Future climate change and upwelling in the California Current

Mark A. Snyder, Lisa C. Sloan, Noah S. Diffenbaugh, and Jason L. Bell
Dept. of Earth Sciences, Univ. of California, Santa Cruz, Santa Cruz, California, USA

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[1] Observations show that wind-driven upwelling along the California coast has increased over the past 30 years. Some have postulated that the increase in wind-driven upwelling is due largely to increased greenhouse gas forcing, but such an association has been speculative. Since global and regional simulations of future wind-driven upwelling do not exist for the California coast, we used a regional climate model (RCM) to estimate changes in wind-driven upwelling under increased CO_2 concentrations. Here we show in both equilibrium and transient climate experiments that there is an intensified upwelling season, with some changes in seasonality of upwelling. This intensification may lead to enhanced productivity along the coast of California and possibly ameliorate increases in sea surface temperature due to greenhouse gas forcing. *INDEX TERMS:* 1610 Global Change: Atmosphere (0315, 0325); 1635 Global Change: Oceans (4203); 3309 Meteorology and Atmospheric Dynamics: Climatology (1620). **Citation:** Snyder, M. A., L. C. Sloan, N. S. Diffenbaugh, and J. L. Bell, Future climate change and upwelling in the California Current, *Geophys. Res. Lett.*, *30*(15), 1823, doi:10.1029/2003GL017647, 2003.

1. Introduction

[2] The California Current system consists of a wind-driven surface current that flows southward along the coast. This current brings cool water from the Gulf of Alaska, which mixes with warmer tropical waters off the coast of southern California. One of the features of this system is the occurrence of wind-driven upwelling during the spring through fall seasons north of Point Conception (Northern region) and to the south (Central region) in all seasons. Heating of the land surface during the summer creates a thermal low pressure, while relatively high pressure remains in place over the cooler ocean surface. This pressure gradient drives northerly winds along the coast, which in turn drives coastal upwelling [*Bakun and Nelson*, 1991].

[3] The Northern region is characterized by upwelling during the months of April through September [*Bakun and Nelson*, 1991]. The onset of the upwelling is gradual, starting in March/April and ramping up to peak values in June/July. Termination of the upwelling season is rapid and typically occurs in October. In the Central region, upwelling occurs in all seasons. Upwelling intensity is greatest in the spring and summer months and diminishes in the fall and winter [*Winant and Dorman*, 1997].

[4] The upwelling process brings cold, nutrient rich water to the surface in coastal areas. These waters in turn support a diverse marine fauna. Changes in upwelling can have a profound effect on a variety of ecosystems, and variations in upwelling can result in large and significant changes in productivity. Changes in ocean temperature have already been linked to changes in marine ecosystems [*Barry et al.*, 1995; *Helmuth et al.*, 2002; *Roemmich and McGowan*, 1995].

[5] The hypothesis of *Bakun* [1990] that increased greenhouse gas forcing will lead to intensified upwelling is supported through observations by *Mendelssohn and Schwing* [2002] and *Schwing and Mendelssohn* [1997]. Bakun's hypothesis and the observations of increased upwelling serve as the primary motivation of this study. If, as has been asserted, the major zones of coastal upwelling have been intensifying as atmospheric greenhouse gas concentrations have grown over the past few decades [*Mendelssohn and Schwing*, 2002; *Schwing and Mendelssohn*, 1997], what might be the future of these systems as the atmospheric composition, and climate, continues to change?

2. Experiments

[6] We used a RCM to examine changes to wind-driven upwelling along the coast of California under conditions of increased atmospheric CO_2 concentrations. The higher resolution of a RCM, relative to that of global climate models, provides more detail of future climate change at regional scales [*Christensen et al.*, 2001; *Giorgi and Francisco*, 2000; *Leung and Ghan*, 1999; *Snyder et al.*, 2002]. The 40 km horizontal resolution of the RCM also represents an improvement over the 2 degree resolution of the COADS observational dataset used to analyze changes in upwelling for the modern day [*Mendelssohn and Schwing*, 2002; *Schwing and Mendelssohn*, 1997].

2.1. Methods

[7] The RCM used in this study was RegCM2.5. RegCM2.5 is a hydrostatic, limited-area model on an equal area grid. For these experiments we used a horizontal resolution of 40 km with 60 by 55 gridcells, and 14 levels in the vertical direction. This RCM has been validated for a number of different regions and is well described elsewhere [*Giorgi and Shields*, 1999; *Snyder et al.*, 2002]. The RCM was run for four separate cases. The first two cases (1X and 2X) are equilibrium climate runs with CO_2 fixed at 280 ppm and 560 ppm, respectively. The driving data for these runs was generated with the National Center for Atmospheric Research (NCAR) Community Climate Model ver. 3.6.6 (CCM3), using fixed sea surface temperatures (SSTs) that were previously calculated in equilibrium with pCO_2 levels [*Snyder et al.*, 2002]. CCM3 was run for 21 years in each case, with the last 18 years of each case used as driving data for RegCM2.5. The final fifteen years of the RCM runs are used in the analysis.

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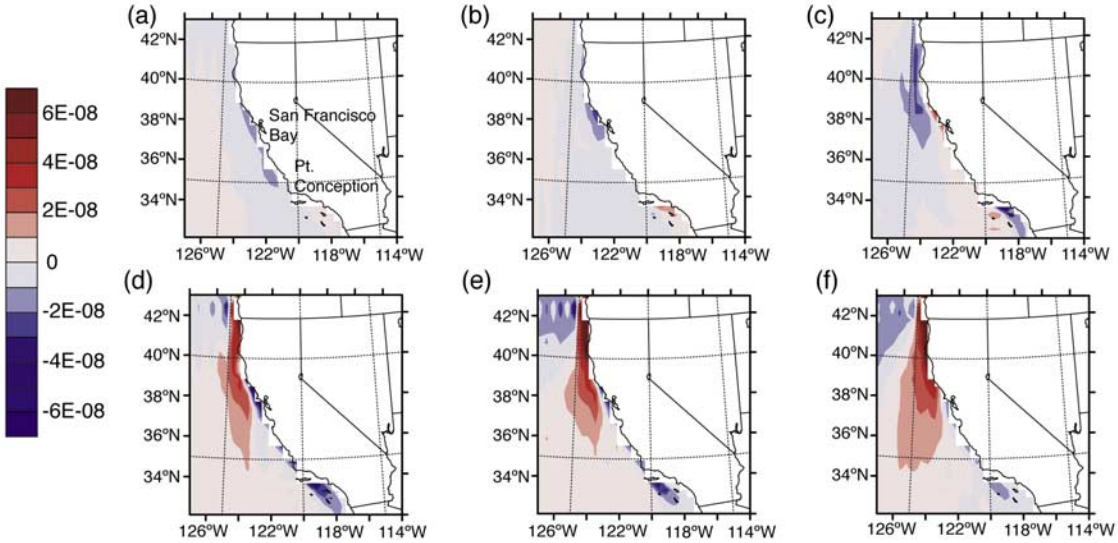

Figure 1. Difference of the monthly average wind-stress curl (N/m^2), calculated as 2X-1X, for (a) Apr, (b) May, (c) June, (d) July, (e) August, (f) September.

[8] The second two cases (MODERN and FUTURE) are transient climate runs in which CO_2 concentrations increased as function of time. Driving data was generated with the NCAR Community Climate System Model ver. 1.3 (CCSM) and is archived at NCAR. CCSM is a fully coupled atmospheric model with dynamic ocean, sea-ice, and land surface models [*Boville and Gent*, 1998]. The two cases here use subsets of a longer CCSM run [*Dai et al.*, 2001]. The MODERN case corresponds to the time period 1980–1999 and the FUTURE case corresponds to the time period 2080–2099. The CO_2 concentrations in the runs are based on the IPCC A1 scenario and are updated yearly in the model. Values in the MODERN run ranged from 338 ppm to 369 ppm, and in the FUTURE run from 635 ppm to 686 ppm. The RCM was run using this driving data for a period of 20 years. The final nineteen years of the RCM runs are used in the analysis.

[9] We are interested in the comparison of the equilibrium cases and the transient cases because in many previous studies, equilibrium experiments have been used to test sensitivity of climate to changes in forcing, such as greenhouse gases. However, most of the climate simulations performed for the Intergovernmental Panel of Climate Change (IPCC) reports are transient experiments with fully coupled models, which are considered to be more accurate at reproducing subtle features of the climate system, such as variability [*Intergovernmental Panel on Climate Change*, 2001].

3. Results

[10] We generated monthly average wind fields for each experiment and calculated the curl of the wind stress. Methods for calculating wind stress curl from RCM surface wind fields followed *Ortiz et al.* [1997], using the variable drag coefficient of *Trenberth et al.* [1990]. The RCM accurately simulates the seasonality and seasonal contrast of wind stress curl in both the northern and southern regions of the California Current, though absolute values of wind stress curl are underestimated in some months [*Diffenbaugh et al.*, 2003].

[11] Because coastal upwelling in the California Current is driven by wind stress curl along the California margin, we can infer the sensitivity of wind-driven upwelling by analyzing the differences in the curl of the wind stress between the experimental and control cases. However, because the RCM is an atmospheric model, actual oceanographic sensitivity to increased atmospheric CO_2 levels has not been simulated. Important factors not considered here include the effects of regional scale bathymetry on upwelling in specific coastal cells, as well as feedbacks between the ocean and the atmosphere induced by anthropogenic greenhouse warming.

[12] Spatial patterns of wind-stress curl are illustrated in Figures 1 and 2 for the equilibrium climate cases (1X, 2X) and transient climate cases (MODERN, FUTURE), respectively. We refer to the Upper Northern (UN), as the region from San Francisco Bay north, the Lower Northern (LN) region as south of San Francisco Bay and North of Pt. Conception, and the Central (CE) as the region south of Pt. Conception to the border with Mexico. It is important to note that for this study results are shown for only the central and northern parts of the California Current System. For the equilibrium climate cases we find in the UN region decreased wind-stress curl for April through June, with increase from July through October (Figure 1). The LN region shows decreased wind-stress curl in April through May and July through September, with small increases in June. The CE region has decreased wind-stress curl for the period June–September, with increases in April–May.

[13] The transient climate cases have some similarities to the equilibrium cases in terms of spatial changes in wind-stress curl. In the UN region we find decreased wind-stress curl in April–May, with increases in June–October. This pattern is similar to that seen in the equilibrium cases. The LN region has little change in all months except August when there is a decrease in wind-stress curl. For the CE region the patterns of the equilibrium and transient

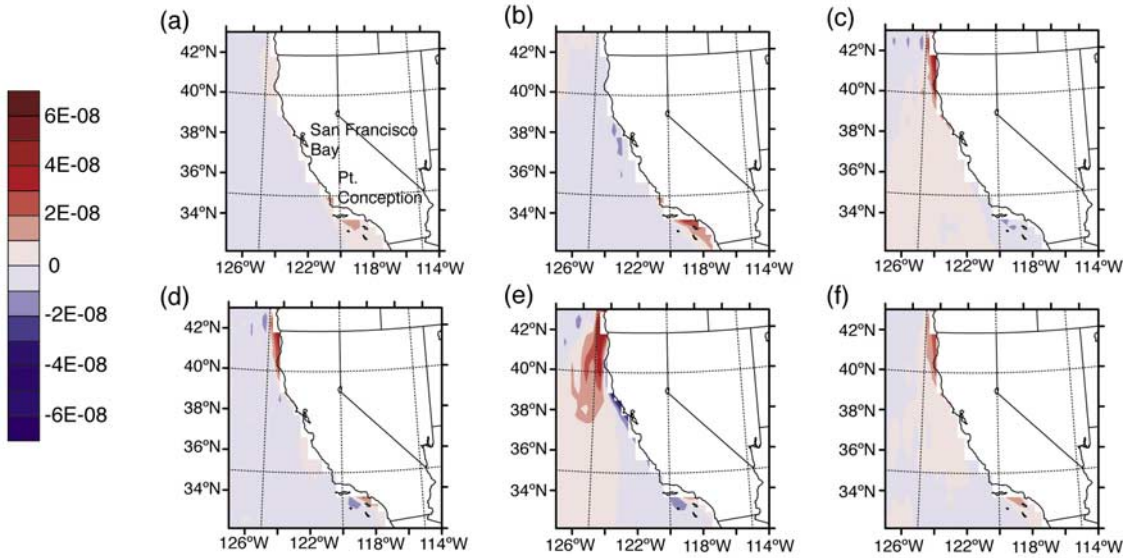

Figure 2. Difference of the monthly average wind-stress curl (N/m^2), calculated as FUTURE-MODERN, for (a) Apr, (b) May, (c) June, (d) July, (e) August, (f) September.

cases are opposed in most months. Increases occur in the CE region during April–May and September, with decreases in June. In July and August there are decreases in wind-stress curl in the western half of the region, and increases in the eastern half.

[14] Figure 3 shows a comparison of the wind-stress curl anomaly for the UN and CE regions as a function of time and latitude. For the UN region we see increased upwelling in the 2X case begins in July and continues through to October (Figure 3a). The largest increases occur in the southern end of the region. This pattern is similar for the transient climate cases. However in the FUTURE case the increased upwelling begins in June and the magnitude of the change is less in the southern part of the region (Figure 3c). In the 2X case for the CE region we find increased upwelling in May, with large decreases in June through September (Figure 3b). The changes are concentrated along the coastline east of Santa Barbara. The FUTURE case shows increased upwelling in April and May and the overall intensity is greater than the 2X case (Figure 3d). There are small decreases in June, and small increases in July–October for the same region.

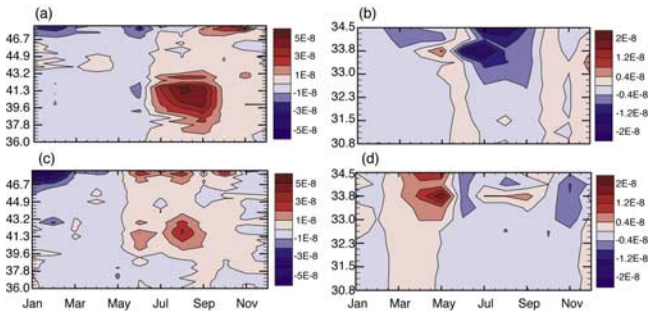

Figure 3. Latitude-Time plot showing the difference of zonaly averaged wind-stress curl. (a) Northern region difference of 2X-1X, (b) Central region difference of 2X-1X, (c) Northern region difference of FUTURE-MODERN, (d) Central region difference of FUTURE-MODERN.

4. Discussion

[15] Our results show that substantial changes in the intensity of upwelling will occur under increased CO_2 conditions. In this study we did not test for statistical

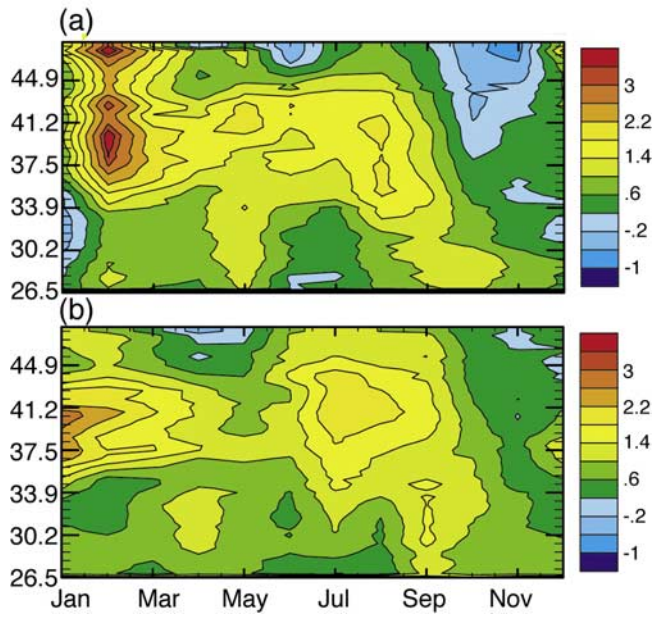

Figure 4. Latitude-Time plot showing the difference of zonaly averaged surface air temperature over land and ocean. (a) Difference of the land surface temperature anomaly (calculated as the difference of 2X land and 1X land surface temperature) and the ocean temperature anomaly (calculated as the difference of 2X ocean and 1X ocean surface temperature). (b) The same as (a), except for FUTURE and MODERN cases.

significance of the results. For the UN region the wind-stress curl increases are concentrated in the warmest months of June through September. Temporally, the peak of the upwelling season has shifted to later in the year for this region, and the onset occurs up to a month later. The difference in the magnitude of change between the equilibrium and transient cases is expected (Figures 1 and 2), as the two cases use dramatically different driving conditions (see Methods). For the CE region the results are inconclusive, with the equilibrium cases indicating decreased wind-stress curl and the transient cases indicating that there is slightly increased wind-stress curl.

[16] Our experiments show that increased CO_2 forcing affects wind-stress curl by causing an increase in the land-ocean temperature gradient. Figure 4 shows the difference of land surface temperature anomalies and ocean surface temperature anomalies for the 1X, 2X cases and the MODERN, FUTURE cases. As CO_2 forcing increases, the land surface temperatures warm more rapidly than ocean surface temperatures (Figure 4). This temperature gradient, which is substantial during the summer months, contributes to the alongshore winds that drive upwelling. Our results support the generalized hypothesis of *Bakun* [1990], but we note that by using a regional climate model we are able to quantify the seasonal pattern of the land-ocean temperature gradient and its influence on wind-stress curl.

5. Conclusions

[17] The intensification of upwelling will likely have impacts on terrestrial and marine ecosystems [*Soto*, 2001]. The Fundamental Triad concept of Bakun provides a framework in which to interpret how changes in upwelling can affect marine ecosystems. The three components of the triad are (1) enrichment of the waters with food sources due to upwelling, (2) concentration of food in great enough quantities to sustain a population, and (3) retention of the organisms and the food sources in the same area [*Bakun*, 1996]. With intensified upwelling, enrichment can be increased which would be beneficial to organisms, however concentration maybe decreased due to increased mixing and retention may also be decreased by increased seaward transport of surface water. Overall this could have a negative effect on the marine ecosystems, as the current balance of these three factors will change with changes in upwelling.

[18] Increased upwelling may also intensify fog development and onshore flow during the summer months. This in turn may lead to decreased temperatures and increased moisture flux over land. Some coastal terrestrial ecosystems, such as that associated with the coastal redwood, could benefit from these changes. Quantification of these and other eco-physical relationships will allow for a better assessment of the impacts of climate change.

[19] Research should continue to focus on the impacts of climate change on complex systems such as the California Current. This study is limited primarily by the lack of a dynamic ocean model coupled to the RCM. The inclusion of regional bathymetry and feedbacks between the ocean and atmosphere are likely to change the results presented here. Therefore work is needed to couple the results of RCMs to other models of oceanographic processes. To that end, our work represents a first step in quantifying the interaction of climate change and coastal upwelling.

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M. A. Snyder, L. C. Sloan, N. S. Diffenbaugh, and J. L. Bell, Dept. of Earth Sciences, Univ. of California, Santa Cruz, 1156 High Street, Santa Cruz, CA 95060, USA.