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Process-oriented modeling studies of the 5500-km-long boundary flow off western and southern Australia

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ABSTRACT

While the unique character of the coastal current system off the western and southern coasts of Australia has been recognized, this vast 5500-km-long boundary flow has been studied far less than other current systems of the world. Recent observational studies from satellite altimetry and climatology are consistent with a continuous current extending from its origin at the North West Cape to the southern tip of Tasmania. To date, coastal modeling studies have focused on either the western Australian coast to Esperance or on southern Australia. There has been no process-oriented modeling study of the entire region that would allow the systematic exploration of the two independent forcing mechanisms (i.e., wind-forcing and thermohaline gradients) and their interactions that have been noted to act in a synergistic manner to maintain the longest continuous coastal current system in the world.

This study uses a regional circulation model (in this case the Princeton Ocean Model (POM)) to systematically address the roles the forcing mechanisms play in generating and maintaining the major features of this continuous coastal current system. Several process-oriented experiments, arranged in order of increasing complexity, are explored. The results show that, even in the absence of bottom topography, a continuous 5500 km coastal current system can be generated by wind forcing or by thermohaline forcing. If wind forcing alone is used, coastal currents in the direction of the wind and opposing undercurrents can be generated. If thermohaline forcing alone is used, coastal currents in the opposite direction of the wind and subsurface currents similar to the Flinders Current can be generated.

The addition of topography shows that topography is responsible for the currents' shelf break locations and, for broad shelf regions, can separate the surface flow into two cores, one at the coast and one over the shelf. On the west coast, topographic beta due to the continental slope prevents currents from becoming broader and drifting offshore. The combination of wind forcing, thermohaline gradients and topography show that swift currents forced by thermohaline gradients are slowed to more realistic speeds by opposing wind and by topography. Meanders and eddies result from the opposition of surface and subsurface currents as well as from thermohaline and wind forcing. The results illustrate that the 5500-km-long current system over the shelf break can be maintained year-long due to the two independent forcing mechanisms, their interactions, and the strong trapping effect of bottom topography.

The seasonal and daily wind-forcing experiments highlight both the seasonal and interannual variability of this complex current system. The Leeuwin Current along the western coast is slightly stronger in winter (July) than summer (January). There is much greater mesoscale activity in January when the opposing winds are strongest. The results also show that, although upwelling has been observed only in the summer in the Capes Current region, upwelling occurs intermittently in the 2001 winter but not in the 2001 summer. This illustrates that, depending on the strength of the forcing mechanism, such as strong equatorward winter 2001 winds, features such as upwelling on the west coast, usually thought to exist in the summer but only intermittently, can occur in different seasons. Along the southern coast, a gyre forms intermittently in the Great Australian Bight in summer, but the flow is constantly eastward across the entire shelf in winter. The production of upwelling in the Great Australian Bight during the 2000 summer but not during the 2001 summer is an indication of the importance of interannual variability. Overall, the results of this process-oriented study compare well with available observations off western and southern Australia.

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1. Introduction

1.1. Observational background

Along a typical subtropical eastern ocean boundary, the prevailing winds are equatorward, or at least have a large equatorward component. These equatorward winds generate an offshore Ekman transport and cause upwelling near the coast. With cold upwelled water along the coast and warmer water offshore, the sea surface slopes down toward the coast, resulting in a geostrophically balanced equatorward current moving in the same direction as the wind. Since the surface slopes downward from the equator toward the pole in the alongshore direction, this surface current flows against a pressure gradient. This pressure gradient forces a poleward undercurrent at depths of 100–300 m (McCreary et al., 1986).

The circulation off the west coast of Australia, the eastern boundary of the Indian Ocean, is quite different from the other subtropical eastern boundary current systems even though the wind is equatorward year-round. There is no persistent upwelling, although there can be areas of seasonal equatorward surface flow favorable for upwelling such as the Ningaloo Current (Woo et al., 2006; Woo and Pattiartchi, 2008) and the Capes Current (Gersbach et al., 1999; Pearce and Pattiaratchi, 1999). The Leeuwin Current (LC) is narrow and flows poleward in opposition to the prevailing wind, and there is an equatorward undercurrent (see Fig. 1a for locations of the large-scale currents and undercurrents off the western and southern coasts of Australia). The sea surface slopes down toward the pole, so the current flows with the pressure gradient (Thompson, 1984; McCreary et al., 1986; Smith et al., 1991; Batteen and Butler, 1998).

There are other examples of surface currents which flow against the wind. The Davidson Current flows poleward off the coast of California when the equatorward winds relax in late fall and winter (Batteen et al., 2003). A poleward countercurrent also appears off the west coast of India in the winter (McCreary et al., 1986). However, the Leeuwin Current along the west coast of Australia is unique. First, the other examples are thought to be undercurrents which surface during a short season of the year when the equatorward winds relax. In contrast, the Leeuwin Current is always a surface current and has beneath it an equatorward undercurrent (Godfrey and Ridgway, 1985; Griffiths and Pierce, 1986; Smith et al., 1991; Morrow et al., 2003). Additionally, these other examples are *countercurrents* which exist in addition to the normal broad, slow eastern boundary current flow. Along the western coast of Australia, however, there is no regular, continuous equatorward surface flow within 1000 km of the coastline and there is no persistent upwelling along the coast (Smith et al., 1991).

The Leeuwin Current flows poleward as a relatively strong and narrow jet along the outer edge of the continental shelf off western Australia. It is ~50 km wide, exists in the upper 250 m of the water column, and averages ~30 cm s^{-1} with a seasonal maximum of ~60 cm s^{-1} (Schott and McCreary, 2001). A series of eddies develop on the seaward side of the current (Griffiths and Pierce, 1986; Smith et al., 1991; Batteen and Butler, 1998; Meuleners et al., 2008). The current carries a relatively warm and low salinity water mass formed from the tropical waters off northwestern Australia (Thompson, 1984; Ridgway and Condie, 2004). There is both a local temperature maximum and salinity minimum along the core of the current (Smith et al., 1991). Below a depth of ~300 m, a more saline undercurrent flows toward the equator just offshore of the continental shelf break (Schott and McCreary, 2001; Morrow et al., 2003). The Leeuwin Undercurrent (LU) carries an equatorward mass transport comparable to the poleward transport of the surface current (Godfrey and Ridgway, 1985). The speed of the undercurrent is about one-third that of the surface current with a mean velocity of ~10 cm s^{-1} at 450 m depth (Smith et al., 1991).

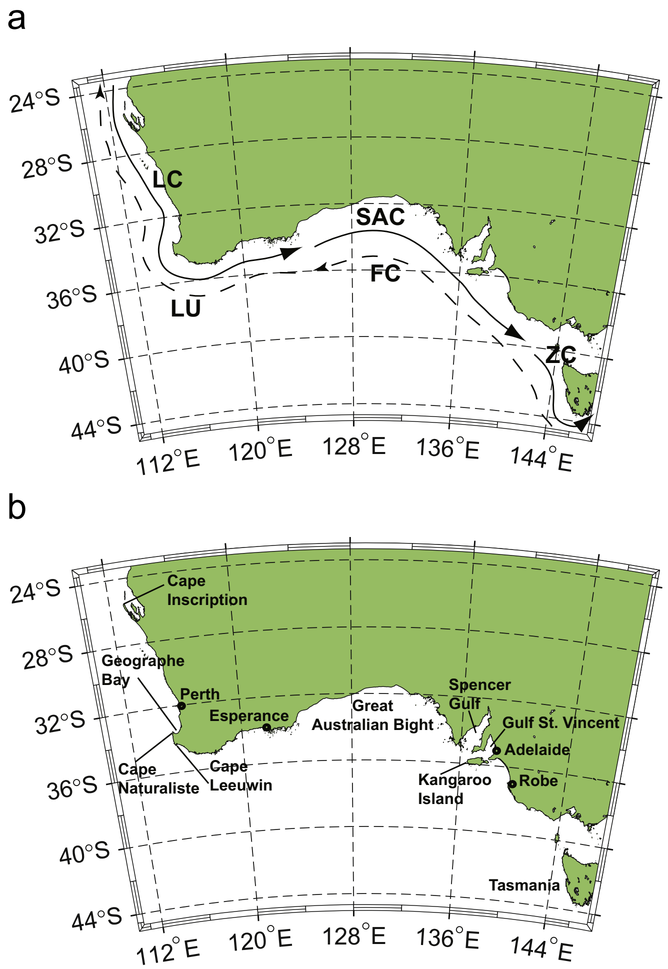

Fig. 1. (a) Schematic of large-scale currents and undercurrents off the western and southern coasts of Australia consistent with suggested naming convention of Ridgway and Condie (2004) (see the text for smaller-scale currents such as the Ningaloo and Capes Current.); (b) Geographical names for locations in the study area.

The sea level drops about one-third of a meter between 20°S and 32°S (Thompson, 1987), which is a far greater sea-level gradient than in the Atlantic and Pacific Oceans (Schott and McCreary, 2001). There is general agreement that the pressure gradient arising from this anomalously large steric height difference is the principal forcing mechanism of the Leeuwin Current (e.g., Thompson, 1984; Godfrey and Ridgway, 1985; McCreary et al., 1986). Even though there is a strong equatorward component to the wind stress year-round, this pressure gradient is strong enough to overwhelm the wind forcing and generate a poleward surface current (Smith et al., 1991).

The Leeuwin Current accelerates as it flows farther south and converges to a width of ~20 km between Cape Naturaliste and Cape Leeuwin (see Fig. 1b for locations of geographical names), where it reaches its maximum speed of ~70 cm s^{-1} (Cresswell and Golding, 1980). In this area, the front separating the warm waters of the current from the colder offshore waters becomes much stronger and sharper, with sea surface temperature in the current as high as 21 °C in contrast to the offshore water of 15 °C (Griffiths and Pierce, 1986). The flow hugs the shelf break around the bend of Cape Leeuwin and flows eastward along the southern coast as