PRELIMINARY STUDY ON THE FORMATION MECHANISM OF COUNTER WESTERN BOUNDARY UNDERCURRENTS BELOW THE THERMOCLINE—A CONCEPTUAL MODEL

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Abstract Based on a simple conceptual model of stratified ocean, the criterion of the geostrophic velocity inversion in and below the thermocline was derived as \( h' \times \eta' < 0 \) and \( \rho_h | \eta' | \leq \Delta \rho | h' | \), meaning that the slopes of the thermocline \( (h') \) and the sea surface \( (\eta') \) must be opposite to each other, and that \( h' \) must be strong enough to satisfy the latter inequality. The criterion was applied to discuss the features of the western boundary undercurrents, the counter undercurrents of the western boundary currents below the thermocline, and to discuss the dynamics of their formation finally resulting from the combination of the basin-scale circulation and local geostrophic balance. The formation mechanism, multi-core structure, and transport variations of the Mindanao Undercurrent and those of other undercurrents, such as the North Equatorial Undercurrent and the Kuroshio undercurrent, can be satisfactorily explained by the above results.

Key words: western boundary undercurrents, formation mechanism, geostrophic velocity, inversion criterion, conceptual model

INTRODUCTION

The western boundary currents (WBC), counter undercurrents observed below the thermocline include the Mindanao Undercurrent (MUC) beneath the Mindanao Current (MC) (Hu and Cui, 1989, 1991; Wang and Hu, 1998a, b; Wang et al., 1998) (Fig. 1a), the southward flow below the Kuroshio (hereinafter, KUC) (Hu and Cui, 1991; Qu et al., 1997; Wang et al., 1998) (Fig. 1b), etc. For clarity, the above counter undercurrents of the WBCs are referred to as the western boundary undercurrents (hereinafter, WBUC) in this paper to distinguish them from the deep western boundary currents (DWBC) found before (Guan, 1990; Warren, 1981). The existence of the WBUC suggests the WBC's baroclinicity, so results of study on their baroclinic structure and dynamics should have strong bearing on the baroclinic theory of oceanic circulation.

However, because of their late discovery, baroclinic WBCs have not yet become an important part in the baroclinic theory of oceanic circulation. They were only studied as to their role in closing the interior circulation near the basin's western boundary or for examining their upstream effect on the interior structure (Huang, 1991). The continuous solu-
tion of the baroclinic WBCs matching the interior has not yet been found (Welander, 1988). It is noteworthy that although a few models of the abyssal circulation included the compensatory counter DWBCs near the bottom (Stommel, 1958), their results can hardly be used to explain the WBUC dynamics. Moreover, the main results of the above authors were similarity solutions which could not satisfy all boundary conditions essential for the physics and thus was imposed too strict restrictions to be valid.

So far the barotropic theory of the WBC has been successfully tested, but the baroclinic theory is still far from perfect, as present knowledge on the baroclinic structure of the WBC, especially on the WBUC, is still only based on observations.

It is remarkable that, although found in different oceans and at different depths and latitudes, the WBUCs above are quite similar in dynamic characteristics. Firstly, their associated near surface WBCs are basically geostrophic, at least in the cross-stream direction; secondly, their upper boundaries coincide somewhat with the thermocline; and last but not least, the thermocline slopes obviously in the cross-stream direction. It is noteworthy that the above-mentioned features are found not only in the WBUCs but also in the North Equatorial Undercurrent (NEUC) below the North Equatorial Current (NEC) (Fig. 1c) (Wang et al., 1998).

![Fig. 1](image_url) Multiyear mean relative density (upper panel) and geostrophic velocity (lower panel) on sections east of the Philippines along (a) 8°N, (b) 18°N and (c) 130°E.