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Relative influence of oceanic and terrestrial pressure systems in driving upwelling-favorable winds

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[1] We use the 20th Century Reanalysis database to assess the influence of oceanic and terrestrial atmospheric pressure systems on winter and summer upwelling-favorable winds in Eastern Boundary Upwelling Systems. The analysis provides baseline information regarding the roles of continental thermal low (CTL) and oceanic high (OH) pressure systems in driving seasonal upwelling modes, which have high biological relevance. We show that variability in upwelling-favorable winds is dominated by OH, particularly in winter, and only weakly influenced by CTL, except at annual time scales. This is most pronounced in the California system given that the North Pacific High dominates wind variability. In contrast, CTL and OH equally influence Benguela upwelling-favorable winds during summer. This work underscores the need to understand how OH systems are likely to respond to climate change and how this might impact coastal winds that drive upwelling and productivity in these ecosystems. **Citation:** García-Reyes, M., W. J. Sydeman, B. A. Black, R. R. Rykaczewski, D. S. Schoeman, S. A. Thompson, and S. J. Bograd (2013), Relative influence of oceanic and terrestrial pressure systems in driving upwelling-favorable winds, *Geophys. Res. Lett.*, *40*, 5311–5315, doi:10.1002/2013GL057729.

1. Introduction

[2] Eastern Boundary Upwelling Systems (EBUS) cover only 1% of ocean surface yet account for up to 20% of global fisheries catch [*Mann*, 2000]. Such high levels of biological productivity are largely due to equatorward alongshore winds [*Seager et al*., 2003], which drive coastal upwelling and nutrient enrichment of euphotic zones. During the warm months, coastal winds strengthen by the development of land-based thermal low-pressure systems, generally located east of permanent but seasonally migrating oceanic high (OH) pressure systems [*Huyer*, 1983; *Seager et al*., 2003; *Montecino and Lange*, 2009]. While biological productivity in EBUS is mainly the result of warm-season upwelling, winter upwelling, although weaker and sporadic, is also important [*Borges et al*., 2003; *García-Reyes et al*., 2013, and references therein]. Therefore, understanding seasonal (i.e., summer versus winter) drivers of upwelling variability is of significance to forecasting ecosystem dynamics.

[3] Many studies have described upwelling variability on interannual and multidecadal time scales [*Mendelssohn and Schwing*, 2002; *Narayan et al*., 2010; *Santos et al*., 2012], including research on the position and strength of OH systems [*Rahn*, 2012; *DeCastro et al*., 2011; *Schroeder et al*., 2013] or, less commonly, continental thermal low (CTL) systems [*Bakun*, 1990; *Risien et al*., 2004]. In all previous studies, though, only one of the pressure systems (oceanic or terrestrial) has been addressed; however, both may drive upwelling winds variability, and the relative roles of each may vary seasonally. In this study, we use the 20th Century Reanalysis data set to test the hypothesis that OH pressure systems dominate interannual to multidecadal variability in upwelling winds in the four EBUS and that CTL pressure systems exert a secondary influence primarily in summer.

2. Data

[4] We use the 20th Century Reanalysis (20CR) *Compo et al*., 2011) provided by NOAA (http://www.esrl.noaa.gov/psd/data/gridded/data.20thC_ReanV2.html). The 20CR is generated by a global atmospheric circulation model, which assimilates surface pressure. Data span 1871 through 2010 with 6 h temporal and 2° spatial resolution, making 20CR the longest and most comprehensive data set of its kind. Data density, however, varies through time and differs between hemispheres; an exponential increase in data density occurs after 1900 in the Northern Hemisphere and about 1940 in the Southern Hemisphere. We chose data from 1920 to 2010 as a compromise between time series length and data density (see supporting information). Monthly values of sea level pressure (SLP; atmospheric pressure corrected to mean sea level while assuming normal atmospheric conditions) and meridional wind speed (V) were analyzed. The mostly north-to-south alignment of upwelling zones allowed us to use V winds as our standardized response variable. Positive values indicate winds directed toward the equator, which are upwelling favorable in all four systems.

3. Methods

[5] Seasonal mean SLP and V fields were calculated for summer and winter. While there are differences in the average timing of upwelling seasons [*Seager et al*., 2003], here

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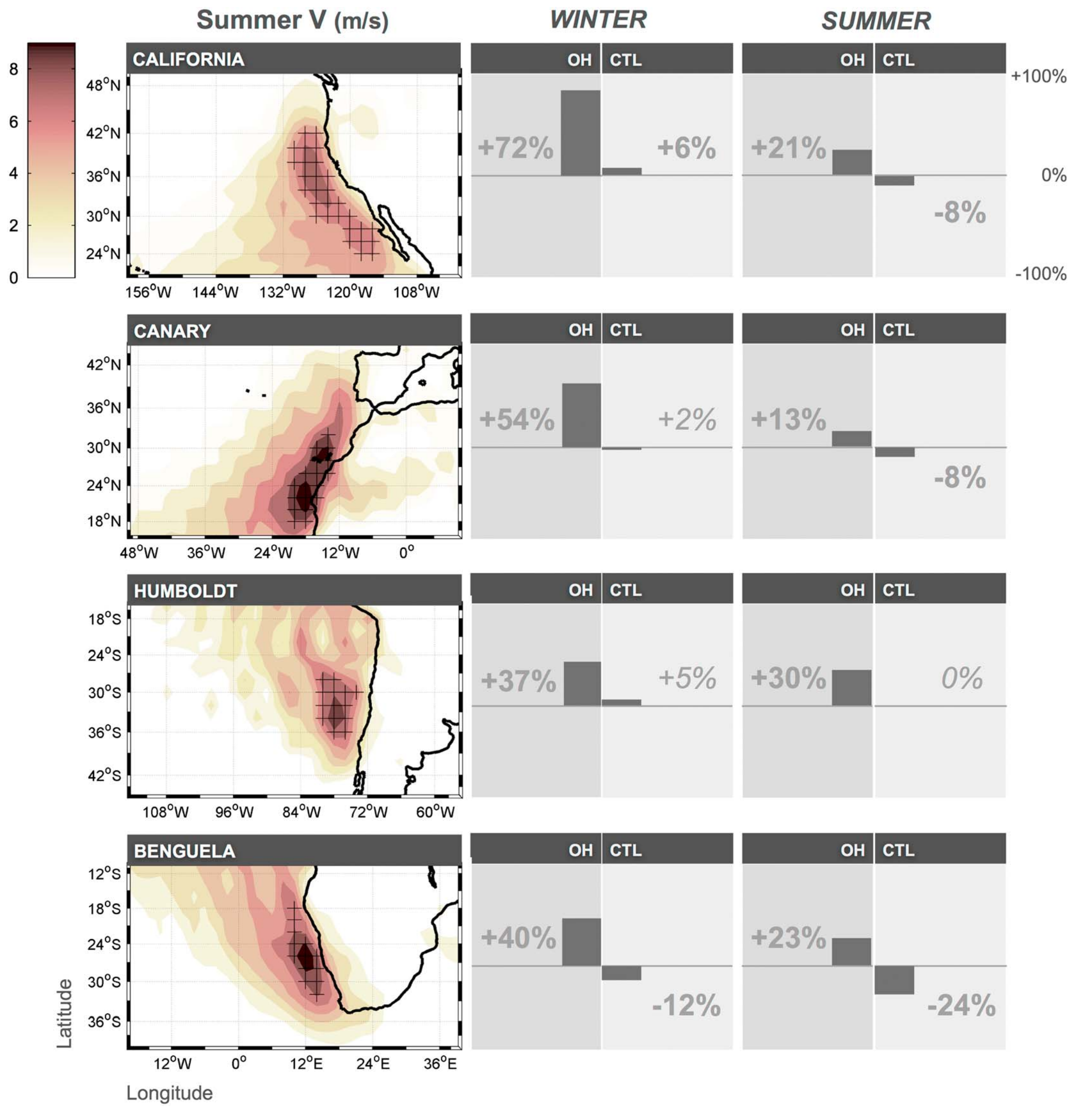

Figure 1. Maps show summer (May–July for the Northern Hemisphere and December–February for the Southern Hemisphere) averages of upwelling-favorable meridional wind speed V (m/s) in the EBUS. Hatched regions indicate the area defined as the "upwelling region" based on the intensity of V. (right) Coefficient of determination (R^2, expressed in percent) between V and the two pressure zones (OH SLP and CTL SLP) for each EBUS and season (winter and summer). Significant values ($P < 0.05$) are indicated in bold.

seasons are defined as December–February for winter (summer) and May–July for summer (winter) in the Northern (Southern) Hemisphere, based on the time when the strongest upwelling-favorable winds occur and the corresponding period 6 months later. Within each system, upwelling regions were demarcated by the isotach of strongest upwelling-favorable winds during the summer months minus 1σ (standard deviation) for each system (Figure 1). The OH pressure system was demarcated by the highest SLP minus 1σ isobar over the ocean, while the CTL was demarcated by the lowest SLP plus 1σ isobar over land (Figure S2 in the supporting information).

[6] Monthly and seasonal time series were calculated by averaging V over the total area of each upwelling region and SLP over the total area of each pressure system (OH and CTL). To analyze the covariability between monthly OH SLP/CTL SLP and V time series, we performed cross-wavelet coherence analysis. Pearson correlations were calculated between seasonal time series of OH SLP/CTL SLP and V after linear trends had been removed. A multiregression model was applied to V to calculate the relative importance (reflected in standardized coefficients, β) of OH SLP and CTL SLP to V variability.

4. Results

[7] Cross wavelets demonstrated coherence of V with the pressure systems' variability across a range of frequencies. V showed coherence with CTL SLP (Figure 2, right) at the annual scale, although some coherence was also observed at decadal scales. In contrast, coherence was more pronounced between V and OH SLP at a range of scales from interannual to decadal, but with less coherence on the annual scale than with CTL SLP (Figure 2, left). Note that the cross-wavelet coherence identifies frequencies at which time series covary, but not necessarily with high spectral power.

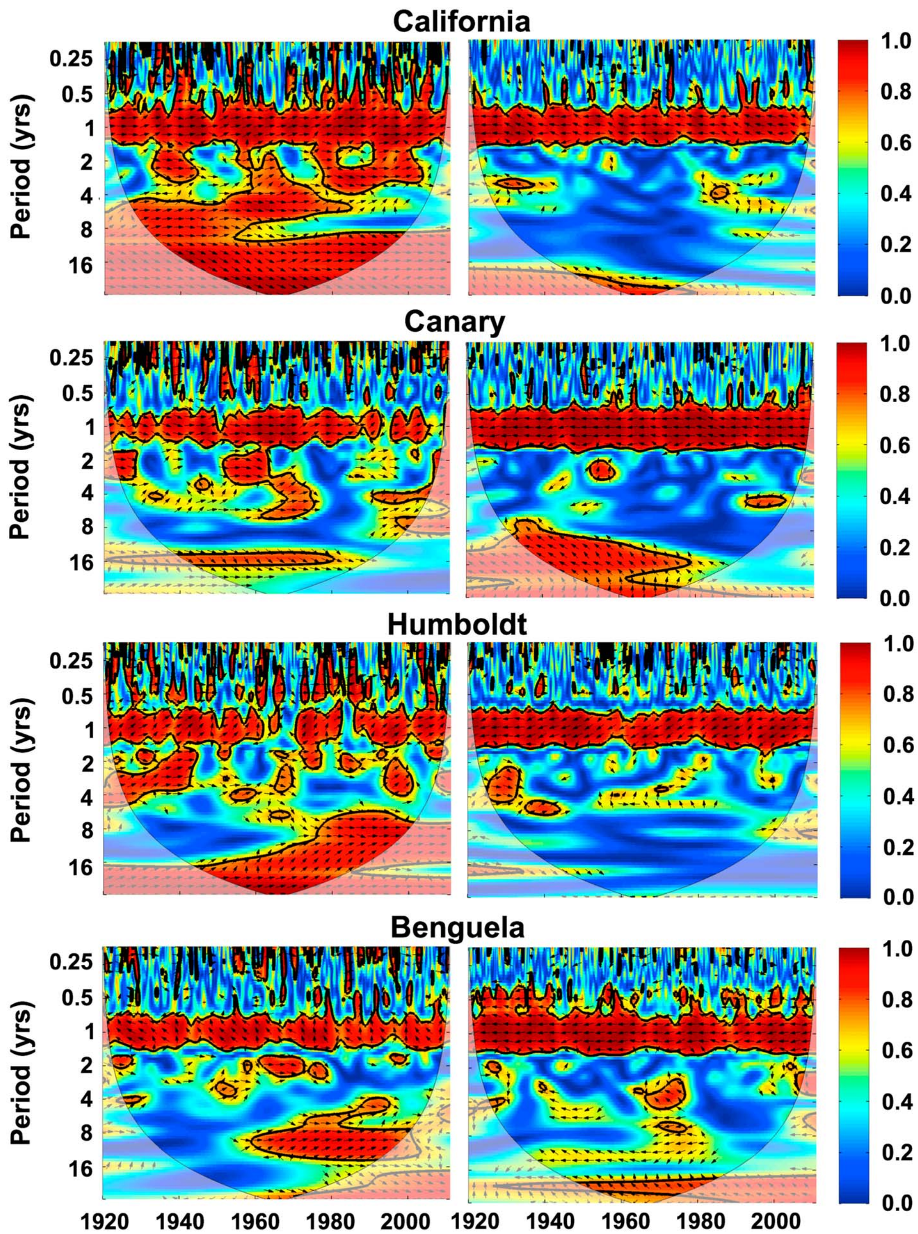

Figure 2. Cross-wavelet coherence analysis between V and (left) OH SLP and (right) CTL SLP for each EBUS. Color indicates the level of covariability between time series, with values between 0 and 1, while arrows indicate the relative phase between the time series. Black lines indicate significant covariability ($P < 0.05$), while white shading highlights the cone of influence where the effects of the time series limits become important.

[8] The multiregression shows the relative contribution of each pressure system on V variability for each EBUS and produced results comparable to univariate analyses (Table 1 and Figure 1). In winter, V was dominated by OH SLP for all EBUS, particularly in California, where the CTL SLP $\beta = \sim 0$. Correlations between V and CTL SLP were significant ($P < 0.05$) but contributed low explanatory power ($R^2 = 0.12$ and $R^2 = 0.06$) in the Benguela and California systems, respectively. In summer, the Pacific systems were also dominated by OH SLP, particularly the Humboldt system. In the Atlantic, OH SLP and CTL SLP showed comparable effects on V (i.e., β of similar magnitude), although for the Canary system, V was poorly explained by SLP in general. It is worth noting that in the Southern Hemisphere, winter and summer coefficients of determination (R^2) were similar, while for the

Table 1. Multiple Regression Results[a,b]

		California		Canary		Humboldt		Benguela	
		R^2	β	R^2	β	R^2	β	R^2	β
Winter	OH	0.72	0.85	0.53	0.81	0.38	0.52	0.52	0.71
	CTL		*0.0*		−0.27		0.22		−0.27
Summer	OH	0.40	0.58	0.21	0.37	0.40	0.64	0.50	0.54
	CTL		−0.35		−0.36		*−0.02*		−0.52

[a]β are the standardized coefficients. All are significant values ($P < 0.05$), except those in italics. The independence of OH SLP and CTL SLP time series was tested in each system and season; only the Canary system showed a significant but low correlation ($\rho = 0.42$, $P < 0.05$) between OH SLP and CTL SLP time series during winter.

[b]The ability of OH SLP and CTL SLP to explain V wind is tested for each EBUS and season (winter and summer).

Northern Hemisphere, they were higher for winter. Finally, a comparison between results from the analysis, including only the first and last four decades of the time series, produced similar results (not shown) in which OH SLP was most closely related to V, especially during wintertime. There were no consistent differences in the strength or signs of correlations between these two periods.

5. Discussion

[9] The power of atmospheric pressure to predict variability of upwelling-favorable winds at seasonal to interannual time scales is moderate (Figure 1 and Table 1). The California and Canary EBUS stand out because variability in winter winds is dominated by the OH, likely related to the strong, persistent, and highly dynamic nature of winter pressure systems in the Northern Hemisphere (OHs, but also high-latitude low-pressure systems, i.e., Aleutian and Icelandic lows). This is particularly relevant for biological populations within the upwelling systems that show high sensitivity to variability in winter upwelling [*Black et al*., 2011; *García-Reyes et al*., 2013], which depends on large-scale features rather than local processes. In summer when winds in the eastern Pacific are strongest, correlations with CTL SLP are weak, which could be due to the discontinuity in winds and pressure fields caused by the coastal mountain ranges not present in the Atlantic systems [*Bakun et al*., 2010]. In addition, relatively low correlations with SLP in general are possibly a consequence of scale, particularly in summer. Pressure systems tend to be highly entrenched and stable in summer months [e.g., *Schroeder et al*., 2013], while variability in upwelling-favorable wind occurs in intervals from hours to weeks in response to diurnal cycles or local atmospheric conditions that could affect temperature and pressure gradients [*Nuss et al*., 2000; *Woodson et al*., 2007]. This is reflected in the low covariability of CTL SLP and V at intraseasonal and lower frequencies (Figure 2), especially in summer. Moreover, *Bane et al*. [2007] suggested that intraseasonal variability associated with the polar jet stream could drive upwelling variability with a periodicity of about 20 days. Other intraseasonal disturbances that have been suggested to influence variability in V include the position of the Intertropical Convergence Zone [*Montecino and Lange*, 2009] and the Madden-Julian Oscillation (periodicity of 30–60 days), particularly for the south Pacific OH [*Rahn*, 2012].

[10] A proposition by *Bakun* [1990] suggesting that rising atmospheric CO_2 concentrations would deepen the CTL, thereby enhancing upwelling-favorable winds, has prompted many studies [*Narayan et al*., 2010; *Patti et al*., 2010, and references therein]. Our results indicate that changes in OH could be equally or more important than changes in CTL in driving upwelling variability over time scales other than seasonal (Figure 2), with the possible exception of the Benguela system, where OH SLP and CTL SLP were equally influential. The relevance of OH variability on winds is particularly important considering that OHs are influenced by a number of atmospheric phenomena like El Niño–Southern Oscillation [*Schwing et al*., 2002] and variability of the North Pacific's Aleutian Low Pressure system [*Bograd et al*., 2002]. In the South Atlantic, the influence of both above mentioned phenomena has been reported [*Rahn*, 2012], along with that of an El Niño–like cycle [*Shannon and Nelson*, 1996] and the North Atlantic Oscillation [*DeCastro et al*., 2011]. These patterns operate primarily at interannual to decadal time scales. Few studies are available that describe longer time scale phenomena, particularly in the Southern Hemisphere.

[11] Future variability of OH is not well known. Based on global climate model projections under increased greenhouse gas concentrations, *Li et al*. [2012] and *Nakamura* [2012] suggested that OH might intensify and migrate west due to increased land-ocean thermal contrast. *Lu et al*. [2007] suggested poleward migrations of OH due to weakening of the Hadley circulation; in contrast, *Mitas and Clement* [2005] showed strengthening of the Hadley circulation in recent decades. Moreover, *Gillett et al*. [2003] showed that over the past several decades, observed ocean SLP trends in the North Pacific and the North Atlantic have opposite signs. Clearly, research is needed to understand how multidecadal and unidirectional climate variability may impact subtropical OH systems and, furthermore, how variability in upwelling-favorable winds in conjunction with variability in ocean conditions [*Di Lorenzo et al*., 2005] would impact populations that depend on them, particularly during wintertime. Our demonstration of the importance of OH provides justification for these investigations.

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