The Tsushima Warm Current and its Various Branches

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LONG-TERM GOALS

The goal of this project is to (i) determine why the Tsushima Warm Current (TWC) splits into three separate branches; and (ii) understand how and why the Ulleung Warm Eddy (UWE) is formed.

OBJECTIVES

We have conducted analytical and numerical investigations of the Tsushima Warm Current to determine the connection between both bifurcation and eddy formation and western boundary currents separation in the Japan/East Sea. We have proposed a new hypothesis, whereby the initial splitting of the TWC is due to the Tsushima Island and its related topography, whereas the secondary splitting of the western part of the TWC is due to a double separation of the western boundary current system. We also propose to investigate the alternative possibility that the secondary bifurcation is topographically induced. In order to understand the formation of the UWE, we propose that this quasi-permanent eddy is formed in order to compensate for the momentum flux of the poleward flowing boundary current. Achievement of these goals will result in improved understanding of the Japan/East Sea.

The nature of my modeling work is that I simultaneously work on several projects; some of these projects are not necessarily closely related to each other. For this reason, some of the publications which are listed at the end of this report may appear to be somewhat disjointed.

WORK COMPLETED

A one-layer and a two-layer configuration of the Japan/East Sea have been run with idealized step-down bottom topography (the step is ten times the base depth of the basin) and idealized subtropical wind stress forcing. An inspection of the results of these simulations indicates that, as expected, the formation of the second branch of the TWC is due to bottom topography. A peculiar step-induced bifurcation of the upper layer is observed. It is attributed to variations in thickness transmitted from below to the upper layer (**Figure 1**). This work which is done with Dr. Monica Stephens has not been submitted for publication yet.

The theoretical and numerical analysis of the UWE has been completed (with Dr. W. Arruda) and has been submitted for publication (publications #7 and #8). This work is Arruda's dissertation and reflects our preliminary efforts.

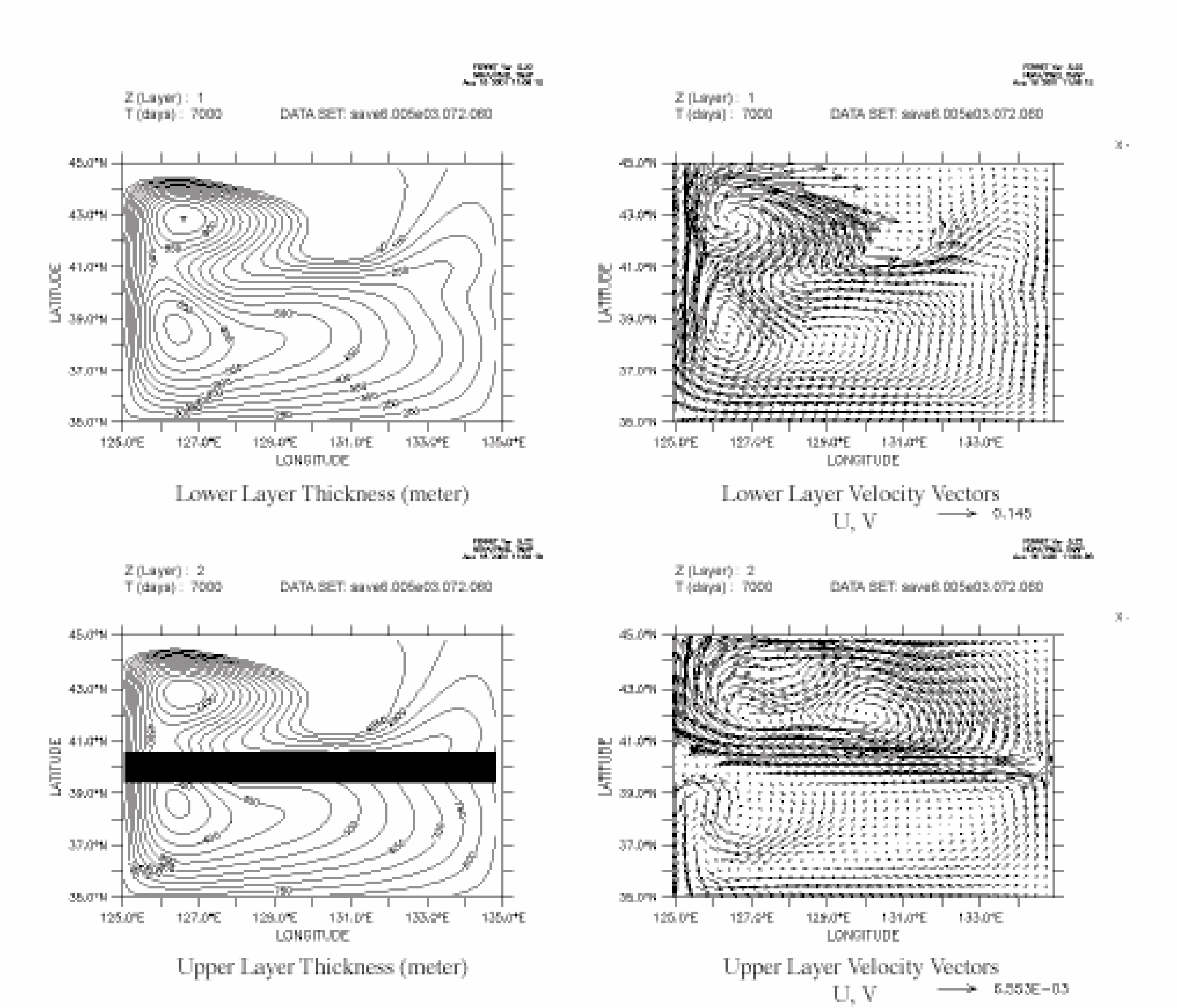

Figure 1. The response of a simple two-layer marginal sea to a varying bottom topography. The bottom is flat everywhere; a zonal step is situated across the basin at approximately 40˚N.

RESULTS

Research that has already resulted in the submission and publication of papers is listed at the end of this report in the order that they were completed. Most have not been supported solely by ONR but also by NSF and NASA.

In what follows I describe a detailed summary of the results (arranged in the order that the manuscripts have been completed during the past year).

The first paper addresses the penetration of North Brazil Current (NBC) rings into the Caribbean Sea. The islands of the Lesser Antilles present a porous meridional barrier to the NBC. To better understand if, when and how a NBC ring could be squeezed into the Caribbean Sea through such a gappy barrier, the encounter of a westward drifting eddy with a porous meridional wall is considered. First an eddy ecountering a single aperture is modeled, followed by numerical experiments that explored eddy collisions with barriers containing many gaps. We found that NBC rings are weak and large; hence, they are likely to enter the Caribbean Sea as coherent structures. Less common small and intense NBC rings are more likely to be broken up.

A quasi-island model addresses the exchange between the Pacific-Indian Ocean system and the Southern Ocean (paper #2). The calculations suggest that the Indian and Pacific Oceans have a meridional overturning cell with a transport of 18 Sv (± 5 Sv). The cell is driven by both winds and thermohaline processes but the calculation does not require solving the complete wind-thermohaline problem. The computational method takes Africa, Asia and Europe to be a "pseudo island;" i.e., the combined continent is entirely surrounded by water but has no net circulation around it. The continuation of sea level around the continent allows one to analytically compute the zonal upper layer transport which is first forced meridionally from the Southern Ocean to the Pacific and Indian Oceans and then forced down to lower levels.

In paper #3, we used a nonlinear one-and-a-half-layer model to examine the spreading of Indonesian Throughflow waters into the southern Indian Ocean. We constructed an analytical solution with the aid of the "slowly varying" approach and performed process-oriented numerical simulations. We found that, immediately after emptying into the ocean, the outflow splits into two branches. One branch forms a chain of high amplitude anticyclonic eddies which drift westward and penetrate into the interior of the Indian Ocean. The second branch carries the remainder of the mass flux via a coastal southward flowing current. Ultimately, this second branch separates from the coast and turns westward. We concluded that the eddies recently observed to the west of the Island of Timor are a result of the above eddies generation process which is not related to the classical eddies generation process associated with instabilities (i.e., the breakdown of a known steady solution). This perhaps explains why some of the Indonesian Throughflow water forms the source of the southward flowing coastal Leeuwin Current.

Paper #4 examines the formation of Reddies (i.e., isolated lenses containing Red Sea water). We propose that the "Reddy maker" is a combination of three processes, the natural reduction in the bottom slope which the outflow senses as it approaches the bottom of the ocean, the entrainment-induced increase in the outflow's thickness, and the entrainment-induced decrease in the outflow's density. This is supported by the idea that, in contrast to Meddies which are formed downstream of abrupt changes in the shape of the boundary against which they lean, Reddies have been observed upstream of such abrupt geographical changes.

In the fifth paper a "quasi-island" approach for examining the meridional flux of warm and intermediate water from the Southern Ocean into the South Atlantic, the South Pacific and the Indian Ocean is proposed. The method, which employs an integration of the linearized momentum equations along a closed contour containing the continents, considers the continents to be "pseudo islands" in the sense that they are entirely surrounded by water but have no circulation around them. The solution shows that, as expected, about 9 ± 5 Sv of upper and intermediate water enter the South Atlantic from the Southern Ocean. It also shows, however, the unexpected result that the Pacific-Indian Ocean system should contain a "shallow" meridional overturning cell carrying 18 ± 5 Sv.

The sixth paper uses existing general circulation modeling studies to suggest that, prior to the closure of the Panama isthmus, low salinity Pacific ocean water invaded the Atlantic ocean via the associated gap between North and South America. According to this scenario, the invasion decreased the Atlantic Ocean salinity to the point where deep water formation was impossible and, consequently, no "conveyer belt" movement was in action. Using simple dynamical principles, analytical modeling and process-oriented numerical experiments, it is shown that one would normally expect a flow from the Atlantic to the Pacific Ocean (rather than from the Pacific to the Atlantic) through an open Panama isthmus. The direction of the flow in both situations is determined by the wind field to the east of the gaps. On this basis it is suggested that if low salinity Pacific water did in fact invade the Atlantic Ocean prior to the closure of the Panama isthmus, then this invasion took place via the Bering Strait rather than through the open Panama Isthmus.

Papers #7 and #8 comprise Arruda's dissertation and reflect our preliminary efforts regarding the South Atlantic. Even though the names of the articles submitted so far for publication show applications to other oceans, this work represents our first attempt to understand the eddies in the western South Atlantic. The Ulleung eddy in the Japan/East Sea is just like the intrusion eddy in the South Atlantic except that it is quasi-permanent and does not detach (probably due to the absence of transport fluctuations). Hence, it is a simpler problem to tackle and we decided to focus on it first. However, our explanation for the formation of the Ulleung Eddy is also applicable to the intrusion eddy in the South Atlantic. The next step for us is to incorporate the detachment and apply it to the South Atlantic (but not to its detachment). This is what is proposed here. Likewise, the Mindanao and Halmahara eddies in the western Pacific are just like the recirculation regions north and south of the Confluence but are somewhat simpler and have been documented in much more detail (perhaps due to the absence of strong long-shore drifts in the Pacific case). Again, we felt that it is wiser to focus first on the Pacific case and then attack the more complicated Confluence Zone problem. On the basis of these studies we (Nof and Arruda) began to deal with the domino problem. Our first attempts to see whether the eddy detaches due to transport fluctuations failed and we suspect that this is because we considered fluctuations whose duration was too short (< week). Although we have not solved the Agulhas-Brazil Current problem yet and thus we do not really know how long the transport fluctuations are, we suspect that it takes the ring a relatively long time (a few weeks or a few months) to be absorbed so that longer fluctuations are in order.

In paper #9, the trajectory of a dense eddy propagating along the bottom of a meridional channel of parabolic cross-section from the Southern to the Northern Hemisphere is described by a two-degrees-of-freedom, Hamiltonian, system. This description explains both the sharp decrease in the amount of AABW water mass in the immediate vicinity of the equator in the Western Atlantic Ocean and the "splitter" effect of the equator, encountered in earlier numerical simulations.

RELATED PROJECTS

This project is closely related to work funded by the Binational Science Foundation, grant # 96–105, which focused on Reddies in the Red Sea rather than flows in the Japan/East Sea. Also, related research on the Leeuwin Current in the southern Indian Ocean has resulted in paper #3 listed below.

PUBLICATIONS

1. Simmons, H. and D. Nof, 2002: The squeezing of eddies through gaps. *J. Phys. Oceanogr.*, **32**, 314-335.
2. Nof, D., 2002: Is there a meridional overturning cell in the Pacific and Indian Oceans? *J. Phys. Oceanogr.*, **32**, 1947-1959.
3. Nof, D., T. Pichevin and J. Sprintall, 2002: Teddies and the origin of the Leeuwin Current. *J. Phys. Oceanogr.,* **32** (9), 2571-2588.
4. Nof, D., N. Paldor and S. Van Gorder, 2002: The Reddy maker. *Deep-Sea Res.*, in press.
5. Nof, D., 2002: The northward meridional flow into the South Atlantic, the South Pacific, and the Indian Oceans. *Prog. Oceanogr.*, in press.
6. Nof, D. and S. Van Gorder, 2002: Did an open Panama Isthmus correspond to an invasion of Pacific water into the Atlantic? *J. Climate*, submitted.
7. Arruda, W. and D. Nof, 2002: The Mindanao and Halmahera eddies are due to the bending of their parent currents, β and nonlinearities. *J. Phys. Oceanogr.*, submitted.
8. Arruda, W., D. Nof and J. J. O'Brien, 2002: The Ulleung eddy owes its existence to β and nonlinearities. *Deep-Sea Res. II*, submitted.
9. Paldor, N., D. Nof and A. Sigalov, 2002: The mechanics of AABW transport to the Northern Hemisphere. *Q. J. Royal Met. Soc.*, submitted.