Trends in Persistent Seasonal-Scale Atmospheric Circulation Patterns Responsible for Seasonal Precipitation Totals and Occurrences of Precipitation Extremes over Canada^①

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ABSTRACT

Both large-scale atmospheric circulation and moisture content in the atmosphere govern regional precipitation. We partition recent changes in mean, heavy, and extreme precipitation for all seasons over Canada to changes in synoptic circulation patterns (dynamic changes) and in atmospheric moisture conditions (thermodynamic changes) using 500-hPa geopotential height and precipitation data over 1979–2014. Using the self-organizing map (SOM) cluster analysis, we identify statistically significant trends in occurrences of certain synoptic circulation patterns over the Canadian landmass, which have dynamically contributed to observed changes in precipitation totals and occurrence of heavy and extreme precipitation events over Canada. Occurrences of circulation patterns such as westerlies and ridges over western North America and the North Pacific have considerably affected regional precipitation over Canada. Precipitation intensity and occurrences of precipitation extremes associated with each SOM circulation pattern also showed statistically significant trends resulting from thermodynamic changes in the atmospheric moisture supply for precipitation events. A partition analysis based on the thermodynamic–dynamic partition method indicates that most (~90%) changes in mean and extreme precipitation over Canada resulted from changes in precipitation regimes occurring under each synoptic circulation pattern (thermodynamic changes). Other regional precipitation changes

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resulted from changes in occurrences of synoptic circulation patterns (dynamic changes). Because of the high spatial variability of precipitation response to changes in thermodynamic and dynamic conditions, dynamic contributions could offset thermodynamic contributions to precipitation changes over some regions if thermodynamic and dynamic contributions are in opposition to each other (negative or positive), which would result in minimal changes in precipitation intensity and occurrences of heavy and extreme precipitation events.

1. Introduction

Extreme weather events such as intensive storms, heat waves, droughts, and cold spells have various social, economic, and environmental repercussions to our society, which include decreases in primary forest productivity (Peng et al. 2011; Tan et al. 2018; Young et al. 2017), increases in mortality (Mazdiyasni et al. 2017; Oudin Åström et al. 2013), damage to infrastructure (Penny et al. 2018), changes in energy consumption (Abrahamse and Shwom 2018; Kingma and van Marken Lichtenbelt 2015), and impacts to food and energy production (Destouni et al. 2013; Liang et al. 2017). It is very likely that global warming has contributed to more frequent and severe hydrologic extremes occurring across the world observed in recent decades (IPCC 2013). Of particular concern is the response of extreme weather events in mid- and high-latitude regions such as Canada to climate change impacts because high-latitude regions tend to experience larger warming compared to midlatitude regions (Barry and Gan 2011; Bonsal et al. 2011; Serreze et al. 2000).

Climate change over Canada is characterized by increasing surface temperature, shifts from snow to rain, and decreasing duration of snow cover (Brown et al. 2010; Mekis and Vincent 2011; Vincent et al. 2015), and these changes are expected to continue in the future under the effects of anthropogenic warming (Vincent et al. 2018). A warming climate over Canada is concurrent with an increase in precipitation amounts (Mekis and Vincent 2011) and increased frequency of heavy and extreme precipitation events (Tan and Gan 2017; Tan et al. 2017), although there are spatial and seasonal variations to precipitation change patterns. Spatially, changes in temperature and precipitation extremes at various temporal scales have been detected in Canada. Vincent and Mekis (2006) found a consistent increase (decrease) in warm (cold) temperature extreme events over 1950–2003 and 1900–2003. However, given Canada's large landmass, no spatially and temporally consistent changes have been found in the occurrences of precipitation extremes (e.g., Kunkel et al. 1999; Vincent and Mekis 2006; Zhang et al. 2001a, 2010). An intensified hydrologic cycle has been observed in northern Canada (Déry et al. 2009; Huntington 2006), while streamflow in southern Canada has decreased (Tan and Gan 2015; Zhang et al. 2001b). An intensified

hydrologic cycle could result in more frequent occurrences of heavy and extreme precipitation events (Allan and Soden 2008).

Changes in hydroclimatic extremes can be either thermodynamic or dynamic in nature (Seager et al. 2010), even though extreme weather conditions are more likely associated with large-scale atmospheric circulation. Changes in precipitation and temperature are caused dynamically by changes in atmospheric circulation (Fig. 1) and thermodynamically by changes in conditions unrelated to atmospheric circulation such as changes in the longwave radiation due to increasing greenhouse gases in the atmosphere, or changes in atmospheric moisture fluxes and/or latent heat fluxes resulted from changes in land cover (Horton et al. 2015; Seager et al. 2010). Recent advances in climate research have examined linkages between the probability of extreme events to changes in atmospheric circulation (e.g., Cassano et al. 2007; Cattiaux et al. 2013; Coumou et al. 2014; Francis and Vavrus 2012; Jézéquel et al. 2018; Petoukhov et al. 2013). For example, Horton et al. (2015) identified changes in the occurrence of atmospheric circulation patterns that have contributed to observed trends in surface temperature extremes over seven midlatitude regions of the Northern Hemisphere. They found that changes in the frequency of extreme temperatures over some regions resulted from recent changes in the frequency, persistence, and maximum duration of regional circulation patterns, even though regional- and global-scale thermodynamic changes contributed to a substantial portion of the observed change in extreme temperature occurrences. Francis and Vavrus (2012) found that a slower progression of upper-level waves resulting from effects of Arctic amplification would cause associated weather patterns in midlatitudes to be more persistent and lead to an increased probability of extreme weather events such as drought, flooding, cold spells, and heat waves.

Previous studies have identified some primary synoptic circulation patterns contributing to surface weather conditions of western Canada. For example, a ridge centered over western Canada is usually linked to low precipitation (Bonsal and Cuell 2017; Romolo et al. 2006; Saunders and Byrne 1996), while high precipitation is associated with zonal flow (Bonsal et al. 2017; Romolo et al. 2006; Stahl et al. 2006) or a ridge centered over the Pacific Ocean

FIG. 1. Trends in midatmospheric 500-hPa geopotential heights during 1979–2014 around Canada in the ERA-Interim. Trends were estimated for the four seasons: (a) spring (MAM), (b) summer (JJA), (c) fall (SON), and (d) winter (DJF). The stippled regions show statistically significant changes, identified by the MK test, at the 5% significance level.

(Cassano and Cassano 2010; Cassano et al. 2006; Finnis et al. 2009). Precipitation over western Canada generally results from the development of lee cyclones at the surface preceded by a midtropospheric low pressure system across the Pacific Ocean (Lackmann and Gyakum 1998). The low pressure system generates a narrow band of moisture influx to southwestern Canada (Liu and Stewart 2003; Smirnov and Moore 2001). Under the influence of a persistent large-scale high (low) pressure system in the summer, much of the recycled water vapor would fall over the southern (northwestern) Mackenzie basin with a relatively low (high) runoff ratio, resulting in a decrease (increase) of its summer discharge (Szeto 2002). Newton et al. (2014a,b) examined the occurrence frequency of synoptic circulation patterns classified using self-organizing maps (SOMs) and their associated patterns to anomalies of temperature and precipitation over western Canada. However, synoptic patterns contributing to the occurrence of temperature and precipitation extremes have not been identified, and changes in the frequency of synoptic patterns have not been linked to changes in the frequency of climatic extremes over Canada.

Changes to atmospheric moisture content with respect to warming are based on the Clausius–Clapeyron equation, which tends to increase with the warming of the troposphere, resulting in changes to surface weather conditions, particularly an intensified hydrological cycle

dominated by extreme precipitation events (Allen and Ingram 2002; Held and Soden 2006; Seager et al. 2012). However, atmospheric moisture contents are also dependent on the supply of available water and energy, so warming may not always result in significant changes in precipitation at time scales larger than, say, 1 day (Allen and Ingram 2002; Panthou et al. 2014). An increase in precipitation intensity at small time scales (e.g., 1 h) has been observed to exceed the Clausius–Clapeyron relation of $7\% \text{ K}^{-1}$, as found in the precipitation of some climate stations with observed temperature changes in Europe (Lenderink and van Meijgaard 2008, 2010), Canada (Panthou et al. 2014), and Australia (Wasko and Sharma 2015). Effects of temperature increases on the regional water vapor and precipitation can be highly nonlinear. Whether the thermodynamic effects of warming have contributed to changes in daily and seasonal precipitation has yet to be well examined. Relative contributions of changes in the atmospheric, thermodynamic, and dynamic conditions to changes in precipitation extremes over Canada are poorly understood.

The primary objective of this study is 1) to evaluate seasonal precipitation and occurrences of precipitation extremes over Canada through identifying midtropospheric circulation patterns using the SOM method, and 2) to apply a partitioning method on climate change impacts to quantitatively relate changes in seasonal

precipitation and occurrences of precipitation extremes over Canada to the thermodynamic and dynamic changes. Section 2 describes data and methodologies used in this analysis. Section 3 presents the temporal trends of occurrence of atmospheric circulation patterns and precipitation changes associated with each SOM circulation patterns, and the relative contribution of changes in thermodynamic and dynamic conditions to precipitation changes. Section 4 discusses the results and the conclusions of this study.

2. Data and methodology

a. Synoptic circulation patterns

We used the SOM method (Cassano et al. 2007; Horton et al. 2015; Kohonen 1998) to identify dominant synoptic atmospheric circulation patterns over the landmass of Canada, the North Pacific, the North Atlantic, and the Arctic. SOM is an unsupervised learning algorithm and a neural network process based on competitive and cooperative learning that clusters and projects data onto a topologically ordered array (Kohonen 1998). Unlike traditional classification methods, such as principal component analysis (PCA), the SOM array represents atmospheric continuity and could visualize relationships between synoptic circulation patterns and associated surface climate (Hewitson and Crane 2002; Lee and Feldstein 2013; Loikith et al. 2017; Reusch 2010; Sheridan and Lee 2011). The SOM method does not require a priori knowledge of the types of circulation patterns and the specific geographic regions in which a circulation pattern might have occurred. The SOM technique to extract synoptic circulation patterns is free from various mathematical restrictions, such as orthogonality and linearity in the PCA (Chu et al. 2012). Synoptic circulation patterns derived by the PCA method are sensitive to the number of eigenvectors retained (Cuell and Bonsal 2009) and are dependent on a covariance matrix, which is not required in the SOM analyses (Sahai et al. 2013). Therefore, the SOM method has been shown to outperform PCA in identifying patterns of climatological data (Liu et al. 2006; Reusch et al. 2005).

The daily geopotential height (GPH) field at 500 hPa from 1979 to 2014 is used to represent the long-term atmospheric circulation conditions. We used daily 500-hPa GPH data from six reanalysis datasets currently available, including NCEP–DOE R2 (Kanamitsu et al. 2002), ERA-Interim (Dee et al. 2011), the North American Regional Reanalysis (NARR) (Mesinger et al. 2006), the Japanese 55-year Reanalysis (JRA-55) (Kobayashi et al. 2015), the Climate Forecast System Reanalysis (CFSR) (Saha et al. 2010), and the Modern-

Era Retrospective Analysis for Research and Applications, version 2 (MERRA2) (Gelaro et al. 2017). MERRA2 is available from 1980 to 2014 while other reanalysis products are available for the full study period (1979–2014). We used six reanalyses to have a multi-reanalysis robustness evaluation on the changes in circulation patterns as suggested by Horton et al. (2015). Instead of training GPH anomalies by the SOM method that was conducted by Horton et al. (2015), we trained GPH fields directly to show the atmospheric circulation patterns explicitly. Newton et al. (2014a,b) and Bonsal et al. (2017) also created a catalogue of dominant synoptic circulation patterns for Canadian regions by training GPH fields, so our results should be comparable to theirs.

According to the similarity of patterns, each daily GPH field was assigned to one of the assumed SOM nodes that were iteratively updated in the learning process. When the Euclidian distance between assumed nodes and their matching daily GPH fields was minimized, these assumed nodes are the final clusters of SOM large-scale circulation patterns. Each SOM pattern is a representative composite for a number of relatively similar daily large-scale circulation conditions. Technical details of the SOM method for identifying or extracting synoptic circulation patterns are described in the literature (e.g., Cassano and Cassano 2010; Cassano et al. 2011; Cassano et al. 2006; Cassano et al. 2007; Johnson 2013; Johnson et al. 2008; Liu et al. 2006; Reusch 2010; Reusch et al. 2005).

Since there are expected uncertainties of reanalysis data in representing regional daily precipitation, we used daily precipitation data from the same six reanalysis datasets. To maintain the physical consistency between GPH and precipitation, the six reanalysis datasets were analyzed individually for the link of circulation patterns and precipitation regimes, and the partition analysis. Then the results from the six reanalyses were intercompared. We also used the ~10-km-resolution gridded, daily station-interpolated precipitation data (1958–2013) of Canada developed by Hutchinson et al. (2009) using the Australian National University Spline (ANUSPLIN) interpolation scheme to identify seasonal precipitation totals and occurrences of heavy and extreme precipitation events. ANUSPLIN precipitation was linked to synoptic circulation patterns derived from ERA-Interim. Because the physical mechanisms behind precipitation intensity and occurrences of precipitation extremes are significantly different in four seasons, we respectively analyzed the regional precipitation of four seasons, that is, winter [December–February (DJF)], spring [March–May (MAM)], summer [June–August (JJA)], and fall [September–November (SON)].

Occurrences of heavy and extreme precipitation are chosen as the top 5% and 1% of days of daily precipitation larger than 0.2 mm (to remove days of very low precipitation in reanalyses) at each grid cell that had occurred in each season over 1979–2014 for both reanalysis and ANUSPLIN precipitation data. The top 5% and 1% of days represent occurrences of heavy and extreme precipitation events, respectively. We previously applied these two percentile-based thresholds to define days of precipitation extremes (Tan et al. 2019a,b).

Even though there are some known dry precipitation biases in the ANUSPLIN dataset in mountainous areas over the Pacific Maritime and Montane Cordillera regions (Eum et al. 2014; Islam et al. 2017) and wet precipitation biases in other regions (Benyahya et al. 2014; Hopkinson et al. 2011; Wong et al. 2017), on the whole the ANUSPLIN dataset provides country-wide, high-resolution daily precipitation data for historical climate analysis. The ANUSPLIN dataset well represents the spatiotemporal variability of daily precipitation extremes over Canada (Tan et al. 2019a,b). Thus, the ANUSPLIN dataset is likely the best published station-based, gridded daily precipitation dataset that has been widely used to study historical climate of Canada (e.g., Benyahya et al. 2014; Cannon et al. 2015; Newton et al. 2014a,b; Radić et al. 2015; Tan et al. 2019a,b).

We studied circulation patterns and their associated precipitation regimes over the regions called herein Canada West (110°–142°W), Canada Central (85°–110°W), and Canada East (50°–85°W) (see Fig. S1 in the online supplemental material) to detect subtle differences in thermodynamic and dynamic changes between different regions of Canada. We used a wider (east–west) region of GPH fields than regions of precipitation to include a larger-scale atmospheric circulation that may affect the precipitation of different regions of Canada. For the windows of GPH data for Canada West, Central, and East, the meridional ranges are 100°–180°, 60°–120°, and 20°–95°W, respectively, while the latitudinal ranges are 40°–85°N for all three regions. Various SOM parameters were tested for all three configurations. Some configuration parameters were set following previous studies (Cassano et al. 2006, 2007), such as the learning rate range (0.01–0.05), neighborhood function (Gaussian), and radius (1). Results show that these parameters do not significantly affect the training process and the dominant GPH patterns. Because the SOM method requires assigning the number of SOM nodes for training the data, we analyzed the sensitivity of pattern similarity to the number of SOM nodes by testing seven SOM configurations (3–9 nodes) to classify the ERA-Interim daily GPH fields for all three regions and four seasons. We found that the 4-node SOM methods generally suffice to

capture the different modes of atmospheric variability (Fig. S2), even though circulation patterns derived from the 4-node SOM method may not capture subtle features of atmospheric circulation for some particular regions (discussed in section 3a). As expected, the SOM configuration with more nodes can identify more subtle features of GPH fields in some regions. SOM patterns derived from the 4-node SOM method are small enough to depict distinct circulations that are associated with occurrences of regional precipitation, which is also indicated by Horton et al. (2015) and Lee and Feldstein (2013) for studies on temperature extremes. The results of four circulation patterns are simple to interpret.

We adopted the 4-node SOM method in this study. Once the 4-node SOM GPH patterns were derived, the GPH fields for each day were assigned to one of the four GPH patterns assumed to have occurred once. We then linked grid daily precipitation to the GPH pattern assigned for that day. Thus, the seasonal mean daily precipitation for each GPH pattern can be estimated for each grid cell. Similar links were conducted to the occurrence frequency of precipitation extremes and GPH patterns for each grid cells.

b. Trends in circulation patterns and associated precipitation

To examine changes in the circulation and precipitation patterns, we calculated three occurrence characteristics for each season in each year: 1) total number of days that each pattern had occurred (occurrence; days yr^{−1}), 2) the mean length of consecutive occurrences of each pattern (persistence; days per event), and 3) the longest consecutive occurrences of each pattern (maximum duration; days per event). These three seasonal characteristics of synoptic circulation patterns could extend beyond the seasonal scale (e.g., annual and interannual scales). Statistically significant trends of annual time series for these three characteristics were detected by the nonparametric Mann–Kendall (MK) test (Kendall 1975; Mann 1945) at a significance level of 5%. Since the time series is longer than 30 years and the time between samples (1 year) is sufficiently large, the effects of serial correlation on the identification of trends could be ignored (Zwiers and von Storch 1995). To consider the effects of short-term or long-term persistence on the statistical significance of trends, following Tan et al. (2017), we also applied three modified version of the MK tests for all trend analyses. They are 1) the trend-free prewhitening method developed by Yue et al. (2002) to remove the lag-1 serial correlation before applying the ordinary MK test to a time series, 2) the modified MK test proposed by Hamed and Rao (1998) that is based on a test statistic computed from an

effective (instead of the actual) sample size to account for the effect of serial correlation, and 3) the MK test of [Hamed \(2008\)](#) considering the influence of long-term persistence. The number of time series showing statistical significance obtained from four different types of the MK test is similar (Table S2), so the serial correlation in time series does not significantly affect our results. We only discuss the trend analysis results obtained from the ordinary MK test in detail. The magnitude of changes (trend slope of a time series) was estimated using the Theil–Sen estimator ([Sen 1968](#); [Theil 1950](#)). We also estimated trends in the regional area-weighted mean seasonal precipitation totals and occurrences of heavy and extreme precipitation.

We calculated SOM patterns independently for each reanalysis dataset such that we respectively trained daily 500-hPa GPH data from each reanalysis dataset using the SOM method to obtain circulation patterns for each reanalysis dataset. Individual SOM patterns must be matched between the six reanalysis dataset in order to determine whether an individual pattern shows robust results across all six reanalyses. We assigned a circulation pattern where all individual circulation patterns of the six reanalyses are closely matched between each other based on the smallest root-mean-square error (Table S1). Thus, we can intercompare the trends for each pattern between six reanalyses. For each pattern, we regarded the trend for a pattern is robust when the trend is 1) statistically significant in five out of six reanalyses and 2) of the same sign in the six reanalyses. We used the methods of the false discovery rate (FDR) ([Wilks 2006](#)) to test the field significance of multiple MK tests for each metric of patterns resulting from four patterns, four seasons, three regions, and six reanalyses. The field significance tests are supposed to identify whether statistically significant trends detected by MK tests for any individual reanalysis occur by chance.

Because the ERA-Interim dataset performs better over northern high-latitude regions than other reanalyses ([Screen 2014](#)) and ANUSPLIN precipitation data are interpolated observed data with a high spatial resolution, we only present figures derived from the ERA-Interim GPH and ANUSPLIN precipitation data analyses, as a representative, in the main text (Figs. 2–7) and the supplemental information (Figs. S3–S8). Similar figures for results derived from the six reanalysis dataset can also be made in the same way (not shown). Each figure is assembled following the flow of the methodology from the top to the bottom rows. Each column in a figure shows a circulation pattern and its associated precipitation regimes, as well as changes in occurrence characteristics of circulation patterns and precipitation regimes.

c. Relative contribution of thermodynamic and dynamic changes

To determine the relative contribution of changes in dynamic and thermodynamic processes to changes in regional seasonal precipitation and occurrences of precipitation extremes, we used the approach of [Cassano et al. \(2007\)](#) to partition the observed changes in precipitation intensity and occurrences of heavy and extreme precipitation to 1) the trends in occurrence of each circulation pattern (dynamic contributions) and 2) the trends in precipitation intensity and occurrences of heavy and extreme precipitation events occurred under each circulation pattern (thermodynamic contribution). The method is extensively adapted to partition changes in regional surface climate to thermodynamic and dynamics changes (e.g., [Higgins and Cassano 2009](#); [Horton et al. 2015](#); [Mioduszewski et al. 2016](#); [Skific et al. 2009](#); [Tan et al. 2019c](#)). Following [Cassano et al. \(2007\)](#),

$$P = \sum_{i=1}^K P_i f_i, \quad (1)$$

$$E = \sum_{i=1}^K E_i f_i, \quad (2)$$

where P and E are the regional, seasonal precipitation totals and the occurrences of heavy and extreme precipitation events, respectively; P_i and E_i are those values when the i th SOM circulation pattern occurs, respectively; f_i is the occurrences of the i th SOM circulation pattern; and K is the total number of SOM circulation patterns. The terms P , E , and f can be decomposed into time (seasonal in this study) mean and transient deviations from the time mean values:

$$P = \sum_{i=1}^K (\bar{P}_i + P'_i)(\bar{f}_i + f'_i), \quad (3)$$

$$E = \sum_{i=1}^K (\bar{E}_i + E'_i)(\bar{f}_i + f'_i). \quad (4)$$

By assuming mean values as constants, we differentiate the above equations with respect to time:

$$\frac{dP}{dt} = \sum_{i=1}^K \left[\bar{f}_i \frac{dP'_i}{dt} + \bar{P}_i \frac{df'_i}{dt} + \frac{d(P'_i f'_i)}{dt} \right], \quad (5)$$

$$\frac{dE}{dt} = \sum_{i=1}^K \left[\bar{f}_i \frac{dE'_i}{dt} + \bar{E}_i \frac{df'_i}{dt} + \frac{d(E'_i f'_i)}{dt} \right]. \quad (6)$$

We partition total changes to seasonal precipitation intensity and precipitation extreme occurrences [the left-hand sides of Eqs. (5) and (6)] into three components shown by terms in the right-hand side from left to right:

1) thermodynamic changes associated with precipitation occurred under all individual circulation patterns, 2) dynamic changes associated with occurrences of all individual circulation patterns, and 3) a combination of both. All trends in changes to precipitation intensity and occurrences of precipitation extremes in Eqs. (5) and (6) are regional area-weighted mean values. The contribution of thermodynamic changes in a circulation pattern to changes in precipitation assumes an invariant occurrence of that circulation pattern, and those changes in precipitation at each grid cell result from changes in thermodynamic conditions such as atmospheric moisture content. In contrast, the contribution of dynamic changes in a circulation pattern to changes in precipitation assumes the occurrence of an invariant precipitation regime under that circulation patterns, and changes in precipitation at each grid cell resulted from changes in occurrences of that circulation pattern. The combined contributions of thermodynamic and dynamic changes to changes in precipitation represent changes in pattern occurrences that resulted in changes in daily precipitation.

3. Results and discussion

a. Changes in midatmospheric geopotential heights

Figure 1 shows the trends in midatmospheric GPH in four seasons. The Arctic regions, especially Greenland, show a statistically significant increase in GPH in spring, summer, and winter but a statistically significant decrease in GPH of the Arctic region of Canada in fall over 1979–2014. Southern Canada experienced a statistically significant decrease in the GPH in spring and summer and a nonsignificant decrease in winter. In the fall season, southern Canada shows contrasting trends with a nonsignificant decrease over southwestern Canada and a nonsignificant increase over southeastern Canada. The GPH of the North Atlantic Ocean showed a statistically significant decrease in spring and summer at about -2 m yr^{-1} . The GPH over most regions of the North Pacific increased in spring and winter but decreased in summer and fall, even though these changes are not statistically significant. These changes in seasonal GPH over the North Pacific, the North Atlantic, the Arctic, and the Canadian landmass could be linked with changes in the occurrence of subseasonal atmospheric patterns and affect the surface climate and the frequency of occurrences of extreme events. Therefore, we attempt to detect changes in occurrence of synoptic circulation patterns and their associated precipitation.

b. Changes in synoptic circulation patterns

The first rows [panels (a)–(d)] of Figs. 2–7 and Figs. S3–S8 displays the four major synoptic midatmospheric

circulation patterns identified by the SOM method for the three regions of Canada over all seasons, while the second rows [panels (e)–(h)] of Figs. 2–7 and Figs. S3–S8 as well as Table S4 show the trends in the occurrence characteristics of those four synoptic circulation patterns. Because circulation patterns around the Canadian landmass in winters and summer show more contrasting features of pressure systems (e.g., zonal flows, ridges, and troughs) representative of the synoptic circulation conditions of Canada, we only show figures derived from partition analyses for the winter and summer in three regions; for other seasons they are presented as supplemental figures.

The four SOM 500-hPa GPH nodes capture a diversity of synoptic-scale midatmospheric circulation patterns over all the three regions including troughing, ridging, and zonal and splitting flows. As expected, there were differences in circulation patterns between different seasons. Circulation patterns are seasonal features of the Arctic (Cassano et al. 2007), southwestern Canada (Bonsal and Cuell 2017; Bonsal et al. 2017; Newton et al. 2014a,b; Romolo et al. 2006; Stahl et al. 2006), and eastern Canada (Girardin et al. 2006).

For Canada West, different spatial configurations of the ridge and zonal flow over western North America and the North Pacific result in four primary circulation patterns (Figs. 2a–d and 5a–d). The ridge over western North America and the North Pacific is much stronger in summer and fall than those in winter and spring (Figs. 2a–d and 5a–d and Figs. S3a–d and S6a–d). Moisture pathways to Canada West are driven by both zonal flow (westerlies) from the Pacific and poleward meridional flow from the northern continental United States (Tan et al. 2019a,b), and the anticyclonic or cyclonic nature of the Rossby wave breaking event (Liu and Barnes 2015). The zonal flow is not well captured by the 4-node SOM circulation patterns, but the zonal flow is much more evident in the 9-node SOM circulation patterns (Tan et al. 2019a,b). However, for Canada West, pattern 1 in winter (Fig. 2a), pattern 3 in spring, and pattern 4 in summer (Fig. 5d) show some similarities to the zonal flow pattern shown in Bonsal et al. (2017), Newton et al. (2014a,b) and our previous studies (Tan et al. 2019a,b).

Different locations and strength of the troughing and zonal flow dominate different circulation patterns for Canada Central (Figs. 3a–d and 6a–d). The troughing and zonal flow is much stronger in winter and spring than that in summer and fall. The axis of the troughing in winter and spring is shifted southward compared to that in summer and fall, and wavier flows dominate the circulation patterns in winter and spring whereas zonal flows dominate the circulation patterns in summer and fall (Figs. 3a–d and 6a–d; see also Figs. S4a–d and S7a–d).

The spatial configurations of both the troughing over the east coast of Canada and ridging over the North Atlantic dominate circulation patterns of Canada East (Figs. 4a–d and 7a–d). Other than the troughing over the east coast of Canada, which also impacts the circulation over Canada Central, the ridging over the North Atlantic also results in wavier flows in winter and spring than those in summer and fall (Figs. 4a–d and 7a–d; see also Figs. S5a–d and S8a–d).

The time series of occurrence characteristics show considerable interannual variability and some trends for all synoptic SOM patterns (Fig. 8 and Table S2). Figure 8 summarizes the statistical significance of all changes in the four seasons at a 5% significance level for both the occurrence characteristics and regional area-weighted precipitation intensity, and the occurrence frequency of precipitation extremes. Of the 48 total circulation patterns analyzed (4 seasons $\times$ 3 regions $\times$ 4 patterns) over 1979–2014, the six reanalysis datasets show statistically significant, robust trends in a total of 22, 9, and 13 pattern occurrence characteristics for the occurrence, persistence, and duration, respectively (Table S2). The majority of robust trends in the occurrence frequency occurred in winter (7) and spring (9), whereas robust trends of pattern persistence and duration are evenly distributed over the four seasons with marginally more robust trends occurred in spring (4 and 5 for persistence and duration, respectively). Patterns with robust trends of all occurrence characteristics occurred more over Canada West (17) and Canada East (18) than Canada Central (8), with the most number of trends for occurrence frequency over Canada West and the most number of trends for the maximum duration over the Canada East. For each season and in each region, an increase in the occurrence of a circulation pattern often occurred at the expense of another circulation pattern with fewer occurrences. Trends of circulation patterns are statistically significant according to the FDR test (Table S3),

which further confirms that circulation changes over Canada in all four seasons are statistically significant.

c. Changes in precipitation

The third [panels (i)–(l)] and fourth [panels (m)–(p)] rows of Figs. 2–7 and Figs. S3–S8 display the spatial distributions of daily precipitation anomalies and occurrences of extreme precipitation events, respectively, which correspond to the four major synoptic midatmospheric circulation patterns, while the fifth rows [panels (q)–(t)] of Figs. 2–4, Figs. S3–S8, and Table S5 show the trends in the precipitation totals and occurrence of heavy and extreme precipitation events corresponding to the four synoptic circulation patterns.

A ridge of large amplitude often results in blocking conditions to displace cyclonic tracks and transport atmospheric moisture away from the regions around the axis of the ridge (Bonsal et al. 2017; Dey 1982; Liu et al. 2004). Conversely, a troughing circulation pattern is associated with the atmospheric flow to steer surface level cyclones over the impacted regions (Shabbar et al. 2011; Tan et al. 2019a,b). The anomalously high (low) precipitation and more (fewer) heavy and extreme precipitation events are linked to midtropospheric convergence occurred over the right (left) of the ridge axis or the left (right) of the trough axis when the trough points south and the ridge points north (Holton 2004). Therefore, negative precipitation anomalies and fewer precipitation extremes are associated with a ridge whose axis locates over western Canada (Bonsal and Cuell 2017; Bonsal et al. 2017) such as pattern 4 in winter (Figs. 2d,l), patterns 2 and 4 in spring (Figs. S3b,d,j,l), and patterns 1 and 3 in summer (Figs. 5a,c,i,k) and fall (Figs. S6a,c,i,k) over Canada West. However, a ridge whose axis is located over the North Pacific is linked to high seasonal precipitation totals and more heavy and extreme precipitation events, such as pattern 1 in winter (Figs. 2a,i) and pattern 4 in fall (Figs. S6d,l,p) over Canada West. A trough whose axis is

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fields. (e)–(h) Time series of SOM circulation pattern occurrences (occurrences; %; black), the mean length of consecutive occurrence (persistence; days per event; red), and maximum duration (max duration; days per event; blue). (i)–(l) Four patterns of daily precipitation anomalies derived from high-resolution ANUSPLIN precipitation dataset mapped onto SOM circulation patterns shown in (a)–(d). Daily precipitation anomalies were calculated as the percentage of mean daily precipitation occurred in days with a SOM circulation pattern in each grid cell relative to the 1979–2014 mean daily precipitation at each grid cell in all days. (m)–(p) Probability that heavy precipitation occurred in each SOM circulation pattern in (a)–(d) derived from high-resolution ANUSPLIN precipitation dataset. (q)–(t) Time series of the area-weighted mean daily precipitation (black; mm day^{-1}) and number of heavy (red) and extreme (blue) precipitation events (days) per pattern occurrence, referred to throughout the text as a measure of the seasonal precipitation totals and occurrence frequency of precipitation extremes associated with each pattern. In (e)–(h) and (q)–(t), the corresponding mean values (first row of numbers) and the Theil–Sen slope of the trend line (second row of numbers) in 1979–2014 are also presented. Statistically significant trends (at the 5% significance level) are shown by boldface font in the scatterplots.

FIG. 4. As in Fig. 2, but for Canada East.

FIG. 5. As in Fig. 2, but for summer over Canada West.

FIG. 8. Trends in seasonal precipitation totals, occurrence of heavy and extreme precipitation extremes, and atmospheric circulation patterns. Trends are calculated for Canada West, Canada Central, and Canada East in four seasons for the period of 1979–2014. Region domains (see the first rows of Figs. 2–4) in which an SOM pattern demonstrates robust, increasing trends in the occurrence (O), persistence (P), and maximum duration (M) of mid-atmospheric circulation patterns is shown by red boxes; a robust, decreasing trend is shown by blue boxes. Regional domains (see the third and fourth rows of Figs. 2–4) with positive (negative) trends in the average seasonal precipitation (A), occurrence of heavy precipitation (H), and extreme precipitation (E) occurring in each SOM circulation pattern is shown by red boxes; negative trends are shown by blue boxes. Trends in a particular circulation pattern are robust when they are statistically significant at the 5% significance level in five out of six reanalyses and show the same sign (positive or negative) of those trends. Gray boxes indicate that trends are not statistically significant or that trend signs are different in the six reanalyses.

located over the west coast of North America results in positive precipitation anomalies and more precipitation extremes such as pattern 2 in winter (Figs. 2b,j,n), pattern 3 in spring (Figs. S3c,k), and pattern 4 in summer (Figs. 5d,l) for Canada West.

High precipitation and more precipitation extremes are associated with strong westerlies or zonal flows such as pattern 2 in winter for Canada Central (Figs. 3b,j,n) and Canada East (Figs. 4b,j,n), pattern 1 in spring for Canada Central (Figs. S4a,i,m), and pattern 3 in spring for Canada East (Figs. S5,k,o) and in summer (Figs. 6c,k,o) and fall (Figs. S7c,k,o) for Canada Central. Because in Canada Central (East) the right (left) side of the trough has an axis pointing south, a southward-shifted trough extending from the Arctic low results in dry (wet) climate over Canada Central (East), such as pattern 4 for Canada Central (Figs. 3d,l,p) and Canada East (Figs. 4d,l,p) in winter. However, a trough with an axis locating over the east coast of Canada was associated with a dry climate over both Canada Central and Canada East such as pattern 1 for Canada Central (Figs. 3a,i,m) and pattern 3 for Canada East (Figs. 4c,k,o) in winter. High (low) precipitation and more (fewer)

precipitation extremes are often linked to the same circulation patterns, even though there are some exceptions such as patterns 2 and 3 in summer for Canada East (Figs. 5b,c,j,k,n,o) where anomalously high precipitation was linked to pattern 3 while anomalously frequent precipitation extremes occurred under pattern 2.

Changes in occurrences of circulation patterns associated with an anomalously wet or dry climate over a region would significantly impact the precipitation of the region. For instance, there was an increase in occurrences of the ridge over the North Pacific (Figs. 2a,i,m) and western North America (Figs. 2b,j,n) that are associated with a wet climate over Canada West, resulting in an increase in winter precipitation intensity and the occurrences of precipitation extremes over Canada West. Occurrences of circulation patterns featuring a split flow over Canada East have increased and contributed to an increase of summer precipitation and occurrences of heavy and extreme precipitation events over Canada East (Figs. 7c,g,k). However, decreased occurrences of circulation patterns associated with anomalously wet climate have contributed to a decrease in precipitation and occurrences of precipitation

extremes such as pattern 1 in spring for Canada Central (Figs. S4a,e,i,m).

Figure 8 shows the robust trends in the occurrence characteristics of circulation patterns and precipitation regimes that were identified from the six reanalysis datasets. There were changes in area-weighted mean seasonal precipitation totals and the likelihood of occurrences of precipitation extremes under some mid-atmospheric circulation patterns; see Fig. 8, Table S2, and the fifth rows [(q)–(t)] of Figs. 2–4 and Figs. S3–S8. A total of 10, 30, and 6 time series of precipitation intensity, occurrence of heavy precipitation events, and occurrence of extreme precipitation events, respectively, show statistically significant and robust trends in the six reanalysis datasets under the 48 total circulation patterns analyzed in the study period. The occurrence of extreme precipitation events has increased under most circulation patterns while occurrences of heavy precipitation events show complementary changes in different patterns (e.g., increases under pattern 1 but decreases under pattern 3 for synoptic summer circulation patterns). There were some differences in the trends between the six reanalyses because of the variations of both regional GPH and precipitation in different reanalyses. Further evaluation of GPH and precipitation data could improve the estimate of changes in circulations and precipitation. However, precipitation changes under each circulation patterns derived from individual reanalysis dataset shows more statistically significant trends (Table S2) than the robust precipitation changes derived from the six reanalysis datasets. Robust trends of precipitation intensity and frequency of heavy and extreme precipitation events are quite evenly distributed over the four seasons and the three regions, except that precipitation intensity over Canada West under six circulation patterns (Canada Central and Canada East are one and three circulation patterns, respectively) has robustly changed. There were no robust statistically significant changes in occurrences of precipitation extremes in spring for all regions, and in Canada East for all seasons. Trends of precipitation changes are statistically field-significant (Table S3), which shows that possible thermodynamic changes in the atmosphere contributed to changes in the precipitation of Canada.

d. Thermodynamic and dynamic contributions to precipitation changes

Similar to changes in the mean precipitation and occurrences of precipitation extremes over Canada that have a large spatial variability (Tan and Gan 2017; Tan et al. 2017, 2018, 2019a,b; Zhang et al. 2001a), the mean precipitation and occurrences of precipitation extremes also show considerable variability under each circulation

pattern. It is useful to investigate relative contributions of thermodynamic and dynamic changes to precipitation changes region by region, since some complementary contributions to some subregions within a large region could be missed when regional average changes over that region are partitioned. There were also seasonal variations in changes to precipitation. For instance, heavy and extreme precipitation events decreased in winter and fall but increased in spring and summer over Canada West during 1979–2014 (Table S6), while precipitation extremes increased in all seasons over Canada Central (Table S8). Canada East shows an increase in extreme precipitation events in winter and summer but a decrease in heavy and extreme precipitation in spring and fall. We expect spatiotemporal variations of changes in precipitation extremes to be much higher than those in temperature extremes, given that a consistently warming trend has been observed in both cold and hot extremes worldwide since 1979 (Horton et al. 2015).

By partitioning changes in precipitation in all seasons for Canada West, Canada Central, and Canada East, respectively, it is shown that thermodynamic changes have contributed to most (~90%) changes in seasonal precipitation totals and occurrence of precipitation extremes (Fig. 9 and Tables S6–S8). This is partly related to the increased atmospheric moisture in a warming climate described by the Clausius–Clapeyron relationship (Emori and Brown 2005). We additionally tested a 4-node SOM (2 rows $\times$ 2 columns), a 9-node SOM (3 columns $\times$ 3 rows), and a 16-node SOM (4 columns $\times$ 4 rows) configuration for the sensitivity of partition results on the node number of SOM. The partition results based on the 4-, 9-, and 16-node SOM methods are only marginally different (Fig. S9), which is also found in previous studies on the partition of changes in occurrences of regional temperature extremes (Horton et al. 2015). This further indicates that the 4-node SOM method is sound for this study.

Limited to the accuracy and resolution of gridded precipitation data in the reanalysis datasets, the partition results for winter precipitation changes in Canada East show higher variations in the percentage of precipitation changes between different reanalysis resulted from thermodynamic changes than in other seasons and regions. The dynamic influence of circulation patterns associated with high (low) precipitation intensity and frequent (occasional) occurrences of precipitation extremes generally contributed less than 50% of the increase (decrease) of precipitation intensity and precipitation extremes (Fig. 9 and Tables S6–S8). In some seasons and regions, thermodynamic (dynamic) changes contributed to the increase (decrease) in precipitation intensity and precipitation extremes (e.g., summer precipitation intensity over Canada

FIG. 9. Percentage of changes in the seasonal precipitation totals (red) and occurrence of heavy (95th percentile; green) and extreme (99th percentile; blue) precipitation events partitioned to thermodynamic, dynamic, or dynamic change acting on thermodynamic change (combined) for the three regions (Canada West, Canada Central, and Canada East) and the four seasons based on data from the six reanalyses. Results from analyses of the ANUSPLIN precipitation data with ERA-Interim GPH circulation patterns are also shown.

West and Canada East; Tables S6 and S8). Instead of the expected thermodynamic contribution to an increase in precipitation intensity and occurrences of extreme precipitation events, partitioning of some reanalyses also shows that thermodynamic (dynamic) changes over some regions have contributed to a decrease (increase) in regional precipitation intensity and precipitation extremes, such as fall and winter precipitation extremes over Canada West (Table S6) and summer precipitation intensity and occurrences of heavy precipitation events over Canada East (Table S8). Both negative and positive contributions of thermodynamic and dynamic changes have complicated regional changes in precipitation intensity and precipitation extremes over Canada.

4. Summary and conclusions

This study uses a SOM-based classification method to partition changes in seasonal precipitation totals and occurrence of extreme precipitation events over Canada to

thermodynamic changes due to changes in atmospheric moisture conditions and dynamic changes due to changes in midatmospheric circulation patterns using 500-hPa GPH and precipitation obtained from the six global reanalysis datasets and the station-interpolated ANUSPLIN precipitation data. Given large spatial variations in changes in seasonal precipitation total and occurrences of heavy and extreme precipitation, three Canadian regions were used to identify the thermodynamic and dynamic contributions to regional and seasonal precipitation changes across Canada. Consistent midatmospheric circulation patterns are found between the six reanalysis datasets, while differences in the precipitation regimes represented by different reanalysis datasets under each circulation pattern result in differences in the partition results. Further evaluation of the accuracy of precipitation intensity and extreme precipitation events represented by different reanalysis dataset could help to select the best available reanalysis dataset for analyzing the influence of atmospheric circulation

patterns on seasonal precipitation totals and precipitation extremes over Canada.

Even though there are some differences between the partition results derived from the six reanalysis datasets, the results generally show dominant thermodynamic contributions to changes in precipitation intensity and occurrences of heavy and extreme precipitation events in most seasons and regions across Canada. Most thermodynamic changes contributed to an increase in precipitation intensity and occurrence of precipitation extremes, because of a general increase in atmospheric moisture under a warmer climate described by the Clausius–Clapeyron scaling relationship. However, as insufficient moisture supply might limit the increase in atmospheric moisture with the warming of the atmosphere over a region, the relative humidity in that region would change. A decrease in relative humidity could lead to decreased precipitation intensity and occurrences of precipitation extremes. For instance, a decrease in relative humidity over Canada West in winter (Vicente-Serrano et al. 2018) has contributed to a decrease in the occurrence of precipitation extremes, even though occurrences of midatmospheric circulation patterns conducive to high precipitation intensity and occurrences of precipitation extremes have increased.

Changes in circulation patterns have also significantly modulated changes in Canadian precipitation. Increased occurrences of ridges centered over western North America and the Pacific Ocean have increased winter precipitation intensity and occurrences of precipitation extremes over Canada West. Increased occurrences of split flows over Canada East have contributed to the increase of summer precipitation and occurrences of extreme precipitation events over eastern Canada. The concurrent increases (decreases) in occurrences of circulation patterns associated with wet climate over a region, and of precipitation intensity or the likelihood of precipitation extremes, have considerably contributed to increases (decreases) in precipitation. In such cases, both thermodynamic and dynamic changes contributed to the same positive or negative trends in precipitation changes. However, for some regions and seasons, thermodynamic changes have contributed an increase (a decrease) in precipitation while dynamic changes have contributed to a decrease (an increase) in precipitation such as in winter for Canada West and in spring for Canada Central and Canada East. This opposite contribution could result in minimal changes in precipitation intensity and occurrences of precipitation extremes.

Over certain regions such as Canada West in spring, fall, and winter, the thermodynamic changes have contributed to an increase (a decrease) in seasonal precipitation totals and simultaneously to a decrease (an

increase) in occurrences of precipitation extremes. This shows the complex nature of changes in precipitation under different characteristics such as intensity, frequency, duration, and area of precipitation. Because some local storms could not be explained by changes in large-scale atmospheric circulations analyzed in this study and thermodynamic changes in the diurnal cycle were not considered in daily data, further analyses are needed to comprehensively explain the effects of local changes in thermodynamic and dynamic conditions on complex changes in the precipitation of Canada.

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