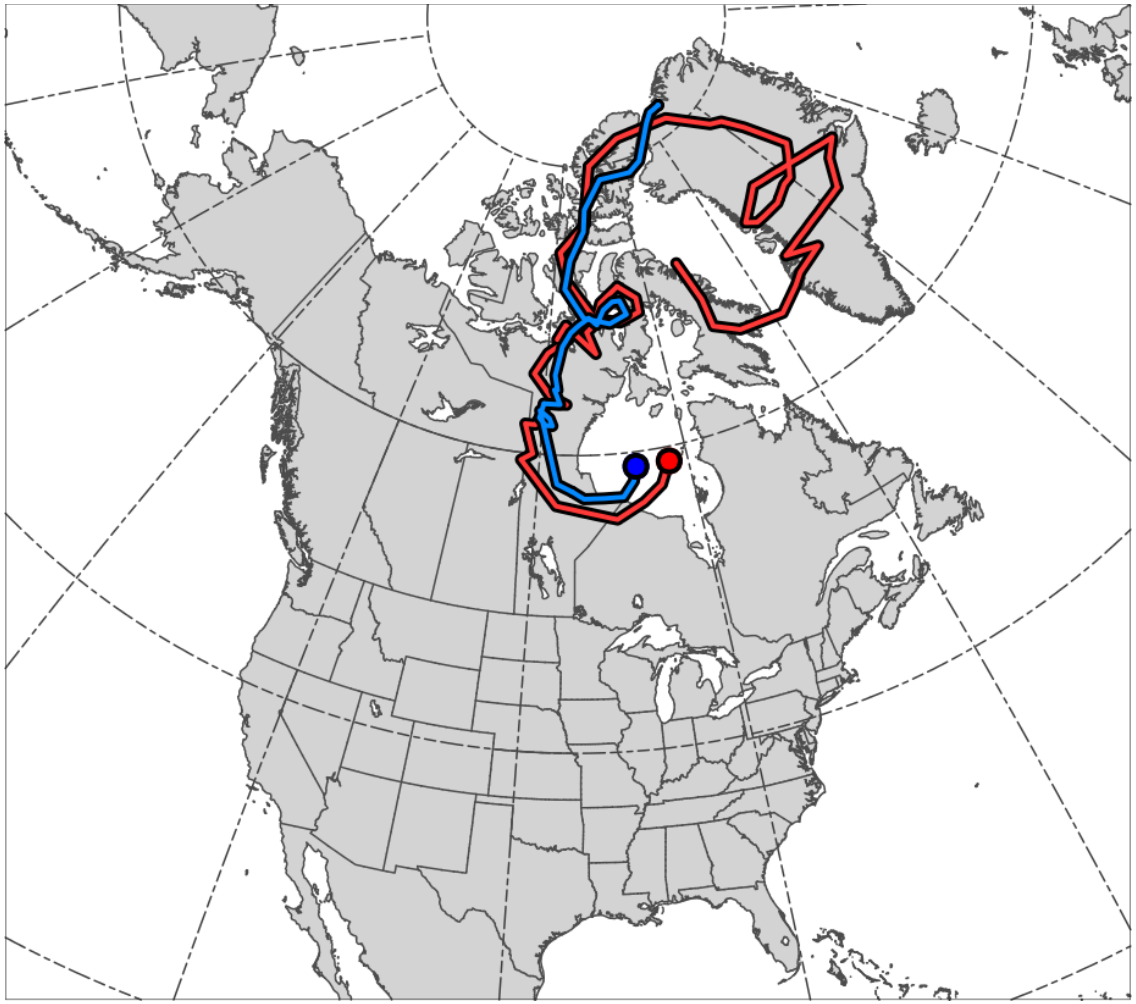
0000 UTC 30 Dec 1981



- **TPV Track:**
  - **Genesis:** 0600 UTC 15 Dec 1981
  - **Lysis:** 0000 UTC 13 Jan 1982
  - **Lifetime:** ~29 days
- **Cold Pool Track:**
  - **Genesis:** 1800 UTC 20 Dec 1981
  - **Lysis:** 1800 UTC 13 Jan 1982
  - **Lifetime:** ~24 days

Tracks for Jan 1982 CAO

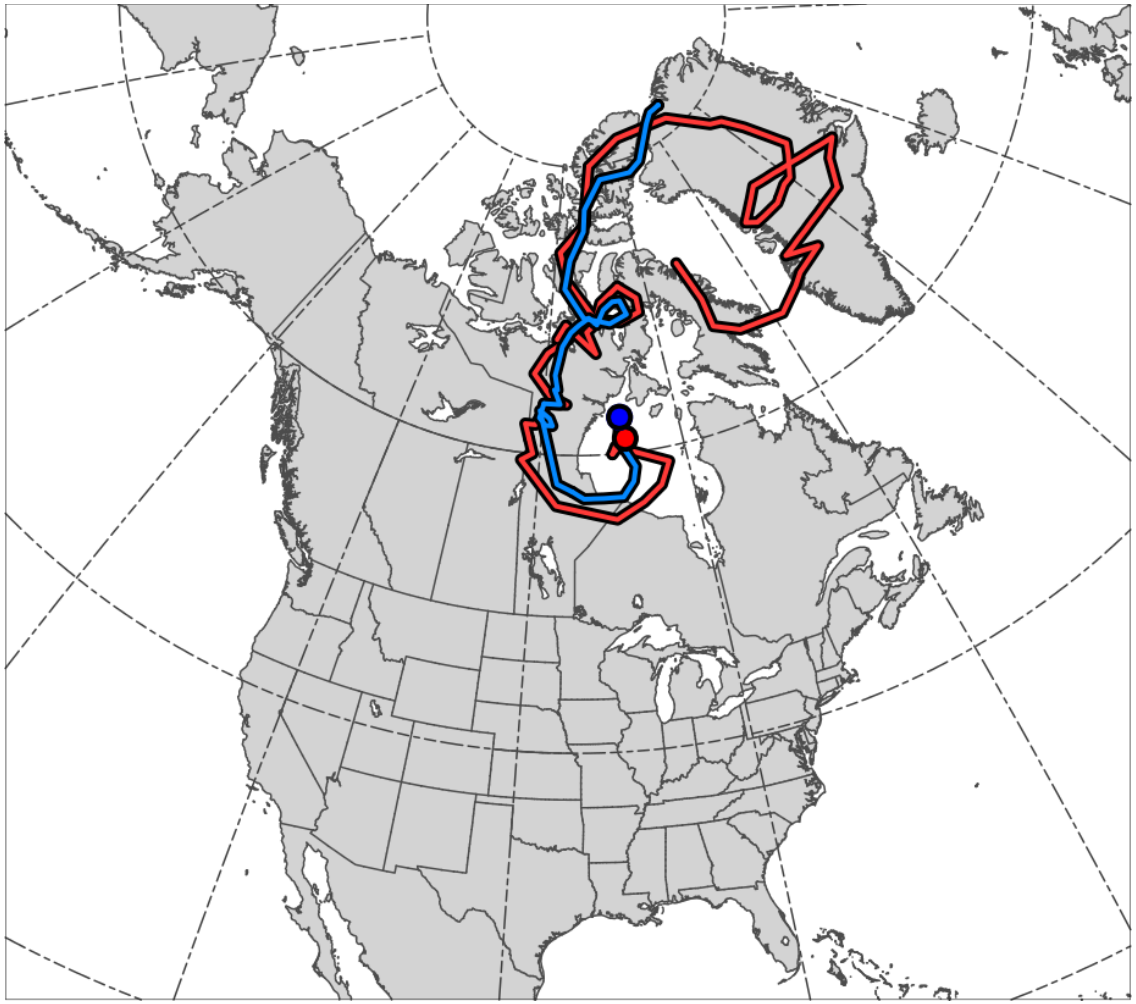
0000 UTC 31 Dec 1981



- **TPV Track:**
  - **Genesis:** 0600 UTC 15 Dec 1981
  - **Lysis:** 0000 UTC 13 Jan 1982
  - **Lifetime:** ~29 days
- **Cold Pool Track:**
  - **Genesis:** 1800 UTC 20 Dec 1981
  - **Lysis:** 1800 UTC 13 Jan 1982
  - **Lifetime:** ~24 days

Tracks for Jan 1982 CAO

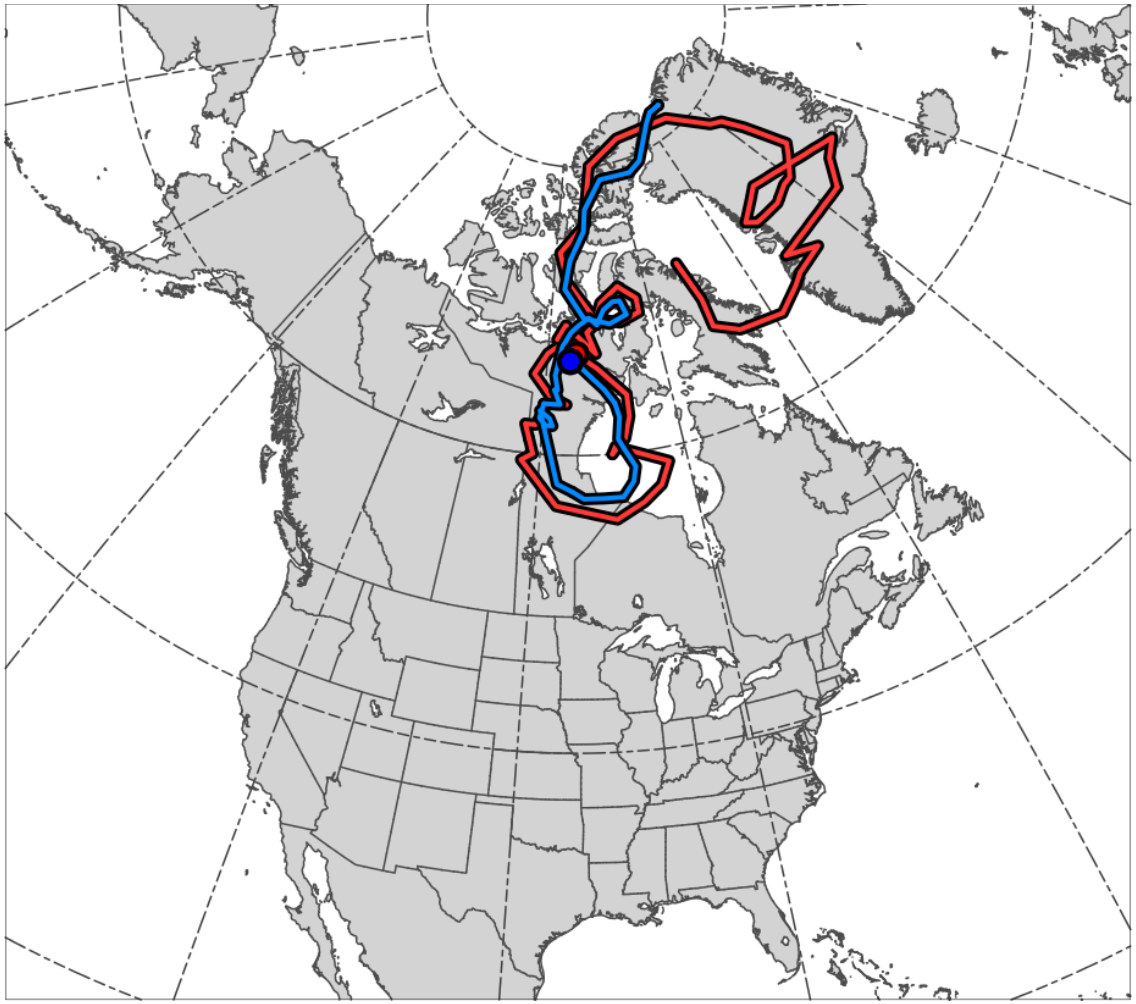
0000 UTC 1 Jan 1982



- **TPV Track:**
  - **Genesis:** 0600 UTC 15 Dec 1981
  - **Lysis:** 0000 UTC 13 Jan 1982
  - **Lifetime:** ~29 days
- **Cold Pool Track:**
  - **Genesis:** 1800 UTC 20 Dec 1981
  - **Lysis:** 1800 UTC 13 Jan 1982
  - **Lifetime:** ~24 days

Tracks for Jan 1982 CAO

0000 UTC 2 Jan 1982

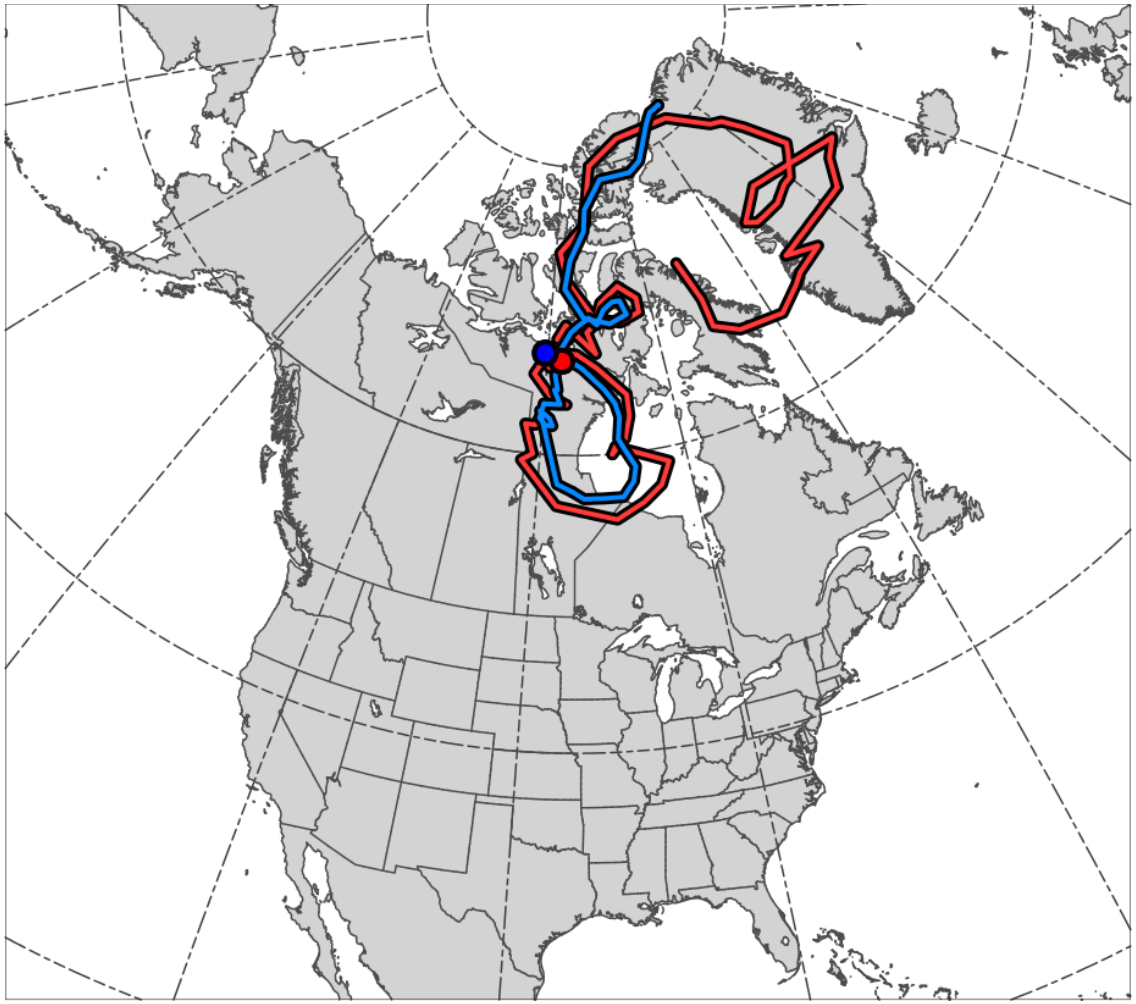


TPV Cold Pool

- **TPV Track:**
  - **Genesis:** 0600 UTC 15 Dec 1981
  - **Lysis:** 0000 UTC 13 Jan 1982
  - **Lifetime:** ~29 days
- **Cold Pool Track:**
  - **Genesis:** 1800 UTC 20 Dec 1981
  - **Lysis:** 1800 UTC 13 Jan 1982
  - **Lifetime:** ~24 days

Tracks for Jan 1982 CAO

0000 UTC 3 Jan 1982

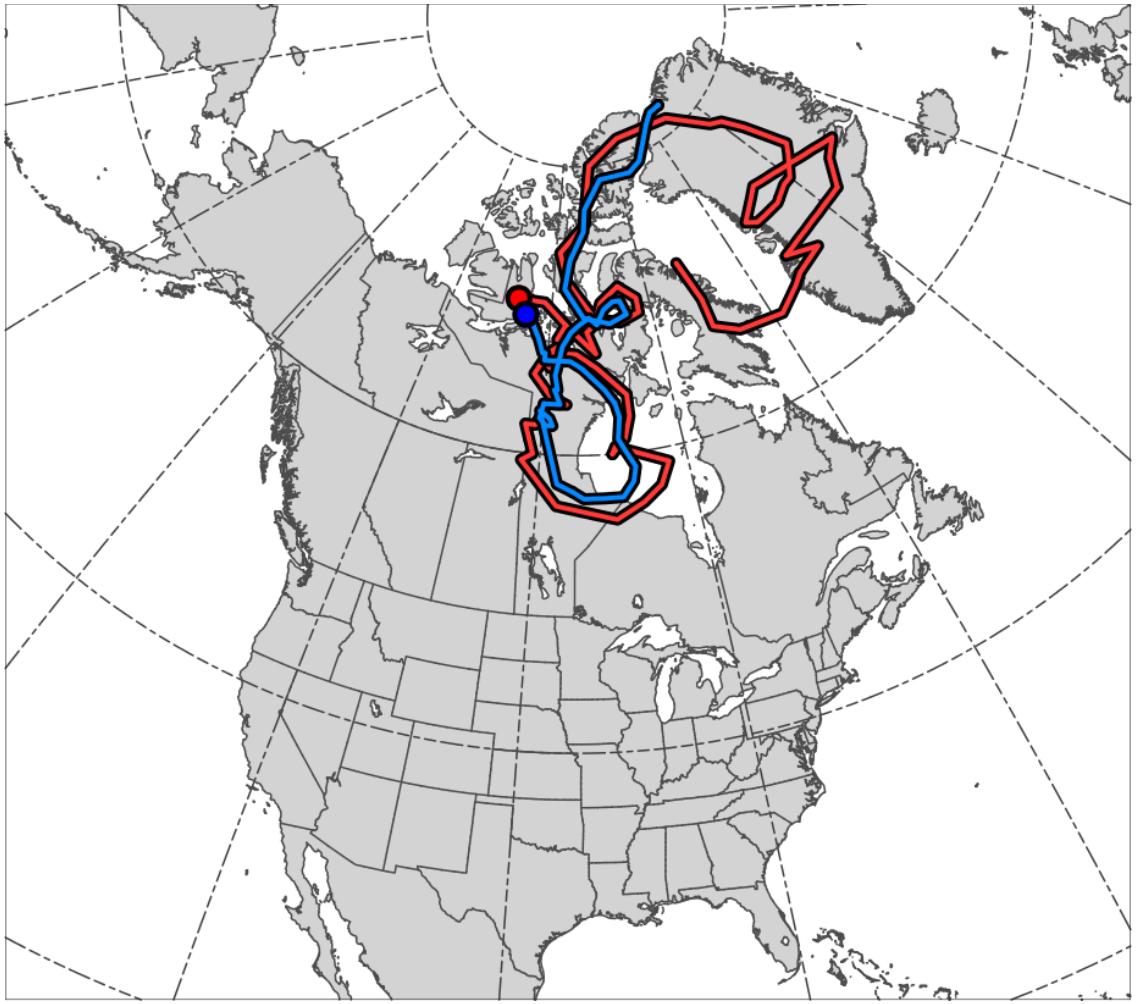


TPV Cold Pool

- **TPV Track:**
  - **Genesis:** 0600 UTC 15 Dec 1981
  - **Lysis:** 0000 UTC 13 Jan 1982
  - **Lifetime:** ~29 days
- **Cold Pool Track:**
  - **Genesis:** 1800 UTC 20 Dec 1981
  - **Lysis:** 1800 UTC 13 Jan 1982
  - **Lifetime:** ~24 days

Tracks for Jan 1982 CAO

0000 UTC 4 Jan 1982

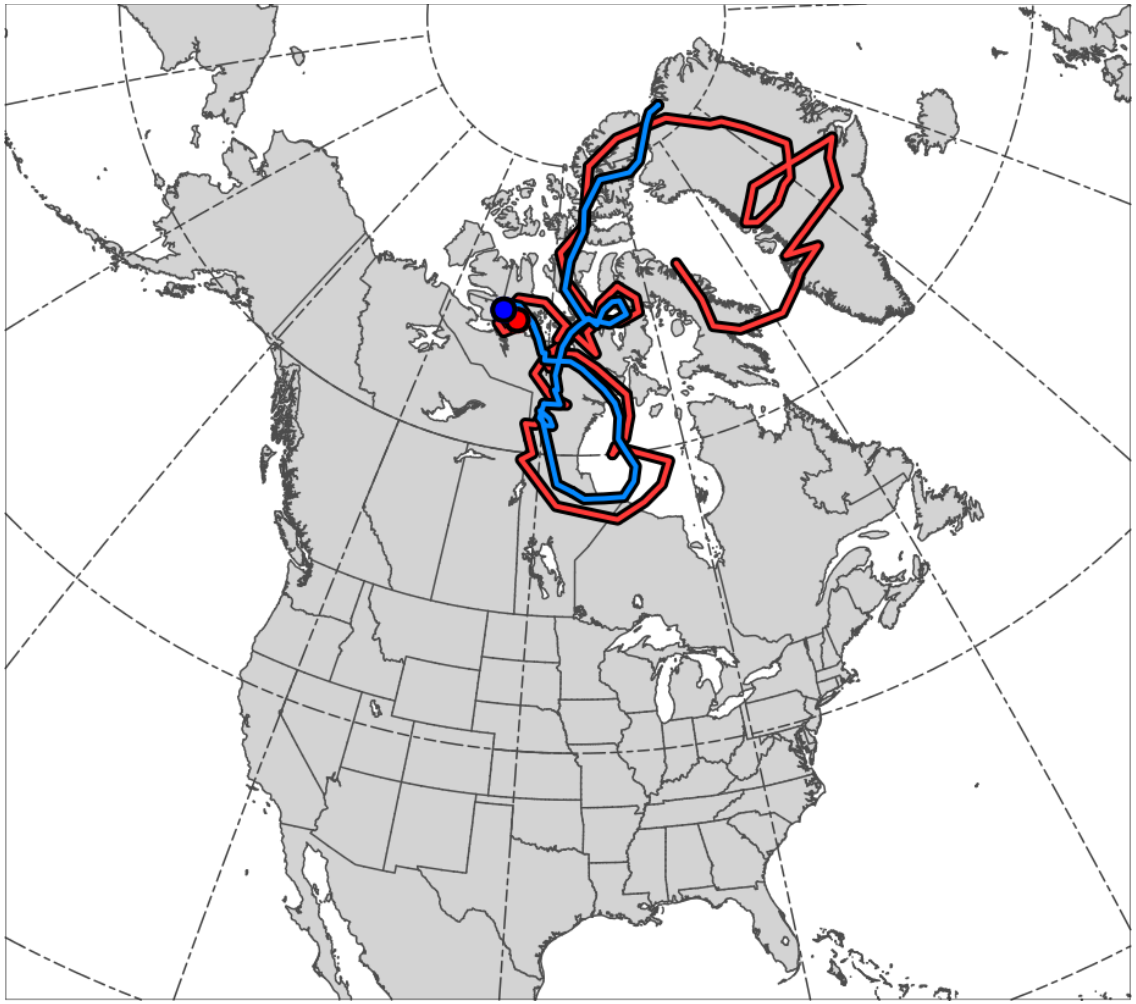


TPV Cold Pool

- **TPV Track:**
  - **Genesis:** 0600 UTC 15 Dec 1981
  - **Lysis:** 0000 UTC 13 Jan 1982
  - **Lifetime:** ~29 days
- **Cold Pool Track:**
  - **Genesis:** 1800 UTC 20 Dec 1981
  - **Lysis:** 1800 UTC 13 Jan 1982
  - **Lifetime:** ~24 days

Tracks for Jan 1982 CAO

0000 UTC 5 Jan 1982

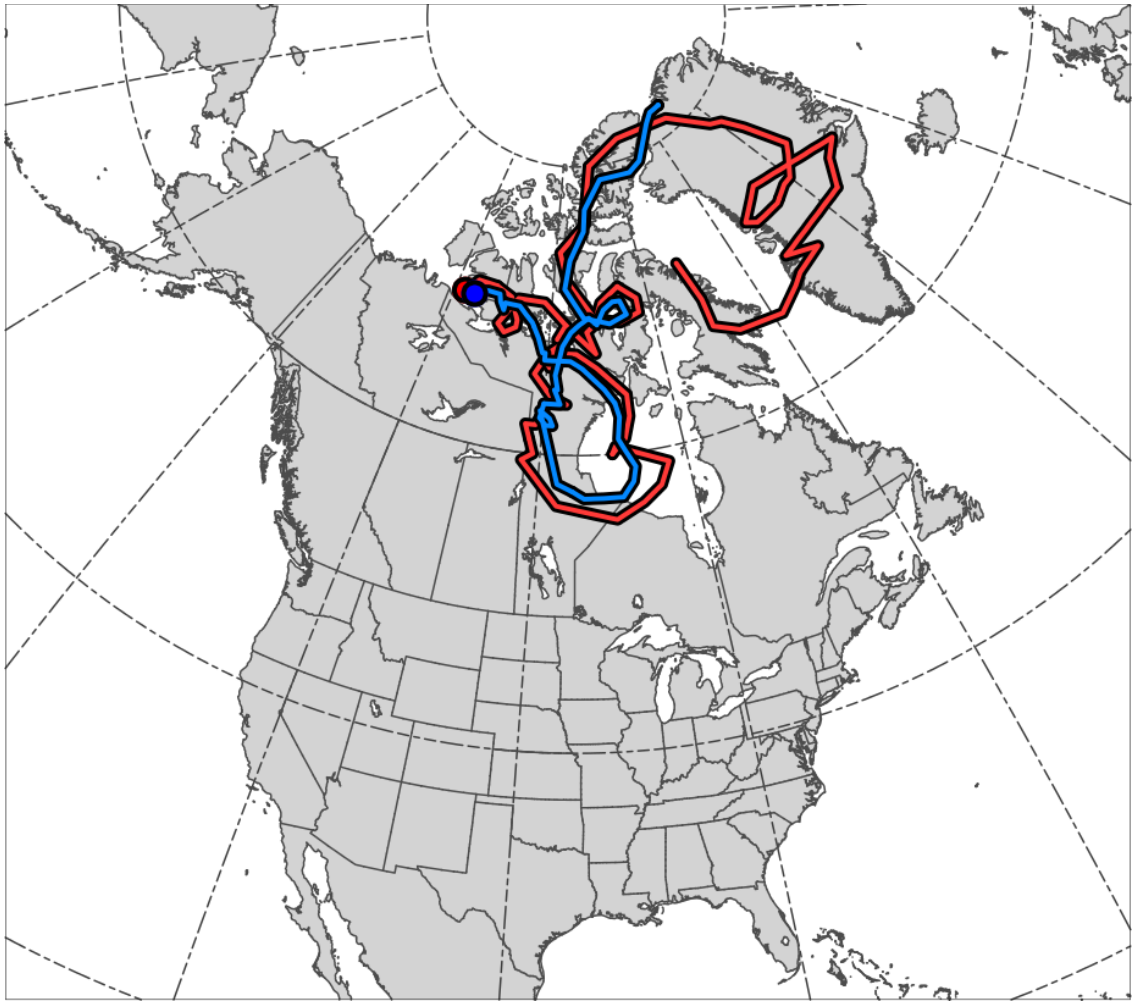


TPV Cold Pool

- **TPV Track:**
  - **Genesis:** 0600 UTC 15 Dec 1981
  - **Lysis:** 0000 UTC 13 Jan 1982
  - **Lifetime:** ~29 days
- **Cold Pool Track:**
  - **Genesis:** 1800 UTC 20 Dec 1981
  - **Lysis:** 1800 UTC 13 Jan 1982
  - **Lifetime:** ~24 days

Tracks for Jan 1982 CAO

0000 UTC 6 Jan 1982

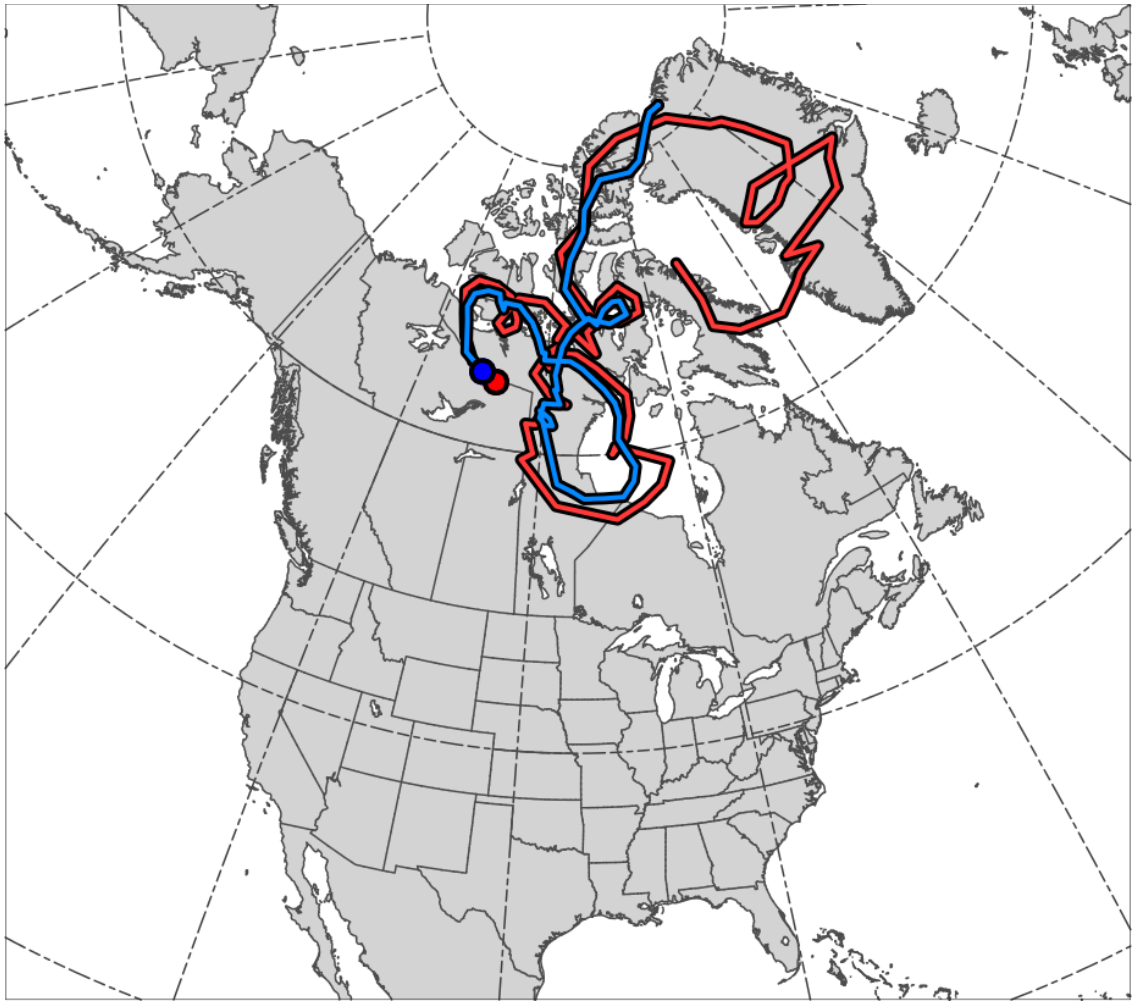


TPV Cold Pool

- **TPV Track:**
  - **Genesis:** 0600 UTC 15 Dec 1981
  - **Lysis:** 0000 UTC 13 Jan 1982
  - **Lifetime:** ~29 days
- **Cold Pool Track:**
  - **Genesis:** 1800 UTC 20 Dec 1981
  - **Lysis:** 1800 UTC 13 Jan 1982
  - **Lifetime:** ~24 days

Tracks for Jan 1982 CAO

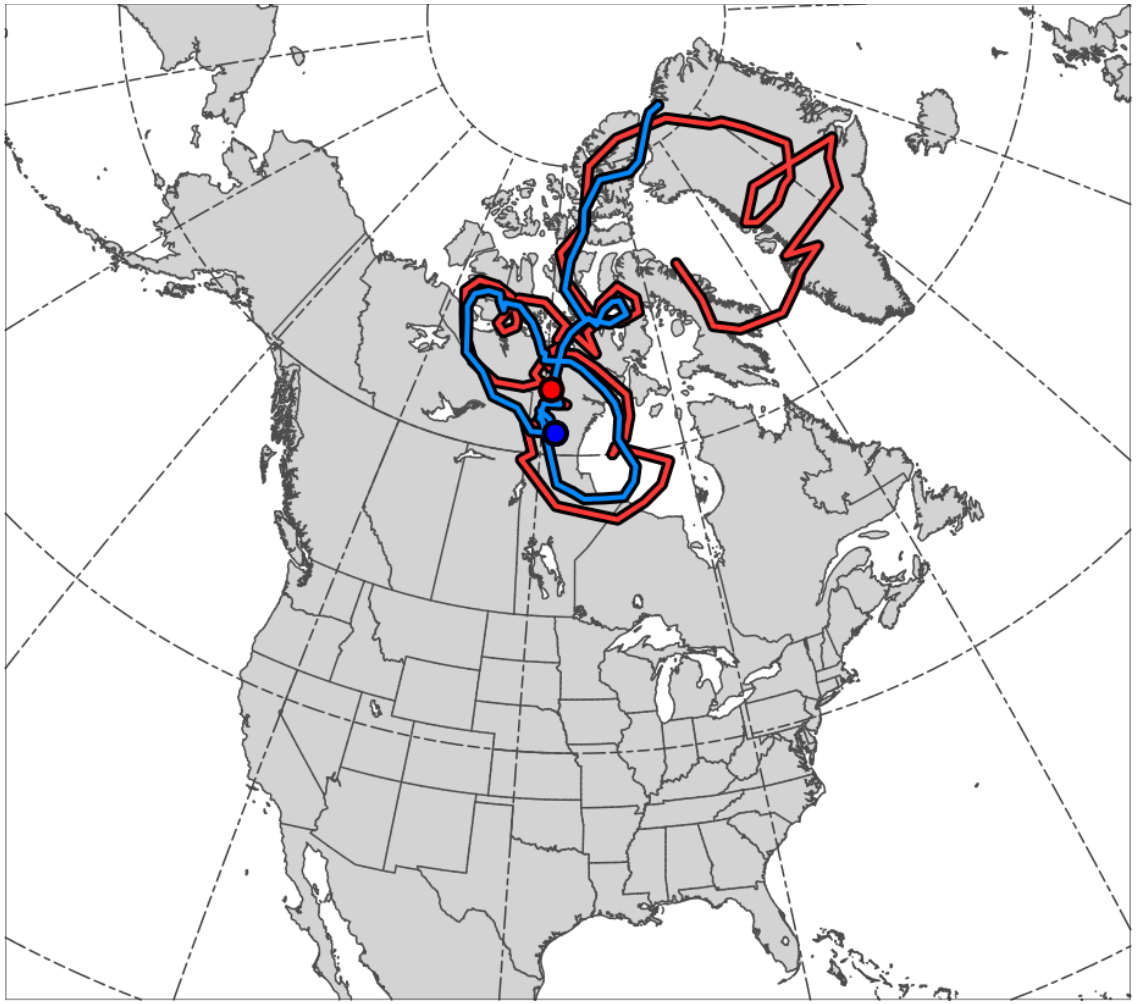
0000 UTC 7 Jan 1982



- **TPV Track:**
  - **Genesis:** 0600 UTC 15 Dec 1981
  - **Lysis:** 0000 UTC 13 Jan 1982
  - **Lifetime:** ~29 days
- **Cold Pool Track:**
  - **Genesis:** 1800 UTC 20 Dec 1981
  - **Lysis:** 1800 UTC 13 Jan 1982
  - **Lifetime:** ~24 days

Tracks for Jan 1982 CAO

0000 UTC 8 Jan 1982

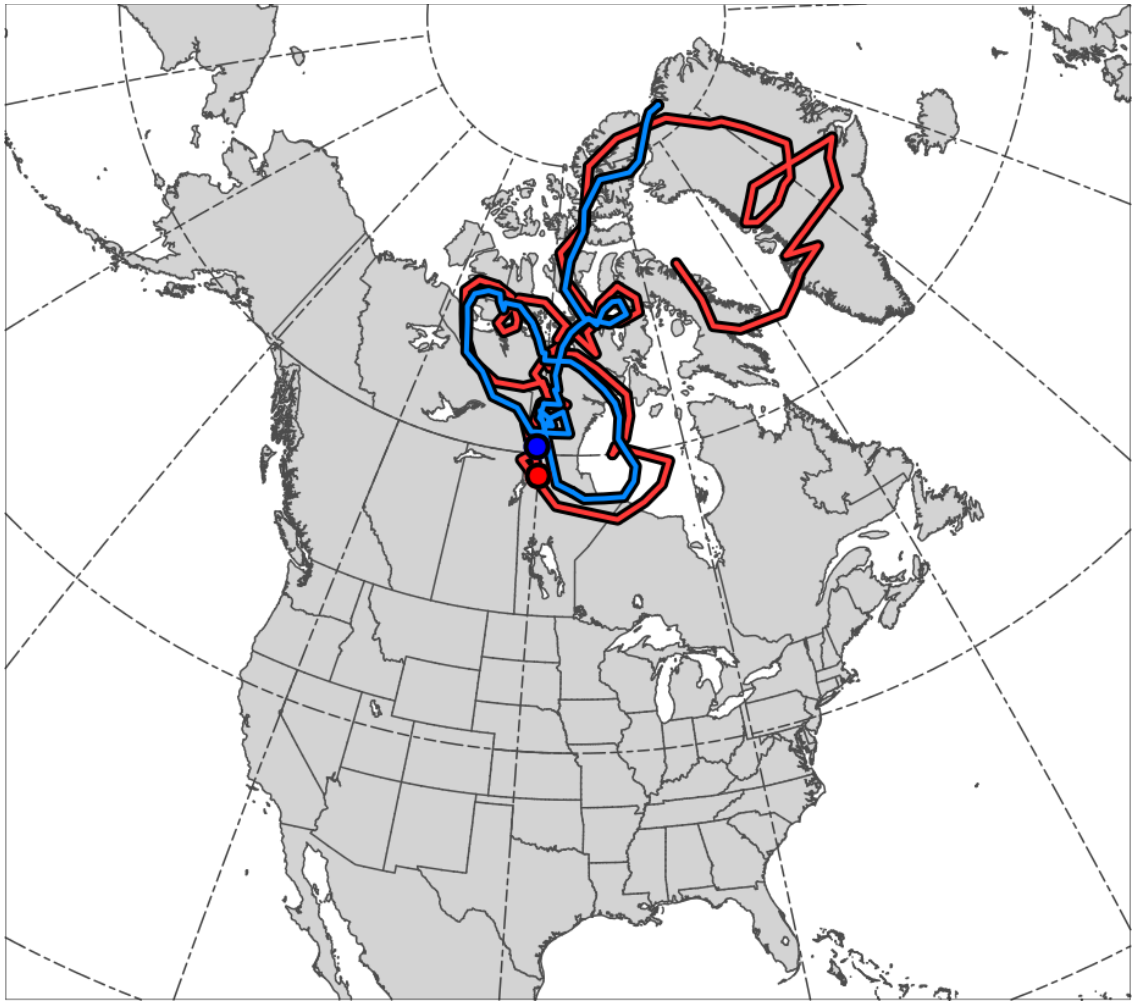


TPV Cold Pool

- **TPV Track:**
  - **Genesis:** 0600 UTC 15 Dec 1981
  - **Lysis:** 0000 UTC 13 Jan 1982
  - **Lifetime:** ~29 days
- **Cold Pool Track:**
  - **Genesis:** 1800 UTC 20 Dec 1981
  - **Lysis:** 1800 UTC 13 Jan 1982
  - **Lifetime:** ~24 days

Tracks for Jan 1982 CAO

0000 UTC 9 Jan 1982

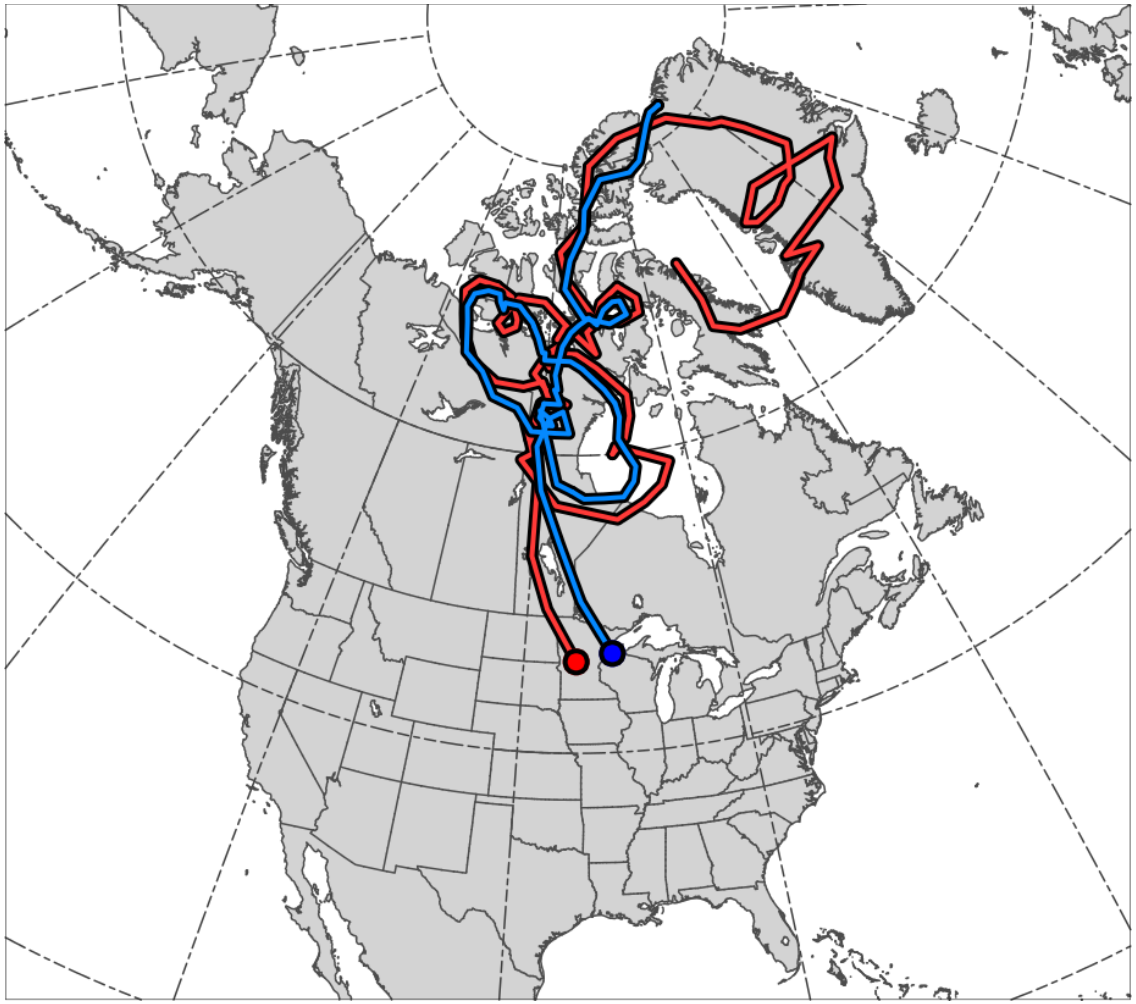


TPV Cold Pool

- **TPV Track:**
  - **Genesis:** 0600 UTC 15 Dec 1981
  - **Lysis:** 0000 UTC 13 Jan 1982
  - **Lifetime:** ~29 days
- **Cold Pool Track:**
  - **Genesis:** 1800 UTC 20 Dec 1981
  - **Lysis:** 1800 UTC 13 Jan 1982
  - **Lifetime:** ~24 days

Tracks for Jan 1982 CAO

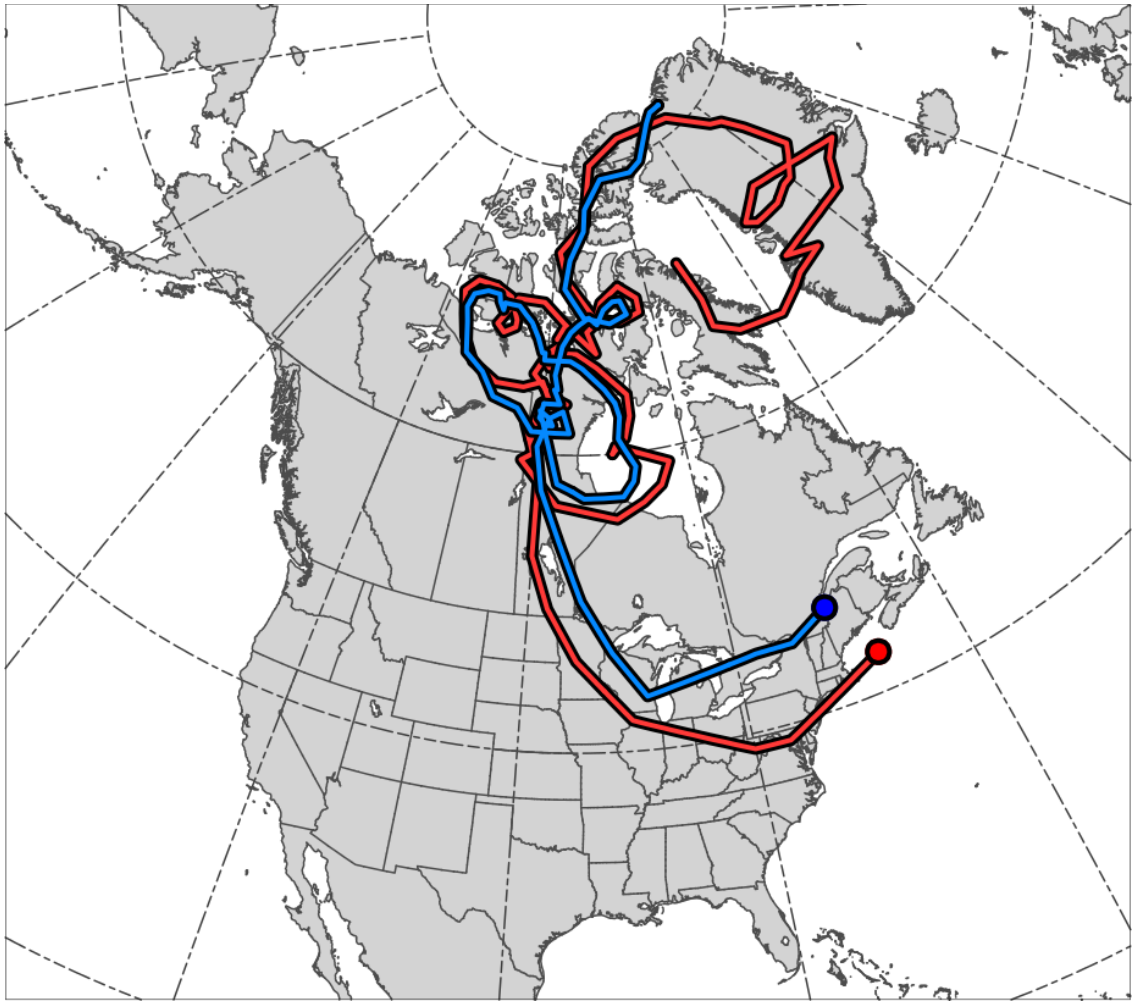
0000 UTC 10 Jan 1982



- **TPV Track:**
  - **Genesis:** 0600 UTC 15 Dec 1981
  - **Lysis:** 0000 UTC 13 Jan 1982
  - **Lifetime:** ~29 days
- **Cold Pool Track:**
  - **Genesis:** 1800 UTC 20 Dec 1981
  - **Lysis:** 1800 UTC 13 Jan 1982
  - **Lifetime:** ~24 days

Tracks for Jan 1982 CAO

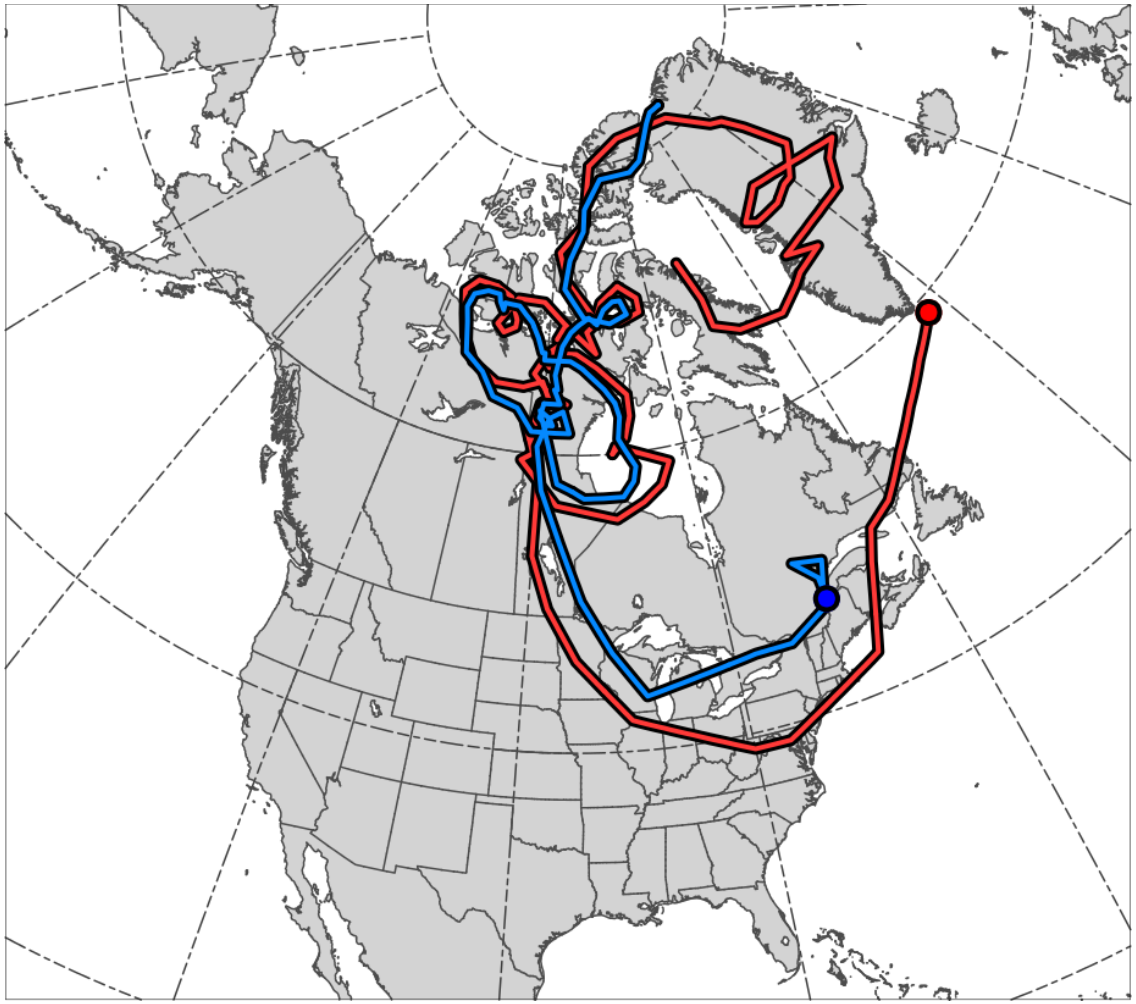
0000 UTC 11 Jan 1982



- **TPV Track:**
  - **Genesis:** 0600 UTC 15 Dec 1981
  - **Lysis:** 0000 UTC 13 Jan 1982
  - **Lifetime:** ~29 days
- **Cold Pool Track:**
  - **Genesis:** 1800 UTC 20 Dec 1981
  - **Lysis:** 1800 UTC 13 Jan 1982
  - **Lifetime:** ~24 days

Tracks for Jan 1982 CAO

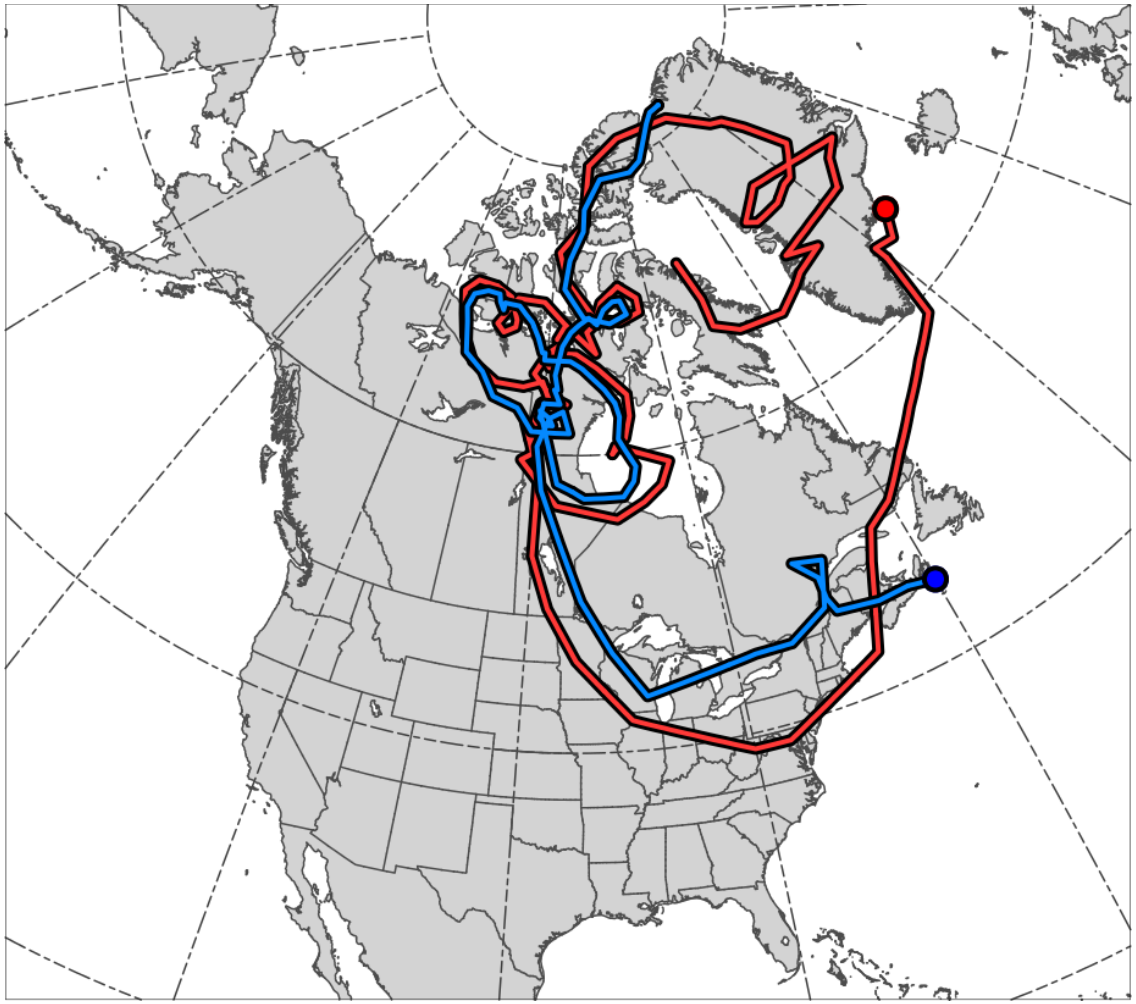
0000 UTC 12 Jan 1982



- **TPV Track:**
  - **Genesis:** 0600 UTC 15 Dec 1981
  - **Lysis:** 0000 UTC 13 Jan 1982
  - **Lifetime:** ~29 days
- **Cold Pool Track:**
  - **Genesis:** 1800 UTC 20 Dec 1981
  - **Lysis:** 1800 UTC 13 Jan 1982
  - **Lifetime:** ~24 days

Tracks for Jan 1982 CAO

0000 UTC 13 Jan 1982



- **TPV Track:**
  - **Genesis:** 0600 UTC 15 Dec 1981
  - **Lysis:** 0000 UTC 13 Jan 1982
  - **Lifetime:** ~29 days
- **Cold Pool Track:**
  - **Genesis:** 1800 UTC 20 Dec 1981
  - **Lysis:** 1800 UTC 13 Jan 1982
  - **Lifetime:** ~24 days

CAO Identification

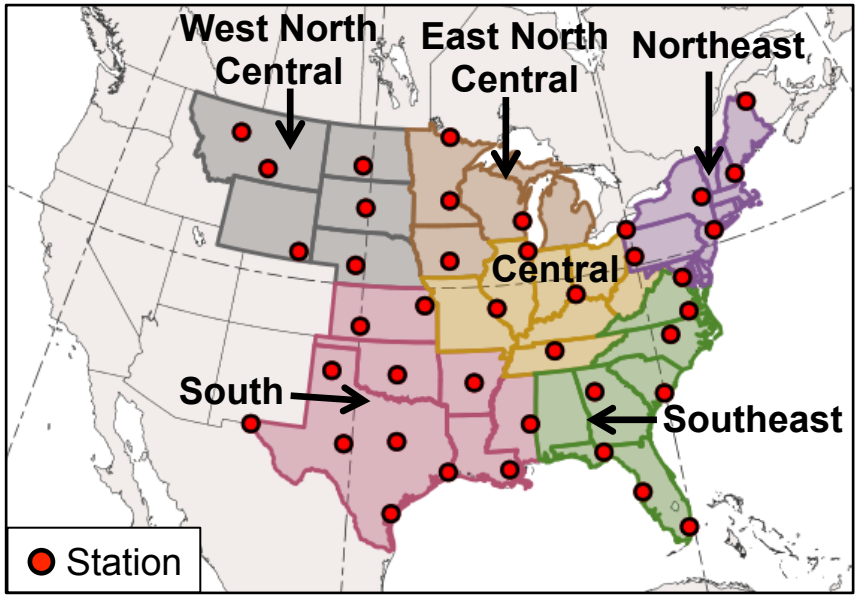
- Regional CAOs are identified using CAO climatology created by Zachary Murphy
  - Refer to poster 966 in Bosart Symposium Poster Session 1 on 25 January 2017
- **Dataset:** Global Historical Climatology Network-Daily minimum temperature data
- **Period of study:** 1979–2015

CAO Identification

- **Regions studied:** Six NCEI regions encompassing central and eastern United States (US) are examined (regions are color shaded in map below)

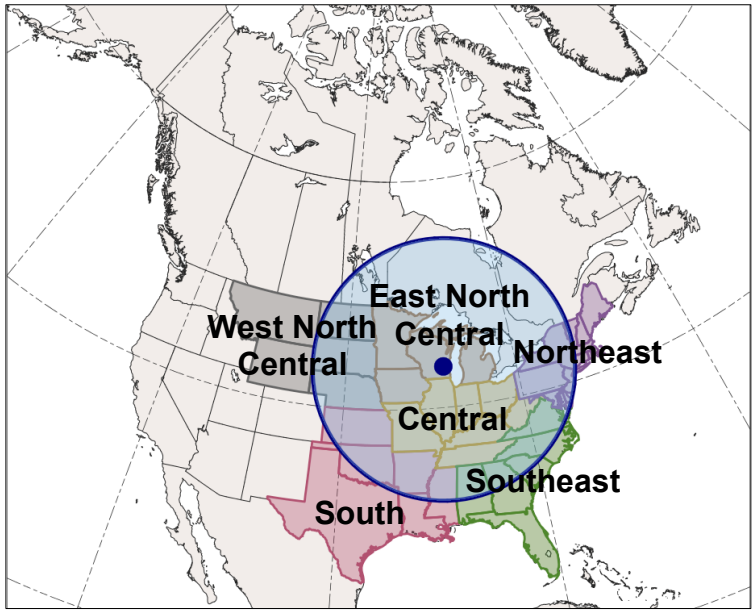
- **Regional CAO Definition:**

  – Two or more stations within an NCEI region experience three or more consecutive days where minimum temperatures fall below the 31-day centered moving average of the 5th percentile minimum temperature for those days and share at least one overlapping day



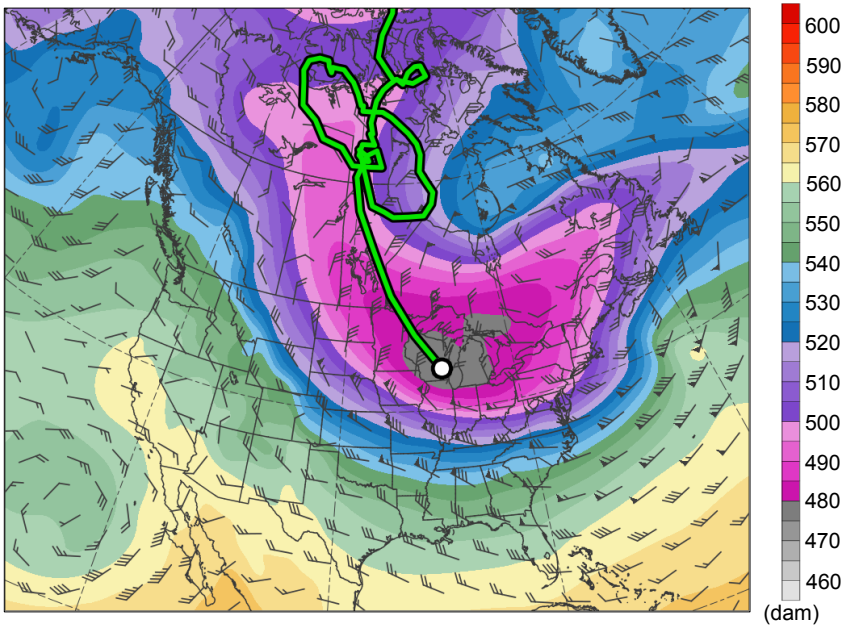
CAOs Linked to Cold Pools

- **Identification of CAOs linked to cold pools:**
  - Circle of radius 1250 km surrounding 1000–500-hPa thickness minimum of a cold pool must overlap at least one grid point (using a 0.5° grid) of region for at least one time stamp (6 h interval) during CAO



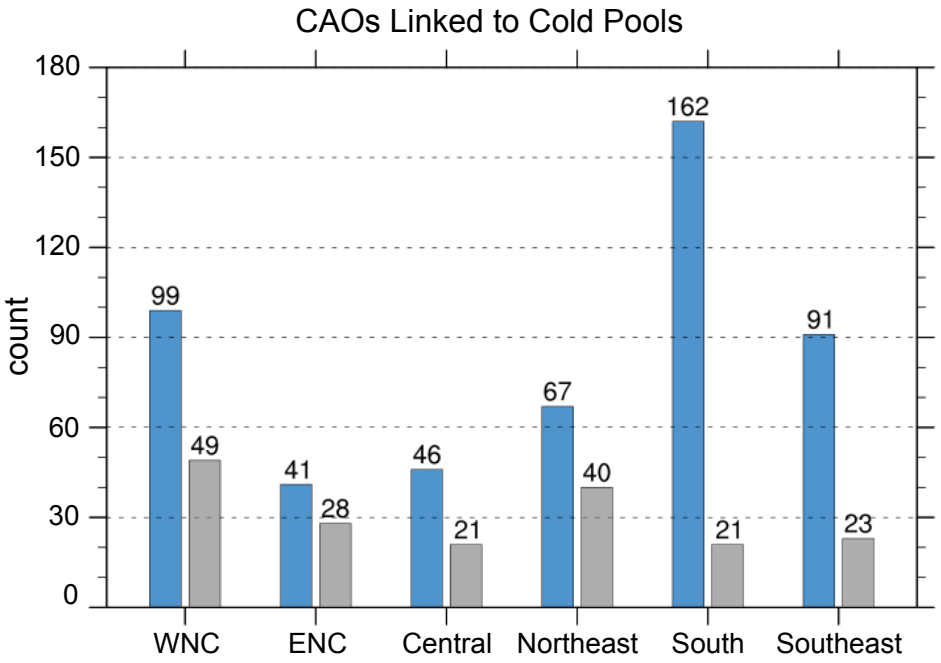
NCEI regions and 1250-km radius circle surrounding cold pool thickness minimum (blue dot)

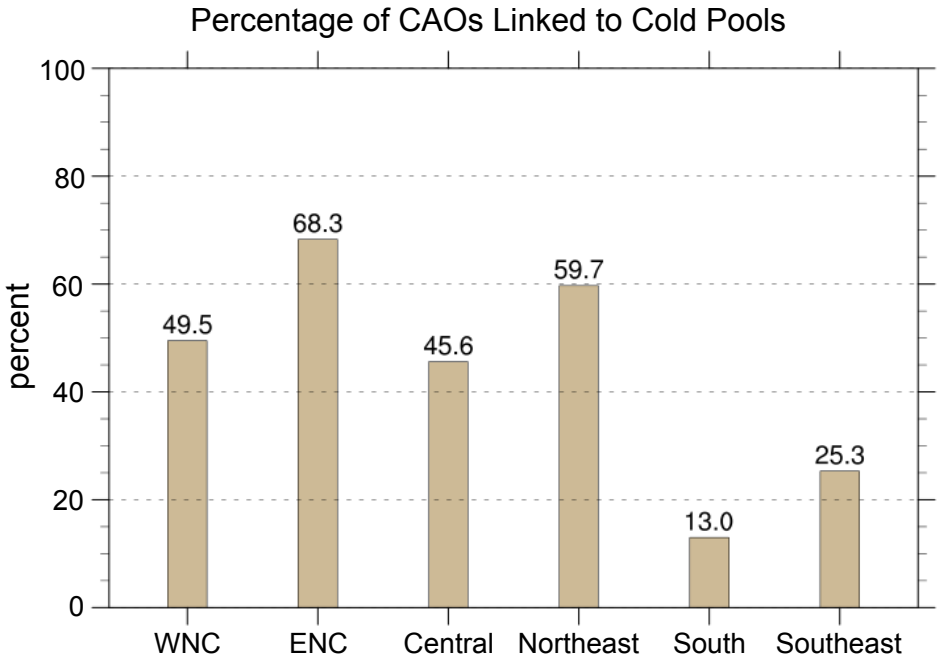
0600 UTC 10 Jan 1982



1000–500-hPa thickness (dam, shaded), 700-hPa wind (m s^{-1}, flags and barbs), cold pool location (white dot), and cold pool track (green line)

CAOs Linked to Cold Pools

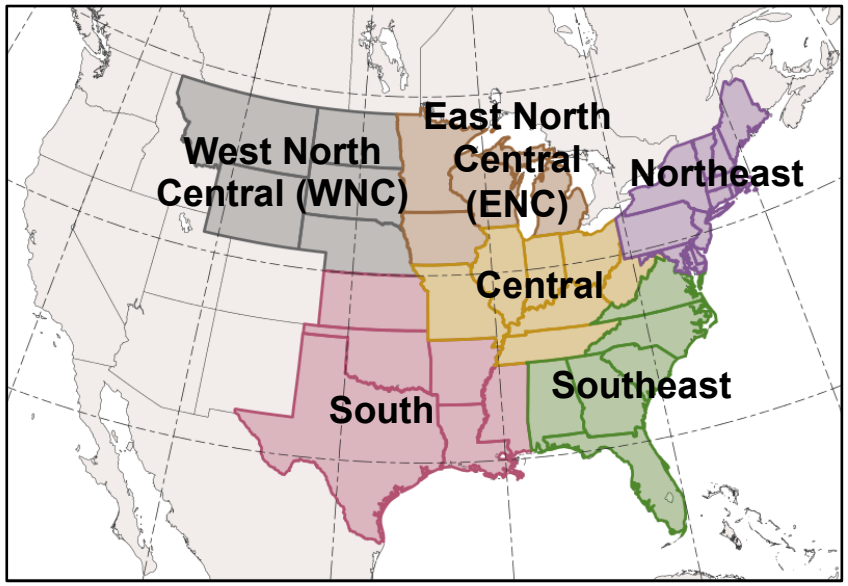




Total number of CAOs

Number of unique CAOs linked to at least one cold pool

Percentage of unique CAOs linked to at least one cold pool [(gray/blue) × 100]



Cold Pools Associated with TPVs

- **Identification of cold pools associated with TPVs:**
  - Centers of TPVs and cold pools must be located within 500 km of one another for at least two consecutive days to be identified as a match

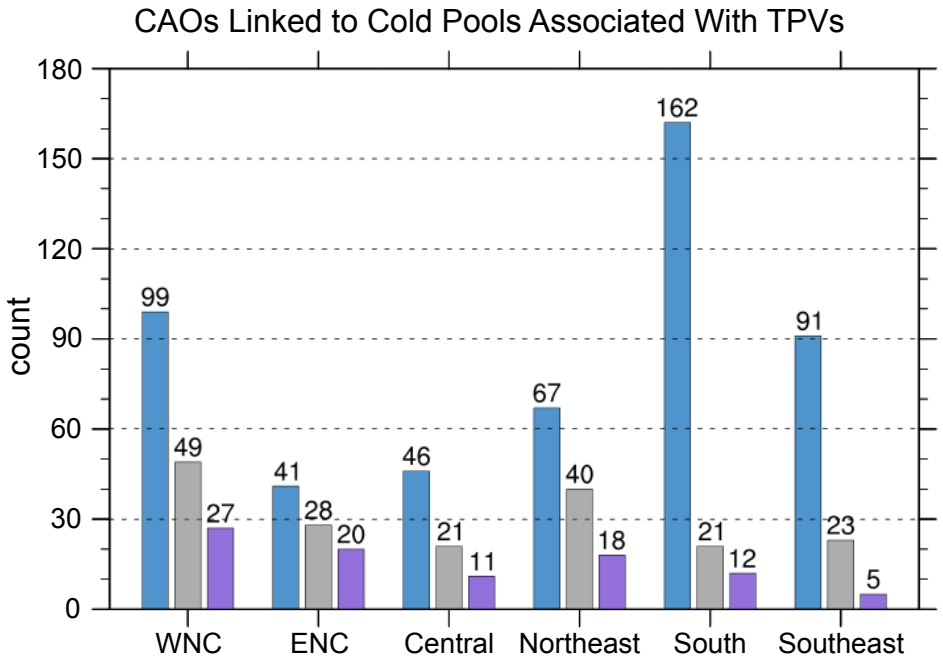
- 347 out of a total of 1262 TPVs or 27.5% match with at least one cold pool

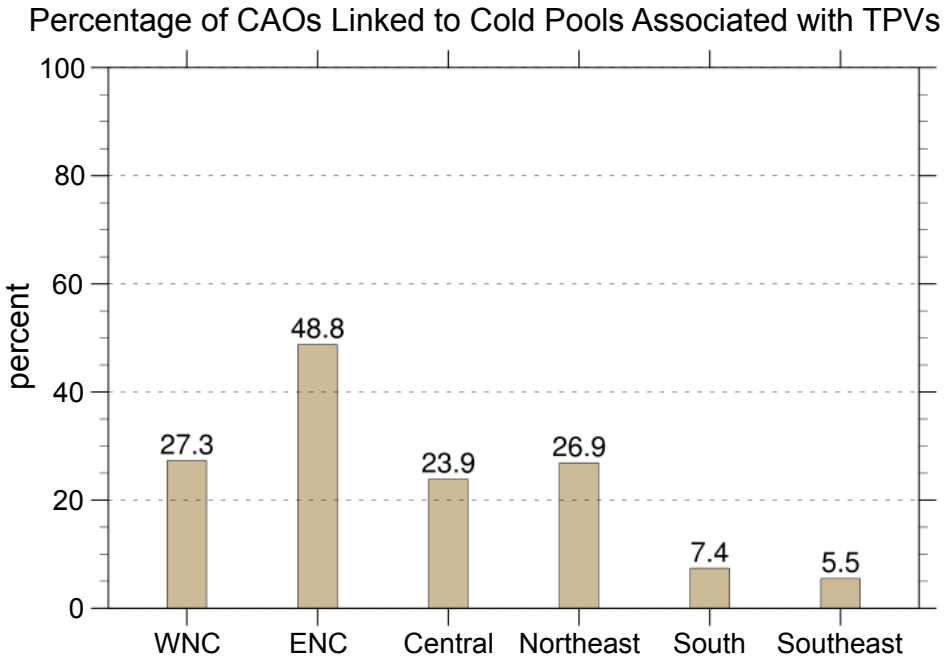
- 348 out of a total of 776 cold pools or 44.8% match with at least one TPV

CAOs Linked to Cold Pools Associated with TPVs

- CAOs that are linked to cold pools associated with TPVs can now be identified

CAOs Linked to Cold Pools Associated with TPVs



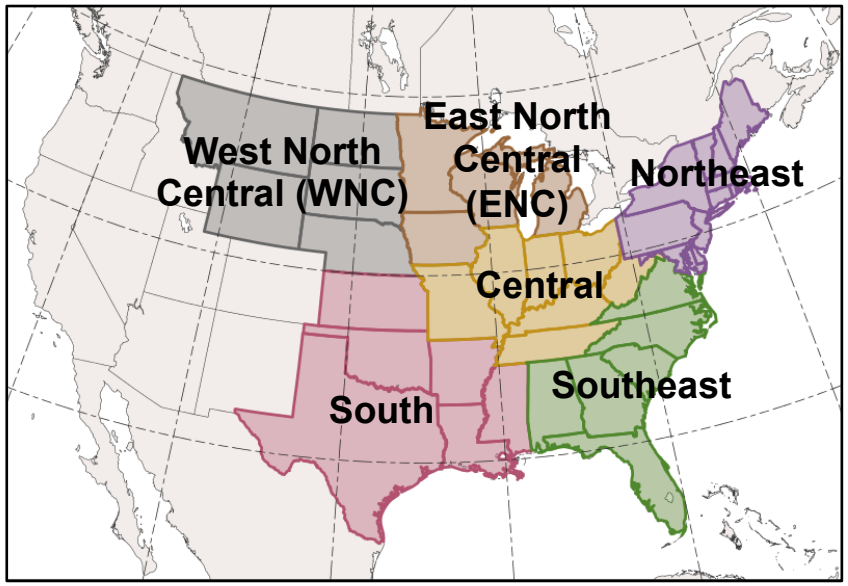


Total number of CAOs

Number of unique CAOs linked to at least one cold pool

Number of unique CAOs linked to at least one cold pool associated with a TPV

Percentage of unique CAOs linked to at least one cold pool associated with a TPV [(purple/blue) × 100]



Conclusions

- Large spatial overlap and temporal coincidence of TPV and cold pool in Jan 1982 CAO case suggests that the TPV and cold pool are dynamically linked, demonstrating that:
  - The influence of TPVs can extend through the depth of the troposphere and over a widespread geographical area
  - The equatorward transport of TPVs can lead to CAO development
- There is a greater number and higher percentage of CAOs linked to cold pools over northern regions of US compared to southern regions

Conclusions

- 347 out of a total of 1262 TPVs or 27.5% match with at least one cold pool
- TPVs may not match with cold pools because:
  - TPVs may be too small or too weak to be associated with trackable cold pools
  - TPVs may be associated with thickness troughs that are not trackable
  - TPVs may match with cold pools not meeting latitude criteria
- It is possible that TPVs that do not match with cold pools may still contribute to CAO development

Conclusions

- There is a greater number and higher percentage of CAOs linked to cold pools associated with TPVs over northern regions of US compared to southern regions

- TPVs play a role in the development of a moderate proportion of CAOs, suggesting that improved understanding of TPVs may lead to improved understanding of CAOs

Conclusions

- There is a greater number and higher percentage of CAOs linked to cold pools associated with TPVs over northern regions of US compared to southern regions

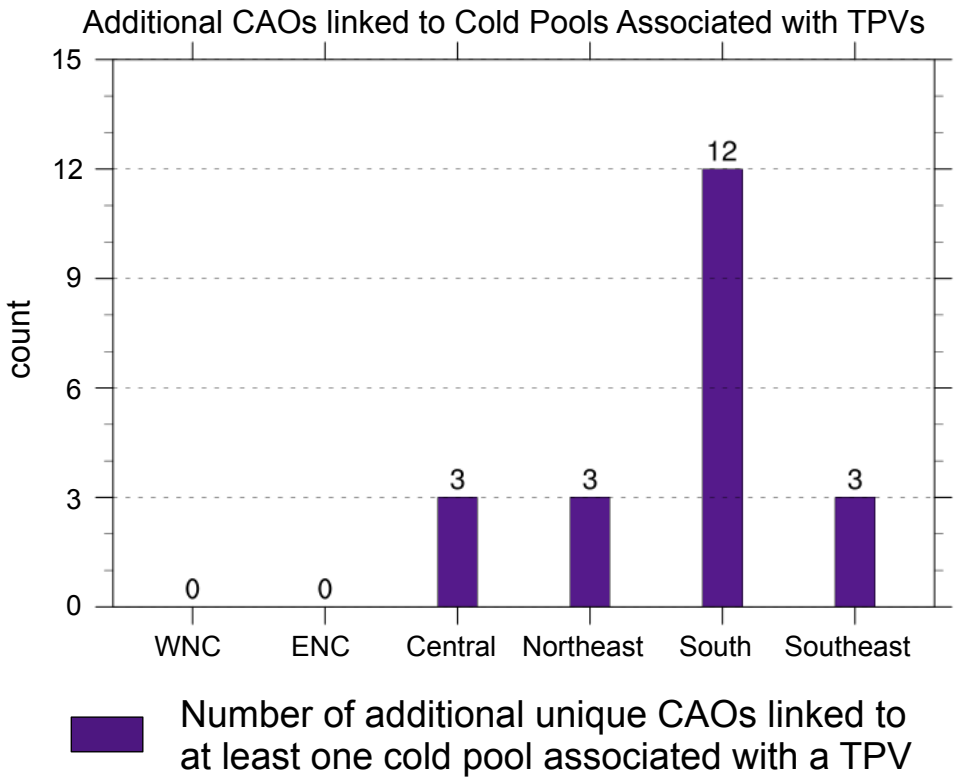
- TPVs play a role in the development of a moderate proportion of CAOs, suggesting that improved understanding of TPVs may lead to improved understanding of CAOs

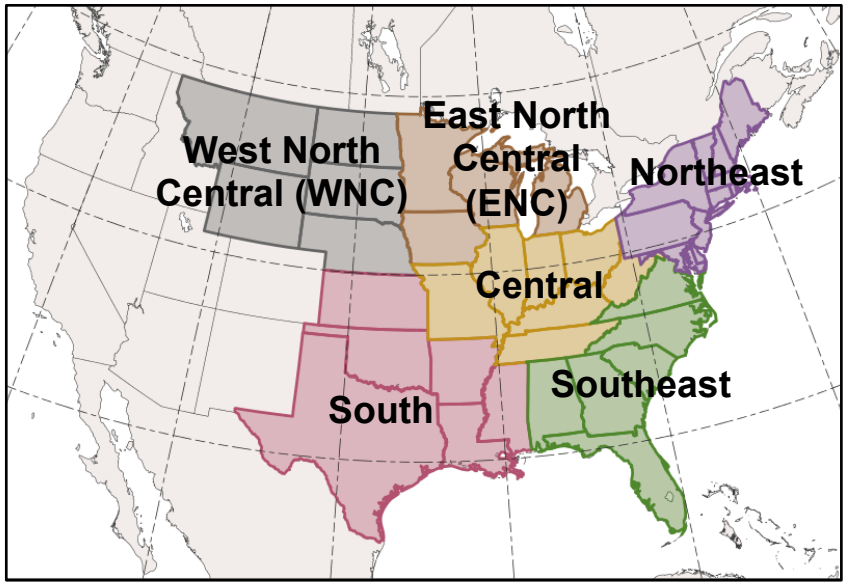
Acknowledgments

Special thanks to Nicholas Szapiro, Steven Cavallo, Zachary Murphy, and Philippe Papin

Extra Slides

Sensitivity to Cold Pool Circle Radius Threshold





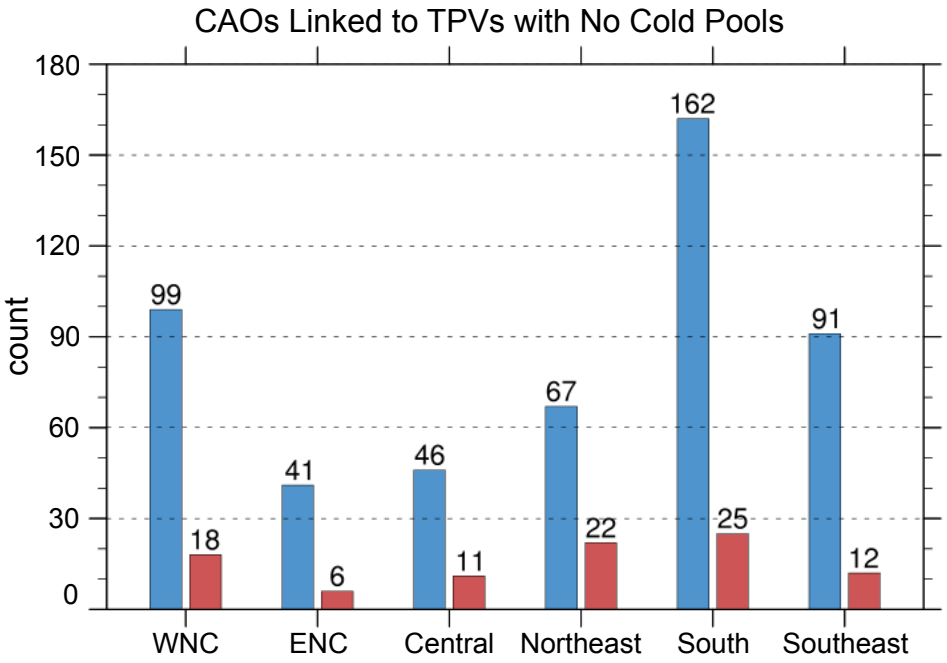
- Additional unique CAOs that are identified as CAOs linked to cold pools associated with TPVs in other regions using the 1250-km cold pool radius, but not in these regions, even though the dates of all of these CAOs overlap

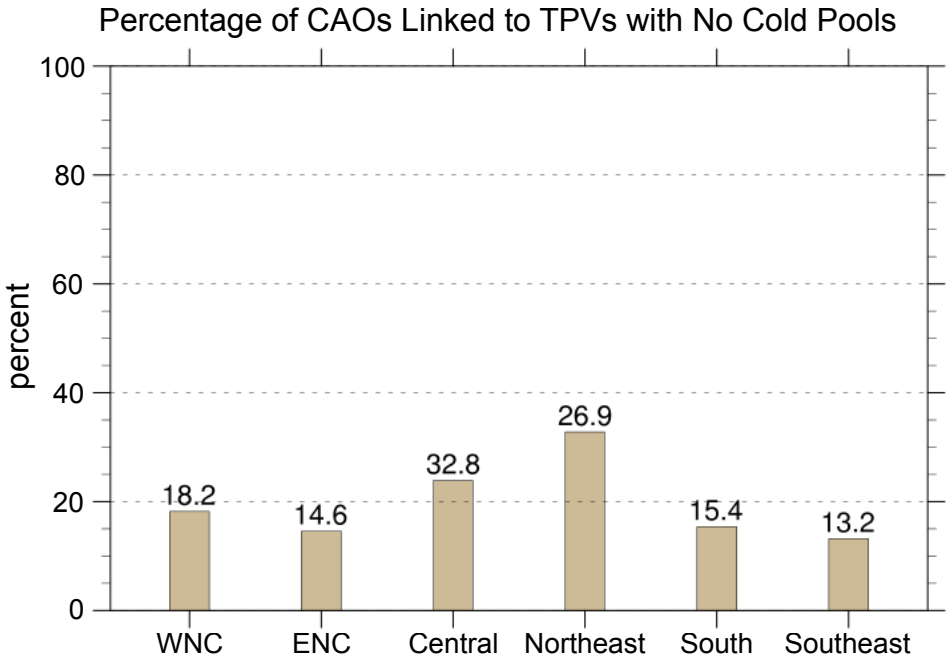
- In these regions, these additional CAOs are only identified using a radius of 1500 km, 1750 km, or 2000 km for the cold pool circle

CAOs Linked to TPVs with No Cold Pool

- The following slide shows the number of unique CAOs that are linked to TPVs not associated with cold pools
  - These unique CAOs are only those that are not included in the list of unique CAOs linked to cold pools associated with TPVs discussed in main presentation
- Require that a circle of radius 1250 km surrounding DT theta minimum of TPV must overlap at least one grid point (using a 0.5° grid) of region for at least one time stamp (6 h interval) during CAO

CAOs Linked to TPVs with No Cold Pool

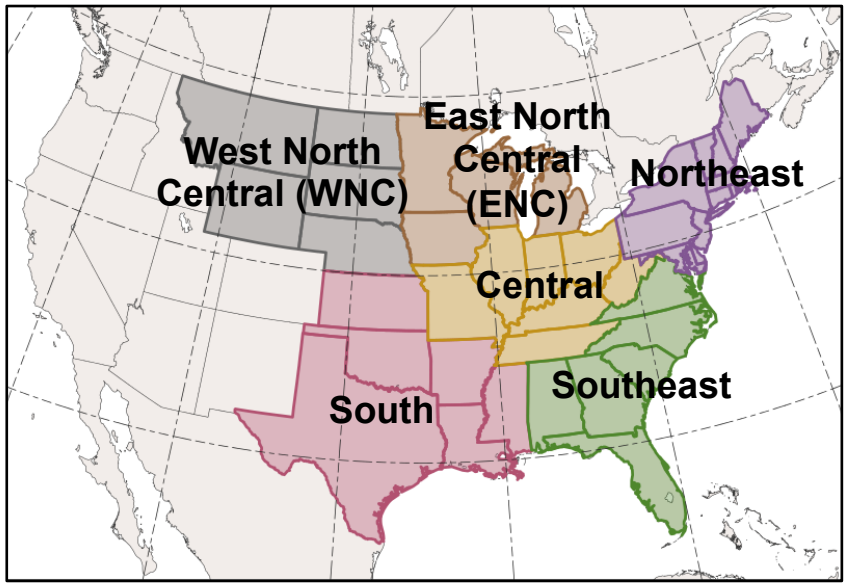




Total number of CAOs

Number of unique CAOs linked to at least one TPV with no cold pool

Percentage of unique CAOs linked to at least one TPV with no cold pool [(red/blue) × 100]



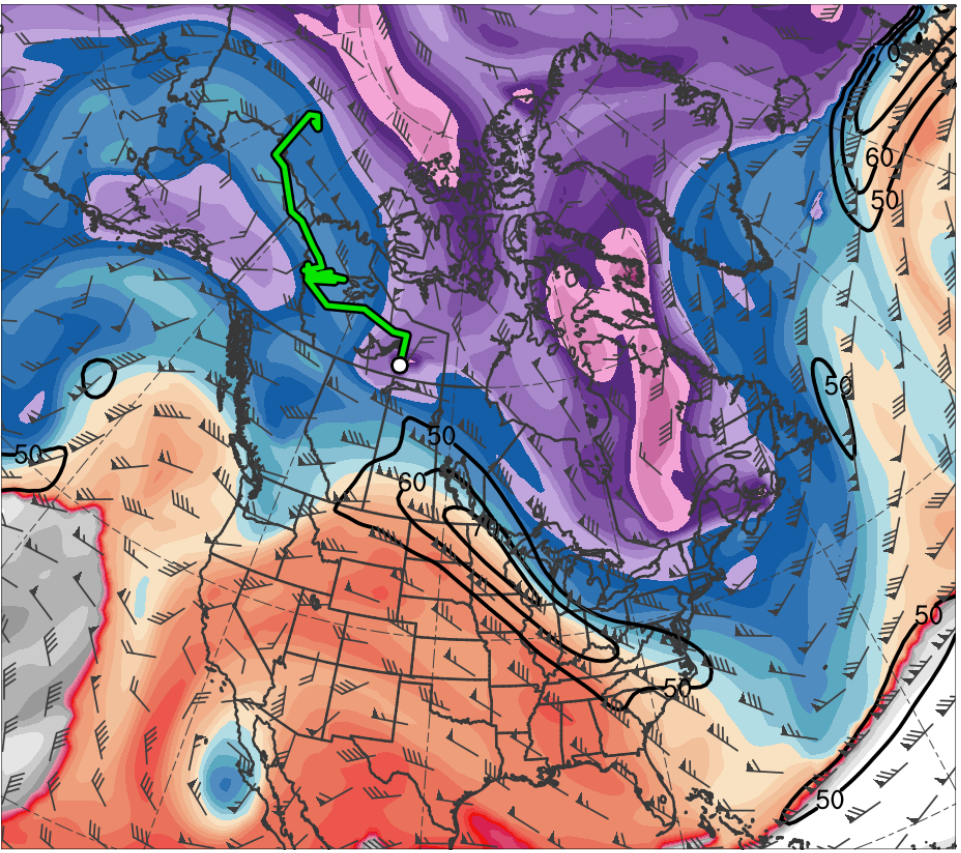
Example of a CAO that is linked to a TPV not associated with a cold pool

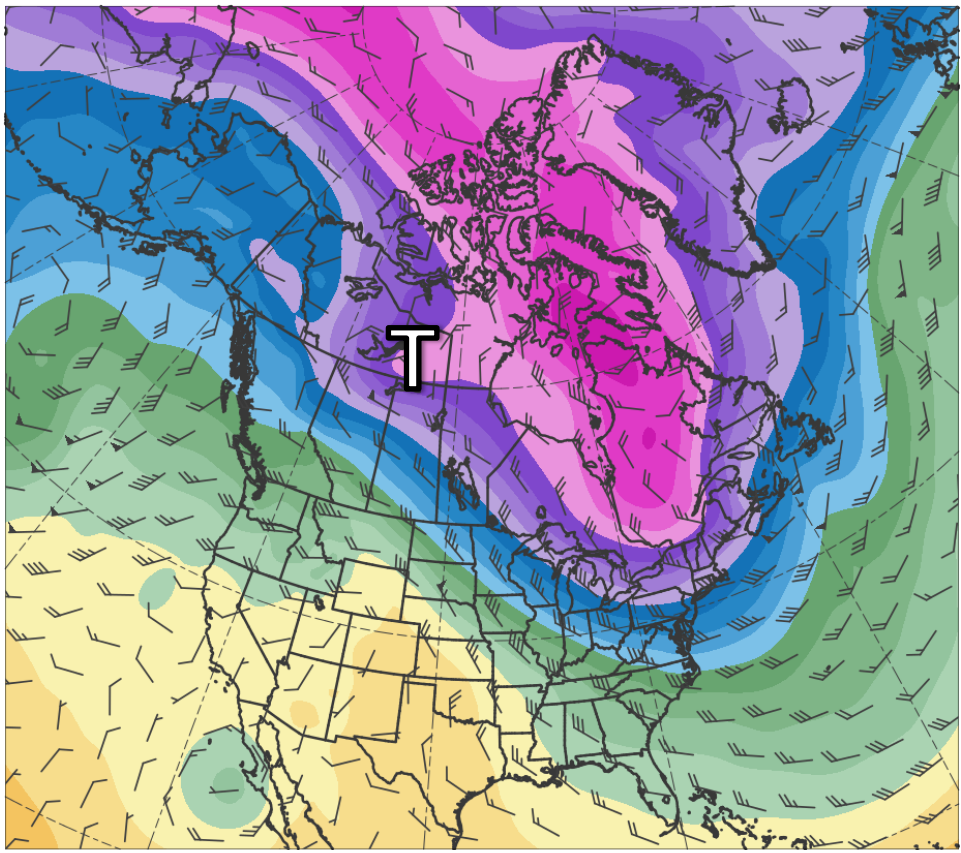
TPV contributes to 21–24 Jan 2005 CAO over Northeast region

TPV with No Cold Pool

0000 UTC 21 Jan 2005

Data Source: ERA-Interim





(K)
252 258 264 270 276 282 288 294 300 306 312 318 324 330 336 342 348 354 360 366 372 378

(dam)
460 470 480 490 500 510 520 530 540 550 560 570 580 590 600

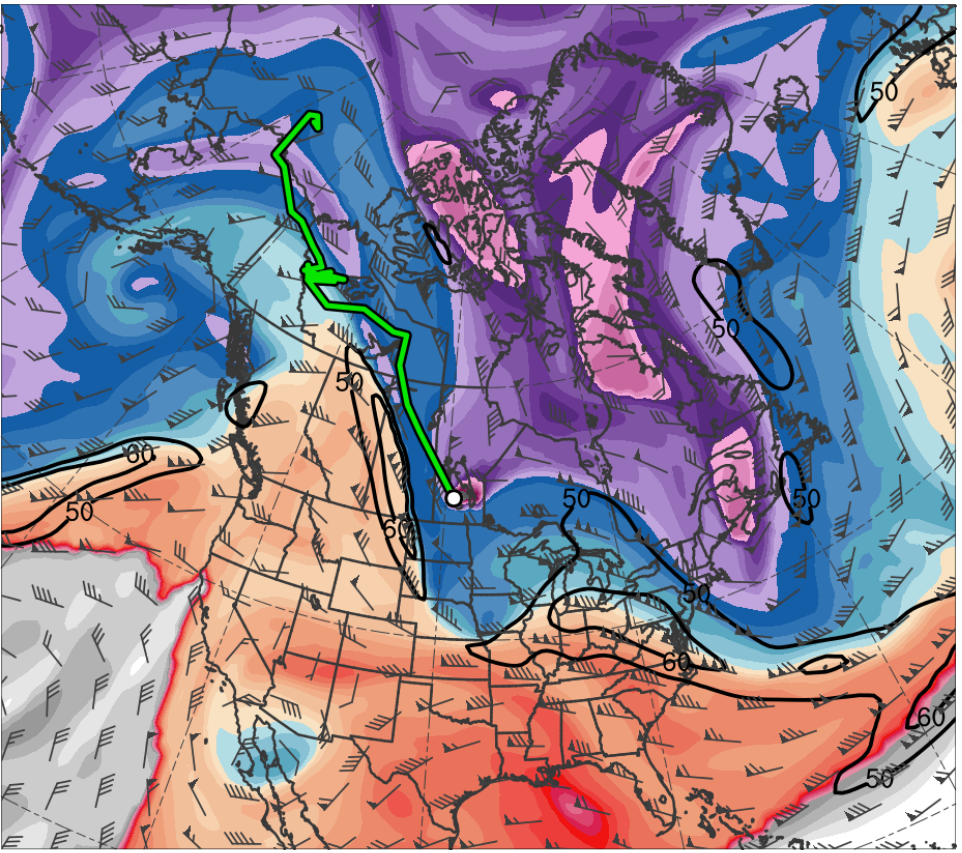
Potential temperature (K, shaded), wind speed (black, every 10 m s^{-1} starting at 50 m s^{-1}), and wind (m s^{-1}, flags and barbs) on 2-PVU surface;
TPV location (white dot) and track (green line)

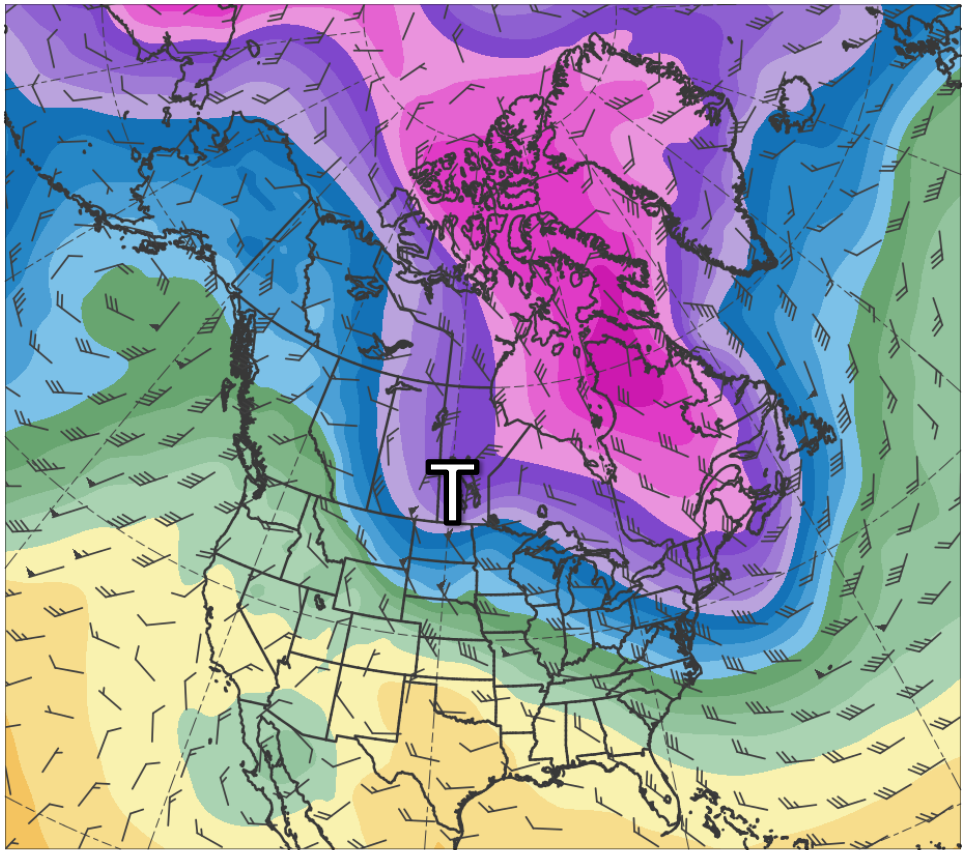
1000–500-hPa thickness (dam, shaded) and 700-hPa wind (m s^{-1}, flags and barbs)
"T" denotes thickness trough

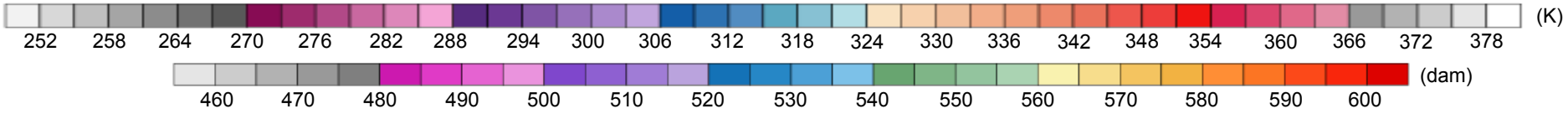
TPV with No Cold Pool

0000 UTC 22 Jan 2005

Data Source: ERA-Interim







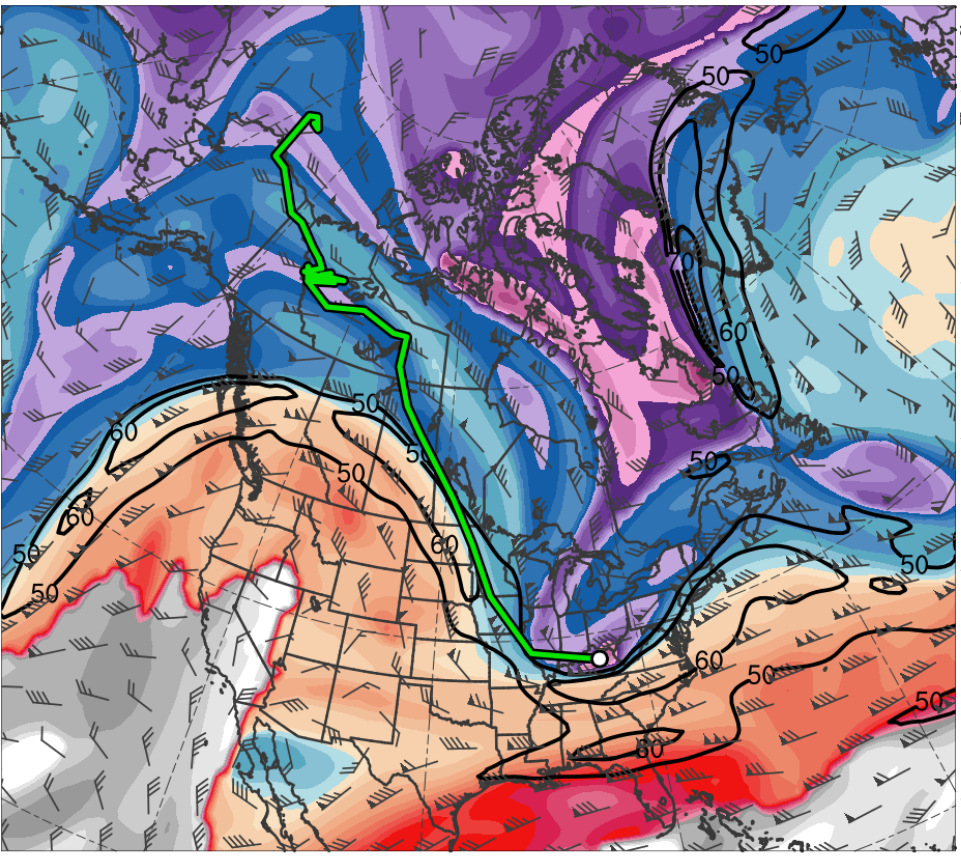
Potential temperature (K, shaded), wind speed (black, every 10 m s^{-1} starting at 50 m s^{-1}), and wind (m s^{-1}, flags and barbs) on 2-PVU surface;
TPV location (white dot) and track (green line)

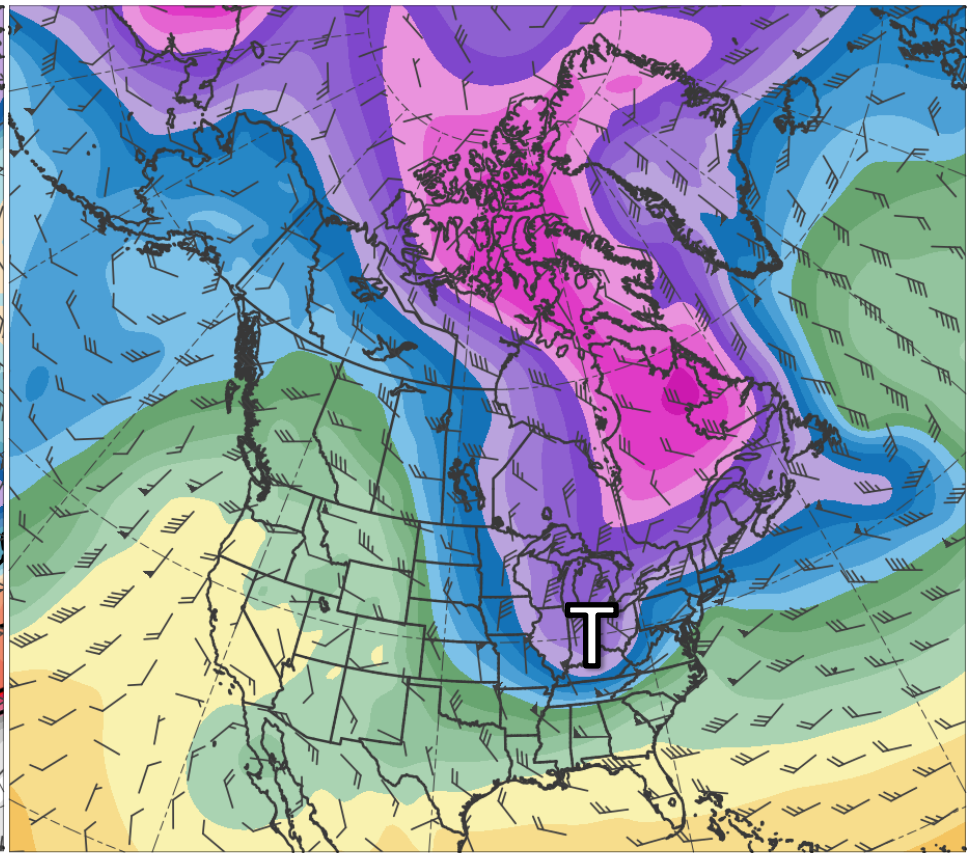
1000–500-hPa thickness (dam, shaded) and 700-hPa wind (m s^{-1}, flags and barbs)
"T" denotes thickness trough

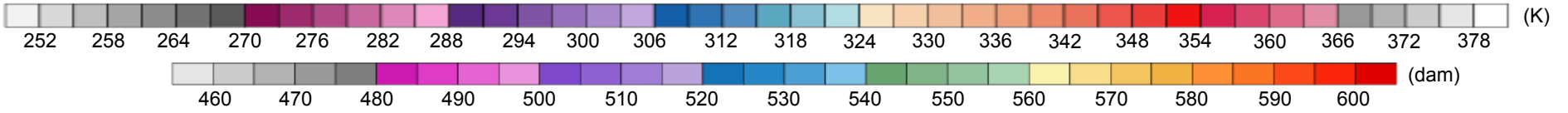
TPV with No Cold Pool

0000 UTC 23 Jan 2005

Data Source: ERA-Interim







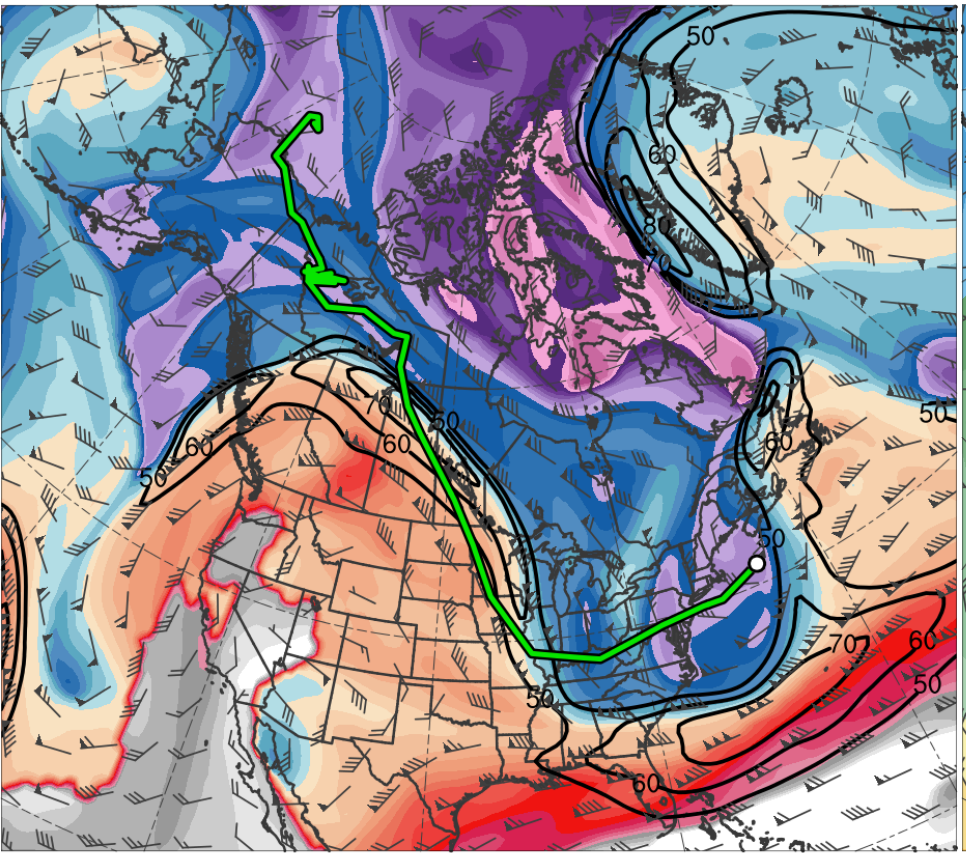
Potential temperature (K, shaded), wind speed (black, every 10 m s^{-1} starting at 50 m s^{-1}), and wind (m s^{-1}, flags and barbs) on 2-PVU surface;
TPV location (white dot) and track (green line)

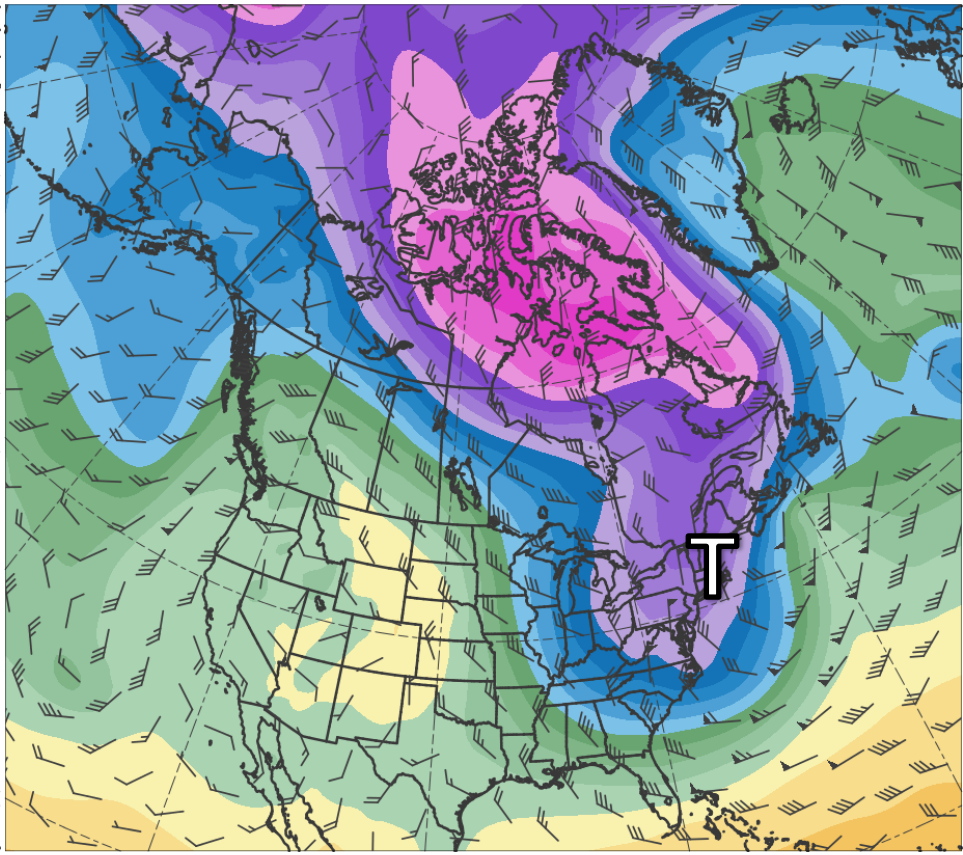
1000–500-hPa thickness (dam, shaded) and 700-hPa wind (m s^{-1}, flags and barbs)
"T" denotes thickness trough

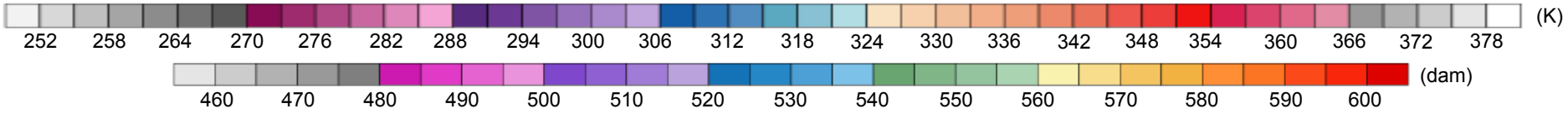
TPV with No Cold Pool

0000 UTC 24 Jan 2005

Data Source: ERA-Interim







Potential temperature (K, shaded), wind speed (black, every 10 m s^{-1} starting at 50 m s^{-1}), and wind (m s^{-1}, flags and barbs) on 2-PVU surface;
TPV location (white dot) and track (green line)

1000–500-hPa thickness (dam, shaded) and 700-hPa wind (m s^{-1}, flags and barbs)
"T" denotes thickness trough

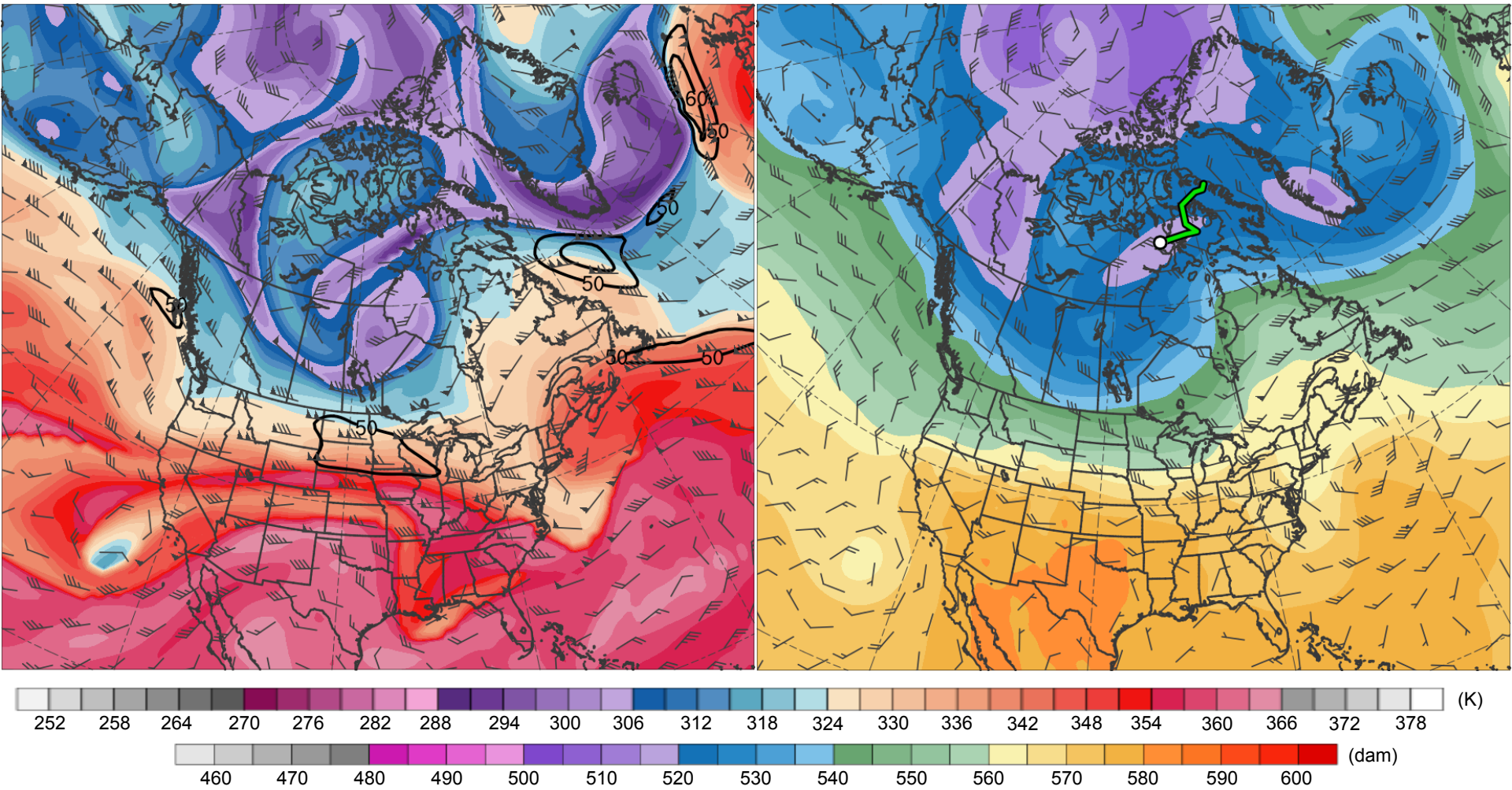
Example of a CAO that is linked to a cold pool not associated with a TPV

Cold pool contributes to 4–15 Oct 2000 CAO over much of central and eastern US

Cold Pool with No TPV

0000 UTC 3 Oct 2000

Data Source: ERA-Interim



252 258 264 270 276 282 288 294 300 306 312 318 324 330 336 342 348 354 360 366 372 378 (K)

460 470 480 490 500 510 520 530 540 550 560 570 580 590 600 (dam)

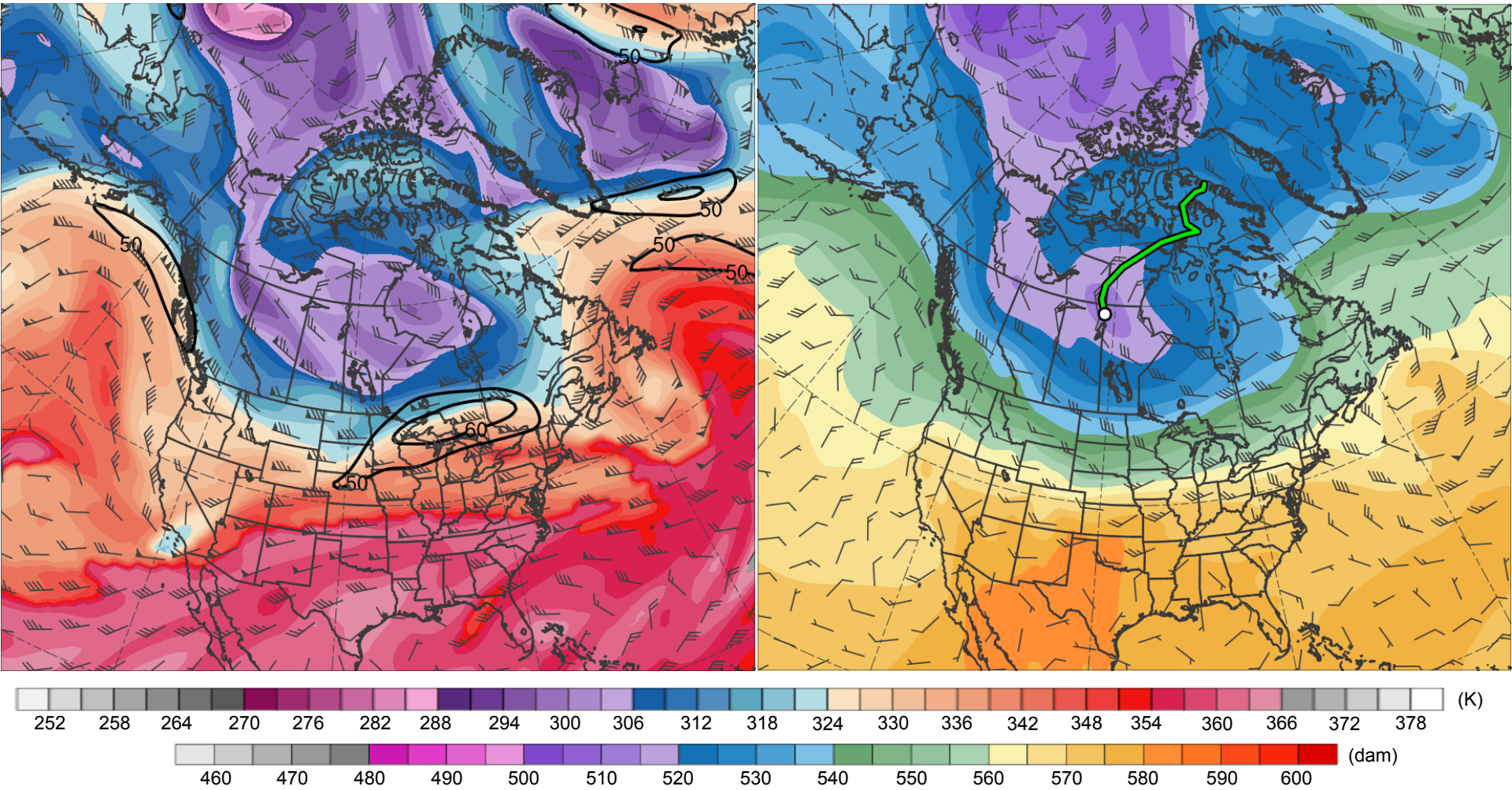
Potential temperature (K, shaded), wind speed (black, every 10 m s^{-1} starting at 50 m s^{-1}), and wind (m s^{-1}, flags and barbs) on 2-PVU surface

1000–500-hPa thickness (dam, shaded) and 700-hPa wind (m s^{-1}, flags and barbs); cold pool location (white dot) and track (green line)

Cold Pool with No TPV

0000 UTC 4 Oct 2000

Data Source: ERA-Interim



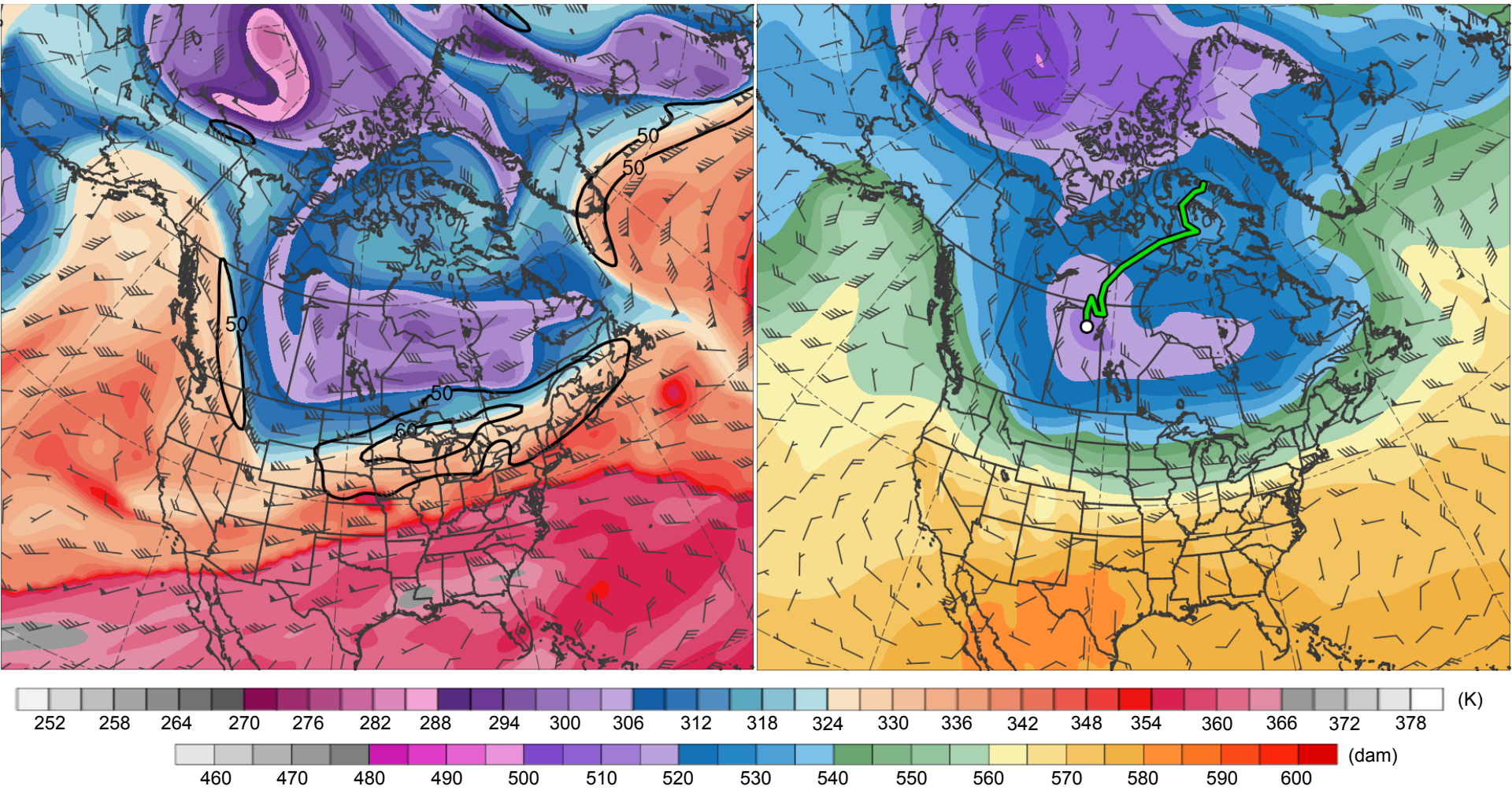
Potential temperature (K, shaded), wind speed (black, every 10 m s^{-1} starting at 50 m s^{-1}), and wind (m s^{-1}, flags and barbs) on 2-PVU surface

1000–500-hPa thickness (dam, shaded) and 700-hPa wind (m s^{-1}, flags and barbs); cold pool location (white dot) and track (green line)

Cold Pool with No TPV

0000 UTC 5 Oct 2000

Data Source: ERA-Interim



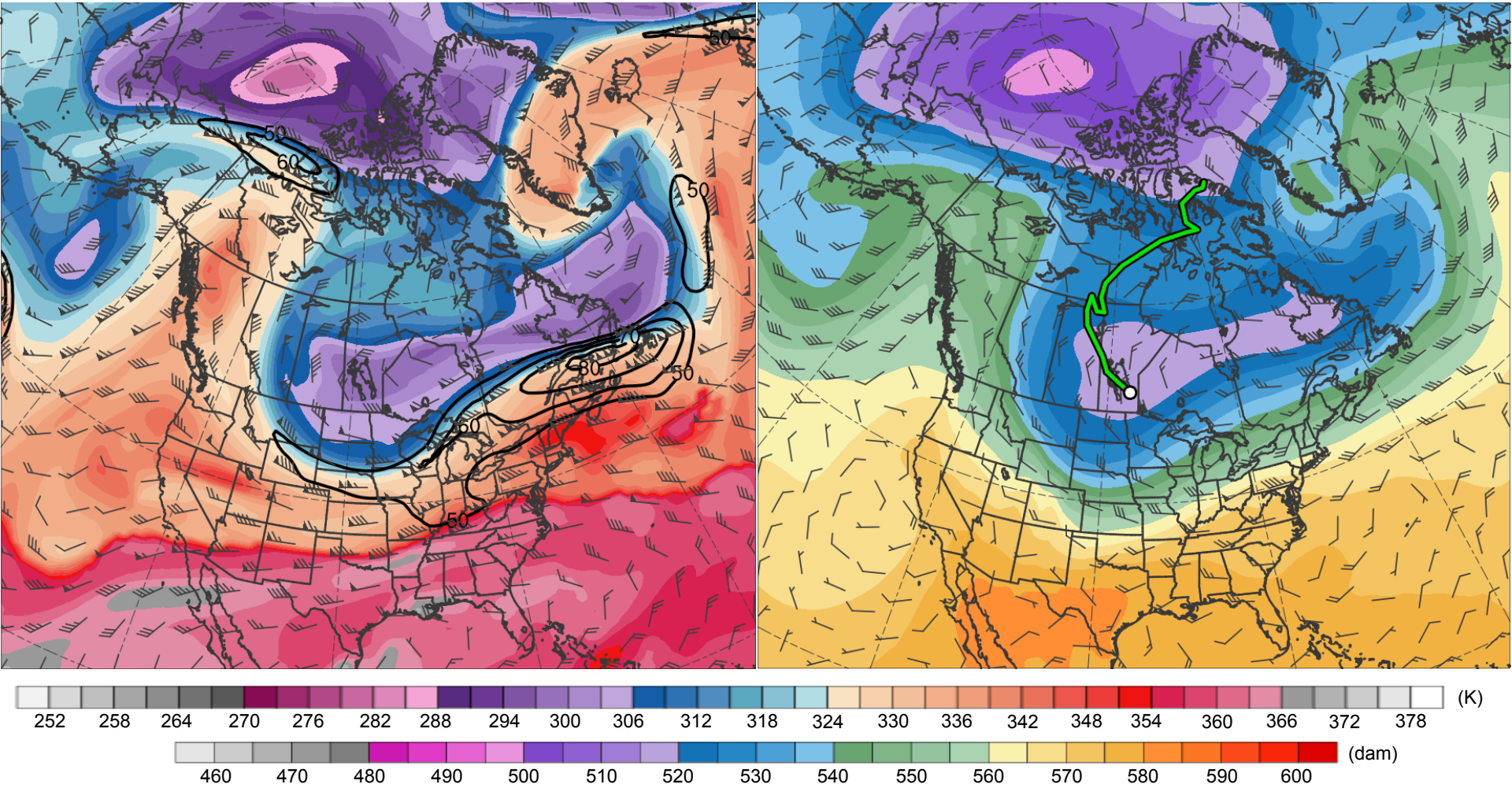
Potential temperature (K, shaded), wind speed (black, every 10 m s^{-1} starting at 50 m s^{-1}), and wind (m s^{-1}, flags and barbs) on 2-PVU surface

1000–500-hPa thickness (dam, shaded) and 700-hPa wind (m s^{-1}, flags and barbs); cold pool location (white dot) and track (green line)

Cold Pool with No TPV

0000 UTC 6 Oct 2000

Data Source: ERA-Interim



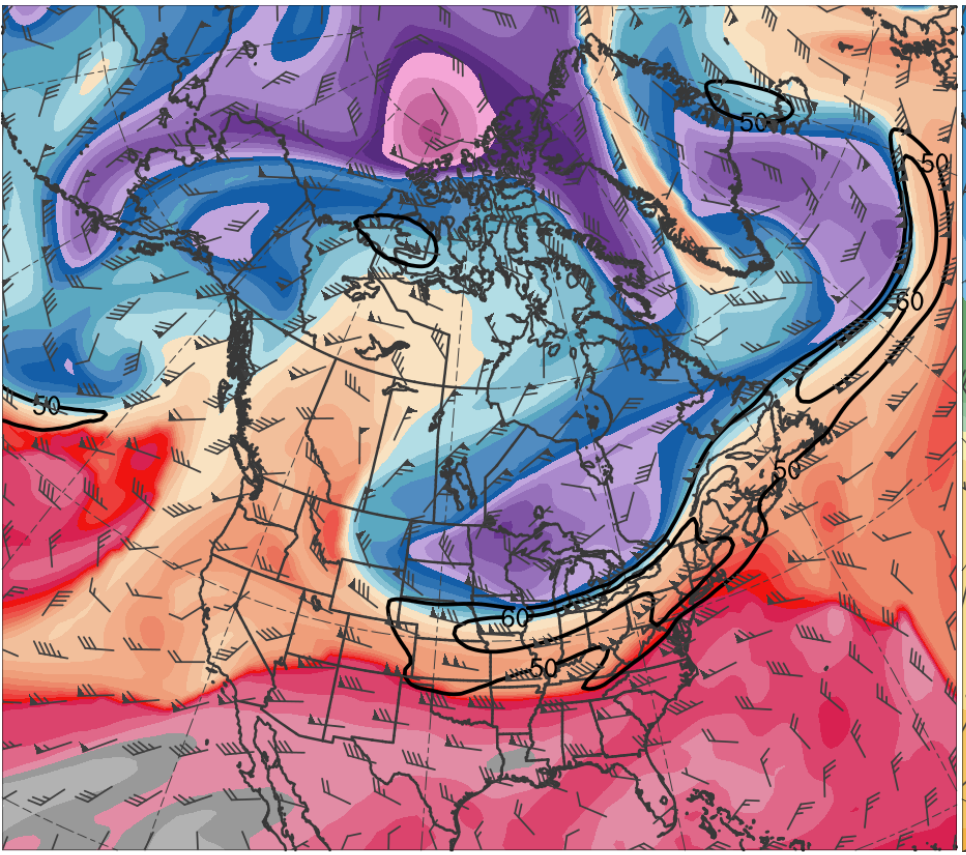
Potential temperature (K, shaded), wind speed (black, every 10 m s^{-1} starting at 50 m s^{-1}), and wind (m s^{-1}, flags and barbs) on 2-PVU surface

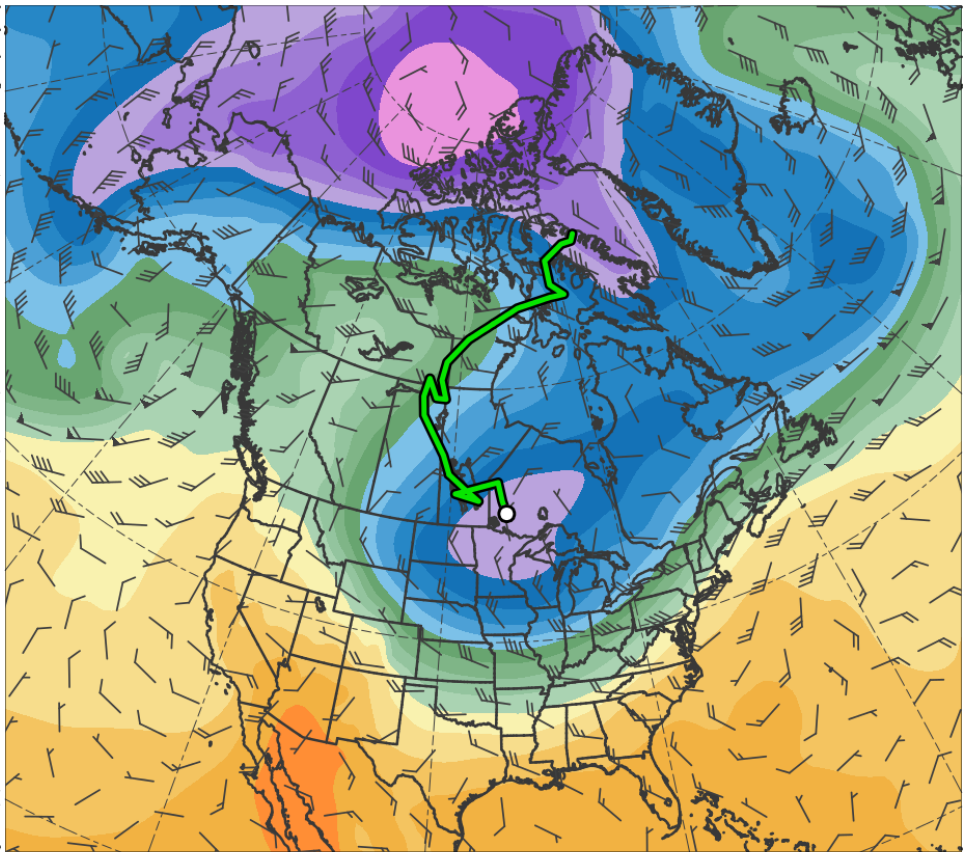
1000–500-hPa thickness (dam, shaded) and 700-hPa wind (m s^{-1}, flags and barbs); cold pool location (white dot) and track (green line)

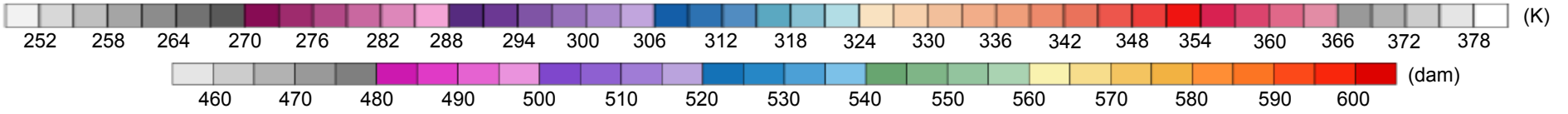
Cold Pool with No TPV

0000 UTC 7 Oct 2000

Data Source: ERA-Interim







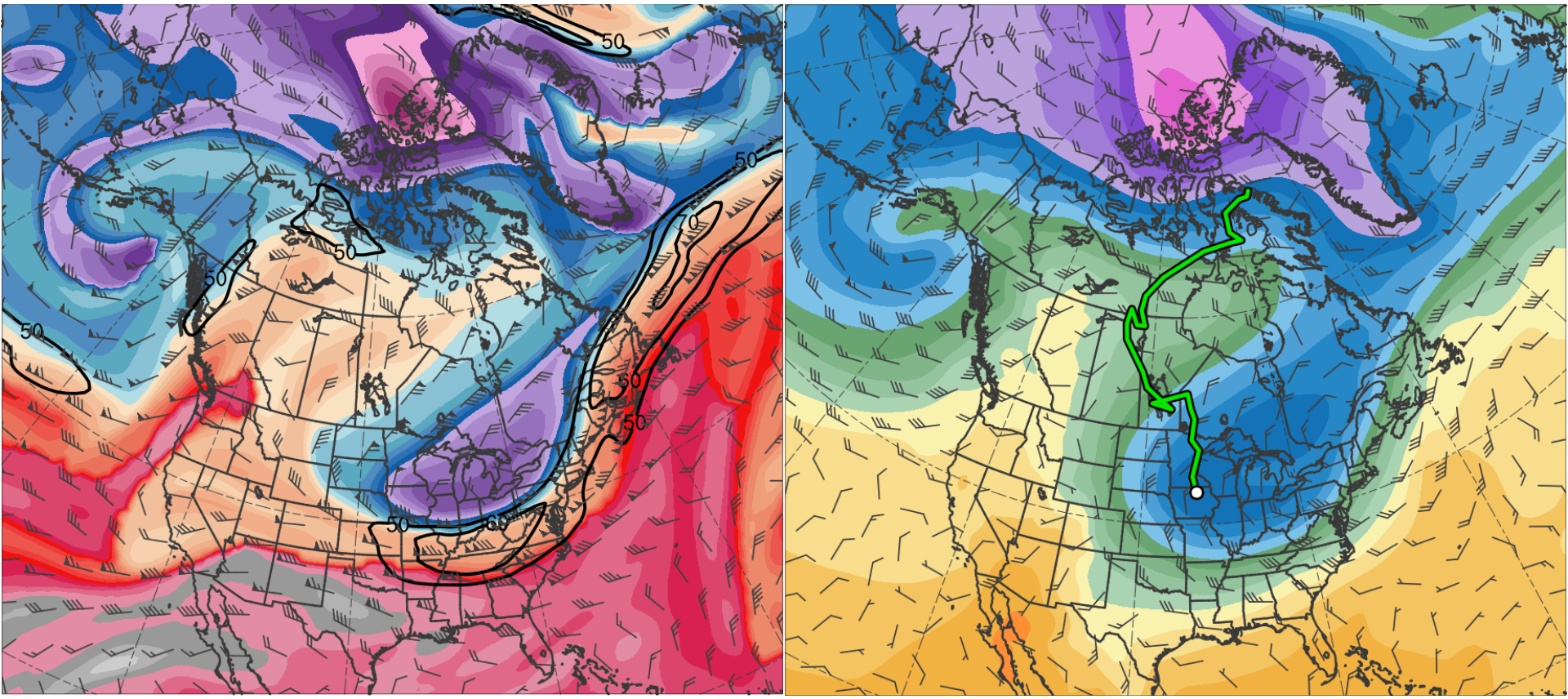
Potential temperature (K, shaded), wind speed (black, every 10 m s^{-1} starting at 50 m s^{-1}), and wind (m s^{-1}, flags and barbs) on 2-PVU surface

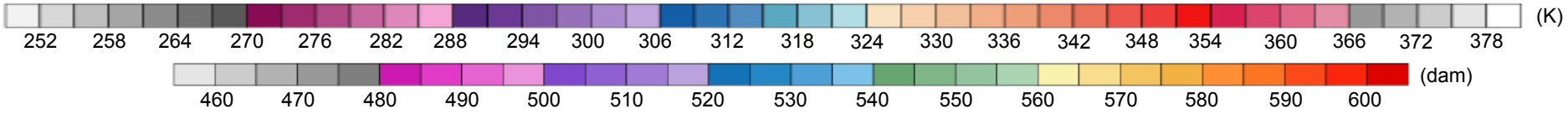
1000–500-hPa thickness (dam, shaded) and 700-hPa wind (m s^{-1}, flags and barbs); cold pool location (white dot) and track (green line)

Cold Pool with No TPV

0000 UTC 8 Oct 2000

Data Source: ERA-Interim





Potential temperature (K, shaded), wind speed (black, every 10 m s^{-1} starting at 50 m s^{-1}), and wind (m s^{-1}, flags and barbs) on 2-PVU surface

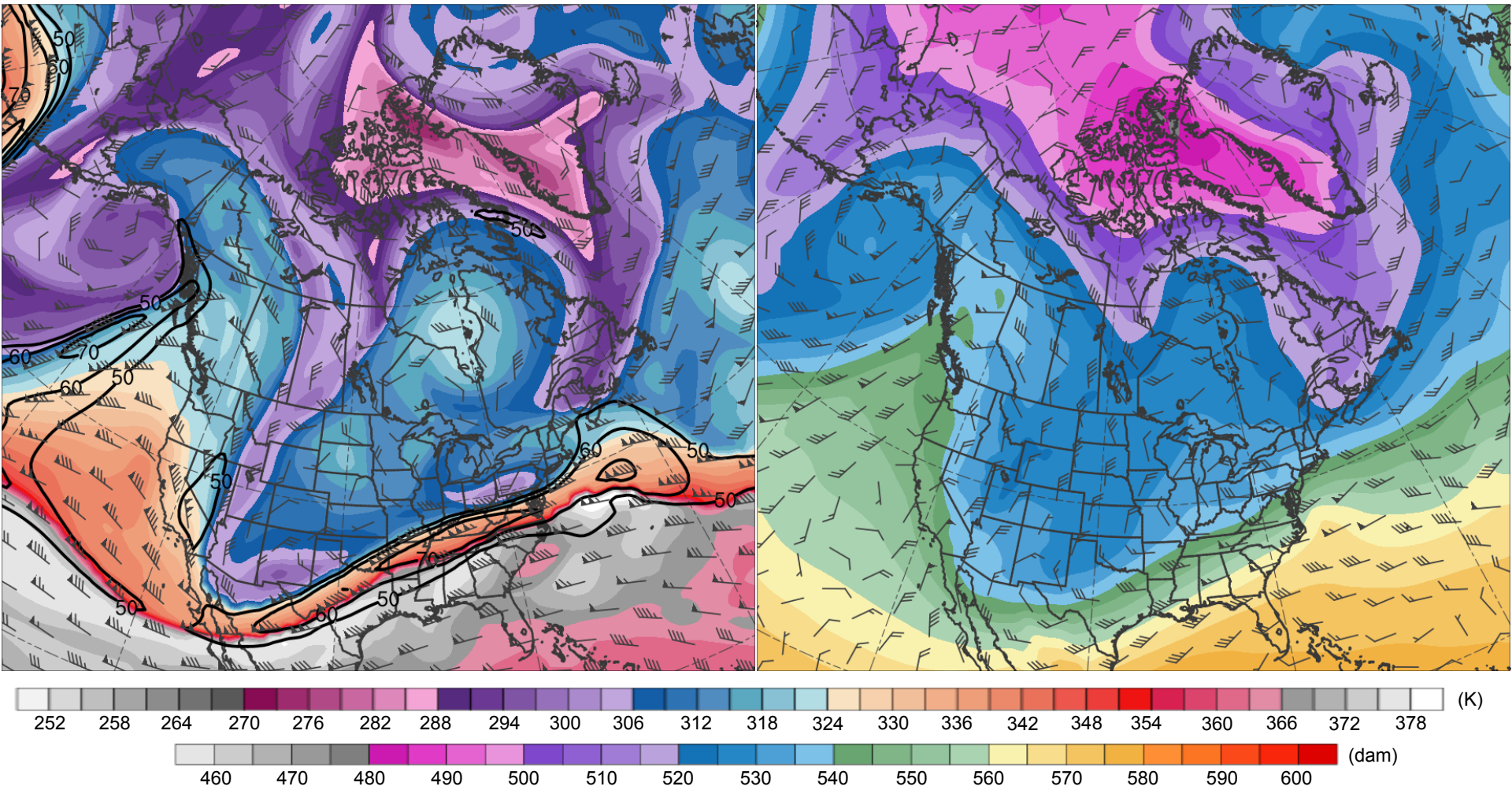
1000–500-hPa thickness (dam, shaded) and 700-hPa wind (m s^{-1}, flags and barbs); cold pool location (white dot) and track (green line)

Example of a CAO with no linkage to a cold pool or TPV

CAO occurs during 12–15 Dec 1997 over South region

CAO with No Cold Pool or TPV 0000 UTC 11 Dec 1997

Data Source: ERA-Interim

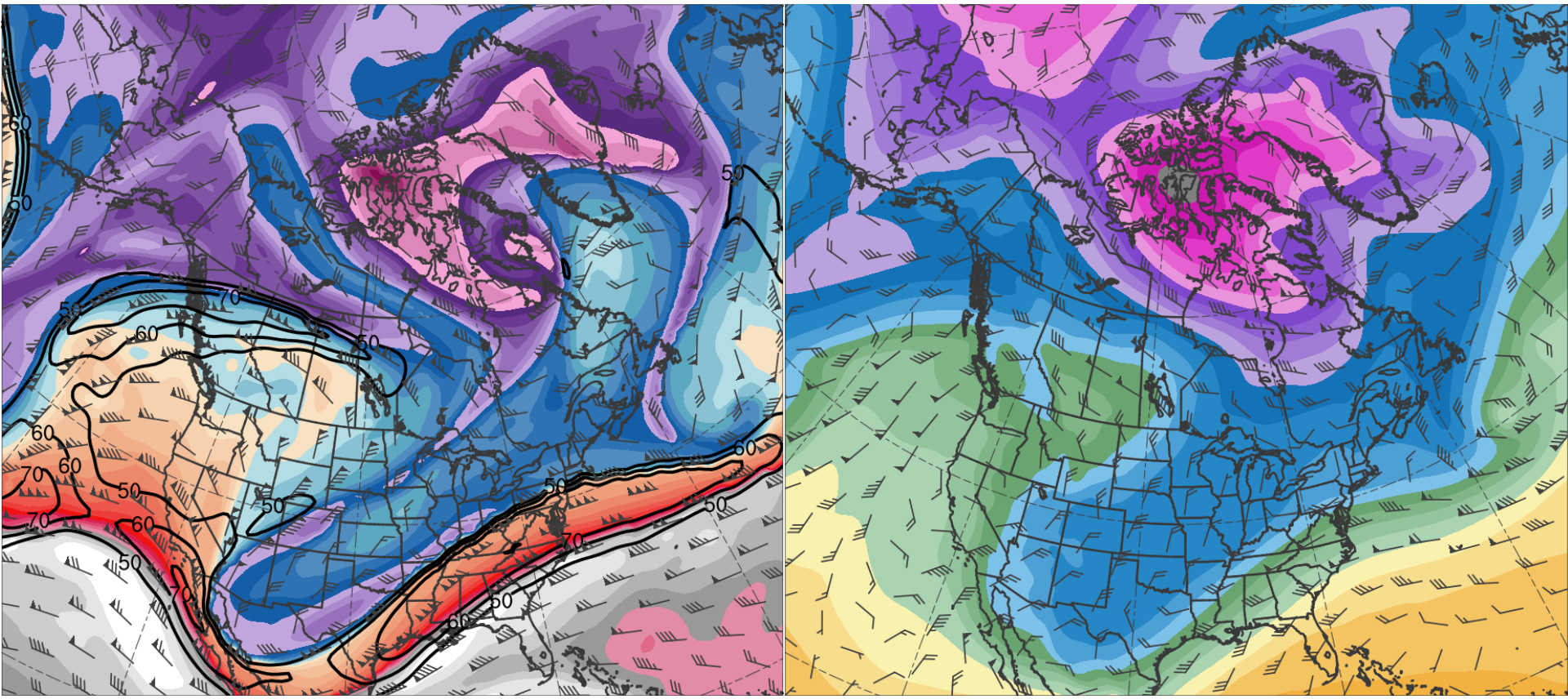


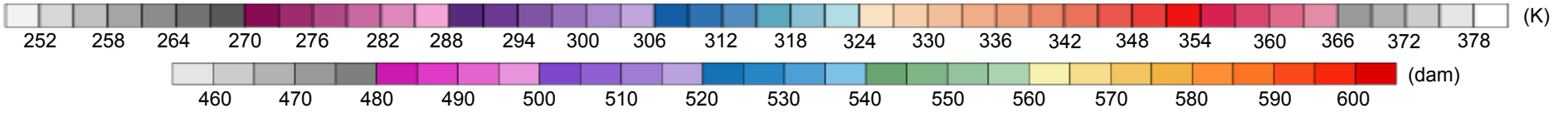
Potential temperature (K, shaded), wind speed (black, every 10 m s^{-1} starting at 50 m s^{-1}), and wind (m s^{-1}, flags and barbs) on 2-PVU surface

1000–500-hPa thickness (dam, shaded) and 700-hPa wind (m s^{-1}, flags and barbs)

CAO with No Cold Pool or TPV 0000 UTC 12 Dec 1997

Data Source: ERA-Interim



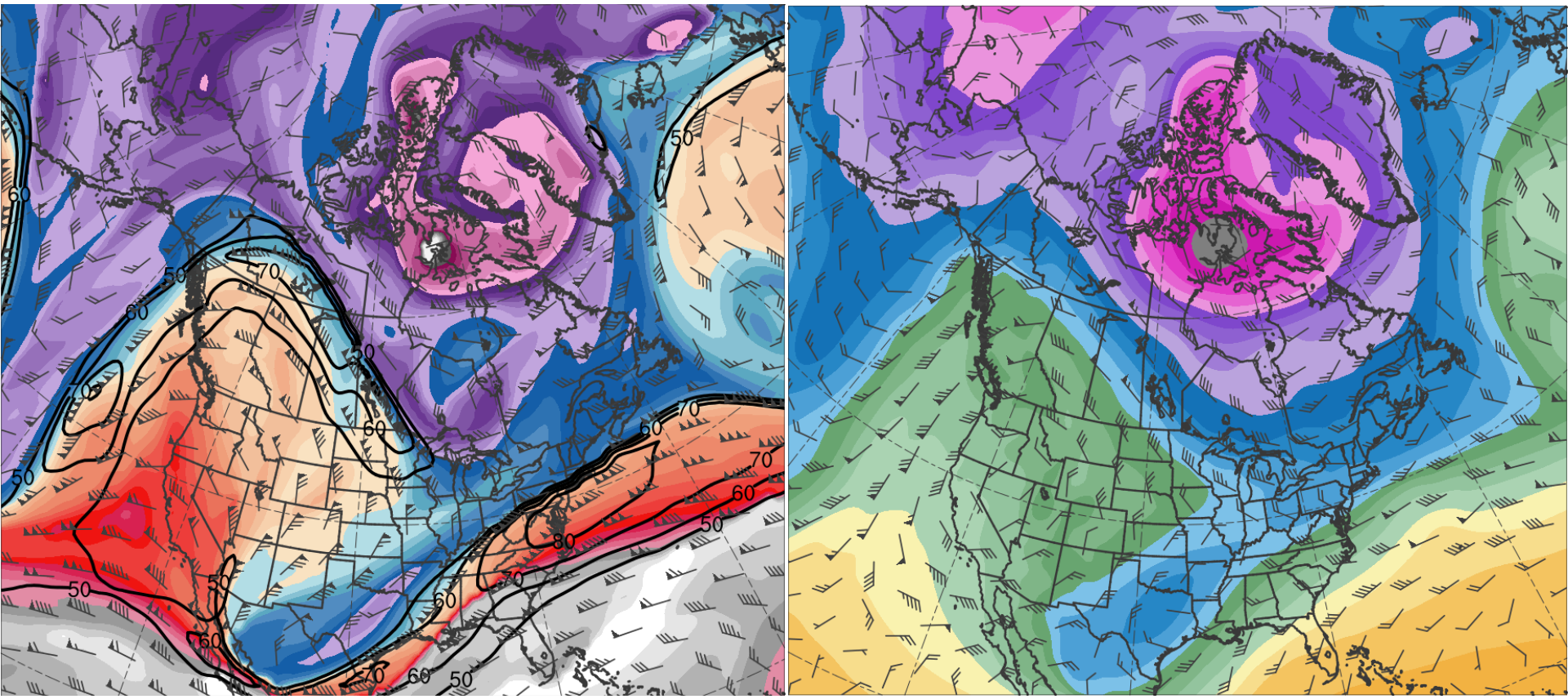


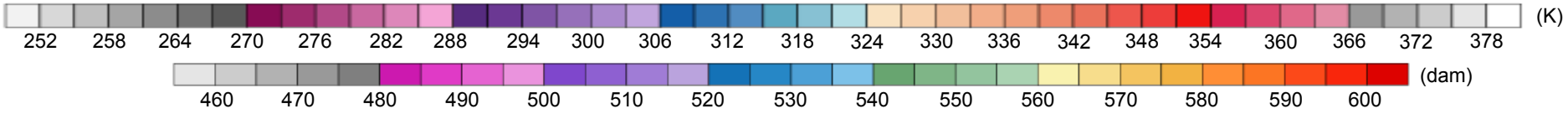
Potential temperature (K, shaded), wind speed (black, every 10 m s^{-1} starting at 50 m s^{-1}), and wind (m s^{-1}, flags and barbs) on 2-PVU surface

1000–500-hPa thickness (dam, shaded) and 700-hPa wind (m s^{-1}, flags and barbs)

CAO with No Cold Pool or TPV 0000 UTC 13 Dec 1997

Data Source: ERA-Interim



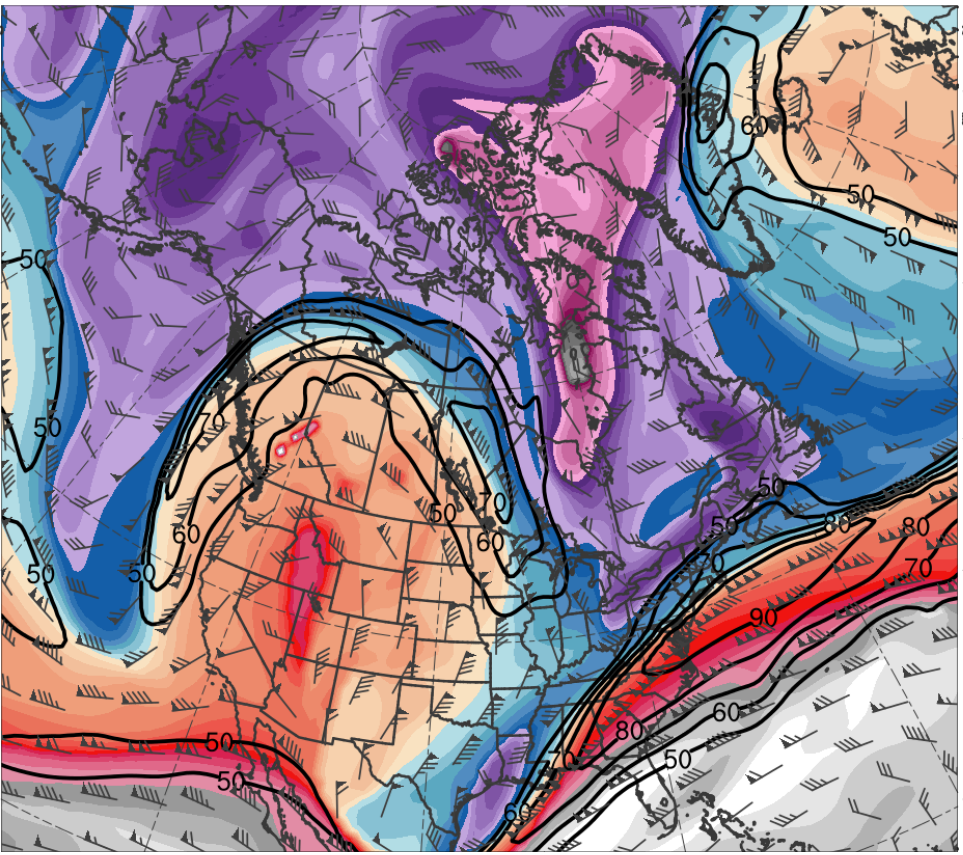


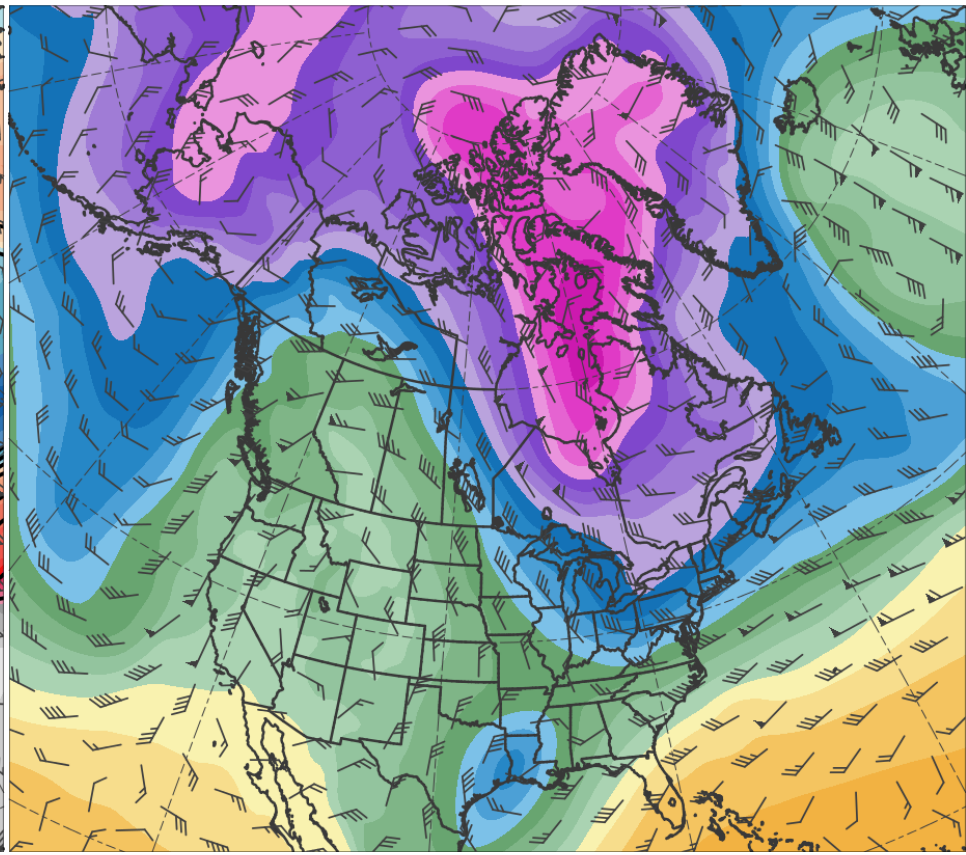
Potential temperature (K, shaded), wind speed (black, every 10 m s^{-1} starting at 50 m s^{-1}), and wind (m s^{-1}, flags and barbs) on 2-PVU surface

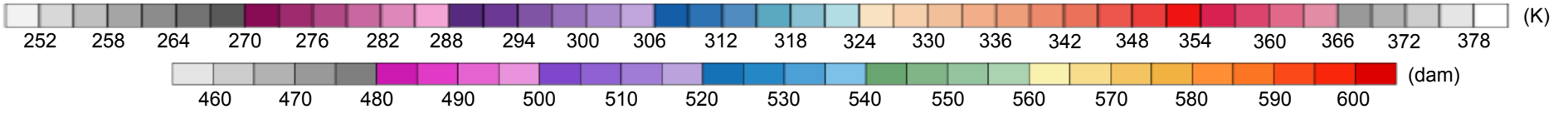
1000–500-hPa thickness (dam, shaded) and 700-hPa wind (m s^{-1}, flags and barbs)

CAO with No Cold Pool or TPV 0000 UTC 14 Dec 1997

Data Source: ERA-Interim





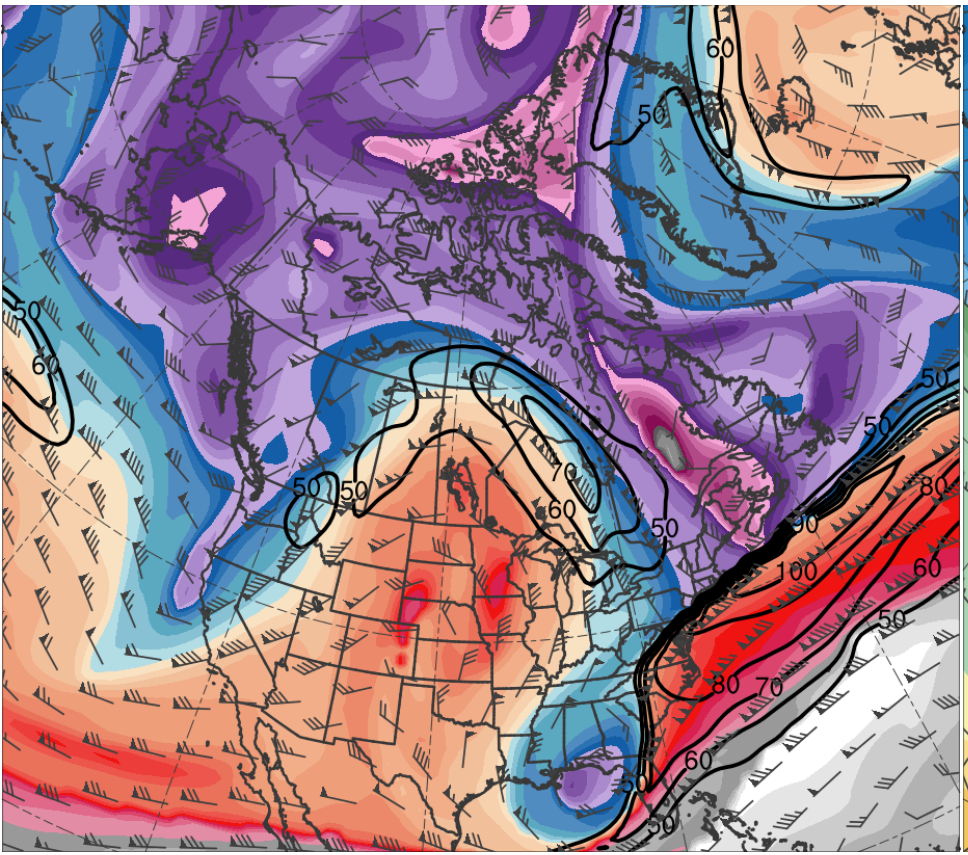


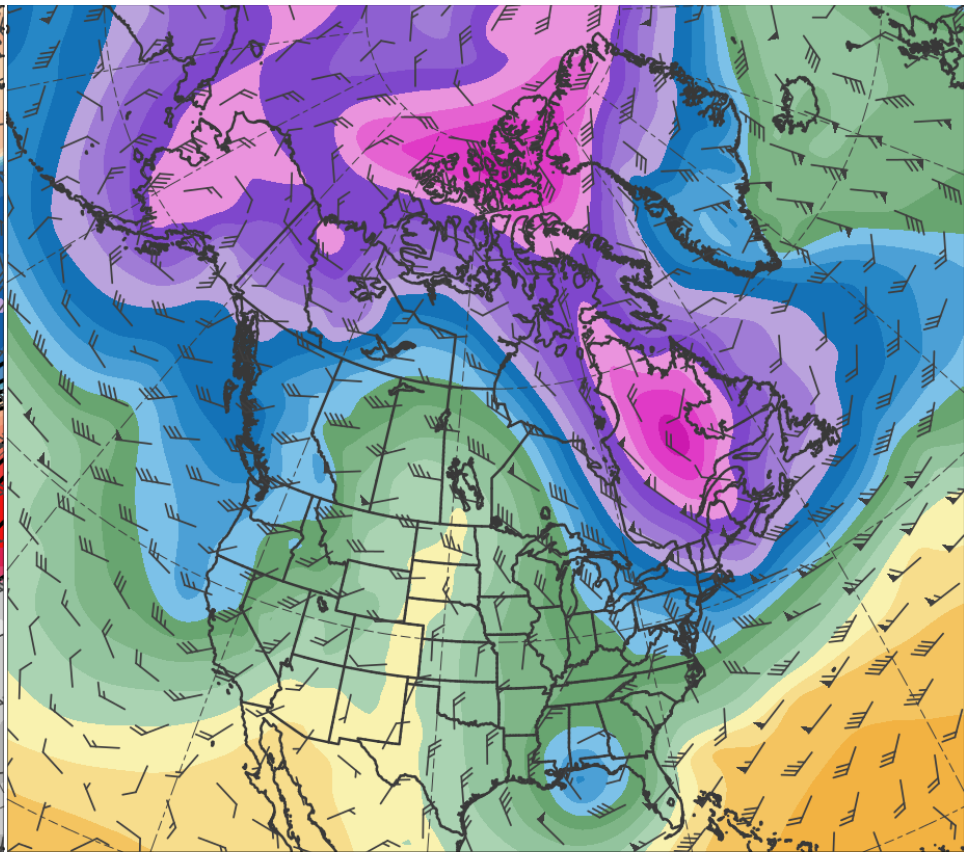
Potential temperature (K, shaded), wind speed (black, every 10 m s^{-1} starting at 50 m s^{-1}), and wind (m s^{-1}, flags and barbs) on 2-PVU surface

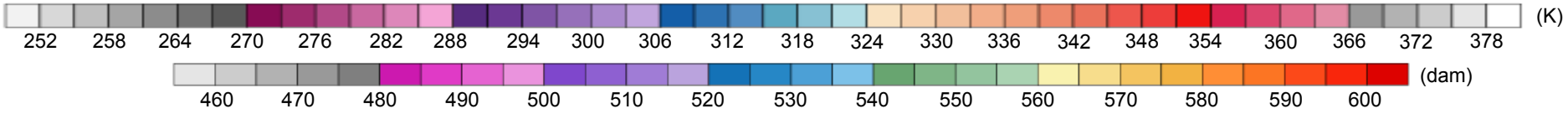
1000–500-hPa thickness (dam, shaded) and 700-hPa wind (m s^{-1}, flags and barbs)

CAO with No Cold Pool or TPV 0000 UTC 15 Dec 1997

Data Source: ERA-Interim







Potential temperature (K, shaded), wind speed (black, every 10 m s^{-1} starting at 50 m s^{-1}), and wind (m s^{-1}, flags and barbs) on 2-PVU surface

1000–500-hPa thickness (dam, shaded) and 700-hPa wind (m s^{-1}, flags and barbs)