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The Mediterranean Sea system: a review and an introduction to the special issue

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Abstract

The Mediterranean is a semi-enclosed sea characterized by high salinities, temperatures and densities. The net evaporation exceeds the precipitation, driving an anti-estuarine circulation through the Strait of Gibraltar, contributing to very low nutrient concentrations. The Mediterranean Sea has an active overturning circulation, one shallow cell that communicates directly with the Atlantic Ocean, and two deep overturning cells, one in each of the two main basins. It is surrounded by populated areas and is thus sensitive to anthropogenic forcing. Several dramatic changes in the oceanographic and biogeochemical conditions have been observed during the past several decades, emphasising the need to better monitor and understand the changing conditions and their drivers.

During 2011 three oceanographic cruises were conducted in a coordinated fashion in order to produce base-line data of important physical and biogeochemical parameters that can be compared to historic data and be used as reference for future observational campaigns. In this article we provide information on the Mediterranean Sea oceanographic situation, and present a short review that will serve as background information for the special issue in Ocean Science on “Physical, chemical and biological oceanography of the Mediterranean Sea”. An important contribution of this article is the set of figures showing the large-scale distributions of physical and chemical properties along the full length of the Mediterranean Sea.

1 Introduction

The Mediterranean is a land-locked sea with limited exchange with the world ocean, an active deep overturning circulation, a shallow circulation cell and a complex upper layer circulation with several permanent and quasi-permanent eddies. The Mediterranean Sea is exporting intermediate depth water to the Atlantic Ocean and is thereby directly, and significantly, influencing the oceanographic conditions there. Also, due to the limited exchange of properties with the world ocean and the internal transformation processes in the Mediterranean Sea, it has been suggested that it can be considered a "laboratory" of a "mini-ocean" representing processes that take place at a larger scale in the world ocean (e.g. Bergamasco and Malanotte-Rizzoli, 2010). The Mediterranean Sea is not in steady-state with sporadic deep water formation events and is potentially sensitive to climatic changes. Much remains to be known with regard to the biogeochemistry, the dynamics of the circulation and ventilation of the Mediterranean system, the connection between circulation, biogeochemistry and biological activity, and the possible implications for climate relevant feedback mechanisms. Monitoring and modeling the evolution of the dynamics of the Mediterranean Sea and the impact on biogeochemistry is an essential part of the observational system in the Mediterranean Sea. This seems particularly relevant in light of the significant changes of the Mediterranean Sea that have been observed during recent decades (e.g. Roether et al., 1996; Tsimplis et al., 2006; Schroeder et al., 2012).

This article provides a brief review of the physical and chemical oceanography in the Mediterranean Sea as background information and introduction to the special issue in Ocean Science on "Physical, chemical and biological oceanography of the Mediterranean Sea". We start this article with introducing the three almost synoptic cruises conducted during 2011 that covered all major basins in the Mediterranean Sea, from the eastern extreme of the Mediterranean Sea through the Strait of Gibraltar. The large-scale data collected during these three cruises will be presented in the form of sections so that the properties and the biogeochemistry of the Mediterranean system can be discussed in this context. Since the *Meteor* cruise M84/3 did cross the length of the Mediterranean Sea from off the coast of Lebanon to through the Strait of Gibraltar, it is possible to draw a quasi-zonal section through the whole Mediterranean Sea. However, there is a data gap in the Sicily Channel since we were not able to survey that area due to political instability. Additionally we present a short meridional section from the Adriatic Sea through the Strait of Otranto to the Ionian Sea. The objective of presenting these sections is to describe the large scale distribution of properties in the

Mediterranean Sea, which will be discussed in more detail in several other papers of the special issue. All panels are split in a shallow and a deep part in order to enhance the upper water column where larger gradients are encountered.

2 Observations during 2011

During spring and early summer of 2011, three cruises in the Mediterranean Sea were conducted in a coordinated way: the RV *Meteor* (cruise M84/3, Istanbul to Vigo, 5–28 April 2011), the RV *Poseidon* (cruise POS414, Genoa to Messina, 31 May–13 June 2011) and the RV *Urania* (cruise EF11, Bari to La Spezia, 22 April–8 May 2011). The CTD-station network for the three cruises is shown in Fig. 1. Even though the goals of the three campaigns had slightly different focus and scopes, it allowed to for a synoptic view of property and parameter distribution across large parts of the Mediterranean Sea, including all major sub-basins. Thus, the combined data set can be used to estimate changes in circulation and ventilation, and, in addition, temporal and spatial changes and variations in the distribution and inventory of properties, such as inorganic carbon, i.e. uptake of anthropogenic carbon, can be quantified. A short description of each cruise will be given below. The three cruises had a few overlapping stations (see Fig. 1) that were useful for the internal consistency check and calibration of measured properties between the campaigns. Due to political unrest, none of the three cruises were able to conduct any sampling in the Sicily Channel; there is thus a gap in the 2011 data coverage for this area that connects the eastern and western basins.

2.1 Meteor cruise 84/3

During a 3 week long cruise on the German research vessel *Meteor* (cruise M84/3, Istanbul to Vigo, 5–28 April 2011) a multidisciplinary investigation covering the main basins and sub-basins of the Mediterranean Sea were performed. The cruise was set-up to follow the demands and requirements of repeat hydrography cruises as specified by the GO-SHIP group (http://www.go-ship.org/), i.e. with a comprehensive set of physical and chemical parameters measured to the highest standards. These ideas are also echoed in a recent initiative to design a repeat hydrography program for the Mediterranean Sea (CIESM, 2012). The goal of the M84/3 cruise was to follow the track of previous cruises through the eastern and western Mediterranean, some of which with extensive chemistry and tracer observational components. The principal scientific objectives for M84/3 had two closely-linked components: (1) understanding and documenting the large-scale water property distributions, their changes and the drivers of those changes and, (2) addressing questions for a future Mediterranean Sea higher in dissolved inorganic carbon, more stratified, which has experienced changes in circulation and ventilation related to climate change. A close related goal was to fill in gaps in the knowledge of the carbonate system of the Mediterranean Sea, including its sub-basins, e.g. to improve estimates of the anthropogenic carbon content and to document the temporal trend in dissolved inorganic carbon.

Measurements conducted during the cruise included:

- Continuous salinity and temperature an oxygen profiles.
- On-board measurements of oxygen, nutrients (nitrate, nitrite, phosphate and silicate), dissolved inorganic carbon (DIC), total alkalinity, pH, and the transient tracers SF_6 and CFC-12.
- Samples were taken for the determination of ^{3}He and tritium, and for the carbon isotopes ^{14}C and ^{13}C, for later shore-based analyzes.
- A sampling program for the surface distribution of persistent organic pollutants (POPs), augmented by sampling for measurements of Polyfluorooctansulfonate (PFOS) on some deep profiles.
- Samples for the determination of dissolved barium were taken at all stations, and large volume samples for determination of Ra isotopes were taken from surface

waters at several stations and 7extra CTD casts for large volume Ra-sampling were performed.

- Samples for determination of microbiological community structure were taken at all stations in surface and bottom waters so that the microbiological community structure can be evaluated as tool for characterization of water masses.
- Samples for determination of the isotopic composition, abundance and size of coccolithophores were taken at all stations.
- Aerosol sampling was carried out during the whole cruise; filters were changed once daily. Incubation experiments for nitrogen fixation were carried out for 6 positions during the cruise.
- Samples for determination of mercury and for neodymium isotopes were taken on several stations.

More details about the cruise can be found in Tanhua et al. (2013)

2.2 *Poseidon* cruise 414

The primarily goal of the cruise on the German RV *Poseidon* (POS414, Genoa to Messina, 31 May–13 June 2011) was to identify and quantify the routes and entrainment rates of the Adriatic Deep Water into the Ionian Sea and to investigate the spatial and temporal variability of the spreading and mixing of the Ionian Deep Water. The cruise carried out was a continuation of the work done during previous cruises in the area that aims at investigating the processes of deep water formation, the origin of the deep water in the eastern Mediterranean and possible switches of those sources. During the cruise 33 full depth CTD stations were carried out and at all stations samples for nutrients and oxygen were taken at 12 depth levels, and samples for oxygen isotopes were taken at 6 depth levels. Continuously measurements were made with the vessel mounted ADCP and thermosalinograph. See Hainbucher (2012) for more information.

2.3 *Urania* cruise EF11

The general objective of the cruise on the Italian research vessel *URANIA* (EF11, Bari to La Spezia, 21 April–8 May 2011) was the development of a dynamic calibration procedure for oceanographic sensors, the continuation of the long-term monitoring of straits, as well as an update of the knowledge on the oceanographic conditions in the study area. The EF11 survey thus was planned to cover the Sicily Channel at a greater detail. Unfortunately the geopolitical situation in 2011 in this region prevented us from completing the planned ship track, and forced us to re-plan the mission and the locations of the stations. Nevertheless two inter-calibration stations were maintained, in order to compare the physical and chemical data at the same stations with those collected by the other two ships. Along with the classical physical measurements (CTD, LADCP, ADCP), samples for dissolved inorganic nutrients, pH, total alkalinity, total organic carbon and dissolved inorganic carbon were collected.

Within this framework, the cruise has been planned to reach the following specific objectives:

- To determine temporal lags in the different sensors' responses, in different conditions of stratification and pressure and to determine the different responses of sensors during CTD casts dedicate to set up procedures of dynamical calibration, using as reference a high quality pre- and post-cruise calibrated probe (SBE911+).

- Update of the knowledge on stratification and ventilation of water masses, using as tracers physical properties (temperature and salinity) and biogeochemical properties (dissolved oxygen, dissolved inorganic nutrients, pH, total alkalinity, total organic carbon and dissolved inorganic carbon), in regions recently studied within the VECTOR and SESAME projects.

- To investigate other regions that have a crucial role since they are directly impacted by interbasin exchanges and deep water dynamics, such as the Corsica and Sicily Channels and the Tyrrhenian Sea. These are locations where moorings are deployed, that needed maintenance. Unfortunately the Sicily moorings could not be maintained because of geopolitical issues.

- To establish 2 inter-calibration stations for chemical parameters with the German groups.

The cruise was strongly influenced by bad weather conditions and by the geopolitical situation in the Sicily Channel, which forced some re-planning of the activities on-board. The first activity was a high-resolution ADCP survey in an area of 18 × 18 nm off the Gargano Cape, to characterize the dynamical conditions that may influence the sedimentological characteristics of the area. After 2.5 days of ADCP lines, a section of 4 stations across the Otranto Strait was sampled. Two deep stations were subsequently performed in the Ionian Sea, along the spreading path of the Adriatic Deep Water. After this, a section along the Sardinian–Sicily channel was sampled. This section has been repeated almost every 1–2 yr since more than 20 yr. A long-term fixed station was visited in the central Tyrrhenian, where a mooring was recovered and redeployed towards the Corsica Channel, where also the last CTD stations were performed. All casts have been performed with the reference SBE9 probe, 2 Idronaut multiparametric Ocean 320+ probes (one standard and one prototype), 2 lowered ADCPs. Water samples for chemical analyses were collected at standard depths for the determination of: dissolved oxygen, salinity, dissolved inorganic nutrients, total organic carbon, dissolved inorganic carbon, total alkalinity, and pH.

3 Hydrography of the Mediterranean Sea

A comprehensive review of the Mediterranean oceanography is provided by Nielsen (1912) in a classic work that sums up the knowledge at the beginning of the 20th century. Almost 50 yr later Wüst (1961) presents property distributions (salinity, temperature and oxygen) of the whole Mediterranean Sea system, and discusses the vertical circulation for both the shallow overturning cell involving the Levantine Intermediate Water (LIW) and the deep water formation in both basins. Several more recent works are reviewing water mass formation, circulation and mixing within the Mediterranean System (e.g. Robinson et al., 2001; Millot and Taupier–Letage, 2005; Bergamasco and Malanotte-Rizzoli, 2010), and Tsimplis et al. (2006) reviews recent changes in the oceanography of the Mediterranean attributed to climate variability. The Mediterranean Sea is clearly a dynamic system with significant temporal and spatial variability and where several permanent structures interact with gyres and eddies (both permanent and intermittent). This can be exemplified with a map of the absolute dynamic topography (ADT) of the Mediterranean Sea averaged over the two last weeks of April 2011, i.e. about the time period of the M84/3 and EF11 cruises (Fig. 2). This map shows some features that are of interest for the interpretation of the data from these cruises. For instance the low ADT in the Ionian Sea that suggests an cyclonic circulation regime, which can be correlated to salinity and nutrient concentrations in the Adriatic Sea (e.g. Civitarese et al., 2010).

3.1 Hydrology of the Mediterranean Sea

The Mediterranean Sea is an evaporation basin, i.e. the mean evaporation exceeds precipitation, which has important implications for the circulation and the biogeochemistry of the Sea. The dominating term in the water balance of the Mediterranean Sea is the exchange with the North Atlantic Ocean through the Strait of Gibraltar. The inflow of Atlantic Water (AW) has been estimated to be 0.72–0.92 Sv (Sverdrup, $10^6\,\mathrm{m^3\,s^{-1}}$) and the outflow of Mediterranean Overflow Water (MOW) to be 0.68–0.88 Sv using combinations of observations – primarily of the outflowing Mediterranean Overflow Water (MOW), models, and evaporation/precipitation data to balance the hydrological budget with the inflowing Atlantic Water (e.g. Bryden and Kinder, 1991; Bryden et al., 1994; Tsimplis and Bryden, 2000; Baschek et al., 2001; García–Lafuente et al., 2011). The Mediterranean Sea is also exchanging water with the Black Sea through the Turkish Strait System, i.e. the Dardanelles, the Marmara Sea and the Bosphorus Strait. This flow shows large temporal variability partly associated with variability in the river runoff to the Black Sea, and is also influenced on shorter time-scales by atmospheric variability. In a review by Ünlüata et al. (1990), the upper layer flow from the Black Sea to the Mediterranean Sea is estimated to be 0.039 Sv whereas the lower layer flow towards the Black Sea is 0.030 Sv. This is very close to the annual averages that are presented by Kanarska and Maderich (2008) based on model calculations. The flows, in both directions, at the Bosphorus exit to the Black Sea are significantly lower; a result of significant recirculation and vertical mixing in the strait system. Although the inflow from the Black Sea to the Mediterranean Sea is small in comparison to the inflow of the AW through the Strait of Gibraltar, it is still significant, in particular due to the low salinity of the Black Sea inflow water.

The Mediterranean Sea also receives significant amounts of fresh water from river discharge. Although various estimates of the river input is found in the literature, a study by Struglia et al. (2004) found the total mean river discharge to the Mediterranean to be approximately 0.010 Sv by compiling monthly discharge time series from a large number of rivers. Significant temporal changes in the river discharge to the Mediterranean is evident; the perhaps most significant is the reduced flow from the river Nile due to damming, but also other parts of the Mediterranean are, and have been, experiencing temporal variations. Adding up to the riverine discharge to the Mediterranean Sea an often overlooked source of freshwater is provided by submarine groundwater discharge (SGD). Although the importance of SGD to the Mediterranean Sea is currently poorly constrained, its magnitude is likely similar to the river discharge. SGD is likely an important source of freshwater, nutrients, trace metals, alkalinity etc. to the Mediterranean System (e.g. Moore, 2006b, a), particularly since the Mediterranean Sea is landlocked. Mariotti et al. (2002) summarizes the hydrological cycle of the Mediterranean Sea and reports on net evaporation and precipitation in the conventional units of $\mathrm{mm\,yr^{-1}}$. In order to compare these estimates with other fluxes to the Mediterranean Sea we convert this to units of Sverdrups ($10^6\,\mathrm{m^3\,s^{-1}}$), using the area of $2.5 \times 10^{12}\,\mathrm{m^2}$ for the Mediterranean Sea. The annual mean precipitation is reported to be 0.026–0.037 Sv, whereas the evaporation is 0.074–0.093 Sv, so that the net E-P difference is approximately 0.039–0.055 Sv (Mariotti et al., 2002).

The flow through the Strait of Gibraltar is thus by far the dominant water exchange across the Mediterranean limits. However in terms of freshwater content, precipitation is the dominating source, followed by river and SGD input. The evaporation is the second largest term in the hydrological budget; its effect can be seen in a section of the salinity through the Mediterranean Sea (Fig. 3).

3.2 The shallow overturning of the Mediterranean Sea

The surface of the eastern Mediterranean Sea is characterized by high salinity, whereas the relatively low salinity inflow of AW through the Strait of Gibraltar is dominating the western Mediterranean Sea. The AW is mainly following a cyclonic circulation of the western Mediterranean (e.g. Millot, 1999; Tsimplis et al., 2006); starting along the North African coast eastwards as the Algerian current. This current generates several short-lived mesoscale and larger open sea eddies that are important for transporting AW to the interior basin (e.g. Fig. 2). The main part of the AW flows through the Sardinia Channel into the Tyrrhenian Sea, and a smaller portion flows into the Eastern Mediterranean Sea through the Sicily Channel. In the Tyrrhenian Sea the AW is following a general cyclonic circulation with several eddies and meanders (e.g. Vetrano et al., 2010). In the northern Tyrrhenian Sea one branch of the AW flows through the Corsica Channel and forms the northern current along the north-western border, completing the cyclonic circulation in the western basin.

The AW that flows through the Sicily Channel enters the Ionian Sea and the Eastern Mediterranean. The principal flow is in a cyclonic circulation with the Libyo–Egyptian current along the north coast of Africa and several mesoscale anti-cyclonic eddies forming to the north of the coastal current, some of which are quasi-permanent (e.g. Millot and Gerin, 2010; Gačić et al., 2011), as seen in Fig. 2. However, recently it has been observed that the dominating upper water circulation in the northern Ionian Sea, i.e. the North Ionian Gyre (NIG), shifts between cyclonic and anti-cyclonic on roughly decadal time-scales (e.g. Borzelli et al., 2009; Gačić et al., 2011). The main effect of this is that the relatively low salinity water of the AW is either preferable flowing northward around the Ionian Sea or on a more direct route towards the Cretan Passage and the Levantine Basin, see discussion below.

A tongue of high salinity water that stretches westward from the Levantine Basin can clearly be seen in Fig. 3; this is the tell-tale of the LIW. AW and LIW are the two main components of a shallow circulation cell of the Mediterranean that transforms inflowing AW to LIW in the Eastern Mediterranean Sea. The LIW is characterized by a salinity maximum layer at approximately 200–500 m depth and potential densities of 29.0–29.1 kg m^{-3} (e.g. Wüst, 1961; Malanotte-Rizzoli and Hecht, 1988; Roether et al., 1998). The formation area of LIW is in the area east of Rhodes and possibly in the Cretan Sea (Roether et al., 1998), from where it spreads both to the east, to the Levantine Basin, and west, to the Ionian Sea, with a significant flow north towards the Adriatic, where the LIW is an important component in the formation of deep water (e.g. Roether et al., 1998). Transport times of LIW from the formation area to the Sicily Channel has been determined to 8 yr from transient tracer data (Roether et al., 1998) or 10–13 yr from salinity anomalies (Gačić et al., 2013). The transport of LIW through the Eastern Mediterranean is also affected by the circulation in the northern Ionian Sea, influencing for instance the conditions in the Adriatic Sea as well. As the LIW passes the Sicily Channel most of it makes a cyclonic tour around the Tyrrhenian Sea and enters the Western Mediterranean Sea through the Sardinia Channel boarding the western coast of Sardinia (Millot, 1999; Vetrano et al., 2010). Due to the high density of the LIW, significant downward mixing is evident within the Tyrrhenian Sea down to about 1800 m depth (Millot, 1999; Roether and Lupton, 2011). A fraction of the LIW flows out of the Tyrrhenian northwards and enters the Ligurian Sea and the Provençal Basin, becoming the preconditioning agent in the dense water formation in the Gulf of Lions. Most of the LIW finally exits the Mediterranean Sea as MOW through the Strait of Gibraltar as the principal water mass that is exported to the Atlantic Ocean from the Mediterranean Sea. The MOW is exiting the Mediterranean Sea below the inflowing AW, i.e. this is a typical anti-estuarine circulation. The outflow of Mediterranean waters into the Atlantic Ocean supports a water layer or high salinity and temperature present over much of the North Atlantic at intermediate depth. The characteristics of the MOW has direct implications for the stability of the North Atlantic Meridional Overturning Circulation, and rises the possibility of feedback mechanisms that, on different time-scales, may have direct climatic implications for the region and, potentially, over larger areas (e.g. Ulbrich et al., 2006).

3.3 The deep overturning of the Mediterranean Sea

The deep water of the eastern basin is significantly more saline and warmer than the deep water of the western basin (Figs. 3 and 4), and consequently the potential density referenced to surface pressure (σ_θ) is higher in the eastern basin (Fig. 5). These differences are a reflection of the different deep water formation regions and the differences in hydrographic pre-conditioning of the water prior to deep water formation.

3.3.1 Eastern Mediterranean Sea

Salinity and temperature sections (Figs. 3 and 4), clearly demonstrate large differences (i.e. salinity and temperature) in the deep and intermediate waters between the eastern and western basin. This is related to the separate deep water formation processes taking place in each basin (i.e. in the western and eastern Mediterranean Sea) that transport water from the upper water column to the deep interior. The Adriatic Sea is the principal deep water formation area in the Eastern Mediterranean Sea. Adriatic Deep Water (AdDW) is formed in the Southern Adriatic Pit (SAP) by means of open ocean convection and over the north and central Adriatic Sea continental shelf (e.g. Lascaratos et al., 1999). Water from the two formation regions within the Adriatic are transported southward and mixes along the Italian slope before exiting through the Otranto Strait (e.g. Cardin et al., 2011). The newly formed deep water sinks to depth in the Ionian Sea forming the Eastern Mediterranean Deep Water (EMDW) (e.g. Hainbucher et al., 2006). The water volume formed is highly variable depending on atmospheric and thermohaline conditions (Cardin et al., 2011). However, in the early 1990's the Aegean Sea became the main deep water formation area, generating an event known as the Eastern Mediterranean Transient (EMT). The EMT and its implications for the water mass properties and circulation has been described extensively in the literature (e.g. Roether et al., 1996, 2007; Klein et al., 1999, 2003; Lascaratos et al., 1999). The new deep water of Aegean origin started to dominate the waters below 1200 m depth; it was characterized by higher temperature and salinity than previously when the deep water was dominated by water of Adriatic origin. Furthermore, the Eastern Mediterranean Deep Water of Aegean origin ($\text{EMDW}_{\text{aegean}}$) production rate during the years of stronger formation was distinctly higher (1.2–1.7 Sv) than the rate of that of Adriatic origin (0.3 Sv) (Roether and Schlitzer, 1991; Gačić et al., 1996; Astraldi et al., 1999). It is now suggested that the EMT was caused by the fact that very strong winters converged with the intrusion of high-salinity waters into the Aegean Sea (Josey, 2003; Gačić et al., 2013). The impact of the EMT on the climatology of the whole Mediterranean Sea are still a matter of active research (e.g. Rohling and Bryden, 1992; Theocharis et al., 1999; Wu et al., 2000). More recently, the Adriatic has returned to be the Eastern Mediterranean Deep Water ($\text{EMDW}_{\text{adriatic}}$) source (Klein et al., 2000), although its salinity and temperature are now higher than the "classical" $\text{EMDW}_{\text{adriatic}}$, and more similar to the deep water formed during the EMT (Rubino and Hainbucher, 2007).

One potentially significant process for the preconditioning of the surface water prior to deep water formation in the Eastern Mediterranean is the so called Adriatic–Ionian Bimodal Oscillation System (BiOS) (Gačić et al., 2010) as described above. The alternating circulation regime of the NIG determines two different AW pathways in the Ionian, and consequently two opposite effects in the Ionian and in the Levantine Basin. When the NIG is anticyclonic, the fresher AW flowing from the Sicily Channel meanders in the northern Ionian, prolonging its pathway and consequently weakening its dilution effect when it mixes in the Levantine Basin. On the other hand, when the NIG is cyclonic, the main AW route is directly toward the Levantine Basin, exerting the maximum dilution effect in the Levantine Basin. Therefore, the salinity of the LIW formed in the Levantine Basin is higher when the NIG is anticyclonic, lower when the NIG is cyclonic (Gačić et al., 2013). This mechanism shows a decadal variability in the thermohaline characteristics of the LIW, and can help explain the switches between Adriatic and Aegean as source regions for the EMDW. It has also been shown that nutrients concentration in the northern Ionian and southern Adriatic are anti-correlated with salinity, and that the abundance of non-indigenous species of Atlantic origin increases during the anti-cyclonic phase of the NIG, whilst in the cyclonic phase, the occurrence of Levantine and Lessepsian species have been reported (Civitarese et al., 2010). It has been suggested that the BiOS mechanism could precondition the waters in the eastern Mediterranean so that events similar to the EMT could happen at regular intervals (Gačić et al., 2011, 2013), if the winter meteorological conditions in the Aegean Sea were severe enough to promote the massive dense water formation. However, the ~ 100 yr instrumental record does not show the occurrence of EMT-like events prior the 1980’s (Roether et al., 2013).

The renewal time of the deep water in the Eastern Mediterranean is significantly longer then the corresponding ages in the Western Mediterranean; about 100 and 20–40 yr, respectively (e.g. Roether et al., 1996; Stratford and Williams, 1997; Stratford et al., 1998). Transient tracer measurements suggest that the mean (or ideal) age of the deep eastern Mediterranean is 30–40 yr in the deep Ionian Sea and about 80 yr in the intermediate layer, for conditions prior to the EMT (Steinfeldt, 2004). However, Steinfeldt (2004) points out that these values are lower bounds due to the limited integration time of the tracers used in the study. Based on CFC data collected in 2001, i.e. well after the EMT, Schneider et al. (2010) calculate mean ages of less than 60 yr in the deep water, and ~ 130 yr in the intermediate “tracer minimum layer”. Based on the knowledge of drastic changes both in the deep water formation rate and in the formation areas temporal differences in ventilation of the deep eastern Mediterranean can be expected. Ventilation rates of the Mediterranean as found during 2011 is discussed by Stöven (2011) using multiple transient tracers.

3.3.2 Western Mediterranean Sea

In the western Mediterranean Basin, deep-water formation primarily takes place in the Gulf of Lions (e.g. Gascard, 1978; Killworth, 1983; Schott et al., 1993; Rhein, 1995; Tsimplis et al., 2006). During winter, dry and cold air mixes the AW and the Winter Intermediate Water (WIW) with the underlying, warmer and saltier LIW. Further heat loss leads to formation of Western Mediterranean Deep Water. The upper part of the deep water can pass the sill in the Sardinia Strait (~ 1900 m) and enter the Tyrrhenian Sea. Here mixing with down-welling water from the Eastern Mediterranean Sea seems to be an important mechanism in mixing the deep waters upward in the water column (Millot, 1999; Rhein et al., 1999; Vetrano et al., 2010). The Tyrrhenian Sea exports Tyrrhenian Deep Water to the western basin, a water mass that is characterized by relatively low transient tracer concentrations and is found between the WMDW and LIW (Rhein et al., 1999). Several studies have shown that the deep waters of the Western Mediterranean have warmed and gained salinity during a large fraction of the instrumental record, i.e. at least since the mid of the 20th century (Béthoux et al., 1990; Rohling and Bryden, 1992; Krahmann and Schott, 1998). Also, a study by Vargas-Yáñez et al. (2010) suggests that also the intermediate and surface waters of the western Mediterranean Sea is warming. The deep water formation is a transient event with time-periods of more or less convective activity in the western Mediterranean Sea. An intense deep water renewal took place in the mid-2000's in the western Mediterranean, with dramatic increase of S and T of the deep water and with the entire basin filled with new deep water within two years (e.g. Schroeder et al., 2008; Schroeder et al., 2010b).This event is known as the Western Mediterranean Transition (WMT). Gačić et al. (2013) has shown that about 60 % of the salinity increase in the WMDW during the WMT can be explained by the decadal variability of salinity in the Eastern Mediterranean in the context of the BiOS. This will likely have significant effects on biogeochemical properties in the western Mediterranean (e.g. Schroeder et al., 2008). In addition to deep waters, intermediate waters are formed during winter at the shelf/slope system in the northern part of the western Mediterranean Basin (Tsimplis et al., 2006) during years of less intense deep convection. The WIW follows the general circulation of the western basin underneath the AW.

3.4 Oxygen in the Mediterranean Sea

The oxygen distribution in the Mediterranean Sea is depicted in Fig. 6. The Mediterranean Sea is well oxygenated, and even the Oxygen Minimum Layer (OML) at intermediate depths has oxygen concentrations in the order of 180 µmol kg^{-1} (the apparent oxygen utilization rate, AOU is 70–80 µmol kg^{-1}). This is primarily related to the active and fast ventilation of the Mediterranean Sea (e.g. Roether and Schlitzer, 1991; Schneider et al., 2010; Stöven, 2011). Due to the low production in the oligotrophic Mediterranean Waters, one would also expect low oxygen utilization rates (OUR), favouring high oxygen concentrations. However Roether and Well (2001) found OUR values similar to other ocean areas in the upper water column (calculated as a function of depth), and significantly higher OUR values in the deep layers (0.53 ± 0.19 µmol kg^{-1} a^{-1}), and speculate that the high temperatures in the deep water could contribute to the high rates. Klein et al. (2003) found that the recently formed deep waters during the EMT contained labile dissolved organic carbon, brought from the surface layer to depth by convection, that enhanced the oxygen consumption rate to be 1.3 µmol kg^{-1} a^{-1} and higher, i.e. more than twice of values reported by Roether and Well (2001) for the conditions prior to the EMT. During a survey in the western Mediterranean Sea in the spring of 2005, oxygen levels above 210 µmol kg^{-1} were found in the deep waters and attributed to recently formed deep waters (Schröder et al., 2006), which is higher than conditions before the WMT. Such high oxygen concentrations were not found during the 2011 *Meteor* survey, perhaps in analogy to the rapidly decreasing oxygen concentrations found in the deep water of the eastern Mediterranean Sea after an initial increase of oxygen due to invasion of recently ventilated surface waters to the deep waters (Klein et al., 2003).

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The two sub-basins show significant differences in the distribution of dissolved oxygen; although both sub-basins exhibit an OML, its vertical positions are different for the two sub-basins. In the eastern basin, the OML core lies in the depth range of 500–700 m, well below the layer of maximum *S* occupied by the LIW, whilst in the western basin the OML coincides with the LIW, with the core in the range of 300–400 m depth. Also the oxygen concentrations in the OML are different, and is lower is the western basin than in the eastern basin (also the AOU is higher in the western basin, not shown). This difference is mirrored by the Nutrient Maximum Layer (NML) for the two basins. The OML is the result of two contrasting process in the water column: the oxygen consumption due to the mineralization of the organic matter produced at surface and the supply of oxygen by vertical and lateral diffusion and advection processes. In the case of the Mediterranean Sea there is additionally a significant contribution of upward motion due to deep water formation processes (e.g. Klein et al., 2003) The balance of these processes sets the position and the oxygen concentration of the OML. It is worth considering that the stratification below 250 m depth is higher in the eastern than in the western Mediterranean Sea, restricting upward diffusive mixing the eastern as compared to the western basin. The horizontal distribution of oxygen (and several other properties) is more uniform in the western compared to the eastern basin. One explanation of this difference is that the morphology of the eastern basin is more complex than that of the Algero–Procençal Basin. These morphological features restrict the spread of new, dense and more oxygenated waters into the abyssal interior of the eastern basin. This suggests that the western basin-wide horizontal mixing is faster in comparison to the eastern basin. This is reflected by the significantly shorter residence times of the deep water in the western as compared to the eastern Mediterranean Sea. Also transient tracer concentrations are higher in the WMDW compared to the EMDW (e.g. Stöven, 2011). However, there are large spatial and temporal variability in the transient tracer concentrations, and thus the ventilation age.

3.5 Nutrients in the Mediterranean Sea

The nutrient distributions in the Mediterranean Sea as found during April of 2011 are shown in Fig. 7 for nitrate (NO_3), Fig. 8 for phosphate (PO_4), and Fig. 9 for silicate (Si). The Mediterranean Sea is generally characterized by very low nutrient concentrations, in particular the Eastern Mediterranean (e.g. Kress et al., 2003). The surface layers are generally almost fully nutrient depleted so that the Mediterranean is an oligotrophic, or even ultra-oligotrophic basin (e.g. Pujo-Pay et al., 2011). In addition, the nutrient distributions show that in the eastern Mediterranean the nutrient depleted surface layer is thicker and the NML is deeper than in the western Mediterranean. The increased oligotrophy towards the east in the Mediterranean Sea is influenced by the higher intermediate and deep water stratification in the eastern Mediterranean Sea. A primary reason for low nutrient concentrations is the anti-estuarine circulation of the Mediterranean Sea, i.e. deep water with higher nutrient values is exported whereas low nutrient AW is imported (e.g. Huertas et al., 2012). However, an increasing trend for nitrate and phosphate concentrations in the deep water of the western Mediterranean has been observed, and attributed to anthropogenic perturbations (Béthoux et al., 1998, 2002).

Apart from the low concentrations, the interior of Mediterranean Sea is characterized by high $NO_3:PO_4$ (usually indicated as N : P) ratios: in the world ocean N : P is classically determined to be around 16 (Redfield et al., 1963) whereas in the deep eastern basin the N : P is 24–27, and 20–22 in the deep western basin. The debate on the origin of this peculiarity, often reported as anomaly, is still open. From the slight N : P increase usually observed in the deeper layer in the eastern Mediterranean, Civitarese et al. (1998) have proposed the Adriatic rivers as one of the possible sources of the N : P anomaly. Other authors suggested the remarkable unbalanced of N : P ratio in the atmospheric inputs as another contribution to the general N : P ratio anomaly in the Mediterranean. Also the lack of de-nitrification in the generally well oxygenated Mediterranean waters and sediments has been proposed as a source of the high N : P ratios (Krom et al., 2004, 2005). The Mediterranean, particularly the eastern basin, has been considered as phosphorus limited for biological growth (Krom et al., 1991, 2004), although recent work suggest N or N and P co-limitations (e.g. Thingstad et al., 2005).

Nitrogen fixation rates in the Mediterranean Sea are generally low (e.g. Ibello et al., 2010; Bonnet et al., 2011), although higher rates were measured during the *Meteor* cruise during spring 2011 (Rahav et al., 2013). The concentrations of nitrate and phosphate in the deep layer are significantly higher in the western basin compared to the eastern basin (Figs. 7 and 8). Yet, the concentrations for silicate in the deep waters of both basins are similar (Fig. 9), although slightly lower in the Adriatic Sea, which influences the western part of the deep Ionian Sea. In a study of nutrient fluxes in the western Mediterranean Sea Schroeder et al. (2010a) conclude that the eastern basin supplies nutrient to the western basin, which is one explanation for the higher nutrient concentrations in the basin. It is conceivable that the recent deep water formation events in the western Mediterranean Sea led to a decreased nutrient concentrations in the deep water, as pointed out by Schroeder et al. (2010a). Observed temporal variability in nutrient and oxygen concentrations must be put in context of observed variability in circulation and overturning.

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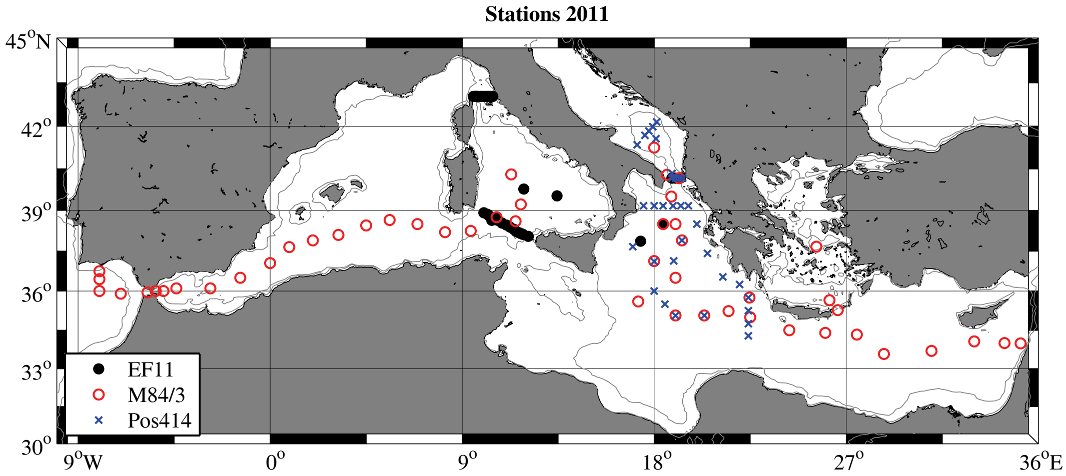

Fig. 1. Map of the Mediterranean Sea with the positions of the three quasi-synoptic cruises marked, see text. The 500 m isobaths is marked with a thin gray line.

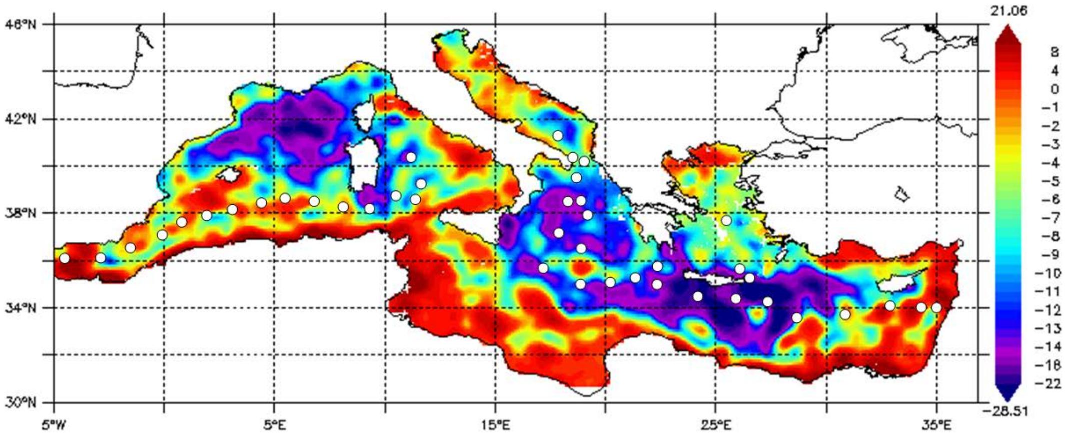

Fig. 2. Absolute Dynamic Topography (ADT) map of the Mediterranean averaged over the second week of April 2011.

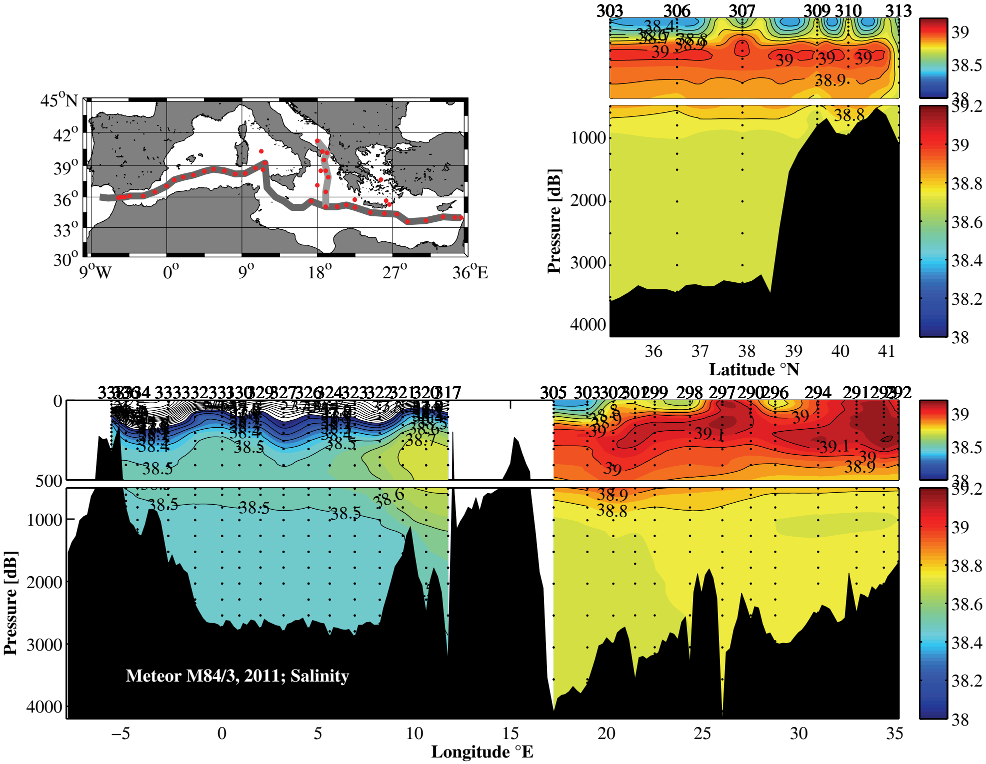

Fig. 3. Sections of salinity in the Mediterranean Sea from the *Meteor* cruise M84/3 in April of 2011. The top right panel is a meriodional section from the Adriatic Sea to the Ionian Sea (light gray line on the map) and the lower panel is the zonal section from the coast of Lebanon in the Eastern Mediterranean Sea to through the Strait of Gibraltar (dark gray line on the map). The depth scale and the color scale are identical for both panels. The top 500 m in each section are slightly expanded. No stations are shown in the Atlantic due to the very different salinities encountered there as compared to the Mediterranean Sea.

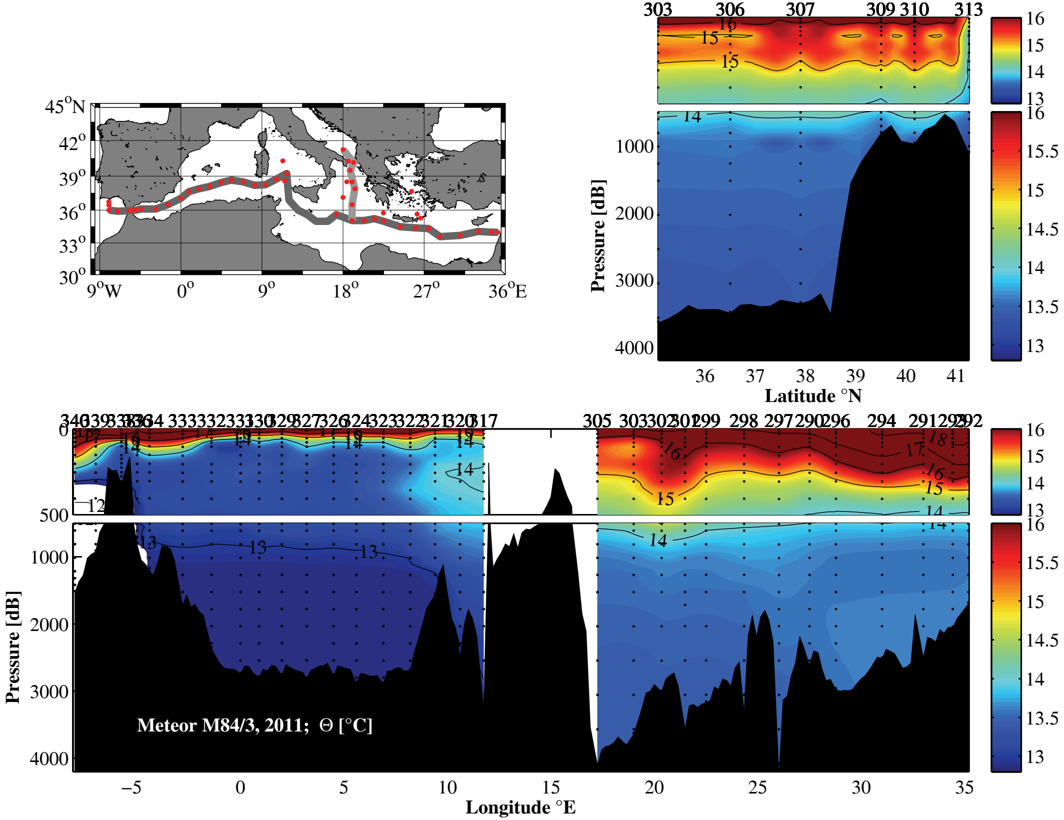

Fig. 4. Similar to Fig. 3, but for potential temperature.

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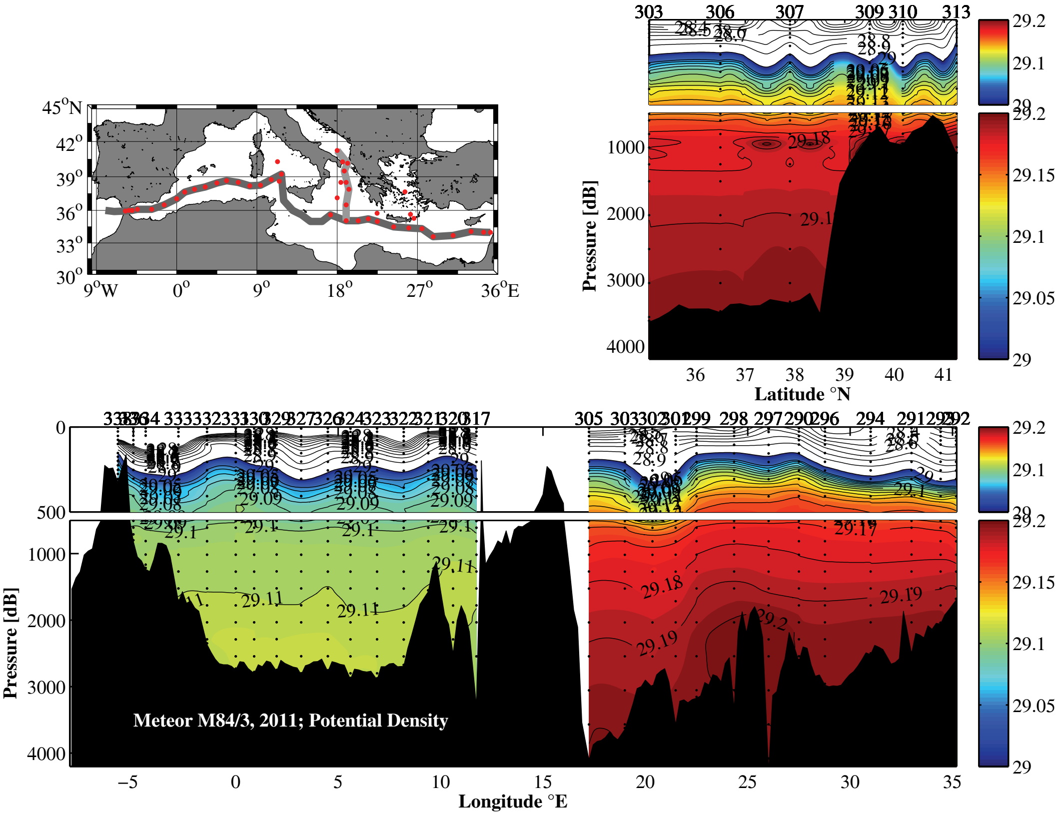

Fig. 5. Similar to Fig. 3, but for potential density (σ_θ). No stations are shown in the Atlantic due to the very different densities encountered there as compared to the Mediterranean Sea.

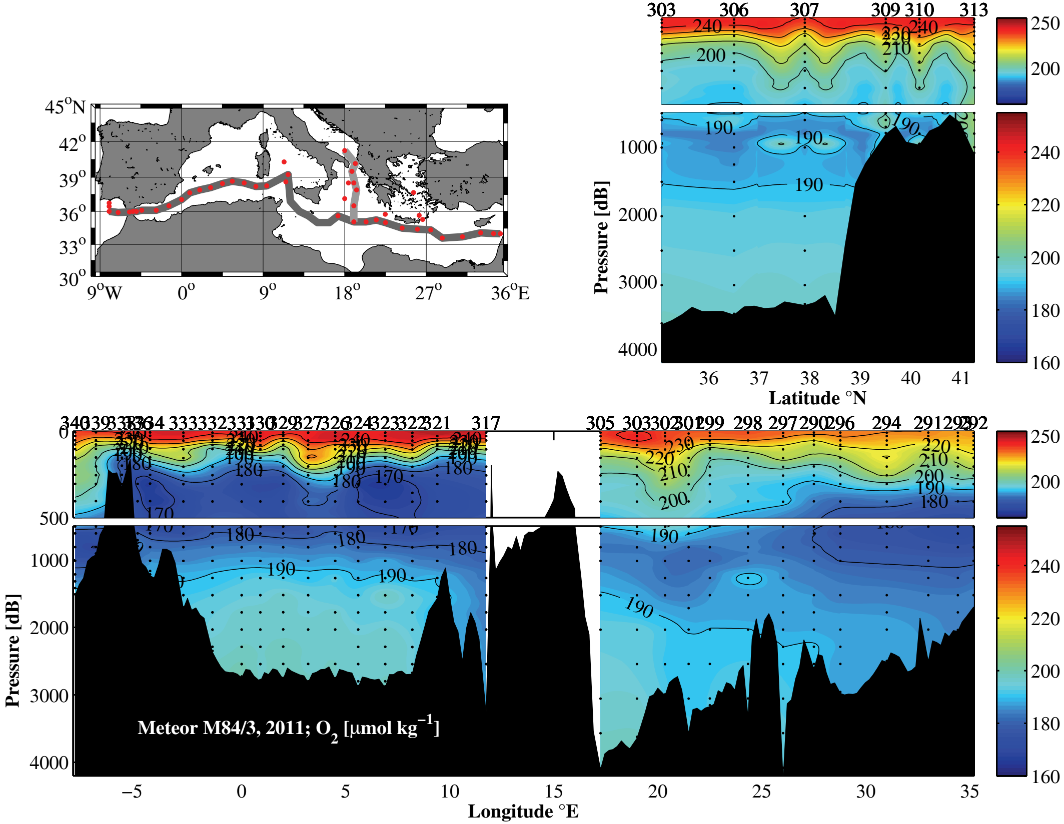

Fig. 6. Similar to Fig. 3, but for oxygen as determined from Winkler titration.

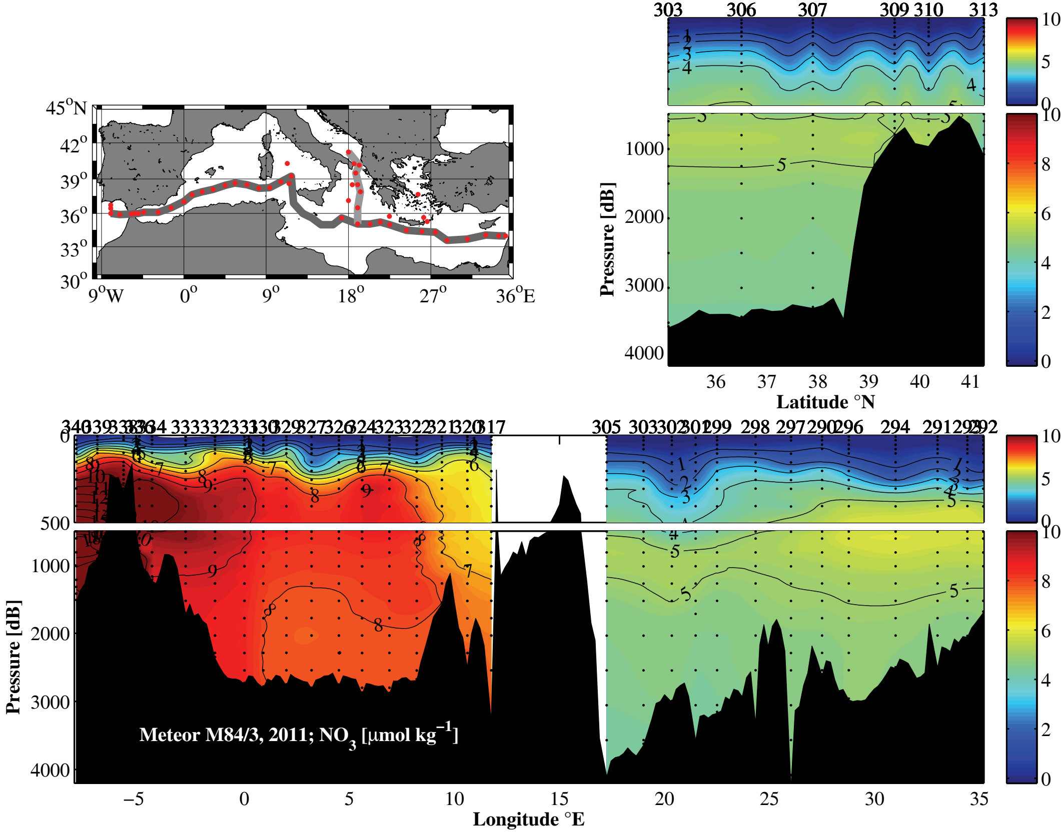

Fig. 7. Similar to Fig. 3, but for nitrate.

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Interactive Discussion

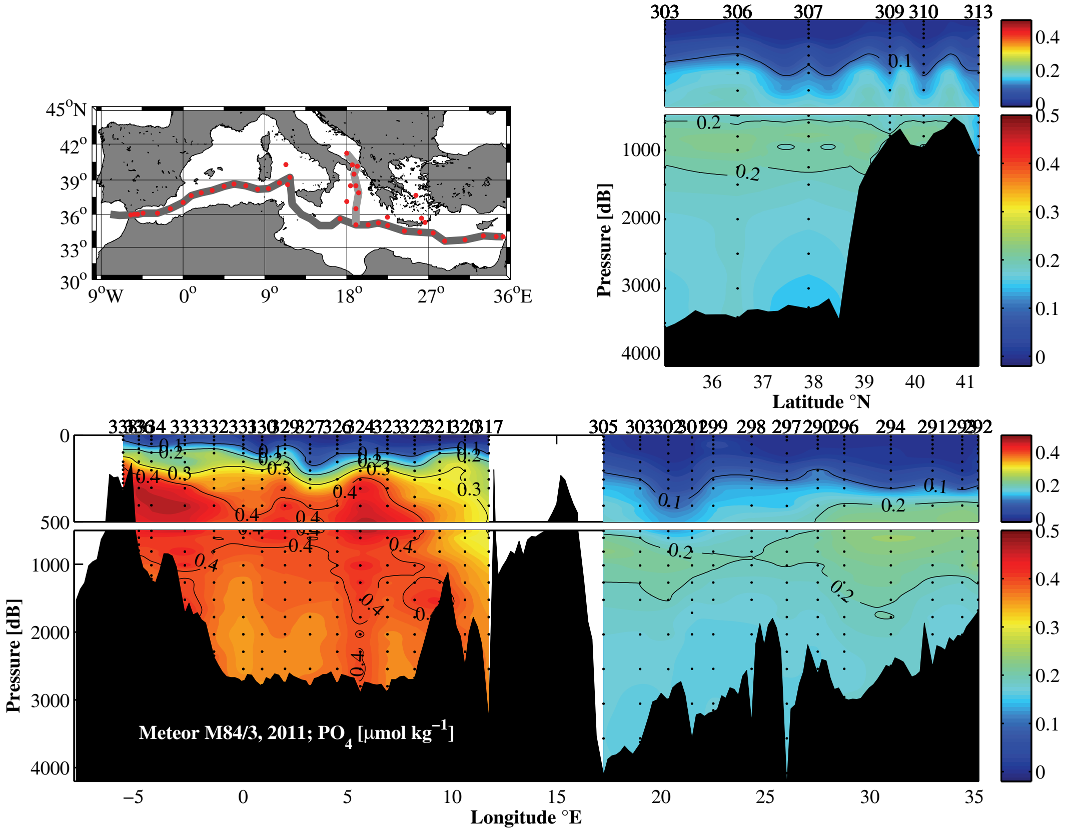

Fig. 8. Similar to Fig. 3, but for phosphate. No stations are shown in the Atlantic due to the very different phosphate values encountered there as compared to the Mediterranean Sea.

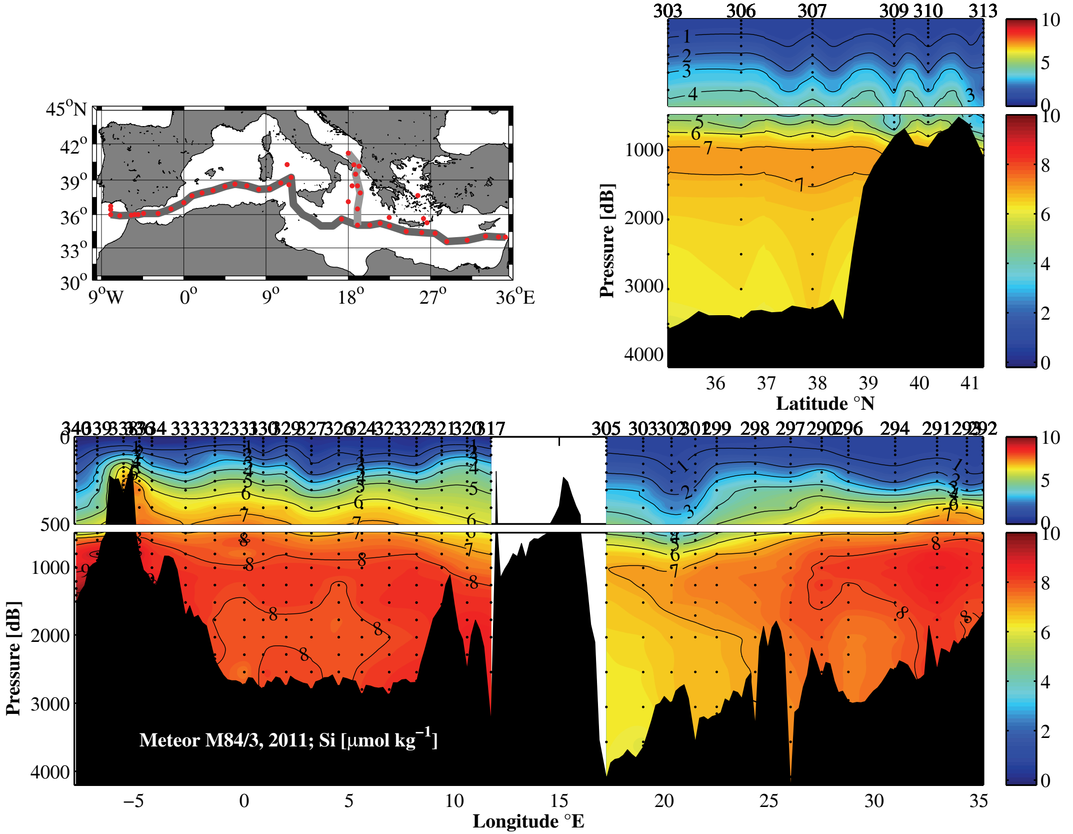

Fig. 9. Similar to Fig. 3, but for silicate.