INTRODUCTION

The four major Eastern Boundary Upwelling Systems (EBUS) occur at the eastern edges of subtropical gyres in the Atlantic and Pacific oceans -- the California (CalCS), Humboldt (HumCS), Canary (CanCS), and Benguela (BenCS) Current Systems. These regions are characterized by seasonal or permanent equatorward winds that cause upwelling due to both offshore Ekman transport as well as wind stress curl-driven Ekman suction within the first 200km of the coastline (Chavez and Messié, 2009). Upwelling delivers deep waters with respired nutrients to the surface, fueling primary production and ultimately supporting fisheries that are highly productive with respect to the small surface area they cover (Ryther, 1969). Upwelled waters also have an elevated dissolved inorganic carbon (DIC) content, which enhances the partial pressure of carbon dioxide (pCO2), tending to make these systems a relatively strong source of CO2 to the atmosphere nearshore. The carbonate chemistry of EBUS is controlled by a complex interplay of physical and biological processes: entrainment of subsurface waters, horizontal advection, upwelling and vertical mixing, temperature changes, photosynthesis, respiration, and calcium carbonate formation and dissolution (DeGrandpre et al., 1998; King et al., 2007). These terms combine to dictate oceanic pCO2, which drives the pCO2 gradient between the ocean and atmosphere (ΔpCO2) thus contributing to the magnitude and determining the direction of air-sea CO2 fluxes.

Although coastal oceans have a small net contribution to the global air-sea carbon flux, they are characterized by a high CO2 flux density, or magnitude of air-sea carbon exchange per unit area (Gruber, 2015; Laruelle et al., 2017, 2014, 2010). Low-latitude upwelling systems, such as the HumCS and CanCS, tend to be net outgassing systems, due to their relatively warm waters and persistent upwelling, which are not fully compensated for by enhanced biological productivity. Because of their colder temperatures and more efficient biology, mid-latitude systems, such as the CalCS and BenCS, act as weak CO2 sinks that can become CO2 sources during certain seasons (Borges and Frankignoulle, 2002; Cai et al., 2006; Gregor and Monteiro, 2013; Hales et al., 2005). Surface ocean pCO2 and thus air-sea CO2 flux in EBUS exhibits high temporal variability at sub-seasonal, seasonal, and interannual time scales (DeGrandpre et al., 1998; Evans et al., 2011; Friederich et al., 2002; González-Dávila et al., 2009; Leinweber et al., 2009; Turi et al., 2014). While the pronounced temporal variability of CO2 fluxes in EBUS has been documented by numerous studies, little work has been done to associate it directly with internal climate variability, or variability arising from unforced interactions between components of the climate system.

Studies have instead focused on associating major modes of climate variability with variability in the physics and biology of EBUS (e.g., Barber and Chavez, 1983; Chavez et al., 2002). This is a reasonable focal point, as coastal systems provide the majority of marine resources harvested by humans (Pauly and Christensen, 1995) and CO2 fluxes are notoriously difficult to measure. However, internal variability in EBUS CO2 fluxes is important to study, as it imposes variability on the fractional uptake of anthropogenic carbon by the ocean as well as modifies the surface ocean pH, potentially leading to intermittent ocean acidification events in the future (Kwiatkowski and Orr, 2018; Landschützer et al., 2018). Previous studies have tended to analyze the influence of internal climate variability on CO2 fluxes for a single EBUS and a single climate event. El Niño Southern Oscillation (ENSO) has been observed to drive anomalous CO2 flux in both the CalCS (Friederich et al., 2002) and HumCS (Chavez, 1999). El Niño (La Niña) tends to cause uptake (outgassing) anomalies in these systems, primarily through modifications to the thermocline depth and upwelling rates of nutrient- and carbon-rich waters, which in turn alters biological activity. However, upwelling-favorable winds can persist during some El Niños in the HumCS (Huyer et al., 1987), leading to persistent or enhanced outgassing of CO2 to the atmosphere (Torres, 2003). Longer-term fluctuations in the CalCS and HumCS arise from Pacific Decadal Variability. Although studies have linked the Pacific Decadal Oscillation (PDO) and North Pacific Gyre Oscillation (NPGO) to low frequency changes in upwelling rates, nutrient fluxes, and fisheries in the CalCS (e.g., Chenillat et al., 2012; Chhak and Di Lorenzo, 2007; Di Lorenzo et al., 2008; Mantua et al., 1997) and HumCS (CITE), no work has been done to directly investigate the effect of decadal variability on Pacific EBUS CO2 fluxes in particular. However, studies have shown that a positive PDO intensifies the trade winds along the equatorial Pacific, leading to intensified upwelling and thus outgassing (Feely et al., 2006; Takahashi, 2003). The response of HumCS CO2 fluxes to the PDO might be similar. To the best of our knowledge, there have been no studies exploring CO2 flux sensitivity to large modes of climate variability in the two Atlantic EBUS. However, (Cropper et al., 2014) found that the North Atlantic Oscillation (NAO) plays a major role in modulating interannual variability of coastal upwelling in the CanCS and (Borges et al., 2003) link the NAO to decadal variability in sardine catch. Variability in upwelling and biology in the BenCS has been linked to Benguela Niños (Shannon et al., 1986), ENSO teleconnections, and the Southern Annular Mode (Hutchings et al., 2009; Reason et al., 2006). However, decadal-scale oscillations like the NAO or PDO do not appear to be present in the South Atlantic (Hutchings et al., 2009). In summary, prior research has illuminated the large temporal variability of pCO2 and CO2 fluxes in EBUS and few have analyzed the impacts of single climate events on anomalous CO2 fluxes in the CalCS and HumCS. Past studies tend to focus instead on linking internal climate variability to upwelling, nutrients, and fish catch. Our study aims to address this gap by identifying the major mode of climate variability associated with anomalous CO2 fluxes in the major EBUS and by further investigating the dynamics that underpin these anomalies.

Previous studies have utilized observations (e.g., Boyd et al., 1987; Di Lorenzo et al., 2009, 2008; Friederich et al., 2002; Santana-Casiano et al., 2007) and high-resolution hindcast simulations (Frischknecht et al., 2015; Jacox et al., 2015; Mogollón and Calil, 2017; Turi et al., 2017) to explore the relationship between internal climate variability and EBUS biogeochemistry, such as dissolved oxygen, pH, nitrate supply, and primary production. Direct observation is of course the most desirable tool for understanding the real world, but it is not feasible for this study due to the sparsity of pCO2 and CO2 flux measurements and the relatively short length of observational time series. Regional hindcast simulations are beneficial for two main reasons. First, they tend to have a higher resolution than the standard 1° x1° resolution of global Earth System Models (ESMs) and thus explicitly resolve the coastal upwelling process. Second, the ocean model component is generally forced by an atmospheric reanalysis product so that the model more closely resembles reality than a freely coupled ESM. However, single realizations provide a limited sample size of internal variability and confound the impacts of external forcing with internal climate variability. The former is problematic, because mid-latitude atmospheric noise can obscure the tropical-extratropical connections associated with climate modes such as ENSO, causing a diversity of responses in EBUS (Deser et al., 2018, 2017). The latter makes it difficult to isolate the internal component of variability in CO2 fluxes from the seasonal cycle and anthropogenic and other external forcing. One solution to this problem is to use a single-model ensemble that is derived by introducing perturbations to the initial state of the climate system. This gives rise to a set of realizations with unique representations of internal climate variability and gives one access to many hundred ENSO events, rather than just a handful. By performing experiments with increasing atmospheric CO2 rather than running a long control simulation, we can account for variability in the air-sea flux of both natural and anthropogenic CO2 as well as for potential modifications to the frequency and amplitude of internal variability with climate change (Cai et al., 2015, 2014; Kuzmina et al., 2005; Sydeman et al., 2013; Timmermann et al., 1999). However, each member of the single-model ensemble carries uncertainty due to structural biases in the representation of the climate system and biogeochemistry, the ensemble’s ability to accurately simulate the magnitude and frequency of internal climate variability, and processes that occur at a finer scale than the grid resolution.

In this study we utilize output from the single-model Community Earth System Model “Large Ensemble” (CESM-LENS; Kay et al., 2015; Lovenduski et al., 2016) to identify major modes of climate variability that are associated with anomalous CO2 fluxes in the major EBUS. We expand on this by investigating the physical and biological drivers that underpin these anomalies. The single-model ensemble is necessary for such an analysis, since the forced signal can be removed to generate anomalies for each simulation that solely represent the CO2 flux response to internal climate variability (Thompson et al., 2015). Since the simulations are forced with historical CO2 emissions, each member accounts for variability in both natural and anthropogenic CO2. Furthermore, the availability of 34 simulations allows us to find statistically robust relationships between anomalous CO2 fluxes and internal climate variability.

BIBLIOGRAPHY

Barber, R.T., Chavez, F.P., 1983. Biological Consequences of El Nino. Science 222, 1203–1210. https://doi.org/10.1126/science.222.4629.1203

Borges, A.V., Frankignoulle, M., 2002. Distribution of surface carbon dioxide and air-sea exchange in the upwelling system off the Galician coast: CO 2 IN GALICIAN UPWELLING. Glob. Biogeochem. Cycles 16, 13-1-13–13. https://doi.org/10.1029/2000GB001385

Borges, M.F., Santos, A.M.P., Crato, N., Mendes, H., Mota, B., 2003. Sardine regime shifts off Portugal: a time series analysis of catches and wind conditions. Sci. Mar. 67, 235–244. https://doi.org/10.3989/scimar.2003.67s1235

Boyd, A.J., Salat, J., Masó, M., 1987. The seasonal intrusion of relatively saline water on the shelf off northern and central Namibia. South Afr. J. Mar. Sci. 5, 107–120. https://doi.org/10.2989/025776187784522577

Cai, W., Borlace, S., Lengaigne, M., van Rensch, P., Collins, M., Vecchi, G., Timmermann, A., Santoso, A., McPhaden, M.J., Wu, L., England, M.H., Wang, G., Guilyardi, E., Jin, F.-F., 2014. Increasing frequency of extreme El Niño events due to greenhouse warming. Nat. Clim. Change 4, 111–116. https://doi.org/10.1038/nclimate2100

Cai, W., Wang, G., Santoso, A., McPhaden, M.J., Wu, L., Jin, F.-F., Timmermann, A., Collins, M., Vecchi, G., Lengaigne, M., England, M.H., Dommenget, D., Takahashi, K., Guilyardi, E., 2015. Increased frequency of extreme La Niña events under greenhouse warming. Nat. Clim. Change 5, 132–137. https://doi.org/10.1038/nclimate2492

Cai, W.-J., Dai, M., Wang, Y., 2006. Air-sea exchange of carbon dioxide in ocean margins: A province-based synthesis. Geophys. Res. Lett. 33, L12603. https://doi.org/10.1029/2006GL026219

Chavez, F.., Pennington, J.., Castro, C.., Ryan, J.., Michisaki, R.., Schlining, B., Walz, P., Buck, K.., McFadyen, A., Collins, C.., 2002. Biological and chemical consequences of the 1997–1998 El Niño in central California waters. Prog. Oceanogr. 54, 205–232. https://doi.org/10.1016/S0079-6611(02)00050-2

Chavez, F.P., 1999. Biological and Chemical Response of the Equatorial Pacific Ocean to the 1997-98 El Niño. Science 286, 2126–2131. https://doi.org/10.1126/science.286.5447.2126

Chavez, F.P., Messié, M., 2009. A comparison of Eastern Boundary Upwelling Ecosystems. Prog. Oceanogr., Eastern Boundary Upwelling Ecosystems: Integrative and Comparative Approaches 83, 80–96. https://doi.org/10.1016/j.pocean.2009.07.032

Chenillat, F., Rivière, P., Capet, X., Di Lorenzo, E., Blanke, B., 2012. North Pacific Gyre Oscillation modulates seasonal timing and ecosystem functioning in the California Current upwelling system. Geophys. Res. Lett. 39, n/a-n/a. https://doi.org/10.1029/2011GL049966

Chhak, K., Di Lorenzo, E., 2007. Decadal variations in the California Current upwelling cells. Geophys. Res. Lett. 34. https://doi.org/10.1029/2007GL030203

Cropper, T.E., Hanna, E., Bigg, G.R., 2014. Spatial and temporal seasonal trends in coastal upwelling off Northwest Africa, 1981–2012. Deep Sea Res. Part Oceanogr. Res. Pap. 86, 94–111. https://doi.org/10.1016/j.dsr.2014.01.007

DeGrandpre, M.D., Hammar, T.R., Wirick, C.D., 1998. Short-term pCO2 and O2 dynamics in California coastal waters. Deep Sea Res. Part II Top. Stud. Oceanogr. 45, 1557–1575. https://doi.org/10.1016/S0967-0645(98)80006-4

Deser, C., Simpson, I.R., McKinnon, K.A., Phillips, A.S., 2017. The Northern Hemisphere Extratropical Atmospheric Circulation Response to ENSO: How Well Do We Know It and How Do We Evaluate Models Accordingly? J. Clim. 30, 5059–5082. https://doi.org/10.1175/JCLI-D-16-0844.1

Deser, C., Simpson, I.R., Phillips, A.S., McKinnon, K.A., 2018. How Well Do We Know ENSO’s Climate Impacts over North America, and How Do We Evaluate Models Accordingly? J. Clim. 31, 4991–5014. https://doi.org/10.1175/JCLI-D-17-0783.1

Di Lorenzo, E., Fiechter, J., Schneider, N., Bracco, A., Miller, A.J., Franks, P.J.S., Bograd, S.J., Moore, A.M., Thomas, A.C., Crawford, W., Peña, A., Hermann, A.J., 2009. Nutrient and salinity decadal variations in the central and eastern North Pacific. Geophys. Res. Lett. 36, L14601. https://doi.org/10.1029/2009GL038261

Di Lorenzo, E., Schneider, N., Cobb, K.M., Franks, P.J.S., Chhak, K., Miller, A.J., McWilliams, J.C., Bograd, S.J., Arango, H., Curchitser, E., Powell, T.M., Rivière, P., 2008. North Pacific Gyre Oscillation links ocean climate and ecosystem change. Geophys. Res. Lett. 35, L08607. https://doi.org/10.1029/2007GL032838

Evans, W., Hales, B., Strutton, P.G., 2011. Seasonal cycle of surface ocean pCO2 on the Oregon shelf. J. Geophys. Res. 116. https://doi.org/10.1029/2010JC006625

Feely, R.A., Takahashi, T., Wanninkhof, R., McPhaden, M.J., Cosca, C.E., Sutherland, S.C., Carr, M.-E., 2006. Decadal variability of the air-sea CO2 fluxes in the equatorial Pacific Ocean. J. Geophys. Res. 111. https://doi.org/10.1029/2005JC003129

Friederich, G.., Walz, P.., Burczynski, M.., Chavez, F.., 2002. Inorganic carbon in the central California upwelling system during the 1997–1999 El Niño–La Niña event. Prog. Oceanogr. 54, 185–203. https://doi.org/10.1016/S0079-6611(02)00049-6

Frischknecht, M., Münnich, M., Gruber, N., 2015. Remote versus local influence of ENSO on the California Current System. J. Geophys. Res. Oceans 120, 1353–1374. https://doi.org/10.1002/2014JC010531

González-Dávila, M., Santana-Casiano, J.M., Ucha, I.R., 2009. Seasonal variability of fCO2 in the Angola-Benguela region. Prog. Oceanogr. 83, 124–133. https://doi.org/10.1016/j.pocean.2009.07.033

Gregor, L., Monteiro, P.M.S., 2013. Is the southern Benguela a significant regional sink of CO2? South Afr. J. Sci. 109, 01--05.

Gruber, N., 2015. Carbon at the coastal interface. Nat. Lond. 517, 148–149.

Hales, B., Takahashi, T., Bandstra, L., 2005. Atmospheric CO2 uptake by a coastal upwelling system. Glob. Biogeochem. Cycles 19. https://doi.org/10.1029/2004GB002295

Hutchings, L., van der Lingen, C.D., Shannon, L.J., Crawford, R.J.M., Verheye, H.M.S., Bartholomae, C.H., van der Plas, A.K., Louw, D., Kreiner, A., Ostrowski, M., Fidel, Q., Barlow, R.G., Lamont, T., Coetzee, J., Shillington, F., Veitch, J., Currie, J.C., Monteiro, P.M.S., 2009. The Benguela Current: An ecosystem of four components. Prog. Oceanogr., Eastern Boundary Upwelling Ecosystems: Integrative and Comparative Approaches 83, 15–32. https://doi.org/10.1016/j.pocean.2009.07.046

Huyer, A., Smith, R.L., Paluszkiewicz, T., 1987. Coastal upwelling off Peru during normal and El Niño times, 1981–1984. J. Geophys. Res. 92, 14297. https://doi.org/10.1029/JC092iC13p14297

Jacox, M.G., Bograd, S.J., Hazen, E.L., Fiechter, J., 2015. Sensitivity of the California Current nutrient supply to wind, heat, and remote ocean forcing. Geophys. Res. Lett. 42, 2015GL065147. https://doi.org/10.1002/2015GL065147

Kay, J.E., Deser, C., Phillips, A., Mai, A., Hannay, C., Strand, G., Arblaster, J.M., Bates, S.C., Danabasoglu, G., Edwards, J., Holland, M., Kushner, P., Lamarque, J.-F., Lawrence, D., Lindsay, K., Middleton, A., Munoz, E., Neale, R., Oleson, K., Polvani, L., Vertenstein, M., 2015. The Community Earth System Model (CESM) Large Ensemble Project: A Community Resource for Studying Climate Change in the Presence of Internal Climate Variability. Bull. Am. Meteorol. Soc. 96, 1333–1349. https://doi.org/10.1175/BAMS-D-13-00255.1

King, A.W., Dilling, L., Zimmerman, G.P., Fairman, D.M., Houghton, R.A., Marland, G., Rose, A.Z., Wilbanks, T.J., 2007. The first state of the carbon cycle report (SOCCR): The North American carbon budget and implications for the global carbon cycle. U.S. Climate Change Science Program, Washington.

Kuzmina, S.I., Bengtsson, L., Johannessen, O.M., Drange, H., Bobylev, L.P., Miles, M.W., 2005. The North Atlantic Oscillation and greenhouse-gas forcing: NAO AND GREENHOUSE-GAS FORCING. Geophys. Res. Lett. 32, n/a-n/a. https://doi.org/10.1029/2004GL021064

Kwiatkowski, L., Orr, J.C., 2018. Diverging seasonal extremes for ocean acidification during the twenty-first century. Nat. Clim. Change. https://doi.org/10.1038/s41558-017-0054-0

Landschützer, P., Gruber, N., Bakker, D.C.E., Stemmler, I., Six, K.D., 2018. Strengthening seasonal marine CO2 variations due to increasing atmospheric CO2. Nat. Clim. Change. https://doi.org/10.1038/s41558-017-0057-x

Laruelle, G.G., Dürr, H.H., Slomp, C.P., Borges, A.V., 2010. Evaluation of sinks and sources of CO2 in the global coastal ocean using a spatially-explicit typology of estuaries and continental shelves. Geophys. Res. Lett. 37, n/a-n/a. https://doi.org/10.1029/2010GL043691

Laruelle, G.G., Landschützer, P., Gruber, N., Tison, J.-L., Delille, B., Regnier, P., 2017. Global high-resolution monthly pCO2 climatology for the coastal ocean derived from neural network interpolation. Biogeosciences 14, 4545–4561. https://doi.org/10.5194/bg-14-4545-2017

Laruelle, G.G., Lauerwald, R., Pfeil, B., Regnier, P., 2014. Regionalized global budget of the CO2 exchange at the air-water interface in continental shelf seas. Glob. Biogeochem. Cycles 28, 2014GB004832. https://doi.org/10.1002/2014GB004832

Leinweber, A., Gruber, N., Frenzel, H., Friederich, G.E., Chavez, F.P., 2009. Diurnal carbon cycling in the surface ocean and lower atmosphere of Santa Monica Bay, California. Geophys. Res. Lett. 36. https://doi.org/10.1029/2008GL037018

Lovenduski, N.S., McKinley, G.A., Fay, A.R., Lindsay, K., Long, M.C., 2016. Partitioning uncertainty in ocean carbon uptake projections: Internal variability, emission scenario, and model structure. Glob. Biogeochem. Cycles 30, 2016GB005426. https://doi.org/10.1002/2016GB005426

Mantua, N.J., Hare, S.R., Zhang, Y., Wallace, J.M., Francis, R.C., 1997. A Pacific Interdecadal Climate Oscillation with Impacts on Salmon Production. Bull. Am. Meteorol. Soc. 78, 1069–1079. https://doi.org/10.1175/1520-0477(1997)078<1069:APICOW>2.0.CO;2

Mogollón, R., Calil, P.H.R., 2017. On the effects of ENSO on ocean biogeochemistry in the Northern Humboldt Current System (NHCS): A modeling study. J. Mar. Syst. 172, 137–159. https://doi.org/10.1016/j.jmarsys.2017.03.011

Pauly, D., Christensen, V., 1995. Primary production required to sustain global fisheries. Nature 374, 255–257.

Reason, C.J.C., Florenchie, P., Rouault, M., Veitch, J., 2006. 10 Influences of large scale climate modes and agulhas system variability on the BCLME region, in: Large Marine Ecosystems. Elsevier, pp. 223–238. https://doi.org/10.1016/S1570-0461(06)80015-7

Ryther, J.H., 1969. Photosynthesis and fish production in the sea. The production of organic matter and its conversion to higher forms of life vary throughout the world ocean. Sci. Wash. 166, 72–76.

Santana-Casiano, J.M., González-Dávila, M., Rueda, M.-J., Llinás, O., González-Dávila, E.-F., 2007. The interannual variability of oceanic CO 2 parameters in the northeast Atlantic subtropical gyre at the ESTOC site: CO 2 VARIABILITY AT THE ESTOC SITE. Glob. Biogeochem. Cycles 21. https://doi.org/10.1029/2006GB002788

Shannon, L.V., Boyd, A.J., Brundrit, G.B., Taunton-Clark, J., 1986. On the existence of an El Niño-type phenomenon in the Benguela System. J. Mar. Res. 44, 495–520. https://doi.org/10.1357/002224086788403105

Sydeman, W.J., Santora, J.A., Thompson, S.A., Marinovic, B., Lorenzo, E.D., 2013. Increasing variance in North Pacific climate relates to unprecedented ecosystem variability off California. Glob. Change Biol. 19, 1662–1675. https://doi.org/10.1111/gcb.12165

Takahashi, T., 2003. Decadal Variation of the Surface Water PCO2 in the Western and Central Equatorial Pacific. Science 302, 852–856. https://doi.org/10.1126/science.1088570

Thompson, D.W.J., Barnes, E.A., Deser, C., Foust, W.E., Phillips, A.S., 2015. Quantifying the Role of Internal Climate Variability in Future Climate Trends. J. Clim. 28, 6443–6456. https://doi.org/10.1175/JCLI-D-14-00830.1

Timmermann, A., Oberhuber, J., Bacher, A., Esch, M., al, et, 1999. Increased El Nino frequency in a climate model forced by future greenhouse warming. Nat. Lond. 398, 694–697. http://dx.doi.org/10.1038/19505

Torres, R., 2003. Continued CO2 outgassing in an upwelling area off northern Chile during the development phase of El Niño 1997–1998 (July 1997). J. Geophys. Res. 108. https://doi.org/10.1029/2000JC000569

Turi, G., Alexander, M.A., Lovenduski, N.S., Capotondi, A., Scott, J.D., Stock, C.A., Dunne, J.P., John, J., Jacox, M.G., 2017. Response of O2 and pH to ENSO in the California Current System in a high resolution global climate model. Ocean Sci. Discuss.

Turi, G., Lachkar, Z., Gruber, N., 2014. Spatiotemporal variability and drivers of pCO2 and air–sea CO2 fluxes in the California Current System: an eddy-resolving modeling study. Biogeosciences 11, 671–690. https://doi.org/10.5194/bg-11-671-2014