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Vertical diffusion processes in the Eastern Mediterranean — Black Sea System

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ABSTRACT

The identification and examination of 'complete' potential density overturns in CTD profiles, within the framework of SESAME project, are employed to assess vertical eddy diffusivities, mostly in the top 100 m of the water column, for a broad area covering the East Mediterranean, the Turkish Straits and the Black Sea. The implementation of this method shows that, mixing induced by mechanical turbulence is enhanced in frontal areas, in the proximity of straits and inside anticyclones; furthermore, that mechanical turbulence is insignificant, down to the scale of CTD resolution, within areas of double diffusive staircases, encountered in deep layers of the water column. Consequently, only laminar theories about double diffusion are applied for assessing diffusivities therein. Susceptibility to different types of double diffusion seems to be related to the interaction of different types of water masses.

1. Introduction

Turbulent and/or double diffusive mixing have proven to be significant for physical chemical and biological oceanic processes (e.g., Cullen et al., 1983; Gargett, 1984; Gargett and Holloway, 1984) and their parameterization to play a key role in the effectiveness of numerical models in 'simulating' oceanic processes (McDougall and Ruddick, 1992). In this work we attempt to assess basic parameters of vertical mixing (eddy diffusivities and dissipation rates) for the broader area encompassing the Eastern Mediterranean and the Black Sea, based on CTD data which were acquired within the framework of the EU funded project SESAME. We estimate diffusivities not only for areas characterized solely by mechanical turbulence, but also for areas where double diffusion might be combined with mechanical turbulence.

The 'state of the art' instruments for resolving the full turbulent spectrum, almost down to the Kolmogorov microscale (a few cm), at which turbulence decays due to molecular dissipation, are the vertically free falling (Gregg et al., 1978; Osborn and Crawford, 1980; Wolk et al., 2001) or horizontally towed microprofilers (Mormorino et al., 1987), equipped with fast response vertical shear, temperature and conductivity probes. These have been invented in the seventies and since then are being continually improved and sparsely deployed in the ocean, due to their high cost and requirements for highly specialized personnel.

However vertical profiles of temperature and salinity, (and hence density) that could be valuable for vertical mixing estimates are also provided by standard CTDs, routinely used in oceanographic expeditions since the second half of the 20th century. Admittedly, their resolution and accuracy cannot compete with the data quality provided by a microprofiler. Still, the abundance of available CTD data from the world's oceans and their comparatively low cost acquisition provide a strong motive for exploiting them as a tool for vertical mixing estimates.

The basis of the CTD use in assessing mixing is that turbulence, being three-dimensional, unavoidably results in the 'overturning' of the water column, a situation in which heavier fluid particles lay instantaneously over lighter ones, forming a temporary, statically unstable, Z-shaped configuration in the vertical potential density (σ_θ) profile. We applied the overturn method for areas of pure mechanical turbulence and also for checking whether mechanical turbulence could be combined with double diffusion (Laurent and Schmitt, 1998).

For the second case in particular where mechanical turbulence coexists with double diffusion, laminar theories are not sufficient and modifications accounting for both mixing processes should be implemented (e.g., McDougall and Ruddick, 1992). In this context we first verified that no valid overturns were present within double diffusive areas, before selecting the suitable laminar models for evaluating double diffusive fluxes and diffusivities.

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This work is divided in 3 sections. In Section 2 we present the spatial and temporal extent of the CTD measurements used in our overturn analysis, in Section 3 we outline the overturn methodology and in Section 4 the results of our data analysis are demonstrated.

2. Spatial and temporal extent of the SESAME CTD measurements

The main goal of the SESAME project was to assess and predict changes in the Mediterranean and Black Sea ecosystems as well as changes in the ability of these ecosystems to provide goods and services. Many participating countries simultaneously launched oceanographic cruises at selected areas, in an effort to conduct both standard and specialized oceanographic measurements over a station grid extending from Gibraltar Strait, Otranto Strait and Ionian Sea, Southeast Mediterranean, through the Aegean Sea, to the Turkish Straits and the Black Sea.

We hereby analyze CTD data of the East Mediterranean branch of the experimental area (Fig. 1). The CTD data profiles, extending through the whole water column, were acquired by four marine research centers, OGS of Italy, HCMR of Greece, IMS-METU of Turkey, and IOLR of Israel, at a sampling rate of $R = 24$ Hz, providing a vertical depth resolution $r = R\,/\,w = 3$–5 cm where w is the CTD descent rate, ranging from 0.7 m/s to 1 m/s. Within the framework of this work, no vertical averaging was performed on the data apart from the standard quality control, so that the structural details of the profile of the potential density could be maximized. Each research center participating in SESAME was assigned a specific area survey to be conducted simultaneously with surveys of the rest of the participating research centers, such that the whole Mediterranean and Black Seas were covered by an extensive grid of oceanographic stations. In an attempt to assess seasonal variability, the stations of the grid were sampled in winter 2008 and in summer 2008, during two different oceanographic cruises, hereafter referred to as SES1 and SES2, respectively. Moreover two additional separate cruises (winter 2008, summer 2008) were conducted right at the aftermath of the two major aforementioned seasonal cruises, at the two seas connected by the strait of Dardanelles, i.e., the North Aegean Sea and the Sea of Marmara. The purpose of the latter cruises was to study the modification and interaction processes of the Black Sea and the East Mediterranean waters along their route (Lagrangian experiments) from the Black Sea into the north Aegean (the area in Fig. 1 below enclosed by an ellipse). The CTD data of these separate cruises are also encompassed within the scope of our analysis.

3. The overturn methodology

The initial step of the data analysis, preceding the overturn identification, was the standard CTD data processing towards eliminating systematic errors such as the ones induced by the short term mismatch of the temperature and conductivity sensor responses or the thermal lag of the conductivity cell (Lueck and Picklo, 1990; Morison et al., 1994). Both of these effects result in spikes that 'contaminate' the data profiles with 'apparent' overturns. Data corresponding to depth reversals were also excluded as probable contaminants, by keeping only records with pressure larger than all the previous records of the profile (Stansfield et al, 2001).

Furthermore, we developed an algorithm identifying the vertical boundaries of complete overturns. Complete overturns are local mixing patches, enclosing the motions of all fluid parcels inside them. They constitute vertical turbulent areas that are distinctly separated from 'calm' waters above and below them. Our whole analysis has been based on the identification of these patches whereby the attribute 'complete' has been omitted for brevity. Within overturn patches fluid parcels are temporarily displaced from their stable positions. The Thorpe displacements L_{Ti} from unstable to stable positions within a complete overturn are known to sum up to zero, i.e., it is valid that $\sum_{i=1}^{i=\eta} L_{Ti} = 0$ due to the conservation of total mass. This relation in discrete form was implemented as a criterion of identifying the complete overturn boundaries in the aforementioned algorithm.

The subsequent quality control of the identified overturns, consisted of an implementation of the methodology initially developed by Galbraith and Kelley (1996), as modified by Johnson and Garrett (2004), towards isolating artifacts from systematic errors, like salinity spikes and instrument noise.

As a matter of fact Galbraith and Kelley (1996) were the first to devise a comprehensive pair of criteria, for distinguishing 'real' from 'apparent' overturns caused by systematic errors and noise respectively.

Their so called 'water mass' criterion addressing the systematic errors, is based on the hypothesis that the data depicting an overturn correspond to the same water mass, both before (stable regime) and after (unstable regime) the overturn creation. Consequently the unstable temperature and salinity values should be well correlated within a real overturn. This criterion expressed mathematically, imposes that two 'water mass' numbers, ξ_T, ξ_S, representing the degree of smooth covariance of temperature and salinity versus density respectively, be less than a threshold value of 0.5 (see Section 1.1 of online supplement). We used a more 'generous' threshold value of 1, counterbalancing this generosity with careful visual inspection of each overturn we identified.

As to testing 'noisy' overturns, the Galbraith and Kelley (1996) criterion regards as 'noisy' the overturns that practically have on average very small 'run lengths', where a run-length is the number of adjacent unstable points within an overturn that will have to move in the same direction (upwards or downwards), towards their stable positions.

This criterion is opposed to noise free overturns with sufficiently large signal to noise ratio, characterized by large run-lengths, induced by the approximate 'Z' unstable shape of their density profiles. Indeed, the Z shape is consistent with top (heavier, overlying) fluid parcels moving downwards, forming a large run, and bottom (lighter, underlying) fluid parcels moving downwards forming a second large run.

Johnson and Garrett (2004) showed however that the Galbraith run-length criterion is both too strict (rejects some real overturns as results of noise) and insufficient in correctly discerning 'real' from 'noisy' overturns. They further suggested an improved noise criterion, where one considers a linear model of the potential density profile of the overturn area and 'superimposes' on it random noise of amplitude equal to the profile instrument's noise amplitude. Discerning between 'noisy' and 'real' overturns is then based on the comparison between

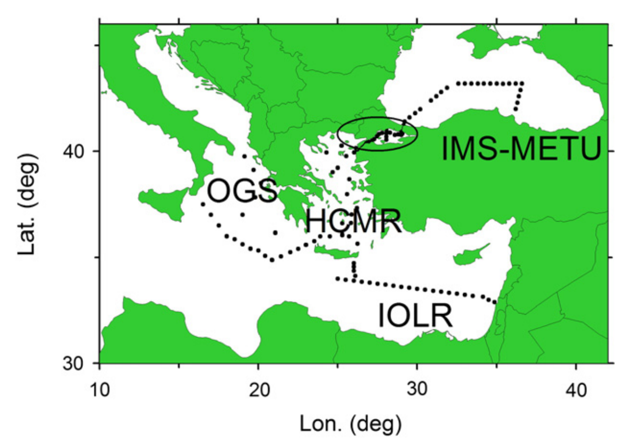

Fig. 1. The grid of oceanographic stations of SESAME2 branch in East Mediterranean and Black Sea.