Hidden Upwelling Systems Associated With Major Western Boundary Currents

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Abstract

Western boundary currents (WBCs) play an essential role in regulating global climate. In contrast to their widely examined horizontal motions, less attention has been paid to vertical motions associated with WBCs. Here, we examine vertical motions associated with the major WBCs by analyzing vertical velocity from five ocean synthesis products and one eddy-resolving ocean simulation. These data reveal robust and intense subsurface upwelling systems, which are primarily along isopycnal surfaces, in five major subtropical WBC systems. These upwelling systems are part of basin-scale overturning circulations and are likely driven by meridional pressure gradients along the western boundary. Globally, the WBC upwelling contributes significantly to the vertical transport of water mass and ocean properties and is an essential yet overlooked branch of the global ocean circulation. In addition, the WBC upwelling intersects the oceanic euphotic and mixed layers, and thus likely plays an important role in ocean biological and chemical processes by transporting nutrients, carbon and other tracers vertically inside the ocean. This study calls for more research into the dynamics of the WBC upwelling and their role in the ocean and climate systems.

Plain Language Summary

This study shows that intense upwelling systems exist along the major western boundary currents (WBCs) around the global ocean. In contrast to other well-known oceanic upwelling systems (e.g., equatorial, coastal upwelling), these WBC upwelling systems, which are essential branches of the global ocean circulation, have been largely unrecognized in the literature. This intense upwelling and the associated overturning circulation in the subtropical ocean basins can transport nutrients, carbon, and heat inside the ocean, and consequently act as an important yet unexplored route through which the oceanic biological, chemical, and physical processes, and consequently the climate system, will be affected. This study calls for more research into the dynamics of the WBC upwelling and its role in the ocean and climate systems.

1. Introduction

Large-scale vertical motion in the global ocean is generally much weaker than horizontal motions (e.g., Stew-ard, 2008). Nevertheless, vertical motions are an important component of the coupled climate system because they can transport heat, carbon, nutrients, and other tracers into and out of the surface mixed layer, where they can then be exchanged with the atmosphere. Also, vertical motions are essential for oceanic biological and chemical processes. For instance, upwelling near the surface brings nutrient-enriched water into the euphotic zone, affecting the ocean primary productivity (Kämpf & Chapman, 2016; Ryther, 1969) and, consequently, CO2 uptake (Ducklow et al., 2001; Pilskaln et al., 1996; Stukel et al., 2013). Downwelling, such as that observed in the Southern Ocean, transports heat and tracers sourced at the surface to the deep and abyssal oceans (Gregory, 2000; Ito et al., 2010; Liang et al., 2015), and is therefore essential for the responses of the ocean interior to changes in climate and human activities.

Based on theoretical understanding (e.g., Ekman dynamics) and the observed distributions of a variety of tracers (e.g., Toggweiler et al., 2019), a number of general patterns of ocean vertical motions have been inferred, including strong upwelling along most eastern boundaries of the subtropical ocean basins and along the equator (Huyer, 1983; Kämpf & Chapman, 2016; Wyrski, 1981), as well as intense vertical motions of both signs in the Southern Ocean (Huyer, 1983; Marshall & Speer, 2012; Wyrski, 1981). However, because the weak vertical velocity associated with the large-scale circulation cannot, in general, be measured directly, quantitative studies of vertical motions are limited, especially in the subsurface ocean. Over the past decades, several ocean synthesis products became available (Balmaseda et al., 2015; Stammer et al., 2016). Some of these ocean data products synthesize various observations and ocean circulation models, provide vertical velocity among many other
variables. Once proven robust, such ocean data products can complement existing observations and advance our quantitative understanding of oceanic vertical motions as well as large-scale three-dimensional ocean circulation.

Western boundary currents (WBCs) are one of the most important ocean regimes regulating the global climate (e.g., Wu et al., 2012). While all major WBCs are three-dimensional features, their role in the climate system has long been studied in terms of lateral transport and air-sea exchange (Hu et al., 2015), generally neglecting the effects of vertical motions. However, there have been several studies indicating that there can be large vertical transports in western boundary current regions. Interaction of the continental slope and the western boundary current has been shown to result in upwelling due to large-scale wind-driven gyres (Holland, 1972); up slope Ekman transport below an adiabatic western boundary current (Condie, 1995); and onshore flow balancing an offshore Ekman transport (e.g., Schaeffer et al., 2013). There have also been very idealized studies that find upwelling along western boundaries for buoyancy-forced flows (e.g., Bire & Wolfe, 2018; Pedlosky & Spall, 2005; Schloessner et al., 2012). Finally, regional observations (e.g., Roughan & Middleton, 2004) and the long-term mean vertical velocity field from a global ocean state estimate (Liang et al., 2017) have revealed considerable vertical motions associated with the WBCs, even in the absence of local upwelling-favorable wind stress. Such WBC-associated vertical motions potentially offer a viable and effective mechanism for the exchange of ocean heat, salt, and other biogeochemical tracers between the mixed layer and underlying layers.

In this study, we examine vertical velocity in the major WBC regions from five ocean synthesis products: Estimating the Circulation and Climate of the Ocean (ECCO), (Forget et al., 2015; Fukumori et al., 2017); European Centre for Medium-Range Weather Forecasts (ECMWF) ora-s3 (Balmaseda et al., 2008); Global Ocean Data Assimilation System (GODAS) (Behringer & Xue, 2004); Simple Ocean Data Assimilation (SODA) (Carton et al., 2018); Ensemble Coupled Data Assimilation System (ECDA) (Chang et al., 2013); and one eddy-resolving ocean simulation-Ocean General Circulation Model For the Earth Simulator (OFES; Sasaki et al., 2008) over their overlapping period (January 1992 to December 2009). Our primary goals are to describe robust large-scale features of vertical motions in the WBC regions and to explore their roles in the vertical transport of volume and ocean properties. In order to demonstrate differences between vertical motions near eastern and western boundaries of ocean basins, we also include the Peruvian upwelling region as a contrasting example.

It is proposed that upwelling near the western boundaries of the subtropical gyres is ultimately driven by a poleward decrease in pressure along the western boundary. This is analogous to the downwelling that is found in models (Cessi et al., 2010; Katsman et al., 2018; Spall, 2010) and inferred from observations (Liang et al., 2017) in regions of pressure gradients at high latitudes of the North Atlantic. Vertical motions are required in these boundary regions to maintain a geostrophic balance. The pressure gradient in the high-latitude downwelling regions is supported by both local buoyancy loss to the atmosphere and lateral eddy fluxes into the basin interior. In the present study we identify analogous regions of pressure gradients along mid-latitude western boundaries and discuss potential mechanisms.

2. Data and Methods
2.1. Data

The vertical velocity from six publicly available datasets, including five ocean synthesis products and one eddy-resolving ocean simulation, are analyzed in this study. The ocean synthesis products utilize general ocean circulation models to assimilate various observational datasets with varying approaches (e.g., Stammer et al., 2016). The ocean simulation does not assimilate observational data but is of much higher spatial resolution. Some basic information on those datasets is provided in the following. The ECCO data utilized in this study are the ECCOv4r3 monthly products (Forget et al., 2015; Fukumori et al., 2017). ECDA is the Ensemble Coupled Data Assimilation System developed at the National Oceanic and Atmospheric Administration /Geophysical Fluid Dynamics Laboratory (Chang et al., 2013). ECMWF product used here is ECMWF ora-s3, an operational ocean analysis/reanalysis system implemented at the ECMWF (Balmaseda et al., 2008). GODAS is the Global Ocean Data Assimilation operated at the National Centers for Environmental Prediction (Behringer & Xue, 2004). We use monthly interpolated values from SODA v3, an ocean data assimilation product developed at the University of Maryland (Carton et al., 2018). Finally, we use the eddy-resolving quasi-global forward ocean model OFES, developed by the Japan Agency for Marine-Earth Science and Technology (Sasaki et al., 2008). Additional information about the data products, such as the grid point numbers and time span, can be found in Table 1.
Monthly vertical velocity data are directly available from all the selected products. The overlapping period covered by all six products is from January 1992 to December 2009. The vertical velocity data were averaged over this 18-years period. For consistency, all available vertical velocity fields from the six products were first transformed to the 1-degree by 1-degree LLC90 (Lat-Lon-Cap 90) grid configuration (Forget et al., 2015) before further processing. A 3 point × 3 point diffusive smoother provided in the gcmfaces package (https://github.com/MITgcm/gcmfaces) was applied to obtain robust large-scale patterns. Other configurations of the same smoother (2 × 2, 4 × 4) were also tested, and the results were roughly the same.

2.2. Analyses

As shown in Figure 1a, we define a box for each major subtropical WBC region and for the Peruvian upwelling region. The regions covered by those boxes are as follows: Kuroshio (120°E–150°E, 21°N–40°N); Gulf Stream (82°W–60°W, 25°N–41°N); Agulhas Current (20°E–38°E, 37°S–27°S); East Australian Current (148°E–158°E, 37°S–20°S); Brazil Current (56°W–30°W, 35°S–10°S); Peruvian upwelling (85°W–70°W, 40°S–8°S).

To examine the vertical distribution of vertical velocity, for each WBC region, we choose a cross section approximately perpendicular to the local coastline and plot the distribution of time-averaged vertical velocity along with the horizontal velocity perpendicular to the cross section. Details of the selected cross sections are as follows: Kuroshio, (139°E, 35°N) to (149°E, 25°N); Gulf Stream (74°W, 38°N) to (64°W, 28°N); Agulhas Current (30°E, 31°S) to (40°E, 41°S); East Australian Current (153°E, 30°S) to (163°E, 30°S); and Brazil Current (41°W, 21°S) to (31°W, 21°S). A contrasting eastern boundary upwelling, the Peruvian upwelling region, was also selected as (70°W, 23°S) to (80°W, 23°S). The cross sections are marked as thick black lines in Figure 1a.

A regional budget analysis is conducted to better understand the dynamics of the WBC upwelling. We choose the Gulf Stream region as an example and calculate the horizontal time-averaged volume transport into and out of a control volume and the time-averaged vertical volume transport through several interfaces. Their depths are subjectively chosen so that the vertical volume transport at the upper interface is just below the Ekman layer and that the transport through the deep interface is relatively weak. Note that the ECCO product on the native grid configuration is used for the budget analysis in order to close the volume flux budget.

The contribution of WBC upwelling to the vertical transport in the subtropical ocean basin is also calculated. At each depth, we select the grid cell with positive mean vertical velocity and calculate the upward vertical volume flux in the domain bounded by each box in Figure 1a. We define the results as the vertical volume transport related to the WBC upwelling. We also calculate the volume transport within all the other grid cells in the same latitude band across the whole ocean basin (domain shown in Figure 1b). The sum of these two terms is the net volume transport within the corresponding latitude band across the ocean basin.

Moreover, we compare the vertical volume transport induced by the WBC upwelling with those associated with other well-known upwelling regimes. We calculate the vertical volume transport at each grid cell where the time-averaged vertical velocity is positive in these four different regimes as marked in Figures 1a and 1c: WBCs, Eastern Boundary Upwelling, Equator (within 8° of the equator) and the Southern Ocean (south to 40°S).
that the Angola Dome is classified into the eastern boundary current region in this paper. These upward volume transports are then summed over the corresponding region and compared with each other.

3. Results

3.1. Vertical Velocity Associated With the Major WBCs

Time-averaged vertical velocity \( \bar{w} \) near 300 m from six selected ocean products is displayed in Figure 1. While there are differences in the detailed regional patterns, intense vertical motions in the Southern Ocean, along the Equator, and in the WBC regions are observed in all of the examined data products. The strong upwelling in the Southern Ocean (Anderson et al., 2009) and in the equatorial regions (Yoshida, 1959) are well known and mainly induced by Ekman dynamics (i.e., wind pumping and suction). To our knowledge, the strong and robust upwelling (~1 m/day) apparent in all major WBC regions in all six products has not been explicitly identified and its dynamics are not well understood. Also, both the strength and vertical extent of the upwelling in the WBC regions are distinctly different from those in the eastern boundary upwelling systems, the latter of which are barely detectable at this depth. Strong upwelling can also be seen at 1,000 m and deeper in WBC regions, especially near the Gulf Stream and the Kuroshio (Figures S1 and S2 in Supporting Information S1). Apart from the boundary current systems, the vast area of the subtropical oceans at this depth is dominated by weak downwelling.

Figure 1. Time-averaged vertical velocity \( \bar{w} \) near 300 m between January 1992 and December 2009. \( \bar{w} \) from six selected products: (a) Estimating the Circulation and Climate of the Ocean (ECCO). (b) Ensemble Coupled Data Assimilation (ECDA). (c) European Centre for Medium-Range Weather Forecasts (ECMWF). (d) Global Ocean Data Assimilation (GODAS). (e) Simple Ocean Data Assimilation (SODA). (f) Ocean General Circulation Model For the Earth Simulator (OFES). The black boxes in (a) show the domains of the five western boundary and one eastern boundary systems investigated in this study. The thick black lines represent the cross sections shown in Figure 2. The black boxes in (b) (at the same latitude band of the corresponding boxes in a) represent the domains where vertical volume flux was calculated. The dashed lines split the domains into western boundary currents regions and the rest of the subtropical ocean basins. Boxes in (c) mark three other well-known upwelling regimes (equatorial, eastern boundary and the Southern Ocean).
There is also strong downwelling along the boundaries at high latitudes. This is the downwelling limb of the Eulerian meridional overturning circulation (Katsman et al., 2018; Spall, 2010). As discussed further below, we argue that the WBC upwelling regions are analogous to these downwelling cells at high latitudes.

We also present selected sections of the time-averaged vertical velocity $\bar{w}$ across the major WBCs from ECCO (Figure 2). Despite differences in resolutions, numerical configurations, and assimilated data, all of the examined products show similar spatial patterns and magnitudes (Figures S3–S8 in Supporting Information S1). The cross sections are marked with thick black lines in Figure 1a. (a) Kuroshio. (b) Gulf Stream. (c) Agulhas Current. (d) East Australian Current. (e) Brazil Current. (f) Peruvian upwelling. The contour lines show the horizontal velocity (cm/s) perpendicular to the cross sections, indicative of the strength of adjacent western boundary currents. Note that the depth axis is stretched for better visualization.

Figure 2. Time-averaged vertical velocity $\bar{w}$ (color) and horizontal velocity (contour lines, unit: cm/s) in selected cross sections from Estimating the Circulation and Climate of the Ocean. The other datasets show similar spatial patterns (Figures S3–S8 in Supporting Information S1). The cross sections are marked with thick black lines in Figure 1a. (a) Kuroshio. (b) Gulf Stream. (c) Agulhas Current. (d) East Australian Current. (e) Brazil Current. (f) Peruvian upwelling. The contour lines show the horizontal velocity (cm/s) perpendicular to the cross sections, indicative of the strength of adjacent western boundary currents. Note that the depth axis is stretched for better visualization.

Intense subsurface upwelling in the WBC regions is co-located with the strong boundary currents, suggesting a dynamical connection between them. Also, the strong time-averaged upwelling (~1 m/day) in WBC regions generally extends from near the surface down to 1,000 m or even deeper. The strong vertical motion is, however, located well above the bottom topography, indicating that it does not result from direct interaction with the sloping bottom. In contrast to the WBC sections, upwelling near the Peruvian coast, an example eastern boundary upwelling region, is confined to a shallower layer and is also much weaker. In addition, weak downwelling resulting from Ekman pumping occurs to the east of the WBC upwelling. Note that the water in the Ekman layer is transported into the subtropical gyre from the north and south and pumped down by Ekman convergence. It is not simply connected to the western boundary upwelling in a local overturning gyre. This downwelling of course forces the anticyclonic subtropical gyres, which do recirculate water through the western boundary current.

We then examine the relationship between the current vectors and the background (zonal) density structure (Figure 3). The meridional averages of the time-averaged current vectors in the WBC regions are approximately aligned with sloping isopycnal surfaces associated with the WBCs, suggesting that the strong upwelling in the WBC regions is primarily along rather than across isopycnals. A decomposition of the vertical velocity from ECCO into diapycnal and isopycnal contributions following Bennett (1986) confirms that the WBC upwelling is mainly associated with along-isopycnal flow (Figure 4). Therefore, the strong WBC upwelling is unlikely to
be related to local mixing, by which vertical velocity will be primarily in diapycnal direction instead of along isopycnals.

3.2. Boundary Pressure and WBC Upwelling

The difference in the pressure between the eastern and western boundaries drives a meridional geostrophic flow, which is the dominant component of the meridional overturning circulation. Due to buoyancy loss to the atmosphere, the upper ocean pressure decreases from low to high latitudes along the eastern boundary of the subtropical and subpolar gyres and, in the North Atlantic, cyclonically around the Nordic Seas. The high pressure at low latitudes results from relatively high sea surface height. The poleward decrease in pressure is mitigated with depth by the increasing density along the boundary. These regions of increasing density have been shown to be where the Eulerian downwelling limb of the meridional overturning circulation are located (Katsman et al., 2018; Marotzke & Scott, 1999; Spall, 2004, 2010).

The potential density in the upper 1,000 m in the ECCO product increases in the poleward direction along all WBCs (Figure 5). The regions of upwelling along the western boundaries of the subtropical gyres are thus also regions of negative meridional pressure gradient along the boundary. As a result, the change in pressure from the eastern boundary to the western boundary is likely larger to the north of the upwelling region than it is to the south. This then requires upwelling at mid-latitudes to provide the required increased poleward geostrophic flow in the upper ocean. Support for such a mid-latitude upwelling cell is provided by the mid-latitude maximum in the meridional overturning circulation in depth coordinates often found in high resolution numerical models (e.g., Hirschi et al., 2020).

Note that this upwelling is different from the well-known upwelling driven by numerical diffusion of density across sloping isopycnals (the so called “Veronis Effect,” Veronis, 1975). For numerical models in which diffusion of density is along horizontal surfaces, in regions of sloping isopycnals, such as in western boundary currents,
diffusion of density is balanced by the vertical advection of the mean stratification, leading to strong upwelling and diapycnal mass transport. This effect is eliminated by rotating the mixing tensor to be along isopycnals (Danabasoglu & McWilliams, 1995), leading to better representations of the meridional overturning circulation and meridional heat transport. All of the non-eddy-resolving data products we have diagnosed use a rotating mixing tensor and the Gent and McWilliams (1990) eddy tracer flux parameterization. The eddy-resolving OFES model (Sasaki et al., 2008) also shows similar upwelling patterns and magnitudes.

The underlying relationship between vertical stratification, horizontal transport, and upwelling is illustrated through a sample volume budget analysis for the Gulf Stream (Figure 6). The surface area of the control volume is triangular and marked in the inset, and the depth range is between 55 m and 2,000 m. The budget analysis (Figure 6a) reveals large horizontal divergences/convergences in different layers, requiring vertical transport to conserve mass. The density structure along the two sections (BA, BC in Figure 6b) provides the dynamical framework for the existence of horizontal convergence. Because the density increases poleward along the western boundary (Figure 5), the density change from the western boundary to the interior point (B) is larger along the northern section (BC) than it is along the southern section (AB). Thermal wind balance thus requires a larger vertical shear in the horizontal velocity along BC. But mass conservation requires that the flow through each section is the same (except for the small transport into the upper 55 m). The only way to close the mass budget is for water to upwell within the control volume. In other words, the WBC upwelling can be explained through mass conservation and geostrophy. In this sense, these upwelling regions are analogous to the high latitude downwelling found in regions of horizontal pressure gradients on the boundary. The requirement that there be upwelling near the western boundary is not dependent on the details of the numerical model, subgrid-scale mixing, or bottom topography. Possible mechanisms for maintenance of this pressure gradient will be discussed in Section 4.

Figure 4. Along- and across-isopycnal components of the time-mean vertical velocity $\vec{w}$ at around 300 m. (a) Isopycnal vertical velocity $\vec{w}_a$, (b) Diapycnal vertical velocity $\vec{w}_c$. 
Figure 5. Potential density anomaly along the western boundary currents (WBCs) and Peruvian upwelling. The potential density anomalies were zonally averaged within the WBC regions marked as boxes in Figure 1a. (a) Kuroshio. (b) Gulf Stream. (c) Agulhas Current. (d) East Australian Current. (e) Brazil Current. (f) Peruvian upwelling.

Figure 6. Time-averaged vertical velocity \( \bar{w} \), potential density anomaly \( \bar{\sigma} \), and volume flux in a triangle-shape domain in the Gulf Stream region. (a) Time-averaged vertical velocity at four depths (colors) and lateral and vertical volume fluxes. The black and blue arrows represent the lateral volume fluxes in Sv, and the purple arrows show the vertical volume fluxes in Sv. (b) Time-averaged potential density anomaly along the southern section and northern section of the triangle-shaped domain between 55 and 2,000 m (shown in the inset). The gray curve in the 55 m section along AC represents the coastline. The results are based on ECCO product on the native grids.
3.3. Vertical Transport Associated With the WBC Upwelling

We now quantify the contribution of the WBC upwelling to the vertical transport of mass/volume in the subtropical ocean basins using ECCO (Figure 7), with the other products generally showing similar results (Figures S3–S8 in Supporting Information S1). Although the WBC regions occupy only a minor portion of the subtropical ocean basins with respect to the ocean surface area, as shown in Figure 1b, the vertical volume transport induced by upwelling in the WBCs is generally of the same order of magnitude as and is almost always opposite in the direction to the vertical volume transport in the rest of the subtropical basin within the same latitudinal band. We also calculate the vertical transport of heat and salt using ECCO (Figures S9 and S10 in Supporting Information S1), and the results are consistent with the volume transport, that the WBC regions dominate subsurface vertical transport of salt and heat in the subtropical ocean basins within certain depth ranges.

Specifically, upwelling in the Kuroshio, Gulf Stream, and Brazil Current regions dominates the net volume transport in the corresponding subtropical ocean basins within the depth ranges between a few hundred and about 2,000 m. As a contrasting example, vertical volume transport in the Peruvian upwelling region is much weaker and shallower compared to the WBC upwelling. The net volume transport in the subtropical basin is in general downward near the surface and changes to upward beneath, reflecting the fact that the upward volume transport in the WBCs generally reaches its maximum around 200–500 m. In contrast, the downward transport in the rest of the subtropical basins has its maximum downward transport near the surface. The surface intensified downwelling is due to the Ekman pumping occurring inside the subtropical ocean basins and the maximum impact of the Ekman pumping generally appears around 100 m and then decreases significantly with increasing depth, as expected from Sverdrup dynamics. Also, the finding that the overturning circulation is not closed within these latitude bands (i.e., non-zero net vertical volume transport) emphasizes that the WBC upwelling is part of a basin-scale three-dimensional overturning circulation (Talley, 2003) and part of this upwelling is balanced by downwelling at higher latitudes.

Figure 7. Vertical volume fluxes in the subtropical ocean basins from Estimating the Circulation and Climate of the Ocean. Vertical volume transport due to the western boundary currents upwelling is shown in red, vertical volume transport integrated across the rest of the corresponding ocean basin within the same latitude band is shown in blue, and the net vertical volume transport is displayed as the magenta dashed line. The six regions, which are marked in Figure 1b, correspond to (a) Kuroshio. (b) Gulf Stream. (c) Agulhas Current. (d) East Australian Current. (e) Brazil Current. (f) Peruvian upwelling. Note that the depth axis is divided into two parts for better visualization.
We also calculate and compare the vertical volume transport associated with the four major upwelling regimes (WBCs, Eastern Boundary Upwelling, Equator and Southern Ocean) around the global ocean with ECCO (Figure 8). Near the surface, equatorial upwelling is the dominant process for the global oceanic vertical volume transport, with a maximum value around 100 Sv. But in the subsurface, the strongest upward transport is associated with the Southern Ocean and the WBC regions. Between 200 and 1,000 m, the WBC-related upward volume transport is generally more than 1/3 of the value in the Southern Ocean, with the maximum value around 25 Sv appearing near 400 m. Below 2,000 m the pressure gradient along the western boundary is weak and thus a reduced contribution to the upward transport is expected. Again, this comparison demonstrates the overlooked role of the WBC upwelling in the subsurface vertical exchanges of ocean properties and materials.

4. Discussion

This study provides evidence for the existence of as well as a dynamical framework for intense subsurface upwelling associated with the major subtropical WBCs around the global ocean. Vertical motions in many regions of the global ocean, such as in most eastern boundary currents, along the Equator, and in the Southern Ocean, show evident upwelling signals in surface temperature and/or chlorophyll fields (Huyer, 1983; Kämpf & Chapman, 2016; Marshall & Speer, 2012; Naveira Garabato et al., 2017; Toggweiler et al., 2019; Wyrtki, 1981) and have been known and studied for a long time. In contrast, vertical motions in WBC regions are generally weak close to the surface and become strong below the surface. Also, the strong horizontal transport and eddies associated with WBCs make direct detection of surface signals of WBC upwelling challenging. The intense subsurface upwelling in WBC regions, therefore, have long been unrecognized in the literature.

Although in this study subsurface upwelling in the WBC regions is not directly observed, a variety of ocean data products provide evidence supporting the inference that WBC upwelling is likely a real phenomenon in the global ocean. The primary reason we believe that the WBC upwelling is real is that in order for the western boundary currents to remain in geostrophic balance to leading order, the observed density gradient along the western boundary requires that there be upwelling. Second, the WBC subsurface upwelling appears in all the examined products (Figures S3–S8 in Supporting Information S1), including coarse-resolution ocean synthesis products and a high-resolution ocean model simulation. Those products differ in many aspects, including ocean model...
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Data Availability Statement


References


umerics, external forcing, mixing parameterizations and assimilated observational data. The apparent robustness of WBC upwelling suggests that it is likely controlled by processes that are well represented in all the products, like geostrophy and the large-scale density field. Third, vertical motions in other regions of the global ocean (e.g., at low latitudes, and in eastern boundary currents) in the examined data products are generally consistent with previous theoretical and observational studies, further increasing our confidence in their representation of the large-scale vertical motions.

The presence of pressure gradients along the boundary implies strong vertical transports, regardless of how those pressure gradients are maintained. In the high-latitude downwelling regions the pressure gradients are supported by a combination of lateral eddy fluxes and local surface buoyancy loss. These processes might also be important along the western boundary of the subtropical gyres, but other dynamics might also be at play. The pressure signal of buoyancy loss at high latitudes will propagate equatorward along the western boundary via coastal/boundary waves, so remote buoyancy forcing might also be important. Purely wind-forced circulations might result in upwelling along the western boundary, as implied by the inertial models of Parsons (1969), Veronis (1966), and Stommel (1965). In these models, conservation of potential vorticity requires a rising and eventual outcropping of isopycnals as the WBC flows poleward. This would produce a pressure gradient on the boundary and subsequent upwelling. Note that, unlike on eastern boundaries, such a pressure gradient on the western boundary can be balanced in a viscous boundary layer and does not require diapycnal mixing. In any case, there must be some ageostrophic process active along the western boundary to balance the pressure gradient and satisfy the no-normal flow boundary condition.

Vertical motions in the WBC regions can reach much deeper than in equatorial and Eastern Boundary upwelling. In addition, while the WBC upwelling is primarily along the isopycnal surfaces, it extends upward into the surface mixed layer. Consequently, they can play an important role in the subsurface exchange of ocean properties and materials and air-sea exchange in the subtropical regions. Given the consistent and strong vertical motions, the vertical transport of heat and carbon in the WBCs may be significant in regulating the heat and carbon content in both the upper ocean and atmosphere over longer timescales. Moreover, the basin-wide overturning circulations spanning the subtropical and subpolar gyres could exchange ocean properties and tracers between the ocean interior and western boundaries, as well as playing a role in the climate system.

Although point-wise values of ocean vertical velocity from models and synthesis products are generally weak and noisy, spatial filtering reveals interesting and robust large-scale patterns that are not readily apparent in other variables. We consider it particularly surprising that we have been able to determine a novel aspect of WBCs, one of the most widely studied ocean processes, simply by examining the time-averaged vertical velocity from available ocean synthesis and modeling products. At present, few ocean synthesis products and climate models provide output of ocean vertical velocity, which we suggest should be archived and examined routinely.


