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# Cool PDO phase leads to recent rebound in coastal southern California fog

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***Abstract***

*The relationship between coastal fog in southern California and the Pacific Decadal Oscillation (PDO) is investigated during the last decade. Fog occurrence was examined at two locations in southern California: San Diego and Los Angeles international airports. Both locations are located near the Pacific coast with strong marine influences. The period looked at was 2001 through 2012. The cool season (October-March) and warm season (April-September) were examined separately because of the different types of fog that prevail in each season. Previous studies have shown a relation between fog and the Pacific Decadal Oscillation (PDO). However, a switch in polarity in the PDO in the mid-1970s (from a cool to a warm phase) coupled with a sharp decrease in particulate concentrations calls into question the strong relationship shown. Further studies suggest that the decrease in dense fog seen from the 1960s through the 1990s was largely due to increasing urban heat island effects coupled with a decrease in atmospheric particulate matter. Since 1998, the PDO again changed polarity and fog frequencies began to rise. However, urban heat island and particulate effects were relatively constant making it easier to isolate any effects of the PDO on fog occurrence. Previous studies examined the occurrence of dense fog (visibility less than 400 meters), but because of the decrease in fog in this category, 800 meters was chosen this time. That also corresponds to the 0.5 mile visibility which triggers special reports at the California airports when visibility moves through this threshold. Although there was no strong relationship between fog and PDO in the most recent period, Pacific Ocean oscillations were found to show significant relationships with fog frequencies historically. Upwelling indices show a significant relationship with fog frequencies when examined by the phase of the PDO. Even stronger relationships are found when selecting La Niña and El Niño events.*

**Zusammenfassung**

Der Zusammenhang zwischen Küstennebel in Südkalifornien und der pazifischen dekadalen Oszillation (PDO) während der letzten Dekade wird untersucht. Die Nebelhäufigkeiten wurden an zwei internationalen Flughäfen in Südkalifornien, in San Diego und Los Angeles, analysiert. Beide Standorte befinden sich nahe der pazifischen Küste und stehen unter ausgeprägt maritimem Einfluss. Die Zeitperiode der Untersuchung erstreckt sich von 2001 bis 2012. Die kühle Jahreszeit (Oktober bis März) und die warme Jahreszeit (April bis September) wurden getrennt ausgewertet, da charakteristisch unterschiedliche Nebeltypen während dieser zwei Jahreszeiten vorherrschen. Frühere Untersuchungen haben gezeigt, dass eine Beziehung zwischen Nebelhäufigkeit und PDO existiert. Allerdings hat ein Wechsel in der Polarität der PDO Mitte der 1970er Jahre (von einer Kalt- zu einer Warmphase) in Verbindung mit einer ausgeprägten Verminderung der (Fein-)Staubbelastung diese Beziehung

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in Frage gestellt. Weitere Untersuchungen kamen zum Schluss, dass die Abnahme der Häufigkeit von dichtem Nebel von den 1960er zu den 1990er Jahre zu einem großen Teil durch die Verstärkung des urbanen Wärmeinseleffekts und der gleichzeitigen Abnahme der Feinstaubbelastung erklärt werden kann. Seit 1998 hat die PDO wiederum einen Wechsel der Polarität erfahren und die Nebelhäufigkeiten haben wieder zugenommen. Allerdings sind sowohl der urbane Wärmeinseleffekt wie auch die Feinstaubbelastung seither relativ konstant geblieben, was es erleichtert, aus den Daten den tatsächlichen Effekt der PDO auf die Nebelhäufigkeit zu isolieren. Frühere Untersuchungen haben sich auf die Häufigkeit von dichtem Nebel mit einer horizontalen Sichtweite bis 400 m konzentriert. Wegen der geschilderten Abnahme der Häufigkeit dichten Nebels wurde in dieser Studie Nebel mit einer horizontalen Sichtweite bis 800 m genauer untersucht. Diese Abgrenzung entspricht sehr gut dem Schwellwert von 0,5 Meilen Sichtweite, der auf Flughäfen in Kalifornien zu speziellen Meldungen führt, sobald er unterschritten wird. In längerfristigen Zeitreihen wurden signifikante Zusammenhänge zwischen Nebelhäufigkeit und PDO gefunden, die sich jedoch nicht in gleicher Stärke in der jüngsten Dekade finden lassen. Hingegen lässt sich ein Zusammenhang mit Indices für den Kaltwasseraufstoß entlang der Pazifikküste und der Nebelhäufigkeit finden, wenn die Daten nach PDO-Phase getrennt analysiert werden. Noch stärkere Zusammenhänge lassen sich finden, wenn La-Niña- und El-Niño-Ereignisse gesondert betrachtet werden.

**Keywords** Coastal fog; fog climatology; Pacific Decadal Oscillation; upwelling; El Niño

## 1. Introduction

Fog is an important part of the coastal California climate. It moderates the temperature in coastal areas and is important in maintaining coastal ecosystems (*O'Brien* et al. 2013). Several researchers have examined the role of fog in these coastal ecosystems. In all coastal areas of California, summer rain is rare. *Azevedo* and *Morgan* (1974) measured the amount of fog water collected beneath the forest crown during the summer fog season from 19 June through 2 September. Although there was considerable variability, they found a maximum of 42.5 cm of fogwater collected below the forest crown. Their area of study was the far northern part of the state along the Eel River at altitudes of 670 m and 475 m. Farther down the coast in coastal Marin and Sonoma counties, just north of San Francisco Bay, *Corbin* et al. (2005) examined the role of fog in maintaining California coastal prairie grasses during the dry summer season. They estimated that 28 % to 66 % of the water taken up by plant roots during the summer months come from fog and the importance of fog decreased as distance from the shore increased. Further south in the California Channel Islands, *Fischer* and *Still* (2007) looked at fogwater deposition. They installed 21 fog collectors that mimicked vegetation collection. They collected fogwater from 9 May to 16 October, 2005 and from 17 March to 16 October 2004. They collected a total of about 16 liters maximum in 2005 and six liters in 2004. The studies all suggest that fogwater is important to maintaining the coastal ecosystems that range from prairie grasses to redwood forests.

### 1.1 Earlier studies

The mechanisms for U.S. west coast fog were well summarized by *Leipper* (1994). The low-level inversion, the role of the coastal range in adiabatic heating that enhances the inversion and air-sea temperature difference are some of the factors. Examining trends in fog since the mid-20th century, other factors have been identified. Through the first few years of the 21st century, we have seen reports on the decreasing fog along the California coast. Several reasons were pointed out for this occurrence including decrease in particulate matter, a switch in polarity of the Pacific Decadal Oscillation (PDO) around the mid-1970s, and climate change (*Witiw* and *LaDochy* 2008; *Johnstone* and *Dawson* 2010; *LaDochy* and *Witiw* 2012). The PDO was described by *Mantua* et al. (1997) as an oscillation of sea surface temperatures (SST) in the North Pacific, with a warm and a cool phase, each lasting about two decades or more. In the warm (positive) phase, warmer than normal SST occur in the eastern North Pacific, while cooler than normal SST occur in the western North Pacific. In the cool (negative) phase, the reverse occurs. However, since the beginning of the 21st century, the PDO has once again switched polarity (from warm to a cool phase), particulate matter concentrations have stabilized, and the amount of fog present along the coast has also appeared to have stabilized or increased somewhat. There have been several studies on the negative influence of particulate matter on visibility in fog and on the structure of stratiform clouds. *Noonkester* (1979) showed that the presence of small particles resulted in decreased visibility. As an example, he discussed Santa Ana fogs that form over the ocean during offshore (Santa Ana wind) flow from the Los Angeles metropolitan area. *Twohy* et al. (1995), while studying stratiform clouds, found that during offshore flow conditions droplet size increased, the number of drops decreased and satellite reflectance decreased with increasing distance from the California coast. More recently, *Thiery* et al. (2009) on the Paris field campaign and *Zhao* et al. (2011) while examining fog and visibility in the Beijing, Tianjin, and Hebei area examined the influence of particulates on visibility.

Atmosphere-ocean interactions have often been implicated in climate variability, including the PDO. Recently, *Chylek* et al. (2014) found an association of both precipitation and temperature in the southwestern United States of America with the indices of both the PDO and the Atlantic multi-decadal oscillation (AMO). Other studies related both PDO and ENSO (El Niño-Southern Oscillation) climate indices with western U.S. precipitation (*Cayan* et al. 1998; *Goodrich* 2007; *DeFlorio* et al. 2013). *Johnstone* and *Dawson* (2010) also show that fog frequencies in northern California correlate strongly with the PDO, with higher summer fogs during the PDO cool phase, when surface wind conditions favor coastal upwelling. Computer simulations also show the interannual variability in northern California fog associated with the PDO (*O'Brien* et al. 2013). Declining low stratus clouds along the west coast from the 1950s to 2012 from Alaska to southern California were also related to the PDO and sea surface temperatures along the eastern North Pacific (*Schwartz* et al. 2014).

Previous studies have shown a relation between fog in urban southern California and the PDO (*Witiw* and *LaDochy* 2008). However, a switch in polarity in the PDO in the mid-1970s (from a cool to a warm phase) coupled with a sharp decrease in particulate matter concentrations calls into question the strong relationship shown. Further studies suggest that the decrease in dense fog seen from the 1960s through the 1990s was largely due to increasing urban heat island effects coupled with a decrease in atmospheric particulate matter (*LaDochy* and *Witiw* 2012). Since 1999, the negative (cool-phase) PDO has been more dominant than the positive (warm-phase) PDO. Additionally, the negative PDO was often in phase with La Niña events during this period (*Blunden* and *Arndt* 2013). In 1995, *Filonczuk* et al. described how ocean-exposed stations generally favored warm season fog, while stations located inland experienced cool season maxima.

Most recently, *Torregrosa* et al. (2014) addressed the 33 per cent decrease in coastal California fog during the 20th century and the possible reasons for this including long-term cycling of ocean temperatures including that represented by the PDO. They emphasized the important role coastal fog had both for ecology and society. They also discussed the wide range of aerosols that serve as condensation nuclei during fog formation and their fluctuations. *Williams* et al. (2015) calculated a 63 % reduction in Los Angeles (LA) subregional fog since 1948, which they believe is caused by increased urbanization and subsequent rising nighttime and early morning temperatures. *Gonçalves* et al. (2008) reported a decline in fog in the São Paulo metropolitan area from 1933 through 2005. They indicated that an increase in South Atlantic sea surface temperatures coupled with increasing urbanization affected the occurrence of fog. *Williams* et al. (2015) reported urbanization to be the cause of decreased fog in coastal southern California. They saw an increase in nighttime minimum temperatures, an increase in dew point depression, and a decrease in fog related to urbanization.

### 1.2 Sea fog

Nearly all the fog that forms on the Pacific Ocean near the California coast is a form of advection fog known as sea fog. The type of sea fog that forms along the west coasts of North America, South America (*Larrain* et al. 2002; *Cereceda* et al. 2008) and southwest Africa (*Cermak* 2012) is associated with the upwelling of cold water along these coasts and has been described by various researchers. Additionally, several studies have been made of sea fog not associated with upwelling that occurs in the Yellow Sea (*Fu* et al. 2006; *Fu* et al. 2010). This study investigates the role of the Pacific, especially the PDO, in explaining the recent increases in fog along the southern California coast. Two mechanisms have been explored in explaining this phenomenon. Early studies indicated that moderately cool or warm summer air moving over a cold ocean is further cooled, with moisture added, leading to the formation of sea fog. Later studies, however, implicate offshore flow with adiabatically warming air depressing the surface marine layer, leaving just a shallow, cold marine layer in which the fog forms (*Koračin* et al. 2014).

### 1.3 Radiation fog

In the cool season, the most common type of fog occurring in California coastal locations is radiation fog.

*Baars* et al. (2002) found that this type of fog typically occurred with marine air over the area following a shift in wind direction to offshore. They hypothesized that the wind shift allowed for a cooling of the air and probably introduced particulates. Radiational cooling at night of stratus and fog layers is an important mechanism for cloud thickening (*Noonkester* 1979). Sufficiently large cloud-top radiational cooling could lower the stratus base to the ground forming fog (*Lundquist* and *Bourcy* 2000). In his overview of fog research, *Eugster* (2008) describes different types of fog including advection fog which frequently affects land areas bordering the ocean and radiation fog which typically forms at night where air temperatures have fallen.

## 2. Data and methodology

Fog occurrences were examined for recent trends at two locations in southern California: San Diego (SAN) and Los Angeles (LAX) international airports. Both locations are located near the Pacific coast with strong marine influences. A third station, Long Beach International (LGB) Airport was looked at, but rejected because of periods of missing data and inconsistent visibility data in recent years. However, LGB data through 2009 were reliable enough to be used in earlier long-term trend studies. The period examined was 2001 through 2012. The cool season (October-March) was examined separately from the warm season as different types of fog prevail in the two different temperature regimes. Advection fog which does not normally penetrate very far inland prevails in the warm season while radiation fog is prevalent in the cooler months and is found farther inland (*Baars* et al. 2002). We determined that fog was present if visibility was at or below ½ statue mile (SM) (nominally 800 m). With one statute mile equal to 1609 meters, a report of ½ SM (800 m) or less would include all visibilities less than 1,000 meters when the rounding used by the Automated Surface Observing System (ASOS) is accounted for. This is very close to the WMO visibility requirement for fog (visibility < 1,000 m).

To eliminate some of the urban effects and test Pacific influences, we also looked at fog data at Pt. Mugu, Naval Air Systems Command, approximately 80 km WNW of downtown Los Angeles, provided by *Charles Fisk* (2013). Although some urban influences still remain, Pt. Mugu's marine airmass does not have a recognizable heat island or high particulate matter load. Hourly data were continuous from 1946 to 2011. There were substantial data gaps in 1946 and 1972 and some incomplete data during the period 1993-2006. However, data were adequate to show the trend during the 1946-2011 period. (Data are available from http://www.ncdc.noaa.gov/.)

### 2.1 ASOS

It is somewhat difficult to compare fog trends prior to the implementation of Automated Surface Observing Systems (ASOS) with observations after their implementation. The National Weather Service ASOS guide admits that "visibility remains one of the most difficult elements to automate" (NOAA 1998). Humans used visibility markers and were subject to physiological constraints. If an observer saw the 800 m marker but could not see the 1200 m marker, visibility was reported as 800 m. ASOS on the other hand rounds visibilities to the closest standard increment. With human observation, visibility just below 1200 m would be reported as 800 m, under ASOS, this visibility would be rounded to the standard increment of ¾ SM (1200 m). ASOS uses standard increments in the lower visibility ranges of < 400 m (probably the only increment where an ASOS observation would usually agree with that of a human), 400 m, 800 m, 1200 m and 1600 m are the standard ASOS increments. If an observation falls halfway between two standard increments, it is rounded down (NOAA 1998).

Both LAX and SAN converted their observations to ASOS in the late 1990s, so there was consistency in the type of observation (NCDC 2014). SAN converted in 1996 and LAX in 1997 (U.S. D.C. 2002). Previous studies examined the occurrence of dense fog (visibility less than 400 meters or ¼ SM), but because of the decrease in fog in this category, 800 meters was chosen this time. That closely corresponds to the 0.5 statute mile visibility which triggers special reports at the California airports when visibility moves through this threshold.

### 2.2 Pacific Decadal Oscillation, Southern Oscillation, sea surface temperatures

The current study concentrates on the period of 2001 through 2012. During this time period, the PDO again changed polarity favoring the cool phase. PDO monthly values were derived at the University of Washington, *Mantua's* website (PDO 2013). However, urban heat island and particulate effects were relatively con-

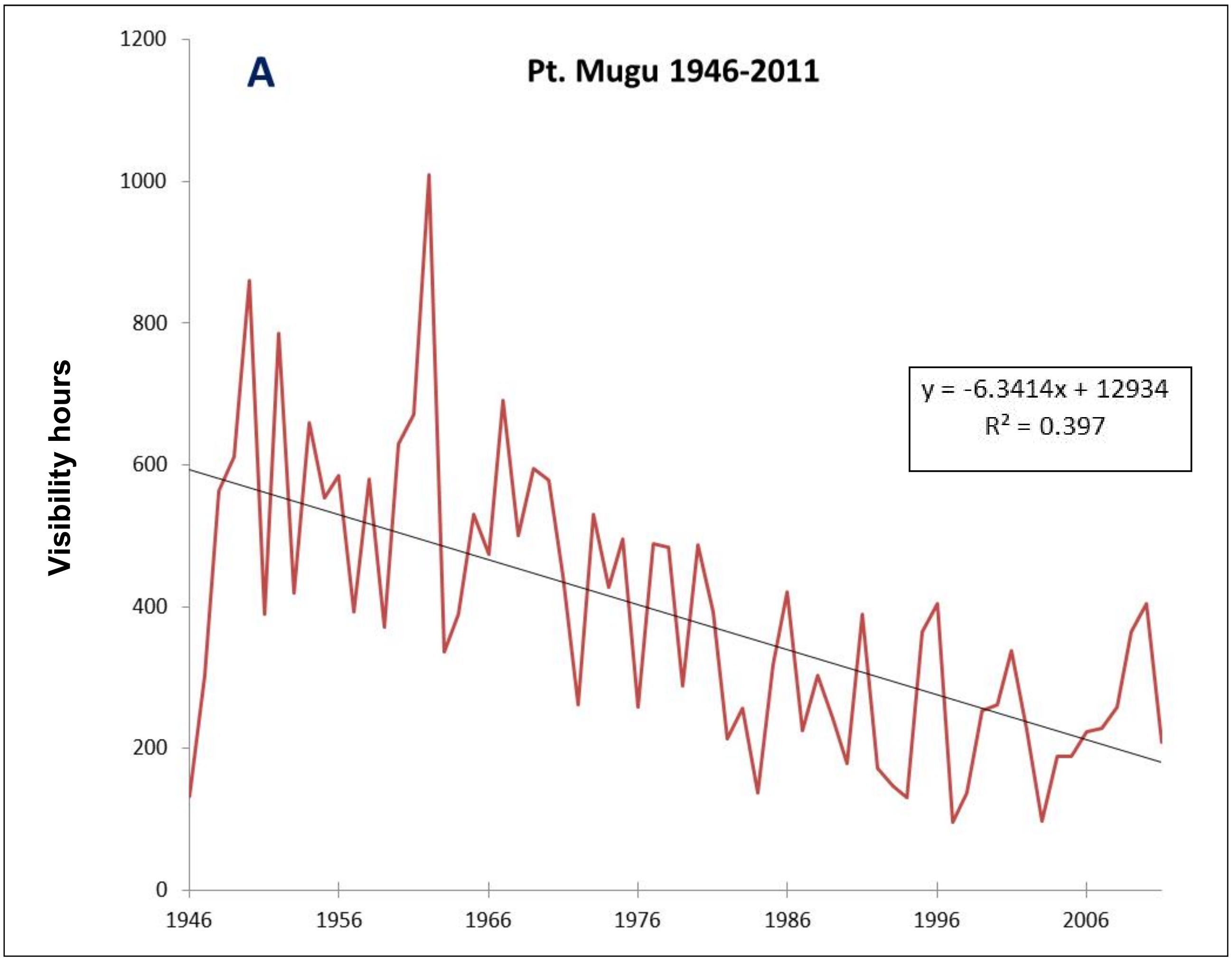

*Fig. 1A* *Annual number of hours with visibility 800 m or less at Pt. Mugu 1946-2011*

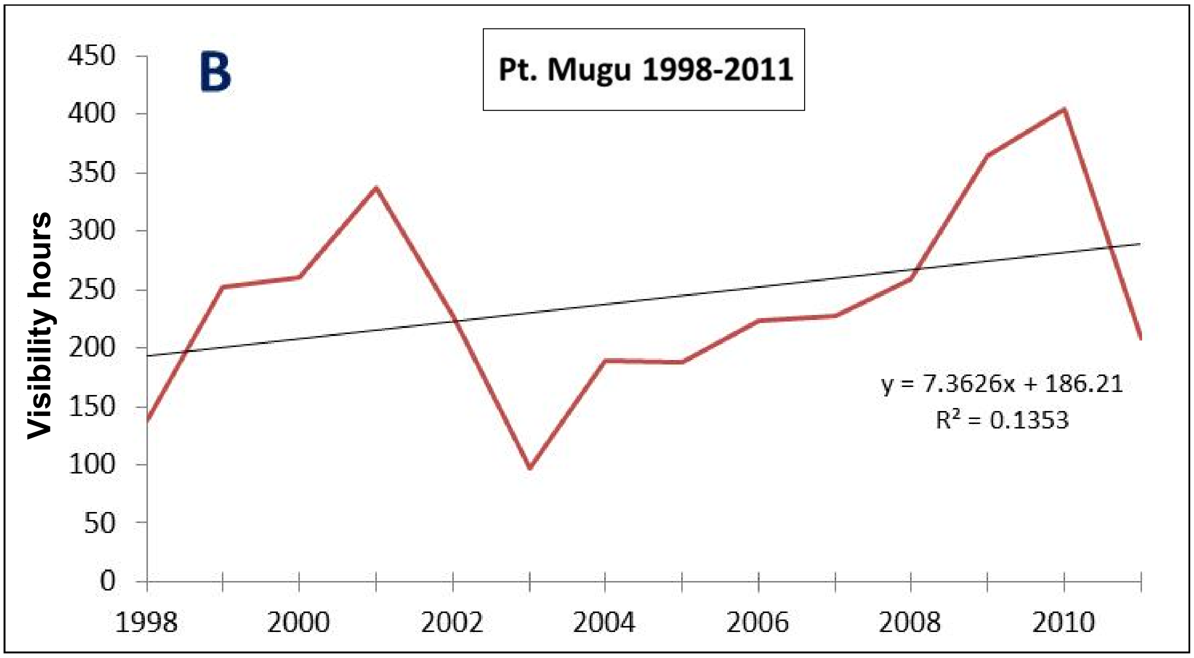

*Fig. 1B* *Annual number of hours with visibility 800 m or less at Pt. Mugu 1998-2011* stant making it easier to isolate any effects of the PDO on fog occurrence during this time period. Also, both LAX and SAN converted their observations to ASOS in the late 1990s, so there was consistency in the type of observation (NCDC 2014). The period examined appeared nearly ideal with a reasonable split between the number of months when the PDO was positive (31) and months when it was negative (41). Fog frequencies were also tested against Southern Oscillation Index (SOI) monthly values and Niño 3.4 sea surface temperature monthly values. Monthly data were available from the Climate Prediction Center, National Center for Environment Program, (NCEP 2013). The SOI measures tropical Pacific pressure differences between Darwin, Australia and Tahiti, which is used as a measure of the strength of El Niño and La Niña events. Sea surface temperatures in the equatorial Nino 3.4 sector are also used in monitoring El Niño and La Niña events.

### 2.3 Upwelling

Another variable not considered previously was upwelling. Since cooler sea surface temperatures were related to more fog, greater upwelling should provide better conditions for fog formation as well. The Pacific Fisheries Environmental Laboratory (PFEL), NOAA, maintains upwelling indices at 33, 36 and 39 degrees North along the California coast. PFEL calculates monthly upwelling indices based upon *Ekman's* theory of mass transport due to offshore wind stress. Wind stress is derived from mean surface atmospheric pressure fields. Upwelling indices are used to generate time series of estimated variations in coastal upwelling (PFEL 2014). We also compared upwelling indices from 1947 until 2012 with the longer fog records from LAX and LGB. Besides looking at the entire record, comparisons were made for PDO phases: the cool phase during the period 1947-1975, the warm phase from 1976 to 1998, and the most recent period tending towards a cool phase 1999-2012. The upwelling fog relationship was also tested for El Niño and La Niña years separately and again by PDO phases using annual (water year) data. Water years (which extend from 1 July to 30 June) were used rather than calendar years as it was found to correlate better to coastal climatic data (*LaDochy* et al. 2007, 2008) since most fog events occur during the cooler season. We used MEI (Multivariate ENSO Index) annual values of over 0.5 to represent El Niño years and MEI annual values of less than -0.5 to represent La Niña years. MEI has been used in several studies and shown to be a better indicator of tropical Pacific conditions than simply using sea surface temperatures or pressure differences (ESRL 2013).

## 3. Results

Pt. Mugu fog (visibility less or equal to 800 m) shows the same sharp decline in annual averages as with LAX and LGB for the 1946-2011 period (*Fig. 1A*). However, the trend since the switch in PDO phase at 1998 shows an increasing trend (*Fig. 1B*). This corroborates similar results for urban LAX and SAN (*Figs. 2-7*) while pointing away from urban factors and towards Pacific variability. However, Pt. Mugu data should be used with caution, because of a large percentage of missing data.

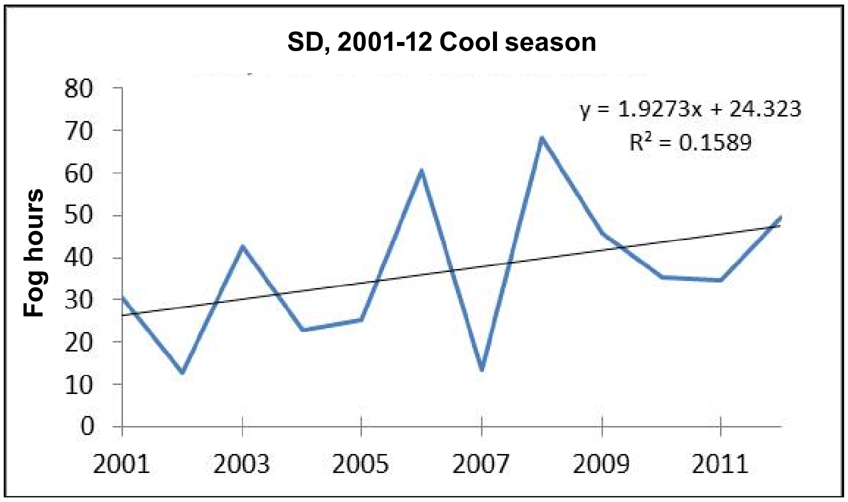

*Fig. 2 Cool season fog trend at San Diego visibility ≤ 800 m*

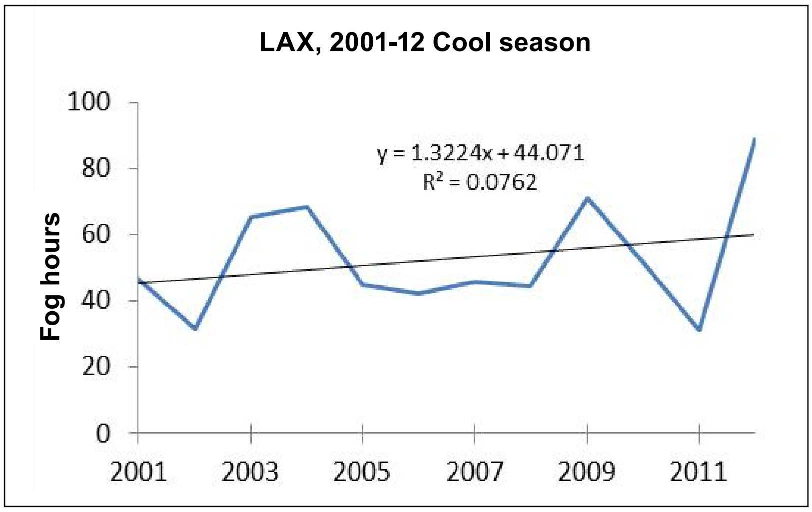

*Fig. 3* *Cool season fog trend at Los Angeles Airport visibility ≤ 800m*

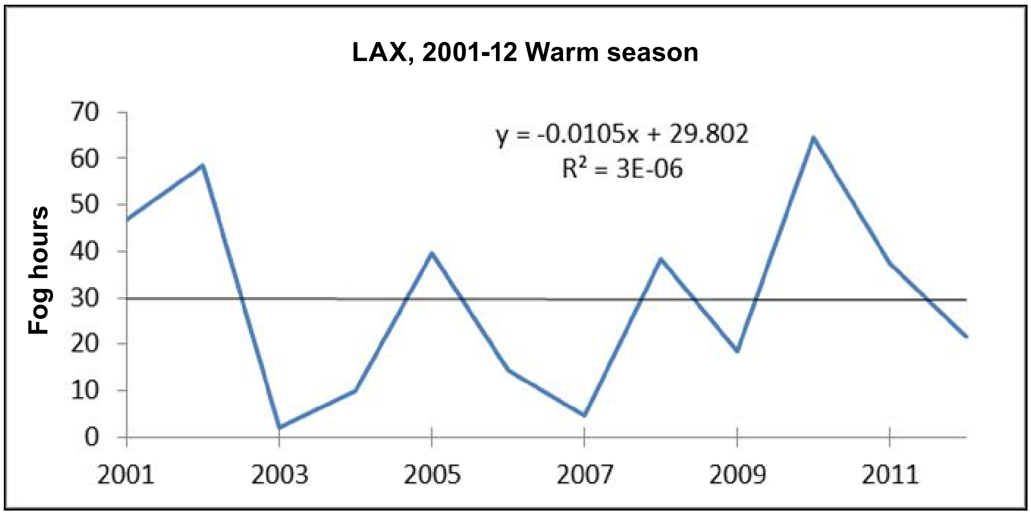

*Fig. 4* *Warm season fog trend at Los Angeles visibility ≤ 800 m*

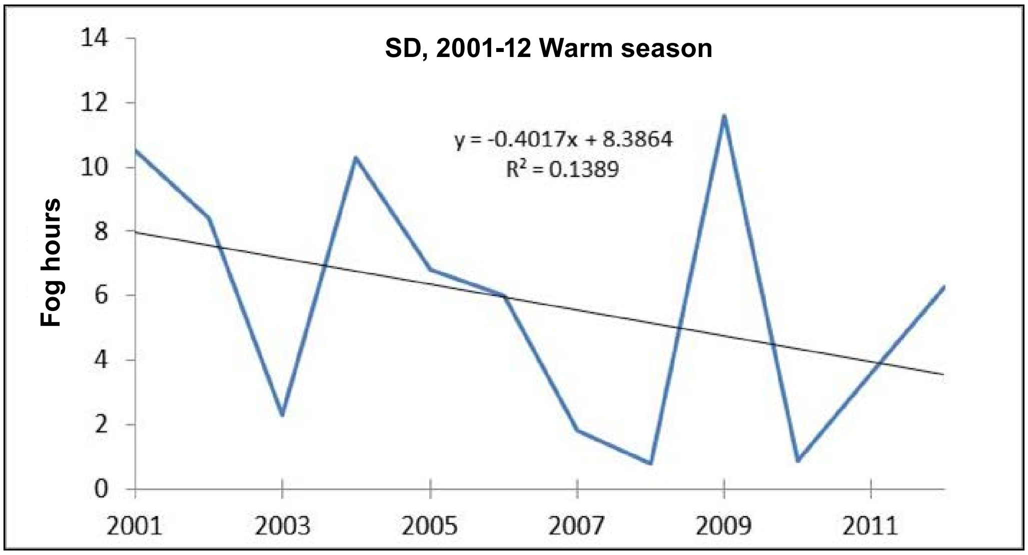

*Fig. 5* *Warm season fog trend at San Diego visibility ≤ 800m*

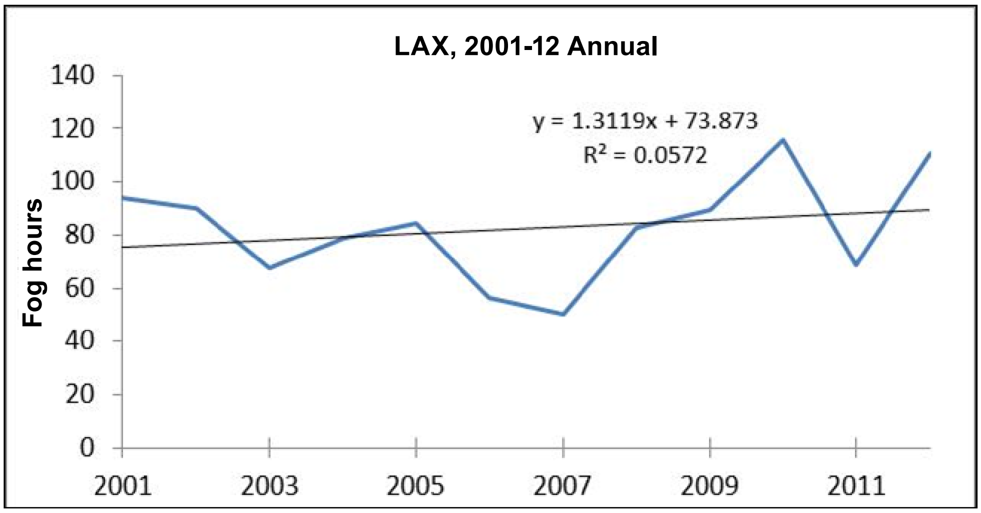

*Fig. 6* *Annual fog trend at Los Angeles Airport visibility ≤ 800 m. The trend is not statistically significant (p=0.45).*

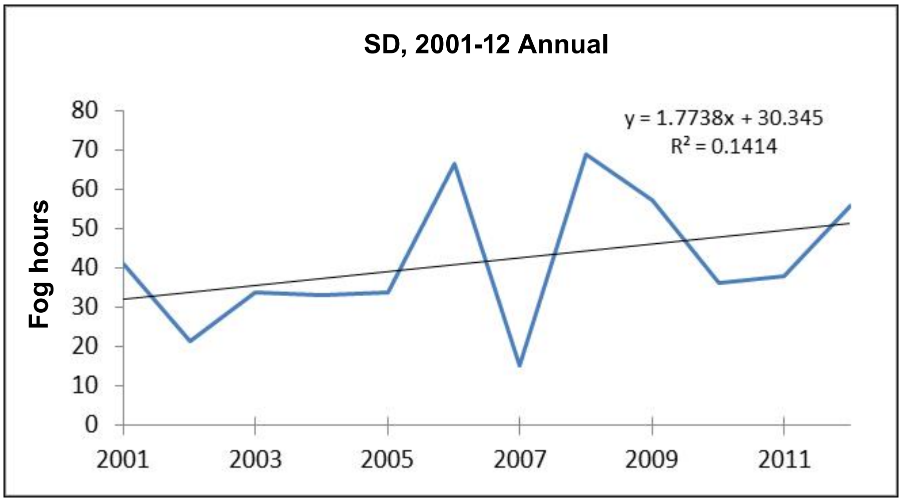

*Fig. 7* *Annual fog trend at San Diego Airport visibility ≤ 800m. The trend is not statistically significant (p=0.22).*

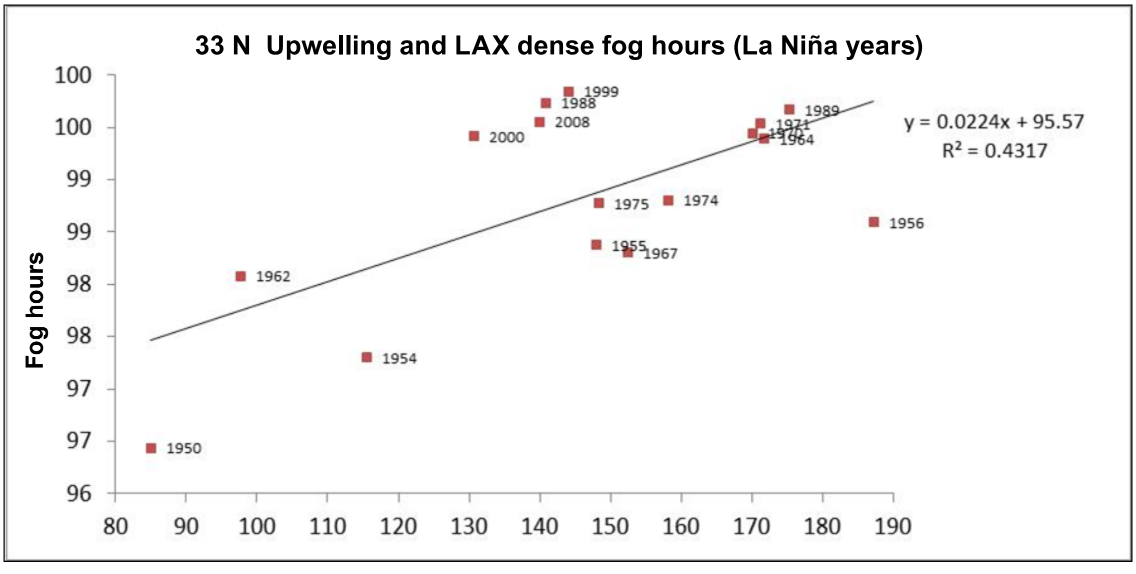

*Fig. 8* *Upwelling indices at 33 N (horizontal axis) vs. hours of dense fog (400 m or less) at LAX (vertical axis) for La Niña water years (MEI < 0.5)*

For the LAX and SAN airport data, regression analyses were completed and hours of fog were tested against the Pacific Decadal Oscillation Index, the Southern Oscillation Index, and the Niño 3.4 Index. A weak, statistically marginally relation was found at San Diego between fog hours and the PDO ($p=0.059$). Additionally, a weak, upward trend can be detected in the number of hours of fog with visibility less than or equal to 0.5 statute miles (800 m) at either location. Los Angeles averaged 49.7 hours per year with a peak of 71.0 hours in 2009 and a minimum of 31.2 hours in 2011 (although 2002 recorded just 31.5 hours). San Diego averaged 36.2 hours with a peak of 68.3 hours in 2008 and a minimum of 12.9 hours in 2002. Total suspended particulates (TSP) in downtown Los Angeles dropped by more than 50 % from the 1960s until the end of the 20th century. TSP are collected using a high-volume air sampler that collects all sizes of particulates. These were previously shown to be an important factor in the formation of dense fog. They continue an unsteady drop through the 21st century ranging from 53 $\mu g/m^3$ in 2010 and 2011 to 78 $\mu g/m^3$ in 2002 (SCAQMD 2012). Although, at these relatively low values and small differences, any effect is not evident in the data.

In *Table 1*, annual cool season dense fog hours varied considerably for both LAX and SAN, although showing a general overall increase and with more hours than during warm season months. The two stations also varied in interannual variability. As can be seen from *Table 2*, warm season fog differences between SAN and LAX were quite large. Warm season fog, being mainly of the advective sea fog type is largely dependent on differences between sea surface temperatures and air temperatures, with differences less than 3 °C being important (*Fu* et al. 2010). The modeling done by *O'Brien* et al. (2013) suggests differences in hours of advective fog along the coast, not necessarily dependent on latitude, but with fog frequency peaking near the central coast. This can be noted by the lack of summer fogs further south in San Diego, where most of the fog hours occur in winter (*Tables 1-3*).

Upwelling indices were also correlated with dense fog records. For 1947-2009, upwelling at 33°N significantly correlated with LAX dense fog, while showing a positive relationship with LGB. When further divided into PDO cool and warm phases, the correlations were much stronger for the 1947-1975 cool phase, weakly negatively correlated for the 1976-1998 warm phase period, and weakly positive for the 1999-2009 period for LAX, with very weak correlations with LGB (*Table 4*).

Since the El Niño-Southern Oscillation is also known to influence the southern California climate, we also tested the upwelling-fog relationships for El Niño and La Niña years separately. Although the sample sizes become smaller, the relationships became stronger. Using MEI (Multivariate ENSO Index) annual values of over 0.5 to represent 19 El Niño years, *Table 5* shows a strong correlation between 33°N upwelling and LAX dense fog of 0.697 for the earlier cool phase, a negative 0.397 for the warm phase. There was only one year for the period after 1999, so that no correlation analysis was done for

*Table 1 Cool season annual hours of fog with visibility ≤ 0.5 miles*

| Year | Los Angeles | San Diego |
|---|---|---|
| 2001 | 46.7 | 30.5 |
| 2002 | 31.5 | 12.9 |
| 2003 | 65.2 | 42.7 |
| 2004 | 68.6 | 22.9 |
| 2005 | 45.1 | 25.2 |
| 2006 | 42.2 | 60.8 |
| 2007 | 45.7 | 13.4 |
| 2008 | 44.5 | 68.3 |
| 2009 | 71.0 | 45.9 |
| 2010 | 51.5 | 35.4 |
| 2011 | 31.2 | 34.6 |
| 2012 | 88.8 | 49.6 |
| Average | 52.7 | 36.9 |

*Table 2 Warm season annual hours of fog with visibility ≤ 0.5 miles*

| Year | Los Angeles | San Diego |
|---|---|---|
| 2001 | 47.0 | 10.5 |
| 2002 | 58.6 | 8.4 |
| 2003 | 2.2 | 2.3 |
| 2004 | 10.0 | 10.3 |
| 2005 | 39.5 | 6.8 |
| 2006 | 14.4 | 6.0 |
| 2007 | 4.5 | 1.8 |
| 2008 | 38.4 | 0.8 |
| 2009 | 18.6 | 11.6 |
| 2010 | 64.5 | 0.9 |
| 2011 | 37.3 | 3.6 |
| 2012 | 21.8 | 6.3 |
| Average | 29.7 | 5.8 |

*Table 3 Annual hours of fog with visibility ≤ 0.5 miles*

| Year | Los Angeles | San Diego |
|---|---|---|
| 2001 | 93.7 | 41.0 |
| 2002 | 90.1 | 21.3 |
| 2003 | 67.4 | 34.0 |
| 2004 | 78.6 | 33.2 |
| 2005 | 84.6 | 34.0 |
| 2006 | 56.6 | 66.8 |
| 2007 | 50.2 | 15.2 |
| 2008 | 82.9 | 69.1 |
| 2009 | 89.6 | 57.5 |
| 2010 | 116.0 | 36.3 |
| 2011 | 68.5 | 38.2 |
| 2012 | 110.6 | 55.9 |
| Average | 82.4 | 41.2 |

the most recent period. For La Niña years, where the MEI is less than 0.5, 33°N upwelling correlated with both LAX and LGB strongly, 0.847 and 0.512, respectively (*Table 6*, *Fig. 8*) for the early cool PDO phase. The sample size was too small to relate upwelling and fog for the warm and recent phases of PDO.

## 4. Discussion

In previous studies of dense fog, urban influences of rising temperatures and decreasing particulates explained the rapid decreases from the 1940s. Using 800 m or less visibility for fog, the downward trends were also seen at LAX and LGB airports. Pt. Mugu also shows this trend from 1946 to 2011 at a more remote coastal location. However, since the

*Table 4 Correlations between upwelling indices and dense fog hours for 1948_2009 water years (top) and for PDO phases (bottom). Bold values are significant at the 95 % confidence level.*

| Upwelling | Years | 30N | 33N | 36N | 39N |
|---|---|---|---|---|---|
| **LAX < 400 m** | **1948-2009** | 0.060 | **0.291** | 0.286 | **0.412** |
| **LGB < 400 m** | **1948-2009** | 0.042 | 0.235 | 0.245 | **0.444** |

| PDO Phase | Years | Correlation |
|---|---|---|
| **LAX < 400 m** | **1948-1975** | **0.642** |
| **LGB < 400 m** | **1948-1975** | **0.518** |
| **LAX < 400 m** | **1976-1998** | -0.115 |
| **LGB < 400 m** | **1976-1998** | -0.144 |
| **LAX < 400 m** | **1999-2009** | 0.117 |
| **LGB < 400 m** | **1999-2009** | -0.086 |

*Table 5 Correlations between upwelling indices and dense fog hours for 19 El Niño water years (MEI > 0.5), and by PDO phases, 1948-2009. Only one year occurred in the last phase 1999-2009 and is not shown. Bold values are significant at the 95 % confidence level.*

| N=19 El Niño years | LAX < 400 m | LGB < 400 m |
|---|---|---|
| **30$^{o}$N** | -0.196 | -0.368 |
| **33$^{o}$N** | -0.096 | **-0.547** |
| **36$^{o}$N** | 0.201 | -0.094 |
| **39$^{o}$N** | 0.261 | -0.722 |
| **PDO Phase** | **1948-1975** | **1976-1998** |
| **LAX < 400 m and 33$^{o}$N** | 0.697 | 0.397 |
| **LGB < 400 m and 33$^{o}$N** | -0.484 | -0.392 |

*Table 6 Correlations between upwelling indices and dense fog hours for 16 La Niña water years (MEI < 0.5) and by PDO phases, 1948-2009. There were too few years in the last two phases (1976-2009). Bold values are significant at the 95% confidence level.*

| **N=16 La Niña years** | **LAX < 400 m** | **LGB < 400 m** |
|---|---|---|
| **30ºN** | 0.289 | 0.123 |
| **33ºN** | **0.657** | 0.381 |
| **36ºN** | 0.565 | 0.353 |
| **39ºN** | 0.580 | 0.394 |
| **PDO Phase** | **1948-1975** | **1976-2009** |
| **LAX < 400 m and 33ºN** | **0.847** | Too few years |
| **LGB < 400 m and 33ºN** | **0.512** | Too few years |

end of the warm PDO phase of 1997, Pt. Mugu's fog has increased, although reaching only a third of late 1940s values. While earlier phases of PDO do not show any slowing of the fog decline, since the last warm phase, fog levels are either stable or, as in the case of Pt. Mugu, increasing.

The importance of the PDO to fog formation can be seen when considering offshore upwelling indices. During the 1948-1975 PDO cool phase, increasing upwelling was associated with increasing fog frequencies at the southern California stations. Even stronger relationships were found when comparing ENSO years, particularly during La Niña years during a PDO cool phase. Other studies on climate variability along the west coast also show that PDO phases enhance El Niño/La Niña impacts, such as on precipitation (*Brown* and *Comrie* 2004).

Looking at PDO influences on fog at LAX and SAN since 1999 and the visibility threshold selected, there was no strong relationship seen between the number of hours of fog and various atmospheric-oceanic indices. There also appeared to be very little relation between fog hours at San Diego and those at Los Angeles. However, this period represents a slow development to a possible long cool phase of the PDO. The first years, 1999-2002, were mostly cool (negative) PDO months, while 2003-2007 were mostly warm (positive) months. Since then, cool months have dominated. With the last PDO cycle (approximately 1947-1997) running about 50 years, we may be seeing only the beginning of a multi-decadal cool phase. Upwelling trends are also increasing in the most recent years. Cool PDO years with greater upwelling along the west coast, especially in southern California, may be seeing a resurgence in fog.

## 5. Conclusions

The authors tested the relationship between the PDO and the number of fog hours in coastal southern California using monthly data for the 1999 to 2012 period. Monthly data may be too variable and the period chosen too short to establish a strong relationship. Other studies conducted on longer durations and using annual values show the PDO to be a major influence on west coast fog, as well as west coast climate. While the PDO is measured using sea surface temperature patterns, local coastal upwelling adds to the relationship in fog formation. Here, the combination of upwelling and PDO, as well as ENSO, helps explain the influence of the Pacific in the resurgence of coastal fog since 1999. Since 1998, the PDO has been mostly in a cool phase of its multidecadal oscillation. As the cool phase of the PDO may continue for several more years, this resurgence in coastal fog in southern California should also continue.

Further investigations are needed. For San Diego, pollution levels may still be rising and need to be included in explaining fog frequencies, along with upwelling indices at lower latitudes, such as 30° N. Sea surface temperatures along southern California do not always act in unison and are influenced by ENSO, PDO and upwelling. And finally, the role of global climate change has not been considered adequately in local fog trends.

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