OCEAN MIXING MATTERS! STIRRING PROGRESS AND EXCITING CHALLENGES

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Mixing processes in the ocean are like clouds in the atmosphere (in being important for the climate system but unresolved in models). They are, however, much less easily observed. Our knowledge of diapycnal mixing rates has come from (i) budgets (particularly of abyssal basins and surface bowls defined by isopycnal surfaces) and model-fitting, (ii) a variety of direct measurements, such as of dye spreading rates and temperature and velocity microstructure, and (iii) an understanding of the underlying processes such as breaking internal waves. All three approaches should agree for today's ocean (and this seems increasingly to be the case), but only process studies can give the formulae, rather than just values, necessary for predictive models.

There are, of course, caveats and questions associated with every approach. Budgetary techniques do not make it clear where mixing occurs (everywhere, or just near boundaries?); "direct" measurements are limited in space and time and often rely on assumptions that may not be universally applicable; process studies are still incomplete. Nonetheless, the WOCE era has seen remarkable progress, particularly in the comparison of different observational approaches. It now seems that (i) mixing is small, perhaps negligible, in much of the ocean interior; (ii) it is larger near rough areas of the sea floor and other topographic features such as seamounts; (iii) significant forcing of the internal wave field comes from the tides as well as the wind.

We are now in a position to propose rough parameterizations that can be used in models and, through sensitivity studies, help to focus further research. It does seem likely, though, that the greatest combination of importance and ignorance can be ascribed to the stratified ocean immediately beneath the surface mixed layer. Mixing rates there are not well described or understood, but have obvious importance for the properties of the surface mixed layer (and hence climate) and for nutrient fluxes.

Observationally, we should aim in the next decade to make the determination of mixing rates as routine as for temperature and salinity. This may depend on advances in microstructure measurement or further validation of approaches based on finescale properties such as strain and shear. Another possibility, for regions where mixing is strong enough to matter, is that improvements in CTD operation and data analysis will permit reliable use of the Thorpe scale technique, in which the statistical properties of density overturns are converted with minimal assumptions into a diapycnal mixing rate.

On the theoretical side, we need a better understanding of nonlinear interaction rates for perturbed internal wave spectra so that we may connect internal wave generation, which is increasingly well understood, to eventual dissipation and mixing. We also need to understand the dependence of the efficiency of mixing on factors such as the level and frequency content of the internal wave spectrum. Further evaluation of double diffusive processes, differential diffusion and the interplay of isopycnal stirring and diapycnal mixing is also important.

BOUNDARY CURRENTS AND INTERBASIN FLOWS: INDICATORS OF THE OCEANS' STATE?

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A main objective for WOCE was to quantify the size of western boundary currents. Current meter arrays were deployed for the first time to measure thermocline western boundary currents at 30°S in the Pacific, Indian and Atlantic Oceans and at 25°N in the Pacific Ocean while the time series Gulf Stream transport through Florida Straits at 25°N continued to be monitored. The direct current measurements at 30°S exhibit an equatorward flowing undercurrent beneath the poleward thermocline flow in each basin. Comparison of measured western boundary current transports versus Sverdrup transports exhibits no clear relationship. Furthermore, array measurements in the Atlantic at 38°N and 42°N and in the Pacific at 32°N demonstrate that the Gulf Stream and Kuroshio transports grow rapidly north of the latitude of maximum wind stress curl. Recirculations of arbitrary size appear to be necessary to explain the transports of the observed thermocline western boundary currents.

Deep western boundary currents were also measured in each ocean basin. In the Atlantic, the southward flowing North Atlantic Deep Water (NADW) transports at 26°N and 18°S are about 40 Sv, more than a factor of 2 larger than expected for the net export of NADW. Again, sizeable recirculations are called upon to explain the magnitude of the boundary currents. Consistent northward flows of Antarctic Bottom Water/Lower Circumpolar Deep Water (AABW/LCDW) were measured in the South Pacific and South Atlantic suggesting bottom water transports of 16 Sv in the Pacific and 6 Sv in the Atlantic, each decreasing in transport toward the equator. The direct measurements of northward bottom water transport in the Indian Ocean across 20°S yield surprisingly small values with the transport in the anticipated major boundary current off Madagascar being effectively zero.

The principal issue for basin-scale circulation and western boundary currents is to understand what sets the size of the circulation or, alternately, what sets the size of the recirculations that can dominate both the thermocline and deep western boundary currents.

A phenomenon of the WOCE period has been the emergence of the global thermohaline circulation as a key concept for describing and understanding ocean circulation and its role in climate. The simplicity of the global conveyor belt figure attributed to Broecker is the source of its influence yet its simplicity strips the complex ocean circulation down to a single pathway. “Improvements” to the conveyor belt have been made by Doos and Webb, who added an Antarctic Circumpolar Current, Southern Ocean upwelling and subsequent subduction of Antarctic Intermediate Water, and by Schmitz whose pipe diagrams attempt to define the vertical-meridional circulation of surface, intermediate, deep and bottom waters in each ocean. These diagrams of global ocean circulation require substantial interbasin flows, across the Atlantic equator in both the shallow and deep waters, across the Pacific equator to feed an Indonesian Throughflow; and they pose fundamental questions such as what determines the size of interbasin exchanges and whether there is a single vertical cell with polar sinking and equatorial upwelling or two vertical cells with a self-contained bottom water-deep water cell with upwelling around Antarctica and a shallower cell where Antarctic Intermediate Water feeds equatorial upwelling. WOCE measurements have addressed some elements of the thermohaline circulation and interbasin exchange.

There is a general consensus that about 17 Sv of NADW flow southward through the North and South Atlantic. Direct current measurements show that the northward bottom water transport is 16 Sv in the South Pacific and 6 Sv in the South Atlantic across 30°S, while inverse analyses of South Indian Ocean circulation appear to be converging on an estimate for the northward transport across 30°S below 2000 m depth of 10 Sv. It remains controversial whether these 32 Sv of deep northward transport in the South Pacific, Atlantic and Indian Oceans upwell into the thermocline and surface waters or whether they return southward as slightly warmer, shallower deep water. Measurement of the Indonesian Throughflow during WOCE has had only partial success so there is still no consistent estimate for its transport. Because the equator represents a dynamical barrier to meridional flow it is of interest to understand how waters cross the equator. In the South Pacific it appears that intermediate and thermocline waters flow northward toward the equator balanced by zonal pressure gradients, that they upwell along the equator as part of the eastward and upward flow of the Equatorial Undercurrent and then move northward into the North Pacific in the wind-driven surface Ekman layer. A similar argument has been made for the northward flow of intermediate and thermocline waters across the equator in the Atlantic required to balance the southward flow of NADW. WOCE observations of deep flows at the Atlantic equator show principally zonal flows with AABW flowing eastward through the Romanche Fracture Zone and westward along the deep continental slope off Brazil and NADW flowing eastward along the Brazilian continental slope.

Arguments persist whether there is enough interior mixing for conversion of deep waters into thermocline waters over the vast expanse of the Indian and Pacific Oceans, and this is the key process in the single vertical cell circulation; and whether there can be southward and upward flow of deep water across the Antarctic Circumpolar Current into the surface layers, which is a key process in the two-cell circulation. There are two views on what determines the overall size of the thermohaline circulation: the amount of vertical mixing and the zonal windstress in the Antarctic circumpolar region. Vertical mixing is stronger over rougher topography and may even be dominated by flow through deep constrictions so quantifying the amount of global mixing may require many regional experiments to define a relationship between mixing and topographic roughness. Upwelling of deep waters around Antarctica appears to involve eddy transports, not fully understood but related to the size of the zonal wind stress, rather than directly to the wind-driven Ekman transport. Outstanding issues in quantifying the thermohaline circulation include: monitoring the thermohaline circulation in the North Atlantic to determine its interannual variability; concerted measurement of the Indonesian Throughflow as opposed to continued spotty measurements in different places and different years; quantifying the amount of Antarctic Intermediate Water subducted and transported northward in the South Atlantic, Pacific and Indian Oceans; measurement of the cross-isopycnal mixing in the Antarctic circumpolar region; and an understanding of how intermediate, deep and bottom waters cross the equator

DO SIMPLIFIED (TWO-DIMENSIONAL/COARSE RESOLUTION/REDUCED PHYSICS) MODELS HAVE ANY USEFUL SKILL?

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Numerical models are important research tools in climate dynamics because they permit the quantitative testing of hypotheses regarding mechanisms of climate change. As the role of the deep ocean circulation for climate variability and rapid climate change was recognized some 40 years ago by Henry Stommel, active ocean components needed to be included in climate models. This immediately brought a serious challenge to the modelers, since adjustment processes involving the deep ocean occurring on time scales of many decades to centuries, now needed to be simulated by their models.

There are several ways to take this challenge. First, the early development has focused on coarse-resolution models of the coupled atmosphere-ocean system. The representation of fundamental processes was limited in these models, with the consequence that unrealistic flux corrections had to be used to obtain stable simulations. Although these involved local sources of heat, freshwater and momentum, many useful predictions could be made that fuelled scientific development and shaped our thinking. Over the last decade, with the growing availability of computing power, grid resolution of these model has been steadily refined, and the parameterizations of important processes have been improved: flux corrrections are no longer necessary in current coupled models. One might be tempted to conclude that the days of coarse-resolution models are over. This would be premature, however. Both paleoclimate research and the study of natural climate variability and sensitivity still require climate models of comparatively low resolution. If used judiciously, they contribute significantly to the scientific progress.

A second possibility is the development of simplified models. Usually, such models are derived from the full set of equations by suitable averaging processes. Energy balance models of the atmosphere, the radiative convective models, the Lorenz model, and the Stommel box model for the thermohaline circulation are extreme examples of such averaging. Nevertheless, these models have been very useful in estimating some fundamental numbers such as climate sensitivity, near-constancy of relative humidity in a warming world, and multiple equilibria of fluid flow regimes. The latter two are important examples of how simplified models can elucidate new dynamical behaviour, and lead to a completely new view of the climate system. Hence, the skill of these types of models does not lie with the ability to make predictions, but with the potential to explore parameter space in a systematic way, and to demonstrate fundamental dynamical concepts which subsequently must be tested with more complex models. In essence, such models only make sense within a hierarchy of models, with which a systematic investigation of processes is possible. Figure 1 shows such a hierarchy of models ordered according to the number of simulated dimensions in ocean and atmosphere, respectively.

Third, one step up in the model hierarchy, we find climate models of reduced complexity. These models involve more processes and dimensions than the simplified models mentioned above, but they are still orders of magnitude simpler than general circulation models. Due to their low computational burden, these models have become increasingly popular in the last few years. This is manifested by special sessions at conferences, the proposal of intercomparison projects, and ongoing activities in many institutes worldwide. These models, sometimes referred to as Earth System Models of Intermediate Complexity (EMICs) are convenient research tools especially for paleoclimatic modeling. It must be emphasized, however, that such simplicity is tempting and treacherous. Application of these models and interpretation of the results requires experience and caution because of many implicit limitations in terms of their dynamics. Some models contain sophisticated parameterizations that apparently bring results closer to observations or produced desired dynamical behaviour. Such tuning is dangerous and can be misleading. As in any modeling effort, the most important question is whether the results are robust; in other words, are they dependent on the grid resolution (e.g., locations of deep water formation), on specific parameter settings (e.g., stability of the thermohaline circulation as a function of mixing parameterisations), or on specific tuning (e.g., proximity of thresholds)? The real goal for these models is not to reproduce certain paleoclimatic records as perfectly as possible, but to make predictions about the dynamical behaviour of the climate system (e.g., the bipolar seesaw), which can then be verified, or falsified, by observations or more complete models. In addition, these models are very useful to construct ensemble simulations. With such ensembles, uncertainty in climate change projections can be quantified in a rational way for the first time.

A fourth approach, which complements the model hierarchy, is to construct substitute models. The goal is to represent the sensitivity of complex models by either linearizing these models by so-called pulse-response models, or to substitute the complex models by approximations. A recent promising avenue is to employ neural networks and train these networks with results from climate models. Reduced-complexity models can thus be used to explore new concepts in ensemble modelling and provide first estimates of probability densities in the framework of climate projections.

While simplified models occupy an important place in climate dynamics, their developers and users bear a special responsibility. It is only through extensive parameter exploration and ensemble siumulations that these models provide added value in climate studies. If used judiciously, they serve as “hypothesis generators” and actually represent useful precursors to targeted simulations with more complete climate models.

THE OCEAN MESOSCALE—IS IT IMPORTANT FOR CLIMATE?

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I will review key ideas concerning the role of eddies in the dynamics of the Antarctic Circumpolar Current (ACC), a central component of the Earth’s climate. In the ACC eddies play a dominant role in circumpolar budgets of momentum, buoyancy and potential vorticity, giving us a clue as to their probable role in other energetic and climatically sensitive regions of the ocean, such as the boundary currents and jets of subtropical ocean gyres and convection sites in subpolar gyres.

In this talk I will review several key elements of ACC dynamics that have been drawn together and brought in to focus by the community in the WOCE era. They are:

1. Observations of the southern ocean, particularly from altimetry, moorings, and, increasingly, from autonomous floats are enabling a dynamical picture of the ACC to be pieced together which incorporates, and puts constraints on, eddy fluxes of heat and momentum in the context of the large-scale circulation. Although there are few direct observations of eddy fluxes in the ACC, the evidence we have points to a very significant role for them.
2. Because of the absence of meridional boundaries, pathways for mean heat transport across the ACC are limited and so eddies must be largely responsible for poleward heat transport across the stream. The eddies also balance the input of momentum by the winds. The southward heat flux is directly related to a downward momentum flux through interfacial drag. This drag allows the surface momentum to be transferred to depth where it can be dissipated by mountain drag as the ACC flows over the high ridges. This has been established as the dominant balance of the ACC in both observations and eddy resolving numerical models. Eddies in the ACC are also thought to play an important role in setting the vertical stratification of the ACC. Finally the

ACC may play a central role in the global climate of the ocean through interplay of southern ocean winds, air-sea buoyancy fluxes, overturning circulation and eddy transport.

3. A theoretical framework has emerged —that of the meteorologist's 'residual-mean theory.' It tells us that advection by the overturning circulation of the ACC induced by eddies, Ψ^*, can offset advection by the mean meridional overturning driven directly by the wind, Ψ, resulting in a much weaker 'residual circulation,' Ψ_R. This is described in the literature as the 'weakening of the Deacon Cell.' Inferences of circulation from tracers (such as Sverdrup's classic schematic of currents and watermasses in the Antarctic region published in 'The Oceans') are now undertood as schematics of Ψ_R rather than the Eulerian mean. Residual mean theory is at the heart of modern parameterizations of eddies in large-scale models. It guided the discussions of eddy-driven subduction, diagnosis of overturning circulation from observations of surface buoyancy fluxes and from eddy fluxes inferred from satellite altimetry. It is also providing the framework for theoretical descriptions of the ACC and its overturning circulation and diagnosis of eddy resolving ocean models.

I will conclude by showing new estimates of southern ocean near-surface eddy diffusivities deduced by studying the evolution of idealised tracer fields driven by 2-d turbulent surface flows derived from satellite altimetry. Methods developed by Nakamura and Haynes and Shuckburgh for application to the stratosphere are used. They reveal values of surface diffusivities between 1000 and 4000 m^2s^{-1} varying across the ACC on horizontal scales of only 500 km or so. These large variations in eddy diffusivity must play a very significant role in ACC dynamics and can be expected to be a feature of eddying jets in other regions of the ocean.

THE INTERACTION OF OCEAN BIOLOGY AND CLIMATE

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The cascade of turbulent energy in the upper ocean creates a continuously fluctuating environment on spatial scales from hundreds of kilometers to millimeters. On scales relevant to individual phytoplankton cells and assemblages, these fluctuations preclude equilibrium conditions, such that multiple species from diverse taxa can physically co-exist within the same water mass without competing to exclusion. However, given a finite number of nutritional elements and a single energy source (the Sun), phytoplankton must compete for resources. Consequently, the selection pressures imposed by competition have led to taxa-level adaptations that have, on geological time scales, formed a set of functional groups or biogeochemical guilds. In this talk, I examine how some of those adaptations, such as the evolution of a storage vacuole, the selection of flagella, and the evolution of a silicious cell wall, co-evolved with changes in turbulent energy on geological and ecological time scales. As the physical structure of the upper ocean will change over the coming decades, it will further select specific functional groups, thereby exerting a biological feedback on the climate system.

WATER MASSES—CLASSIFICATION, FORMATION, AND MODIFICATION

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One of the sensible and fairly common definitions of a water mass is given, for example by Tomczak (1999), as "a body of water with a common formation history, having its origin in a particular region of the ocean." This definition implies that our ability to classify water masses depends on our knowledge about formation processes of water masses. It is common practice, however, to define a water mass before we fully understand its formation process. In this context, many of "water masses" are only incompletely defined and can be regarded as sort of "working hypotheses" posed in order to understand various processes related to water mass formation and modification, including air-sea interaction, flow fields and mixing process in particular parts of the ocean. That is, meaningful classification of water masses should help us to understand those processes. Actually, recognition of a certain water mass often leads to understanding of some important process in the ocean. Awareness of Central Waters of the world ocean is a good example, which has led to recognition of subduction process in the subtropical permanent pycnocline. The high-quality WOCE data have improved our ability to classify potentially meaningful water masses. The present talk will show some examples of such water masses newly defined or classified during the WOCE period and what we have learned from them about the oceanic processes. The examples include the varieties of subtropical mode waters and tropical intermediate waters in the North Pacific.

THE SOUTHERN OCEAN

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The existence of the “Drake Passage gap,” a circumpolar band of latitudes unblocked by continents, has profound consequences for the global ocean circulation and climate. The Antarctic Circumpolar Current (ACC) flows through this gap to connect the ocean basins and so allows a global-scale overturning (or thermohaline) circulation to exist. Density surfaces slope upward to the south across the Southern Ocean, in geostrophic balance with the strong eastward flow of the ACC, and as a result the deep layers of the ocean are in direct communication with the atmosphere there. Air-sea interaction where these layers outcrop results in the formation of water masses which ventilate a large fraction of the world ocean and regulate the storage of heat and carbon by the ocean.

During WOCE, dramatic advances in observations, models and theory have led to substantial new insights into the dynamics of the Southern Ocean and its connection to the rest of the global ocean. The WOCE circumpolar survey of high quality hydrography and tracer measurements has allowed the formation and circulation of Southern Ocean water masses to be quantified for the first time. Comparison of the WOCE data set to historical measurements has revealed large-scale changes in water mass properties throughout much of the water column. Repeat sections and the development of simple proxy techniques have provided multi-year, near-continuous time series of the baroclinic transport variability of the ACC. Shipboard measurements and remote sensing have revealed multiple filaments of the ACC, which merge and split along the circumpolar path of the current. Interaction of these jets with bathymetry is a dominant term in the momentum and vorticity budgets of the Southern Ocean. The zonal and meridional circulations in the Southern Ocean are intimately linked, with eddy fluxes playing a key role in the heat budget, zonal momentum balance, and meridional overturning cells. Buoyancy exchange with the atmosphere converts upwelled deep water to lighter intermediate water to close the global overturning circulation, in contrast to the traditional view that this conversion was accomplished by vertical mixing in the thermocline. Together these results have led to a deeper appreciation of the fundamental role played by the Southern Ocean in the Earth’s climate system.