JP2.25 SOUTHERN CALIFORNIA UPWELLING: IS RECENT WEAKENING A RESULT OF GLOBAL WARMING?

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1. BACKGROUND

Variations in the coupled oceanic/atmospheric system impact upwelling patterns and influence other climatic elements in the southern California area. Changes in the upwelling system in turn modify sea surface temperatures (SSTs), sea level heights, and coastal climate. This study examines upwelling patterns from 1946 to the present at three coastal locations, 30N, 119W; 33N, 119W; and 36N and 122W, and ties these patterns to variations in air-sea interactions. While upwelling is controlled daily mostly by local characteristics of winds, the California Current (CC), coastal topography and bathymetry, larger atmospheric feature such as El Niño/La Niña episodes dominate local conditions. During strong El Niño events, more southerly winds bring warmer waters northward along the California coast. More anomalous northerly winds dominate during La Niña events. These events persist for months and are often influenced by larger, longer-lasting atmospheric trends, such as the PDO.

Atmospheric patterns during the last warm phase of the PDO, from approximately 1977-1997, were on the whole different than those occurring during the preceding cold phase, from about 1946 to 1976. A recent possible switch back to the cold phase that started in 1998 is more variable and complex (Overland et al. 2000). Our results indicate that air-sea interactions on a large-scale do explain trends and variability of upwelling along the southern California coast. Additionally, these findings also point to the possible influences of global warming. Furthermore, local climatic records, reveal the influence of coastal atmospheric/oceanic variations on southern California climate.

2. INTRODUCTION

Upwelling, which is strongest during the spring and summer seasons in the southern Califonia coastal area is associated with the eastern boundary California Current.

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Fig 1a. The study area-the southern California coast (map source: National Geographic).

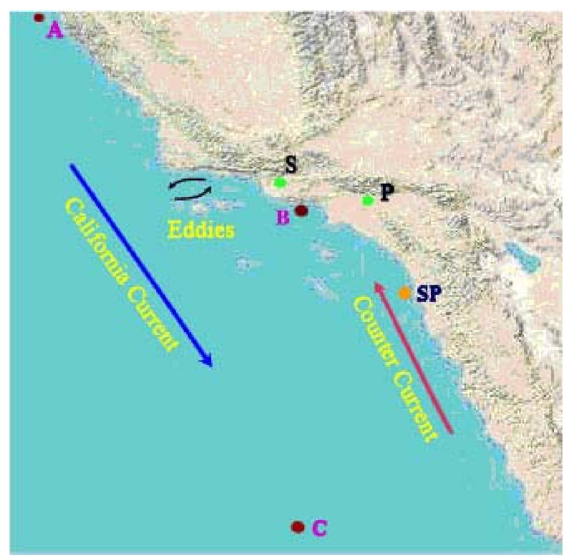

Fig 1b. Inset shows upwelling stations A, B and C; climate stations P (Pasadena), and S (Santa Paula); SP, Scripps Pier; and the 3 components of the CCS in southern California.

Consequently, upwelling patterns are influenced by variations in the California Current System (CCS). The strength of the California Current varies according to wind speed and direction. Variability of the CC combined with the complex bathymetry (islands, shallow banks, basins and troughs, and the irregular coastline) of the southern California coast results in spatial and temporal changes in upwelling trends (Lynn and Simpson 1990). Three major components comprise the CA Current System (Fig. 1b). First is the eastern Pacific boundary current moving cold water equatorward from the N. Pacific. Another component is poleward flowing undercurrent generally confined to the continental slope and which surfaces as a counter-current. A third component of the CCS is the Southern California Eddy (SCE) within the Bight, which results when the CA Current turns inshore south of Pt. Conception and poleward (Bray, et al. 1999). Within Bight circulation is complex, often leading to small coastal eddies. DiGiacomo and Holt (2001) used SAR satellite imagery to identify six unique synoptic patterns in the Bight circulation from eddy formations. Any investigation of upwelling trends in the southern California area must address the complexities of the California Current System.

Ultimately, the California Current System, and consequently, upwelling trends are controlled by regional winds along the west coast control. Coastal winds are used to calculate upwelling and upwelling indices. Local winds, such as the offshore blowing Santa Ana's prevalent during the fall, propel surface water away from the coast towards deep ocean area thereby intensifying upwelling (Hu and Lui 2003).

Large scale atmospheric/oceanographic changes related to annual occurrences of El Niño\La Niña events and decadal shifts associated with the PDO impact wind speeds, sea surface temperatures, and, consequently, upwelling patterns. For example, warmer waters and decreased upwelling is associated with El Niño events and the opposite occurs during a La Niña. Similarly, a negative phase of PDO should result in increased upwelling while decreased upwelling occurs with positive PDO. PDO regime shifts occur on the scale of ocean basins (Mantua et al., 1977). As previously mentioned, these atmospheric changes should manifest themselves in the upwelling record. For example, Bograd and Lynn (2003) note significant change in the nearshore CCS after the 1976-77 N. Pacific climate regime shift. They show significant sea level height increases within the Bight, warming and increased stratification of ocean waters along with decreased upwelling particularly during the late spring and summer.

Global warming trends, which span decades, may also be another important factor influencing upwelling trends in the southern California area. Diffenbaugh, et al. (2004) suggest that increased land-sea thermal contrast enhances peak and late-season nearshore upwelling in the northern limb of the California Current and decreases peak and late-season near-shore upwelling in the southern limb. Bakun (1990) relates the alongshore wind that drives upwelling to the strong pressure gradient set by differential heating between land and sea. However, for California (at 39N), he related increased upwelling from 1945 to 1975 to the possible influence of global warming, but the upwelling trend declined back towards the mean since 1975.

Di Lorenzo, et al. (2005) state that warming along the California coast and increased marine stratification from 1950 to recently, reduces the efficiency of upwelling, despite the increase in upwelling-favorable winds. The authors note that SSTs have risen along the southern California coast 1.3^{o}C between 1950 and 1999, but that this warming could as easily be attributed to large-scale changes in the Pacific basin, such as the PDO, rather than by global warming or changes in the trend in surface heat flux. Similarly, coastal temperature records correlate significantly to the monthly and annual PDO values, while precipitation amounts correlate well to the Southern Oscillation Index (SOI) levels (LaDochy et al 2004).
Upwelling trends and patterns at three coastal locations for the past 60 years are examined and related to local winds, sea level heights, SSTs and Pacific climatic indices to establish trends and mechanisms responsible for changes observed. Possible ties of upwelling to global warming and climate change are also investigated and speculation of their future impacts on southern California upwelling presented. Finally, we relate coastal variability to changes in southern California climate and speculate how trends will impact future climatic variability.

3. PARAMETERS EXAMINED

3.1 Upwelling Indices. Monthly upwelling indices for northern Baja (station C), southern California Bight (station B) and Monterey Bay, station A (30N, 119W; 33N, 119W and 36N, 122W) for 1946 to 2005 were obtained from the Pacific Fisheries Environmental Laboratory (PFEL), NOAA (http://www.pfel.noaa.gov/products/PFEL/modeled/indices/upwelling /upwelling.html). These three sites are closest to our study area.

3.2 Sea Surface Temperatures. Sea surface temperature data used in the analyses were derived from measurements made from buoys off of Scripps Pier, LaJolla and the Santa Monica Pier.

The Scripps buoy is maintained by U.C. San Diego and the data extend from 1917-present, while Santa Monica Pier data runs 1948-present. Sea surface temperature data from buoys centered at 35N, 125W and operated by NOAA were also used in this study (NOAA NCEP Reynolds-Smith Reanalysis). Monthly and annual temperatures and anomalies were calculated for each location. These locations were chosen as they overlapped the upwelling sites and provided continuous, long-term data.

3.3 Mean Sea Level. Mean monthly sea level data for Los Angeles, Santa Monica and Scripps Pier, LaJolla, were available from Proudman Oceanographic Laboratory, Permanent Service for Mean Sea Level (PSMSL) (http://www.pol.ac.uk) and for recent data from NOAA Center for Operational Oceanographic Products and Services, Tides & Currents website: http://tidesandcurrents.noaa.gov/index.shtml. Los Angeles records were continuous since 1924, Santa Monica from 1933, and Scripps from 1925.

3.4 Meridional and Resultant Winds. Meridional winds and anomalies, monthly and annual, are available from NOAA NCEP-NCAR CDAS-Monthly Intrinsic Pressure Level Meridional Wind data: http://iridl.ldeo.columbia.edu/SOURCES/.NOAA/.NCEP-NCAR/.CDAS-1/.MONTHLY/.Intrinsic/.PressureLevel/.v/X/-125./VALUE/Y/35./VALUE/P/1000/VALUE/T+exch/. Meridional wind data (m/sec) show the strength of the northerly (negative) or southerly (positive) wind component at 35N, 125W; 30N, 120W, and 30N, 115W from 1949-2005.
Resultant wind speeds (m/sec) and anomalies were available from the same source for 35N, 125W from 1949-2005.

3.5 Climatic Indices. Climatic indices, both monthly and annual, were downloaded from NOAA NCEP Climate Diagnostic Center: http://www.cdc.noaa.gov/ClimateIndices/Analysis/ Indices included in the analyses are: SOI, PDO, NOI, NP, PNA, WP, MEI and others (NOAA-CIRES CDC http://www.cdc.noaa.gov/ClimateIndices/Analysis/, mostly from 1950 to present, although some have values back to 1900.

3.6 Climatic Data and Weather Charts. Atmospheric weather charts were found at: NOAA NCEP Climate Diagnostics Center, Monthly, Seasonal Composites page, http://www.cdc.noaa.gov/cgi-bin/Composites/printpage.pl Temperature and precipitation monthly and annual data were acquired for CA6 climate division, which is the southern CA coastal climate division, from NOAA NCEP CDC, http://www.cdc.noaa.gov/cgi-bin/Timeseries/timeseries1.pl for 1950-present, to look at impacts of oceanic conditions on southern California climate variability. Precipitation data for Pasadena and Santa Paula from 1948-2005 are from Western Regional Climate Center, Desert Research Institute, Reno, NV at: http://www.wrcc.dri.edu .

3.7 Streamflow (Discharge) Data.
In the southern California area, numerous rivers and streams drain the San Gabriel and Santa Monica Mountains. Urbanization and the need for water storage and flood control has resulted in the modification of many of these rivers. Only two rivers we examined, Arroyo Seco near Pasadena and Sespe Creek near Santa Paula, meet the USGS definition of remaining unadulterated and are used in this study relating to climate variability. Stream flow discharge anomalies were calculated and plotted, in water years. Monthly streamflow for Arroyo Seco and Sespe Creek are available from USGS National Water Information System, NWIS, for the years 1948 to 2005 at: http://waterdata.usgs.gov/nwis .

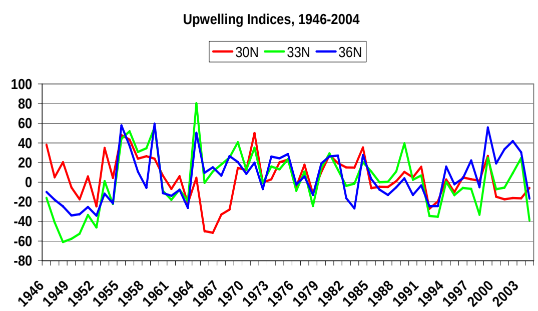

Fig 2a. Annual mean upwelling indices for Stations A, B and C, 1946-2004.

4. RESULTS

4.1 Upwelling
Using monthly and annual upwelling indices, 1946-2005, for 36N, 122W (Stn A) and 33N, 119W (Stn B), and 30N, 119 W (Stn C), several patterns appear. While Stns A and B show fairly close similarities throughout the record, Stn C differs, particularly in magnitude (Fig 2a). Although the general trends of increases and decreases seem to agree for the three locations, Stn C shows an overall decrease in upwelling values, while A and B show increases. This analysis would agree with the ideas of Diffenbaugh, et al. (2004) if the three stations examined were all a part of the CCS. Station C appears to be situated in the Davidson counter-current and therefore would be affected more than the other two by tropical intrusions, ie., ENSO. For example, a much greater decrease in upwelling occurs in the 1960s at Stn C in

comparison to A and B. These decreases correspond to prominent El Niño episodes, especially 1965-66 and to a lesser extent the weak episode in 1968-69. Stations A and B also show

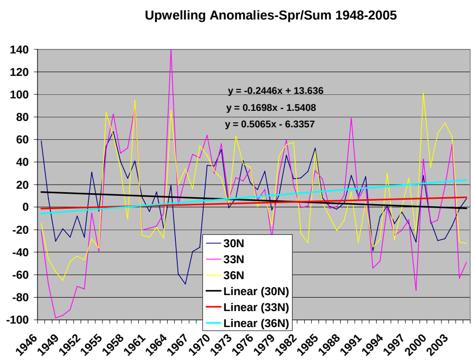

Fig 2b. Annual upwelling indices, Stations A, B and C for Spring/Summer 1948-2005.

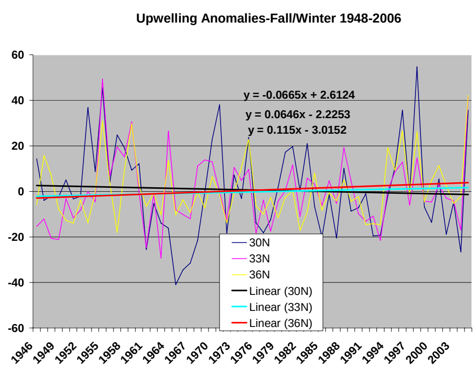

Fig 2c. Annual upwelling indices, Fall/Winter, 1948-2006.

decreasing values during this period, but to a lesser extent than C. More broadly, an increase in the indices at both northern locations (A and B) occurs from 1946 to approximately the mid-70s. Both stations also show a gradual decrease in upwelling until the late 1990s, increasing again until early 2003, after which indices plunge. These long-term trends resemble the switches in PDO phases. Looking at seasonal trends, for both the spring/summer and fall/winter periods, shows upwelling is increasing at Stns A and B and decreasing at Stn C for the whole period of record, similar to trends in the annual values (Fig 2b, 2c).

Although these indices represent local measurements, they are based on pressure gradients that rely on larger scale atmospheric dynamics. The broad shifts in values mentioned above seem to coincide with the decadal shifts in N. Pacific oceanic SSTs or the PDO. Because the PDO SST pattern is associated with W. coast temperature, precipitation and wind fields, the connection with upwelling is not surprising. The cold phase of PDO, between about 1946 and 1976, is associated with more northerly winds along the west coast and more upwelling-favorable conditions. The shift to the warm phase of PDO, about 1976-77, was accompanied by a more southerly component to E. Pacific winds, warmer SSTs offshore and less favorable conditions for upwelling.

Since the strong 1997-98 El Nino, conditions have been more favorable for upwelling and coastal cooling (Peterson and Schwing, 2003), although weak El Niño events occurred in 2002-3 and again in 2004-5. Also, stronger ENSO features are identifiable on a shorter scale. While Stns. A and B show similarities in overall upwelling values, there are also differences. This is not unexpected noting that Stn B is within the southern California Bight and Stn A resides near Monterey Bay within the CCS. Both locations show high variability in inter-annual values, yet correspond quite well to extreme ENSO episodes. For example, spikes in the record show the rapid decreases in upwelling associated with strong El Niños of 1957-58, 1965, 1972, 1977, 1982-83, 1991 and 1997-98. Sharp increases correspond to strong La Niñas of 1955-56, 1973-75, 1988, 1998-99, and 2000-01.

Stn C follows the inter-annual variations of the other 2 stations, although the values do not always correspond. After 1998, Stn C shows decreases in upwelling while Stn A and B increase until 2001-2002. Upwelling values decrease from the north to south. Meridional winds at 30N, 115W during this period were mostly southerly, which suppresses upwelling. The meridional wind trend for the entire period shows decreasing northerly component winds concurrent with decreased upwelling.

4.2 SSTs. Comparing coastal SSTs with upwelling show the PDO signal, with a shift from the cool phase to the warm phase leading to a warming trend for the 1950-2005 period (Fig. 3). Both Scripps Pier and the 35N, 125W locations show the warming trend as well as a non-linear cycle following PDO shifts (Mantua, et al. 1997; Chao, et al. 2000). The rapid drop in SSTs in 1998, a strong La Niña, corresponds with increased upwelling at Stns A and B. After five cool summers in southern California, weak El Niños brought warmer waters and reduced upwelling in 2002-3 and again in 2004-5. Coastal winds were unusually weak in 2004, 2005. The relationship between SSTs and upwelling is not simple. Large-scale Pacific SST patterns influence atmospheric circulation, which in turn drives the CC. However, local upwelling leads to cooling, so that cyclonic eddies within the Bight may cause upwelling and cooling at Stn A and not necessarily at Stn B. But in most cases, stronger northerly winds and increased alongshore current would contribute to both greater upwelling at Stn A and more small coastal eddies in the region of Stn B.

4.3 Meridional winds. A close correlation exists between the strength of the N. Pacific subtropical High and E. Pacific meridional winds, with strengthening in the High, especially during the upwelling season, generating a more vigorous CC. During lulls, such as with El Niño events, the High weakens and more southerly wind flow occurs along the CA coast. Figure 4 indicates that the pattern of annual anomalies in meridional winds at

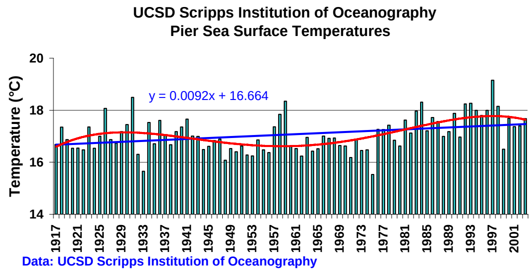

Fig 3. Scripps Pier Annual SSTs, 1917-2003. Blue line shows trend, red a 4th order curve.

35N,125W generally follows that of upwelling, with a strengthening and more northerly trend over the 1949-1977 period, and a weakening until the late 1990s for both. At 30N, 115W, the trend is more southerly winds with slight decreasing upwelling (not shown). As with upwelling, the interannual variability of annual wind anomalies is quite high. The PDO pattern is less recognizable with meridional wind, however ENSO events show up clearly. A much stronger relationship occurs between the meridional winds at 35N, 125W and the North Pacific Oscillation Index, NOI (r^2 = .604, highly significant). The NOI represents the surface atmospheric pressure difference anomaly between the N. Pacific High and Darwin and is the N. Pacific equivalent of the SOI (Schwing et al., 2001). NOI was above average from 1948 to about 1976, then below average from 1977 to about 1997, and again above after 1998. During the winter of 2001-2, a large anticyclonic wind anomaly occurred in the NE Pacific, the fourth consecutive winter for this pattern (Murphree et al., 2003). The anomaly resulted in abnormal transport of subarctic water into the North Pacific Current and anomalous strong upwelling in the CCS as far south as southern California (Bograd and Lynn, 2003). The large positive NOI was accompanied by more northerly meridional winds, greater upwelling and lower SSTs. NOI turned negative for 2003, and positive for 2004. The aforementioned trend follows the PDO values fairly well. The spring of 2005 followed a weak El Niño and positive PDO, along with strong SW surface wind anomaly to the west of CA and more cyclonic circulation in the Gulf of Alaska. These weak meridional winds were coupled with negative

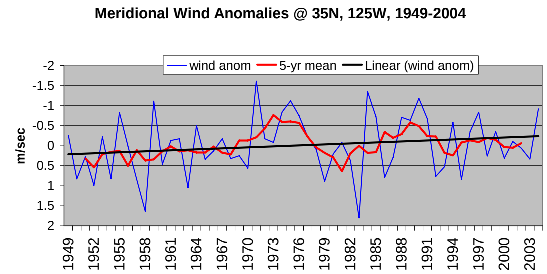

Fig 4. Mean annual meridional wind anomalies at 35N, 125W. Trend shows increased N (-) winds.

upwelling anomalies in southern CA, warmer SSTs and the end of a record rain year for downtown LA (Patzert et al., 2006).

4.4 Mean sea levels. Mean sea levels measurements taken at three local coastal stations, Los Angeles, Santa Monica, and at Scripps, LaJolla, show a gradual increasing trend (Fig. 5). The sea level trends increase rates from Los Angeles to Scripps. For most of the last 50-60 years the MSL has been rising at about 2.3 mm/yr at Scripps. A detailed analysis of the data shows that within this time frame, non-linear patterns occur as well. During major El Niño years, MSLs are higher, while during major La Niña years they drop at all three stations. The Scripps station shows that rates increase from 1.67 mm/yr for the 1925-1945 period to 4.29 mm/yr for the 1974-97 period. Afterwards, sea levels decrease. A definite change in the MSL values coincides with phase changes in the PDO cycle. The 1976-77 and 1998 shifts show prominent increase and decrease respectively.

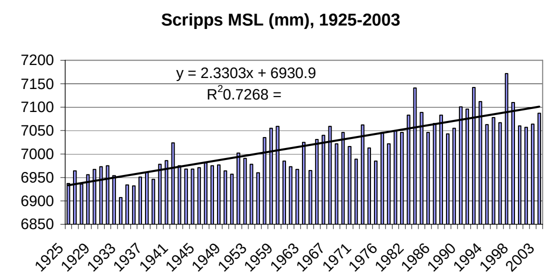

Fig 5. Mean annual sea level (mm) at Scripps Pier, 1925-2003.

4.5 Coastal climate. SSTs, coastal meridional winds, and upwelling patterns are reflected in the temperature and precipitation patterns along the California coast. PDO is a good predictor of California coastal temperatures with a lag of up to two seasons (LaDochy et al., 2004). Removal of the global warming trend reveals a stronger correlation with the PDO. A five-yr drought in southern California in the late 1980s corresponds to a period of greater upwelling, cooler coastal SSTs and stronger northerly meridional winds. SOI is a better predictor of precipitation for the SW than PDO, although there seems to be interactions between the two. When ENSO and PDO are in-phase, that is warm PDO and negative ENSO, or cool PDO and positive ENSO, SW precipitation anomalies are strongly positive and negative respectively. However, when the two indices are out of phase, these relationships are quite weak and prediction of precipitation is not as reliable (Schmidt and Web, 2001). The precipitation record for the coastal southern California climate division (CA6), exhibits a general increase over the 1948-2005 period (Fig. 6). However, considerable interannual variability occurs. Additionally, a general switch from lower precipitation before 1977 (with the cool phase of the PDO) to greater values afterwards (with a warm PDO phase until 1998) is evident in the records examined. Since 1998, precipitation is lower, except for two weak El Niño periods for 2002-3 and 2004-5. Interestingly, summers were cooler and foggier from 1998 through 2002 (LaDochy 2005). Presently, if the PDO has returned to the cool phase, the prospect for cooler, drier years in southern California is a distinct possibility.

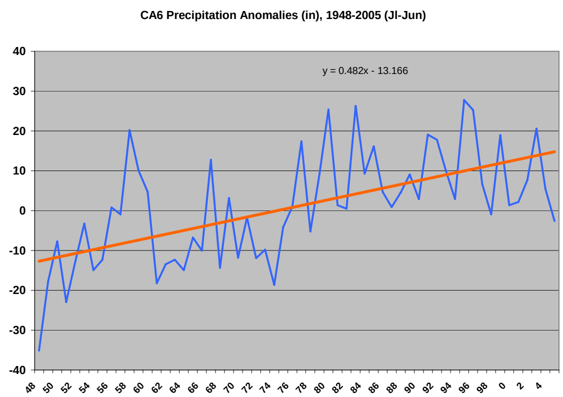

Fig 6. California climate division 6 (southern California) annual precipitation anomalies, 1948-2005.

Pasadena and Santa Paula are located in southern CA coastal valleys. They both average close to 500 mm (20 inches) rainfall annually. However, as with most location in the extreme southwest, rainfall is highly variable (Bruno and Ryan 2000). Figure 7 shows the highly variable nature of rainfall for the two stations. Pacific influences are apparent as peaks and drops in the time series correspond to ENSO extreme events-peaks with El Niños, drops with La Niñas. PDO phases also show up as more dry spells and La Niñas occur during cold phases, while wetter years and more El Niños occur with warm phases. The result of rainfall variability also shows up in the streamflow records of nearby streams. Streamflow for the Arroyo Seco mirrors nearby Pasadena, while streamflow for the Sespe Creek follows rainfall patterns for nearby Santa Paula. Streamflow values have generally increased over the study period following precipitation.

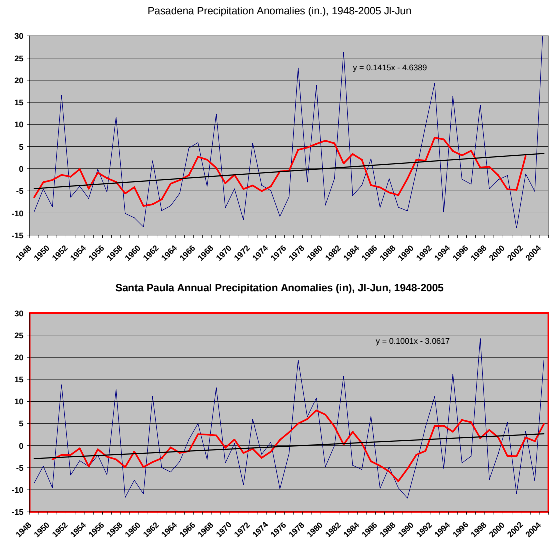

Fig 7. Pasadena and Santa Paula annual precipitation anomalies and 5-yr running mean, 1948-2005.

5. CONCLUSIONS

Upwelling trends from 1946 to 2005 were generally increasing for southern California, while slightly decreasing at 30N. These trends are consistent both in the annual and seasonal record. Meridional wind anomalies are increasingly southerly (positive) during the same period. However, these trends might more accurately reflect phase changes of the PDO from negative (cool phase) to positive (warm phase) occurring at about 1976-77. Upwelling index values were generally higher prior to the 1976-77 phase shift, decreased afterwards until 1997, then increased since then. Meridional winds also shifted to more southerly until 1997-98 then to more northerly than average. These winds in turn correspond to the changing strength of the N. Pacific High and its climatic indicator, the NOI.

Increased upwelling is related to meridional winds and large-scale Pacific air-sea interactions such as the PDO and ENSO. But what about the influence of global warming? While trends in SSTs, MSLs and meridional winds follow the gradual warming taking place for the last few decades, they are also explained in terms of large-scale switches in phases of the PDO. Weak upwellings and red tides occur due to the shorter term variability in Pacific air-sea patterns, with more southerly air flow occurring, especially during weak El Niño periods. The real test of whether global warming influences upwelling in southern California would be if greater stratification due to warming becomes dominate in spite of the apparent switch to a cooler phase of the PDO as speculated by Di Lorenzo et al. (2005). Such results could be shown within the coming decade. Our findings show the following:

1. PDO are reflected in upwelling, meridional winds, SSTs, MSLs and coastal temperatures.
2. ENSO events also are reflected in shorter-termed rises/falls in the parameters above.
3. Impacts of global warming on upwelling may just be starting, but will require at least another decade of measurements to determine whether it will have long-term effects.
4. Coastal climate follows both patterns along the immediate coast and large-scale air-sea interactions, such as the PDO.

Acknowledgements

The authors wish to thank JPL for continued support.

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