Combined Impacts of ENSO and MJO on the 2015 Growing Season Drought over the Canadian Prairies

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Abstract

Warm-season precipitation over the Canadian Prairies plays a crucial role in activities in environment and society and has particular importance to agricultural production over the region. This research investigates how a warm season precipitation deficit over the Canadian Prairies is related to tropical Pacific forcing in the early summer 2015 drought. The significant deficit of precipitation in May and June of 2015 were coincident with a warm phase of El Nino-Southern Oscillation (ENSO) and a negative phase of Madden-Julian Oscillation (MJO)-4 index as they both favor a positive geopotential height anomaly in western Canada. Further investigation during the instrumental record period (1979-2015) shows that the warm-season precipitation in the Canadian Prairies and the corresponding atmospheric circulation anomalies over western Canada teleconnected with the lower boundary conditions in the tropical western Pacific. MJO may play a crucial role in determining the summer precipitation anomaly in the western Canadian Prairie when equatorial central Pacific is warmer than normal (NINO4 > 0) and MJO is more active. The mechanism of this teleconnection may be due to the propagation of stationary Rossby wave that is generated in the MJO-4 index region. When the tropical convection around MJO-4 index regions (western tropical Pacific, centered over 140 E) is more active than normal when NINO4 >0, a Rossby wave train originates from western Pacific and propagates into the midlatitude North America causing an anomalous ridge in the upper level over western Canada.

1 Introduction

The Canadian Prairies are highly dependent on summer precipitation especially during the early to mid-growing season (May through July) when the majority of annual precipitation normally occurs (Bonsal et al. 1993). High natural variability in growing season precipitation causes periodic occurrences of extreme precipitation (Li et al. 2017) and droughts that are often associated with reduced agriculture yields, low stream flow, and increased occurrence of forest fires (Wheaton et al. 2005, Bonsal and Regier 2007). Drought events with great environmental and economic impacts have occurred in 1961, 1988, 2001-2002, and as recent as 2015 (Dey 1982, Liu et al. 2004, Bonsal et al. 1999, Wheaton et al. 2005, Shabbar et al. 2011, Bonsal et al. 2013, Szeto et al. 2016). The sub-seasonal forecasting of precipitation during the growing season are crucial for the agriculture, water resource management, and the economy in the region. Therefore, an investigation into the potential causes of the inter-annual variability of growing season precipitation of the Canadian Prairie is much needed to provide important information for the agriculture and economy in the region.

Low precipitation and extended dry periods on the Canadian Prairies are often associated with upper-level ridge and a persistent high pressure centered over the Prairies (Dey 1982, Liu et al. 2004). These prolonged atmospheric anomalies often concurred with abnormal boundary conditions such as large-scale sea surface temperature (SST) anomalies in the Pacific (Shabbar and Skinner 2004). Large scale oscillation in the SST anomalies in Pacific Ocean, namely El Nino, the Pacific Deccadal Oscillation (PDO), can affect the hydroclimatic pattern in North America, although the strongest impacts of these boundary conditions occur during the boreal winter. Inter-annual variabilities such as El Nino-Southern Oscillation (ENSO) events are found to be linked with extended droughts in the Prairies (Bonsal et al. 1999, Shabbar and Skinner 2004). Interdecadal oscillation such as the PDO, and the Atlantic Multi-decadal Oscillation (AMO) have also been found to affect the seasonal temperature and precipitation in the Canadian Prairies (Shabbar et al. 2011).

ENSO's relationship with the Canadian Prairies' precipitation has been studied extensively. The warm phase of ENSO often favours drought in the Canadian Prairies, especially during the growing season after the mature phase of El Nino with North Pacific Mode (NPM) like North Pacific SST anomaly pattern (Bonsal and Lawford 1999, Shabbar and Skinner 2004). Previous investigations (e.g., Shabbar *et al*. (2011)) have found El Nino events are associated with a summer moisture deficit in the western Canada while La Nina events cause an abundance of moisture in extreme western Canada (British Columbia and Yukon). However, they also noted that although tropical SST variability accounted for some aspects of the large-scale circulation anomalies that influence Canadian Prairies drought, a consistent and clear-cut relationship was not found. North Pacific SST warm anomalies, which often follow a matured El Nino, and accompanying atmospheric ridging leads to extended dry spells over the Prairies during the growing season (Bonsal and Lawford 1999). For the recent North Pacific SST anomaly from 2013 to 2014, researchers have attributed the precipitation deficit in California during 2013 to the anomalous upper-level ridge over the western North America (Wang *et al*. 2014, Szeto et al. 2016).

The formerly mentioned SST variations (ENSO, PDO, etc.) mostly vary on interannual and decadal scales. Another important factor that affects the weather patterns in North America is the Madden-Julian Oscillation (MJO), an intra-seasonal (40-90 days) oscillation in convection and precipitation pattern in the Tropics (Zhang 2005, Madden and Julian 1971, Riddle *et al.* 2013, Carbone and Li 2015). MJO is a coupled atmosphere-ocean oscillation involving convections and large-scale equatorial waves, which produces an eastward movement of tropical convection anomaly on an intraseasonal scale (Madden and Julian 1971). MJO has been found to affect the winter temperature and precipitation in North America and Europe through its impact on moisture transport associated with “Pineapple Express” and its effects on North Atlantic Oscillation and stratospheric polar vortex (Cassou 2008, Garfinkel *et al.* 2012, Rodney et al. 2013). MJO has been found to be connected to precipitation anomalies to summer precipitation in the Southwest United States (Lorenz and Hartmann 2006). During spring and summer, MJO's impact on the Canadian Prairies' precipitation has not been thoroughly investigated as MJO’s amplitude is weak during summer. The amplitude of MJO in spring and early summer, however, is related to the interannual variation of tropical SST, especially the SST in central Pacific (Hendon et al. 2007, Marshall et al. 2016). The amplitude of MJO in terms of the Real-time Multivariate MJO index (RMM, Wheeler and Hendon 2004) was extremely strong in the early spring of 2015 with high SST anomaly in the central Pacific and El Nino became strong.

MJO activities in the western Pacific under the modulation of interannual variability of SST have the potential to act together and impact mid-tropospheric circulation over western Canada and thus, warm season precipitation over the Canadian Prairies. The goal of the study is to demonstrate that the mechanism involved MJO may cause the meteorological drought in growing season in the Canadian Prairies in 2015. Subsequently, further investigations are carried out to determine if similar relationships exist in association with other summer extreme precipitation events during instrumental record (1979-2016). Section 2 provides the datasets and methodologies used in this paper while section 3 presents analyses of the upper-level circulation anomaly and SST pattern associated with the 2015 drought. This is followed by examination of the effects of central Pacific SST anomaly and MJO on the summer precipitation in the Canadian Prairies using data during instrumental record period.The potential mechanism by which MJOaffects summer precipitation when equatorial central Pacific SST is warmer than normal is discussed in section 4 followed by a summary of the results and concluding remarks in section 5.

2 Data and Methodology

2.1 Data

Multiple observation and reanalysis datasets are used to investigate the circulation anomalies associated with Canadian Prairie growing season (May-August) precipitation. Observed precipitation is taken from the Climate Prediction Center (CPC) Merged Analysis of Precipitation (CMAP) dataset (Xie and Arkin 1997). Geopotential height fields include those from the National Center for Environmental Predictions (NCEP) Reanalysis (Kalnay *et al.* 1996) and the European Center for Medium-Range Weather Forecast (ECMWF)'s ERA-interim (Dee *et al.* 2011), and are used to analyze upper-level (200 hPa and 500 hPa) atmospheric circulation patterns.

To represent the central Pacific SST anomaly, NINO4 SST index (Rayner et al. 2003) from CPC of National Oceanic and Atmospheric Administration (NOAA) is used since the NINO4 region is near central Pacific and spans over the dateline (5°S-5°N, 160°E-150°W). Multivariate ENSO Index (MEI) data are retrieved from National Oceanic and Atmospheric Administration (NOAA)'s Climate Data Center (CDC) website and are used to determine the ENSO phase (Wolter 1987, Wolter and Timlin 1993). In particular, an El Nino condition is defined when the monthly mean index of MEI is larger than 0.5 as it identifies El Nino events consistently (Andrews et al. 2004).

The Real-time Multivariate MJO series (RMM1 and RMM2) developed by Wheeler and Hendon (2004) are used to identified the periods of strong MJO activities as the MJO amplitudes are readily available by the calculation of the square root of RMM1 + RMM2. For MJO intensities in a region, we used the monthly averaged pentad MJO indices from NOAA CPC's MJO index (Xue *et al.* 2002) which have 10 indices representing locations around the globe. The CPC's MJO index is based on Extended

Empirical Orthogonal Function (EEOF) analysis on pentad velocity potential at 200-hPa. Ten daily MJO indices are constructed by projecting the daily (00Z) velocity potential anomalies at 200-hPa (CHI200) onto the ten time-lagged patterns of the first EEOF of pentad CHI200 anomalies (Xue *et al.* 2002). Negative values of ten MJO indices correspond to enhanced convections to 10 regions centered on 20°E, 70°E, 80°E, 100°E, 120°E, 140°E, 160°E, 120°W, 40°W and 10°W in the tropics. A negative value of the CPC's MJO indices (usually varies between -2 to 2) indicates an above average convective activities in the corresponding region. Because boreal summer corresponds to a period of weaker amplitude of MJO than winter, we choose monthly mean value of -0.3 as the criterion of strong convections that are connected to MJO. The monthly mean MJO-4 index less than -0.3 is the criterion considered as a relatively strong convection associated with MJO in the western Pacific where has been found to be a source region of stationary Rossby waves (Simmons 1980). SST observations include Extended Reconstructed Sea Surface Temperature (ERSST) v4 (Huang *et al.* 2015). Outward Longwave Radiation (OLR) data from NOAA Interpolated Outgoing Longwave Radiation (hosted at http://www.esrl.noaa.gov/psd/map/clim/olr.shtml) are used to derived the composite anomalous field of OLR for a certain phase of MJO as described below.

3 Results

This study focuses on the growing season precipitation in the provinces of Alberta and Saskatchewan in the Canadian Prairies, where the largest deficits were observed in 2015. Specifically, the regional mean precipitation over 115°-102.5°W, 50°-57.5°N is used (boxed arear in Figure 1) to represent the

Canadian Prairies east of the Rocky Mountains and south of the boreal forest. The region chosen also covers most of the arable land in the Canadian Prairies for datasets with 2.5-degree resolution. As the indicated by the MJO-4 and NINO4 index for 2015, the relationship between the Prairies' warm season (May-August) precipitation with MJO-4 and ENSO during the instrumental records are investigated using correlation and regression. The possible mechanism behind the correlation between MJO-4 and the Prairie's warm season precipitation during El Nino condition is further investigation by analyzing the upper-level circulation associated with convections in the Tropics and stationary Rossby waves in the midlatitudes.

3.1 The 2015 Summer Drought

Almost all of western Canada including British Columbia, the southern Northwest Territories, Alberta and Saskatchewan had significant negative precipitation anomalies during May and June 2015. The warm season precipitation is represented by the monthly mean precipitation from May to August (Bonsal *et al*. 1999, Shabbar *et al.* 2011). For the 2015 case study, during May-June, the prairies' precipitation was significantly below average. The top plot in Fig. 1 shows the precipitation anomaly in percentage relative to climatology (1981-2010 long term mean) in Canada during May and June 2015. The bottom plot in Fig. 1 presents the monthly precipitation anomaly averaged over the region encompassed by the dash lines (50N-57.5N, 115W-102.5W). The annual cycle of the regional precipitation has, in average, a dry period between February and May. Regarding the precipitation climatology, June has the largest precipitation in all months with significantly more rain than neighboring months. When both May and June 2015 witness much less precipitation than normal in addition to a relatively dry period from February to April, the region gets little precipitation.

Fig. 1 Top: Precipitation anomalies (mm) from CMAP over the region (115 W-102.5 W, 50 N-57.5 N) during May and June 2015. Bottom: time series of monthly precipitation anomaly over boxed region between September 2013 and August 2015.

The upper-level geopotential height anomaly averaged in May and June are examined together with SST anomaly and ENSO, MJO-4 indices for 2014 and 2015. The 500 hPa geopotential height (GPH) anomaly for the May and June 2015 shows strong positive anomalies near Alaska and British Columbia coast in Fig. 2, which is consistent with the findings for other growing season droughts (e.g., Dey 1982; Bonsal and Wheaton, 2005). Accompanying this anomalous ridge extending from Alaska to Pacific Northwest of the US is an above normal warm SST in the northeast Pacific off the coast of North America and the central-eastern Pacific (Fig. 3). Both ENSO and North Pacific Mode (NPM) (Hartmann et al. 2015) are in positive phases that corresponds to a warmer SST near the Pacific coast of North America, consistent with the positive GPH anomalies in western Canada and Alaska. The ridge in Alaska/Bering Straits and the one near British Columbia coast are associated with El Nino and North Pacific SST anomaly such as NPM (Shabbar *et al.* 2011). The monthly mean anomalous ridge indicates a tendency to prevent storms from reaching the British Columbia coast and the Canadian Prairies causing extended dry spells. The GPH anomaly in early growing season in 2015 is consistent with the precipitation anomaly in these regions. The anomalous upper-level ridge in the Western United States and Canada in 2014 and 2015 have also been associated with the developing El Nino and the other main components of Pacific sea surface temperature (SST) variation such as NPM by several recent studies (Hartmann 2015, Lee *et al*. 2015, Li et al. 2017).

Fig. 2 NCEP GPH anomaly at 500hPa during May and June 2015 when the precipitation deficit was the largest.

Fig. 3 shows the average SST anomaly during the growing season (May-August) of 2015. The strong positive anomaly in the Northeast Pacific and eastern equatorial Pacific is evident and persistent through the summer, which corresponds to the warm phase of NPM and ENSO, respectively. SST in the eastern tropical Pacific warms increasingly since the end of 2014 and qualifies as an El Nino in early 2015. The NPM becomes positive since fall 2013 and turns to exceptionally strong in 2014 and persist to 2015 (Hartmann 2015). The anomalous ridge is concurrent with strong SST anomalies in both tropical Pacific and extratropical North Pacific. NPM, as the third EOF of Pacific SST (30S-65N), also has a strong connection to the anomalous ridge in the western North America and trough in the eastern US and Canada in 2013-2014 winter (Hartmann 2015, Lee *et al.* 2015). During the ENSO-neutral condition in 2013 and 2014, the precursor of ENSO, so-called "footprinting" mechanism is considered by some researchers to cause this anomalous ridge in the western North America (Wang *et al.* 2014).

Summer of 2015 is the first summer after the developing El Nino during 2014-2015 winter. Though the upper-level GPH pattern seen in summer 2015 can be attributed to the SST modes in the Pacific Basin, namely ENSO and NPM, the precipitation in the Western Canadian Prairie is not strongly correlated with either of them. Bonsal and Lawford (1999) found that more extended dry spells tend to occur during the second summer following the mature stage of the El Nino events. The winter precipitation in Canada has been shown to have a strong connection to ENSO (Shabbar et al. 1997), whereas summer precipitations in most regions of western Canada (except the coast of British Columbia and Southern Alberta) do not have significant correlations with ENSO. This is consistent with our investigation using instrumental records from 1948 to 2016.

The variation of the Canadian Prairies' precipitation and its relationship with SST modes and MJOs shown in Fig. 4. The time series of monthly RMM amplitude anomaly, NINO4 index, MJO-4 indices and the Canadian Prairies precipitation anomaly from January 2014 to December 2015 shows the atmospheric-oceanic circulation condition for the drought in 2015. In 2015 both May and June saw a strong MJO-4 negative indices, whereas in July the MJO-4 index became positive. This corresponds quite well with the precipitation anomaly in Fig. 1. As shown in Fig. 3, the 0El Nino continued to strengthen in July and August 2015; in the meantime, the MJO-4 index increased in July and August 2015. The increase of MJO-4 index corresponded to the active convections associated with MJO in West Pacific propagated eastward into the central Pacific; the precipitation in the Canadian Prairie returned to slightly above normal in July.

The good correspondence of MJO-4 index and negative precipitation anomaly suggests a link between MJO related tropical convection anomaly and the prairie precipitation during growing season. Though El Nino and associated Northeast Pacific warm anomaly (i.e., NPM) in summer 2015 can be a contributing factor for the upper-level ridge on the west coast of Canada, it cannot fully explain the drought condition in West Canada as these SST conditions does not guarantee a prolonged dry spell as shown by correlation analysis. The negative MJO-4 index concurred with the negative anomaly of Prairie precipitation in 2015, which prompts the investigation of their relationship in the instrumental records.

Fig. 3 The mean SST anomaly(ºC) from ERSST v4 in May-August 2015.

Fig. 4 RMM amplitude anomaly, NINO4, MJO 4 indices and precipitation anomaly of Canadian Prairies from January 2014 to Dec 2015.

3.2 Instrumental record

El Nino and its associated North Pacific SST anomaly may contribute to extended dry spells in Canadian Prairies after the matured phase of El Nino (Bonsal et al. 1993) on an interannual time scale. ENSO, however, is not a strong intra-seasonal to seasonal predictor of Canadian Prairie summer precipitation. Here we present a new result showing that under warm central Pacific SST condition

(NINO4 >0), a certain phase of MJO, which connected to the active convections in the tropical western Pacific (Li and Carbone 2012), plays an important role to determine the precipitation in the Canadian Prairies in the early summer months.

Table 1 Correlation between mean precipitation anomaly from CMAP in the prairie and MEI, MJO indices 4. MJO indices and are from 1979 to 2016. CMAP covers 1979 to 2016.

The correlation coefficients between the mean regional precipitation anomaly over Canadian Prairies and MJO-4 indices and MEI from May to August are shown in Table 1. The correlation between MEI and the precipitation anomalies is not significant. The negative MJO-4 index represents a stronger than normal convection in the Maritime Continents and the tropical Western Pacific. The correlation between MJO-4 index and precipitation in the Prairies indicates that stronger tropical convections in the Equatorial region centered around 140ºE favor less precipitation in the Canadian Prairies from May to August. The correlation between MJO-4 index and the growing season Prairie precipitation anomaly is 0.18 with a p-value of 0.023. The correlation between MJO-4 index and the precipitation anomaly during growing season when NINO4 >0 is much higher at 0.33 with a p-value of 0.0015. The correlation between MJO-4 and the Canadian Prairie precipitation when NINO4 < 0 is -0.01.

Fig. 5 The scatterplot of monthly precipitation anomaly (mm/month) as a function of MJO-4 and NINO4. Each asterisk represents a month from May to August 1979-2016. Circled asterisk denotes a month with precipitation anomaly larger than 18 mm/month. The blue circles are months with positive precipitation anomaly and the red circles are months with negative precipitation anomaly. The sizes of circles denote the magnitudes of the anomalies (large > 30 mm/month, medium > 24 mm/month, small >18 mm/month). The shaded area denotes NINO4>0 and MJO-4 index < 0.

The scatter plot in Fig. 5 shows the distribution of monthly precipitation anomaly versus MJO-4 index and NINO4 index, which together affect the precipitation anomaly from May to August. Circled asterisk denotes a month with precipitation anomaly larger than 18 mm/month and the red (blue) circles denote negative (positive) precipitation. The sizes of the circle represent the magnitude of the monthly precipitation anomalies. In the bottom-right region indicated by shading, under NINO4 > 0 condition, negative MJO-4 corresponds to many more dry months than wet months. We noticed that some significant dry months are not in the shaded region which corresponds to the dry months occur in La Nina condition or in the period after the mature phase of El Nino (Bonsal et al. 1999).

Fig. 6 The box-percentile plot of Canadian Prairies precipitation anomaly during growing season for ENSO conditions.

To investigate the impact of ENSO on the growing season precipitaiton over Canadian Prairies, the distribution of precipitation anomaly along ENSO conditions are plotted. The box-percentile plot in Fig. 6 shows the distribution of monthly Canadian Prairies' precipitation anomalies from May to August along ENSO condition. In general, under El Nino and ENSO neutral condition the precipitation anomalies centered on 0, and there is no bias toward either end. Under La Nina condition, the mean precipitation has a positive bias. There are only 10 summer months under La Nina condition, whereas both El Nino and neutral condition have 71 months.

The distributions of precipitation anomalies versus MJO-4 index under different ENSO conditions are shown in Fig. 7. Under warm central Pacific SST condition (NINO4 >0), the precipitation anomaly has a negative tendency for MJO-4 < -0.3. Under NINO4 >0 condition, there is no such negative tendency for the precipitation anomaly under the condition of MJO-4 < -0.3. Based on Fig. 6 and 7, the significant correlation between precipitation and MJO-4 under NINO4 > 0 condition relative to ENSO in Table 1 is demonstrated in detail.

Fig. 7 Box-percentile plots of Canadian Prairies' precipitation anomaly during growing season versus MJO-4 under warm NINO4 (NINO4> 0, left) and cold NINO4 (NINO4<0, right) condition.

The strong correlation between MJO-4 and the prairie precipitation during growing season leads us to investigate the underlying circulation anomalies. Fig. 8 presents the regressed stream function and wind field at 200 hPa in the midlatitudes (north of 30N) on the negative MJO-4 index from May to August under warm NINO4 SST condition (NINO4 > 0.). In the tropics (10S-20N, considering it is during Northern Hemisphere summer), the OLR, velocity potential, and divergent wind vector are plotted. Only regression patterns have p-values lower than 0.05 are plotted for OLR and velocity potential. The negative MJO-4 index corresponds to a negative anomaly in OLR, stronger convection and larger than average divergence in the region centered on 150 E. The strong convection anomaly centers on 150 E, 5 N with divergent wind extending well into the subtropics in the Northern Hemisphere. The positive GPH/stream function anomaly extended from Japan to central Pacific is associated with the enhanced convection and divergence in the upper troposphere over the western tropical-subtropical Pacific. A Rossby wave train linked to the OLR anomaly and strong divergence in the western Pacific propagate eastward into North America.

4 Discussion

The growing season precipitation in the Canadian Prairies are affected by many factors and precipitation deficit can occur under various circulation and lower boundary conditions. Thus it is not expected to find a universal condition for all the significant droughts in the region. In fact, extreme drought conditions have been found in both El Nino years and La Nina years. Though previous research by Bonsal and Lawford (1999) indicates the meteorological drought often occurs after the mature phase of El Nino, which is not the case for 2015, the associated changes in the North Pacific represented by

NPM positive phase is consistent with their results. The direct linkage between ENSO and the summer precipitation in the Canadian Prairies is still not clear. In fact, the correlation between MEI and precipitation in the investigated region is -0.096 ($p=0.2389$, sample size = 152). It is not a significant correlation which is consistent with other researchers' findings (Dai and Wigley 2000).

The regression pattern is consistent with stationary Rossby wave theory as shown in a hierarchy of theoretical and modeling studies (Karoly *et al.* 1989, Simmons *et al.* 1983, Hoskins and Ambrizzi 1993, Ambrizzi and Hoskins 1997, Held *et al.* 2002). A similar wave train extends from the western Pacific toward South America in the extratropics but at lower latitudes compared to its counterpart in the Northern Hemisphere (not shown). The node of the wave train in Western Canada and Northwest Pacific of the US corresponds to an anomalous ridge, which is in-phase of El Nino forcing. When the convection in the region associated with MJO-4 is weaker than normal (MJO-4 > 0), a wave train with the opposite sign would reach western Canada which would counterac El Nino forcing. Thus, the weak correlation between Canadian Prairie precipitation and ENSO is understandable as MJO plays an additional role that enhances or cancels out the GPH anomaly caused by El Nino.

The atmospheric response in midlatitude North America to the tropical forcing in the western Pacific depends on the mean circulation condition associated with tropical SST. Intraseasonal tropical convection oscillation in the western Pacific associated with MJO-4 index cannot determine the sign of precipitation anomaly in the prairie. Both warm SST in central Pacific and strong tropical convection in western Pacific and Maritime Continent are necessary to cause a significant precipitation deficit in the western Canadian Prairies. Warm SST in central Pacific causes an eastward expansion of Pacific warm pool that favors enhanced MJO activity in the western-central Pacific (Hendon et al. 1999, Marshall et al. 2016). For the year of 2015, while the anomalous positive GPH associated with strong negative MJO4 indices in addition to the SST anomaly in the Pacific (e.g. ENSO, NPM) forced the anomalous ridge on the west coast of Canada which reduces precipitation in the Canadian Prairies in the early summer. Although the El Nino continued to strengthen in July and August 2015, the active convections associated with MJO in West Pacific propagated eastward into the central Pacific, as the convection in the western Pacific/Maritime Continent waned, the precipitation in the Canadian Prairie returned to slightly above normal in July.

Fig. 8 The regression of stream function, wind field in the extratropics on MJO-4 for May-August with MEI > 0.5. Bottom: OLR, velocity potential, and divergent wind in the tropics on MJO-4 indices for May-August with $NINO4 > 0$. The shaded region for the tropical OLR has p-value < 0.05. Blue shading indicates active convection region. Red dashed contour and solid blue contour corresponds to negative and positive velocity potential, respectively.

5 Conclusions

The cause of the summer precipitation deficit in the western Canadian Prairies is investigated regarding atmospheric circulation anomalies, sea surface temperature, and intraseasonal tropical convection oscillation, MJO. The drought in western Canada is immediately related to the anomalous ridge in the upper-level. The persistent anomalous upper-level ridge hovering around the west coast of Canada and Alaska since fall 2014 is likely associated with SST anomaly in the tropical (ENSO) and extratropical Pacific (NPM) as both SST patterns tend to associate with an anomalous high in Alaska and western Canada. However, the anomalous ridge itself explains the drought in the western Canada, the underlying cause of the anomalous ridge and whether it is related to ENSO need investigation . After all the significant deficit of precipitation concentrated in May and June 2015 when El Nino was still growing in intensity. The correlation of ENSO with the prairie precipitation is also not significant during summer. Instead, the intraseasonal oscillation in tropical convection, MJO, plays an important role in determining precipitation anomaly during months with warm central Pacific SST (NINO4 > 0).

In general, MJO-4 indices demonstrate significant correlation with the meteorological drought from May to August with warm SST in central Pacific (NINO4 >0) when MJO amplitude is also often stronger. The new finding in our investigation is that MJO phase/strength is connected to the anomalous ridge in Western Canada when NINO4 is positive through the propagation of stationary Rossby wave from the western Pacific. The connection between the Canadian Prairie precipitation deficit and MJO is stronger when NINO4 is positive because MJO amplitude is stronger when the central Pacific SST is warmer than normal (NINO4 >0). The underlying cause of this significant correlation between MJO-4 indices and the prairie precipitation in May-August is a stationary Rossby wave train originates from Maritime Continent and western Pacific and propagate into Canada. The intra-seasonal predictability in MJO amplitude and phase can be potentially instrumental for medium-range/intra-seasonal projection of the growing season precipitation in the Canadian Prairies when the central-Pacific SST is warm.

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References

Ambrizzi T and Hoskins B J 1997: Stationary Rossby-Wave Propagation in a Baroclinic Atmosphere, *Quart. J. Roy. Meteor. Soc.,* **123** 919–28.

Andrews, E.D., R.C. Antweiler, P.J. Neiman, and F.M. Ralph 2004 Influence of ENSO on Flood Frequency along the California Coast. *J. Climate,* **17**, 337–348, doi: 10.1175/1520-0442(2004)017.

Bonsal, B.R., Chakravarti, A.K. and Lawford, R.G. 1993: Teleconnections between North Pacific SST Anomalies and Growing Season Extended Dry Spells on the Canadian Prairies, Int. J. Climatol., 13, 865-878.

Bonsal, B.R., Zhang, X. and Hogg, W.D., 1999: Canadian Prairie growing season precipitation variability and associated atmospheric circulation, *Climate Research*, *11*(3), 191-208.

Bonsal B and Lawford R 1999: Teleconnections between El Niño and La Niña Events and Summer Extended Dry Spells on the Canadian Prairies, *International Journal of Climatology,* **19,** 1445–58.

Bonsal B R, Shabbar A and Higuchi K, 2001: Impacts of Low Frequency Variability Modes on Canadian Winter Temperature, *Int. J. Climatol.* **21,** 95–108.

Bonsal B R and Regier M, 2007: Historical Comparison of the 2001/2002 Drought in the Canadian Prairies, Climate Research, **33**, 229-242.

Bonsal, B R, Aider, R, Gachon, P and Lapp S, 2013: An Assessment of Canadian Prairie Drought: Past, Present, and Future, Climate Dynamics, **41**, 501–516.

Carbone R. E., Yanping Li, 2015: Tropical Oceanic Rainfall and Sea Surface Temperature Structure: Parsing Causation from Correlation in the MJO, *Journal of Atmospheric Science*, Vol. 72, No. 7, 2703–2718.

Cassou C, 2008: Intraseasonal Interaction Between the Madden-Julian Oscillation and the North Atlantic Oscillation, *Nature,* **455** 523–7.

Dai A and Wigley T M L, 2000: Global Patterns of ENSO-Induced Precipitation, *Geophys. Res. Lett.,* **27** 1283–6.

Dee D P, Uppala S M, Simmons A J, Berrisford P, Poli P, Kobayashi S, Andrae U, Balmaseda M A, Balsamo G, Bauer P, Bechtold P, Beljaars A C M, Berg L van de, Bidlot J, Bormann N, Delsol C, Dragani R, Fuentes M, Geer A J, Haimberger L, Healy S B, Hersbach H, Hólm E V, Isaksen L, Kållberg P, Köhler M, Matricardi M, McNally A P, Monge-Sanz B M, Morcrette J-J, Park B-K, Peubey C, Rosnay P de, Tavolato C, Thépaut J-N, and Vitart F, 2011: The ERA-Interim Reanalysis: Configuration and Performance of the Data Assimilation System, *Quarterly Journal of the Royal Meteorological Society,* **137,** 553–97.

Dey B, 1982: Nature and Possible Causes of Droughts on the Canadian Prairies-Case Studies, *Journal of Climatology,* **2,** 233–49.

Garfinkel C I, Feldstein S B, Waugh D W, Yoo C and Lee S, 2012: Observed Connection Between Stratospheric Sudden Warmings and the Madden-Julian Oscillation, *Geophys. Res. Lett.,* **39.**

Hartmann D L, 2015: Pacific Sea Surface Temperature and the Winter of 2014, *Geophys. Res. Lett.,* **42,** 1894–902.

Held I. M., Ting M. and Wang H., 2002: Northern Winter Stationary Waves: Theory and Modeling *J. Climate,* **15**, 2125–44.

Hendon, H. H., C. Zhang, and J. D. Glick, 1999: Interannual variation of the Madden-Julian Oscillation during Austral summer, J. Clim., 12, 2538–2550

Hong, C. C., Hsu, H. H., Tseng, W.-L., Lee, M. Y., Chow, C.-H., & Jiang, L.-C. 2017: Extratropical Forcing Triggered the 2015 Madden–Julian Oscillation–El Niño Event. *Sci*. *Rep*. **7**, 46692; doi: 10.1038/srep46692.

Hoskins B J and Ambrizzi T, 1993: Rossby Wave Propagation on a Realistic Longitudinally Varying Flow. *J. Atmos. Sci.* **50** 1661–71

Huang B, Banzon V F, Freeman E, Lawrimore J, Liu W, Peterson T C, Smith T M, Thorne P W, Woodruff S D and Zhang H-M, 2015: Extended Reconstructed Sea Surface Temperature Version 4 (ERSST. v4). Part I: Upgrades and Intercomparisons *Journal of Climate,* **28** ,911–30.

Kalnay E, Kanamitsu M, Kistler R, Collins W, Deaven D, Gandin L, Iredell M, Saha S, White G, Woollen J, Zhu Y, Chelliah M, Ebisuzaki W, Higgins W, Janowiak J, Mo K, Ropelewski C, Wang J, Leetmaa A, Reynolds R, Jenne R and Joseph D, 1996: The NCEP/NCAR 40-Year Reanalysis Project *Bull. Amer. Meteor. Soc.* **77** 437–71

Karoly D J, Plumb R A, and Ting M, 1989: Examples of the Horizontal Propagation of Quasi-Stationary Waves. *J. Atmos. Sci.* **46** 2802–11

Lee M Y, Hong C C and Hsu H H 2015: Compounding Effects of Warm Sea Surface Temperature and Reduced Sea Ice on the Extreme Circulation Over the Extratropical North Pacific and North America During the 20132014 Boreal winter *Geophys. Res. Lett.,* **42**, 1612–8.

Yanping Li, Richard E. Carbone, 2012: Excitation of rainfall over the tropical western Pacific. *Journal of Atmospheric Science,* Vol. 69, No. 10, 2983–2994.

Yanping Li, Kit Szeto, Ron Stewart, Julie Theriault, Liang Chen, Bob Kochtubajda, Anthony Liu, Sudesh Boodoo, Ron Goodson, Curtis Mooney, Sopan Kurkute, 2017: The June 2013 Alberta Catastrophic Flooding: Water vapor transport analysis by WRF simulation. *Journal of Hydrometeorology,* Vol. 18, 2057-2078.

Zhenhua Li, Alan Manson, Yanping Li, Chris Meek, 2017: Circulation Characteristics of Persistent Cold Spells in Central-Eastern North America. *Journal of Met. Res*., Vol. 31, 250-260.

Liu J, Stewart R E and Szeto K K, 2004: Moisture Transport and Other Hydrometeorological Features Associated With the Severe 2000/01 Drought Over the Western and Central Canadian Prairies *Journal Of Climate,* **17**, 305–19.

Lorenz, D.J. and D.L. Hartmann, 2006: The Effect of the MJO on the North American Monsoon. *J. Climate,* **19**, 333–343, doi: 10.1175/JCLI3684.1.

Madden R A and Julian P R, 1971: Detection of a 40-50 Day Oscillation in the Zonal Wind in the Tropical Pacific, *J. Atmos. Sci.,* **28**, 702–8

Marshall, A. G., H. H. Hendon, and G. Wang, 2016: On the role of anomalous ocean surface temperatures for promoting the record Madden-Julian Oscillation in March 2015, Geophys. Res. Lett., 43,472–481.

Riddle E E, Stoner M B, Johnson N C, L'Heureux M L, Collins D C and Feldstein S B, 2013: The Impact of the MJO on Clusters of Wintertime Circulation Anomalies Over the North American region *Climate Dynamics,* **40**, 1749–66.

Rodney, M., Lin, H., & Derome, J. 2013: Subseasonal Prediction of Wintertime North American Surface Air Temperature during Strong MJO Events. *Monthly Weather Review*, *141*(8), 2897–2909. http://doi.org/10.1175/MWR-D-12-00221.1.

Ropelewski C F and Halpert M S 1986: North American Precipitation and Temperature Patterns Associated with the El Niño/Southern Oscillation (ENSO), *Monthly Weather Review*, **114**, 2352–62.

Shabbar, A., Bonsal, B. and Khandekar, M., 1997: Canadian precipitation patterns associated with the Southern Oscillation. Journal of Climate 10:3016-3027.

Shabbar A and Skinner W, 2004: Summer Drought Patterns in Canada and the Relationship to Global Sea Surface Temperatures, *Journal of Climate,* **17**, 2866–80.

Shabbar A, Bonsal B R and Szeto K, 2011: Atmospheric and Oceanic Variability Associated with Growing Season Droughts and Pluvials on the Canadian Prairies, *Atmosphere-Ocean,* **49**, 339–55.

Simmons A J, Wallace J M and Branstator G W, 1983: Barotropic Wave Propagation and Instability, and Atmospheric Teleconnection Patterns, *J. Atmos. Sci.,* **40**, 1363–92.

Szeto, K., X. Zhang, R.E. White, and J. Brimelow, 2016: The 2015 Extreme Drought in Western Canada. *Bull. Amer. Meteor. Soc.,* **97**, S42–S46,https://doi.org/10.1175/BAMS-D-16-0147.1.

Wang S Y, Hipps L, Gillies R R and Yoon J-H, 2014: Probable Causes of the Abnormal Ridge Accompanying the 2013-2014, California Drought: ENSO Precursor and Anthropogenic Warming footprint *Geophys. Res. Lett.,* **41** 3220–6.

Xie P and Arkin P A, 1997: Global Precipitation: A 17-year Monthly Analysis Based on Gauge Observations, Satellite Estimates, and Numerical Model Outputs. *Bulletin of the American Meteorological Society,* **78,** 2539–58.

Xue Y, Higgins W and Kousky V 2002: Influences of the Madden-Julian Oscillations on Temperature and Precipitation in North America during ENSO-neutral and Weak ENSO Winters, *Proc. workshop on prospects for improved forecasts of weather and short-term climate variability on subseasonal (2 week to 2 month) time scales.*

Wheaton, E, Wittrock V, Kulshreshtha S, Koshida G, Grant C, Chipanshi A, Bonsal BR, 2005: Lessons Learned from the Drought Years of 2001 and 2002: Synthesis Report. Agriculture and Agri-Food Canada, Saskatchewan Research Council Publ No. 11602–46E03, Saskatoon.

Wheeler, M. C., & Hendon, H. H., 2004: An all-season real-time multivariate MJO index: Development of an index for monitoring and prediction. *Monthly Weather Review*, *132*(8), 1917–1932.

Wolter, K., 1987: The Southern Oscillation in surface circulation and climate over the tropical Atlantic, Eastern Pacific, and Indian Oceans as captured by cluster analysis. J. Climate Appl. Meteor., 26, 540-558.

Wolter, K. and M.S. Timlin, 1993: Monitoring ENSO in COADS with a seasonally adjusted principal component index. Proc. of the 17th Climate Diagnostics Workshop, Norman, OK, NOAA/NMC/CAC, NSSL, Oklahoma Clim. Survey, CIMMS and the School of Meteor., Univ. of Oklahoma, 52-57.

Zhang C, 2005: Madden-Julian Oscillation *Reviews of Geophysics,* **43.**

Table 1 Correlation between mean precipitation anomaly from CMAP in the prairie and MEI, MJO indices 4. MJO indices and are from 1979 to 2016. CMAP covers 1979 to 2016.

	Correlation	p-value	No. of sample
MEI	-0.096	0.24	156
MJO-4	0.18	0.023	156
MJO-4(NINO4>0)	0.33	0.0015	90
MJO-4(NINO4<0)	-0.01	0.94	66

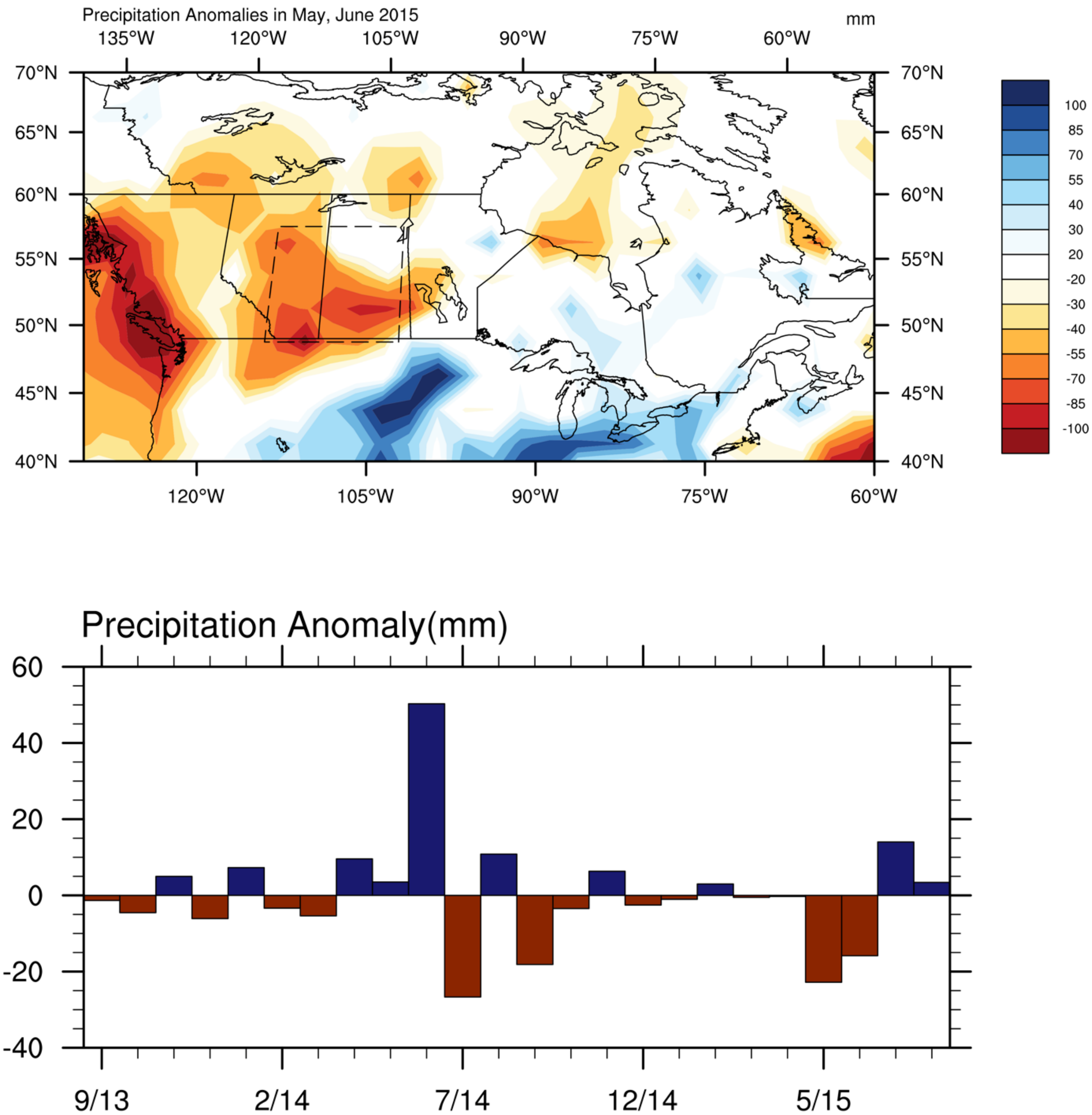

Fig. 1 Top: Precipitation anomalies (mm) from CMAP over the region (115 W-102.5 W, 50 N-57.5 N) during May and June 2015. Bottom: time series of monthly precipitation anomaly over boxed region between September 2013 and August 2015.

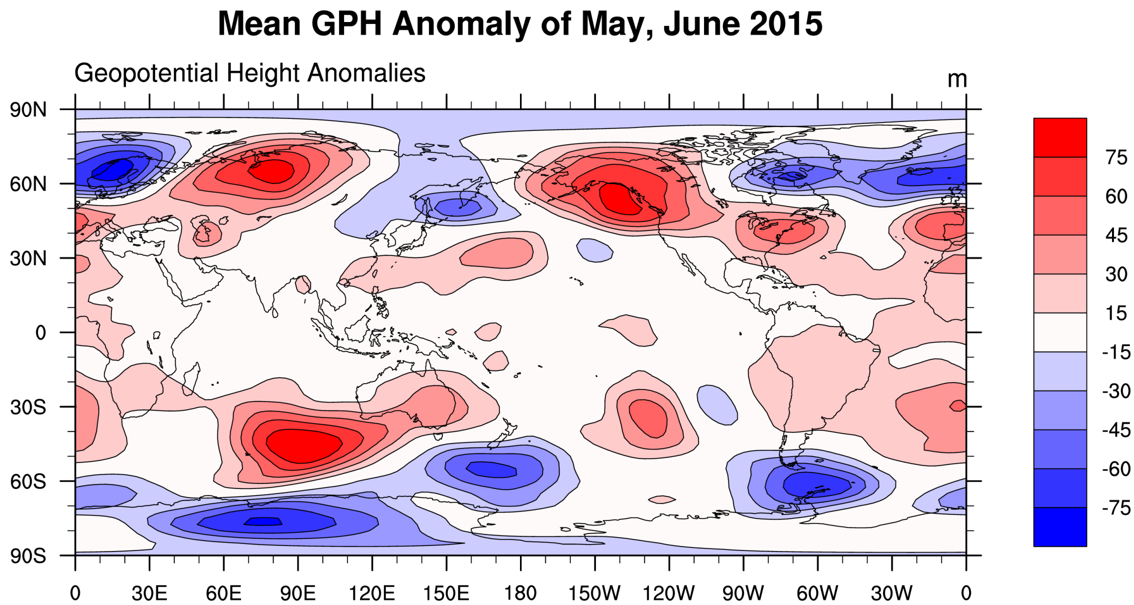

Fig. 2 NCEP GPH anomaly at 500hPa during May and June 2015 when the precipitation deficit was the largest.

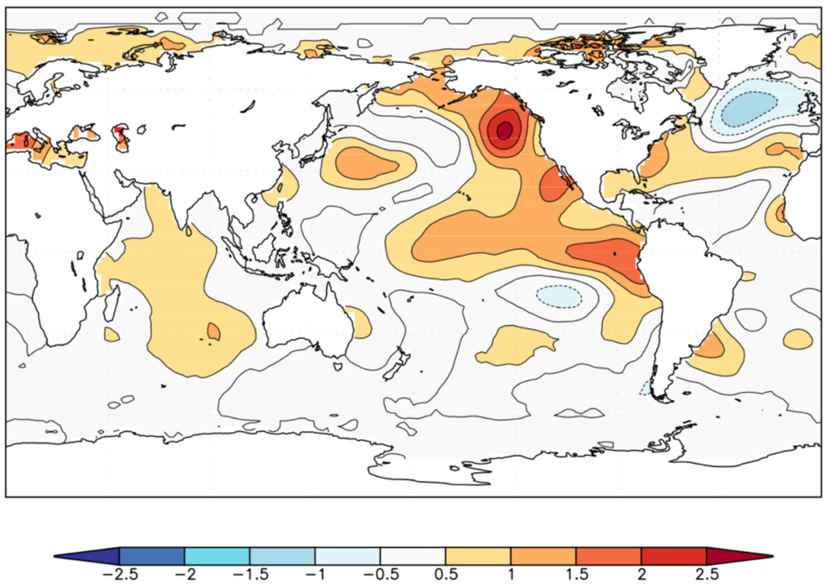

Fig. 3 The mean SST anomaly(ºC) from ERSST v4 in May-August 2015.

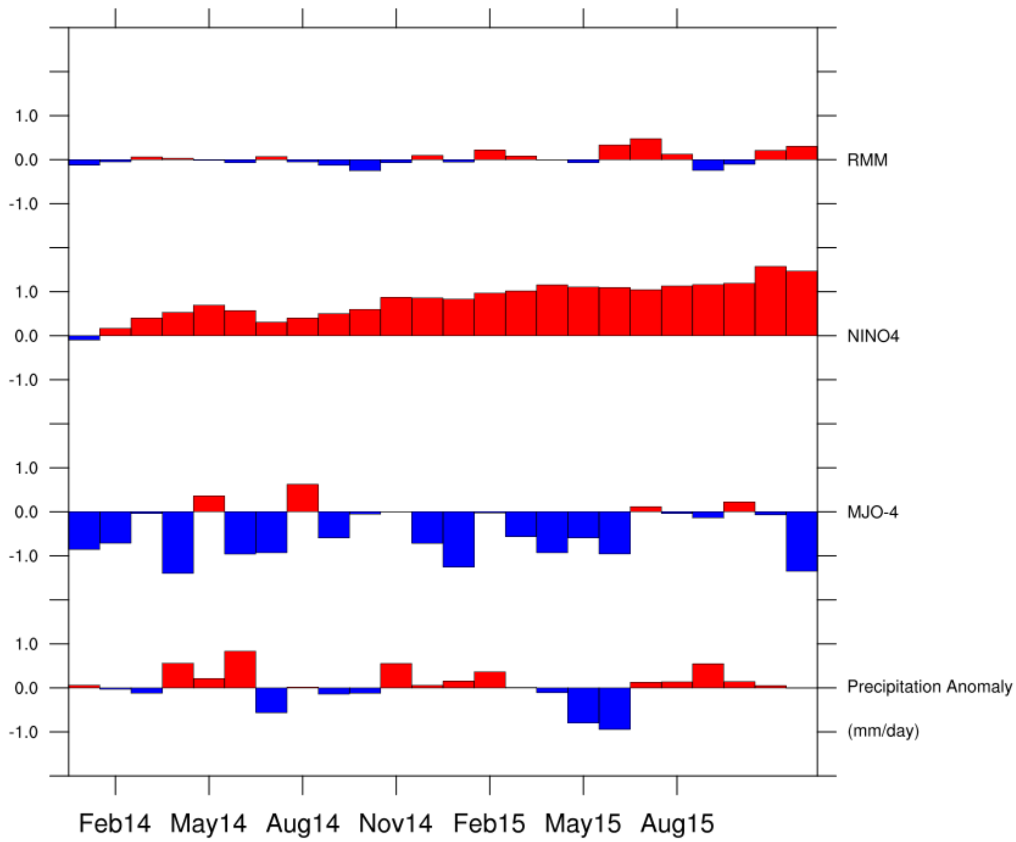

Fig. 4 RMM amplitude anomaly, NINO4, MJO 4 indices and precipitation anomaly of Canadian Prairies from January 2014 to Dec 2015.

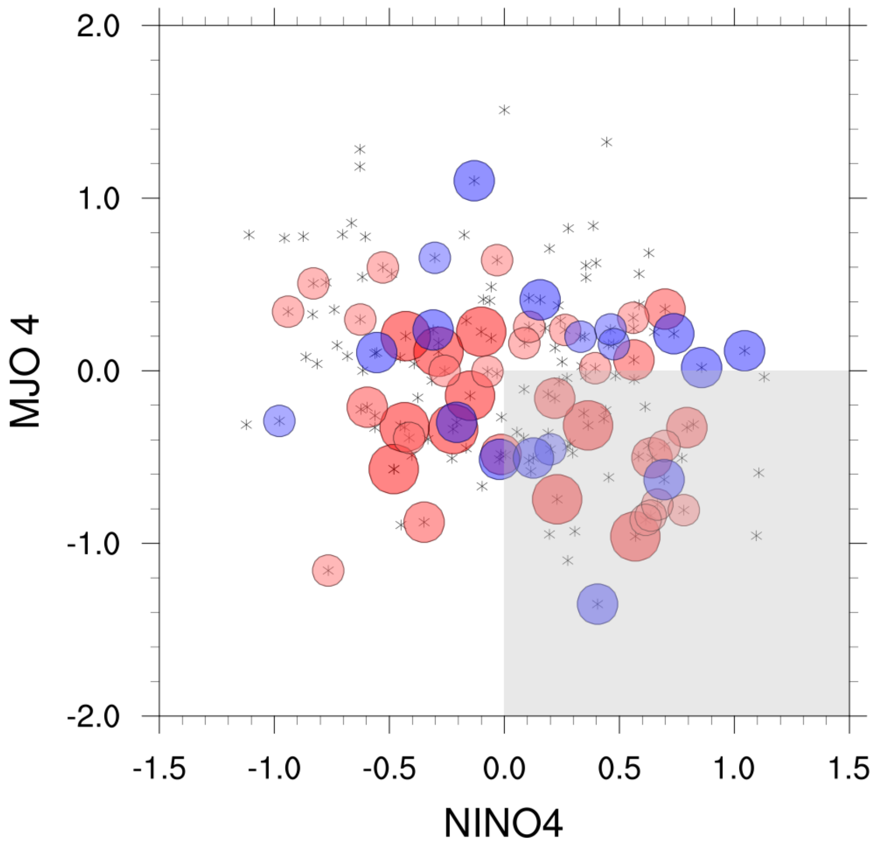

Fig. 5 The scatterplot of monthly precipitation anomaly (mm/month) as a function of MJO-4 and NINO4. Each asterisk represents a month from May to August 1979-2016. Circled asterisk denotes a month with precipitation anomaly larger than 18 mm/month. The blue circles are months with positive precipitation anomaly and the red circles are months with negative precipitation anomaly. The sizes of circles denote the magnitudes of the anomalies (large > 30 mm/month, medium > 24 mm/month, small >18 mm/month). The shaded area denotes NINO4>0 and MJO-4 index < 0.

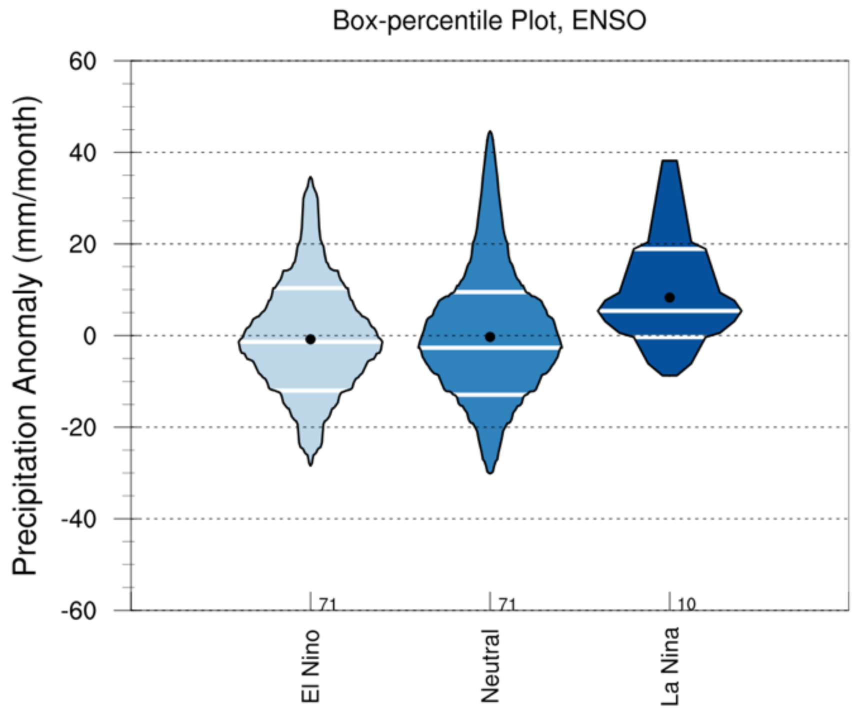

Fig. 6 The box-percentile plot of Canadian Prairies precipitation anomaly during growing season for ENSO conditions.

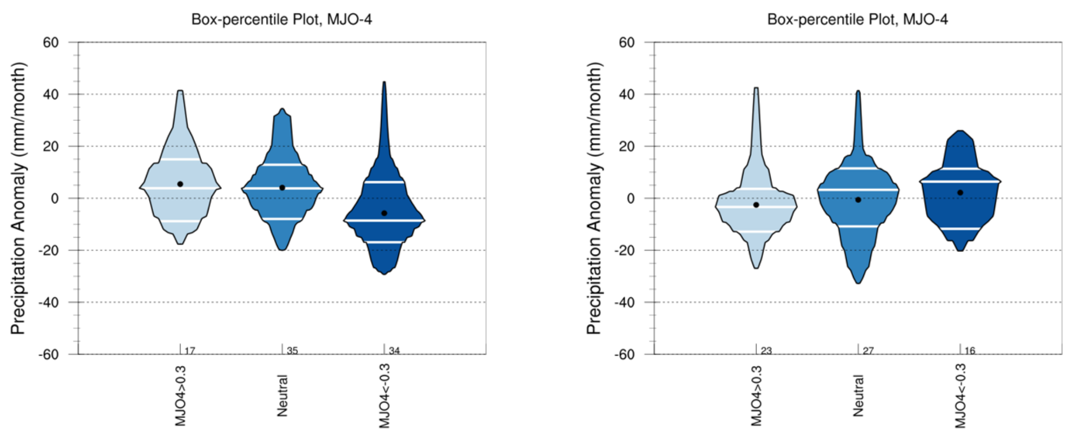

Fig. 7 Box-percentile plots of Canadian Prairies' precipitation anomaly during growing season versus MJO-4 under warm NINO4 (NINO4> 0, left) and cold NINO4 (NINO4<0, right) condition.

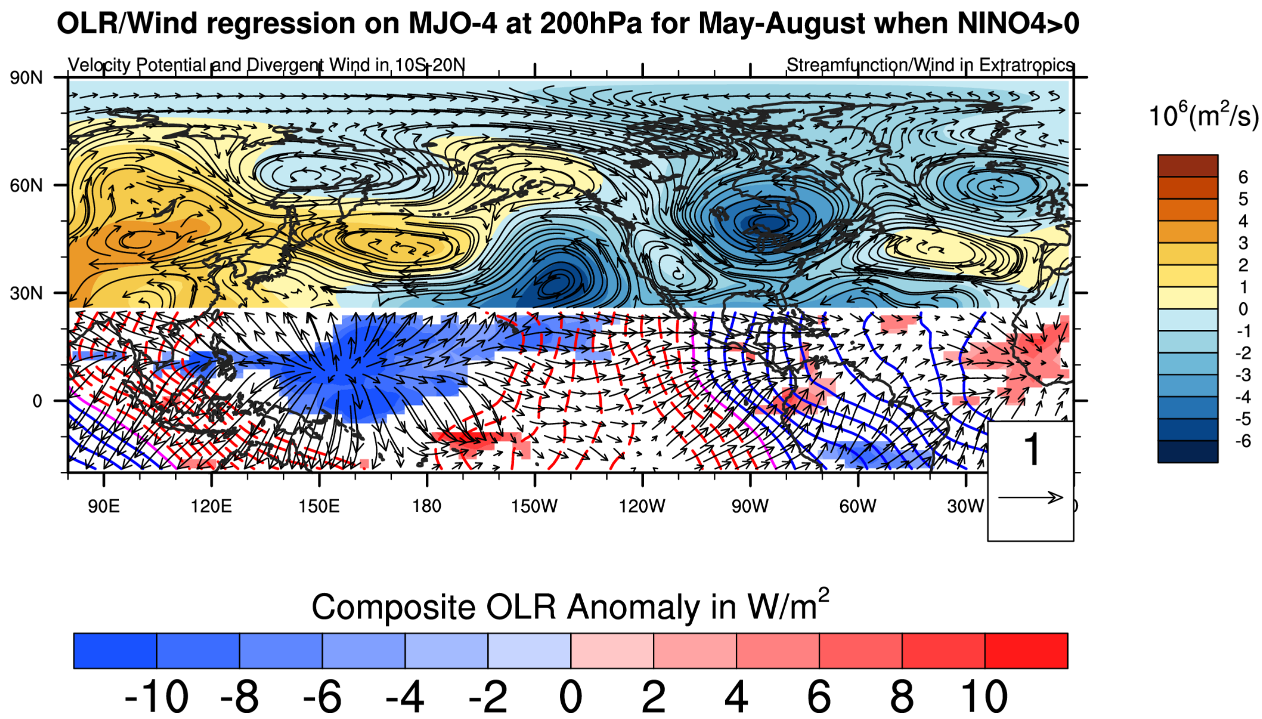

Fig. 8 The regression of stream function, wind field in the extratropics on MJO-4 for May-August with MEI > 0.5. Bottom: OLR, velocity potential, and divergent wind in the tropics on MJO-4 indices for May-August with $NINO4 > 0$. The shaded region for the tropical OLR has p-value < 0.05. Blue shading indicates active convection region. Red dashed contour and solid blue contour corresponds to negative and positive velocity potential, respectively.