Submitted: 01/14/19

Research Article

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Winter Mid-Tropospheric Weather Regimes in the Eastern North Pacific

Keywords

500-hPa geopotential height, Mid troposphere, Weather regime

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Abstract

Background: The eastern North Pacific (ENPac) is a region of climatologically significant cyclone activity, often associated with extreme weather in North America. Regions of high (ridges) and low (troughs) 500-hPa height typically drive this activity. We identify 500-hPa height time variability extremes as "regimes." Our objectives are to determine the regimes' characteristics, predictability, and relationships to North American extreme weather.

Methods: We define weather regimes, separating them into two types based on whether the 500-hPa height variance is extremely low or high. We analyze their general characteristics during the winter (December, January, and February) and relationships to extreme North American weather. To analyze the regimes' predictability, we define forecast discontinuities as significantly improved extreme 500-hPa height variability model forecasts compared with model forecasts verifying at the same time, but initialized 24 hours earlier. We analyze their effects on anticipated weather.

Results: ENPac low variance regimes are usually dominated by one or two large, slow-moving features, usually a trough with an associated surface cyclone 200-700 km to the west and a ridge with an associated surface anticyclone 200-700 km to the east. This pattern leads to anomalous southerly winds and moisture transport. Low variance regimes are generally associated with anomalous wetness in northwestern Canada, warmth in western North America, and dryness in the southwest U.S. High variance regimes are usually dominated by smaller, faster-moving features that alter the 500-hPa heights substantially. These regimes are more varied, but there is a tendency to have a ridge 200-700 km to the west and a trough 200-700 km to the east, leading to anomalous northerly winds and transport of drier polar air into the ENPac region. High variance regimes are generally associated with anomalously cold air in western North America and wetness in the western U.S. Some forecast discontinuities are associated with changes in anticipated weather locally in the ENPac region, while other discontinuities are associated with changes in anticipated weather on a much larger scale, extending to North America.

Limitations: Limitations include the small sample of regimes found during the period of record (18 low variance and 10 high variance), the metric being limited to the 500-hPa level, and the study of only the ENPac winter.

Conclusion: Low and high variance regimes generally lead to different ENPac weather patterns and North American extreme weather. Forecast discontinuities differ significantly from each other in their spatial extents. Further work is necessary to identify their causes and characteristics.

Introduction

The eastern North Pacific is a region of climatologically significant cyclone activity (1), often associated with extreme weather downstream in North America, such as an extreme cold-air outbreak. Middle-tropospheric weather patterns are key drivers of this storm activity (1). By characterizing and studying them in further detail, we may be able to better predict these patterns and their impacts further in advance. A better understanding of why certain model forecasts simulate certain weather patterns better than others may help give a better sense of predictability.

Many previous studies (e.g., (2), (3), and (4)) focused on weather patterns or regimes characterized by persistent, quasi-stationary features such as atmospheric blocks—a nearly stationary, persistent ridge that redirects or splits atmospheric flow in the mid-upper troposphere around it. Locations underneath a block usually experience persistent dryness, while areas on the periphery of the block experience persistent storminess. However, there is no widely used single definition of a block or weather regime. In (2), blocking is defined based on the presence of certain upper-level flow characteristics; upper-level charts would be inspected by a researcher to determine if there was blocking. The areas of most frequent occurrence, characteristic movement and persistence, and seasonal and yearly trends of blocking activity are determined. In (3), a zonal index suitable for identification of blockings is defined and translated into a computer program, and the characteristics of Northern Hemisphere blocking situations are assessed. In (4), a slightly modified version of the objective zonal index used in (3) is used to quantify both observed and forecasted occurrence of blocking. To expand the scope of studies of weather regimes, we produce a new objective definition of regimes, split into two categories: Low variance regimes, where the synoptic-scale weather pattern changes relatively little, compared to climatology; and High variance regimes, where the synoptic-scale weather pattern changes substantially, compared to climatology.

We also analyze weather patterns associated with extreme North American weather during the regimes and objectively define and analyze forecast discontinuities, which are significantly improved forecasts of 500-hPa geopotential height—the height where the atmospheric pressure is 500 hPa, which is about half that of sea level—variability during regimes compared with forecasts verifying at the same time, but initialized 24 hours earlier. We analyze the relationship between these forecast discontinuities and sensible weather, both locally in the ENPac region and more broadly over North America.

Definitions

500-hPa geopotential height: the height where the atmospheric pressure is 500 hPa, approximately half that of sea level.
Mid-troposphere: around 5-6 km altitude, often indicated by the altitude of the 500-hPa level
Weather regime: a large-scale recurrent atmospheric flow pattern with various specific definitions depending on study

Methods

Defining a Regime

We define regimes based on the variability of the 500-hPa height, a mid-tropospheric level that is typically at around 5 km above sea level. We use the National Centers for Environmental Prediction (NCEP) reanalysis 2 dataset (2.5° × 2.5° resolution) (5) to calculate the areally-averaged 500-hPa height over the ENPac region during the winters (December, January, and February) of 1979-1980 to 2015-2016. As shown in Fig. 1, we choose the ENPac region such that it is in the left exit region of a climatological North Pacific jet stream, which is a favorable region for surface cyclogenesis, or the formation or strengthening of a surface low-pressure system. A jet stream is an elongated zone of very strong westerly winds at the upper-levels of the atmosphere.

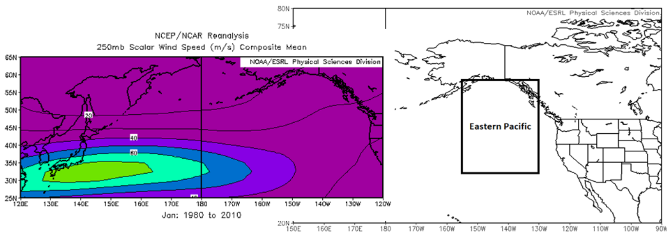

Figure 1. Left: Composite mean of 250-hPa wind speed (m/s) in January from 1980-2010. Right: The ENPac region we chose.

In this case, the synoptic-scale variability, rather than the seasonal variability, of the 500-hPa height is of interest, so we perform linear regression on the seasonal 500-hPa height and then subtract the resulting line from the 500-hPa height to obtain the de-trended 500-hPa height for each season. We then compute the 7-day running standard deviation of the de-trended areally-averaged 500-hPa height and its daily climatology. We obtain the standard deviation anomaly by subtracting the daily climatology from the standard deviation. For brevity, we call this final quantity the *height variance*. We use this metric to capture the departure of the 500-hPa variability from the climatological average. We define a *regime* as a period of at least five days during which the height variance is continuously below the 10th percentile (low variance regime) or above the 90th percentile (high variance regime). Fig. 2 shows examples of such regimes.

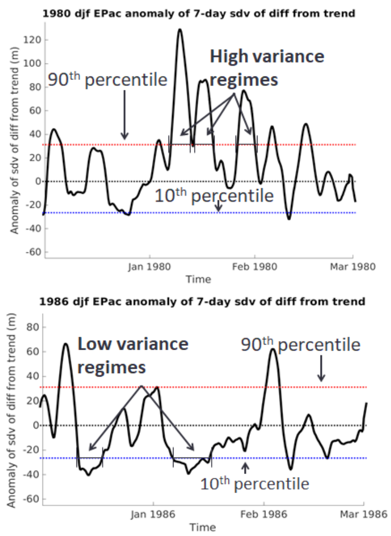

Figure 2. Height variance (anomaly of standard deviation in meters) in winter 1979-1980 (top) and winter 1985-1986 (bottom) in the ENPac region, with the regimes marked.

Analyzing Weather Patterns During Regimes

To analyze the average weather pattern in the ENPac region during low and high variance regimes, we calculate composites (averages) of various metrics during the times at which low and high variance regimes are at peak intensity. These metrics include anomalies of 500-hPa height, 250-hPa meridional wind (the 250-hPa level is typically at around 11 km altitude), precipitation rate, and mean sea-level pressure (MSLP), as well as the composite MSLP, thickness, and thickness anomaly map. The peak of a (low/high) regime occurs when the height variance is the (lowest/highest). The map consists of MSLP in solid black lines for every 8 hPa, 1000-500 hPa thickness in green dashed lines for every 60 m, and 1000-500 hPa thickness anomaly in meters shaded. We also construct plots on individual days during regimes to show the time-evolution of regimes and what patterns can be found at any given time during a regime (not shown).

To analyze extreme weather over North America, we use the North American Regional Reanalysis (NARR) dataset (6), a much higher-resolution dataset (0.3° × 0.3° resolution) specifically for North America and surrounding areas. In this study, we define North America to be the land area from 20-72°N and 50-165°W. From the NARR, we derive three variables to identify extreme weather: daily average 2-meter temperature, daily average 850-hPa equivalent potential temperature (theta-e), and daily precipitation. The 850-hPa theta-e is an atmospheric variable describing how warm and humid the air is at the height where the atmospheric pressure is 850 hPa, at approximately 1.5 km altitude. Theta-e is a conserved variable for air parcels in the absence of heat exchange with the environment, and 850-hPa corresponds approximately to the base of the precipitation layer. We use the 850-hPa theta-e in addition to the 2-meter temperature to assess how warm and moist the air through a deeper layer of the atmosphere, not just near the surface. The formula for theta-e is given in the following equation (Eq. 1):

$$\theta_e \approx \left(T + \frac{L_v}{c_{pd}} r\right)\left(\frac{p_0}{p}\right)^{\frac{R_d}{c_{pd}}}$$

where T is temperature, L_v is the latent heat of evaporation, c_{pd} is the specific heat of dry air at constant pressure, p_0 = 1000 hPa is the standard reference pressure, p is the pressure at the point, r is the mixing ratio of water vapor, and R_d is the specific gas constant for dry air. The extreme limits are 10th and 90th percentiles for 2-meter temperature and 850-hPa θ_e; and 90th percentile of daily precipitation ≥ 0.2 mm. We calculate the percentiles for each grid point based upon the monthly climatology (e.g. one value for the 10th percentile in January, another value for February, etc) using the NARR data from the winters of 1979-1980 to 2015-2016. Then, we compute the geographic areas and areal percentage of North America for extremes of each of the three variables on a daily basis for all winters from 1979-1980 to 2015-2016.

Defining and Analyzing Forecast Discontinuities

To assess the predictability of the ENPac regimes, we also study instances in which a model run is appreciably better (closer to actual) than the previous model run that was initialized 24-h earlier, using the Global Ensemble Forecast System (GEFS) reforecast model ensemble (1.0° × 1.0° resolution) (7). The model ensemble consists of one "original" control run and ten ensemble members. Ensemble members are simulations run, each with a slight variation of its initial conditions from the control run, to convey the forecast uncertainty caused by imperfect initial conditions. The reforecast is run once a day initialized at 0000 UTC. So far in this study, we focus on the control run. We define a *forecast discontinuity* as an instance where the GEFS reforecast control run height variance is at least 30 m for a low variance regime (or 45 m for a high variance regime) closer to the actual height variance than the previous run averaged over a 2-day period. These values correspond roughly to the 90th percentile of height variance changes modeled by the GEFS control run. We use a higher threshold for high variance regimes because modeled height variances are more variable for high variance regimes than low variance regimes. We compare the previous run, subsequent run, and reanalysis that are valid at the same time for the discontinuities.

Results

ENPac Weather Patterns During Regimes

Using the criteria specified in the previous section, we find 18 low vari ance regimes and 10 high variance regimes (Tab. 1). In low variance regimes, there are on average anomalously low 500-hPa heights, typically associated with a surface cyclone 200-700 km west of the ENPac region, and anomalously high 500-hPa heights, typically associated with a surface anticyclone 200-700 km east of the ENPac region (shown in Fig. 3a and Fig. 3g). This pattern leads to anomalous southerly winds and moisture transport in the ENPac region (shown in Fig. 3d and Fig. 3f). The structure and exact placement of these features depends on the regime: on one extreme, the 14 Dec-21 Dec 2010 regime had the surface cyclone right in the ENPac region; while at the other extreme, the 10 Feb-17 Feb 2013 regime had it around 1000 km to the west. The average for high variance regimes is roughly the opposite, with anomalously high 500-hPa heights 200-700 km west of the ENPac region and an associated surface anticyclone in the ENPac region, as well as a trough 200-700 km east of the ENPac region (shown in Fig. 3b and Fig. 3h). However, for high variance regimes, the patterns are more varied, and this “average” setup usually is only present for a part of a regime due to the rapid changes in the weather pattern. For example, in the 7 Jan-13 Jan 1980 high variance regime, a strong surface anticyclone to the north of the ENPac region moved westward and cold air moved into the ENPac region from northwestern Canada, while in the 12 Jan-17 Jan 2008 high variance regime, there was a quick succession of surface cyclones and anticyclones moving eastward through the ENPac region.

Regime Classification	Regime Cases	Notable Weather (if any)
Low	30 Nov 1984 - 8 Dec 1984	Rossby wave break and buildup of anomalously high available potential energy period (11)
Low	6 Jan 1985 - 12 Jan 1985	Pineapple express 3 days after (9)
Low	11 Dec 1985 - 17 Dec 1985	Pineapple express 3 days after (9)
Low	6 Jan 1986 - 16 Jan 1986	Northwest U.S. floods 1 day after (10)
Low	5 Feb 1988 - 14 Feb 1988	
Low	22 Dec 1989 - 27 Dec 1989	Cold air generation 1-5 days before (12)
Low	28 Dec 1998 - 2 Jan 1995	
Low	12 Jan 1996 - 18 Jan 1996	Pineapple express (8)
Low	9 Dec 1997 - 14 Dec 1997	Rossby wave break and buildup anomalous period 4-14 days after (11) and pineapple express (9)
Low	5 Feb 1998 - 14 Feb 1998	
Low	24 Nov 2002 - 5 Dec 2002	Pineapple express (9)
Low	20 Jan 2005 - 26 Jan 2005	
Low	9 Feb 2007 - 16 Feb 2007	
Low	14 Dec 2010 - 21 Dec 2010	
Low	12 Dec 2011 - 18 Dec 2011	
Low	14 Feb 2012 - 19 Feb 2012	
Low	10 Feb 2013 - 17 Feb 2013	
High	7 Jan 1980 - 13 Jan 1980	Deep cold air generation over northwestern Canada (13)
High	14 Jan 1980 - 19 Jan 1980	
High	27 Jan 1980 - 1 Feb 1980	Deep cold air generation over northwestern Canada (13)
High	7 Feb 1982 - 13 Feb 1982	
High	23 Dec 1982 - 27 Dec 1982	Long duration freezing rain (C. McCray, 2018, personal communication) and extreme θ_e for Montreal (14)
High	28 Jan 1991 - 2 Feb 1991	
High	16 Jan 1993 - 23 Jan 1993	
High	29 Nov 2007 - 7 Dec 2007	
High	12 Jan 2008 - 17 Jan 2008	Extremely high 850-hPa θ_e for Montreal 3 days before (14)
High	8 Feb 2011 - 13 Feb 2011	Rossby wave break and buildup of anomalously high available potential energy (11)

Table 1. All regime cases with notable weather found in previous research if any.

At any given time during a low variance regime, there tends to be one or two large, slow-moving features that make the 500-hPa height field relatively steady in the ENPac region with small fluctuations. On the other hand, at any given time during a high variance regime, there tends to be faster-moving features that change the 500-hPa height field substantially in the ENPac region.

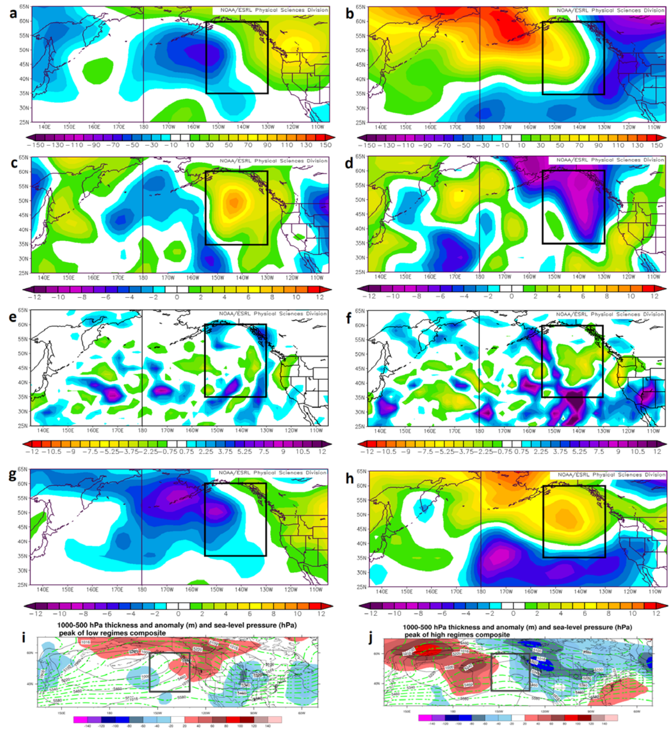

Figure 3. Anomalies of various meteorological fields composited at the time of peak regime intensity during low variance regimes (left) and high variance regimes (right) with the ENPac region boxed. a)-b): anomalies of 500-hPa height (m); c)-d):500-hPa meridional wind (m s-1), e)-f); precipitation rate (mm day-1); g)-h): mean sea level pressure (hPa); i)-j): MSLP, thickness, and thickness anomaly map.

North American Extreme Weather During Regimes

As shown in Fig. 3i (low variance regime composite), the counterclockwise circulation around the surface cyclone in the Central Pacific brings southerly winds and anomalous warmth measured by anomalously high 1000-500 hPa thickness near the West Coast of North America. (The 1000-500 hPa thickness is a measure of the average temperature of the air column between the surface and 500 hPa.) The southerly winds sometimes bring moisture plumes northward into the West Coast and southern Alaska, which in conjunction with the surface cyclone in the central Pacific, causes heavy precipitation. Meanwhile, the southwest U.S. is drier as the upper-level ridge near the West Coast (shown in Fig. 3a) deflects most of the moisture and surface cyclones to the north and west. One specific case (a day in the 6 Jan-16 Jan 1986 regime) is shown in Fig. 4a-4d, which shows deep warm air (shown in very high 2-meter temperature, 850-hPa theta-e, and 1000-500 hPa thickness) over parts of western Canada and heavy precipitation in British Columbia. Different regimes have somewhat different regions affected by the moisture plumes; for example, in the 6 Jan-12 Jan 1985 regime, the precipitation was directed from southern Alaska to northern British Columbia, while in the 6 Jan-16 Jan 1986 regime, the precipitation was directed into British Columbia and Washington.

As shown in Fig. 3j (high variance regime composite), the clockwise circulation around the weak surface anticyclone near the middle of the ENPac region brings northerly winds and anomalous cold measured by anomalously low 1000-500 hPa thickness in western North America, especially in western Canada. The cold anomalies to the north and less cold anomalies to the south indicate that the meridional temperature gradient is anomalously strong. The upper-level trough in western North America (shown in Fig. 3b) allows surface cyclones to penetrate farther south and into the western U.S., sometimes leading to extreme precipitation there. Also, the southwest U.S. is relatively dry on average, so a heavy precipitation event there is more extreme for that area than it would be for other parts of North America. A specific case (a day in the 7 Jan-13 Jan 1980 regime) is shown in Fig. 4e-4h, which shows deep cold air (shown in very low 2-meter temperature, 850-hPa theta-e, and 1000-500 hPa thickness) over a significant part of western North America and heavy precipitation in the western U.S. One particular exception is the 12 Jan-17 Jan 2008 regime mentioned earlier, which had warmer than normal temperatures in central and northern Canada and colder than normal temperatures in the southern U.S.

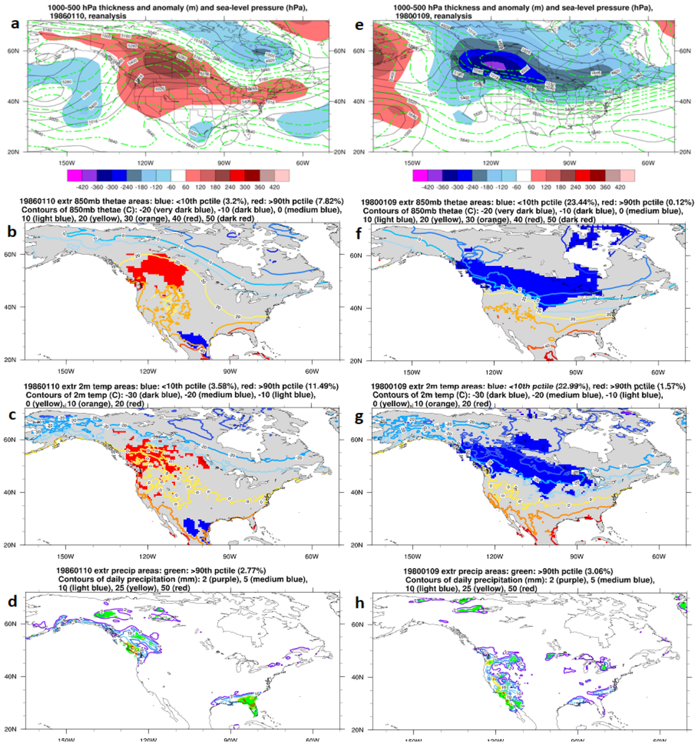

Figure 4. a)-d): Daily extreme weather metrics for 10 Jan 1986 low regime peak. a): MSLP, thickness, and thickness anomaly map. b): 2-meter temperature (contoured every 10 °C), extremes (blue–low, red–high). c): same as b) for 850-hPa theta-e. d): precipitation (contoured 2-100 mm), extremes (green). e)-h): same as a)-d) for 9 Jan 1980 high regime peak.

Forecast Discontinuities

Using the criteria specified in the previous section, we find 30 forecast discontinuities: 24 associated with low variance regimes and 6 associated with high variance regimes. Forecast discontinuities sometimes are associated with changes in anticipated weather over a large part of North America. For example, as shown in Fig. 5a-5c, the large-scale weather pattern over North America at 1200 UTC 31 Jan 1991 from the GEFS model forecast initialized on 24 Jan is almost the opposite of that shown by the forecast initialized on 23 Jan. The later run output is much closer to the reanalysis, or what actually happened. Other forecast discontinuities only have an impact on the anticipated weather conditions within the ENPac region. For example, as shown in Fig. 5d-5f, the large-scale flow pattern over North America at 1200 UTC 22 Jan 2005 from the GEFS model forecasts initialized on 14 and 15 Jan are very similar to each other. The main difference is the structure and position of the surface cyclone in the ENPac region, which was better predicted by the later run.

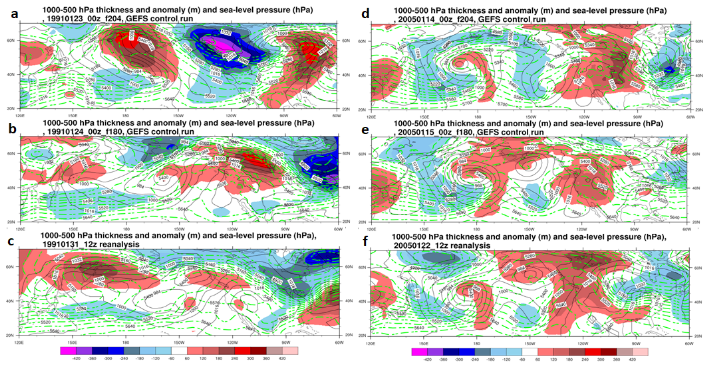

Figure 5. a)-c): MSLP, thickness, and thickness anomaly map of GEFS 23 Jan 1991 control run (a), GEFS 24 Jan 1991 control run (b), and reanalysis (c), all valid on 31 Jan 1991 at 1200 UTC. d)-f): same as a)-c) but for GEFS 14-15 Jan 2005 runs and valid on 22 Jan 2005 at 1200 UTC.

Discussion & Conclusion

Not surprisingly, low and high variance regimes can lead to different ENPac weather patterns and different types of high-impact weather over North America. Five of the low variance regimes (Tab. 1) are associated with a "pineapple express", or a narrow, moisture-rich plume, extending into parts of western North America, leading to heavy precipitation events in those areas (8), (9). A sixth event is associated with northwest U.S. floods (10). This is consistent with a persistent southerly, moisture-rich flow in the ENPac and West Coast regions during low variance regimes.

In contrast, two of the high variance regimes are associated with deep cold air generation over northwestern Canada. The combination of this deep cold air generation and a generally northerly flow of polar air into the ENPac region is consistent with the tendency for cold air outbreaks to occur in western North America and the ENPac region during high variance regimes. Also, one of the high variance regimes is associated with a long duration freezing rain event, and two of them are associated with extremely high 850-hPa theta-e for Montreal (and its vicinity in southeastern Canada and the northeast U.S.), which is not found during any of the low variance regimes.

Freezing rain results from warm, moist air from the south rising and moving over cold, sub-freezing air to the north, which is easier with a stronger meridional temperature gradient. Extremely high 850-hPa theta-e in southeastern Canada and the northeast U.S. occurs during a normally brief surge of warm and moist air from the Gulf of Mexico, southeast U.S., and/or western Atlantic. Consequently, having anomalously warm temperatures in those regions increases the probability for the development of extremely positive theta-e anomalies in Montreal. On average, as shown in Fig. 3i and Fig. 3j, the Gulf of Mexico to western Atlantic region is warmer than normal during high variance regimes. Additionally, it is colder than normal in most of Canada, indicating an anomalously strong north-south temperature gradient. These factors are consistent with high variance regimes featuring an increased likelihood of extremely high 850-hPa theta-e in southeastern Canada and the northeast U.S., yet still maintaining enough cold air at low-levels for the potential for a long duration freezing rain event.

To date, we have not investigated in detail the causes of the forecast discontinuities, but we hypothesize that differences in cyclogenesis between the different model forecasts play a major role in producing forecast discontinuities. Forecast variability of cyclogenesis is high due to the complicated dynamics of cyclones and the higher sensitivity of cyclogenesis to the initial state of the atmosphere (15).

There are some noteworthy limitations of this study. The relatively small sample size of regimes (18 low variance and 10 high variance) and the relatively large variability between regimes in the same category precludes us from drawing too detailed or specific conclusions. Nonetheless, we believe the general statements in the results section are valid, since they are physically consistent, involve areas closest to the ENPac region, and have a plausible meteorological explanation. Also, the fact that height variance at 500-hPa does not always directly impact the surface weather raises some caveats. Two model runs can have the same height variance yet have significantly different weather patterns. Two model forecasts can have very different height variances that could result from differences locally in the ENPac region and have similar larger-scale features over North America. Additionally, model forecasts can perform poorly in one area and well in another area. Finally, the study focuses on the ENPac winter; the characteristics of regimes and forecast discontinuities could be different for other seasons and regions.

Acknowledgements

This work was funded by two Science Undergraduate Research Awards (SURA), a NOAA NGGPS (#NA16NWS4680018) Grant, and a Natural Sciences and Engineering Research Council of Canada (NSERC) Discovery Grant. Thanks to the McGill Faculty of Science and Dr. Rubin Gruber for funding the SURAs. Thanks to supervisor Prof. John Gyakum and to Dr. Eyad Atallah for guiding my project.

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