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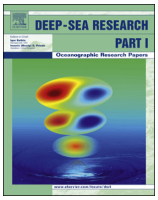

Decadal variability of the Turner Angle in the Mediterranean Sea and its implications for double diffusion

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ABSTRACT

The physical reanalysis component of the Mediterranean Forecasting System is used to construct a high-resolution three-dimensional atlas of the Turner Angle. An assessment of the model quality shows a maximum degree of agreement with observations in the water column between 150 and 1000 m depth. The mean state of the favourable conditions for double diffusion processes is evaluated and the recent decadal variability is studied in terms of changes in the water mass properties. The results show that approximately 50% of the Mediterranean Sea is favourable to double diffusion processes, from which around 47% is associated with salt fingering. The Tyrrhenian, Ionian and southwestern Mediterranean are the most vulnerable basins to salt fingering, and the strongest processes can occur in the Tyrrhenian deep waters. Diffusive convection is most likely to occur in the Ionian, Aegean and eastern Mediterranean at vertical levels deeper than 1000 m. The observed gradual warming and salinification of the Mediterranean after 1997 decreased and increased the possibilities of the occurrence of salt fingers and double diffusive convections, respectively. The climatological atlas that is presented in this paper provides a three-dimensional picture of the regions that are either doubly stable or favourable to double diffusion instability and allows for the characterization of the diffusive properties of the water masses.

1. Introduction

Double diffusive instability can occur when density is stably stratified in the vertical direction but causes one of its components, either potential temperature (θ) or salinity (S), to be unstably stratified. The potential energy that is locked in the unstable component is released through molecular diffusion, which is 100 times faster for heat than for salt (Stern, 1960; Schmitt, 2001). When relatively warm and salty waters overlay cold and fresh waters, that is, both θ and S decrease with increasing depth, the salinity profile has an unstable, gravitational contribution to the potential density profile. In this case, double diffusive instability, which is commonly referred to as salt fingering, can occur (Turner, 1973). However, the temperature profile is gravitationally unstable if both θ and S increase with increasing depth and relatively cold and fresh waters lay above warm and salty waters. In this case, double diffusive instability that is called diffusive convection can occur (Turner, 1973). Although this process occurs on molecular scales, it affects larger spatial extents by mixing water mass properties. For instance, double diffusion is particularly widespread in the main thermocline (Radko, 2013) and therefore contributes to the vertical transport of heat and dissolved carbon dioxide, affecting air-sea fluxes and, thus, the global climate. The prevalence of double diffusion in the upper ocean can enhance the mixing of nutrients, which directly controls biological productivity (Radko, 2013).

Under the assumption that the stratification is gravitationally stable, the strength of the double diffusion can be quantified by the stability ratio or density ratio R_ρ (Turner, 1973), which is defined as

$$R_\rho=[\alpha(d\theta/dz)/\beta(dS/dz)], \tag{1}$$

where $\alpha = -\rho^{-1}(d\rho/d\theta)$ is the thermal expansion coefficient; $\beta = \rho^{-1}(d\rho/dS)$ is the haline contraction coefficient; ρ is the water density; and $d\theta/dz$ and dS/dz are the temperature and salinity vertical gradients, respectively. Both salt fingering and diffusive convection are most intense when $R\rho$ approaches unity, provided that the water column is gravitationally stable. To facilitate this

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interpretation, Ruddick (1983) introduced the Turner Angle *Tu*:

$$T_u(^\circ)=tan^{-1}[\alpha(d\theta/dz)-\beta(dS/dz);\,\alpha(d\theta/dz)+\beta(dS/dz)], \tag{2}$$

which is expressed in the form of a four-quadrant arctangent and is related to the density ratio by

$$R\rho=-\,tan\ (Tu+45^\circ). \tag{3}$$

The types of instability are determined by the signs of the θ and *S* gradients rather than by their absolute values. In particular, when $|Tu|<45^\circ$, the water column is stable; when $|Tu|>90^\circ$, then the water column is doubly unstable with respect to both the temperature and salinity profile. Two options are applicable in the intermediate range. If $-90^\circ<Tu<-45^\circ$, then diffusive convection is possible, whereas salt fingering can be expected if $45^\circ<Tu<90^\circ$. This classification offers only a preliminary assessment of the double diffusive characteristics of the environment because the respective conditions, albeit necessary, are not sufficient. Ruddick (1983) exposed the advantages of using *Tu* rather than $R\rho$ in the analysis of water mass composition. First, complications regarding the singularity of $R\rho$ when the salinity stratification is nearly homogeneous do not arise for *Tu* because this variable has a finite range between 0 and 2π. Second, concurrently reversing the sign of the gradients yields the same $R\rho$ value but a different *Tu* value, although the nature of the resulting instabilities changes. Finally, the definition of *Tu* distinguishes between unstable and stable water columns, avoiding the implicit assumption in the $R\rho$ definition that the stratification is gravitationally stable.

The Mediterranean Sea (Fig. 1), which covers an area of approximately 2.5 million km^2, is a concentration basin and is therefore characterized by reverse-estuarine circulation. The relatively fresh and warm Atlantic Water (AW) that enters through the Strait of Gibraltar balances the negative heat and freshwater budgets. The AW occupies the upper layer between 50 and 100 m and becomes Modified Atlantic Water (MAW) along its path to the eastern basin. This water overlies the relatively salty Levantine Intermediate Water (LIW), which forms in the Levantine basin (Lascaratos et al., 1993) and is located at approximately 400 m. Below that depth, deep waters are distinct between the eastern and western Mediterranean Sea, which are connected by the Sicily Channel. The Western Mediterranean Deep Water (WMDW) forms in the Gulf of Lion by means of deep winter convection (Leaman and Schott, 1991). The Eastern Mediterranean Deep Water (EMDW) has contributions from both the Southern Adriatic (Schlitzer et al., 1991) and Aegean seas (Roether et al., 1996). Deep waters can also form in the Rhode Gyre area as Levantine Deep Water (LDW; Gertman et al., 1994) and in the Sea of Crete as Cretan Deep Water (CDW; Tsimplis et al., 1999). Transitional waters that are situated between intermediate and deep layers may be found because of the alteration of the water masses. Even if the Sicily Channel is shallow at its extremes (maximum depth of approximately 350 and 530 m at its eastern and western entrances, respectively), transitional waters may flow from the eastern to western Mediterranean (Sparnocchia et al., 1999). For a schematic representation of the Mediterranean thermohaline circulation, the reader is referred to Tsimplis et al. (2006).

The water mass transformations that occur in the Mediterranean Sea suggest that thermohaline mixing processes are of great importance. However, this semi-enclosed basin exhibits relatively small tides and weak winds compared to the oceans. Therefore, the vertical diffusion from mechanical mixing is expected to be small. In general, the Mediterranean is characterized by large vertical extents of deep water where both θ and *S* vertical gradients share the same sign (Onken and Brambilla, 2003), a fact that favours double diffusive structures. For instance, the WMDW is fresher and colder than the LIW above, which conditions those layers for the occurrence of salt fingering. In fact, thermohaline staircase structures, which are driven by either salt fingers (Turner, 1967) or double diffusive convection (Kelley, 1984; Kelley, 1990; Kelley et al., 2003), are commonly observed in the western Mediterranean (see for example Zodiatis and Gasparini, 1996; Bryden et al., 2014).

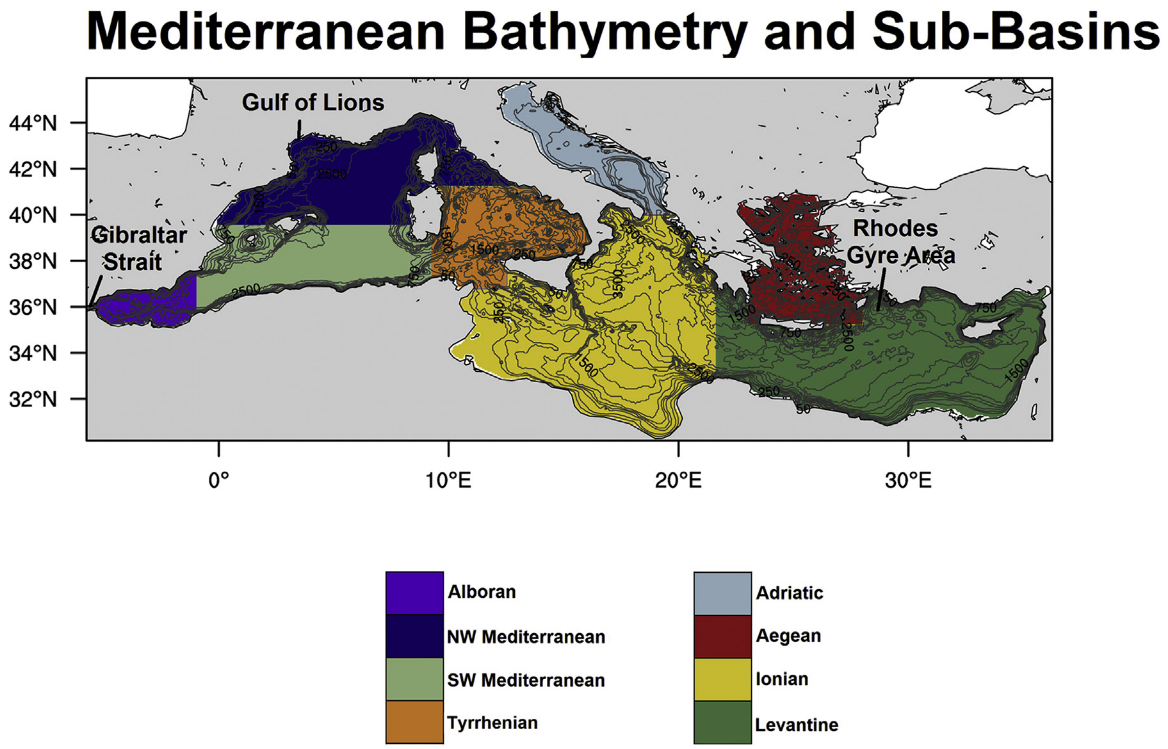

Fig. 1. Map of the Mediterranean Sea, divided into sub-basins.