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Change in the Leading Mode of North America's Wintertime Stationary Eddies

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1. Background

Extreme winter weather events in North America have become more frequent and increasingly destructive. According to the National Centers for Environmental Information report (NOAA 2019), during 1985-2005, Florida was the only state suffering billion-dollar losses related to freeze events in the eastern U.S. After 2006, the number of eastern states affected by these costly freeze-related disasters has doubled, along with a marked increase in the number of billion-dollar disasters caused by drought in western states. Past studies focusing on the 2013-2014 winter anomaly showed that the striking division of western U.S. drought and eastern U.S. cold-snaps have resulted from an atmospheric pattern referred to as the "North American Winter Temperature Dipole" (Singh *et. al.* 2016) or the "North American Winter Dipole" (Wang *et. al.* 2015), hereafter Dipole.

The polarity and location of this Dipole coincide with the wintertime stationary waves over North America, which feature a high-pressure ridge in the west and a low-pressure trough in the east. Oscillating in sync with the stationary waves, the positive-phase Dipole is associated with an anomalous ridge over the Gulf of Alaska and a deepened trough near the Great Lakes, thereby enhancing the east-west temperature contrast in North America (Voelker *et al.* 2019). While past studies suggested that the ridge in western U.S. (Swain *et al.* 2014) and the Dipole itself have amplified (Singh *et. al.* 2016), the trend suggests a one-sided response (*i.e.* only the positive phase inducive to drought in western U.S.) to internal and external variabilities, such as tropical Pacific heating (Hartmann 2015; Schulte and Lee 2017) and Arctic warming (Francis and Varus 2012; Overland *et al.* 2016). The intense Dipole reversal seen in 2016-17 winter suggests that the variation amplitude also increases leading to extreme conditions such as wet winters in California (Wang *et al.* 2017; Swain *et al.* 2018). These observations imply a change in the atmospheric circulation regime over North America, which is examined herein.

2. Analyses

Empirical orthogonal function (EOF) is the main analysis technique for this study. We subjected the monthly anomalies of geopotential height (Z) at 250 hPa from November through February, with the zonal mean removed to depict the stationary eddies (herein ΔZE250). For a running 30-year period, each EOF analysis contains 120 realizations (30 years x 4 months). The month-by-month arrangement of ΔZE250 reflects the strong sub-seasonal variability of winter climate over North America (Higgins *et al.* 2000). For the initial analysis of the atmospheric circulation, we use NCEP–NCAR reanalysis (Kalnay *et al.* 1996).

2.1 Change in leading patterns

The first mode of ΔZE250 during the earlier period of 1948-1979 is shown in Figure 1a. Explaining 18.6% of the variance, this leading EOF features a wave train emanating from the central Pacific to the U.S., coincident with the well-known Pacific North American (PNA) pattern. By superimposing the PNA contours, which was produced by correlating ΔZE250 with the PNA index from the NOAA Climate Prediction Center, the two patterns of EOF1 and PNA are in-phase. By comparison, the post-1980 EOF1 (Fig. 1b) shows a similar wave train but the wave centers are shifted from the PNA pattern by about a quarter phase. It appears that the post-1980 EOF1 becomes phase coincident with the Dipole centers (marked with X and + in North America). This result suggests that the leading mode of ΔZE250 variability has changed from a PNA-like pattern to one that resembles the Dipole. We should note that, by repeating the EOF analysis with seasonal mean instead of

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monthly interval, the leading pattern of the latter period would still be PNA, whereas the Dipole remains secondary (not shown).

By correlating the first principal component (PC1) time series with the monthly SST anomalies (Nov-Feb; using Extended Reconstructed SSTv4), the pre-1980 EOF1 corresponds to a La Niña-like pattern resembling the cold-phase Pacific Decadal Oscillation (PDO) (Fig. 1c), which supports the associated PNA atmospheric wave train (Fig. 1a). After 1980, the SST correlation map with respect to EOF1 changed dramatically and is absent of the PDO alongside most tropical signatures (Fig. 1d). This post-1980 SST pattern corresponding to EOF1 reveals the oceanic "Blob" along the West coast (Kintisch 2015), as well as robust negative anomalies in the Western North Pacific and the Bay of Bengal. This latter SST feature coincides with an ENSO precursor, called the Western North Pacific pattern (WNP), that saw amplification in recent decades (Wang *et al.* 2013). The marked difference between these SST patterns accompanying EOF1(ΔZE250) of two eras implicates two very different modes of sub-seasonal variability influencing North American winter.

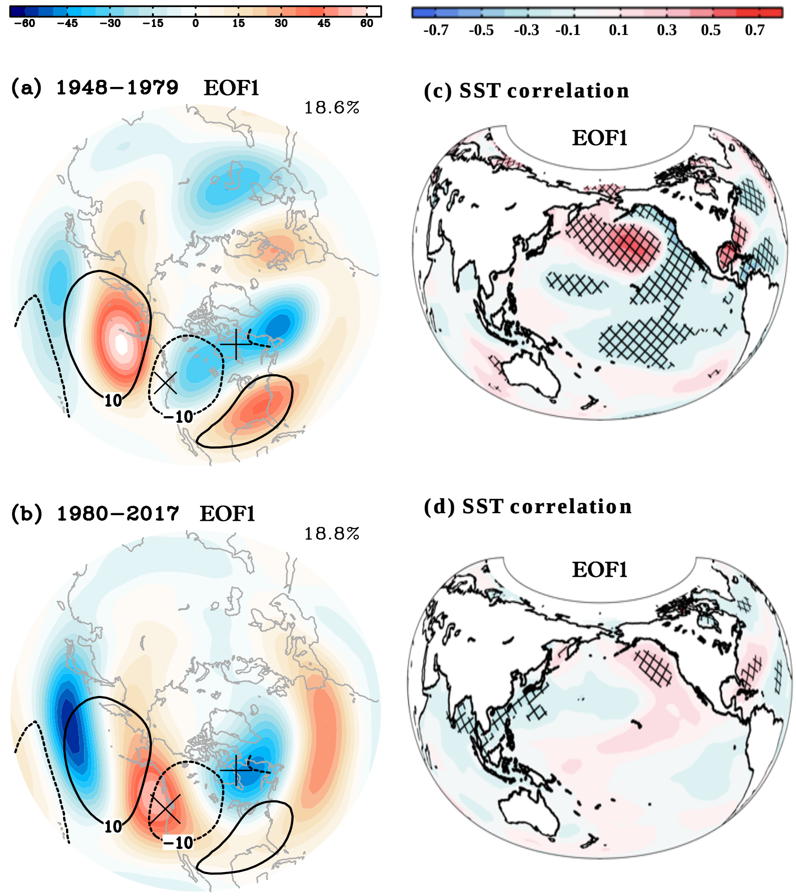

Fig. 1 First EOF mode of monthly $\Delta Z_E 250$ during (a)1948-1979 and (b) 1980-2017 winters (EOF1 shading), superimposed with with the PNA pattern (contour) and the Dipole centers (marked with X and +) in North America. The correlation maps between monthly SST anomalies and the first principle component (PC1) are shown for the (c) 1948-1979 and (d) 1980-2017 periods. Hatched areas indicate significant values ($p<0.01$).

2.2 Evolution of the change

To examine the evolution in which the leading mode of ΔZE250 started to change, we adopted the running-EOF method, following Zhang *et al.* (2008). A series of EOF analysis was conducted in the 30-year window and repeated every five years. The leading EOFs are then subject to a spatial correlation analysis with the PNA pattern and the Dipole, forming a series of correlation coefficients with each 30-year period. This analysis was performed on newer reanalysis data: the ECMWF 20-Century Reanalysis (ERA20C) and the ERA-Interim. As shown in Fig. 2a, the running-EOF computed with all reanalysis data shows a decreasing trend in the correlations between EOF1 and PNA from 1970 to 2000. Meanwhile, the correlations increase between EOF1 and the Dipole, computed from the ΔZE250 of the 2013-2014 winter (Wang *et al.* 2014). Correspondingly, sliding correlations of the second running-EOF (EOF2) with the PNA show an opposite trend (Fig. 2b), suggesting that the Dipole used to be the second mode but has intensified, overtaking EOF1 during the 1990s.

The mechanism behind this decadal shift in the prevailing modes of variation is manifold. Previous studies proposed that the ENSO-forced PNA would move eastward in response to the spatial shift of the mean SST warming (Zhou *et al.* 2014). Interdecadal variability of the North Pacific sea level pressure can induce a shift in the PNA (Johnson and Feldstein 2010). Moreover, one could relate the Dipole to the maintenance of wintertime stationary waves (*e.g.*, Chang 2009). The western ridge of the North American stationary waves is primarily linked to the orographic forcing of the Tibetan Plateau, while the Rocky Mountains amplify the eastern/downwind trough. Diabatic heating from the Western Pacific and North Pacific further enhances and shapes this ridge-trough pattern. Therefore, the observed Dipole amplification could be related to such forcings combined, *i.e.* jet stream-terrain interactions and diabatic heating.

2.3 Past and future of Dipole

The transition between the leading and secondary modes of atmospheric circulation suggests that the Dipole variance has increased (Singh *et. al*, 2016; Wang *et al.* 2015). To put the Dipole variances into historical and projected perspectives, we further examined the NOAA 20-Century Reanalysis data and the Community Earth System Model (CESM) Large-Ensemble Project with 40 members (Kay *et al.* 2015). By calculating the 30-year running variance of the Dipole index derived from Wang *et al.* (2014), we found that the Dipole variance has undergone a pronounced low-frequency fluctuation. As shown in Fig. 3, an inter-decadal variation on the order of 60 years is observed, evidenced in the longer-term reanalysis data. Both the NCEP-NCAR and ERA-Interim reanalyses indicate that the Dipole variance was largest in the early 21st century. Similar analysis of the CESM ensemble means reveal an increase in Dipole variance during the historical period (up to 2005 with increasing greenhouse gas) that is projected to continue under the high-emission (RCP 8.5) scenario. However, the projected ensemble-mean variance starts to decline after 2050, despite an increase in the ensemble spread; this suggests a rather uncertain future concerning the Dipole fluctuation. At this point, we can only attribute this late-21st century decline to natural variability as observed.

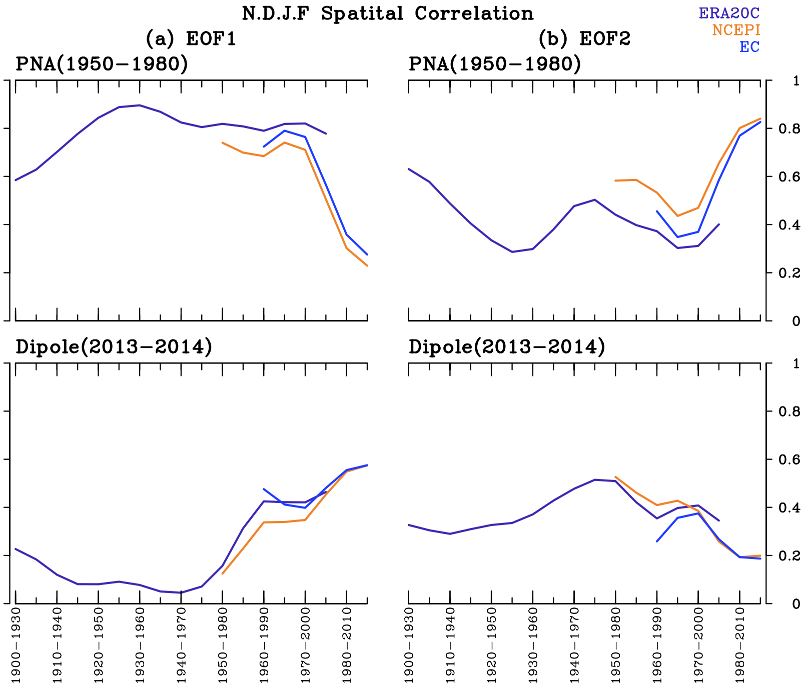

Fig. 2 Spatial correlation coefficients between the PNA/Dipole pattern and (a) EOF1 (b) EOF2 of $\Delta Z_E 250$ as in Fig. 1. This analysis is repeated throughout a 30-year Running-EOF window done every 5 years using three different reanalysis data sets as indicated on top of (b).

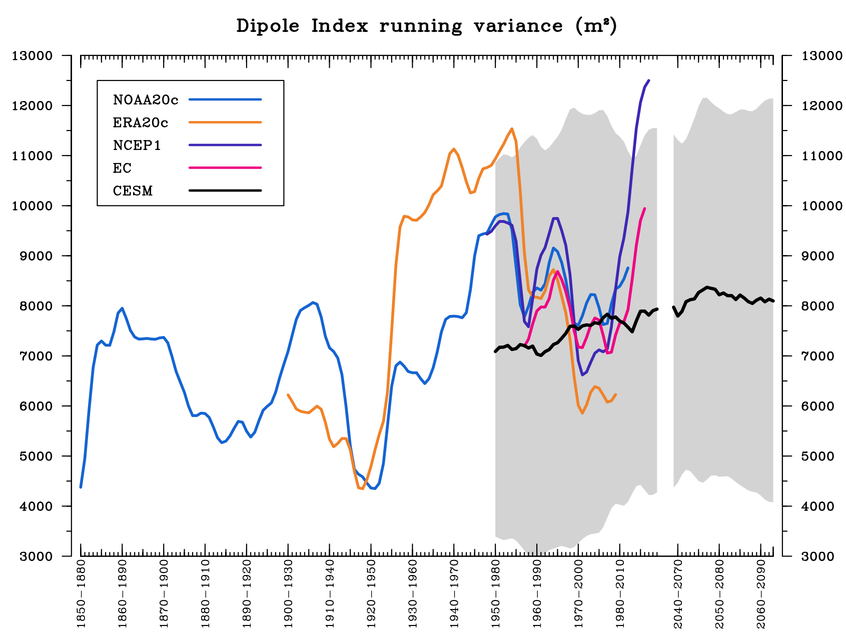

Fig. 3 The 30-years running variance of the Dipole index derived from Wang *et al.* (2014) using multiple reanalysis data sets as indicated at upper left. Gray shaded represents the spread of CESM 40-member ensemble calculated from two standard deviations above and below the ensemble mean.

3. Summary

The diagnostics undertaken here suggest that the leading mode of Northern Hemispheric atmospheric stationary waves underwent a notable change. Since the 1980s, the first mode of winter stationary eddies has changed from the PNA to the Dipole. Given that the EOF describes the variance of individual patterns, this finding also echoes the increased amplitude of the Dipole as observed. The CESM large-ensemble simulations forced with increasing greenhouse gas indicate that the Dipole variance will generally amplify alongside its low-frequency natural variability. This result implies that the variation of the atmospheric circulations over North America, especially in the subseasonal timescale, could continue to be dominated by the Dipole with the potential to sharpen the east-west temperature division across North America. Future examination of the dynamic processes leading to the Dipole amplification should consider jet-terrain interactions, tropical and extratropical diabatic heating, and the effect of Arctic amplification.

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