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COMMENTARY

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Key Points:
- Rising greenhouse gases are expected to cause changes in surface wind stress that extend western boundary currents poleward.
- A recent paper is discussed that claims this is already occurring.
- How natural and forced changes in winds caused recent changes in western boundary currents is discussed along with expectations for the future.

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Western boundary currents and climate change

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Abstract A recent paper in *Journal of Geophysical Research-Oceans* connects recent changes in atmospheric circulation to poleward movement and intensification of western boundary currents. Causes and characteristics of past and future trends in surface wind stress and western boundary currents are discussed here.

If the physical features of the oceans had the equivalent of charismatic megafauna, then the western boundary currents (WBCs), the Gulf Stream lead amongst them, would probably be the sole candidates. The WBCs—the Gulf Stream in the North Atlantic, Kuroshio in the North Pacific, Brazil Current in the South Atlantic, East Australia Current in the South Pacific, and Agulhas Current in the South Indian Ocean—are narrow streams of intense poleward flow that transport subtropical waters into the midlatitudes. They exist on the western boundaries of the great subtropical ocean gyres off the east coasts of North America, Asia, South America, Australia, and southern Africa. There are no such intense currents along the oceans' eastern boundaries.

The existence of the WBCs was explained by the great oceanographers Munk and Stommel in the 1940s and 1950s. Considering the northern hemisphere, westerly winds in midlatitudes and easterly winds in the subtropics input clockwise spin (negative vorticity) into the ocean, which, as pointed out before by Sverdrup, must be balanced locally by southward flow advecting higher planetary vorticity water from the north. The winds, due to the rotation of Earth, drive water to their right, creating mass convergence and higher sea levels in between the westerlies and easterlies. Geostrophic balance requires an eastward current poleward and westward current equatorward of the high sea level at the center of the gyre. Munk and Stommel showed that, in the presence of friction, whether at the bottom or lateral boundaries of the ocean, an intense northward WBC completes the gyre and, because the flow goes to zero at the coast itself, allows the generation of positive vorticity. This leads to an overall basin-wide balance between negative vorticity input to the ocean by the wind and positive vorticity generation at the western boundary. The same processes in the southern hemisphere generate southward flowing WBCs. Later work in the 1960s showed that it was the westward propagation of Rossby waves and their reflection at the coast that transmitted information from the ocean interior to the WBC regions.

The WBCs are not just geophysical wonders but play an important role in the Earth's climate system as well. They move considerable amounts of heat from the subtropical oceans into the midlatitudes. By virtue of being immediately downwind of cold, dry continents during winter, much of that heat is lost by sensible and latent heat transfer into the atmosphere. Because of this the poleward ocean heat transport takes a notable nosedive at the latitude of the WBCs and, poleward of the WBCs, is totally overwhelmed by the atmospheric heat transport. The Gulf Stream and Kuroshio Current are also the locations of the beginnings of the North Atlantic and North Pacific storms tracks. The turbulent winds within the storms enable some of the heat lost from the WBCs to be advected west onto the continents ameliorating harsh winters in eastern Asia and North America. At the same time, warm WBCs immediately east of cold continents enhance baroclinicity in the atmosphere and aid the generation and maintenance of the storm tracks [*Hoskins and Valdes*, 1990]. Eddies that form in the WBCs also mix nutrient poor water from the subtropical gyres with nutrient-rich waters from the subpolar gyres and play an important role in regional ecosystems and fisheries.

That rising greenhouse gases will cause a poleward shift in the midlatitude westerlies and expansion of the Hadley Cell and its associated easterly trade winds was first noted three decades ago [*Wilson and Mitchell*, 1987] but only gained common currency in the last decade as more attention was paid to the atmospheric circulation response to human-induced climate change. Given that the WBCs are driven by the winds, we would expect a poleward extension of the WBCs too. Oddly enough this seems to not have been examined until a recently published paper in *J. Geophys. Res.-Oceans* by *Yang et al*. [2016]. Yang et al. began by using ocean reanalyses to identify the WBCs based on the locally enhanced SSTs (due to warm water advection) and surface heat loss to the atmosphere. They then showed, rather remarkably given the well-known deficiencies of these reanalyses arising from limited data input, that there have been clear trends over past decades in the locations of the WBCs. Notably, all three southern hemisphere WBCs have extended poleward. In the northern hemisphere, the Gulf Stream has also shifted poleward but the Kuroshio current has actually shifted equatorward.

Yang et al. also show that over the same period the climate models that were assessed for the Intergovernmental Panel on Climate Change Assessment Report Five in 2013 predict that a poleward extension of all WBCs except for the Gulf Stream (which Yang et al. claim weakens due to reduction of the meridional overturning circulation) should have occurred as a consequence of changes in radiative forcing of the climate system. This is the oceanographic expression of the now famed expansion of the tropics, Hadley Cell expansion, and poleward shift of the midlatitude jets that models project to occur as a consequence of rising GHGs. But, despite the general model-data agreement, it is not time to declare victory and go home, and there are three reasons why matters are more complex.

First, in the southern hemisphere much of the poleward shift of WBCs that has occurred is likely a result of ozone loss rather than GHG rise. In recent years considerable work has revealed that ozone depletion from the 1960s through to about 2000 (when the phasing out of CFCs after the 1987 Montreal Protocol achieved stabilization ahead of slow recovery) was the main radiative driver of southern hemisphere circulation change. Rising CO_2 and reducing O_3 have both tended to shift the southern hemisphere tropospheric jet stream poleward because both tend to cool the stratosphere and strengthen the pole-equator temperature gradient and stratospheric jet [*Wu et al*., 2013], but with the ozone effect being stronger [*McLandress et al*., 2011; *Polvani et al*., 2011]. In the coming decades O_3 recovery and CO_2 increase will tend to drive the southern hemisphere jet and WBCs in opposite directions. Focusing on southern hemisphere summer, it has been claimed [*Barnes et al*., 2014] that this tug-of-war will lead to little movement in either direction until later in the century when the CO_2 increase starts to dominate. For whether the southern WBCs will continue to move poleward in the current century, we need to examine the seasonality of the wind stress changes and the relative influences on them by O_3 and CO_2 changes.

The second complicating matter is natural variability. As Yang et al. note, over the last decades of the 20th century, the Kuroshio shifted south and the Gulf Stream shifted north whereas the CMIP5 models predict, respectively, a northward shift and an in place weakening. The disagreement probably lies with natural modes of variability such as Pacific Decadal Variability (PDV) and the North Atlantic Oscillation (NAO). Yang et al. analyze trends from 1958 to 2001, but a warm state of the tropical Pacific Ocean occurred beginning with the 1976/1977 El Niño and lasted until the 1997/1998 El Niño. As in individual El Niño events, the warm phase of PDV is associated with an equatorward shift of the North Pacific jet. The southward shift of the Kuroshio over the same period is therefore broadly consistent with being an element of PDV behavior as previously noted [*Seager et al*., 2001; *Taguchi et al*., 2007]. The northward shift of the Gulf Stream over the same period is almost certainly associated with the strong upward trend of the NAO from the 1960s to the late 1990s. For future decades, how the northern WBCs move will continue to depend on natural climate variability as well as the radiatively forced response, which could combine to produce either no changes, ones that are opposite to the forced response, or ones that are much larger than the forced response.

Third, the expansion of the tropics/poleward jet stream shift concept is very much based on analysis and thinking of the zonal mean. In the southern hemisphere, due to the absence of midlatitude continents that disrupt zonal symmetry, the jet stream change at any longitude is close to the zonal mean. However, in the northern hemisphere changes in the jet stream in response to radiative forcing are more complex [*Simpson et al*., 2014]. During spring and fall both the Pacific and Atlantic jets shift poleward, but during winter, when the jets are strongest, the Pacific jet shifts poleward off Asia and equatorward west of North America, while the Atlantic jet stays in place but extends further northeast into Europe (where it will have no effect on the ocean). The simplicity of the southern hemisphere changes in surface wind stress and the complexity of the northern hemisphere response are shown in Figure 1, which shows the difference in surface zonal wind stress for the end of the current century minus a recent period evaluated as the multimodel mean of the CMIP5 ensemble with a high emissions scenario.

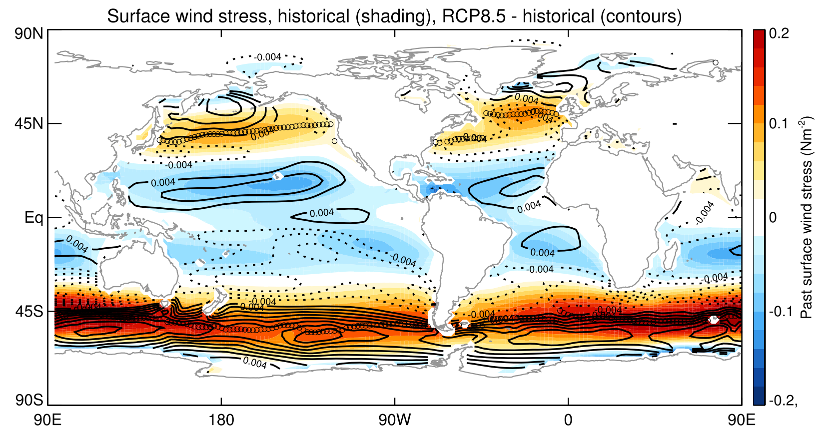

Figure 1. The historical (shading) and change (contours) from 1979–2005 to 2070–2099 in annual mean surface zonal wind stress evaluated as the multimodel mean of CMIP5 historical simulations and projections with the RCP85 high emissions scenario. The black circles denote the location of the maximum in climatological wind stress at each longitude in the historical period. The contour interval for the anomalies is 0.004 N/m^2 with the zero line omitted. The models used are as in *Simpson et al*. [2014].

The Yang et al. study is important in that it shows that rather remarkably the WBCs are already responding to climate change, most notably in the southern hemisphere. In the northern hemisphere, the impact of natural variability on the WBCs seems, for now, dominant. In terms of the future, in the southern hemisphere, O_3 recovery and CO_2 increase will tend to move the WBCs in opposite directions, but, at least according to Yang et al., CO_2 will win out and a further poleward movement and intensification can be expected. In the northern hemisphere, purely from the likelihood that the PDV will someday switch from its post 1998 cold tropics phase back to its warm phase (maybe heralded by the just completed massive El Niño of 2015/2016?), an equatorward movement of the Kuroshio would be expected, but this could be offset by CO_2-induced circulation change that would favor a poleward shift. For the Atlantic we have little reason to be able to anticipate future behavior of the NAO and how it will influence the Gulf Stream, and the seasonal and longitudinal variations of the wind response to rising CO_2 makes it hard to anticipate the wind-forced response of the Gulf Stream. However, if the models are right that the AMOC will weaken, then the Gulf Stream will progressively flow less strongly.

Yang et al. note that these changes in the WBCs will have influences on local regional climates in Asia and North America. Presumably the Brazil, Agulhas, and East Australian currents similarly impact regional climates in eastern South America, southeast Africa, and eastern Australia, but we are unaware of much research on that. But in all locations near WBCs, it will be interesting to determine how the future evolution of the intensity and location of the WBCs influences regional oceanography, ecosystems, and climate. Doing so will require improved understanding of the changes in surface wind stress that will occur. Yang et al. make it clear that this research is eminently doable and well-worth carrying out.

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