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Journal
Geophysical Research Letters, 38(3)

ISSN
0094-8276

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Publication Date
2011-02-01

DOI
10.1029/2010gl046376

GEOPHYSICAL RESEARCH LETTERS, VOL. 38, L03609, doi:10.1029/2010GL046376, 2011

Underwater gliders reveal rapid arrival of El Niño effects off California's coast

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Received 5 December 2010; accepted 30 December 2010; published 8 February 2011.

[1] The 2009–2010 El Niño marked the first occurrence of this climate phenomenon since the initiation of sustained autonomous glider surveillance in the California Current System (CCS). Spray glider observations reveal the subsurface effects of El Niño in the CCS with spatial and temporal resolutions that could not have been obtained practically with any other observational method. Glider observations show that upper ocean waters in the CCS were unusually warm and isopycnals were abnormally deep during the El Niño event, but indicate no anomalous water masses in the region. Observed oceanic anomalies in the CCS are nearly in phase with an equatorial El Niño index and local anomalies of atmospheric forcing. These observations point toward an atmospheric teleconnection as an important mechanism for the 2009–2010 El Niño's remote effect on the mid-latitude CCS. **Citation:** Todd, R. E., D. L. Rudnick, R. E. Davis, and M. D. Ohman (2011), Underwater gliders reveal rapid arrival of El Niño effects off California's coast, *Geophys. Res. Lett.*, *38*, L03609, doi:10.1029/2010GL046376.

1. Introduction

[2] El Niño conditions, identified as anomalously warm upper ocean temperatures in the central and eastern equatorial Pacific [*Philander*, 1983; *McPhaden*, 1999], returned to the tropical Pacific from June 2009 through May 2010. Effects of El Niño events extend beyond the tropical Pacific; they have had dramatic impacts on the hydrography and dynamics of the California Current System (CCS) [*Simpson*, 1984; *Dever and Winant*, 2002; *Lynn and Bograd*, 2002; *Strub and James*, 2002] and on biological productivity and community structure [*Lavaniegos et al.*, 2002; *Chavez et al.*, 2002; *Lavaniegos and Ohman*, 2007] in this ecologically and economically important eastern boundary upwelling system. Mechanisms by which El Niño may affect the CCS are changes in basin-wide atmospheric conditions and surface forcing (atmospheric teleconnections) [*Simpson*, 1984; *Emery and Hamilton*, 1985; *Ramp et al.*, 1997; *Schwing et al.*, 2002], propagation of coastally trapped waves from the tropics [*Enfield and Allen*, 1980; *Chelton and Davis*, 1982; *Meyers et al.*, 1998; *Ramp et al.*, 1997; *Strub and James*, 2002], and anomalous advection of warmer water masses of southern or western origin into the CCS [*Simpson*, 1984; *Bograd et al.*, 2001; *Lynn and Bograd*, 2002].

[3] The effects of the strong 1997–1998 El Niño [*McPhaden*, 1999] were heavily studied in the CCS using ship-based observations [*Lynn and Bograd*, 2002], moorings and drifters [*Dever and Winant*, 2002], and satellite observations [*Strub and James*, 2002]. Of these methods, only ship-based methods provided spatially broad observations of the subsurface effects of El Niño, and this only with great expense and substantial manpower. The 2009–2010 El Niño marks the first time that autonomous instruments have been able to provide spatially broad observations at the temporal resolution needed to study the effects of El Niño in the CCS.

[4] We use continuous upper ocean observations collected by autonomous underwater gliders to show the effects of the 2009–2010 El Niño on the upper ocean off the coast of California. The observations show oceanic anomalies that are consistent with an atmospheric teleconnection being an important mechanism for this event while ruling out an advective influence. Glider observations can neither confirm nor exclude the influence of coastally trapped waves. This is the first use of a network of autonomous underwater vehicles to resolve the mechanisms of an El Niño event in the upper ocean.

2. Glider Observations and Ancillary Data

[5] Spray gliders [*Sherman et al.*, 2001; *Rudnick et al.*, 2004] are buoyancy-driven autonomous underwater vehicles that profile along a sawtooth path through the upper ocean. Gliders have been continuously surveying along three established California Cooperative Oceanic Fisheries Investigations (CalCOFI, www.calcofi.org) survey lines in the CCS (Figure 1) since late 2006 [*Todd et al.*, 2011]. Line 66.7 extends 550 km offshore from Monterey Bay; Line 80 extends 350 km offshore from Point Conception; and Line 90 extends 550 km from near Dana Point and through the Southern California Bight (SCB). Gliders provide observations of temperature, salinity, density, and velocity in the upper 500 m with horizontal resolution of 3 km and transects repeated about every 3 weeks (Figures 2a–2c). Differences between the glider's velocity over land and velocity through the water for each dive give estimates of vertically averaged velocity [*Todd et al.*, 2011]. This analysis uses glider observations collected between October 2006 and October 2010.

[6] To aid in interpreting the glider observations, we use equatorial sea surface temperature (SST) anomalies in the form of the Oceanic Niño Index (ONI, Figure 3a) and wind stress from the U.S. Navy's operational eastern Pacific COAMPS product [*Hodur*, 1997]. The ONI is provided by the NOAA Climate Prediction Center (www.cpc.noaa.gov); it is the three-month running mean of SST anomalies in the Niño 3.4 region (5°S–5°N, 120°W–170°W) relative to a 1971–2000 base period. COAMPS output was generated by the Fleet Numerical Meteorology and Oceanography Center and provided online by the U.S. Global Ocean Data

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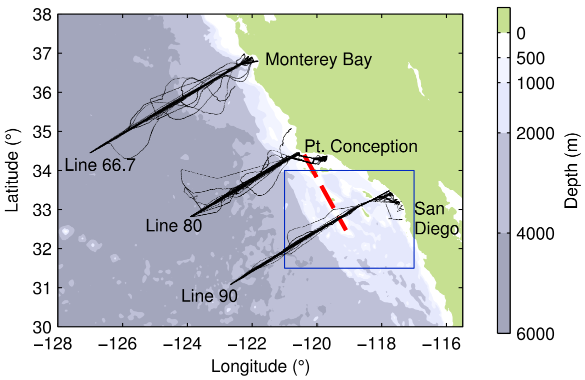

Figure 1. Location of all glider observations used in this analysis. Glider tracks along CalCOFI Lines 66.7, 80, and 90 are in black. Bathymetry is shown in grey. The dashed red line indicates the topographic ridge at the western boundary of the SCB. The blue box denotes the region over which surface forcing data are averaged in Figure 3.

Assimilation Experiment (www.usgodae.org). The COAMPS product provides wind stress with sufficient resolution (27 km) to calculate wind stress curl in the SCB, and it is immediately available so that we can compare with recently collected glider observations. COAMPS wind stress curl compares favorably with optimized wind stress curl from a numerical state estimate of the CCS for the period 1 January 2007 to 30 July 2009 [*Todd et al.*, 2011] at monthly time scales, so we believe the COAMPS wind product is sufficient for use in this analysis.

3. Results and Discussion

[7] Upper ocean temperatures in the SCB were unusually warm during winter 2009–2010, a characteristic manifestation of El Niño in the CCS [*Lynn and Bograd*, 2002; *Dever and Winant*, 2002]. Along Line 90, temperatures at 50 m depth and within 200 km of the coast (Figure 2c) exceeded 15 °C in early 2010. These were the warmest winter temperatures observed in the area since glider observations began. Temperatures within 200 km of shore along the other two survey lines (Figures 2a and 2b) and at other depths (not shown) were similarly warm in early 2010.

[8] Removing a mean annual cycle more clearly shows the distribution of unusually warm waters. We define temperature anomalies at 50 m on each survey line relative to mean annual cycles constructed by objectively mapping [*Bretherton et al.*, 1976] observations from all years into a single year. Warm (positive) anomalies at 50 m (Figures 2d–2f) appeared in mid-2009 within 200 km of the coast on Lines 80 and 90 and 100–200 km offshore on Line 66.7, coincident with the onset of El Niño in the equatorial Pacific. Soon after, there was a brief period of negative temperature anomalies at 50 m along Lines 80 and 90 that we attribute to upwelling that continued longer than during previously sampled years; the timing and magnitude of upwelling in the CCS are known to vary interannually [*Schwing et al.*, 2006]. From late 2009 through the spring of 2010, warm anomalies of 0.5–1.5°C at 50 m extended over most of the three survey lines. The westward propagation of El Niño anomalies apparent in Figure 2 is consistent with observations during previous events [*Lynn and Bograd*, 2002].

[9] We create various indices of the physical state of the CCS by averaging anomalies of properties in the across-shore direction. As above, anomalies are defined relative to mean annual cycles constructed by objective mapping. Since El Niño-related temperature anomalies were largest within 200 km of the coast on Line 90 (Figure 2), we focus on this region when averaging anomalies. This region is the portion of Line 90 inshore of the topographic ridge that defines the western boundary of the SCB (Figure 1). We compare these glider-based indices to the ONI, an equatorial gauge of El Niño. We do not report correlation statistics between indices because the currently available observations capture only a single El Niño-La Niña cycle and test statistics therefore have a limited number of effective degrees of freedom.

[10] Temperature anomalies at 10 m and 50 m (Figures 3b and 3c) generally varied in phase with the ONI over the observation period. Upper ocean temperatures in the CCS were anomalously warm at the end of the mild 2006–2007

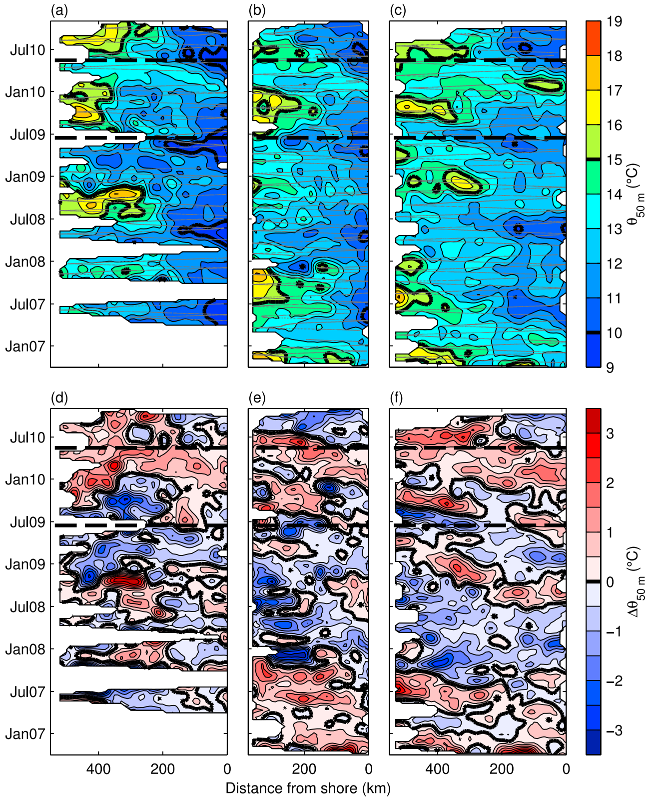

Figure 2. Hovmöller plots of (a–c) potential temperature (θ) and (d–f) potential temperature anomaly ($\Delta\theta$) at 50 m along Line 66.7 (Figures 2a and 2d), Line 80 (Figures 2b and 2e), and Line 90 (Figures 2c and 2f). Observations were objectively mapped using a Gaussian covariance with 30-km and 60-day scales. Anomalies are defined relative to a mean annual cycle constructed by objectively mapping observations from all years into a single year. Small grey dots in Figures 2a–2c show the across-shore and temporal sampling by gliders; each point indicates a single glider profile. Dashed horizontal lines indicate the beginning and end of the 2009–2010 El Niño based on the ONI.

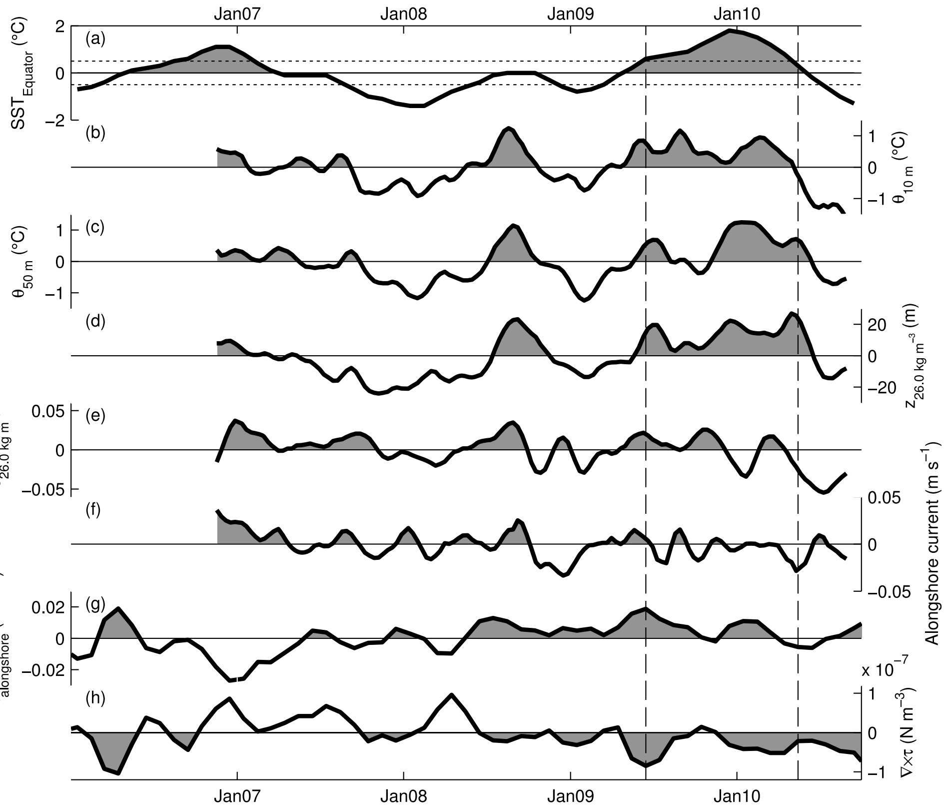

Figure 3. Time series of property anomalies. (a) Equatorial SST in the Niño 3.4 region (the Oceanic Niño Index, ONI). Anomalies averaged within 200 km of the coast on Line 90: (b and c) potential temperature (θ) at depths of 10 m and 50 m, respectively; (d) depth (z) of the 26.0 kg m^{-3} isopycnal (positive anomalies are deeper); (e) salinity (s) on the 26.0 kg m^{-3} isopycnal; and (f) alongshore currents (positive poleward) averaged over the upper 500 m. (g and h) Alongshore wind stress (τ, positive poleward) and wind stress curl ($\nabla \times \tau$), respectively, over the boxed region in Figure 1 from the 27-km COAMPS product. Monthly COAMPS anomalies are defined relative to means over 2003–2010. Dotted horizontal lines in Figure 3a indicate the thresholds for El Niño and La Niña conditions. Dashed vertical lines indicate the start and end of the 2009–2010 El Niño based on the ONI.

El Niño, became cool during the 2007–2008 La Niña, and warmed again with the onset of the 2009–2010 El Niño in June 2009. Warm anomalies persisted from June 2009 through May 2010 with the exception of a period of cool anomalies at 50 m in late 2009 due to variability in the timing and magnitude of upwelling. A return to cool anomalies in the CCS accompanied the onset of La Niña in the summer of 2010. There is little, if any, phase lag between warming of equatorial sea surface temperatures and warming in the upper ocean off California.

[11] Anomalous depth of the 26.0 kg m^{-3} isopycnal (Figure 3d) was also in phase with the ONI. Generally found within the thermocline, the isopycnal was deeper during El Niño events and shallower during La Niña events. The depression (elevation) of isopycnals during El Niño (La Niña) events is consistent with the observed elevation (depression) of sea surface height (SSH) along the west coast of North America during previous El Niño (La Niña) events [*Enfield and Allen*, 1980; *Chelton and Davis*, 1982; *Lynn and Bograd*, 2002].

[12] Glider observations of salinity anomalies and alongshore currents rule out an advective influence of the 2009–2010 El Niño in the CCS. Salinity anomalies on an isopycnal indicate changes in water masses; a salty (and therefore warm) anomaly indicates water of southerly origin [*Lynn and Simpson*, 1987] advected into the region. Salinity on the 26.0 kg m^{-3} isopycnal (Figure 3e) did not show consistent, positive anomalies during the 2009–2010 El Niño, implying that there was little advection of warm, salty waters into the SCB. Local alongshore currents in the upper 500 m (Figure 3f) also did not show anomalous poleward transport consistently throughout the 2009–2010 El Niño. This result contrasts with the strong 1997–1998 El Niño, which produced isopycnal salinity anomalies along Line 90 that indicated advection of waters from equatorward of 27°N along the coast [*Lynn and Bograd*, 2002]. The 2009–2010 event has been identified as a central-Pacific El Niño with relatively weak temperature anomalies in the eastern equatorial Pacific [*Lee and McPhaden*, 2010; *Lee et al.*, 2010], possibly explaining the lack of coastal advection.

[13] Recent analysis of euphausiid (krill) abundance in Southern California waters (M. D. Ohman, unpublished data, 2010) also indicates a lack of an advective influence on the CCS by the 2009–2010 El Niño. In spring 2010, the two species of subtropical euphausiids that have been elevated in abundance in Southern California during some previous El Niño springs [see *Brinton and Townsend*, 2003] were either completely undetectable (*Nyctiphanes simplex*) or present at extremely low abundance (*Euphausia eximia*). The absence of these planktonic species suggests that the

subtropical waters in which they live were not present in the SCB during this El Niño, in contrast to previous events.

[14] Surface forcing by alongshore wind stress and wind stress curl (Figures 3g and 3h) shows anomalies during the 2009–2010 El Niño that could have caused the observed oceanic anomalies. Anomalies of alongshore wind stress and wind stress curl were downwelling favorable during the 2009–2010 El Niño. Given a shallow upwelling overturning cell [*Davis*, 2011], depression of isopycnals cuts off the supply of cold, subsurface water that is upwelled and mixed in the surface layer, leading to the observed warming in the upper ocean. Anomalies of wind stress curl and, to a lesser degree, alongshore wind stress in the SCB peaked with the onset El Niño conditions in May 2009 and the initial appearance warm temperature anomalies and depressed isopycnals. The decrease in wind stress curl anomalies in late 2009 is consistent with the observed cooler temperatures, shallower isopycnals and extended upwelling season. From late 2009 through the end of the El Niño event, downwelling favorable wind stress and wind stress curl anomalies persisted over the SCB. The switch to La Niña conditions in summer 2010 saw alongshore wind stress anomalies change sign and wind stress curl anomalies decrease in magnitude. The correspondence between observed hydrographic anomalies in the CCS and anomalies of alongshore wind stress and wind stress curl over the SCB points to an atmospheric teleconnection as an important mechanism for the 2009–2010 El Niño's effects in the CCS.

[15] El Niño-related SSH anomalies have been shown to propagate poleward as coastally trapped waves at phase speeds ranging from 0.4–3 m s^{-1} [*Enfield and Allen*, 1980; *Chelton and Davis*, 1982; *Ramp et al.*, 1997; *Meyers et al.*, 1998]. The fastest of these propagation speeds agree with the theoretical speed of first-mode baroclinic Kelvin waves and would result in propagation from the equator to the CCS in a month or less, consistent with the near zero phase lag between anomalies in the CCS and the ONI. Our glider observations are spread over about 525 km along the coast with transects repeated every three weeks, so we are unable to resolve possible poleward propagation at Kelvin wave speeds; a wave traveling poleward at 3 m s^{-1} would take about two days to travel from Line 90 to Line 66.7. We cannot rule out poleward propagating coastally trapped waves as a mechanism for the 2009–2010 El Niño's effect on the CCS. However, previous studies haves hown that the mouth of the Gulf of California near 23°N can act as a barrier to coastally trapped waves [*Ramp et al.*, 1997; *Strub and James*, 2002]. Satellite observations of SSH and tide gauge observations, which have greater alongshore coverage and temporal resolution, are necessary to identify the influence of coastally trapped waves.

4. Conclusion

[16] The three ways that El Niño events may affect the CCS are (1) atmospheric teleconnections, (2) oceanic advection, and (3) oceanic coastally trapped waves. We conclude that an atmospheric teleconnection was likely important during the 2009–2010 El Niño, and that advection of southern waters into the CCS did not occur. The glider observations and local atmospheric data examined here do not allow a definitive conclusion concerning the importance of coastally trapped waves.

[17] **Acknowledgments.** Spray glider deployments were supported by the Instrument Development Group (IDG) at the Scripps Institution of Oceanography. We acknowledge funding from the Gordon and Betty Moore Foundation, the Coastal Ocean Currents Monitoring Project (COCMP), NSF through the California Current Ecosystem LTER site, and NOAA through the Consortium on the Ocean's Role in Climate (CORC) and the Southern California Coastal Ocean Observing System (SCCOOS). R.E.T. was partially supported by an Achievement Rewards for College Scientists (ARCS) scholarship.

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