

Coastal upwelling in a warmer future

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[1] Coastal upwelling helps set the physical context for marine ecosystems, and upwelling zones are among the most productive regions of the global ocean. Unlike earlier models, two state-of-the-art climate models exhibit little change during the next century in the magnitude and seasonality of coastal upwelling, but climate models are still probably not sufficiently developed (for example, they underestimate interdecadal variability in upwelling) to provide valid projections of this key component of the coastal environment. *INDEX TERMS:* 4279 Oceanography: General: Upwelling and convergences; 1635 Global Change: Oceans (4203); 4215 Oceanography: General: Climate and interannual variability (3309); 0315 Atmospheric Composition and Structure: Biosphere/atmosphere interactions; 4815 Oceanography: Biological and Chemical: Ecosystems, structure and dynamics. **Citation:** Mote, P. W., and N. J. Mantua, Coastal upwelling in a warmer future, *Geophys. Res. Lett.*, 29(23), 2138, doi:10.1029/2002GL016086, 2002.

1. Introduction

[2] By replenishing the nutrients needed for biochemical activity, oceanic upwelling sustains vastly greater productivity than can be sustained in most locations. Wind-driven coastal upwelling is a consequence of persistent large-scale features of atmospheric circulation around high pressure cells over midlatitude oceans combined with “Ekman drift” — the deflection caused by the rotation of the Earth.

[3] Ocean temperatures and the nutrient content produced by oceanic upwelling are among the most important large-scale variables influencing the marine environment. Predicting the response of marine ecosystems to these large-scale variables is difficult owing to the complexity of these ecosystems, but clues about changes in these large-scale variables would be an important first step. Observed shifts in climate in the North Pacific are associated with complex and surprising shifts in ecosystems [Mantua *et al.*, 1997; McGowan *et al.*, 1998; Hare and Mantua, 2000]. Earlier efforts to quantify the influence of climate change on coastal upwelling [e.g., Hsieh and Boer, 1992] used climate models with much simpler representations of the ocean than are common today. Hsieh and Boer, for example, used an atmospheric model coupled to a mixed-layer ocean model. They found that in a doubled-CO₂ climate, midlatitude coastal upwelling decreased.

[4] In this paper we examine output from two state-of-the-art climate models to see how the seasonality and intensity of coastal upwelling changes. Mantua and Mote [2002] examined the same two models and found generally smaller changes in the sea-level-pressure distribution (an

important indicator of surface wind circulation and hence coastal upwelling) than Hsieh and Boer [1992].

2. Climate Model Output

[5] The formula used in CSM to compute wind stress can only be solved during integration.

[6] In order to provide some estimate of the sensitivity to assumptions about the nature of climate change, we used two simulations of 20th and 21st century climate. State-of-the-art simulations that would be useful here satisfied three criteria. (1) The simulations were performed with a model that did not rely on artificial “flux adjustment” [McAvaney *et al.*, 2001], a practice commonly used for correcting systematic biases in energy and water fluxes between ocean and atmospheric models. (2) They used the recent “SRES” scenarios of greenhouse gas concentrations [see Cubasch *et al.*, 2001], rather than the 1%/year equivalent CO₂ increase that was common for climate model simulations performed during the 1990’s. (3) Monthly vector wind and sea surface temperature must be available.

[7] Model output is available as monthly means for each month from at least 1990 to 2090. We have looked at the full 110 years of each simulation, but for this study, we calculate 10-year averages of monthly means and compare the 2080’s and 1990’s.

[8] Using distributions of upwelling calculated from observed winds [Xie and Hsieh, 1995] and remotely sensed chlorophyll (using SeaWiFS; see seawifs.gsfc.nasa.gov for maps and Kaufman *et al.*, 1998 for description), we selected 4 key west coast upwelling zones: western North America (latitudes 34–44°N), NW Africa (latitudes 13–30°N), SW Africa (latitudes 15–33°S), and western South America (latitudes 20–40°S). Wind stress is a useful surrogate for coastal upwelling, which is calculated in the oceanic component of climate models but is not easily available and is more likely to be affected by the neglect of small-scale topography. CSM output includes surface wind stress; HadCM3 output was provided as surface winds, which we convert to surface wind stress using the formula

$$\tau = -c_D \rho u u \quad (1)$$

where u is the magnitude of the vector wind \mathbf{u} , and the drag coefficient

$$c_D [\kappa / \ln(\rho g z / a \tau)]^2 \quad (2)$$

depends nonlinearly on the wind stress; κ is the von Karman constant, ρ is atmospheric density, $z = 10$ meters, a is the Charnock constant, and τ is the magnitude of the wind

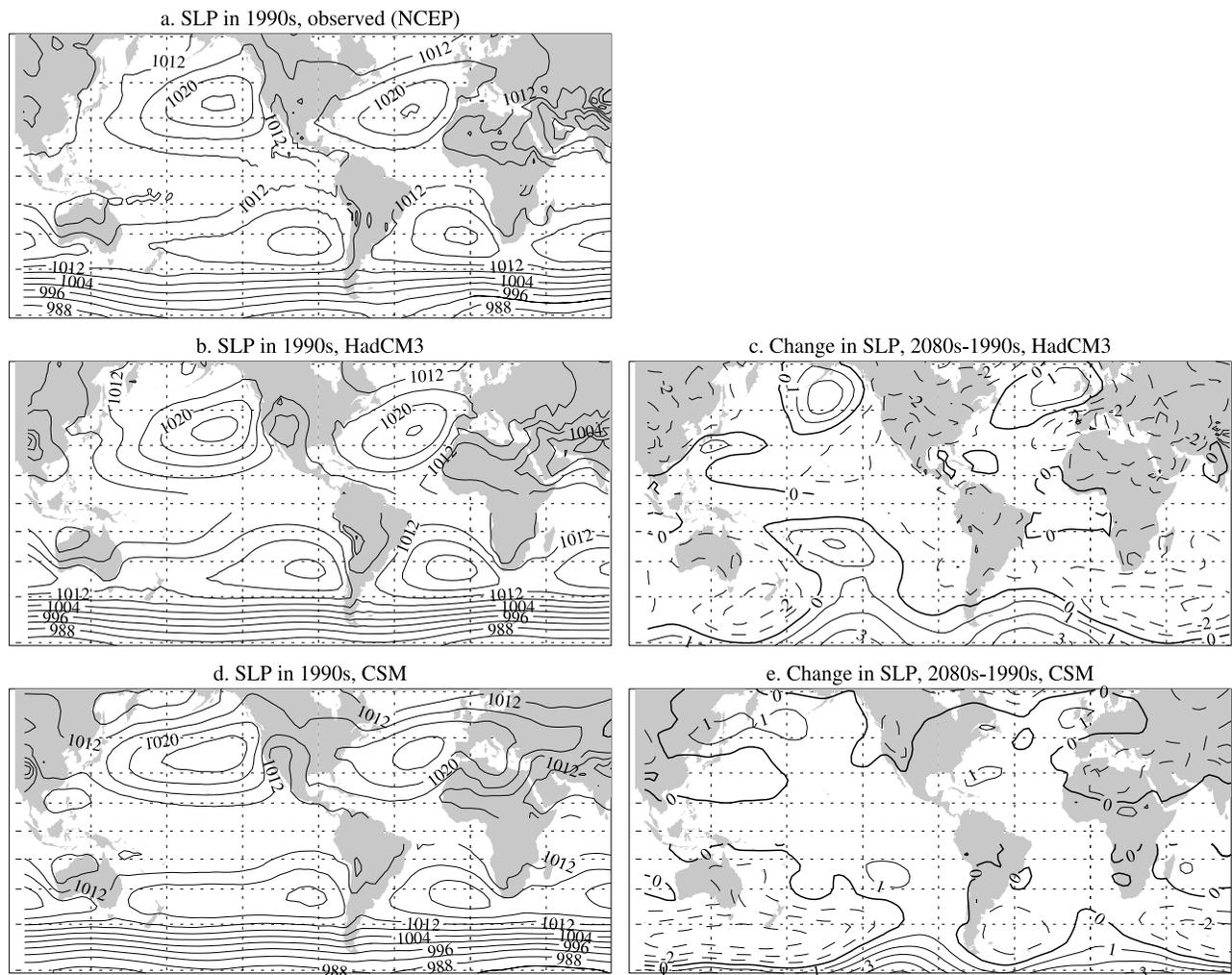


Figure 1. Summertime sea-level pressure distributions from (a) observations (see text for details) and (b, d) climate model simulations for the 1990s, and (c, e) for the 2080s minus 1990s. Results are shown for the HadCM3 simulation (b, c) and CSM (d, e). In the northern hemisphere, results are shown for June–July–August, and in the southern hemisphere results are shown for December–January–February. Contour interval 5 hPa in panels (a), (b), and (d); contour interval 1 hPa in panels (c), (e), and negative contours are dashed.

stress vector τ [see Gill, 1982, pp 29–30]. The two equations are solved iteratively.

[9] For each of these zones, we calculated an upwelling index as the alongshore component of the wind stress, an approximation valid to within a few degrees of the equator [Hsieh and Boer, 1992] where friction becomes more important than the coriolis force.

3. Results and Discussion

[10] Low-level winds outside the tropics are well characterized by the sea-level pressure (SLP) field. Climate models simulate large-scale distributions of SLP almost as well as temperature, with correlations between observed and modeled SLP of about 0.8 for most models (Figure 8.4 of McAvaney *et al.* [2002]). In Figure 1, the observed SLP (mean for 1990s data from the National Centers for Environmental Prediction, available via www.cdc.noaa.gov) is compared with SLP simulated by the two climate models, with data in each hemisphere shown for that

hemisphere's summer. That is, in each panel, the values shown in the northern hemisphere are for June–August and the values in the southern hemisphere are for December–February. The summertime pressure distributions for the 1990s (Figures 1b and 1d) are similar to each other and to observed 10-year means (Figure 1a), including the elongated shape of the south Pacific high. HadCM3 has a somewhat better mean and variance of SLP than CSM [McAvaney *et al.*, 2002].

[11] Biologically important coastal upwelling in mid-latitudes occurs in favored locations during summer in each hemisphere (and year-round in some locations), owing to the development of oceanic high-pressure cells and the accompanying anticyclonic circulation. These high-pressure cells are robust features of the climate and are relatively unaffected by climate change in the two simulations examined here (Figure 1). Changes from the 1990s to 2080s are generally larger for HadCM3 (Figure 1c), whose northern summer high pressure cells edge northward and strengthen slightly, than for CSM (Figure 1e),

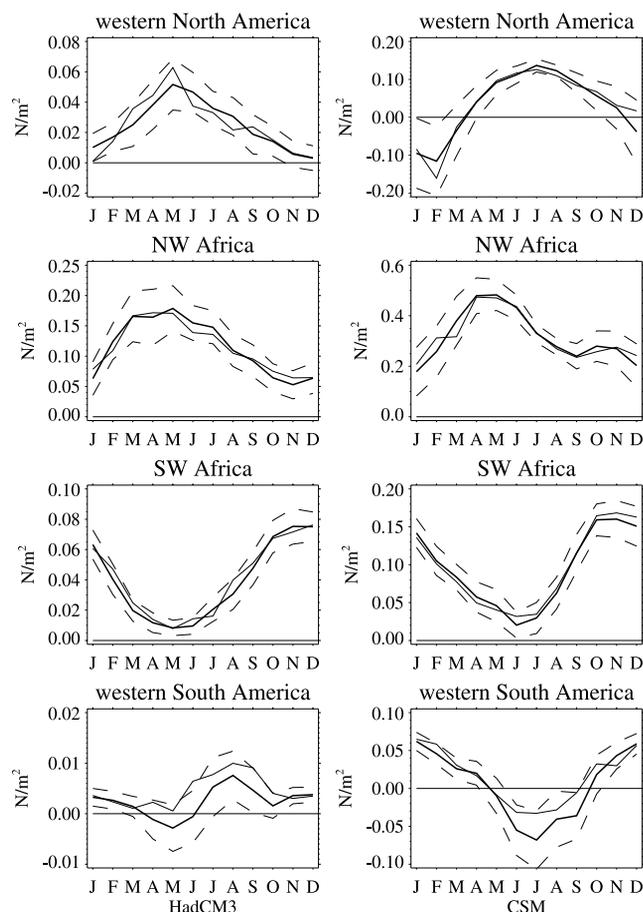


Figure 2. Seasonal cycle of alongshore wind stress for each of the four upwelling zones, as simulated for the 1990s and 2080s by the HadCM3 (left column) and CSM (right column). In each frame, the mean for the 1990s is shown as a bold curve and the mean for the 2080s is the thin curve. The dashed curves indicate $\pm 1\sigma$, where the standard deviation σ is calculated for each month from 100 years of model output.

especially in the key upwelling zones. For both models, sea-level pressure changes are larger in wintertime (not shown) when biological productivity is lower owing to the seasonal reductions in sunlight, temperature, and coastal upwelling.

[12] In each of the upwelling zones, the seasonal cycle of upwelling remains nearly unchanged throughout the 21st century (Figure 2). Of the various types of variability (seasonal, interannual, decadal, long-term trend), only seasonal variability is larger than the differences between the models. Model differences are especially large on the west coast of North America, where differences in the models' wintertime pressure distribution lead to a seasonal reversal in upwelling winds in CSM but not HadCM3, and on the west coast of South America, where the mean upwelling is smaller than at other locations and the HadCM3 upwelling has a weak seasonal cycle. Interannual variability (indicated by the dashed lines in Figure 2) is smaller than the seasonal cycle and is generally smallest in summer. Interdecadal variability is smaller still; the differences in upwelling between decades at each end of the 21st century (bold vs

thin curves in Figure 2) are larger than the differences between successive decades.

[13] We compare the simulated upwelling with an upwelling index calculated from observed monthly SLP fields using a geostrophic approximation [Bakun, 1990]. The index is available at several west coast locations for 1946–1999, and we use the index at $39^\circ N$, $125^\circ W$, which lies in our western North America region. Although it is derived differently from our model-derived indices, there is no reason to expect the interannual and interdecadal variability to be affected by the different derivations. The mean seasonal cycle (Figure 3) of the simulated western north America upwelling index shares the summer peak and winter minimum that are observed, but are quite different in winter (e.g., the CSM winter downwelling is as strong as the summer upwelling). Interdecadal variance in the models is smaller than in the observations (Figure 4, for HadCM3 in western North America) and is also small at other locations.

[14] Upwelling regions are characterized by persistent marine stratus clouds, which are often poorly simulated by climate models [e.g., Boville and Gent, 1998]. Errors in cloudiness in these regions contribute to errors in sea surface temperature, and perhaps to (smaller) errors in upwelling wind stress.

[15] The models' underestimation of interdecadal variability has important implications. It complicates detection of an anthropogenic influence on upwelling; detection usually involves comparison of observed trend patterns with trend patterns simulated by climate models when forced by changes in greenhouse gases and sulfate aerosols [see Mitchell *et al.*, 2001]. If the simulations presented here are correct, then no long-term trend in upwelling would be expected, and the variability and trends in observed upwelling have no anthropogenic component. If, on the other hand, the models' underrepresentation of interdecadal variability is somehow connected with an inability to represent anthropogenic influence, for instance through unrealistic locking to geographic features, then these projections of a changeless upwelling regime are unlikely.

[16] Large-scale wind fields provide a good indication of the potential for coastal upwelling, but the influence of wind

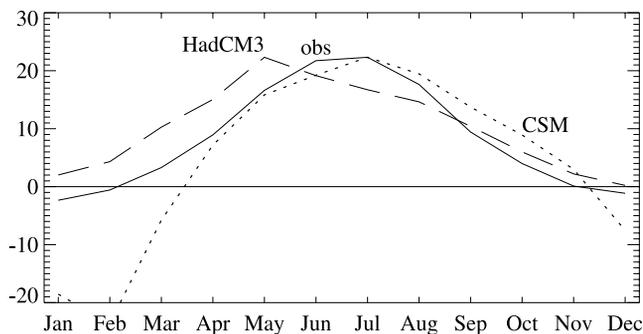


Figure 3. Comparison of observed and simulated (HadCM3, CSM) seasonal cycle in upwelling index for western North America. Because of differences in how upwelling is calculated, the modeled fields have been normalized so the maximum matches the maximum observed upwelling.

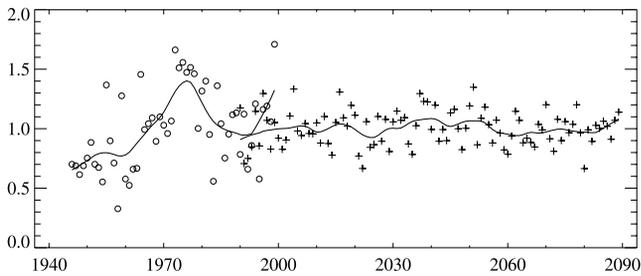


Figure 4. Comparison of observed (circles) and simulated (HadCM3, + symbols) annual mean upwelling index for western North America. Each time series is normalized to a mean of 1.0 and lowpass filtered (solid curves).

on biological productivity involves a long and complex chain of factors. First, local topography and bathymetry play an important role in shaping and intensifying upwelling, but such details are absent from global-scale ocean models. Second, the link between upwelling and nutrients is neither linear nor compact; *R. K. Takesue et al.* [unpublished manuscript] show results of monthly sampling at six sites in the two American upwelling zones. From their figures, concentrations of phosphorous and cadmium do not appear to be very tightly correlated with either daily or monthly upwelling, though they do show some relationship to the seasonal cycle and interannual variations. *Logerwell et al.* [2002] showed that a variety of large-scale environmental conditions, including upper ocean stratification, the onset date of upwelling, and total springtime upwelling, played an important role in Oregon coho (*Oncorhynchus kisutch*) marine survival.

[17] Hence, the lack of significant changes in upwelling found here should not be taken to mean that marine ecosystems dependent on coastal upwelling will be unaffected by climate change. Other aspects of the coastal marine environment could change substantially and even suddenly, leading to substantial reorganization at many trophic levels as has happened in the past [*McGowan et al.*, 1998; *Anderson and Piatt*, 1999; *Hare and Mantua*, 2000].

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References

- Anderson, P. J., and J. F. Piatt, Community reorganization in the Gulf of Alaska following ocean climate regime shift, *Mar. Ecol. Prog. Ser.*, 189, 117–123, 1999.
- Bakun, A., Global climate change and intensification of coastal ocean upwelling, *Science*, 247, 198–201, 1990.
- Boville, B. A., and P. R. Gent, The NCAR Climate System Model, Version One, *J. Clim.*, 11, 1115–1130, 1998.
- Cubasch, U., G. A. Meehl, G. J. Boer, R. J. Stouffer, M. Dix, A. Noda, C. A. Senior, S. Raper, and K. S. Yap, Projections of future climate change, in *Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change*, edited by J. T. Houghton, et al., pp. 525–582, Cambridge University Press, 2001.
- Dai, A., T. M. L. Wigley, B. A. Boville, J. T. Kiehl, and L. E. Buja, Climates of the Twentieth and Twenty-first centuries simulated by the NCAR Climate System Model, *J. Clim.*, 14, 485–519, 2001.
- Gill, A. E., *Atmosphere-Ocean Dynamics*, Academic Press, San Diego, 1982.
- Gordon, C., C. Cooper, C. A. Senior, H. T. Banks, J. M. Gregory, T. C. Johns, J. F. B. Mitchell, and R. A. Wood, Simulation of SST, sea ice extents, and ocean heat transports in a version of the Hadley Centre coupled model without flux adjustments, *Clim. Dyn.*, 16, 147–168, 2000.
- Hare, S. R., and N. J. Mantua, Empirical evidence for North Pacific regime shifts in 1977 and 1989, *Prog. Oceanog.*, 47, 103–146, 2000.
- Hsieh, W. W., and G. J. Boer, Global climate change and ocean upwelling, *Fish. Oceanog.*, 1, 333–338, 1992.
- Kaufman, Y. J., D. D. Herring, K. J. Ranson, and J. G. Collatz, Earth Observing System AM1 mission to Earth, *IEEE Trans. on Geosci. and Remote Sensing*, 36, 1045–1055, 1998.
- Logerwell, E. A., N. J. Mantua, P. W. Lawson, R. C. Francis, and V. Agostini, Tracking environmental processes in the coastal zone for understanding and predicting Oregon coho (*Oncorhynchus kisutch*) marine survival, *Fish. Oceanog.*, in review, 2002.
- Mantua, N. J., and P. W. Mote, Uncertainty in scenarios of human-caused climate change, *Amer. Fish. Soc. Symp.*, 32, 263–272, 2002.
- Mantua, N. J., S. R. Hare, Y. Zhang, J. M. Wallace, and R. C. Francis, A Pacific interdecadal climate oscillation with impacts on salmon production, *Bull. Amer. Meteorol. Soc.*, 78, 1069–1079, 1997.
- McAvaney, B. J., C. Covey, S. Joussaume, V. Kattsov, A. Kitoh, W. Ogana, A. J. Pigman, A. J. Weaver, R. A. Wood, and Z.-C. Zhao, Model Evaluation, in *Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change*, edited by J. T. Houghton, et al., pp. 471–523, Cambridge Univ. Press, 2001.
- McGowan, J. A., D. R. Cayan, and L. M. Dorman, Climate-ocean variability and ecosystem response in the northeast Pacific, *Science*, 281, 210–217, 1998.
- Mitchell, J. F. B., D. J. Karoly, G. C. Hegerl, F. W. Zwiers, M. R. Allen, and J. Marengo, Detection of climate change and attribution of causes, in *Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change*, edited by J. T. Houghton, et al., pp. 695–738, Cambridge University Press, 2001.
- Xie, L., and W. W. Hsieh, The global distribution of wind-induced upwelling, *Fish. Oceanog.*, 4, 52–67, 1995.

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