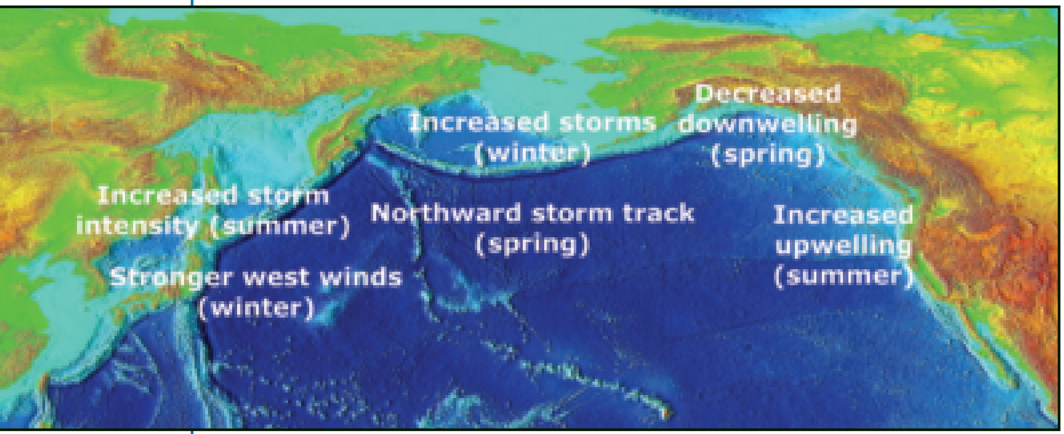
Ocean & Climate Changes

highlights



[Figure 23] Major changes in ocean/climate during the last five years

- Many atmospheric indices associated with the low pressure region in the central North Pacific in winter (the "Aleutian Low") featured a strong shift in 1976/1977. The Pacific Decadal Oscillation (based on North Pacific sea surface temperatures) experienced a phase shift from generally negative to positive. This change corresponded with significant changes in marine ecosystems and fisheries in 1976/77, but the effect varied depending on location.

- Synchronous changes in marine ecosystems occurred again in 1989; this change was associated with a mode shift from a predominantly PDO pattern prior to 1989 to what we are calling a Victoria pattern thereafter. The Victoria pattern differs from PDO pattern by a significant reduction of the North American coastal domain, an eastward shift of the central domain and a northeastward expansion of the subtropical domain.

- Significant changes in North Pacific climate and marine ecosystems followed the 1997/98 El Niño. These changes lacked the coherent shift that occurred in 1976/77 because they represented a phase reversal (from negative to positive) of the Victoria pattern rather than a change in the PDO pattern. The winter of 2002/03 was an ENSO winter that resembled the period after the 1976/77 shift. Whether the future will continue with the Victoria pattern, or whether the Victoria pattern is transitional to another state is uncertain.

- Local indices for the eastern and northeastern North Pacific for spring and summer, i.e., the coastal upwelling indices, are characterized by changes since the late 1990s. The North Pacific Index contains a switch from positive values to more neutral values that would indicate a more eastward storm track compared to the previous northeasterly storm track during spring.

introduction

This chapter provides a critical assessment of the state of the North Pacific atmospheric climate system in recent years within the context of the historical record beginning in 1950. Most analyses are based on the National Oceanic and Atmospheric Administration (U.S.A.) NCEP/NCAR Reanalysis which synthesizes historical observations in an atmospheric model. This provides a four-dimensional (3D + time) representation of a large number of atmospheric measurements. To understand the evolution of the North Pacific climate system, we reduce the complexity by using time series that represent relevant features of atmospheric variability. These time series are referred to as indices.

No single index represents all of the spatial and temporal variability of the atmosphere over the North Pacific so we present a subset of atmospheric indices. Different indices are relevant at different times of the year; we consider separately summer, spring and winter. This is followed by a more complete discussion of recent changes in sea level pressure (SLP) and sea surface temperature (SST), comparing them with their counterparts in the "cold" years of the early 1970s and the "warm" years of the late 1970s/early 1980s. The final section of this chapter discusses the issue, "how many indices are enough"; we examined 19 (Table 2) and discuss our selection.

Atmospheric Indices

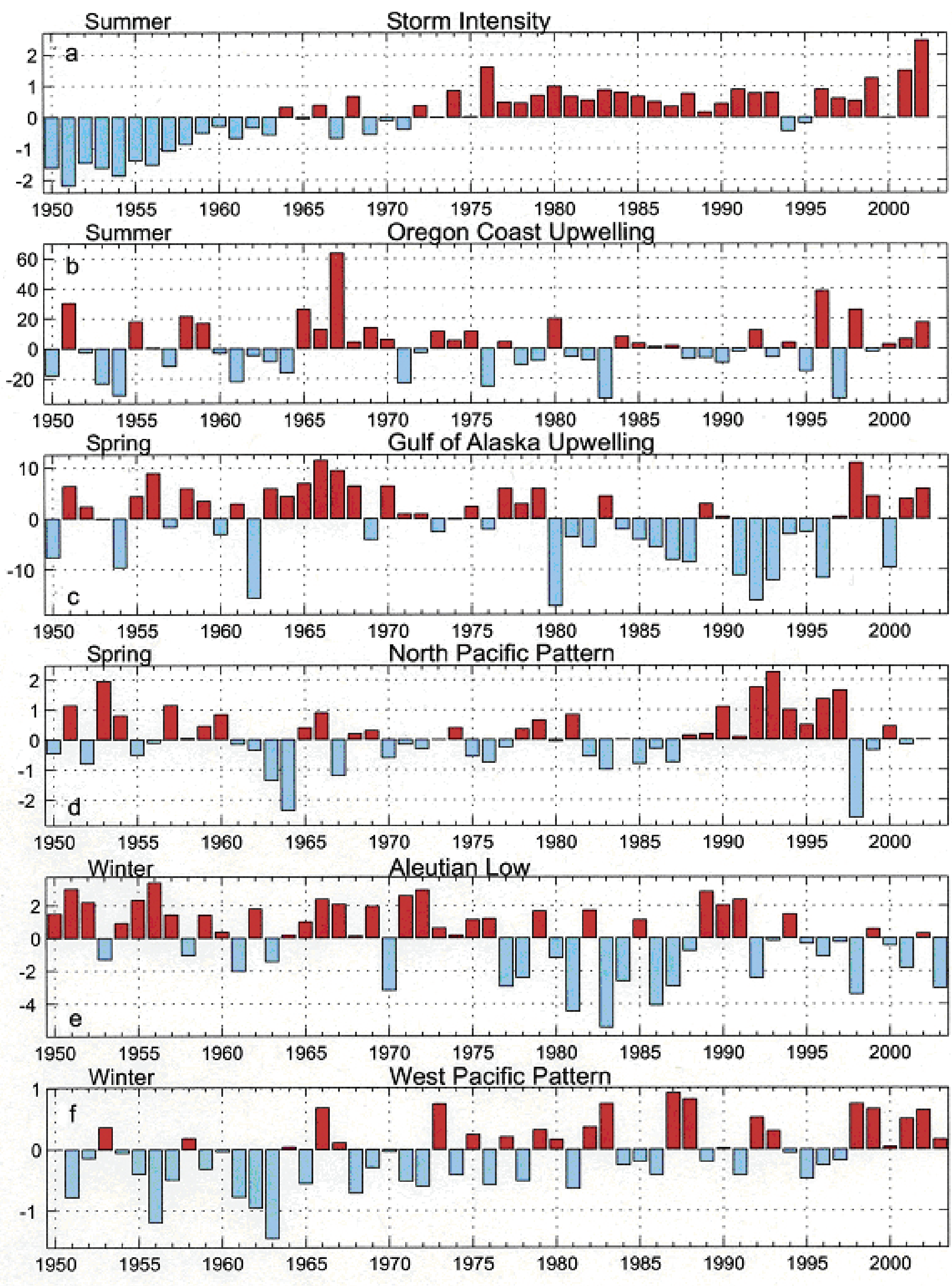
We selected two indices to represent the North Pacific climate for each of summer, spring and winter seasons, and to represent geographic diversity. In summer (June to August), interactions between the sea and atmosphere are strongly influenced by wind and sun. The first index for the northwestern Pacific is centered in a region east of Japan (near 40°N, 160°E). It reflects year to year and decade to decade variability in the summertime storm track which, in turn, are coupled to local SSTs and cloudiness. Storm intensity is estimated from daily vertical wind speed.[15]

Both the vertical velocity and cloud cover intensified and these zones moved toward the equator between 1952 and 1975, and notably, three of the largest values of this index occurred after 1999 (Figure 24a). Certainly the long-term trend over the previous 50 years and the recent large values are a noteworthy change. Weak relationships between this index and large-scale atmospheric circulation patterns suggest that the atmosphere of the northwestern Pacific in summer is dominated by local processes.

[Table 2] Summary of North Pacific Indices*

Name	Abbrev.	Type	Location	Source
Summer (June–August)				
Storm intensity /clouds[15]	STMI	Direct	West	PMEL*
Upwelling	UPWL	Direct	North, East	PFEL
North Pacific High[31]	NPH	Direct	East	PMEL
East Pacific Pattern[16]	EP	Mode	E. Central	CPC
Pacific Decadal Oscillation (SST)[23]	PDO	Mode	Central	JISAO
Spring (April–May)				
Aleutian Low SLP[21]	AL	Direct	Central	NCAR
Upwelling[17]	UPWL	Direct	North, East	PFEL
Northern Oscillation Index[31]	NOI	Mode	East	PMEL
North Pacific Pattern[16]	NP	Mode	Central	CPC
Stratospheric Wind (200 hPa)[17]	U200	Zonal	Central	PMEL
Pacific Decadal Oscillation (SST)[23]	PDO	Mode	Central	JISAO
Winter (November–March)				
Aleutian Low SLP[21]	AL	Direct	Central	NCAR
Ridge/Trough counts[33]	R/T	Direct	Central	PMEL
Pacific North American (500 hPa)[22]	PNA	Mode	Central	JISAO
Pacific Decadal Oscillation (SST) [23]	PDO	Mode	Central	JISAO
West Pacific Pattern[16]	WP	Mode	West	CPC
Stratospheric Wind (200 hPa)[17]	U200	Zonal	Central/ Hemispheric	PMEL
Zonal Wind Index-W(500 hPa winds)[34]	ZWI	Zonal	Central/ Hemispheric	PMEL
Zonal Circulation Index-P (SLP)[35]	ZCI	Zonal	Central	PMEL
Arctic Oscillation[36]	AO	Mode	Hemispheric	CPC

*Re-calculated from NCEP Reanalysis data based on definitions from the original reference



[Figure 24] Representative atmospheric indices for the North Pacific for summer (a,b), spring (c,d) and winter (e,f)

The second summer index is for ocean upwelling off the Oregon coast (45°N, 125°W) in the eastern North Pacific (Figure 24b)[18]. Upwelling here is caused by winds from the north that arise from higher atmospheric pressure offshore in summer. Water at the ocean surface tends to be blown away from the coast and replaced by water that is upwelled from below. The main feature of the index is the persistence of enhanced upwelling during summer since the mid-1990s with several large events, including 2002. This recent period is even more striking when one considers that the anomalous downwelling in 1997 was likely associated with the early seasonal development of the 1997–1998 El Niño. The recent period contrasts with the lack of strong upwelling from 1976 through the early 1990s.

For spring (April–May), the upwelling index for the northern Gulf of Alaska (60°N, 149°W) is examined (Figure 24c).[18] With low pressure storms generally moving eastward across the North Pacific or curving into the Gulf of Alaska, the winds there tend to be easterly, or downwelling-favorable (pushing water toward the coast). Greater downwelling occurred from 1980–1996, relative to the previous decades. Of particular interest is that four of the five most recent years (1998–2002) experienced lessened downwelling. This switch may have affected the regional ecosystem in spring.

The second index for spring is the North Pacific (NP) pattern (Figure 24d).[19] Unlike the previous "direct" indices, a second kind of index is based on mathematical analysis of atmospheric patterns. They are called modal or teleconnection patterns. They often portray two or more "centers of action" in distinct geographic regions, where the variables are negatively correlated. The NP pattern is the primary atmospheric mode during spring in the North Pacific. It consists of a primary center which spans the central latitudes of the western and central North Pacific, and a weaker region of opposite sign to the north which spans eastern Siberia, Alaska, and the intermountain region of North America. Pronounced positive phases of the NP pattern are associated with a southward shift of the Pacific jet stream and suppressed storm activity over the Bering Sea and Alaska.[20] The NP index tended to be positive from 1990 through 1997 which is consistent with the relatively warm springs of the Bering Sea in the 1990s, but this trend has recently been broken.

For winter (November–March), the Aleutian low pressure center is the dominant atmospheric feature of the North Pacific (Figure 24e). It represents the average of storms that move across the North Pacific during the winter; thus it measures both the intensity and the tracks of these storms. One such index is the regional average sea level pressure in the central North Pacific.[21] A feature of this time series is the shift to lower pressures for the years beginning with 1977. The main interruption is three years of positive anomalies 1989–1991, which were caused by a pan-Pacific influence from a strengthened polar vortex (winds). While there is an increase in the frequency of years with smaller magnitudes of the Aleutian low index after 1994, there is no indication of a return to the weaker Aleutian lows that characterized the years prior to 1976. In fact, 1998 and 2003 had strong (deep) Aleutian lows of similar magnitude to those observed during the 1980s.

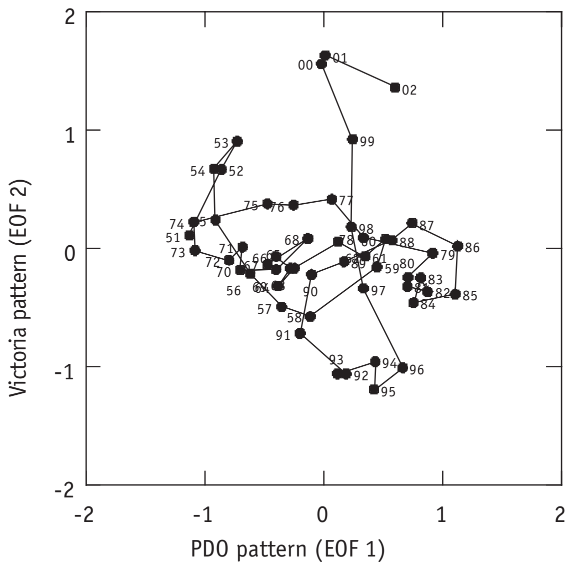
The Aleutian low in winter is correlated with two other North Pacific indices. The Pacific North American (PNA)[22] is the primary mode for winter based on 500 hPa geopotential heights which tracks both the intensity of the Aleutian low and whether storms track eastward (negative phase) or curve northeastward into the Gulf of Alaska (positive phase); the PNA is highly correlated (–0.86) with the Aleutian low index for five-month winter averages over the 54 year sample period. A second related index is the Pacific Decadal Oscillation (PDO) which is the primary mode for North Pacific SST during the last century.[23] This SST signal is related to a deeper Aleutian low in its positive phase through enhanced wind mixing of colder, deeper water in the central Pacific and advection of warm SST anomalies in the northeast Pacific. The PDO is correlated with the Aleutian low at (–0.73) and the PNA at (0.70), but these correlations increase to (–0.89) and (0.80) if five-year running means are applied before taking the correlations. Thus the PDO represents a more low frequency component while the Aleutian low and PNA include both low frequency and significant interannual variability.

The West Pacific (WP) pattern (Figure 24f) is second in importance to the PNA in winter.[24] It consists of a north-south oriented dipole in 700 hPa geopotential height anomalies, one centered over the Kamchatka Peninsula and another broad center of opposite sign south of 40°N from east Asia to about 150°E. Strong positive or negative phases of WP reflect pronounced zonal or meridional variations in the location and intensity of the entrance region of the jet stream over the western Pacific. This pattern is influenced by the winter monsoonal meteorology over eastern Asia and influences the downstream storm track over the northwest Pacific.[25] The WP index has considerable interannual variability and some longer-term persistence. Of particular note is the run of positive values beginning in 1998; this represents stronger winds over the far northwestern Pacific and presumably increased storm generation. The WP is weakly correlated with the Aleutian low. The correlation is (–0.27) but this magnitude increases to (–0.47) when the low frequency variation (five-year running mean) is considered.

Change in 1998/99

As mentioned previously, the PDO pattern of SST variability has had greater influence than any other pattern during the past century, but it appears that the PDO has not been the dominant pattern since 1989.[20] There were significant changes in marine ecosystems in 1976/77 when the PDO changed from negative (cold along N. America, warm in the central Pacific) to positive (the reverse).[23] Rather abrupt changes also occurred in 1989 with their greatest impact in the California Current region.[26,27] There was, however, general agreement that whatever happened in 1989 was qualitatively different from what had occurred in 1976/77 and definitely not a reversal to conditions that existed before 1977. Then 1998/99 brought equally dramatic changes that, again, did not appear to match any recent period. Initially, there was debate about whether the post-1998 period was simply a reflection of a very strong La Niña, but the changes persisted longer than the La Niña and even through a mild El Niño in 2002/03. What is now clear is that the change in 1998/99 was a reversal of an SST pattern that became established in 1989.

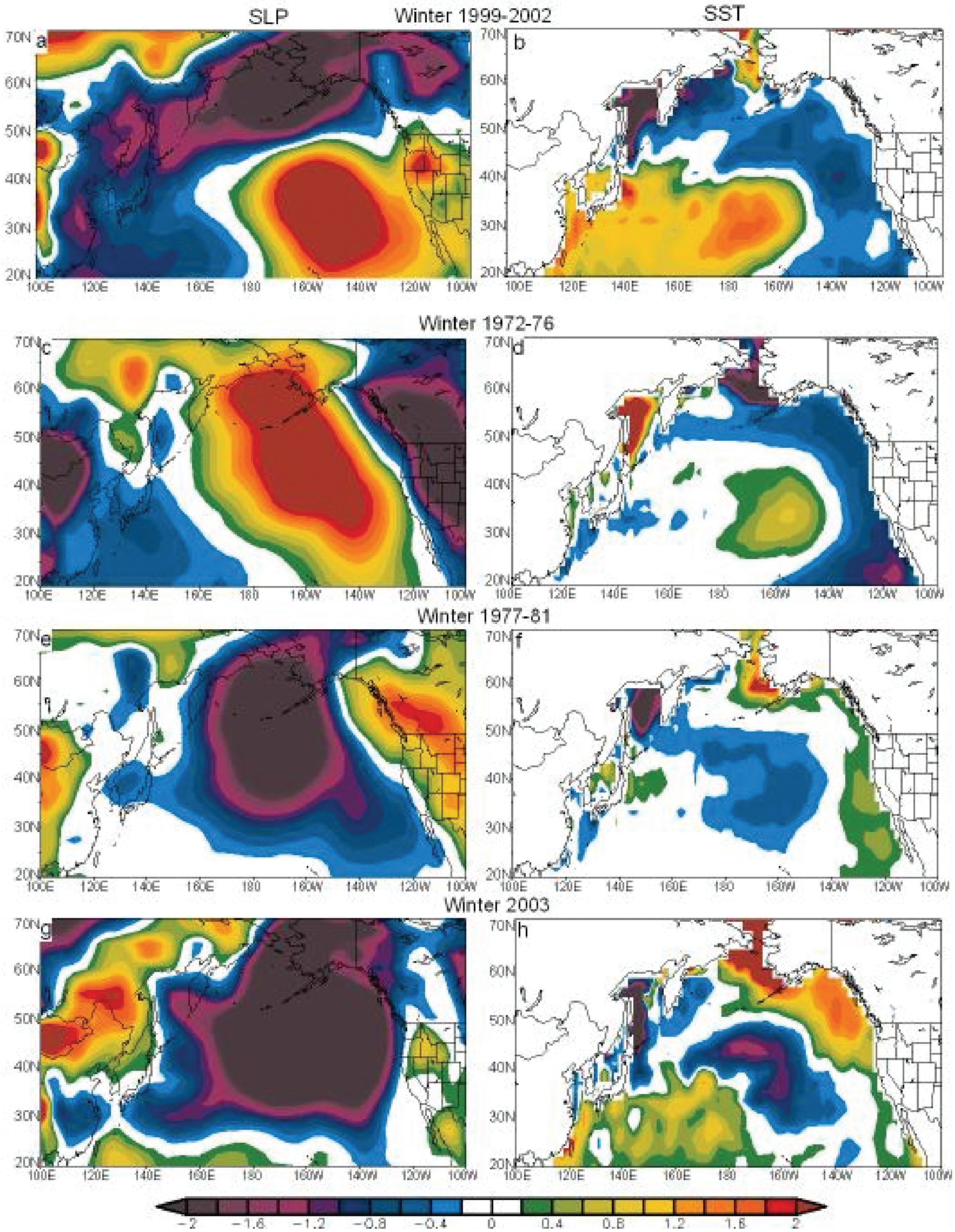
In fact, after 1989, the PDO pattern was no longer the dominant pattern of SST variability in the North Pacific. It was replaced by what is now called the *Victoria Pattern*.* This is best illustrated in Figure 25 where it is possible to follow the average state of winters with respect to both the PDO and Victoria patterns from 1950 to the present. Before 1989, variability is largely along the horizontal (PDO) axis. After 1989, the years vary little on the PDO axis, but begin to vary along the negative part of the vertical (Victoria) axis. In 1999, a strong shift to the positive phase of the Victoria pattern occurred that persisted until 2003 when the PDO pattern reappeared.



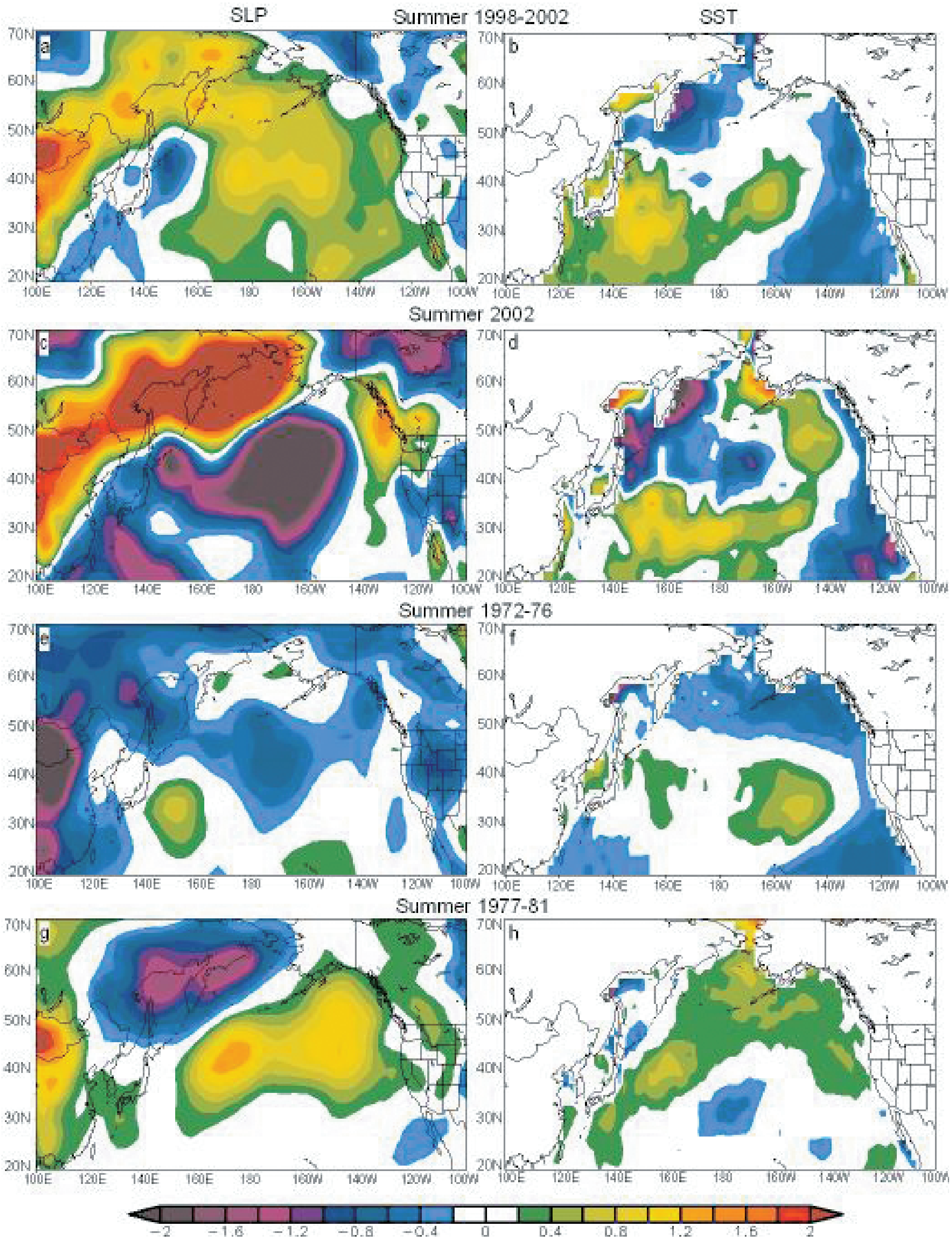
[Figure 25] Trajectory of dominant SST patterns in the North Pacific based on data from 1950-2003. Labels indicate 5 year running means, except for endpoints which are based on 3 year means[28]

The SLP and SST anomalies (hereafter identified as SLPA and SSTA) for the winters (Nov.–Mar.) of 1998–99 through 2002–03 are shown in Figure 26. The primary feature in the SLPA field (Figure 26a) is a NNW-SSE oriented dipole in the eastern Pacific with lower pressure in the north.

* The seeds of this line of thinking germinated at the PICES North Pacific Ecosystem Status Report Working Group meeting in Victoria, Canada in August 2003.

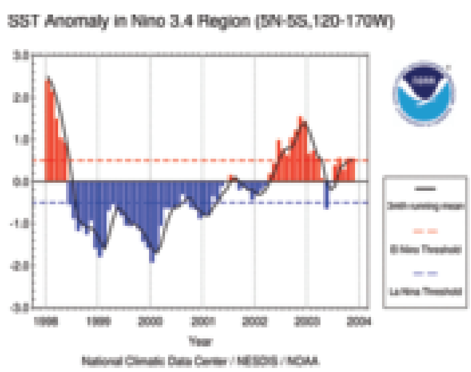


[Figure 26] Spatial anomaly fields of (a) SLP and (b) SST for winter (November–March) covering 1999–2002, 2003, 1972–1976, and 1977–1981[28]



[Figure 27] Same as Figure 2 but for summer

The corresponding SSTA pattern (Figure 26b) consists of a cold anomaly extending from off California across the Pacific to the western Bering Sea and Sea of Okhotsk, with a prominent warm anomaly south of 40°N extending from the coast of Asia to about 150°W. This pattern has not been static over the last five winters. In particular, the SLPA during the winter of 2002–03 (Figure 26c) was dominated by a single negative center south of Alaska; the SSTA (Figure 26d) featured a tri-pole pattern (warm in the SW and NE, and cold in the central North Pacific). The primary differences in the SSTA between this individual winter and the five winter average is a southwestward shift in the pattern as a whole and the development of strong warm anomalies in the Gulf of Alaska and northeastern Bering Sea. The winter of 2002–03 in the North Pacific was affected by an El Niño (Figure 28), but it remains to be seen whether this winter represents a temporary or long-lasting return of warmer SST along the west coast of North America.



[Figure 28] SST anomalies in Nino 3.4 region (5°S-5°N, 120°W-170°W)[29]

It is instructive to compare the recent SLPA and SSTA patterns with their equivalents before and after the regime shift of 1976–77. The five winters before the regime shift (1971–72 through 1975–76) tended to have anomalously high SLP in a NW-SE oriented strip extending from eastern Siberia to off the coast of California (Figure 26e), and anomalously warm SST in the central North Pacific, especially north of Hawaii, with cold anomalies along the entire west coast of North America (Figure 26f). Similar patterns, but in an opposite sense, occurred in the five winters (1976–77 through 1980–81) after the regime shift (Figure 26g,h). Essentially, these two 5-year periods characterize canonical examples of the negative and positive phases of the PDO.

Tight coupling between the atmosphere and ocean is seen in all four sets of maps. In general, cold (warm) SST anomalies are co-located with anomalous north through west (south through east) winds. Different forcings can yield similar SST signals in particular locations. For example, the SST was cold off the west coast of North America both before the regime shift (Figure 26f) and from 1998 through 2002 (Figure 26b) but in the first case in association with anomalous northerlies and presumably cold air accompanying a weak Aleutian Low, and in the second case in association with enhanced west winds and hence greater mixing of cold water from depth.

The counterparts to the previous series of maps for summer (June–August) are shown in Figure 27a-h. The SLPA pattern for 1998–2002 (Figure 27a) indicates higher than normal SLP over almost the entire North Pacific; the corresponding SSTA pattern (Figure 27b) includes relatively warm conditions in the SW and cold conditions in the far eastern portion of the basin and in the eastern Bering Sea. As for the winter season, significant change occurred in the last year. In this case, the primary change in summer was the development of a strongly anomalous low pressure center in the central North Pacific (Figure 27c). On the other hand, the SSTA in the summer of 2002 (Figure 27d) was not markedly different from that for the five previous summers as a whole, with the exception of the presence of warmer SST in the Gulf of Alaska and eastern Bering Sea.

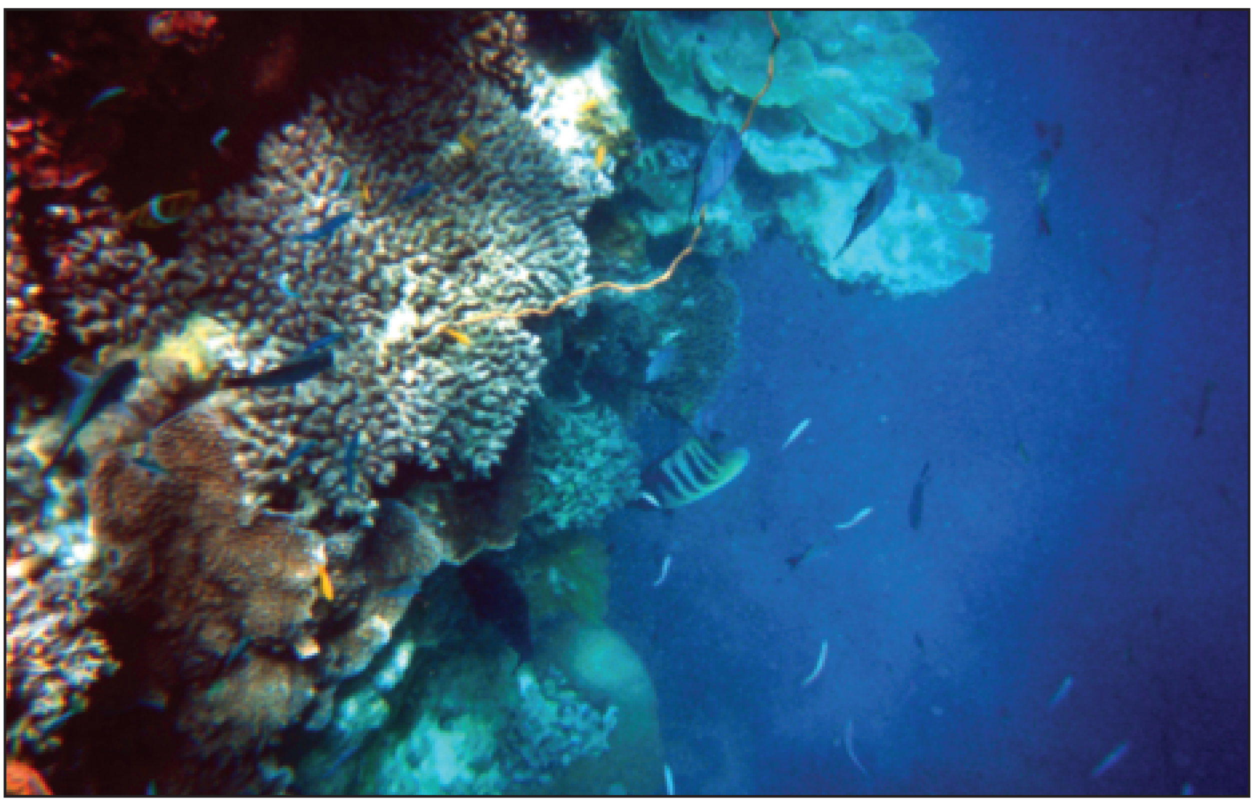
The recent 5-year average summer conditions are unlike those found for either before (Figure 27e) or after (Figure 27g, h) the 1976/77 regime shift. For both before and after the regime shift, the sea level pressure anomaly patterns in summer are similar to those in winter, but of opposite sign. With regard to SSTA, the pre-regime shift map for summer (Figure 27f) corresponds quite closely to that for winter (Figure 26f), while for the post-regime period, there is similarity but less of a match in the patterns between summer (Figure 27h) and winter (Figure 26h). In general, these sets of maps suggest that the summertime SSTA in the North Pacific is determined more by the atmospheric forcing during the winter (as signified by the SLPA) than that during the summer.

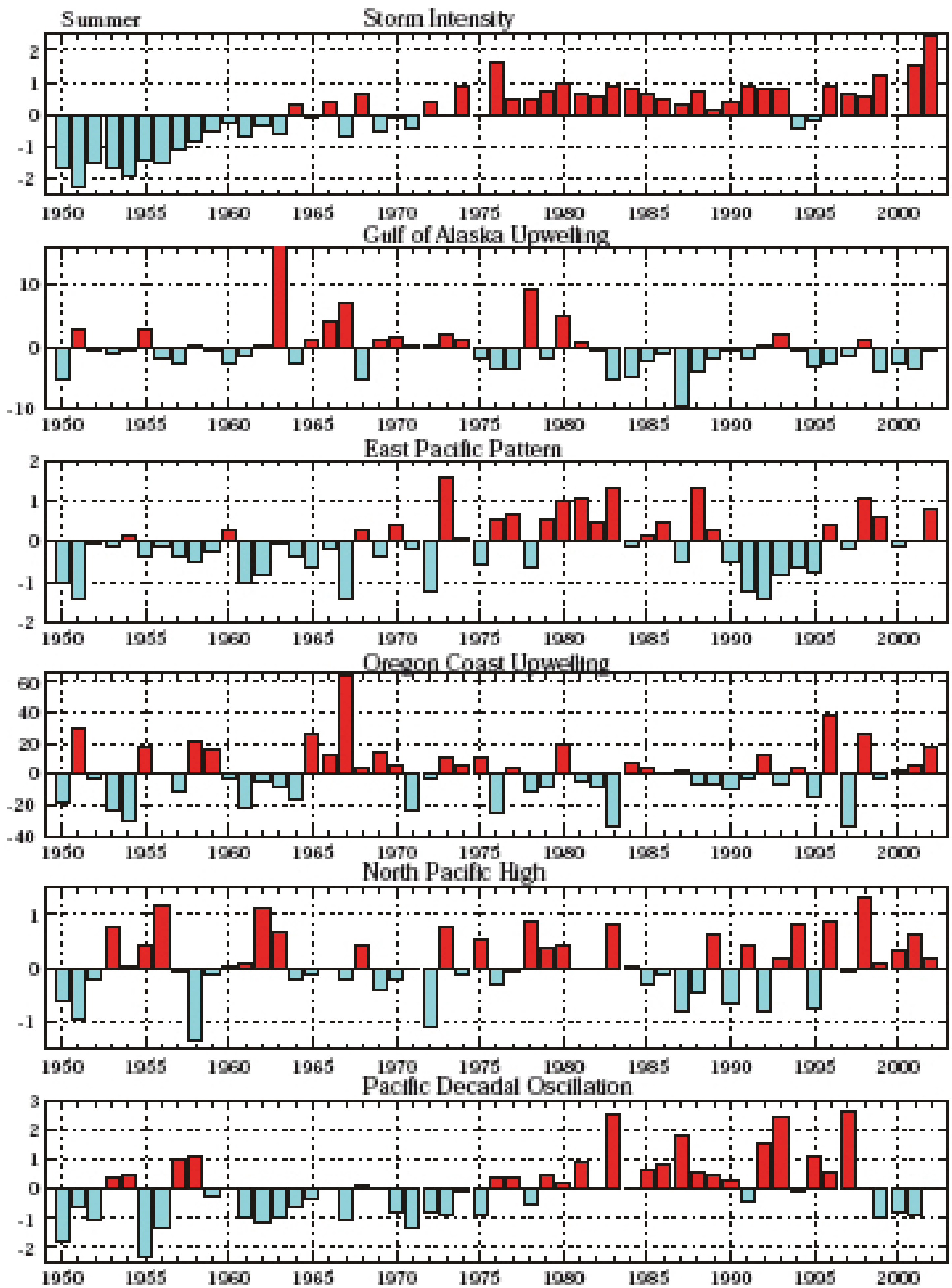
The period 1998-2002 (Figure 26a) resembles neither the period before nor after the 1976/77 regime shift. Our interpretation of these results is that climate variations associated with the Victoria Pattern rather than the PDO have characterized the state of the North Pacific since 1989. The evidence for a major regime shift in 1998[30], at least from the viewpoint of Pacific Basin-wide SLP and SST fields, is the strong phase reversal from the negative to positive Victoria Pattern that occurred in 1999. The winter of 2002/03 was an ENSO winter that resembled the period after the 1976/77 shift. Whether the future will continue with the Victoria pattern, or whether the Victoria pattern is transitional to another state is uncertain.

Comparison of Atmospheric Indices

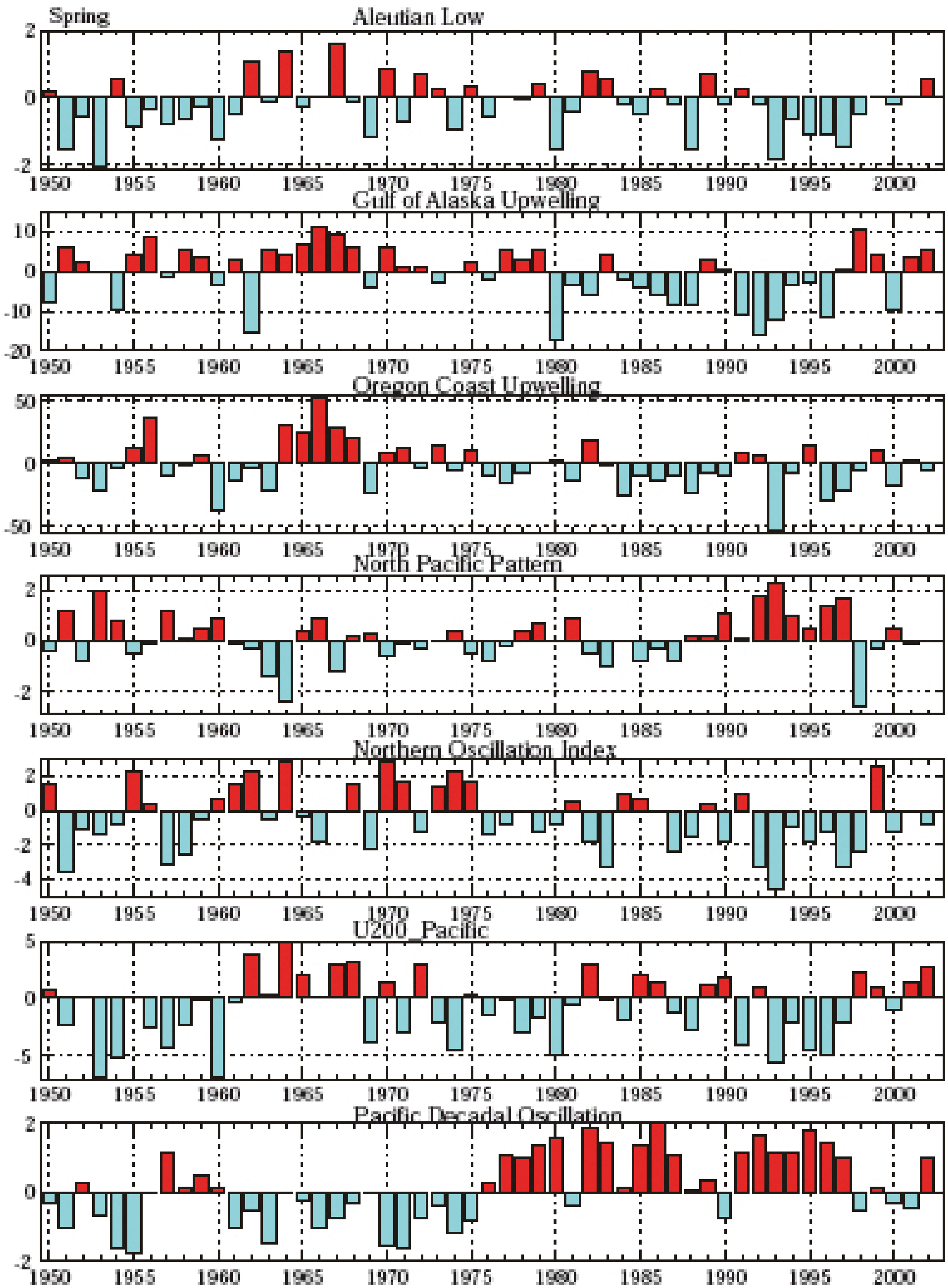
We investigated how indices listed in Table 1 are correlated. Time series for summer (June–August) are shown in Figure 29. In addition to the storm intensity/clouds (STMI) for the northwestern Pacific and the upwelling index for Oregon, we considered the North Pacific High (NPH), the East Pacific (EP) pattern, and the summer months of the PDO and the Gulf of Alaska upwelling.

The NPH represents a major summer meteorological feature and the SLP value at 35°N, 130°W was chosen to represent its annual characteristic.[31] The EP pattern is the primary mode for the Northern Hemisphere in June and July.[32] It is represented by a dipole in 700 hPa geopotential height between a southern center located in a broad area east and west of Hawaii and a weak northern center in the Gulf of Alaska. The EP positive phase has anomalous westerly winds into northern California, while the negative phase is associated with weak westerlies over the eastern Pacific. The EP tended to be negative from 1950 through 1972 and in the early 1990s, and was positive from the mid-1970s through late 1980s. Lately, it has tended to be positive.

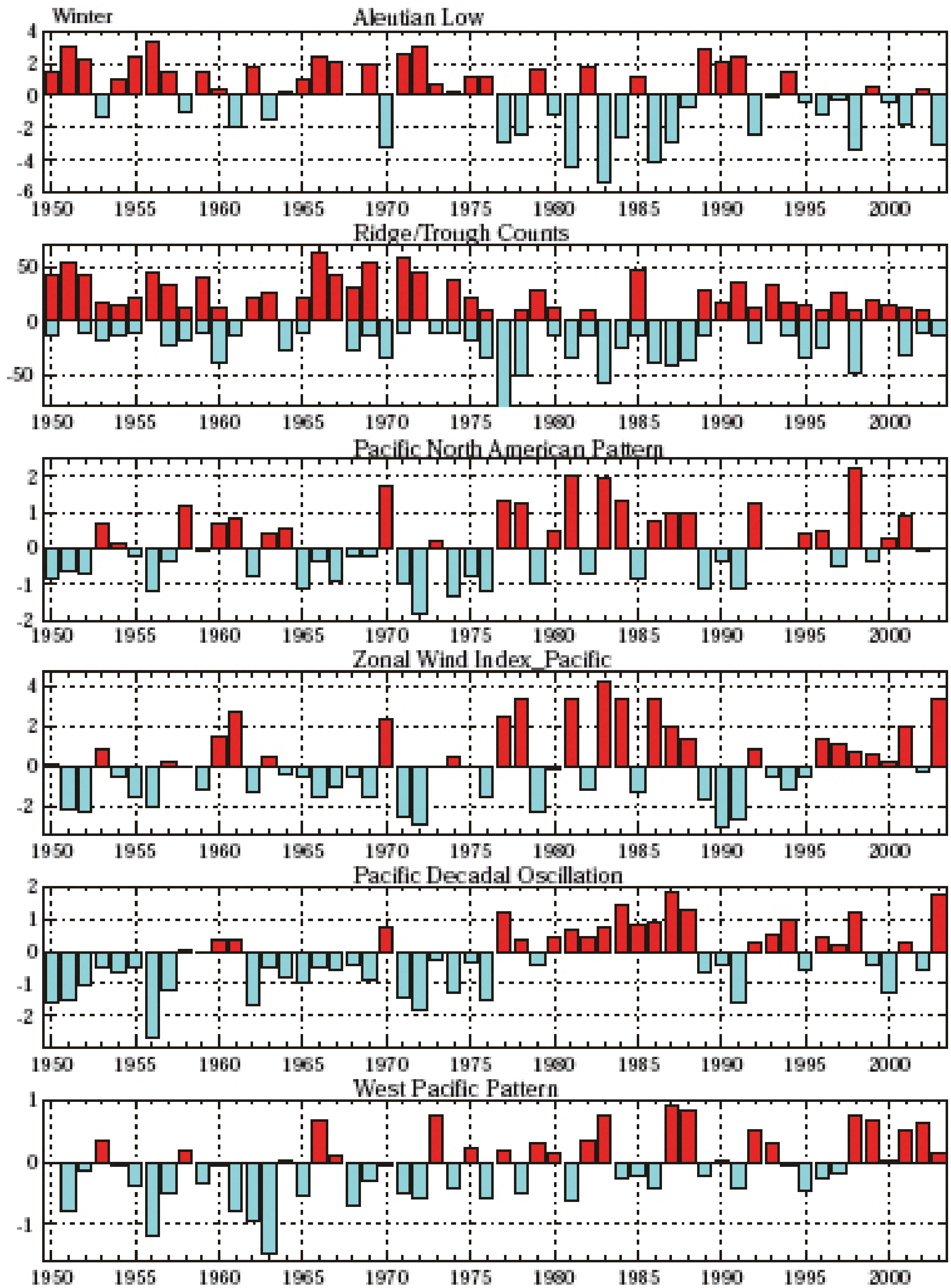




[Figure 29] North Pacific indices for summer (see Table 2 and text for details)



[Figure 30] North Pacific indices for spring (see Table 2 and text for details)



[Figure 31] North Pacific indices for winter (see Table 2 and text for details)

[Table 3] Correlations among summer climate indices in the North Pacific

Index	UPWL_AK	EP	UPWL_OR	NPH	PDO
STMI	−0.171	0.405	0.022	0.097	0.355
UPWL_AK		−0.144	0.272	0.171	−0.277
EP			−0.126	0.347	0.192
UPWL_OR				−0.026	−0.244
NPH					−0.193

[Table 4] Correlations among spring climate indices in the North Pacific

Index	UPWL_AK	UPWL_OR	NP	NOI	U200	PDO
AL	0.221	0.489	−0.536	0.400	0.711	−0.097
UPWL_AK		0.423	−0.337	0.123	0.341	−0.384
UPWL_OR			−0.319	0.312	0.433	−0.201
NP				−0.399	−0.579	0.176
NOI					0.279	−0.417
U200						−0.120

[Table 5] Correlations among winter climate indices in the North Pacific

Index	(R-T)	(R+T)	PNA	ZWI_Pa	PDO	WP
AL	0.795	0.081	−0.864	−0.919	−0.732	−0.269
(R-T)		0.009	−0.773	−0.774	−0.657	−0.309
(R+T)			−0.018	−0.071	−0.087	−0.090
PNA				0.784	0.700	0.335
ZWI_Pa					0.695	0.244
PDO						0.485

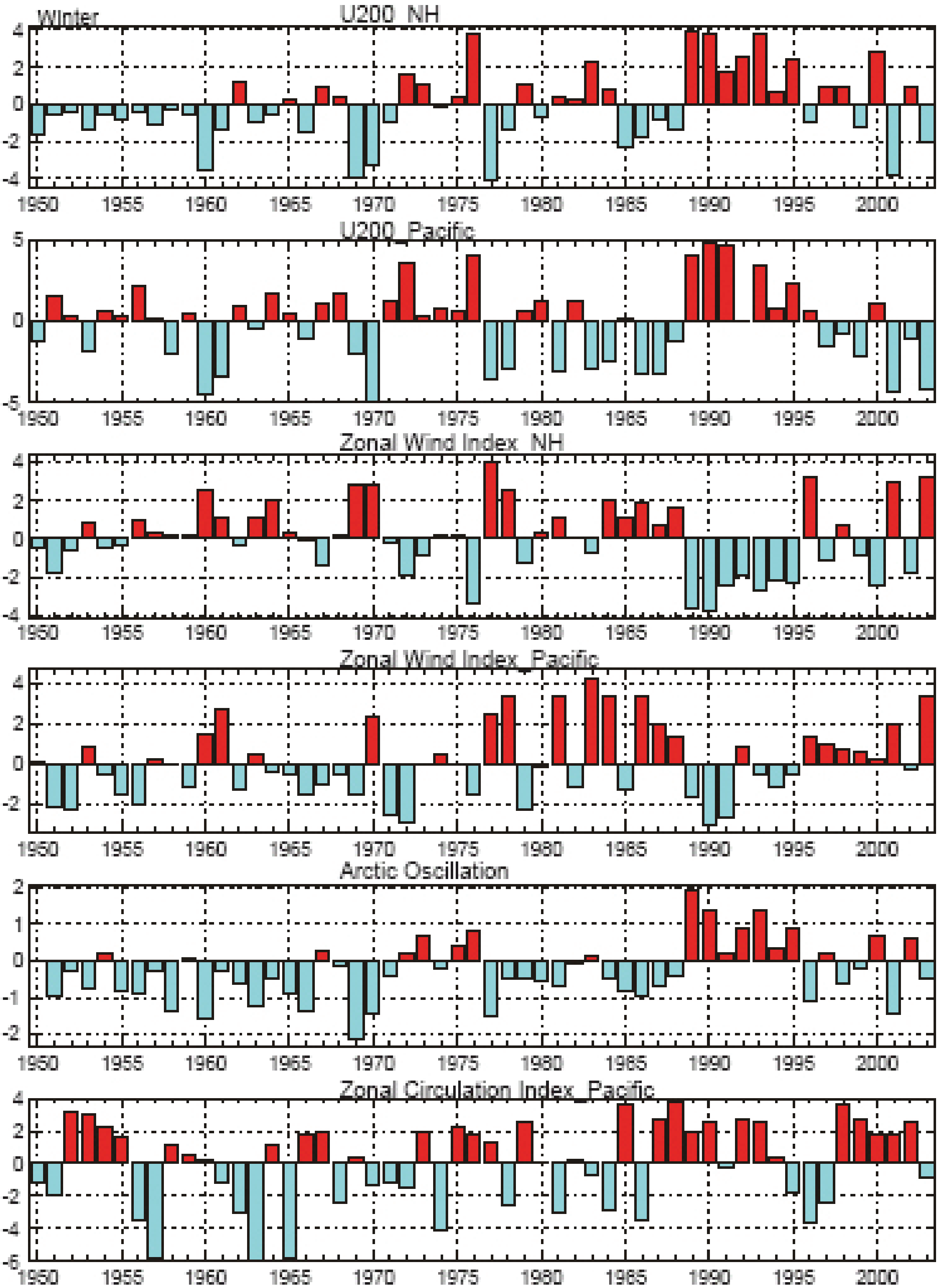
Table 3 shows the correlation matrix for summer indices; abbreviations for the index names are listed in Table 2; most summer correlations are weak. There are modest correlations between the NPH index and the large-scale EP pattern, between the NW Pacific storm intensity/cloud index, and between the EP pattern and the PDO.

For spring (April–May), in addition to the Gulf of Alaska upwelling and the North Pacific (NP) pattern, we include the Aleutian low, the PDO, Oregon upwelling, the zonal wind over the North Pacific across 60°N at 200 hPa from 130°E to 130°W, and the Northern Oscillation Index (NOI).[31] The NOI represents the difference in SLP between the NP and Darwin, Australia. The NOI often reflects ENSO events.

The time series for spring indices are shown in and Figure 30 the correlations are shown in Table 4. While larger than summer, the correlations are still modest.

Upwelling is modestly correlated between regions and with the NP. The Aleutian low is strongly correlated with the upper-level atmospheric circulation (U200) as expected, and has some projection on or relationship with the NP Pattern. The magnitude of the NOI is modestly correlated (~0.4) with the broad-scale indices: the Aleutian low, NP pattern, and PDO.

For winter (November–March), in addition to the Aleutian low, the PNA, the PDO, and the WP, we include a ridge and trough index[33] and zonal wind index. The ridge-trough events represent the number of days in winter that the 500 hPa geopotential height anomalies at 45°N, 170°W exceeded 100 m for at least 10 days. Rather than being based on monthly or seasonal means, this index highlights meteorological events. The zonal wind index represents the difference between the westerly component of the 500 hPa wind at 35°N minus 55°N over the region from 130°E to 130°W.[34]



[Figure 32] Comparison of several zonal (longitudinally averaged) atmospheric indices. ***NH*** indicates average around the North Hemisphere, and ***Pacific*** indicates average only over the Pacific sector of the hemisphere.

Figure 31 shows the winter indices and Table 5 shows their correlation matrix. Table 6 shows the correlation matrix after the time series have been smoothed with a five-year running mean. The correlations for winter are generally strong with the Aleutian low correlating with the excess of troughs over ridges, the PNA, and the zonal wind.

The strong correlation of the PDO with atmospheric indices increases further after a low pass filter is applied. The number of troughs (negative values) increases after 1976 and the number of extreme events, either ridges or troughs, seems to have decreased in the 1990s.

[Table 6] Correlations among 5 year running mean smoothed climate indices in winter

Index	(R-T)	(R+T)	PNA	ZWI_Pa	PDO	WP
AL	0.855	0.198	−0.857	−0.949	−0.887	−0.471
(R-T)		0.063	−0.688	−0.845	−0.769	−0.382
(R+T)			−0.273	−0.140	−0.150	−0.154
PNA				0.806	0.797	0.312
ZWI_Pa					0.789	0.355
PDO						0.559

[Table 7] Zonal Index correlations

Index	U200_Pa	ZWI_NH	ZWI_Pa	AO	ZCI
U200_NH	0.696	−0.843	−0.331	0.847	0.124
U200_Pa		−0.727	−0.799	0.614	0.064
ZWI_NH			0.598	−0.805	−0.256
ZWI_Pa				−0.270	−0.211
AO					0.269

Zonal indices indicate the variation of the large-scale hemispheric circulation and its potential impact over the North Pacific. In addition to the 200 hPa zonal wind component at 60°N and the 500 hPa wind components at 35°N minus 55°N (ZWI), a zonal circulation index (ZCI) of SLP between 35°N and 65°N was included.[35] For the two zonal wind indices, both the hemispheric values for each winter and the values over the Pacific were included. The Arctic Oscillation (AO)[36] index, defined as the dominant pattern of winter monthly sea level pressure north of 20°N has strong covariability with the stratospheric zonal wind.

Figure 32 shows the time series and Table 7 shows the correlation matrix. As expected there is strong agreement in the two wind indices over the northern hemisphere (−0.84) and the North Pacific (−0.80). The relation between the hemispheric and regional stratospheric wind is (0.70) while for the 500 hPa wind index it is (0.60). The AO tracks the hemispheric zonal winds. These results combined with those for other winter series, make the case for the use of a regional zonal wind as a North Pacific index.

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