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What determines the spatial pattern in summer upwelling trends on the U.S. West Coast?

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1. Summary

1. The summertime over-shelf water temperature off the U.S. West Coast has been declining in 1980-2010 at an average rate of -0.19 °C decade^{-1}.
2. The cooling trend is greater off south-central California than off Oregon and northern California.
3. North of SF, Ekman transport by trend in alongshore wind stress plays a dominant role in SST trend.
4. In Central to Southern CA, the trend in Ekman pumping associated with wind stress curls better explains the stronger and statistically more significant cooling trend.
5. Coast-wide variability and trend in SST are primarily determined by the multi-decadal variability in PDO.
6. But, they do not predict the southward intensification of the trends in SST and wind stress curl.
7. The local wind stress curl, often topographically forced, may have played a significant role in producing a regionally distinct trend pattern in upwelling.

2. Data

- NDBC Buoys: Hourly SST (0.6 m depth), wind (5 m height). 1980-2010.
- NOAA OI SST: Daily 25 km. 1981-2010.
- CaRD10: Dynamically downscaled, 1-hourly, 10 km atmospheric reanalysis over CA. 1948-2010.

3. Observed summer upwelling trends and spatial pattern in 1980-2010

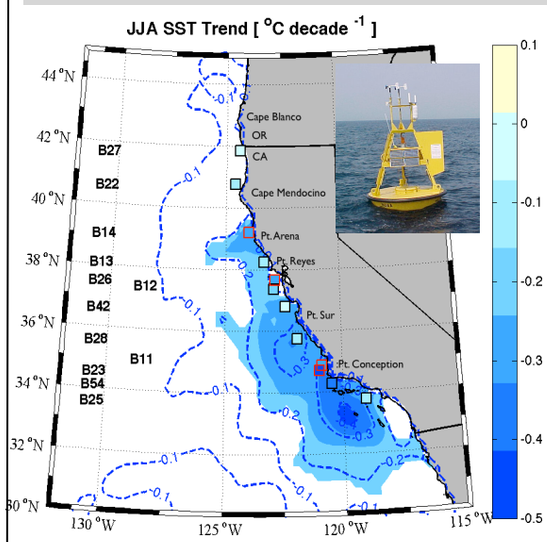

Fig. 1 JJA SST trends in NOAA SST in 1982-2010, overlaid with those from 12 NDBC buoys (squares).

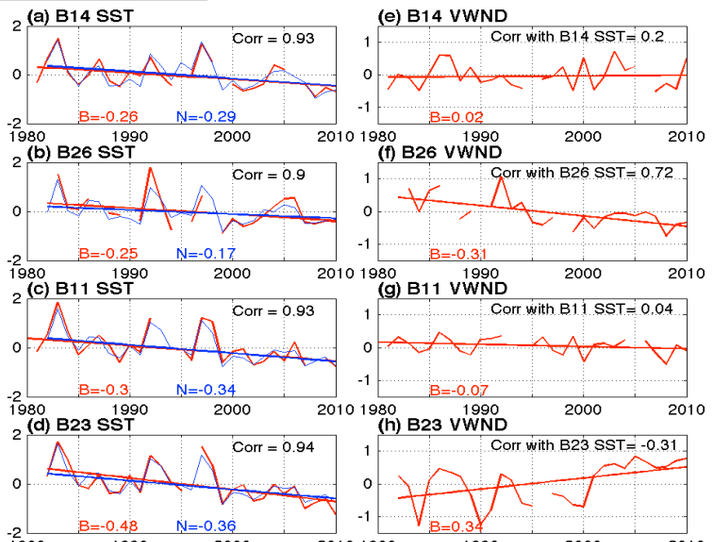

Fig. 2 (a-d) JJA SST (red, °C) from 4 buoys, overlaid with NOAA SST (blue), and (e-h) meridional wind speed (VWND)

- The summertime cooling off the entire West Coast since the 1980s (-0.19 °C decade^{-1})
  - The greater cooling trend south of central California than Oregon to northern California

What are the physical mechanisms for this multi-decadal trend, and what determines its spatial pattern?

- In the northern 6 buoys, SST and VWND have the negative trends. They are also positively correlated.
  - SST trend is primarily controlled by the trend in offshore Ekman transport.
- In the southern 6 buoys, SST and VWND have the opposite sign, and they are negligibly correlated.
  - Other mechanism(s) than Ekman transport should be at work in driving a stronger SST trend.

Can the trend in wind stress curl come into play in the observed SST trend pattern?

	NOAA SST	Buoy SST	Buoy VWND	r(SST,VWND)
All 12 buoys	-0.26	-0.19	-0.03	0.16
Northern 6 buoys	-0.19	-0.14	-0.11	0.30
Southern 6 buoys	-0.32	-0.24	+0.06	0.02

Table 1. Trends in JJA SST and VWND, and the correlation coefficients.

4. Trends in wind and wind stress curls

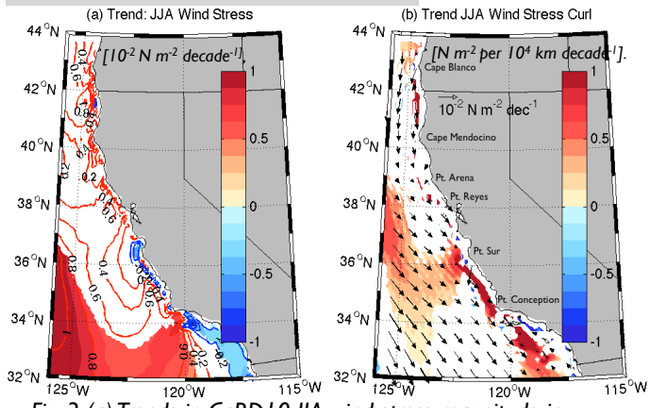

Fig. 3 (a) Trends in CaRD10 JJA wind stress magnitude in 1980-2008. (b) As in (a) except showing trends in JJA wind stress vectors and wind stress curls

- The upwelling-favorable wind stress has been intensified in 1980-2008, but far more significantly off of southern CA.
- The prevalent southeastward trends in wind stress are conducive to a significant positive near-shore curl.

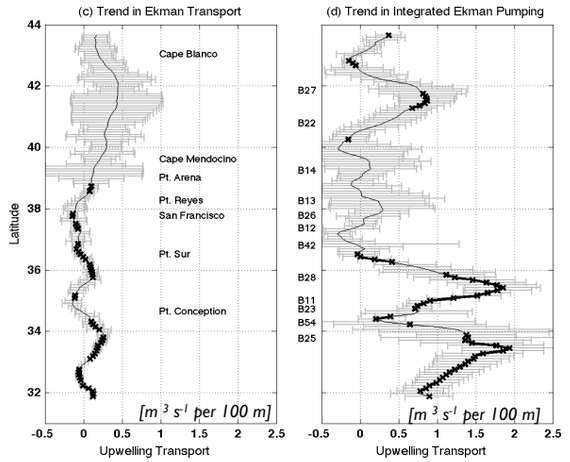

Fig. 4 Trends in JJA offshore volume transport by (a) Ekman transport and (b) Ekman pumping.

- North of Cape Mendocino, the trends for the wind driven upwelling by ASW and wind stress curl are both increasing, but mostly not significantly.
- South of SF, the greater and more significantly increasing trend is with the wind stress curl.

The spatial correspondence in the trends between wind stress curl and SST strongly implies the important role of the near-coast wind stress curl in the pattern of upwelling trend.

5. Role of large-scale modes of climate variability

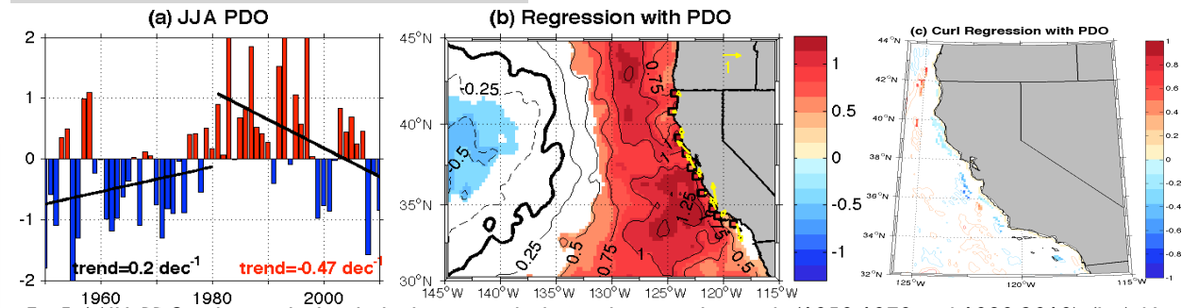

Fig 5. (a)JJA PDO index overlaid with the linear trends during the two sub-periods (1950-1979 and 1980-2010). (b-c) Maps of simultaneous regression coefficients in (b) SST and buoy wind and (c) CaRD10 wind stress curls for the period 1980-2010.

- The observed trend and variability in SST are driven primarily by the multi-decadal variability in PDO.
- In 1980-2010, PDO was in a positive phase with a negative trend.
- The West Coast SST anomalies exhibit a canonical PDO pattern.
  - The positive PDO phase is generally associated with less upwelling-favorable alongshore condition.

	PDO	
	Reg. Coeffs	Inferred Trend
All 12 buoys	+0.88	-0.42
Northern 6 buoys	+0.87	-0.41
Southern 6 buoys	+0.90	-0.42

Table 2. The regression coefficients of JJA buoy SST in each region against the PDO index Also shown are the inferred trend values obtained by multiplying the Reg. Coeffs. by the trend in PDO index in 1980-2010.

- However, PDO does not predict the specific patterns (i.e., southward intensification) in SST and curl.
- Summer near-coast wind stress curl is negligibly correlated with PDO index.

The extent to which the near-coast wind stress curls are independent of large-scale natural and anthropogenic forcings needs a long-term high-resolution coupled modeling study.

6. Acknowledgement

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