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Comments on Johnson's Paper, "On the Wind-driven Circulation of a Stratified Ocean"

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Johnson (1971) has made a useful contribution to ocean-circulation theory by establishing more definitely the role of the thermal structure in the larger context of the theory of wind-driven ocean circulations. However, serious objections should be raised to his treatment of the eastern-boundary region and to his results on coastal upwelling.

In §§ 2 through 4, Johnson has presented a systematic derivation of the governing equations for various regimes (surface Ekman, intermediate thermal, and lower homogeneous layers) of the open ocean. For the intermediate layer he has used the known exponential similarity solution for the temperature and velocity fields from thermocline theory, and he has partially evaluated that solution by matching intermediate-layer upwelling to the wind-induced upwelling given by the surface-layer solution. Thus, at the end of § 4, he has arrived at an explicit form for temperature in the open ocean, showing its theoretical dependence on sea-surface wind stress. The expression [his eq. (33) together with eq. (27)] contains an arbitrary scale factor and an arbitrary function of integration $T^*$ that is roughly sea-surface temperature near the eastern boundary.

To this point the analysis appears to be correct.

In § 5, Johnson departed somewhat from his systematic approach. Here, as acknowledged by him, he did not analyze the higher-order dynamics appropriate to coastal-boundary layers but merely assumed that the net transport of water from the interior into the eastern boundary region is zero at every latitude. This may seem plausible, but it is not obviously true because a net change in north-south flow in the boundary region between some two latitudes might, from continuity, require net east-west flow to or from the interior at inter-

1. Accepted for publication and submitted to press 15 October 1972.
vening latitudes. He assumed further that there is no inflow from the deeper layer, thereby obtaining a balance between transports in the upper and intermediate layers. This balance, when applied to the foregoing intermediate-layer solution, determines the form of the arbitrary function of integration, $T^*$, which becomes inversely proportional to the square of the Coriolis parameter. In general this leads to values of temperature that increase too rapidly with decreasing latitude to agree with nature.

The unrealistic feature may be less apparent in Johnson’s illustrative examples because the results have been cast in dimensionless form. His fig. 2 shows several cases for a northern-hemisphere basin in which dimensionless sea-surface temperatures have typical values of 0.25 toward the north and 2.0 toward the south. If, as Johnson has suggested, we apply the results to the subtropical North Atlantic between latitudes of zero wind-stress curl (roughly between 15–20°N and 45–50°N), we might identify the 0.25 value toward the north with the 5°C or 10°C isotherm, corresponding to winter or summer conditions, respectively. (These values are on the low side.) The value of 2.0 toward the south in Johnson’s examples then corresponds to about 40°C for winter conditions, 80°C for summer. In nature, of course, sea temperatures in low latitudes seldom get as high as 30°C.

The point is that Johnson’s results concerning the eastern-boundary region and upwelling are based on assumptions rather than complete analysis, and the resulting observable quantity, i.e., temperature (as opposed to upwelling, which is not generally measurable), does not agree with nature. This tends to invalidate one or more of the assumptions made. One or both of Johnson’s assumptions regarding zero east-west mass transport at every latitude may be incorrect (also a point of interest in the more detailed theories of coastal upwelling; e.g., O’Brien and Hurlburt 1972). Conversely, the interior solution [Johnson’s eq. (33)] may be inadequate. Here, the exponential solution was assumed, but the most general solution to the thermocline problem has apparently not yet been found (Welander 1971).

My opinion is that the exponential solution represented by Johnson’s eq. (33), with $T^*$ arbitrary, is reasonably correct for middle-latitude regions of the open ocean and that one or both transport conditions may be at fault. In earlier work I derived a similar but less general expression than Johnson’s. I, too, attempted to satisfy a transport condition at the eastern boundary but eventually abandoned the theoretical approach in favor of a semiempirical method. It turned out that empirical evaluation of $T^*$ (and the arbitrary scale constant) gave reasonable resulting temperature distributions. The semiempirical method, while theoretically less satisfying, is nevertheless correct in a more limited sense and can be used, for instance, in studies of the interior heat balance (Alexander 1971). Further evidence supporting the adequacy of the exponential solution in thermocline theory has been given by Needler (1971), who searched for the most general solution to the thermocline problem possessing an arbitrary baro-
tropic (deep-circulation) mode; he was led back to the same exponential similarity solution.

Nevertheless, it seems clear that the question of what assumption may be invalid in the foregoing will likely remain unsettled until a more complete analysis is done for the eastern-boundary region. Unfortunately, the analytical problem for that region, complete with bottom topography and thermal stratification, is probably an order of magnitude more difficult than the thermocline problem has been for the open ocean.

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