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Deep-Sea Research II 51 (2004) 2883–2887

DEEP-SEA RESEARCH
PART II

www.elsevier.com/locate/dsr2

Small and mesoscale processes and their impact on the large scale: an introduction

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Abstract

Great progress has been made in understanding the role of small- and mesoscale processes on the large-scale structure and circulation of the oceans. However, many questions remain regarding the sensitivity of the large-scale ocean circulation and hence the earth's climate, to rates of stirring, mixing, and dissipation supported by ocean eddies, internal waves, and boundary layers. Although such relatively small-scale oceanic phenomena are ubiquitous, we lack detailed knowledge about their interaction with the large-scale motions, as well as their interactions amongst themselves.

Contributions are presented from observational, theoretical, and modeling studies that focus on small- and mesoscale ocean processes, and some parameterizations of these processes for use in studies of the large-scale circulation. The range of topics is relatively broad, with most focus on internal wave generation, flow–topography interaction, and small- and mesoscale processes involved in ocean mixing. General conclusions emphasize the notion of localized mixing and the importance of interaction between waves, eddies, and topography, and the importance of interactions between oceanic motions and the background density stratification.

1. Introduction

Recent public concern over the impact of human activity on climate has sustained strong scientific interest in this subject. It has long been recognized that the large water content near the earth's surface, whether in vapour form as in the atmosphere, in liquid form as in the oceans, or in solid form as in ice, is crucial for understanding the variability of weather and climate. Each of the three states of water has received its own field of scientific interest, and many problems remain to be resolved. Since most of the water is found in the oceans, this has become the focus of many studies.

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0967-0645/$ - see front matter
doi:10.1016/j.dsr2.2004.09.010

Early studies of the role of the oceans in climate and climatic change focused on modelling the large-scale ocean circulation. However, it quickly became apparent that the large-scale circulation is not maintained solely by large-scale processes. Rather, small- and mesoscale processes, responsible for turbulent diffusion and the redistribution of heat, salt, and suspended materials, can have a very significant impact on the larger scale. While the importance of small-scale processes has long been recognized, it is difficult to study large-scale ocean circulation and small-scale processes at the same time. This has led to two distinct branches of physical oceanographic studies. One branch is focused on the proper implementation ('parameterization') of the net effects of small-scale processes on large-scale motions. The other branch is focused on the detailed dynamics of the relevant small-scale processes.

Recent work has broadened our understanding of the dominant small- and mesoscale processes in the oceans (e.g., see the reviews in Munk and Wunsch, 1998; Wunsch and Ferrari, 2004). Specifically, these studies have revealed the importance of tidal forcing and surface wind forcing on both the small- and large-scale dynamics of the ocean. Motions at near-inertial and tidal frequencies are communicated into the ocean interior by propagating internal waves that may break in certain areas, thereby causing mixing. Especially important is the recognition of possible mixing in localized areas instead of globally uniform and omnipresent mixing (Wunsch and Ferrari, 2004). The interaction of ocean oscillatory motions with bottom topography is not just important for mixing, but also for the generation of internal tides. Typical horizontal length scales for internal waves are O(10 km), while typical vertical length scales are O(100–1000 m). These scales and smaller are considered "small-scales" here. Bottom topography also appears to be important for the intensification of boundary currents that may become unstable (meander) and split-off eddies of "mesoscale" size, O(100 km) horizontally and O(1000 m) vertically. Such eddies can be long-lived (1–2 yr), but eventually dissipate, thereby distributing their contents in a different environment than where they were generated. However, for these small- and mesoscale processes, the mechanisms controlling the energy cascade to irreversible turbulent dissipation are still in question.

The papers in this volume represent a range of studies working to reveal some of the aforementioned details for parameterization of small- and mesoscale processes in models of the large-scale circulation. These studies cover a wide range of scales and use a wide variety of techniques from laboratory and numerical process modelling, to large-scale modelling and analysis of observations.

2. Small and mesoscale processes…

As noted above, one of the main candidates for ocean mixing is the breaking of internal waves, which are mainly generated externally via tides or atmospheric forcing. A quite different scenario is presented by Sutherland et al. (2004), who discuss the generation of internal gravity waves following a mixing event. By way of laboratory experiments and fully non-linear numerical simulations, they study the collapse of a mixed region of uniform density into a surrounding region of stratified fluid, the latter thereby able to support internal waves. Complex interactions are found, for specific types of stratification, when internal waves are excited with such large amplitudes that the collapsing mixed region is distorted through strong interactions with the waves. This study shows that complex interactions are possible between internal waves, allowing for breaking and subsequent "re"generation [possibly at different frequencies] in the intrinsic system of deep-ocean motions. A similar unexpected interaction is observed in a two-dimensional (2-D) model for the near-surface ocean, where air- bubbles influence the vertical stratification and consequently the propagation of internal gravity waves (Grimshaw and Khusnutdinova, 2004). This model shows that the effective stratification due to bubbles leads to the possibility of existence of internal [gravity] waves and a change of their dispersion relation in the otherwise homogeneous upper mixed layer.

The above studies emphasize the importance of the interaction between internal waves and their supporting background. This theme is found in many other studies in this volume. At the finescale end, Bouruet-Aubertot et al. (2004) study intermittent variations in density gradients caused by non-linear interactions among internal gravity waves. Sheets of strong stable density gradients result from convergent motion produced by surrounding breaking events. From their statistics of layers and sheets, the authors infer a vertical eddy diffusivity of $5 \times 10^{-4}\,m^2\,s^{-1}$. This value is five times larger than the canonical value considered necessary to maintain the large-scale meridional overturning circulation in the ocean (Munk, 1966) and an order of magnitude larger than typical values observed and attributed to internal wave breaking (e.g., Gregg and Kunze, 1991; van Haren et al., 1999). This and other studies lead to the suggestion (Garrett, 1990, and others) that particular topographic sites may be important for internal wave breaking and thus localized enhanced mixing.

Indeed very high vertical diffusivities of $O(10^{-1}\,m^2\,s^{-1})$ are observed in a detailed observational study using fast and accurate sampling instrumentation above a sloping side of the Faeroe-Shetland Channel (Hosegood and van Haren, 2004). Such high values are observed during a very limited period of time only, associated with turbulence generated by the passage of strongly non-linear wave trains (solibores) propagating up the slope. As the events are separated by approximately 4 days, the long-term average vertical diffusivity exceed $10^{-4}\,m^2\,s^{-1}$, despite the relatively strong tidal currents in the area. It is concluded that solibores probably cannot sustain sufficient deep-sea mixing required for the large-scale circulation. In contrast, daily averaged sediment fluxes measured near the bed were O(100) times larger than the background value during the day of one particular event, implying solibores are the dominant sediment transport mechanism over the slope, despite their intermittent character. The sediment fluxes (and hence the turbulence intensity) vary with the propagation direction of the solibore. The times between the events (larger than a tidal period) lead to the suggestion that boundary current variations or eddies govern the deep (~500–800 m) mixing events at the slope, possibly triggered by variations in passing atmospheric disturbances. This quasi-4-day sub-inertial periodicity does not seem to be influenced by the bottom topography, as the slope is very smooth in the area of investigation.

The effect of stratification intersecting sloping topography, specifically abrupt topography, on sub-inertial boundary waves is studied by Dewar and Leonov (2004) using analytical and numerical methods. Both baroclinic and barotropic waves are considered. It is argued that such waves possess a number of unusual linear dispersive and non-linear steepening tendencies. As a result, baroclinic waves on finite topographic slopes are shown to mix barotropic and baroclinic dynamics in a manner distinct from those on weak topographic slopes. This study confirms the recent notion of the importance of complex ‘rough’ topography of steep slopes and rapid along-slope variability (e.g., canyons). On the other hand, as demonstrated in the previous study, smooth sloping sides can support vigorous processes as well, and are still considered important for substantial internal wave generation.

Internal tides in one of the most renowned source areas, the shelf-break of the Bay of Biscay, are studied by Gerkema et al. (2004) using a numerical, linear, hydrostatic internal-tide generation model. They compare their model results with unique observations made near the continental shelf-break in early summer using a towed acoustic Doppler current profiler. The modelling focus is on the seasonal changes in the generation and dynamics. The authors find that in reproducing the observed patterns with the numerical model, the presence of the seasonal pycnocline is essential. However, the main region of generation for internal tides is below the seasonal pycnocline, and the permanent pycnocline determines the integrated energy conversion rates. Future observational investigations should seek to confirm the result, from the numerical model, that the energy radiated in internal wave beams becomes diffuse after a few reflections with the surface and bottom boundaries, even without considering dissipation. In addition, the reflection points could be important sites for mixing.

Localized enhanced mixing not only occurs near internal wave generation sites, but also in the open ocean where mesoscale eddies are found. By definition, mesoscale eddies carry water masses that are different from their surroundings. Mixing eventually occurs as the eddies dissipate. Many studies have examined the characteristics of mesoscale eddies near the surface (e.g., Gulf Stream warm core rings) and in the ocean interior (e.g., Mediterranean outflow eddies—Meddies). Mesoscale eddies have also been studied using satellite observations, such as in the study by Isern-Fontanet et al. (2004). They examine three eddies observed in the western Mediterranean Sea using satellite altimetry and sateillite observations of sea-surface temperature, both referenced to in situ data. They find that the observed eddies have a spatial structure in close resemblance to that found in coherent vortices of 2-D turbulence. The distinction between the coherent vorticity-dominated core of the eddy and the outer region dominated by deformation is important for understanding the role of transport and stirring properties associated with the eddies.

2.1. …And their impact on the large scale

The role of small-scale processes has also been assessed relative to the large-scale energy budgets of the ocean. St. Laurent and Nash (2004) present measurements of internal tide energy flux from the Mid-Atlantic Ridge and the Hawaiian Ridge. They find significant differences in both level and modal content in the radiated internal tide at these distinct generation sites. The lateral decay scale of energy flux generated at the Hawaiian Ridge is found to be O(1000) km, due to the stability of the low modes which characterize the radiation. In contrast, the energy flux generated at the Mid-Atlantic Ridge is comprised of higher modes which dissipate more efficiently, leading to a decay scale of O(1 0 0) km. Despite these differences, St. Laurent and Nash point out that the level of turbulent mixing at each site remains comparable.

Simmons et al. (2004) also consider the large-scale implications of the internal tide energy budget. They present numerical simulations of internal tides at 10-km lateral scales over the global domain. For the first time, patterns of baroclinic radiation are visible on basin scales, and complex patterns of energy flux generation and radiation emerge. Simmons et al. show that their energy flux estimates agree well with independent estimates for prominent generation sites. This is a noteworthy accomplishment, as their model solution results solely from the forward problem of solving the governing baroclinic equations subject to the astronomical tidal forcing.

Arbic et al. (2004) also consider forward solutions for the ocean tides, but strive to achieve accuracy in the barotropic (surface) mode as a primary goal. Their solution for the surface tide meets an accuracy previously met only by models that use assimilation of observed data. To achieve this, Arbic et al. use a topographic drag scheme based on the energy transfer from the barotropic to baroclinic tides. Both one- and two-layer models are examined, and the inclusion of the barotropic to baroclinic transfer is shown to be crucial in providing accurate forward estimates of the tides. Thus, Arbic et al. have demonstrated a clear link between a global-scale phenomena, the surface tides, and the small-scale process of internal tide generation.

3. Suggestions for future research

As is clear from the papers presented in this volume, we are still lacking so much knowledge of the detailed dynamics of the small- and mesoscale processes, that it remains hard to give conclusive closure schemes and parameterizations of their effects on the larger scale. In particular, the representation of small- and mesoscale processes in models of the global-scale climate remains as a major goal for future research. Recent studies on small- and mesoscale motions have shown that such parameterizations should be spatially variable, as generation, dissipation, and mixing occur in localized areas only. Topography, or more precisely, topography with certain specifications like matching the slope angle of internal wave rays, seems a key factor influencing the generation and dissipation of waves and eddies. More detailed studies are needed on the precise scale dependence of topography and on the types of interaction with oceanic motions. Furthermore, studies focused on the interactions between internal waves, eddies, and their oceanic background, are still needed. This requires finescale modelling down to the smallest scales and resolution of the relevant time-scales of variation. It also requires new observational techniques resolving finescales in time of order 1 s, and in space of order 1 m vertically and of order 100 m horizontally, with high accuracy for sufficiently long periods to examine climate variations of interest. Given the advances in modern computing, such goals are becoming more and more realistic.

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