ENERGETICS OF OCEAN MIXING

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Introduction

One of the defining features of the ocean's physical environment is its nearly ubiquitous stable stratification (Figure 1). Aside from a relatively thin and homogeneous layer that is widely found near the surface (the so-called upper ocean mixed layer), the density of the ocean increases monotonically with depth in a perceptible manner, the rate of this increase generally declining toward the ocean floor. Current views on the origin of the ocean stratification began to take form in the early twentieth century, as the oceanographers Georg Wüst and Albert Defant and other pioneers obtained the first clear picture of the temperature, salinity, and density distributions of the deep ocean. These unprecedented observations brought about the revelation that much of the ocean is occupied by a few relatively cold and dense water masses that are formed and sink within two specific high-latitude regions: the northern North Atlantic and the Southern Ocean. Critically, as each of these water masses flows away from its formation region and pervades large areas of the globe, its initially distinct properties are eroded by mixing with surrounding waters that are, on average, lighter. As a result, the density of water masses originating at high latitudes often decreases along their path, to a point where the waters become light enough to return to the surface.

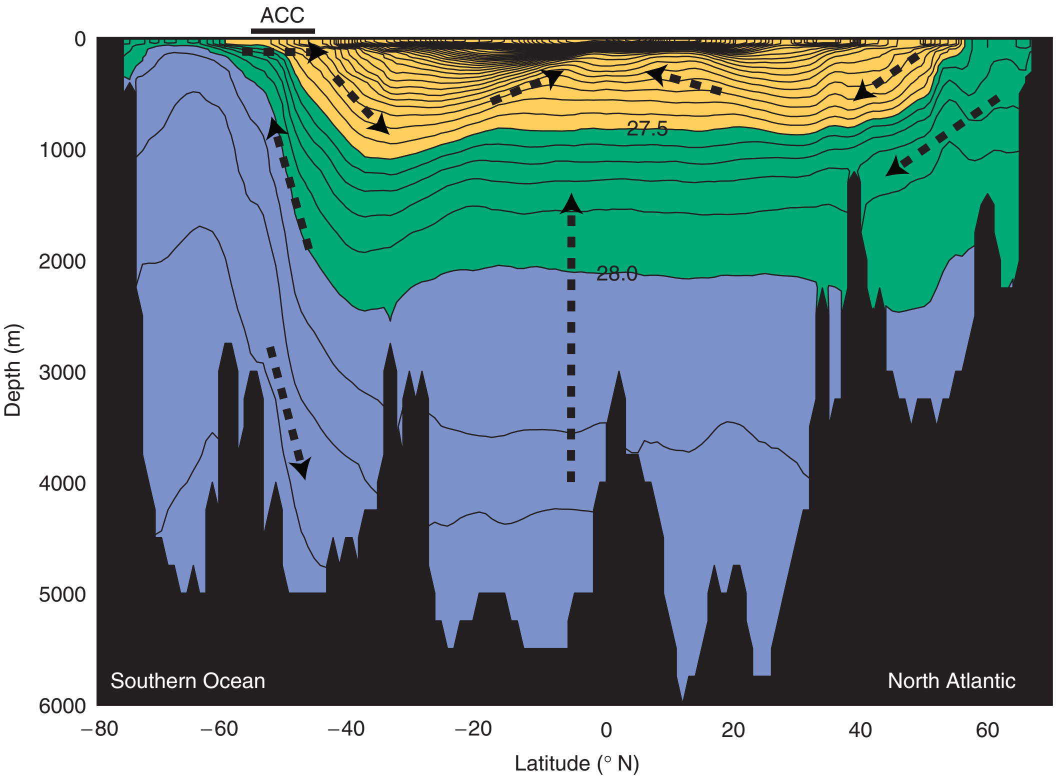

Figure 1 Vertical distribution of neutral density in the Atlantic Ocean along 30° W. Contours denote isopycnal surfaces with values between 23 and 28.4 kg m^{-3} at intervals of 0.1 kg m^{-3}. Colors indicate three density classes (separated by the 27.5 and 28.0 kg m^{-3} isopycnals) that are subject to different mixing regimes. The stratification in the abyssal ocean (purple) arises primarily from the balance between upwelling of dense water produced in the high-latitude Southern Ocean and turbulent diapycnal mixing elsewhere. In contrast, the stratification within and above the permanent pycnocline (orange) is mainly shaped by the wind- and eddy-driven subduction of near-surface water masses along isopycnals. Finally, the thick layer at the base of the permanent pycnocline, which outcrops into the upper ocean mixed layer within the Antarctic Circumpolar Current (ACC), represents a transition between the pycnocline and abyssal mixing regimes and is subject to a combination of both. The dashed arrows indicate the broad sense of the global ocean overturning driven by this set of mixing processes.

This simple conceptual model lies at the heart of present views of the climatically key overturning circulation of the ocean. Implicit in the model is a competition between the removal of buoyancy from the deep ocean by dense water formation at high latitudes, and the addition of buoyancy to the deep ocean by downward mixing of light upper ocean waters, which are warmed directly by the sun.

Come the second half of the century, the realization that the existence of the ocean's overturning circulation entails the antagonistic interaction between buoyancy forcing at the sea surface and mixing in the ocean interior excited an animated debate around the driving forces of the circulation that has persisted to this day. The focus of the discussion has been on understanding the circulation's energetics, as it is the way in which energy enters, flows through, and exits the ocean that strictly defines how the overturning circulation is driven. It is on the basis of energy considerations that early notions of surface buoyancy forcing as the governing rate-limiting process of the overturning have been challenged most convincingly in favor of ocean mixing. A central ingredient of this line of reasoning is a result put forward by Johan Sandström in 1908, stating that a fluid's motion cannot be sustained by heating and cooling at the fluid's surface if the source of heating lies at the same level as or above the source of cooling, such as is the case with buoyancy forcing at the sea surface. In other words, heating and cooling at a fluid's surface do only minimal work on (i.e., input very little energy to) the fluid. Although subtle differences between the ocean and the idealized fluid that Sandström described have been argued to limit his result's applicability to the oceanic context, it is now widely believed that mixing processes constitute the primary driving force of the overturning circulation. In this prevalent view, buoyancy forcing at the sea surface exerts an important influence on the structure of the ocean's overturning and stratification that is particularly pronounced in transient oceanic states associated with large-scale climatic change, but cannot by itself sustain the circulation indefinitely. Thus, the problem of understanding how the overturning circulation is driven can be reduced to that of determining the energetics of ocean mixing.

The Global Ocean's Energy Budget

In order to fully appreciate the intimate link between the overturning circulation and mixing in the ocean interior, it is helpful to consider the global ocean's energy budget. This can be formally synthesized in the global budgets of kinetic, potential, and internal energy, which can respectively be written as:

$$\begin{aligned}\partial/\partial t\int\!\!\int\!\!\int \rho K\,\mathrm{d}V = &-\int\!\!\int \rho K(\mathbf{u}-\mathbf{u}_\mathrm{s})\cdot\mathbf{n}\,\mathrm{d}A\\ &-\int\!\!\int [p\mathbf{u}+\mu\nabla K]\cdot\mathbf{n}\;\mathrm{d}A\\ &-C_{\mathrm{K}\leftrightarrow\mathrm{P}}+C_{\mathrm{I}\leftrightarrow\mathrm{K}}-C_{\mathrm{K}\rightarrow\mathrm{I}}\end{aligned}\qquad[1]$$

$$\begin{aligned}\partial/\partial t\int\!\!\int\!\!\int \rho P\,\mathrm{d}V = &-\int\!\!\int \rho P(\mathbf{u}-\mathbf{u}_\mathrm{s})\cdot\mathbf{n}\,\mathrm{d}A\\ &+\int\!\!\int\!\!\int \rho\partial P_{\mathrm{tide}}/\partial t\;\mathrm{d}V\\ &+C_{\mathrm{K}\leftrightarrow\mathrm{P}}\end{aligned}\qquad[2]$$

and

$$\begin{aligned}\partial/\partial t\int\!\!\int\!\!\int \rho I\,\mathrm{d}V = &-\int\!\!\int \rho I(\mathbf{u}-\mathbf{u}_\mathrm{s})\cdot\mathbf{n}\,\mathrm{d}A\\ &-\int\!\!\int [\mathbf{F}_{\mathrm{rad}}-\rho c_p\kappa_T\nabla T\\ &-\partial H/\partial S\;\;\rho\kappa_S\nabla S]\cdot\mathbf{n}\;\mathrm{d}A\\ &-C_{\mathrm{I}\leftrightarrow\mathrm{K}}+C_{\mathrm{K}\rightarrow\mathrm{I}}\end{aligned}\qquad[3]$$

In these expressions, K, P, and I are the kinetic, potential, and internal energies per unit mass. The terms on the left-hand side of each equation denote the rate of change with time (t) of K, P, and I scaled by the water's potential density (ρ) and integrated over the global ocean volume. These terms equal zero in the steady-state limit that is relevant to our discussion. In turn, the first terms on the equations' right-hand sides describe the advection of the various forms of energy through the ocean surface, with $\mathbf{u}$ indicating the oceanic velocity, $\mathbf{u}_\mathrm{s}$ the velocity of the free ocean surface, $\mathbf{n}$ a unit vector normal to that surface, and the integral being taken over the global ocean surface area. These advective terms are thought to constitute a significant source of energy to the ocean, but much of it is expended in small-scale turbulence within the upper ocean mixed layer and does not penetrate into our domain of interest, the stratified ocean interior.

The second terms on the equations' right-hand sides represent the three remaining candidate sources of the ocean interior's energy. The term in the kinetic energy equation stands for the work done on the ocean by differential pressure (p) and viscous stresses (μ is the kinematic viscosity of seawater) associated with the wind blowing on the sea surface. The differential pressure contribution is the dominant one. The term in the potential energy equation denotes the transfer of energy (expressed as a time-varying potential energy per unit mass, P_{tide}) from the Earth–

Moon–Sun system to the ocean by the continuous tidal displacement of the oceanic mass by gravitational forces. Finally, the term in the internal energy equation embodies surface and geothermal buoyancy forcing and amalgamates three different contributions: the radiative flux of internal energy between the near-surface ocean and overlying atmosphere/ice ($\mathbf{F}_{\mathbf{rad}}$), and the diffusive fluxes of internal energy brought about by molecular-scale mixing of temperature (T) and salinity (S) with diffusivities κ_T and κ_S (c_p and H are the specific heat capacity of seawater at constant pressure and the enthalpy of water, respectively). As advanced by Sandström's result and reiterated by most (though not all) available recent estimates, the net buoyancy work done on the ocean by exchanges with the atmosphere is likely to be minimal. Since this has also been shown to be the case for the geothermal heating contribution, the second term on the right-hand side of the internal energy equation can be neglected, and our discussion of energy supply to the ocean will hereby focus on the two outstanding sources: the winds and the tides.

The remaining terms on the right-hand sides of the three expressions above indicate the processes by which energy can be converted between its various forms. $C_{\mathrm{K}\leftrightarrow\mathrm{P}}$, defined as $\iiint \rho\mathbf{u}\cdot\nabla P\ \mathrm{d}V$, characterizes the transformation of kinetic energy into potential energy (or vice versa) associated with the raising or lowering of the ocean's center of mass by advection. Although this term is often important in regional energy budgets, it averages out to a negligible value in the global budget. $C_{\mathrm{I}\leftrightarrow\mathrm{K}}$ is defined as $\iiint p\ \nabla\cdot\mathbf{u}\ \mathrm{d}V$ and represents a bidirectional transfer between the internal and kinetic energy pools due to the compressibility of seawater, which causes density to vary with pressure. This term has been estimated to be small away from the upper ocean mixed layer. $C_{\mathrm{K}\to\mathrm{I}}$ is the only irreversible energy conversion term and is defined as $\iiint \rho\varepsilon\ \mathrm{d}V$, where ε is the rate at which internal energy (heat) is produced by the viscous dissipation of turbulent kinetic energy per unit mass. This process represents the only significant sink of kinetic (and, indirectly, potential) energy in the ocean, and must therefore balance the energy input by winds and tides. Thus, the dominant global energy budget for the ocean interior can be synthesized as

$$-\int\int \rho\mathbf{u}\cdot\mathbf{n}\ \mathrm{d}A + \int\int\int \rho\partial P_{\mathrm{titde}}/\partial t\ \ \mathrm{d}V \approx C_{\mathrm{K}\to\mathrm{I}} \qquad [4]$$

The validity of this balance in the characterization of the ocean's kinetic and potential energy sources and sinks is widely accepted by oceanographers. Nonetheless, establishing the physical controls and sensitivities of the overturning circulation demands that the flow of energy through the ocean be understood as well. It is the physical means of this energy flow that has been the focus of the ocean mixing debate in recent decades. In the following, we review the two most salient views of the subject to date, and provide an outlook on the major avenues of future development.

The Traditional Paradigm of Ocean Mixing: The Abyssal Ocean

The longest-standing and most influential paradigm of ocean mixing and its driving of the overturning circulation was first formulated by Walter Munk in 1966. The paradigm describes how the ocean stratification below a nominal depth of 1000 m (i.e., below the ocean's permanent pycnocline) may be explained by a simple one-dimensional balance between the upwelling (at a rate of *c.* $1\times10^{-7}\,\mathrm{m\,s^{-1}}$ or $3\,\mathrm{m\,yr^{-1}}$) of dense abyssal waters formed at high latitudes, and the downward turbulent mixing (at a rate defined by a turbulent diffusivity k_ρ of *c.* $1\times10^{-4}\,\mathrm{m^2\,s^{-1}}$) of lighter overlying waters. In energetic terms, the balance is established between a decrease in the ocean's potential energy associated with high-latitude production of dense waters, which lowers the ocean's center of mass, and a compensating potential energy increase brought about by the lightening of those waters by turbulent diapycnal (i.e., across density surfaces) mixing as they upwell, which restores the ocean's center of mass to its original level. A key fact that is made evident in this view is that, when oceanic turbulence ensues, not all the turbulent kinetic energy is dissipated into internal energy, but a fraction of it is expended in mixing water masses of different densities and thus leads to a vertical buoyancy flux. The relationship between the turbulent diapycnal diffusivity k_ρ and the rate of turbulent kinetic energy dissipation ε may then be expressed as

$$k_p = \Gamma\varepsilon N^{-2} \qquad [5]$$

where the buoyancy frequency $N = (g\rho^{-1}\ \partial\rho/\partial z)^{1/2}$ is a measure of the stratification, g is the acceleration due to gravity, and Γ is the so-called mixing efficiency, commonly (and somewhat controversially) thought to be about 0.2. Using [5], it has been shown that driving the global overturning circulation across the observed ocean stratification requires that 2–3 TW is dissipated by turbulence in the ocean interior, and that *c.* 0.5 TW is consumed by turbulent mixing in raising the ocean's center of mass.

The plausibility of this ocean mixing paradigm is suggested by the broad correspondence between the power required to support it (2–3 TW) and estimates of the rate at which work is done on the ocean by winds and tides. The wind contribution is thought to be very large, perhaps on the order of 10 TW, but an overwhelming fraction of this is likely dissipated within the upper ocean mixed layer or radiated as surface waves toward the coastal boundaries where the waves' energy is dissipated. The principal pathway for wind energy to enter the interior ocean is, in all likelihood, the wind work on the surface geostrophic flow (i.e., on the oceanic general circulation), which has been shown to occur at a rate of *c.* 0.8 TW and to be focused on the Antarctic Circumpolar Current (ACC), the broad, eastward-flowing current system that circumnavigates the Southern Ocean (Figure 2). Approximately 80% of the global wind work on the general circulation is

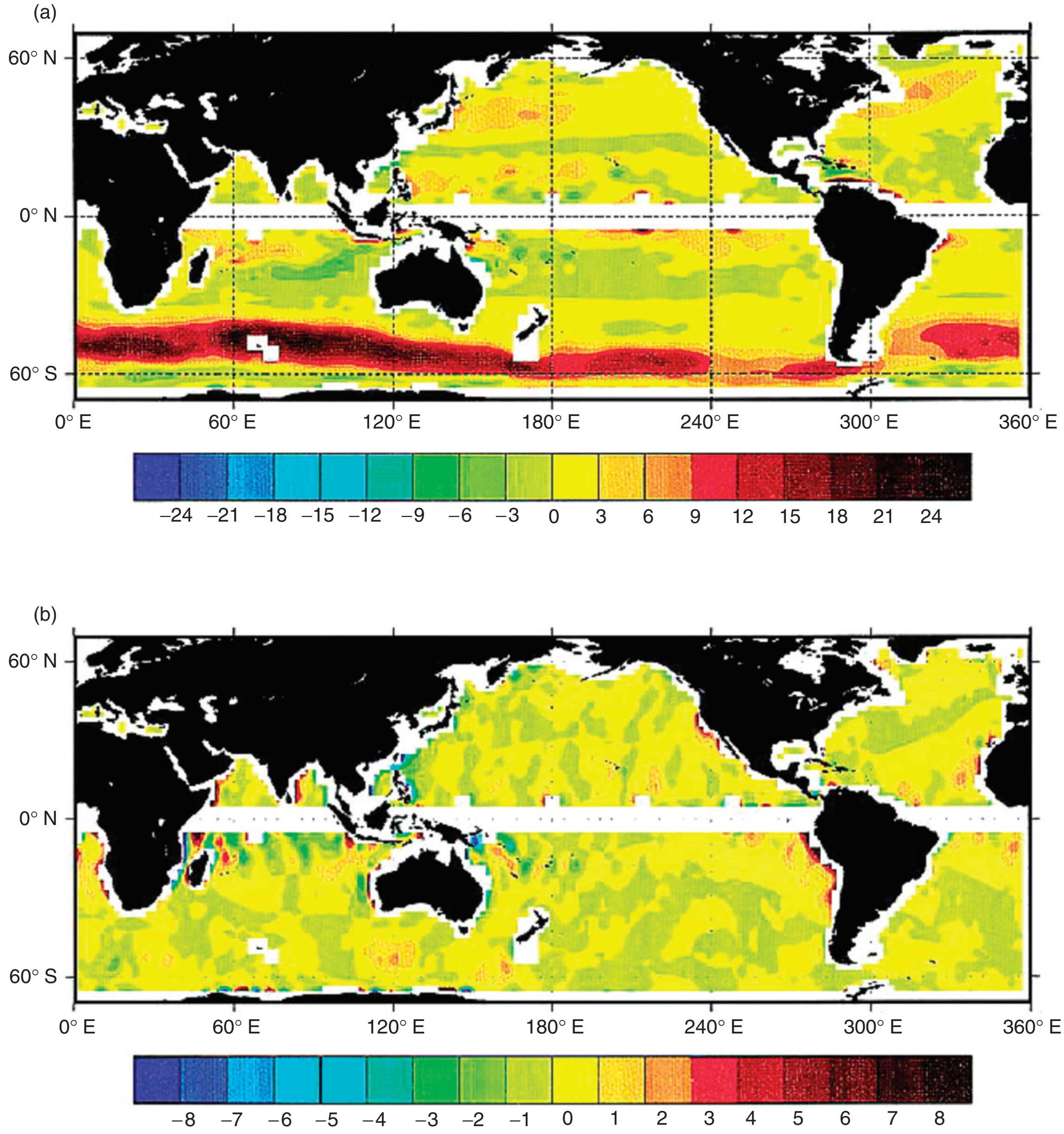

Figure 2 (a) Eastward and (b) northward components of the wind work on the oceanic general circulation in units of $10^{-3}\,\mathrm{W\,m^{-2}}$, estimated using 4 years of satellite sea level measurements and atmospheric reanalysis winds. Reproduced from Wunsch C (1998) The work done by the wind on the oceanic general circulation. *Journal of Physical Oceanography* 28(11): 2332–2340.

thought to enter the ocean in the ACC. The manner in which this energy flows in the ocean interior and its ultimate fate represent one of the most significant unknowns in the ocean mixing problem. It is generally accepted that the bulk of the wind energy input to the general circulation is transferred to mesoscale eddies via the action of baroclinic instability (a further 0.2 TW may be transferred from the wind to the mesoscale eddy field directly, as eddies are generated by variable wind forcing). However, the energy's subsequent pathway toward dissipation is uncertain. The traditional paradigm of ocean mixing proposes that a large fraction of the energy in the large-scale circulation and the mesoscale eddies may be eventually passed onto the ocean's ubiquitous field of internal waves, through one or several poorly understood energy transfer processes. These include the generation of internal waves by geostrophic flow over small-scale topography; the spontaneous emission of internal waves by loss of geostrophic balance in mesoscale motions; and the nonlinear coupling between mesoscale eddies and internal waves propagating through them. Once in the internal wave field, energy is rapidly cascaded to increasingly smaller scales, to a point where wave breaking and turbulence ensue and a large fraction $(1 - \Gamma)$ of the energy is dissipated through turbulence to heat. Aside from internal wave processes, it is also thought that a potentially large proportion of the wind work on the general circulation may be dissipated in turbulence generated by flows over sills within spatially confined abyssal passages, fracture zones, and mid-ocean ridge canyons, although estimates of this contribution vary widely.

A second significant mechanism via which the wind supplies energy to the ocean interior is the wind work on upper ocean inertial motions. As the wind blows on the sea surface, it generates upper ocean mixed layer currents that rotate at the local inertial frequency and can force downward- and equatorward-propagating near-inertial internal waves. The magnitude of the wind work on upper ocean inertial motions has been estimated as 0.5 TW, although energy losses to turbulence at the base of the mixed layer mean that this figure is likely to be an overestimate of the rate at which near-inertial internal waves transport energy into the ocean interior. Much of the wind work on upper ocean inertial motions occurs at mid-latitudes and exhibits a marked seasonal cycle (Figure 3), being primarily forced by winter storms.

Together with the wind work on the general circulation, tides represent the primary source of the energy required to sustain ocean mixing. The rate at which the sun and the moon work on the ocean via tidal forces has been estimated to be as large as 3.5 TW, but a substantial fraction of this energy (*c.* 2.6 TW) is dissipated on shallow continental shelves and does not access the ocean interior. The remaining *c.* 0.9 TW enters the deep ocean as a barotropic tide that forces flow over rough and steep topography and, in doing so, generates internal waves of tidal periodicity (internal tides) and boundary layer turbulence. The spatial distribution of this generation process is patchy, with enhanced barotropic tidal dissipation rates found over mid-ocean ridges, continental slopes, and other elongated features such as island arcs (Figure 4). Although the bulk of tidally induced mixing occurs in the close vicinity of the generating topography, there is observational evidence of low-mode internal tides being able to transmit their energies over long distances and support turbulent mixing many hundreds of kilometres away from their generation site. Current estimates suggest that this process accounts for *c.* 0.2 TW, a small yet significant fraction of the total tidal energy input to the ocean interior. Recent observations suggest that a further noteworthy contribution to tidal energy dissipation may be associated with sill overflow turbulence within mid-ocean ridge canyons and other canyon-like topographic features.

The final potentially significant source of energy to the ocean interior is also the most surprising and uncertain: the kinetic energy input by the marine biosphere. Net primary production in the euphotic zone produces roughly 60 TW of energy bound in carbohydrates, most of which is used in chemical form by organisms in the biosphere. However, it has been suggested that an amount of the order of 1 TW may be ultimately converted to biomechanical work done by animals swimming in the aphotic ocean. This estimate is subject to many uncertainties and remains exploratory.

We conclude, therefore, that the traditional paradigm of ocean mixing, applicable below the permanent pycnocline, may be synthesized as a one-dimensional balance between the upward buoyancy flux associated with the upwelling of dense abyssal waters, and the downward buoyancy flux driven by internal wave breaking and near-boundary turbulence, whose primary energy sources are tides and the wind work on the general circulation. In the last two decades, the validity of this conceptual model has been disputed somewhat imprecisely on the basis of a growing body of measurements indicating that k_ρ is often an order of magnitude smaller than the paradigm's canonical value of $1 \times 10^{-4}\,\mathrm{m^2\,s^{-1}}$ within and above the permanent pycnocline, that is, outside the

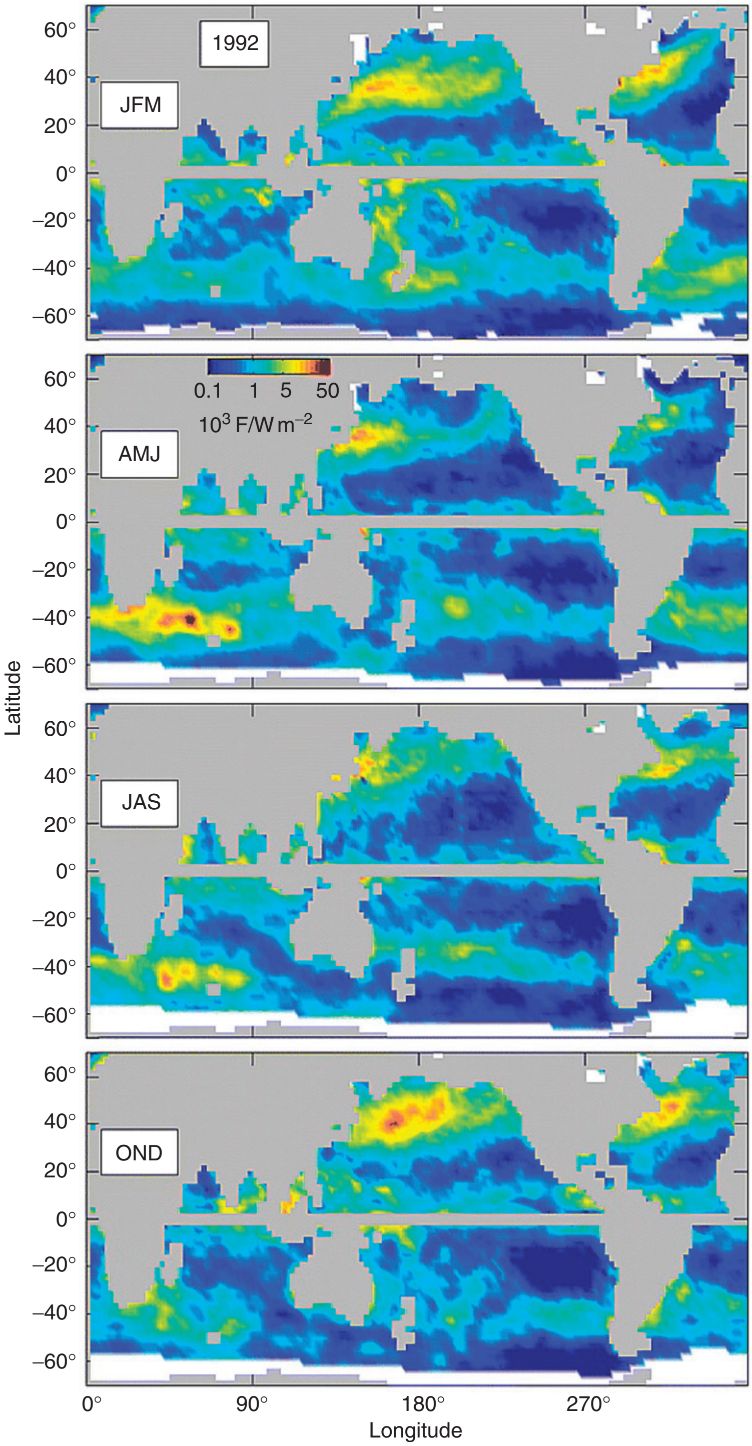

Figure 3 Seasonal maps of the work done by the wind on upper ocean near-inertial motions in units of $10^{-3}\,\mathrm{W\,m^{-2}}$, estimated using atmospheric reanalysis winds from 1992 and climatological hydrographic data. Each panel is a seasonal average over the months indicated at the upper left corner. Ice is indicated in white. Reproduced from Alford MH (2003) Improved global maps and 54-year history of wind work on ocean inertial motions. *Geophysical Research Letters* 30(8): 1424.

paradigm's depth range of applicability. Despite its partially misguided motivation, this challenge has nonetheless stimulated the emergence of an alternative paradigm of ocean mixing and its energetics that is consistent with observations of weak diapycnal mixing in the permanent pycnocline. The essential elements of this model are outlined in the following section.

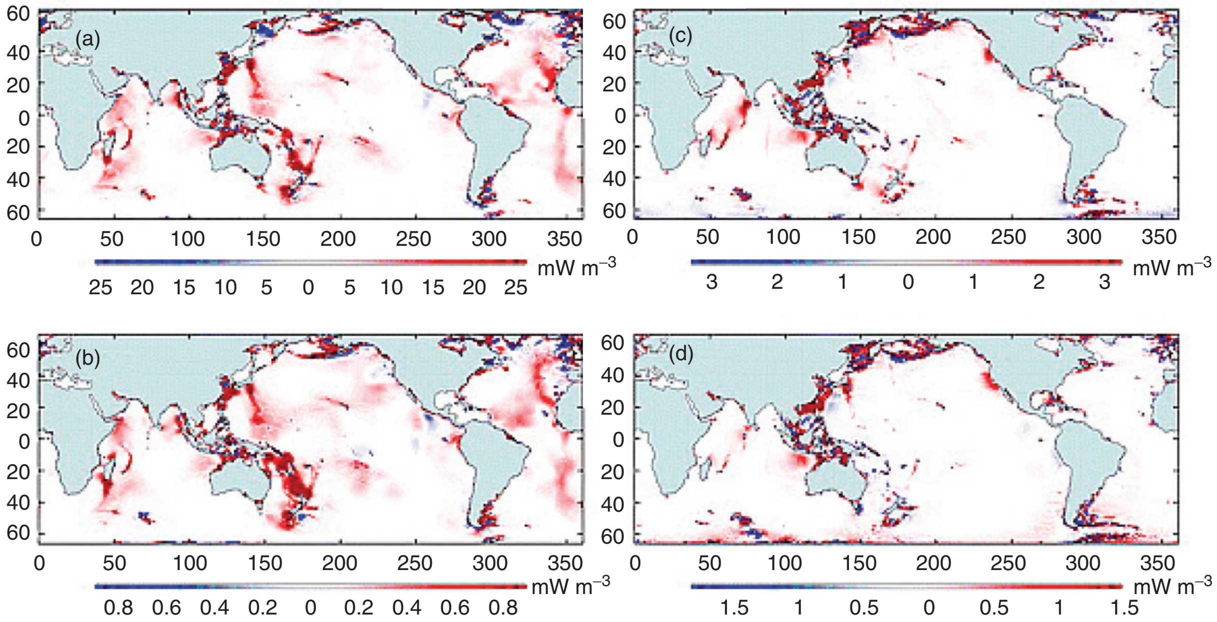

Figure 4 Maps of dissipation of the four major tidal constituents in units of $10^{-3}\,\mathrm{W\,m^{-2}}$, estimated using the TPXO.5 assimilation of satellite sea level measurements. (a) M_2, (b) N_2, (c) K_1, (d) O_1. Reproduced from Egbert GD and Ray RD (2003) Semi-diurnal and diurnal tidal dissipation from Topex/Poseidon altimetry. *Geophysical Research Letters* 30(17): 1907.

An Alternative Paradigm of Ocean Mixing: The Permanent Pycnocline

The role of air–sea interaction in setting the stratification of the permanent pycnocline was first highlighted by Columbus Iselin in the first half of the twentieth century, when he noticed that the temperature–salinity relationships imprinted horizontally in the wintertime upper ocean mixed layer of the North Atlantic are reflected in the pycnocline's vertical structure. This observation inspired the development of a family of conceptual models describing the renewal of water masses in the permanent pycnocline, and showing that a realistic stratification may be obtained in the upper kilometer of the ocean interior without any diapycnal mixing. A common ingredient of these models is the appeal to a three-way interaction between wind-forced (Ekman) vertical motion, isopycnal (i.e., along-density surfaces) stirring of water masses by mesoscale eddies, and atmospheric buoyancy forcing at the sea surface to explain how the subduction of relatively unmodified upper ocean waters into the ocean interior comes about. In energetic terms, the flow defined by the models is primarily driven by the wind work on the general circulation, which is then transferred to the mesoscale eddy field by the action of baroclinic instability. The models do not address the issues of how the subducted waters return to the surface and how the wind work is ultimately dissipated, that is, the mass and energy budgets of the modeled circulation are not closed.

The Southern Ocean arguably represents the most notorious manifestation of the above mechanism at work, and is thus at the heart of this alternative paradigm of ocean mixing. There, a range of density surfaces found at great depth over much of the global ocean, including some of the waters implicated in the traditional paradigm, are seen to outcrop into the upper ocean mixed layer of the ACC (Figure 1). This suggests that a considerable volume of water in the global ocean interior (roughly the layer between depths of 1000 and 2000 m) may not necessarily undergo turbulent mixing with lighter overlying water masses in order to return to the upper ocean, but that it may upwell along the steeply sloping isopycnals of the Southern Ocean instead. This notion finds support in recent studies of the Southern Ocean circulation and the dynamics of the ACC. The first indicate that upwelling of deep water (with original sources in the North Atlantic) to the surface does indeed occur over a substantial fraction of the ACC water column. Much of the upwelled water is returned northward as a wind-forced Ekman flow in the upper ocean mixed layer, where its properties are modified by air–sea interaction, and is subsequently subducted back into the interior at the ACC's northern edge, from where it spreads northward and pervades vast areas of the global ocean's permanent pycnocline. Studies of the dynamical balances of the ACC suggest, in turn, that the upwelling of deep water may be largely sustained by the current's vigorous mesoscale eddy field, in which nonlinear eddies act to drive a rectified southward flow across the time-mean geostrophic ACC streamlines. It thus becomes apparent that the Southern Ocean eddy field is pivotal to the two paradigms of ocean mixing presented here. On the one hand, it channels a large fraction (*c.* 0.65 TW, around 25–30%) of the net oceanic energy input toward dissipation scales, thereby contributing to sustain turbulent mixing across isopycnals in the traditional paradigm. On the other, it drives isopycnal upwelling of deep water masses that lie at the base of the permanent pycnocline in the mid- and low-latitude oceans. The extent to which these seemingly conflicting roles may be reconciled is unclear, but some light can be shed on the issue by considering the energetics of the alternative ocean mixing paradigm.

The key assumption that this paradigm makes in proposing that mesoscale eddies may sustain isopycnal upwelling across the ACC is that their energy must be largely dissipated in viscous boundary layers at the ocean surface and floor, with minimal turbulent mixing anywhere in the ocean interior. The notion of bottom drag as a significant factor in the dissipation of the eddy field does find some support in the theory of geostrophic turbulence, which predicts that the evolution of newly generated mesoscale eddies involves a gradual vertical stretching that fluxes kinetic energy downward. Nonetheless, recent observations indicate that a significant fraction of the wind work on the ACC may instead contribute to sustain intense internal wave generation in areas of complex topography and ultimately lead to strong turbulent dissipation and mixing in the interior, much as described by the traditional paradigm.

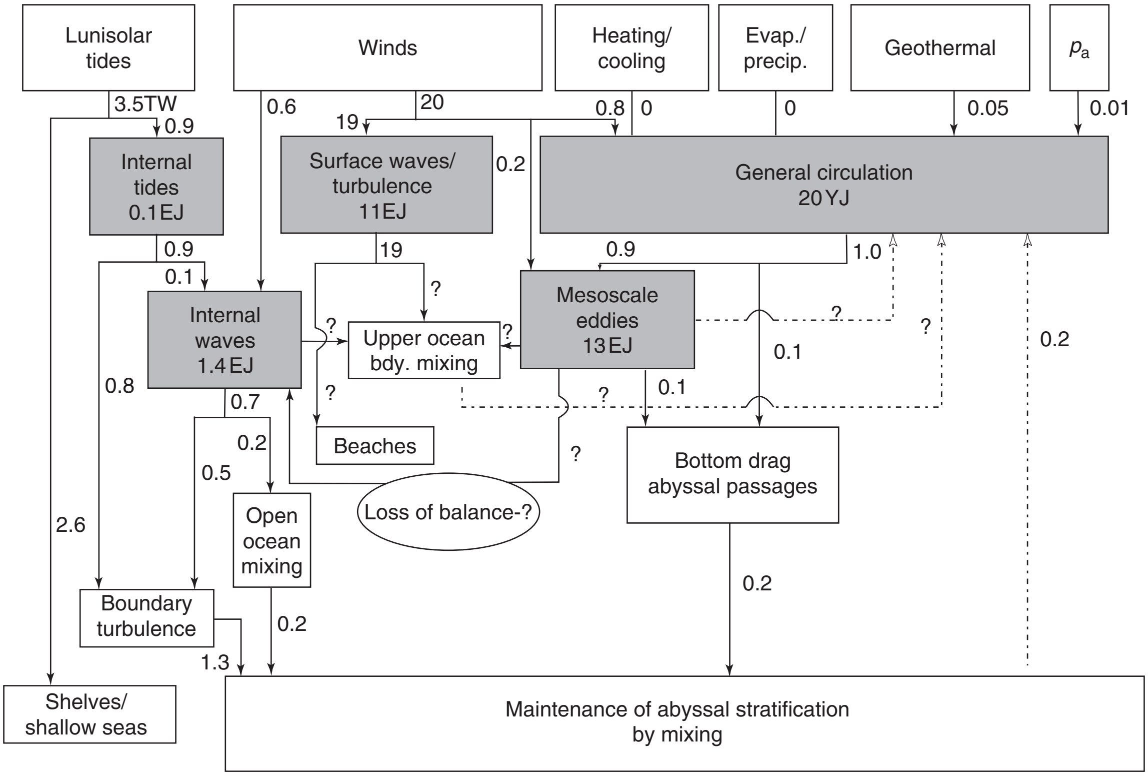

Figure 5 Schematic energy budget of the global ocean circulation, with uncertainties of at least factors of 2 and possibly as large as 10. The top row of boxes represents possible energy sources, with p_a denoting atmospheric pressure loading. Shaded boxes are the principal energy reservoirs in the ocean, with energy values given in exajoules (EJ, 10^{18} J) and yottajoules (YJ, 10^{24} J). Fluxes into and out of the reservoirs are in terawatts (TW). The tidal input of 3.5 TW is the only accurate number here. The essential energetics consists of the conversion of *c.* 1.6 TW of wind work and *c.* 0.9 TW of tidal work into oceanic potential and kinetic energy through the generation of the large-scale circulation, and the ultimate viscous dissipation of that work into internal energy via internal wave breaking and near-boundary turbulence. The ellipse indicates the likely but uncertain importance of a loss of balance in the geostrophic mesoscale and other related processes in transferring eddy energy to the internal wave field. Dashed-dot lines indicate energy returned to the general circulation by turbulent mixing, and are first multiplied by the mixing efficiency Γ. Open ocean mixing by internal waves includes the upper ocean. Reproduced from Wunsch C and Ferrari R (2004) Vertical mixing, energy, and the general circulation of the oceans. *Annual Review of Fluid Mechanics* 36: 281–314, © Annual Reviews.

Although the evidence available to date points to topographic internal wave generation in the ACC as a key agent in the transfer of eddy energy to the internal wave field, the other mechanisms introduced in the previous section are likely to enhance this transfer, and be more widely spread across the global ocean. On the whole, this points to the fascinating possibility that the two paradigms of ocean mixing presented here may be physically coupled, and suggests that it may no longer be appropriate to consider diapycnal and isopycnal water mass pathways in isolation. The emerging picture of ocean mixing is thus best described by the combination of two spatially and physically intertwined 'pycnocline isopycnal' and 'abyssal diapycnal' regimes.

Conclusion

We conclude that the oceanic stratification and overturning circulation owe their existence to mechanical (rather than buoyancy) forcing. This principle is reflected in a state-of-the-art synthesis of the energy budget of the global ocean shown in Figure 5. The essential energetics consists of the conversion of 2–3 TW of wind and tidal work into oceanic potential and kinetic energy through the generation of the large-scale circulation, and the ultimate viscous dissipation of that work into internal energy via internal wave breaking and near-boundary turbulence. There are many uncertainties regarding the energy flow between the large-scale circulation and the small dissipation scales, but available evidence points to the existence of two physically coupled, spatially overlapping ocean mixing regimes. In the abyssal ocean, at depths in excess of *c.* 1000 m, the circulation is driven by turbulent mixing, which allows dense waters to upwell across the stable stratification and acts to counteract the decrease of the ocean's potential energy brought about by high-latitude dense-water production. In contrast, the waters above and in the vicinity of the ocean's permanent pycnocline, that is, roughly in the upper 2000 m, tend to flow along isopycnals primarily in response to the release by baroclinic instability of the potential and kinetic energy imparted by the wind on the general circulation. The likely subsequent transfer of some of this energy to the internal wave field couples the pycnocline and abyssal mixing regimes physically, and so may introduce important subtleties in the way the ocean responds to climatic changes in forcing.

Significant open questions remain regarding all aspects of how energy enters the ocean, cascades to small scales, and dissipates. These are summarized in several major avenues of future development, of which the most prominent are: (1) quantitative assessment of the energy budget of the upper ocean mixed layer, and of the mechanisms regulating the flow of wind energy across its base; (2) quantification of the energy sources to the internal wave field, and of the processes regulating its rate of dissipation; (3) determination of the mechanisms responsible for coupling internal waves and mesoscale eddies and for dissipating the latter; (4) evaluation of the global significance of sill overflow turbulence within confined passages and mid-ocean ridge canyons; (5) assessment of the global importance of double and differential diffusion, nonlinearities in the equation of state, and biomechanical mixing. In the light of the preceding discussion, it is probable that our attempts to understand the ocean's state in past and future climates will be dangerously misguided until these issues are resolved.

Nomenclature

A	area
c_p	specific heat capacity of seawater at constant pressure
$C_{I \leftrightarrow K}$	global rate of transfer between internal and kinetic energies due to the compressibility of seawater
$C_{K \to I}$	global rate of transfer of kinetic to internal energy due to turbulent dissipation
$C_{K \leftrightarrow P}$	global rate of transfer between kinetic and potential energies due to advection
$\mathbf{F}_{\mathbf{rad}}$	radiative flux of internal energy between the near-surface ocean and overlying atmosphere/ice
H	enthalpy of water
I	internal energy per unit mass
k_ρ	turbulent diapycnal diffusivity
K	kinetic energy per unit mass
$\mathbf{n}$	unit vector normal to the ocean surface
N	buoyancy frequency
p	pressure
P	potential energy per unit mass
P_{tide}	tidal potential energy per units mass
S	salinity
t	time
T	temperature
$\mathbf{u}$	three-dimensional velocity vector
$\mathbf{u}_\mathrm{s}$	three-dimensional velocity vector of the free ocean surface
V	volume
x	eastward coordinate
y	northward coordinate
z	vertical coordinate

Γ	mixing efficiency
ε	rate of turbulent kinetic energy dissipation per unit mass
κ_S	molecular diffusivity of salinity
κ_T	molecular diffusivity of temperature
μ	kinematic viscosity of seawater
ρ	potential density
∇	three-dimensional gradient operator $(\partial/\partial x, \partial/\partial y, \partial/\partial z)$

See also

Antarctic Circumpolar Current. Bottom Water Formation. Breaking Waves and Near-Surface Turbulence. Dispersion and Diffusion in the Deep Ocean. Double-Diffusive Convection. Flows in Straits and Channels. Internal Tidal Mixing. Internal Tides. Internal Waves. Mesoscale Eddies. Ocean Circulation. Ocean Circulation: Meridional Overturning Circulation. Ocean Subduction. Overflows and Cascades. Three-Dimensional (3D) Turbulence. Tidal Energy. Upper Ocean Mixing Processes. Vortical Modes. Wind- and Buoyancy-Forced Upper Ocean. Wind Driven Circulation.

Further Reading

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