Climate Dynamics (2006)
DOI 10.1007/s00382-005-0101-9

Alice Favre · Alexander Gershunov

Extra-tropical cyclonic/anticyclonic activity in North-Eastern Pacific and air temperature extremes in Western North America

Received: 28 February 2005 / Accepted: 11 November 2005

Abstract Synoptic extra-tropical cyclone and anticyclone trajectories have been constructed from mean daily sea level pressure (SLP) data using a new automated scheme. Frequency, intensity and trajectory characteristics of these transients have been summarized to form indices describing wintertime cyclonic and anticyclonic activity over the North-Eastern Pacific (east of 170°W) during 1950–2001. During this period, the strength of anticyclones gradually diminished and their frequency became more variable, while cyclones intensified in a discrete shift with deeper lows and further southerly trajectories occurring since the mid-1970s. These changes in synoptic transients translate into anomalously low seasonal mean SLP in the Aleutian Low, a low-level circulation anomaly consistent with the positive phase of the North Pacific Decadal Oscillation, with positive sea surface temperature (SST) anomalies along the west coast of North America and negative in the central North Pacific Ocean. A link between cyclonic/anticyclonic activity and tropical SST anomalies also exists, but this link only becomes significant after the mid-1970s, a period that coincides with more southerly cyclone trajectories. Southward excursions of mid-latitude cyclones during El Niño/positive NPO winters accomplish the northward advection of tropical air and discourage the southward penetration of polar air masses associated with transient anticyclones. Naturally, these changes in cyclonic/anticyclonic activity directly impact surface air temperatures, especially at night. We document these profound impacts on observed wintertime minimum temperatures over Western North America.

A. Favre
Centre de Recherches de Climatologie (CRC),
UMR 5210 CNRS—Université de Bourgogne,
6 Boulevard Gabriel, 21000 Dijon, France

A. Gershunov (✉)
Climate Research Division—0224,
Scripps Institution of Oceanography,
UC San Diego, La Jolla, CA, 92093-0224 USA
E-mail: sasha@ucsd.edu
Tel.: +1-858-5348418
Fax: +1-858-5348561

1 Introduction

On seasonal timescales, North-Eastern Pacific climate variability is determined mainly by variations of two centers of action: the Aleutian Low and the Subtropical High. During winter, the Aleutian Low is most intense and its area of influence is at its maximum while the Subtropical High is displaced southward enabling temperate atmospheric circulation to penetrate to lower latitudes. This mean wintertime atmospheric configuration favors the propagation of perturbed systems across a large latitudinal domain, which directly affects Western North American surface climate from Alaska to Baja California as well as inland regions. In the lower troposphere and at synoptic scale, atmospheric circulation is organized in a succession of migratory cyclones and anticyclones which move, on average, in north-eastward and south-eastward trajectories, respectively (Petterssen 1956; Klein 1957; Zishka and Smith 1980; Harman 1987; Wallace et al. 1988). These transitory perturbations are responsible for large-scale meridional heat exchanges with warm air being advected poleward by cyclones and cold air—equatorward by anticyclones.

Important changes in cyclonic activity have been observed in the wintertime circulation of the Pacific–North American sector during the second-half of the twentieth century. These changes generally fall into two categories: a gradual ~50-year trend or a discrete shift around 1976–1977 both amounting to an intensification of cyclonic activity with related changes in Western-North American surface climate. Graham and Diaz (2001) observed a gradual intensification of cyclonic activity in the North Pacific sector, which is characterized by more frequent intense cyclones (i.e., deep lows) associated with increasing relative vorticity and wind speeds. In agreement with this gradual view, spring has been observed to arrive progressively earlier to the Western United States as manifested in rising late-winter–early-spring average temperatures, resulting in increasingly early snowmelt as well as earlier blossoming of lilac and honeysuckle (Cayan et al. 2001).

On the other hand, a discrete shift in the North Pacific Ocean and atmosphere climate has been observed to occur in 1976–1977 in connection with the so-called North Pacific Decadal Oscillation (NPO or PDO: Mantua et al. 1997). Many studies documented a sudden modification in the North Pacific sector atmospheric and ocean circulation that occurred in the late 1970s (e.g., Nitta and Yamada 1989; Trenberth 1990; Trenberth and Hurrell 1994; Latif and Barnett 1996; Mantua et al. 1997; Nakamura et al. 1997). During the winter half-season especially, the Aleutian Low has become deeper and shifted eastward, creating an intensification of southerly winds along the west coast of North America. Increased frequency of heavy daily wintertime precipitation events over the South-Western U.S. accompanied the late 1970s Pacific climate shift (Gershunov and Cayan 2003). Trend or shift, North-Eastern Pacific wintertime cyclonic activity has intensified notably in the last half-century, accompanied by consistent changes in Western North American surface climate.

Extra-tropical surface transient anticyclonic activity, although equally important as cyclonic activity for describing and understanding the nature of observed climatic changes as well as for determining surface climate conditions, has been largely neglected in the literature on recent North Pacific climate change. This is in spite of a suggested role of transient anticyclones as active determinants of climatic variability (Leroux 1998). In this work, by considering cyclones together with anticyclones, we take a comprehensive view of North-Eastern Pacific recent climate variability. We attempt to ascertain whether changes in the behavior of anticyclones have been consistent with those observed in cyclonic activity. Since transient surface anticyclones play a leading role in determining the occurrence of extreme wintertime cold temperature outbreaks, seasonal statistics of daily temperature observations are considered in the same framework.

The succession of cyclones and anticyclones is the synoptic pulse of winter climate. These transient features together with topographic characteristics of a region determine the frequency and intensity of local high-frequency temperature and precipitation variability. In particular, transient anticyclones determine daily wintertime temperature minima ($T_{\min}$, i.e., nighttime temperatures) at middle and high latitudes by advecting polar air masses and promoting clear skies, i.e., efficient radiational cooling (Durre and Wallace 2001). Mid-latitude cyclones have the opposite effect on $T_{\min}$, mainly by inhibiting radiational cooling through associated cloud cover. Decreasing trends in diurnal temperature range observed over the North American mid-latitudes (Karl et al. 1984) have been associated with warming trends in $T_{\min}$ larger than those in $T_{\max}$ (Easterling 2002; Groisman et al. 2004). Climate models project similar trends in response to anthropogenic climate modification (Cao et al. 1992). However, no dynamical mechanisms accounting for these preferential trends in minimum temperature have been identified. Considering synoptic transients provides an opportunity to verify whether changes in cyclonic/anticyclonic activity consistent with observed trends in $T_{\min}$ have occurred. An additional goal of our research, therefore, is to investigate the wintertime relationship between observed daily $T_{\min}$ in Western North America and cyclonic/anticyclonic activity over the Eastern North Pacific.

In order to analyze the wintertime variability of cyclonic and anticyclonic behavior, we first constructed seasonal climatologies of their day-to-day trajectories derived using an original automated procedure (Sect. 2.1) and described their climatological features (Sect. 2.2). We then created seasonal statistics of individual cyclone/anticyclone tracks over the North-Eastern Pacific sector, organized them into wintertime indices and examined their variability over the past half-century (Sect. 2.3). In Sect. 3, northeastern Pacific cyclonic/anticyclonic activity was viewed in the context of global climate variability [i.e., sea level pressure (SLP), surface air temperature and winds] and possible connections with relevant regional climate modes (e.g., NPO and ENSO) were explored. In Sect. 4, we identified the influence of cyclonic/anticyclonic activity on synoptic temperature extremes by relating our transient circulation indices to seasonal mean as well as frequencies of cold and warm nighttime air temperature extremes observed at stations over Western North America.

2 Quantifying mid-latitude transient activity

Different automated schemes have been developed specifically to track cyclonic systems (Alpert et al. 1990; Le Treut and Kalnay 1990; Murray and Simmonds 1991; Jones and Simmonds 1993; Koenig et al. 1993; Sinclair 1994; Serreze 1995; Serreze et al. 1997; Blender et al. 1997; Graham and Diaz 2001; Gulev et al. 2001, Hoskins and Hodges 2002; Hodges et al. 2003). Most were not applied to track anticyclones, but those that were, did not perform adequately. Anticyclones are larger and less spatially coherent than cyclones. Automated cyclone tracking schemes typically identify local maxima in instantaneous cyclonic gradient wind vorticity; however, anticyclonic vorticity maxima do not typically occur near pressure maxima, regions of light winds, which are the centers of transient anticyclones (e.g., Sinclair and Watterson 1999). Specific automated methodology to track surface anticyclones was developed and successfully applied, to our knowledge, only in the Southern Hemisphere (Jones and Simmonds 1994; Sinclair 1996; Sinclair and Watterson 1999; Pezza and Ambrizzi 2003), and these are based on locating and tracking pressure maxima in instantaneous surface or near-surface pressure fields. Similar pressure-based schemes have, on the odd occasion, been applied to track mid-latitude cyclones (e.g., Graham and Diaz 2001). To quantify anticyclonic and cyclonic activity by the same methodology, we developed our own simple automated scheme based on selectively connecting daily mean SLP maxima and minima. We refined this scheme to perform equally well tracking both high and low pressure systems. It is presented below followed by a description of transient activity over the North-Eastern Pacific.

2.1 Establishment of trajectories: data and methodology

The first step is to identify the surface centers of low and high pressure defined by the local minimum/maximum of SLP. To construct the cyclone and anticyclone tracks at the surface, we follow low and high pressure centers in daily mean SLP (MSLP) data from the NCEP-NCAR Reanalysis (Kalnay et al. 1996; Kistler et al. 2001), over its 2.5° by 2.5° grid. Our domain of interest is between 80°E and 110°W, from the North Pole to the Equator for the winters 1950–2001. The spatial limits have been fixed for the following reasons: (1) the easternmost origin region of transients, especially anticyclones, which circulate over the North Pacific, is Eastern Siberia, (2) they can travel across the Pacific and reach the Western North American Cordillera which marks the ‘‘limit’’ between the North Pacific and North Atlantic domains, (3) they can circulate in the higher or lower latitudes with influence ranging between the Pole and the Equator. The choice of mean daily SLP instead of a time-step of 6, 12 or 24 h, is motivated by the reduced space–time variability of the pressure field. The smoother pressure field aids in the identification of transient highs and does not degrade the detection of lows. January, February and March (JFM) represent the season when the contrast between cyclonic and anticyclonic activity is maximum (Petterssen 1956; Klein 1957, 1958; Zishka and Smith 1980). Moreover, the inter-annual variability of extra-tropical cyclones characteristics of each of these 3 months presents a better positive relation with each other than with December (Gulev et al. 2001) and these three months tend to be most consistent with respect to the inter-annual mean atmospheric circulation anomalies over the Pacific–North American region (e.g., Livezey et al. 1997). The time period, which spans 52 winters, is sufficiently long to establish a climatology of cyclonic/anticyclonic activity as well as to study its year-to-year variability and relationships to air temperature.

The tracking routine first determines the daily average position of local pressure minima and maxima by computing the local partial derivatives of MSLP with respect to latitude and longitude locations for all days. It then identifies the coordinates of each local pressure minimum below 1,005 hPa (i.e., cyclone trough) and maximum above 1,015 hPa (i.e., anticyclone ridge). The routine then connects these ridges and troughs from one day to the next as follows. The nearest pressure centers within a radius of 2,000 km and most similar MSLP values with day-to-day variation smaller than 20 hPa for cyclones and 15 hPa for anticyclones (a choice that reflects weaker day-to-day variation of MSLP observed for anticyclones), are connected in trajectories. The choice of correct trajectories is facilitated by a preferred, but not imposed, northeastward propagation for cyclones and southeastward propagation for anticyclones according to numerous observations (Petterssen 1956; Klein 1957; Zishka and Smith 1980; Harman 1987; Wallace et al. 1988). Trajectories are allowed to split or converge as observed by Zishka and Smith (1980). Next, a main focus of this study being the influence of relatively persistent extra-tropical cyclones and anticyclones on the winter climate of mid-latitude Western North America, the trajectories are filtered to conserve only those wintertime (i.e., JFM) transients having a lifetime more than 3 days (e.g., Klein 1958; Gulev 2001), that have ventured into the zone 30°–60°N (i.e., mid-latitudes) and next, into the region 170°–110°W (i.e., North-Eastern Pacific) for at least one day of their existence (Fig. 1a). Comparison of trajectories identified thus with those recognized subjectively (i.e., by eye) over the course of two winters indicate that about 80% of cyclones and 75% of anticyclones are captured by our automated scheme. Trajectories identified for selected winters can be seen in Fig. 1 (to be discussed in Sect. 2.3).

The following characteristics are recorded along each trajectory: day, spatial position (longitude/latitude) and central pressure. We summarize these characteristics into monthly time series where each track's features are classified by month of its apparition. The frequencies are cumulated, while pressure and spatial position (longitude and latitude) are averaged into minima, maxima and means along the track.

2.2 Cyclone/anticyclone general features

During the winter season (JFM), an average of 18.67 cyclones circulate, during one day at least, in the North-Eastern Pacific. We observe their mean pressure at around 987.3 hPa, with a minimum average pressure for each trajectory of 977.1 hPa. They travel at mean latitude of 51°N (as in Klein, 1957, 1958) with a mean latitudinal range situated between 44.29°N and 58.52°N. A maximum frequency of cyclones is observed in the Gulf of Alaska, agreeing with previous studies (e.g., Anderson and Gyakum 1989; Gyakum et al. 1989; Graham and Diaz 2001).

Anticyclone frequencies are similar to the frequency of cyclones with 18.28 transient highs for an average winter in the North-Eastern Pacific. Their mean pressure averaged over their lifetimes is 1,025.9 hPa with a maximum average pressure observed along all tracks of 1,032.5 hPa. Their mean latitudinal circulation domain is larger than that of cyclones: it stretches from 59°N to 31.45°N with mean latitude of 42.16°N. The North-

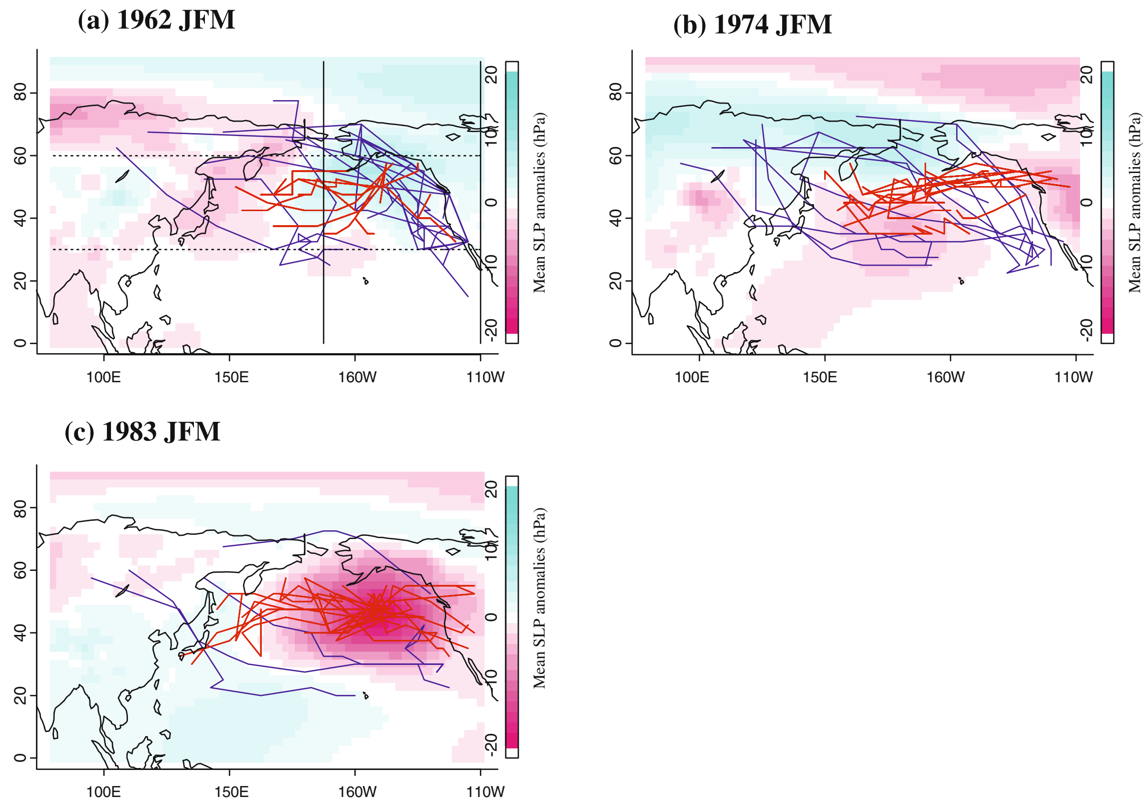

Fig. 1 shows three examples (winters) of cyclones' (*red*) and anticyclones' (*blue*) trajectories that reached the North-Eastern Pacific sector superimposed on anomalies of JFM mean SLP for those winters (*background colors*). Panels (**a**), (**b**) and (**c**) correspond, respectively, to extreme anticyclonic, neutral and extreme cyclonic winters identified by phases of Index *CA* (discussed in Sect. 2.3) Panel (**a**) the *dotted horizontal* and *solid vertical lines* represent the two successive spatial filtering limits (discussed in Sect. 2.1)

Eastern Pacific domain is traversed by anticyclones originating mainly in higher latitudes: Bering/Alaska or North-Eastern Siberia regions that reach the Pacific Ocean by Okhotsk, Japan or China seas. These latter anticyclones penetrate into the North-Eastern Pacific by lower latitudes. The maximum frequency of anticyclones in our region is observed in the subtropical zone, to the west of California.

We note here that these climatological mean statistics, especially frequencies, are sensitive to the MSLP threshold definitions of transients. However, the general spatial structure and the inter-annual variability of these features do not depend on the specific thresholds used to identify them.

Time series of trajectory characteristics show high levels of variability over inter-annual and inter-decadal timescales (Fig. 2). From the mid-1970s to the mid-1990s, cyclone frequencies vary tremendously one winter to the next (Fig. 2a). The maximum number of cyclones is observed in 1983 with 26 transient lows, while the minimum is 13 lows in 1960, 1976, 1991 and 1993. Since the mid-1970s, cyclones have become generally stronger; i.e., lower mean, and especially minimum (not shown) pressures; rather abruptly in 1977 (Fig. 2b), while their trajectories have gradually expanded their latitudinal range (Fig. 2c) mainly by venturing further south. The latitudinal position of cyclone trajectories (not shown) presents a change in the mid-1970s with more southerly trajectories after 1976. This is reflected in the minimal latitudes reached by cyclones, which ventured on average 1.1° further south after 1976. So, the latitudinal domain of cyclones broadened by around 1° (Fig. 2c) although maximal northerly extent of cyclone trajectories did not change (result not shown). These results agree with the well-known intensification of North Pacific cyclonic activity, more southerly storm tracks, and an eastern extension of the Aleutian Low (e.g., Trenberth and Hurrell 1994; Graham and Diaz 2001). Of course, large inter-annual variability is superimposed on these sweeping changes. For example, the period from 1977 to 2001 is characterized by below normal pressures but punctuated by positive anomalies (i.e., weaker cyclones) in winters 1989–1990 and 1994–1996 (Fig. 2b).

For anticyclones, a major part of the story is that from the late 1970s, their wintertime frequencies assumed a strong inter-annual variability (Fig. 2d). During the first-half of the record, until the late 1970s, anticyclone frequencies remained between 13 and 25 highs per winter. The latter-half of the record was marked with very frequent highs in 1979, 1990 and 1994 (30, 26 and 27 highs, respectively) and very few in 1980, 1983, 1987 and 1998 (9, 4, 7 and 10 highs, respectively; i.e., those exceeding ±1 standard deviation). The mean

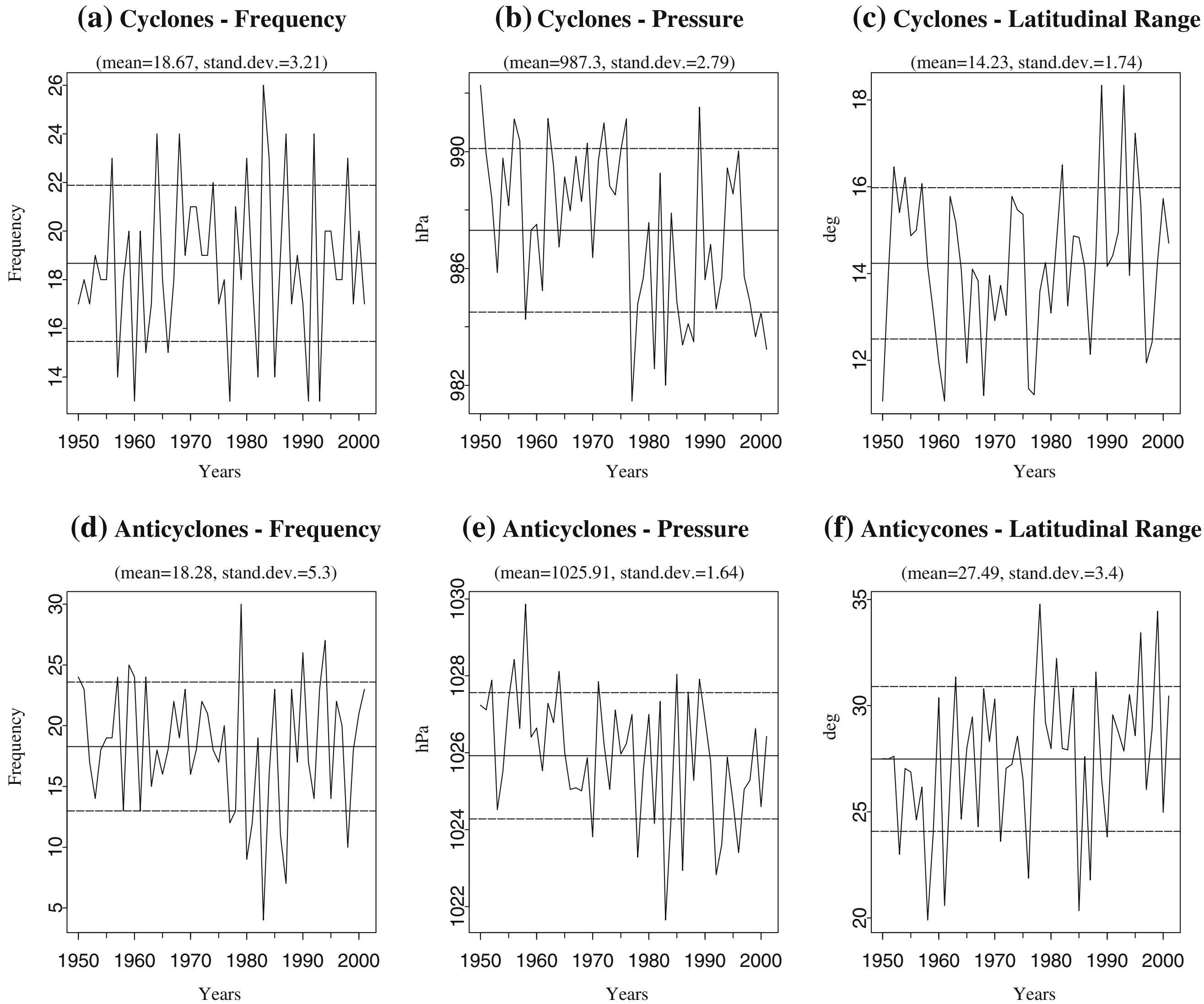

Fig. 2 Time series features of winter (JFM) cyclones and anticyclones which had a life time of 3 days at least and circulated during one day at least in North-Eastern Pacific (to the east of 170°W): **a** cyclone frequency, **b** cyclone mean pressure calculated along the track, **c** cyclones latitudinal range defined by the difference between maximum and minimum latitude reached along the tracks, **d** anticyclone frequency, **e** and **f** as in (**b**) and (**c**), respectively, but for anticyclones. *Solid horizontal lines* represent means of each time series, while *dashed lines* depict 1σ intervals

anticyclone pressure (Fig. 2e) diminished gradually by around 2 hPa with strong inter-annual variability observed from the late 1970s to the early 1990s. The minimal latitudes reached by anticyclones (not shown) extended by about 2° (linear trend) with the most southerly tracking highs in 1983 (27°) and 1987 (27.5°) and the latitudinal domain of anticyclonic circulation (Fig. 2f) tended to expand more or less linearly by around 3.5° over the 52-year study period.

The cyclone and anticyclone frequencies are negatively correlated ($r = -0.46$, sig. > 99%), so that when cyclones are frequent, anticyclones venture rarely into our sector. The cyclones' intensity (mean pressure along the track) is not correlated with their frequency or with anticyclones' intensity but is related with anticyclones' frequency ($r = 0.42$, sig. > 99%). So, when cyclones are deeper (negative anomalies of mean pressure), anticyclones are less numerous in the North-Eastern Pacific. The latitudinal features of cyclone tracks are in modest relation with their frequency: when lows are more numerous, they have southerly trajectories (correlation with mean latitude of cyclone tracks: $r = -0.25$, sig. > 95%). However, southerly trajectories of cyclones are associated with less frequent, weaker and larger latitudinal amplitude circulations of anticyclones ($r = -0.33$, sig. > 99%; $r = -0.30$, sig. > 95%; $r = 0.28$, sig. > 95%, respectively). So, on the first glance, when cyclones are frequent, more tend to track further south, and this appears to inhibit anticyclones from penetrating into the region, especially into its central, most cyclonically active zone. Note, e.g., how the few anticyclones track around the enhanced area of cyclonic activity in the expanded Aleutian Low region in 1983 (Fig. 1c). Although significant, it appears that generally, the relations between cyclone and anticyclone features are not very strong and, in particular, the frequencies of lows and highs are not correlated with their respective intensities.

The seasonally varying frequency of transients, of course, is the size of the seasonal sample and so has a stochastic effect on the seasonal mean cyclone/anticyclone statistics (e.g., pressure, latitudinal range, etc.) because these are based on varying sample sizes. This sampling effect is not systematic, but it must influence relationships discussed here. If not properly dealt with, it could hamper a more rigorous statistical analysis than the unsophisticated assessment performed here. Estimating the sampling effect and its influence is beyond the scope of this paper, but we are mindful that it exists.

2.3 Circulation indices

Statistical summaries of frequency or pressure of the transient systems independently cannot adequately describe the intensity of cyclonic and anticyclonic activity. Pezza and Ambrizzi (2003) reached a similar conclusion for southern hemisphere transients. In the previous section, we observed that there is no relation between frequency and intensity characteristics for North-Eastern Pacific highs or lows. Only together can these characteristics provide a useful summary of transient high and low activity over a region. Consequently, we combine frequency and pressure statistics to quantify the activity of cyclones and of anticyclones. The positive phase of a cyclonic index (C) and of an anticyclonic index (A) is defined as follows:

- A positive anomaly of frequencies (F)
- A negative anomaly of pressure averaged over the trajectories (P) for cyclonic activity and a positive anomaly for anticyclonic activity

$$C = F_{\text{cyclones}} - P_{\text{cyclones}}$$
$$A = F_{\text{anticyclones}} + P_{\text{anticyclones}}$$

Naturally, F and P are standardized a priori.

Figure 3a presents the cyclonic activity index. From 1950, it tends to rise and shows a change in the mid-1970s. So, from 1950 to 1976, the first major period, cyclonic activity was less intense and four years are remarkable for their strong negative values: 1950, 1957, 1960 and 1962. On the other hand, the following period of heightened cyclonic activity shows high values during the late 1970s to the late 1980s especially during winters 1978, 1981, 1983 and 1987, with one remarkably non-cyclonic winter 1982. The later period also appears to be more variable with an alternation of neutral/low mode (from 1988 to 1991 and from 1993 to 1997) punctuated by stronger positive values in 1992, 1998, 2000 and 2001.

Index A (Fig. 3b), which represents anticyclonic activity, shows a decrease from 1950 to 2001. The mid-1970s change is less marked in terms of phase and magnitude than for index C but is clearly visible in a drastic increase in variability of wintertime anticyclonic activity since 1977. In general, three periods distinguish themselves. The first, from 1950 to 1964, is characterized by a predominantly positive activity. This is the anticyclonic phase of the North-East Pacific. Only two winters show noteworthy negative values: 1953 and 1961. The second period from 1965 to 1977 shows moderate anticyclonic activity. During the third period, from 1978 to 2001, anticyclonic activity is overwhelmingly weak (i.e., negative) with strong negative values in winters 1978, 1981, 1983, 1986 and 1992. However, this is also the period of heightened inter-annual variability containing three record anticyclonic winters: 1979, 1985 and 1990. This period of diminished anticyclonic activity was by and large cyclonic. It has also been rather warm and wet in the Western U.S., except after 1998, when the region began experiencing a persistent drought marked by continuing anomalous warmth (Piechota et al. 2004) coinciding with close to average anticyclonic activity in the North-East Pacific.

Indices C and A are negatively correlated with $r = -0.62$ (sig. > 99%) over the entire period. However, we note that from 1950 to 1977 the relation is weaker ($r = -0.45$, sig. > 99%) than from 1978 to 2001 ($r = -0.77$, sig. > 99%). So, the strength of the inter-annual association between wintertime cyclonic and anticyclonic activity in the North-East Pacific appears to be modulated at longer timescales. Some amount of such modulation is, of course, to be expected from any pair of climatic indices due to sampling variability alone (e.g., Gershunov et al. 2001). In the case of North-Eastern Pacific high and low transient activity, the association changes significantly in phase with the late 1970s North Pacific climate shift.

To have a fuller picture of the variability of lower atmospheric circulation, we synthesize the two indices into one representing wintertime transient activity over the North-East Pacific (Index $CA = C - A$; Fig. 3c). The winters, which are characterized by preponderantly cyclonic activity, are identified by the positive phase of CA, while those characterized by largely anticyclonic activity, by the negative phase. From 1950 to 1962, anticyclones dominate in the North-Eastern Pacific, with the strongest negative values in 1950, 1951, 1957, 1960 and 1962 (Fig. 1a). From 1963 to 1977, a relative equilibrium between transient cyclones and anticyclones is established (Fig. 1b). Finally, from 1978 to 2001 cyclonic activity is preponderant, with noteworthy positive values in 1978, 1981, 1983, 1986, 1987, 1992 and 1998 (Fig. 1c). Figure 1 shows the actual trajectories for three selected winters: vigorously anticyclonic 1962, average winter 1974, and strongly cyclonic 1983. The superposition of wintertime cyclone and anticyclone trajectories on anomalous JFM average SLP maps illustrates the action of synoptic transients in

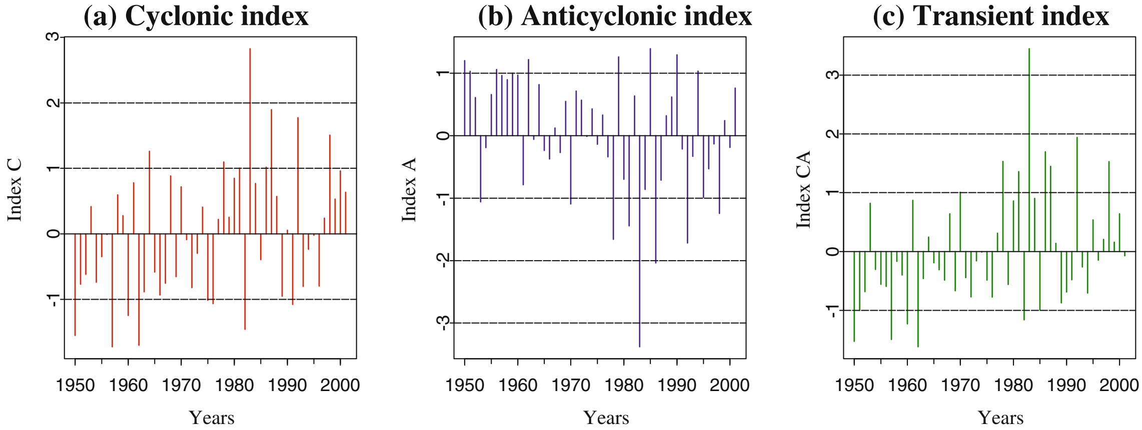

Fig.3. **a** Cyclonic activity index (Index *C*), **b** anticyclonic activity index (Index *A*) and **c** transient activity index (Index *CA*) over North-Eastern Pacific (JFM). The scale is in standard deviation (σ) units

determining the more familiar seasonal average surface pressure fields.

3 North-Eastern Pacific cyclonic/anticyclonic activity and global climate

We have documented the general negative association between North-Eastern Pacific cyclonic and anticyclonic activity as well as the clear change in synoptic transients that took place in the late 1970s when cyclonic activity intensified at the detriment of anticyclones. How are these synoptically derived indices connected to the more familiar seasonally averaged climate? Synoptic changes on such space and timescales, translate directly into seasonally averaged climate fields and the 1970s North Pacific climate change has been certainly well documented in various mean climatic fields and numerous studies. In this section, we relate our dynamic indices describing the inter-annual variability of synoptic transient activity over the North-Eastern Pacific to the seasonally averaged climate over the globe as described by the near-surface atmospheric seasonal mean circulation and air temperature fields. To this end, linear temporal correlations are computed between Index *CA* and JFM mean atmospheric fields (Fig. 4) from NCEP–NCAR Reanalysis, e.g., SLP, zonal and meridional wind at 10 m (u10 and v10, respectively), and air temperature at 2 m [T_{a2m}, an excellent proxy for sea surface temperature (SST) over the ocean]. Since these are correlations, please keep in mind that the patterns described below are relative to the respective mean fields.

3.1 Global surface circulation

When cyclones dominate anticyclones (i.e., Index *CA* is positive), a dipole of SLP is distinct with anomalously deep Aleutian Low and high pressure in the Western Pacific inter-tropical zone, i.e., the Warm Pool region (Fig. 4a). This configuration is associated with a quasi-symmetry with respect to the Equator, a robust feature of the main mode(s) of inter-annual and decadal Pacific climate variability (e.g., Dettinger et al. 2001). This combination of warm ENSO and positive NPO phases is also clearly evident in the near-surface temperature and wind field structure over the Pacific Basin (Fig. 4b). The magnitude of the correlation coefficients suggest the NPO as the dominant mode with ENSO secondary, however, it is no surprise that both are jointly related to synoptic transients over the Eastern North Pacific, as the interaction of the two is known to be related with strong and consistent climate signals over North America (e.g., Gershunov and Barnett 1998).

In the extra-tropical North Pacific, a vast zone of abnormally low pressure centered around 155°W and 47.5°N covers the central and eastern North-Pacific, Alaska sector and an appendix of negative anomalies of pressure stretch along the coast to Southern Baja California (Fig. 4a). This area of abnormally low pressure is the enhanced Aleutian Low associated with anomalous cyclonic circulation in the entire extra-tropical North Pacific (Fig. 4b). Anomalous southerlies and above normal temperatures extend along the west coast of North America, while anomalous northerlies and lower temperatures manifest themselves over the central and Western North Pacific.

When cyclones dominate anticyclones (high *CA* index), the Northern Pacific temperate circulation influences penetrate southward, into the tropical–subtropical belt. We remark a clearly weaker intensity of the subtropical High of North-Eastern Pacific (i.e., negative SLP and southerly wind anomalies). Normally in winter, the subtropical high extends from California to Hawaii and is associated with anticyclonic circulation and the trade winds with a northerly component in the entire North Pacific tropical zone. During winters with preponderant cyclonic activity in North-Eastern Pacific, when low systems are increased in frequency, intensity and spatial extent, the subtropical high is weakened and/

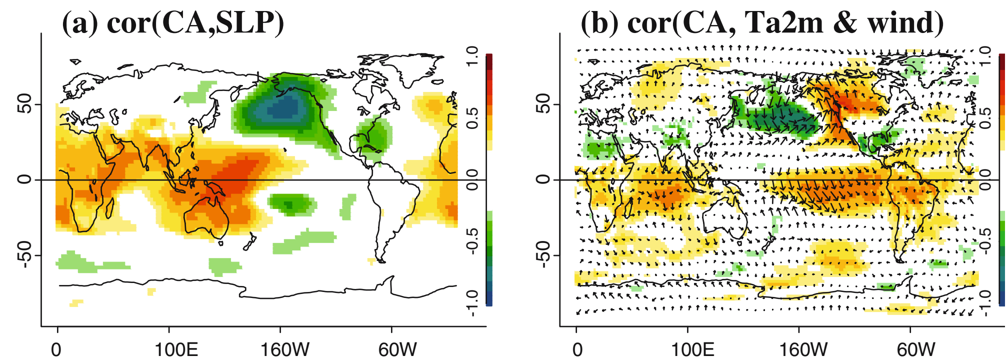

Fig. 4 Maps of temporal correlation coefficients between Index *CA* and **a** SLP, **b** T_{a2m} (*colors*, sig. > 98%) and u10/v10 (vectors) for the entire record 1950 to 2001 (JFM)

or pushed towards the equator, and trade winds intensity is lower. Because of this, anomalous surface wind divergence is evident in the northern tropics globally and particularly in the North-Eastern Pacific. There is also anomalous northerly cross equatorial flow and anomalous convergence into the South Pacific convergence zone (SPCZ) during cyclonic winters in North-Eastern Pacific. Are these anomalies generated by the transient conditions in the North-Eastern Pacific, or are they a result of positive temperature anomalies associated with El Niño conditions?

In the Western Pacific inter-tropical zone, a vast area of positive pressure anomaly is centered along the equator. This sector is not associated with temperature and wind anomalies in the same area, but with positive anomalies of air temperature and anomalous northerly winds in central and eastern Pacific equatorial and sub-equatorial zone (NINO zone). It reveals a decrease in southern hemisphere trade wind intensity and an anomalous shift to the south of the ITCZ in this same sector. In spite of moderate relation between Index *CA* and South Pacific mean circulation, there is a relative symmetry with respect to the Equator in the Pacific Basin (Evans et al. 2001; Dettinger et al. 2001). Anomalously cyclonic winters in the North-Eastern Pacific that go together with negative SLP anomalies in central and eastern North Pacific as well as warmer air temperature and anomalous southerly wind in the North-Eastern Pacific correspond to negative anomaly of pressures in central and eastern South Pacific, warmer air temperatures and northerly wind anomalies in the central equatorial and tropical South Pacific, making for a stronger convergence into the SPCZ. Perhaps when northern temperate circulation acts to displace the northern subtropical high southward and enhance the northerly cross-equatorial transport of moisture, the SPCZ responds with stronger convection that leads to lower surface pressure and stronger convergence from the south and north. Could an enhanced SPCZ then feed back onto the northern temperate transient circulation? It might be able to encourage the anomalously equatorward subsidence in the tropical North Pacific as the south-tracking North-Eastern Pacific cyclones might also encourage it. This line of thought is purely speculative, of course. However, there is some observational and modeling evidence to back it up: normally, summertime tropical convection is fueled by moisture evaporated and advected from the winter hemisphere tropics and subtropics (Gershunov and Roca 2004); so there is a direct hydrodynamic link between temperate circulation, that acts to displace the subtropical high equatorward in the winter hemisphere, and tropical convection in the opposite, summer hemisphere.

Transient activity in the North-Eastern Pacific, furthermore, appears to be linked with coherent global climatic anomalies beyond the Pacific Basin. Symmetry with respect to the equator exists also in the global structure of SLP. A large zone of positive anomalies of SLP stretches from Eastern Atlantic to Western Pacific inter-tropical zone covering Western Europe, Mediterranean and North Africa, the north of Indian Ocean, Indian sub-continent and Indonesia, and positive anomalies of air temperature reign over most of the equatorial zone. On the other hand, anomalous low pressures associated with colder temperatures appear to be centered on Florida. This is also in keeping with a positive NPO–warm ENSO combination (e.g., Gershunov and Barnett 1998).

Conversely, a preponderance of anticyclonic activity at the expense of cyclones in the North-Eastern Pacific, suggests the negative phase of the NPO with anomalous cold northerly flow along the west coast of North America, possibly La Niña conditions but at least a low pressure over the tropical Pacific Warm Pool, weaker than normal or even interrupted northerly cross-equatorial flow, and a weaker than normal SPCZ.

3.2 Relationships with Pacific climate modes: NPO, ENSO and PNA

The strongest mean climate signal associated with a preponderant cyclonic activity in the North-Eastern Pacific is an intense Aleutian Low (Fig. 4a) that goes together with the positive NPO near-surface temperature pattern (Fig. 4b). Furthermore, Index *CA* appears to be linked with the tropical Pacific surface pressure dipole and near-surface temperatures (i.e., ENSO). To examine these relationships more carefully, we compute the NPO and ENSO indices from observed SST data. We use the Kaplan extended statistically homogenous concatenation of Kaplan et al. (1998) and Reynolds and Smith (1994) SST analyses. The NPO is defined as the leading principal component of North Pacific JFM SST North of 20°N (Mantua et al. 1997) and NINO3.4 (JFM SST averaged over 5°N–5°S and 120°W–170°W) is used as the ENSO index. Table 1 presents the correlation coefficients of the index of North-East Pacific transient activity (*CA*) versus NPO and ENSO indices. Index *CA* is well correlated with NPO. The phases of Index *CA*, corresponding to a preponderant cyclonic (positive)/ anticyclonic (negative) activity in North-Eastern Pacific, are associated with anomalously cyclonic/anticyclonic wind circulation, oppose /promote the oceanic gyre circulation, creating warmer/colder SST along the North American west coast and colder/warmer SST in the central and Western North-Pacific. As far as tropical SST is concerned, Anderson and Gyakum (1989), Gyakum and al. (1989), Rogers (1990), Graham and Diaz (2001) show that the relation between Northern Pacific cyclonic activity and Nino 3.4 SST Index is modest. For the entire period the correlation coefficient between NINO 3.4 index and Index *CA* is also modest ($r = 0.45$). But we can observe that from 1977 to 2001, the relation is stronger than from 1950 to 1976 (Table 1), when tropical SSTs present strong positive phases in conjunction with strong positive phases of NPO (e.g., JFM 83, 87, 92 and 98). Consequently cyclone/anticyclone features seem to be significantly influenced by tropical SST after the NPO shift of the mid-1970s.

And it is also from the mid-1970s that transient activity in the North-Eastern Pacific shows a better relation with the Pacific North American (PNA) teleconnection index (Wallace and Gutzler 1981, source: http://www.cdc.noaa.gov/ClimateIndices). It is commonly affirmed that North Pacific SST and the cyclogenesis variability in the North-Eastern Pacific is related with the PNA pattern variability during the winter season (e.g., Barnston and Livezey 1987; Kushnir and Wallace 1989; Wallace et al 1990; Gulev et al 2001). The PNA measures the mid-tropospheric circulation induced by four centers of action in the 500 hPa geopotential height field: the Aleutian, Hawaii, Northwestern America and Southeast United States areas (the first and the last centers varying together and in opposition with the two others). A strong wave pattern is associated with the occurrence of a positive phase of the PNA that manifests itself as a warm ridge (southerly flow) along the western coast and a cold trough over Eastern North America. This type of mid-tropospheric circulation corresponds to the positive phase of Index CA, a preponderant cyclonic activity in North-Eastern Pacific. Also, it can be noted that the PNA index is better correlated with anticyclonic than cyclonic activity indices and particularly from mid-1970s.

4 Relationships with air temperatures over Western North America

One characteristic consistently observed and predicted by global climate models in response to human modification of the atmosphere's radiative and cloud generating properties is a stronger rise of diurnal minimum (nighttime) than maximum (daytime) temperature and a consequent decrease of the diurnal temperature range (Karl et al. 1984 1993; Cao et al. 1992; Easterling 2002; Groisman et al. 2004). The causes are attributed to increased cloud cover (Sun et al. 2001) perhaps due to anthropogenic activities. Previous studies suggest that in Western North America, and especially in Alaska, this effect is stronger than for the rest of North America. It is observed throughout the year, but strongest during winter and spring. A dynamical mechanism directly responsible for these changes is likely related to changes in cyclonic and anticyclonic activity, a relationship that,

Table 1 Linear temporal correlation coefficients between Index *C*, Index *A*, Index *CA*, NPO, NINO3.4 and PNA indices, for 1950–2001, 1950–1976 and 1977–2001 periods (JFM)

		Index*C*	Index*A*	Index*CA*	NPO	NINO3.4	PNA
Index *C*	50-01	1					
	50-76	1					
	77-01	1					
Index *A*	50-01	***−0.62***	1				
	50-76	**−0.36**	1				
	77-01	***−0.66***	1				
Index *CA*	50-01	***0.90***	***−0.90***	1			
	50-76	***0.86***	***−0.78***	1			
	77-01	***0.90***	***−0.92***	1			
NPO	50-01	***0.56***	***−0.59***	***0.64***	1		
	50-76	**0.38**	***−0.50***	***0.53***	1		
	77-01	***0.52***	***−0.54***	***0.58***	1		
NINO3.4	50-01	***0.38***	***−0.43***	***0.45***	***0.54***	1	
	50-76	0.18	−0.24	0.25	***0.46***	1	
	77-01	***0.46***	***−0.49***	***0.52***	***0.55***	1	
PNA	50-01	***0.66***	***−0.73***	***0.78***	***0.69***	***0.53***	1
	50-76	**0.41**	**−0.34**	***0.45***	***0.60***	**0.38**	1
	77-01	***0.74***	***−0.86***	***0.88***	***0.63***	***0.59***	1

Bold (italic) values are significant at the 95% (99%) level to our knowledge, has not been demonstrated. A formal and thorough investigation of the anthropogenic effect is beyond the scope of this study and will be taken up in future work; however, here we document the relationship between North-Eastern Pacific transient activity and observed winter minimum temperatures as well as frequencies of extremely cold and warm nights. We try to determine if transient systems are responsible for observed trends as well as for inter-annual variability in minimum temperatures, an important variable for many climate applications.

4.1 Data and methodology

Minimum and maximum daily temperature data from 276 stations distributed non-homogenously across Canada, United States and Mexico, west of 100°W are used. These stations were selected from available US (NCDC 2003), Mexican (Miranda 2003) and Canadian (Vincent and Gullett 1999) networks, all quality controlled and homogenized. The best quality stations were selected to give a reasonable coverage for the winters 1950–2001 over Western North America.

Besides the average JFM minimum temperature, we define two frequency–intensity temperature variables: the frequency of extremely cold and warm nights. Extremely cold temperatures are defined as in Gershunov (1998) to be temperatures (T_{min}) below the tenth percentile of all winter nights at each station for our 52-year record. Frequencies of extremely warm nights correspond to T_{min} warmer than the 90th percentile of the local JFM climatology (1950–2001). For each station, annual time series recording the percentage of winter days (daily frequency) with T_{min} colder than the 10th or warmer than the 90th percentiles were computed (T_{min} 10 and T_{min}90, respectively). Then, in order to have a better understanding of the influence of inter-annual variability of North-Eastern Pacific cyclonic/anticyclonic activity on North-Western American air temperatures, we have computed linear temporal correlations between our atmospheric C, A and CA indices and selected climatic variables at each station. Similar results were also computed using daytime temperatures (T_{max}), but only correlations based on T_{min} and *CA* are shown in Fig. 5.

4.2 Results

Figure 5 shows that stronger cyclonic and weaker anticyclonic activity in the North-Eastern Pacific, lead to a profound modification of the winter temperature regime with fewer cold and extreme cold days and more warm and extreme warm days over a large part of Western North America (except for Mexico which presents non-significant or anti-phase correlations). It is especially true for night temperatures (T_{min}) where the correlation coefficients and spatial extent of the signal are larger than for daytime temperatures (T_{max} not shown). The decline of anticyclonic activity in the North-Eastern Pacific is responsible for decreasing arctic air advections along the western part of North America. Simultaneously, more frequent and intense cyclones contribute to rising nighttime temperatures, in particular by advecting warm air from the south and by decreasing the number of clear sky nights favorable for radiational cooling. Daytime temperatures (T_{max}) are less sensitive to transient forcing becuase of the additional radiational complexity in daytime in the presence and absense of clouds. The phases of preponderant cyclonic activity correspond to a reduction of diurnal T_{range} (T_{max}–T_{min}) and a reduction of inter-daily T_{min} variability (not shown). These observed relationships/changes are due to changes in cyclonic/anticyclonic activity on both multi-decadal and inter-annual timescales.

It appears that the anticyclonic activity (Index *A*) is better related with extreme warm nights (T_{min}90) than Index *C* (not shown), and inversely, the cyclonic activity tends to have a greater influence on the extreme cold nights (T_{min}10) than index *A* (not shown). This stronger influence of lows on extreme minimal temperature reveals itself for diurnal temperature range and with inter-daily temperature variability (not shown). Consequently, the reduction of anticyclonic activity tends to increase the frequency of extreme warm nights, and the intensification of cyclonic activity contributes to reduce the extreme cold nights frequency, the diurnal temperature range, and the inter-daily T_{min} contrasts.

The spatial structure of correlation shows an orographic effect in the North-Western U.S. (Fig. 5c, d). In a general manner, the zone situated between 40°N and 60°N, is most typically affected by low system centers, which are less hindered by topography than anticyclones and can cross the Cordillera to affect inland temperatures. Stronger correlations further inland in this region also result from the lower topography in the Columbia River valley, which permits further penetration of anticyclonic influences here than elsewhere along the North American west coast. Anticyclonic, and to a smaller degree, cyclonic influences elsewhere in the mountainous west are generally confined to coastal regions. Moreover, some of the most elevated stations in the high Rocky Mountains show negative correlations between *CA* and T_{min}90, possibly due to the temperature inversion associated with heightened anticyclonic activity (Fig. 5c).

5 Summary and conclusions

Cyclonic and anticyclonic activities have been quantified for North-Eastern Pacific winters 1950–2001 and a general competition became apparent between transient cyclones and anticyclones. A clear climatic change appears around 1976–1977 when a generally anticyclonic period gives way to more intense cyclonic activity. After 1976, anticyclonic activity tends to diminish: their mean

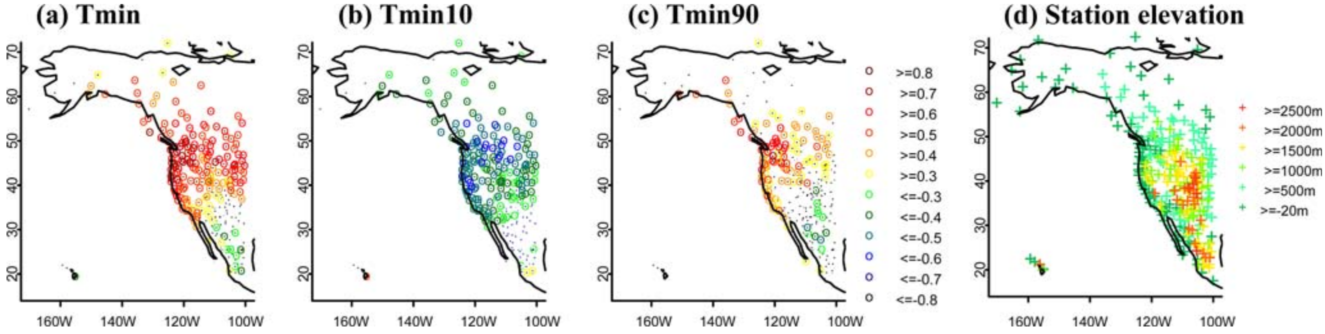

Fig. 5 Maps of temporal correlation coefficients between Index *CA* and **a** mean $T_{\min}$, **b** frequency of $T_{\min}$ colder than the tenth percentile ($T_{\min}10$) and **c** $T_{\min}$ warmer than the 90th percentile ($T_{\min}90$) for the entire record 1950 to 2001 (JFM). *Colors* signify correlations significant at >98%. **d** Map of station elevations

central pressure decreases by over 2 hPa and their frequency becomes more variable. Conversely, North-Eastern Pacific cyclonic activity becomes stronger more abruptly, with markedly deeper systems. In a traditional seasonal mean view, these synoptic-scale modifications translate into well-known large-scale near-surface circulation, pressure and temperature features associated with the NPO and, to a lesser extent, with ENSO.

The chicken and egg problem naturally arises. We frequently explain the statistical likelihood of synoptic features through slowly varying large-scale climatic forcings, in fact this is the philosophy behind seasonal prediction of high-frequency weather statistics (e.g., Gershunov 1998). However, long-term changes in synoptic transient activity directly set up anomalous surface-level "mean" cyclonic or anticyclonic circulations on the scale of the entire North Pacific basin, which can act to decelerate or accelerate upper ocean currents contributing to basin-wide SST anomalies such as those associated with the NPO. In concord, surface-level temperatures have become warmer along the North American west coast and colder in the central North Pacific (e.g., positive NPO phase). The relation between our synoptic transient activity index and the NPO is highly significant (>99%). A significant link between cyclonic/anticyclonic activity and tropical SST anomalies (NINO3.4) appears only from the mid-1970s, the period coinciding with more intense cyclonic activity and more southerly cyclones trajectories. This deeper cyclonic penetration to the south associated with strong positive phases of ENSO, permits the propagation of tropical air features to the north, into the temperate zone. In this way, cyclonic activity is intensified and contrarily, anticyclonic activity is reduced further on ENSO timescales but only during positive NPO phases.

The increasing/decreasing cyclonic/anticyclonic activity has had a profound impact on air temperatures over Western North America, especially on minimum (nighttime) temperatures. From the mid-1970s, the intensification/reduction of cyclonic/anticyclonic activity in North-Eastern Pacific induced a stronger reduction in the frequency of cold nights than cold days and a stronger augmentation in the frequency of warm nights compared to warm days in Western North America. Wintertime mean minimum temperatures have thus risen more than mean maximum temperatures, which led to a reduction of the diurnal temperature range. This is a well-known phenomenon, that has been observed and also projected using dynamical climate models in response to anthropogenic climate modification. It would be worthwhile, although beyond the scope of the current work, to check whether dynamical models produce and project this temperature signal for the right dynamical reasons, i.e., the competition and inter-play of synoptic highs and lows, as shown here.

This is a strictly observational study documenting changes in wintertime synoptic cyclonic/anticyclonic activity over the North-Eastern Pacific and their relationships to global climate as well as to Western North American temperatures. In this observational framework, we cannot elaborate causes of observed changes in transient activity, especially at low frequencies. Important questions regarding the causes of the observed changes in NE Pacific transients, possible human influences, long-term projections and the possibility of seasonal prediction are deferred to future studies. We hope to eventually improve seasonal and longer-term predictions of regional daily temperature extremes by understanding climatic behavior of their synoptic causes.

Acknowledgments The work presented here is part of the first author's Ph.D. thesis. Partial funding was provided by the California Climate Change Center, sponsored by the California Energy Commission's Public Interest Energy Research Program, by the NOAA Office of Oceanic and Atmospheric Research under the California Energy Security Project, grant #NA17RJ1231, and by the NOAA Office of Global Programs, under the California Applications Program.

References

Alpert PB, Neeman U, Shau-El Y (1990) Climatological analysis of Mediterranean cyclones using ECMWF data. Tellus 42A:65–77

Anderson JR, Gyakum JR (1989) A diagnostic study of Pacific Basin circulation regimes as determined from extratropical cyclone tracks. Mon Weather Rev 117:2672–2686

Barnston AG, Livezey RE (1987) Classification, seasonality and persistence of low-frequency atmospheric circulation patterns. Mon Weather Rev 115:1083–1126

Blender R, Fraedrich K, Lunkeit F (1997) Indentification of cyclone track regimes in the North Atlantic. Q J R Meteorol Soc 123:727–741

Cao HX, Mitchell JFB, Lavery JR (1992) Simulated diurnal range and variability of surface temperature in a global climate model for present and doubled CO_2 climates. J Clim 5:920–943

Cayan DR, Kammerdiener SA, Dettinger MD, Caprio JM, Peterson DH (2001) Changes in the onset of spring in the Western United States. Bull Amer Meteor Soc 82:399–415

Dettinger MD, Battisti DS, Garreaud McCabe GJ, Bitz CM (2001) Interhemispheric effects of interannual and decadal ENSO-like climate variations on the Americas. Present and past interhemispheric climate linkages in the Americas and their societal effects, Markgraf edn, pp 1–16

Durre I, Wallace JM (2001) Factors influencing the cold-season diurnal temperature range in the United States. J Clim 14:3263–3278

Easterling DR (2002) Recent changes in frost days and the frost-free season in the United States. Bull Amer Meteor Soc 83:1327–1332

Evans MN, Kaplan A, Cane MA, Villalba R (2001) Globality and optimality in climate field reconstructions from proxy data. Present and past interhemispheric climate linkages in the Americas and their societal effects, Markgraf edn, pp 53–72

Groisman PY, Knight RW, Karl TR, Easterling DR, Sun B, Lawrimore JM (2004) Contemporary changes of the hydrological cycle over the contiguous United States: trends derived from in-situ observations. J Hydrometeor 5:64–85

Gershunov A (1998) ENSO influence on intraseasonal extreme rainfall and temperature frequencies in the contiguous US: implications for long-range predictability. J Clim 11:3192–3203

Gershunov A, Barnett T (1998) Inter-decadal modulation of ENSO teleconnections. Bull Amer Meteor Soc 79:2715–2725

Gershunov A, Schneider N, Barnett T (2001) Low frequency modulation of the ENSO-Indian monsoon rainfall relationship: signal or noise. J Clim 14:2486–2492

Gershunov A, Cayan D (2003) Heavy daily precipitation frequency over the contiguous United States: Sources of climatic variability and seasonal predictability. J Clim 16:2752–2765

Gershunov A, Roca R (2004) Coupling of latent heat flux and the greenhouse effect by large-scale tropical/subtropical dynamics diagnosed in a set of observations and model simulations. Clim Dyn 22:205–222

Graham NE, Diaz HF (2001) Evidence for intensification of North Pacific winter cyclones since 1948. Bull Amer Meteor Soc 82:1869–1992

Gulev SK, Zolina O, Grigoriev S (2001) Extratropical cyclone variability in the Northern Hemisphere winter from the NCEP/NCAR reanalysis data. Clim Dyn 17:795–809

Gyakum JR, Anderson JR, Grumm RH, Gruner EL (1989) North Pacific cold-season surface cyclone activity. Mon Weather Rev 117:1141–1155

Harman JR (1987) Mean monthly North America anticyclone frequencies, 1950–1979. Mon Weather Rev 115:2840–2848

Hodges KI, Hoskins BJ, Boyle J, Thorncroft C (2003) A comparison of recent reanalysis dataset using objective feature tracking : storm tracks and easterly waves. Mon Weather Rev 131:2012–2037

Hoskins BJ, Hodges KI (2002) New perspectives on the Northern Hemisphere winter storm tracks. J Atmos Sci 59:1041–1061

Jones DA, Simmonds I (1993) A climatology of Southern Hemesphere extra-tropical cyclones. Clim Dyn 9:131–145

Jones DA, Simmonds I (1994) A climatology of Southern Hemisphere anticyclones. Clim Dyn 9:333–348

Kalnay E, Kanamitsu M, Kistler R, Collins W, Deaven D, Gandin L, Iredell M, Saha S, White G, Woollen J, Zhu Y, Leetmaa A, Reynolds B, Chelliah M, Ebisuzaki W, Higgins W, Janowiak J, Mo KC, Ropelewski C, Wang J, Jenne R, Joseph D (1996) The NCEP/NCAR 40-year reanalysis project. Bull Amer Meteor Soc 77:437–471

Kaplan A, Cane MA, Kushnir Y, Clement AC, Blumenthal MB, Rajagopalan B (1998) Analysis of global sea surface temperature: 1856–1991. J Geophys Res 103:567–18589

Karl TR, Kukla G, Gavin J (1984) Decreasing diurnal temperature Range in the United States and Canada from 1941 through 1980. J Appl Meteor 23:1489–1504

Kistler R, Kalnay E, Collins W, Saha S, White G, Woollen J, Chelliah M, Ebisuzaki W, Kanamitsu M, Kousky V, van den Dool H, Jenne R, Fiorino M (2001): The NCEP–NCAR 50-year reanalysis: monthly means CD-ROM and documentation. Bull Amer Meteor Soc 82:247–267

Klein WH (1957) Principal tracks and mean frequencies of cyclones and anticyclones in the Northern Hemisphere. Weather Bureau Research Paper No.40, U.S. Department of Commerce, NOAA, Washington, DC, p 60

Klein WH (1958) The frequency of cyclones and anticyclones in relation to the mean circulation. J Atmos Sci 15:98–102

Koenig WR, Sausen R. Sielmann F (1993) Objective identification of cyclones in GCM simulations. J Clim 6:2217–2231

Kushnir Y, Wallace JM (1989) Low frequency variability in the Northern Hemisphere winter-geographical-distribution, structure and time scale dependence. J Atmos Sci 46:3122–3142

Latif M, Barnett TP (1996) Decadal climate variability over the North Pacific and North America: dynamics and predictability. J Clim 9:2407–2423

Leroux M (1998) Dynamic Analysis of weather and climate: general circulation, perturbations, climatic evolution. In: Wiley J (ed) Praxis-Wiley series in Atmospheric Physics, London, New York, Sydney, pp 365

Le Treut H, Kalnay E (1990) Comparison of observed and simulated cyclone frequency distribution as determined by an objective method. Atmosfera 3:57–71

Livezey RE, Masutani M, Leetmaa A, Rui H, Ji M, Kumar A (1997) Teleconnective response of the Pacific–North American region atmosphere to large central equatorial Pacific SST anomalies. J Clim 10:1787–1820

Mantua NJ, Hare SR, Zhang Y, Wallace JM, Francis RC (1997) A Pacific interdecadal climate oscillation with impacts on salmon production. Bull Amer Meteor Soc 78:1069–1079

Miranda S (2003) Actualizacion de la base de datos ERIC II. Final report of the project TH-0226, IMTA internal reports

Murray RJ, Simmonds I (1991) A numerical scheme for tracking cyclone centres from digital data. Part I: development and operation of the scheme. Aust Meteorol Mag 39:155–166

Nakamura H, Lin G, Yamagata T (1997) Decadal climate variability in the North Pacific during the recent decades. Bull Amer Meteor Soc 78:2215–2225

NCDC (2003) Data documentation for data set 3200 (DSI-3200) Surface land daily cooperative summary of the day. National Climatic Data Center, Asheville, NC, pp 36 [Available on line at: http://www.ncdc.noaa.gov/pub/data/documentlibrary/tddoc/td3200.pdf.]

Nitta T, Yamada S (1989) Recent warming of tropical sea surface temperature and its relationship to the Northern Hemisphere circulation. J Meteor Soc Jpn 67:375–382

Petterssen S (1956) Weather analysis and forecasting, vol 1, McGraw-Hill, New York, pp 422

Pezza AB, Ambrizzi T (2003) Variability of southern hemisphere cyclone and anticyclone behavior: further analysis. J Clim 16:1075–1083

Piechota T, Timilsena J, Tootle G, Hidalgo H (2004) The Western U.S. drought: how bad is it? Eos 85:301–308

Reynolds RW, Smith TM (1994) Improved global sea surface temperature analysis using optimum interpolation. J Clim 7:929–948

Rogers JC (1990) Patterns of low-frequency monthly sea level pressure variability (1899–1986) and associated wave cyclone frequencies. J Clim 3:1364–1379

Serreze MC (1995) Climatological aspects of cyclone development and decay in the Arctic. Atmosphere–Ocean 33(1):1–23

Serreze MC, Carse F, Barry RG, Rogers JC (1997) Icelandic low cyclone activity: climatological features, linkages with the NAO, and relationships with the recent changes in the northern hemisphere circulation. J Clim 10:453–464
Sinclair MR (1994) An objective cyclone climatology for the Southern Hemisphere. Mon Weather Rev 122:2239–2256
Sinclair MR (1996) A climatology of anticyclones and blocking for the Southern Hemisphere. Mon Weather Rev 124:245–264
Sinclair MR, Watterson IG (1999) Objective assessment of extra-tropical weather systems in simulated climates. J Clim 12:3467–3485
Sun B, Ya P, Groisman I, Mokhov I (2001) Recent changes in cloud-type frequency and inferred increases in convection over the United States and the Former USSR. J Clim 14:1864–1880
Trenberth KE (1990) Recent observed interdecadal climate changes in the Northern Hemisphere. Bull Amer Meteor Soc 71:988–993
Trenberth KE, Hurrell JW (1994) Decadal atmosphere–ocean variations in the Pacific. Clim Dyn 9:303–319
Vincent LA, Gullett DW (1999) Canadian historical and homogeneous temperature datasets for climate change analyses. Int J Clim 19:1375–1388
Wallace JM, Gutzler DS (1981) Teleconnections in the geopotential height field during the northern hemisphere winter. Mon Weather Rev 109:748–812
Wallace JM, Lim GH, Blackmon (1988) Relationship between cyclone tracks, anticyclone tracks and baroclinic waveguides. J Atmos Sci 45:439–462
Wallace JM Smith C, Jiang Q (1990) Spatial patterns of atmosphere–ocean interaction in the Northern winter. J Clim:990–998
Zishka KM, Smith PJ (1980) The climatology of cyclones and anticyclones over North America and surrounding ocean environs for January and July, 1950–1977. Mon Weather Rev 108:387–401