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Dominant Modes of Variability in the Western U.S. Coastal Cyclonic Activity: Dynamical Origins and Impacts on the Precipitation Characteristics

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1. Introduction

Coastal cyclones developing over the central and eastern North Pacific are responsible for majority of the winter precipitation in the western U.S. When approaching the land, these cyclones can bring hurricane-force winds and heavy precipitation to the coastal area causing flooding and mudslides in the Pacific Northwest and California (Ely *et al.* 1993; 1994). Moving further inland, they also directly contribute to or trigger significant snowfall events in the Sierra Nevada and Rockies, therefore partly control the depth of mountain snowpack that is crucial for the spring and summer water supply in the Southwest (Serreze *et al.* 1999). The characteristics of coastal cyclonic activity, including location, frequency and intensity, therefore have strong implications for natural hazards mitigation and water resource management in the western U.S. Past studies have examined the climatology of the winter cyclones focusing on either their spatial distributions or the variations of their occurrence frequency across various timescales (*e.g.*, Sanders and Gyakum 1980; Parker *et al.* 1989; Sinclair 1994; Lefevre and Nielsen-Gammon 1995; Serreze *et al.* 1997; Key and Chan 1999). Anomalous cyclone tracks are also recognized as an integral part of the extratropical response to El Niño that is characterized by wetter (drier) than normal conditions in the southern (northern) part of the western U.S. (Schonher and Nicholson 1989; Dettinger *et al.* 1998; Mo and Higgins 1998). Raphael and Cheung (1998) further pointed out that the dryness in California during the second half of 1980s was related to the diminished extent of coastal cyclonic activity near California. Despite the obvious significance, few studies, however, have attempted to give a systematic account of the variability in coastal cyclones. Here we made an initial effort to quantify the dominant modes of interannual variability in the western U.S. coastal cyclonic activity, explore their likely dynamical origins, and examine their impacts on both the total amount and intensity of the winter precipitation.

2. Data and Methods

The analysis was focused on 27 winters (DJF, 1979/80-2005/06). A cyclone tracking data based on the NCEP/NCAR reanalysis (Sinclair 1997) was used to identify coastal cyclones, which include those making actual landfalls and those bypassing the west coastline. For each coastal cyclone identified, the latitude, longitude, sea level pressure (SLP) and 1000mb geostrophic vorticity at the first track point that gets within 475km distance from the coastline were recorded for further analysis. Based on the latitude and vorticity of the coastal cyclones, a cyclonic activity function (CAF) was

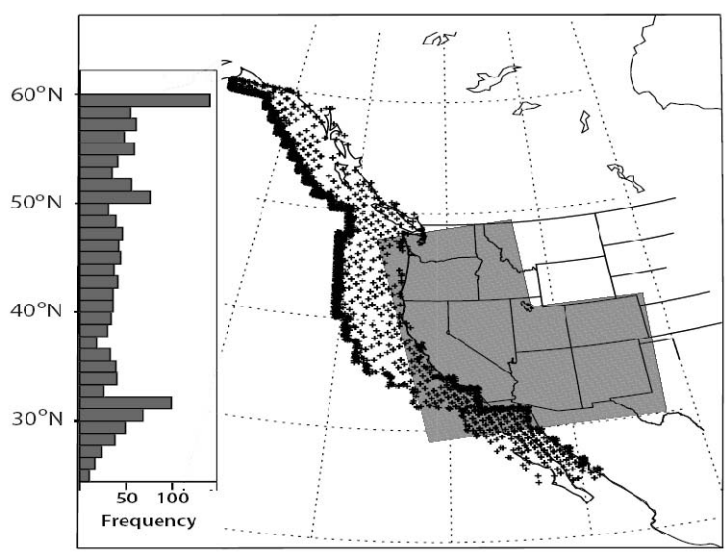

Fig. 1. Locations of the coastal cyclones ("+") and the histogram of their occurrence frequency across latitudes. (Myoung and Deng 2009)

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defined as the accumulated intensity of the coastal cyclones (*e.g.*, sum of the vorticities of the coastal cyclones) in a winter in each 1º latitude interval from 26ºN to 52ºN.

Daily precipitation from the North American Regional Reanalysis (NARR) (Mesinger *et al.* 2006) was used in conjunction with the cyclone tracking data to estimate the contributions of the cyclone-induced precipitation to the winter total precipitation. In particular, the NARR daily accumulated precipitation was mapped onto the area under a cyclone's precipitation sectors. Such an area is assumed to encompass 4/cosθ to the west, 8/cosθ° to the east and 7.5° to the north and south from the center of the cyclone, where θ is the latitude of the track point.

Empirical Orthogonal Function (EOF) analyses were applied to the CAF and the DJF-mean precipitation in 27 winters to identify the principal modes of interannual variability in the coastal cyclonic activity and in the precipitation, respectively. Linear correlation analysis was conducted to quantify the relationship between the CAF and the winter precipitation, and to seek the dynamical origins of the principal modes of CAF variability. Composite analysis based upon the extreme phases of the CAF variability was performed to quantify the impacts of anomalous cyclonic activity on both the frequency and intensity of the winter precipitation in the western U.S.

3. Results and discussions

All the coastal cyclones observed in the 27 winters (1979/80-2005/06) are indicated by "+" in Fig. 1. The histogram on the left shows the frequency distribution of the cyclones across different latitudes. The peak frequency is located in the northern Canada at 60°N. The southern and northern U.S. borders are another two regions with relatively high frequency of cyclone passages.

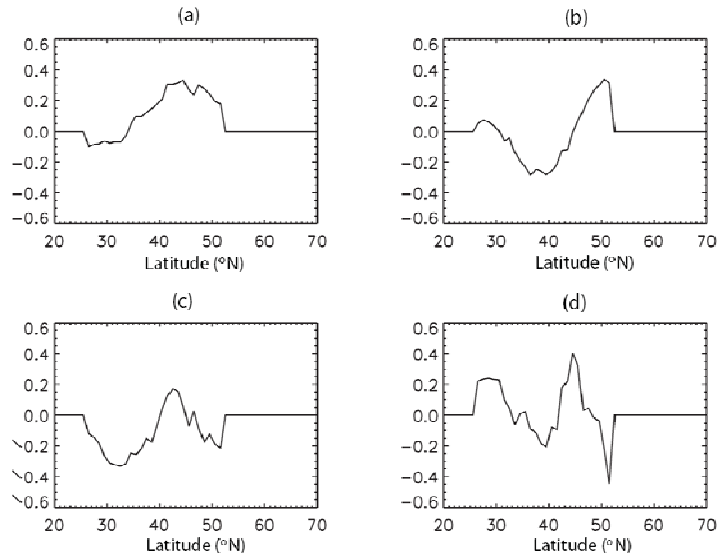

Fig. 2. EOF1 (a), EOF2 (b), EOF3 (c), and EOF4 (d) of the cyclonic activity function (CAF). (Myoung and Deng 2009).

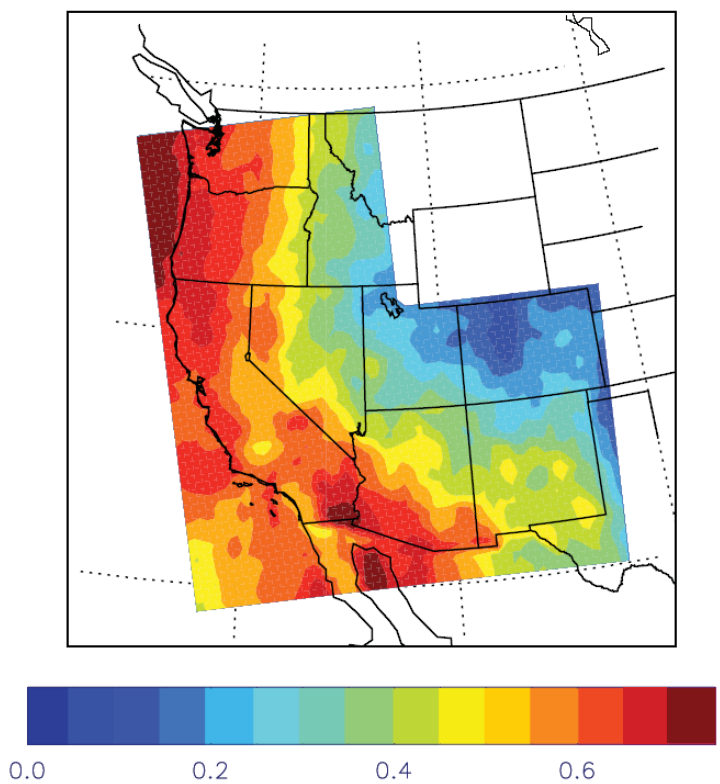

Fig. 3. Ratio of the cyclone-induced precipitation amount to the winter total precipitation in the western U.S. Contour interval is 0.05. (Myoung and Deng 2009)

Figure 2 shows the four leading EOF modes of the CAF, *i.e.*, $EOF_{CAF}1$, $EOF_{CAF}2$, $EOF_{CAF}3$, and $EOF_{CAF}4$. They account for 40.7%, 29.6%, 14.4% and 3.9% of the total interannual variance, respectively. $EOF_{CAF}1$ is characterized by a monopole with peak amplitude between 40°N and 50°N (Fig.2a). $EOF_{CAF}2$ (Fig. 2b) on the other hand has a dipole structure with opposite signs between the south (35°N-42°N) and north (45°N-52°N). It indicates that above-normal

cyclonic activity along the northwest coast of U.S. tends to be accompanied by below-normal activity along the southwest coast and vice versa. The third mode (Fig. 2c) shows opposite signs between 40°N-44°N and 26°N-38°N/47°N-52°N. Enhanced cyclonic activity over the central west coast of U.S. (40°N-44°N) is associated with weakened activity over the southern California and the US-Canada border and vice versa. The fourth mode (Fig. 2d) is characterized by a quadruple with peak amplitudes occurring north of 40°N.

The ratio of the precipitation induced by coastal cyclones to the winter total precipitation is displayed in Fig. 3. The value increases rapidly from about 0.45 in the inland region to about 0.65 in the coastal area with maximum values at the Pacific Northwest and southern California exceeding 0.7. On average, this ratio is above 0.6 at most coastal areas indicating that more than 60% of the total winter precipitation is associated with the Pacific cyclones. If only the cyclones that made actually landfalls were considered, this ratio dropped to about 0.3, showing the substantial contributions to precipitation by those bypassing cyclones.

To establish the linkage between the variability in coastal cyclonic activity and in precipitation, we first examined the leading EOFs of the DJF-mean precipitation in the western U.S. (Fig. 4). The first mode ($EOF_{PRECIP}1$) is characterized by a monopole with maximum amplitude over the Pacific Northwest and northern California. The second mode ($EOF_{PRECIP}2$) shows a dipole structure with opposite signs between the Pacific Northwest and California. Correlation analysis between the principal components (PCs) of the precipitation and those of the CAF reveals that $EOF_{PRECIP}1$ and $EOF_{PRECIP}2$ are significantly related to $EOF_{CAF}1$ and $EOF_{CAF}2$ at the 95% level, respectively (Table 1).

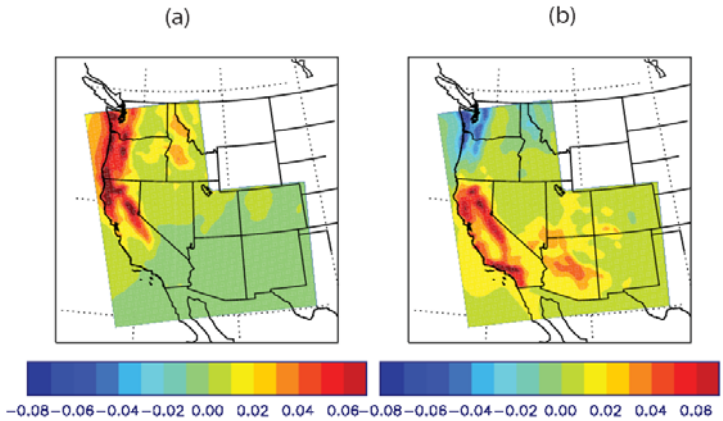

Fig. 4. EOF1 (a) and EOF2 (b) of the western U.S. winter precipitation. Contour interval is 0.02. (Myoung and Deng 2009)

CC	$PC_{PRECIP}1$	$PC_{PRECIP}2$
$PC_{CAF}1$	**0.50**	-0.08
$PC_{CAF}2$	-0.07	**-0.53**
$PC_{CaF}3$	0.03	0.18
$PC_{CAF}4$	0.11	-0.35

Table 1. Correlation coefficients between PCs of the winter precipitation and PCs of the cyclonic activity function, CAF. Bolds are statistically significant at the 95% level. (Myoung and Deng 2009)

	$PC_{CAF}1$	$PC_{CAF}2$	$PC_{CAF}3$	$PC_{CAF}4$
PNA	0.11	-0.31	0.36	0.13
TNH	-0.17	**0.59**	-0.05	-0.06
AO	-0.29	-0.11	**-0.47**	-0.21
NP	0.00	0.29	**-0.50**	-0.19

Table 2. Correlation coefficients of PCs of CAF with DJF-averaged indices of PNA, TNH, AO and NP. Bolds are statistically significant at the 95% level. (Myoung and Deng 2009)

As the most pronounced interannual signal in the climate system, ENSO is expected to modulate the coastal cyclonic activity (Noel and Changnon 1998). This was demonstrated by a significant correlation of -0.38 between $PC_{CAF}2$ and the NINO3.4 SSTA. Given also the linkage between $PC_{CAF}2$ and $PC_{PRECIP}2$, these results support the speculation that ENSO contributes to the dipole of precipitation variability by inducing changes in the preferred latitudes of cyclone tracks.

To identify other large-scale processes that are potentially coupled to the CAF variability, we computed the correlations between PCs of the CAF and indices of major teleconnection patterns that are active over the North Pacific in winter (Table 2). The positive PNA or negative TNH phase features a negative height

anomaly west of the North America and a strengthened, eastward-displaced subtropical jet (Mo and Livzey 1986; Livzey and Mo 1987). This anomalous circulation pattern tends to bring more storms to the lower latitudes. A relatively weaker correlation (-0.31) was found between $PC_{CAF}2$ and PNA compared to the one (0.59) between $PC_{CAF}2$ and TNH. This difference is actually consistent with the fact that $PC_{CAF}2$ is strongly modulated by ENSO and TNH is a more direct response to ENSO compared to PNA (Mo and Livzey 1986; Livzey and Mo 1987). Both the Negative AO and NP phase correspond to a deepening of the Aleutian Low and a stronger subtropical jet, which tend to enhance the eastward propagation of synoptic-scale eddies over the eastern North Pacific and therefore increase cyclonic activity at the Pacific Northwest and northern California. The significant, negative correlations of $PC_{CAF}3$ with AO (-0.47) and NP (-0.5) are consistent with this argument. On the one hand, the teleconnection patterns discussed above may dynamically drive key variability in the coastal cyclonic activity. On the other hand, it is equally important to recognize that anomalous cyclonic activity often provides positive feedback to a teleconnection pattern and plays a key role in initiating and maintaining large-scale flow anomalies characteristic of such teleconnection (Holopainen and Fortelius 1987; Mullen 1987; Lau and Nath 1991; Nakamura *et al.* 1997).

As the last step, we will try to quantify the impacts of the principal CAF variability on the characteristics of winter precipitation. Composite anomalies of various precipitation statistics were calculated based upon the extreme phases of the CAF EOFs. Fig. 5 shows the differences of these statistics between the composite PC+ and PC- winters which are defined respectively as the average over the 5 winters with the highest and lowest values of each CAF PC. The three statistics we examined are the number of rainy days per winter, the 95th percentile of the daily rate, and the probability of precipitation being heavy given a rainy day. The first statistics quantifies precipitation frequency and the latter two are measures of precipitation extremes.

For PC1 (Fig. 5a-c), drastic differences at 38°N-49°N (Fig. 5a) are associated with significant changes of the cyclonic activity at 40°N-50°N (Fig. 2a). The maximum difference exceeds 14 days (out of 90 days per winter) at certain locations, which is equivalent to 48% of the average number of rainy days per winter at those locations. Significant differences in the 95th percentile of the rain rate (Fig. 5b) are found along the northwest coast and in its adjacent inland regions. Changes are greater than 16 mm/day in part of the northern California and southern Oregon. The increased probability of heavy precipitation from PC1- to PC1+ winter is evident in the northwestern U.S. (Fig. 5c).

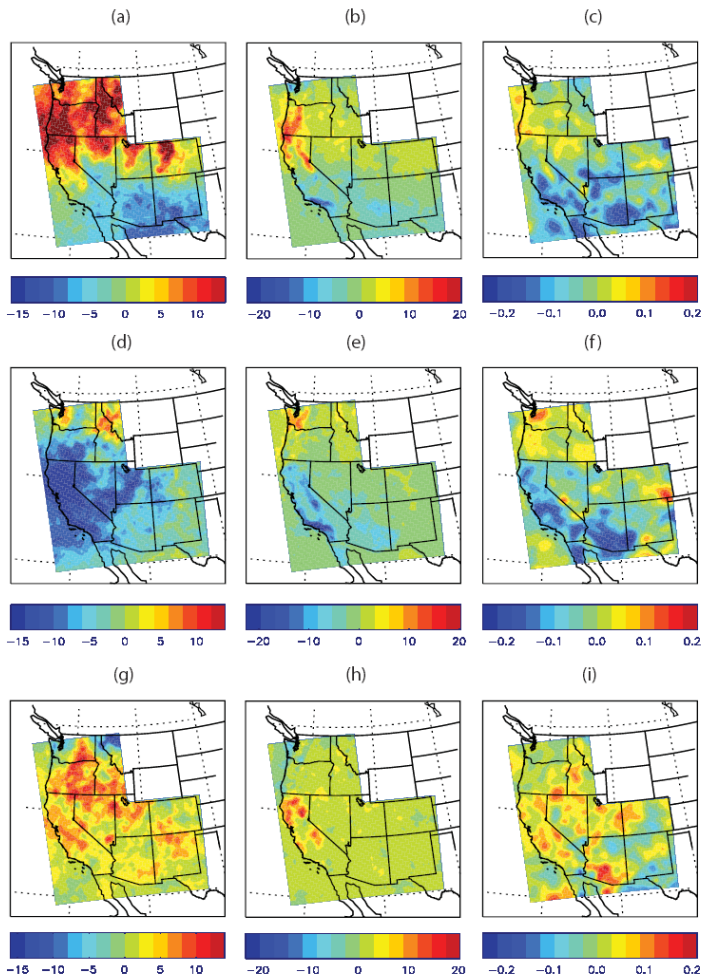

Fig. 5. Differences of the number of rainy days per winter (a), the 95th percentile of the daily rain rate (unit: mm/day) (b) and the probability of precipitation being heavy given a rainy day (c) between PC1+ and PC1- winters (See the text for definitions). (d)-(f) and (g)-(i) are the same as (a)-(c) except for the differences between PC2+ and PC2- winters and between PC3+ and PC3- winters, respectively. (Myoung and Deng 2009)

Fig. 5d, e and f (Fig. 5g, h and i) are the same as Fig. 5a, b and c but between PC2+ and PC2- winters (PC3+ and PC3- winters). For PC2, the most distinct feature is the dipole between the northwestern and the southwestern U.S. Negative phases of $EOF_{CAF}2$ are clearly leading to increases not only in the winter total precipitation but also in the extremeness of precipitation in the Southwest. The differences found for PC3 (Fig. 5g, h and i) are also in agreement with the mean precipitation changes driven by $EOF_{CAF}3$ (Fig. 2c). In the central California, while the increase in the number of rainy days (Fig. 5g) is equivalent to 20-45% of its mean values, changes exceeding 100% of the corresponding mean values are found in the 95th percentile of the daily rain rate.

4. Summary and conclusion

This study examined the interannual variability in the cyclonic activity along the U.S. Pacific coast and quantified its impact on the characteristics of winter precipitation in the western U.S. A cyclonic activity function (CAF) was derived from objectively-identified cyclone tracks in 27 winters (1979/80-2005/06). EOF1 of the CAF was found to be responsible for the EOF1 of the winter precipitation in the western U.S., which is a monopole mode centered over the Pacific Northwest and northern California. EOF2 of the CAF contributes significantly to the EOF2 of the precipitation, which indicates that above-normal precipitation in the Pacific Northwest and its immediate inland regions tends to be accompanied by below-normal precipitation in California and the Southwest and vice versa. While EOF2s of the CAF and precipitation are linked to the ENSO signal on interannual time scales, EOF3 of the CAF shows robust relationship with NP and hemispheric-scale variability such as AO. A composite analysis revealed that the leading CAF modes increase (reduce) the winter total precipitation by increasing (reducing) both the number of rainy days per winter and the extremeness of precipitation.

Recent modeling studies have shown that the Pacific storm track, where most west coast cyclones originate, tends to shift poleward in a warm climate (Hall *et al.* 1994; Yin 2005). It is of great socioeconomic significance for us to understand how this poleward shift projects onto the coastal cyclonic activity and how the changes in the cyclonic activity affects the trend and variability of winter precipitation in the western U.S. In this regard, an improved understanding of the large-scale circulation features that determine the characteristics of coastal cyclones and their sensitivity to increased atmospheric concentrations of greenhouse gases will certainly benefit the society from perspectives of both the natural hazards mitigation and the water resource management.

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