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Key Points:
- Comprehensive assessment of pressures, temperatures, and coastal upwelling winds in CMIP5 models
- Poleward shift in distribution of coastal upwelling-favorable winds projected with climate change
- Changes due to displacement of high-pressure systems, not land-sea surface air temperature contrasts

Supporting Information:
- Figures S1–S7 and Table S1

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Poleward displacement of coastal upwelling-favorable winds in the ocean's eastern boundary currents through the 21st century

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Abstract Upwelling is critical to the biological production, acidification, and deoxygenation of the ocean's major eastern boundary current ecosystems. A leading conceptual hypothesis projects that the winds that induce coastal upwelling will intensify in response to increased land-sea temperature differences associated with anthropogenic global warming. We examine this hypothesis using an ensemble of coupled, ocean-atmosphere models and find limited evidence for intensification of upwelling-favorable winds or atmospheric pressure gradients in response to increasing land-sea temperature differences. However, our analyses reveal consistent latitudinal and seasonal dependencies of projected changes in wind intensity associated with poleward migration of major atmospheric high-pressure cells. Summertime winds near poleward boundaries of climatological upwelling zones are projected to intensify, while winds near equatorward boundaries are projected to weaken. Developing a better understanding of future changes in upwelling winds is essential to identifying portions of the oceans susceptible to increased hypoxia, ocean acidification, and eutrophication under climate change.

1. Introduction

High levels of primary production that support massive populations of small pelagic fish and lucrative commercial fishing operations are dependent on the upwelling of nutrient-rich waters along subtropical eastern boundaries of the world's major ocean basins. In these systems, coastal upwelling is driven by alongshore winds stimulated by steep cross-shore gradients in sea level pressure (SLP). Large surface-air temperature (T_{as}) differences between the relatively cool ocean and warm continents during summer are hypothesized to contribute to the development of the steep SLP gradients of the California, Canary, Humboldt, and Benguela Current systems [*Huyer*, 1983; *Seager et al.*, 2003]. This conceptual understanding of the upwelling process at seasonal scales motivated *Bakun* [1990] to suggest that coastal upwelling intensification will occur in response to continued global warming. Specifically, Bakun noted that anthropogenic climate change is anticipated to increase T_{as} over landmasses to a greater extent than over adjacent oceans [*Manabe et al.*, 1991]; consequent deepening of the thermal low-pressure systems over the continents, intensification of the land-sea SLP gradients, and subsequent increases in summertime upwelling-favorable winds (τ_{upw}) are plausible expectations.

Efforts to test Bakun's hypothesis of upwelling intensification are challenged by the limited spatial and temporal extent of observations and changes in methodology of wind measurements during the mid-20th century [*Cardone et al.*, 1990]. Additionally, low-frequency (interannual to multidecadal) variability in the ocean-atmosphere system [*Di Lorenzo et al.*, 2008; *Peterson and Schwing*, 2003; *Schwing and Mendelssohn*, 1997] may confound trends in time series that are relatively short in duration. Recognition of the potential sensitivity of short time series to low-frequency, natural variability has motivated a number of recent efforts to reexamine trends in τ_{upw} using global, multidecadal data sets. In an investigation of trends in annual τ_{upw} in the four systems during the 1960–2001 period, *Narayan et al.* [2010] reported disagreement among three global data sets, finding positive trends in τ_{upw} in Comprehensive Ocean-Atmosphere Data Set time series but discrepancies in trends present in National Centers for Environmental Prediction/National

Center for Atmospheric Research and ERA-40 reanalysis data sets. To better understand the reasons for inconsistencies in reported τ_{upw} trends, *Sydeman et al.* [2014] performed a meta-analysis of published reports and found that studies conducted in poleward portions of the upwelling systems were more likely to report long-term increases in τ_{upw} than analyses of winds in equatorward portions of the systems.

Examining output of coupled atmosphere-ocean general circulation models (AOGCMs) developed in association with the Intergovernmental Panel on Climate Change (IPCC) offers an alternative method to investigate the sensitivity of upwelling to increased greenhouse gas concentrations. As AOGCMs simulate an internally consistent representation of climate dynamics, they allow examination of the intermediate steps of the hypothesized intensification mechanism that can clarify the relationships among T_{as}, SLP, and τ_{upw}. Simulations have typically included representation of the 20th century climate conditions as well as projections forced by future emissions scenarios (i.e., Special Report on Emissions Scenarios (SRES)), Representative Concentration Pathways (RCPs) [*van Vuuren et al.*, 2011], or by increased concentrations of greenhouse gases at a quasi-stable equilibrium (i.e., doubling or quadrupling of atmospheric CO_2 concentrations).

The earliest attempt to examine Bakun's intensification hypothesis in AOGCM simulations was performed by *Hsieh and Boer* [1992]. Under a doubling of CO_2 concentrations, these authors reported projected increases in summertime T_{as} over the landmasses relative to the ocean, as suggested by *Bakun* [1990]. However, corresponding changes in SLP and τ_{upw} were absent. *Mote and Mantua* [2002] examined simulations from two AOGCMs and found no significant changes in τ_{upw} in response to 21st century warming, and a more geographically limited analysis of 23 AOGCMs by *Wang et al*. [2010] reported mixed results when comparing τ_{upw} between the 1980s and 2030s (forced by SRES A1B) in the California, Humboldt, and Canary systems. A suite of recent investigations have considered the dynamics influencing projected changes in upwelling off Chile and Peru [*Belmadani et al*., 2014; *Echevin et al*., 2012; *Garreaud and Falvey*, 2009; *Goubanova et al*., 2011]. *Garreaud and Falvey* [2009] found that three AOGCMs (forced by SRES A2) indicated intensification of τ_{upw} during spring and summer in poleward portions of the climatological upwelling zone and more limited increases in τ_{upw} during fall and winter in equatorward portions of the region. *Belmadani et al*. [2014] reported similar responses in experiments forced by a doubling and quadrupling of atmospheric CO_2 concentrations. Although they noted significant increases in land-sea T_{as} differences, *Belmadani et al*. [2014] found these increased differences to be insufficient to stimulate increased SLP gradients and concluded that the mechanism proposed by *Bakun* [1990] is not the dominant process influencing anthropogenic changes in τ_{upw}. Instead, both *Belmadani et al*. [2014] and *Garreaud and Falvey* [2009] noted that steep topography along the coast of the Humboldt system permits a significant ageostrophic influence and projected increases in τ_{upw} at midlatitudes are a consequence of a poleward migration of the oceanic high-pressure system and the resultant shift in the location of the primary alongshore atmospheric pressure gradient.

Continued concern for the future of the upwelling process motivated us to compare projected changes in τ_{upw} across eastern boundary current systems using the most recent AOGCM simulations developed in association with the Fifth Assessment Report of the IPCC [*Taylor et al*., 2012]. We also examine changes in T_{as} and SLP to assess the suitability of Bakun's intensification hypothesis as a description of simulated changes in upwelling systems.

2. Methods

Here we utilize output from 21 AOGCMs to investigate the proposed mechanism of upwelling intensification with climate change following RCP 8.5, a high radiative forcing scenario [*Riahi et al*., 2011]. Model projections of oceanic and atmospheric properties during the 2071–2100 period are compared to an 1861–1890 base period using paired Student's *t* tests [*Press et al*., 1992]. Monthly fields of T_{as}, SLP, and meridional wind stress are obtained from AOGCM output contributed to the Coupled Model Intercomparison Project Phase 5 (CMIP5) database. Criteria for model selection include availability of monthly output for the 1861–2005 period parameterized with estimates of historical greenhouse gas concentrations (i.e., the CMIP5 "historical" experiment) and for the 2006–2100 period parameterized as specified by RCP 8.5. Selected models and their horizontal resolutions are listed in Table S1 in the supporting information.

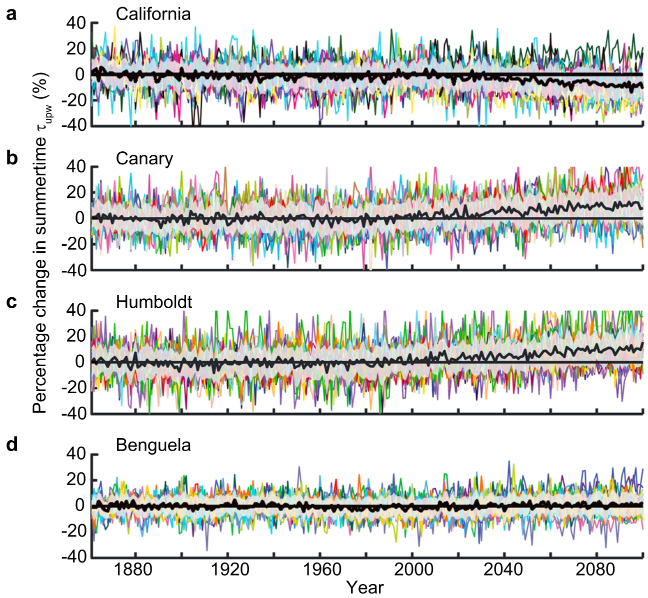

Figure 1. Time series of percentage change in summertime τ_{upw} relative to an 1861–1890 base period for the (a) California, (b) Canary, (c) Humboldt, and (d) Benguela Current systems. In each panel, the colored lines represent the projections of individual models, and the bold, black line indicates the multimodel ensemble mean. The gray boundary represents ±1 standard deviation of the multimodel ensemble. Average changes and standard deviation are reported in Table 1.

Model data are subset to regions relevant for the four major coastal upwelling ecosystems. For each region, wind stresses are examined from the coast to 600 km offshore, broadly representative of the area of upwelling-favorable winds [*Jacox et al*., 2014]. To represent the major oceanic SLP and T_{as} fields relevant to forcing of the upwelling process [*Schroeder et al*., 2013], these properties are extracted from 600 km offshore to a meridian about 2500 km offshore (155°W for the California, 45°W for the Canary, 130°W for the Humboldt, and 15°W for the Benguela Current systems). For representation of SLP and T_{as} over western portions of the continents, properties are examined from the coastline to 600 km inland. Latitudinal domains are chosen to include eastern boundary current regions of seasonal upwelling and are 26°N to 49°N for the California, 26°N to 44°N for the Canary, 16°S to 44°S for the Humboldt, and 16°S to 34°S for the Benguela Current systems. The summer season is defined as June–August (January–March) in the Northern (Southern) Hemisphere. Positive values of τ_{upw} correspond to northerly (southerly) wind stress for the Northern (Southern) Hemisphere.

To estimate model means and intermodel standard deviation for data plotted spatially, variables are interpolated onto a common 1° × 1° grid. Significance of projected changes are defined relative to the intermodel spread and are considered robust where the multimodel mean change exceeds the intermodel standard deviation. To interpret seasonal and latitudinal sensitivity of changes in τ_{upw}, Hovmöller diagrams are created by averaging values across zonal bands after interpolation onto the common grid.

3. Model Results and Analyses

We find that projected changes in summertime τ_{upw} are inconsistent across the four eastern boundary currents (Figure 1 and Figure S1 in the supporting information). In the Humboldt and Canary Current systems, *t* tests indicate that a majority (62% and 86%, respectively) of models project significant increases in regionally averaged τ_{upw} (Figure 2); by the final three decades of the 21st century, the mean, summertime intensity of τ_{upw} (as assessed by the AOGCM ensemble mean) is expected to increase in comparison to the 1861–1890 mean by 10% (±12% standard deviation) in the Humboldt Current (Figure 1c) and by 10% (±10% standard deviation) in the Canary Current (Figure 1b and Table 1). None of the models project a significant decrease in τ_{upw} for these two systems.

Projected changes are less consistent in the Benguela Current system, with 29% of models indicating significant increases in τ_{upw}, 24% indicating significant decreases, and the remainder projecting no significant changes (Figures 1d and 2d). The multimodel mean increase in summertime τ_{upw} for the Benguela system is 1% (±7% standard deviation) from the 1861–1890 to 2071–2100 period (Table 1). The California Current stands out as the only system for which the majority (71%) of models project significant decreases in summertime τ_{upw}. The multimodel average change in τ_{upw} for this region is −8% (±10% standard deviation; Figure 1a and Table 1). Of the 21 models examined, only one model projects a significant increase in τ_{upw} in the California Current system (Figure 2a).

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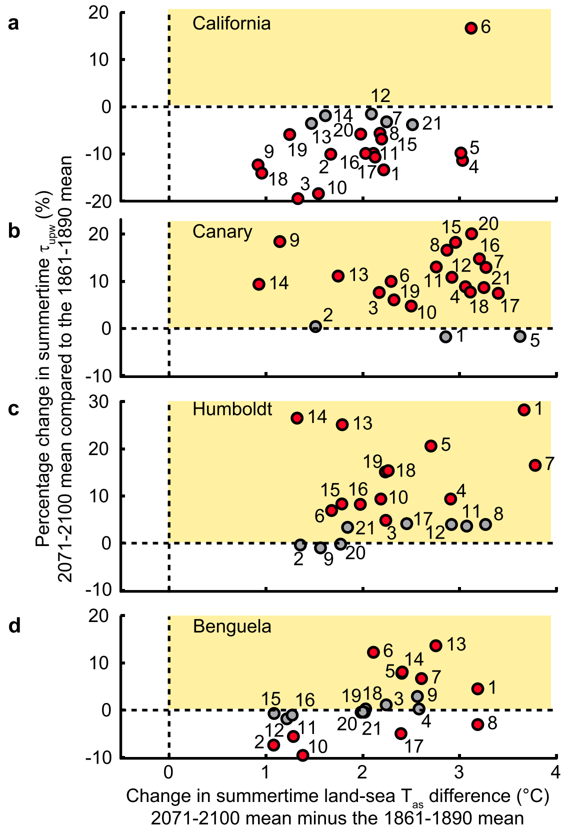

Figure 2. Individual model projections of summertime changes in land-sea T_{as} differences versus changes in τ_{upw}. Regional changes between the 1861–1890 and the 2071–2100 periods are displayed for (a) California, (b) Canary, (c) Humboldt, and (d) Benguela Current systems. Models for which the projected change in τ_{upw} is significant (as determined by a *t* test; $P < 0.05$) are indicated in red. All increases in T_{as} differences are significant. Models falling within the upper right quadrant (noted in yellow) indicate those for which the increase in land-sea T_{as} difference is accompanied by an intensification of τ_{upw}. The numbers identify the individual model's results (see Table S1).

The hypothesis of upwelling intensification [*Bakun*, 1990] relies on a series of relationships that can be considered in a piecewise fashion. The major steps include (1) greater increases in T_{as} over continents relative to adjacent ocean areas, (2) decreases in the climatological thermal low pressures over the warming continents and steeper cross-shore SLP gradients, and (3) intensification of τ_{upw}. As noted above, the third step of this hypothesis is not a general characteristic of AOGCM projections; only in two of the four major upwelling systems do a majority of models project increased summertime τ_{upw}, and in no system does the multimodel mean of projected change exceed the intermodel standard deviation (Table 1). However, in all systems, each AOGCM projects intensification of land-sea T_{as} differences through the 21st century (Figures 2 and 3a and Figure S2), a result consistent with previous global analyses [*Lambert et al.*, 2011] and likely a consequence of differences in boundary layer lapse rates (i.e., the rate of change in atmospheric temperature with altitude), relative humidity, and heat fluxes between land and ocean regions [*Collins et al.*, 2013]. These unambiguous increases in summertime land-sea T_{as} differences are not accompanied by clear decreases in SLP over continents (Figure 3b), increases in cross-shore SLP gradients, or increases in τ_{upw} (Figures 2 and 3c). The Canary Current system is the only region for which significant deepening of the continental thermal low-pressure system (i.e., SLP over the western Iberian Peninsula and Sahara) is projected across models. SLP changes projected in other upwelling regions are generally more variable, although consistent increases in SLP are projected along poleward boundaries of Southern Hemisphere systems in association with a projected increase in the Southern Annular Mode and poleward expansion of the Hadley cell [*Gillett and Fyfe*, 2013; *Lu et al.*, 2007].

While increases in regionally averaged summertime τ_{upw} in response to global warming are not commonly projected by AOGCMs examined here, spatial plots of τ_{upw} changes (Figure 3c) indicate some robustness in responses common across systems. A meridional gradient in the magnitude of projected changes in τ_{upw} is present in each system; poleward portions of the domains tend to exhibit intensified τ_{upw}, while τ_{upw} in equatorward portions of the domains tend to decrease (Figure 3 and Table 1 and Figures S3 and S4). This consistency in latitudinal patterns of τ_{upw}

Table 1. Percentage Change in Summertime τ_{upw} During the 2071–2100 Period Relative to an 1861–1890 Base Period

	Complete Region	Poleward Portion	Equatorward Portion
California	−8% (±10 SD)	−2% (±18 SD)	−13% (±10 SD)
Canary	10% (±10 SD)	26% (±18 SD)	2% (±11 SD)
Humboldt	10% (±12 SD)	47% (±34 SD)	−9% (±9 SD)
Benguela	1% (±7 SD)	9% (±10 SD)	−6% (±9 SD)

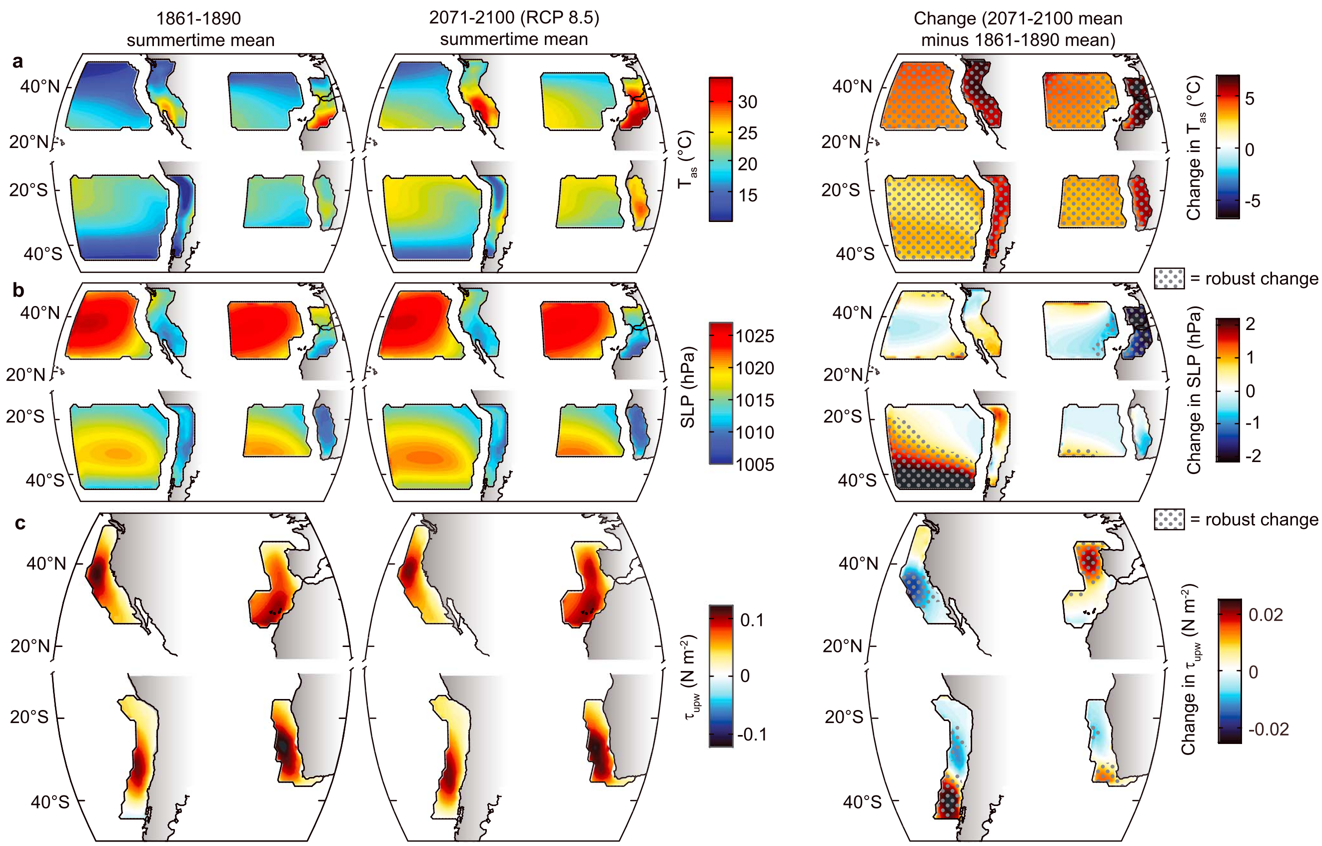

Figure 3. Ensemble mean plots of properties relevant to the upwelling intensification hypothesis. (a) T_{as}, (b) SLP, and (c) τ_{upw}. For each property, (left) the multimodel summertime mean for the 1861–1890 period, (middle) the 2071–2100 period, and (right) the change between the two periods (2071–2100 mean minus 1861–1890 mean) are displayed. Stippling indicates the areas of robust change across models. In Figure 3c, the positive values consistently indicate upwelling-favorable winds (and increases in upwelling-favorable winds in Figure 3c, right).

changes, paired with lack of common trends in regionally averaged τ_{upw}, highlights the sensitivity of trend estimates to spatial domains examined.

Projected changes in latitudinal and seasonal characteristics of τ_{upw} are plotted in Figure 4 and Figure S5. The AOGCMs represent major geographic patterns of the seasonal cycle in τ_{upw} as identified by previous investigators examining observational records; upwelling is generally persistent year round in equatorward portions of each upwelling region, and the amplitude of the seasonal cycle of τ_{upw} increases toward the poles with a tendency for downwelling in winter and upwelling in summer [*Bakun and Nelson*, 1991; *Huyer*, 1983; *Schwing and Mendelssohn*, 1997]. When comparing these seasonal characteristics between the 1861–1890 and 2071–2100 periods, intensification of summertime τ_{upw} is evident in poleward portions of each region, but this intensification is coincident with decreased τ_{upw} in equatorward portions of the domains. Such changes may be interpreted as a poleward shift in the latitudinal locations of peak summertime τ_{upw}, and we found a positive relationship across models when comparing meridional shifts in the locations of the oceanic high-pressure systems with the latitudes of maximal upwelling-favorable winds (Figure S6). Locations of continental low-pressure systems are not sensitive to anthropogenic warming (Figure S7), likely due to the association of these continental lows with fixed topographic features. Outside of the summer season, some increases in τ_{upw} are projected in equatorward portions of upwelling regions, but consistency of wintertime changes across models is reduced in comparison to summertime changes (particularly for Northern Hemisphere systems; Figure 4). The California Current differs from other regions, in that model agreement is limited to regions between 30°N and 38°N where the multimodel mean indicates future decreases in summertime τ_{upw} except for a portion of the central and northern California coastline where models project intensification in April and May (respectively, Figure 4a). Further consideration of the ecological implications of such seasonally specific

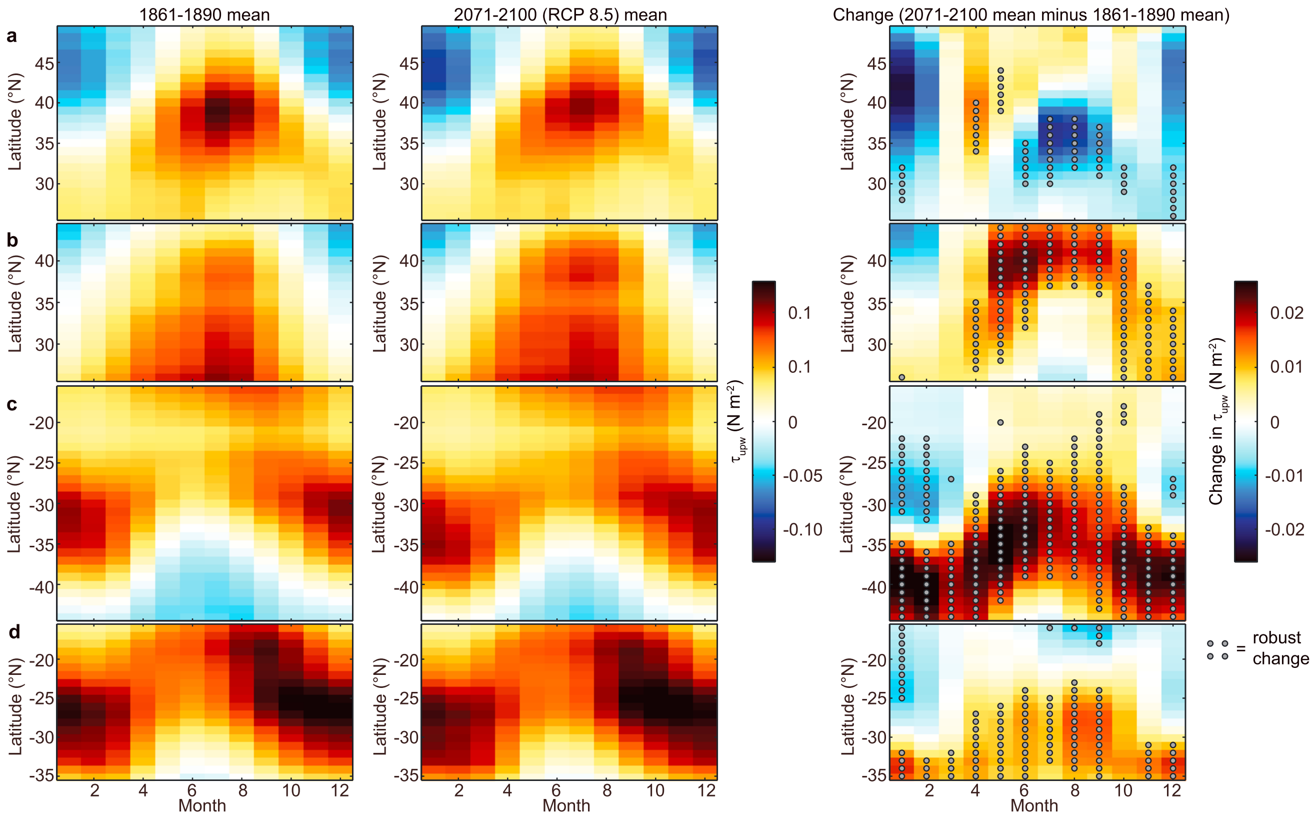

Figure 4. Hovmöller diagrams of τ_{upw} over the seasonal cycle across latitudes. (left) The multimodel mean for the 1861–1890 period, (middle) the 2071–2100 period, and (right) change between the two periods (2071–2100 mean minus 1861–1890 mean) are displayed for (a) California, (b) Canary, (c) Humboldt, and (d) Benguela Current systems. Stippling indicates the areas of robust change across models.

changes in the intensity of τ_{upw} are warranted, as many populations of the California Current have exhibited increased sensitivity to upwelling variability at the end of winter and early spring [*Black et al.*, 2011; *Schroeder et al.*, 2013]. The consequences of such phenological shifts in the other eastern boundary currents should also be explored.

4. Discussion

The ensemble of models analyzed here do not support the hypothesis that intensified τ_{upw} or SLP gradients will result from the increased land-sea T_{as} differences associated with global warming. The T_{as} differences between eastern ocean basins and adjacent midlatitude landmasses will increase in the future, but consequent increases in SLP gradients are not evident. This lack of a direct response of SLP to T_{as} indicates that anthropogenic changes in τ_{upw} are more complex than proposed by *Bakun* [1990] and demonstrates the need to consider changes in both thermal and hydrodynamic (i.e., water vapor content) processes when interpreting the full dynamical response of the coupled atmosphere-ocean system to climate warming. In this aspect, our conclusions differ markedly from those presented in another recent manuscript [*Wang et al.*, 2015] in which the authors examine AOGCM simulations and suggest a causal relationship between increasing summertime land-sea T_{as} differences and intensified τ_{upw} in response to anthropogenic climate change. However, in their consideration of the impact of climate processes on τ_{upw}, *Wang et al.* [2015] limit their analysis to the latitudes in which significant positive trends in τ_{upw} were evident, a posteriori, and reach a biased conclusion supporting the hypothesis proposed by *Bakun* [1990]. We find that increased land-sea T_{as} differences are ubiquitous in projections of future conditions (simulated by each of the climate models and in all regions), but positive trends in summertime τ_{upw} are limited to the poleward extremes of upwelling zones, indicating that increased land-sea T_{as} differences do not have a dominant influence on SLP gradients and τ_{upw}.

Our analyses have identified a tendency for projected increases in τ_{upw} in poleward portions of each system and decreases in these winds in equatorward portions of the domains. This result regarding the latitudinal dependency of changes in τ_{upw} is consistent with the meta-analysis of historical changes performed by *Sydeman et al*. [2014] and the model analysis of *Wang et al*. [2015]. However, in contrast to these recent analyses that indicated some support for the upwelling intensification hypothesis of *Bakun* [1990], we demonstrate that projected changes in upwelling-favorable winds are not directly related to broad increases in land-sea T_{as} differences associated with anthropogenic climate change. Instead, we propose an alternate hypothesis: anthropogenic changes in the intensity of upwelling-favorable winds will be associated with shifts in the seasonal development and geographic positioning of the four major atmospheric high-pressure systems. Poleward shifts in SLP fields are expected in response to increased greenhouse gas concentrations [*Gillett and Fyfe*, 2013; *Lu et al*., 2007], and these shifts will stimulate changes in the magnitude, timing, and location of upwelling winds that are more consequential than increases in land-sea T_{as} differences. Consideration of shifts in the intensity and latitudinal location of upwelling will be essential for identifying portions of the coasts most at risk of increased hypoxia, ocean acidification, and eutrophication under conditions of future warming.

Our conclusions regarding the seasonal and latitudinal sensitivity of projected trends in upwelling intensity are consistent with more focused analyses of the Humboldt Current system [*Belmadani et al*., 2014]. The momentum budget performed by *Belmadani et al*. [2014] highlights the sensitivity of τ_{upw} to changes in the location and intensity of the oceanic high-pressure system and demonstrates the need to consider both geostrophic and ageostrophic processes affecting the boundary layer of the coastal ocean. Such analyses may offer insight to the dynamics regulating changes in other upwelling zones. While the conclusion that future increases in land-sea T_{as} differences do not stimulate increased cross-shore SLP gradients or increased τ_{upw} has been a consistent finding of AOGCM analyses over the past three decades, these models still have fairly coarse spatial resolutions that do not represent regionally specific topographic features likely to influence SLP and τ_{upw} at fine scales. Changes in SLP and τ_{upw} involve a complex interplay among a suite of dynamic and thermodynamic processes of the surface and troposphere [*Garreaud and Falvey*, 2009; *Seager et al*., 2003], and these AOGCM simulations are certainly not the last word regarding the impact of anthropogenic climate change on τ_{upw}. Increased model resolution and improved representation of clouds, fog, and other atmosphere-ocean-land feedback in the narrow zone between coastal topographic features and the open ocean will facilitate better understanding of boundary layer structure and wind stress in upwelling systems. Furthermore, long-term change in local, alongshore wind forcing is one of several processes necessary to consider when exploring the sensitivity of the upwelling process to climate change [*Bakun et al*., 2015]. Properties of source waters supplied to upwelling systems, including nutrient concentrations and ratios, characteristics of the ocean carbonate system, and dissolved oxygen levels, are sensitive to climate change [*Deutsch et al*., 2011; *Feely et al*., 2008; *Monteiro et al*., 2011; *Rykaczewski and Dunne*, 2010] and have important ecological impacts [*Bograd et al*., 2008; *Grantham et al*., 2004; *Zhang et al*., 2010]. Additionally, changes in water-column stratification can alter upwelling efficacy [*Chhak and Di Lorenzo*, 2007; *Roemmich and McGowan*, 1995], and the offshore distribution of maximal τ_{upw} (and associated changes in wind-stress curl) can influence the rate and spatial location of upwelling [*Jacox et al*., 2014; *Rykaczewski and Checkley*, 2008]. Interactions among basin-scale processes and subsurface biogeochemistry that alter source-water properties of upwelled water masses, stratification, and mesoscale hydrographic features should be considered in concert with atmospheric forcing to develop a comprehensive understanding of the implications of climate change for the world's upwelling ecosystems.

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