The Development of the North Pacific Jet Phase Diagram at the NCEP-WPC as a Tool to Characterize the Upper-Tropospheric Flow Pattern

Lance F. Bosart, Daniel Keyser, and Andrew C. Winters

Department of Atmospheric and Environmental Sciences
University at Albany, State University of New York, Albany, NY 12222

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Motivation

- Previous work highlighted the considerable North Pacific Jet (NPJ) variability during the medium-range period that characterizes the antecedent environments associated with continental U.S. extreme temperature events.

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- This NPJ variability motivated the development of the NPJ phase diagram as an objective tool to characterize the instantaneous state of the upper-tropospheric flow pattern over the North Pacific.
- Consideration of the NPJ phase diagram offers the potential to increase confidence in operational probabilistic temperature forecasts during the medium-range period.

The Development of the NPJ Phase Diagram

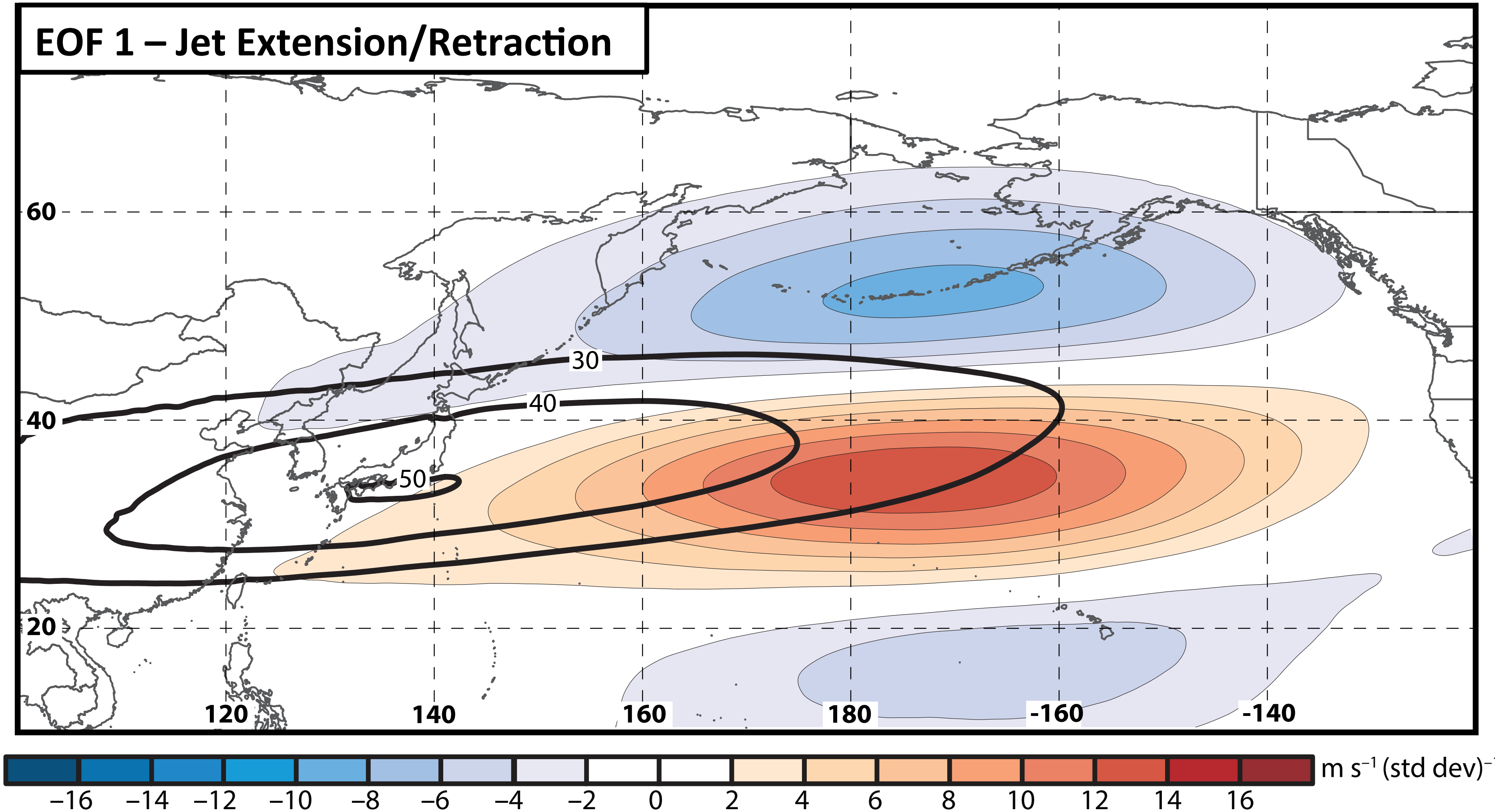
The NPJ Phase Diagram

- Removed the mean and the annual and diurnal cycles from 6-hourly, 250-hPa zonal wind data from the CFSR (1979–2014) (Saha et al. 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 (2017)

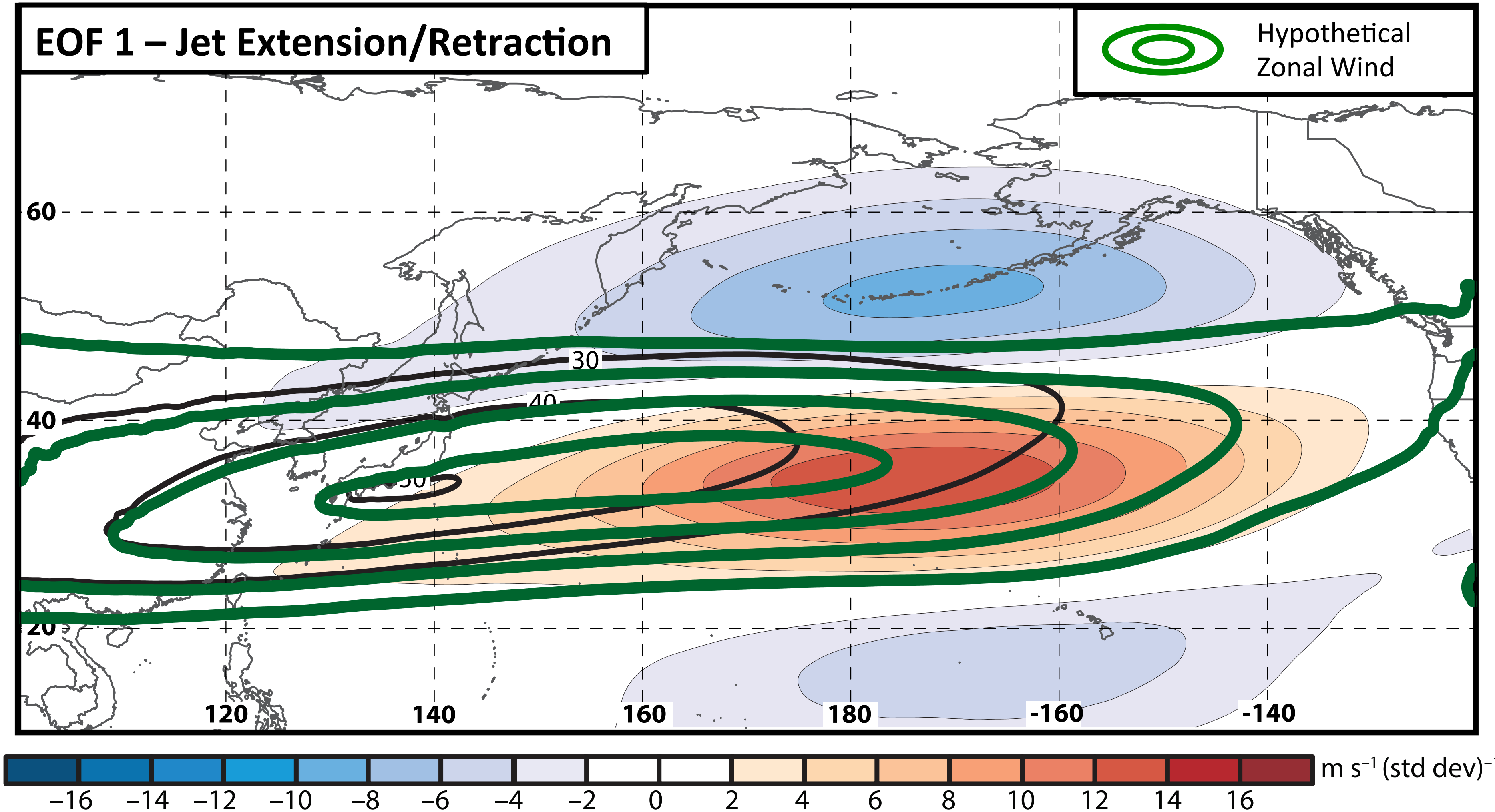
The NPJ Phase Diagram



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

The NPJ Phase Diagram



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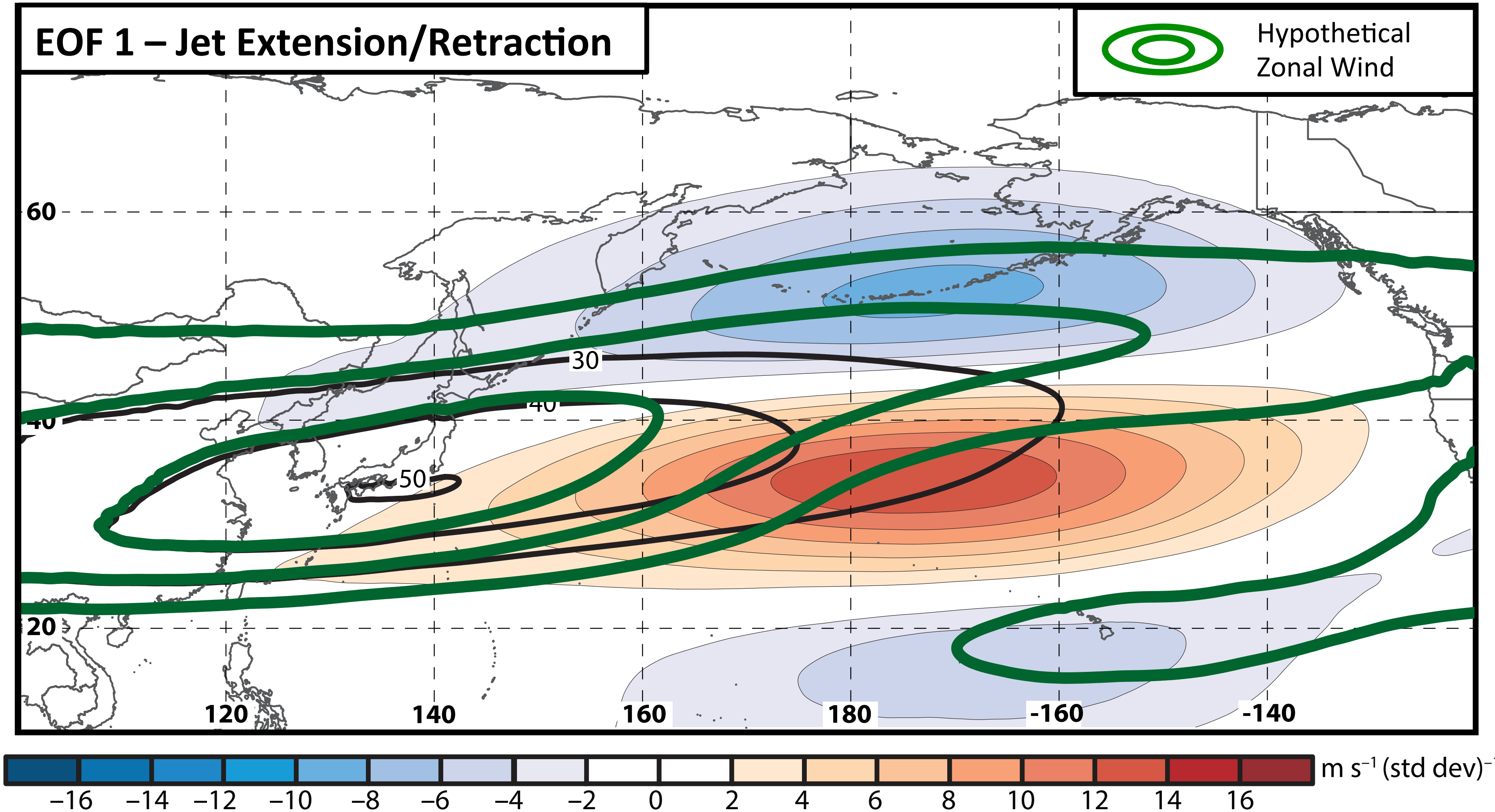

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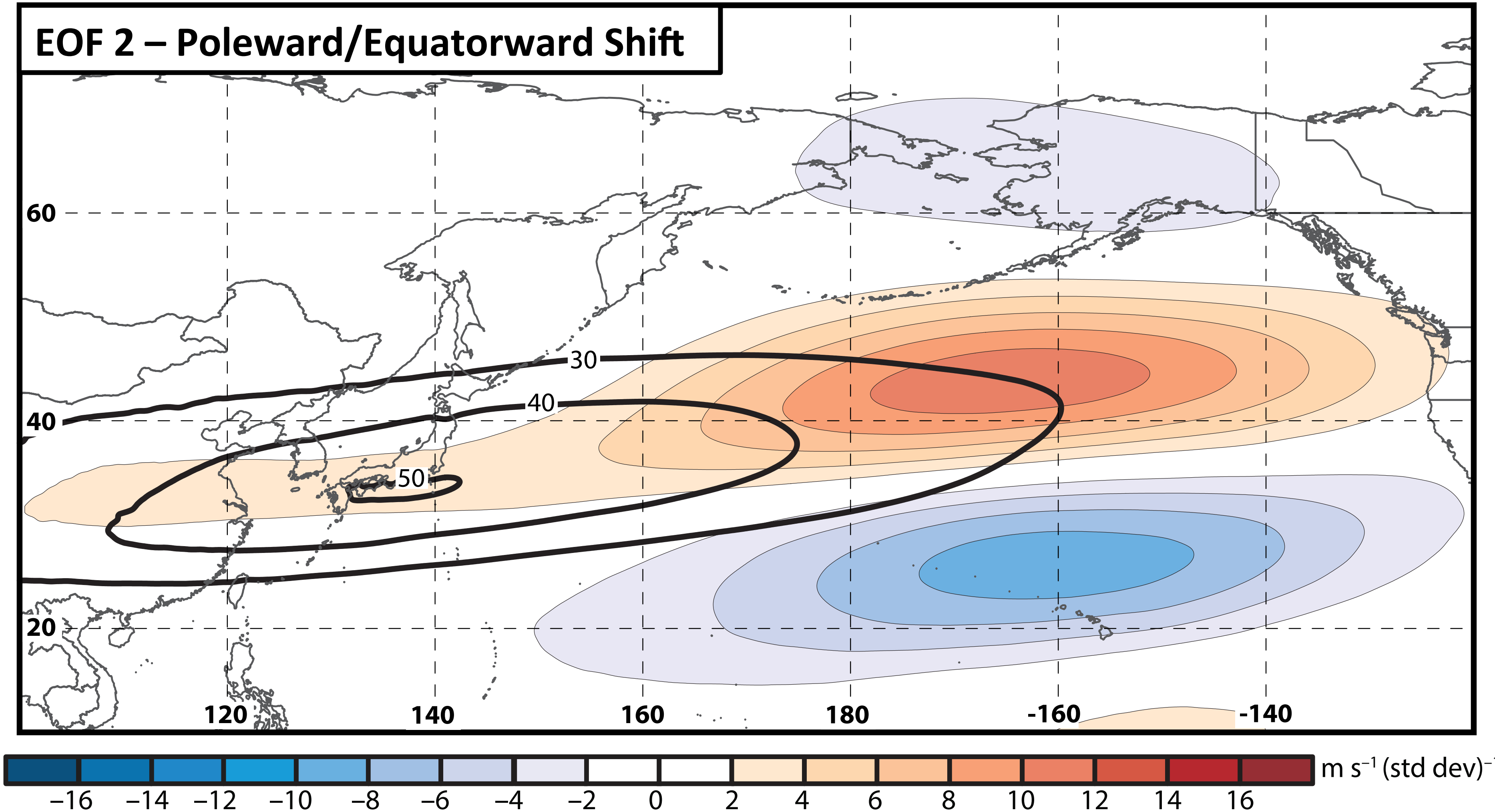
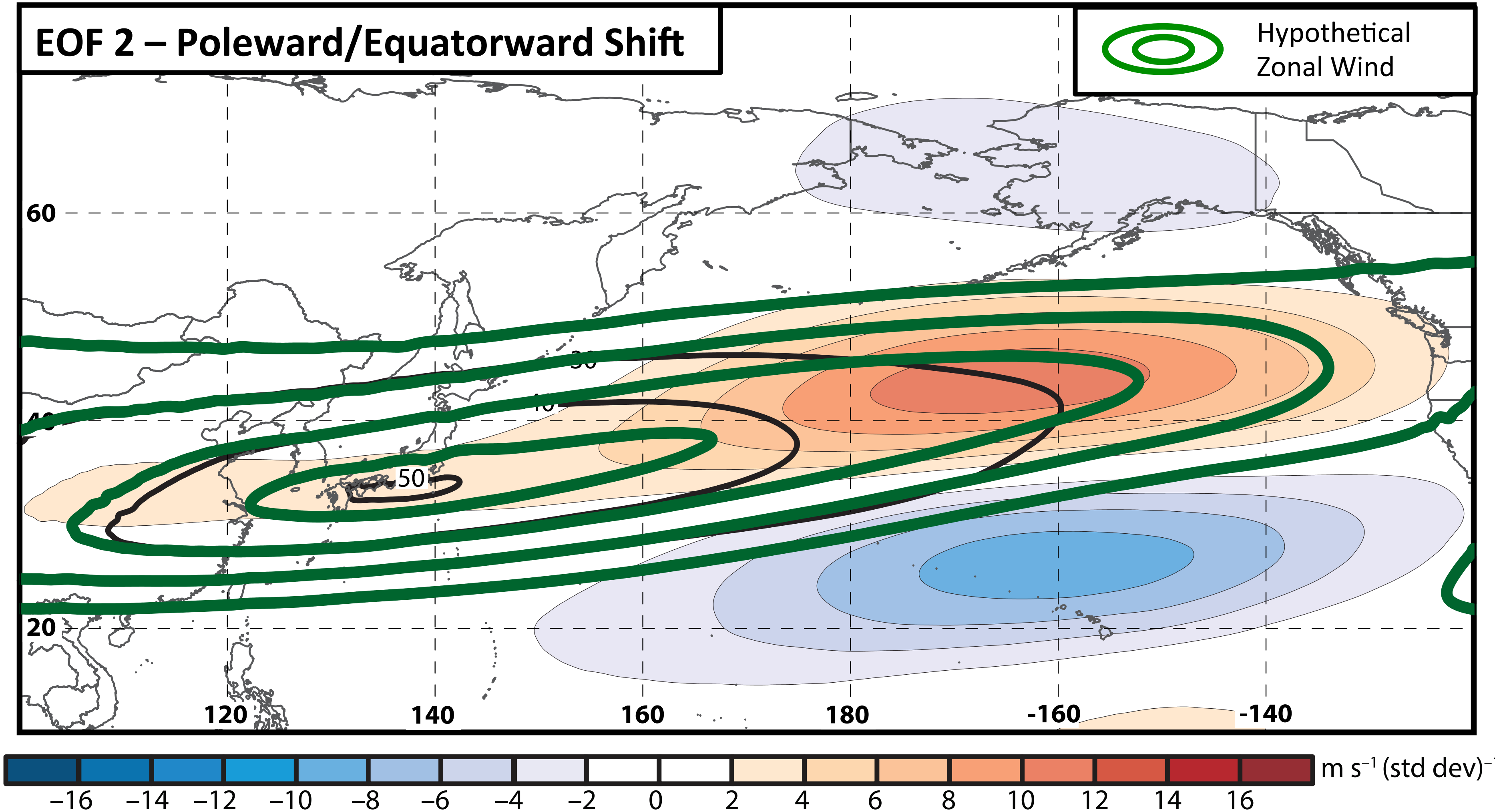


Sept.–May mean 250-hPa zonal wind: black contours
Sept.–May 250-hPa zonal wind EOF 2 pattern: shading

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

The NPJ Phase Diagram



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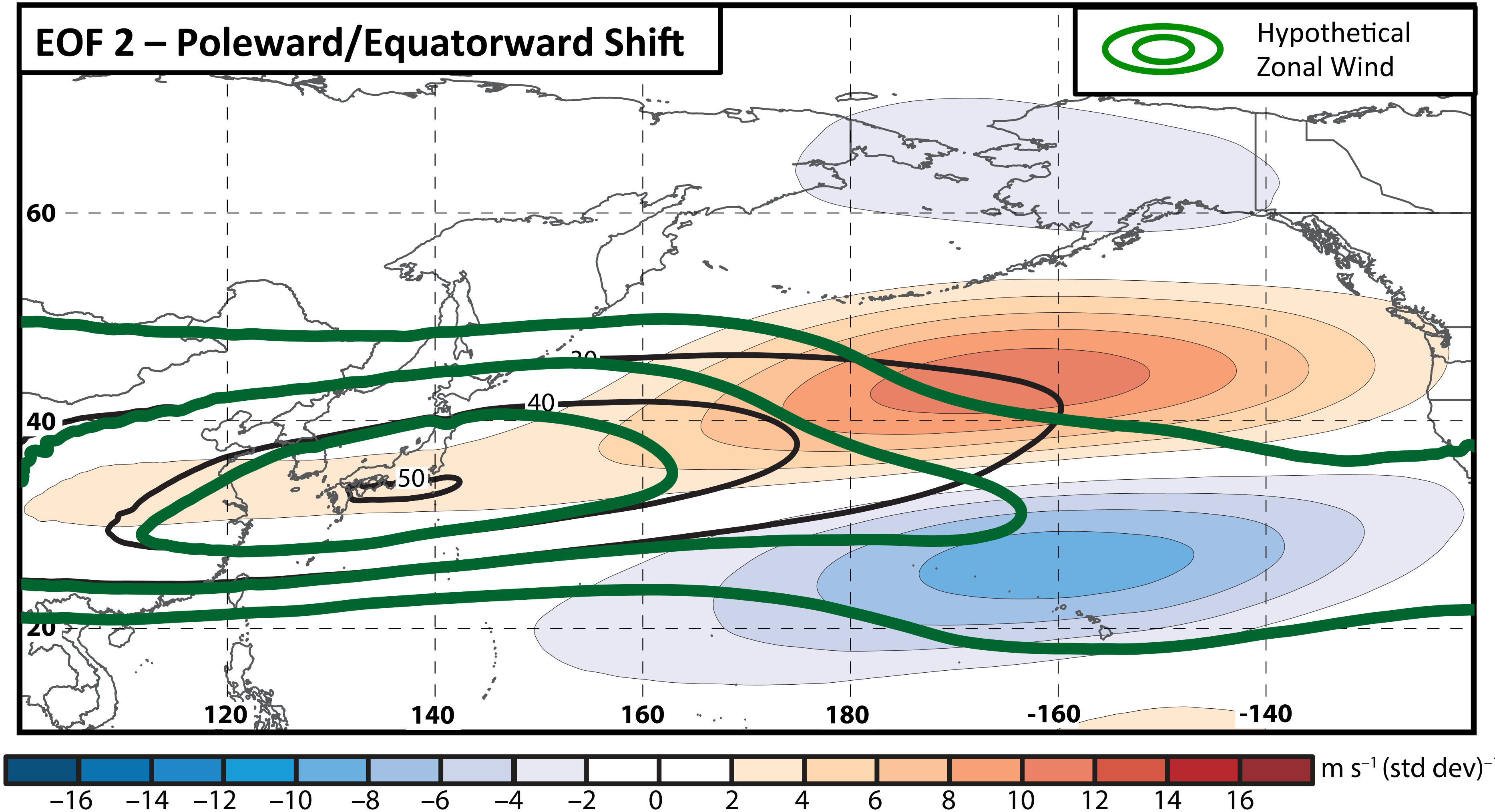

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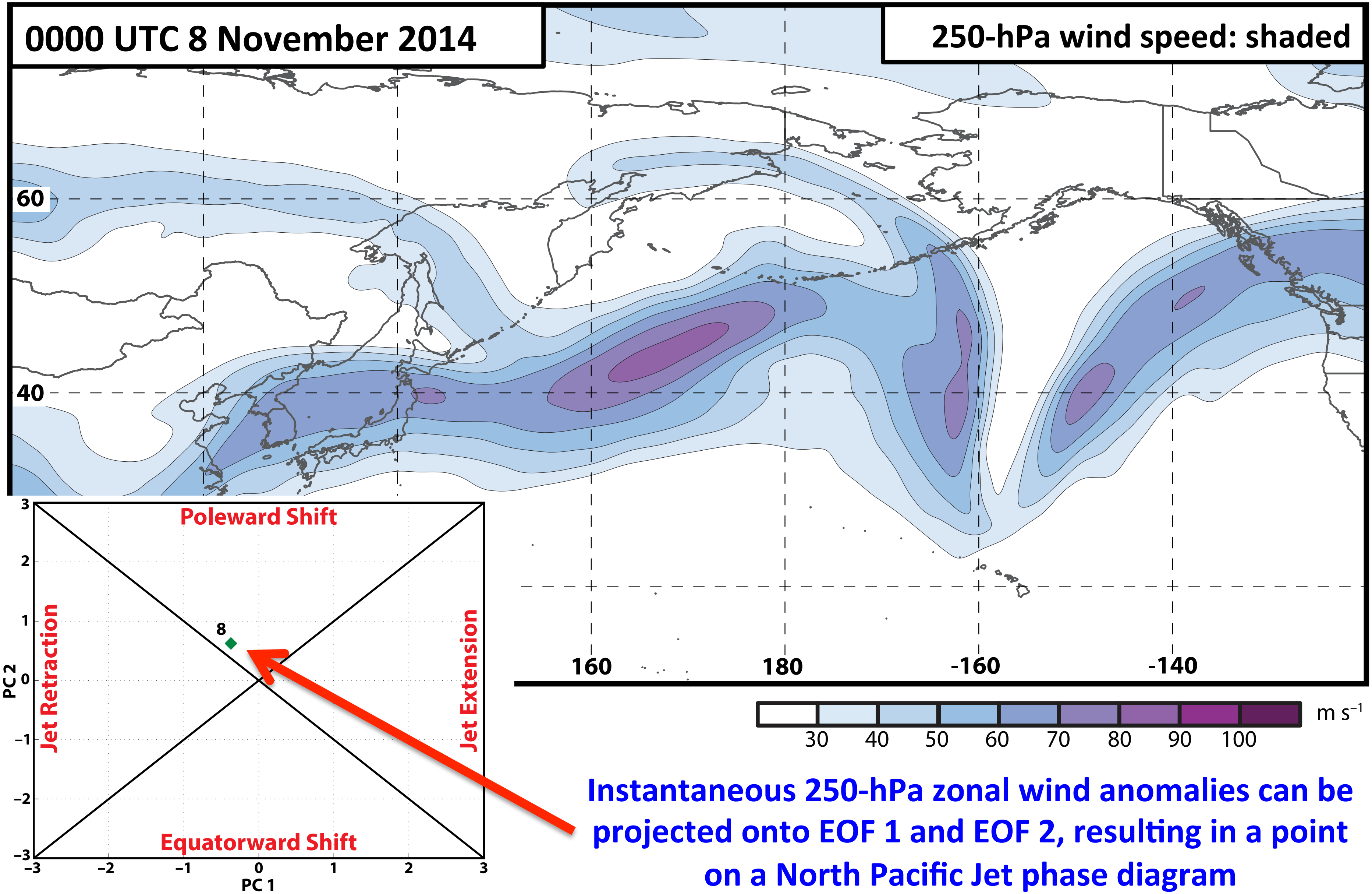
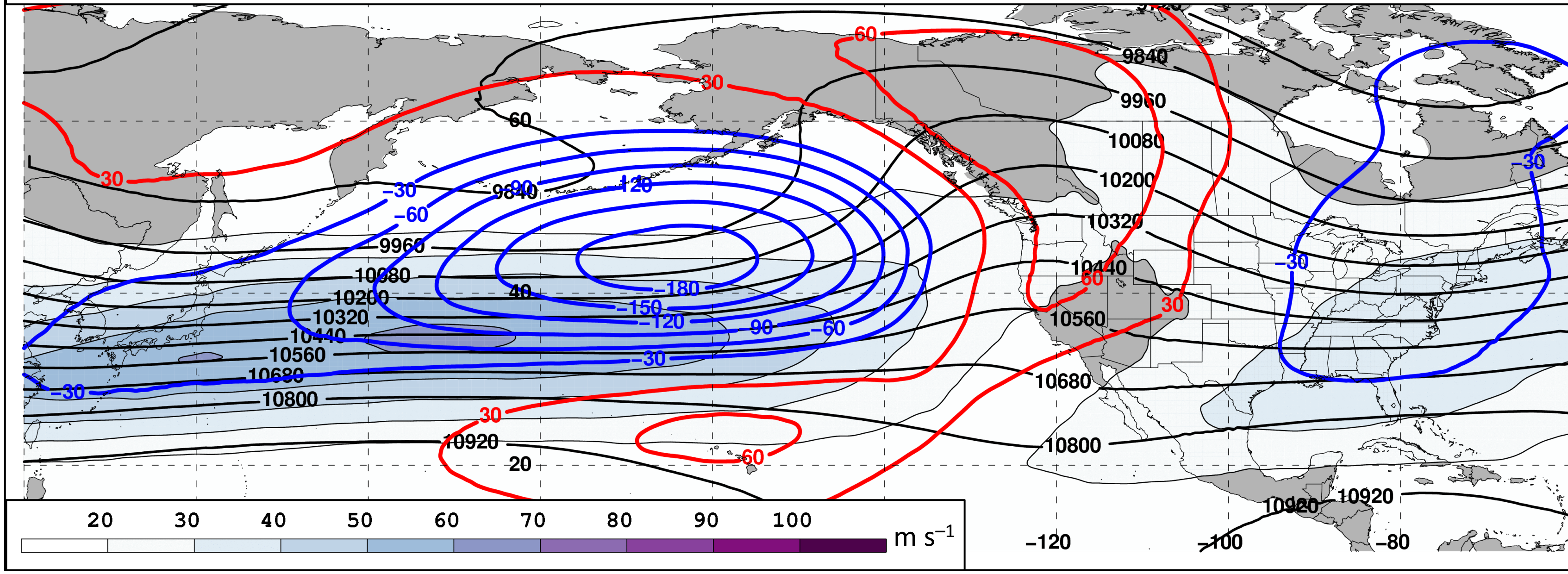
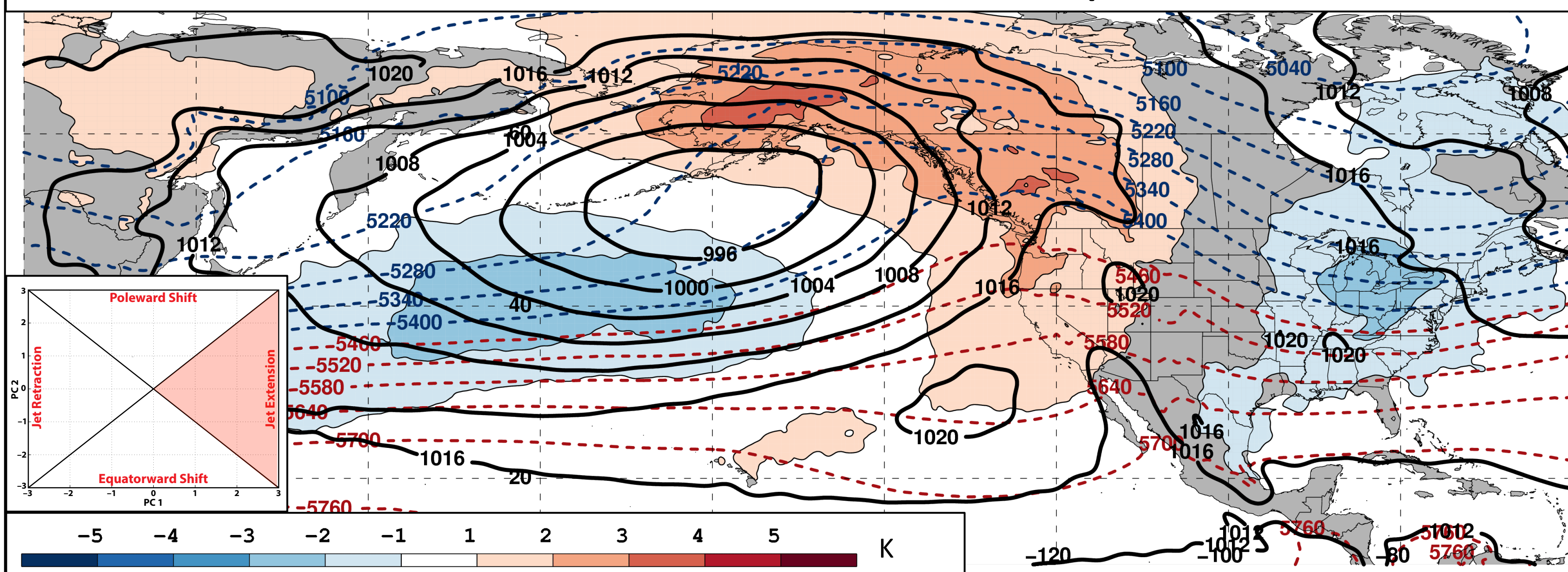


Instantaneous 250-hPa zonal wind anomalies can be projected onto EOF 1 and EOF 2, resulting in a point on a North Pacific Jet phase diagram

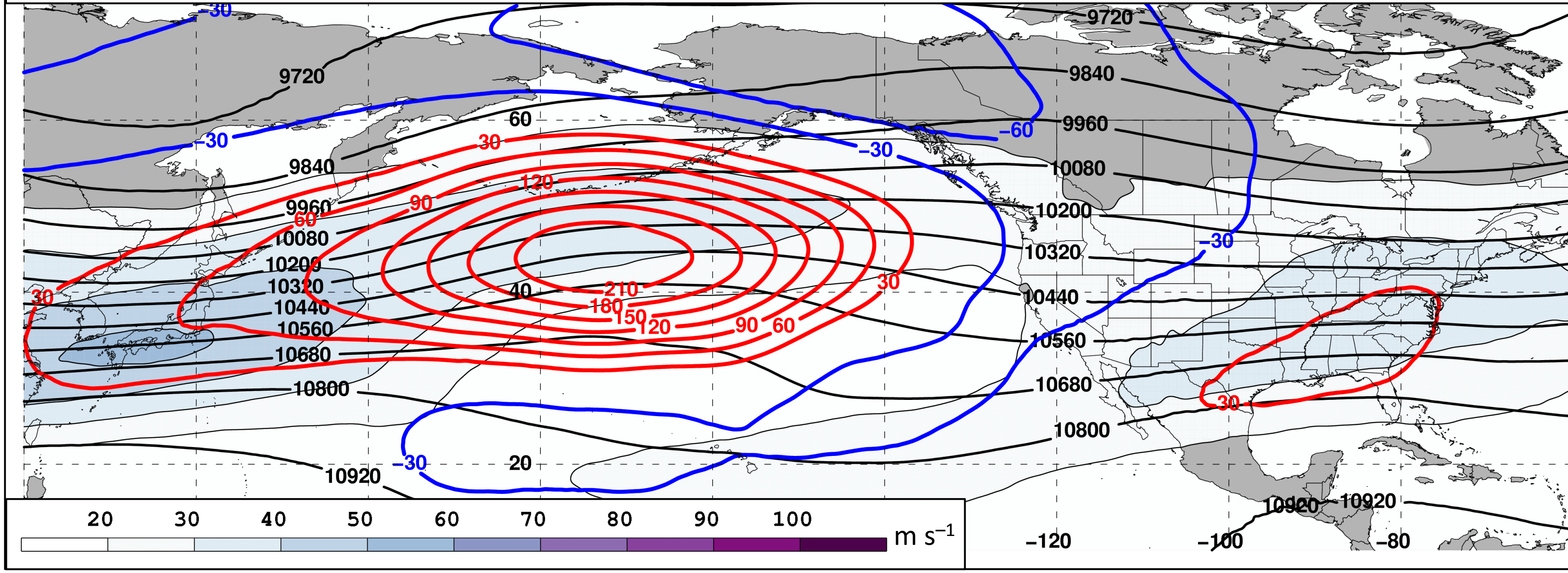
250-hPa Wind Speed, Geo. Heights, Geo. Height Anomalies: Jet Extension



Mean Sea-Level Pressure, 1000–500-hPa Thickness, 850-hPa Temp. Anomalies: Jet Extension



250-hPa Wind Speed, Geo. Heights, Geo. Height Anomalies: Jet Retraction



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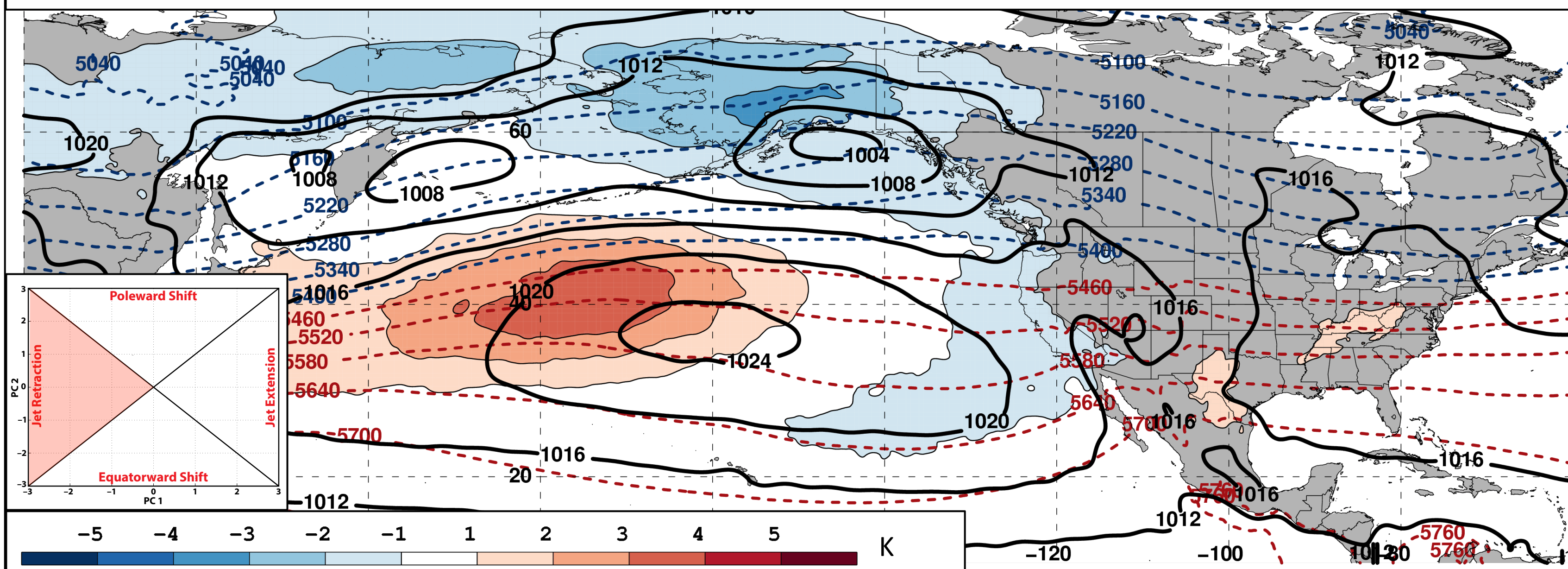
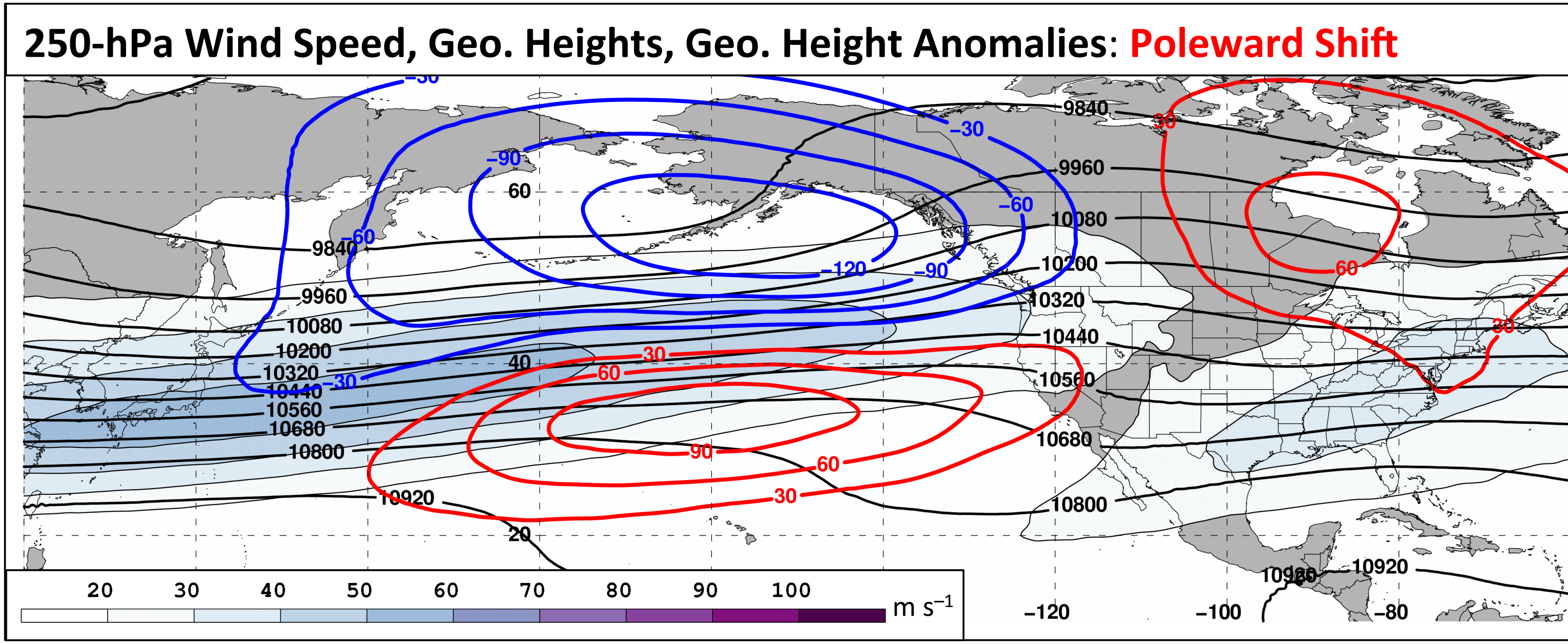
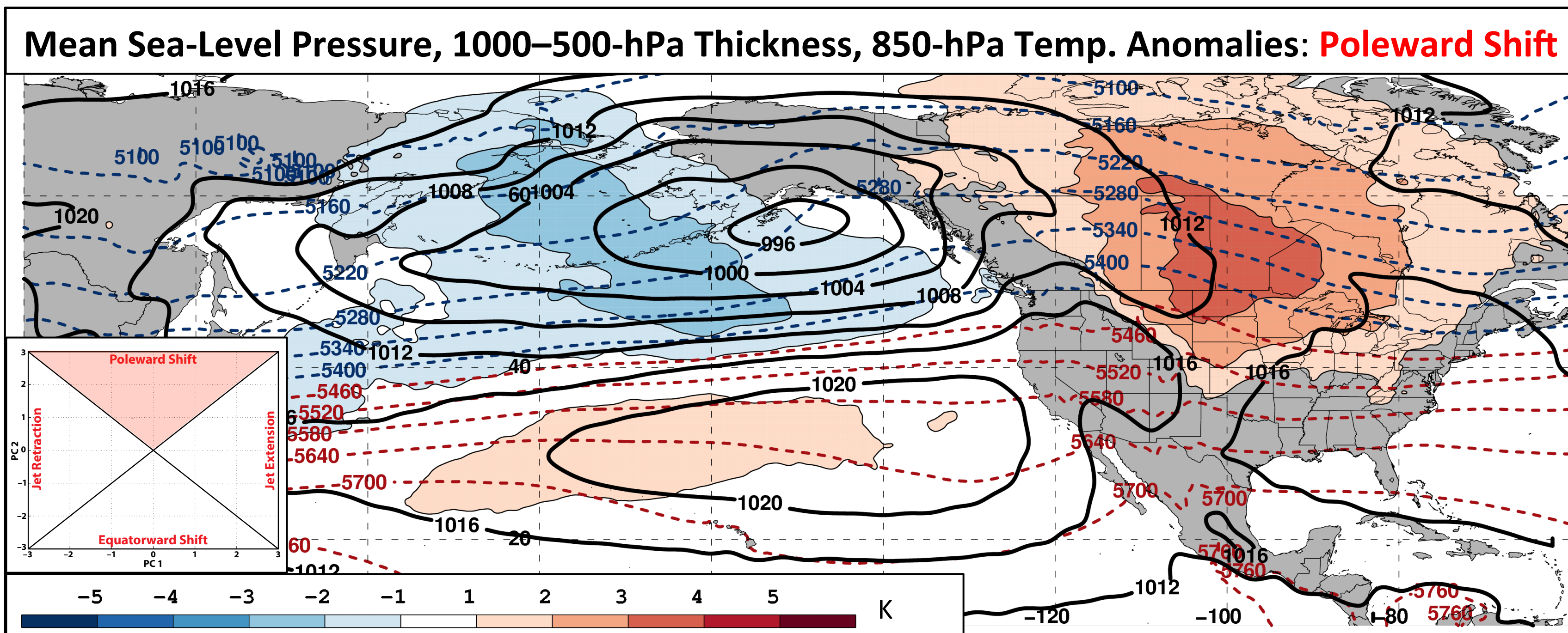



250-hPa Wind Speed, Geo. Heights, Geo. Height Anomalies: Poleward Shift
20 30 40 50 60 70 80 90 100
m s^{-1}
−120 −100 −80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Poleward Shift
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Equatorward Shift
PC 1
PC 2
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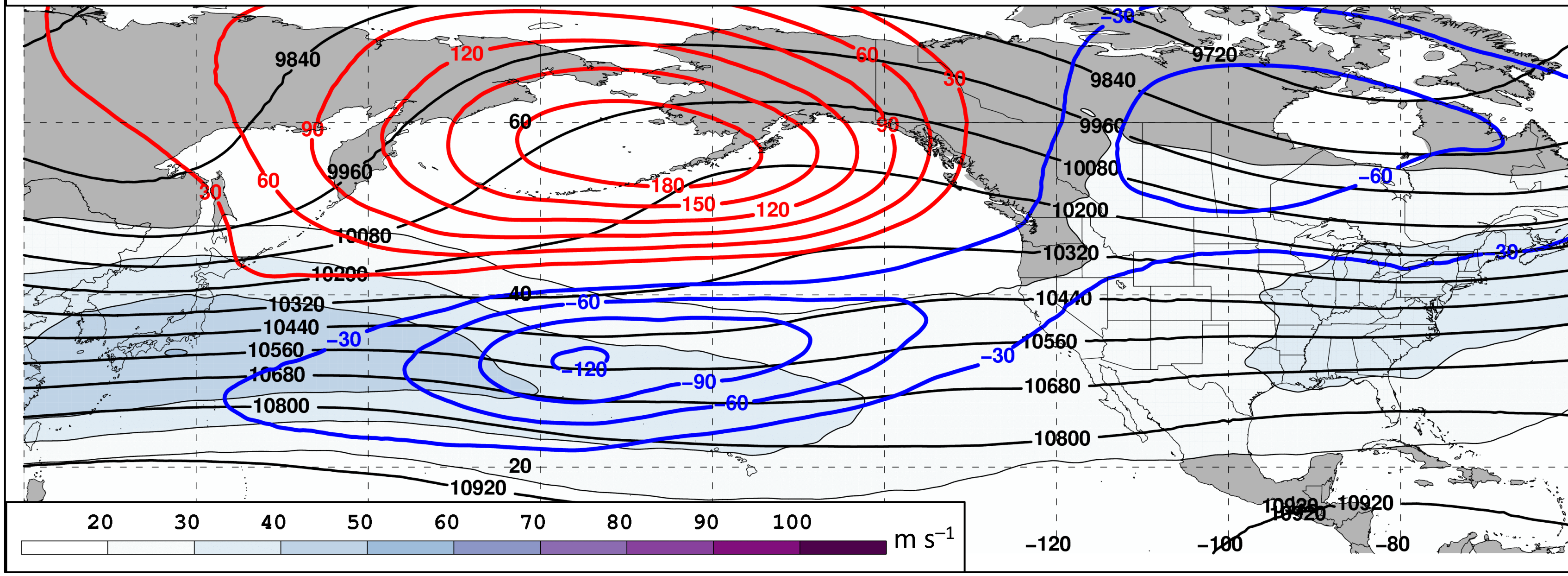
K
−120 −100 −80

250-hPa Wind Speed, Geo. Heights, Geo. Height Anomalies: Equator. Shift



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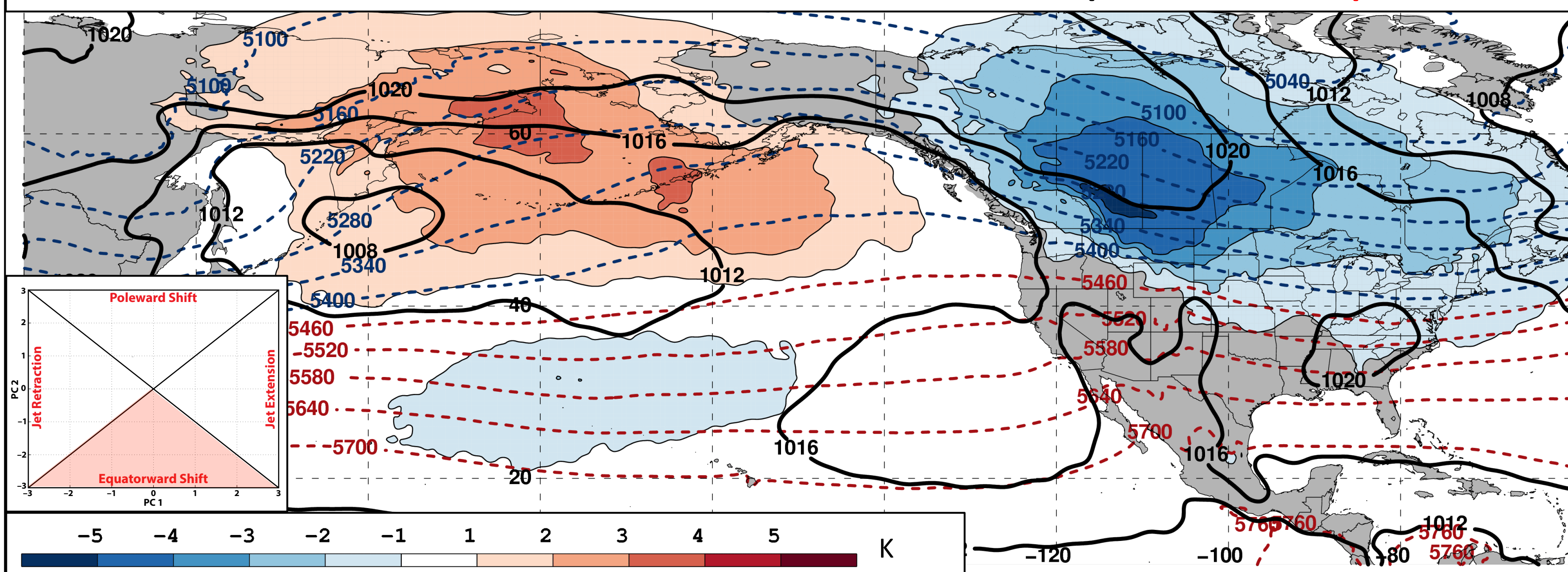

NPJ Phase Diagram Web Interface

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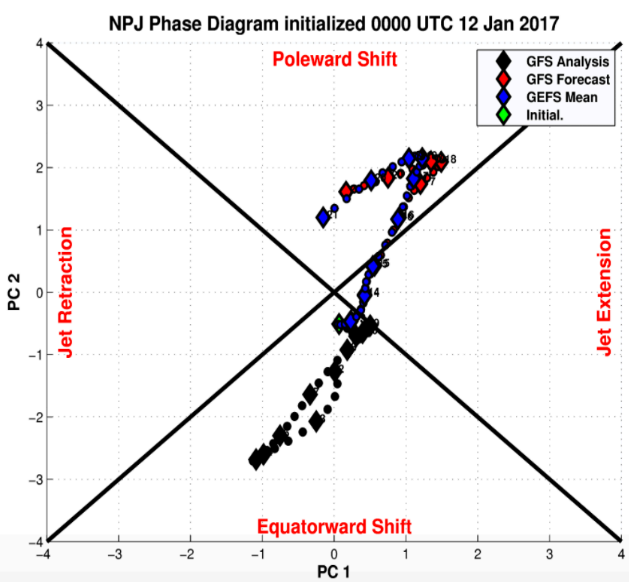
Phase Diagram (left): Shows the GFS analysis trajectory over the previous 10 days in black with diamonds corresponding to a position in the phase diagram at 00Z on the day labeled to the upper-right of its respective diamond. The red and blue symbols show the forecasted GFS and GEFS ensemble mean trajectories, respectively, within the phase diagram over the next 9 days with diamonds corresponding to a position in the phase diagram at 00Z on the day listed to the upper-right of its respective diamond. The green diamond shows the position within the phase diagram at 00Z on the day listed in the title.

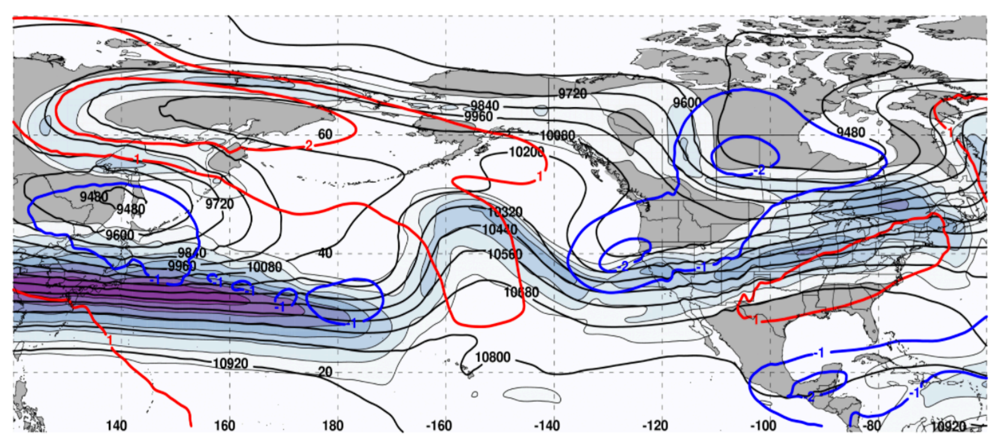
Synoptic Maps (right): Depicts GFS deterministic forecasts of (1) 250-hPa wind speed, geo. heights, and standardized geo. height anomalies, (2) 500-hPa relative vorticity, geo. heights, and standardized geo. height anomalies (3) mean sea level pressure, 1000-500-hPa thickness, and 850-hPa standardized temperature anomalies, and (4) 24-h accumulated precipitation. The 24-h forecasted accumulated precipitation is also used as 'verification' in Days -10 to 0.

Deterministic Forecast | Probabilistic Forecast | Ens. Spread Forecast | D(prog)/Dt

Arrow keys for navigation | Space = play/pause | Swipe for navigation on touchscreen

250-hPa Jet/Hght/Hght'	-10	-9	-8	-7	-6	-5	-4	-3	-2	-1	0	+1	+2	+3	+4	+5	+6	+7	+8	+9
500-hPa Vort/Hght/Hght'	-10	-9	-8	-7	-6	-5	-4	-3	-2	-1	0	+1	+2	+3	+4	+5	+6	+7	+8	+9
MSLP/Thick/Temp'	-10	-9	-8	-7	-6	-5	-4	-3	-2	-1	0	+1	+2	+3	+4	+5	+6	+7	+8	+9
24-h Accum. Precip	-10	-9	-8	-7	-6	-5	-4	-3	-2	-1	0	+1	+2	+3	+4	+5	+6	+7	+8	+9





170112/0000V000 250 hPa Wind Speed (m/s), Geo. Hght & Std. Hght Anom (m)

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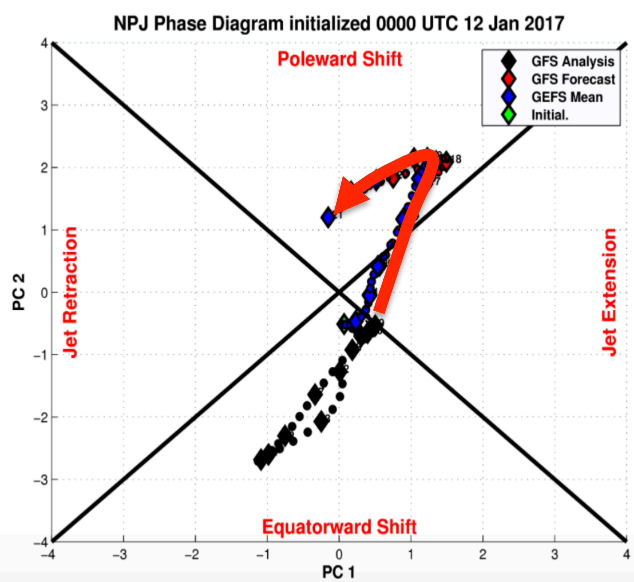

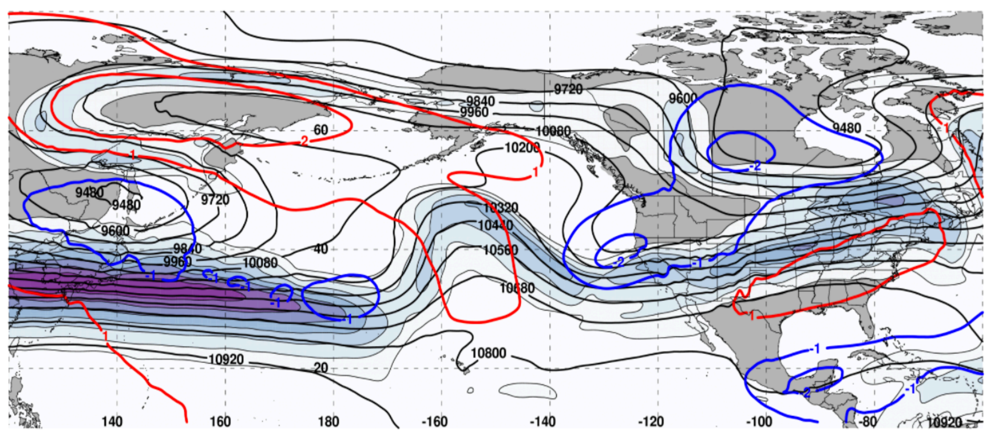

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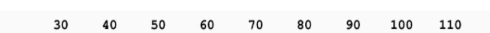

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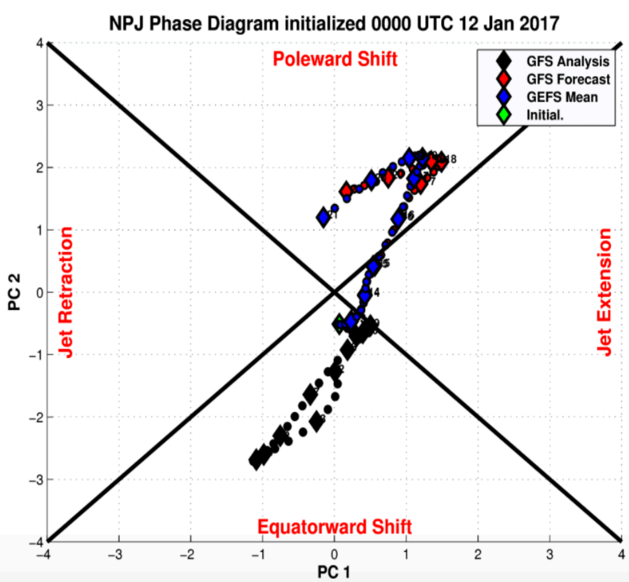

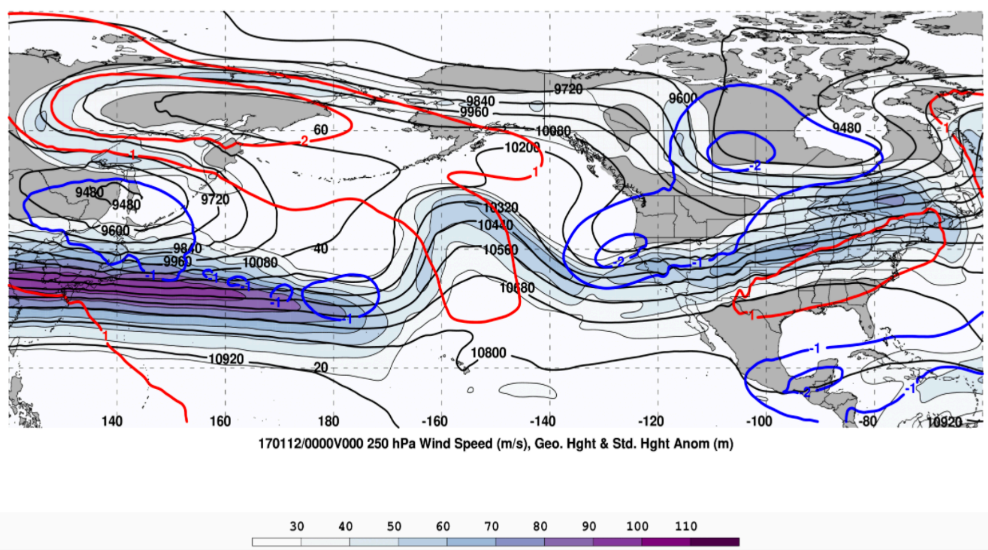

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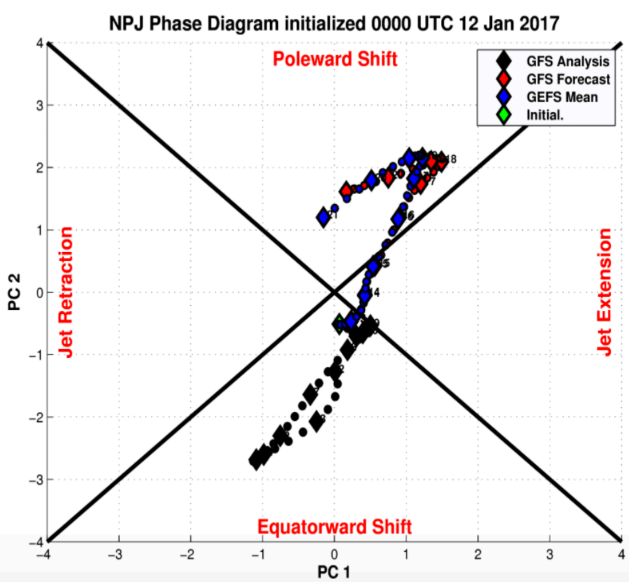
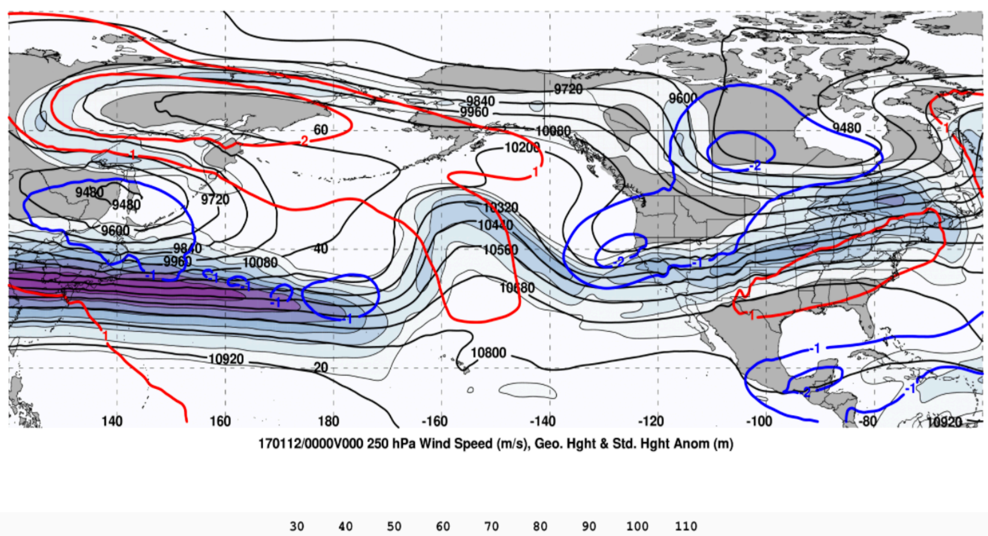
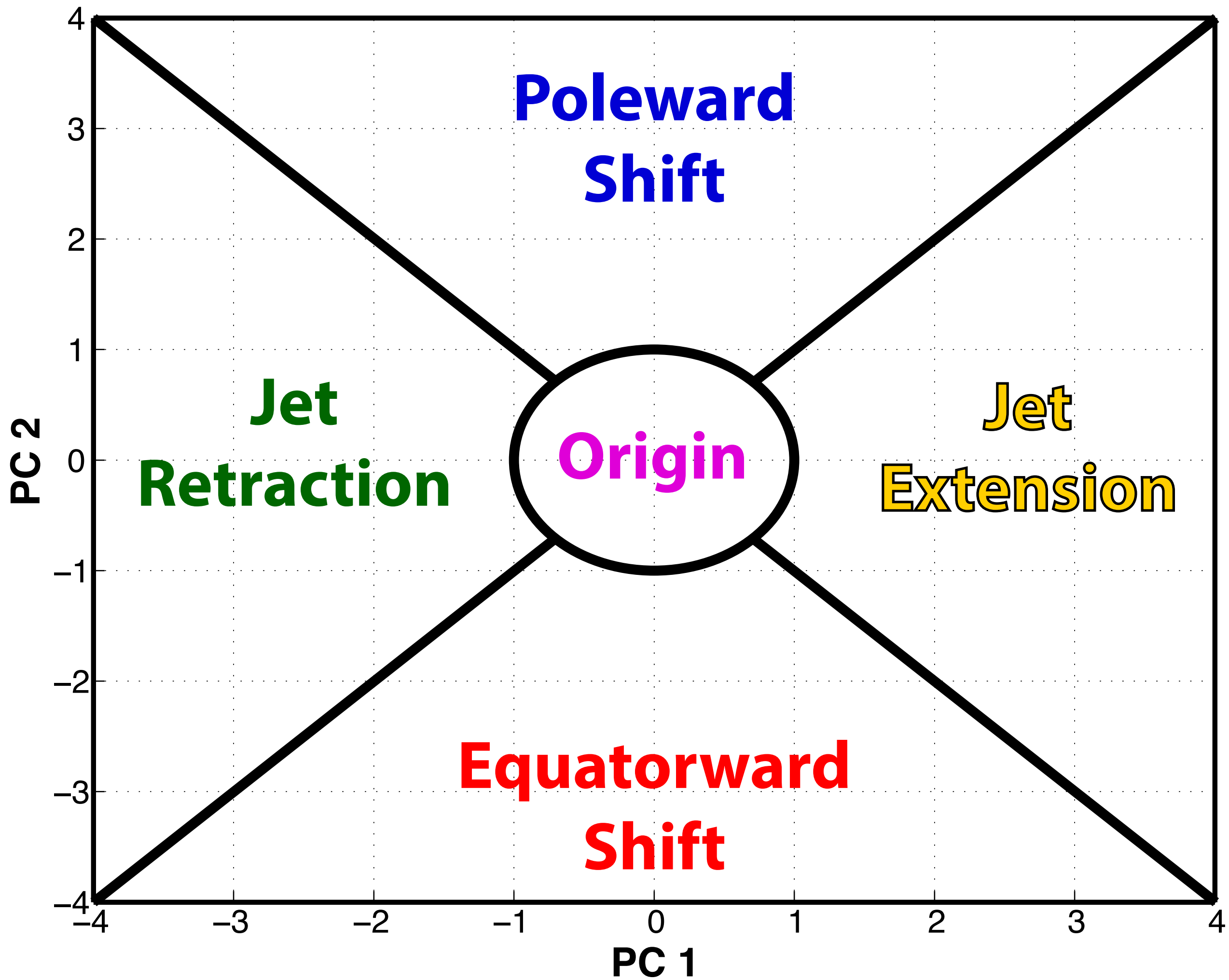




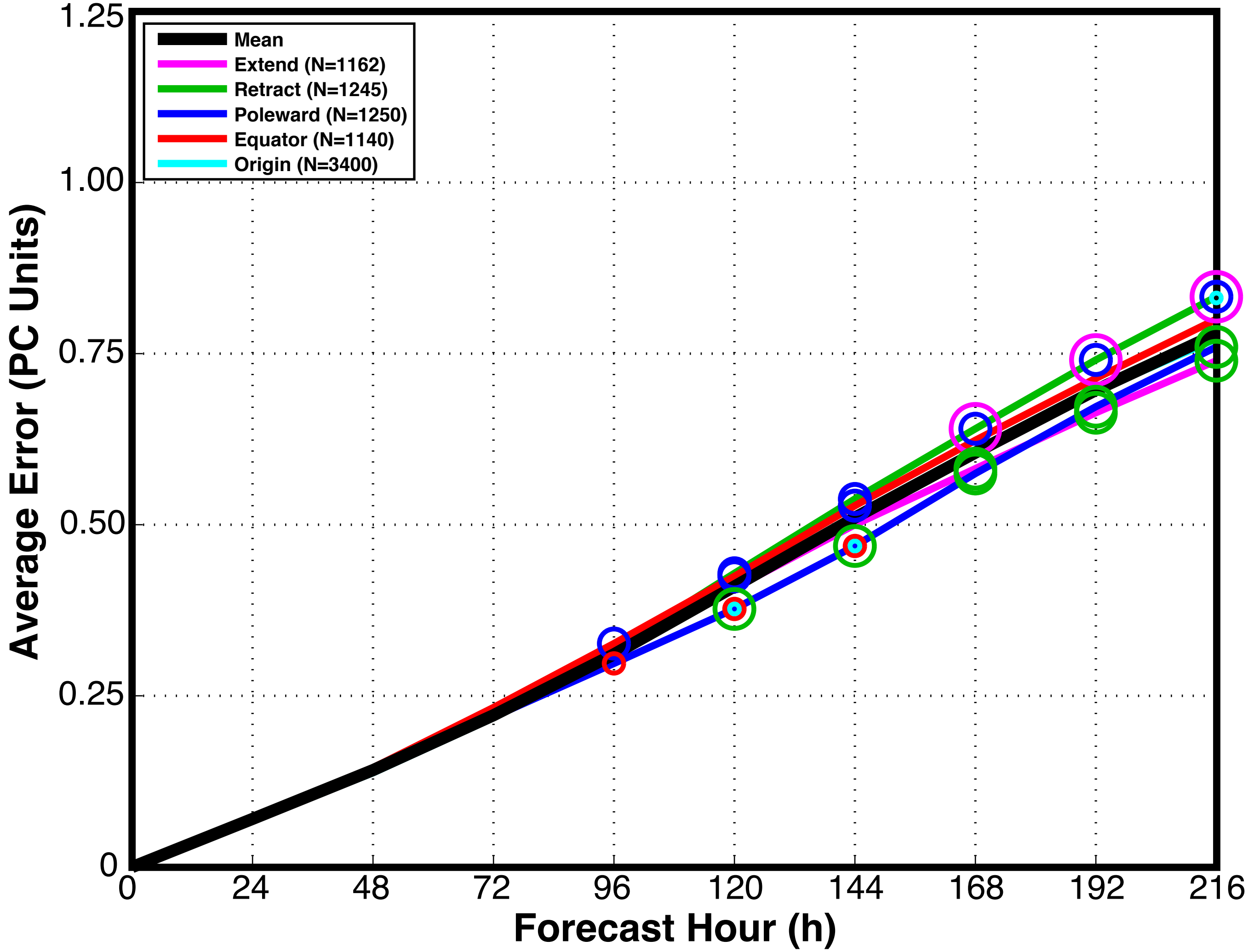
GEFS Forecast Skill in the Context of the NPJ Phase Diagram

NPJ Phase Diagram Forecast Skill

Determined the position within the NPJ phase diagram for all 0-h forecasts during Sept.–May 1984–2014 in the GEFS Reforecast V2 (Hamill et al. 2013)



GEFS Ensemble Mean Error by NPJ Regime



GEFS Reforecasts *initialized* within a particular NPJ regime

Circles on a particular line indicate statistically significant differences at the 95% confidence level with respect to another NPJ regime

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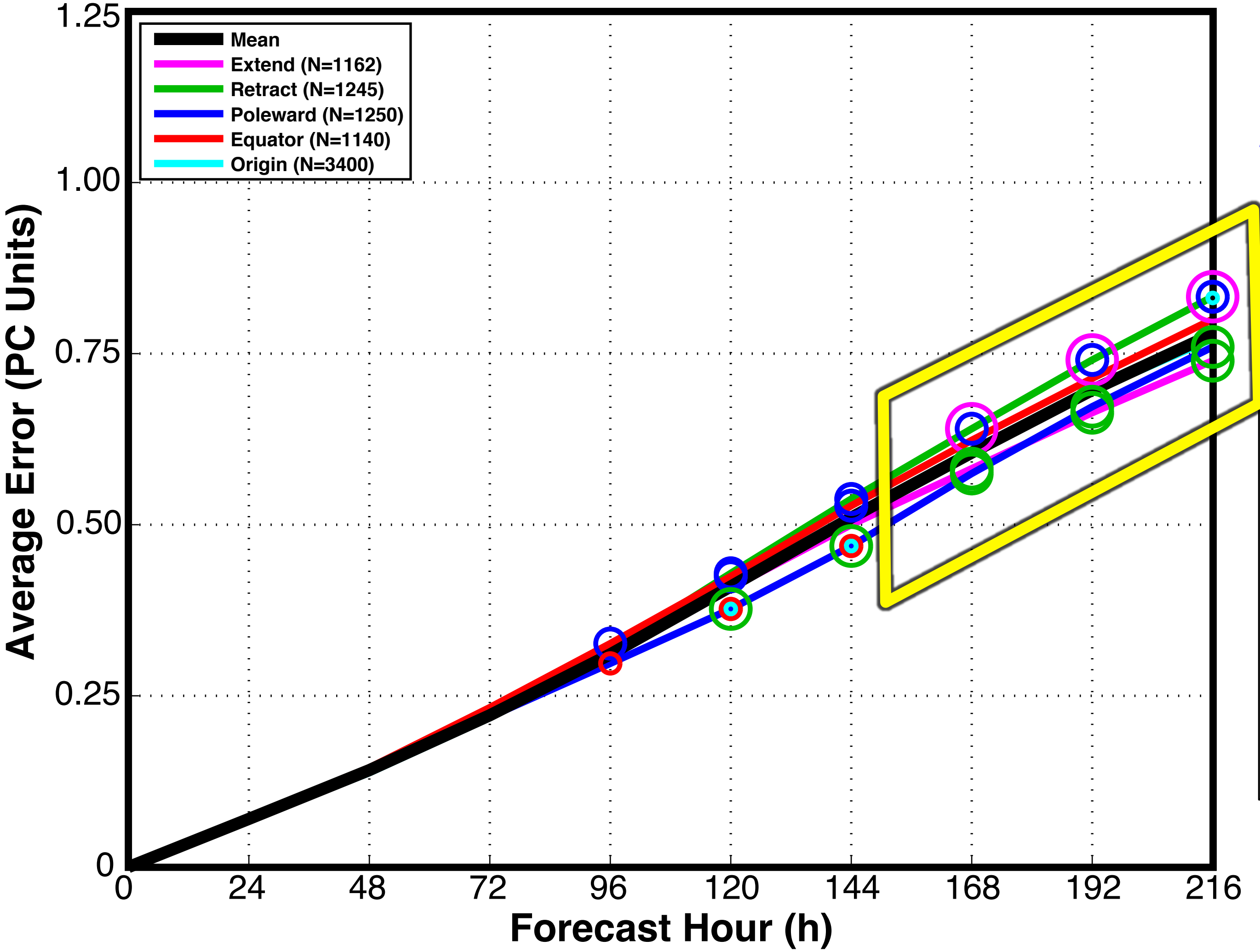

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Forecasts initialized during jet retractions exhibit significantly larger errors than jet extensions and poleward shifts in the 168–216-h forecast period

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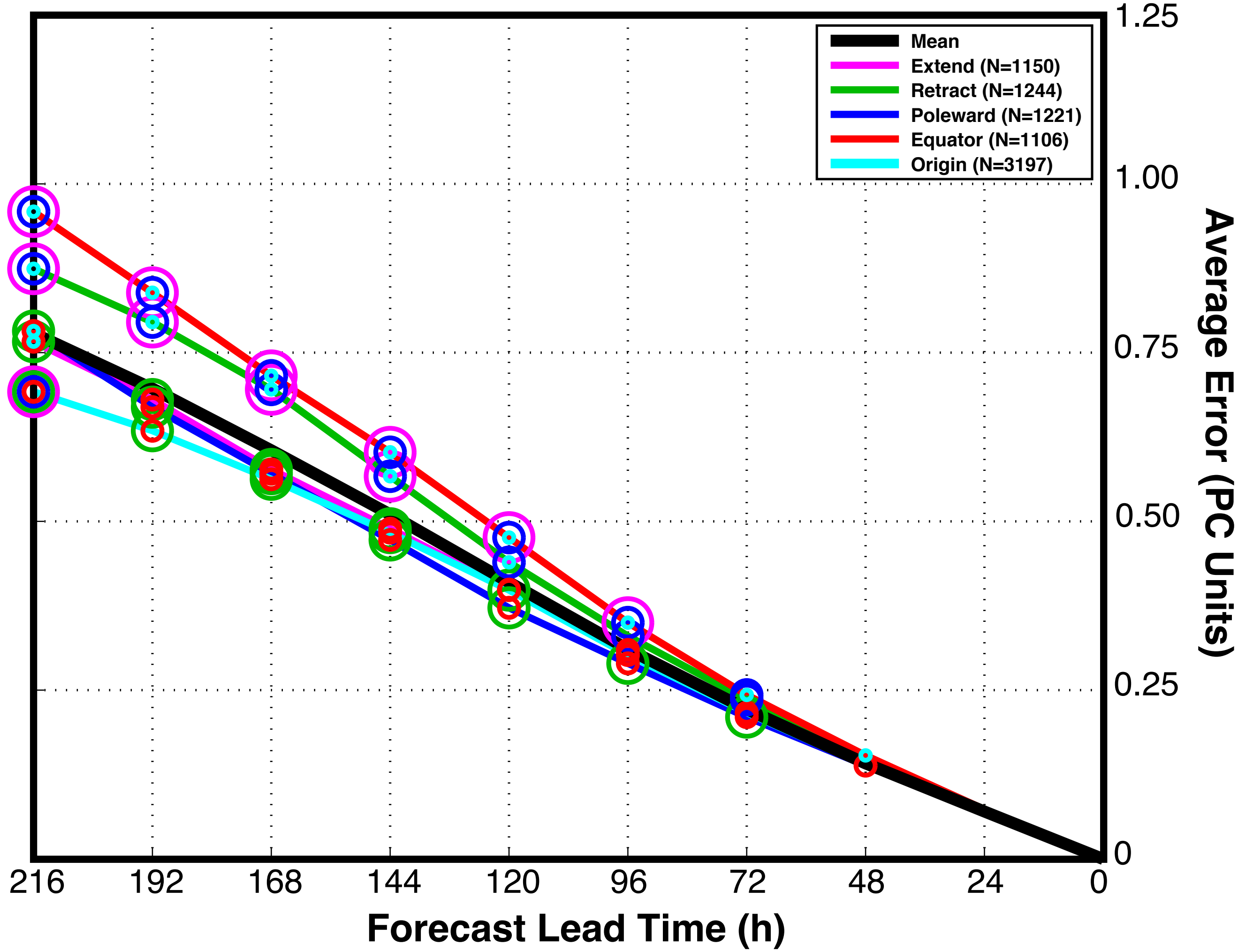

GEFS Reforecasts *verifying* within a particular NPJ regime

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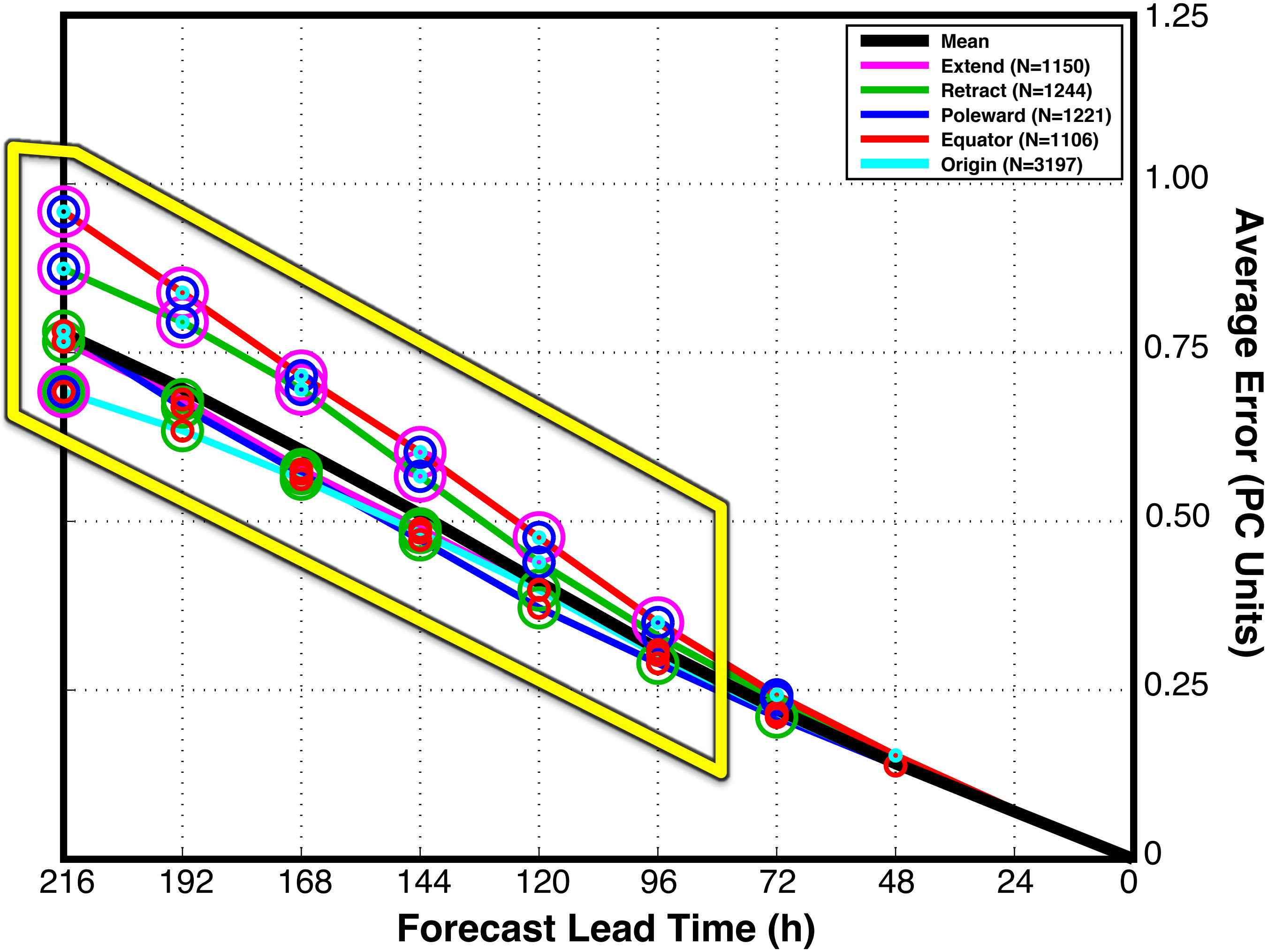
GEFS Ensemble Mean Error by NPJ Regime



GEFS Reforecasts *verifying* within a particular NPJ regime

Circles on a particular line indicate statistically significant differences at the 99% confidence level with respect to another NPJ regime

Forecasts verifying during equatorward shifts and jet retractions exhibit significantly larger errors than jet extensions and poleward shifts in the 96–216-h forecast period

Best/Worst NPJ Phase Diagram Forecasts

Comparison between the periods characterized by the best/worst medium-range forecasts

Criteria: Forecasts must rank in the top/bottom 10% in terms of *both*:

(1) The average GEFS ensemble mean error in the Day 8 and 9 forecasts

(2) The average GEFS ensemble member error in the Day 8 and 9 forecasts

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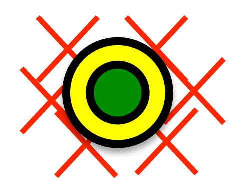
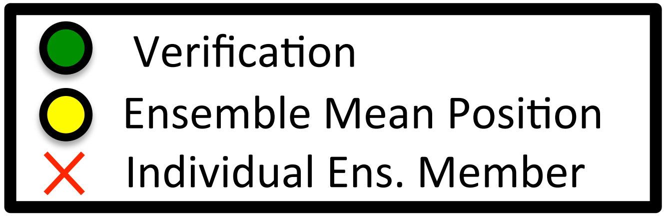
Hypothetical Best Forecast





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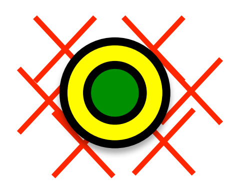
Represents a forecast with negligible ensemble mean error

(1) Ens. Mean error ≈ 0 ✓

Hypothetical Best Forecast



Verification

Ensemble Mean Position

Individual Ens. Member

Best/Worst NPJ Phase Diagram Forecasts

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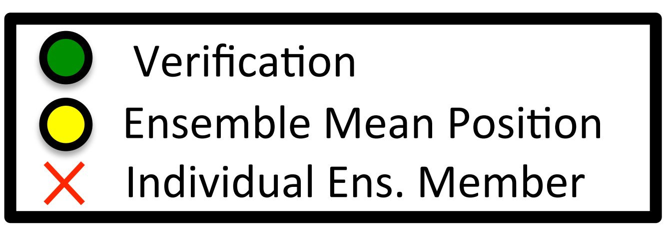
(2) The average GEFS ensemble <u>member</u> error in the Day 8 and 9 forecasts

Represents a forecast with negligible ensemble member error

(1) Ens. Mean error ≈ 0

(2) Avg. Ens. Member error ≈ 0



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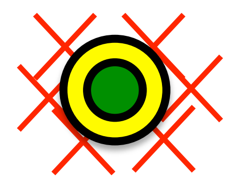


Best/Worst NPJ Phase Diagram Forecasts

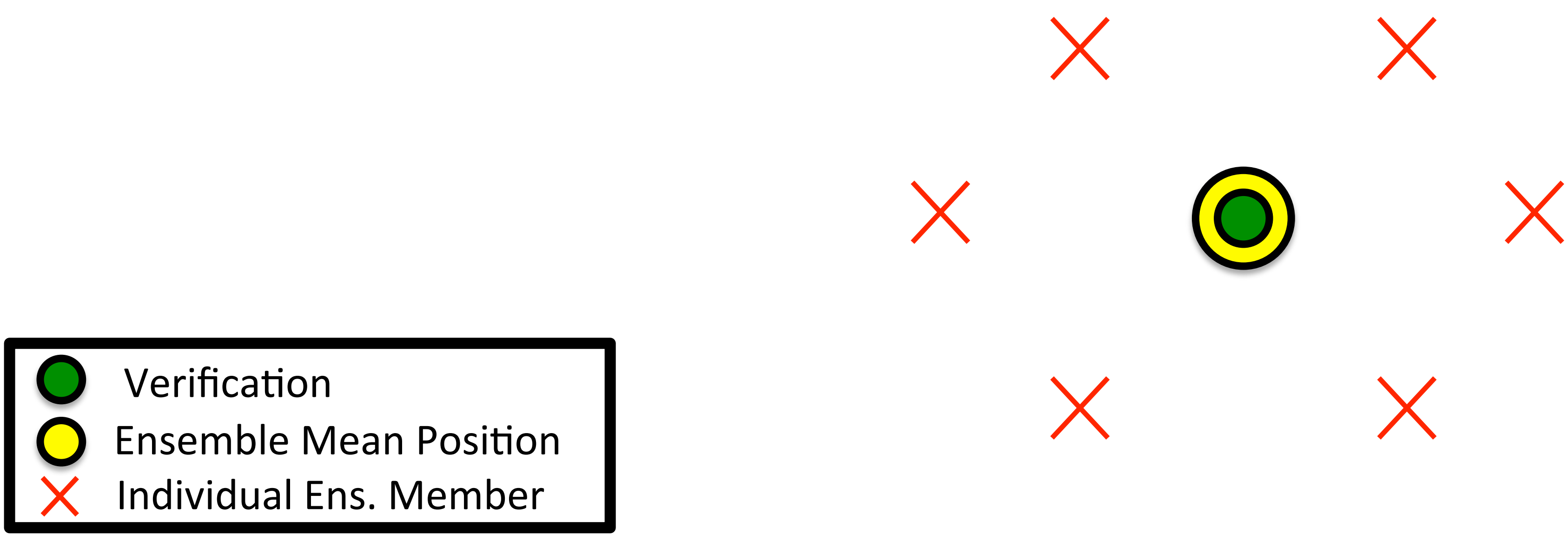
Comparison between the periods characterized by the best/worst medium-range forecasts

Criteria: Forecasts must rank in the top/bottom 10% in terms of *both*:

(1) The average GEFS ensemble mean error in the Day 8 and 9 forecasts

(2) The average GEFS ensemble member error in the Day 8 and 9 forecasts

Hypothetical Intermediate Forecast



Best/Worst NPJ Phase Diagram Forecasts

Comparison between the periods characterized by the best/worst medium-range forecasts

<u>**Criteria**</u>: Forecasts must rank in the top/bottom 10% in terms of *both*:

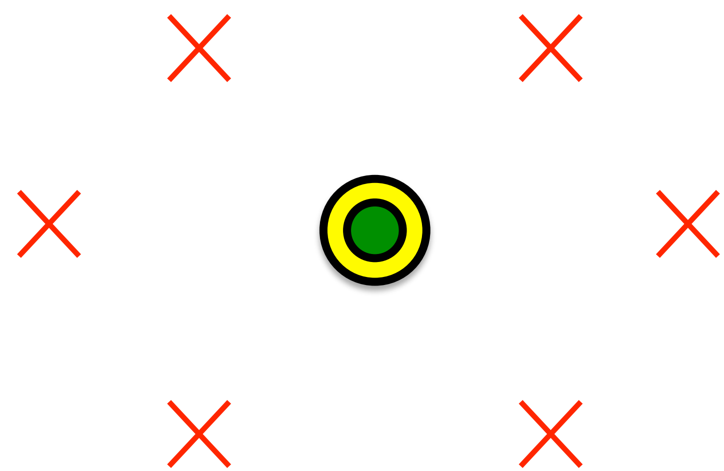
(1) The average GEFS ensemble <u>mean</u> error in the Day 8 and 9 forecasts

(2) The average GEFS ensemble <u>member</u> error in the Day 8 and 9 forecasts

Represents a forecast with negligible ensemble mean error

(1) Ens. Mean error ≈ 0 ✓

Hypothetical Intermediate Forecast



Verification

Ensemble Mean Position

Individual Ens. Member

Best/Worst NPJ Phase Diagram Forecasts

Comparison between the periods characterized by the best/worst medium-range forecasts

Criteria: Forecasts must rank in the top/bottom 10% in terms of *both*:

(1) The average GEFS ensemble mean error in the Day 8 and 9 forecasts

(2) The average GEFS ensemble member error in the Day 8 and 9 forecasts

Represents a forecast with considerable ensemble member error

(1) Ens. Mean error ≈ 0 ✓

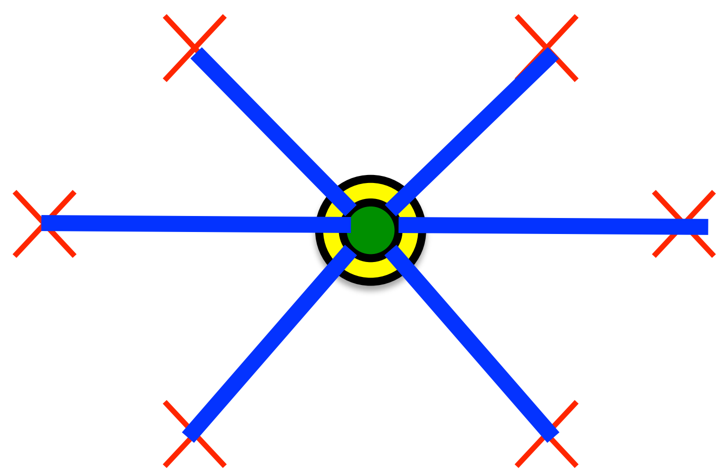
(2) Avg. Ens. Member error >> 0 ✗

Verification

Ensemble Mean Position

Individual Ens. Member

Hypothetical Intermediate Forecast



Best/Worst NPJ Phase Diagram Forecasts

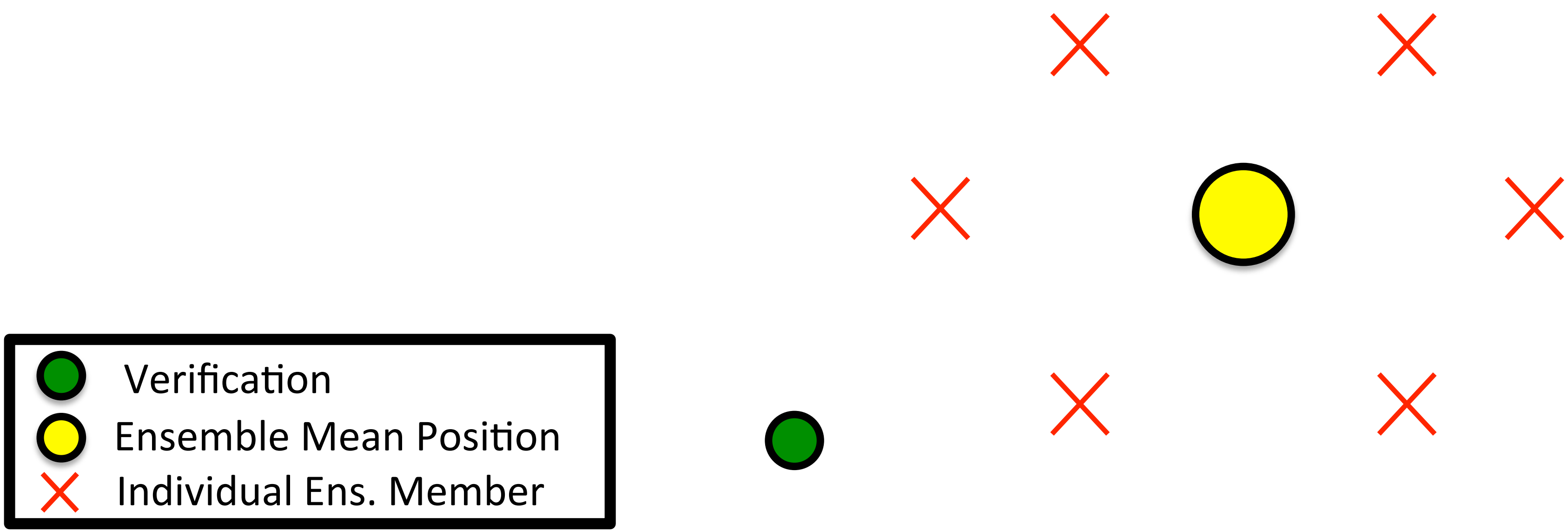
Comparison between the periods characterized by the best/worst medium-range forecasts

Criteria: Forecasts must rank in the top/bottom 10% in terms of *both*:

(1) The average GEFS ensemble mean error in the Day 8 and 9 forecasts

(2) The average GEFS ensemble member error in the Day 8 and 9 forecasts

Hypothetical Worst Forecast



Best/Worst NPJ Phase Diagram Forecasts

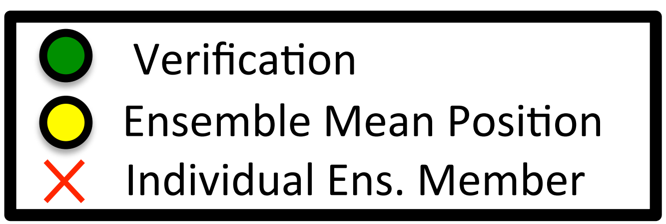
Comparison between the periods characterized by the best/worst medium-range forecasts

<u>Criteria</u>: Forecasts must rank in the top/bottom 10% in terms of *both*:

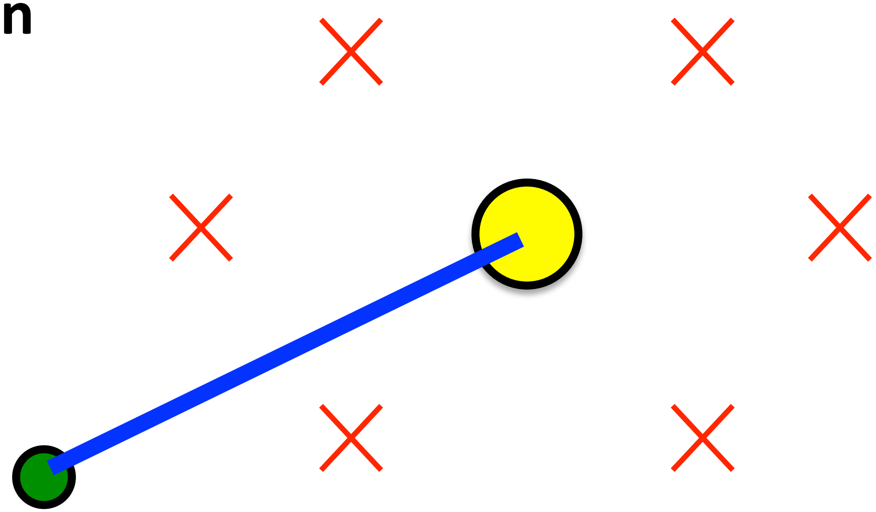
(1) The average GEFS ensemble <u>mean</u> error in the Day 8 and 9 forecasts
(2) The average GEFS ensemble <u>member</u> error in the Day 8 and 9 forecasts

Represents a forecast with considerable ensemble mean error

(1) Ens. Mean error >> 0 ✗



Hypothetical Worst Forecast



Best/Worst NPJ Phase Diagram Forecasts

Comparison between the periods characterized by the best/worst medium-range forecasts

<u>**Criteria**</u>: Forecasts must rank in the top/bottom 10% in terms of *both*:

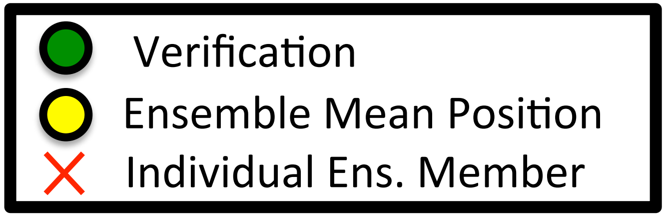
(1) The average GEFS ensemble <u>mean</u> error in the Day 8 and 9 forecasts

(2) The average GEFS ensemble <u>member</u> error in the Day 8 and 9 forecasts

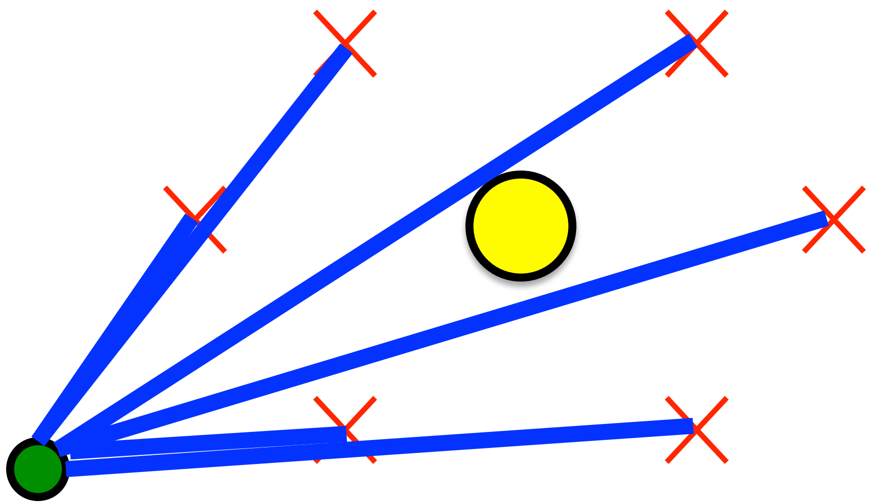
Represents a forecast with considerable ensemble member error

(1) Ens. Mean error >> 0 ✗

(2) Avg. Ens. Member error >> 0 ✗



Hypothetical Worst Forecast

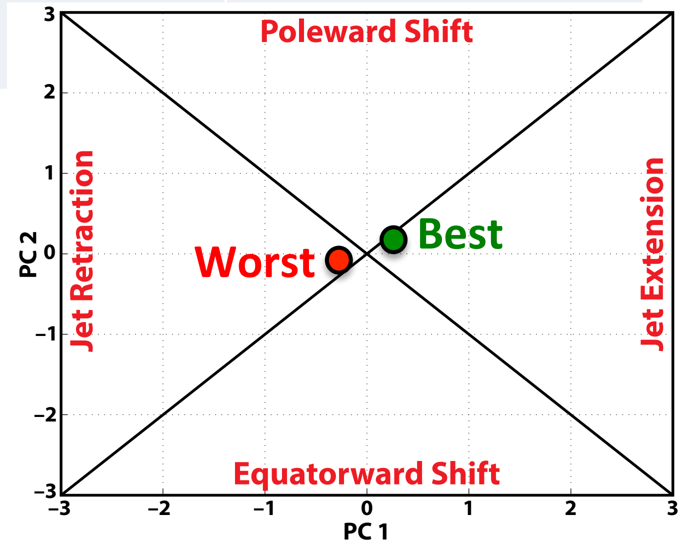


Best/Worst NPJ Phase Diagram Forecasts

Comparison between the periods characterized by the best/worst medium-range forecasts

	$PC1_{start}$	$PC2_{start}$	Avg. ΔPC1	Avg. ΔPC2	Avg. 10-d Traj. Dist.
Best Forecasts (N=475)	0.09	0.04	0.09	0.16	3.50 PC units
Worst Forecasts (N=763)	–0.18	–0.08	–0.01	–0.21	4.33

- The best forecasts typically initialize more frequently within jet extension and poleward shift NPJ regimes
- The worst forecasts typically initialize more frequently within jet retraction and equatorward shift NPJ regimes



Best/Worst NPJ Phase Diagram Forecasts

Comparison between the periods characterized by the best/worst medium-range forecasts

	$PC1_{start}$	$PC2_{start}$	Avg. ΔPC1	Avg. ΔPC2	Avg. 10-d Traj. Dist.
Best Forecasts (N=475)	0.09	0.04	0.09	0.16 Poleward Shift	3.50 PC units
Worst Forecasts (N=763)	–0.18	–0.08	–0.01	–0.21 Equatorward Shift	4.33 PC units

- The best forecast periods are typically characterized by poleward shifts over the next 10 days and anomalously short trajectories within the NPJ phase diagram
- The worst forecast periods are typically characterized by equatorward shifts over the next 10 days and anomalously long trajectories within the NPJ phase diagram

Discussion

- Forecasts initialized/verifying during jet extensions and poleward shifts are characterized by lower errors than those initialized/verifying during jet retractions and equatorward shifts.
- The best NPJ phase diagram forecasts are most frequently initialized during jet extensions and poleward shifts and are typically characterized by periods with shorter trajectories through the NPJ phase diagram.
- A topic of future research is to explain from a synoptic-dynamic perspective why jet extensions and poleward shifts exhibit greater forecast skill compared to jet retractions and equatorward shifts.

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), Josh Kastman (WPC), and Sara Ganetis (WPC)

References

Athanasiadis, P. J., J. M. Wallace, and J. J. Wettstein, 2010: Patterns of wintertime jet stream variability and their relation to the storm tracks. *J. Atmos. Sci.*, **67,** 1361–1381.

Griffin, K. S., and J. E. Martin, 2017: Synoptic features associated with temporally coherent modes of variability of the North Pacific jet stream. *J. Climate, **29**,* in press.

Hamill, T. M., G. T. Bates, J. S. Whitaker, D. R. Murray, M. Fiorino, T. J. Galarneau, Y. Zhu, and W. Lapenta, 2013: NOAA's Second-Generation Global Medium-Range Ensemble Forecast Dataset. *Bull. Amer. Meteor. Soc.*, **94,** 1553–1565.

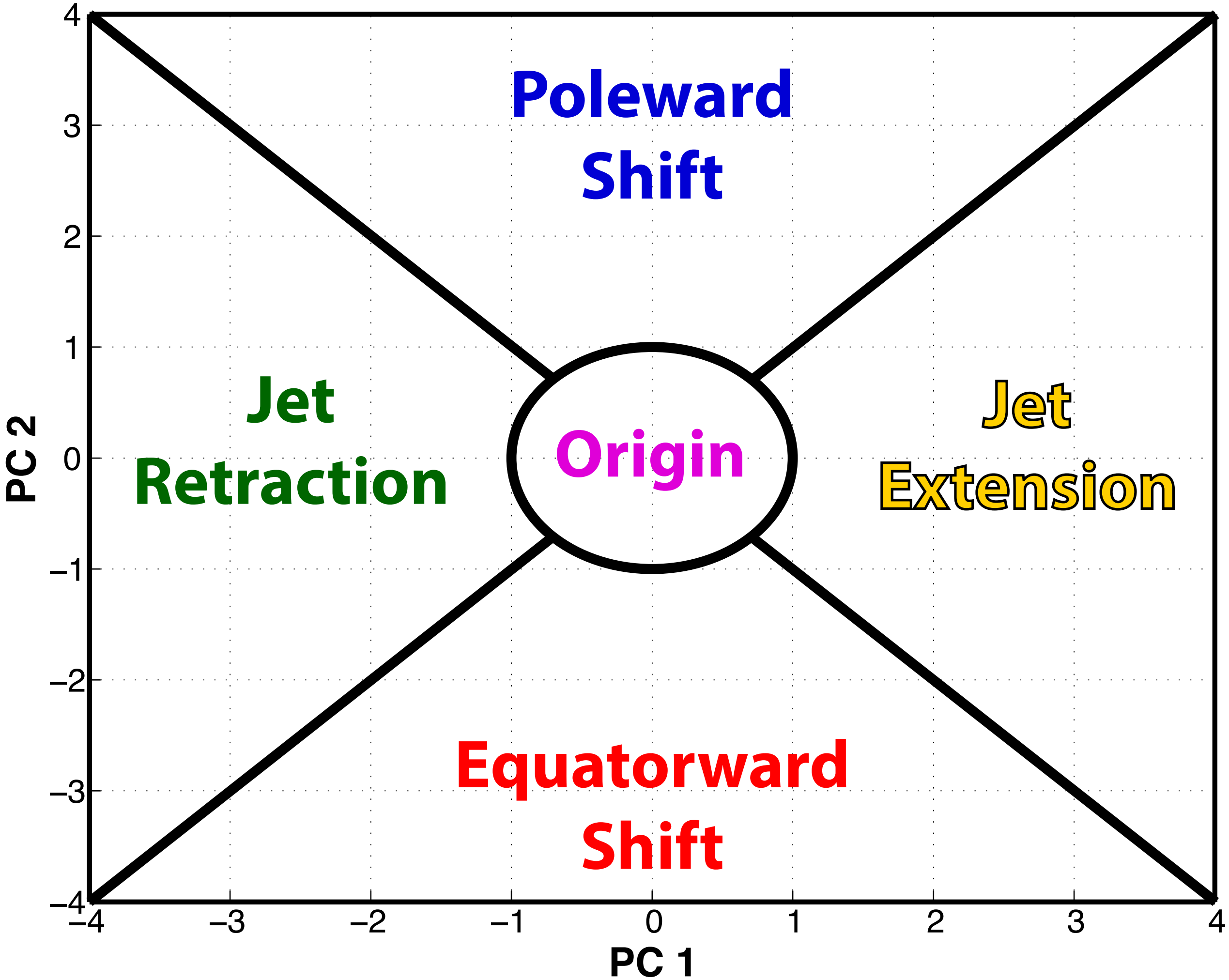
Jaffe, S. C., J. E. Martin, D. J. Vimont, and D. L. Lorenz, 2011: A synoptic climatology of episodic, subseasonal retractions of the Pacific jet. *J. Climate*, **24,** 2846–2860.

Saha, S., and Coauthors, 2014: The NCEP Climate Forecast System Version 2. *J. Climate*, **27,** 2185–2208.

Supplementary Slides

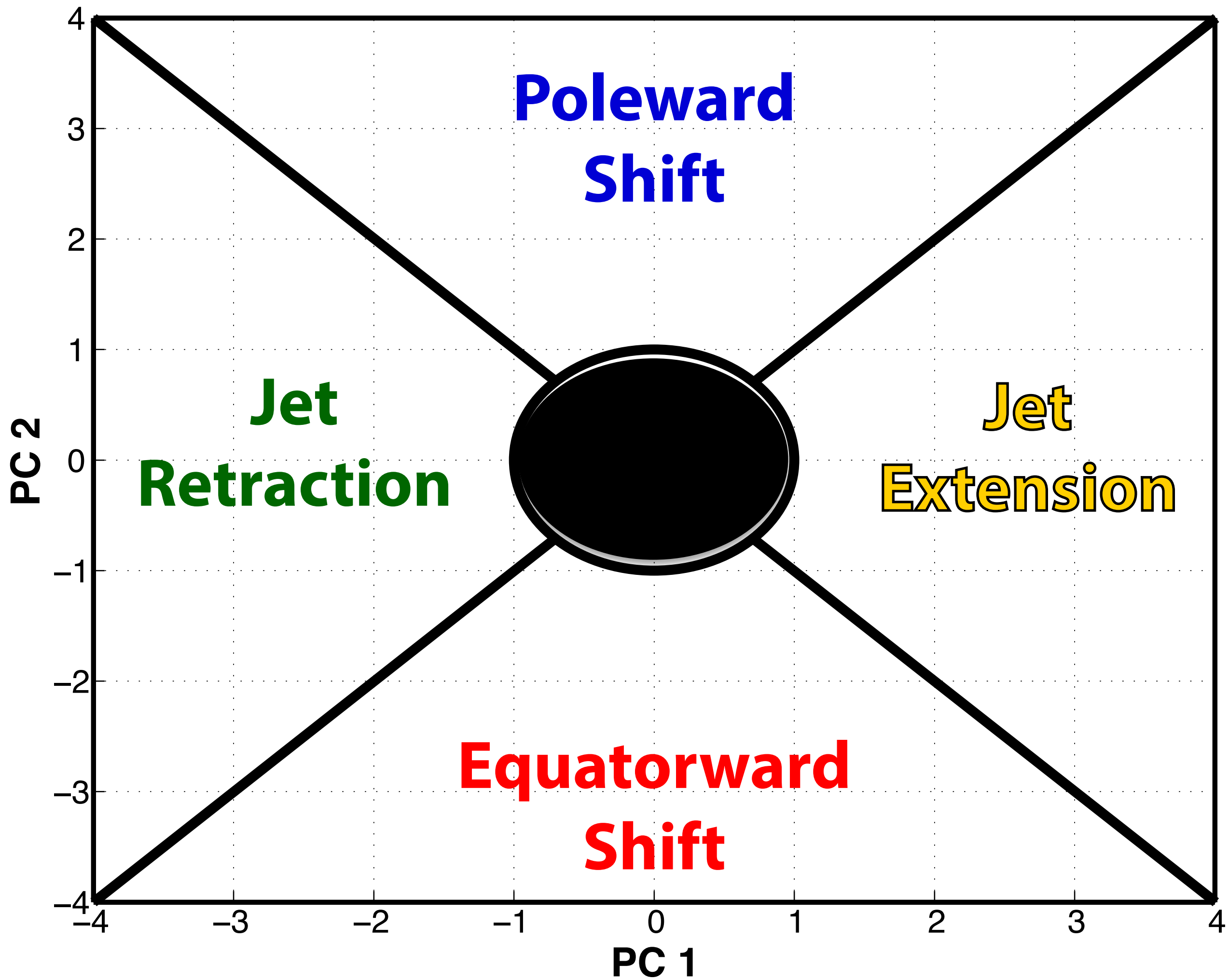
NPJ Regime Composites

Determined the position within the NPJ phase diagram at all analysis times in the CFSR at 6-h intervals between Sept.–May 1979–2014



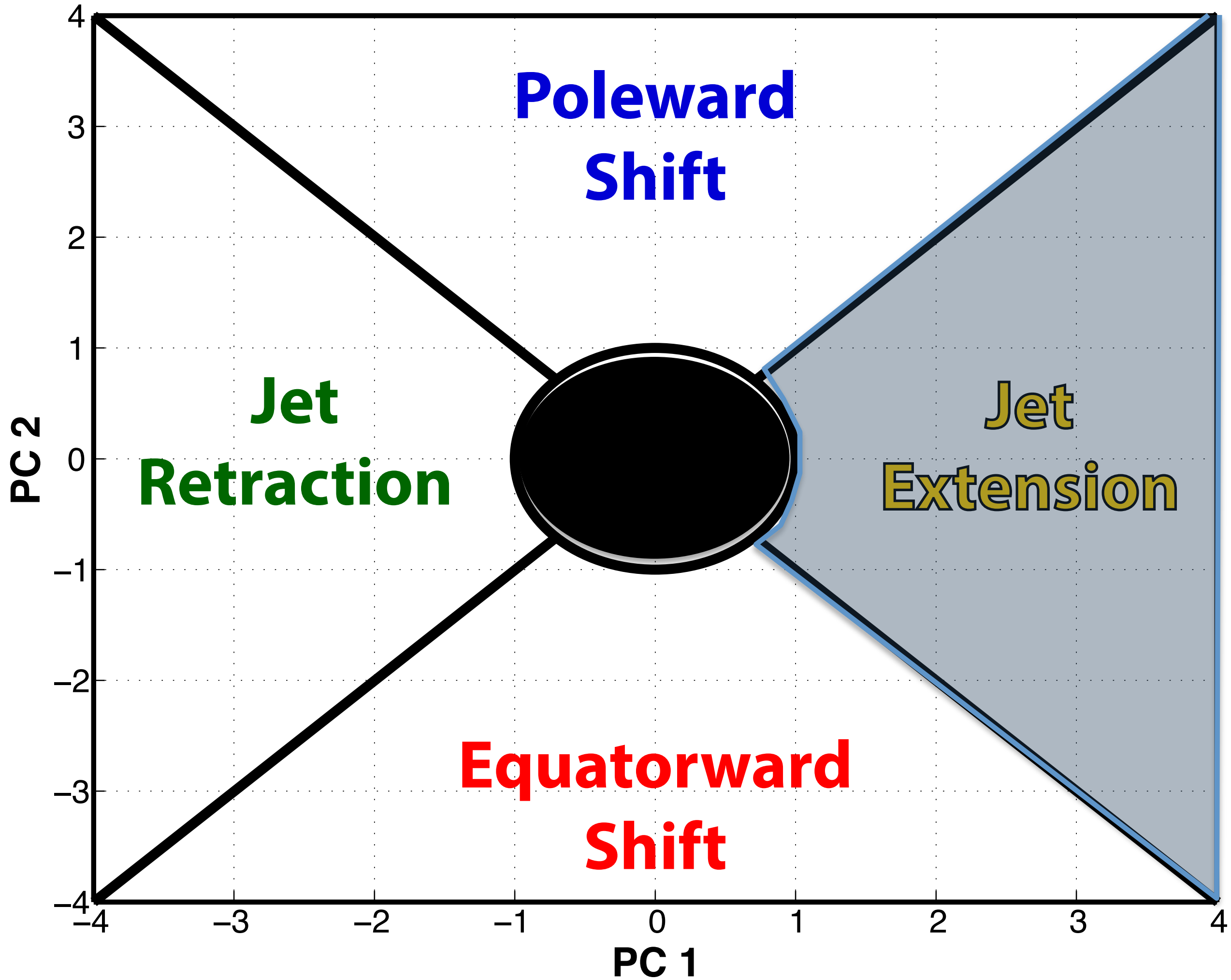
NPJ Regime Composites

Isolated the analysis times during which there was a strong projection onto one of the four NPJ regimes (i.e., >1 PC unit from the origin)



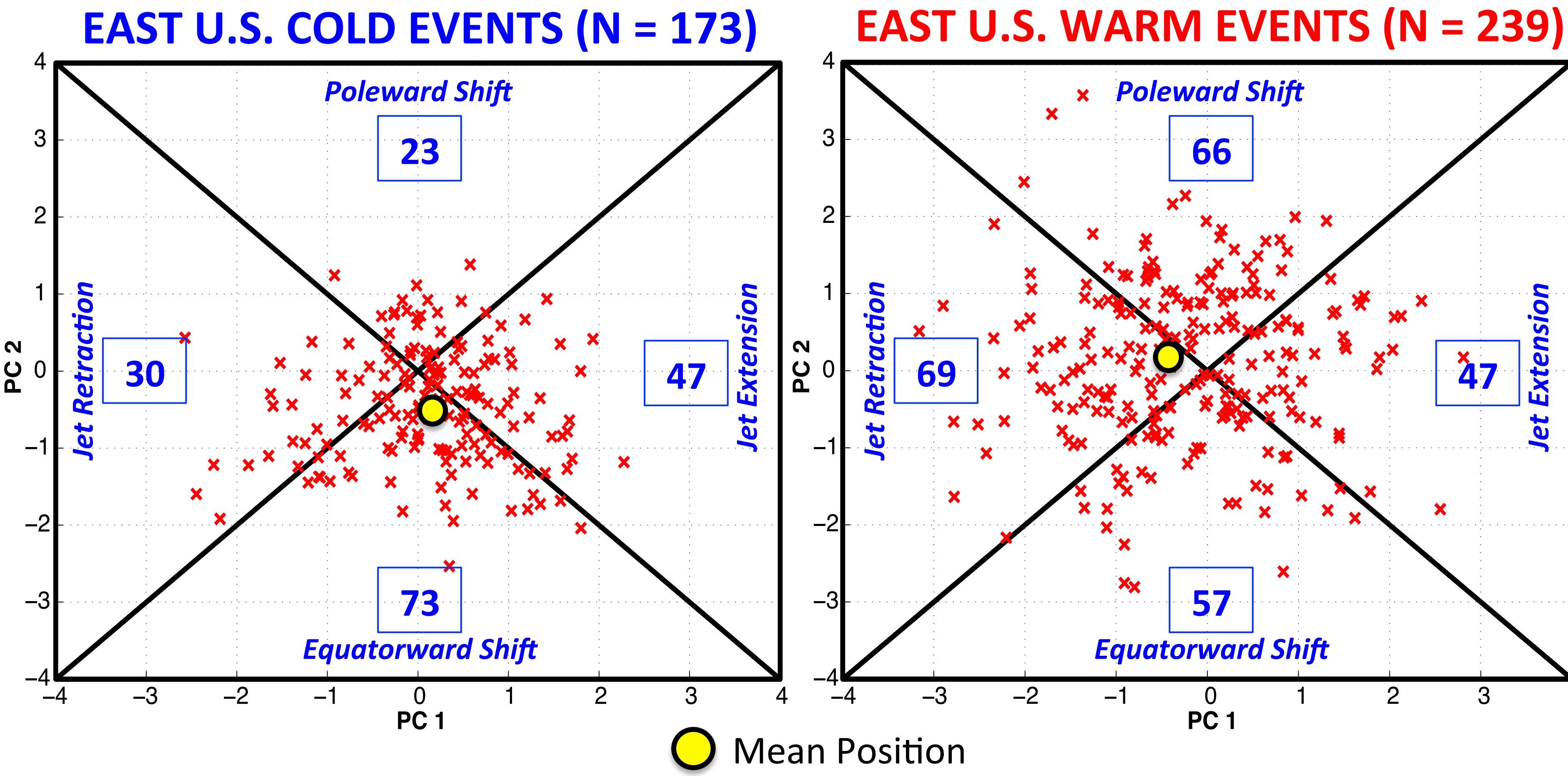
NPJ Regime Composites

Isolated periods during which the NPJ resided within the same quadrant of the NPJ phase diagram for 3 consecutive days



Inter and Intraannual Characteristics of the NPJ Phase Diagram

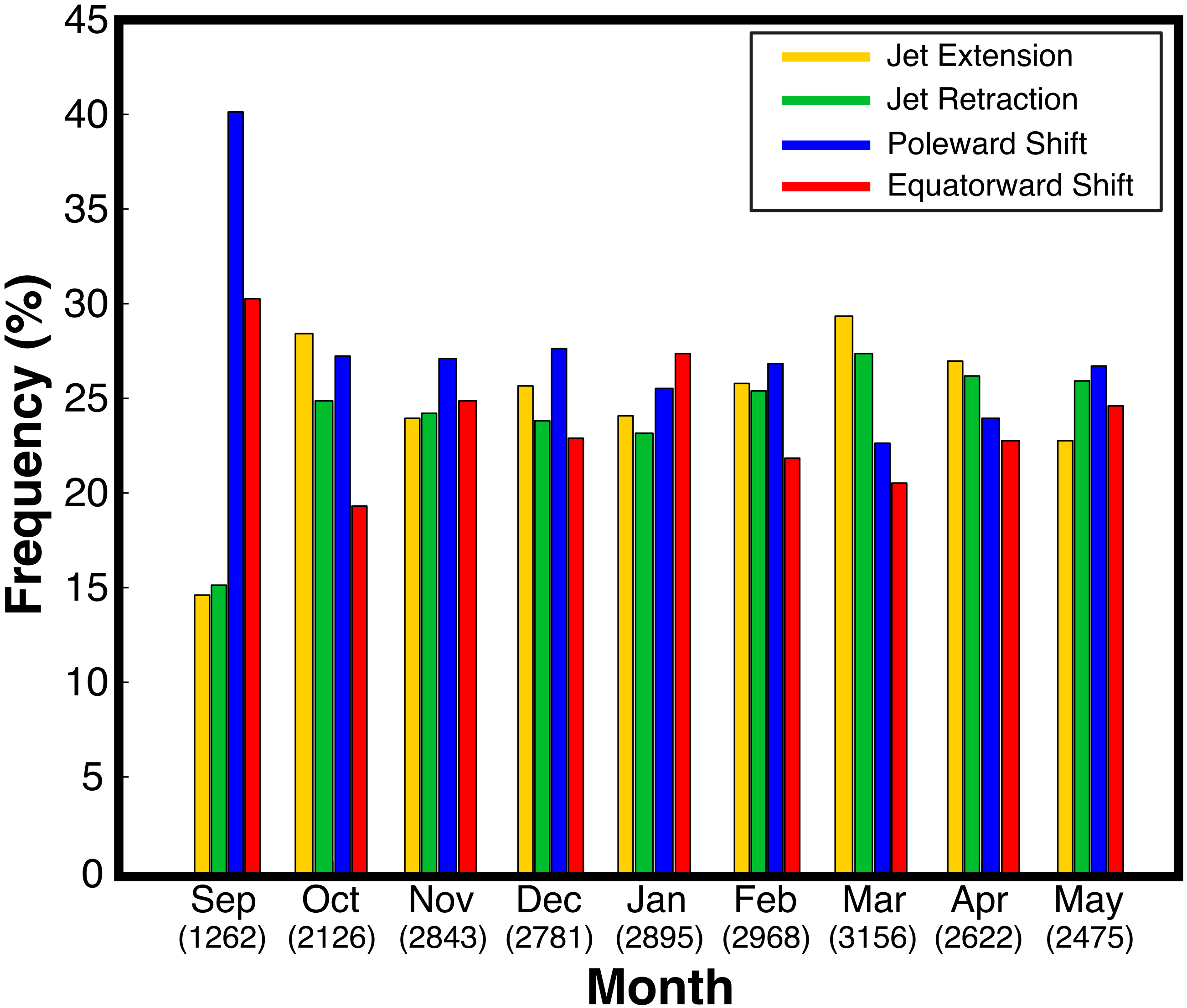
The NPJ Phase Diagram and ETEs



ETEs during Sept. – May are projected onto the NPJ phase diagram

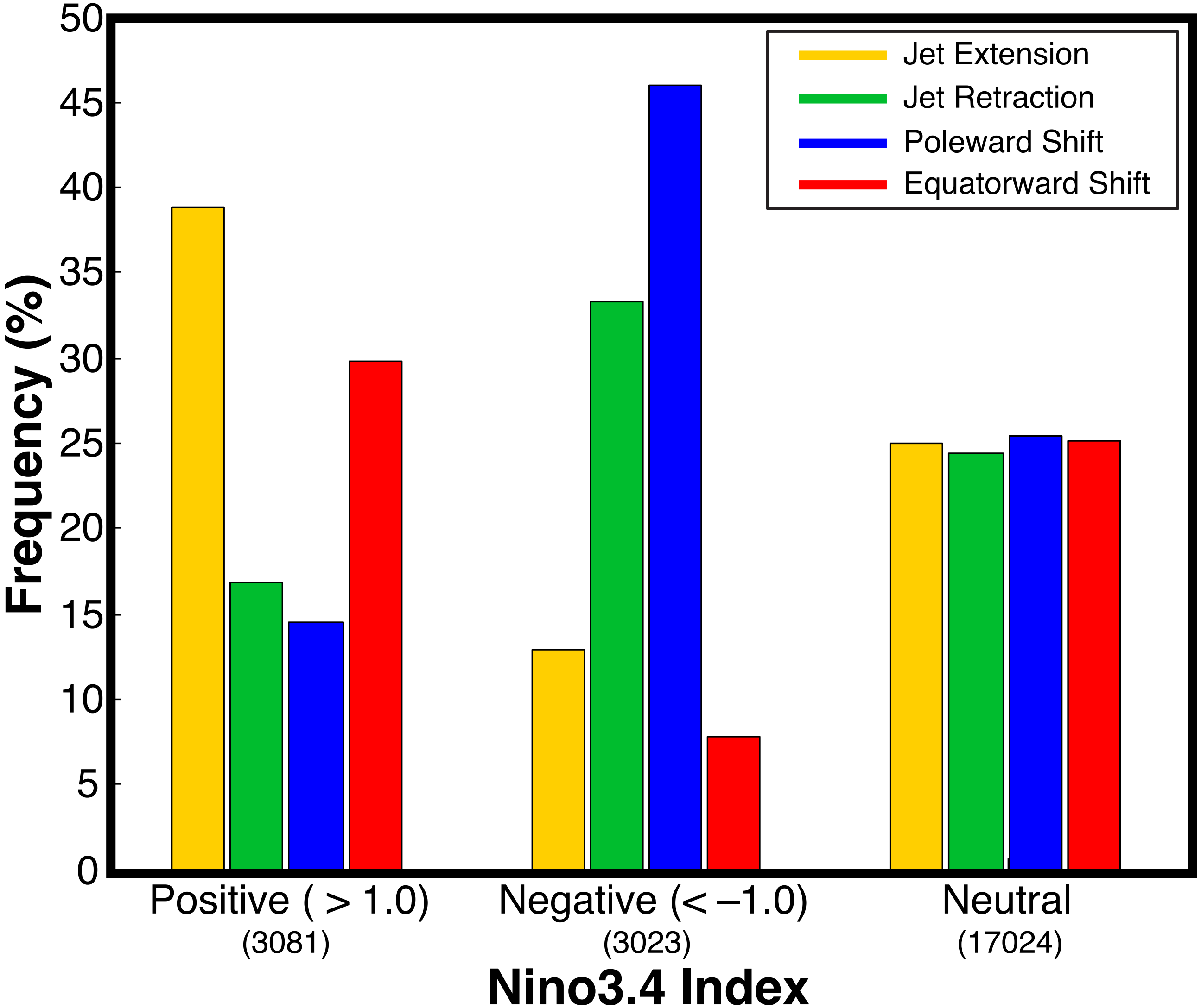
Each 'x' is the average position within the NPJ phase diagram 3–7 days prior to an ETE

NPJ Regime Frequency by Month



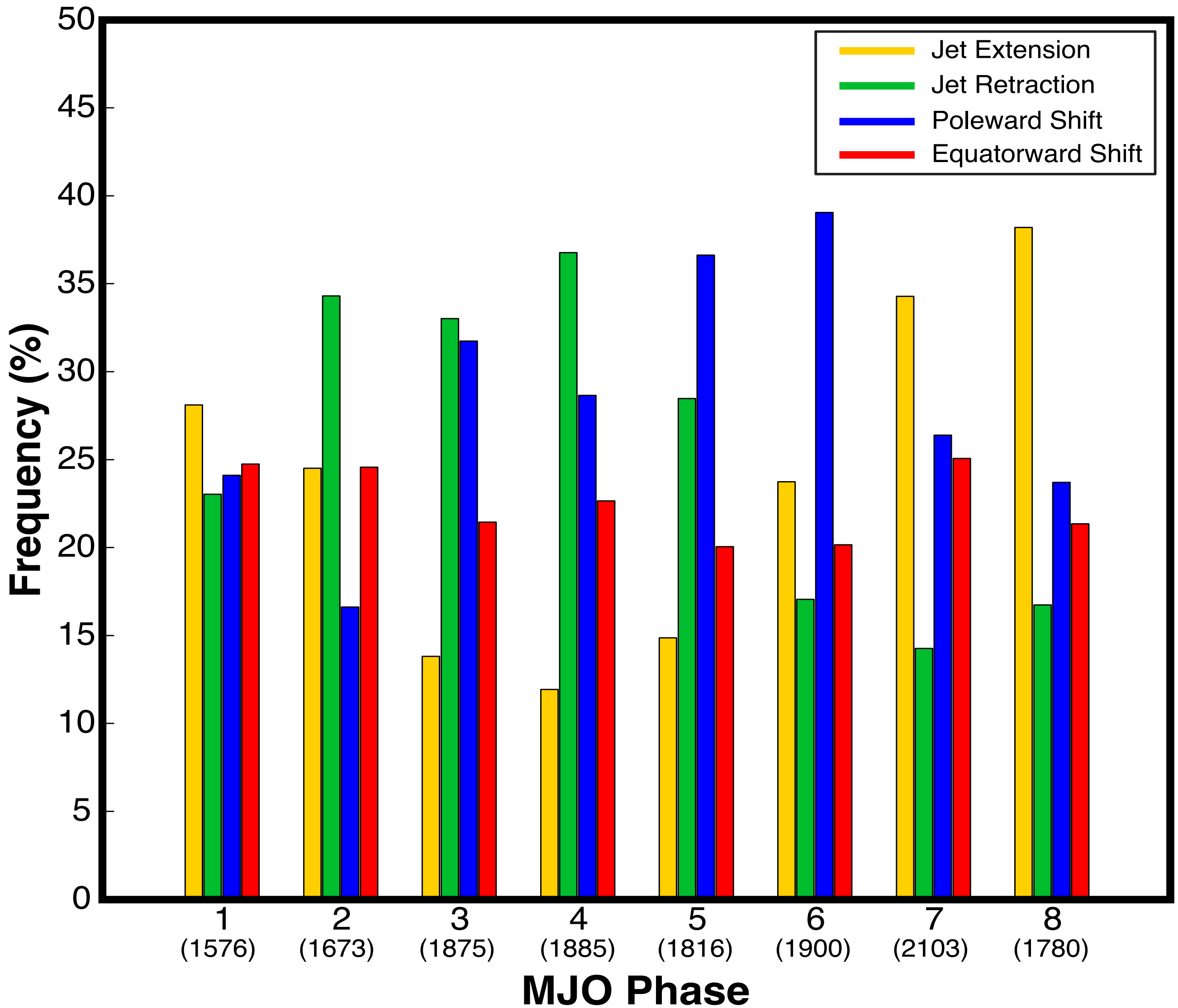
- Poleward and Equatorward Shifts are favored during September
- NPJ regime frequencies are nearly equivalent during all other months

NPJ Regime Frequency and ENSO



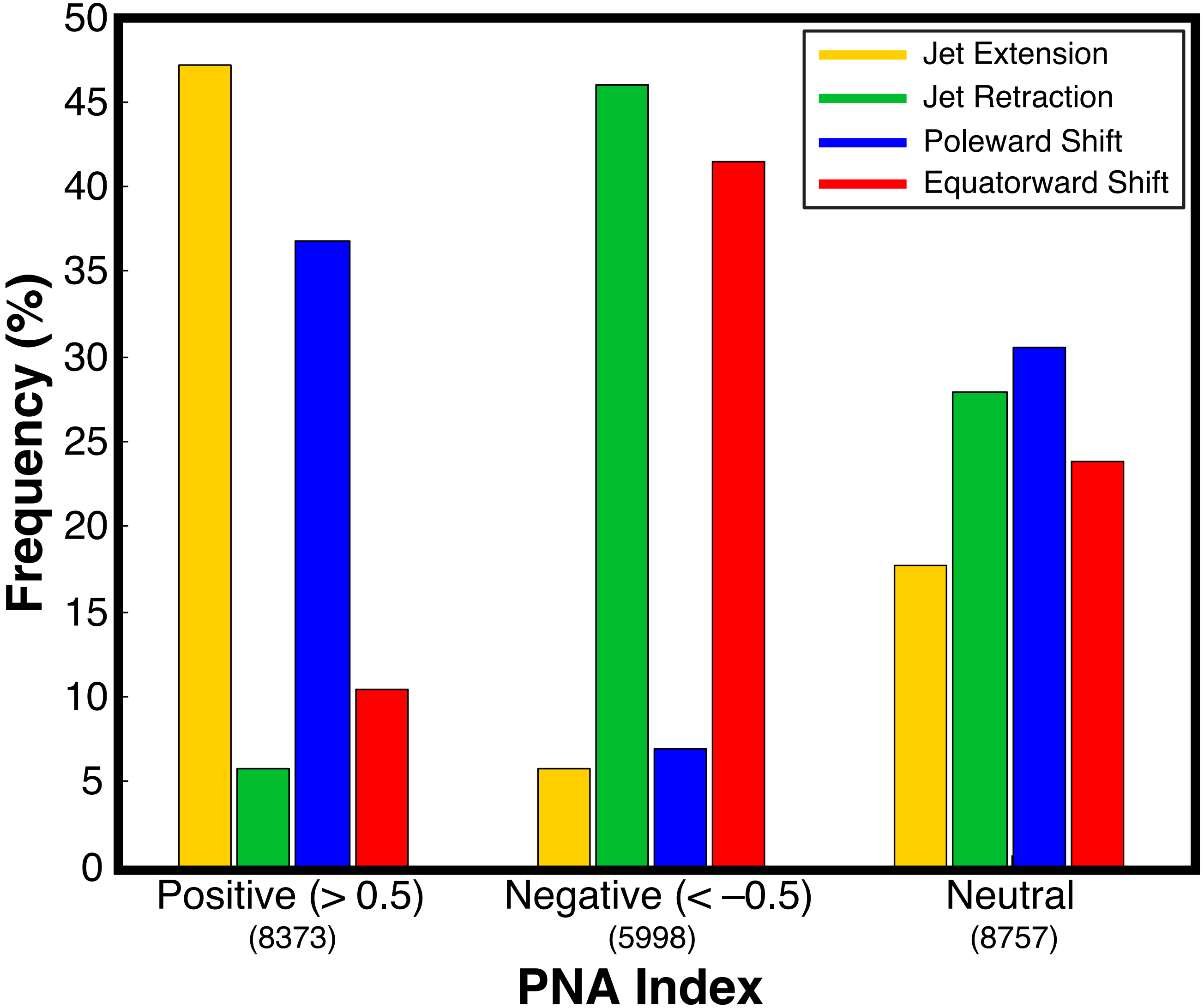
- Jet Extensions and Equatorward Shifts are favored during an El Niño
- Jet Retractions and Poleward Shifts are favored during a La Niña

NPJ Regime Frequency and the MJO



- Jet Retractions are favored during Phases 2, 3, and 4
- Poleward Shifts are favored during Phases 5 and 6
- Jet Extensions are favored during Phases 7, 8, and 1

NPJ Regime Frequency and the PNA



- Jet Extensions and Poleward Shifts are favored during a positive PNA
- Jet Retractions and Equatorward Shifts are favored during a negative PNA

NPJ Regime Forecast Frequency

The percent frequency that an NPJ regime is over/under forecast relative to verification at various forecast lead times in the GEFS ensemble mean reforecasts

NPJ Regime

Forecast Lead Time	Extension	Retraction	Poleward	Equator	Origin
24 h	1.54%	0%	1.92%	−3.07%	−0.21%
48 h	3.94%	−0.16%	7.96%	−6.38%	−2.11%
72 h	3.50%	−2.31%	10.59%	−7.93%	−1.61%
96 h	2.37%	−1.27%	8.77%	−9.21%	−0.48%
120 h	2.28%	−4.04%	8.46%	−11.64%	1.55%
144 h	3.37%	−2.37%	0.80%	−13.32%	3.98%
168 h	0%	−2.93%	−2.08%	−16.84%	7.65%
192 h	−3.20%	−6.40%	−6.16%	−18.56%	12.18%
216 h	−9.14%	−7.33%	−12.50%	−25.51%	19.33%

Negative: under forecast // Positive: over forecast

NPJ Regime Forecast Frequency

The percent frequency that an NPJ regime is over/under forecast relative to verification at various forecast lead times in the GEFS ensemble mean reforecasts

NPJ Regime

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96 h	2.37%	−1.27%	8.77%	−9.21%	−0.48%
120 h	2.28%	−4.04%	8.46%	−11.64%	1.55%
144 h	3.37%	−2.37%	0.80%	−13.32%	3.98%
168 h	0%	−2.93%	−2.08%	−16.84%	7.65%
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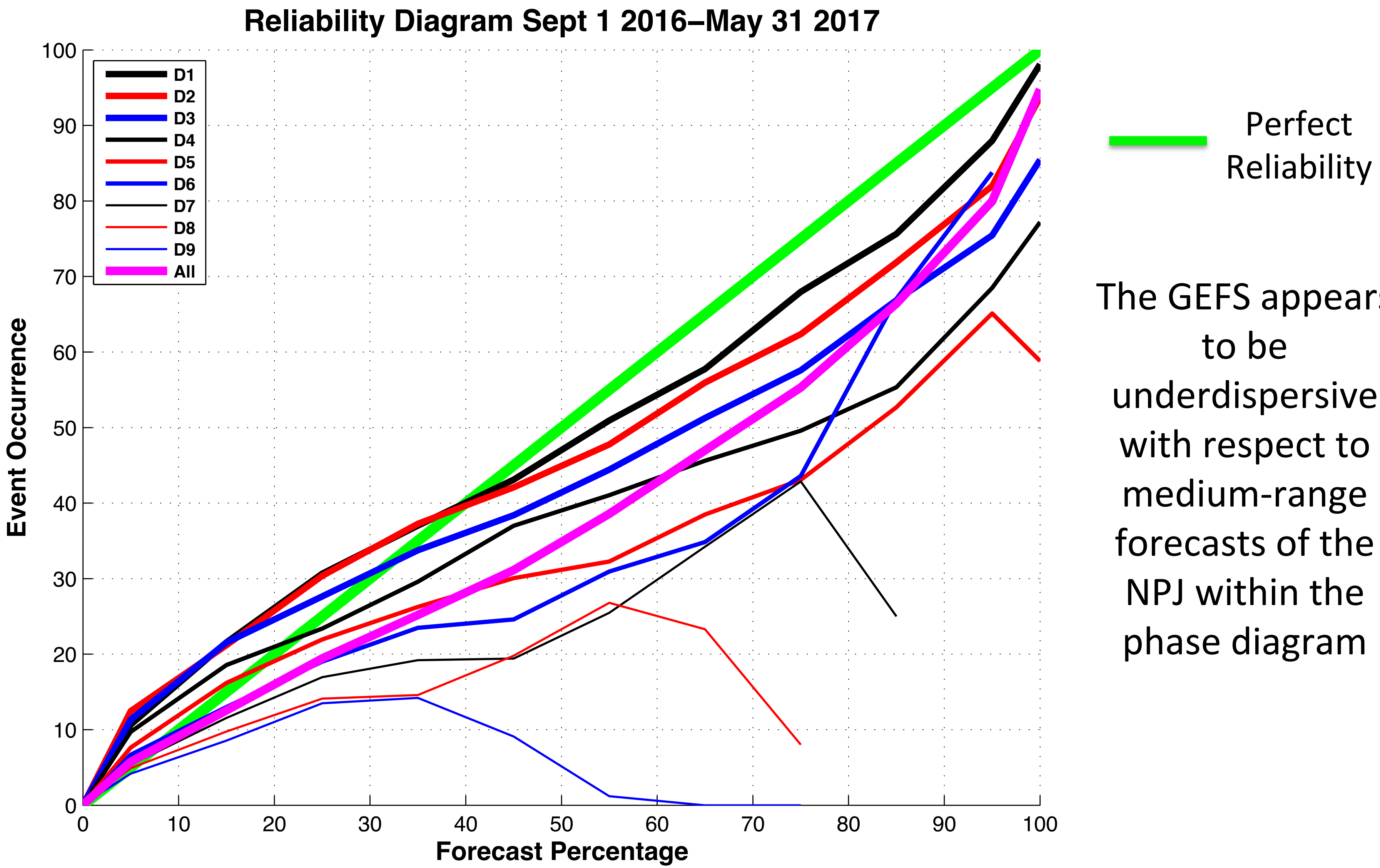
216 h	−9.14%	−7.33%	−12.50%	−25.51%	19.33%

Negative: under forecast // Positive: over forecast

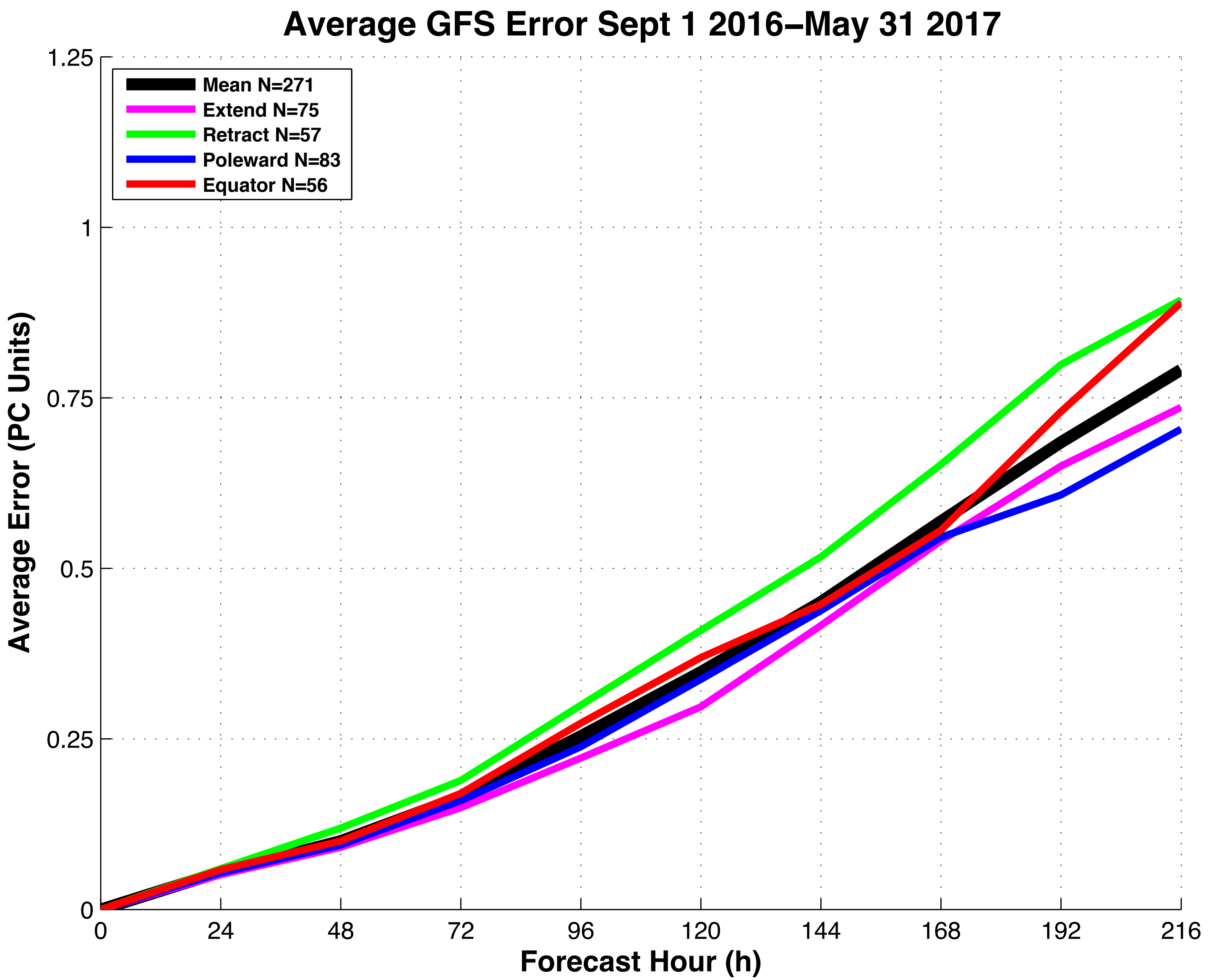
Real time NPJ Phase Diagram Verification Statistics 2016–2017

Reliability Diagram (Sept 1 – May 31)

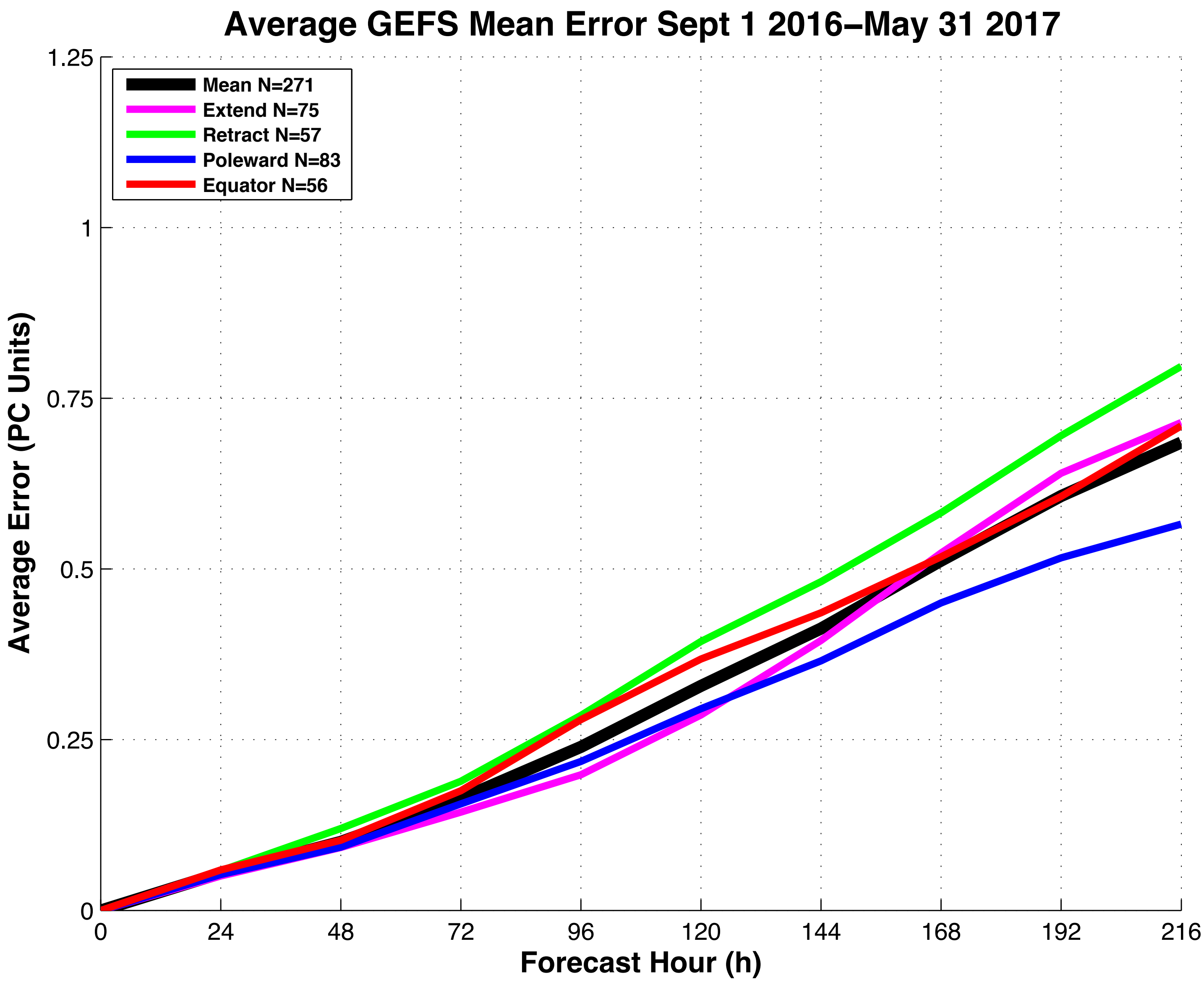


The GEFS appears to be underdispersive with respect to medium-range forecasts of the NPJ within the phase diagram

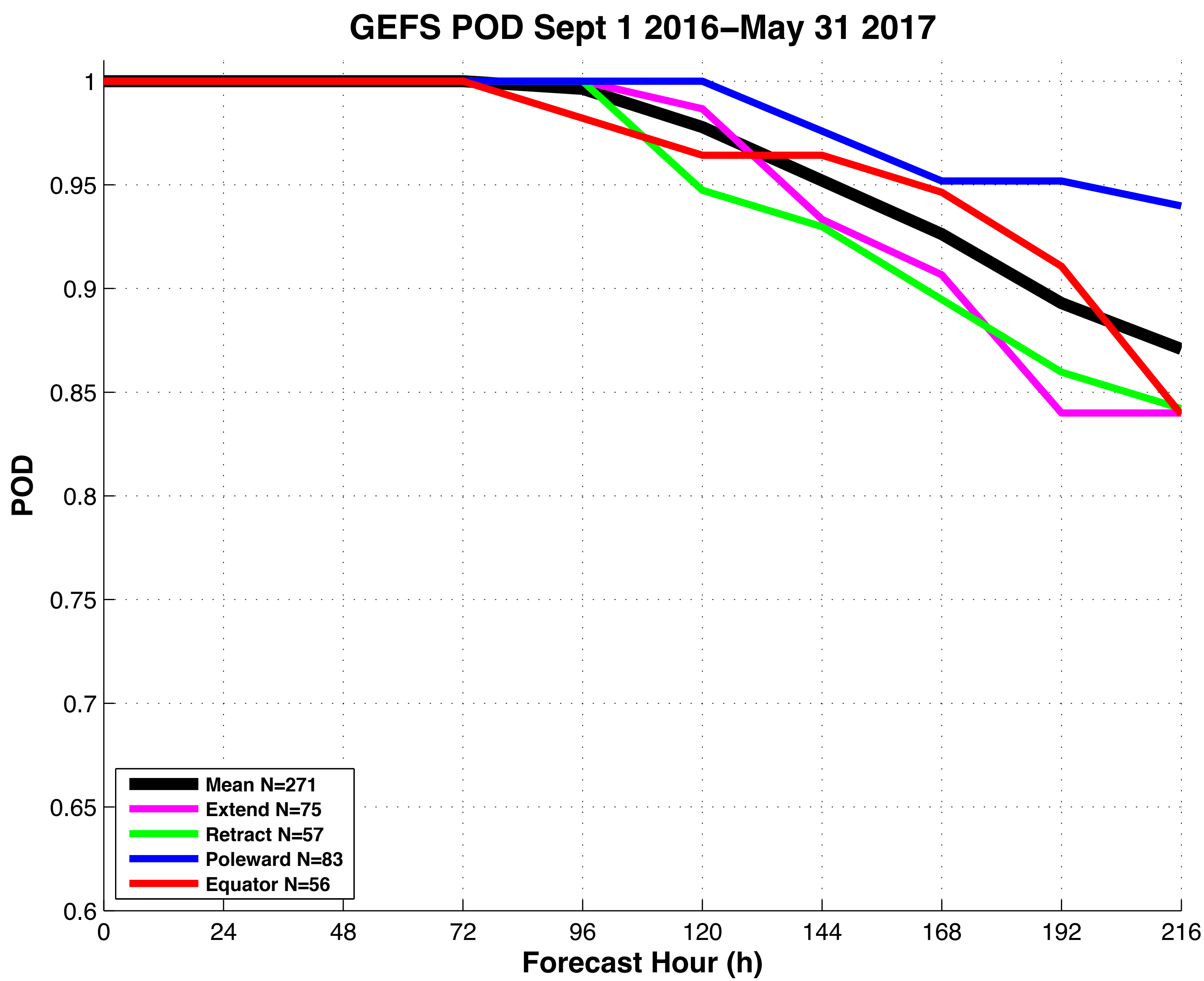
GFS Average Error – Regime



Average GEFS Mean Error – Regime

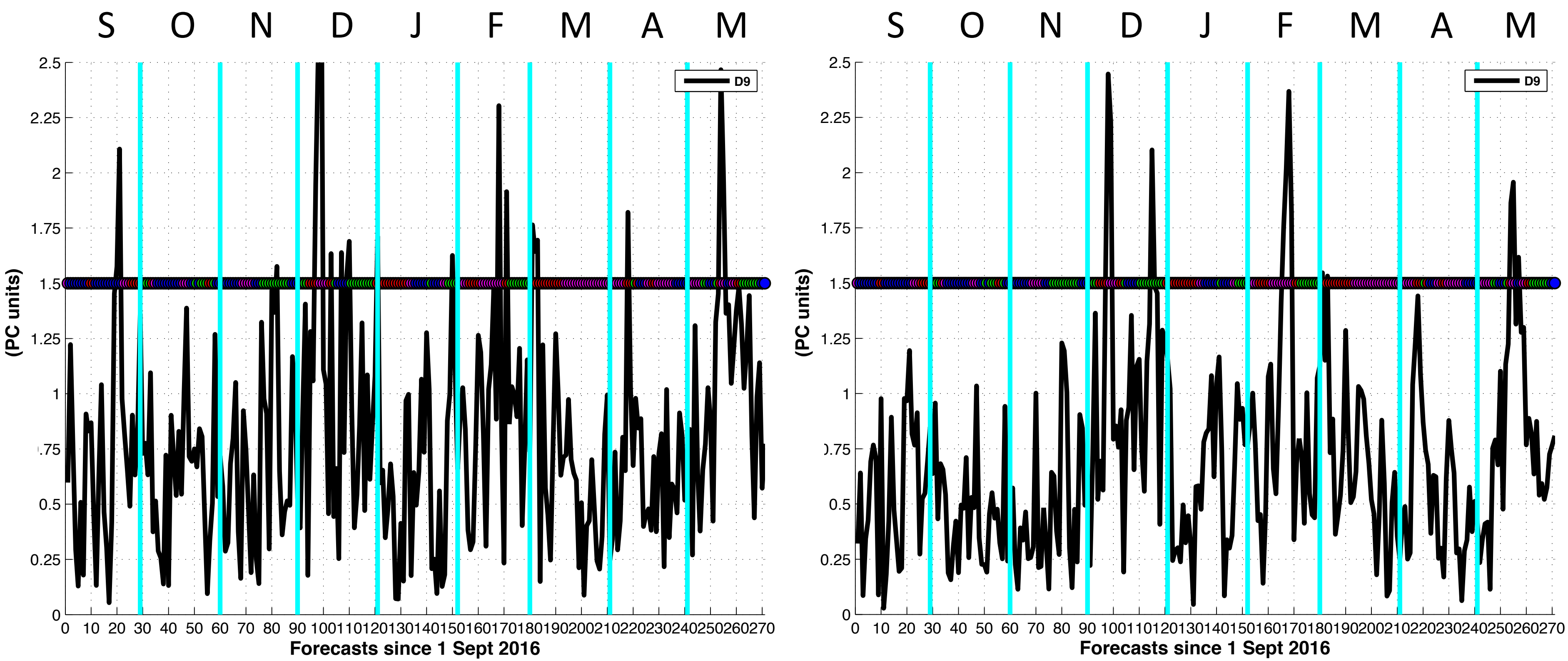


GEFS Probability of Detection – Regime



Time Series of GFS and GEFS Mean Error

GFS 9-Day Forecast GEFS Mean



Extend N=75

Retract N=57

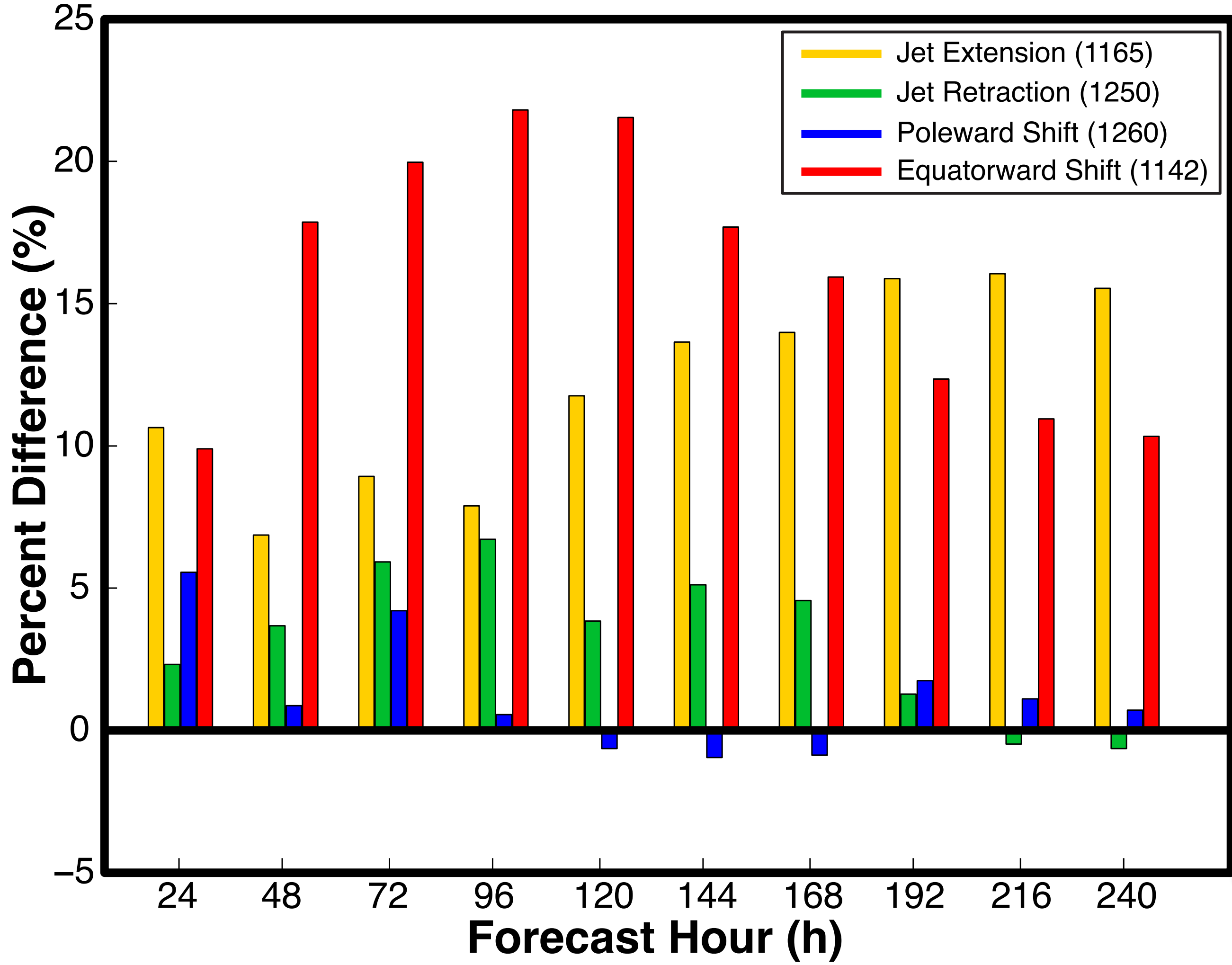
Poleward N=83

Equator N=56

Colored dots identify the NPJ regime on a particular day

Jet Regime-Dependent Forecast Skill

Percent Difference Between the Frequency of Forecasts with Below-Normal and Above-Normal RMSE



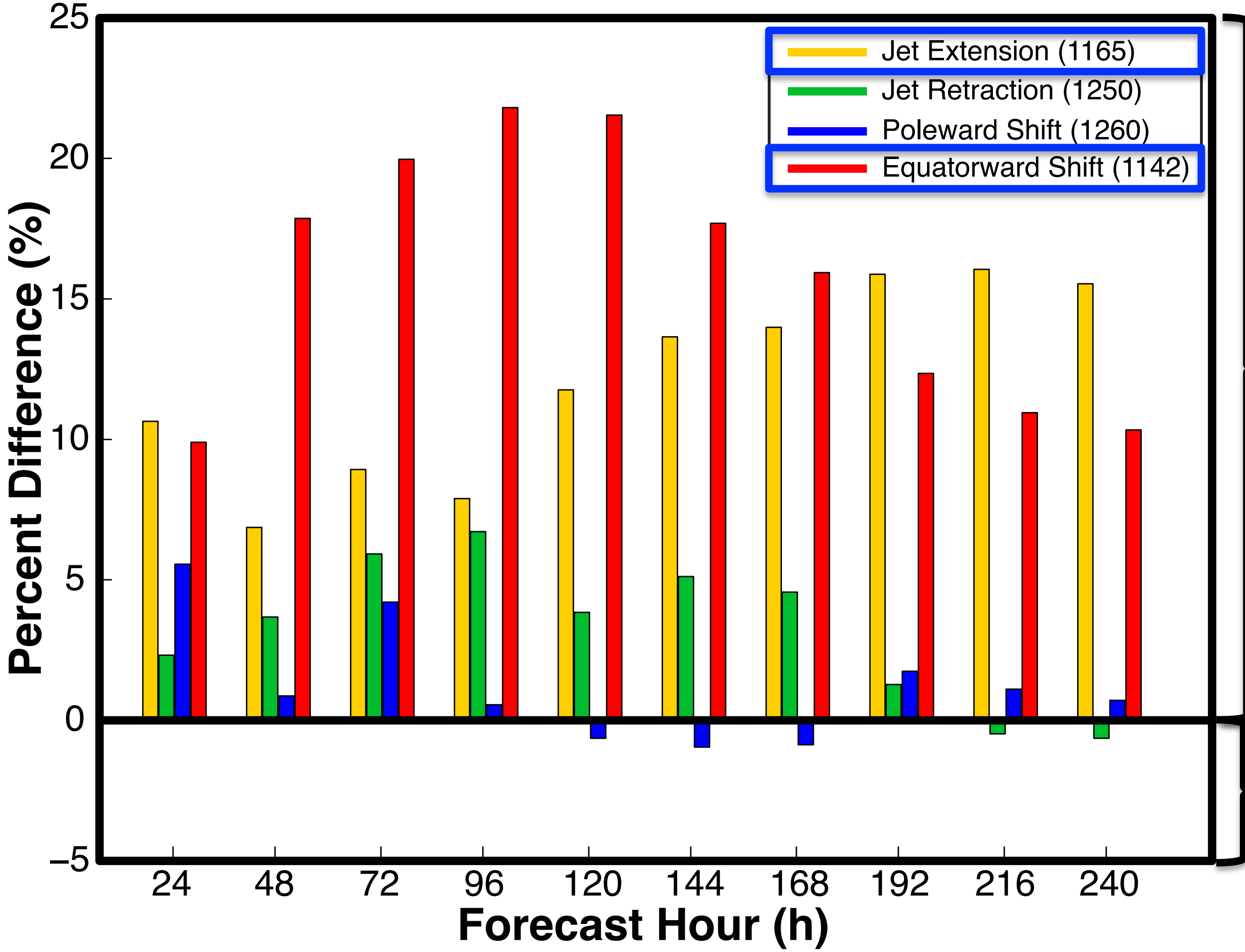
$$Freq_{below-normal} - Freq_{above-normal}$$

Higher frequency of forecasts with <u>below-normal</u> RMSE (i.e., more good forecasts)

Higher frequency of forecasts with <u>above-normal</u> RMSE (i.e., more bad forecasts)

Jet Regime-Dependent Forecast Skill

Percent Difference Between the Frequency of Forecasts with Below-Normal and Above-Normal RMSE



$$Freq_{below-normal} - Freq_{above-normal}$$

Higher frequency of forecasts with below-normal RMSE (i.e., more good forecasts)

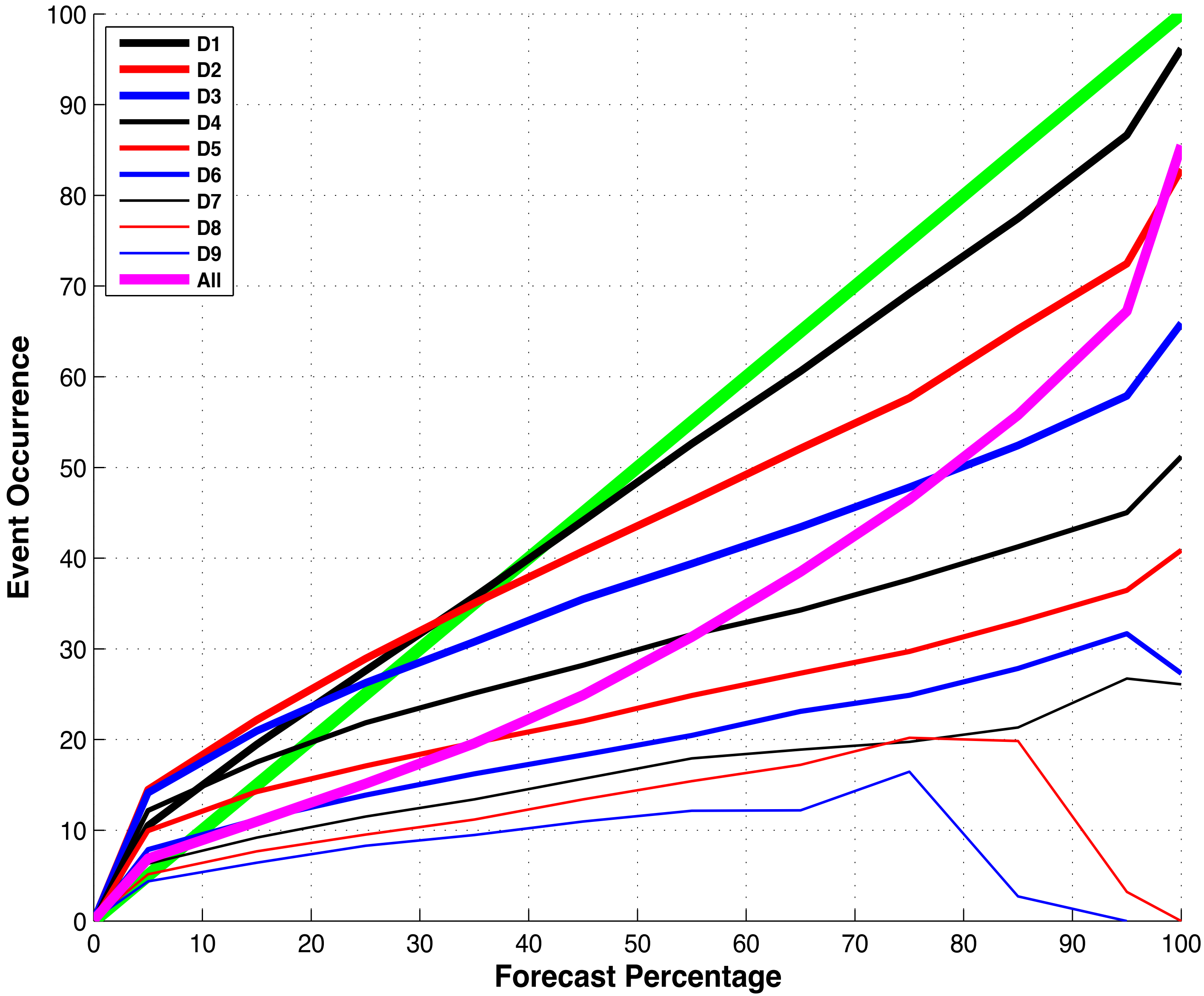
Higher frequency of forecasts with above-normal RMSE (i.e., more bad forecasts)

Best/Worst Forecast Statistics

10-d trajectory comparison between periods characterized by the best/worst medium-range forecasts

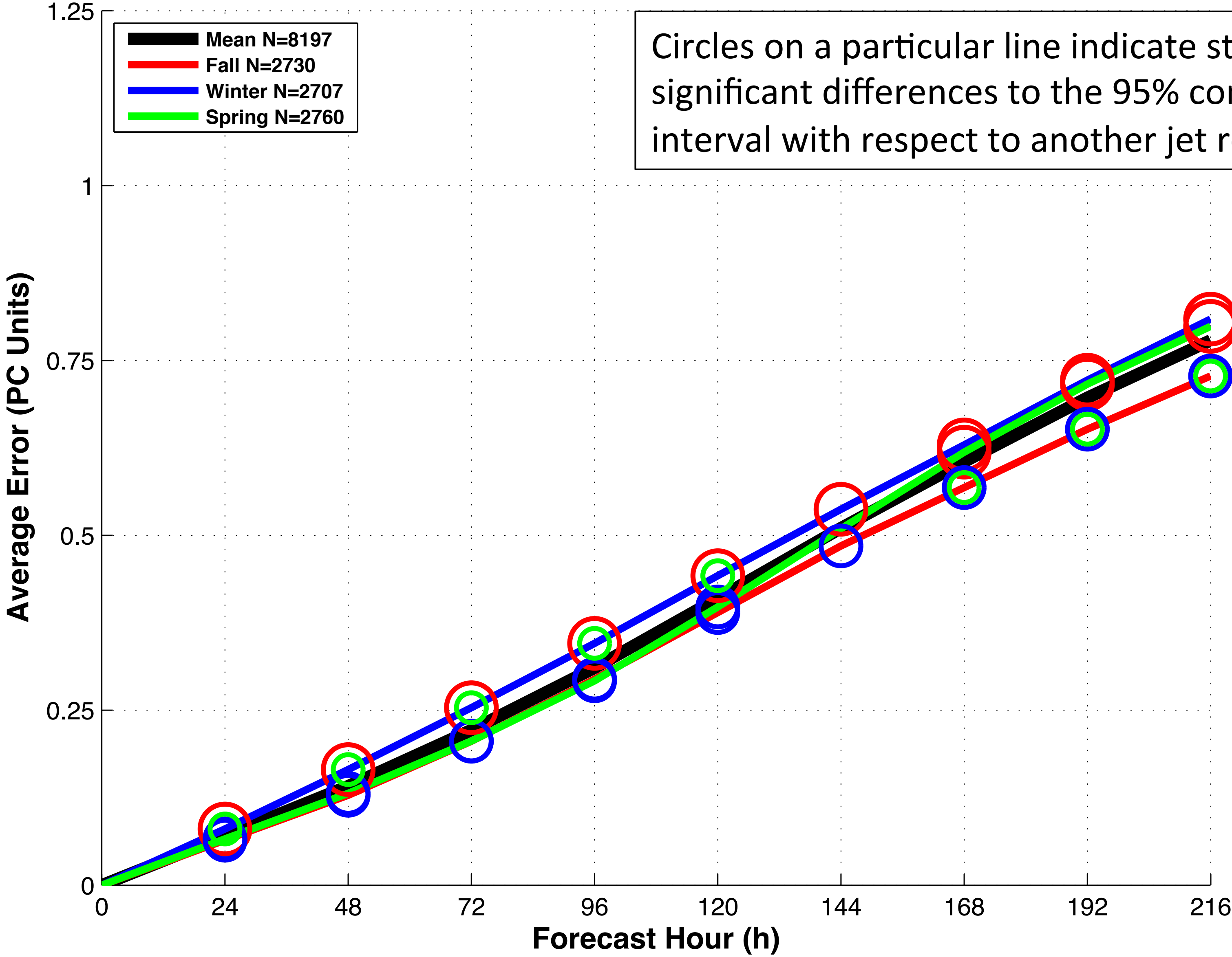
All Events	$PC1_{start}$	$PC2_{start}$	$\Delta PC1$	$\Delta PC2$	Mean Traj. Dist
Good Forecasts (475)	0.09	0.04	0.09	0.16	3.50
Bad Forecasts (763)	−0.18	−0.08	−0.01	−0.21	4.33
Jet Extensions	$PC1_{start}$	$PC2_{start}$	$\Delta PC1$	$\Delta PC2$	Mean Traj. Dist
Good Forecasts (77)	1.54	−0.09	−0.98	0.40	3.69
Bad Forecasts (90)	1.35	−0.01	−1.41	−0.14	4.57
Jet Retractions	$PC1_{start}$	$PC2_{start}$	$\Delta PC1$	$\Delta PC2$	Mean Traj. Dist
Good Forecasts (63)	−1.36	0.14	1.09	0.04	3.77
Bad Forecasts (145)	−1.58	−0.11	1.18	−0.25	4.56
Poleward Shifts	$PC1_{start}$	$PC2_{start}$	$\Delta PC1$	$\Delta PC2$	Mean Traj. Dist
Good Forecasts (63)	0.12	1.45	0.00	−0.81	3.59
Bad Forecasts (90)	−0.02	1.40	−0.31	−1.44	4.62
Equatorward Shifts	$PC1_{start}$	$PC2_{start}$	$\Delta PC1$	$\Delta PC2$	Mean Traj. Dist
Good Forecasts (61)	0.20	−1.42	0.36	1.08	3.52
Bad Forecasts (112)	−0.17	−1.52	0.05	1.09	4.36
Origin	$PC1_{start}$	$PC2_{start}$	$\Delta PC1$	$\Delta PC2$	Mean Traj. Dist
Good Forecasts (211)	−0.03	0.07	0.13	0.12	3.31
Bad Forecasts (326)	−0.04	0.01	−0.06	−0.31	4.08

Reliability Diagram



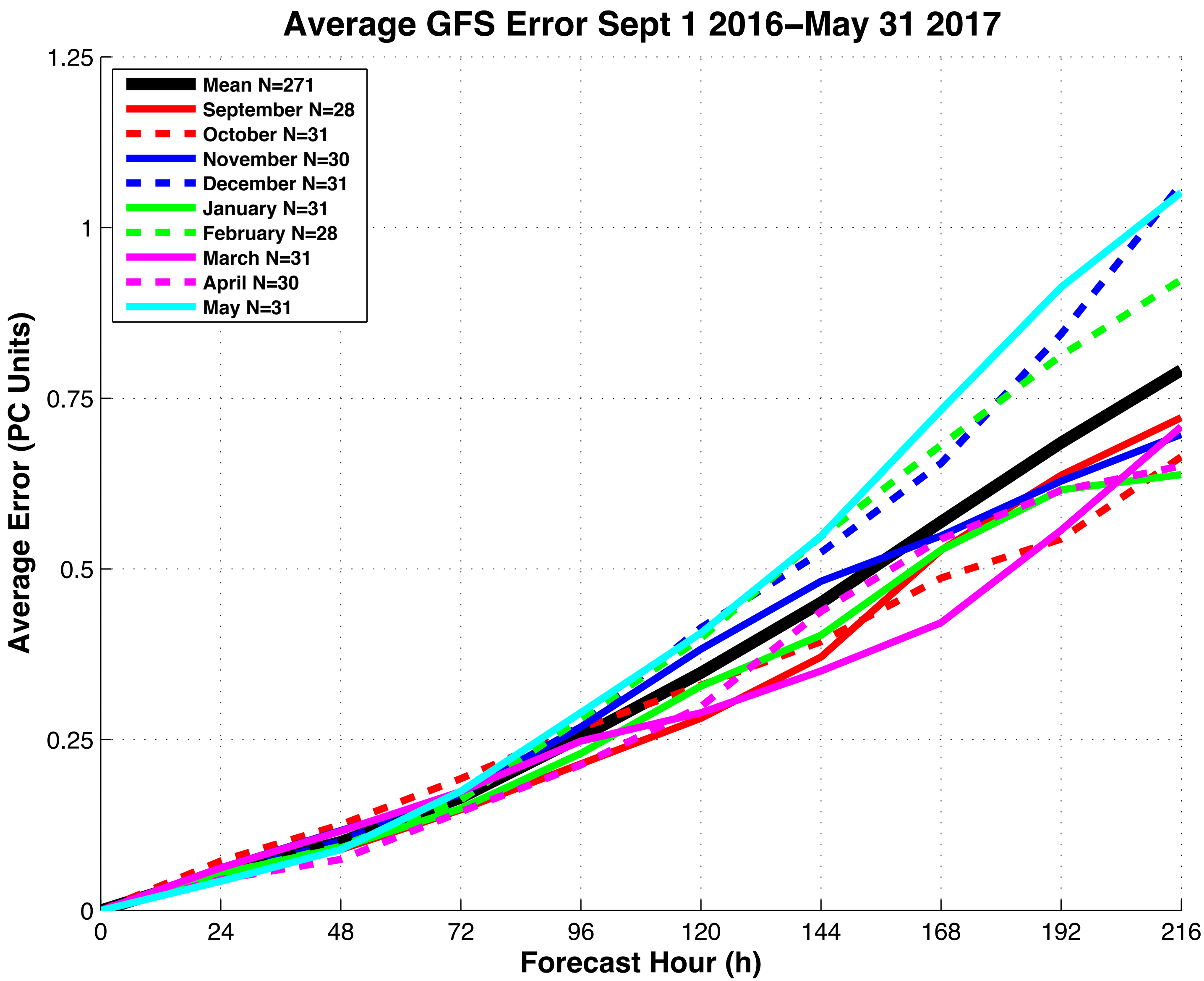
GEFS Reforecasts appear to be underdispersive with respect to medium-range forecasts of the North Pacific Jet in the phase diagram

GEFS Ensemble Mean Error – Season

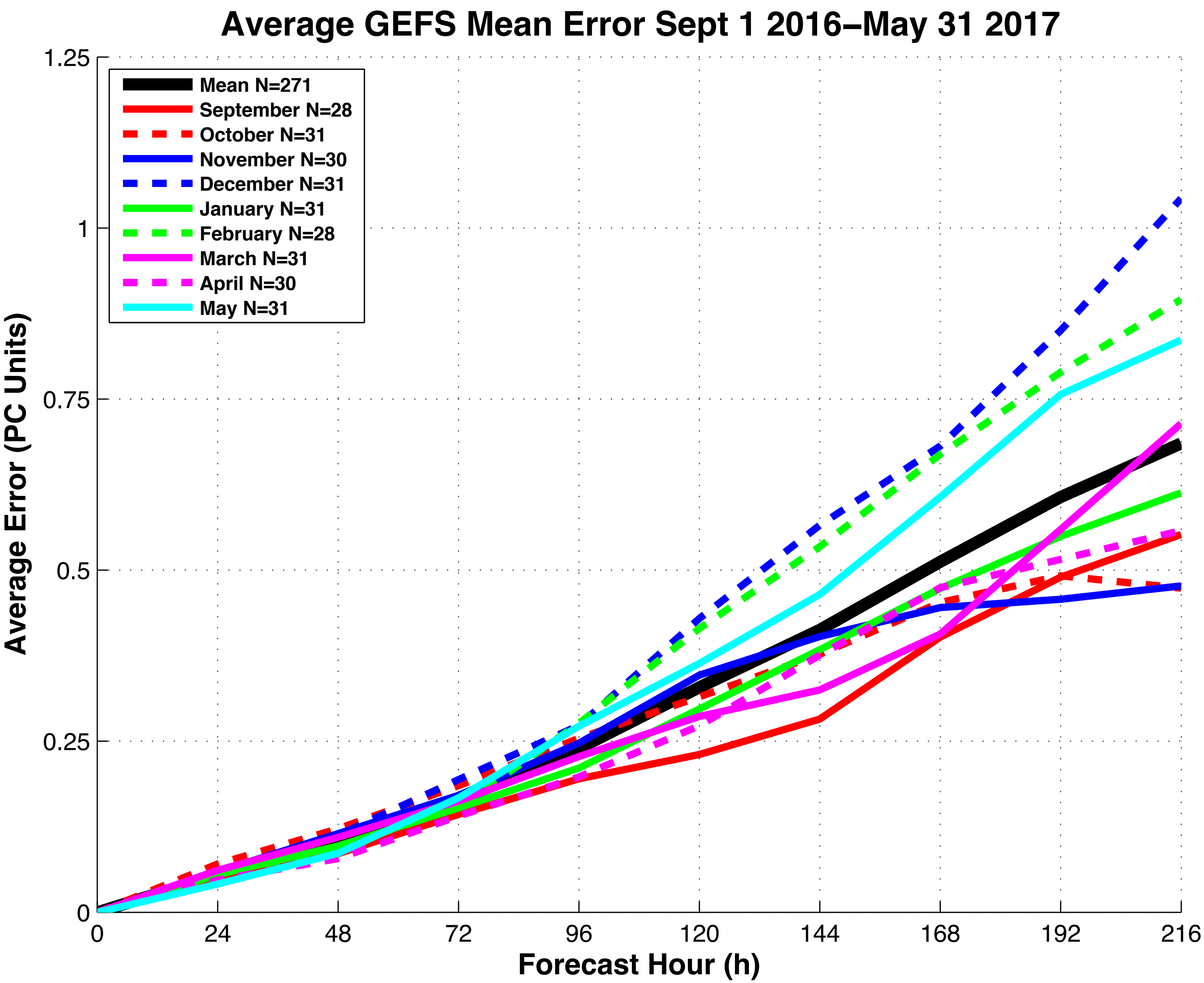


Circles on a particular line indicate statistically significant differences to the 95% confidence interval with respect to another jet regime.

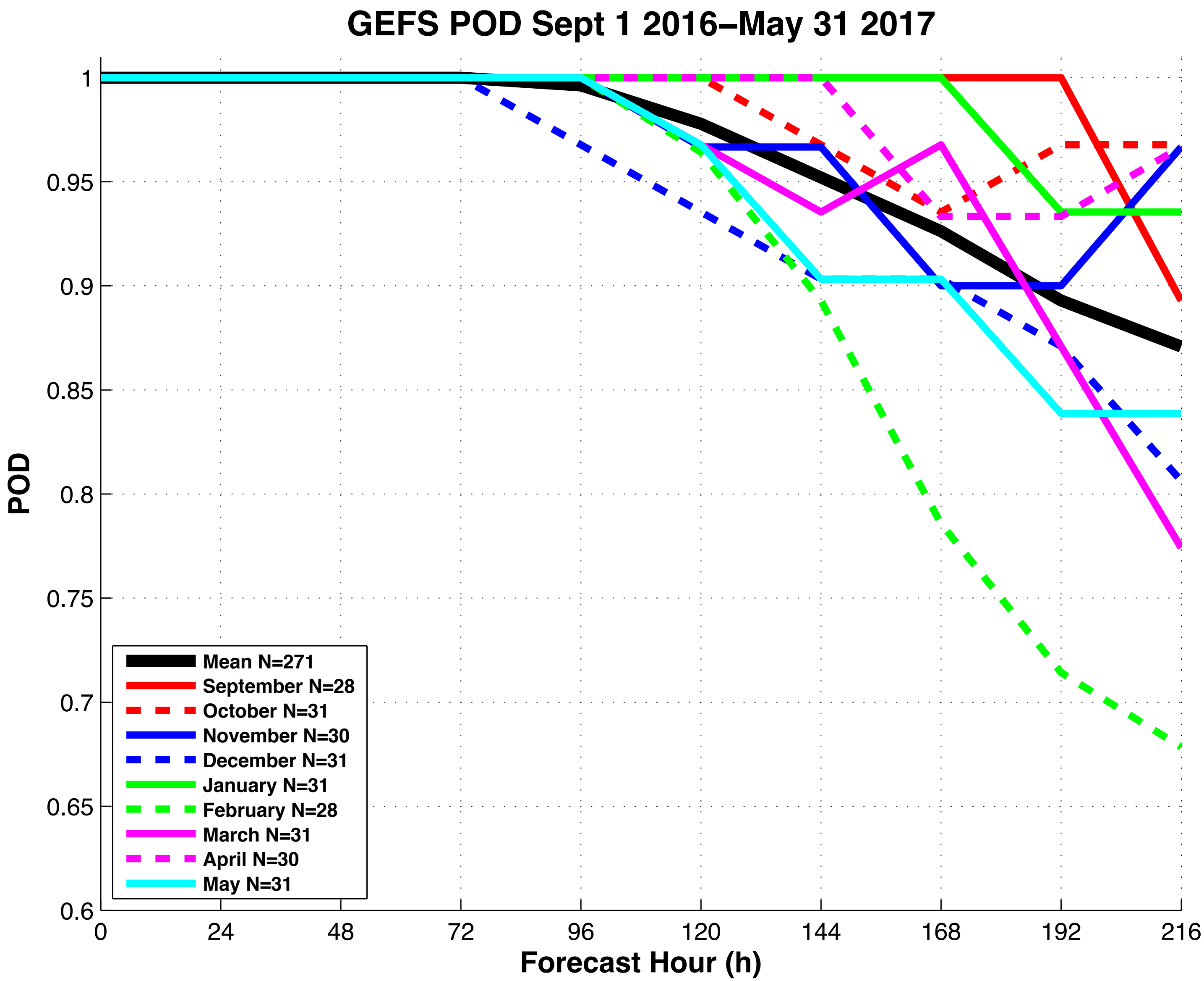
GFS Average Error – Month



Average GEFS Mean Error – Month

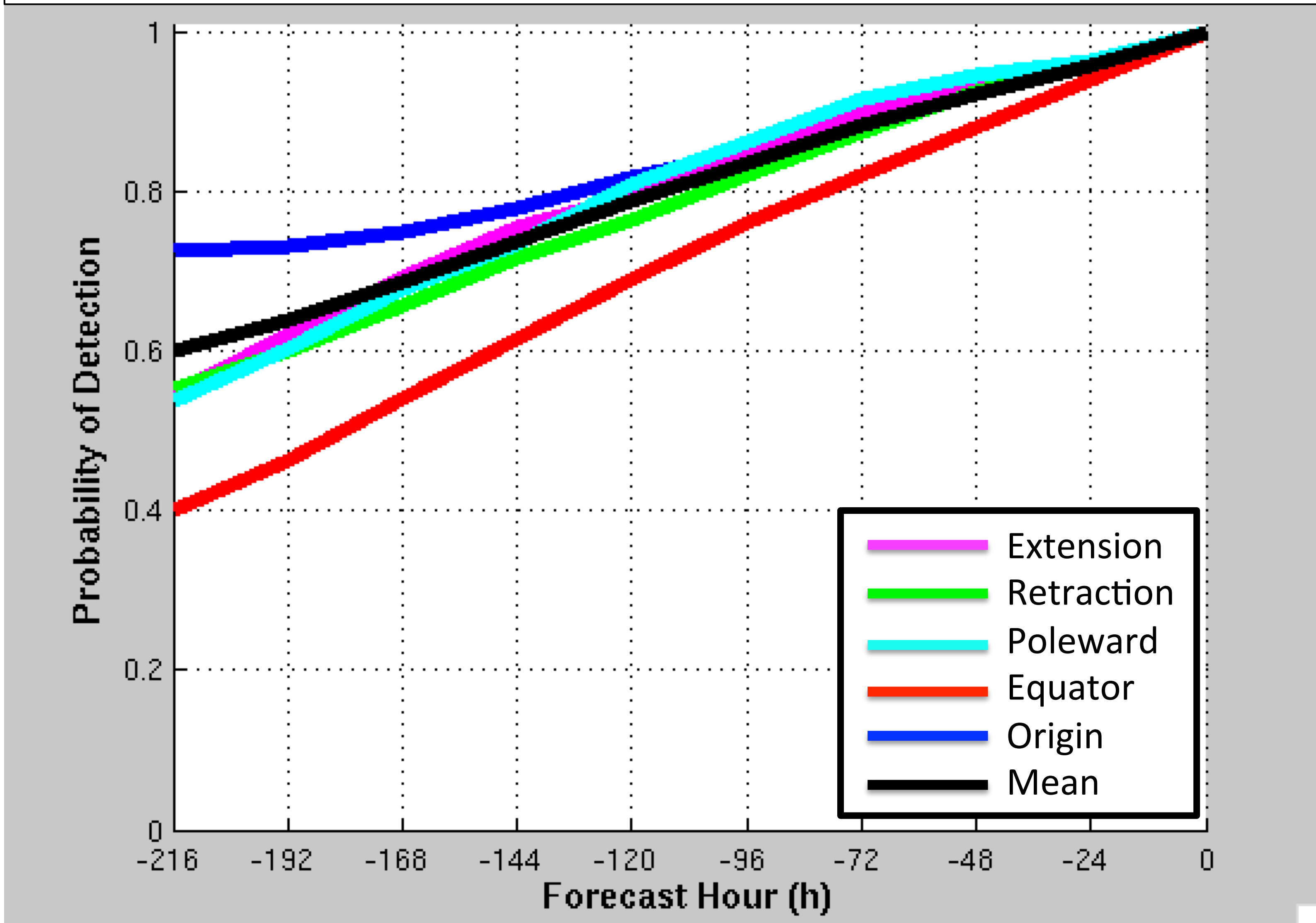


GEFS Probability of Detection – Month



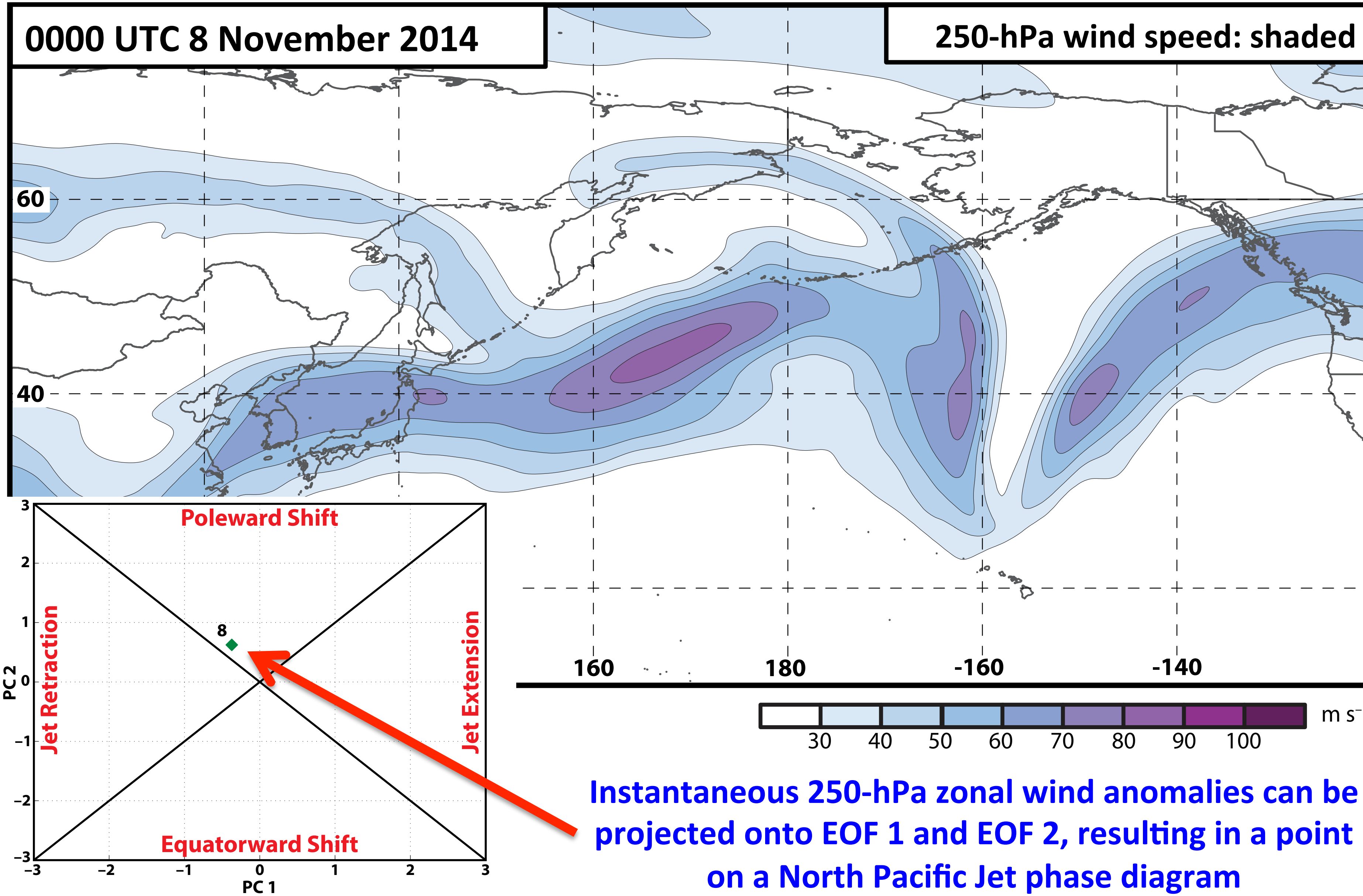
GEFS Ensemble Mean POD by NPJ Regime

For forecasts **verifying** within a particular NPJ regime



NPJ Phase Diagram Technical Slides

Real Time North Pacific Jet Phase Diagram

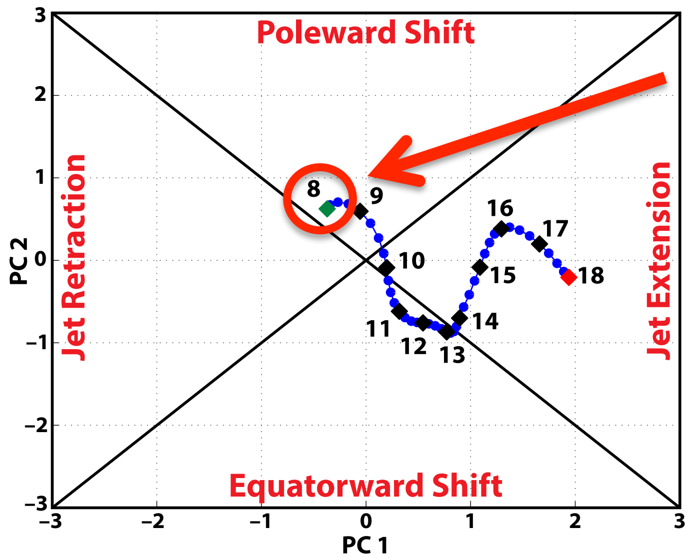


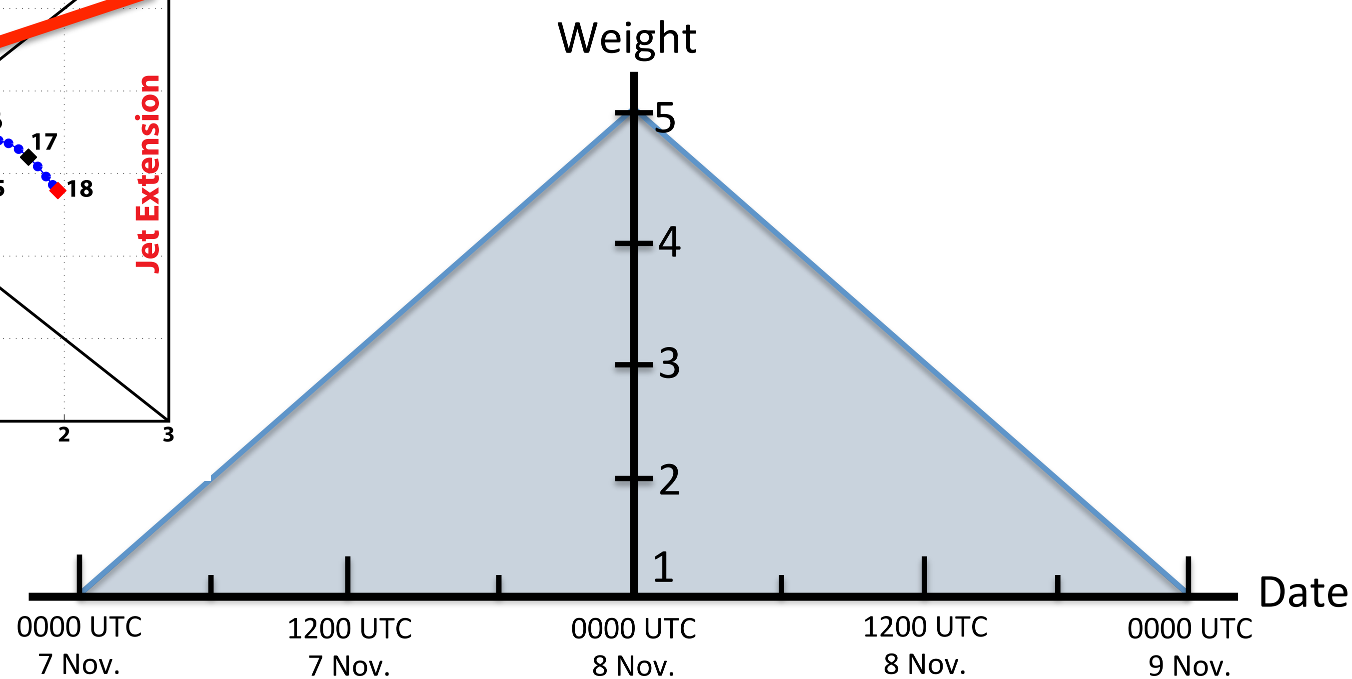
Instantaneous 250-hPa zonal wind anomalies can be projected onto EOF 1 and EOF 2, resulting in a point on a North Pacific Jet phase diagram

Real Time North Pacific Jet Phase Diagram

- Each point on the phase diagram is a weighted average of the principal components within +/– 1 day of the time under consideration

Example: 0000 UTC 8 November 2014





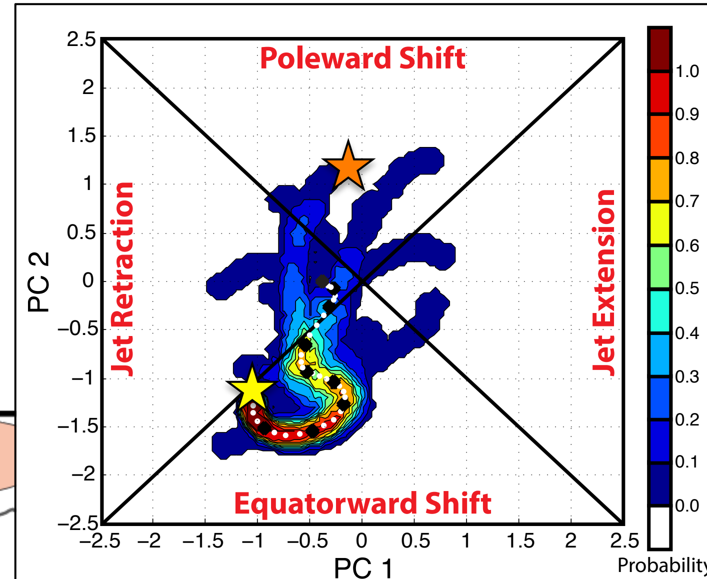
Real Time North Pacific Jet Phase Diagram

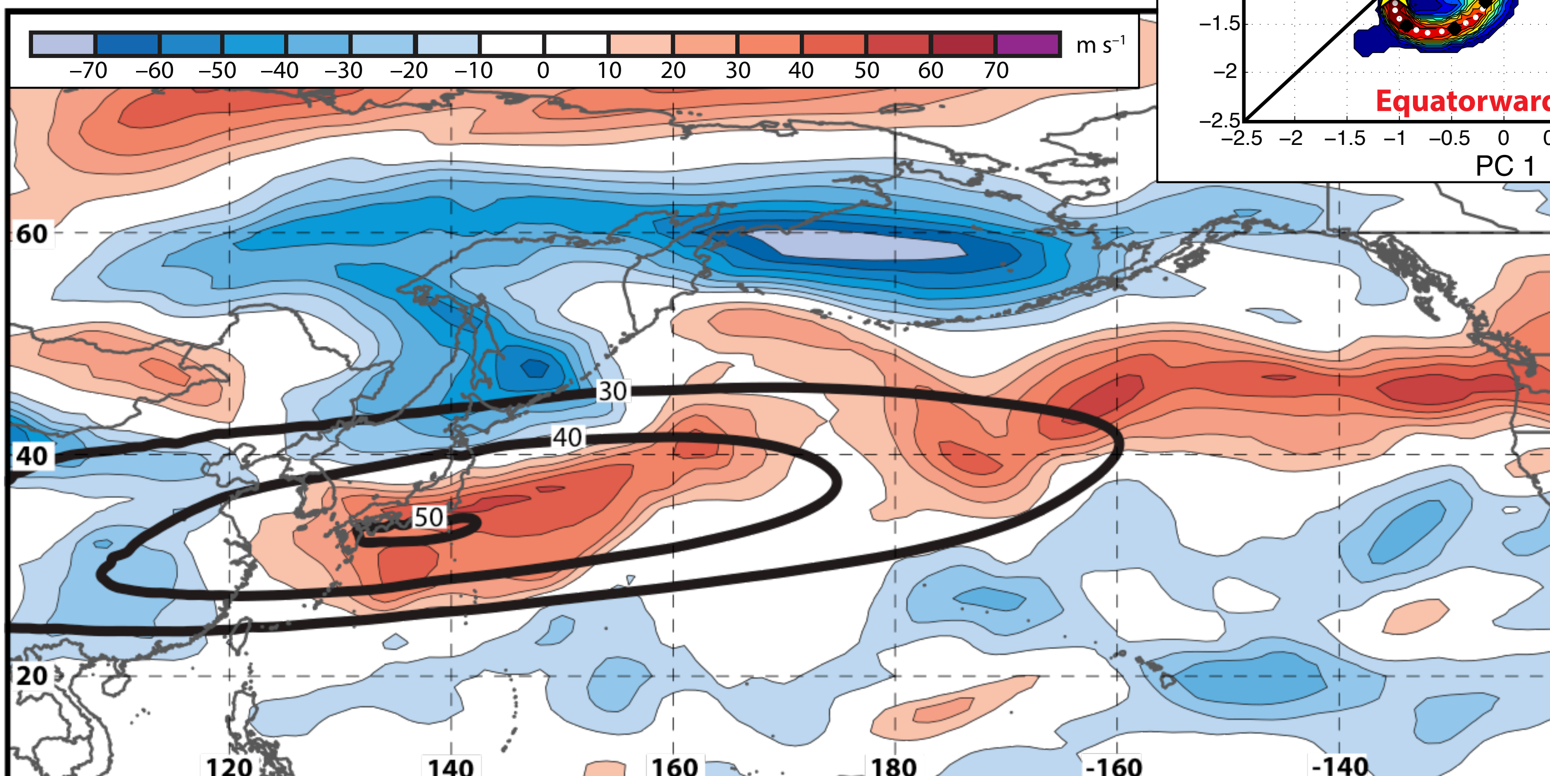
250-hPa zonal wind at 0000 UTC 2 Jun minus 250-hPa zonal wind at 0000 UTC 24 May (shading) in the GFS analyses shows the transition to a poleward-shifted jet regime

0000 UTC 24 May (0-h forecast)

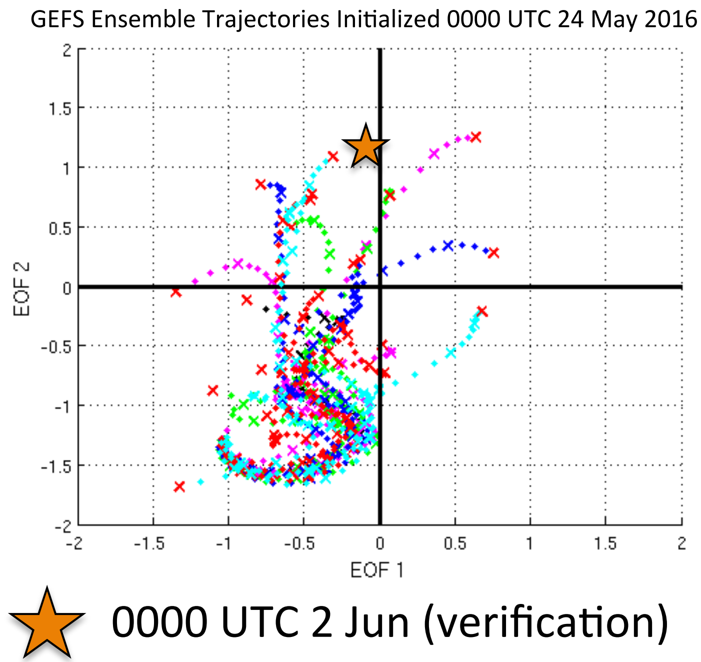
0000 UTC 2 Jun (verification)

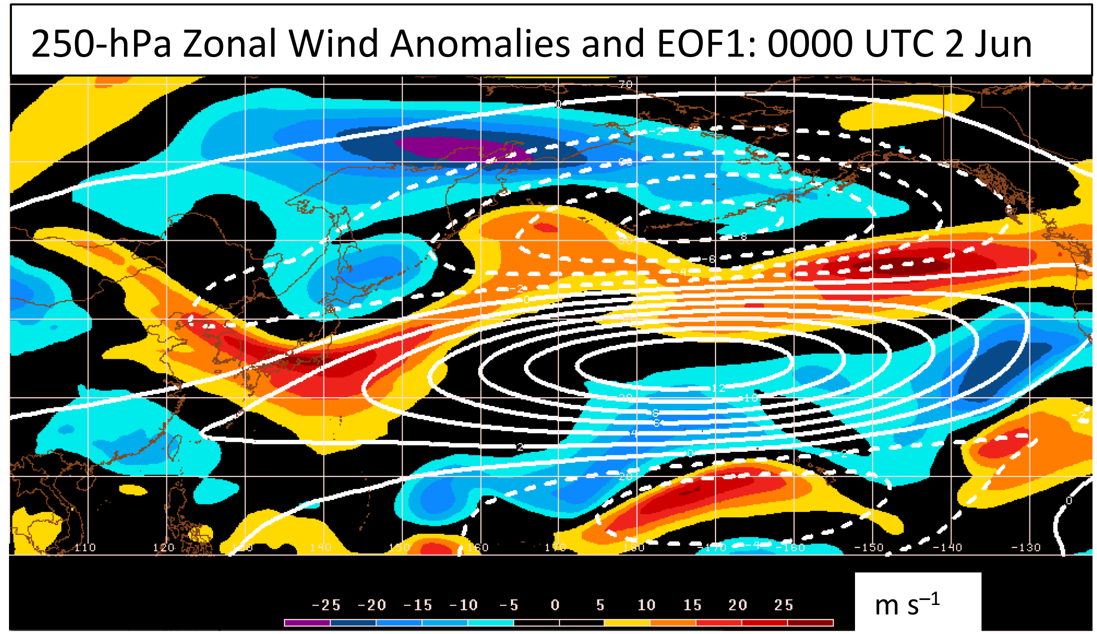
Ensemble mean





Sept.–May mean 250-hPa zonal wind: black contours





250-hPa zonal wind anomalies at 0000 UTC 2 Jun project strongly onto EOF2 > 0