Rossby Wave Breaking as a Governor of Atmospheric River Evolution and the Occurrence of Extreme Weather Events

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(with a contribution by Andrew C. Winters)

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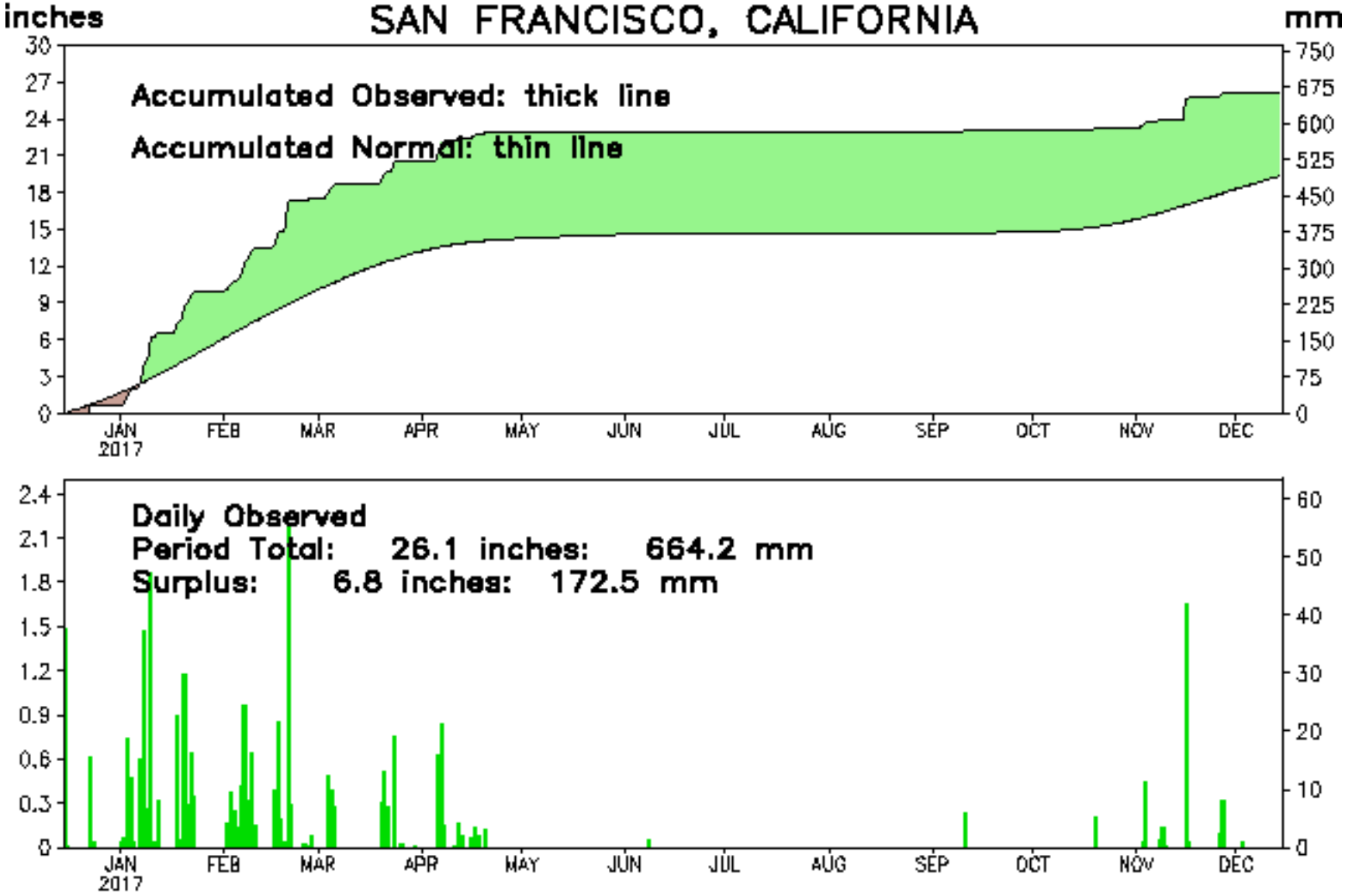
Motivation (1)

What Drove the Relatively Abrupt Onset of Heavy Rains in California and Extended Cold, Snow, and Ice in the Pacific Northwest in Early 2017?

Precipitation

SAN FRANCISCO, CALIFORNIA

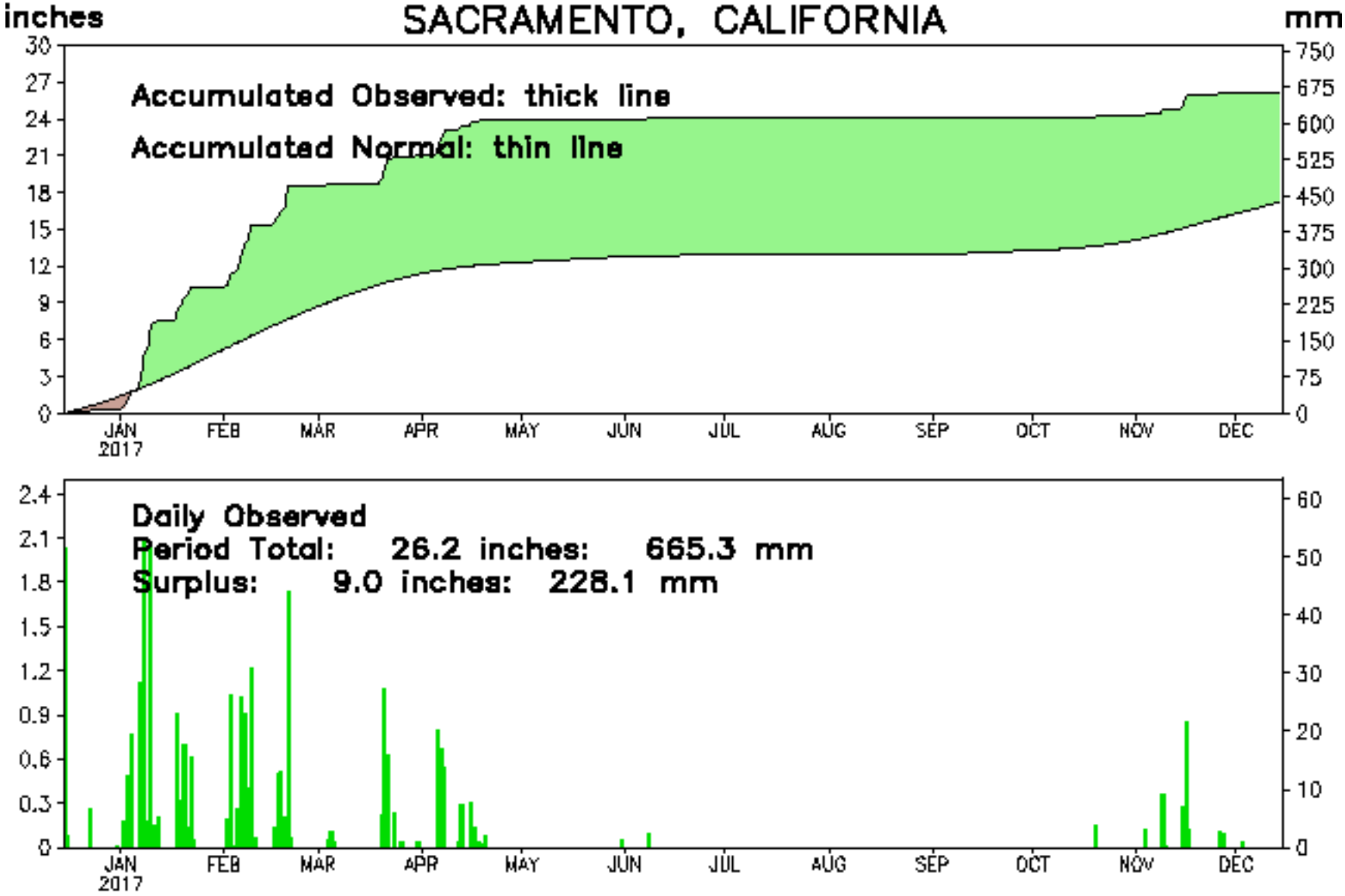


Data updated through 14 DEC 2017

CLIMATE PREDICTION CENTER/NCEP

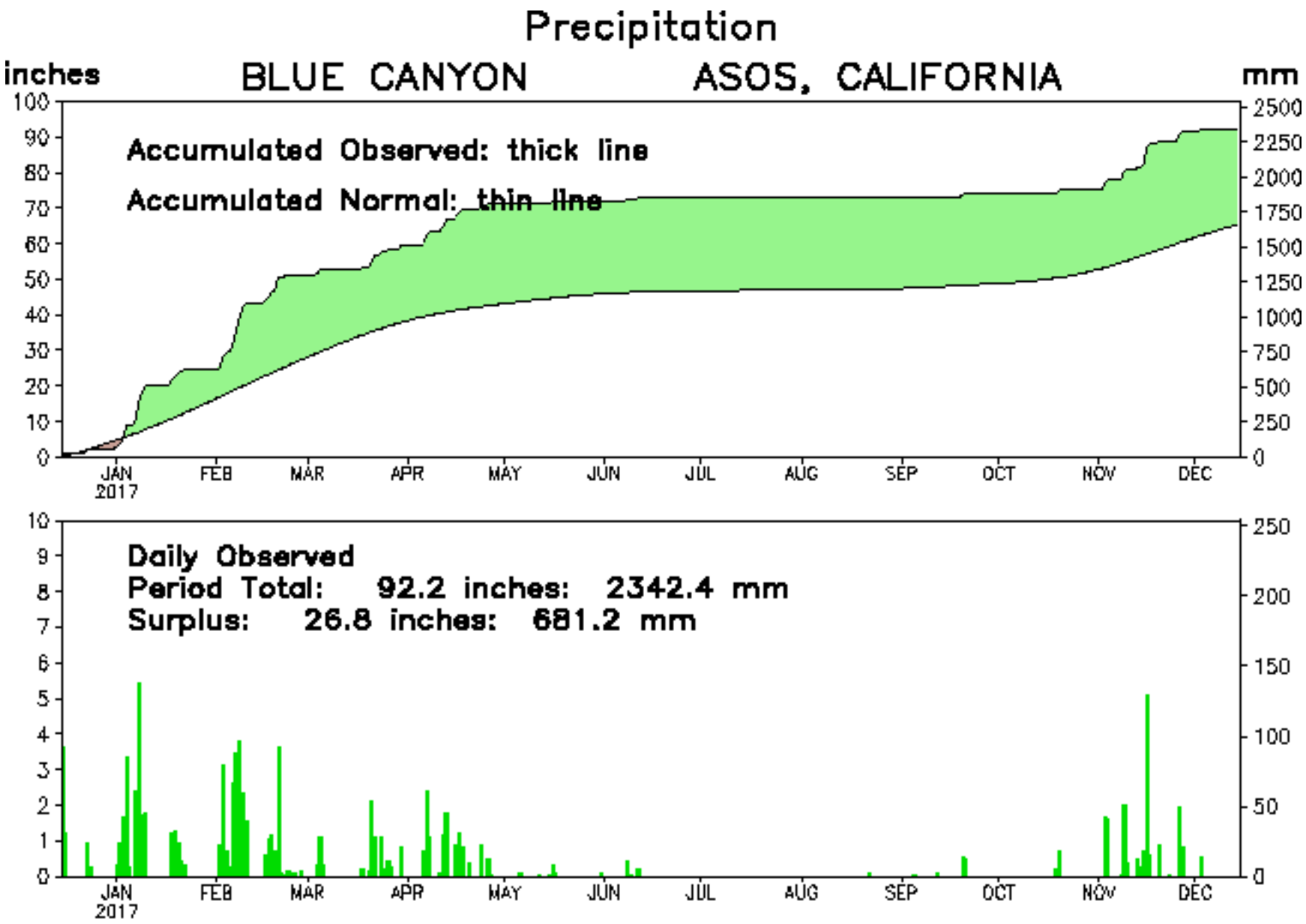
Precipitation

SACRAMENTO, CALIFORNIA



Data updated through 14 DEC 2017

CLIMATE PREDICTION CENTER/NCEP


Precipitation
inches
BLUE CANYON
ASOS, CALIFORNIA
mm
Accumulated Observed: thick line
Accumulated Normal: thin line
JAN 2017
FEB
MAR
APR
MAY
JUN
JUL
AUG
SEP
OCT
NOV
DEC
Daily Observed
Period Total: 92.2 inches: 2342.4 mm
Surplus: 26.8 inches: 681.2 mm
Data updated through 14 DEC 2017
CLIMATE PREDICTION CENTER/NCEP

Amid a torrent of rain, the Russian River swelled to its highest level in a decade on Jan. 11, 2017, forcing hundreds of people in and around Sonoma County and the town of Guerneville to flee to higher ground.

Source: SFGATE

Monterey Bay recorded the largest waves it has seen in 30 years with the swell reaching 34.12 feet at one point. The previous record was 32.8 feet in 2008. The S.S. Palo Alto, otherwise known as the 'Concrete Ship,' was tossed and broken up by high waves in the bay in January.

Source: SFGATE

Storms dump record-breaking snow on Tahoe in January 2017. Storms pummeled the Sierra at the start of the year and by Jan. 23 the snowpack above 6,000 feet was around 10 feet and up to 20 feet at the highest peaks.

Source: SFGATE

Tree branches, broken from the weight of heavy snow, are scattered on the ground of the park blocks across from the Portland Art Museum in Portland, OR, Wed 11 January 2017 (AP Photo/Don Ryan)

Motivation (2)

Monthly and Subseasonal Forecasts: Regime Change Challenges

CFSv(2) and CPC Outlooks for Jan 2017 and Jan-Feb-Mar 2017

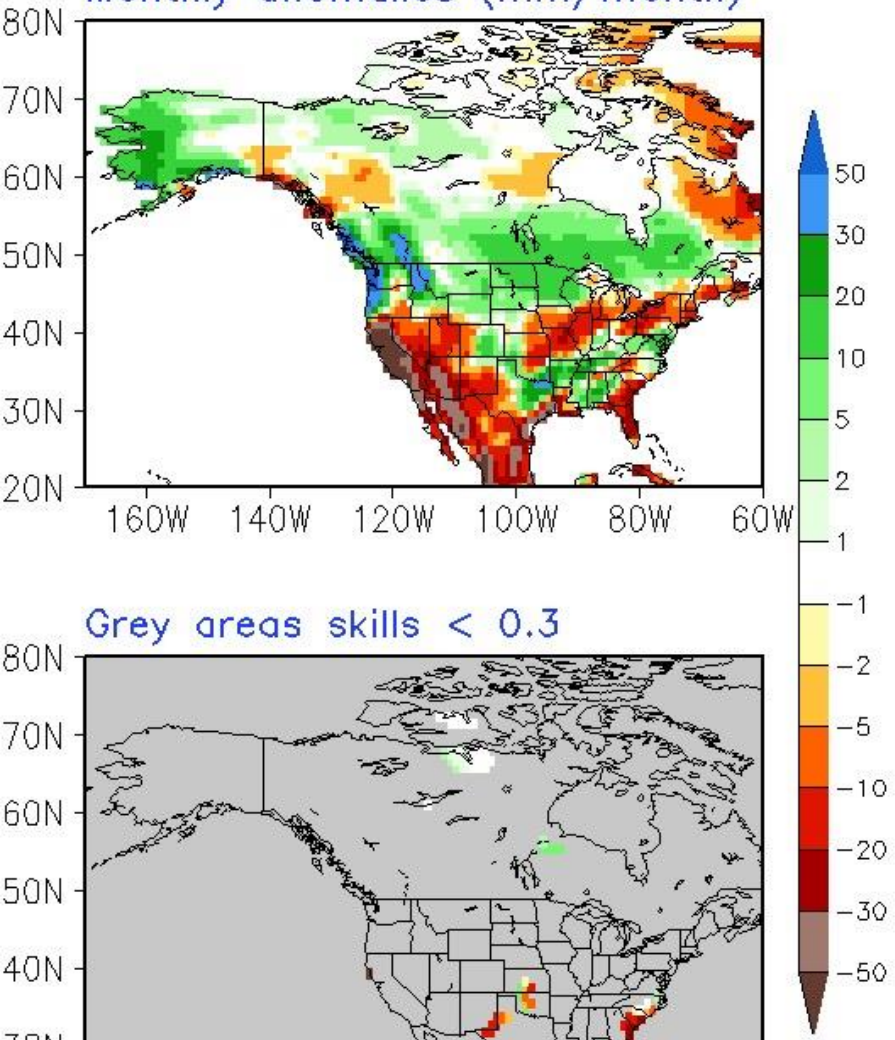
NWS/NCEP/CPC

Last update: Thu Dec 1 2016

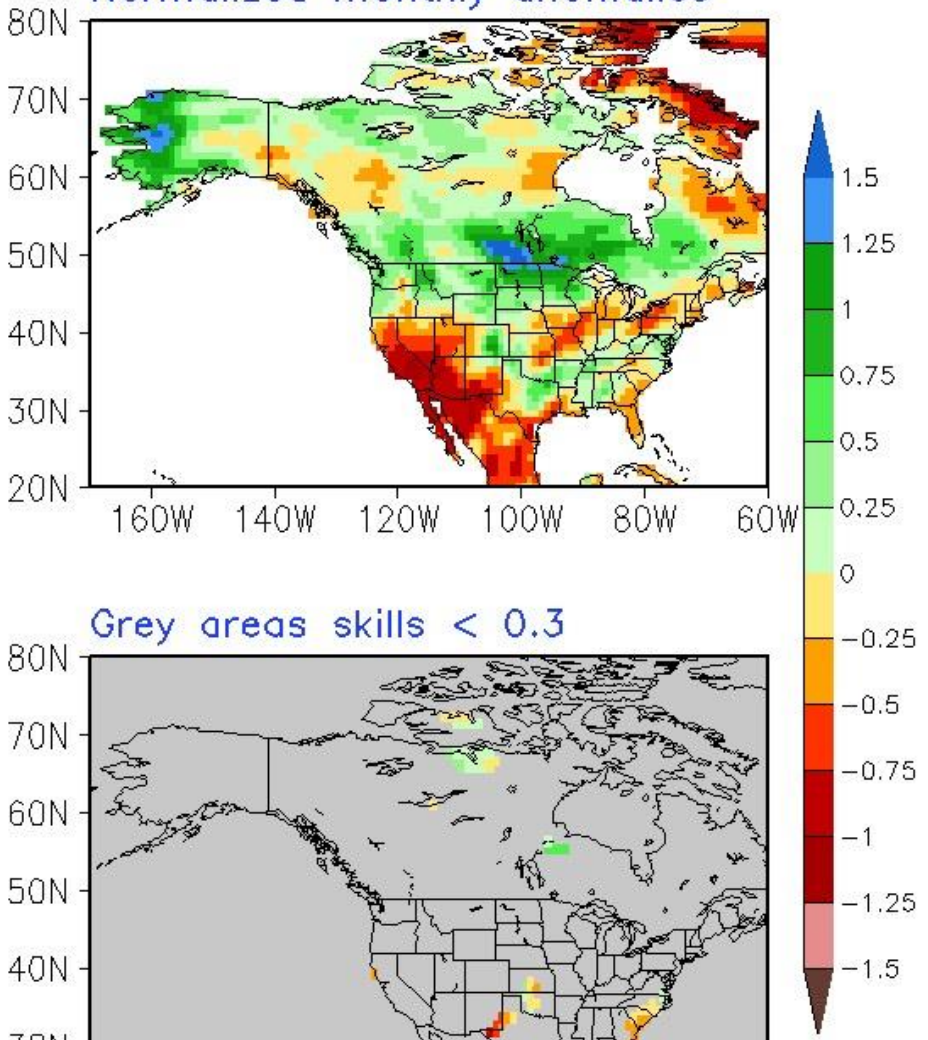
Initial conditions: 00Z01Dec2016(4 members)

CFSv2 monthly Prec forecast for Jan2017

Monthly anomalies (mm/month)



Normalized monthly anomalies



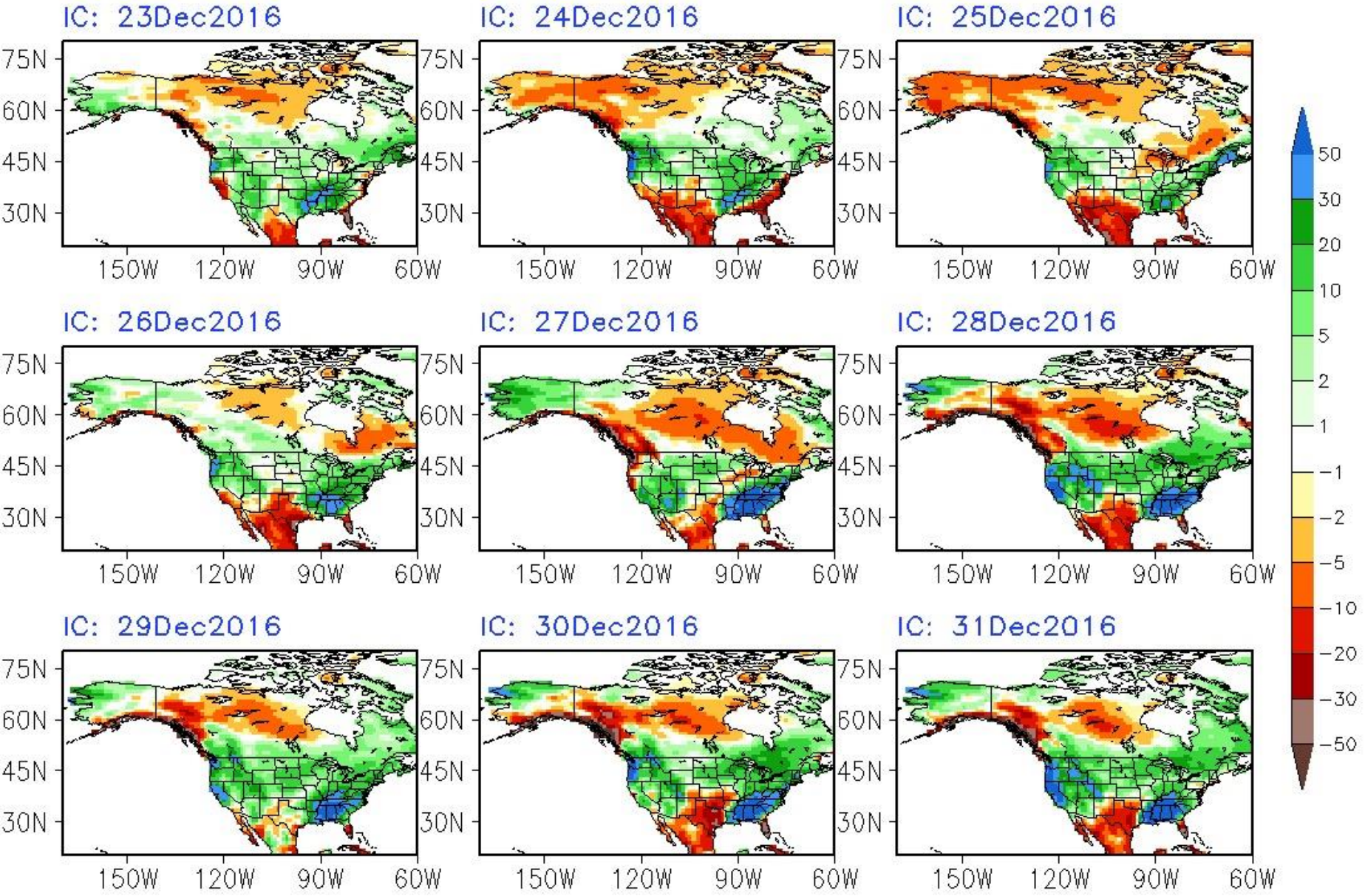
Grey areas skills < 0.3

Grey areas skills < 0.3

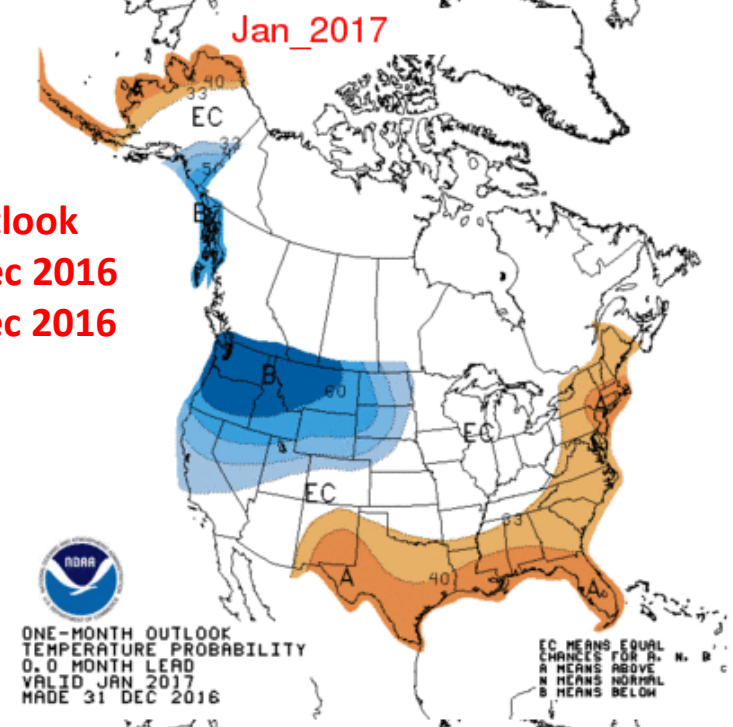
Last update: Sat Dec 31 2016

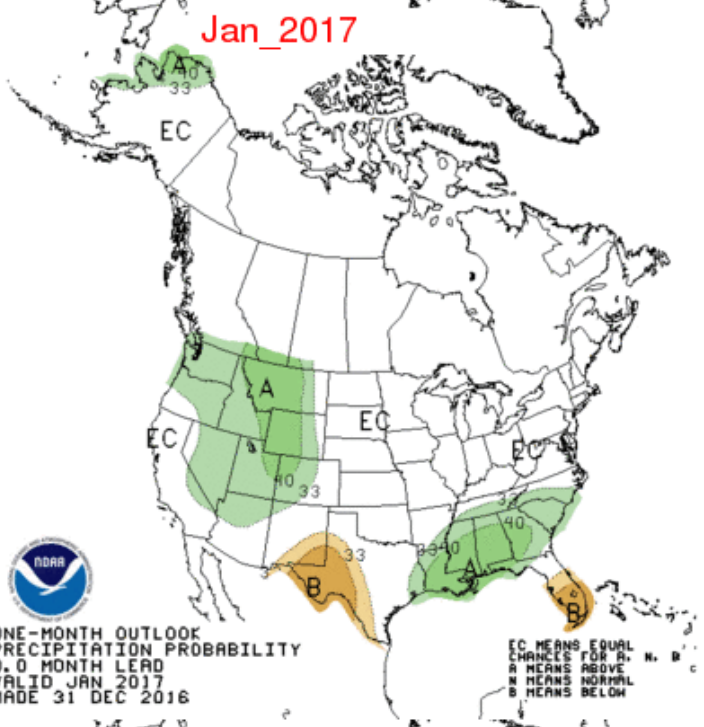
NWS/NCEP/CPC

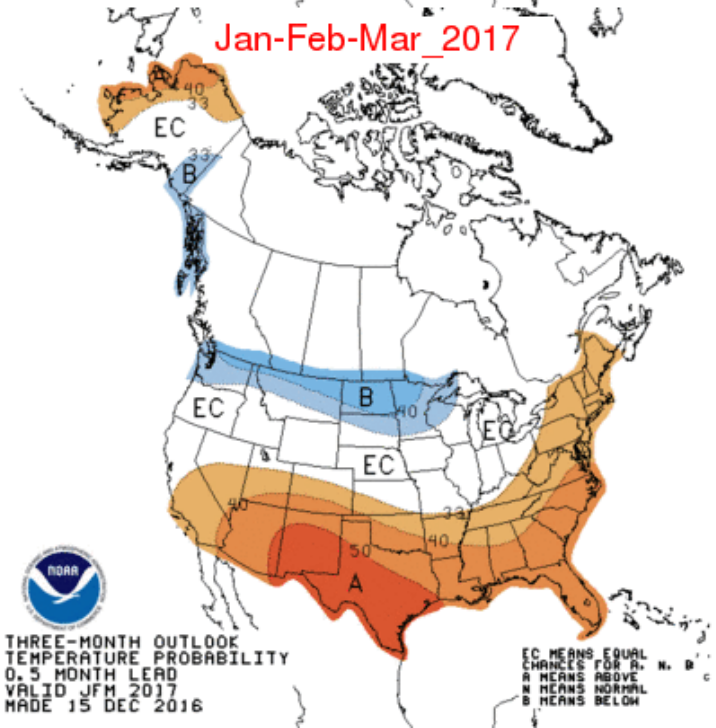
CFSv2 monthly Prec(mm/month) forecast for Jan2017

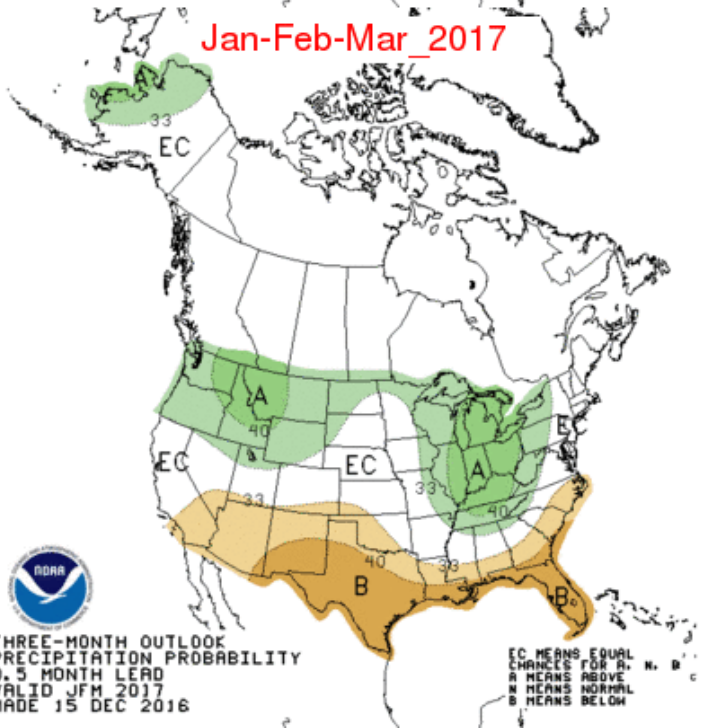


CPC Outlook
Top: 31 Dec 2016
Bot: 15 Dec 2016



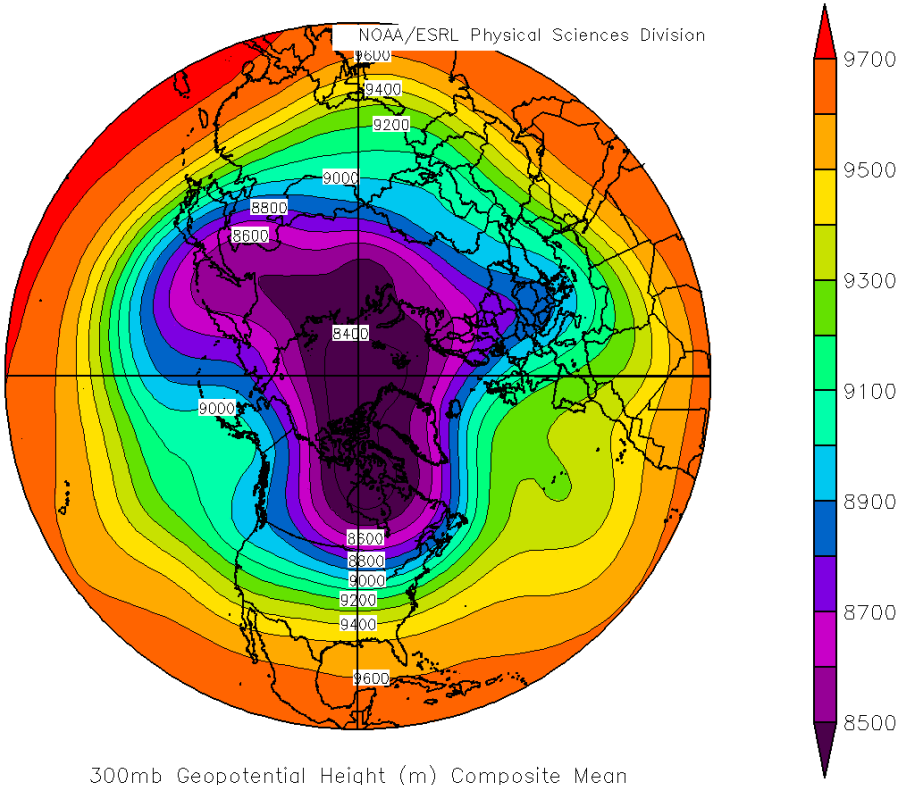




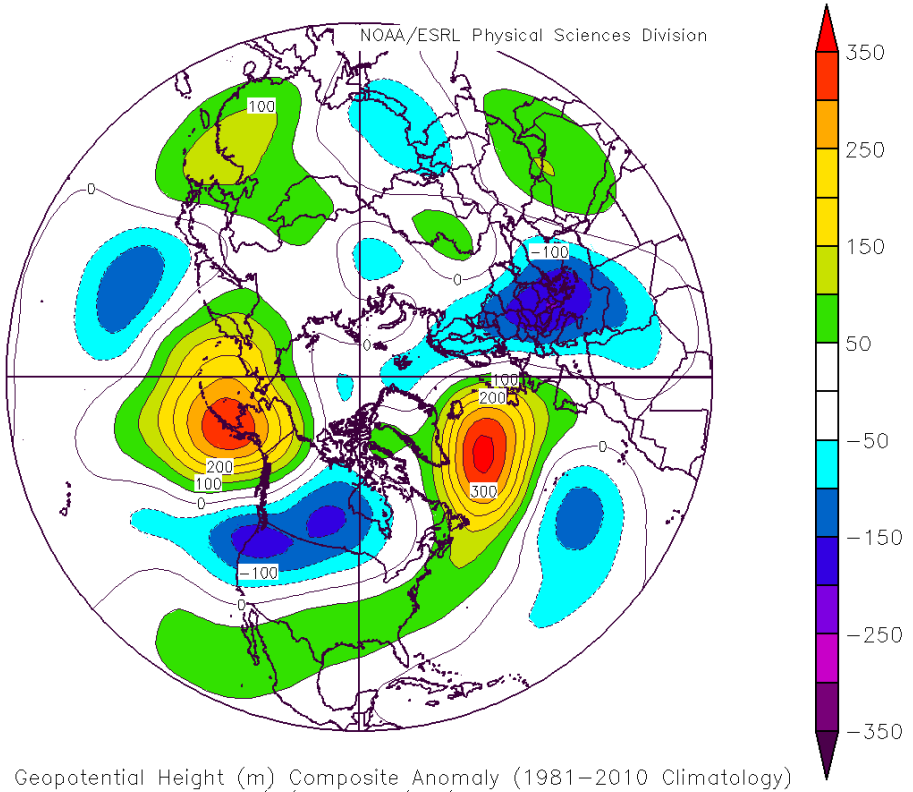


Northern Hemisphere
Mean and Anomaly Fields
1–15 January 2017

300-hPa Geopotential Height for 1–15 January 2017
Mean (left, dam) and Anomaly (right, m)

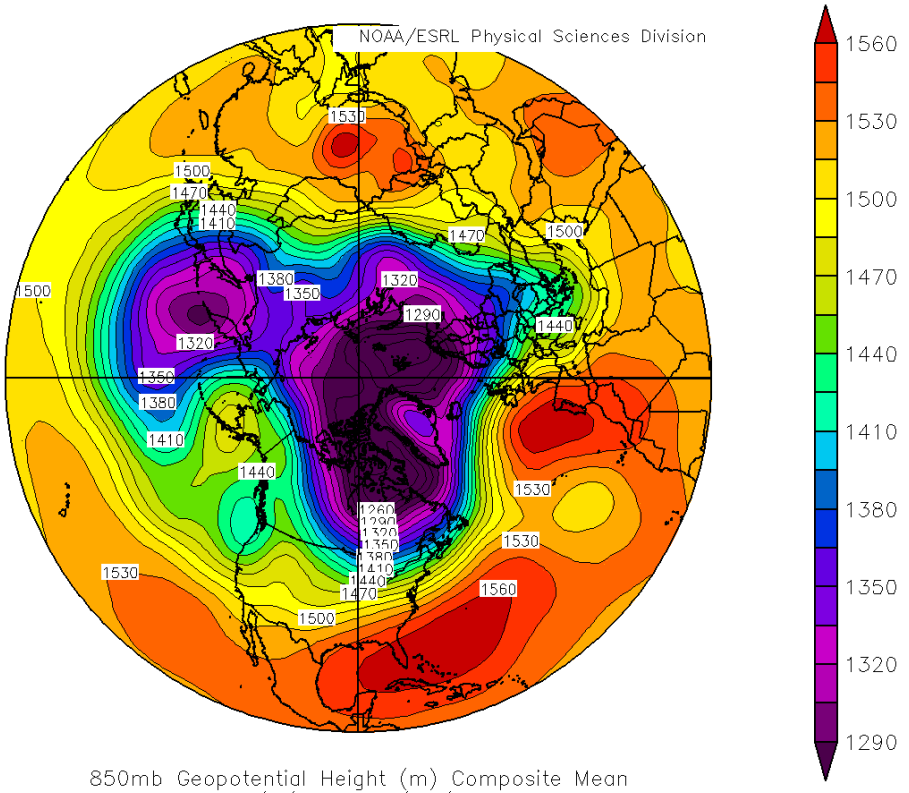


300mb Geopotential Height (m) Composite Mean
1/1/17 to 1/15/17
NCEP/NCAR Reanalysis

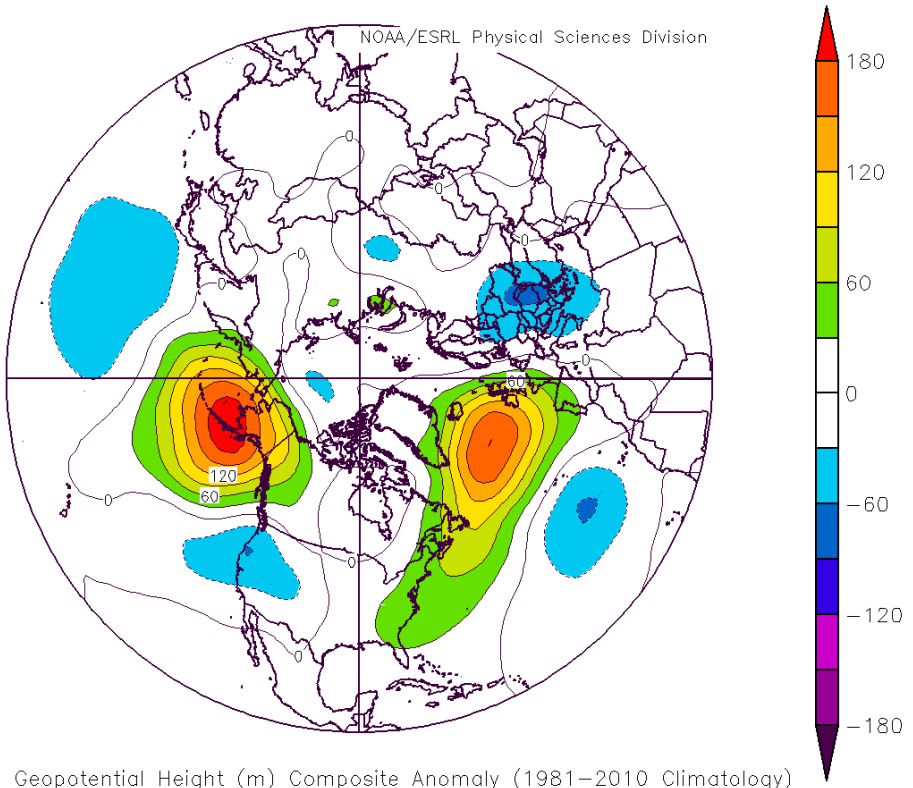


Geopotential Height (m) Composite Anomaly (1981–2010 Climatology)
1/1/17 to 1/15/17
NCEP/NCAR Reanalysis

850-hPa Geopotential Height for 1–15 January 2017
Mean (left, dam) and Anomaly (right, m)

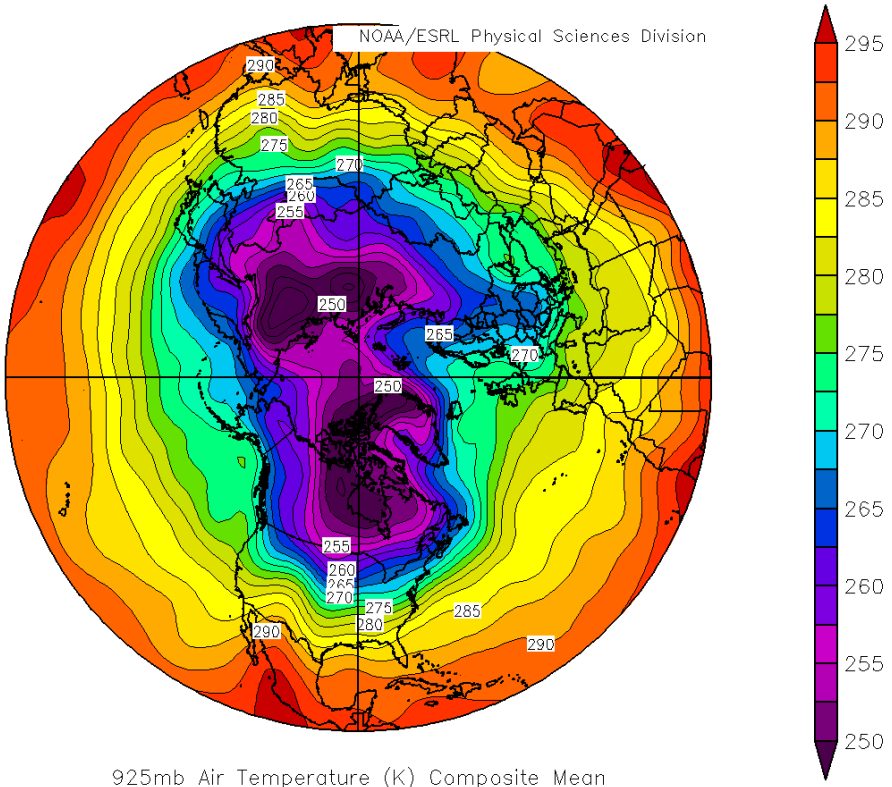


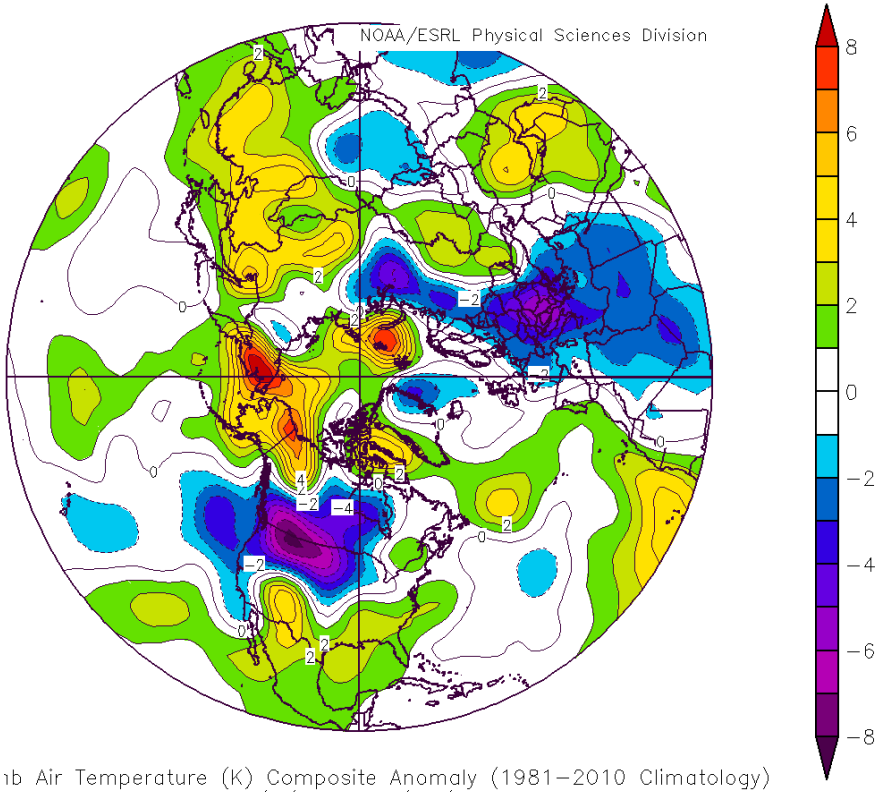
850mb Geopotential Height (m) Composite Mean
1/1/17 to 1/15/17
NCEP/NCAR Reanalysis



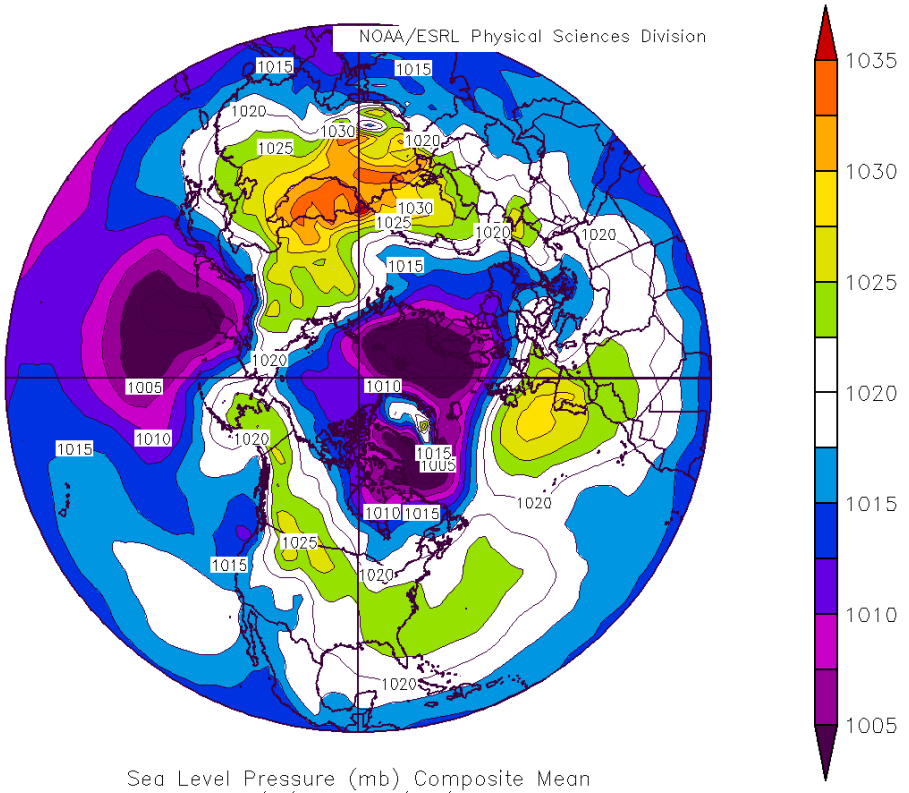
Geopotential Height (m) Composite Anomaly (1981–2010 Climatology)
1/1/17 to 1/15/17
NCEP/NCAR Reanalysis

925-hPa Air Temperature for 1–15 January 2017
Mean (left, °C) and Anomaly (right, °C)

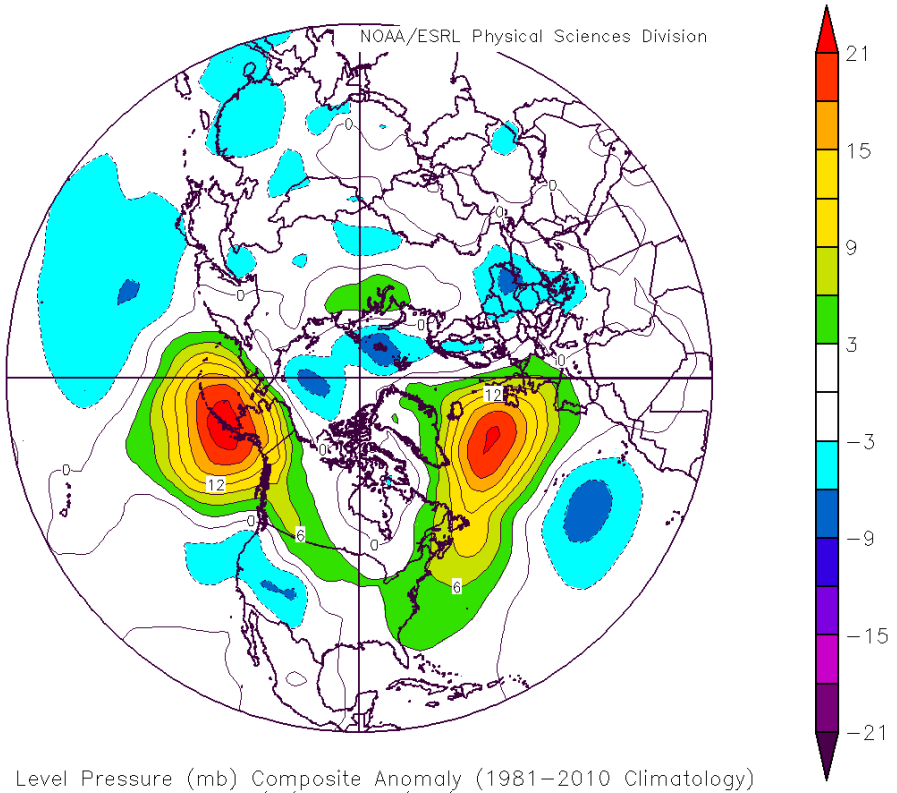




Mean Sea Level Pressure for 1–15 January 2017
Mean (left, hPa) and Anomaly (right, hPa)



Sea Level Pressure (mb) Composite Mean
1/1/17 to 1/15/17
NCEP/NCAR Reanalysis

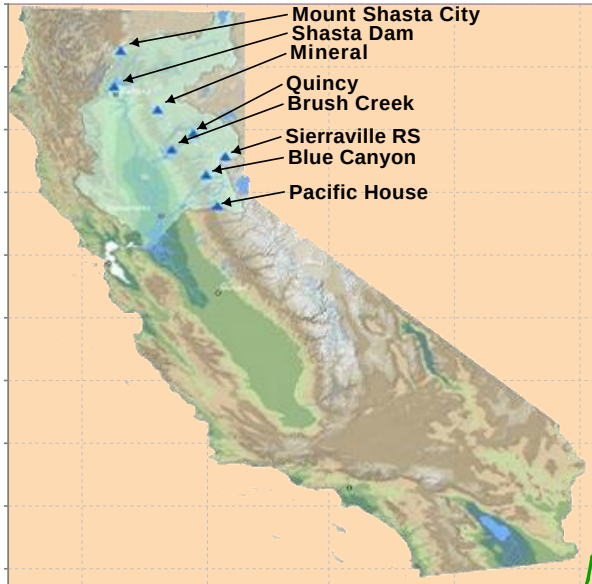


Level Pressure (mb) Composite Anomaly (1981–2010 Climatology)
1/1/17 to 1/15/17
NCEP/NCAR Reanalysis

The California Deluge of 8–9 January 2017

California Department of Water Resources
https://cdec.water.ca.gov

North Sierra Precipitation: 8-Station Index, December 22, 2017



Percent of Average for this Date: 79%

2016-2017 Daily Precip (wettest) 94.7

1982-1983 (2nd wettest) 88.5

1997-1998 82.4

Average (1966-2015) 51.8

2014-2015 Daily Precip 37.2

1976-1977(2nd driest & driest thru Aug) 19.0

Current Daily Precip:12.6

Cumulative Daily/Monthly Precipitation (inches)

Total Water Year Precipitation

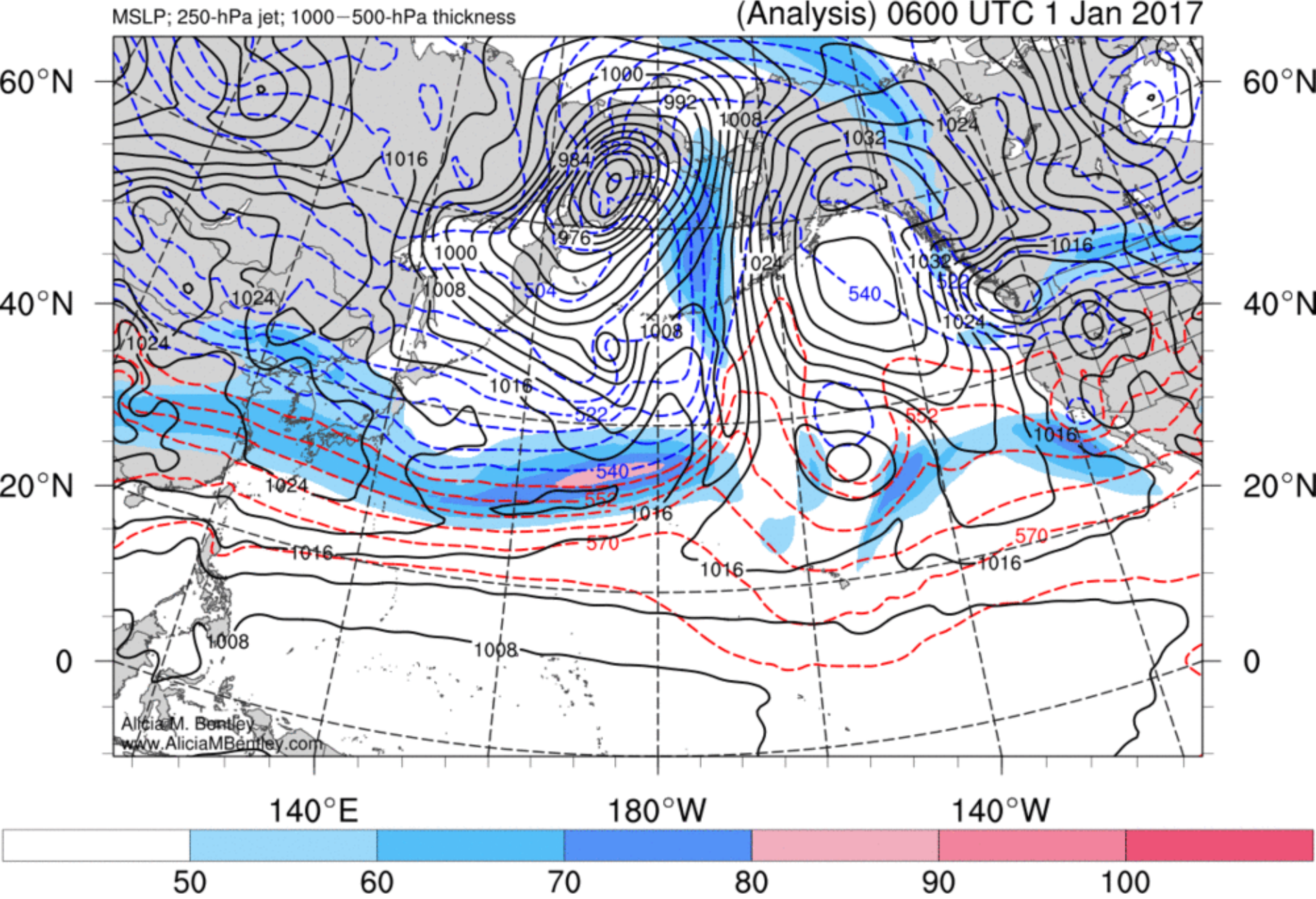
0 5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80 85 90 95 100

Oct 1 Nov 1 Dec 1 Jan 1 Feb 1 Mar 1 Apr 1 May 1 Jun 1 Jul 1 Aug 1 Sep 1 Oct 1

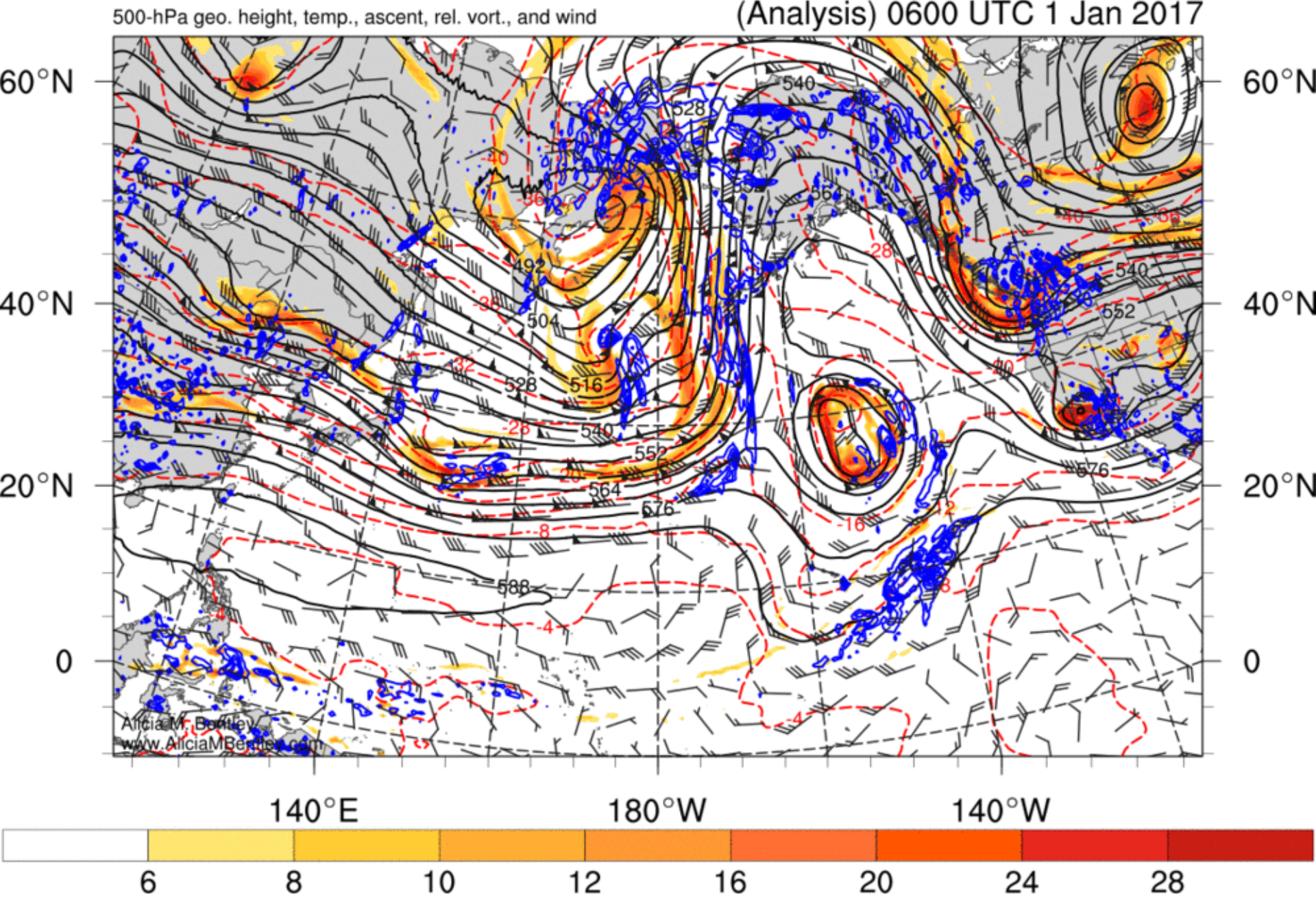
Water Year (October 1 - September 30)

North Pacific Loops for 31 Dec–15 Jan 2017

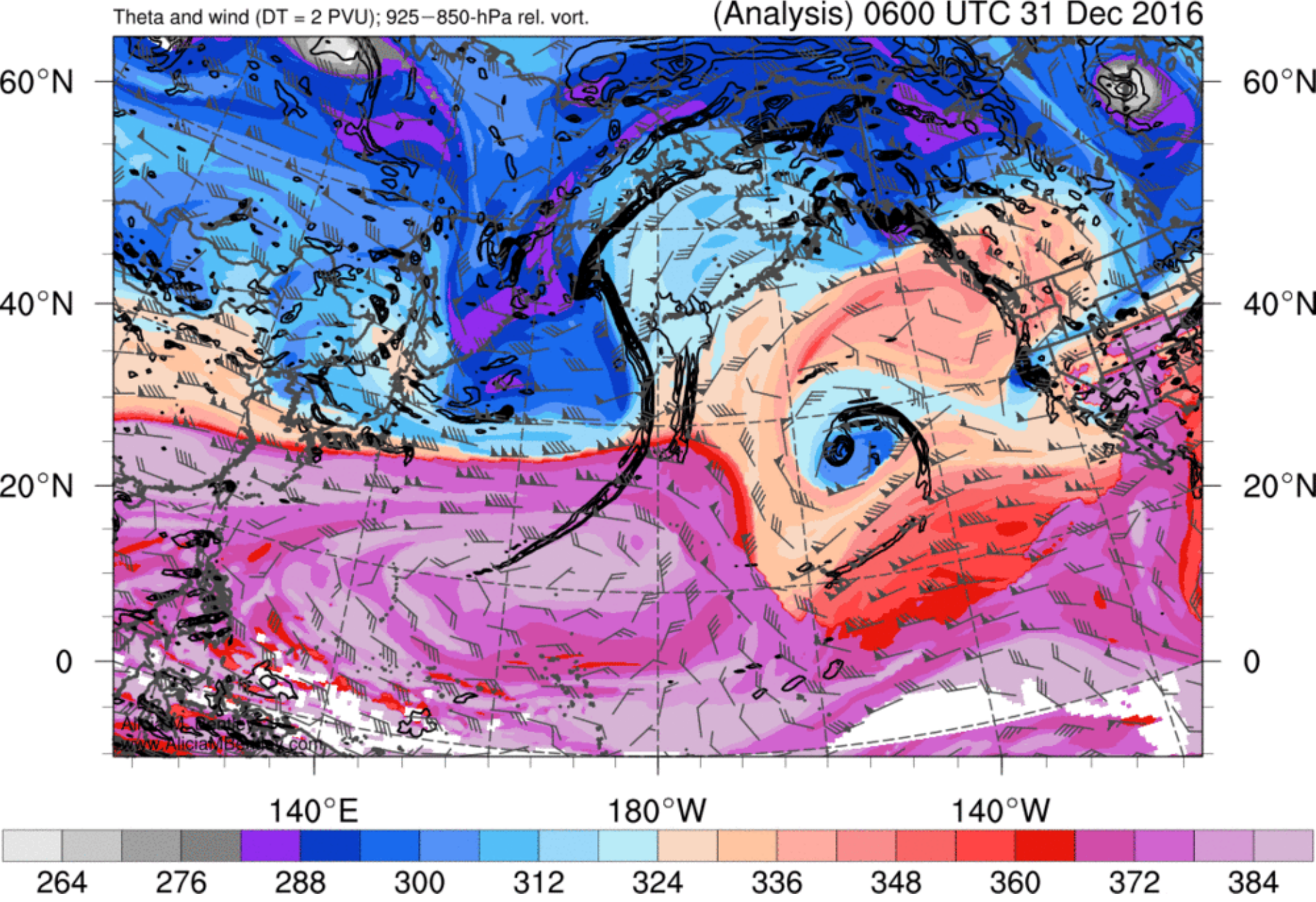
- **Mean sea level pressure, 1000–500-hPa thickness, and 250-hPa wind speeds (shaded above 50 m s^{-1})**
- **500-hPa geopotential heights, relative vorticity, winds, and vertical motion (ascent only)**
- **DT (2 PVU surface) pot temp (K) and winds (barbs, kt), and 925–850-hPa layer-mean vorticity (contours, x 10^{-5} s^{-1})**



Source: Alicia Bentley

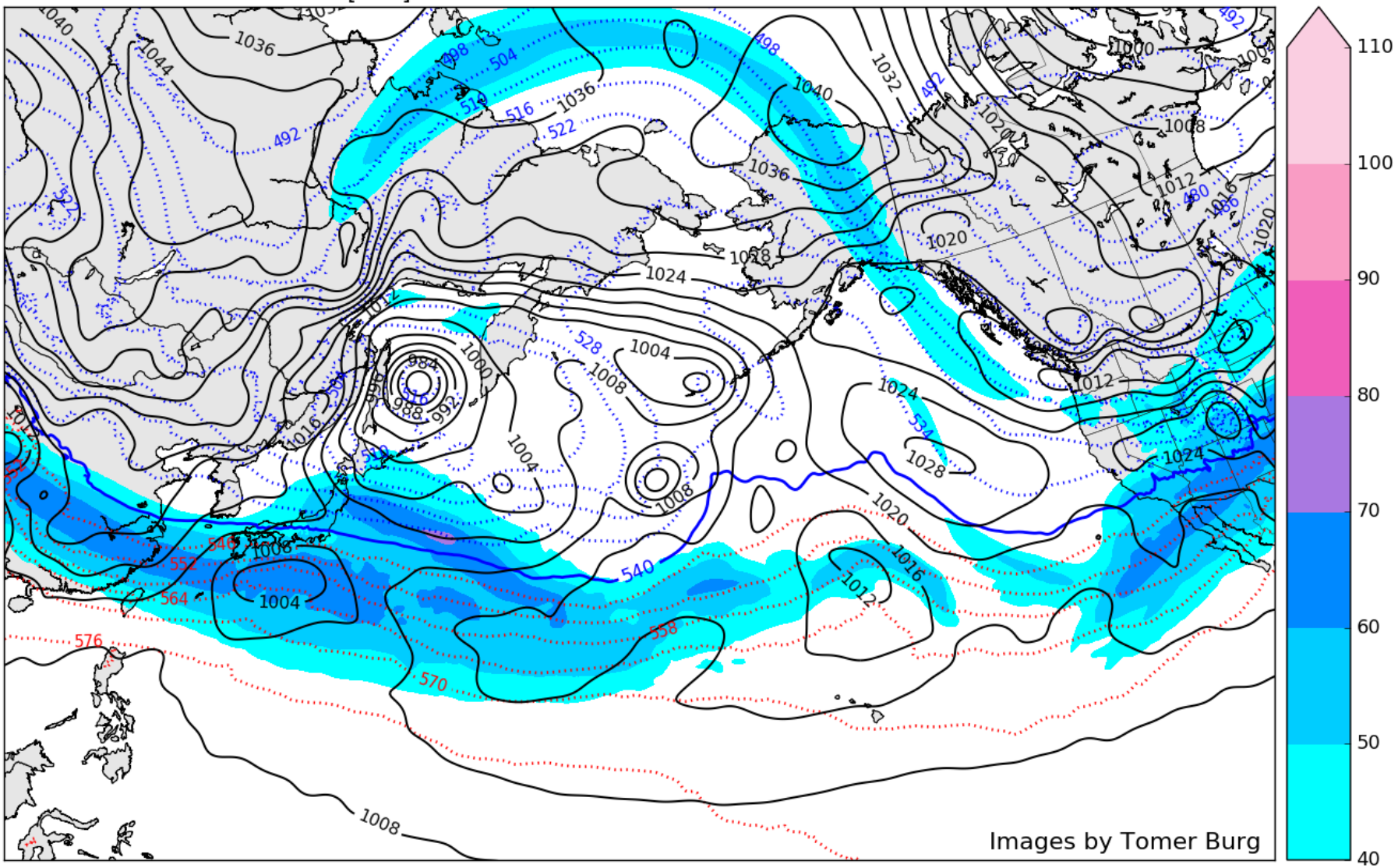


Source: Alicia Bentley

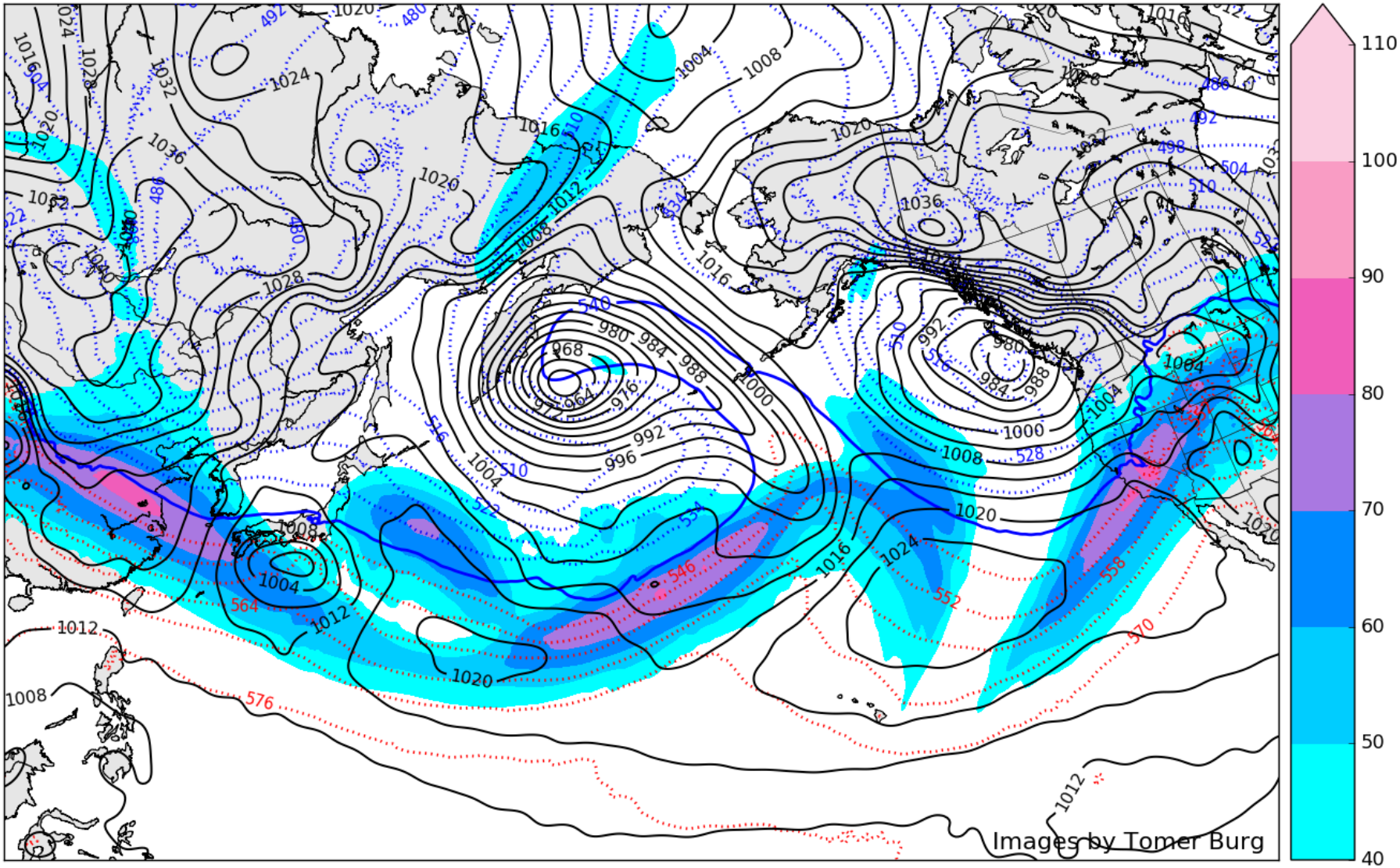


Source: Alicia Bentley

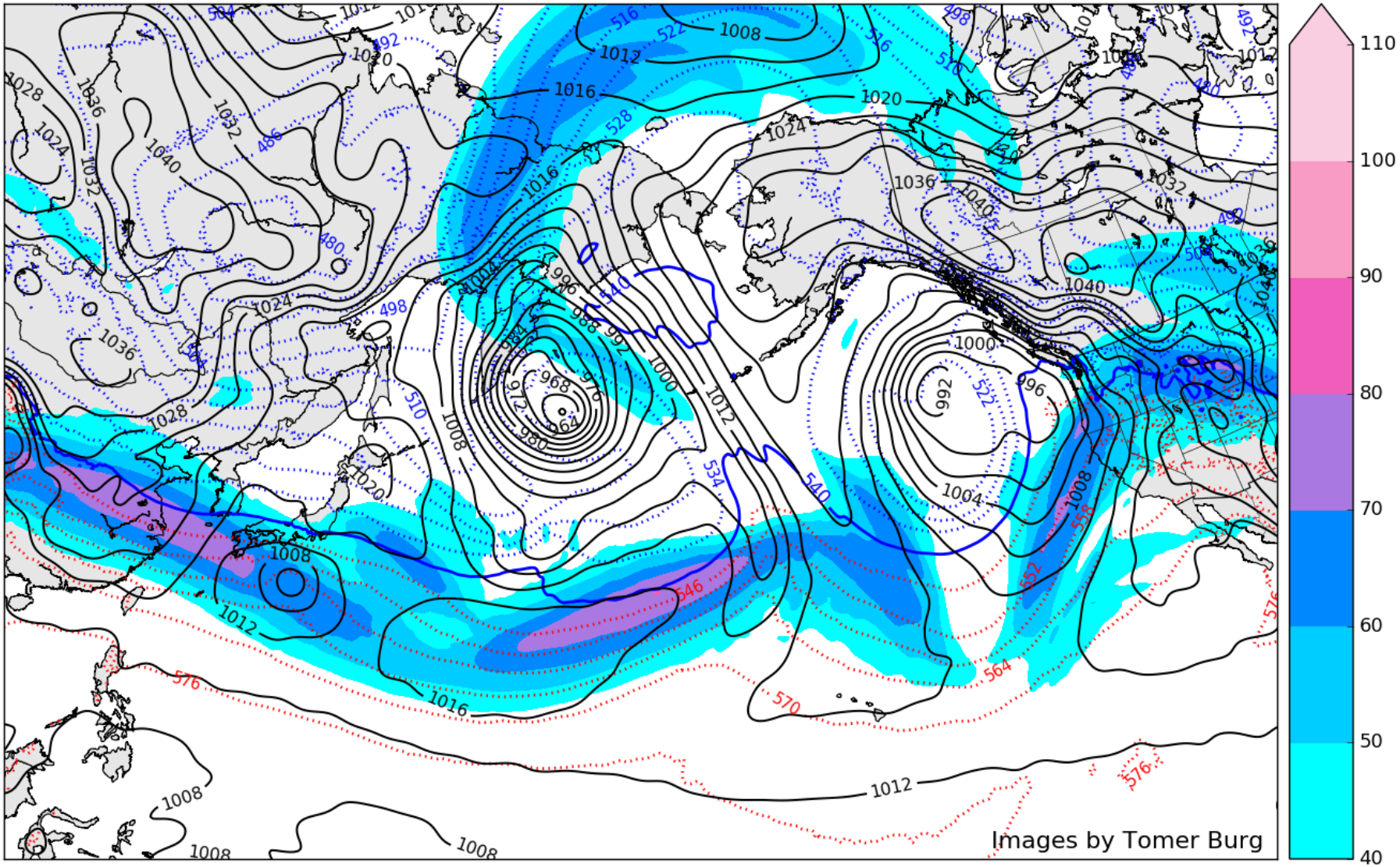
GFS forecast d(prog)/dt Analysis Deterministic Forecasts Verifying at 1200 UTC 8 January 2017



210 h GFS Forecast: Weak Pacific Flow and Absence of Westerly Flow toward California



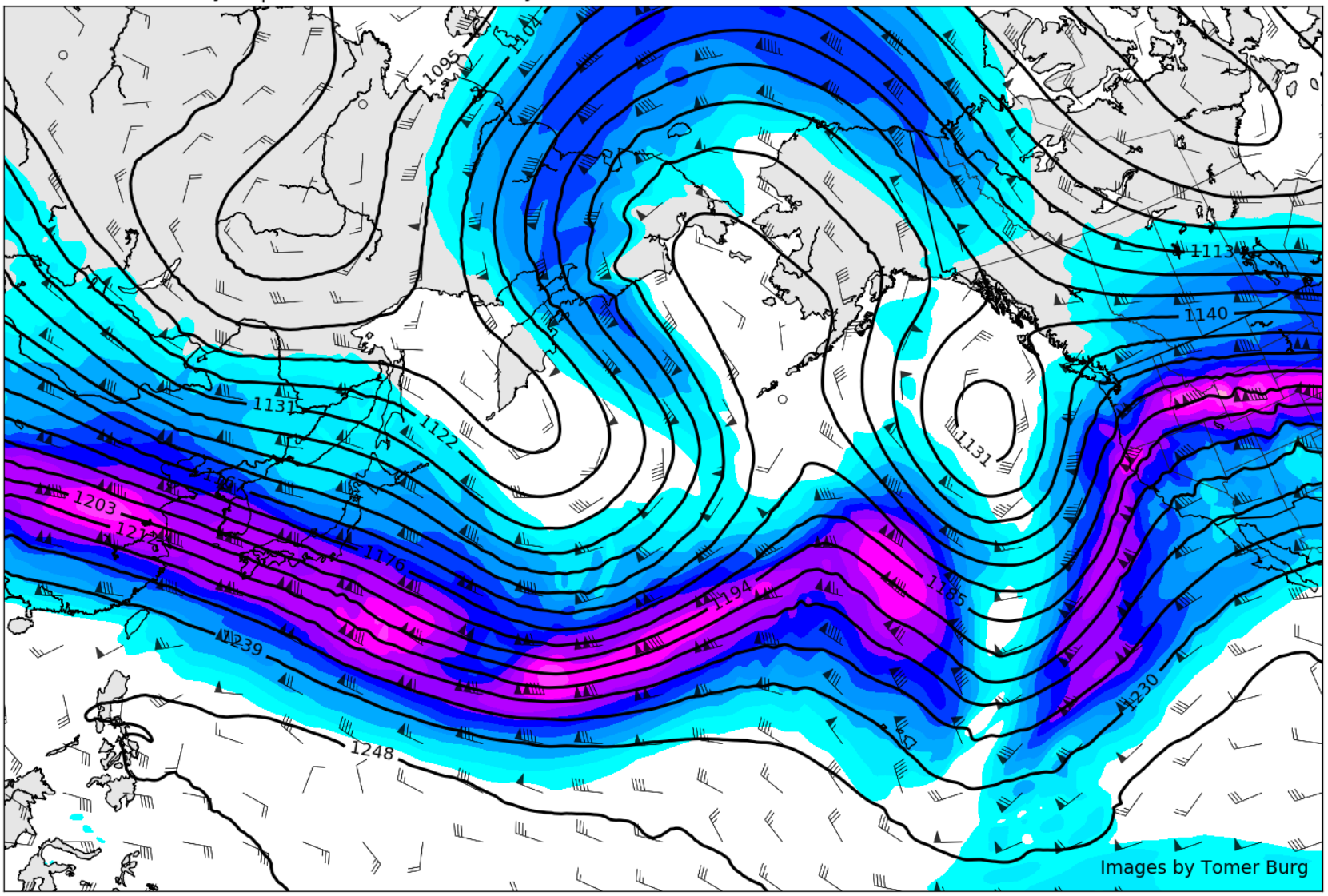
180 h GFS Forecast: Cyclones; California Jet Forms; Anticyclonic Flow over most of California

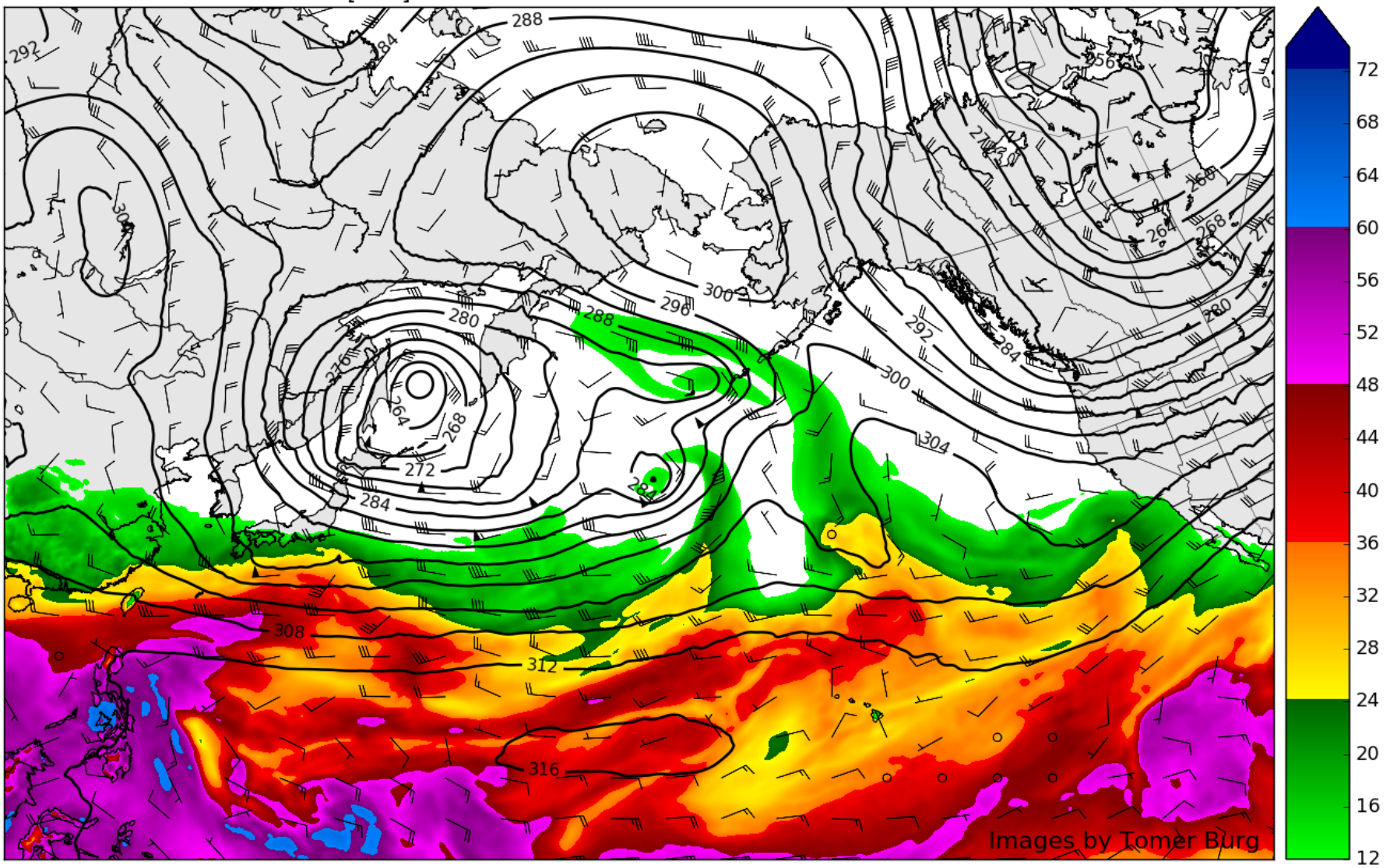


90 h GFS Forecast: EPAC Trough, Frontal System and Jet Axis Extend to Lower Latitudes

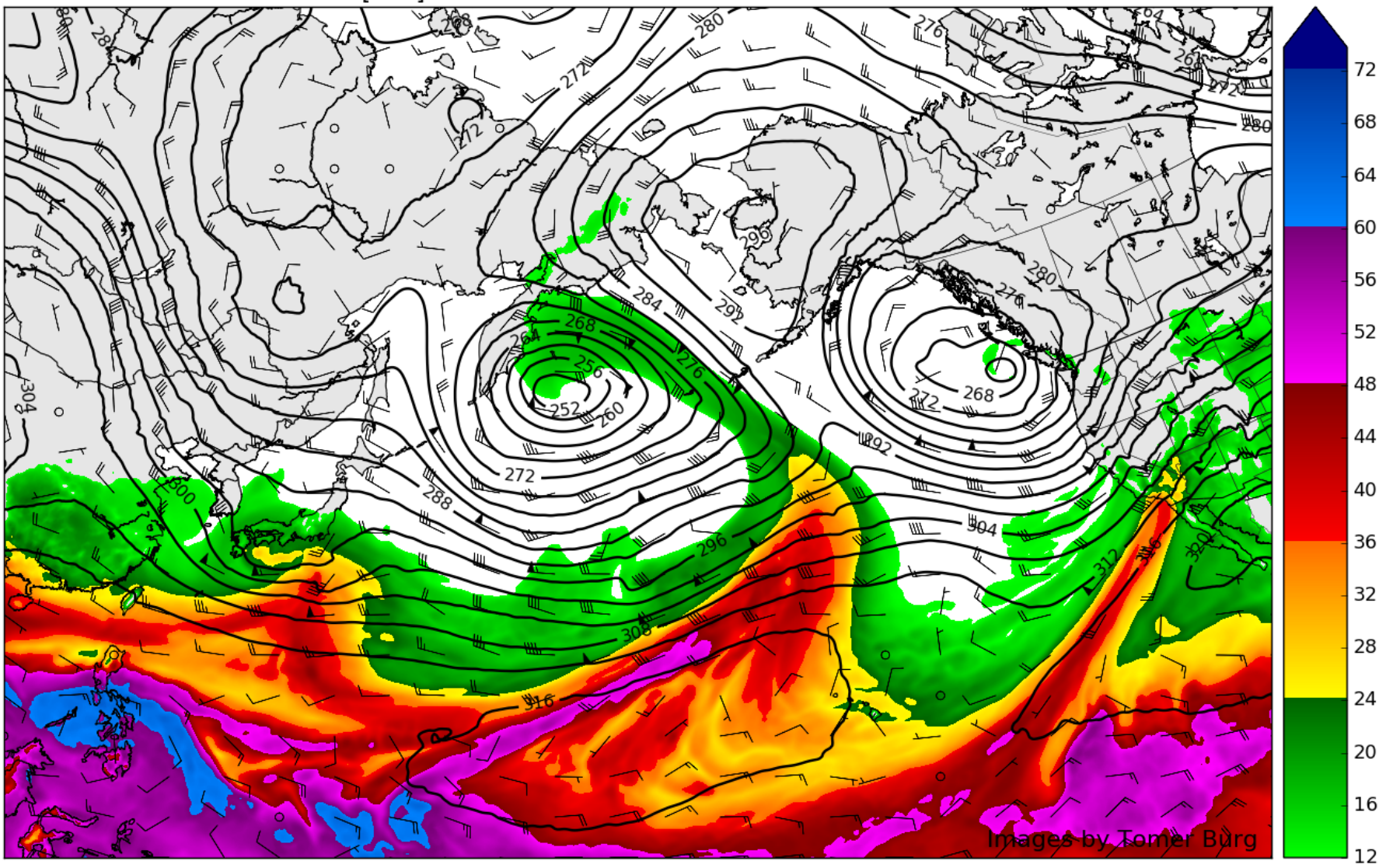
200 hPa Wind Isotachs, Geopotential Height (dam), Wind (kt)

0.25° ERA-5 Reanalysis | Valid 1200 UTC Sun 08 Jan 2017

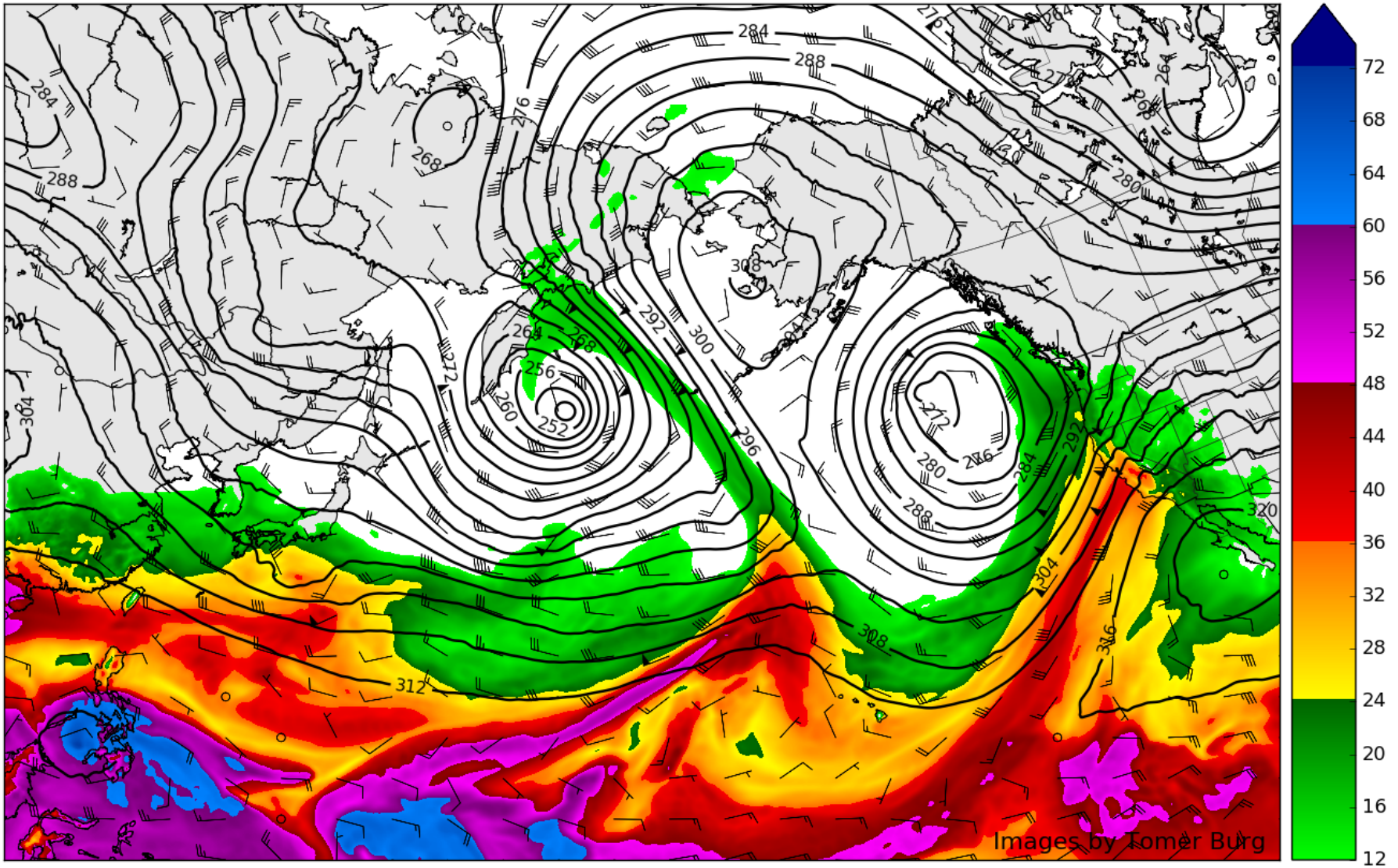




210 h GFS Forecast: Precipitable Water Remains Mostly Confined to the Tropics



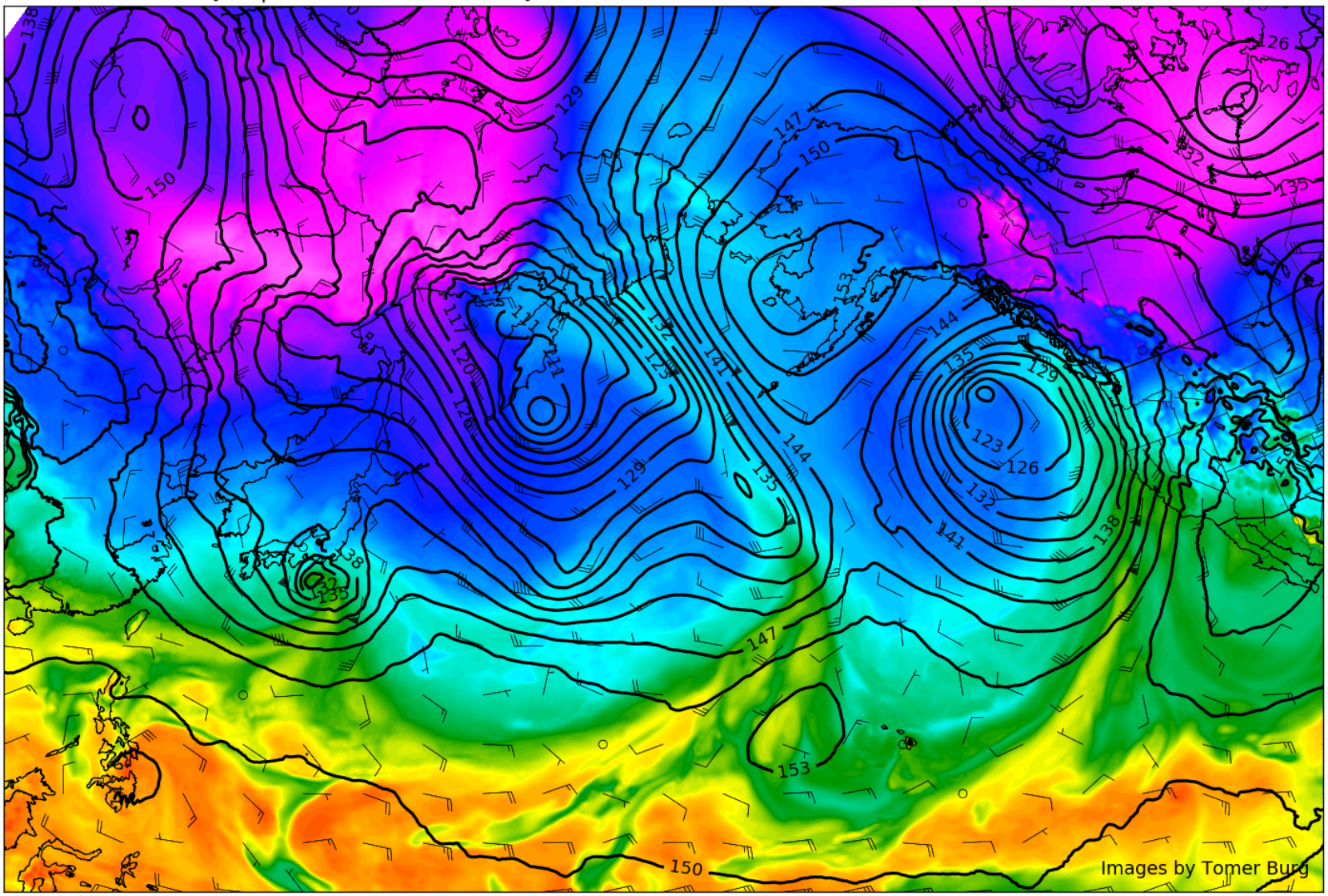
180 h GFS Forecast: Atmospheric Rivers are Evident in Central/Eastern Pacific



90 h GFS Forecast: Strong Easternmost Atmospheric River Targets Northern California

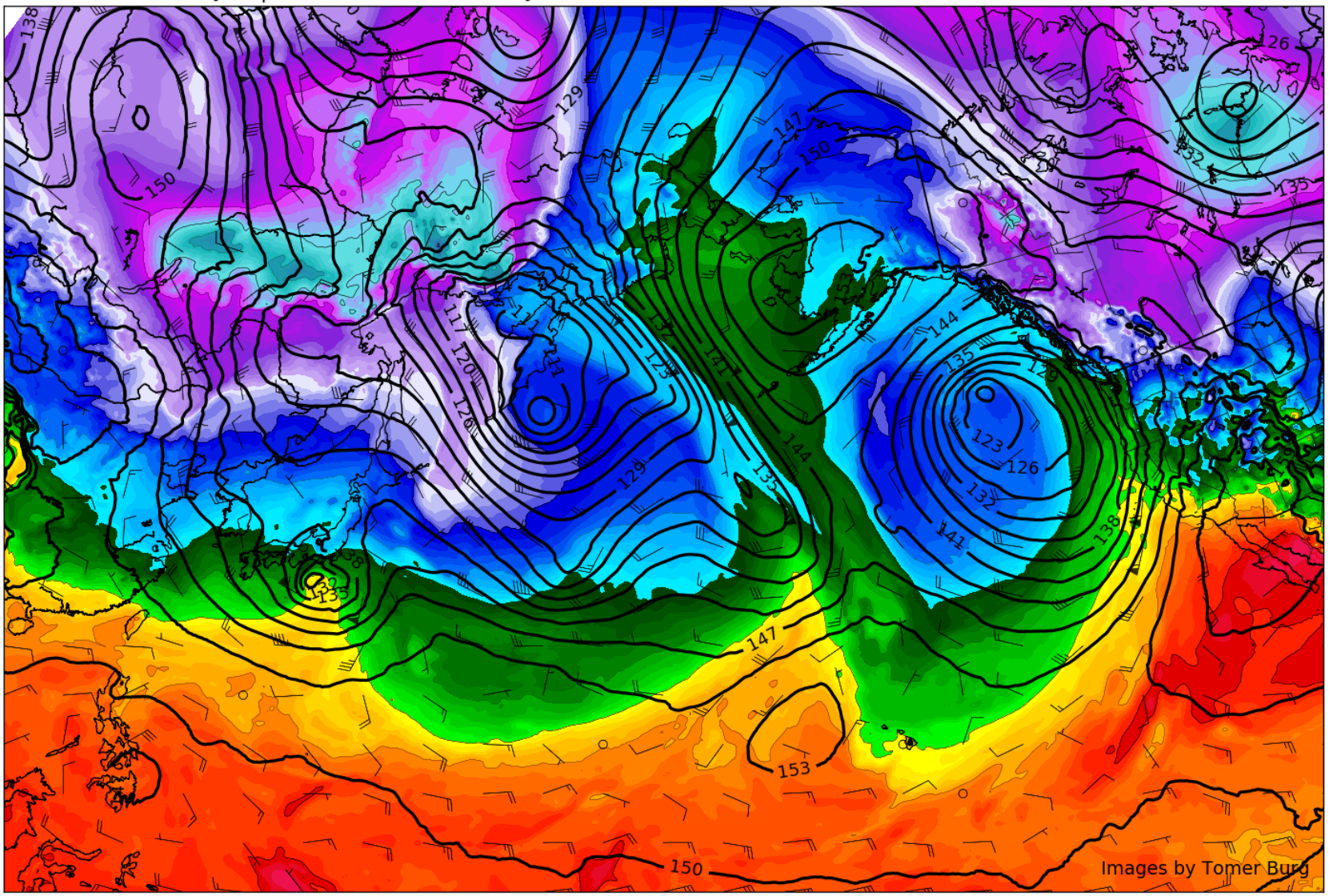
850 hPa Theta-e (K), Geopotential Height (hPa), Wind (kt)

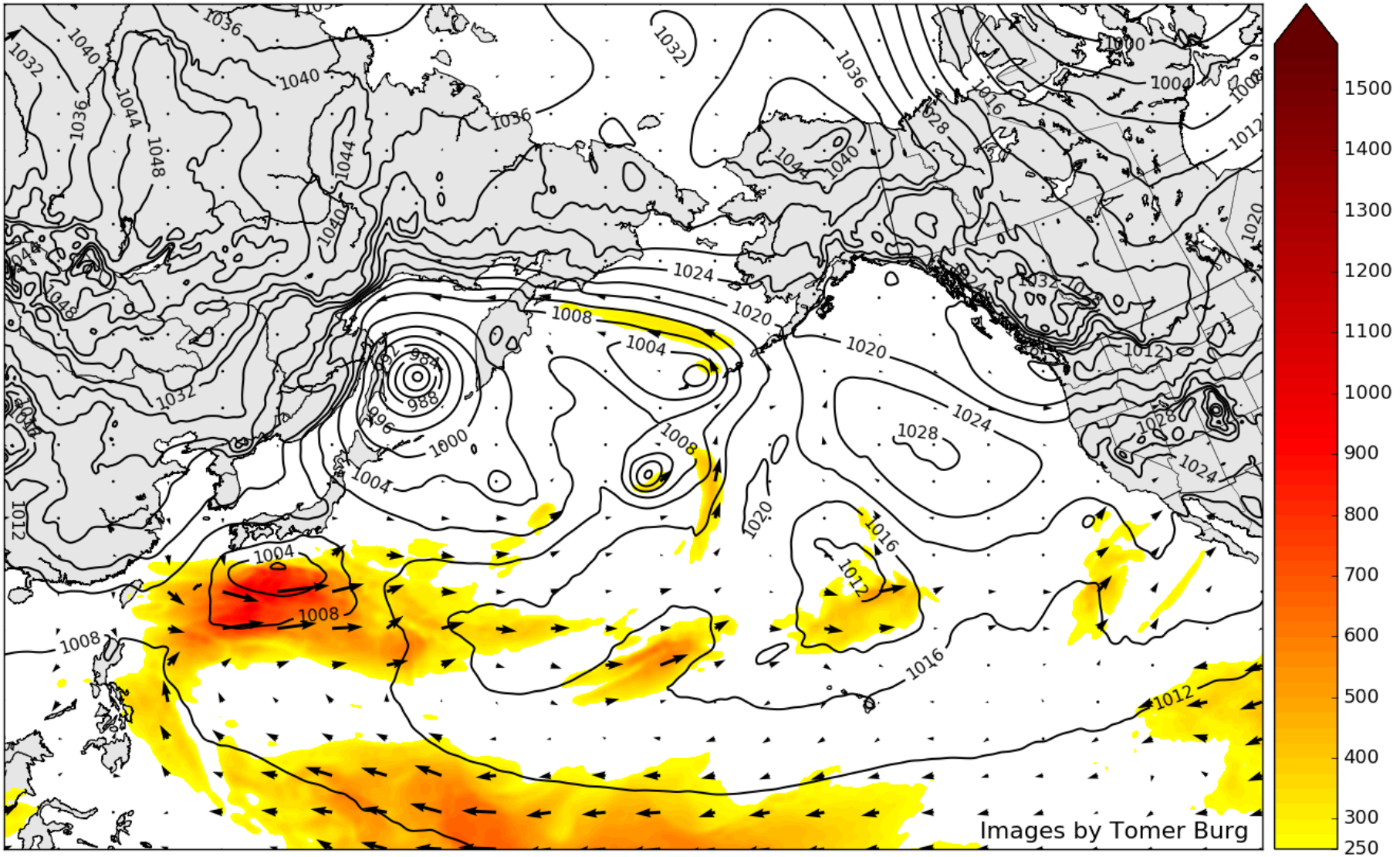
0.25° ERA-5 Reanalysis | Valid 1200 UTC Sun 08 Jan 2017



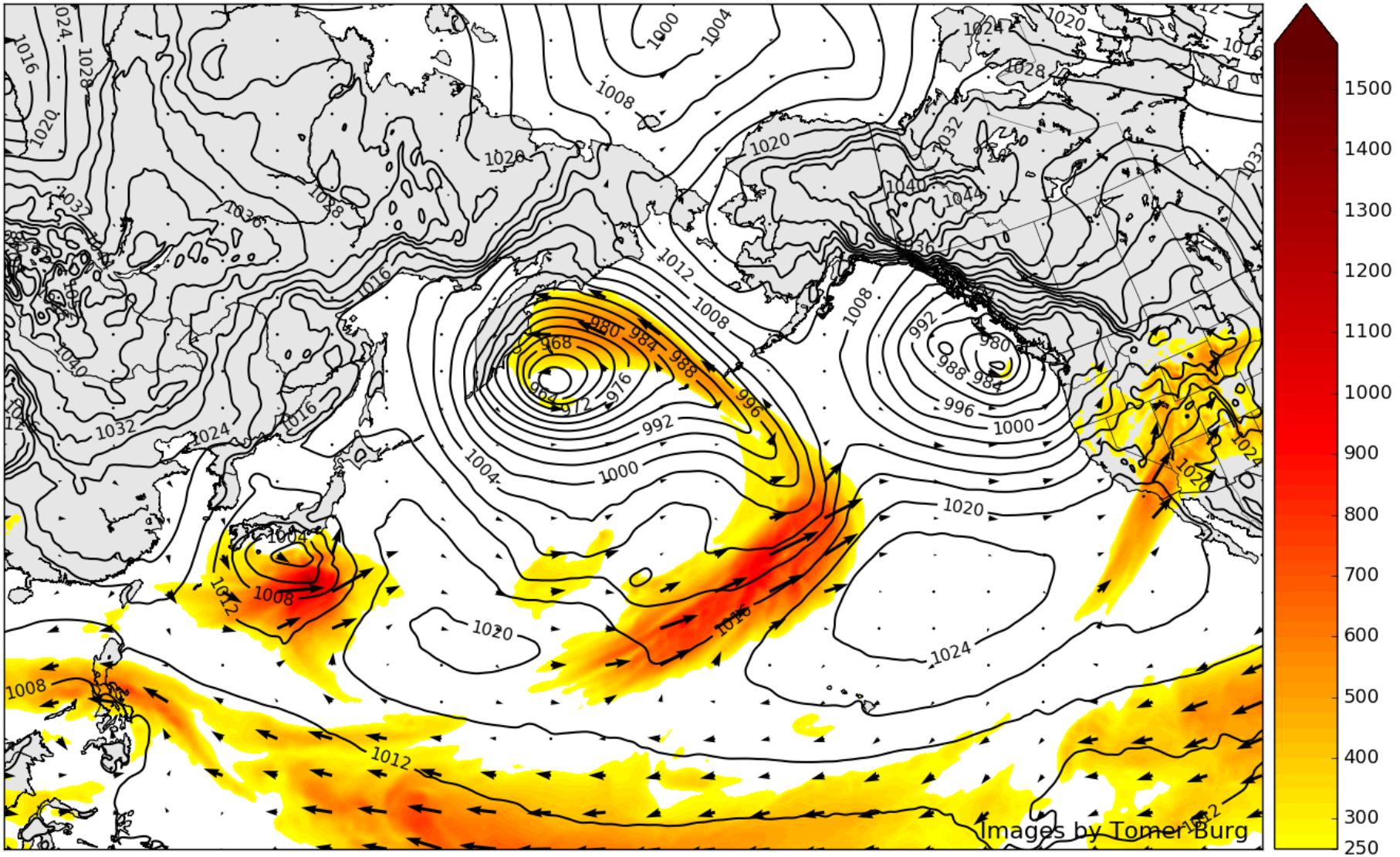
850 hPa Temperature (C), Geopotential Height (dam), Wind (kt)

0.25° ERA-5 Reanalysis | Valid 1200 UTC Sun 08 Jan 2017

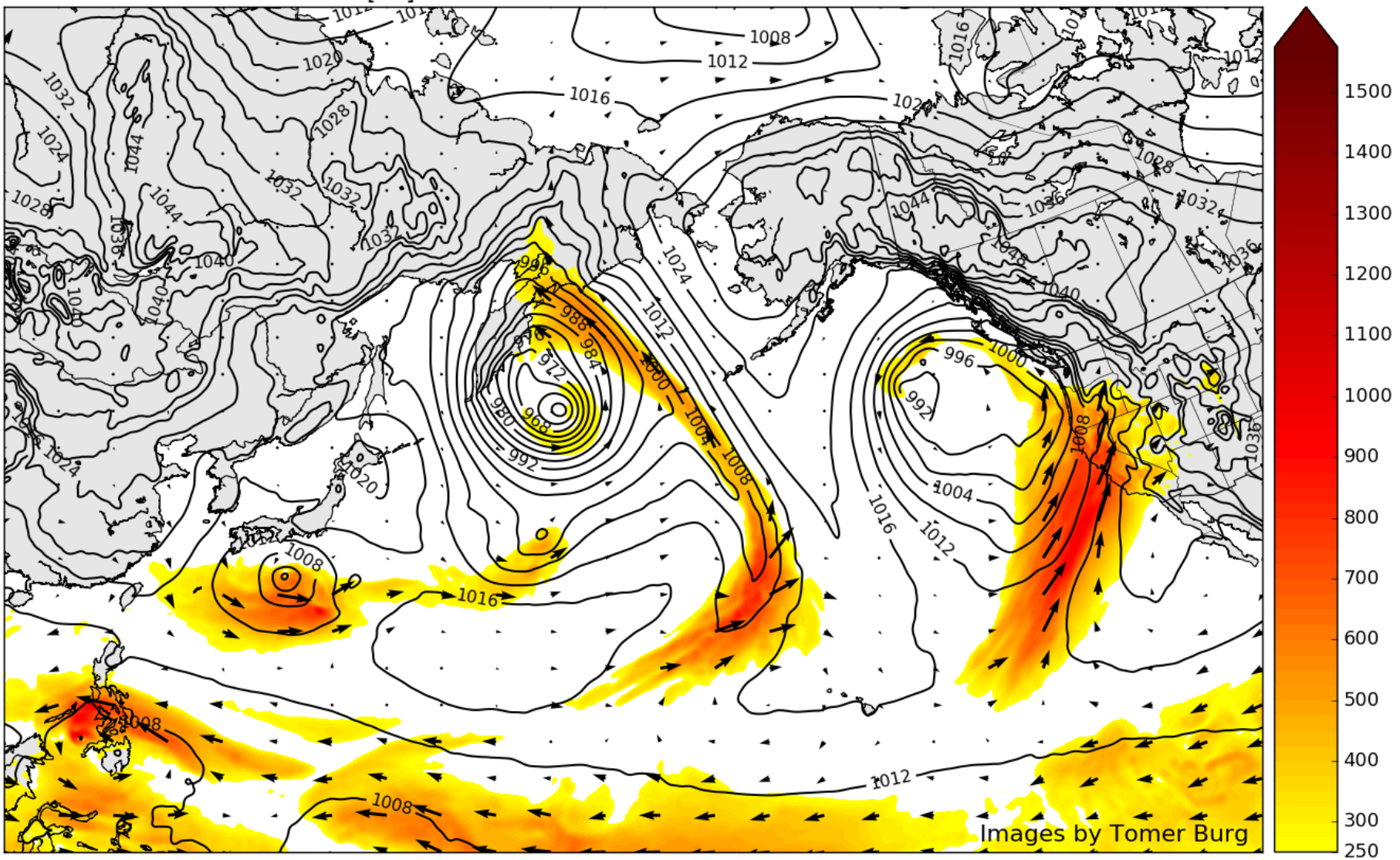




210 h GFS Forecast: Little Evidence for IVT Directed Toward West Coast



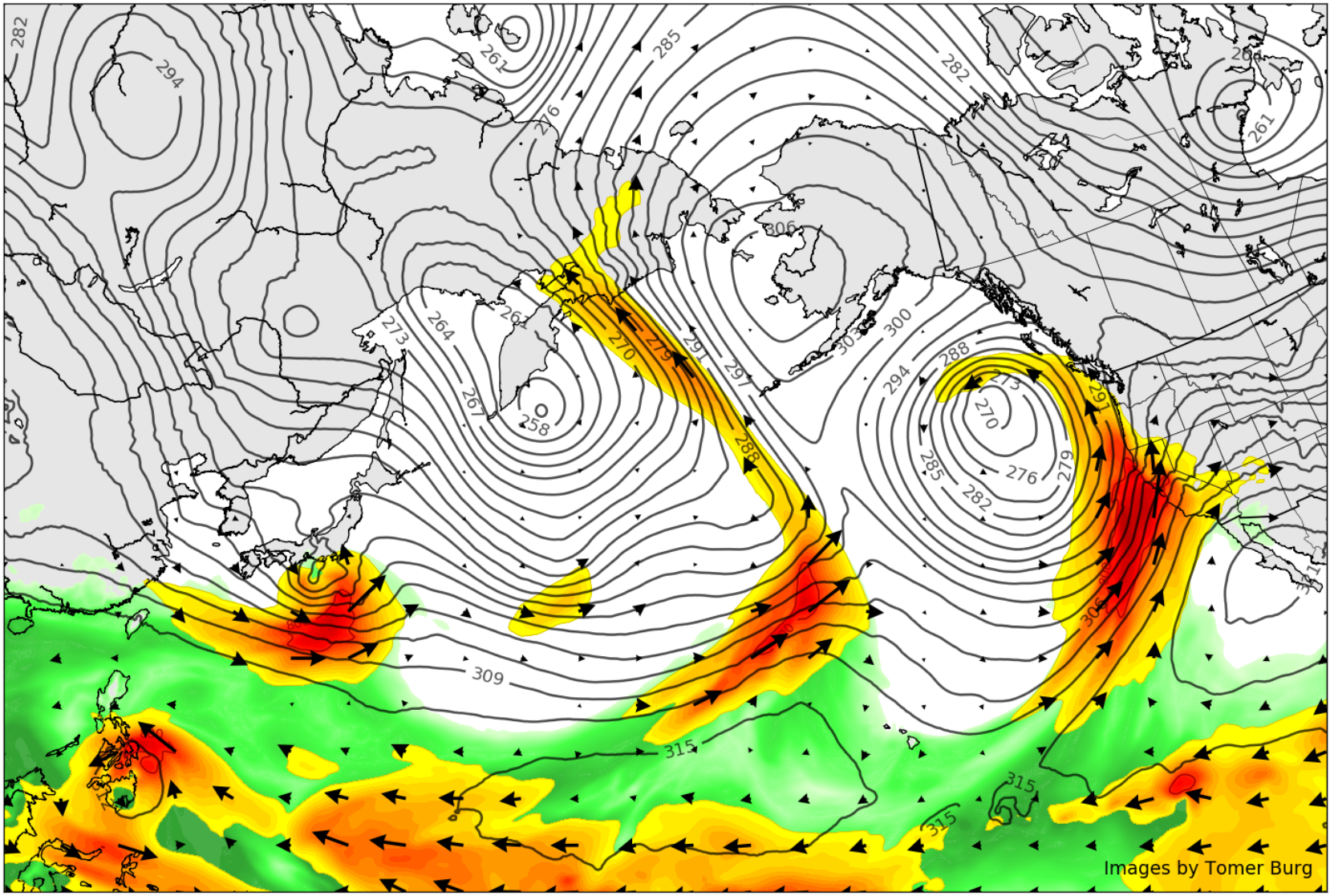
180 h GFS Forecast: Weak IVT is Directed Toward Southern California



90 h GFS Forecast: Significant IVT shift toward northern California and Oregon

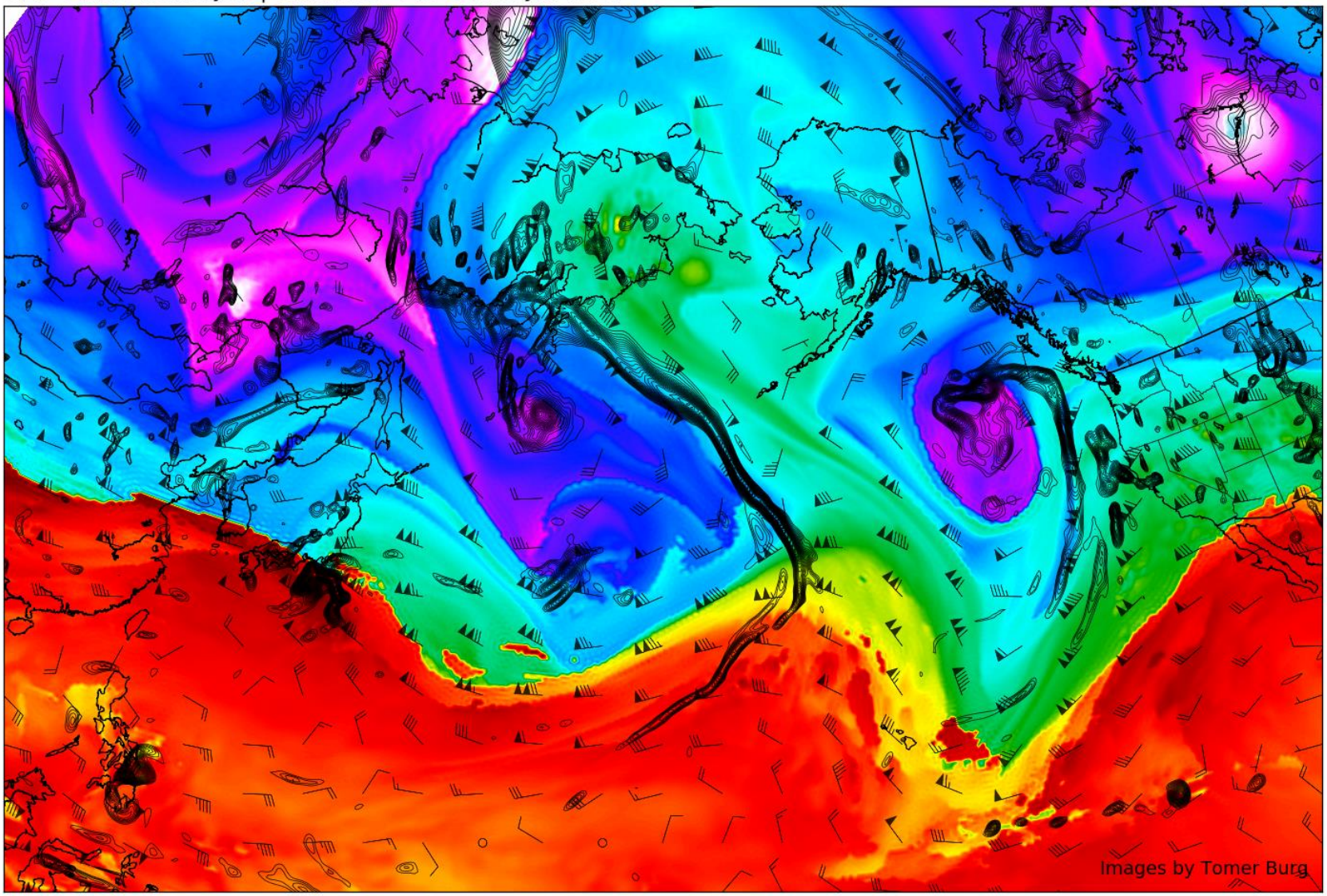
Integrated Vapor Transport (kg/m/s), 700-hPa Height (dam), PWAT > 20mm

0.25° ERA-5 Reanalysis | Valid 1200 UTC Sun 08 Jan 2017



2 PVU Potential Temperature (K), 850-hPa Relative Vorticity (1/s), Wind (kt)

0.25° ERA-5 Reanalysis | Valid 1200 UTC Sun 08 Jan 2017



Western CONUS Extreme Weather January 2017: Key Takeaways

- East Asian cold surges link to WPAC subtropical jet (STJ) locatiom
- Cyclogenesis in the STJ exit region reinforces Omega block
- Omega block enables Arctic air to reach the Pacific NW
- Anticyclonic wave breaking (AWB) focuses AR locations
- STJ disturbances associated with AWB strengthen pre-frontal ARs
- WAA and orographic lift leads to excessive coastal/inland rainfall
- Predictability horizon for the California deluge was 4–6 days
- Monthly/subseasonal California rainfall forecasts were irrelevant

Motivation: North Pacific Jet Phase Diagram

- **The North Pacific Jet (NPJ) phase diagram serves as an objective tool to characterize the instantaneous state and evolution of the upper-tropospheric flow pattern over the North Pacific**

- **The prevailing NPJ regime, as determined by the NPJ phase diagram, has important implications for the character of the downstream upper-tropospheric flow pattern over North America**

A North Pacific Jet (NPJ) Perspective

- **EOF analyses of 250-hPa zonal winds are used to identify characteristic NPJ regime phase spaces***
- **Four NPJ regimes are identified: extended and retracted; poleward- and equatorward-shifted**

***Andrew Winters Real-Time NPJ Phase Diagram (Real-Time NPJ Phase Diagram http://www.atmos.albany.edu/facstaff/awinters/realtime/About_EOFs.php)**

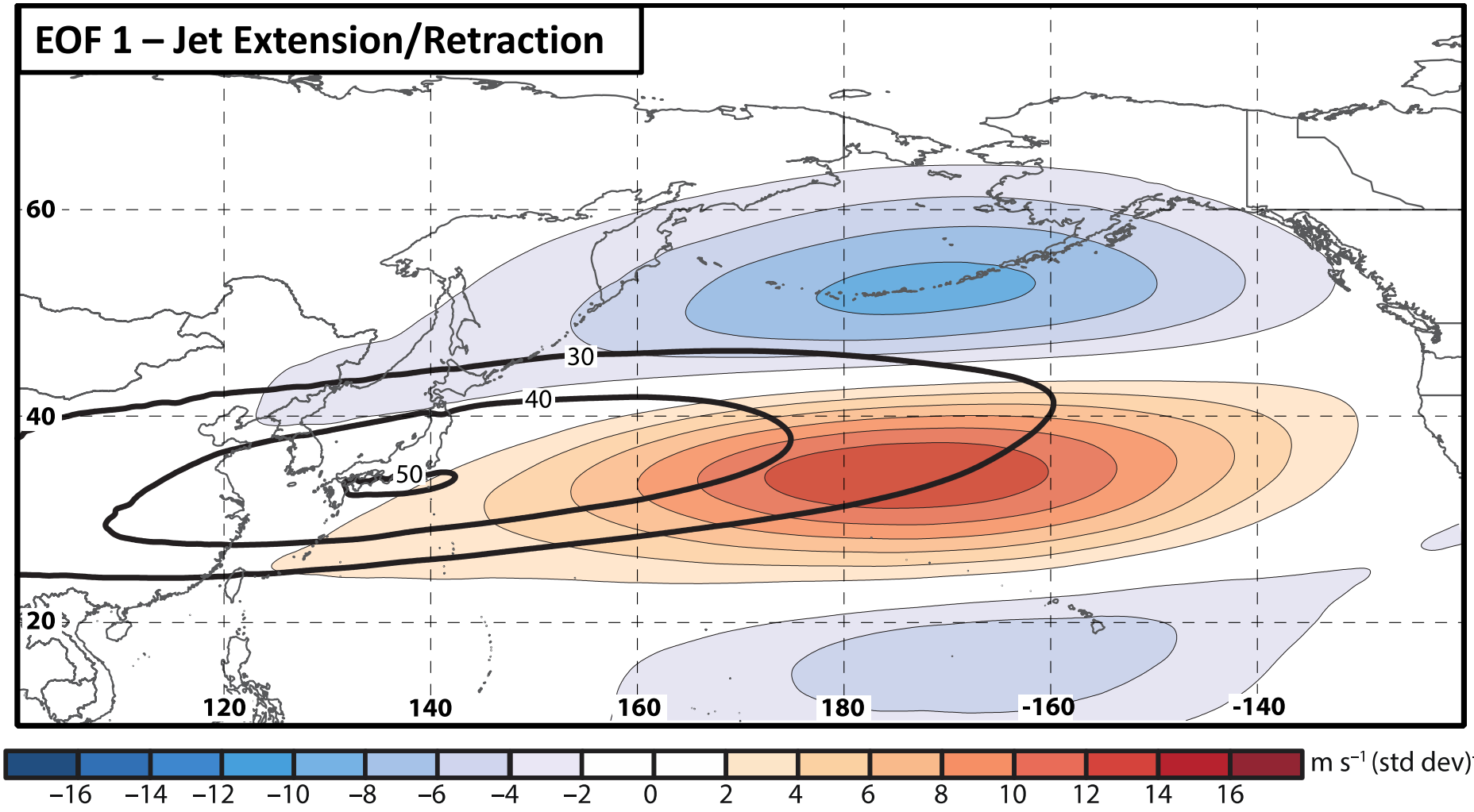
250-hPa North Pacific Zonal Wind Variability

- Removed the mean and the annual and diurnal cycles from 6-hourly, 250-hPa zonal wind data from the CFSR (1979–2014)
- Restricted data to the cool season (Sept.–May)
- Performed an EOF analysis on the zonal wind anomalies within the domain: 10–80°N ; 100°E–120°W

Analysis techniques and resultant EOF patterns are consistent with related work on the North Pacific Jet:

- Athanasiadis et al. (2010)
- Jaffe et al. (2011)
- Griffin and Martin (2016)

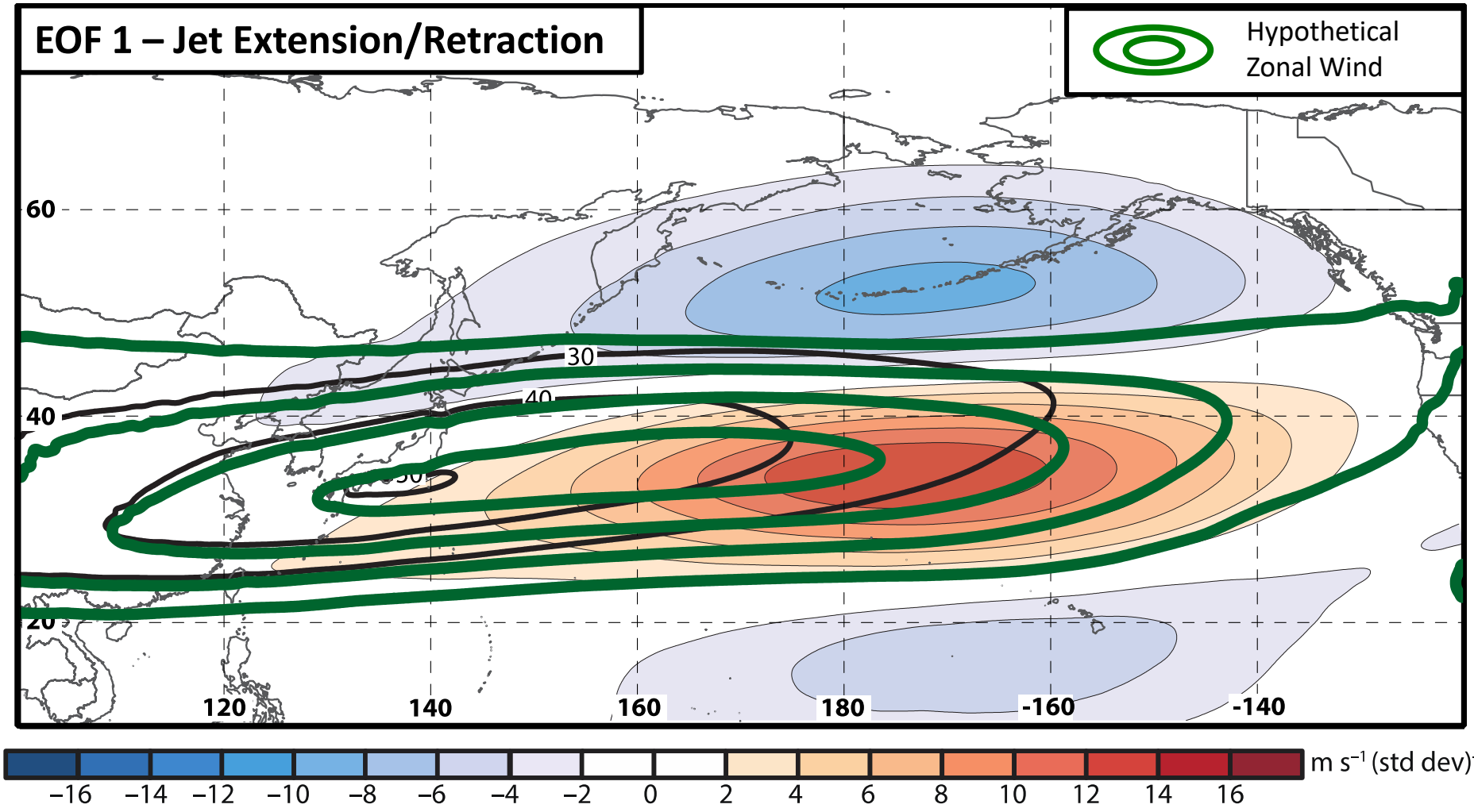
250-hPa North Pacific Zonal Wind Variability



Sept.–May mean 250-hPa zonal wind: black contours
Sept.–May 250-hPa zonal wind EOF 1 pattern: shading

+ EOF 1: Jet Extension
– EOF 1: Jet Retraction

250-hPa North Pacific Zonal Wind Variability



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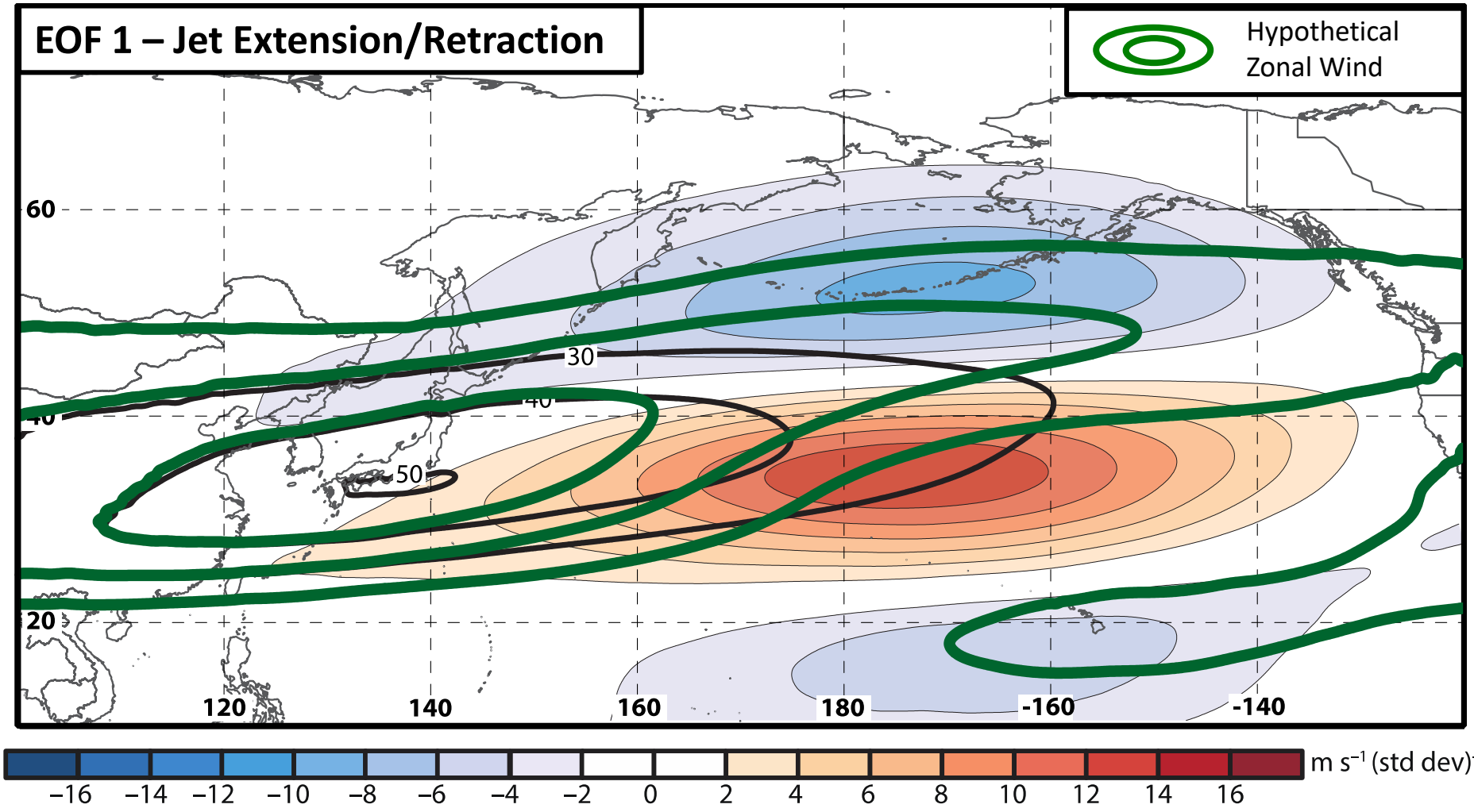
250-hPa North Pacific Zonal Wind Variability



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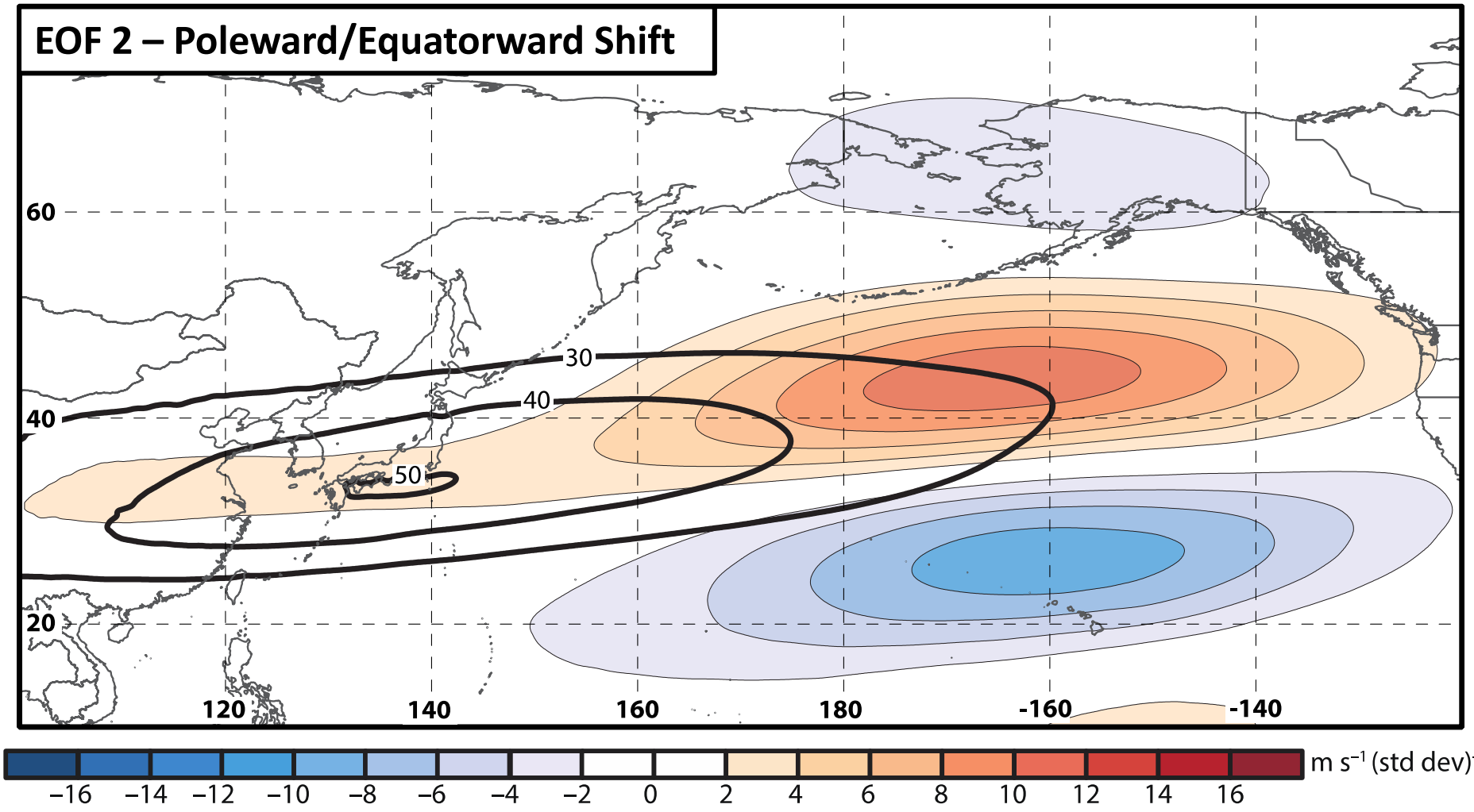
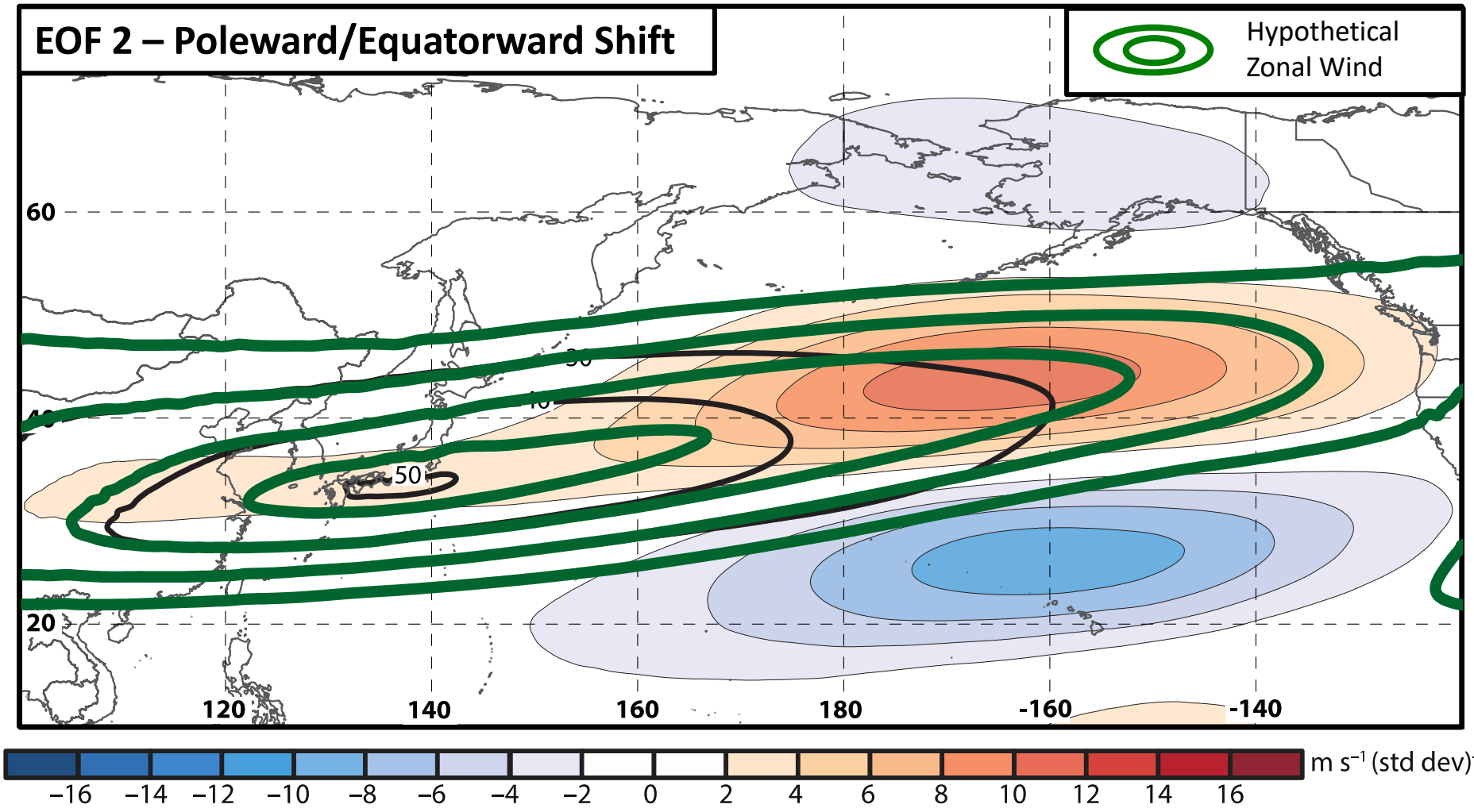
250-hPa North Pacific Zonal Wind Variability



Sept.–May mean 250-hPa zonal wind: black contours
Sept.–May 250-hPa zonal wind EOF 2 pattern: shading

+ EOF 2: Poleward Shift
– EOF 2: Equatorward Shift

250-hPa North Pacific Zonal Wind Variability

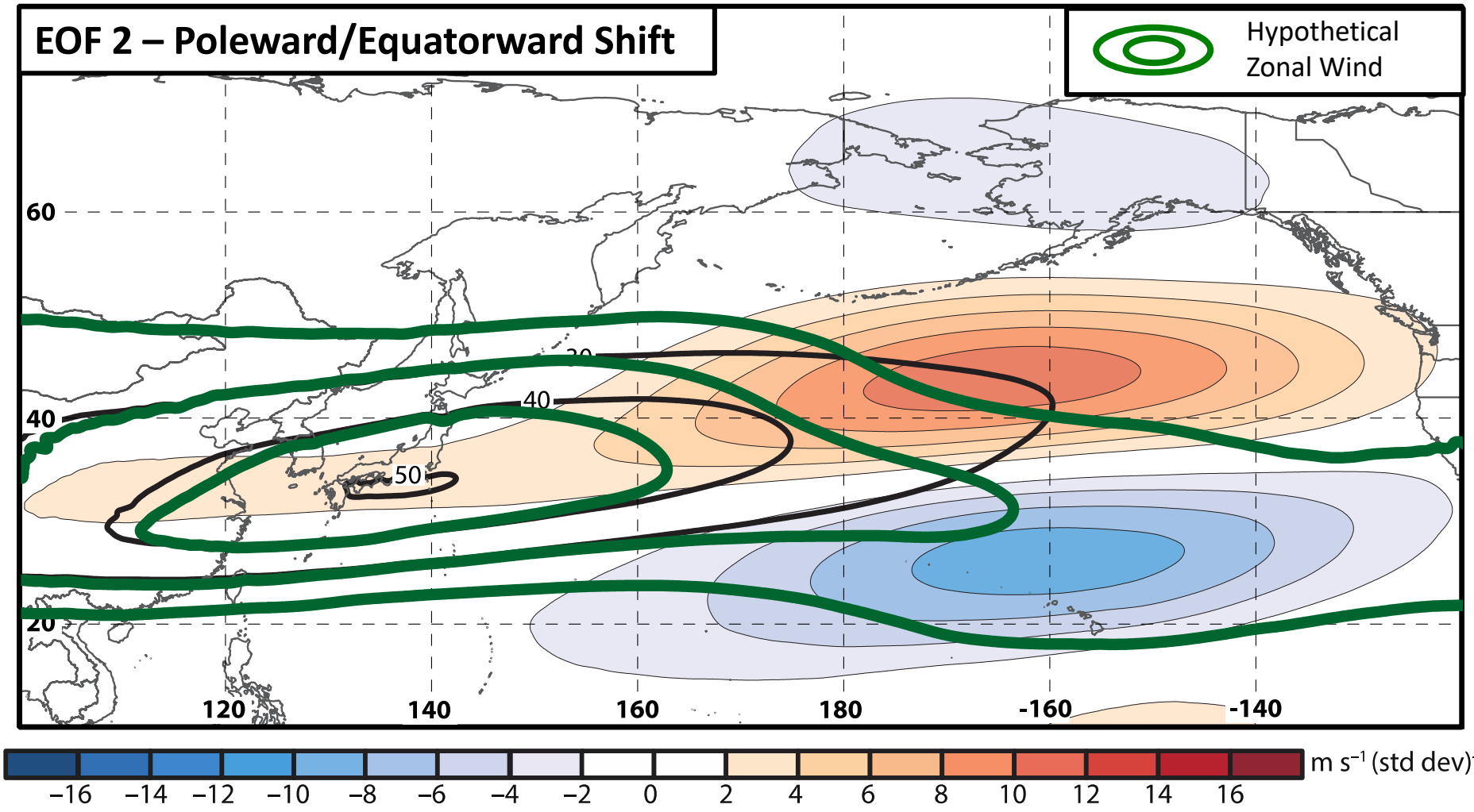


Sept.–May mean 250-hPa zonal wind: black contours
Sept.–May 250-hPa zonal wind EOF 2 pattern: shading

+ EOF 2: Poleward Shift

– EOF 2: Equatorward Shift

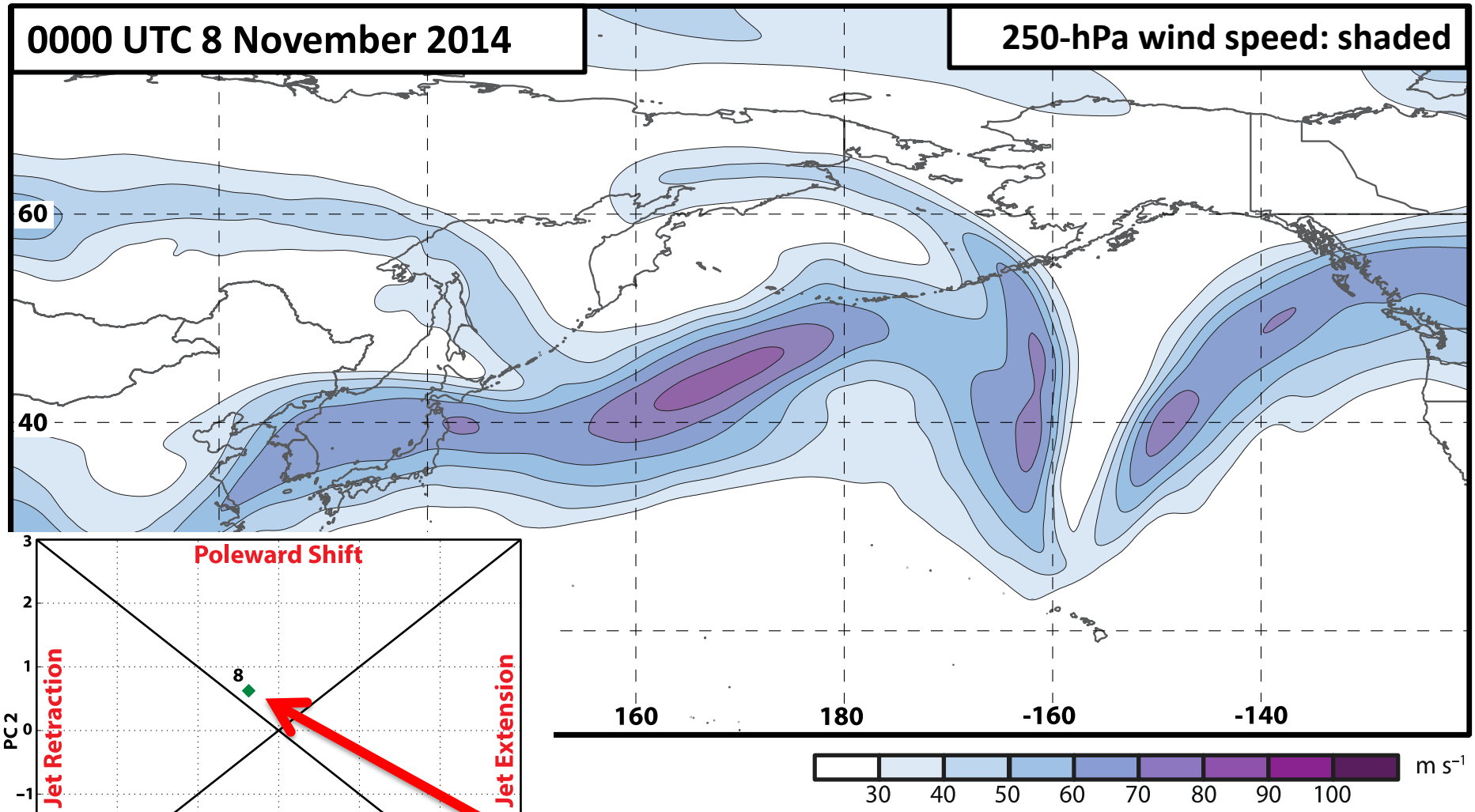
250-hPa North Pacific Zonal Wind Variability



Sept.–May mean 250-hPa zonal wind: black contours
Sept.–May 250-hPa zonal wind EOF 2 pattern: shading

+ EOF 2: Poleward Shift
– EOF 2: Equatorward Shift

250-hPa North Pacific Zonal Wind Variability



Instantaneous 250-hPa zonal wind anomalies can be projected onto EOF 1 and EOF 2, resulting in a point on a North Pacific Jet phase diagram

North Pacific Jet (NPJ) Regimes

- **Griffin and Martin (2017) highlight synoptic-scale flow evolution patterns associated with NPJ regimes**

- **EOF analyses of 250-hPa zonal winds are used to identify four NPJ regime phase spaces (zonal NPJ extension/retraction; poleward/equatorward NPJ shift)***

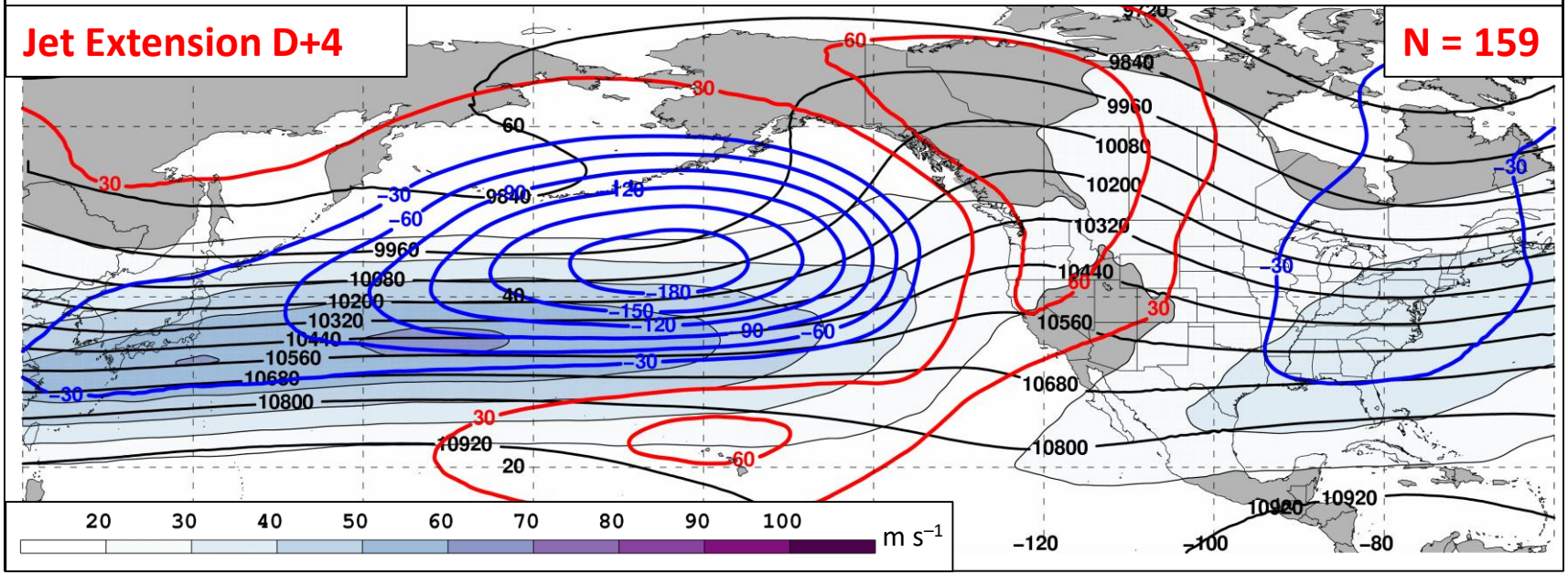
- **Composite upper-tropospheric flow patterns associated with these four NPJ regime four days after the development of that NPJ regime are shown next**

***Winters et al. 2018: The Development of the North Pacific Jet Phase Diagram as an Objective Tool to Monitor the State of the Upper Tropospheric Flow Pattern (sent to WAF June 2018)**

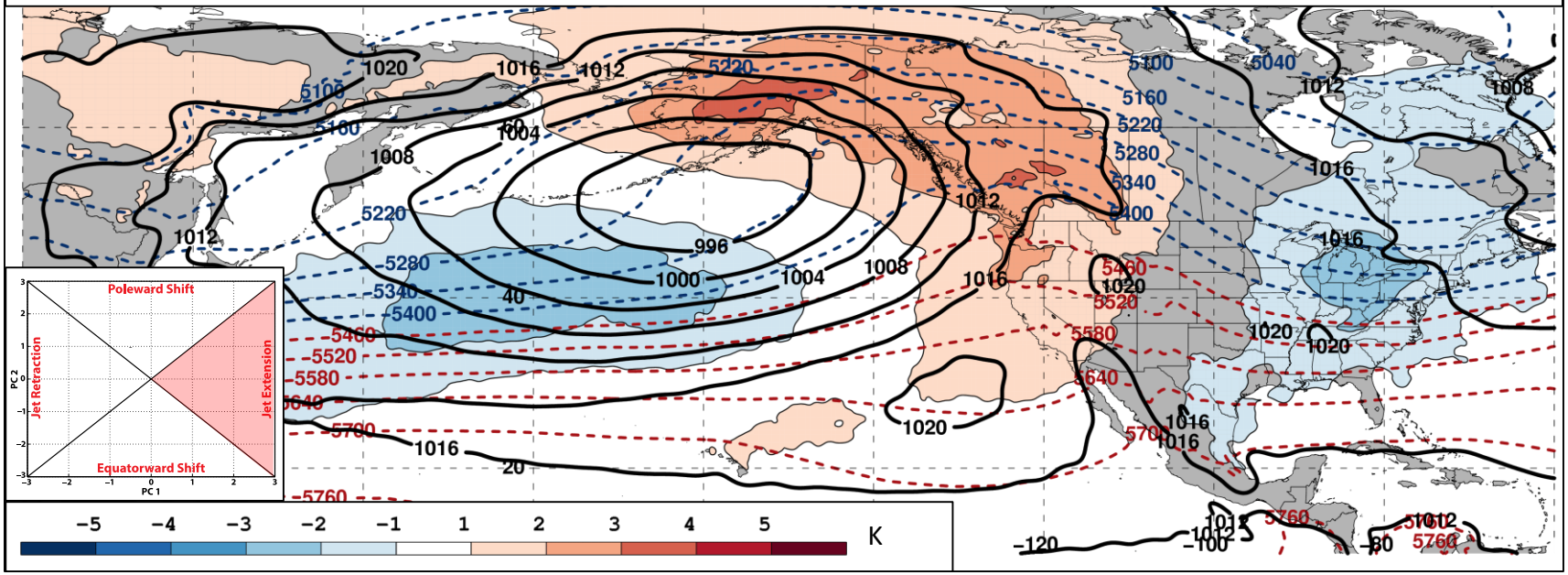
Griffin, K. S. and J. E. Martin, 2017: Synoptic features associated with temporally coherent modes of variability of the North Pacific jet stream. Mon. Wea. Rev., 30, 39–54.
https://journals.ametsoc.org/doi/abs/10.1175/JCLI-D-15-0833.1

Real-Time NPJ Phase Diagram
http://www.atmos.albany.edu/facstaff/awinters/realtime/About_EOFs.php
(Contact Andrew Winters: acwinters@albany.edu)

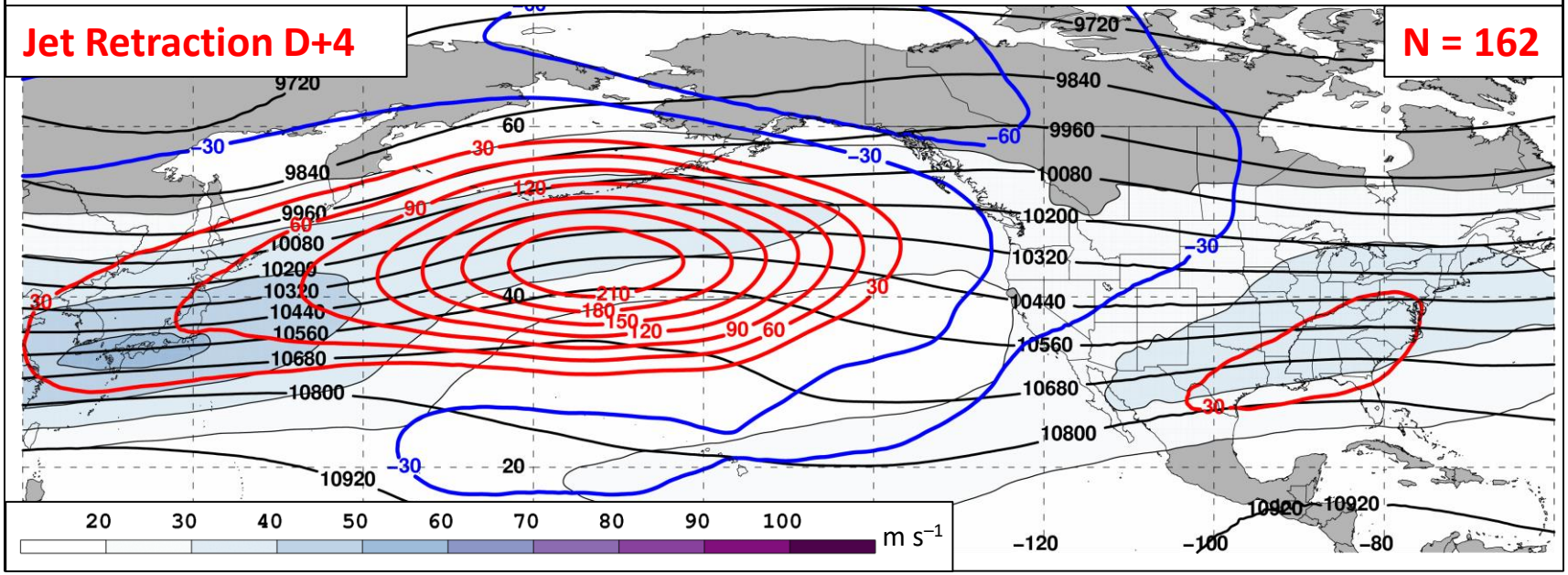
250-hPa Wind Speed (shading), Geo. Heights (contours), Geo. Height Anom. (contours):



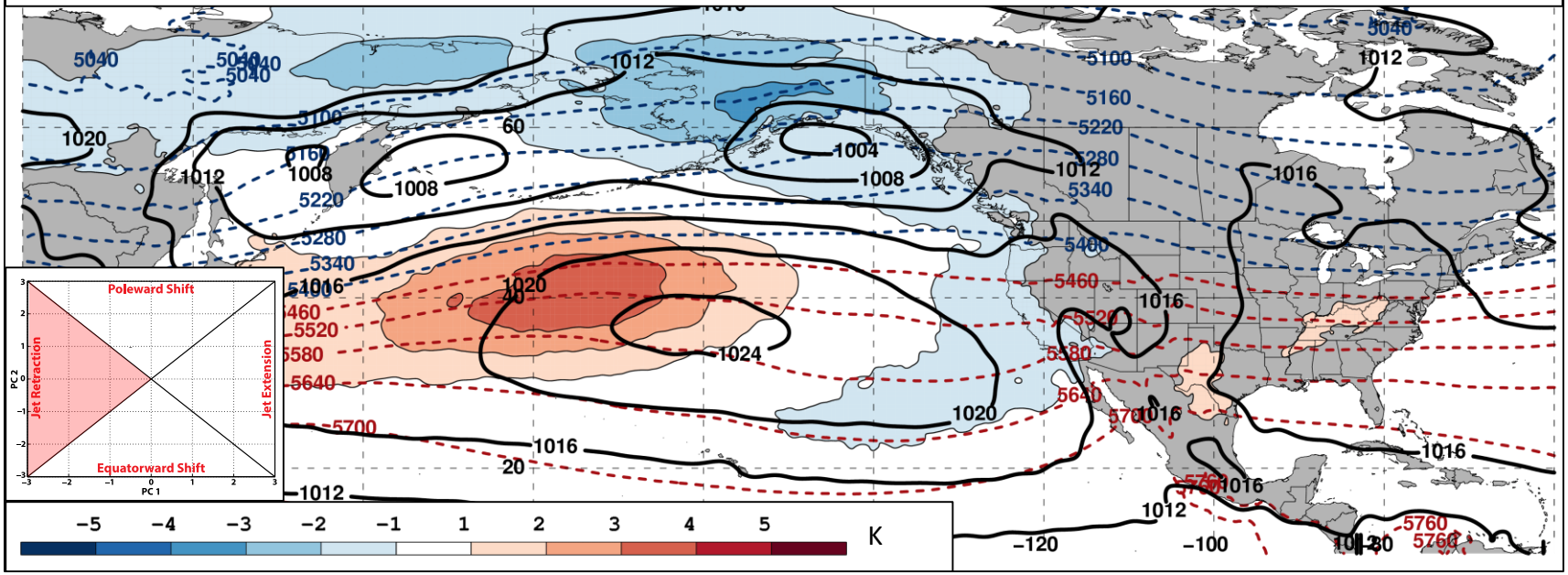
Mean SLP (contours), 1000–500-hPa Thick. (contours), 850-hPa Temp. Anom. (shading):



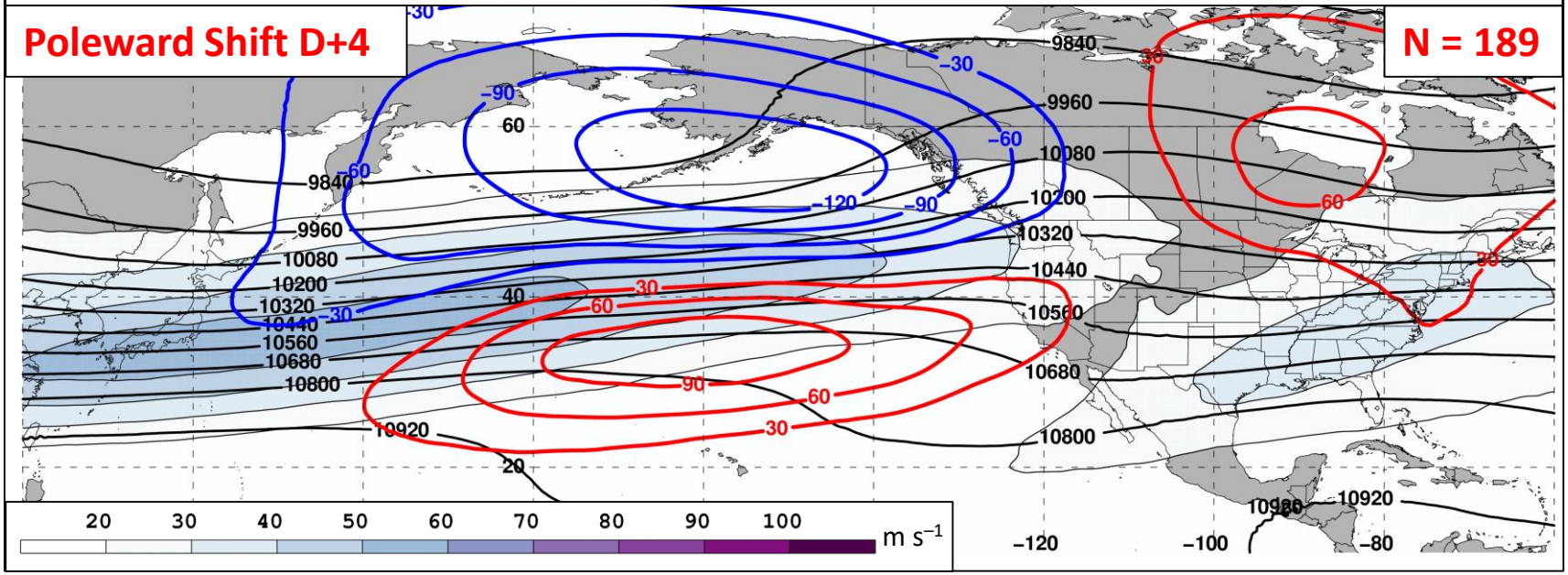
250-hPa Wind Speed (shading), Geo. Heights (contours), Geo. Height Anom. (contours):



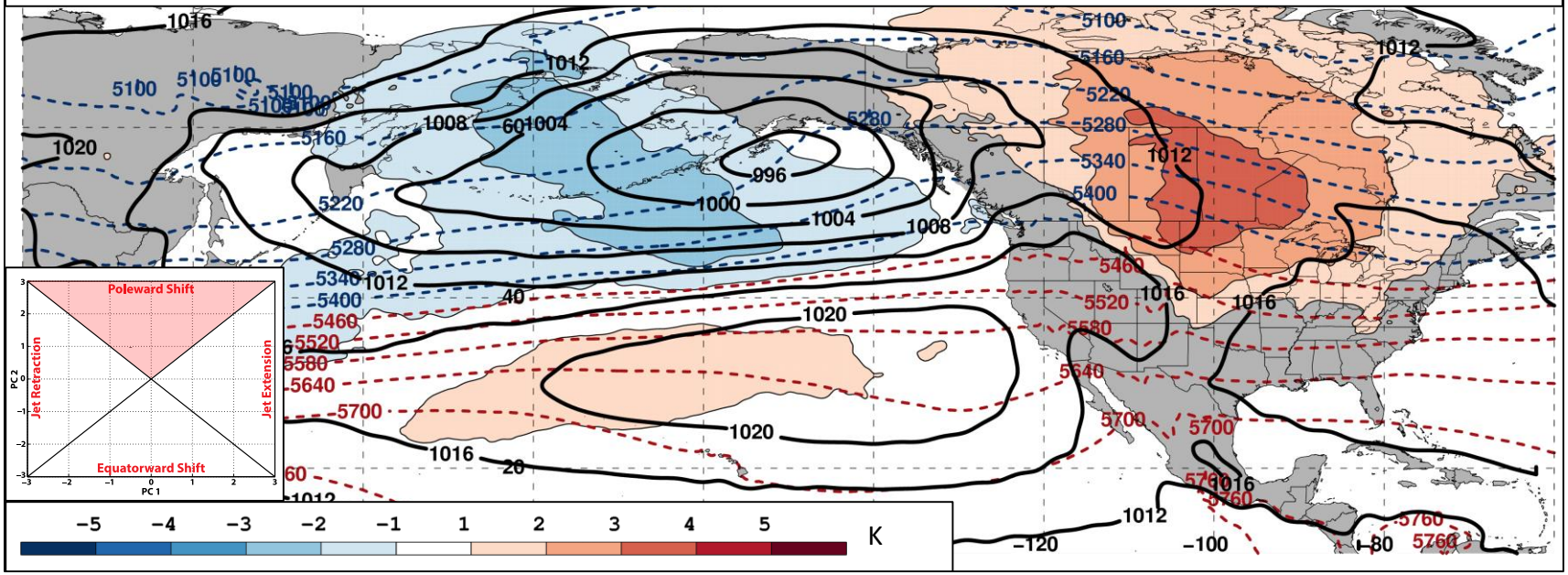
Mean SLP (contours), 1000–500-hPa Thick. (contours), 850-hPa Temp. Anom. (shading):



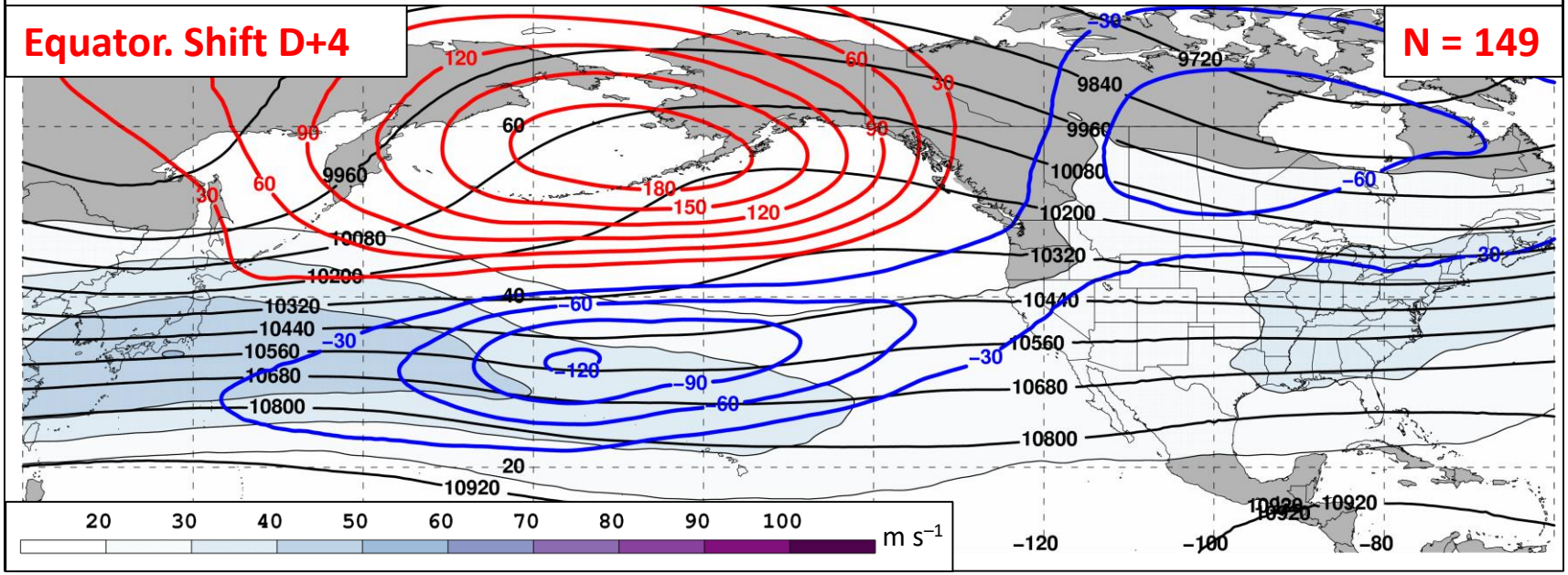
250-hPa Wind Speed (shading), Geo. Heights (contours), Geo. Height Anom. (contours):



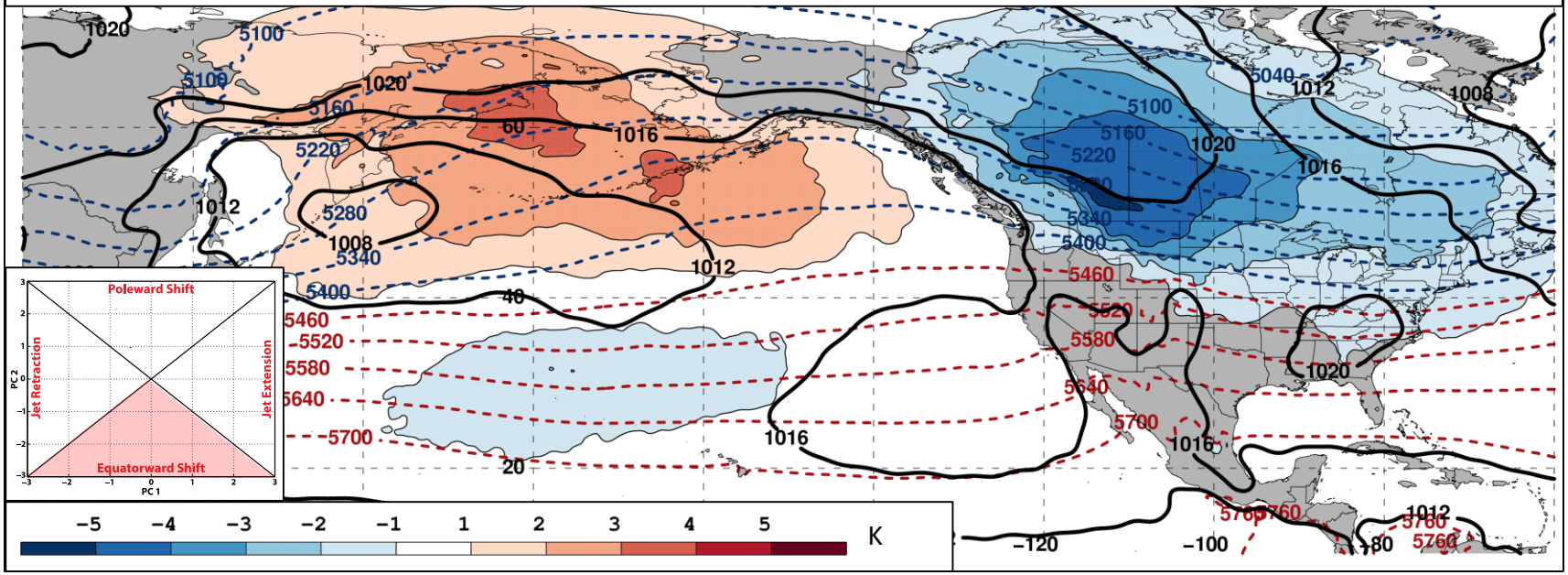
Mean SLP (contours), 1000–500-hPa Thick. (contours), 850-hPa Temp. Anom. (shading):



250-hPa Wind Speed (shading), Geo. Heights (contours), Geo. Height Anom. (contours):



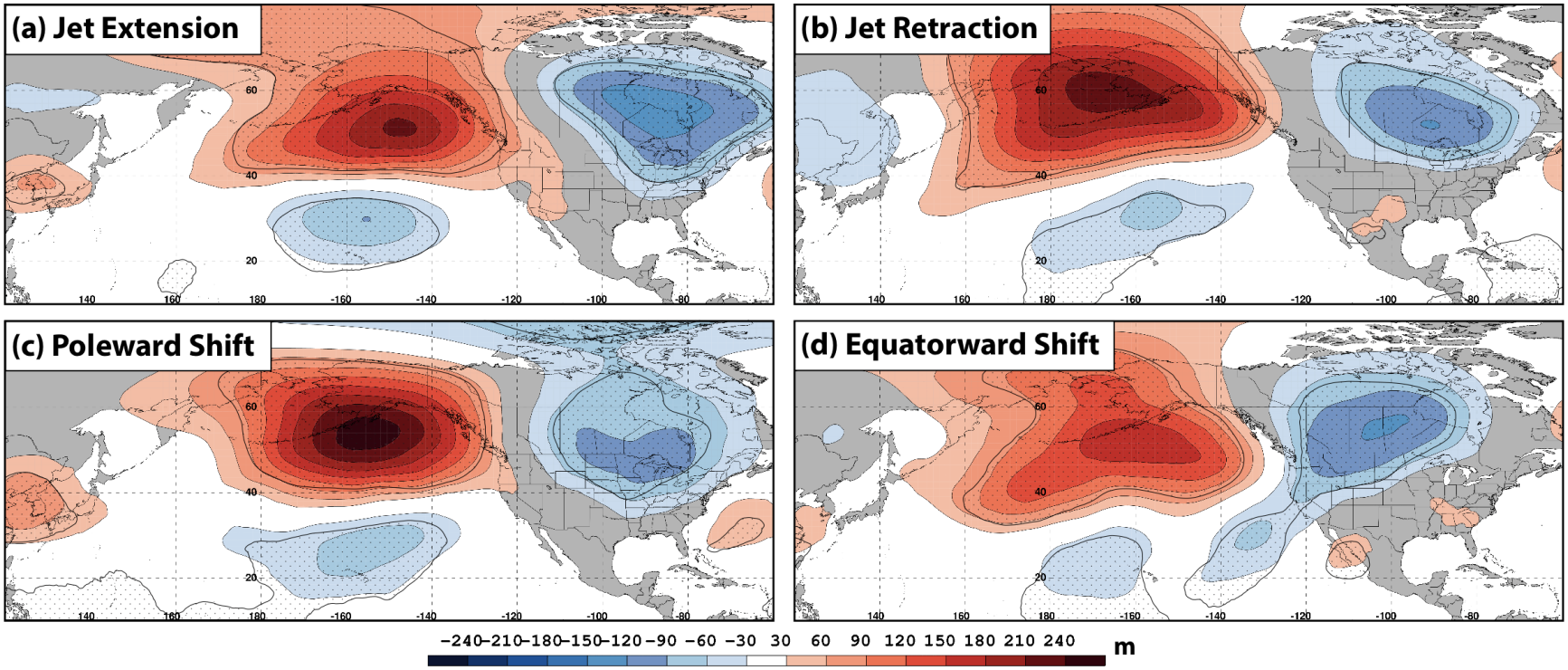
Mean SLP (contours), 1000–500-hPa Thick. (contours), 850-hPa Temp. Anom. (shading):



Antecedent NPJ Flow Patterns Associated with Poor Downstream GEFS Forecasts

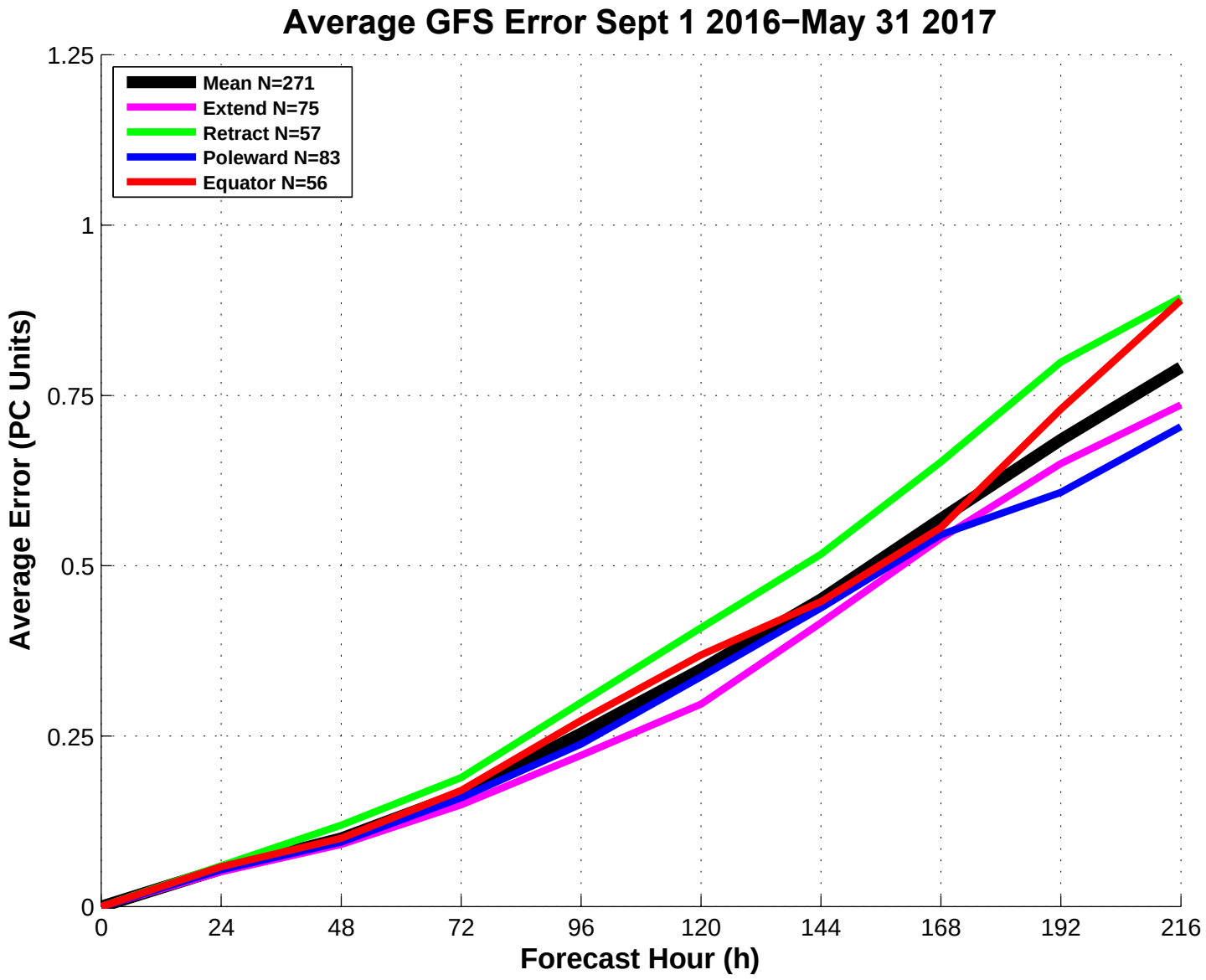
Best & Worst NPJ Day 8–9 Forecasts

GEFS Reforecasts



The difference in composite geopotential height anomalies 8 days following the initialization of a worst and best NPJ Phase Diagram forecast (worst – best)

2016 –2017 Average GFS Error – Regime



NPJ Phase Diagram Web Interface

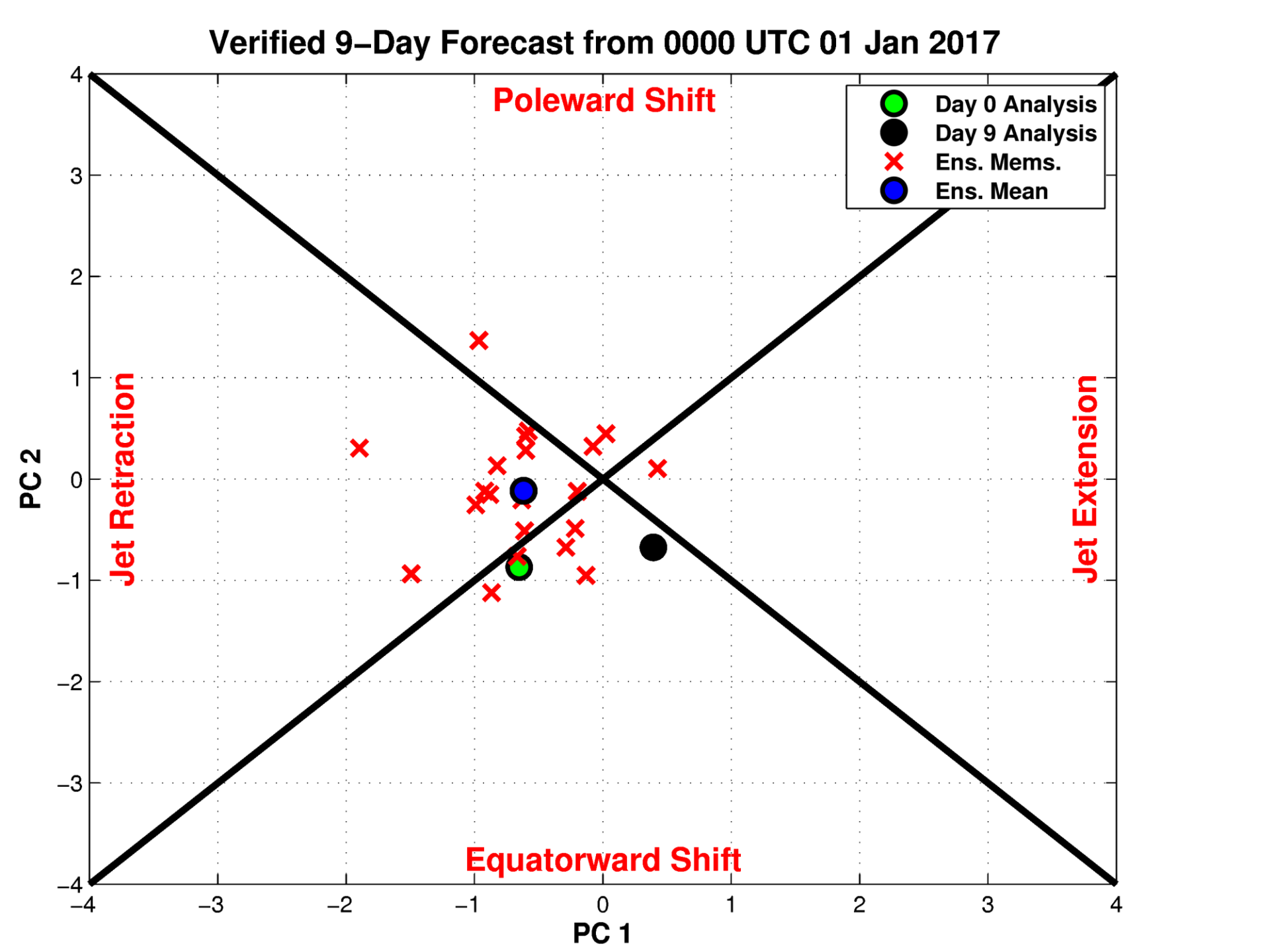
- **A web interface has been developed and implemented at WPC that offers real time NPJ phase diagram forecasts and NPJ regime composites.**

http://www.atmos.albany.edu/facstaff/awinters/realtime/About_EOFs.php

Contact: acwinters@albany.edu

Collaborators: Mike Bodner (WPC), Arlene Laing (NOAA), Dan Halperin (WPC), Bill Lamberson (WPC), Josh Kastman (WPC), and Sara Ganetis (WPC)

GEFS NPJ Phase Diagram Example from 1 January 2017


Verified 9–Day Forecast from 0000 UTC 01 Jan 2017
Poleward Shift
Equatorward Shift
Jet Retraction
Jet Extension
Day 0 Analysis
Day 9 Analysis
Ens. Mems.
Ens. Mean
PC 1
PC 2
4
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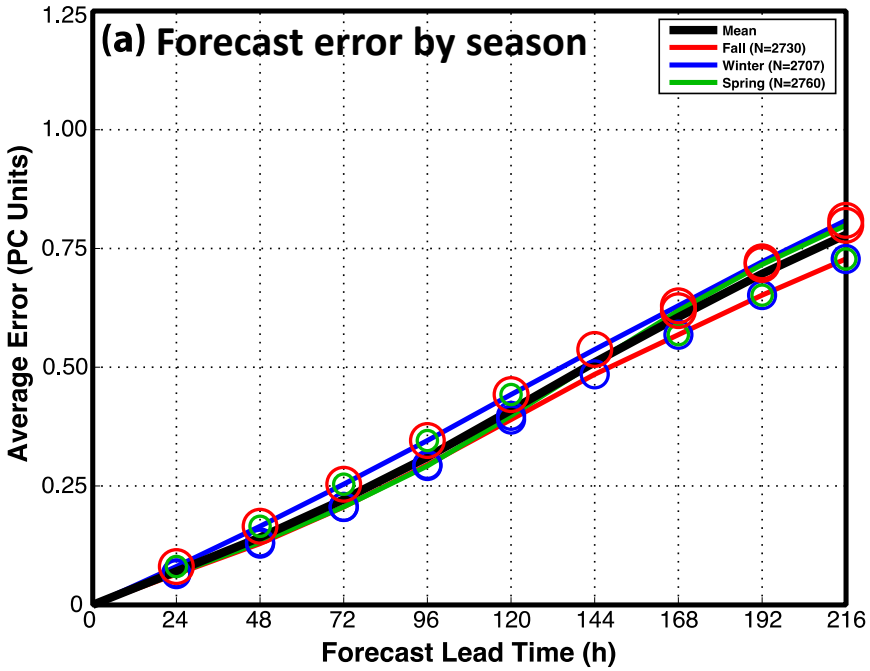
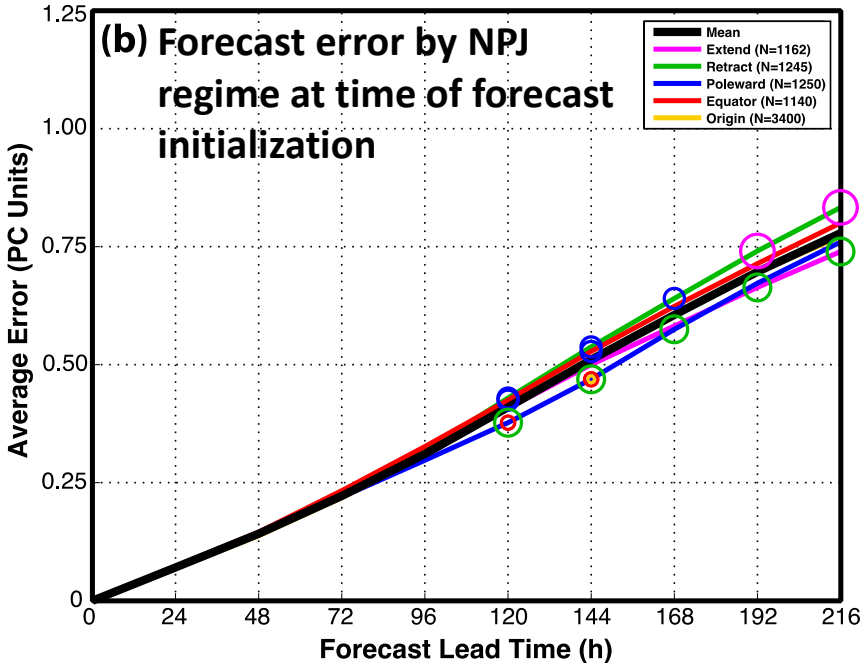
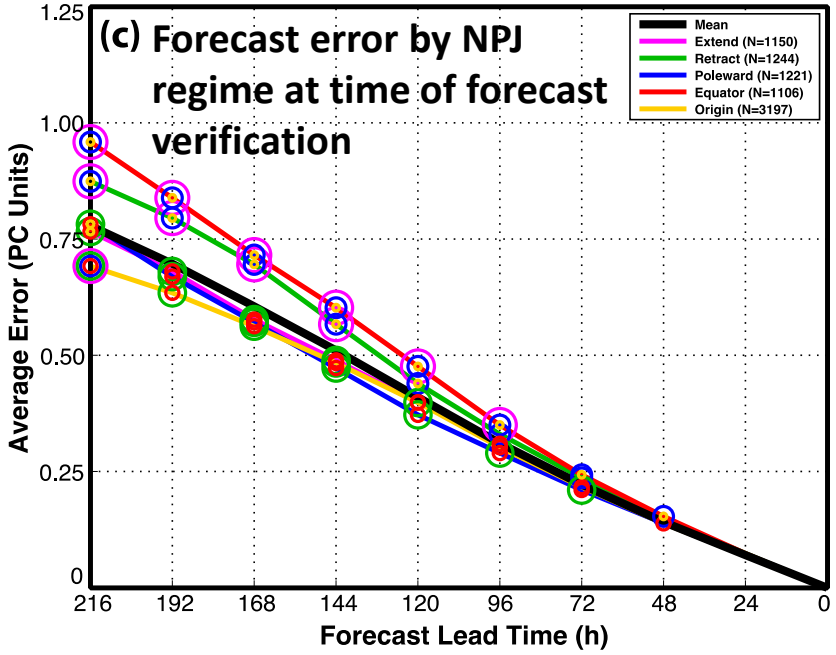
−4

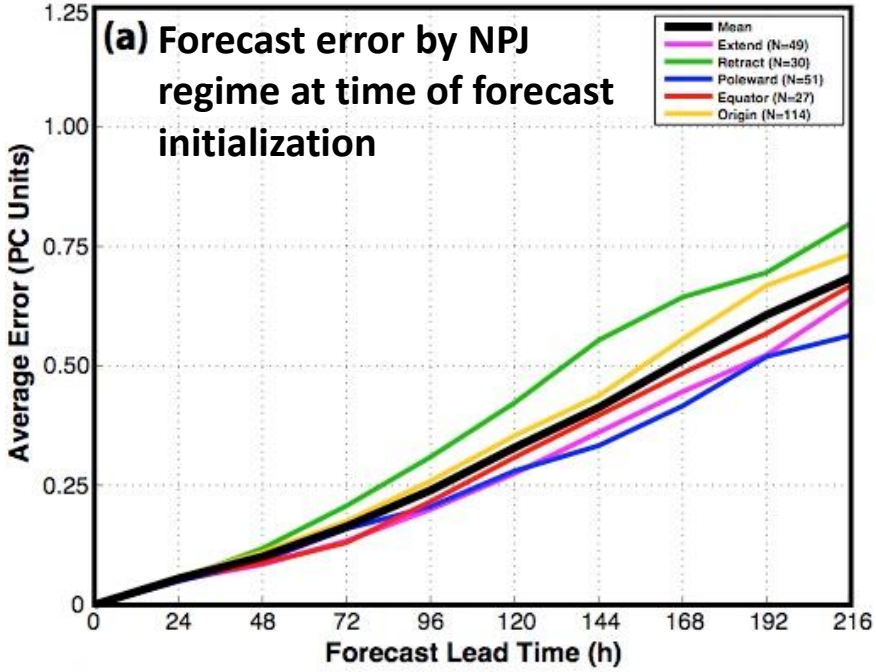
Summary of GEFS Reforecast Statistics and 2016–2017 Verification Statistics

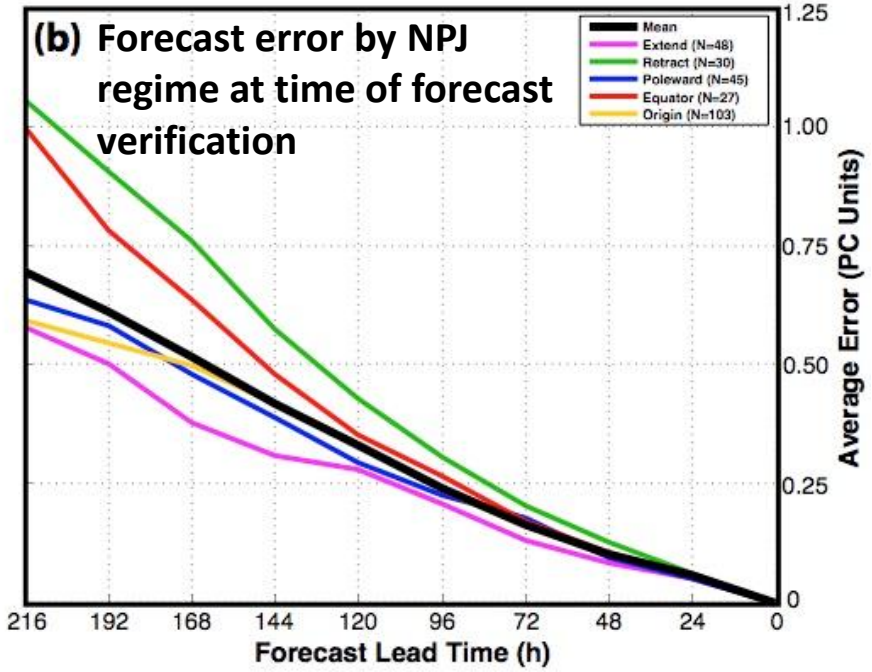


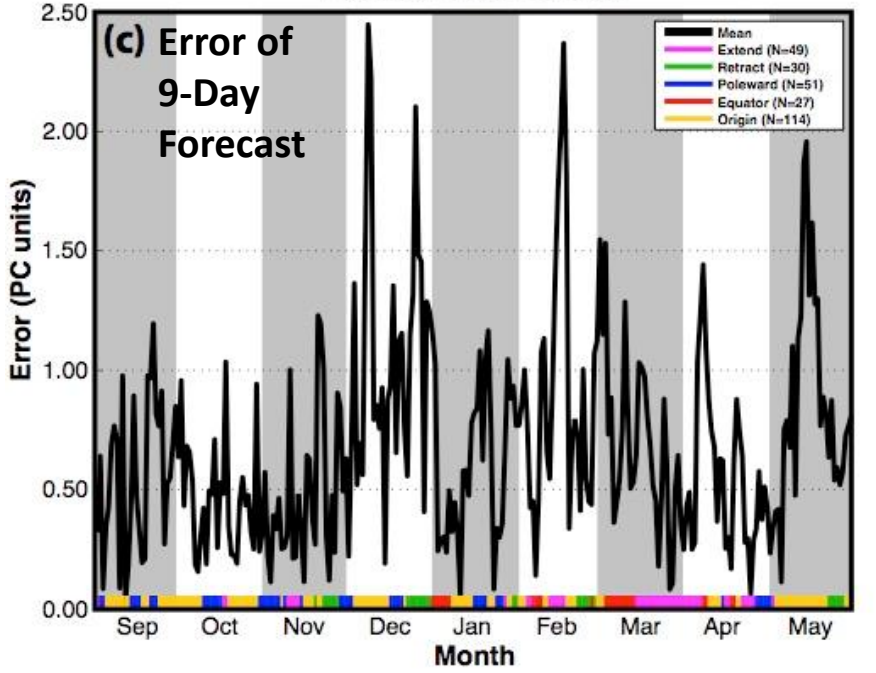




Verification Statistics – GEFS Reforecasts

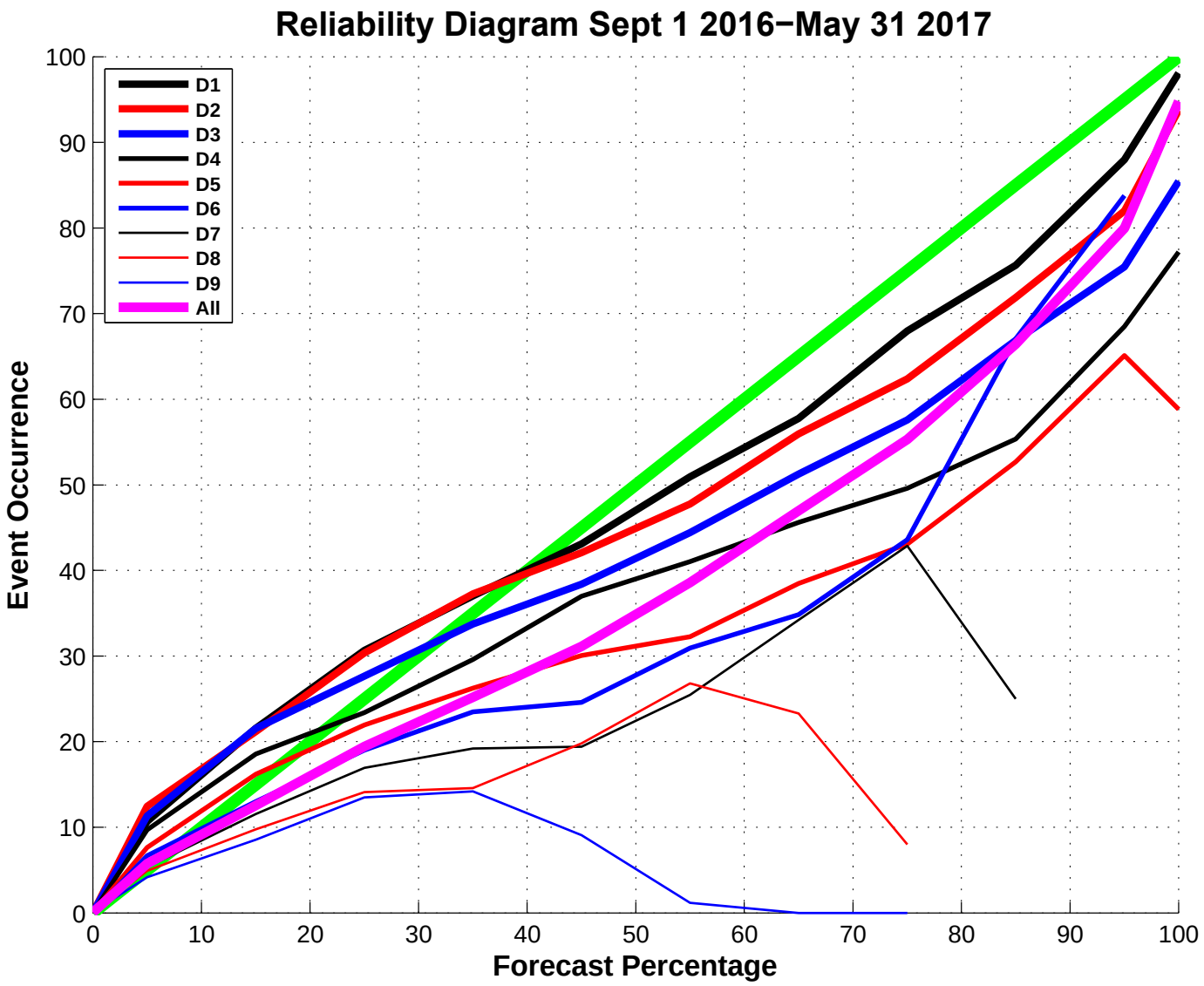






2016–2017 Verification Statistics – GEFS Ensemble Mean

2016–2017 Reliability Diagram – GEFS Ensemble



Perfect Reliability

The GEFS appears to be underdispersive with respect to medium-range forecasts of the North Pacific Jet in the phase diagram

Conclusions: NPJ Phase Diagram Attributes

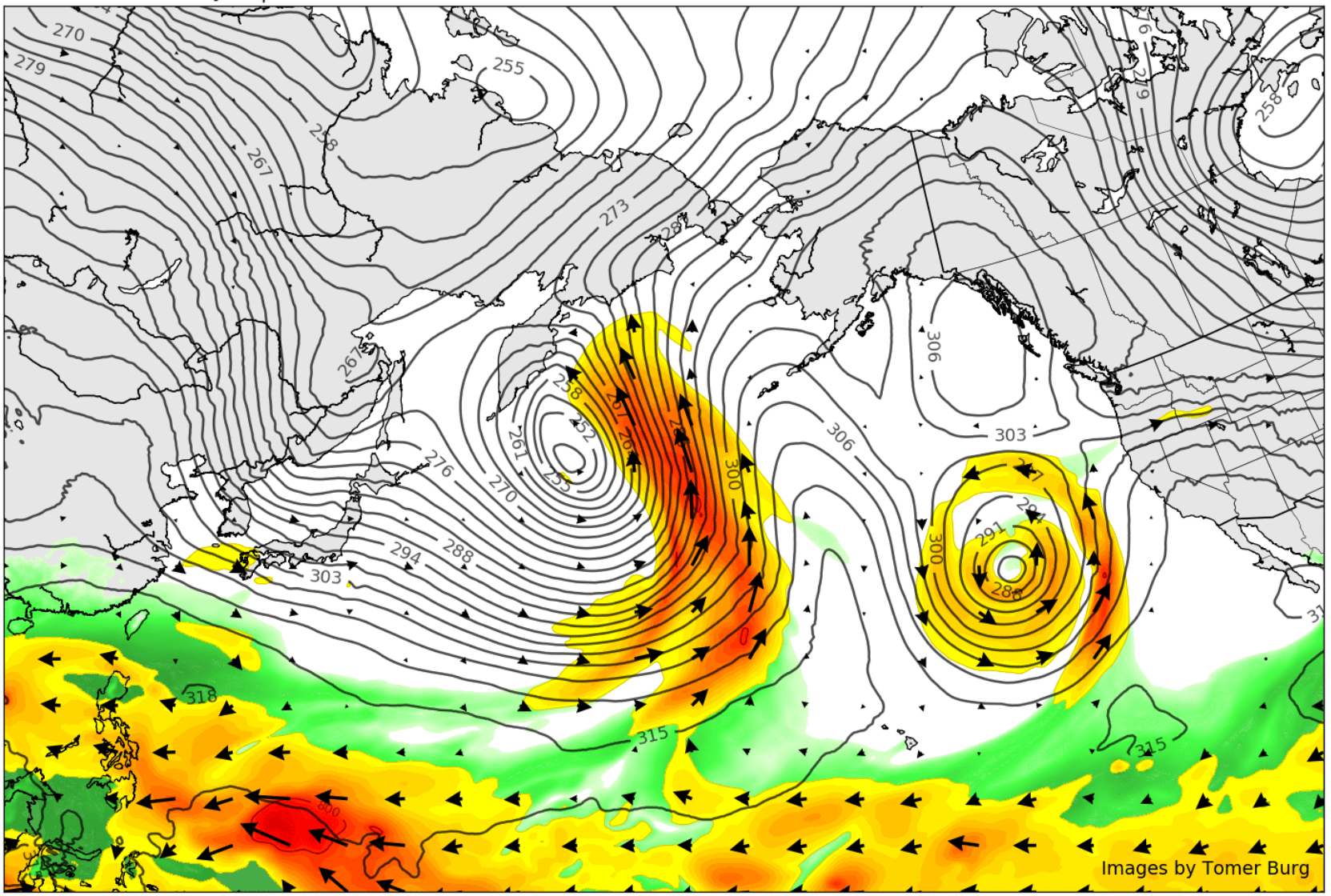
- **Depicts a quantitative measure of the structure and evolution of the NPJ**
- **Reveals that GEFS 9-day NPJ forecast errors are largest during North Pacific blocking regimes**
- **Illustrates that GEFS forecasts are underdispersive with respect to medium-range forecasts of the NPJ**
- **Shows that GEFS 9-day NPJ forecast errors occur most often in winter and spring and least often in autumn**
- **Indicates that GEFS mean forecast errors maximize during NPJ retraction regimes at initialization and verification times**

Extra Slides

Selected Loops for 1–15 February 2017 (Oroville Dam Near Failure)

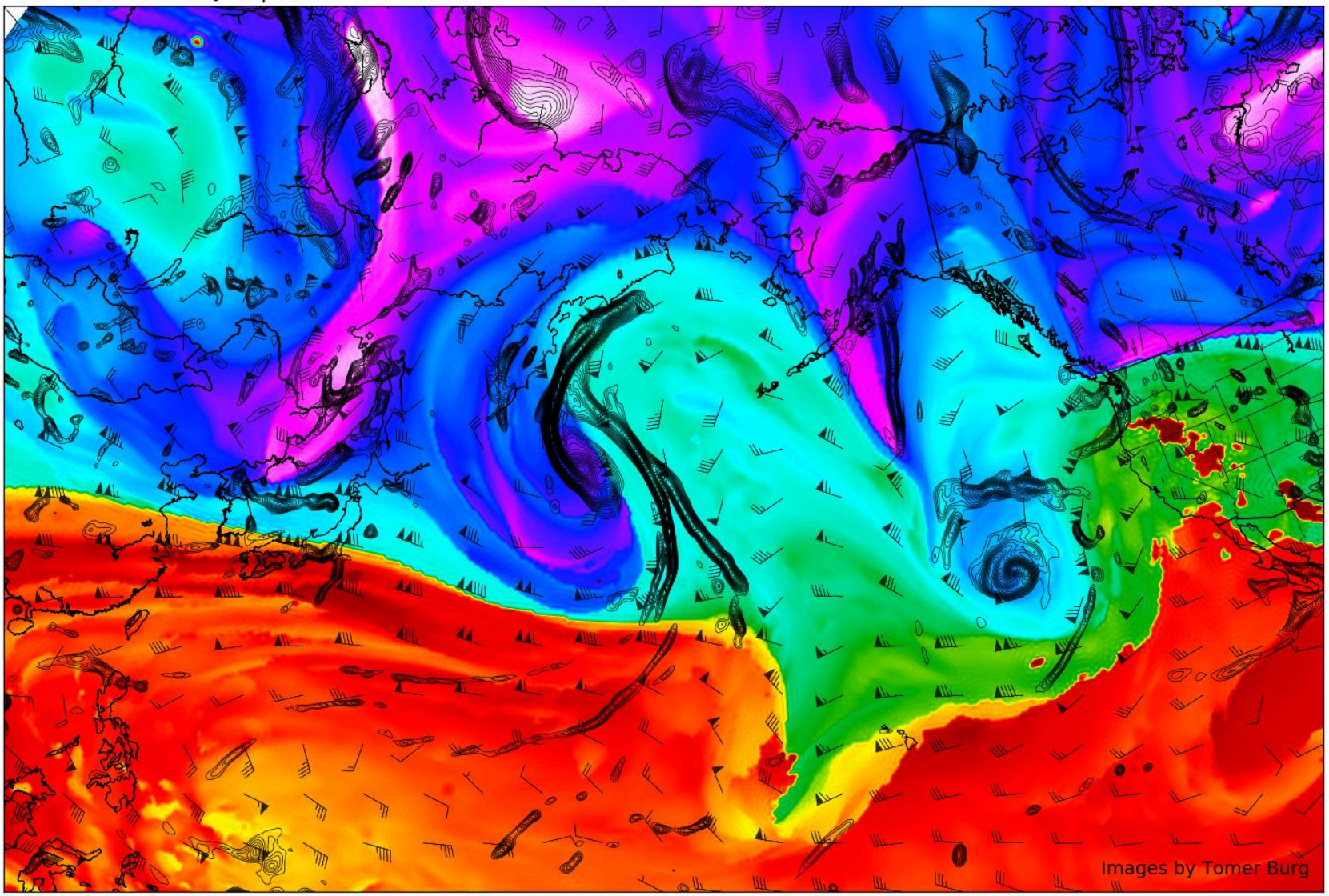
Integrated Vapor Transport (kg/m/s), 700-hPa Height (dam), PWAT > 20mm

0.25° ERA-5 Reanalysis | Valid 0000 UTC Wed 01 Feb 2017



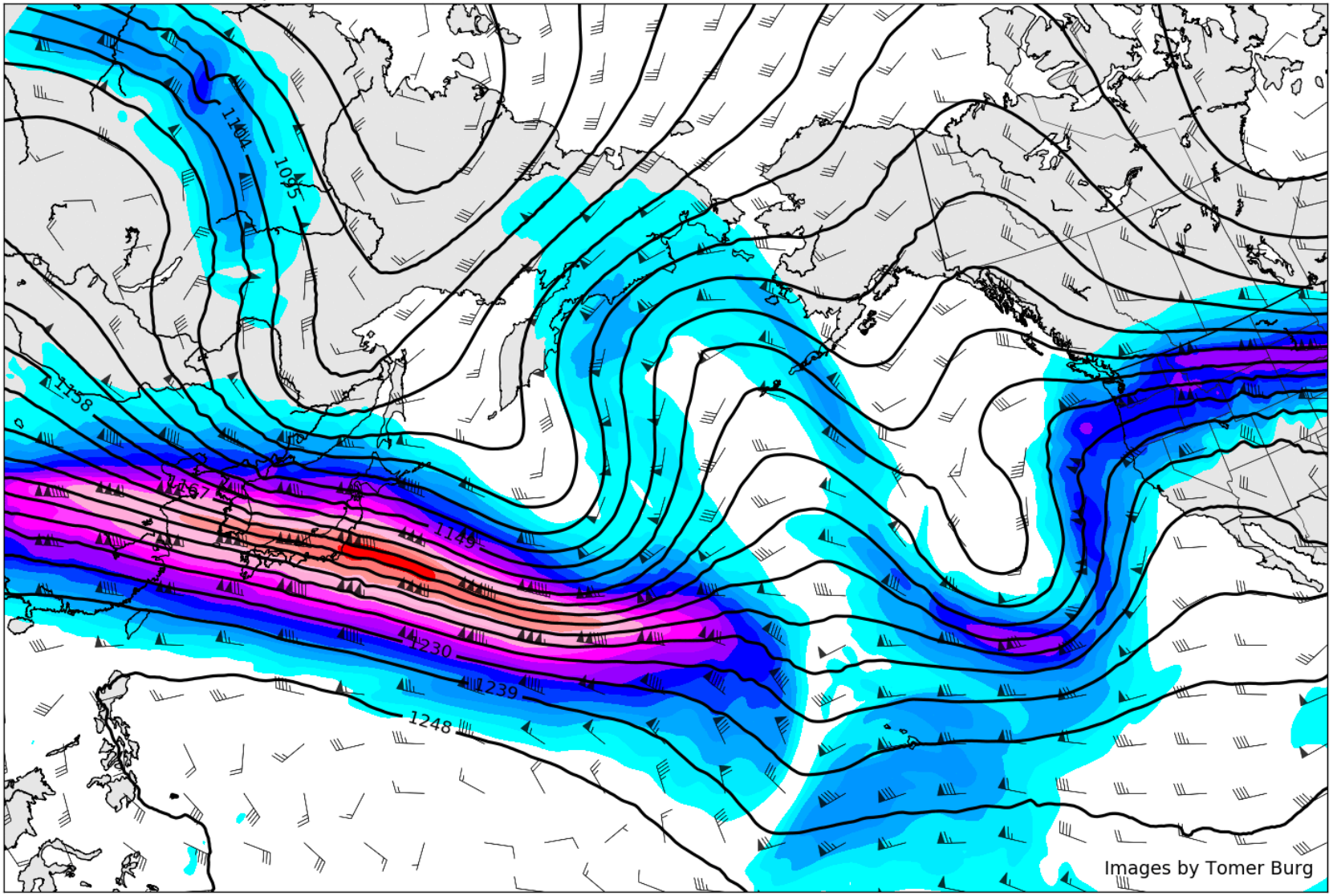
2 PVU Potential Temperature (K), 850-hPa Relative Vorticity (1/s), Wind (kt)

0.25° ERA-5 Reanalysis | Valid 0000 UTC Wed 01 Feb 2017



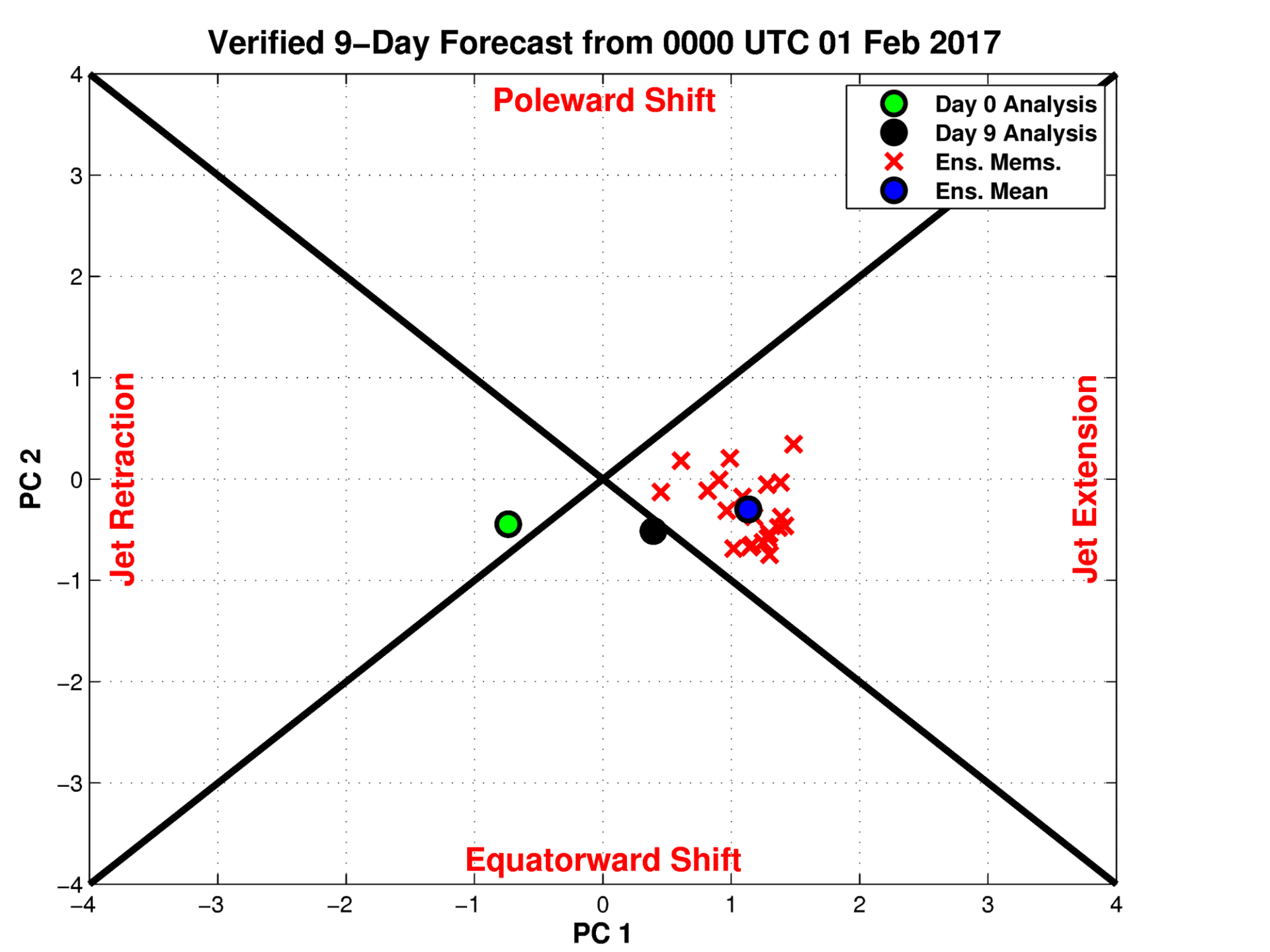
200 hPa Wind Isotachs, Geopotential Height (dam), Wind (kt)

0.25° ERA-5 Reanalysis | Valid 0000 UTC Wed 01 Feb 2017



NPJ Phase Diagrams: 1–3 February 2017

Observed NPJ poleward and eastward shift is much greater than forecast by the underdispersive GEFS


Verified 9–Day Forecast from 0000 UTC 01 Feb 2017
Poleward Shift
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Day 0 Analysis
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Ens. Mems.
Ens. Mean
PC 1
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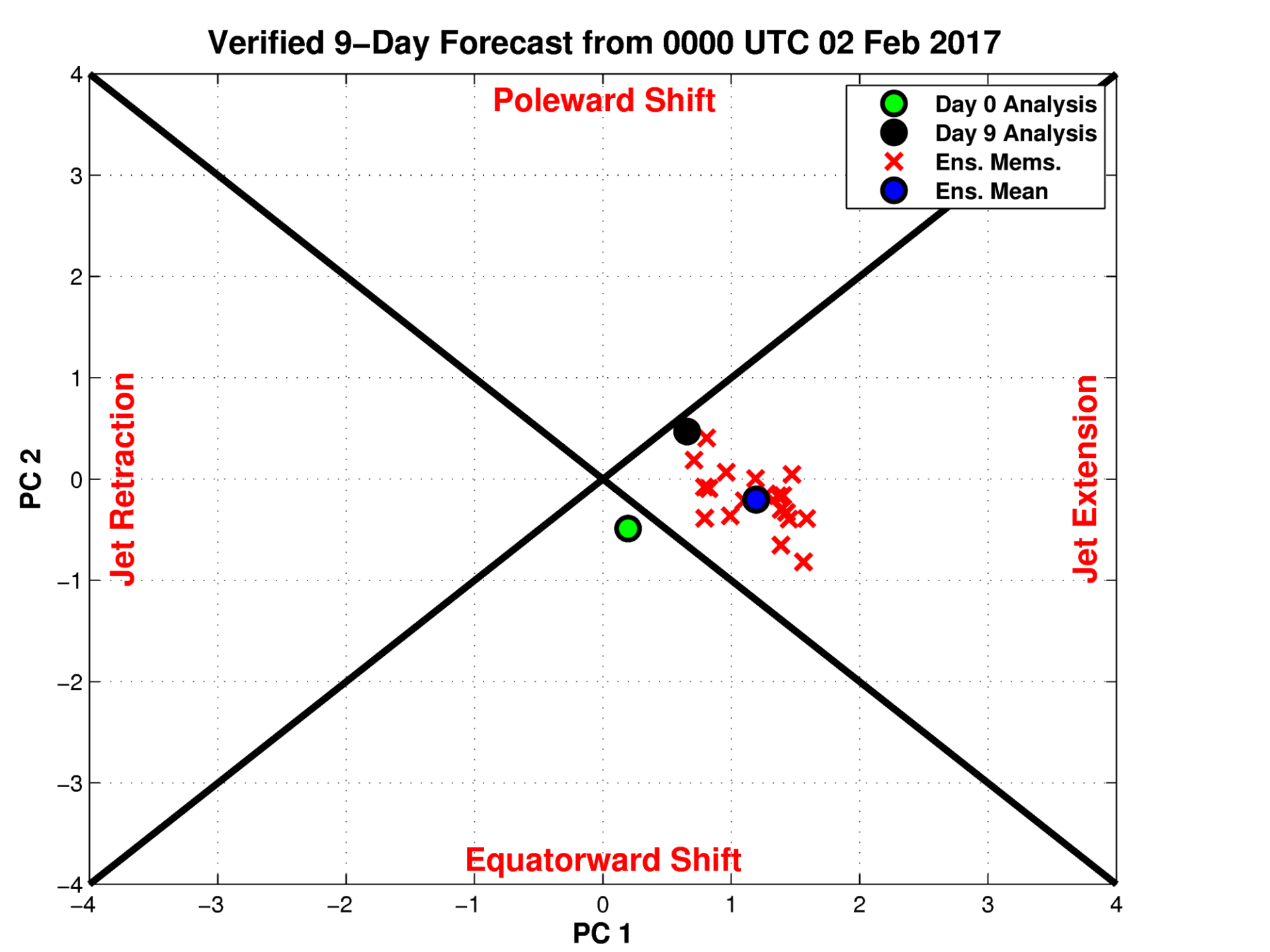
Verified 9–Day Forecast from 0000 UTC 02 Feb 2017
Poleward Shift
Equatorward Shift
Jet Retraction
Jet Extension
Day 0 Analysis
Day 9 Analysis
Ens. Mems.
Ens. Mean
PC 1
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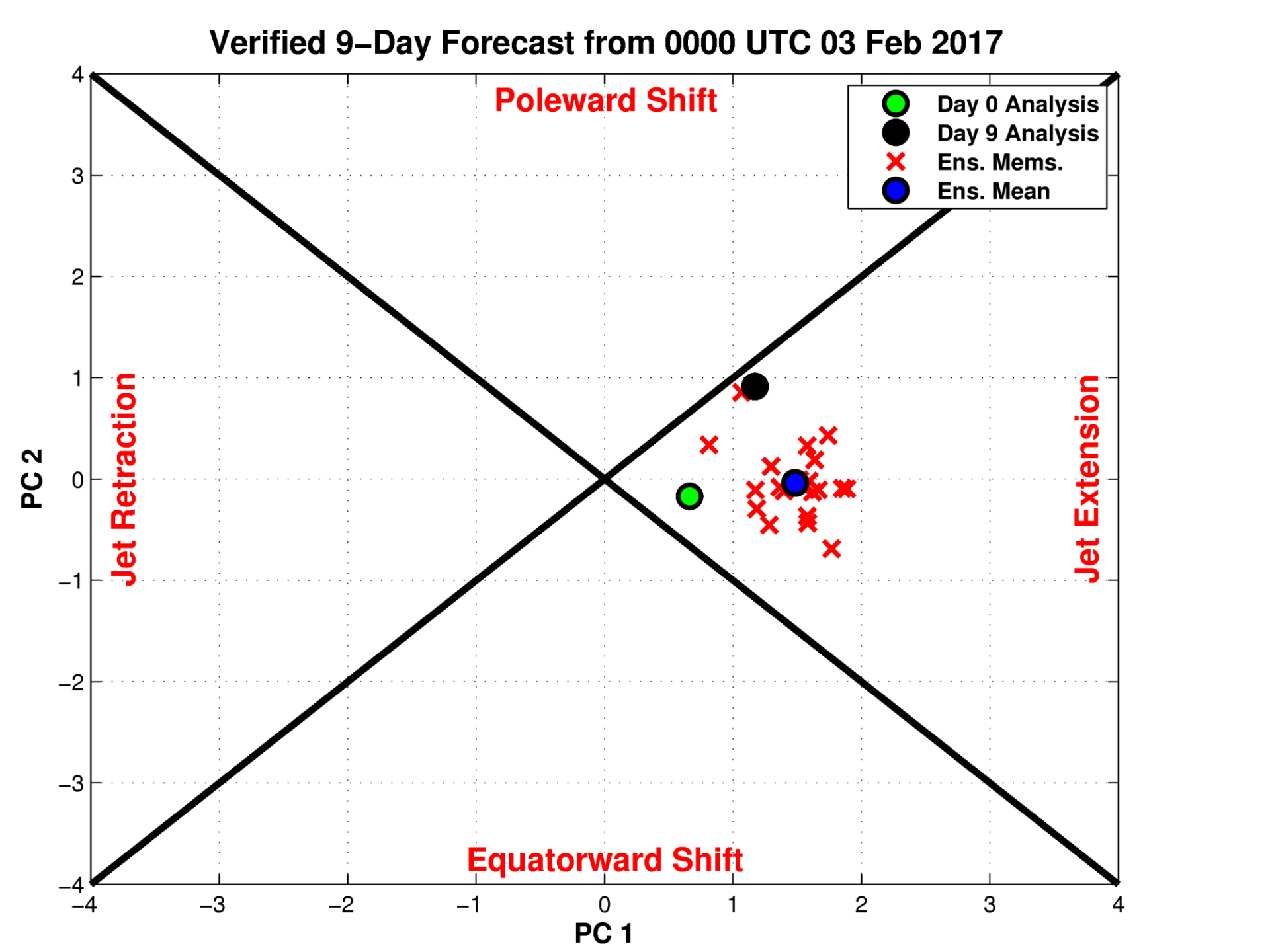
Verified 9–Day Forecast from 0000 UTC 03 Feb 2017
Poleward Shift
Equatorward Shift
Jet Retraction
Jet Extension
Day 0 Analysis
Day 9 Analysis
Ens. Mems.
Ens. Mean
PC 1
PC 2
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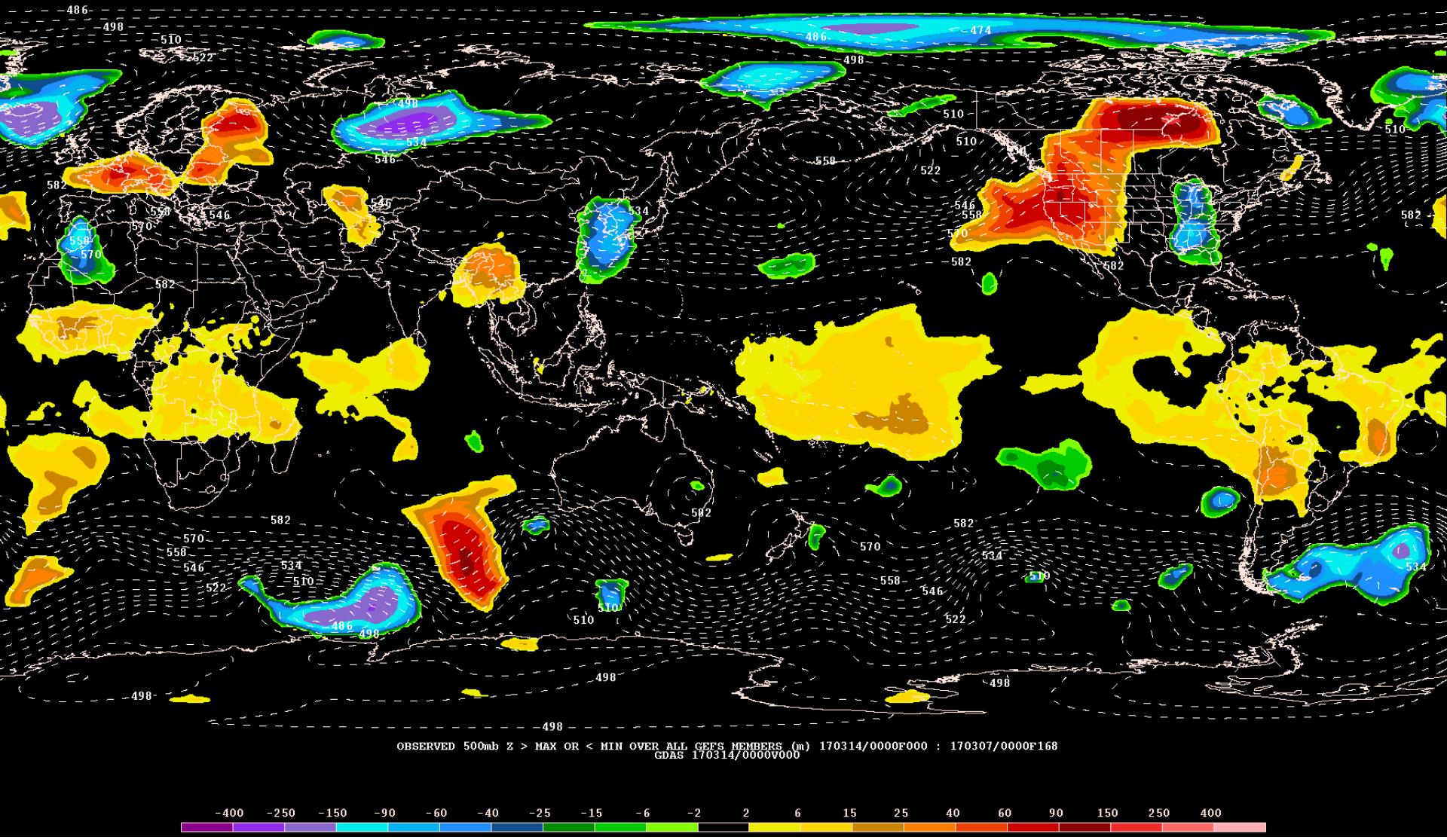
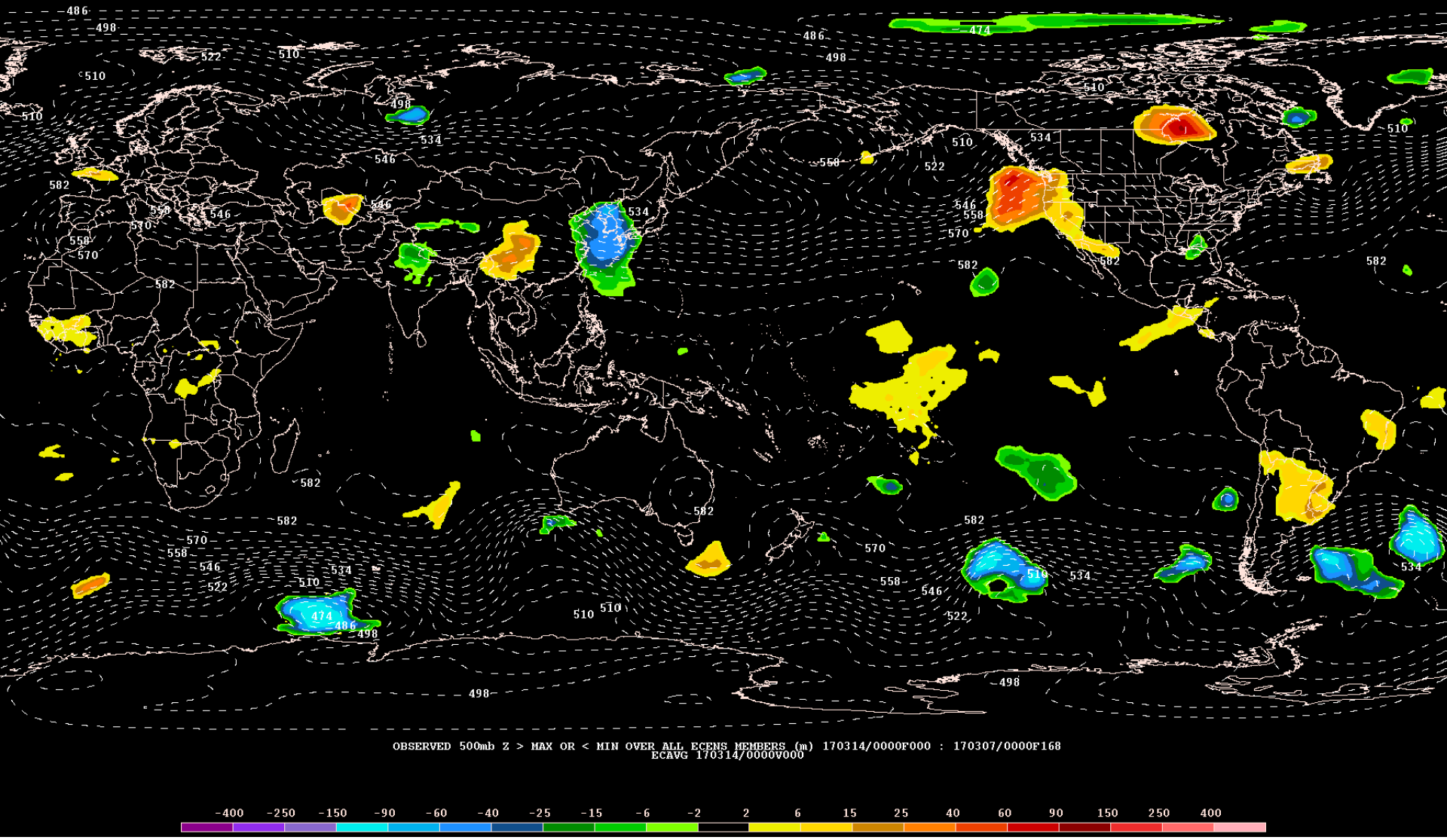
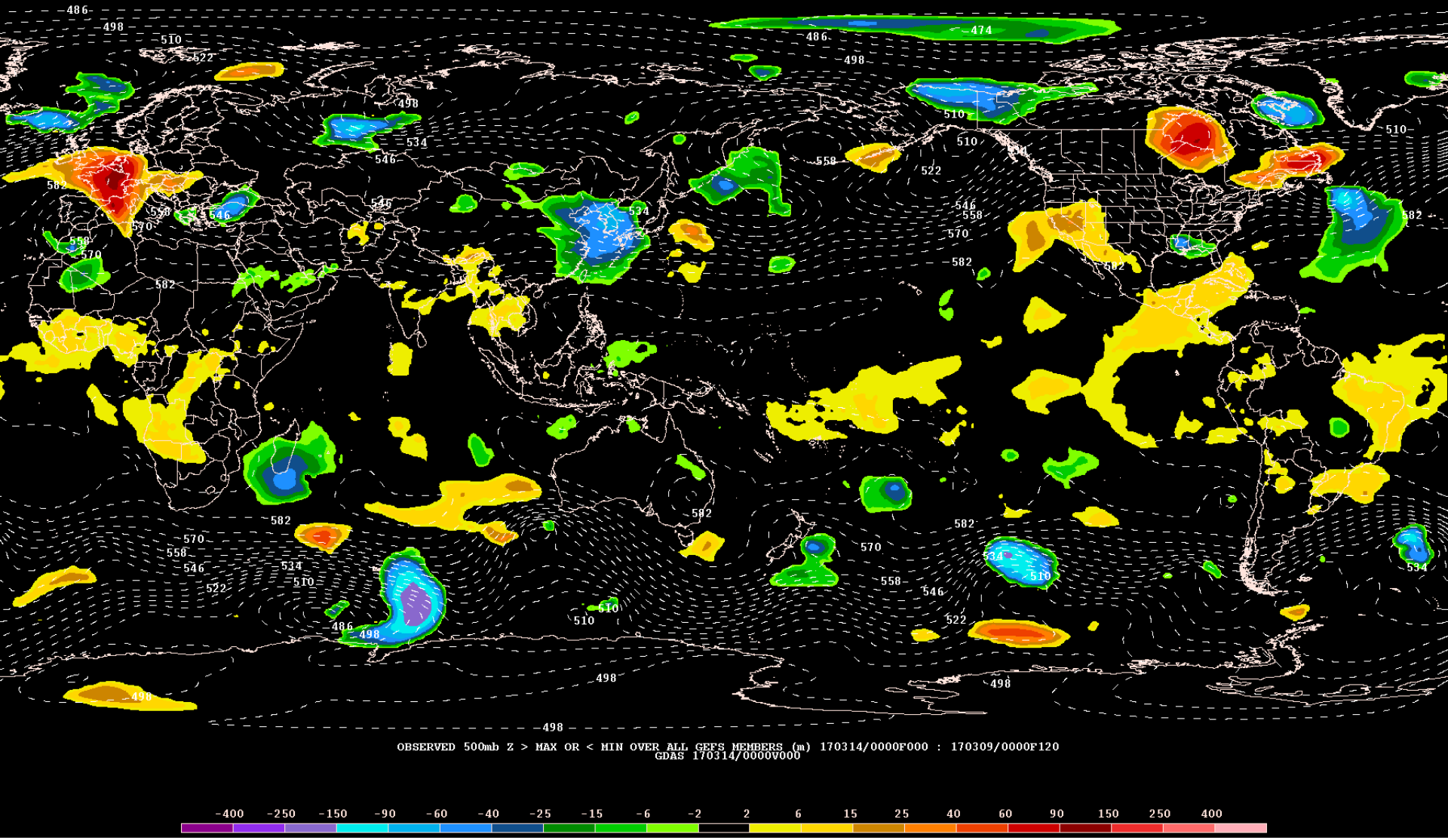


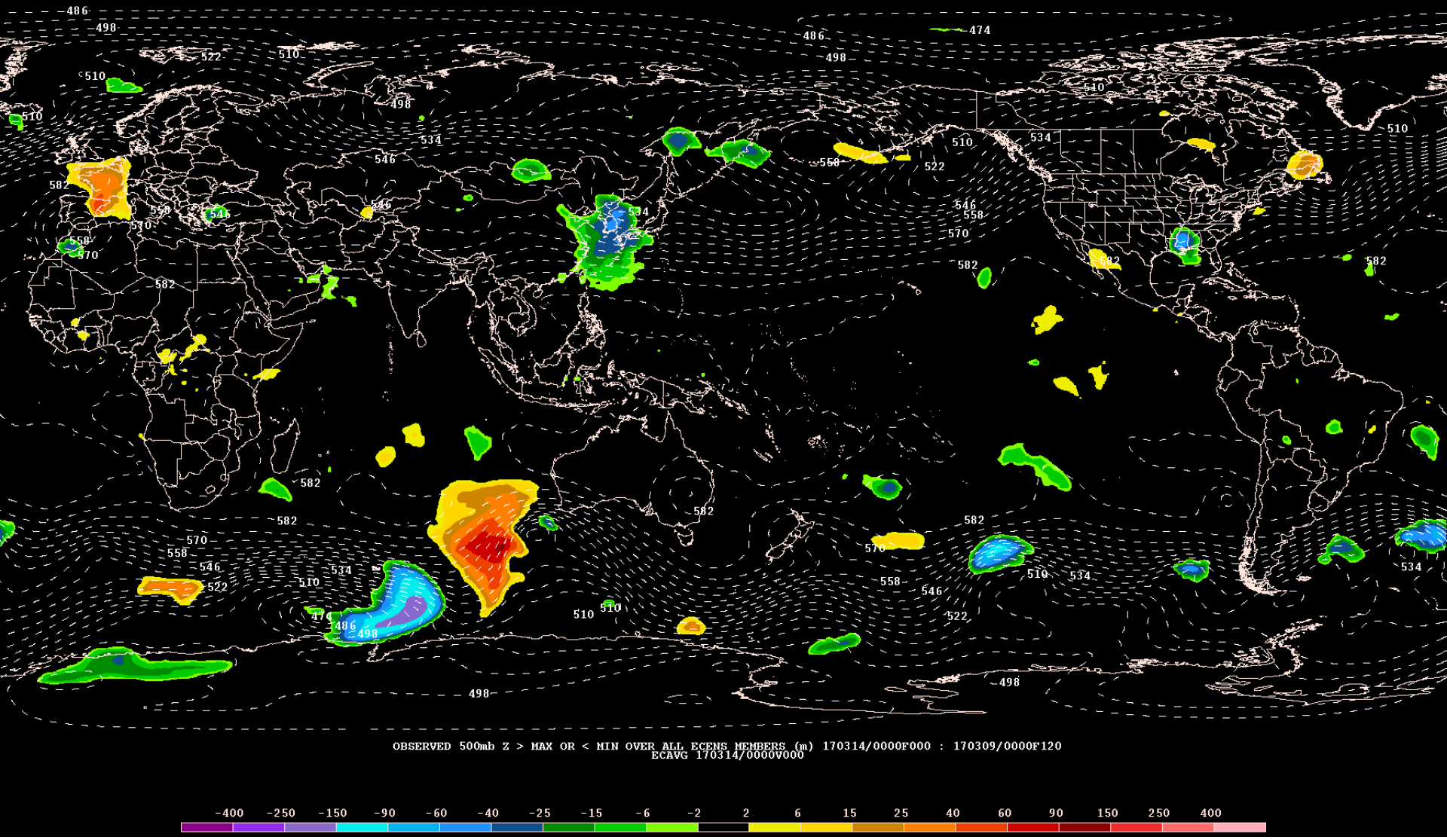
GEFS "Outside the Envelope" Magnitude (m) for 168 h 500-hPaGeopotential Height Forecasts Verifying 0000 14 March 2017 (Source: Tony Fracasso at NCEP-WPC)



ECENS "Outside the Envelope" Magnitude (m) for 168 h 500-hPa Geopotential Height Forecasts Verifying 0000 14 March 2017 (Source: Tony Fracasso at NCEP-WPC)



GEFS "Outside the Envelope" Magnitude (m) for 120 h 500-hPaGeopotential Height Forecasts Verifying 0000 14 March 2017 (Source: Tony Fracasso at NCEP-WPC)



ECENS "Outside the Envelope" Magnitude (m) for 120 h 500-hPa Geopotential Height Forecasts Verifying 0000 14 March 2017 (Source: Tony Fracasso at NCEP-WPC)