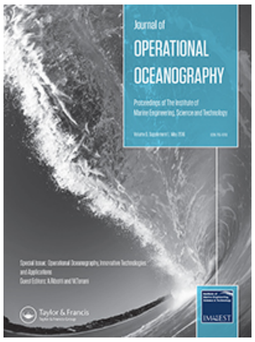

Journal of Operational Oceanography

ISSN: 1755-876X (Print) 1755-8778 (Online) Journal homepage: http://www.tandfonline.com/loi/tjoo20

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**To cite this article:** C. Fratianni, N. Pinardi, F. Lalli, S. Simoncelli, G. Coppini, V. Pesarino, A. Bruschi, M.L. Cassese & M. Drudi (2016) Operational oceanography for the Marine Strategy Framework Directive: the case of the mixing indicator, Journal of Operational Oceanography, 9:sup1, s223-s233, DOI: 10.1080/1755876X.2015.1115634

**To link to this article:** http://dx.doi.org/10.1080/1755876X.2015.1115634

Published online: 10 Jun 2016.

JOURNAL OF OPERATIONAL OCEANOGRAPHY, 2016
VOL. 9, NO. S1, s223–s233
http://dx.doi.org/10.1080/1755876X.2015.1115634



# Operational oceanography for the Marine Strategy Framework Directive: the case of the mixing indicator

C. Fratianni[a], N. Pinardi[a,b], F. Lalli[c], S. Simoncelli[a], G. Coppini[d], V. Pesarino[c], A. Bruschi[c], M.L. Cassese[c] and M. Drudi[a]

[a]Istituto Nazionale di Geofisica e Vulcanologia, Sezione di Bologna, Italy; [b]Department of Physics and Astronomy, Alma Mater Studiorum, University of Bologna, Italy; [c]Italian Institute for Environmental Protection and Research, Rome, Italy; [d]Centro EuroMediterraneo sui Cambiamenti Climatici, Lecce, Italy

**ABSTRACT**
In this paper we show that operational oceanography products can be used to develop indicators as required by the Marine Strategy Framework Directive (MSFD). We present a mixing indicator that is calculated using MyOcean Marine Service reanalysis products. Seasonal climatology data of the Brunt–Väisäla frequency (BVF) were computed for 2001–2010 and the vertical mixing coefficient was defined. A vertical mixing indicator was then computed in order to differentiate between different mixing conditions depending on the seasons and differentiating between the shelf and the open ocean in the central Mediterranean Sea.



## Introduction

The Mediterranean marine ecosystem is subject to a strong pressure related to pollution, coastal development, climate change and overfishing. Marine environment protection, preservation and restoration, when possible, requires an integrated approach together with the continuous monitoring and modelling of physical and biochemical processes. The Marine Strategy Framework Directive (MSFD) embraces such an approach and requires European member states to prepare national plans for monitoring and modelling the state of the marine ecosystem, from the coasts to offshore areas (Figure 1). MSFD reporting should also be coordinated in accordance with the Water Framework Directive (WFD) and the Mediterranean Pollution Monitoring and Research (MEDPOL) programme of the Barcelona Convention. Meiner (2010) report that future developments in MSFD assessments should contribute to a better characterisation of maritime space and marine ecosystems, hand in hand with the Copernicus Marine Environment Service (CMES) which produces space–time-consistent data for the development of geospatial information systems for the integrated management of the marine territory.

Operational oceanography scientific approach and practices are the basis of the CMES, which was first implemented in the Mediterranean Sea in 2000 (Pinardi et al. 2003; Pinardi & Coppini 2010). Today, the Copernicus programme – previously known as the Global Monitoring for Environment and Security (GMES) programme – provides accurate, timely and easily accessible information to improve the management of the terrestrial, marine and atmospheric environment. Since 2009, a pre-operational marine service has been in place with the MyOcean projects (Bahurel et al. 2009) delivering products on the ocean state from the global to regional scales (main European basins and seas).

The MyOcean Marine Service at present delivers value-added information, including observations, analyses, reanalyses and forecasts describing the physical state of the ocean and its primary biogeochemical parameters. It also contributes to research on the climate by providing long time series of reanalysed parameters.

The Mediterranean Forecasting System (MFS) is currently one of the monitoring and forecasting production centres of the pre-operational MyOcean service (Dombrowsky et al. 2009). The system produces 10-day forecasts daily for several ocean state variables such as currents, temperature, salinity and sea level. The system also provides a so-called reanalysis – an optimal reconstruction of the state of the marine environmental variables for the Mediterranean Sea over the past few decades (Adani et al. 2011).

The MSFD defines 11 descriptors of good environmental status (GES). This paper focuses on No. 7, ‘hydrographic conditions’ and the physical features contained in Table 1 of Annex III of the MSFD

CONTACT C. Fratianni claudia.fratianni@ingv.it

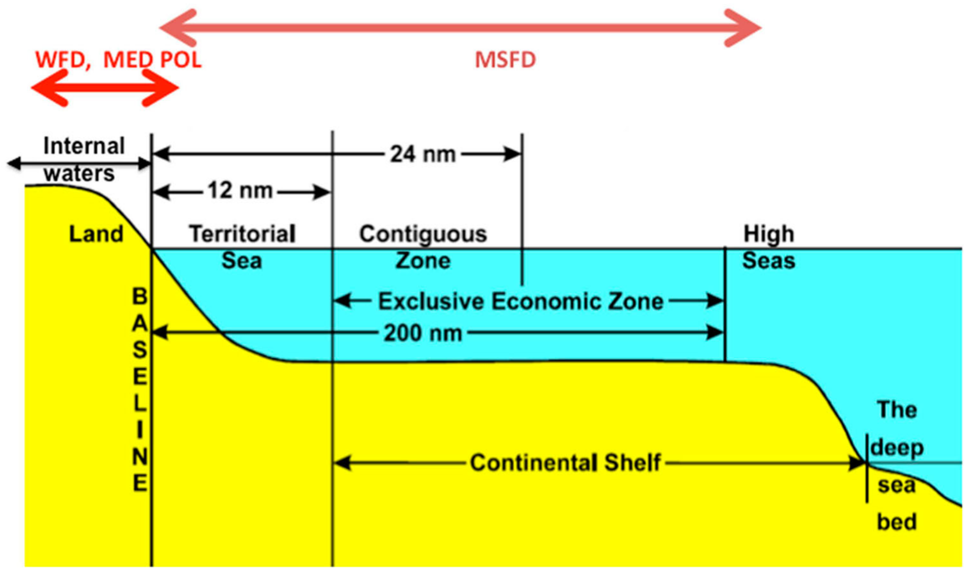


**Figure 1.** The various marine territorial waters as defined by the United Nations Convention of the Law of the Sea (UNCLOS) with the indication of the area that is considered by the international agreements (MEDPOL) and the European directives (WFD and MSFD) considered in this paper.

(European Union 2008). Among other characteristics required, 'mixing' is listed as follows: in oceanography mixing regulates the stratification/destratification cycle of the water column from seasonal to hourly scales (Gaspar et al. 1990; Moum & Smyth 2001). This is connected to the oxygenation of the water column which occurs through air–sea gas exchanges and is a primary indicator of GES in the shelf areas of the European seas. Low mixing allows eutrophication conditions to produce oxygen depletion with a subsequent impact on the ecosystem's health and productivity. Rinaldi et al. (this issue) address several additional MSFD-relevant indicators derived from in situ and satellite-based observations and made routinely available within operational marine services.

In this paper we construct a mixing indicator from the MyOcean Marine Service products at the Mediterranean Sea basin scale. Firstly, the Brunt–Väisäla frequency (BVF) is calculated from the reanalysis temperature and salinity fields for the shelf and open ocean areas of the Central Mediterranean Sea. Secondly, the BVF is connected to a vertical mixing coefficient. After a threshold has been set between low and high mixing conditions, a mixing indicator is defined for each climatological month and for the Central Mediterranean Sea areas, covering the relevant MSFD regions.

The paper is organised as follows. In the next section we describe the MSFD Italian sea implementation areas, which is followed by a description of the reanalysis data and the method used to compute the BVF. The mixing indicator is then defined in and some conclusions are drawn in the final section.

## The MSFD and the Italian sea assessment areas

The activities which unfold in the marine and maritime sectors have always been of crucial importance to the socio-economic and cultural development of Europe. The European seas and coasts are a vital resource, providing Europeans with natural resources as well as access to trade and transport. In general all activities related to it are very important components of the European gross national product (GNP) – and the sea, in particular the Mediterranean, is a challenging natural and cultural heritage. Over the last decade, the awareness of the need for an integrated approach for the protection, preservation and restoration of the marine environment has grown.

**Table 1.** Legislative references for the various MSFD implementation stages.

| Actions | Article |
|---|---|
| Initial assessment of the current environmental status of national marine waters and an analysis of the environmental and socio-economic impact of human activities on these waters. | Art. 8 – Annex III |
| Determination of a set of characteristics for GES for the marine waters. | Art. 9 – Annex I |
| Establishment of a comprehensive set of environmental targets and associated indicators to guide progress towards achieving GES in marine waters. | Art. 10 – Annex III and IV |
| Establishment and implementation of monitoring programmes for the ongoing assessment of the environmental status of the marine waters and the regular update of targets. | Art. 11 – Annex III and V |
| Establishment and practical implementation of measures to achieve the targets. | Art. 13 |

The pillar for this integrated policy is Directive 2008/56/EC, which establishes a framework for community action in the field of the marine environmental policy, known as MSFD, formally adopted by the European Union (EU) in July 2008 and transposed into Italian law in 2010 (Decree No. 190) (European Union 2008).

The directive is the basis of the Integrated European Maritime Policy and sets out a common framework based on cooperation between member states to promote the sustainable use of the seas and the conservation of marine ecosystems. The directive establishes a framework within which member states must take the necessary measures to achieve or maintain GES of their marine waters by 2020, thus confirming the fundamental role played by environmental monitoring in such an assessment. Each member state is required to develop a marine strategy for its marine region or subregion, subdivided into a *preparation phase* and a *programme of measures*, all of which is described in various articles of the directive (Table 1).

Each member state is required to report on the current state of nature and environment of their marine waters (in accordance with Art. 8) and define the desired state of their marine waters (Art. 9). In case of a deviation between the current and desired state of marine waters, in order to achieve or maintain GES, the member state must establish environmental targets (Art. 10). These first three stages must be reported to the European Commission (EC) by 15 October 2012. Based on these reports, the EC has to 'assess whether, in the case of each Member State, the elements notified constitute an appropriate framework to meet the requirements of this Directive (Art.12)' (European Union 2008). By 2015, the Programme of Measures (Art. 13) must be established, based upon the first three stages (initial assessment, GES and targets) and the preparation of monitoring programmes (Art. 13). MSFD implementation is a step-by-step process in which each step builds upon the previous one. Since the directive follows an adaptive management approach, these stages should be kept up to date and reviewed every six years to ensure that the aims of the directive are adequately met, adjusting GES targets, monitoring and programmes of measures where necessary (Art. 17) (European Union 2008).

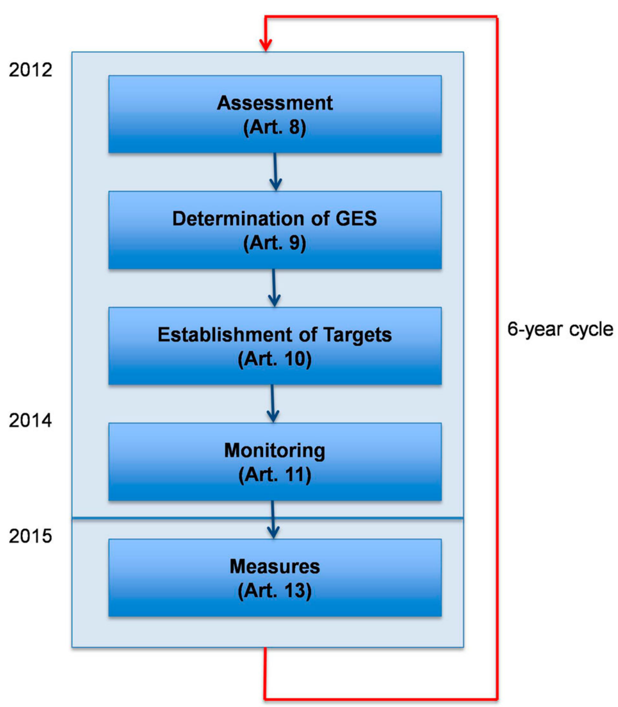


**Figure 2.** Implementation stages for the MSFD.

The MSFD applies to the area of marine waters over which a member state exercises jurisdictional rights (Figure 1). The Mediterranean Sea is subdivided into five marine subregions: the Western Mediterranean Sea, the Adriatic sea, the Ionian Sea, the Central Mediterranean Sea and the Aegean-Levantine Sea (Figures 2–3).

Member States can define specific subdivisions within their (sub)region based on the specific nature of that area and conduct separate assessments for each subdivision. For this work, the Italian seas were subdivided into eight assessment areas (Figure 4): the Northern Adriatic Sea (1) , Central Adriatic Sea (2), Southern Adriatic Sea (3), Ionian Sea (4), Central Mediterranean Sea (5), Tyrrhenian Sea (6), Ligurian Sea (7) and Sardinian Sea (8). This subdivision is mainly geomorphological, considering deep basins and straits separately.

## Data and methods

The data used in this work is the reanalysis from the MyOcean Marine Service (www.myocean.eu). The reanalysis covers the 10-year period 2001–2010 and considers all the available in situ temperature and salinity observations, along-track satellite sea level anomalies (SLAs) and satellite sea surface temperatures (SSTs) to produce gridded optimal estimates of the three-dimensional thermohaline, sea level and current conditions in the Mediterranean Sea. The grid resolution is 1/16 deg (~6.5 km) in the horizontal and 71 unevenly spaced levels in the vertical. This reanalysis was produced for the MyOcean Marine Service following the same scheme presented in Adani et al. (2011) but only real-time data were used since most of the in situ temperature and salinity data in this period came from the voluntary observing ship (VOS) programme for the Mediterranean Sea (Manzella et al. 2007) and the Argo profiling float programme (Poulain et al. 2007).

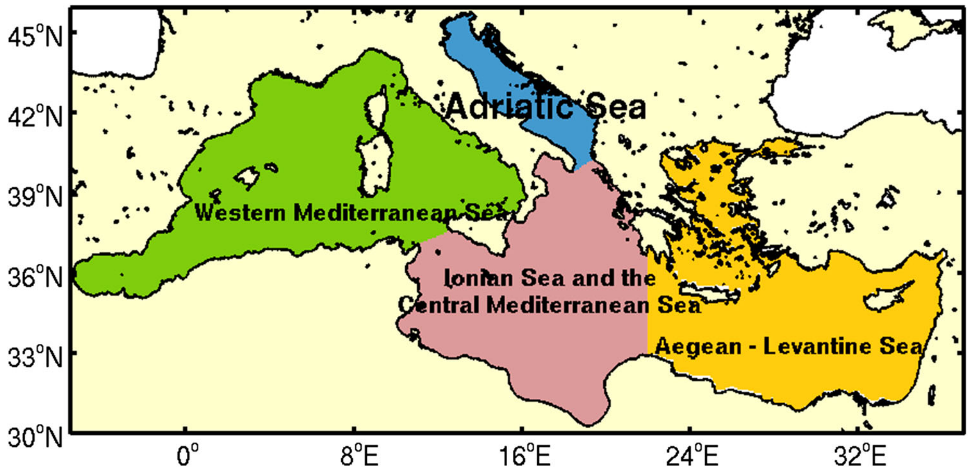


**Figure 3.** Subregions for Mediterranean Sea according to MSFD.

## The relationship between vertical mixing and stratification

Vertical mixing in the ocean is a key driver of the marine ecosystem response, from the coastal areas to the open ocean. The marine food web (Pinardi et al. 2006) develops differently depending on the marine stratification conditions, which are themselves connected to different vertical mixing processes. In the Mediterranean Sea coastal areas, mixing occurs in winter and produces a very homogeneous water column, which in turn is dominated by a herbivorous food web and highly oxygenated waters. On the other hand, during summer both in the coastal and open ocean areas, stratification may be persistent, which can increase the carbon flux through the bacteria components of the food web, thus producing oxygen consumption and possible hypoxia, potentially even resulting in anoxic conditions.

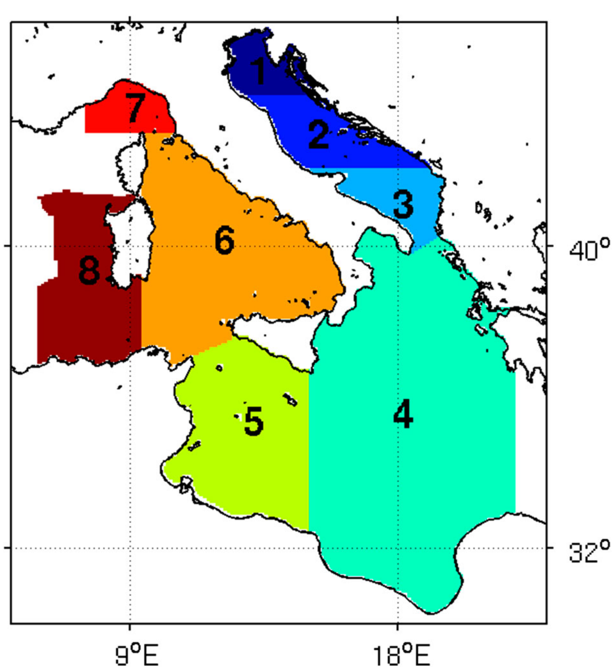


**Figure 4.** Italian MSFD assessment subregions.

Vertical mixing is dependent on the momentum and buoyancy fluxes at the air–sea interface and the pre-existing water column vertical stratification as well as the energy dissipation rate. Vertical stratification is important in the mixing process since more turbulent kinetic energy from the wind is required to displace water across a strong vertical density gradient (Gargett & Holloway 1984). In the open waters of the Mediterranean Sea, the vertical stratification undergoes seasonal changes (Hecht et al. 1988; Lascaratos 1993; Artegiani et al. 1997a, 1997b; Pinardi et al. 2015) while near the coasts it is maintained by the river runoff. During the winter, the Mediterranean Sea open ocean and coastal waters become vertically homogeneous due to the intense air–sea interaction fluxes which create favourable conditions for high mixing. In some coastal areas, on the other hand, where the river input is persistent, stratification is permanent.

The stratification can be quantified by the buoyancy frequency or BVF, which is defined as

$$N = \sqrt{-\frac{g}{\rho_0}\frac{d\rho}{dz}} \tag{1}$$

where $g$ is the gravity acceleration (9.8 m s$^{-2}$), $\rho_0$ is the mean density and $d\rho/dz$ is the local vertical density gradient. The depth of the BVF maximum is normally taken to be representative of the pycnocline depth.

According to Osborn (1980), the relationship between the BVF and vertical mixing coefficient, $K$, or vertical diffusivity, can be expressed as

$$K = \varepsilon \Gamma N^{-2} \quad (\mathrm{m^2 s^{-1}}) \tag{2}$$

where the mixing efficiency $\Gamma$ is assumed to be equal to 0.2 following Shih et al. (2005) and the rate of turbulent kinetic energy dissipation for the Mediterranean Sea is set as $\varepsilon = 1.510^{-9}\mathrm{m^2s^{-3}}$ as an average from the values of Cuypers et al. (2012). From Equation (2) it is evident that high and low values of $N^2$, indicating high and low stratification, respectively, are inversely correlated to the vertical mixing – therefore, calculating the BVF enables $K$ to be defined as a mixing indicator.

## Analysis of the climatological stratification

Using the temperature and salinity profiles from the reanalysis data set, the average BVF was estimated in each of the eight assessment areas (Figure 4) from the surface to 200 m. The squared BVF seasonal profiles (considering three-month periods starting from January) are plotted in Figure 5. The Adriatic Sea (regions 1, 2 and 3 in Figure 5) is characterised by the largest squared BVF values of the different areas, and the maximum values are reached in the first 80–100 m. In the other areas, the maximum values are found in the first 140 m while the squared BVF is practically zero below such depths. The squared BVF vertical profiles show an ample seasonal stratification cycle, from the maximum values attained in the homogenisation period in the first 20 m during summer and the minimum values reached during winter. The BVF value distinguishing between autumn/winter and spring/summer conditions in Figure 5 is 0.1 $10^{-3}$ $\mathrm{s^{-2}}$ as indicated by the vertical grey line. Thus this was chosen as the threshold $N_0^2$ to define well-stratified versus non-stratified water column conditions.

In order to estimate a vertical average stratification value for each assessment area, the average volume squared BVF values were taken, where the volume is defined as the assessment area multiplied by the water column depth up to 100 m. The average volume squared BVF values for each region are shown in Figure 6. It is now evident that region 1 (the Northern Adriatic area) is always stratified on the Italian side (since it is influenced by the Po River), while all the other areas start to be stratified in April/May and become homogeneous from October to March.

Figure 7 shows the seasonal horizontal distribution of the vertical mixing coefficient calculated using Equation (2), averaged along the first 100 m for all the assessment areas. As expected, the values vary both in time and space between open ocean and coastal areas: areas of high vertical mixing develop all along the coastlines of the basin during winter, while the open ocean shows relatively low values all year long.

## The mixing indicator

In order to define an indicator, we need to set thresholds and reference values for $K$ so that we can then obtain an indicator referring to occurrences of higher and lower values than the threshold for the quantity of interest. As shown in Figure 7 the vertical mixing conditions for the Italian seas are very variable and distinct between the open ocean and coastal zones. If we want to get a good indicator of vertical mixing, the latter should be able to distinguish between these regions for each area.

Using Equation (2) we define a threshold mixing indicator based on the $N_0^2$ values established in Figures 5 and 6 thus differentiating between stratified and non-stratified conditions during summer and winter. Consequently the vertical mixing threshold value is

$$K_0 = N_0^{-2} \varepsilon \Gamma \tag{3}$$

Invoking the values for $\varepsilon$, $\Gamma$, $N_0^2$ indicated above, the threshold value of the mixing parameter is $K_0$ = $310^{-6}$ $\mathrm{m^2\ s^{-1}}$. This value is one order of magnitude larger than molecular thermal diffusivity (approx. $10^{-7}$ $\mathrm{m^2\ s^{-1}}$) and accounts for the turbulent mixing of the upper water column. The mixing indicator, Imx, is then defined as

$$\mathrm{Imx}(x_i, y_i, t_j) = 100 \frac{\sum_{k=1}^{N} P(x_i, y_i, t_{jk})}{N}, \tag{4}$$

where $P$ is set to

$$\begin{aligned} P &= 1 \text{ if } K > K_0, \\ P &= -1 \text{ if } K < K_0. \end{aligned} \tag{5}$$

The sum in Equation (4) is intended for each available year $k$ of each month $j$, which in our case provides 10 different realisations for each month from 2001 to 2010. In addition,$(x_i, y_i)$ indicate the model field grid points. In summary, low and high mixing coincide with negative and positive values, respectively.

The resulting monthly maps of Imx are displayed in Figure 8. All the areas show high values of the mixing indicator for January to April with the exception of the Northern Adriatic Sea and the Po-River-influenced marine waters which always have low mixing indicator values. In the transition season (May/June) and summer (July–September) all the assessment areas show low mixing values from the open ocean to the coastal areas. The only exception is the extended area of the Tunisian shelf in the Strait of Sicily where relatively high mixing conditions are found all year long. The mixing indicator is

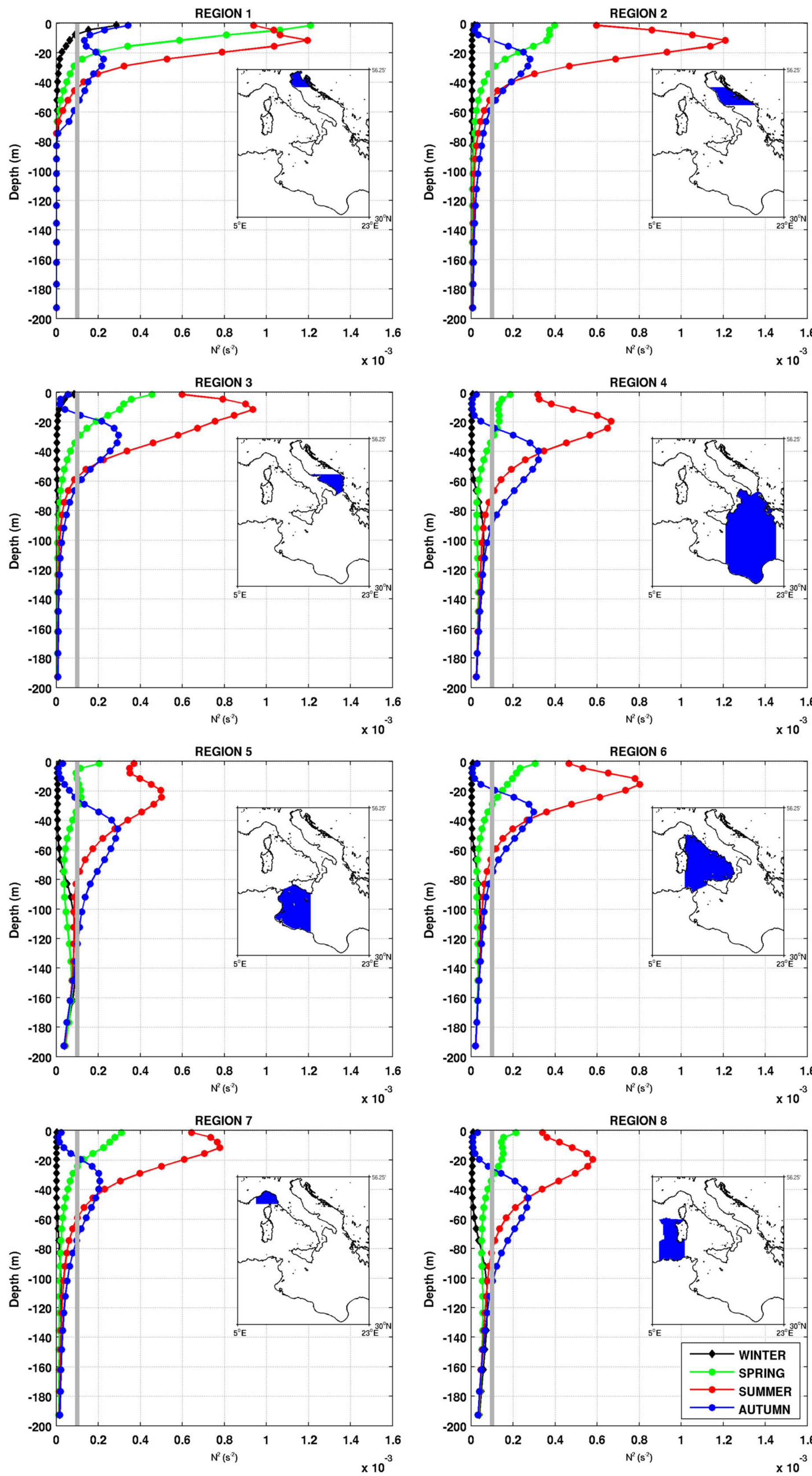


**Figure 5.** Averaged area seasonal squared BVF profiles for each Italian assessment area. Note: The vertical grey line corresponds to the $N_0^2$ threshold ($10^{-4}$ $s^{-2}$).

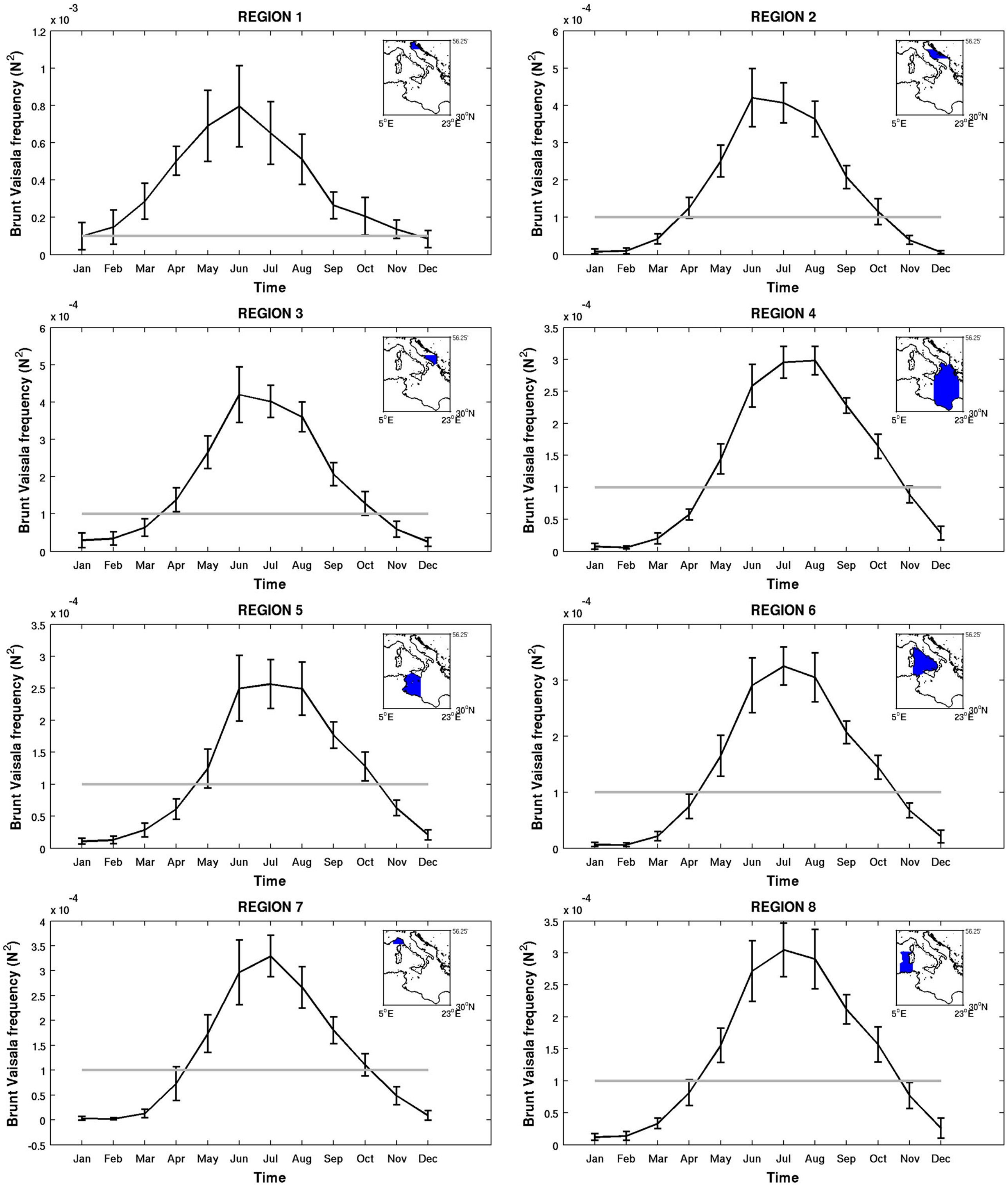


**Figure 6.** Averaged volume squared BVF monthly climatology for each of the assessment areas in Figure 4.

also relatively low in October in the Southern Ionian Sea (region 4 in Figure 4). This is a region well known for its anticyclonic circulation (Pinardi et al. 2015), which maintains the summer stratification longer than in areas of opposite sign circulation. The Ligurian Sea, the Northern Tyrrhenian Sea (regions 7 and 6 in Figure 4, respectively) and the Northern Adriatic Sea (region 1 in Figure 4) show an increase in the mixing rate in October due to the favourable pre-conditioning cyclonic circulation in these areas.

There is a narrow band of high mixing values all along the Croatian and Italian coastlines in September and

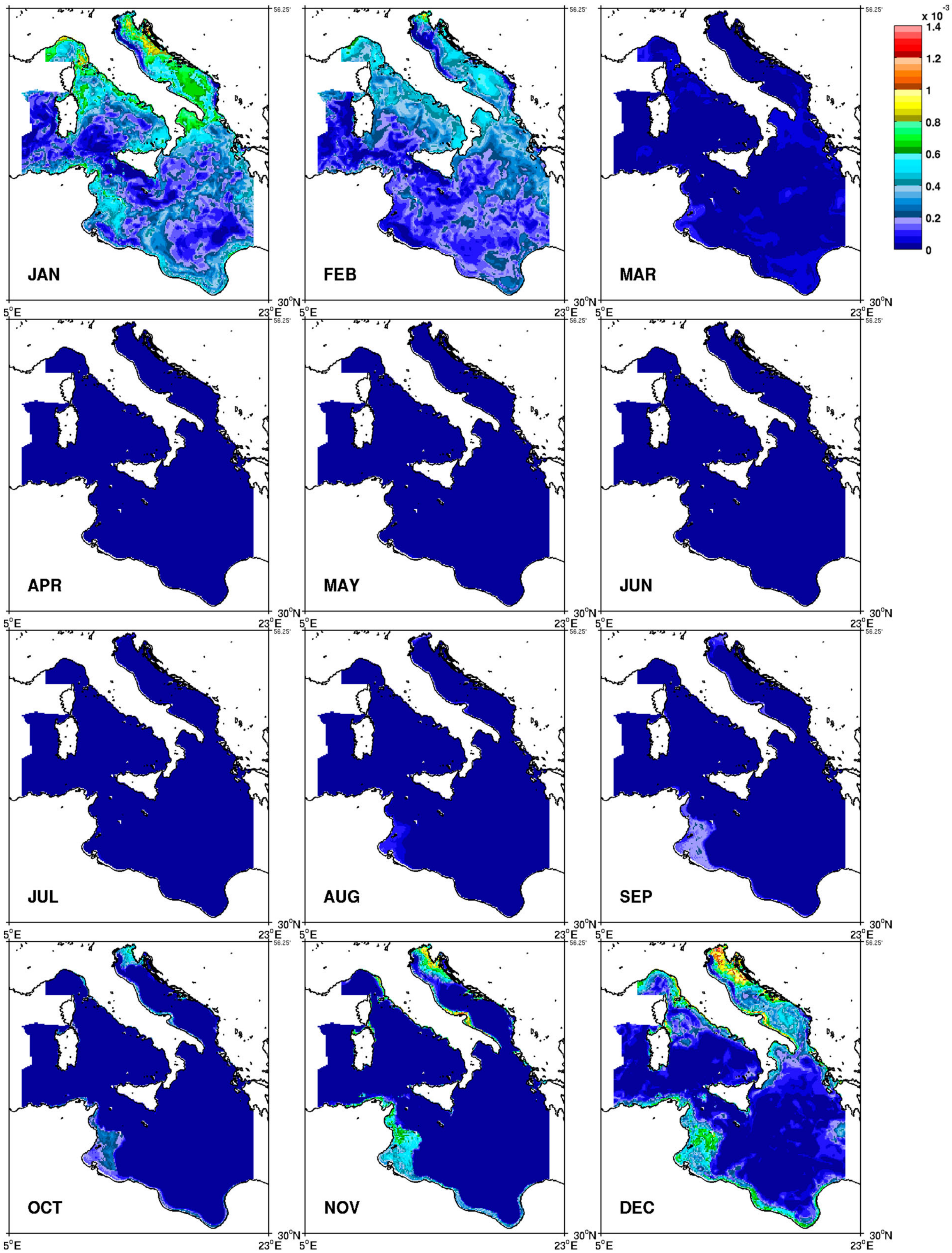


**Figure 7.** Monthly horizontal distribution of the first 100 m averaged vertical mixing coefficient calculated from Equation (2).

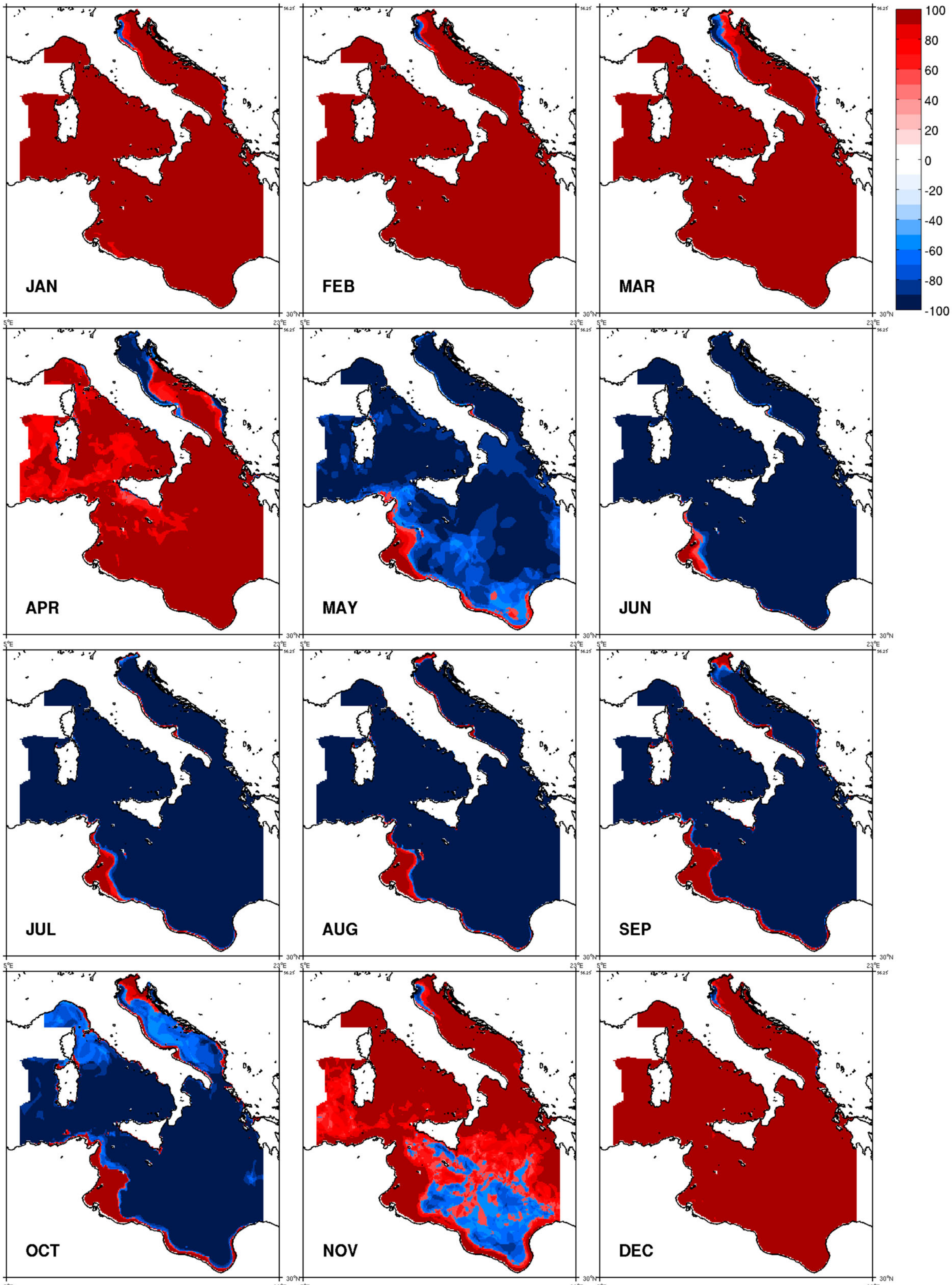


**Figure 8.** Monthly maps of the mixing indicator for all the Italian assessment areas.

October, indicating that these shelf areas already have detectable and specific vertical mixing conditions with respect to the adjacent open ocean areas.

Several regions show relatively large mixing indicator gradients throughout the year. In August and September, the Northern Adriatic Sea (region 1 in Figure 4) shows contrasting mixing values between the Gulf of Trieste, the Northern Adriatic Sea and the Po-River-influenced waters where the minimum values of mixing are found. In May the southern regions of the Strait of Sicily and the Ionian Sea (regions 4 and 5 in Figure 4) show relatively large values of the mixing indicator, while all other regions already show minimum values.

## Conclusions

We have presented an application of the MyOcean Marine Service products which is used to define a mixing indicator for the MSFD assessment of 'hydrographic conditions'. Among all MyOcean Marine Service products, here we use the reanalysis and optimal reconstruction of the thermodynamic characteristics of the Mediterranean Sea from observations and a numerical model. The high space–time coverage of the reanalysis products resolves the seasonal cycle and the major differences between the shelf and open ocean areas.

The vertical mixing coefficient is defined as being inversely proportional to the BVF squared, which can be computed from the reanalysis temperature and salinity fields. The mixing indicator is then defined as the number of occurrences where the value of the mixing coefficient is larger than a given threshold. The mixing coefficient threshold only depends on the threshold value of the BVF. A comprehensive subregional analysis of the BVF seasonal cycle was thus carried out in order to set the threshold. A threshold value of $N_0^2 = 10^{-4}$ allows differentiation between stratification and destratification seasons and consequently the threshold value of mixing was determined to be $K_0 = 310^{-6}$ m$^2$ s$^{-1}$.

The low mixing conditions permanently found in the Po River have been shown to influence waters that extend several hundred km from the river mouth, highlighting the area's particular sensitivity to oxygen consumption even during the winter months. Most of the other shelf areas, and in particular the Tunisian shelf (the southern part of region 5 in Figure 4), are generally characterised by high vertical mixing, although the model resolution cannot fully resolve some of the narrow shelf areas prevailing in most of the investigated subregions. Particular evidences of high mixing conditions along the shelves include the Eastern Adriatic Sea, the Northern Tyrrhenian Sea and the Ligurian Sea (regions 6 and 7 in Figure 4).

The open ocean areas were found to be affected by high mixing during the winter and low mixing during the summer. This is a specific characteristic of the Mediterranean Sea due to the high seasonality of the winds and the high stratification conditions encountered during the summer due to the rather intense warming of the sea surface at these latitudes. In general though, the basin completely loses its summer thermocline and does not develop a main deep thermocline (Pinardi & Masetti 2000).

The mixing indicator developed here, based on the MyOcean Marine Service Mediterranean Sea reanalysis, could contribute to the integrated assessment of GES. Although still in its early stages, the method seems to be robust. Future research could consider a longer time series of reanalysis data and different values of the BVF threshold depending on the Central Mediterranean Sea subregions.

## Acknowledgements

This work was carried out within the framework of the scientific collaboration agreement for the Marine Strategy between the ISPRA and the INGV.

## Disclosure statement

No potential conflict of interest was reported by the authors.

## Funding

The work was supported by the MyOcean2 project [grant number 283367]; Nextdata: National Research Programme (PNR) 2011-2013-Founded by the Italian Ministry of University and Research (MIUR); and RITMARE: National Research Programme (PNR) 2012-2016-Founded by the Italian Ministry of University and Research (MIUR).

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