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INTRODUCTION TO A SPECIAL SECTION

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Special Section:
Dense water formations in the North Western Mediterranean: from the physical forcings to the biogeochemical consequences

Key Points:

- The results of the Dewex operation quantify and accurately describe the dynamics of dense water formations and their effects at subscale and mesoscale
- Advances concern physics but also biogeochemical budgets, planktonic biodiversity, and trophic levels functioning
- The special issue also deals with the potential evolution of mechanisms and their impacts on biogeochemistry in the context of global change

Correspondence to:
P. Conan,
pascal.conan@obs-banyuls.fr

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Preface to the Special Section: Dense Water Formations in the Northwestern Mediterranean: From the Physical Forcings to the Biogeochemical Consequences

Pascal Conan[1], Pierre Testor[2], Claude Estournel[3], Fabrizio D'Ortenzio[4], Mireille Pujo-Pay[1], and Xavier Durrieu de Madron[5]

[1]Laboratoire d'Océanographie Microbienne, Observatoire Océanologique de Banyuls, Sorbonne Université, UPMC, Université Paris 06, INSU-CNRS, UMR 7621, Banyuls-sur-Mer, France, [2]Laboratoire d'Océanographie et du Climat: Expérimentation et Approches Numériques, IPSL, Sorbonne Université, UPMC, University Paris 06, CNRS-IRD-MNHN, Paris, France, [3]Laboratoire d'Aérologie, Université de Toulouse, Toulouse, France, [4]Laboratoire d'Océanographie de Villefranche, Sorbonne Université, UPMC University Paris 06 INSU-CNRS, UMR 7093, Villefranche-sur-Mer, France, [5]Centre d'Etude et de Formation sur les Environnements Méditerranéens, Université de Perpignan Via Domitia, CNRS UMR 5110, Perpignan, France

Abstract The northwestern Mediterranean Sea is one of the few sites of open-sea deep convection and dense water formation. The area is characterized by intense air-sea exchanges favored by the succession of strong northerly and northwesterly winds during autumn and winter that eventually induce deep convection episodes and the formation of the *Western Mediterranean Deep Water*. This region exhibits a significant spring phytoplankton bloom, which appears to be largely influenced in intensity and diversity by the winter mixing. To understand and resolve the interplay between the atmosphere and ocean, and the impact of ocean circulation and mixing on biogeochemistry, we carried out an unprecedented observational effort during a large experiment between July 2012 and July 2013. A multiplatform approach—combining aircraft, balloons, ships, moorings, floats, and gliders - aimed both at characterizing the dynamics of the atmosphere and at quantifying the physical, biogeochemical, and biological properties of the water masses. Beyond a better understanding of the wind dynamics, the interannual variability of the deep convection, and the seasonal variability of the nutrient distribution and plankton structure in the pelagic ecosystem, the experiment provided a reference data set that was used as a benchmark for advancing the modeling of the surface fluxes, convective processes, dense water formation rates, and physical-biogeochemical coupling processes. It also represented an opportunity for complementary investigations such as evaluating model parameterizations or studying the role of submesoscale eddies in dense water spreading and biogeochemistry.

1. Introduction

Open sea deep convection and dense water formation constitute an important driving mechanism for the ocean circulation and ventilation. This mechanism also strongly impacts the nutrient distribution and controls the triggering of the blooms of the first producer levels and then the structure and organization of the whole trophic network. It is particularly sensitive to changes in environmental conditions. It is expected to increase/decrease because of weaker/stronger stratification due to ocean warming and evaporation. The northwestern Mediterranean Sea is one of the few sites of open-sea deep convection and dense water formation. The area is characterized by intense air-sea exchanges favored by the succession of strong northerly and northwesterly winds during autumn and winter that eventually induce deep convection episodes and the formation of the *Western Mediterranean Deep Water*. This region exhibits a significant spring phytoplankton bloom, which appears to be largely influenced in intensity and diversity by the winter mixing. High-resolution, realistic, three-dimensional atmospheric and oceanic models are essential for assessing the intricacy of buoyancy fluxes, horizontal advection, and convective processes, but they need to be validated by data that describe the variability of convection at small spatial scales (a few kilometers) and at high frequency (typically a day), and by accurate concomitant observations throughout the water column and atmosphere, especially during strong wind events. Likewise, the lack of in situ observations simultaneously inferring the main physical and biogeochemical variables was a major obstacle to unify a

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consensual description of the variability of the phytoplankton spring bloom and finally to equilibrate matter fluxes and budgets over an annual cycle. To understand and resolve the interplay between the atmosphere and ocean, and the impact of ocean circulation and mixing on biogeochemistry, we carried out an unprecedented observational effort during a large experiment between July 2012 and July 2013. A multiplatform approach—combining aircraft, balloons, ships, moorings, floats, and gliders—aimed both at characterizing the dynamics of the atmosphere and at quantifying the physical, biogeochemical, and biological properties of the water masses. Beyond a better understanding of the wind dynamics, the interannual variability of the deep convection, and the seasonal variability of the nutrient distribution and plankton structure in the pelagic ecosystem, the experiment provided a reference data set that was used as a benchmark for advancing the modeling of the surface fluxes, convective processes, dense water formation rates, and physical-biogeochemical coupling processes. It also represented an opportunity for complementary investigations such as evaluating model parameterizations or studying the role of submesoscale eddies in dense water spreading and biogeochemistry.

2. Rationales

The Mediterranean Sea is recognized to be particularly sensitive to climate change (Adloff et al., 2015; Cacho et al., 2002; Giorgi, 2006; Somot et al., 2006). The basin is affected by an increasing anthropogenic pressure, linked to strong economical and touristic activities (i.e., Attané & Courbage, 2001). Its semienclosed nature, together with its smaller inertia (Paluszkiewicz, 1994) compared to large oceans (Lacombe & Richez, 1982), makes it more sensitive to natural variations in the atmosphere-ocean and land-ocean interactions and exchanges, which can, in turn, enhance the effects of climatic perturbations. The Mediterranean Sea is one of the most intricate marine environments on Earth as most of the critical physical processes characterizing the global circulation (dense water formation, thermohaline circulation, subbasins gyres …) can be observed in a narrow latitudinal belt at midlatitudes. They act on a large spectrum of spatial and temporal scales (Marine Ecosystems Response in the Mediterranean Experiment [MERMEX] group, 2011) and induce a pronounced biological heterogeneity (Conan et al., 1999; Crise et al., 1999; Robinson et al., 2001). It combines a clear west-east gradient in nutrient distribution and oligotrophy (D'Ortenzio & Ribera d'Alcalà, 2009; Pujo-Pay et al., 2011; Ribera d'Alcalà et al., 2003) with a high spatio-temporal variability in the dynamics of nutrients and organic matter (Pujo-Pay et al., 2011; Pujo-Pay & Conan, 2003; Santinelli et al., 2010), which is propagated through diverse bottom-up and top-down controls within primary, secondary, and upper trophic levels.

The Mediterranean Sea can thus be regarded as a reduced model of the global ocean, and, in this context, the northwestern Mediterranean (NWM hereafter) is consensually assumed as a critical region for the functioning of the whole basin. In this relatively small portion of the Mediterranean Sea, deep convection is regularly observed in winter. If the three phases of convection (preconditioning, vertical mixing, and spreading/restratification) have been defined for several decades (MEDOC group, 1970), it appears that these phases overlap and that the physical processes that govern them interact in a wide range of spatial and temporal scales. In particular, small-scale and submesoscale dynamics play a particularly important role, for example, convective plumes whose size is less than 1 km and which are important mixing agents, or submesoscale coherent vortices of radius (~5 km) which are involved in the large-scale circulation of the newly formed deep water (Testor & Gascard, 2003).

Convection induces a redistribution of organic and inorganic matters all over the water column. Moreover, in the same area (although with a larger extension and with a greater interannual variability than the region of deep convection) a large and intense spring bloom is observed (D'Ortenzio & Ribera d'Alcalà, 2009; Mayot et al., 2016), presenting a high variability from mesoscale to small scale, often clearly coupled to the physical one (Diaz et al., 2000). The bloom represents the most important process of the basin in terms of primary and secondary productions at the origin of large carbon exports to the deep layers (MERMEX group, 2011). In such areas, the intermittent nutrient enrichment promotes a switching between a small-sized microbial community and diatom-dominated populations (Conan et al., 1999; Siokou-Frangou et al., 2010). In the Ligurian Sea, for example, Marty and Chiavérini (2010) found a strong relationship between the depth of the wintertime convection and nutrient enrichment of the surface layer, triggering short and intense diatom production and deep vertical flux before the onset of the stratification and the development of the regular spring bloom (Stemmann et al., 2002). Higher abundance of zooplankton in the 1980s and late 1990s was also correlated with dry and cold winters (Vandromme et al., 2011). Besides, the modeling results of Auger et al. (2014) indicated that the total annual phytoplankton biomass is favored by convection because of the reduced zooplankton grazing pressure in winter and early spring while the annual primary production is not affected due to a compensation of its reduction in winter by its increase in spring.

All the above demonstrates that the NWM area concentrates several physical biological and chemical processes that are absolutely critical for the Mediterranean functioning but that are also dramatically relevant to understand the complex interplay between physical forcing and biogeochemical responses at a synoptic view. However, and despite of several national and international initiatives, the strong imbrications of spatial (from mesoscale to large scale) and temporal (from episodic scale to interannual scale) scales of the main processes involved limited our comprehension of the functioning of the area and of its role in a Pan-Mediterranean context.

In a review paper devoted to the Mediterranean Sea (MERMEX group, 2011), the inadequacy of the observational approaches, which were in the past for the most based on punctual cruises or a small number of fixed observing systems (and as such cannot be extrapolated to a wider spatial context or only under very specific hypotheses) was identified as the critical limitation for our understanding of the region. The deep water formation (DWF hereafter) process generally occurs during a period of less than one month, with a low interannual variability in the timing of the deep convection phase (Houpert et al., 2016). On the other hand, the DWF is preconditioned during at least the whole previous fall (Madec et al., 1996) and possibly previous winter periods. Moreover, the impact of the Levantine Intermediate Water (LIW) on the DWF was acknowledged (Grignon et al., 2010). The previous observational approaches were inadequate to completely describe the succession of the DWF phases. For the biological and chemical observations, this inadequacy was even more flagrant, with a consequence that despite of some fixed stations or satellite monitoring, the seasonality of the biogeochemical dynamic of the area was still missing.

A large experiment coupling the exploration of the ocean from the physical and biological point of views to observations of the air-sea interface and atmospheric boundary layer was then designed to couple the recent technological breakthroughs for small and intelligent autonomous platforms with satellite remote sensing (altimetry, sea surface temperature, and color) information, with more *classical* data acquisition by ship and aircraft sampling, and with existing fixed point moorings. The number of oceanic observations was dramatically high compared to previous experiments, and more importantly, observations were obtained all along a seasonal cycle. These data were directly used in combination with models, before, during, and after the observational phase. The strategy was focused on the following:

- The understanding, in a wide range of spatial and temporal scales of the physical mechanisms and forcing that precondition the convection zone, form dense water, and disperse it.
- The role of deep winter convection on the biogeochemical properties of the water masses, on the resulting organization of the pelagic ecosystems in spring and on the organic matter export

The modeling activity was central for driving the sampling strategy before the observation phase, for integrating the observations in a complete 4-D frame during the observation phase, while favoring the understanding of the integrated system and improving our long-term simulations and scenarii. All these efforts allowed us to obtain a unique and comprehensive data set to validate and improve the physical/biogeochemical coupled models.

The objective of this special issue is to synthesize the major results of these experiments and related operations. These results bring significant advances in our understanding of the dynamics of DWF and the related functioning of marine ecosystems that have been organized according to six major axes:

- Dynamics of the atmosphere and air-sea fluxes
- Interannual variability of dense water formation
- DWF during winter 2013
- Effects of small scales and intrinsic ocean variability on dense water formation
- Effect of DWF on biogeochemical budgets and primary production
- Response of zooplankton community to dense water formation

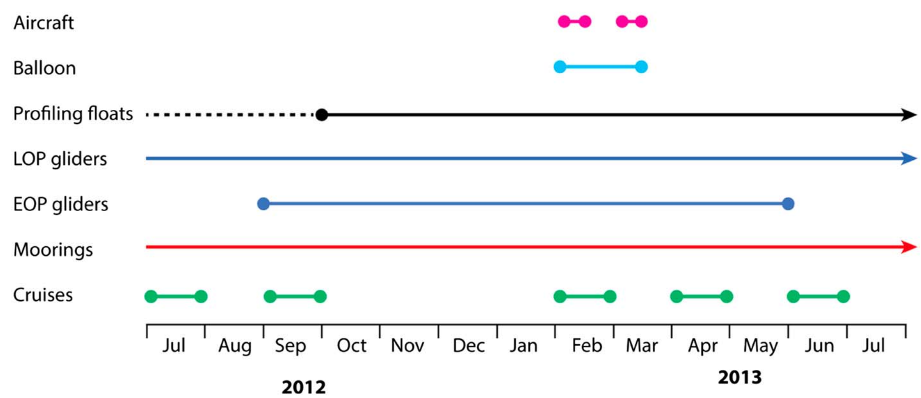

Figure 1. Time schedule of the different platforms and means used during the Deep Water formation Experiment (DEWEX) between July 2012 and July 2013.

3. Strategic Plan

The experimental strategy was based on pooling the Deep Water formation Experiment (DeWEX; Testor et al., 2018) and Hydrological cycle in the Mediterranean EXperiment (HyMeX) SOP2 (Estournel, Testor, Taupier-Letage, et al., 2016) projects respectively supported by the Marine Ecosystems Response in the Mediterranean Experiment (MerMEX) and HyMEX programs (both components of Mediterranean Integrated Studies at Regional And Local Scales [MISTRALS]). Several National and European projects (i.e., RemOCEAN ERC, Novel Argo Ocean observing System (NAOS) EquipEx, FP7-GROOM, FP7-JERICO, and FP7-PERSEUS), combined with the long-lasting monitoring activity of MOOSE and with some additional surveys (i.e., MerMEX WP2-SPECIMED), provided a solid and favorable context contributing to the success of this experiment.

The observational strategy was mainly driven by the need to obtain pertinent observations all along a seasonal cycle. Six cruises were then programmed at key moments of the year 2012–2013 (see Figure 1). This intensive ship-based observation effort, carried out from July 2012 to September 2013, was completed by a large variety of tools, for the most robotic or semirobotic, to obtain a quasi-synoptic view of the area, to interpolate between the cruises, and to provide enough observations to initialize models (Figure 1).

The observation strategies involved then several airborne (aircraft and atmospheric boundary layer balloons), surface (boat, fixed, and drifting buoys), and oceanic (physical and bio-optical Argo floats and gliders, mooring lines equipped with CTD sensors, current-meters, and sediment traps) platforms (Figures 2 and 3). Space observations of the sea surface altimetry and ocean color were used to monitor the interannual variability and spatial extent of the convection. The ATR-42 aircraft operated by the “Service des Avions Français Instrumentés pour la Recherche en Environnement (SAFIRE),” investigated the mean and turbulent characteristics of the marine atmospheric boundary layer above the oceanic convection region. Boundary layer pressurized balloons, developed by the “Centre National d’Etudes Spatiales,” were used to document the evolution of the thermo-dynamical characteristics along the trajectory of air parcels during northern wind (Mistral) events.

Measurements from research vessels (R/V L’Atalante, R/V Le Suroît, and R/V Tethys II) were intended to be operated over periods of 3 weeks in order to cover most of the NWM during different key phases of the seasonal cycle of the region. The six cruises were carried out in July–August 2012 (summer stratified period), September 2012 (summer-to-fall transition stratified period), February 2013 (prebloom, winter mixing period), April 2013 (spring bloom, restratification, and spreading period), July 2013 (post bloom and restratified period), and September 2013. The February DeWEX 2013 cruise, which took place during the period of intense mixing, overlapped with the airborne observations. Only during naval operations, a very large set of chemical and biological data were collected, in particular to provide stocks, fluxes, diversities, and biological activities. During all the cruises, a CTD carousel composed of 12 Niskin bottles was deployed and discrete samples were collected. About 440 surface-to-bottom profiles of CTD and of biogeochemical parameters

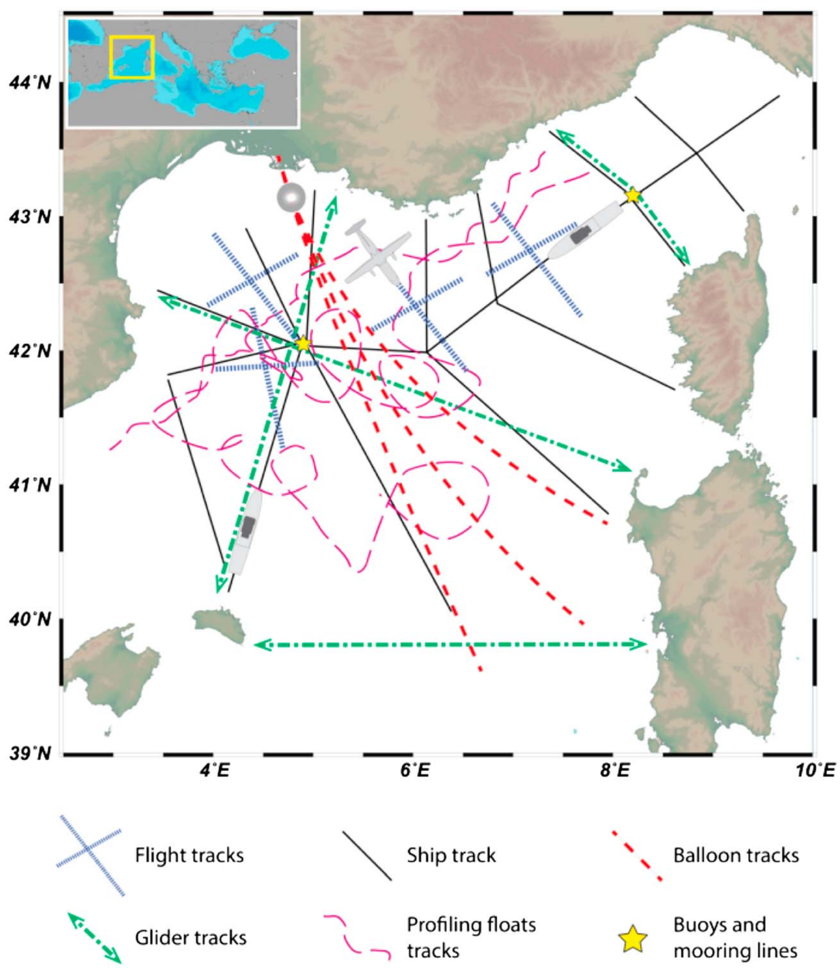

Figure 2. Sketch of sampling strategy and examples of trajectory for airborne and oceanic platforms during the Deep Water formation Experiment (DEWEX) in the northwestern Mediterranean.

(chlorophyll-a, dissolved oxygen, turbidity, currents, aggregates, and zooplankton images) and 9,240 water samples for nutrients, dissolved, and particulate organic matter, pigments, microbial diversity were collected. During February and April 2013 cruises, primary and bacterial productions were measured, and additional vertical net hauls were performed to collect zooplankton.

Surface and ship-based observations were also collected over the whole NWM. Numerous profiles in the upper layer between the surface and 1,000- or 2,000-m deep were collected with Argo and BGC-Argo profiling floats and gliders. All these platforms were equipped with CTD sensors, and some platforms also carried biogeochemical sensors (i.e., chlorophyll-a, dissolved oxygen, nitrate, and optical backscattering). After interoperability processes, the moorings, profiling floats, and gliders provided an opportunity to characterize the temporal variability of the oceanic conditions throughout the year, and small-scale features, such as submesoscale eddies and convective plumes. Surface drifters (SVP and Marisonde buoys) and fixed meteorological buoys (*Lion* and *Azur Météo-France* buoys) were used to collect air-sea interface parameters. Long mooring lines in the convection region (Lion) and in the Ligurian Sea (Dyfamed) provided additional observations of the evolution of the mixed layer depth, water masses, currents, and particle fluxes.

4. Major Outcomes

4.1. Dynamics of the Atmosphere and Air-Sea Fluxes

The winter-integrated buoyancy loss over the Gulf of Lion was identified as the primary driving factor of the DWF interannual variability (Somot et al., 2016). At a daily scale, the Atlantic Ridge weather regime was

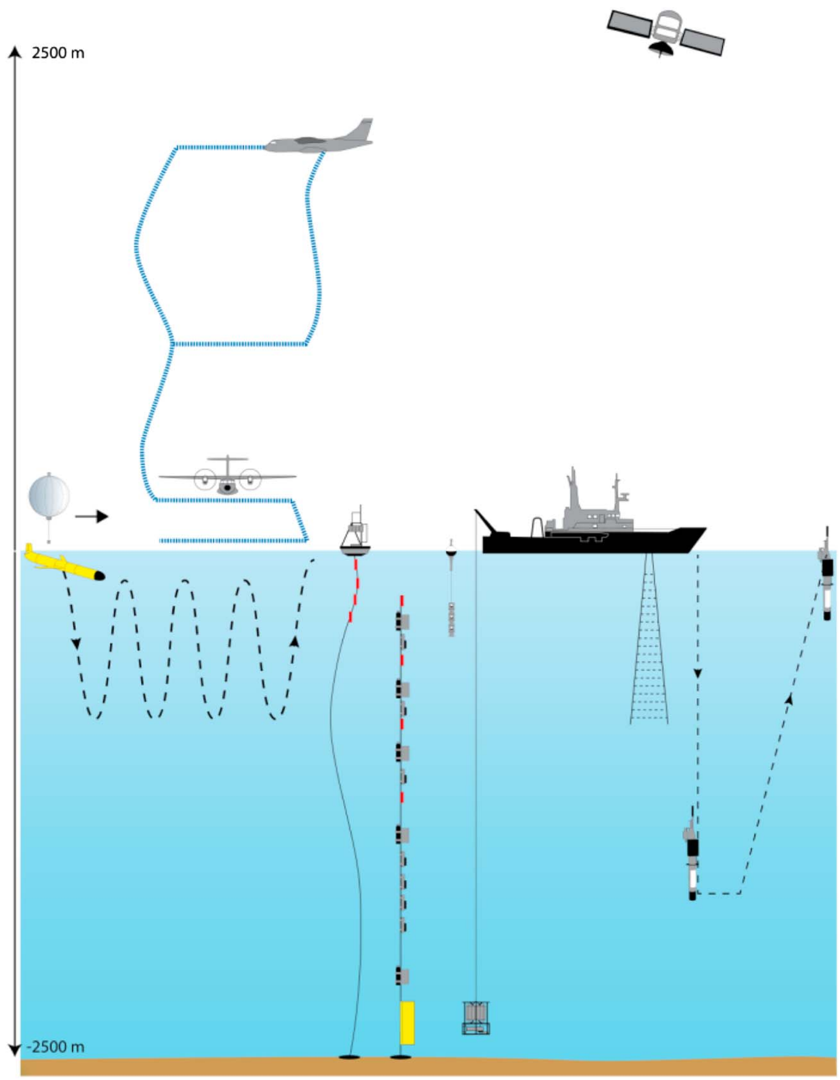

Figure 3. Side view of the airborne and oceanic platforms used during the Deep Water formation Experiment (DEWEX).

identified as favorable to the Mistral wind and associated strong buoyancy losses and therefore to DWF, whereas the positive phase of the North Atlantic Oscillation was unfavorable. The mesoscale dynamics of the Mistral wind over the Gulf of Lion was detailed in Drobinski et al. (2017). They related boundary layer balloons observations in the marine atmospheric boundary layer with the AROME-WMED weather forecast model and analyzed all the terms of the Lagrangian formulation of the momentum conservation equation to identify forces acting in the injection, ejection and deceleration regions of the Mistral flow.

Several articles have addressed the determination of air/sea fluxes at different spatial and temporal scales. Airborne measurements enabled to characterize the mean and turbulent structure of the marine atmospheric boundary layer (Brilouet et al., 2017). They showed that a one-dimensional description of the vertical exchanges remains problematic because of the presence in the marine atmospheric boundary layer of organized structures such as two-dimensional rolls favored by strong winds and surface heat fluxes. Caniaux et al. (2017) using measurements at the air sea interface and in the water column implemented an inverse method to estimate heat and water fluxes during 1 year for the NWM basin at a fine-scale resolution. They compared air-sea fluxes adjusted using observations, with some operational numerical weather prediction models (such as ARPEGE, NCEP, ERA-Interim, ECMWF, and AROME) and concluded that these models were unable to retrieve the mean annual patterns and values of fluxes. Song and Yu (2017) performed an analysis of the whole Mediterranean Sea surface energy budget using nine surface heat flux climatologies obtained from atmospheric reanalyses, satellite, or ship observations. They compared them with the heat flux associated to the net transport through the Strait of Gibraltar and to data-assimilated global ocean state estimation.

Uncertainties on heat and water fluxes, in particular related to uncertainties in the parameterization of turbulent fluxes under strong wind conditions, remain an important problem for ocean modeling in the Mediterranean, as shown by the sensitivity study by Seyfried et al. (2017) on the modeling of the convection during winter 2012–2013. Unfortunately, no direct observation of the turbulent fluxes was available during the strong wind events of DeWEX/HyMeX SOP2. However, it can be noted that the uncertainties of turbulent fluxes parameterization are not specific to the Mediterranean.

4.2. Interannual Variability of Dense Water Formation

The currently well-accepted hypothesis based on the climate projections predicts a strong decrease of DWF rate, as surface layers will become too warm to produce dense waters. On the other hand, increasing evaporation should increase the surface water salinity, which could, in turn, raise density and result in convection. So at least cyclically the Mediterranean should continue to produce dense water through different mechanisms; however, under this scenario, deep water characteristics should be deeply modified, affecting nutrient budgets and the whole ecosystem functioning.

The interannual variability of convection in the Gulf of Lion over the last few decades has not been monitored consistently and uniformly; CTD profiles and short-term mooring lines have been used to document the period from 1970 to 2000 (see Béthoux et al., 2002 ; Mertens & Schott, 1998). It is only since 2007, with the implementation and simultaneous use, in the framework of MOOSE in particular, of fully instrumented mooring lines and buoy at the Lion site, satellite data, gliders, profiling floats, and annual cruises throughout the NWM that a reference data set has been established to characterize the DWF interannual variability in terms of mixed layer depth, convective surface, DWF rate, or water mass characteristics, which allowed to evaluate accurately long-term model simulations.

High-frequency temperature, salinity, and current measurements, collected at the Lion site (Durrieu de Madron et al., 2017; Houpert et al., 2016), revealed that from 2007 to 2015, bottom reaching convection and production of new WMDW, denser than 29.11 kg/m^3, occurred every winter between 2009 and 2013. The overlapping of the mixing and restratification phases was regularly observed, with a secondary vertical mixing event of 2- to 4-day long occurring after the beginning of the restratification phase (generally in April). This pattern is retrieved in the simulations produced by Léger et al. (2016) or in situ data detailed by Severin et al. (2014, 2016).

As expected, the succession of bottom-reaching convection episodes between 2009 and 2013 altered the deep-water masses thermohaline characteristics, which already underwent a significant change after exceptional winter 2005 convection event (see Herrmann et al., 2010, and references therein). The stepwise rise in temperature, salinity, and density, observed consecutively to each bottom-reaching convection event, led between 2009 to 2013 to an increasing trend in salinity ($+3.3 \pm 0.2 \cdot 10^{-3}$/a) and potential temperature ($+3.2 \pm 0.5 \cdot 10^{-3}$ °C/a) for the deep layer (Houpert et al., 2016). This confirmed the increase in rate observed from literature ($+9.2 \cdot 10^{-4}$/a in salinity and $+2 \cdot 10^{-3}$ °C/a in temperature for 1945–2000 period; Vargas-Yáñez et al., 2010). These increasing trends in the deep layers would result from a heat and salt accumulation during the 1990s in the surface and intermediate layers of the Gulf of Lion, transferred stepwise toward the deep layers when intense convective events occur (like in 1999, 2005, and later; Somot et al., 2016).

The evolution of the deep water thermohaline characteristics due to winter convection depends directly on the volume of newly formed dense water. However, to get such estimates remains a complex issue since there is currently no objective criterion for assessing them. Two different methods were primarily used to estimate the volume of new WMDW, the advantages, and disadvantages of each are explained by Testor et al. (2018). First, as the vertical dilution effect of convection reduces the chlorophyll concentration (Severin et al., 2014), the volume of new WMDW can be approximated as the extent of the chlorophyll depleted mixing zone seen by ocean color satellite times the mixed layer depth. Second, the volume of new WMDW can be estimated by quantifying the amount of new water exceeding a given density threshold (e.g., $>$29.11 kg/m^3, the maximum density of the *old* deep water) over the NWM basin. Houpert et al. (2016) estimated that between 2009 and 2012, the new WMDW formation rate varied between 0.91 and 1.25 Sv (when averaged over 1 year). As for them, Herrmann et al. (2017) used altimetry and ocean color satellites data to obtain a wider annual volume range of 0.0 to 2.67 Sv for the 1998–2016 period.

4.3. Deep Water Formation During Winter 2013

The winter buoyancy fluxes in 2012–2013 were sufficient to trigger deep convection and significant production of new WMDW during DeWEX operations. With an observing system simulation experiment approach, Waldman et al. (2016) confirmed the ability of the observation network (ship track in Figure 2) to correctly quantify the spatial extent of convection and the seasonal evolution of dense water volume. Several estimations of DWF rate deduced from observations of the mixed patch volume (Herrmann et al., 2017), dissolved oxygen ventilation of the deep waters (Coppola et al., 2017), and the newly formed dense water volume (Herrmann et al., 2017; Testor et al., 2018) were coherent and ranged between 1.27 and 2.0 Sv. This last method, which appears to be the most robust, was used to quantify the rate of dense water formation for the different models used.

All the observations provided important results for model evaluation and sensitivity studies. Numerical models were generally able to simulate realistic DWF (location, triggering, and chronology characteristics) during winter 2013 (Estournel, Testor, Damien, et al., 2016; Lebeaupin Brossier et al., 2017; Léger et al., 2016; Waldman, Herrmann, et al., 2017; Waldman, Somot, et al., 2017) and calculated DWF rates between 1.33 and 2.59 Sv.

Sensitivity analysis revealed that models are mostly affected by fine-scale ocean structures, such as shelf DWF and export, eddies, and fronts at the rim of the convective patch well evidenced by glider observations (Testor et al., 2018). The resolution of the mesoscale definitively improved the realism of the simulations and their agreement with observations, by increasing the eddy kinetic energy and enhancing the stratifying effect of advection through the mixed patch (Estournel, Testor, Damien, et al., 2016; Lebeaupin Brossier et al., 2017; Waldman, Somot, et al., 2017). Models also showed a large sensitivity to the initial and boundary conditions (introducing bias on the stratification), the wind intensity, and air-sea fluxes (Estournel, Testor, Damien, et al., 2016; Léger et al., 2016), which affect the water masses characteristics and the volume of dense water formed during convection.

4.4. Effects of Small Scales and Intrinsic Ocean Variability on Dense Water Formation

The distinction between the internal (intrinsic) and external (atmospherically forced) components of the ocean variability is central to understand the forcings modulating DWF intensity and water mass transformations. The large presence of mesoscale and submesoscale eddies and current instabilities in the NWM basin are sources of ocean intrinsic variability that can retroact on the basin-scale circulation through an inverse energy cascade. The multiple platforms used during the experience allowed identifying new dynamical processes at small scales or better characterizing already known processes (frontal instabilities, convective plumes, and vortices). Indeed, Giordani et al. (2017) described a symmetric instability at the western edge of the deep convection area when current and dominant northerly winds are in the same direction. This instability results from a cross-front ageostrophic circulation, which subducts surface low-potential vorticity waters on the dense side of the front and obducts high-potential vorticity waters from the pycnocline on the light side of the front.

In the convection area, Margirier et al. (2017) were able from glider navigation data to describe the statistical physical and biogeochemical characteristics of the convective plumes. It appears that these plumes, which had radius of about 350 m and significant vertical velocities (up to 18 cm/s), covered about one third of the deep convection area. Vertical velocities are scaled by atmospheric fluxes inducing downward buoyancy fluxes with a vertical diffusion coefficient of 7 m^2/s. Bosse et al. (2016) provided an inventory of the different types of cyclonic and anticyclonic submesoscale coherent vortices (SCVs) observed in the NWM by gliders, cruises, and mooring data during a four-year period (2009–2013). They showed that these energetic features prevailed over the large-scale geostrophic circulation and remained coherent for long periods of time (typically 1 year). Bottom-reaching convection might favor the formation of cyclonic vortices. Using a realistic high-resolution (1 km) numerical model, Damien et al. (2017) simulated the formation and spreading of SCVs during intermediate and deep convection events. They reproduced similar long-lived cyclonic and anticyclonic coherent structures. Both studies showed the prominent role of SCVs in the spreading of the convected waters, their contribution to the ventilation of the deep basin, and their influence on the convection onset the following winter.

Estournel, Testor, Damien, et al. (2016) discussed the interaction in autumn of the surface and Ekman buoyancy fluxes associated with displacements of the front bounding the convection zone to the south. They show that these processes are important for the convection preconditioning processes. Waldman, Herrmann, et al. (2017) showed that intrinsic variability has a strong impact on the timing and geographical extent of a convective event but has little impact on the rate of convection in the constrained 2012–2013 case. Waldman et al. (2018) further showed that intrinsic variability also explains a significant fraction of the deep convection interannual variability, although it has only modest impacts on the long-term mean state.

4.5. Effect of Dense Water Formation on Biogeochemical Budgets and Primary Production

The DWF in the NWM impacts the nutrients distribution, matter export, and development of the trophic network, and it strongly contributes to the modification of the deep stocks of these components at the basin level. Three different areas of the western basin were identified by contrasting vertical mixing regimes: deep convection, shallow convection, and stratified area (Kessouri et al., 2018). Using a 3-D high-resolution coupled hydrodynamic-biogeochemical model, these authors showed in all three regions that the mixed layer deepening during the destratification process induced an upward nutrients flux, triggering in turn, an autumnal phytoplankton bloom. In contrast at the end of winter, the end of turbulent mixing favored the onset of an intense spring bloom only in the deep convection region. The authors concluded that despite these seasonal variations, annual primary production in all three regions is quite similar, but total organic carbon exported to deep waters was 3 and 8 times higher for moderate and deep convective areas respectively, compared to stratified ones.

The depth reached by the convection directly drives the nutrient stoichiometry of water masses in winter (Severin et al., 2014; Severin et al., 2017), which influences the phytoplankton community structure in spring (Mayot, D'Ortenzio, Uitz, et al., 2017; Severin et al., 2016), which in return controls the nutrient availability for the rest of the year by direct uptake (Kessouri et al., 2017). The general emerging pattern is that the spatial (horizontal) extension of the convective area in winter influences the intensity of the resulting bloom in spring (because of variable amount of nutrients injected into the surface layer), but the depth (vertical) reached by the convection (and in particular when deep convection reaches the nepheloïd boundary layer) plays a key role in the bloom diversity (notably due to different nutritional stoichiometry and higher Si:NO_3 ratio when convection is deeper; Leblanc et al., 2018; Mayot, D'Ortenzio, Uitz, et al., 2017). These variations could be partly the result of pore water release loaded with nutrients because of sediment resuspension enhanced by the bottom-reaching mixing (Durrieu de Madron et al., 2017).

Moreover, the deep convection events result in a homogenization of hydrological characteristics but also of the prokaryotic communities over the entire convective cell, resulting in a surprising predominance of typical surface bacteria (such as *Oceanospirillale* and *Flavobacteriale*; Severin et al., 2016). However, physical turbulences only were not sufficient to explain this new distribution but act in synergy with quantity and quality of exported organic matter. Indeed, the authors explained this dominance by the rapid export of fresh and labile organic matter to the deep layers. Finally, the rapid return of specific prokaryotic communities and classic activities in the intermediate layer less than 5 days after the intense mixing (and before hydrological restratification) indicates a marked resilience of the communities, apart from the residual deep mixed water patch (Severin et al., 2016; Severin et al., 2017). Finally, the heterogeneous surface distribution of nutrients during the winter deep convection event in the NWM was shown to impact the phytoplankton distribution and community structure several weeks after the end of convective events (Mayot, D'Ortenzio, Uitz, et al., 2017; Severin et al., 2016; Severin et al., 2017).

The multiple platforms of physical, bio-optical, and biochemical measurements provided a detailed characterization of the spatial and temporal structuring of the main biogeochemical variables at different scales, from small-scale vortex structures to the basin as a whole. The role of the post convective SCVs on nutrient distribution and phytoplankton communities, as well as on the subsequent enhanced primary production and higher carbon sequestration, was revealed by Bosse et al. (2017). They showed that SCVs present important dynamical barriers that drastically reduce lateral exchanges between their cores and the surroundings thus enabling them to keep their core characteristics the same for a long time. This suggests that they locally have a great imprint on both physical and biogeochemical cycles. At larger scale, two distinct trophic regimes as *High Bloom* centered on the convection area and a *Bloom* bioregion located at its periphery were identified (Mayot, D'Ortenzio, Taillandier, et al., 2017; Mayot, D'Ortenzio, Uitz, et al., 2017), in agreement with regions mentioned above and defined by Kessouri et al. (2018).

The interannual variability of the physical and biogeochemical coupling of the NWM was also assessed using satellite ocean color observations (Mayot, D'Ortenzio, Uitz, et al., 2017) and a 3-D hydrodynamic-biogeochemical coupled model (Ulses et al., 2016). Both studies showed that phytoplankton biomass during the spring bloom is larger in years associated with intense deep convection events. Modeling gave further evidence that amounts of nutrients annually injected into the surface layer is clearly linked to the intensity of the convection but does not significantly modify the overall primary production budget. Indeed, the primary production is inhibited during severe winters and transiently explodes during the restratification phase, while it increases continuously during both phases when winters are milder. As seen above, the occurrence of a highly productive bloom is also related to an increase in the phytoplankton bloom size area. For the period including winter 2013, the processes responsible for the stoichiometry variability at the seasonal scale were disentangled by using a coupled physical-biogeochemical model able to correctly reproduce the general observed seasonal dynamics of the physical and biogeochemical events (Kessouri et al., 2017). The dynamics of the nutrients, phytoplankton and zooplankton biomass, and their interactions during the convection period and the spring bloom were well reproduced. The authors estimated nutrient budgets for the entire year and showed that the convection region represented a sink of inorganic and a source of organic nitrogen and phosphorus. This process can efficiently export organic carbon below the photic layer (Kessouri et al., 2017; Kessouri et al., 2018 ; Severin et al., 2017).

4.6. Zooplankton Community Response to Dense Water Formation

The deep convection zone is likely an area of both enhanced energy transfer to higher trophic levels and organic matter export (Kessouri et al., 2018; Severin et al., 2017). The two trophic regimes observed on the primary producer level are also reflected on higher trophic levels. Indeed, in winter, low zooplankton abundance and biomass were observed in the deep convection zone, but higher values on its periphery. In spring, this pattern reversed with high biomass dominated by herbivorous species in the deep convection zone and lower values on the periphery (Donoso et al., 2017). The potential grazing impact of phytoplankton by zooplankton was estimated to increase by 1 order of magnitude from winter to spring. In April, all areas except the deep convection zone incurred top-down control by zooplankton (Siokou-Frangou et al., 2010).

Despite this significant seasonal variability of zooplankton biomass, the community composition was comparable for both winter mixing and spring bloom periods, typified by high copepod dominance (Donoso et al., 2017). Using stable isotope mixing models, Hunt et al. (2017) estimated that micro–particulate organic matter never contributed more than 20% to zooplankton biomass, even in regions where microphytoplankton was plentiful, indicating that a large part of its biomass may have remained ungrazed.

Program acronyms

DeWEX:	Deep Water formation Experiment
HyMEX:	Hydrological cycle in the Mediterranean EXperiment
MERMEX:	Marine Ecosystems Response in the Mediterranean Experiment
MISTRALS:	Mediterranean Integrated Studies at Regional And Local Scales
MOOSE:	Mediterranean Ocean Observing System on Environment
NAOS:	Novel Argo Ocean observing System
PERSEUS:	Protection EuRopean Seas and borders through the intelligent Use of surveillance

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