United Nations Educational, Scientific and Cultural Organization

Intergovernmental Oceanographic Commission

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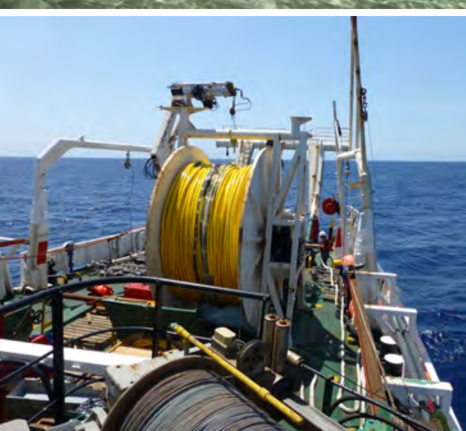
Physical forcing and physical/biochemical variability of the Mediterranean Sea: a review of unresolved issues and directions for future research

by

Paola Malanotte-Rizzoli and the Pan-Med Group



For bibliographic purposes this document should be cited as:

Malanotte-Rizzoli P. and the Pan-Med Group. 2012
Physical forcing and physical/biochemical variability of the Mediterranean Sea:
A review of unresolved issues and directions of future research.
Report of the Workshop “Variability of the Eastern and Western Mediterranean circulation and thermohaline properties: similarities and differences”
Rome, 7-9 November, 2011, 48 pp.

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The Pan-Med Group

Malanotte-Rizzoli, Paola[1] rizzoli@mit.edu
Artale, Vincenzo[2] vincenzo.artale@enea.it
Borzelli-Eusebi, Gian Luca[3] luca_borzelli@yahoo.it
Brenner, Steven[4] sbrenneril@yahoo.com
Civitarese, Giuseppe [3] gcivitares@ogs.trieste.it
Crise, Alessandro[3] acrise@ogs.trieste.it
Font, Jordi[5] jfont@icm.csic.es
Gacic, Miro[3] mgacic@ogs.trieste.it
Kress, Nurit[6] nurit@ocean.org.il
Marullo, Salvatore salvatore.marullo@enea.it
Ozsoy, Emin[7] ozsoy@ims.metu.edu.tr
Ribera d'Alcalà, Maurizio[8] maurizio@szn.it
Roether, Wolfgang[9] wroether@physik.uni-bremen.de
Schroeder, Katrin[10] katrin.schroeder@ismar.cnr.it
Sofianos, Sarantis[11] sofianos@oc.phys.uoa.gr
Tanhua, Toste[12] ttanhua@geomar.de
Theocharis, Alexander[13] alekos@hcmr.gr
Alvarez, Marta[14] marta.alvarez@co.ieo.es
Ashkenazy, Yosef[15] ashkena@bgu.ac.il
Bergamasco, Andrea[10] andrea.bergamasco@ismar.cnr.it
Cardin, Vanessa[3] vcardin@ogs.trieste.it
Carniel, Sandro[10] sandro.carneil@ismar.cnr.it
D'Ortenzio, Fabrizio[16] dortenzio@obs-vlfr.fr
Garcia-Ladona, Emilio[5] emilio@icm.csic.es
Garcia-Lafuente, Jesus Manuel[1] glafuente@ctima.uma.es
Gogou, Alexandra[13] agogou@hcmr.gr
Gregoire, Marilaure[18] m.gregoire@ulg.ac.be
Hainbucher, Dagmar[19] dagmar.hainbucher@zmaw.de
Kontoyannis, Harilaos[13] hk@hcmr.gr
Kovacevic, Verdana[3] vovacevic@ogs.trieste.it
Krasakapoulou, Eva[13] ekras@hcmr.gr
Krokos, George[13] gkrokos@hcmr.gr
Incarbona, Alessio[20] alessinc@unipa.it
Mazzocchi, Maria Grazia[8] grazia@szn.it
Orlic, Mirko[21] orlic@irb.hr
Pascual, Ananda[22] ananda.pascual@imedea.uib-csic.es
Poulain, Pierre-Marie[3] ppoulain@ogs.trieste.it
Rubino, Angelo[23] rubino@unive.it
Siokou-Frangou, Joanna[13] isiokou@hcmr.gr
Souvermezoglou, Ekaterini[13] katerinasouv@hcmr.gr
Sprovieri, Mario[24] mario.sprovieri@iamc.cnr.it
Taupier-Letage, Isabelle[25] isabelle.taupier-letage@univ-amu.fr
Tintore', Joaquin[22] jtintore@uib.es
Triantafyllou, George[13] at@hcmr.gr

Affiliation

[1]Massachusetts Institute of Technology, Cambridge, MA – USA
[2]ENEA, Agenzia nazionale per le nuove tecnologie, l'energia e lo sviluppo economico sostenibile. Centri ricerca Frascati e Roma- Italia
[3]Istituto Nazionale di Oceanografia e di Geofisica Sperimentale –OGS - Trieste Italy
[4]Department of Geography and Environment, Bar Ilan University, Ramat Gan 52900 –Israel
[5]Institut de Ciencies del Mar – CSIC - Barcelona – Spain
[6]National Institute of Oceanography, Israel Oceanographic & Limnological Research, Haifa - Israel
[7]Middle East Technical University, Institute of Marine Sciences, Erdemli Turkey
[8]Stazione Zoologica Anton Dohrn, Napoli – Italy
[9]University of Bremen, Bremen-Germany
[10]CNR ISMAR, Istituto di Scienze Marine, Venezia-Italy
[11]University of Athens, Division of Environmental Physics, Ocean Physics and Modelling Group, Athens, Greece
[12]GEOMAR Helmholz Centre for Ocean Research, Kiel, Germany
[13]Institute of Oceanography, Hellenic Centre for Marine Research – Greece
[14]Instituto Espanol de Oceanografia-Spain
[15]Department of Solar Energy & Environmental Physics. The Jacob Blaustein Institutes for Desert Research - Israel
[16]Laboratoire d'Oceanographie de Villefranche (LOV), CNRS and Universite' Pierre et Marie Curie, Paris 06, UMR 7093, Villefraneche-sur-mer, France
[17]Physical Oceanography Group University of Malaga – Spain
[18]Universite de Liege –Laboratoire d'Oceanologie – Centre MARE, Liege – Belgium
[19]University of Hamburg – Institute of Oceanography, Hamburg – Germany
[20]Università di Palermo, Dipartimenti di Geologia & Geodesia, Palermo – Italy
[21]University of Zagreb, Faculty of Science Andrija Mohorovicic Geophysical Institute, Zagreb- Croatia
[22]Instituto Mediterraneo de Estudios Avanzados, IMEDEA (CSIC-UIB), Balearic Islands, Spain
[23]Università Ca' Foscari di Venezia, Venezia-Italy
[24]CNR IAMC, Unita Operativa di Capo Granitola, Trapani – Italy
[25]Aix-Marseille Universite', USTV,CNRS/INSU,IRD, La Seyne sur Mer, France

Foreword

The members of the **POEM** (Physical Oceanography of the Eastern Mediterranean) and **POEM-BC** (Biology and Chemistry) programme who have contributed to this **Report** for the establishment of a **Pan-Mediterranean Initiative** gratefully acknowledge the crucial support provided through the years to the Programme by the **Intergovernmental Oceanographic Commission (IOC/UNESCO Ocean Sciences)** and the **Mediterranean Science Commission (CIESM).**

IOC hosted the meetings of the POEM Organizing Committee - most of which were held at the UNESCO headquarters in Paris - and published the reports of these meetings, as well as the reports of POEM annual scientific workshops, as *UNESCO Reports in Marine Science*.

CIESM gave ample exposure to the Programme by offering special congress sessions and round tables at its tri-annual Congresses since the early 1980s. In fact the very idea of launching a scientific Programme focused on the Eastern Mediterranean was introduced in a Round Table held at the CIESM General Assembly in Monaco, Monte Carlo, 1982.

This Report wants to be the first step in an initiative extending beyond POEM and the POEM community and reaching out to include Western Mediterranean scientists sharing the common vision of the Mediterranean Sea as a laboratory basin for processes of global importance. Many of these scientists were gathered at a seminar organized on 7-9 November 2011 at Accademia Nazionale dei Lincei in Rome, with the kind support of the Italian Space Academy Foundation, to mark the 25th Anniversary of POEM and have substantially contributed to the ideas and the writing of the present Report. This newly formed Pan-Med Group wants to send out a call for the establishment of a Pan-Mediterranean interdisciplinary oceanographic community to investigate the still unresolved issues and provide directions for future research.

The present Report is undergoing restructuration to become a full-fledged review paper for *Progress in Oceanography*.

1. Introduction and Background

The motivation for this Report stems from a workshop held in Rome in November 2011, on the occasion of the 25th anniversary of the POEM (Physical Oceanography of the Eastern Mediterranean) Programme. The objectives of the workshop were however rather more ambitious that having simply a memorial. First, the workshop was meant to provide a synopsis of the state-of-the-art of research and present knowledge of the Mediterranean Sea physical/chemical/biological properties. Second, it wanted to offer the opportunity to scientists working in different regions of the sea, both in the Western and Eastern basins, to meet and share ideas, and hence foster pan-Mediterranean collaborations.

The importance of the Mediterranean Sea for the world ocean has long been recognized. First, the Mediterranean sea has a profound impact on the Atlantic ocean circulation and, consequently, on the global thermohaline conveyor belt. Maps of the Mediterranean salty water tongue exiting from the Gibraltar strait at intermediate depths and spreading throughout the Atlantic interior are well known since the 1950s. Through direct pathways to the Atlantic polar regions or through indirect mixing processes, the salty Mediterranean water preconditions the deep convection cells of the polar Atlantic. There the North Atlantic Deep Water is formed which successively spreads throughout the world ocean constituting the core of the global thermohaline circulation.

Even more importantly, the Mediterranean sea is a laboratory basin for the investigation of processes of global importance, being much more amenable to observational surveys because of its location in mid-latitude and its dimensions. Both the western and eastern basins in fact possess closed thermohaline circulations analogous to the global conveyor belt. A unique upper layer open thermohaline cell connects the eastern to the western basin and, successively, to the north Atlantic through the Gibraltar strait. In it, the Atlantic water entering into Gibraltar in the surface layer, after travelling to the easternmost Levantine basin, is transformed into one of the saltiest water masses through air-sea heat and moisture fluxes. This is the salty water which, crossing the entire basin in the opposite direction below the surface Atlantic water, finally exits from the Gibraltar strait at mid-depths.

Both the western and eastern basins are endowed with deep/intermediate convection cells analogous to the polar Atlantic deep convection cells or to the intermediate mode water ones. Deep and intermediate water masses are therefore formed in different sites of the entire basin. Because of their easily accessible locations, these convection cells are much more amenable to direct observational surveys and mooring arrays.

An ubiquitous, energetic mesoscale and sub-mesoscale eddy field is superimposed to and interacts with the sub-basin scale, wind-driven gyres that characterize the upper thermocline circulation. Three different scales of motion are therefore superimposed producing a richness of interaction processes which typify similar interactions in unexplored ocean regions.

Both wide and narrow shelves are present separated by steep continental slopes from the deep interiors. Cross-shelf fluxes of physical as well biogeochemical parameters are crucial in determining the properties of the shallow versus deep local ecosystems and their trophic chain. Most importantly, the Mediterranean sea is a basin of contrasting ecosystems, from the strongly oligotrophic deep interiors to the fully eutrophic northern Adriatic characterized by recurrent, anomalous algal blooms and related anoxia events.

For reasons that may be linked to geographical locations and related national scientific policies, the western and eastern basins have been mostly investigated independently from each other. International collaborative programs such as the Gibraltar Experiment, the Western Mediterranean Circulation Experiment (WMCE), the Programme de Recherche Internationale en Méditerranée Occidentale (PRIMO) and POEM itself have continued to investigate separately individual subbasins in the western or eastern sides.

Hence the major motivation for this report: it is a call for a Pan-Mediterranean initiative bringing together the western and eastern oceanographers. It is a call for the initiation of a broader, fully interdisciplinary collaboration to create a Mediterranean community of physical, chemical, biological oceanographers and, hopefully, also of Mediterranean climate scientists. This review focuses on the identification of the major unresolved issues and wants also to provide directions for future research leading to the formulation of an implementation plan to address these issues both theoretically and observationally.

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2. Differences and similarities between the Western and Eastern Mediterranean

2.1 Scales of variability of the Mediterranean circulation

State of knowledge

Scales of oceanic circulation are crucial for two reasons. First, from the theoretical point of view, since the ratio between horizontal scales of a baroclinic motion and the deformation radius determines the baroclinic stability of the motion (*Saunders*, 1973) and, second, from the practical point of view, since in oceanography the properties of the investigated system vary in space and time. Therefore, to capture the variability of the phenomena that characterize a given oceanic region, specific sampling strategies accounting for the characteristic spatial and temporal scales of variability of the phenomena that characterize the region, need to be adopted.

One source of variability of scales and energy fluxes through the ocean is the one connected to dense water production process and the linked downslope flow (*Winters et al*., 1995; *Nycander et al*., 2007; *CIESM* 2009; *Winters and Young*, 2009).

Wintertime Dense Shelf Water Cascades (DSWC) can transport large amounts of water and sediment through submarine canyons, reshaping the canyons and affecting the deep water environment in the process. An excellent example was presented by *Canals et al.* (2006) from observations in the Cap de Creus Canyon in the Gulf of Lions in the Mediterranean Sea (one of his figure shows measurements made during a gravity/turbidity current event, which shows current speeds as high as 80 cm/s and high sediment concentrations). Similar events can be expected to occur in the Bari Canyon when North Adriatic Deep Water (NADW) formed in the northern parts reaches Bari Canyon System (BCS) in a few months. BCS intercepts sediments derived from Po and southern Apennine rivers and funnels this material into the deep South Adriatic Basin (we may reproduce a couple of figure from the above mentioned papers).

A useful approach to describe scales of oceanic circulation relates to the vertical partitioning of oceanic energy into barotropic and baroclinic components (*Wunsch and Stammer*, 1995; *Stammer*, 1997; *Wunsch*, 1997). This allows identifying the dominant components of the motion and estimate its characteristic scales in terms of Rossby radii of deformation (*Lermusiaux and Robinson,* 2001). However, the quantification of the relative importance of the barotropic and baroclinic mode(s) in determining the horizontal circulation is difficult, due to the fact that, for a faithful description of a given region of the ocean, nearly continuous sampling over wide areas is necessary.

Another possible approach is based on satellite remote sensing, which allows gaining data over wide areas of the ocean nearly continuously. This approach implies direct evaluation of the scales of variability of a specific passive scalar, assumed to be a tracer of the surface circulation (*Barron and Kara*, 2006; *Borzelli and Ligi*, 1999; *Borzelli*, 2008), or evaluation of the scales of variability of the sea surface structure (*Ioannone et al*., 2011). This approach, however, leads to great uncertainties since, first, through direct evaluation of scales, it is difficult to determine which is the dominant vertical component determining the horizontal circulation and, second, interacting components due to nonlinearities and active over short scales are filtered out.

Even though after POEM and PRIMO the dominant scales of the horizontal Mediterranean circulation have been identified (overall basin scale, sub-basin scale and mesoscale), the relationship between the intensity of the Mediterranean overturning circulations and deep mixing rates is not yet understood. Mixing in the deep global ocean is an important process that triggers the global overturning circulation as it controls the diffuse upwelling counteracting the formation of deep and bottom water masses, thus maintaining the stratification. Mixing occurs via the breaking of internal gravity waves or via tidal dissipation over shelves and near major topographic features. Two closed thermohaline cells, and related overturning circulations, exist in the Mediterranean. The amount of mechanical energy required for the mixing is believed to be small due to the absence of strong tides in the Mediterranean as compared to the world oceans. However, the question remains: how can the Mediterranean overturning circulations be so large if the mechanical energy available for mixing is so low?

Specific issues

1. The horizontal circulation is the result of the superposition of vertical modes. To which extent changes in the energy contained in individual vertical components determine the variability of the scales of the horizontal circulation?

2. Vertical changes in the vertical advection are related to horizontal changes of the horizontal advection. How does the variability in the horizontal scale modify the distribution of scalars (i.e. energy included) over the entire water column?

3. Are specific vertical modes responding selectively to external forcing or does this affect equally all the vertical modes?

4. Which are the mechanisms of energy exchanges between different vertical modes and how do these exchanges affect the scales of the horizontal circulation?

5. How are the scale and strength of the Mediterranean overturning circulations related to deep mixing rates?

2.2 Differences and similarities between circulation, forcing and water mass conversion in the Western and Eastern Mediterranean and interactions between the basins

State of knowledge

The Western and Eastern Mediterranean (WMed, EMed) are connected by the Straits of Sicily (sill depth ~500 m). Forcing is dominated by exchange with the Atlantic Ocean through the Strait of Gibraltar in the west (sill depth about 300 m) and, to a lesser degree, also with the Black Sea through the Strait of Dardanelles in the northeast. There is also a number of straits and channels that connect both the WMed and EMed with the marginal seas. They play a crucial role in determining the water mass exchanges and related properties (*Astraldi et al*., 1999). The other factor is atmospheric forcing, primarily in the form of net evaporation. Local climate variability exists due to both the different impacts of large scale teleconnection patterns (NAO, EA/WR, etc) on the WMed and EMed (*Josey et al*., 2010) and the regional characteristics (*Xoplaki et al*., 2003, 2004). The induced eastward salinity increase in the upper waters results in two kinds of thermohaline cells. The upper, open conveyor belt consists of eastward flow of low-salinity Atlantic Water (AW) and the formation in the Levantine and subsurface westward spreading of the warm and saline Levantine Intermediate Water (LIW) in 200-400 m (i.e. at depths shallower than the Sicily and Gibraltar Strait sills; Schroeder et al., 2012), enriched sporadically by Cretan Intermediate Water (CIW). It enters the WMed and finally outflows through the Gibraltar Strait. A further ingredient in this is the Winter Intermediate Water (WIW), both cooler and fresher than the LIW, formed in the WMed (*Send et al*., 1999). Secondly, there exist internal, or quasi-closed thermohaline cells in both Mediterranean Basins driven by deep water formation processes in the northern regions of the seas. These deep waters are partly involved in the Sicily and Gibraltar overflows. The WMDW is formed in the open region of the NW Mediterranean, while the EMDW originates in marginal seas, regularly mostly the Adriatic but also the Aegean and, sporadically, in the NW Levantine (*Kontoyiannis et al*., 1999).

The eastward flow of AW is concentrated in the southern parts of both basins (Algerian Current and Libyo-Egyptian Current, respectively). That flow is unstable and generates (anticyclonic) eddies ~50-100 km (up to 200) in diameter. In the northern part of the WMed, AW flows westward as a surface permanent current along slope, which is a recirculating branch that detaches AW from southern latitudes in the SW area of Sicily (*Millot and Taupier-Letage*, 2005). This westward Northern Current shows a marked seasonal variability, with increased mesoscale activity during wintertime (*Millot*, 1999). In the Levantine Basin, the AW is topped by the more saline Levantine Surface Waters during the warm period of the year. The Eastern Mediterranean upper circulation, in contrast, is characterized by sub-basin scale gyres and permanent, or quasi-permanent, cyclonic and anticyclonic structures interconnected by intense jets and meandering currents (*Robinson et al.*, 1991; *POEM Group*, 1992; *Malanotte-Rizzoli et al.*, 1999). The difference may arise from the highly structured bathymetry in the EMed, compared to the WMed, which has a virtually flat bottom east and south of the Balearic Islands. In the Tyrrhenian Sea, the WMDW and the overflow from the Eastern Mediterranean mix, lifting the former component to allow it to take part in the Sicily Strait outflow (*Millot*, 1999), and, at the same time, forming a deep salinity source for the WMDW (Gasparini et al., 2005).

The classical view that the thermohaline circulation of the Mediterranean was quasi-stable has more recently been overruled. During the 1990s the Aegean deep water formation took over from the Adriatic. Huge amounts of dense waters characterized by enhanced salinity and temperature were released for a few years, forming the Eastern Mediterranean Transient (EMT; *Roether et al*., 1996, 2007; *Theocharis et al*., 1999, 2002; *CIESM*, 2000), significantly influencing the thermohaline structure and stratification of the entire eastern Basin. A specialty is that the Aegean dense-water outflow feeds into the Hellenic Trench region before being transferred into the EMed at large. Recently it was suggested that the EMT could be a recurrent phenomenon (*Borzelli et al*., 2009; *Pisacane et al*., 2006). EMT-induced changes have been communicated through the Sicily Strait to the WMed, with the role of the Tyrrhenian becoming enhanced for some years (*Gasparini et al*., 2005; *Roether and Lupton*, 2011). Indeed, a significant warming and salinification of the whole water column has been observed also in the Western Mediterranean, comparable to the EMT, both in terms of intensity and observed effects (*Schroeder et al*., 2008). This event of high production of anomalously warm and salty new deep water during winters 2004/2005 and 2005/2006 (*Font et al.,* 2007) is now known as the Western Mediterranean Transition (WMT). Currently, thus, the subsurface distributions of temperature and salinity, as well as of most other properties in the entire Mediterranean are far from a steady state.

While the eddies in the southwest part of the WMed are believed to be freely moving, some authors support the view that a similar situation holds also further east and all through the EMed (*Millot and Taupier-Letage*, 2005), while others support the idea of permanent or recurrent eddies in the EMed (*Robinson et al*., 1991; *POEM Group*, 1992; *Malanotte-Rizzoli et al*., 1999). There is a discussion of the eddies found along the slopes of Libya and Egypt in relation to an assumed instability of the Libyo-Egyptian Current (*Alhammoud et al*., 2005; *Hamad et al*., 2005; 2006). It seems that bottom topography is important in that context. There is an expressed need to develop a coherent combination of observations with modelling studies. Only that combination is believed to show the true nature of the circulation in both basins, and also to optimize future observations.
There is furthermore a need for clarification of the role of the characteristic atmospheric circulation patterns (west vs. east), also in the context of large climatic variations and trends, that are associated with variability of the circulation and with deep water formation events.

The changes observed in the circulation during the last decades, such as the reversals in the Ionian circulation (*Borzelli et al*., 2009; *Gacic et al*., 2011) and the transport of the EMT effects westwards (*Gasparini et al*., 2005) dictate a more thorough study on water mass spreading pathways and their variability and on water mass conversion, as well as temporal and spatial variability in the marginal seas of the EMed (Adriatic/Aegean). Only if these items have been resolved will it be possible to come up with quantitative answers on the geochemistry and ecology of the Mediterranean Sea.

Specific issues

1. A principal concern is to improve the understanding of the long-term variability and evolution of the Mediterranean circulation. A special item that is urgent to be amended is scarce data in the southern part of the EMed in consequence of the political situation in the past. One need is to monitor the path and characteristics of the AW after it entered the Mediterranean at Gibraltar, to find the causes of its path variability after passing the Sicily Channel, and to determine the fraction that continues in the south along the African coast. Furthermore, it is needed to monitor the characteristics of the overflows of the Gibraltar and in the Sicily Straits, and relate their variability with that observed in both Mediterranean Basins. Additionally, we need to improve our understanding of the eddies and their different natures (permanent/transient) and lifetimes.

2. A further subject is the changes relevant to the EMT since the mid-1990s and the corresponding changes in the WMed, and the related variability over decadal or longer time scales in the entire Mediterranean, also in relation to the ongoing climatic changes (IPCC report). Analysis of such timescales is also needed for the past, because past occurrence can enlighten future scenarios. This analysis is straightforward for water properties based on historical hydrographic data after the early 50s, but the question of the past circulation patterns is more difficult so that one has to employ model simulations. Finally, the interaction between subsurface Eastern and Western Mediterranean waters must be further clarified.

3. These targets dictate the field observations that will have to be undertaken. One direction is to reapply past observational strategies, such as multi-ship multi-national hydrographic surveys on a decadal timescale for both Mediterranean Basins that will extend to the near-Africa areas, but including presently available technology on direct current measurements. Mostly latitudinal deep transects should be added (as useful extension of the CIESM-HydroChanges program). The transects can ideally be serviced by merchant ships equipped with ADCPs and XCTDs (or XBTs). The other is to continuously monitor certain parameters at key locations, such as straits and water formation areas.

2.3 Forcings and variability in the stock of nutrients in the Eastern and Western Mediterranean

State of Knowledge

Despite the large effort to describe biogeochemical processes in the Mediterranean during programs such as POEM-BC, MATER and SESAME, a basin-wide picture of the different processes determining the biogeochemical functioning of the basin has rarely been attempted.

In this section we use the term biogeochemical in a restrictive sense, focusing on the distributions of basic elements involved in the basin. Based on nutrient concentrations, the western and the eastern Mediterranean are classified as oligotrophic or extremely oligotrophic. However, nutrient concentration is not the unique indicator of the trophic regime. The inclusion of atmospheric deposition, riverine inputs and exchanges with the Black Sea provides a less dramatic picture of the elemental availability in the photic zone. Atmospheric deposition is indeed the source of at least half of the macronutrients input in the Mediterranean Sea (*Guerzoni et al.,* 1999). *Krom et al.* (2004) presented a detailed nutrient budget for the eastern Mediterranean and showed that atmospheric input of dissolved inorganic nitrogen (DIN) and dissolved inorganic phosphorus (DIP) accounts for 61% and 28% of the total budget of nitrogen (N) and phosphorus(P) respectively.

The non-Redfieldian N:P ratio that characterize nitrogen and phosphorus present in the atmospheric deposition processes, in dissolved or soluble inorganic forms (*Ridame et al.*, 2003), is the natural candidate to explain the anomalous high N:P ratio typical of the Mediterranean. Indeed, it displays an eastward increasing trend, from about 20:1–24:1 in the western basin to 28:1 in the eastern one (*Markaki et al.*, 2008).

In the Mediterranean, river loads, even relatively important, have limited shelves (with the noticeable exception of the Po and West Adriatic rivers) and release their nutrient content directly into the open ocean. General circulation processes, such as the recurrent meandering of the northern current over the Provencal-Catalan shelf, facilitate the export of nutrients from the coastal region offshore. Irregular bathymetric features near the coastal region, such as canyons, enhance the export of water properties and suspended material offshore (see also sections 3.2 and 4.1), contributing to an efficient transfer of coastal signals to the open-ocean (*Gomez et al.*, 2003).

These processes contribute to mitigate the unbalance in phosphate and nitrate budget estimated at Gibraltar (surface waters with low nutrient concentration, about 3-4uM N enter the Alboran Sea in the upper layer of ~ 200 m., while roughly twice as much exits in the lower layer). In addition, the large differences in water fluxes at Gibraltar Strait (0,81 Sv in, 0.76 out, CANIGO group) and the exchanges at the Sicily channel (around 1.2 Sv), suggest that in the western Mediterranean a relevant recirculation (with an associated supply of nutrients) must take place between the intermediate and upper layer, even if wind-driven upwellings are relatively small and not permanent. This is testified by the relatively steady concentration of the nutrients in the deep layers of the Mediterranean.

Specific issues

1. *Understanding the functioning of the Gibraltar valve*
   The Mediterranean is connected to the Atlantic through a shallow sill at Gibraltar which is expected to decrease the runover of tracers passing through the Gibraltar strait. While numerous budget estimates exist for the steady state, a dynamical reconstruction of the exchange with the Atlantic has never been attempted. A better understanding of the functioning of the Gibraltar valve at different time scales (from decadal to centennial) is a necessary step to analyze the Mediterranean internal variability and changes in nutrient stocks.

2. *Turnover rates and exchanges between Mediterranean sub-basins*.
   The turnover rates of Mediterranean nutrient stocks in different basins depend not only on advective processes and exchanges through the straits, but also on water mass transformation rates and biogeochemical processes. Constraining the physical drivers with classical approaches based on passive tracers and modelling would allow one to determine the coupling between surface biology and internal remineralization, which would also help in building scenarios of future trends in the basin. Furthermore, biogeochemical processes in filaments, fronts and eddies may be very important in coupling the surface and deep layers

3. *Time scales of internal variability*.
   To assess the scales of internal variability a careful analysis about possible longer term oscillations/trends is required. Existing data bases, even in present reviewed forms display high internal noise and dispersion of data. Despite this an updated assessment of pluri-decadal trends in nutrient concentrations for the eastern and western Mediterranean must be carried out starting from the existing data base.

4. *Data on stable isotopes collection.*
   Points 2 and 3 above may profit from an increase in data production on stable isotopes. Stable isotopes have been recently used to discriminate the different atmospheric inputs in the eastern basin. Less is known for the western basin and, overall, data available are still too few. $\delta^{15}N$ have also been used to infer trophic levels of copepods or top predators

(e.g., *Koppelman et al.*, 2009) still without covering the whole basin. Future surveys should consider those parameters, especially to approach the problem of external vs. internal contribution of elements to the basin production.

5. *Silicon dynamics*.
   As pointed out by *Ribera d'Alcalà et al.* (2003), balancing the silicon budget in the Mediterranean is difficult with the existing data. The silicon distribution in the Mediterranean shows a different gradient with respect to nitrogen and phosphorus, indicating that a better representation of the silicon sources is necessary to quantify its variability in the open sea. In addition, there are sediment trap data that show a large proportion of biogenic silica, in contrast to the low primary production (at least in the Eastern Basin).

6. *Mutual feedbacks between biogeochemical functioning and community structure*.
   These feedbacks display differences among the sub-basins of the Mediterranean which need to be better addressed. Furthermore, the functioning of the biological pump should be investigated, combining estimates of pCO2, satellite PP , Chl-a data and POC fluxes measured by sediment traps at various depths along with the role of community structure (*D'Ortenzio and Ribera D'Alcalà*, 2009).

7. *Biogeochemical processes in intermediate and deep layers*.
   These processes should be analyzed in relation to the higher respiration rates and the very low values of dissolved organic carbon (DOC, *Santinelli et al.*, 2010).

2.4 Modeling and assessing ecosystems in the Mediterranean sea

State of knowledge

The merge of the whole Mediterranean sea in a single bio-province, as proposed by *Longhurst* (1998), has been questioned by other papers based on different approaches: in situ data (*Bianchi and Morri,*2000), remotely sensed surface chlorophyll (*D'Ortenzio and Ribera d'Alcalà,* 2009), and decadal simulation of hydrodynamical-biogeochemical models (*Lazzari et al.,* 2012). In fact, even being smaller, the WMed displays a larger number of trophic regimes than the eastern basin with the exception of a limited area of Adriatic sea (*D'Ortenzio and Ribera d'Alcalà,* 2009).
This is largely due to the different forcings and their modulation by the morphology of boundaries, which may in turn produce a different internal dynamics. The link between differences in multiannual through pluri-decadal variability in the internal dynamics of the two basins and the biotic dynamics is still an unexplored trait of the Mediterranean sea. This issue deserves even more attention considering the recent finding of multiannual oscillations in the eastern Mediterranean (*Gacic et al.,* 2011). This fact, in turn, highlights that processes occurring in the basin should be approached through their appropriate space and time scales, spanning from the climatological to the decadal (and longer) variability. The need to investigate the impacts of the internal and forced variability on longer time scales on the Mediterranean community structures and composition requires better, qualified, problem-oriented models and model systems. A number of 3D models were developed at the basin scale using a simplified food web (NPD) (*Crise et al.,* 1998; *Crispi et al.,* 1998) to study/simulate the east-west gradient in nutrient limitation and DCM depth, as well as the impact of the general circulation on the ecosystem dynamics. More complex 1D (water column) configurations based on the ERSEM and BFM model were used to study the ecosystem functioning in more detail, although mostly at the regional scale, addressing the dynamics of the microbial loop, the bacterial dynamic and primary production (*Allen et al.,* 1998; *Anderson et al.,* 2003; *Polimene et al.,*2007; *Lazzari et al.,* 2012). A significant effort has focused on the data assimilation of biophysical parameters into an ecosystem model of the eastern Mediterranean (*Triantafyllou et al.,* 2005; *Triantafyllou et al.,* 2007). To fulfill the above needs information derived from experimental evidence,

and scenarios provided by model studies should be merged in order to be able to describe the whole dynamics of the Mediterranean ecosystem(s).

Specific issues

1. The Mediterranean ecosystem structure(s) are clearly influenced by the overall physical/chemical processes and exchanges active in the basin which on one hand sustain a large level of endemism, most pronounced in the EMed and, on the other hand, favoured the immigration of many species of Atlantic origin which dominate the Mediterranean communities and the invasion of alien species from either Gibraltar, Suez and anthropogenic transport. The short time needed by several new immigrants hints at the presence of open niches, which should be investigated.
2. The relative oligotrophy in the Mediterranean Sea is zonally modulated and has two different aspects, one related to the upper layer above the nutricline, the second below it. The first one is related to the combined effect of estuarine inverse circulation, and the biological pump. More nutrients enter in the WMed through Gibraltar Strait that those entering the Ionian Sea through Sicily Strait, largely because of the rescue of exiting nutrients by the enhanced tidal mixing and entrainment within the Atlantic surface water. This in turn favours a plankton community structure more effective in the carbon and nutrient export into the ocean interior than the EMed that functions as a nutrient trap. In the EMed internal vertical dynamics seems weak, and plankton communities have to rely either on regenerated production (the microbial loop paradigm) or on the atmospheric inputs. All the above implies that there should be significant differences in the structure of communities, unless organisms' plasticity may compensate for such differences in environmental conditions. Differences should be explored, and be detected, in the higher trophic levels. This has very seldom been done and must be addressed revisiting existing data but also profiting of new approaches, e.g., metagenomics.

3. The mesoscale has a typical length smaller than the major oceans (about 15-20 Km according *Pinardi and Masetti*, 2000) but the coherent structures found in the satellite images are roughly three-four times the Rossby internal deformation radius. Larger, long-lasting anticyclonic eddies are regularly generated in the Algerian Current, most probably because of baroclinic instability of this current rimming the African coast. A number of large, recurrent, continuously evolving structures connected by jets and separated by fronts (*Robinson and Golnaraghi*, 1994) have been observed in the surface waters both sub-basins, but the response in surface chlorophyll is not clearly connected to the vorticity polarity and in the EMed during the stratified season no Chl-a features are evident. This dynamics may be related to the apparent optical properties of the surface waters, which exhibit a clear increment of the light extinction coefficient going westward whose origin has to be thoroughly investigated.

4. The Dissolved Oxygen vertical structure in the Mediterranean, even considering the short residence time compared to the global ocean, shows only a slightly pronounced oxygen minimum layer (if any) compared to other bio-provinces (i.e. Equatorial Pacific). This highlights a relatively small export likely due to the peculiar community structure and composition. This in turn further reduces the concentration of macronutrients in basin interior, which suggests that the community exploits most of the nutrients in the surface layer. Whether this feature is linked to a specific community structure has to be investigated.

5. Recent analysis of model results and data from the Dyfamed station (NW.Med)and E2M3A observatory (S.Adriatic sea) exhibits a peculiar behaviour, which confirms that the increase of the biomass/chlorophyll is concomitant with deepening of the mixed layer (in contrast to the Sverdrup paradigm) even in sites where deep water formation recurrently takes places. This mechanism is not fully understood and needs further investigation.

6. While recent analyses hint at a relevant role of interannual variability in the EMed, existing data show that the seasonal cycle is the dominant component of variation. However the 50-year Mediterranean climatology provides evidence for consistent temperature changes in the WMed and the N-Atlantic, explained by similarities in the atmospheric heat fluxes anomalies strongly correlated to NAO (*Rixen et al*, 2005). Whether this long term trend is impacting on the food web has still to be assessed.

7. The interannual variability of primary production, standing crop and other Essential Climatic Variables in Mediterranean Sea are of order of 10-20% if compared with the seasonal cycle, however the copepod community composition and abundance (even with a clear seasonal cycle) exhibits for the Ionian Sea a much less variability suggesting that the predator-prey relationships cannot be understood and modeled only on the basis of the statistical encounter rate.

8. Global increases in atmospheric CO_2 and temperature are associated with changes in ocean chemistry and circulation, altering light and nutrient regimes. Resulting changes in phytoplankton community structure are expected to have a cascading effect on primary and export production, food web dynamics and the structure of the marine food web as well the biogeochemical cycling of carbon and bio-limiting elements in the sea. A review of current literature indicates that cell size and elemental stoichiometry often respond predictably to abiotic conditions and follow biophysical rules that link environmental conditions to growth rates, and growth rates to food web interactions, and consequently to the biogeochemical cycling of elements. This suggests that cell size and elemental stoichiometry must be monitored to allow modelling and tracking changes in phytoplankton community structure in response to climate change. In turn, these changes are expected to have further impacts on phytoplankton community structure through as yet poorly understood secondary processes associated with trophic dynamics (*Finkel et al*., 2010).

9. Autonomous observational techniques profiting of the advancement of technology for measuring parameters which have been traditionally linked to bottle sampling, should be implemented because they provide new relevant information on distributions and internal dynamics. This may also shed light on how the spectrum of variability in vertical motions is different among the two basins and how this links to the differences observed in trophic regimes. Special processing techniques and sampling strategies should be developed to separate the different spatial/temporal scales present in the most advanced observing platforms (gliders, bio-ARGOs).

10. Scenarios should be built of future trends which may be constructed on the basis of the general view of how the fluxes form the boundaries, as well as of the exchange with the ocean that will change due to the present Earth system functioning. An evolutive trait based approach in description of the key functional groups should be developed as well to match the time rate of changes of the habitat (natural and anthropic) variability

11. The Mediterranean orography, as well as, its circulation functioning, is composed of 7-8 sub-basins connected by straits. In their interior, sub-basins have internal (in some way independent) dynamics, where the impact of the other sub-basins is ruled by the exchanges at the connecting straits. In this context, the Mediterranean nutrient dynamics could be simplified as several, interconnected boxes. This simplified picture should allow the testing of scenarios (i.e. modifications of boxes internal functioning, changing fluxes at the connecting boundaries, steady state *vs* interannual/decadal variability, connections/ feedbacks/ linkages with climate alteration), directly focusing on the impact of the internal *vs* external forcing on the nutrients, spatio-temporal repartition between sub-basins.

3. Relative importance of external forcing functions (wind stress, heat/moisture fluxes, forcing through straits) versus internal variability

3.1 Major forcing of the Mediterranean circulation

State of knowledge

The Mediterranean circulation is characterized by three predominant interacting spatial scales: basin, sub-basin and mesoscale.

The basin scale circulation is broadly described in terms of a surface flow from the Atlantic ocean entering through the Strait of Gibraltar and proceeding to the eastern basin, and a return flow of intermediate water, originating in the Levantine basin, proceeding towards Gibraltar and finally exiting into the Atlantic. This basin scale open cell is mainly driven by thermohaline forcing: an east-west density gradient, associated with enhanced heat and moisture fluxes in the Levantine sea, drives the eastward flow of surface Atlantic water. In the Levantine basin the ocean release buoyancy to the atmosphere through heat loss and an evaporation/precipitation deficit. The buoyancy loss reduces the stability of the water column, with loss of potential energy in the Levantine. This energy deficit is compensated by a buoyancy gain associated with the inflow of the fresh surface Atlantic water. For this open cell, the forcing of the Mediterranean basin-scale circulation are the inflows through the Gibraltar and Sicily straits.

Sannino et al. (2009) discuss the importance to include variations of the Atlantic water inflow through the Gibraltar Strait to describe decadal variations in the western Mediterranean circulation pattern. Similarly, *Malanotte-Rizzoli and Bergamasco* (1991), investigating the relative contribution of wind forcing, thermohaline surface fluxes and boundary conditions to the EMed circulation, showed that flow changes in the Sicily Strait can induce variability in the circulation pattern at the basin scale. *Pierini and Rubino* (2001) modeled the remotely forced dynamics in the areas surrounding the Strait of Sicily and, imposing steady fluxes along the open boundaries, obtained in the absence of meteorological forcing, quasi-stationary circulations representing the local manifestation of the large-scale Mediterranean conveyor belt.

It is interesting to note that *Demirov and Pinardi* (2002), discussing changes in the Ionian circulation in relation to the variability in the thermohaline properties of the water mass formed in the Levantine, provided evidence that variations in the latter one could be associated with changes in the Ionian circulation. *Gacic et al.,* (2010, 2011) showed that these changes may be responsible for modifications of the eastern Mediterranean thermohaline cell, thus impacting the overall structure of the eastern Mediterranean circulation. This finding constitutes an example in which changes in the sub-basin scale alter the basin scale circulation pattern.

By comparing Lagrangian velocities from drifters deployed in the Mediterranean in the period 1993-2008 and geostrophic velocities from altimeter data in the same period, *Poulain et al.* (2012) showed that the basin scale upper-layer Mediterranean circulation can be reasonably described by geostrophy over time scales longer than a week, with the notable exception of the Aegean and Adriatic seas. *Borzelli et al.* (unpublished manuscript) analyzed altimeter and wind data over the same period and showed that the work by the wind on the geostrophic circulation was on average negative, indicating that during that period the wind worked against the circulation. These results open the issue of the energy reservoir sustaining the Mediterranean circulation.

Air-sea heat and moisture fluxes drive also the eastern and western convection cells through formation of dense water in the southern Adriatic and Gulf of Lion, respectively. The same process occurs on shallow shelves and the dense shelf water can sink into the deep sea through coastal canyons. Sub-basin scale gyres are the building blocks of the thermocline circulation, they are present both in the western and eastern basins and strongly topographically controlled. At a scale intermediate between the sub-basin and the mesoscale, permanent features such as the Iera-Petra Gyre and the Pelops Gyre in the eastern Mediterranean are driven by the wind in areas of strong wind curl. Mesoscale instabilities modulate the coastal currents and the outer rims of the sub-basin features such as the Rhodes gyre in the eastern basin or the Gulf of Lions gyre in the western one. The existence of these multiple scales is not only due to the multiple external forcings but also to internal dynamical processes and topographic control. The external forcings include the wind stress, the air-sea heat/moisture fluxes as well as the exchanges through the straits of Gibraltar and Sicily.

Specific issues

1. If the work done by the wind on the geostrophic Mediterranean circulation is negative and heat is on average lost from the ocean, what is the source of energy sustaining the geostrophic circulation?

2. Which are the dominant space/time scales of energy and momentum transfer from the wind to the ocean?

3. Assuming that the surface Mediterranean circulation is basically geostrophic, is the transfer of energy among different time/space scales sufficient to sustain it? What is the dissipative time scale?

4. What are the dominant mechanisms for energy transfer between the different scales of the circulation? Are they barotropic or baroclinic in nature?

3.2 Interactions between the shelf/slope circulation and open sea in the Mediterranean

State of knowledge

Most of the Mediterranean Sea is characterized by relatively narrow shelf/slope zones so that through much of the basin the open sea is in close proximity to the coastal region. On the other hand, in the adjacent basins of the eastern Mediterranean - the Adriatic and Aegean Seas – the shelf is relatively wide but laterally confined. These seas are subjected to pronounced wind forcing and surface buoyancy loss in winter, and to considerable fresh water inflow (rivers in the Adriatic; Black Sea outflow in the Aegean). The interaction between the shelf/slope zone and the open sea regimes has many facets and occurs over a range of spatial and temporal scales. The dynamical processes and circulation features are constrained by the interaction between the smaller/limited scales of the shelf dynamics and the larger scales of the open sea circulation. A prominent feature of the shelf/slope zone is a jet which usually flows along the bathymetry near the shelf break or over the slope. Often it meanders and generates eddies or filaments, thereby leading to a net cross shelf flow. Another process that leads to cross shelf flow is dense shelf water cascading (DSWC) in which dense water formed by cooling and evaporation over the relatively shallow continental shelf spills over the shelf edge and sinks as a bottom-trapped gravity current until reaching a level of neutral density. Such features and processes are important for the shelf – open sea exchange of dissolved and suspended material and therefore have a major effect on biogeochemical processes and the ecosystem.

The circulation in the Alborán Basin is characterized by the intense inflow/outflow regime due to the exchange of water between the Atlantic and the Mediterranean through the Strait of Gibraltar. Atlantic Water entering the Mediterranean in the upper layer forms the intense Atlantic Jet. This jet meanders and forms the quasi-permanent West Alborán Gyre (e.g., *Baldacci et al.*, 2001), and an intermittent Eastern Alborán Gyre (EAG). The eastern boundary of the EAG is formed by the Almería-Oran front (e.g., *Ruiz et al*. 2009a) and marks the start of the Algerian Current (AC) (*Millot*, 1985). As the AC progresses eastward, it forms baroclinically unstable meanders that can evolve into coastal eddies. Only anticyclonic eddies are long-lived (*Puillat et al*., 2002; *Isern-Fontanet et al.,* 2006).

They usually propagate along the bathymetry, can detach from the current and become open-sea eddies (*Millot and Taupier-Letage*, 2005 and references therein). Some eddies are quasi-permanent and can divert the AW flow offshore as far as the south of the Balearic Islands (*Taupier-Letage and Millot*, 1988).

The Ligurian-Provençal Basin in the northwestern Mediterranean is dominated by the Northern Current. The flow is maximum during winter with significant mesoscale variability, and weakens during summer (*Millot and Taupier-Letage*, 2005). In the Balearic Basin it splits in two branches, one recirculating into the Balearic Current (e.g., *Ruiz et al*., 2009a) and the other continuing south through the Ibiza Channel (*Pinot et al*., 2002). The Balearic Basin is also characterized by shelf-slope exchange due to mesoscale eddies (*Pinot et al.* 2002; *Bouffard et al*. 2010), filaments, and shelf-slope flow modifications (*Wang et al*., 1988; *La Violette et al*. 1990). The bathymetry also plays a key role in controlling the transport between the northern and southern regions (*Astraldi et al*., 1999) and also may enhance sub-mesoscale activity (*Bouffard et al*. 2012).

The jet that enters the Eastern Mediterranean through the Straits of Sicily (the Atlantic Ionian Stream, AIS) usually follows the southern coast of Italy and the western coast of Greece (*Robinson and Golnaraghi*, 1994). Recent studies (e.g., *Borzelli et al*., 2009; *Gacic et al*., 2010) have shown that during certain periods the AIS can follow a more southerly pathway when the overall northwestern Ionian circulation switches from anticylonic to cyclonic. According to the POEM results (e.g., *Robinson and Golnaraghi*, 1994; *Malanotte-Rizzoli et al*., 1999) the AIS continues primarily as the eastward flowing Mid Mediterranean Jet which meanders through the center of the Levantine Basin. However it may also feed into the eastward flowing Libyo-Egyptian Current, which flows along the coast of North Africa (*Alhammoud et al*., 2005; *Hamad et al*., 2005; *Millot and Taupier-Letage*, 2005). That current generates baroclinically unstable mesoscale eddies that dispatch AW offshore (*Gerin et al*., 2009). The AW flowing along the Egyptian slope turns north following the coasts of Israel and Lebanon, and then turns west following the coast of Turkey as the Asia Minor Current (*Oszoy et al*., 1993). Based on ten years of extensive current measurements, *Rosentraub and Brenner* (2007) found that over the shelf and slope of Israel, the flow through most of the year is directed northward, following the bathymetry, with strong currents of nearly 50 cm/s in both winter and summer. The current meanders and forms anticyclonic eddies, which drift westward and transport shelf water to the open sea. In the near bottom layer at the shelf break the authors found evidence of a net seaward, cross shelf flow.

Understanding DSWC's interaction with bottom morphology is a theme of paramount relevance. These energetic cascades, lasting up to few weeks, are considered one of the main drivers at the oceanic margins. During DSWC events, cold, dense shelf waters spill over the shelf edge and flow along topographic features as a bottom-trapped gravity current. Upon reaching the level of neutral density they spread laterally. Of the 61 confirmed cases of dense water cascades around the globe (e.g., *Ivanov et al*., 2004), three occur in the Mediterranean. Over the broad northern Adriatic shelf the North Adriatic Dense Water (NAdDW) forms in the area exposed to the cold, dry Bora winds during the winter. One branch of NAdDW flows southward with a vein-like shape reaching the shelf break, while a second branch enters the Jabuka pit, from where the spillover can reach the Bari Canyon and the South Adriatic Pit. The cascading water is diluted by entrainment of ambient water masses. While DSWC in the Northern Adriatic or at the northern side of the Cretan arc does not play a direct role in the exchange with the open sea, it is nevertheless important since this process is crucial for the formation of the dense deep water that eventually fills the Eastern Mediterranean. Over the Gulf of Lions shelf DSWC does not occur every year, but if so, it can reach the bottom (*Dufau-Julliand et al*., 2004; *Palanques et a*l., 2009; *Pascaual et al*., 2010 and references therein) and can be an important source of deep water along with that formed by open sea convection.

Specific issues

An important step forward towards further the understanding of both phenomena described above will be to develope an integrated approach that combines model simulations and observations, designed to address the multiscale processes and to assess the associated forcing. Both phenomena are complex and highly nonlinear and are not easily amenable to either observations or modeling alone due to the small spatial scales involved and the intermittent or episodic nature of the processes. The models need to be run at sufficiently high resolution and be tuned to address the processes of interest. To be effective, the field measurements must make use of ongoing observational programs and networks, but must also build on a series of targeted campaigns. Overall, the future research activities should shed light on (1) the dynamics of the shelf break jet, front, and associated mesoscale and submesocale processes, and (2) the precise conditions needed for dense water formation over the shelf and the processes that determine the eventual fate of this water. It will be necessary to develop a capability to model these events with sufficient fidelity so that the resulting models can be used for further process studies and prediction.

1. Meandering coastal currents, fronts, and eddies

The establishment of ocean observing networks is being adopted as an important component of marine strategy by many countries with economically significant coastal areas. These new facilities are delivering new insight into coastal and open ocean variability. They also contribute to a more science-based and sustainable management of the coastal area. In the Western Mediterranean, MOOSE (Mediterranean Ocean Observing Site for Environment) and SOCIB (Balearic Islands Coastal Observing and Forecasting System), are two examples of such networks. SOCIB addresses multidisciplinary research on mesoscale and frontal dynamics as a key element in the physical and ecosystem variability (*Tintoré et al*., 2012). It includes multi-platform observations and modeling services distributed through an integrated system. Such information, when used in synergy with satellite observations, will be particularly helpful for societal benefits, and for better understanding of 3D biogeochemical (*Lévy et al*., 2009) and energy transfers (*Lapeyre and Klein*, 2006) occurring at meso- and submesoscales. Similar networks should be established at other select locations in the eastern Mediterranean in order to provide continuous, long term measurements. Field campaigns to investigate specific aspects of the jet and frontal dynamics should be planned, and very high resolution models for specific shelf regions should be developed. Present high resolution models used for ocean forecasting typically have a horizontal resolution of 1 km (e.g., *Brenner et al*, 2007) which is barely adequate for resolving the narrow shelf circulation regime. Models should be refined and extend far enough into the open sea. Non-hydrostatic models may also be necessary.

2. Dense shelf water cascading

Dense water formation is primarily a local phenomenon and therefore amenable to study by local models. Present models do not have sufficient resolution to capture the small-scale processes responsible for dense water formation and entrainment. In particular, turbulent mixing in the water column, driven by surface cooling and by tidal and storm-driven mixing near the bottom, is the key to homogenizing the shallow shelf waters so that they can be subsequently cooled. Second moment closure (SMC) models of turbulent mixing (e.g., *Kantha and Clayson*, 2007) have enabled more accurate simulation of oceanic mixing processes, although there is still room for improvement. Recently, *Kantha and Carniel* (2009) have refined turbulence models of stably stratified flows to allow mixing at all values of the gradient Richardson number. Non-local mixing models are the key to accurate depiction of mixing processes dominated by convection, prevalent during dense water formation. Water mass preconditioning is crucial to dense water formation and should be studied using high vertical resolution, two-dimensional models. The role of tidal and storm mixing are to a large extent unknown and should also be clarified. It would also be of interest to know if down- slope flow induces visible surface patterns.

Additional aspects in the study of the DSWC events in the Mediterranean region should include: (1) numerical simulations of the basin at adequate resolution to simulate the circulation for specific years of known DSWC; (2) process-oriented studies exploring the parameter space for dense water formation episodes, using models with very high horizontal and vertical resolutions; (3) ad-hoc observational campaigns to sample the state of the shelf water; (4) parameterization of dense gravity currents for inclusion in larger scale models; (5) development of turbulence closure models following state-of-the-art findings, while addressing the role of tidal mixing in dense water formation and in triggering the cascading processes; (6) investigate the gravity currents near the bottom with a high-resolution numerical model, addressing the principal off-shelf sediment transport and evaluating the relative importance of different processes in the down-canyon sediment transfer; and (7) investigation of the effect of wind waves on mixing in shallow areas of dense water formation, using a coupled hydrodynamic model - wave model.

3.3 The role of salinity decadal oscillations in triggering the thermohaline circulation and the Mediterranean conveyor belt.

State of knowledge

The Mediterranean Sea open circulation cell is driven by the salinity differences between the inflowing low-salinity Atlantic Water (AW) and the highly saline Eastern Mediterranean waters, mainly the Levantine Intermediate Water (LIW). The salinity differences established between the two water masses are maintained due to the prevalence of the evaporation over precipitation. Deep closed circulation cells are driven by the air-sea heat losses at specific locations resulting in vertical convection and dense water formation. This average circulation pattern is subject to interannual and decadal variability due to both external meteorological and internal forcings. Temporal variability of the closed circulation cells is primarily determined by the intensity of the dense water formation, which in turn depends on the air-sea heat fluxes and the preconditioning. Deep circulation was thought for a long time invariable and on the basis of that the residence time of the Eastern Mediterranean was estimated to about 100 years. Recent long term simulations gave evidence that the alteration of the two sources of dense waters (Adriatic and Aegean Seas) in the EMED could be a recurrent phenomenon, connected to salinity out-of-phase decadal oscillations between the two basins (*Borzelli et al.*, 2009), given the necessary intense local atmospheric forcing. The salt content in each formation site, along with the intensity of the atmospheric forcing, determines the depth of the convection and thus the density of the produced new water. In the early 70s a high-salinity event was documented in the Levantine and Aegean, but with lower formation rates and thus without significant signature of Aegean dense water in the adjacent sub-basins (*Beuvier et al.*, 2010). *Theocharis et al.* (2002) noted that the 70's episode was evident in all three basins, Levantine, Ionian and Aegean, with a maximum signal in the Levantine. The total volume of the produced waters was lower than those during the EMT, thus its effect vanished quickly.

In mid-1990's, experimental evidence was presented on the Eastern Mediterranean Transient (EMT) and it was shown that the abyssal circulation is not in a steady state but can be subject of episodic sudden changes (*Roether et al.*, 1996). The EMT involves the passage of the Eastern Mediterranean dense water formation site from the Adriatic to the Aegean. This then resulted in important changes in the abyssal circulation of the entire basin. Changes were however evidenced over the upper part of the water column as well. Generally, the most prominent variations in the upper layer circulation have taken place in the northwest Ionian where they not only became manifest as the circulation inversion in 1997 reinforced by the EMT, but also as the other two events which were documented in 1987 and 2006 (*Gacic et al.*, 2011). These inversions of the upper-layer circulation pattern in the Ionian determine the salt redistribution between the Adriatic on one hand and the Levantine/Cretan Sea on the other. This is due to a preferential pathway of the relatively fresh AW; in the cyclonic circulation pattern in the Ionian the AW preferential pathway is towards the Levantine/Cretan Sea while during the Ionian anticyclonic circulation mode the northern Ionian and the Southern Adriatic are subject to freshening due to the increased spreading of the AW northeastward. Therefore, the salt content and buoyancy in the upper layers of the Adriatic and Levantine/Aegean are out of phase suggesting that one or the other sub-basin is more prone to the convective mixing. This suggests that the EMT, i.e. the Cretan Sea undertaking a role of the main dense water source for the Eastern Mediterranean, is potentially a recurrent phenomenon if the winter air-sea heat losses were strong enough. Important decadal variability in the thermohaline properties and the deep circulation were evidenced in the Western Mediterranean as well. Again salinity forcing seems to play an important role since at decadal scale there is important building-up of the highly saline water spreading over the entire bottom layer and increasing continuously in thickness since 2004 up to present days. The phenomenon is called the Western Mediterranean Transition and can presumably be connected to the inflow of the LIW of varying salinity from the Eastern Mediterranean (*Schroeder et al*., 2009). The replenishment of the deep basin by newly formed Western Mediterranean Deep Water that, depending on its density, can either uplift old resident waters or lay above them, leaving in any case a cold signature in the temperature series (*Garcia-Lafuente et al*., 2009). This mechanism then determines interannual variability of thermohaline properties of the outflowing Mediterranean waters possibly changing their impact on the global conveyor belt.

Finally, *Millot et al*. (2006) demonstrated that the hydrological changes which were caused by the EMT have a clear impact on the outflowing water into the Atlantic Ocean. The Mediterranean outflow is a constant source of warm and salty intermediate water, and has been shown to play an important role in water formation processes in the Atlantic and hence in the global circulation (*Candela*, 2001). Understanding the interannual variability of the Mediterranean Sea itself appears to have a more global importance than previously thought (*Millot*, 2007).

Specific issues

1. During the last years there has been put considerable effort in identifying past changes in the water mass characteristics of the Mediterranean Sea from historical hydrographic records related to salinity oscillations. The investigation of this long-term variability by using historical databases such as MEDAR-MEDATLAS, has been proven to be inadequate due to spatial inhomogeneity of data and high noise levels (*Schroeder et al*. in press). Efforts should be made to construct new and extend existing datasets for climatic analysis accompanied by coupled atmosphere-ocean reanalysis simulations.

2. Moreover, studies about DWF and circulation on decadal and interdecadal scales, must take into account the variability of the inflowing AW and in particular its observed increasing salt content (*Lauzier and Sindlinger*, 2009).

3. The salinity oscillations are manifest at a decadal timescale and, as proposed, modulated by internal mechanisms, but could also be influenced by the intensity of atmospheric forcing. The large scale atmospheric circulation such as the NAO (North Atlantic Oscillation), which largely determines Mediterranean winter precipitation (*Xoplaki et al*., 2003) and EA (East Atlantic) which also play an important role over most of the region (*Fernandez et al*. 2003, *Krichak et al*., 2002, *Josey* 2010), also exhibit variability in decadal timescales. Therefore it is important to investigate combined effects of internal processes and external forcing.

4. The intensity of the EMT compared to similar past events is a major issue. Both the increase in salinity and the huge amount of dense waters (8 Sv years, *Roether et al.,* 2007) produced in the Aegean were exceptional. Further study is needed to clarify whether the EMT can be attributed to coincidence of the salinity preconditioning of the area with intense atmospheric forcing. Diagnostic long term simulations give evidence of internal modes of variability even at interdecadal timescale (*Pisacane et al*. 2006). It is important to find out whether the Mediterranean as a whole exhibits internal variability modes, similar to or inferred by the decadal oscillations evidenced in the EMed.

5. Therefore, it is of great interest to study the variability and trends in the EMED in response to climatic changes and improve knowledge about the functioning of internal feedback mechanisms and related processes.

6. Finally, biogeochemical variability in response to circulation changes should be considered as well, under the concept of the decadal Mediterranean variability (*Civitarese et al*. 2010).

3.4 Residence times and ventilation of water masses in the Mediterranean sea: implications for dynamical and biogeochemical processes.

State of knowledge

Water mass characteristics, structure and distribution in the Mediterranean, as well as the associated circulation patterns, are complex and show significant variability and sensitivity. This can be attributed to the complex topography of the basin, the diversity of mixing processes involved, the variability of atmospheric forcing at various time scales and the variety of water mass formation processes present in the basin. Regional and local observational efforts and modeling studies of the Mediterranean and of its sub-basins reveal a complete picture of the water masses structure and evolution. Even in the same sub-basin and nearby depressions, water mass characteristics and tracer concentrations of the deep waters present a remarkable diversity (*Vervatis et al.,*2011), while significant and sometimes abrupt changes are encountered in the deep and intermediate layers (*Roether et al.,* 1996; *Schroeder et al.*2010).

If we want to understand the dynamical and biogeochemical functioning of the Mediterranean Sea, we need to construct a clear picture of the water mass structure and characteristics, monitor their variability and relate it to internal and external forcing mechanisms. Evaluation of the renewal times and processes of Mediterranean water masses is crucial for understanding the variability of the thermohaline circulation and for investigating the biogeochemical cycles at basin-wide or regional/local scales. Using a variety of observational and modeling approaches, the evaluation of residence times and the investigation of aging processes of the various water masses can be achieved. Specific questions that need to be answered include:

1. What is the temporal and spatial variability of the deep water masses in the Mediterranean Sea (physical and biogeochemical) and how it is related to external and internal mechanisms?
2. What is the residence time of the various water masses in the basin and how is this connected to external forcing and internal process time scales?
3. What are the renewal processes of the various water masses and how do they affect the ventilation?
4. What are the important mixing processes related to the stratification of the deep layers?
5. What is the effect of these processes on the biogeochemical cycles of the Mediterranean and its sub-basins?

Specific issues

1. *Investigation of spatial and temporal variability of deep water masses in the Mediterranean Sea, using historical data and modeling reanalysis.*

A series of research projects was devoted to constructing oceanographic databases at the global and regional scale. Today a wealth of data exist that can be used for analyzing the spatio-temporal variability of physical and biogeochemical parameters in the Mediterranean Sea. Modeling techniques and computer power have been greatly improved during the last decades, enabling an ever increasing accuracy of results that can be applied at the Mediterranean and sub-basin scale for the investigation of long term variability. Blending the two approaches through data assimilation procedures can produce useful results for filling spatio-temporal gaps. It is important that an additional quality control of existing data collections for, in particular, biogeochemical parameters are performed to ensure that the data sets are internally consistent and that measurement biases are removed so that temporal trends can be correctly estimated.

2. *Investigation of ventilation processes in water masses and monitoring spatio-temporal variability.*

Based on past observations, numerical model techniques and a strategy for observational process-orientated campaigns, renewal patterns and mixing processes that affect the characteristics and ventilation of the water masses can be revealed and explained. Places like deep depressions, straits and water-mass formation areas are key sites for understanding renewal processes. Monitoring of the spatio-temporal variability can also take advantage of national and international observational networks, among which the HydroChanges CIESM Programme deserves special mention (http://www.ciesm.org/marine/programs/hydrochanges.htm).

3. *Estimation of residence times of water masses.*

The overall observational and modeling strategy should target the estimation of the residence time of the various water masses in the Mediterranean Sea. Simpler and more elaborated techniques (box models, GCMs, etc.) can both be applied. In this way, the effects of residence time and renewal processes on the physical and biogeochemical cycles can be better understood. Regular measurement of transient tracers in the Mediterranean Sea is an important and valuable tool to monitor ventilation processes, and any spatio-temporal changes of ventilation.

4. *Attribution of renewal processes.*

All the above should be related with the investigation of the relative importance of external forcing and internal modes of variability. The imprint of these on the deep water masses is very significant in understanding the dynamical and biogeochemical functioning of the Mediterranean Sea

3.5 Paleo-climate and past physical/biogeochemical changes in the Mediterranean

State of knowledge

The investigation of marine archives (like sediment cores) provides new and relevant evidence on physical and biogeochemical processes, which drove the dynamics of the Mediterranean basin, in terms of response to regional/global climate, exchanges with the Atlantic Ocean and internal processes at the sub-basin scale. This backward glance could extend our potential to understand the deeper physical forces, which presently drive the 3D circulation system of the basin and regulate its relationships with the climate system.

So far the existing paleoclimate records provide datasets for different environmental indices including: microfaunal abundances (planktonic and benthic foraminifera), microfloral abundances (coccolithophores, dinocysts) and pollen. The analysis of stable isotopes and biomarkers/alkenones, indicate rich and interesting dynamics in the eastern and western Mediterranean sub-basins in the past.

Despite the large amount of existing data, comparison between different records is problematic as archives are featured mainly by different time resolution and spatial distribution, while data collection is characterized by different methodological approaches. This lack of a systematic comparison between the paleoceanographic records inhibits an overall climatic consideration, which is an important step to improve our understanding of the physical climate and its variability in response to natural and anthropogenic forcing.

Detailed study of the last 20 kyrs of Mediterranean sea dynamics was focused on selected time intervals like the transition from the last glacial maximum (LGM, ~20 kyr BP) to the Holocene, a distinctive cooling between 13 and 11.7 kyr BP (Younger Dryas), a rather mild climatic period between 10 and 6 kyr BP, a warm and wet period within Mid Holocene followed by the abrupt climatic deterioration observed all over the northern hemisphere at 4.2 kyr BP and several cooling and warming events during the last 2 kyrs.

As an example of climatic reconstruction, the Eastern Mediterranean circulation experienced a major phase of reduced thermohaline ventilation, causing anoxic sediment (sapropel) deposition between ~ 10 and 6 ka BP (Holocene climatic optimum and S1 deposition). A remarkable interruption, centred at 8.2 ka BP and reflecting an invigorated thermohaline circulation, occurred during this event in both the Adriatic and Aegean seas, with repopulation of deep-sea sediments by benthic foraminifera that had been absent before and after because of the anoxia (*De Rijk et al*., 1999). The 8.2 ka BP cooling event was found to be part of a repetitive sequence of rapid climate shifts (*Bond et al*., 1997) that can be recognized also in the Mediterranean sea (*Incarbona et al*., 2008). The close association of these climatic shifts with abrupt changes in bottom water oxygenation and organic-rich matter (sapropel) deposition makes them uniquely suitable for the investigation of the changes in climatic forcing that caused thermohaline shutdowns/restarts.

Climatic reconstruction of the time interval during the last 20Kyr, however, is not simple. This is because regional factors, associated with the hydrologic, chemical-physical and climatic features of the Mediterranean, largely determine climatic variability (*Cacho et al*., 2002, *Rohling et al*., 2002). Moreover, despite the fact that currently the deep waters of the Mediterranean are well ventilated (*Bethoux and Gentili*, 1999), the presence of sapropels in the eastern Mediterranean indicates that this mechanism has been absent several times in the past. Over the past million years, relatively small changes in the Mediterranean water budget had a profound impact on the thermohaline circulation of the basin. Many studies have addressed the relationship between enhanced freshwater input into the basin at times of summer, insolation maxima in the northern hemisphere and the formation of sapropels; enhanced burial of organic carbon in sediments was likely initiated by the influx of low-salinity waters which slowed or halted the convective overturning in the eastern Mediterranean and reduced deep-water oxygenation (*Rohling et al*., 2002).

In the western Mediterranean, there is no record of sapropel deposits, but organic-rich, nonlaminated layers (ORL) deposit records are available. Although these cannot be considered as true sapropels, some paleoceanographic studies dated and correlated eastern Mediterranean sapropels (*Rohling,* 1994) with ORL in the western Mediterranean (*Perez-Folgado et al.*, 2004).
As the Mediterranean enhances the paleoceanographic and paleoclimatic signals, the basin can be used as a laboratory for climate change. This is the time to establish a paleoceanographic comparison between the east and the west side of the Mediterranean and evaluate paleoproductivity trends related to paleoclimatic events.

Although the analysis of proxy records to study the climate of the past is important, it provides only partial information regarding the state of the past ocean and of the processes that regulate it. To complete our knowledge, model simulations are necessary. The modelling experiments have first to be validated with observations and can then be used to study the fully realistic, three-dimensional ocean dynamics.

The use of simple box models can clarify some mechanisms underlying the variability in the circulation of the Mediterranean. These simple models, which include the Stommel's pioneering box model (*Stommel*, 1961), are useful to study the multiple states of the Mediterranean thermohaline circulation (THC) in the different basins as well as the oscillations between them
(e.g. the Bimodal Oscillating System, *Gačić et al*., 2010). An example of such a box model for the Eastern Mediterranean THC showing the shift of the deep water formation cell from the Adriatic to the Aegean sea has recently been proposed by *Ashkenazy et al.* (2012). These models, although not realistic, provide a conceptual view of the dynamics and of the mechanisms underlying its variability.

On the other end, hypotheses made by using simple models can be verified by using more complex ocean global circulation models and proxy data.

Specific issues

1. *Impact of the Atlantic circulation on the Mediterranean THC.*
   No investigation exists about how the changes in the Atlantic waters inflowing at Gibraltar affect the Mediterranean thermohaline circulation as opposed to changes in surface heat fluxes.

2. *Analysis of the limiting factors of the past interaction between North Atlantic and Mediterranean THC.*
   A proto-modern circulation was established in the Mediterranean when the eastern connection with the Indian Ocean was interrupted ~ 18 million years ago (*Sprovieri et al*., 2007). Thereafter, the Gibraltar sill regulated the Mediterranean circulation. In a broad sense, the North Atlantic and the Mediterranean can be seen as one connected system, whose internal dynamics is modulated by the exchanges at Gibraltar (*Artale et al*., 2006).

3. *Investigation of the nonlinear behaviour of the Mediterranean circulation.*
   The present state-of-the-art numerical climate models are able to provide reasonable simulations of the present climate but are unable to reproduce the rapid transitions from one climate state, such as glacial climate, into another such as the present state. These transitions are inherently nonlinear and involve the competition and interactions between external forcing, such as wind stress and heat/moisture fluxes, and internal dynamical mechanisms such as BIOS (*Gacic et al*, 2010, see also section 3.6).

4. *Study of the patterns of climate change of the Northern Hemisphere influencing Mediterranean climates*.
   The available evidence suggests that forced changes in dynamical modes of variability in the global ocean, such as the North Atlantic Oscillation (NAO), El Nino-Southern Oscillation (ENSO) and the Atlantic Multi-decadal Oscillation (AMO) play a key role in the patterns of climate variability in the Mediterranean region and investigations are needed for remote times (see also section 3.6).

3.6 Short-term and climatic variability in the SST and mixed layer heat budget over the Mediterranean and effects on the circulation and biota surface concentrations.

State of knowledge

Instrumental records of increasing duration and spatial coverage as well as modeling efforts have documented substantial Mediterranean variability on time scales ranging from one day or less to decades and more. Part of this variability can be related to known forcing mechanisms, but in many cases, the relationship between observed variability and forcing has not been fully understood. Variability in the strength and location of local fluxes of heat, moisture and momentum are reflected in changes in the surface fields. Among these fields, the Sea Surface Temperature (SST) is the more extensively measured surface parameter and, since it responds directly to the atmosphere-ocean interactions, represents a candidate to investigate the space-time surface variability of the Mediterranean system. Satellite SST data are available, at least twice a day, since 1982. They have been used in a variety of studies to investigate the surface variability of the Mediterranean from the annual and interannual time scales (*Borzelli and Ligi*, 1999a and b; *Marullo et al*., 2007; *Notarstefano et al*., 2008; *Borzelli*, 2008; *Borzelli et al*., 2009) to the daily SST cycle (*Marullo et al*., 2011). The

European Research Network for Estimation from Space of Surface Temperature (ERNESST) and the Diurnal Variability Working Group (DVWG) of GHRSST (Group for High Resolution SST) coordinate these research activities.

Marullo et al. (2011) used lagged-correlation analysis, multitaper method (MTM) and singular spectral analysis (SSA) to reveal the presence of a significant oscillation with period of about 70 yrs., which is close to the Atlantic Multi-decadal Oscillation (AMO) period. They found that, during winter, the Mediterranean SST and the North Atlantic Oscillation (NAO) vary coherently over periods longer than about 40 yrs., with a confidence limit between 90% and 95%. Over periods longer than 85-100 years, Mediterranean SST and AMO vary coherently with a confidence limit that exceeds the 95%–99%.

From the above analysis the question arises whether the Mediterranean sea can be considered a component of the entire North Atlantic climate system, taking part in the deterministic mechanism, proposed by *Dima and Lohamnn* (2007), based on the interaction between atmosphere, ocean and ice. Furthermore, the system composed by the North Atlantic, the Mediterranean sea/Gibraltar strait (*Artale et al*, 2006) and the Arctic sea/Fram strait might work as a unique oceanographic entity, with the physical processes within the straits determining the exchange of the fresh and salty waters between the marginal seas and the open ocean (*Sannino et al*., 2009). The analysis of the Mediterranean SST variability alone, however, cannot provide a full answer to whether the forcing of the observed multi-decadal signal has an atmospheric origin or it is determined by changes in the Mediterranean Thermohaline Cell (THC).

Coupled ocean-atmosphere models could contribute to answering this question and to investigating the origin of the Mediterranean multi-decadal oscillation, separating the contributions of the atmosphere and of the Mediterranean THC.

A very important link exists between SST and the heat content of the surface mixed layer with the phytoplankton distribution. The variability of the mixed layer temperature is governed by the heat equation which includes horizontal advection of the mean and eddy components and the entrainment at the base of the mixed layer. The heat equation is forced by the heat budget at the air-sea interface minus the short wave radiation (SWR) not absorbed within the mixed layer. The portion of SWR absorbed within the mixed layer depends on the value of a diffuse attenuation coefficient for solar light. Several formulations are available to estimate the latter one, such as the one proposed by *Foltz et al*. (2003). The diffuse attenuation coefficient depends on the environmental conditions, being a measure of the water turbidity caused by the presence of suspended sediments and/or biological components. For the open sea, phytoplankton is the main factor determining this coefficient. *Morel et al*. (2007) proposed an empirical equation to determine its value from chlorophyll concentrations, obtaining a relationship that directly links the chlorophyill concentration to the percent of absorbed solar radiation in the mixed layer. As an example of such a calculation, consider a typical April condition in the northwest Mediterranean when the mean mixed layer depth is typically between 15 and 30 m, with a mean incoming SWR of 200 W/m^2 and chlorophyll concentrations ranging from 1 to 0.1 ng/m^3 inside and outside the most productive area. The SWR contribution to the mixed layer heating would be 180 and 160 W/m^2 for the two regions respectively (*D'Ortenzio et al*., 2005). This example emphasizes the importance of including the effect of biota concentrations in determining the mixed layer thermodynamics.

Specific Issues

1. Changes in the Mediterranean thermohaline cell take place over time scales of the decade. Can these changes be recognized in long series of the SST?

2. Atlantic indices are coherent over multi-decadal time scales with oscillations of the Mediterranean SST field. Can variability over these time scales of the SST field modulate the Mediterranean thermohaline cell?

3. Is there a feedback between changes in the Mediterranean thermohaline and multidecadal variability of the SST?

4. From the energetic point of view: Which is the energy reservoir that sustains oscillations in the Mediterranean SST field?

5. The Mediterranean is a negative basin, in the sense that evaporation exceeds precipitation and river run-off. In this basin dense water is formed. During dense water formation episodes energy is released from the ocean to the atmosphere. Is there a physical mechanism to replace this energy (wind forcing, heat fluxes, boundary conditions at Gibraltar, etc.) or is the energy lost from the ocean to the atmosphere?

6. Are there specific mechanisms to transform energy from thermodynamical to mechanical form? In case there are, do they leave their signature on long series of SST data?

7. What is the impact of the variable phytoplankton concentration on the heat content variability of the Mediterranean mixed layer?

3.7 The carbonate system in the Mediterranean

State of knowledge

The characteristics of the Mediterranean Sea are such that it has the potential to sequester large amounts of anthropogenic CO_2, C_{ant}. The buffer capacity of the Mediterranean Sea is particularly high due to the high alkalinity and temperatures throughout the water column. Furthermore the active deep overturning circulation is effective in transporting the atmospheric imprint on the carbon cycle to the interior of the Mediterranean Sea. In fact, the column inventories of C_{ant} are higher in the Mediterranean than anywhere else in the world ocean (Schneider et al., 2010), and the C_{ant} storage in the Mediterranean is a significant portion of the global anthropogenic emissions of CO_2. However, the carbon observations in the Mediterranean are so scarce that it is difficult to quantify the sink of anthropogenic carbon in the Mediterranean, and to quantify changes in the carbon cycles.

The last few decades have seen dramatic changes in the circulation of the Mediterranean Sea. This is manifest among other features as a shift of deep water formation from the Adriatic to the Aegean Seas, and back again to the Adriatic being more important for deep water formation. The deep water formed from these two sources has different properties of salinity and temperature and different biogeochemical signatures. Very little is known about how the recent changes in the Mediterranean overturning circulation have affected the storage rate of C_{ant}.

The increasing inorganic carbon content of the Mediterranean sea leads to changes in the carbonate system, such that the concentrations of the carbonate ion decreases and the pH decreases. Even though the pH of the Mediterranean is high in comparison to the world ocean, it is possible that these changes in the carbonate system can impact the ability of certain groups of marine organisms (e.g. coccolithophores) to thrive. Changes in the community structure as a direct effect of the changing carbonate system are conceivable.

Scientific questions that need to be addressed by observations of the carbonate system in the Mediterranean Sea include:

1. What are the distributions and controls of natural and anthropogenic carbon (both organic and inorganic) in the interior of the Mediterranean Sea?
   - Key areas for CO_2 penetration in the Mediterranean Sea
   - Evaluation of the role of the intermediate and deep water formation areas
   - Evaluation of the impact of shelf events (flood, storms, shelf water formation).
2. How does the interior carbonate system change over time?
3. How does this relate to increasing atmospheric CO_2 concentrations and changing climate, i.e. to the relation between anthropogenic and natural forcing ?
4. What is the air-sea flux of CO_2 in the Mediterranean Sea; on an annual and seasonal basis for the different sub-basins.
5. What is the inter-annual to inter-decadal variability of pCO_2 in the Mediterranean Sea?
6. Which is the most appropriate method (within the existing) of anthropogenic carbon content calculation in the Mediterranean Sea?
7. What is the quantity of anthropogenic carbon exchanged through the Strait of Gibraltar?
8. How do surface changes connect with the interior ocean?

Specific issues

1. Observations of the interior ocean carbonate system on a regular basis on selected hydrographic sections.
This concept has been presented in some detail in the latest CIESM Monograph (CIESM, 2012) which proposes a program, called Med-SHIP (MEDiterranean Ship-based Hydrographic Investigation Program) for repeat hydrography in the Mediterranean Sea. Currently, ship-based observations is the only means of obtaining reliable carbonate data of the interior ocean of sufficient high accuracy for determining temporal variability. This is particularly true for the regions of the Mediterranean Sea deeper than 2000 meters, i.e. the maximum depth of the present day Argo floats. As described above, there are large amounts of anthropogenic carbon contained at all depths of the Mediterranean Sea. The MED-SHIP concept relevant for interior carbon data is based on zonal and meridional sections in the Mediterranean Sea repeated on regular intervals; more frequent for the meridional sections than for the zonal section. This could be the corner stone in an observational program for interior ocean carbon in the Mediterranean Sea.

2. Regular observations of surface pCO_2 on ships of opportunity.
Observations of pCO_2 on commercial vessels (cargo ships and ferries) that regularly crosses the oceans is a well proven and useful concept. However only a limited number of surface pCO_2 observations are available for the Mediterranean Sea, although time series like the DYFAMED site south of France provide important long time information.
Installation and operation of pCO_2 system on a number of commercial vessels would be very useful to understand the air-sea flux of CO_2, and its spatial and temporal variability. Ideally, these measurements should be coupled with measurements of additional biogeochemical variables concurrently, to help establishing the forcings in the CO_2 variability.

3. Attribution of observed variability and trends to processes
The understanding of processes responsible for observed trends and variability is important and is probably best undertaken with the help of some modeling scheme, data assimilation or inverse method. Observations and modeling efforts need to go hand in hand and will benefit from close cooperation between the modeling and observational community.

4. Use of moorings and autonomous platforms
Information from sensors mounted on gliders, floats and moorings are invaluable for the understanding of the temporal and spatial variability. Currently reliable pCO_2 sensors are available for surface vehicles, such as the wave-rider, and surface moorings. Development of other sensors is rapid and any observational program needs to take advantage of additional sensors for a better understanding of the total carbonate system.

5. Anthropogenic CO_2 invasion into the Mediterranean Sea

Estimation of the anthropogenic CO_2 penetration in the Mediterranean Sea using the existing limited historical data and the existing calculation techniques. Investigation of a new scheme, appropriate for the Mediterranean Sea, for anthropogenic CO_2 calculation.

4. Shelf/deep sea interactions and exchanges of physical/biogeochemical properties and how they affect the sub-basin circulation and property distribution

4.1 Formation mechanisms of filaments and eddies in the Mediterranean, their effects on the biogeochemical processes of the basin or of some specific areas and their impact on physical/biogeochemical exchanges through straits

State of knowledge

Frontal zones, filaments and eddies (FZFE hereafter, ranging from mesoscale (10–100 km) to submesoscale (1–10 km) dimensions) are dynamical features with sharp gradients having a large effect on circulation and on the distribution of heat, salt and matter in the ocean (*Robinson*,1983; *McGillicuddy et al*., 1998). It has been shown that they are important routes of the energy cascade and dissipation in the ocean, and of the transport of mass, energy, chemical compounds, flora and fauna between water masses by turbulent advection and mixing. Their characteristics and distributions play a major role at the basin scale and in the local energetics and circulation.They contribute to shaping the spatio-temporal distribution of biogeochemical variables, by creating physical boundaries (separating distinct areas of completely different properties from the surroundings in the open sea) and by modulating the seasonal evolution (inducing, for example, sporadic events). In the coastal areas, they can transport land-based coastal and continental shelf material to the open sea and vice versa.

Often the dynamic features created or destroyed by atmospheric interactions as well as internal instability mechanisms interact with each other exchanging pulses of physical properties or materials that contribute to the synoptic or average state of the ocean. These interactions often go down to the small scales of sub-mesoscale filaments and streamers only captured in high resolution simulations and by satellite observations. Through energy cascading mechanisms of geophysical turbulence some features disintegrate or dissipate, while other small scale features can coalesce to become coherent structures that persist for extended periods.

The challenges of characterizing these processes imply precise and high-resolution observations in addition to multi-sensor approaches. Accordingly, multi-platform experiments have been designed and carried out in the different sub-basins, highlighting the need of synergetic approaches through the combined use of observing systems at several spatial/temporal scales. Some exemplar multi-sensor studies in the Western Mediterranean (Alboran and Balearic basin) are available and reported below.

Alboran Basin
The Alborán Sea plays a crucial role as it represents a transition zone between the Mediterranean Sea and the Atlantic Ocean. The Atlantic water flows into the Alborán Sea at the surface through the Strait of Gibraltar and generally forces two anticyclonic gyres, the WAG and EAG (*La Violette*, 1984; *Allen et al*., 2001). The combination of satellite altimetry with independent in-situ data has demonstrated the benefits for improving our knowledge on mesoscale dynamics. *Ruiz et al*. (2009b) reported the first attempt to combine high-resolution (~0.5 km) hydrographic observations using the new glider technology and altimetry measurements to quantify vertical exchanges in an area with intense horizontal density gradients. By autonomously collecting high-quality observations in three dimensions, gliders allow high-resolution oceanographic monitoring and provide useful contributions for the understanding of mesoscale dynamics and multidisciplinary interactions (e.g., *Hodges and Fratantoni*, 2009). However, isolated measurements from fleets of gliders are not sufficient, as, glider measurements remain scarce, both in space and time for many small scale processes. That is the main reason why a multi-sensor approach that combines such in situ sampling and remote-sensing measurements should be suited to advance our knowledge on mesoscale features. The experiment carried out by *Ruiz et al.* (2009a,b) was designed to be coincident with an OSTM/Jason-2 passage in the Eastern Alborán Sea. Using the quasi geostrophic dynamics (*Hoskins et*

al. 1978), they reported vertical velocities of about 1 m day^{-1}, partially explaining an observed subduction of chlorophyll. More recently, *Navarro et al.* (2011) analysed the coupled patterns of variability between satellite altimetry and chlorophyll data in the Alborán Sea. They demonstrated that the pelagic ecosystem in the Alborán Sea is controlled by the inverse barometer effect (first mode). They also show that the distribution of chlorophyll-rich and poor areas of can be explained by the second mode.

Balearic basin

The Balearic Sea is a key sub-basin of the western Mediterranean due to its strategic location separating the Gulf of Lions in the north and the Algerian Basin in the south, playing a major role in the north-south exchanges. The general surface circulation (*Font et al.,*1988) is controlled by the presence of the Northern Current flowing southwestward along the continental slope until it either exits into the basin through the Ibiza channel (*Pinot et al.,* 2002), or retroflects cyclonically over the insular slope forming the Balearic Current (*Pascual et el.,* 2003). It is also characterized by frontal dynamics near the slope areas: mesoscale eddies have been found to modify not only the local dynamics but also the large-scale patterns, as shown by *Pascual et al.* (2002) in a detailed study of the blocking effect of a large anti-cyclonic eddy, as well as a clear influence of the basin circulation on the phytoplankton biomass (*Jordi et al.,*2009).

In a recent work, *Ruiz et al*., (2009a) provided first positive insights concerning the use of autonomous underwater vehicles (gliders) in synergy with altimetry in order to monitor dynamics in the Balearic Sea. *Bouffard et al*., (2010) developed innovative strategies to characterize horizontal ocean flows, specifically in terms of current velocity associated with filaments, eddies or shelf-slope flow modifications close to the coast. These methodologies were applied to a series of glider missions carried out almost simultaneously and well co-localized along the satellite tracks, as part of a pilot initiative lead by IMEDEA (CSIC-UIB). In this context, *Pascual et al*. (2010) showed that the high-resolution hydrographic fields from the gliders combined with coastal altimetry revealed the presence of permanent and non-permanent signals, such as relatively intense eddies. Moreover, the almost synoptic view from altimetry and SST images during the glider missions provided a more detailed picture of regional small-scale features.

Since January 2011, a new sustained observational program in the Balearic Channels is being conducted by IMEDEA (CSIC-UIB) and SOCIB, the new Balearic Islands Coastal Observing and Forecasting System (*Tintoré et al*., 2012). This monitoring program consists of repeated transects between Mallorca, Ibiza and Denia. During 2011, 7 glider missions have been successfully carried out in the Ibiza Channel reporting an unprecedented spatial and temporal variability in transports (*Heslop et al*., 2011) compared to the literature values (*Pinot et al*., 2002). These new findings will have relevant consequences to improve our understanding of local ecosystem changes, as it is known that the variability of Atlantic Water through the Balearic Channels is critical for the understanding of Bluefin Tuna spawning south of the Balearic Islands (*Alemany et al*., 2010). The combination of glider data with information from other platforms (satellite, ships cruises, high frequency radars and buoys) will support the investigation of unresolved scientific questions such as mesoscale, seasonal and inter-annual variability of the water exchanges in the Ibiza and Mallorca Channels. In a near future, the worldwide challenge of (sub)mesoscale dynamics characterization will have to be addressed through an integrated approach combining both observations and numerical simulations.

Eastern Mediterranean and Levantine Basin

Multi-scale interactions are especially relevant for the eastern Mediterranean, where coherent eddies either reinforce or block seasonal circulations, divert or entrain water masses of contrasting properties and indirectly contribute to inter-basin transports (Feliks and Itzikowitz, 1987; Malanotte-Rizzoli et al., 1999; Zodiatis et al., 2005). In the Levantine basin fast current systems known as the Mid-Mediterranean Jet and the Asia Minor Current (Robinson et al.,1991, 2001) bear the energy that can sustain unstable FZFEs or evolve into long-lived features such as the Iera-Petra, Antalya and Shikmona eddies. Interaction among various eddies along the Asia Minor Current, from their genesis to decay, have often been observed in great detail (Onken and Yuce, 2000; Hamad et al., 2005, 2006). Modified Atlantic Water propagating from the west and the Levantine Intermediate Water created through convection events are entrained and transported by these eddies and jets and exchanged by FZFE interactions (Özsoy et al., 1989,1991,1993; Sur et al.,1992; Lascaratos and Nittis, 1998).

The abundance and chemical composition of nutrients and particulate organic matter in the euphotic zone of the cyclonic/anticyclonic eddies and across frontal zones have great spatial and temporal variability (Özsoy et al., 1993; Ediger et al., 1999, 2005), with consequent impacts on the productivity (Salihoğlu et al., 1990; Bingel et al., n1993; Yılmaz and Tuğrul,1998).Increases in algal biomass (Chl-a) are observed especially on shelf zones where rivers supply nutrients. This also occurs on the Rhodes cyclonic gyre and its peripheral front during Winter and the following early Spring because of the nutrients supplied by deep Winter mixing, upwelling and lateral entrainment processes. The surface and deep chlorophyll maxima formed near the base of the euphotic zone depend on light and biochemical variability imposed by FZFEs (Yılmaz et al., 1994; Yacobi et al., 1995; Ediger et al., 1996,2005).

Specific issues

1. Characterization of the importance of frontal zones, filaments and eddies (FZFE) in various areas of the Mediterranean Sea, using remote sensing and modeling results.What is the spatial and temporal variability of the FZFE distribution and energetics, how are they affected by the atmospheric forcing and interaction with topographic features and how deterministic is this distribution? Thermal NOAA/AVHRR satellite images were used to identify sites of highest frequency in cold filaments in the Mediterranean Sea (*Bignami et al*., 2008). Satellite altimetry and ocean color data and modeling techniques can be also used to characterize the population and energetic of these features.

2. FZFE require horizontal and vertical redistribution of vorticity. The physical mechanisms underlying this redistribution are several (i.e. baroclinic instabilities, bottom discontinuities, wind field) and determine the characteristics of the FZFE (i.e. characteristics length and time scales of variability along with duration of the phenomenon).What are the physical processes involved in the FZFE generation and interactions in the open sea and in coastal areas of the Mediterranean basin? What relationships or differences exist between surface signatures and deep structures of FZFEs? What differences do they have in different parameter regimes and regions?

3. What is the FZFEs role in the basin-wide and local energy budget of the Mediterranean Sea? How do the multi-scale interactions transfer and partition this energy at different scales? In which way does the energy transfer occur from mean currents to the FZFEs?

4. Which instability conditions or forcing mechanisms are responsible for the generation and decay of FZFEs? How stable are the latter ones once generated ? What are their typical life histories ? What are the conditions that either lead to long life spans or rapid disintegrations of these features ?

5. Characterization of the transport patterns using satelite altimetry and Lagrangian numerical analysis. Studies were performed in the open sea, also in the Mediterranean (*d'Ovidio et al*., 2004). Recently, this methodology was adapted to the coastal area using in situ observations to correct for the uncertainties connected to satelite altimetry data close to shore (*Nencioli et al*., 2011). These patterns are important to predict the distribution and transfer of characteristics and matter between areas.

6. The Mediterranean basin is characterized by very complex topography, including a complicated strait system that constrains (or sometimes controls) the exchange flow and sub-

basin dynamics. FZFEs interact with the complex topography (mid-basin ridges, shelf zones, steep continental slopes, canyons and headlands, island arcs) and can affect shelf-open sea exchanges and strait fluxes. Questions: What is the role of Mediterranean complex topography in the FZFE dynamics and variability? What is the role of these features in the exchange flows in the various straits of the Mediterranean Sea and can they influence/control the fluxes at various time scales?

7. Satellite images have revealed a connection between FZFE and surface phytoplankton biomass (chlorophyll) in the Mediterranean Sea, while the impact of FZFE on the horizontal distribution of chemical parameters and plankton composition was observed at some areas studied by conventional methodology (bottles, nets). Can we have “pictures” of the chemical and biological (other than chlorophyll) distribution at basin scale that could reveal the influence of FZFE? Which is the relative role of the FZFE versus the large scale driven forcing mechanisms (i.e. seasonal overturning) on the spatio-temporal distribution of the Mediterranean chemical and biological parameters? Do FZFE affect similarly the chemical and biological parameters distribution in the entire Mediterranean Sea e.g. are there differences between Algerian and Cyprus anticyclonic eddies? Questions 1 and 3-4 relate to the surface only, that is accessible to satellite imagery. The following questions refer to the deeper layers.

8. Once the FZFE areas are identified from their surface signature, how deep are the structures? Is the penetration depth constant or seasonal and area dependent? Is the penetration depth a function of the strength and character of the physical forcing causing the FZFE?

9. FZFE play an important role in the redistribution of chemical elements at horizontal and vertical scales; at the boundaries it is possible to observe increases or decreases in the concentrations of chemical compounds. Similar influence is observed at some FZFE areas of the Mediterranean Sea. To what extent these chemical compounds can be used as passive tracers of the vertical and horizontal currents associated with FZFE? And, whenever these compounds would be identified, how could these tracers provide us with information on the physical processes sustaining the FZFE? In a recent study, *Niewiadomska et al*. (2009) use gliders equipped with optical biogeochemical sensors to detect upwards and downward motions not easily detected by direct measurements.

10. It has been found that, in some Mediterranean areas, FZFE affect the distribution of plankton biomass and community composition either directly, due to the physical characteristics (e.g. salinity and temperature boundaries, convergence or divergence processes), or indirectly, through the influence on the chemical parameters (*Fiala et al*., 1994; *Van Wambeke et al*., 2004; *Riandey et al*., 2005; *Siokou-Frangou et al*., 2009, among others). Do other FZFE areas of the Mediterranean Sea present similarly differentiated plankton distribution? Can the FZFE cause patchiness in the biomass distribution and if so, can we identify areas more likely to have this patchiness? How different is the picture of the phytoplankton biomass distribution at 50m depth from the picture obtained by satellite images and if appreciable, can it change our estimation of the entire basin production? Are the recently observed deep layers of diatoms assemblages related to eddies (*Crombet et al*., 2011) and do they occur in other FZFE areas of the Mediterranean Sea? Which could be their contribution to the estimation of primary production of the entire Mediterranean Sea and to the carbon flow towards higher trophic levels through mesozooplankton? An increase of the estimated primary production in the Mediterranean Sea could answer the question of the apparently high yield of fisheries compared to the low primary production (*Estrada*, 1996).

11. Very thin layers of plankton (on the order of centimetres to few meters) are found in stable stratified water columns, as those characterizing frontal areas, especially those with convergent processes (*Sullivan et al*., 2010).Can we find such thin layers in the Mediterranean? What areas would be more likely to have them? If we find those thin layers, how important are they for the productivity of the Mediterranean? How will they change the

nutrient and C budget calculations for the Mediterranean? Are they characterized by different species composition, being able to use to their advantage the different physical and chemical environment? Recently, it was hypothesized that thin layers of diatoms may be present at specific areas of the Mediterranean (*Crombet et al.*, 2011).

4.2 On the role of surface forcing in the shelf/slope circulation

State of knowledge

The Mediterranean Sea is a region in which air-sea interaction plays a crucial role in shaping both the atmospheric and oceanic circulation. For the sea, the main components of the surface forcing are: the wind stress, the surface heat flux, the direct surface fresh water flux (evaporation minus precipitation), and the terrestrial based water flux in the form of runoff and river discharges. While early modelling studies of the Mediterranean used relatively coarse horizontal grid resolutions of ~25 km (e.g., *Roussenov et al.* 1995; *Zavatarelli and Mellor*, 1995), more recent studies have used higher resolution grids which are nearly eddy-resolving (e.g., ~10 km in *Beuvier et al.*, 2010) and even eddy resolving (~7 km in *Tonani et al.*, 2008). Other studies of sub-basins (e.g., *Lascaratos and Nittis*, 1998) have also used eddy resolving grids (~ 5 km) for process studies such as LIW formation. These studies show that a model with a reasonable spatial resolution is able to reproduce circulation features of basin-scale, sub-basin scale and mesoscale in agreement with the small Rossby radius of deformation for this sea. However, the common feature of these and other studies is that the surface forcing fields have been extracted from large scale climatological or reanalysis data sets in which the horizontal resolution is at best on the order of 50-100 km. In most of these studies, the temporal resolution of the forcing was also relatively coarse (daily or longer), with the exception of *Tonani et al.* (2008) who used 6 hourly data.

While these studies indicate significant progress in understanding the circulation of the Mediterranean, it is clear that these models and the associated forcing are not able to adequately resolve the fine details of the shelf and slope regions, which are relatively narrow (typical width of a few tens of kilometers). As discussed by the *Chelton et al.* (2004), small-scale features in ocean winds, as well as the influences of the coastal and island orography on the wind stress curl and divergence are observed from the 25-km horizontal resolution of the wind stress from the Quickscatt radiometer. Such features, even at smaller scales (of about 1 km) are of great importance for the Mediterranean Sea and its adjacent basins, where orography and coastal geometry influence the wind pattern. The effects of these small-scale variations have long been recognized in controlling the wind driven circulation in the Adriatic Sea. Recent studies of the role of Bora wind events forcing the circulation in the northern Adriatic have demonstrated the importance of sufficiently high resolution in the observations (*Lee et al.*, 2005) and models (*Cushman-Roisin and Korotenko*, 2007) for understanding the sea's response to the fine-scale atmospheric forcing. These studies also demonstrate the complex interaction that can occur in the shelf zone due to the combined effects of wind forcing and river discharge.

Another important process that occurs in the northern Adriatic is the formation of dense water by cooling and/or evaporation. It forms on the broad, shallow northern shelf (generally shallower than 50 m) which is exposed to cold, dry air flowing down from the Dinaric Alps during the winter. The resulting intense cooling (as much as 1000 W/m^2) produces dense water (11 °C, 38.5 psu), which spills over the shelf edge and then flows along the Italian coast as a gravity current all the way to the Mid Adriatic Pit, South Adriatic Pit and the Bari Canyon. In the South Adriatic Pit particularly it mixes with the Levantine Intermediate Water (LIW) flowing cyclonically around the Pit before exiting to the Ionian Sea through the Otranto Strait, both as a shelf vein or a slope vein mixed within the Adriatic Deep Water (*Zoccolotti and Salusti*, 1987; *Manca et al.*, 2002). *Bignami et al.* (1990) observed the cascading dense waters at the Bari canyon in October 1987 and estimated the transit time from its formation in the north to its arrival in the Bari canyon to be 4-5 months. Such dense-water formation events are episodic in nature and this, combined with their small spatial scales, makes them difficult to observe. Based on observational evidence from 1981, 1987 and 1999, *Vilibic and Supic* (2005) found that the reduction of river discharges in the months preceding dense water generation is a precondition for North Adriatic Dense Water (NAdDW) formation. The reduced river discharge may also permit LIW to penetrate to the northern Adriatic and bring highly saline water masses which when cooled sufficiently can form very dense water that is capable of cascading into the interior. In any event, sustained cooling by severe Bora outbreaks during the November-January time frame is necessary to cool the water column and form the dense NAdDW. In addition to the convective mixing driven by air-sea heat loss and evaporation, the tidal mixing at the bottom as well, as mixing from wind-driven waves may also play a role in triggering the cascading process.

In other basins of the Mediterranean a strong current usually flows along the bathymetry near the shelf break or over the slope. In the western Mediterranean, the Algerian Current meanders along the North African coast and often generates coastal eddies due to baroclinic instability (*Millot*, 1985) while the Balearic Basin in the northwestern Mediterranean is also characterized by frontal dynamics and shelf-slope exchanges, in terms of mesoscale eddies and filaments (e.g., *Bouffard et al.* 2010). In the eastern Mediterranean the coastal, baroclinicly unstable Libyo-Egyptian Current generates mesoscale eddies that modify the pathway of Atlantic Water, dispatching it offshore (*Gerin et al.*, 2009). Along the eastern boundary of the Levantine Basin, the northward flowing shelf break current (*Rosentraub and Brenner*, 2007) also meanders, generating coastal eddies which drift out to the open sea, and occasionally separates from the shelf break (*Brenner,* 2003). All of these current systems are an integral part of the general circulation of the Mediterranean Sea and play an important role in shelf-open sea interaction. The contribution of the high resolution and high frequency surface forcing is not well understood and warrants further investigation.

Specific issues

1. While it is clear that high spatial and temporal resolution surface forcing is important for properly simulating the ocean response in terms of mesoscale dynamics in the various basins and sub-basins of the Mediterranean Sea, it is crucial also for understanding the fundamental processes of the shelf and slope zone circulation. Remotely sensed winds on a continuous basis (with no interruptions due to the termination of the satellite mission) with at least a daily time step would be a valuable source of information on the synoptic wind patterns over the Mediterranean. This kind of data should be complemented with data from a coastal network which should fill the gap near land (15-30 km, *Bourassa et al.*, 2010) where the satellite remotely sensed winds are not available. Moreover, there is a need of the atmospheric forcing with adequate temporal resolution from in situ observations at platforms such as buoys/moorings/drifters, located in the offshore regions, especially where wind driven eddy/gyre systems are observed. Ideally, the remotely sensed wind data should be integrated with the data from autonomous self-recording and transmitting platforms with meteorological sensors moored in the regions of the shelf/slope interaction. Such instruments can provide the local meteorological conditions that cannot be remotely sensed with a sufficient temporal detail and duration.

2. This approach should also be applied to regions where other important oceanic phenomena occur as response to the local forcing, or dense water formation (Gulf of Lions, Southern Adriatic, and the Southern Aegean). For example, *Vilibic and Supic* (2005) suggest that the importance of the preconditioning phase in NAdDW formation needs to be studied by examining the specific years in which NAdDW formation has been observed and documented. They also suggest investigating the precise location(s) of NAdDW formation and spreading in the northern Adriatic using more realistic, high resolution surface forcing based on observational data and model simulations. The same conclusion was reached by *Signell et al.* (2005) when assessing the relevance of high resolution meteorological models in the Adriatic.

3. The use of high-resolution regional atmospheric models for downscaling of the surface forcing is a promising approach (e.g., *Cushman-Roisin and Korotenko*, 2007; *Beuvier et al.*, 2010).

The logical next step would be to develop a high resolution, multi-decadal, regional reanalysis data set. In this respect, close cooperation with the operational ocean forecasting community would be important since regional atmospheric models are routinely used to force the nested sub-basin and shelf scale models in the Mediterranean Operational Oceanography Network (MOON, http://www.moon-oceanforecasting.eu). However, in order to make long-term surface forcing data sets reliable and useful, care must be taken to implement good quality control and to ensure consistency of the data.

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