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Spring Precipitation in Intermountain West Influenced by Quasi-Biennial Oscillation

Jason A. Phelps
Utah State University

SPRING PRECIPITATION IN INTERMOUNTAIN WEST INFLUENCED BY

QUASI-BIENNIAL OSCILLATION

by

Jason A. Phelps

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in

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Approved:

Peter Wilcock, Ph.D.
Major Professor

Sarah Null, Ph.D.
Committee Member

Robert Davies, Ph.D.
Committee Member

Richard S. Inouye, Ph.D.
Vice Provost for Graduate Studies

UTAH STATE UNIVERSITY
Logan, Utah

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ABSTRACT

Spring Precipitation in Intermountain West Influenced by Quasi-Biennial Oscillation

by

Jason A. Phelps, Master of Science

Utah State University, 2019

Major Professor: Dr. Peter Wilcock
Department: Watershed Sciences

Abnormally wet spring seasons in the Intermountain West (IW) have been linked to alternations in upper-atmospheric zonal wind known as the Quasi-Biennial Oscillation (QBO). When this pattern produces strong upper-atmospheric westerlies during October-January, abnormally wet conditions are often observed over the IW the following spring. Using a time series of average 30 mb zonal winds near the equator, the QBO can be split into different phases according to wind direction: westerly (positive), easterly (negative), and transitions. Composites of winter and spring precipitation anomalies based on different QBO phasing show that the QBO is oriented in a positive and maximum phase during October-January prior to most extreme spring precipitation events. Drier springs tend to occur with minimum phases of the QBO the preceding fall. We explore the dynamic processes causing the QBO to affect rainfall in the IW. Our findings suggest that the intensity of spring precipitation in the IW may be forecast months in advance, based on QBO phase. These findings are important for the IW because extreme wet springs can lead to floods, such as those in spring 1983 and 2011, and affect the amount of water available from spring runoff. (39 pages)

PUBLIC ABSTRACT

Spring Precipitation in Intermountain West Influenced by Quasi-Biennial Oscillation

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Unusually wet spring seasons in the Intermountain West (IW) have been linked to a wind fluctuation in higher levels of the atmosphere near the equator. Strong westerly winds during October-January often result in unusually wet conditions in the following spring. Average winds near the equator at 75,000 feet above the earth's surface can be split into different categories according to wind direction: westerly (positive), easterly (negative), and transitional. Composites of winter and spring precipitation anomalies based on these different categories show that strong westerly winds occur in October-January prior to most extreme spring precipitation events. Drier springs tend to occur after easterly winds the preceding fall. Analysis of the atmospheric processes causing this wind pattern suggests that the intensity of spring precipitation in the IW may be forecast, based on winds in the upper atmosphere months in advance. These findings are useful for the IW because extreme wet springs could lead to floods, such as those in spring 1983 and 2011, and affect the amount of water available from spring runoff.

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Jason A. Phelps

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CHAPTER 1

INTRODUCTION

Water has long been a critical natural resource in the Intermountain West (IW) region of the United States. Understanding the interactions of climatology and hydrology is increasingly important for water management as demands on water resources have grown both within and beyond the region and climate alters water quantity and timing (Cooley et al. 2011). In the IW, most precipitation occurs in the spring (Wang et al. 2009), while interannual and decadal variability in precipitation manifests as drought or floods (DeRose et al. 2014; Jain and Lall 2000; Wang et al. 2010). Predicting spring precipitation in the IW can prove difficult because the IW region falls into a transition zone when it comes to commonly known climate patterns used for predicting precipitation six to twelve months in advance. These patterns include El Niño Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (Allen et al. 2013). Since the IW lies in a transition zone, these patterns have less direct and predictable effect on the region, and other climate patterns are needed to help predict precipitation in advance. This study will delve into one such climate pattern that could help.

Spectral analysis applied on the monthly IW precipitation averaged over the domain 40-42.1°N, 109-113°W reveals a significant peak around 2-3 years, a quasi-biennial feature (Fig. 1a). A distinct and localized signal over the IW is evident in a precipitation correlation plot (NCDC 1994) between spring precipitation and the phase of the winter Quasi-Biennial Oscillation (QBO) appears over the IW (Fig. 1b). In seasons other than spring, the QBO signal is less dominant. Why is this pattern so seasonal toward spring and so focused on such a particular region?

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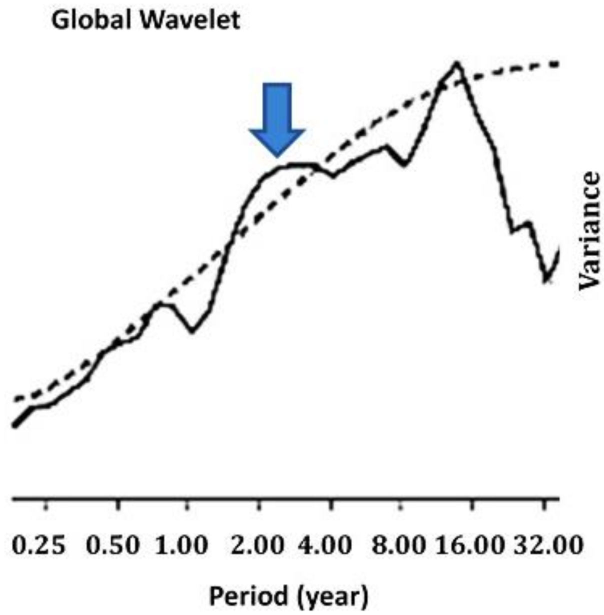

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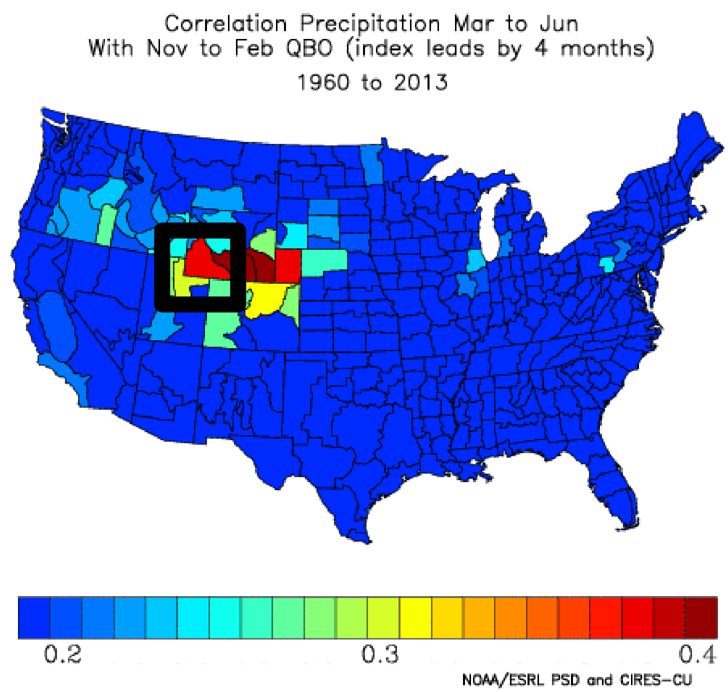

Fig. 1
a Power spectra for average March-June precipitation in the Intermountain West, 1960-2014. **b** National Climate Data Center (NCDC) plots of correlation for the QBO versus precipitation. Correlation coefficient of March-June precipitation versus the QBO index 4 months prior.

Until the 1950s, little was known about the QBO, a type of upper-atmospheric wind pattern. In 1883, the Krakatau volcanic eruption delivered ash to the stratosphere (Rampino and Self 1982). Visual tracking of subsequent volcanic ashes led to the discovery of tropical *easterlies* between 25 and 30 km above the surface. However, in 1908 a study over Lake Victoria in Africa observed *westerlies* at a similar level (Heaps et al. 1998; Rohli and Vega 2012). These conflicting wind patterns were not resolved until the 1950s, when a global radiosonde network provided regular wind measurements. This subsequently led to the identification of the now well-known QBO, an alternating tropical easterly-westerly wind pattern that propagates downward from the middle stratosphere to the upper troposphere (Naujokat 1986; Holton and Tan 1980). The QBO occurs in the equatorial stratosphere from 10 mb to the tropopause, with maximum wind occurring near the 20 mb level. It takes 18-36 months to complete one full cycle, but it usually lasts slightly over two years (Naujokat 1986). It takes about 3-5 months for the phase of the QBO to propagate from stratospheric levels to the level at which variation of jet streams would affect storm tracks and weather (Baldwin et al. 2001). Due to its unique frequency, the QBO phase does not lock in with season, meaning the strongest westerly or easterly winds will not always occur the same time of year.

Further understanding of the QBO was achieved in the 1970s and 1980s. Richard Lindzen and James Holton found that the QBO was forced by atmospheric waves originating from lower levels of the atmosphere in tropical regions. These waves travel upward and are later dissipated in the stratosphere due to radiative cooling (Lindzen 1987). While some mysteries remain, it has been suggested that mesoscale gravity waves, planetary waves, inertia-gravity waves, and short-period Kelvin waves are involved in

driving the QBO (Dunkerton 1997). More recently, the Weather Research and Forecasting (WRF) model showed that inertia-gravity waves that are large in horizontal scale play an important role in driving the QBO. It was numerically demonstrated that gravity waves account for 60% of the total eastward forcing during the westerly shear phase and 80% of the total westward forcing during the easterly shear phase (Evan et al. 2012). Other studies have shown gravity waves potentially fueling the QBO, including a study conducted by Giorgetta et al. (2002). A 2016 publication states that the period of the QBO is controlled mostly by the magnitude of gravity wave vertical fluxes of horizontal momentum and that such fluxes force the QBO (Geller et al. 2016). Atmospheric modelling experiments conducted by Richter et al. (2014) and Rind et al. (2014) support these findings. It is further argued that QBO amplitude is controlled by the phase speed of the gravity waves (Richter et al. 2014; Rind et al. 2014). These concepts of gravity waves illustrate a possible cause for the effect of ENSO on QBO period and amplitude (Geller et al. 2016; Richter et al. 2014; Rind et al. 2014). Some have proposed that changes in the ENSO pattern can influence the QBO by suppressing Rossby-gravity wave activity when in the El Niño phase (Maruyama and Tsunseoka 1988).

Even though the QBO occurs in the stratosphere, many studies have shown its possible effects on the troposphere and regional climate anomalies. For instance, there is a quasi-periodic behavior on the scale of 2.2-2.4 years in rainfall variability in Africa that may suggest a relationship between the QBO and African precipitation (Nicholson and Entakhabi 1986). The QBO has been theorized to influence Atlantic hurricane strength and frequency (Baldwin et al. 2001; Gray 1984). As much as 15% of rainfall variability

during the summer Indian monsoon may be associated with the pattern of the QBO (Mukherjee et al. 1985). Seo et al. (2013) suggest that during the westerly phase of the QBO, the midlatitude spring rainband extending from southeastern China to eastern Japan is displaced southward, resulting in the decrease in spring rainfall over Korea and Japan.

Regarding the dynamical processes that connect the QBO to various regional climates, some studies have investigated effects of the QBO on the Polar Vortex. The Polar Vortex is a prominent winter pattern in which an area of low pressure over the poles is encircled by a circumglobal jet known as the polar night jet. This region of low pressure extends from the tropopause to the mesosphere (Hitchman and Huesmann 2009). The Polar Vortex forms due to an increase in the equator-to-pole temperature gradient in winter, as the Arctic is plunged into polar night. This enhanced equator-pole temperature gradient leads to an increase in vertical wind shear in accordance with thermal wind balance, causing a vortex of westerly winds to form in the stratosphere around the Arctic (Watson et al. 2011). Studies suggest a significant correlation between the polar night jet and QBO westerlies at 50 mb. The QBO modulates propagation and absorption of extratropical Rossby waves, influencing the strength of the polar night jet (Holton and Tan 1980; Hitchman and Huesmann 2009). Another study states that planetary waves provide a tropical-extratropical coupling mechanism for the QBO to affect the Polar Vortex. In the QBO easterly phase, extratropical Rossby waves are confined farther north, closer to the vortex at QBO levels, weakening the vortex relative to that in the QBO westerly phase (O’Sullivan and Young 1992).

In this study we investigate the mechanism by which the phase of the QBO in early winter influences IW spring precipitation. This research examines how the QBO might affect spring precipitation in the IW and evaluates whether the QBO may be useful for future spring precipitation forecasts in the IW. This research is new because little study has been done linking the QBO to spring precipitation in the IW. Monthly precipitation and global reanalysis data are utilized to depict the QBO phase, stationary wave patterns, and precipitation impacts. These data are introduced in Section 2.

CHAPTER 2

DATA AND THE QBO INDEX

The QBO was reconstructed by taking an area average of zonal winds for the global region from 12°N to 12°S at 30 mb using National Centers for Environmental Prediction (NCEP) reanalysis data, then creating a time series of monthly zonal wind from January 1960 to December 2012. Since it takes the QBO 18-36 months to complete one full cycle, a 36-month high-pass filter was applied to the QBO index.

In order to analyze atmospheric conditions for different phases of the QBO, a reconstruction of the QBO was created using NCEP reanalysis data (Kalnay et al. 1996) for zonal winds at 30 mb. Precipitation data were obtained using NOAA’s PRECipitation REConstruction Dataset (PREC) (Chen et al. 2002). Stream function anomaly composites used NCEP reanalysis data for U- and V-wind components.

A script to evaluate the horizontal component of a Rossby wave activity flux was also applied (Nishii and Nakamura 2011). This script was used to determine the wave energy transferred between higher and lower density waves, represented by Rossby wave activity flux. In order to implement this script, it was necessary to determine stream function anomaly to identify the areas of lower or higher wave density from which wave energy could be transferred between such waves. The resolution used was 2.5°.

An ION (Ionic) Research Systems wavelet spectral analysis script was implemented (Torrence and Compo 1998). Only March through June precipitation averaged over the domain 40-42.1°N, 109-113°W was entered into this script. This script was then analyzed to see what periods in number of years had the highest variance in

precipitation for the domain. This was to figure out the frequency of precipitation patterns over the IW region.

National Climate Data Center (NCDC) cross-correlation charts were used in order to calculate the correlation coefficient of March through June precipitation based on the QBO wind speed and direction the prior November to February (NCDC 1994). These charts were analyzed for the entire continental United States to see where there was a statistically significant relationship between March through June precipitation and QBO wind speed and direction four months prior. The range for correlation coefficient was given to be 0.2 to 0.4.

CHAPTER 3

RESULTS

3.1 Rainfall vs. QBO- Phasing and Phase Composites

This work examines precipitation in the portion of the IW that encompasses northeast Utah, southeast Idaho, and southwest Wyoming (Fig. 1b). A yearly time series of March-June average precipitation during 1960-2011 was created for this region and plotted in Fig. 2a. Using two standard deviations to identify cases with larger March-June IW precipitation, eight wet cases were identified in which the QBO had been at its maximum phase the preceding October-January. The 24-month evolutions of the QBO, for which the QBO was at its maximum in October-January and its minimum in September-November, are plotted in Fig. 2b and 2c, respectively. In Fig. 2a, the color indicates standard deviations about the average, shown as a black line. When the QBO peaks around January, the IW tends to experience extreme high precipitation events. Similarly, when the QBO reached its minimum phase around October in the previous year, spring precipitation in the IW was below normal.

The regional features of precipitation and circulation anomalies during the October-January maximum and September-November minimum QBO phases were made into composites for two subsequent seasons: January-March through April-June, leading up to 2012. Here, maximum and minimum phases of the QBO are defined as months during which the QBO index is within one-half standard deviation of the respective peak or trough. This resulted in 12 positive QBO cases in October-January and 12 negative QBO cases in September-November.

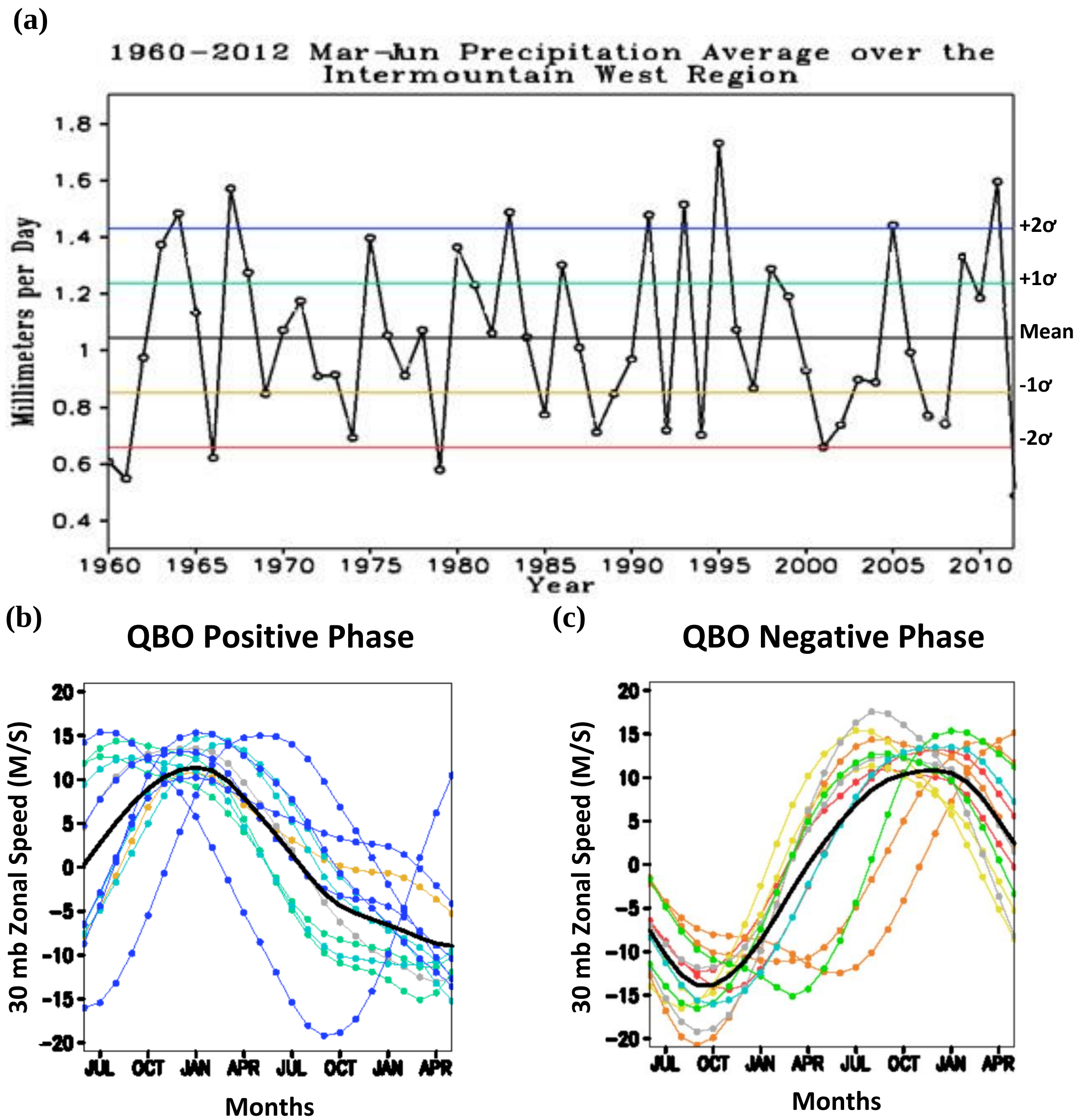

Fig. 2

a Yearly March-June average precipitation in mm/day for initial region of study. **b** Phase curves of 30 mb zonal wind (m/s) for years in which QBO was positive in October-January. Black curve represents average of curves. Blue curves are years in which IW March-June precipitation was at least two standard deviations wetter than normal, light blue or turquoise curves at least one standard deviation wetter than average, gray curves average precipitation, and orange curves represent at least one standard deviation drier than normal for IW March-June precipitation. **c** Phase curves of 30 mb zonal wind (m/s) for years in which QBO was negative in September-November. Black curve represents average of curves. Green curves represent wetter than normal by less than one standard deviation, light blue curves at least one standard deviation wetter than normal, gray curves average precipitation, yellow curves less than one standard deviation drier than normal, orange curves at least one standard deviation drier than normal, and red curves at least two standard deviations drier than normal for IW March-June precipitation.

The composite anomalies of precipitation and 200 mb stream function are shown in Fig. 3a and 3b. For the case with positive QBO in October-January, an area of anomalous low pressure began to form southwest of California in February-April, intensifying and shifting to the Oregon-California coast in March-May and April-June. For the case with negative QBO in September-November, anomalous high pressure appears north of Hawaii in January-March, moving inland to the Oregon-California coast by April-June. For the positive QBO phase in October-January, precipitation in the following April-June was 0.3 mm/day higher than normal from northern Utah through southern Wyoming. For the negative QBO phase, the composites show a drier spring with precipitation 0.1-0.2 mm/day below normal. A 0.4-0.5 mm/day difference in precipitation existed between the positive QBO phase and negative QBO phase cases for April-June precipitation. About 12% of the variance in the IW's March-June precipitation can be explained by the extreme phases of the QBO four months prior, and this increases to as much as 16% for southern Wyoming.

3.2 Dynamical Process

In order to understand the process by which the QBO influences IW climate, composites were made for the QBO wet-spring and dry-spring cases based on stream function anomalies at four different levels above 150 mb in different seasons during the October-January positive QBO case. These composites started with July-September through October-December, focusing on the 50 mb level where the greatest impacts of planetary waves existed. Such plots were constructed for both QBO cases (Fig. 4a; Fig. 4b). The November-January through January-March data were analyzed in order to connect with atmospheric circulation patterns in January-March (Fig. 4a; Fig. 4b).

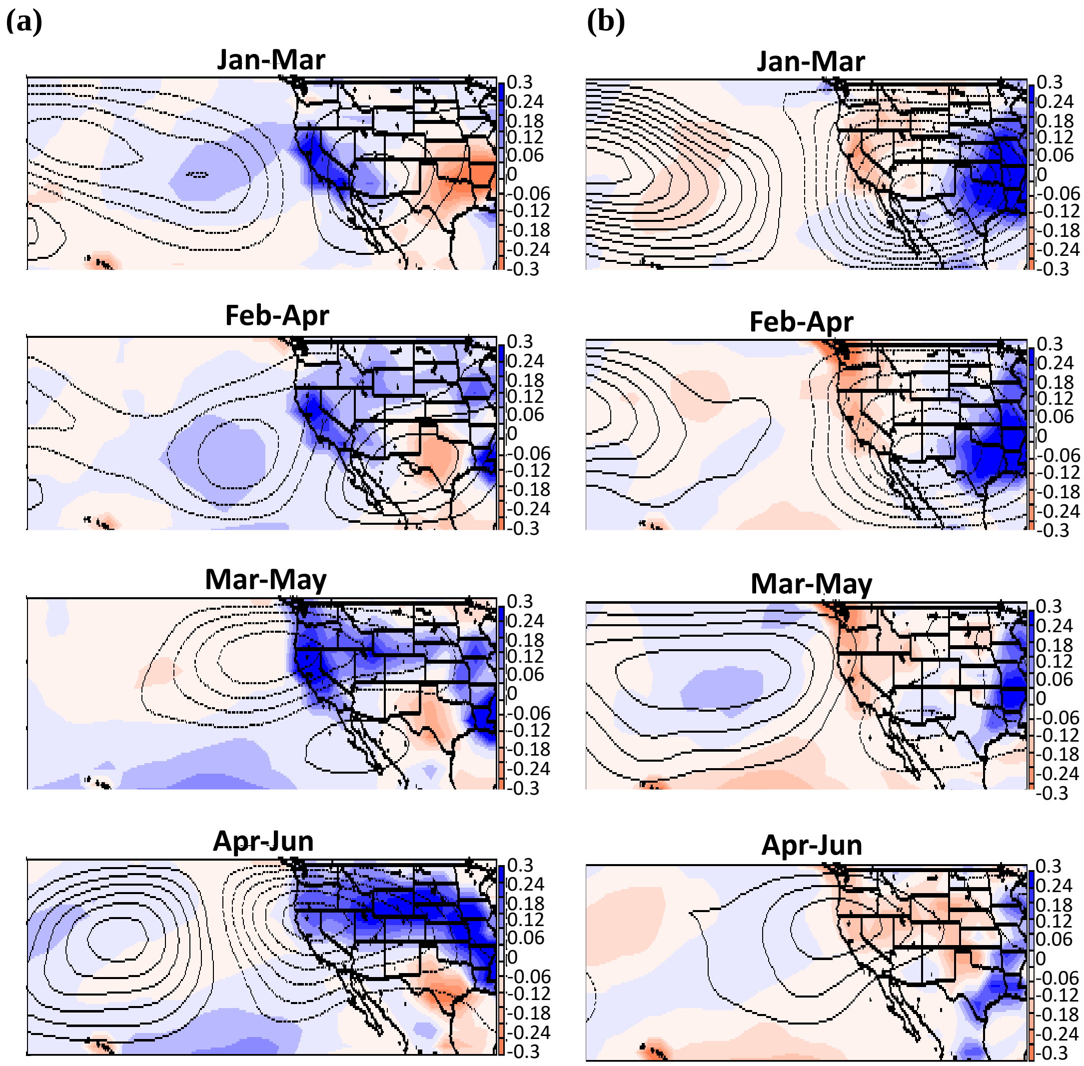

Fig. 3

a 3-month composites of average 200 mb stream function and precipitation anomaly for years in which the QBO phase was positive in October-January. Contour interval for stream function anomaly is 0.3 mb. Precipitation anomaly is in mm/day. Dashed contours are lows and solid contours are highs. **b** 3-month composites of average 200 mb stream function and precipitation anomaly for years in which the QBO phase was negative in September-November. Contour interval for stream function anomaly is 0.3 mb. Precipitation anomaly is in mm/day. Dashed contours are lows and solid contours are highs.

These composites reveal that during positive QBO years, the July-September season featured higher-than-normal wave energy over the western Pacific stretching to East Asia. This leads to higher-than-normal wave density toward Japan, which persists through January-March, leading to the dynamical process associated with the wet spring in the IW.

For the negative QBO years, an anomalous region of lower-than-normal wave density exists at the 50 mb level of the western Pacific to East Asia during July-September. A region of higher-than-normal wave density at the same atmospheric level also exists over Africa. In August-October a Rossby wave activity flux associated with these regions of higher- and lower-than-average wave density leads to the magnification of higher-than-normal wave density over northeast Eurasia and the growth of a lower-than-normal wave density toward northeast Asia. The anomalous Rossby wave activity fluxes associated with these anomalous wave density regions leads to the growth of lower-than-normal wave density over northeast Asia and the development of higher-than-normal autumn atmospheric pressure over Canada through the enstrophy process of dissipation. The Rossby wave activity flux associated with the higher pressure over Canada eventually leads to a lower-than-normal pressure area developing over western Alaska by January-March. This is the same 50 mb January-March lower-pressure area as mentioned in Section 3.2 and shown in Fig. 4b, contributing to the slightly drier-than-normal spring for the IW. The November-January through January-March Rossby wave activity fluxes and stream function anomalies were analyzed in order to connect with atmospheric circulation patterns in January-March (Fig. 4a; Fig. 4b).

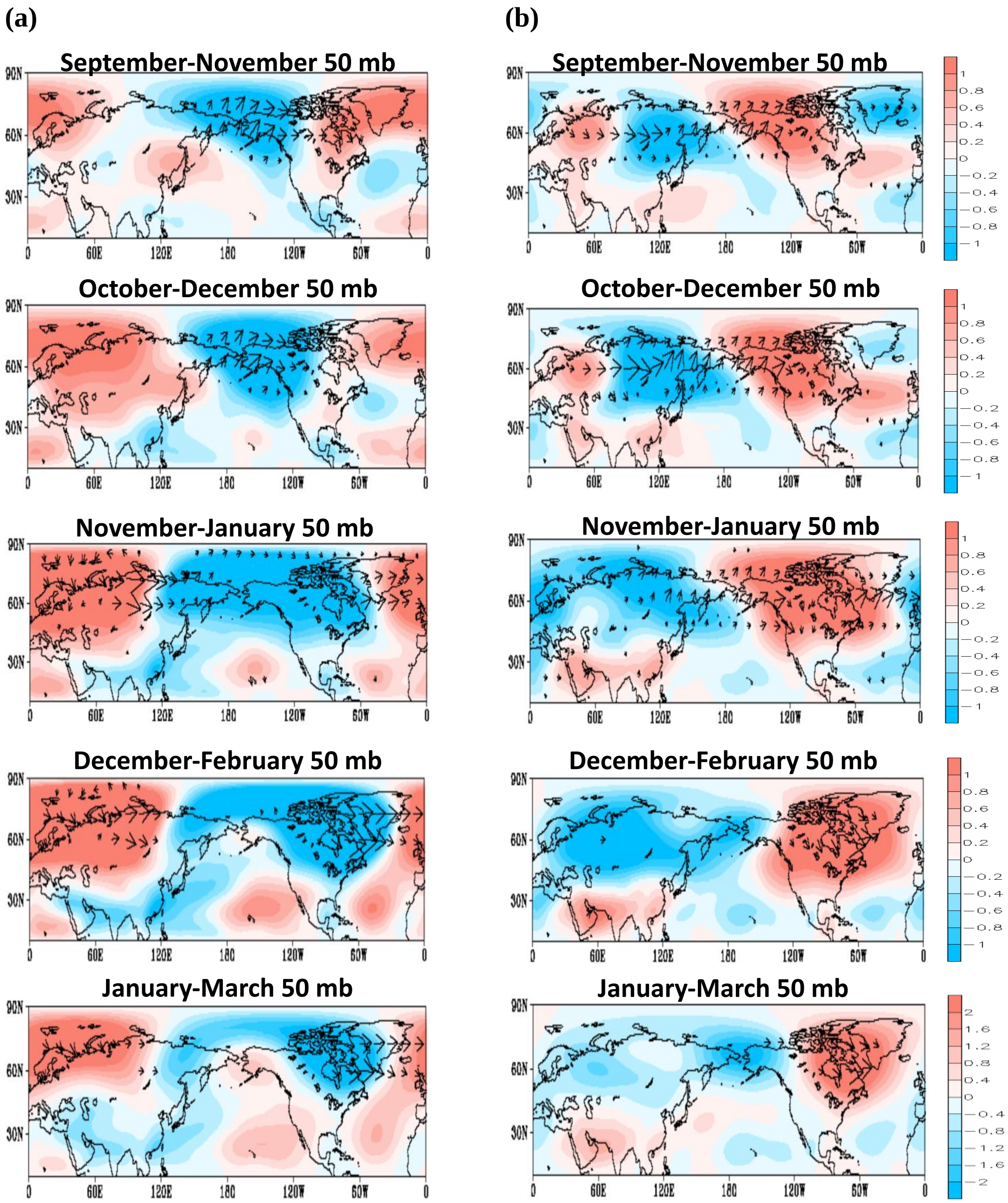

Fig. 4

a Composite of 3-month stream function anomaly for years in which the QBO phase was positive in October-January. Rossby wave activity flux represented by arrows. Stream function anomaly is in mb. The top four panels range -1 to 1 mb, and the bottom panel ranges -2 to 2 mb from normal. **b** Composite of 3-month stream function anomaly for years in which the QBO phase was negative in September-November. Rossby wave activity flux represented by arrows. Stream function anomaly is in mb. The top four panels range -1 to 1 mb, and the bottom panel ranges -2 to 2 mb from normal.

The January-March through March-May composites for the QBO wet-spring cases reveal a couple anomalies (Fig. 5a). A higher-than-normal wave density over northern Eurasia and a lower-than-average wave density over western Russia to eastern Canada occur in January-March. Associated with this dipole is an increase in the wave activity flux over northern Eurasia spanning 20-150°E, 60-80°N, suggesting the source of circulation anomalies there. An area of cyclonic anomaly forms from northern California to southern Oregon in March-May and April-June. The development of this cyclonic anomaly begins in January-March and is connected with an anomalous anticyclone in northern Eurasia.

To explore the feeding mechanism, the Rossby wave activity flux was applied following the derivation by Takaya and Nakamura (2001) to represent the source of Rossby energy propagating along the mean flows. Rossby wave energy leads to dissipation effects that amplify atmospheric waves downwind, which can amplify the adjacent stationary waves. The Rossby wave activity flux (vectors) depicts energy feeding into the cyclonic cell to the west of the IW developing in February-April near the 200 mb level (Fig. 5a). In the case of negative QBO developed in September-November (Fig. 5b), an anticyclone forms subsequently from southern Oregon to northern California in March-May and April-June. Further examination reveals that the wet-spring case in the IW is accompanied by a wave train pattern across the Pacific, starting from East Asia and connecting to southern Oregon and northern California. For the dry-spring case in the IW, this trans-Pacific wave pattern is also present with the opposite polarity.

To understand the pathway through which the QBO influences high-latitude climate, we expanded the stream function anomaly and Rossby wave activity flux

composites to the global domain at six levels between 50 and 200 mb. For the QBO dry-spring case at 50 mb in January-March, an anomalous area of lower-than-normal wave density existed over western Alaska, while an anomalous area of higher-than-normal wave activity dominated eastern Canada to western Greenland (Fig. 5b), triggering a downwind response across the North Pacific.

For the QBO wet-spring case in February-April and March-May, the wave activity progressed to 40-70°N, 20-60°E, enhancing an anomalous low northwest of India (Fig. 5a). This can be seen at the 70 mb level in February-April (Fig. 5b). In March-May for the QBO wet-spring case, the downward and westward propagation of the aforementioned Rossby wave activity flux led to a high-density wave region over East Asia at 30°N, 120°E. A very strong Rossby wave activity flux formed over this East Asian region in March-May at 100-150 mb in the positive QBO cases as well (Fig. 5a). This anomalous Rossby wave flux continued westward and downward across the North Pacific in March-May. The resulting dissipation through the enstrophy process led to the downward and westward amplification of anomalously cyclonic and anticyclonic regions from East Asia to the western United States. This includes a cyclonic region from northern California to southern Oregon, responsible for the wet spring in the IW (Fig. 5a). The cyclonic regions mentioned for the QBO dry-spring case reach the 100 and 150 mb levels in March-May, and the Rossby wave activity flux split such that part of it was over western Alaska and eastern Russia, and part resided closer to Hawaii, near 20°N, 180°E (Fig. 5b).

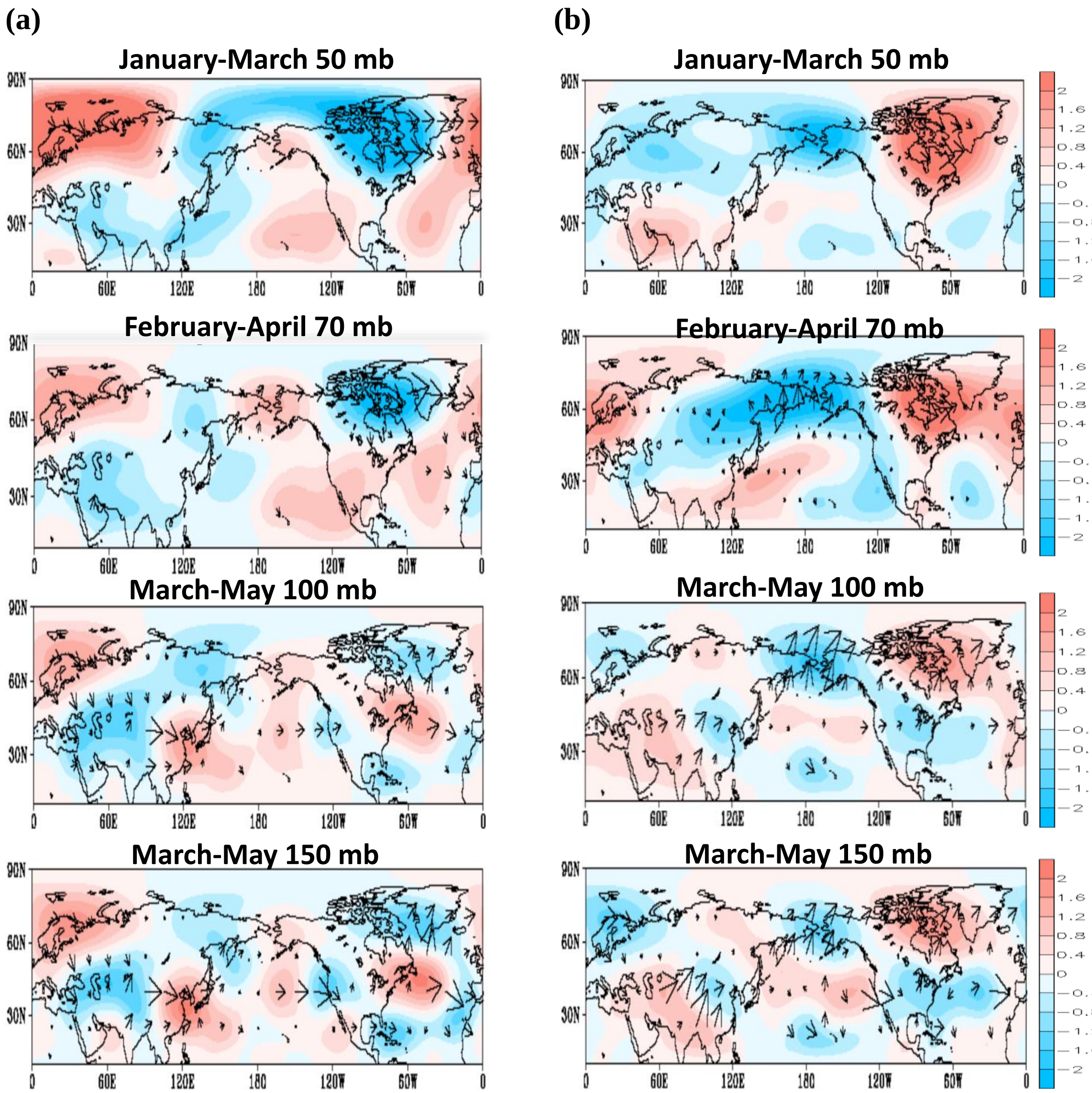

Fig. 5

a Composite of 3-month 50, 70, 100, and 150 mb stream function anomaly for years in which the QBO phase was positive in October-January. Rossby wave activity flux represented by arrows. Stream function anomaly is in mb. **b** Composite of 3-month 50, 70, 100, and 150 mb stream function anomaly for years in which the QBO phase was negative in September-November. Rossby wave activity flux represented by arrows. Stream function anomaly is in mb.

3.3 Polar Vortex and Further Dynamics

The observation that the winter-time anomalous Rossby wave activity flux occurs over northern Eurasia for positive QBO echoes the finding by O'Sullivan and Young (1992) concerning the QBO interaction with the Polar Vortex. Following O'Sullivan and Young, we constructed a polar stereographic long-term mean plot of the 50 mb stream function for January-March; Fig. 6a reveals the typical winter time polar stratospheric low. Likewise, we constructed the stream function anomaly based on negative QBO phases (Fig. 6b) and positive QBO phases (Fig. 6c). These composites are based on the QBO being at least one standard deviation below or above zero for November-March; this led to 15 cases for each respective QBO phase. The comparison in Fig. 6 reveals that during years in which the QBO phase is negative, the stratospheric low was not as deep, meaning a weaker Polar Vortex. The feature of note here is the stationary trough over northern Asia, as indicated by the blue line in Fig. 6a-c. This permanent trough becomes deeper during fall seasons in which the QBO phase is positive and fills during years in which the QBO phase was negative in the fall. This difference in the strength of the north Asian trough in winter months leads to the wave pattern that sets up in the spring as shown in Fig. 5.

3.4 QBO-ENSO Implications

Several previous studies have suggested that ENSO, a sea surface temperature (SST) anomaly in the tropical Pacific, influences the QBO. One such study suggested that El Niño may suppress mixed Rossby-gravity wave activity (Maruyama and Tsuneoka 1988). It is also known that the combination of gravity waves, planetary waves, and

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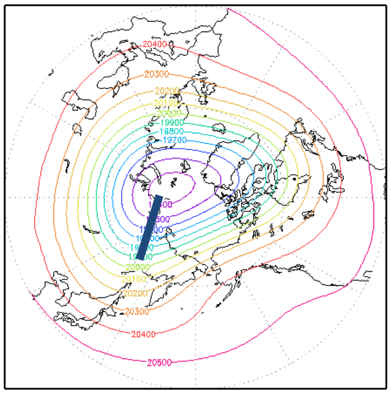

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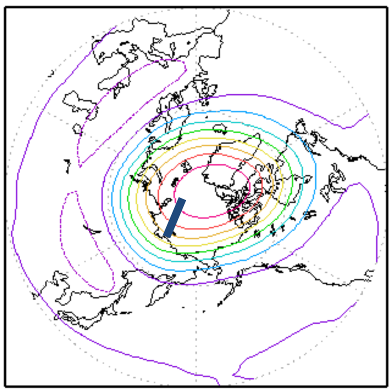

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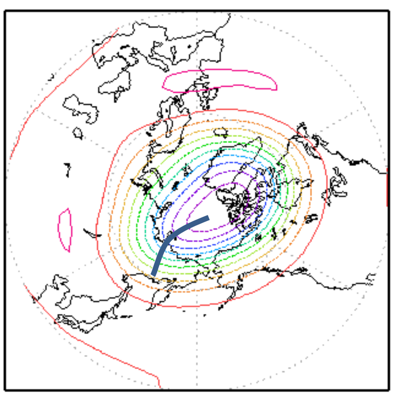


Fig. 6

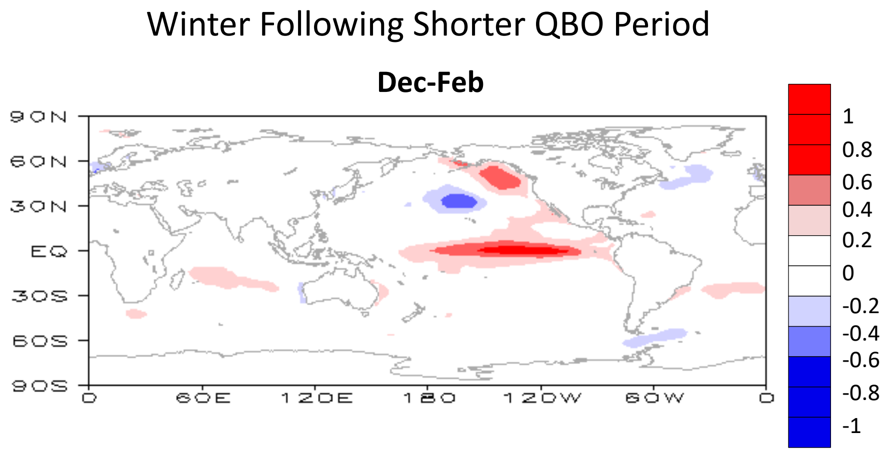
a Long-term mean plot shows the average 50 mb stream function conditions for 1960-2012 averaged for January-March. Blue line represents trough toward northern Eurasia associated with Polar Vortex. **b** QBO negative phase-composites show average 50 mb January-March stream function anomaly. Short blue line represents lack of trough toward northern Eurasia associated with Polar Vortex. **c** QBO positive-phase composites show average 50 mb January-March stream function anomaly. Blue line represents trough toward northern Eurasia associated with Polar Vortex.

tropical advection provides the necessary forcing mechanism for the QBO, with 60-80% of the forcing coming from gravity waves (Evan et al. 2012).

Here, we test these findings regarding the influence of ENSO on the QBO. Three-month average SST anomaly plots were constructed for December-February based on the length of the QBO phase the prior year. The length of the QBO phase or period was determined by whether the phase length was one-half standard deviation or more from the average. The average phase length for the negative phase of QBO was 15.9 months with a standard deviation of 3.1 months, whereas for the positive phase it was 12.7 months with a standard deviation of 2.3 months. One whole cycle of the QBO takes 28.6 months on average with a standard deviation of 3.2 months. For years in which the QBO phase length is shorter, the following winter tended to favor La Niña conditions, whereas a longer QBO phase length led to El Niño in many cases (Fig. 7a). A significance test for the years 1960-2013 was conducted. This was done computing R-squared for a linear regression of the QBO phase length versus the change in the ENSO index that came the following December-February. This resulted in a significance level of 99%.

Plots of the average April-June precipitation anomaly for the western United States were constructed based on combined QBO and ENSO phases. These were compared to plots of average April-June precipitation based on only the QBO phase. These plots show that during El Niño the effects of the QBO were more pronounced for the IW and a larger portion of the western United States. For La Niña years, the QBO wet case was focused mainly over western Washington, western Oregon, and north-central Utah, while the QBO dry case had no drying effect for the IW (Fig. 8a-f).

(a)



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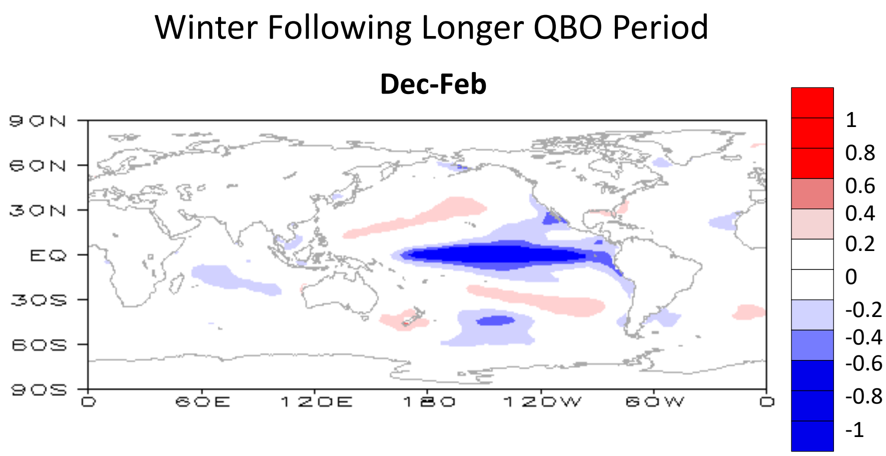

Fig. 7
a Composite of 3-month mean SST anomaly for years in which QBO phase length had been a half standard deviation or more shorter than normal the previous year. SST anomaly is in degrees Celsius. **b** Composite of 3-month mean SST anomaly for years in which QBO phase length had been a half standard deviation or more longer than normal the previous year.

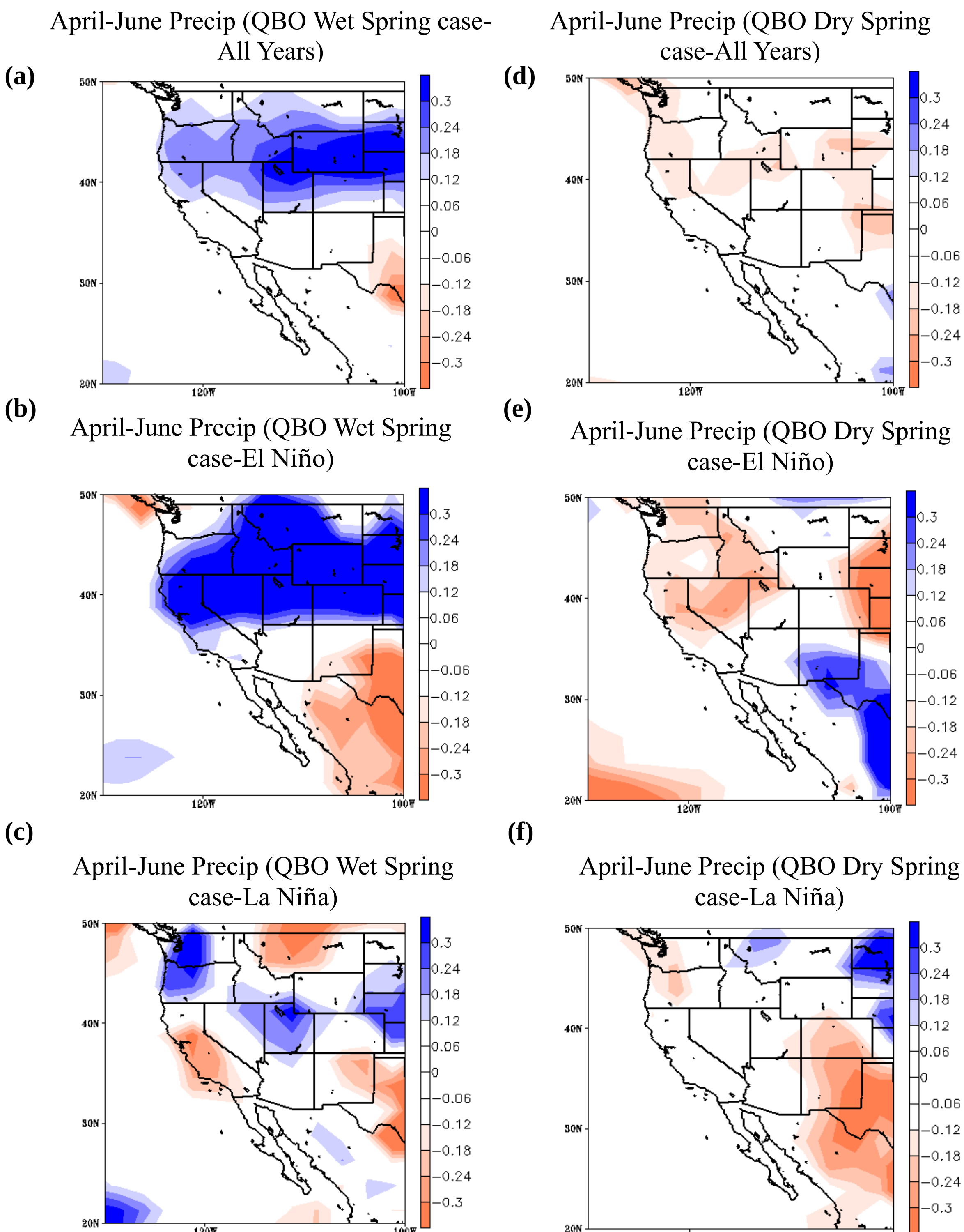

Fig. 8

a April-June average precipitation in mm/day plot for all QBO wet-case years. **b** for QBO wet-case El Niño years. **c** for QBO wet-case La Niña years. **d** for all QBO dry-case years. **e** for QBO dry-case El Niño years. **f** for QBO dry-case La Niña years.

CHAPTER 4

CONCLUDING REMARKS

Previous studies have stated that stratospheric planetary waves provide a necessary coupling that allows tropical Rossby waves associated with the QBO to influence extratropical Rossby waves and the Polar Vortex (Dunkerton 1997; Maruyama and Tsuneoka 1988). The analysis in this study supports such a coupling. Further, this research supports past studies that the western Pacific planetary waves associated with the QBO lead to a high-low pressure anomaly dipole in the extratropical to southern polar region in the fall (O'Sullivan and Young 1992; Watson et al. 2011). Due to the effect of the QBO on the Polar Vortex, a positive QBO phase in fall leads to an anomalous Rossby wave activity flux over northern Eurasia in winter at stratospheric levels. This feeds Rossby wave energy into an atmospheric wave pattern across the Pacific, causing a wetter-than-normal climate in March-June for the IW. A negative QBO phase in fall leads to a slightly drier-than-normal March-June for the IW. We illustrate the dynamical pathway by which the QBO influences the Polar Vortex and in turn leads to the generation of Rossby wave activity flux over East Asia. This leads to an area of higher-than-normal pressure near 40°N over the Pacific, resulting in the observed precipitation deficit in spring for the IW. On the other hand, a positive QBO phase in fall leads to a generally opposite polarity in the circulation anomalies and a subsequent wetter-than-normal spring in the IW.

Our results suggest that the fall QBO phase may improve predictability for spring precipitation in the IW, especially for extreme wet springs. This could be useful for

(a)

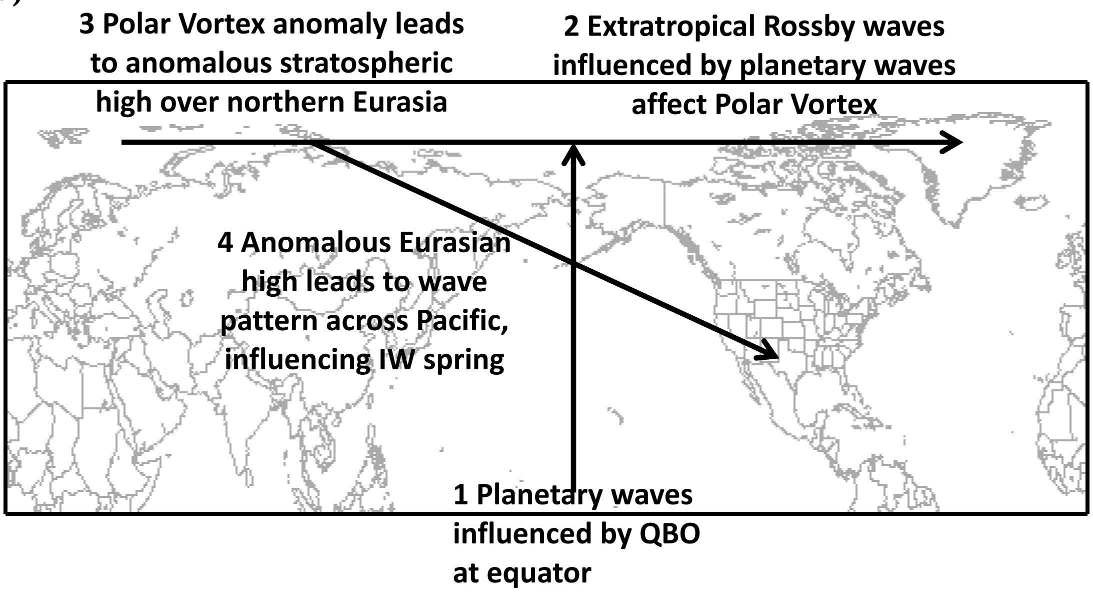

Fig. 9
a Schematic of the processes that cause the QBO to influence spring precipitation in the IW.

predicting flood events and spring runoff, with the highest degree of predictability for flood events in the IW, because the dry case was less robust. It is also important to remember that Scaife et al. (2014) suggested that the phase of the QBO can be predicted one to three years in advance with a high level of accuracy. If this is true, there may be some predictability of March-June precipitation for the IW up to several years in advance.

Based on the high predictability of the QBO, as of February 2019, a forecast could be made for this year's spring precipitation, as well as for that of one to three years in advance. In order to make such a forecast, one could look at the QBO wind speed and direction for the period from September to February. For 2019, the QBO switched from easterly to westerly wind direction in November. This likely means the QBO will not reach the strongest westerly winds until the spring months. Based on past records, there

has never been a year in which the QBO switched from easterly to westerly in the month of November since upper air data became reliable in the late 1950s. However, in 1977, 1994, and 2001, the QBO wind direction changed from easterly to westerly in December. In 1978 and 2002, the IW spring was drier than normal or near average precipitation. For 1995, the IW spring was wetter than normal. One could also analyze this year's stream function anomaly plots for the fall to early winter months to see if the pattern appears similar to the wet or dry spring case. This year's stream function anomaly plot for November to January appears significantly different than the wet spring or dry spring case. Based on 1978, 1995, and 2002 spring IW precipitation, and this year's fall to early winter stream function anomaly varying significantly from either the wet or dry spring case, it appears unlikely the QBO will have a significant effect on spring precipitation in the IW in 2019.

In order to make a prediction of spring precipitation in the IW a year or more in advance, one would construct a model of the QBO similar to that constructed by Scaife et al. (2014). Based on the wind direction predicted by that model for one to three years in advance, it would be possible to predict spring precipitation for that time interval. This assumes the season for strongest westerly or easterly winds could be accurately forecast, as it is necessary for the strongest westerly or easterly winds to occur in fall or early winter.

A more reliable long-term forecast of spring precipitation in the IW has several benefits. Water managers or forecasters could use this information to help predict floods, landslides caused by increased rainfall, and the amount of water available in the summer season. Firefighters could implement these forecasts to help predict the severity of the

fire season months or years in advance. The energy sector may find these forecasts useful for determining how much hydroelectricity will be available in a given year, based on how spring precipitation will affect summer water levels. City managers may be interested in these predictions for knowing how much spring precipitation will occur and how that might affect drinking water for a city in the summer months. This analysis of the QBO effects on IW spring precipitation and predicting the QBO in advance thus proves important for the IW region, its citizens, and forecasters alike.

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