Understanding Mixing Efficiency in the Oceans:

Do the Nonlinearities of the Equation of State for Seawater Matter?

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Turbulent mixing in stratified fluids is well known to contribute for a significant fraction --- called the mixing efficiency --- of the total irreversible decay of kinetic energy. In the classical theory, such an irreversible decay is associated with the dissipation of available potential energy (APE) by molecular diffusion into mean gravitational potential energy (GPE). Recent theoretical results, however, suggest that this view conflicts with the second law of thermodynamics, and that turbulent mixing actually dissipates the kinetic energy converted into APE into dead internal energy, that is, the same subcomponent of internal energy into which the viscously dissipated kinetic energy is converted. Moreover, the new results also suggest that the mean GPE variations occur by exchange of energy with the exergy part of internal energy. The main result of this paper is to show that the rate of dissipation of APE is largely unaffected by the nonlinearities of the equation of state of sea water, in contrast with the rate of change of background GPE, which can be either positive or negative as a result. This result suggests that the important concept of mixing efficiency must also be largely unaffected by the nonlinearities of the equation of state for sea water, and that existing published values of mixing efficiency are likely to be valid for a large range of pressure, temperature, and salinity.

Introduction

As is well known, turbulent mixing in the oceans is a physical process that it is crucially important to parameterize correctly in numerical ocean models. Indeed, it is the quality of the parameterized irreversible diabatic processes in such models that largely determine the realism of the simulated distribution of water masses properties, as well as of the behaviour of the so-called meridional overturning circulation and its associated heat transport, which are two essential components of the large-scale ocean circulation that may interact with Earth climate. For this reason, much effort has been devoted over the past decades to understand the fundamental characteristics of turbulent mixing in stratified fluids, in order to design physically-based parameterizations of irreversible mixing processes suitable for implementation in numerical ocean models used for climate change simulations.

At a fundamental level, turbulent mixing in stratified fluids is important for at least two distinct --- although inter-related --- reasons: 1) for its role as a mechanism responsible for a significant fraction --- called the mixing efficiency, denoted by $\gamma_{\text{mixing}}$ --- of the total irreversible decay of kinetic energy; 2) for its role as a mechanism responsible for the diapycnal mixing of temperature, thus permitting the downward transfer of heat from the surface that is required to counterbalance the effect of high-latitudes cooling associated with deep water formation. In the turbulence literature, these two distinct roles of turbulent mixing are often regarded as being part of a common process. Specifically, it is generally assumed that the increase of mean gravitational potential energy occurring as the result of the turbulent mixing induced diapycnal mixing occurs at the expenses of the turbulent kinetic energy dissipated by turbulent mixing, e.g., [1,2]. Although there exists a considerable literature about how one should parameterize turbulent mixing, the model most often used appears to be that of [11], viz.,

$$K_\rho = \frac{\gamma_{\text{mixing}} \varepsilon}{N^2},$$

where $K_\rho$ is the turbulent diapycnal diffusivity, $\varepsilon$ is the rate of viscous kinetic energy dissipation, and $N^2$ is the squared buoyancy frequency.

To the extent that $\gamma_{\text{mixing}}$ can be regarded as some kind of universal parameter, as is often assumed, then the above model for $K_\rho$ states that the amount of turbulent mixing is proportional to the available sources of stirring. In the ocean modelling practice,
however, the value of $K_\rho$ is usually adjusted so that the simulated meridional heat transport in numerical ocean models agrees well with the observational estimates of the heat transport. Such an approach was pioneered by [11] which led to the widespread idea that the canonical value of $K_\rho=10^{-4}$ m$^2$/s was apparently needed to allow for a meridional transport of heat consistent with observed values. However, since such an approach is indirect, it implicitly assumes that there is enough mixing energy available to achieve such a value of mixing, which was never checked until about ten years ago by [3]. Whether this is the case was questioned in subsequent years, with several observational studies suggesting that $K_\rho$ in the oceans interior was in general typically smaller by an order of magnitude than the [11]'s value, stirring much debate in the ocean community as to the correctness and accuracy of [11]'s estimate. On the other hand, it is also widely recognized that turbulent mixing in the oceans is highly variable, both spatially and temporally, and therefore certainly not well described by a single value independent of space and time. For that reason, [3] suggested to resolve the dilemma by regarding the value $K_\rho=10^{-4}$ m$^2$/s as a bulk-averaged value to be interpreted as resulting from the overall effect of weak interior values combined with intense turbulent mixing values occurring in coastal areas or over rough topography. In a second step, they also proposed to use [11]'s model to see whether there is enough stirring energy available in the oceans.

Recently, these ideas have been used to examine the energetics of the large-scale ocean circulation. For instance, [3,4] examined the budget of gravitational potential energy, and argued that in the latter the loss of GPE due to cooling is balanced by the increase of GPE due to turbulent mixing. If we know the loss of GPE due to cooling, then [3,4] argue that $\gamma_{mixing}$ times the mechanical energy input of energy is required to ensure a circulation in steady state. If the GPE loss due to cooling is 0.4 TW for instance, and if a value of 0.2 is assumed for the mixing efficiency, then 2 TW of mechanical energy input are required to maintain the circulation in a steady state. The energetics constraints derived by [3,4], however, critically rely on the validity of the classical view of turbulent mixing. Among other things, this view relies on the idea that the mean GPE necessarily increases as the result of turbulent mixing. Yet, [5,6] suggested that the nonlinearities of the equation of state may be responsible for the mean GPE to decrease as the result of turbulent mixing, raising questions about the validity of the classical view. In particular, the validity of [3]'s approach relies on the two following assumptions:

1) that the kinetic energy dissipated by turbulent mixing is converted into mean gravitational potential energy;

2) that the increase of mean GPE due to turbulent mixing is accurately described by the classical formula:

$$\left(\frac{d(GPE)}{dt}\right)_{mixing} = \int K_\rho \rho N^2 dV$$

The first of these issues was addressed by [7] who proposed a new partitioning of internal energy into an available part $AIE$, an exergy part $IE_{exergy}$, and a dead internal energy part $IE_0$. The main results were to show that: 1) the kinetic energy dissipated by turbulent mixing appears to end up into dead internal energy, as does the viscously dissipated kinetic energy; 2) the rate of change of mean GPE appears to occur at the expenses of the exergy part of internal energy, not of the turbulent kinetic energy. Moreover, it also appears that the mean GPE does not necessarily increase as the result of turbulent mixing. Whether this is the case appears to depend on the sign of the parameter $dP/dz/[\alpha \rho/C_p]$, where $\alpha$ is the thermal expansion coefficient, $P$ is the pressure, $\rho$ is the density, and $C_p$ the specific heat capacity at constant pressure. Such a condition is consistent with one previously derived by [5,6]. As a result, the expression used by [3,4] to estimate the rate of change of mean GPE is not generally valid, for this expression only predicts an increase in mean GPE. In fact, such an expression is easily shown to be an artefact of using a linear equation of state.

Until now, most theoretical and numerical descriptions of turbulent mixing in stratified fluids have most often relied on the incompressible Navier-Stokes equations, often in the context of the Boussinesq approximation. With regard to the thermodynamics of the fluid, it is generally considered to be unimportant at leading order, and as a result, a linear equation of state is generally considered to be accurate enough for the purposes of describing turbulent mixing. As is well known, however, the equation of state for seawater --- which is the one appropriate for describing the oceans --- is strongly nonlinear in temperature, pressure, and salinity. The question arises, therefore, of which particular properties of turbulent mixing, if any, might be affected by the nonlinear nature of the equation of state for seawater.
In order to examine this issue, this paper seeks to investigate the question of whether the nonlinearities of the equation of state for sea water may affect values of mixing efficiency. The issue is important, because the latter is usually regarded as some kind of universal parameter, and it is important to establish whether there is any physical basis for such an idea. In order to address this issue, this paper examines the mixing efficiency from the viewpoint of the two different perspectives it is usually looked at in the literature, i.e., from the viewpoint of the dissipation of available potential energy \( APE \), as well as from the viewpoint of the rate of change of mean \( GPE \). Although these two perspectives are generally regarded as equivalent, [7] suggested that this is because the APE dissipation rate and the \( GPE \), rate of change appear to be strongly correlated for a linear equation of state, giving the impression that the second may indeed respond directly to the first, but this overlooks the fact that such a correlation fails to be robust to the use of a nonlinear equation of state.

In this paper, we examine the role of nonlinearities on the nature of mixing efficiency. To that end, we computed the non-viscous rate of dissipation of kinetic energy (i.e., the diffusive dissipation of \( APE \)) for a range of different stratifications all possessing the same buoyancy frequency \( N \), but different mean temperature, pressure, and salinity profiles. As will be shown, we find that the non-viscous dissipation of kinetic energy achieved by turbulent mixing appears to be largely unaffected by the nonlinearities of the equation of state, whereas the latter are crucially important to understand the turbulent rate of change of the background gravitational potential energy. The latter result is consistent with those anticipated in a series of papers by N. Fofonoff, e.g., [5,6], but apparently little known in the turbulence and oceanographic communities.

**Theoretical formulation of the problem**

An important issue in the study of turbulence is to be able to distinguish the adiabatic and reversible process of stirring from the irreversible process of mixing. From a theoretical viewpoint, the stirring and mixing processes are most easily distinguished if the gravitational potential energy is partitioned into its available and non-available components, as initially proposed by [8] to study atmospheric energetics, and more recently by [1] and [2] to study stratified turbulence. This is because by construction, irreversible processes only affect the un-available part of the \( GPE \), so that it allows for a natural quantification of the irreversible part of the density flux. In such an approach, one may write evolution equations for the volume-integrated kinetic energy (\( KE \)), available \( GPE \) (\( AGPE \)), and background \( GPE \), in the following form:

\[
\frac{d(KE)}{dt} = -C(KE, AGPE) - D_{\text{viscous}},
\]

\[
\frac{d(AGPE)}{dt} = C(KE, AGPE) - D_{\text{diffusive}},
\]

\[
\frac{d(GPE_r)}{dt} = W_r,
\]

where \( C(KE, AGPE) \) is the reversible conversion of \( KE \) and \( AGPE \), \( D_{\text{viscous}} \) is the viscous rate of \( KE \) dissipation, \( D_{\text{diffusive}} \) is the diffusive rate of \( KE \) dissipation, and \( W_r \) is the rate of change of mean \( GPE \). As shown by [7], the above evolution equations appear to be generic, in the sense that they can be shown to apply to the general case of the fully compressible Navier-Stokes equations using a fully nonlinear equation of state, as well as to many different forms of the incompressible Boussinesq approximation using a linear or nonlinear equation of state. The explicit form of the conversion coefficients appearing in such equations, however, will depend on the particular set of equations considered. Some explicit expressions for \( D_{\text{diffusive}} \) and \( W_r \) have been given by [1,2] in the case where a linear equation of state and the Boussinesq approximation is used. In such an approach, the process of stirring is associated with the reversible conversion of turbulent kinetic energy into \( AGPE \) via the energy conversion \( C(KE, AGPE) \), whereas the irreversible process of mixing acts in two ways: 1) by dissipating \( APE \) via the term \( D_{\text{diffusive}} \); 2) by irreversibly altering the mean centre of gravity at the rate \( W_r \).

The usefulness of the above energy equations is most easily illustrated by averaging the latter over a turbulent mixing event. Here, a turbulent mixing event is defined as an episode of intense mixing followed and preceded by laminar conditions for which \( AGPE = 0 \) to a very good approximation. In that case, denoting time average by an overbar, one obtains:

\[
\Delta KE = -\overline{C(KE, AGPE)} - \overline{D_{\text{viscous}}},
\]

\[
0 = \overline{C(KE, AGPE)} - \overline{D_{\text{diffusive}}},
\]

\[
\Delta GPE_r = \overline{W_r}.
\]

The first two equations can be summed to yield:

\[
\Delta KE = \overline{D_{\text{viscous}}} - \overline{D_{\text{diffusive}}},
\]

which shows that both molecular viscous and diffusive processes can contribute to the irreversible decay of turbulent kinetic energy. The relative
importance of the non-viscous dissipation of kinetic energy over the total viscous and non-viscous dissipation is often measured by the concept of mixing efficiency, defined here following [2] by:

\[
\gamma_{\text{mixing}} = \frac{D_{\text{diffusive}}}{D_{\text{viscous}} + D_{\text{diffusive}}}
\]

In the turbulent mixing literature, mixing efficiency is also often defined as follows:

\[
\gamma_{\text{mixing}} = \frac{W_r}{D_{\text{viscous}} + D_{\text{diffusive}}}
\]

so that in order for the two definitions to be equivalent, we need \( W_r \approx D_{\text{diffusive}} \) to a good approximation. In the turbulence literature, the idea that the two definitions are generally equivalent appears to be widespread, and based on the idea that the AGPE dissipated by turbulent mixing is entirely converted into background GPE. As far as we understand it, the idea seems to originate in the result that in the Boussinesq approximation based on using a linear equation of state, then \( D_{\text{diffusive}} \) and \( W_r \) are indeed nearly identical and therefore highly correlated. The fact that these two terms are nearly equal, however, is not sufficient to prove that the dissipated AGPE is necessarily converted into GPE. As discussed by [7], and further illustrated below, it is easy to show that \( D_{\text{diffusive}} \) and \( W_r \) become very dissimilar when a nonlinear equation of state is used. As a consequence, it is not true that the above two definitions of mixing efficiency are equivalent, in contrast with popular belief. In fact, only the first definition is valid as a measure of the relative importance of non-viscous dissipation over total dissipation of kinetic energy, and the only one able to produce a number between 0 and 1. The rate of change \( W_r \), indeed, is not directly related to the dissipated APE, and can either decrease or increase, depending on the stratification, so that definition 2 can in general produce a negative number, which conflicts with the properties generally attributed to mixing efficiency in the literature.

Methodology

In order to get insight into how the nonlinearities of the equation of state of seawater affects turbulent mixing, we computed the behaviour of \( D_{\text{diffusive}} \) and \( W_r \) for a number of different stratifications possessing the same buoyancy frequency profile \( N \), but different profiles of the parameter \( \alpha P_r \), as illustrated in Fig. 1. In order to compute \( D_{\text{diffusive}} \) and \( W_r \), we used the explicit expressions derived by [7], which are given by:

\[
W_r = \int \frac{\alpha P_r}{\rho C_p} \nabla \left( \kappa \rho C_p \nabla T \right) dV.
\]

\[
D_{\text{diffusive}} = -\int \frac{T - T_r}{T} \nabla \left( \kappa \rho C_p \nabla T \right) dV.
\]

These two expressions were estimated numerically for the case of a two-dimensional square domain discretized equally in the horizontal and vertical direction. In these expressions, \( \kappa \) is the molecular diffusion, \( P \) is the pressure (assumed to be hydrostatic), \( \rho \) is the density, and \( C_p \) is the specific heat capacity at constant pressure. Also, the subscript ``r'' is used to refer to the quantities in their reference state.

![Figure 1](image_url)

Figure 1: (Top panel) The squared buoyancy frequency \( N^2 \) common to all stratifications considered. (Bottom panel). The thermodynamic efficiency-like quantity \( \alpha P_r(\rho C_p) \) corresponding to the 27 different cases considered. Note that the Fofonoff regime, i.e., the case for which GPE decreases as the result of mixing, is expected whenever the latter quantity decreases for increasing pressure. The classical case considered by the literature, i.e., the case for which GPE increases as the result of mixing, corresponds to the case where the latter quantity increases with increasing pressure.
In total, 27 different types of stratifications were considered, all possessing the same squared buoyancy frequency \(N^2\) illustrated in the top panel of Fig. 1, but different mean temperature, salinity, and pressure resulting in different profiles for the \(dP/(\rho C_p)\) parameter illustrated in the bottom panel of Fig. 1. In all cases considered, the pressure varied from \(P_{\text{min}}\) to \(P_{\text{max}} = P_{\text{min}} + 10\) dbar, with \(P_{\text{min}}\) taking the three values (0 dbar, 1000 dbar, 2000 dbar). In all cases, the salinity was assumed to be constant, and taking one of the three possible values \(S = (30\text{ psu}, 35\text{ psu}, 40\text{ psu})\). With regard to the temperature profile, it was determined by imposing the particular value \(T_{\text{max}} = T(P_{\text{min}})\) at the top of the fluid, and determining all remaining values by inversion of the buoyancy frequency \(N^2\) common to all profiles by an iterative method.

We computed \(D_{\text{diffusive}}\) and \(W_r\) in the case of a two-dimensional domain that was discretized into \(N_p \times N_p\) points in the horizontal and vertical, with \(N_p = N_{z} = 100\). Mass conserving coordinates were chosen in the vertical, and regular spatial Cartesian coordinate in the horizontal. For practical purposes, the vertical mass conserving coordinate can be regarded as standard height \(z\), as the differences between the two types of coordinates were found to be insignificant in the present context, and thus chose \(\Delta x = \Delta z\). In order to compute \(D_{\text{diffusive}}\) and \(W_r\) for turbulent conditions, we modelled the stirring process by randomly shuffling the fluid parcels adiabatically from resting initial conditions. Shuffling the parcels in such a way requires a certain amount of stirring energy, which is equal to the available potential energy \(\text{APE}\) of the randomly shuffled state.

Results

For any particular stratification, several hundreds of random permutations were generated to shuffle the parcels adiabatically, each yielding particular values of \(D_{\text{diffusive}}\) and \(W_r\) which we plotted in Fig. 2 as a function of the amount of \(\text{APE}\) required to accomplish the random permutation of the parcels. The main result is that for all 27 different particular stratifications, and corresponding hundred of randomly generated permutations of the parcels, the diffusive dissipation of \(\text{APE}\) conversion term \(D_{\text{diffusive}}\) was found to be well approximated by a linear function of \(\text{APE}\) represented in the top panel of Fig. 2 as a thick red line. With regard to \(W_r\), i.e., the rate of change of \(\text{GPE}_v\), it is depicted in both panels of Fig. 2 as crosses, with the top panel being restricted to the particular stratification for which \(W_r\) is positive, and with the bottom panels including all cases considered. What these results show is that for each particular stratification considered, \(W_r\) appears to be either an increasing or decreasing function of \(\text{APE}\), depending on the overall behaviour of the parameter \(dP/(\rho C_p)\) depicted in Fig. 1. Unlike \(D_{\text{diffusive}}\), which appears to be a linear function of \(\text{APE}\), the dependence of \(W_r\) upon \(\text{APE}\) appears to be nonlinear in general. As discussed in [7], \(W_r\) is expected to be positive only when the vertical gradient of \(dP/(\rho C_p)\) is negative, which is obviously the case when the vertical variations of \(d\rho/(\rho C_p)\) are negligible compared to the vertical variations of pressure if the latter is hydrostatic.

![Figure 2](image-url)

**Figure 2:** (Top panel) The dissipation rate of \(\text{APE}\) as a function of \(\text{APE}\). Since all the points were lying along a straight line, a linear regression was superimposed (thick red line). The crosses represent the rate of change \(W_r\) of \(\text{GPE}_v\), for the particular experiments for which the rate of change of \(\text{GPE}_v\) was positive. (Bottom panel) The rate of change \(W_r\) of \(\text{GPE}_v\) as a function of \(\text{APE}\) for all cases considered. Units are arbitrary but the same in both panels.

The case when the vertical gradient of \(dP/(\rho C_p)\) is positive was extensively discussed by [5,6,10], and can be easily encountered in the oceans. Based on Fig. 2, \(W_r\) appears to be always smaller than
of internal energy appear to be decoupled at leading order, so that the dissipated $APE$ ending up into the dead subcomponent of internal energy $IE_o$ has no way to feed the exergy subcomponent $IE_{ex}$ of internal energy; otherwise, it would not be possible to exclude the possibility that the $APE$ dissipated by turbulent mixing is converted into mean $GPEr$.

This result has important consequences for how the concept of mixing efficiency should be defined. At the moment, there exist two commonly encountered definitions: 1) as the ratio of the dissipation rate of $APE$ over the total dissipation rate of kinetic energy; 2) as the ratio of the mean $GPE$ increase over the total dissipation rate of kinetic energy, e.g. [1,2]. These definitions would be equivalent if the $APE$ dissipated by turbulent mixing were actually converted into $GPEr$, but not otherwise. In this paper, we find that definition 1) always yields a number between 0 and 1, whereas definition 2), while always yielding a number smaller than 1, does not necessarily yield a positive number, which conflicts with the usual expectations for mixing efficiency. As a result, only definition 1) appears to be consistent with the properties usually associated with $t$ The case when the vertical gradient of $dP/(\rho C_p)$ is positive was extensively discussed by [5,6,10], and can be easily encountered in the oceans. Based on Fig. 2, $Wr$ appears to be always smaller than $D_{diffusive}$, which was already pointed out by [7] as implying that values of mixing efficiency based on measuring $GPE$ change are likely to underestimate the latter.

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The main result of this paper is to suggest that the non-linearities of the equation of state of seawater are crucially important to understand how turbulent mixing controls the rate of change $Wr$ of Lorenz’s background $GPEr$. On the other hand, the non-linearities of the equation of state appear to play only a minor role on the rate $D_{diffusive}$ of $APE$ dissipation. In this respect, this paper further confirms the conclusions of [7] that the $APE$ dissipated by turbulent mixing cannot possibly be converted into mean $GPEr$, as is classically assumed in the turbulent mixing literature, e.g., [1,2]. This is attested by the fact that $D_{diffusive}$ and $Wr$ appear to have very distinct behaviour in general, even if there exist particular cases for which both appear to be strongly correlated, as usually occurs when the vertical variations of the parameter $\alpha(\rho C_p)$ in the parameter $\alpha P/(\rho C_p)$ are small relative to the vertical variations of pressure. As shown in [7], the distinct behaviour of $D_{diffusive}$ and $Wr$ results from the fact that the $APE$ dissipated by turbulent mixing is converted into dead internal energy $IE_o$, i.e., the same subcomponent of internal energy which viscously dissipated kinetic energy is converted into, whereas the rate of change of $GPEr$ occurs by energy exchange with what we call the exergy subcomponent $IE_{ex}$ of internal energy. As shown in [7], the dead and exergy subcomponents of internal energy appear to be decoupled at leading
correlated, as can be sometimes the case, see the top panel of Fig. 2 for particular examples. The present results motivate a re-examination of published values of mixing efficiency based on definition 2, which we hope to report in a subsequent paper. So far, such test has never been carried out, as far as we can judge, for the assumption of equivalence between the definitions 1) and 2) has never been questioned before. Hopefully, the present results will provide a sounder physical basis for understanding the very important concept of mixing efficiency, and how to measure it in the laboratory and in the oceans.

Literature

[1] K. B. Winters, P. N. Lombard, J. J. Riley, and E. d’Asaro: Available potential energy and mixing in density-stratified fluids. J. Fluid Mech., 289, 115-128 (1995).
[2] W. R. Peltier and C. P. Caulfield: Mixing efficiency in stratified shear flows. Ann. Rev. Fluid Mech., 35, 135-167 (2003).
[3] W. Munk and C. Wunsch: Abyssal recipes II: Energetics of tidal and wind mixing. Deep-Sea Res., 45, 1977-2010 (1998).
[4] C. Wunsch and R. Ferrari: Vertical mixing, energy, and the general circulation of the oceans. Ann. Rev. Fluid Mech., 36, 281-314 (2004).
[5] N. Fofonoff: Nonlinear limits to ocean thermal structure. J. Mar. Res., 56, 793-811 (1998).
[6] N. Fofonoff: Thermal stability of the world ocean thermoclines. J. Phys. Oceanogr., 31, 2169-2177 (2001).
[7] R. Tailleux: On the energetics of stratified turbulent mixing, irreversible thermodynamics, Boussinesq models, and the ocean heat engine controversy. J. Fluid Mech., submitted (2008).
[8] E. N. Lorenz: Available potential energy and the maintenance of the general circulation. Tellus, 7, 157-167 (1955).
[9] R. Feistel: A new extended Gibbs thermodynamic potential of seawater. Progr. Oceanogr., 58, 43-114 (2003).
[10] T. J. McDougall, J. A. Church, and D. R. Jackett: Does the nonlinearity of the equation of state impose an upper bound on the buoyancy frequency? J. Mar. Res., 61, 741-844 (2003).
[11] T. R. Osborn: Estimates of the local rate of vertical diffusion from dissipation measurements. J. Phys. Oceanogr., 10, 83-89 (1980).
[12] W. Munk: Abyssal recipes. Deep-Sea Res., 13, 207-230 (1966).