Dear Dr. Li et al.

Based on two reviewers' comments on your article titled ""Combined Impacts of ENSO and MJO on the 2015 Growing Season Drought over the Canadian Prairies", I am happy to say that final acceptance will take place, if you are able to address the re- viewer's comments and suggestions - major revisions are required. Both reviewers have some excellent points and all of them can be reasonably addressed. I only point out some of the more major comments (and commonalities) below, however, each of the reviewer's points should be addressed as well.

We thank the editor and the two reviewers' valuable comments and advices to improve the original draft. Many improvements have been made to the draft according to the suggestion by the reviewers.

1) Both reviewers point out many typographical and grammatical errors. Please read over the manuscript carefully and make appropriate edits. One reviewer provided their marked-up manuscript to assist with this, as well as other comments requiring edits.

We have revised the draft accordingly to correct these errors.

2) Does the study period span 1979-2015 or 1979-2016?

The study period spans 1979-2016.

3) Manitoba is not included in the analysis. Hence, the title of the manuscript requires changing.

We acknowledge that the research only covers about the 2/3 of the agriculture land over the Prairies. We still hope to keep the title to "Combined Impacts of ENSO and MJO on the 2015 Growing Season Drought on Canadian Prairies" so that it is easier for researchers who are interested in the Prairies' precipitation to find the paper.

4) B.C. was not included in the analysis, but does appear to be affected. One reviewer is suggesting inclusion of B.C. or explaining why it was not included.

We choose to focus on the Prairie drought due to the fact the majority of the precipitation occur in summer for the Prairie whereas for BC coast the precipitation mainly occurs in winter. Though the precipitation deficit percent is high for BC coast. We have added some comments in the data section.

5) More quantitative analysis of the relation between Rossby waves and the drought should be addressed where possible.

We have added more analysis in terms of wave propagation.

6) Reviewer #2 suggests adding some detail about the unexplained drought events under NINO4>0 and MJO-4<0 (in the shaded region in Fig. 5), while connecting these events to the previously proposed teleconnection mechanisms in the introduction. At least some discussion should be made here.

We have added more discussions on the drought under NINO4>0 and MJO-4>0 and La Nina events.

7) The MJO-4 and ENSO are likely not independent. Some discussion of this should be made.

We have added discussions on the relationship between MJO and ENSO in the discussion section.

Once you have addresses each of the reviewer's comments, your manuscript will be considered for final publication.

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

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**Abstract**

Warm-season precipitation on the Canadian Prairies plays a crucial role in agricultural production. This research investigates how the early summer 2015 drought across the Canadian Prairies is related to tropical Pacific forcing. The significant deficit of precipitation in May and June of 2015 coincided with a warm phase of El Nino-Southern Oscillation (ENSO) and a negative phase of Madden-Julian Oscillation (MJO)-4 index, which favour a positive geopotential height anomaly in western Canada. Our further investigation during the instrumental record (1979-2016) shows that 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. Our results indicate that MJO can play a crucial role in determining the summer precipitation anomaly in the western Canadian Prairies when the equatorial central Pacific is warmer than normal (NINO4 > 0) and MJO is more active. This teleconnection is due to the propagation of a stationary Rossby wave that is generated in the MJO-4 index region. When the tropical convection around MJO-4 index region (western tropical Pacific, centered over 140°E) is more active than normal (NINO4 >0), a Rossby wave train originates from western Pacific and propagates into midlatitude over North America causing a persistent anomalous ridge in the upper level over western Canada, which favours dry conditions over the region.

## 1 Introduction

The Canadian Prairies depends on summer precipitation especially during the early to mid-growing season (May through August) when the majority of annual precipitation normally occurs (e.g.,

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Bonsal *et al*. 1993). High natural variability in growing season precipitation causes periodic occurrences of extreme precipitation (Li *et al*. 2017; Liu *et al.* 2016 and droughts that are often associated with reduced agriculture yields, low streamflow, 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 forecast of precipitation for the growing season is crucial for the agriculture, water resource management, and the economy of the region. Therefore, an investigation into the causes of inter-annual variability in the growing season precipitation of the Canadian Prairie is needed.

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

ENSO's relationship with Canadian Prairie precipitation has been studied extensively. The warm phase of ENSO often favours drought in this region, especially during the growing season after the mature phase of El Nino with the North Pacific Mode (NPM, Hartmann *et al.* 2015) positive like North Pacific SST anomaly pattern (Bonsal and Lawford 1999, Shabbar and Skinner 2004). Previous

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investigations (e.g., Shabbar *et al*. (2011)) have found that El Nino events are associated with a summer moisture deficit in western Canada while La Nina events cause an abundance of moisture in far 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 meteorological 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). Furthermore, in association with 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).

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The aforementioned SST variations mostly vary on inter-annual 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 over the Tropics (Madden and Julian 1971, Zhang 2005, Riddle *et al.* 2013, Carbone and Li 2015). MJO is a coupled atmosphere-ocean oscillation involving convection and large-scale equatorial waves, which produces an eastward propagation of tropical convection anomaly (Madden and Julian 1971). The MJO affects the winter temperature and precipitation in North America and Europe through its impact on moisture transport associated with the "Pineapple Express" and its effects on the North Atlantic Oscillation and stratospheric polar vortex (Cassou 2008, Garfinkel *et al.* 2012, Rodney *et al*. 2013). MJO is also connected to the summer precipitation anomalies in the Southwest United States (Lorenz and Hartmann 2006). During warm season, MJO's impact on Canadian Prairie precipitation has not been thoroughly investigated as MJO's amplitude is weak during spring and early summer. The amplitude of MJO in spring and early summer is related to the inter-annual variation of tropical SST, especially the SST in central Pacific (Hendon *et al*. 2007, Marshall *et al*. 2016). MJO in terms of the Real-time

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Multivariate MJO index (RMM, Wheeler and Hendon 2004), was extremely strong in the early spring of 2015 with a positive PDO-like SST anomaly in the central Pacific and at the same time, El Nino started to strengthen.

MJO activities in the western Pacific under the modulation of inter-annual SST variability have the potential to act together with ENSO and impact mid-tropospheric circulation over western Canada and thus, warm season precipitation over the Canadian Prairies. The goal of this study is to demonstrate that MJO have contributed to the 2015 growing season drought in the Canadian Prairies through the propagation of stationary Rossby wave. 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 methodology used in this paper while section 3 presents the analysis of the upper-level circulation anomaly and SST pattern associated with the 2015 drought. This is followed by the examination of the effects of central Pacific SST anomalies and MJO on the summer precipitation in the Canadian Prairies. The mechanism by which MJO affects summer precipitation when equatorial central Pacific SST is warmer than normal is discussed in section 4 followed by a summary and concluding remarks in section 5.

## 2 Data and Methodology

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 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 reanalysis (Dee *et al.* 2011) are used to analyze the mid- and upper-level (200 hPa and 500 hPa) atmospheric circulation patterns.

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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 the central Pacific and spans over the dateline (5°S-5°N, 160°E-150°W). Multivariate ENSO Index (MEI) data are retrieved from NOAA's Climate Data Center (CDC) website and is used to determine the ENSO phase (Wolter 1987, Wolter and Timlin 1993). In particular, El Nino condition is defined when the monthly mean index of MEI is larger than 0.5 (Andrews *et al*. 2004).

The Real-time Multivariate MJO series (RMM1 and RMM2) developed by Wheeler and Hendon (2004) are used to identify periods of strong MJO activity as the MJO amplitudes are directly calculated by the square root of RMM1 + RMM2. For MJO intensities, 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 MJO indices on a daily scale 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 convection in the 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. MJO indices usually vary between -2 to 2 with negative values indicating above average convective activities in the corresponding region. Because boreal summer usually corresponds to a period of weaker amplitude of MJO than the winter, we chose the monthly mean value of -0.3 as the criterion of strong convection which is connected to MJO as the index generally vary between -1 and 1. An MJO-4 index (centered on 140°E) of less than -0.3 was considered a relatively strong convection in the western Pacific, which 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

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(OLR) data from NOAA Interpolated Outgoing Longwave Radiation are used to derived the composite of anomalies of OLR for a certain phase of MJO.

Our study focuses on 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 area in Fig. 1, top panel) 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. Considering the unique MJO-4 and NINO4 indices 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. Though the dry months of the 2015 growing season are May and June when MJO-4 was in negative phase, we want to study the statistical relationship between MJO-4 and the Praries' precipitation in growing season (May-August). The possible mechanism behind the correlation between MJO-4 and the Prairie's warm season precipitation during El Nino condition is further investigated by analyzing the upper-level circulation associated with convection in the tropical Pacific and stationary Rossby waves in mid-latitudes.

# 3 Results

## 3.1 The 2015 Summer Drought

Almost all of western Canada including British Columbia, the southern Northwest Territories, Alberta and Saskatchewan had negative precipitation anomalies during May and June 2015. The top plot in Fig. 1 shows the precipitation anomaly in percentage relative to the climatology (1981-2010 long

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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 (top panel in Fig. 1). The average annual cycle of the regional precipitation has a dry period between February and May and June has the largest precipitation in all months. The May and June 2015 precipitation deficit was also accompanied by a relatively dry period from February to April [Szeto *et al.* 2016], which added to the drought conditions.

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 mid- and upper-level geopotential height (GHP) anomaly averaged in May and June are examined together with SST anomaly and ENSO, MJO-4 indices for 2014 and 2015. The 500 hPa GPH anomaly for May and June 2015 shows strong positive anomalies near Alaska and the British Columbia coast (Fig. 2), which is consistent with the findings for other episodes of growing season droughts (e.g., Dey 1982; Bonsal and Wheaton, 2005). Accompanying this anomalous ridge, are above normal SSTs in the northeast Pacific off the coast of North America and the central-eastern Pacific (Fig. 3). Both ENSO and the NPM 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 have been previously associated with El Nino and North Pacific SST anomaly such as NPM (Shabbar *et al.* 2011). The monthly mean anomalous ridge prevents storms from reaching the British Columbia coast and the Canadian Prairies causing extended dry spells. Therefore, 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

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components of Pacific SST variation such as NPM by several recent studies (Hartmann *et al.* 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.

The average SST anomaly during the growing season (May-June, July-August) of 2015. shows a persistent strong positive anomaly in the northeast and eastern equatorial Pacific (Fig. 3), which corresponds to the warm phase of NPM and ENSO. SSTs in the eastern tropical Pacific warmed increasingly since the end of 2014 and qualified as an El Nino in early 2015. The NPM became positive in the fall 2013, turned exceptionally strong in 2014 and persisted to 2015 (Hartmann 2015). The anomalous ridge is concurrent with strong SST anomalies in the tropical Pacific and extratropical North Pacific. NPM, as the third EOF of Pacific SST (30°S-65°N), has also a strong connection to the anomalous ridge in 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 to cause this anomalous ridge in western North America (Wang *et al.* 2014).

The variation of Canadian Prairies' precipitation and its relationship with SST modes and MJOs are shown in Fig. 4. The time series of monthly RMM amplitude, NINO4 index, MJO-4 indices and the Canadian Prairies precipitation anomaly from January 2014 to December 2015 shows the atmospheric-oceanic circulation indices for the drought in 2015. In May and June 2015, the western Pacific witnessed a strong MJO-4 negative index, whereas in July the MJO-4 index became positive. This corresponds well with the precipitation anomaly in Fig. 1. As shown in Fig. 3, El Nino continued to strengthen in July and August 2015; while at the same time the MJO-4 index increased. The increase of the MJO-4 index corresponded to the active convection associated with MJO that moved away from the

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**Deleted:** 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 [1]
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tropical western Pacific region and propagated eastward into the central Pacific. Coincident with this change in MJO, the precipitation in the Canadian Prairies then returned to slightly above normal in July.

The good correspondence of MJO-4 and the negative precipitation anomaly suggests a link between MJO and Prairie precipitation during growing season. Although El Nino and associated Northeast Pacific SST warm anomaly (i.e., NPM) in summer 2015 can be a contributing factor for the persistent upper-level ridge over the west coast of Canada, it cannot fully explain the drought condition in west Canada, as these SSTs do not guarantee a prolonged dry spell as shown by correlation analysis (Table 1). The negative MJO-4 index concurred with the negative anomaly of Prairie precipitation in 2015, which prompts the investigation of their relationship with 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 mature phase of El Nino (Bonsal *et al*. 1993) on an inter-annual time scale. ENSO, however, is not a strong intra-seasonal to seasonal predictor of Canadian Prairie summer precipitation. The lack of strong correlation between the Prairies' precipitation and ENSO index can be caused by many factors that affect  the Prairies' precipitation on a seasonal and sub-seasonal scale. Shabbar and Skinner (2004) showed the connection between the warm phase of ENSO and western Canadian drought through singular value decomposition analysis. However, they also found other modes of SST variation (e.g., positive phase of PDO) can produce wet condition in the Prairies. Here we present a new result showing that under warm central Pacific SST conditions (NINO4 >0), a certain

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phase of MJO, which connected to the active convection in the tropical western Pacific (Li and Carbone 2012), plays an important role in modulating the growing season precipitation in the Canadian Prairies.

Table 1 Correlation between mean precipitation anomaly in the Prairies from CMAP and MEI, MJO indices 4. MJO indices and CMAP are from 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 alone and the precipitation anomalies is not significant. The correlation between MJO-4 and precipitation in the Prairies is 0.18 with a p-value of 0.023, which indicates that stronger tropical convection in the equatorial region centered around 140°E favours less precipitation in the Canadian Prairies from May to August. When NINO4 is larger than 0, the correlation between MJO-4 and growing season precipitation is 0.33 with a p-value of 0.0015. Conversely, the correlation between MJO-4 and Canadian Prairie precipitation is -0.01 when NINO4 < 0.

Fig. 5 The scatter plot 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. Circled asterisk denotes a month with precipitation anomaly larger than 18 mm/month and the red (blue) circles denote a negative (positive) precipitation anomaly. The criterion for precipitation anomaly to be emphasized by the circles is roughly one third of the mean monthly precipitation in the growing season. The size of the circle represents the magnitude of the monthly precipitation anomalies. The bottom-right region indicated by shading, under NINO4 > 0 condition,

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negative MJO-4 corresponds to a quadrant that have many more dry than wet months. We noticed that some significant dry months are not in the shaded area, which corresponds to the dry months occurring during La Nina or in the period after the mature phase of El Nino (Bonsal *et al*. 1999). Summer drought in the Prairies can occur in both phases of ENSO or any other teleconnection indices. For example, for the summer drought that happened in the Prairies from 1999 to 2005, the large-scale anomalous patterns of SST first showed La Nina conditions and then became a weak El Nino in the latter half of the period (Hanesiak *et al* 2011). Bonsal and Wheaton (2005) showed that the tropospheric atmospheric circulation patterns in 2001 and 2002 lacked the typical meridional flow in the North Pacific and North America during drought in western Canada. Their results show that the drought in 1999-2005 was related to the expansion of the continuous drought happened in the US to the north.

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

The impact of ENSO on the growing season precipitaiton over Canadian Prairies is investigated. The box-percentile plot in Fig. 6 shows the distribution of monthly Canadian Prairies' precipitation anomalies from May to August along with different ENSO conditions. In general, under El Nino and neutral ENSO conditions, the precipitation anomalies are centered around 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 there are 71 months under El Nino and neutral condition.

The distributions of precipitation anomalies versus MJO-4 index under different ENSO conditions are shown in Fig. 7. For NINO4 > 0, the precipitation anomaly has a negative tendency when MJO-4 < -0.3. With NINO4 ≤ 0, there is no negative tendency for MJO-4 < -0.3. Therefore, Fig. 6 and 7 agrees with the significant correlation between precipitation and MJO-4 under NINO4 > 0 relative to ENSO in Table 1.

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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) SST condition.

The correlation between MJO-4 and the Prairies' 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 mid-latitudes (north of 30°N) on the negative MJO-4 index from May to August under warm NINO4 SST condition (NINO4 $\geq$ 0.5). In the tropics (10°S-20°N), during Northern Hemisphere summer, the OLR, velocity potential and divergent wind vector are presented. Only regression patterns having 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 around 150°E. The strong convection anomaly centers around 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. To better demonstrate the propagation of the wave train, we conducted a ray tracing of stationary Rossby wave following the nondivergent barotropic Rossby wave theory of Hoskins and Karoly (1981) and Hoskins and Ambrizzi (1993). Equation 1 describes the group velocity, which represent the propagation of wave activity. $C_{gx}$ and $C_{gy}$ are the group velocity components on zonal and meridional directions; $\bar{U}$ and $\bar{V}$ are the mean zonal and meridional winds; q is the mean absolute vorticity; K, k, l are the total wave number, zonal wavenumber and meridional wavenumber, respectively. The ray path is integrated using a fourth-order Runge-Kutta method.



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$$C_{gx} = \overline{U} + \frac{(k^2 - l^2)q_y - 2klq_x}{K^4}$$

Equation (1)

$$C_{gy} = \overline{V} + \frac{(k^2 - l^2)q_x + 2klq_y}{K^4}$$

Under average conditions in May-August derived from ERA-Interim at 200 hPa with NINO4 > 0.5 or NINO4 < -0.5, we released rays with a total wavenumber matching with the mean flow at the extratropical location of the OLR anomaly (140°E-150°E, 25°N-30°N). For quasi-stationary waves, the wavenumber is determined by the basic zonal flow and background absolute vorticity gradient through the dispersion relation. For NINO4 >0.5 May-August condition, K = 4.14. With this total wavenumber and launching angle from 0- 60° relative to the zonal direction, Rossby wave rays (colored by red, orange to blue according to their angle from 0° to 60°) released at 140°W, 20°N can propagate successfully to the western Canada for those with smaller launching angles as shown the right in Fig. 9. With NINO4<-0.5, the zonal wind in the source region is weaker, and the meridional gradient of absolute vorticity is stronger due to its relative further southern position to the subtropical jet. The total wavenumber for stationary Rossby waves is 6.2, determined by the mean May-August condition for NINO4 < -0.5. The waves with shorter wavelength tend to be evanescent near the source region as shown in the left plot in Fig. 9. However, there is no significant difference in ray-path under NINO4 < -0.5 condition compared to NINO4 > 0.5, if the source wavenumbers are set to the same value (results not shown). The changes in the mean conditions from El Nino to La Nina are not sufficient to alter the propagation condition for Rossby waves.

## 4 Discussion

Summer of 2015 is the first summer after the developing of 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, namely ENSO and NPM, the precipitation in the Western Canadian Prairie is not strongly correlated with either. Bonsal and Lawford (1999) found that more extended dry spells tend to occur in Canadian Prairies during the second summer following the mature stage of the El Nino events. The winter precipitation in Canada has a strong connection to ENSO (Shabbar *et al*. 1997), whereas summer precipitation, in most regions of western Canada (except the coast of British Columbia and Southern Alberta), does not have a significant correlation with ENSO. This is consistent with our investigation using instrumental records from 1948 to 2016.

Growing season precipitation in the Canadian Prairies is affected by many factors, precipitation deficits can occur under various circulation and lower boundary conditions. Thus, it is not expected that a universal condition for all the significant droughts in the region can be identified. In fact, extreme drought events have been found in both El Nino and La Nina years. A previous study 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 not clear. In fact, the correlation between MEI and precipitation in the investigated region is -0.096 (p=0.239, sample size = 152). The region's growing season precipitation does not possess a significant correlation with ENSO, 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

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1993, Ambrizzi and Hoskins 1997, Held *et al.* 2002). A similar wave train extends from the western Pacific toward extra-tropical South America 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 $\geq$ 0), a wave train with the opposite sign will reach western Canada which then counteracts the 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.

In mid-latitude North America, the atmospheric response 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 prairies alone. Both warm SST in central Pacific and strong tropical convection in western Pacific and Maritime Continent are essential 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 favours enhanced MJO activity in the western-central Pacific (Hendon *et al.* 1999, Marshall *et al.* 2016). In the year 2015, the SST anomaly in the Pacific (e.g. ENSO, NPM) forced the anomalous ridge on the west coast of Canada. This positive GPH anomaly was associated with the strong negative MJO4 indices, it then caused a blocking pattern and suppressed precipitation in the Canadian Prairies in the early summer. Although the El Nino continued to strengthen in July and August 2015, the active convection associated with MJO in the western 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.

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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>0.5. 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 2015 summer precipitation deficit in the western Canadian Prairies is investigated in relation to atmospheric circulation anomalies, SST, and intraseasonal tropical convection oscillation, MJO. The drought in western Canada is immediately related to an anomalous upper-level ridge that persisted over the west coast of Canada and Alaska since fall 2014. This ridge was likely associated with a developing El Nino that was enhanced by the MJO.

In general, MJO-4 indices demonstrated significant correlation with the meteorological drought happened over west Canadian Prairies from May to August when warm SST presented in central Pacific (NINO4 > 0) with strong MJO amplitude. Our study discovered that MJO phase/strength is connected to the anomalous ridge over western Canada through the propagation of stationary Rossby wave from the western Pacific when NINO4 is positive. Though seasonally MJO is weaker in summer, the spring and early summer MJO amplitude is larger than normal when the central Pacific SST is warmer than normal (NINO4 >0). The teleconnection between the Canadian Prairie precipitation deficit and MJO is stronger when NINO4 is positive. The underlying cause of this significant correlation between MJO-4 indices and the prairie precipitation in May-August is a stationary Rossby wave train originating from the Maritime Continent and western Pacific which propagates into Canada. The raytracing experiments show the main difference between a warm phase of NINO4 and a cold phase is the changes in stationary Rossby wave wavenumber over the source region. Under NINO4 > 0.5 May-August condition, the total

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wavenumber is about 4 and can propagate into western Canada if they oriented relatively zonally. Compared to NINO4 > 0.5, NINO4 < -0.5 corresponds to a weaker zonal wind and stronger meridional gradient of absolute vorticity in the subtropics of the source region (140-150E), hence the wavenumbers of stationary Rossby waves from the source region are larger (about 6), and fail to reach the Western Hemisphere. The intra-seasonal predictability of the growing season precipitation in the Canadian Prairies can be potentially improved by including the MJO amplitude and phase factors for medium-range/intra-seasonal projection in addition to ENSO effect especially when the central-Pacific SST is warm.

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

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| | 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 |

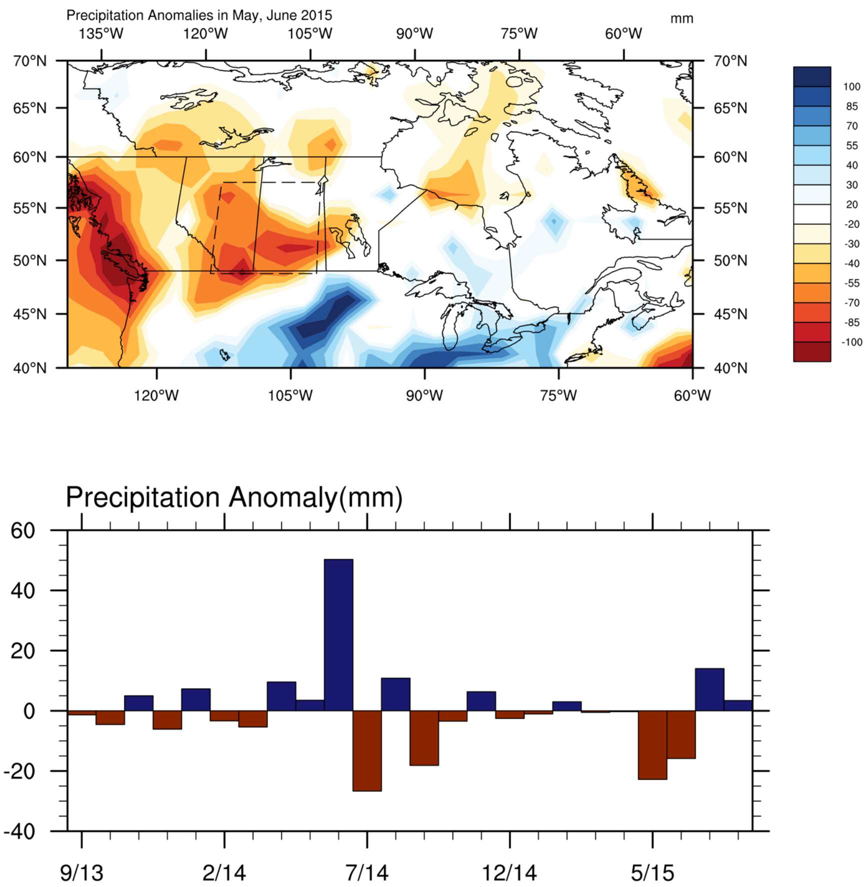
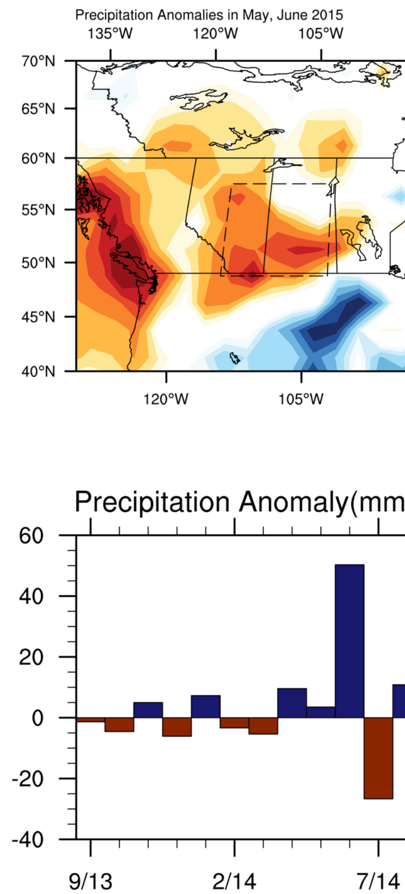



Fig. 1 Top: Precipitation anomalies (mm) from CMAP over the region (115 W-102.5 W, 50 N-57.5 N) during May and June 2015. Bottom: time series of monthly precipitation anomaly over boxed region between September 2013 and August 2015.

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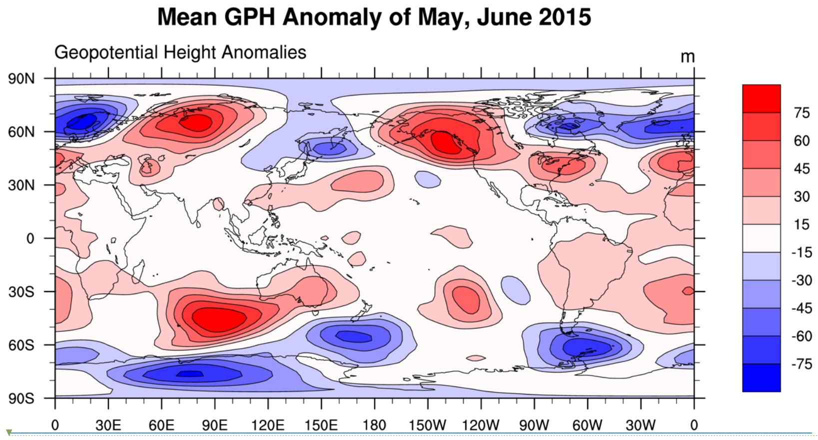


Fig. 2 NCEP GPH anomaly at 500hPa during May and June 2015 when the precipitation deficit was the largest.

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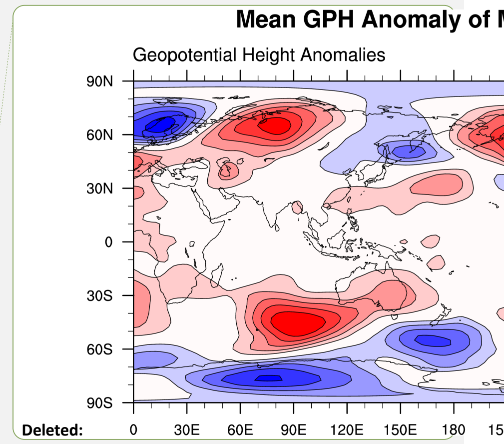


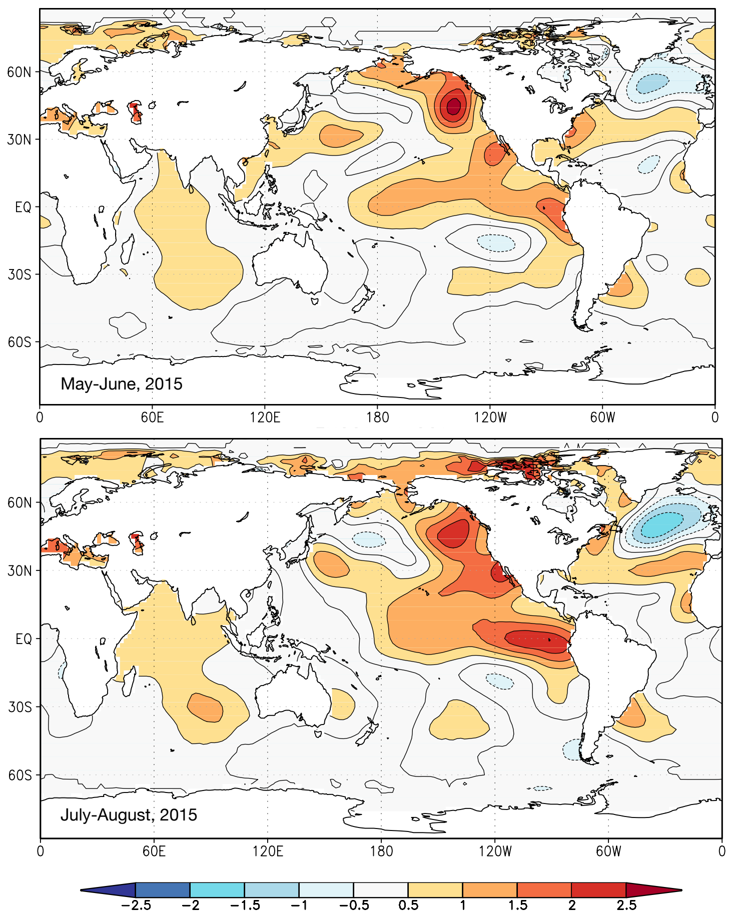
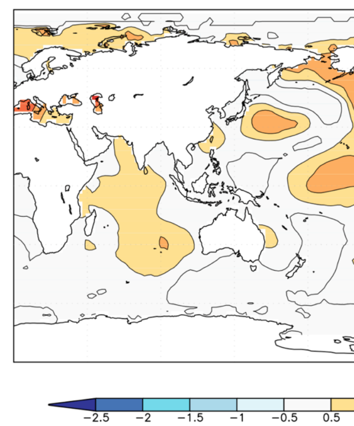



Fig. 3 The mean SST anomaly (ºC) from ERSST v4 for May-June and July-August 2015.



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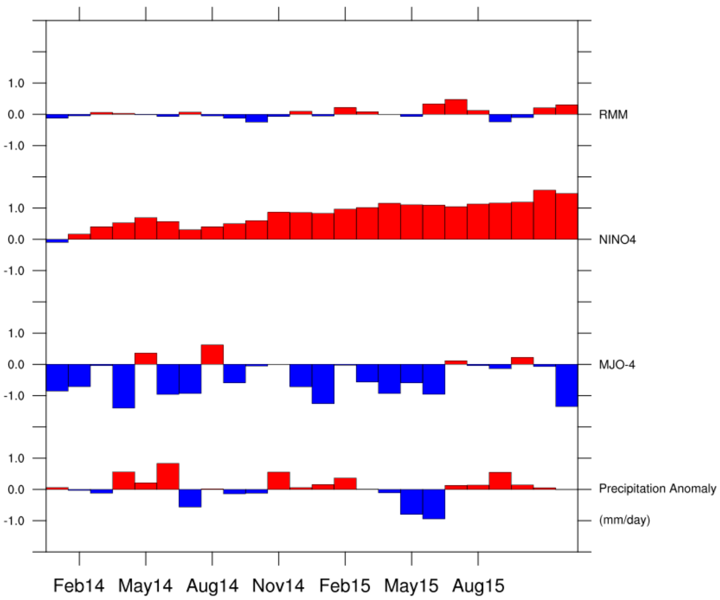
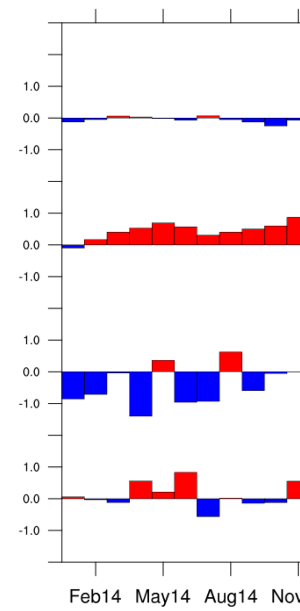



Fig. 4 RMM amplitude anomaly, NINO4, MJO 4 indices and precipitation anomaly of Canadian Prairies from January 2014 to Dec 2015.

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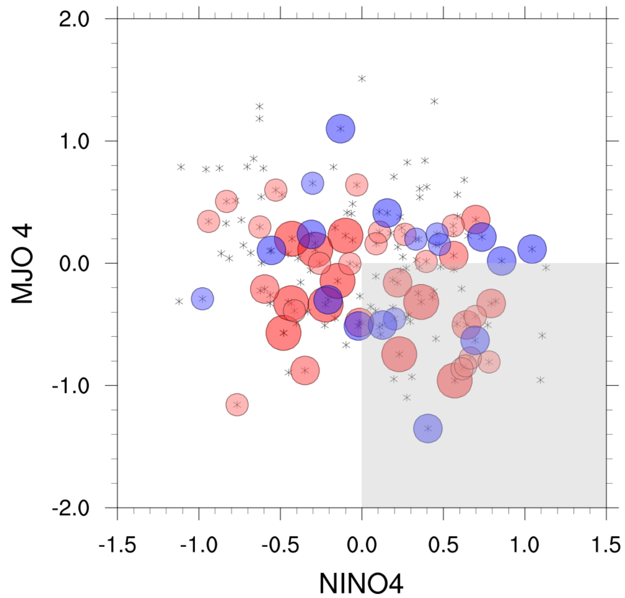
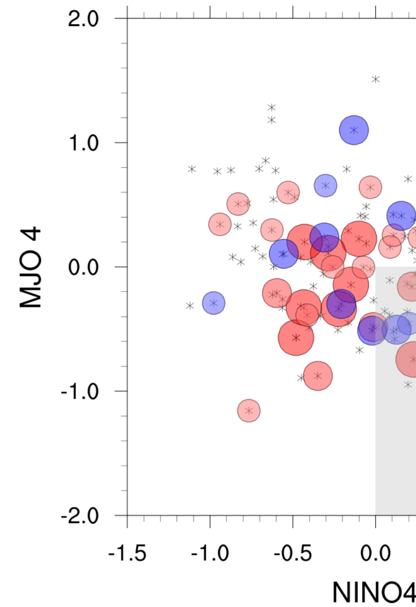



Fig. 5 The scatter plot of monthly precipitation anomaly (mm/month) as a function of MJO-4 and NINO4. Each asterisk represents a month from May to August 1979-2016. Circled asterisk denotes a month with precipitation anomaly larger than 18 mm/month. The blue circles are months with positive precipitation 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.

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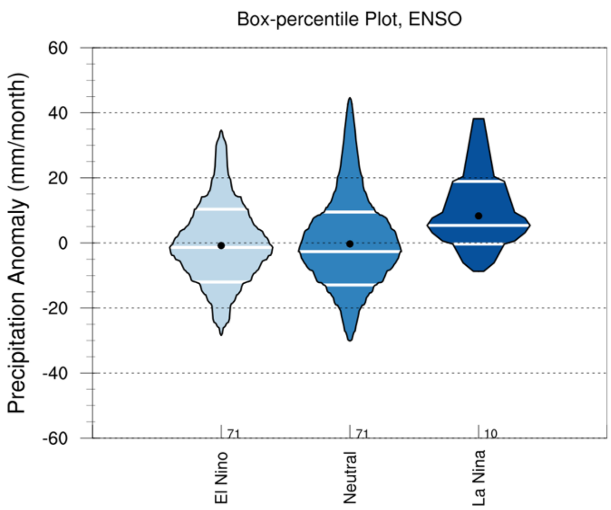
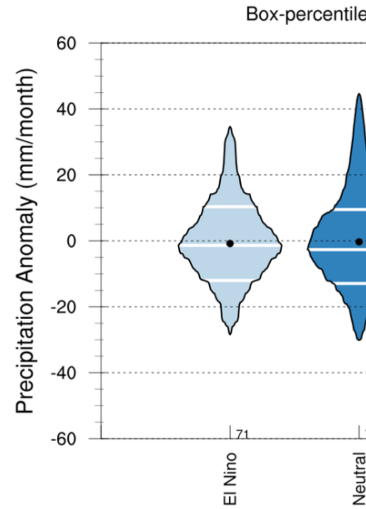



Fig. 6 The box-percentile plot of Canadian Prairies precipitation anomaly during growing season under different ENSO conditions.

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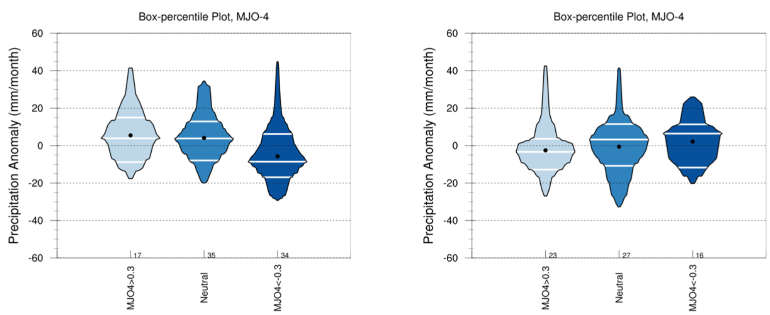
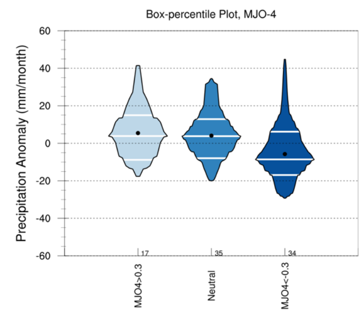



Fig. 7 Box-percentile plots of Canadian Prairies' precipitation anomaly during growing season versus MJO-4 under warm NINO4 (NINO4> 0, left) and cold NINO4 (NINO4<0, right) SST condition.

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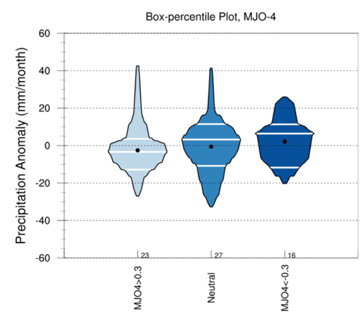


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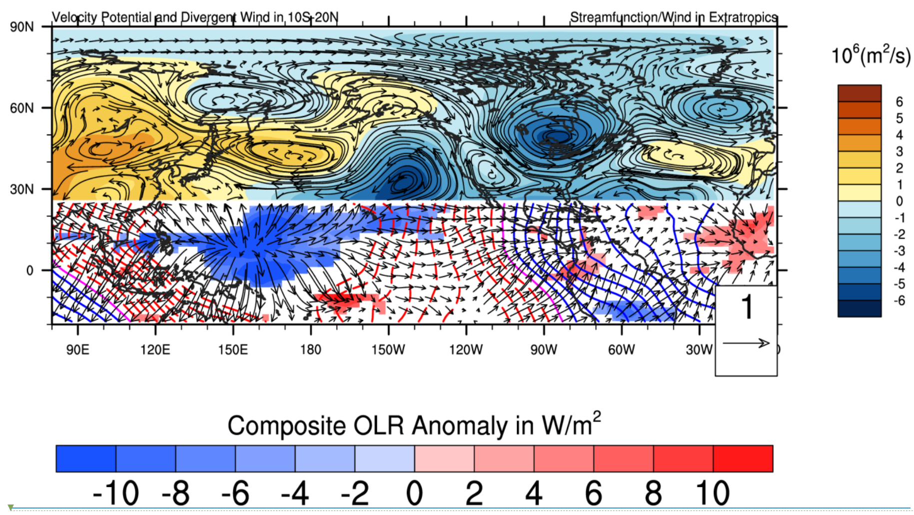


Fig. 8 The regression of stream function, wind field in the extratropics on MJO-4 for May-August with NINO4 $\boxed{>}$ 0.5. OLR, velocity potential, and divergent wind in the tropics on MJO-4 indices for May-August with $\boxed{NINO4 > 0}$.5. The shaded region for the tropical OLR has p-value $\boxed{<}$ 0.05. Blue shading indicates active convection region. Red dashed contour and solid blue contour corresponds to negative and positive velocity potential, respectively.

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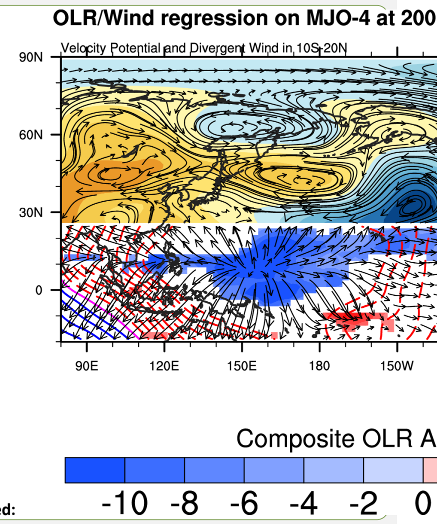


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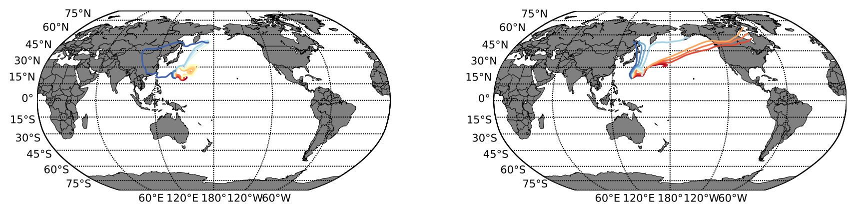


*Fig. 9: Ray-tracing result with total wavenumber specified by the mean flow 140-150W and 20-30N for mean May-August condition with NINO4<-0.5 (left) and NINO4>0.5 (right). Rays originate from 140E, 20N with angles ranging from 0 (red) to 60 degree (dark blue) from zonal direction.*

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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.