Modélisation de la variabilité climatique de la circulation et des masses d'eau en Méditerranée : impacts des échanges océan-atmosphère.

Jonathan Beuvier

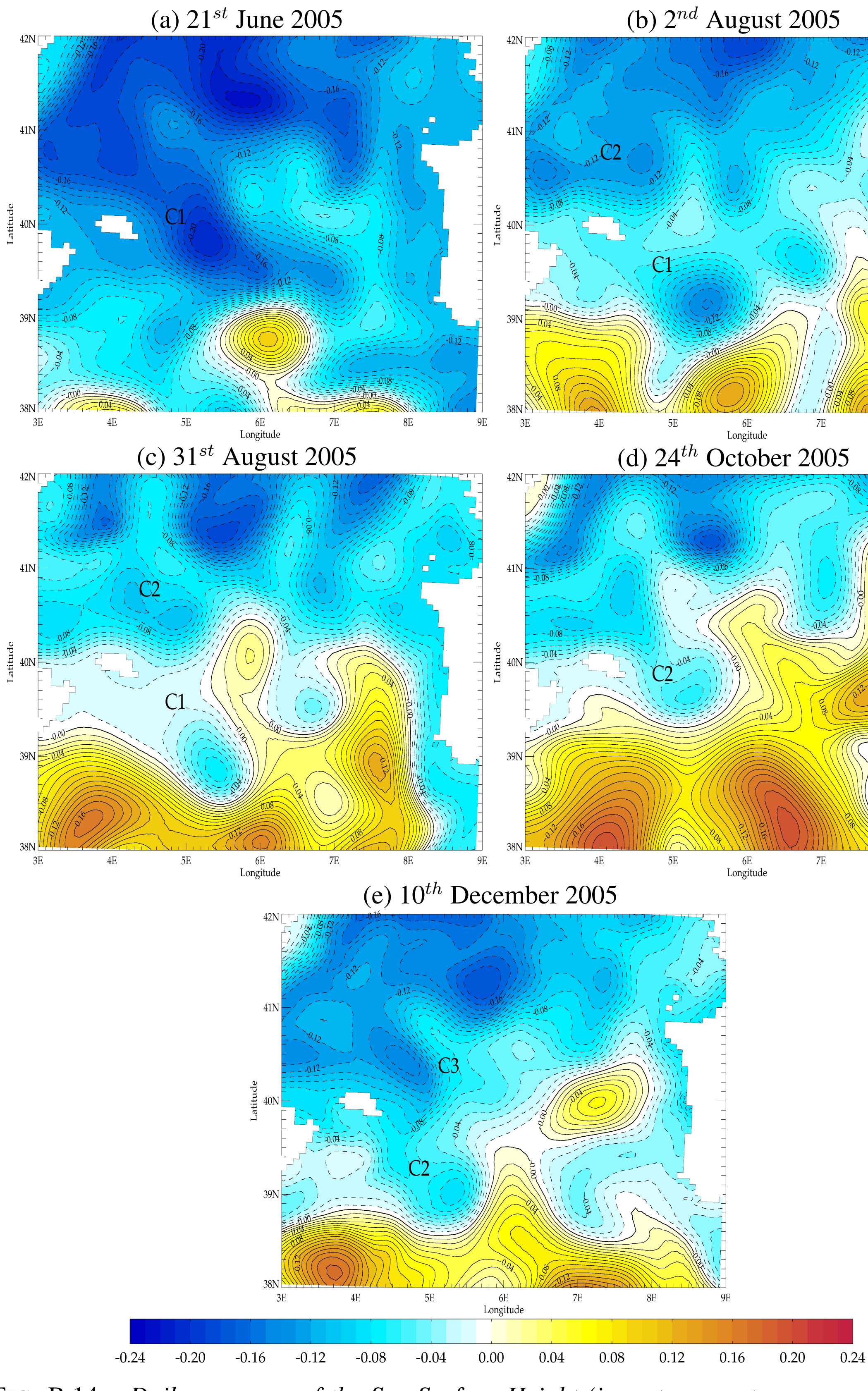

FIG. B.14 – *Daily averages of the Sea Surface Height (in meters, contours every 0.01 m), in simulation MED12-ARPERA-3, in the center of the Western Mediterranean, for (a) the 21^{st} June 2005, (b) the 2^{nd} August 2005, (c) the 31^{st} August 2005, (d) the 24^{th} October 2005 and (e) the 10^{th} December 2005. C1 ,C2 and C3 identify the three successive deep cyclones.*

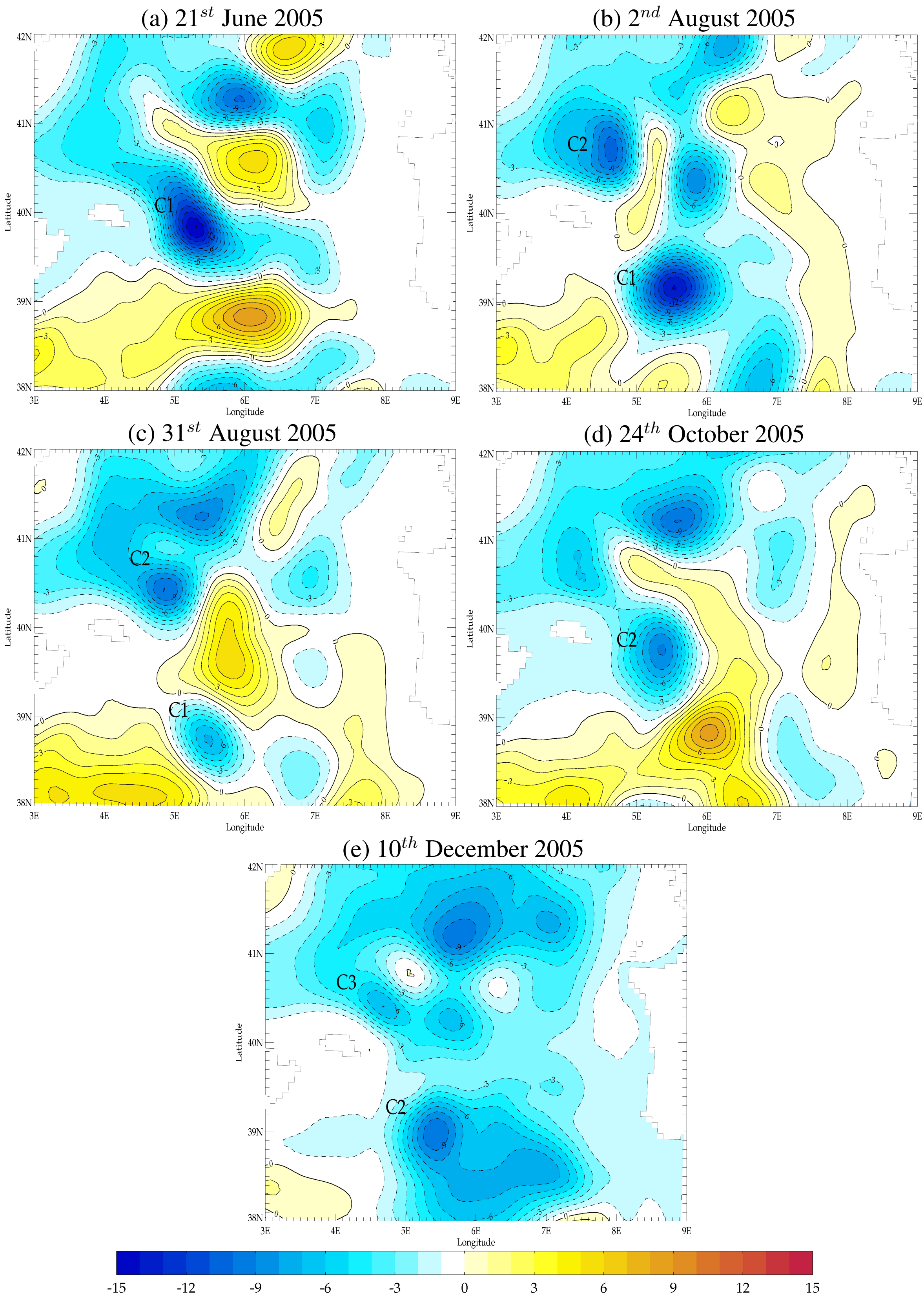

FIG. B.15 – *Daily averages of the Barotropic Stream Function (in Sv, contours every 1 Sv), in simulation MED12-ARPERA-3, in the center of the Western Mediterranean, for (a) the 21st June 2005, (b) the 2nd August 2005, (c) the 31st August 2005, (d) the 24th October 2005 and (e) the 10th December 2005. C1 ,C2 and C3 identify the three successive deep cyclones.*

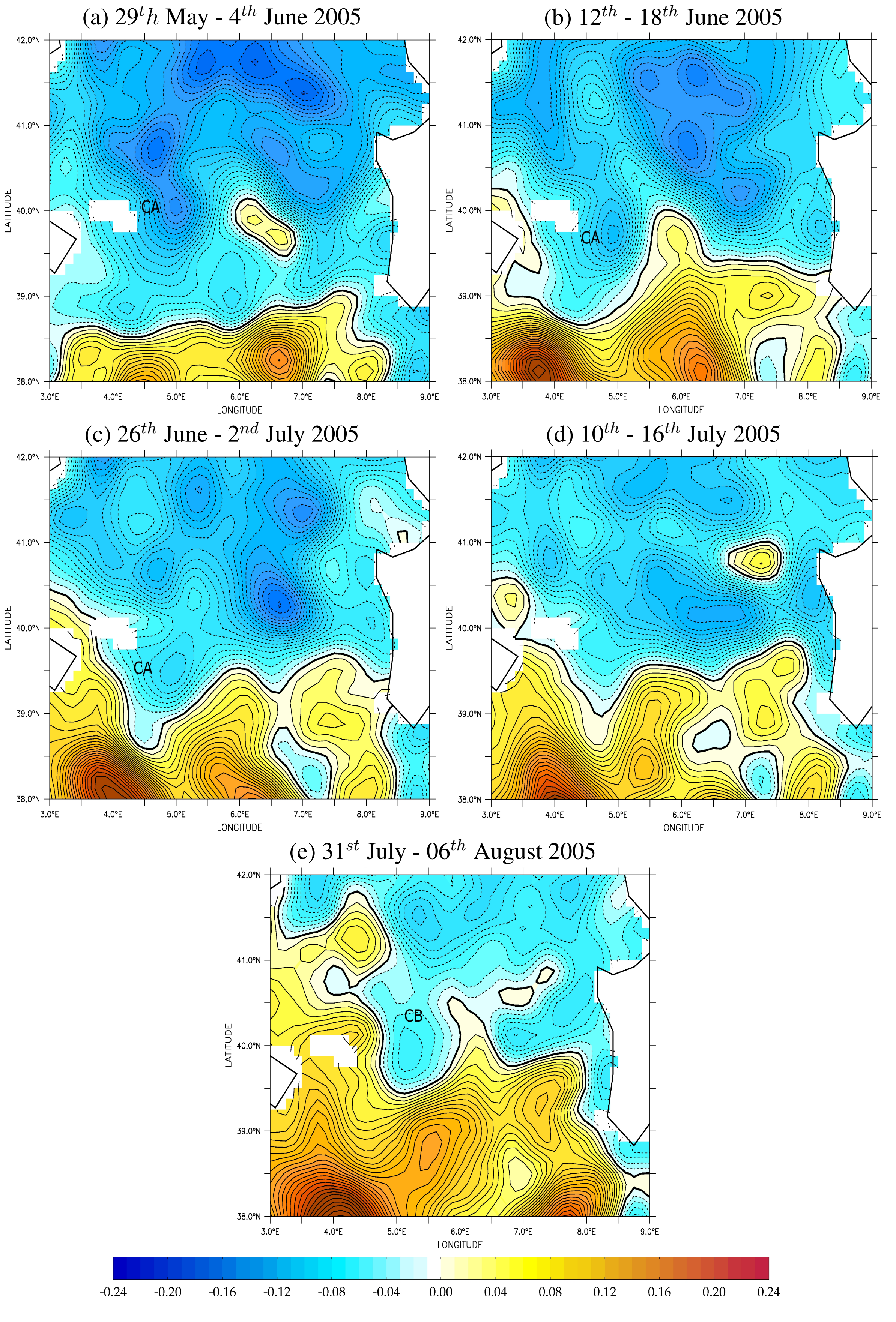

FIG. B.16 – *Weekly averages of the Sea Surface Height (in meters, contours every 0.01 m), in AVISO observations, in the center of the Western Mediterranean. CA and CB identify two successive cyclones.*

of the deep layers in the model could also explain the difficulty of the model to horizontally propagate such dense water mass quickly enough. Finally, *Herrmann et al.* (2008) have shown that the horizontal resolution of the model plays also a role, not only on the spatial scale of the processes that can be resolved by an ocean circulation model, but also on the formation of more energetic eddies. Increasing the horizontal resolution would thus certainly lead to a better representation of the advection time of deep water by barotropic eddies.

B.4.3.2 Lagrangian view

We adopt here a Lagrangian approach to follow the spreading of the new WMDW formed in winter 2005. We use ARIANE (*Blanke and Raynaud*, 1997), a lagrangian simulator of particles, in an offline configuration with the daily outputs of horizontal and vertical velocities from the simulation MED12-ARPERA. In ARIANE, particles are only advected in 3D, they are not affected by mixing or diffusion. We thus start the ARIANE simulation at the end of the deep mixing phase, that is to say on the 1^{st} March 2005, with an ensemble of particles initialised as follow (Figure B.17a) : we put one particle in each ocean grid-mesh (one every 0.08 ° horizontally and one in each vertical level), at seven different vertical levels below 1100 m to track dense waters (1100 m, 1300 m, 1500 m, 1700 m, 2000 m, 2300 m and 2600 m), in the area corresponding to the maximal extent of the deep convection (see Figure B.8).It gives an ensemble of 2839 particles. We perform an ARIANE simulation until the 31^{st} December 2008 (1402 days of simulation). During the almost 4 years of ARIANE simulation, the particles initialised in the Gulf of Lions spread in all the Algero-Provencal, Catalan and Ligurian subbasins (Figure B.17b). A few of them are uplifted to the surface layers and then carried faster, but they do not exit the Western Mediterranean (red and orange trajectories in Figure B.17c). Figure B.17d focuses on the particles whose final position is deeper than 1100 m, the shallowest initial depth. The deep spreading is mainly constrained by the bathymetry. No particule reaches the Alboran subbasin (Asb in Figure B.1). Only four of them cross the Channel of Sardinia and only one propagates in the Tyrrhenian subbasin (Figure B.17e). The trajectory of this latter particle, with its position at different dates, indicates that the spreading, globally southeastwards, is quite fast in a first time. Then, this particle needs more than two years to cross the Channel of Sardinia. During its path, around 40.5 °N – 5.5 °E, this particle seems to be trapped in an eddy. The particle with the westernmost trajectory (Figure B.17f) shows a similar behaviour : a quick southwards propagation in a first time, then towards the Strait of Gibraltar and progressively this particle goes slower (it takes 2 years to cross a distance of 3 ° of longitude). In the area [38 °N ;40 °N]-[5 °E ;6 °E], this particle seems also to be trapped in an eddy.

To better characterise the fast spreading during the first year of the ARIANE simulation, we display the trajectories deeper than 1100 m by periods of two months from March 2005 to March 2006 (Figure B.18). It appears that, during this first year, the spreading occurs mainly on a North-South axis, from the Gulf of Lions to the Algerian coast. Even if it is a deep propagation, it seems quite fast, since the quickest particles, which are deeper than 2000 m depth, reach the 38 °N line the 1^{st} July, $i.e.$ after 4 months of spreading (Figure B.18b). Then, the spreading on the West-East axis, towards the Strait of Gibraltar and the Channel of Sardinia, is slower, since particles first cross the 3 °E line near the 1^{st} January 2006 (Figure B.18e). However, as for the comparison with satellite observations, this spreading is slower than in in-situ observations, since *Schroeder et al.* (2008) observed the presence of new WMDW off the Algerian coasts near 1 °E during June 2005. The spreading towards the Channel of Sardinia is even slower, after one year no particle is in the box defined earlier in this area (Figure B.18f). On all these two-month trajectories, particles are obviously carried by eddy induced circulations in the center of the Algero-Provencal subbasin (see Figures B.18c, d and e). Given the dates on which these

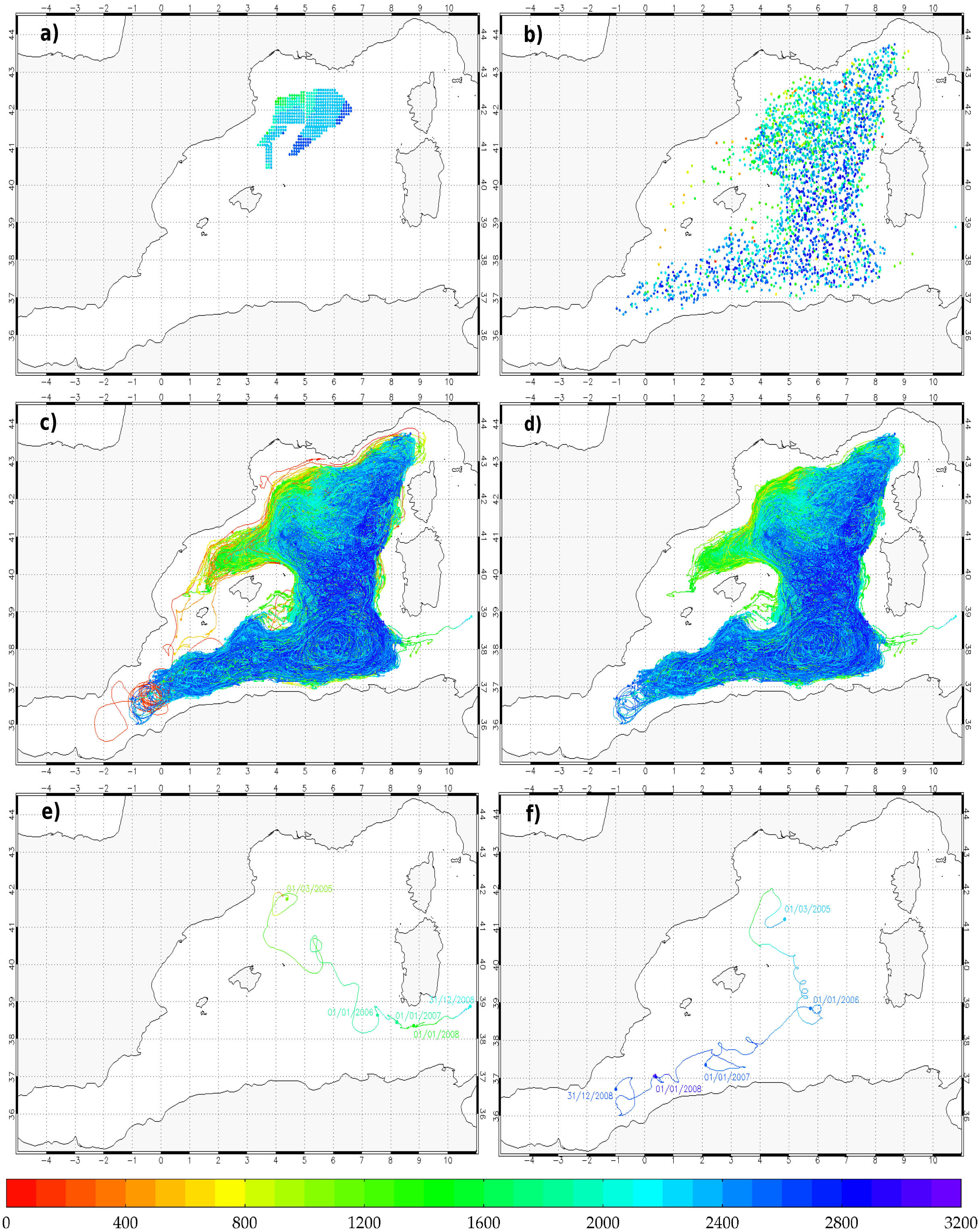

FIG. B.17 – *Overview of the main characteristics of the ARIANE simulation : (a) initial positions (1*st *March 2005), (b) final positions (31*st *December 2008), (c) all 1402-day trajectories, (d) trajectories with final positions under 1100 m, (e) easternmost trajectory and (f) westernmost trajectory. The colors indicate the depth (in meters) of positions and trajectories.*

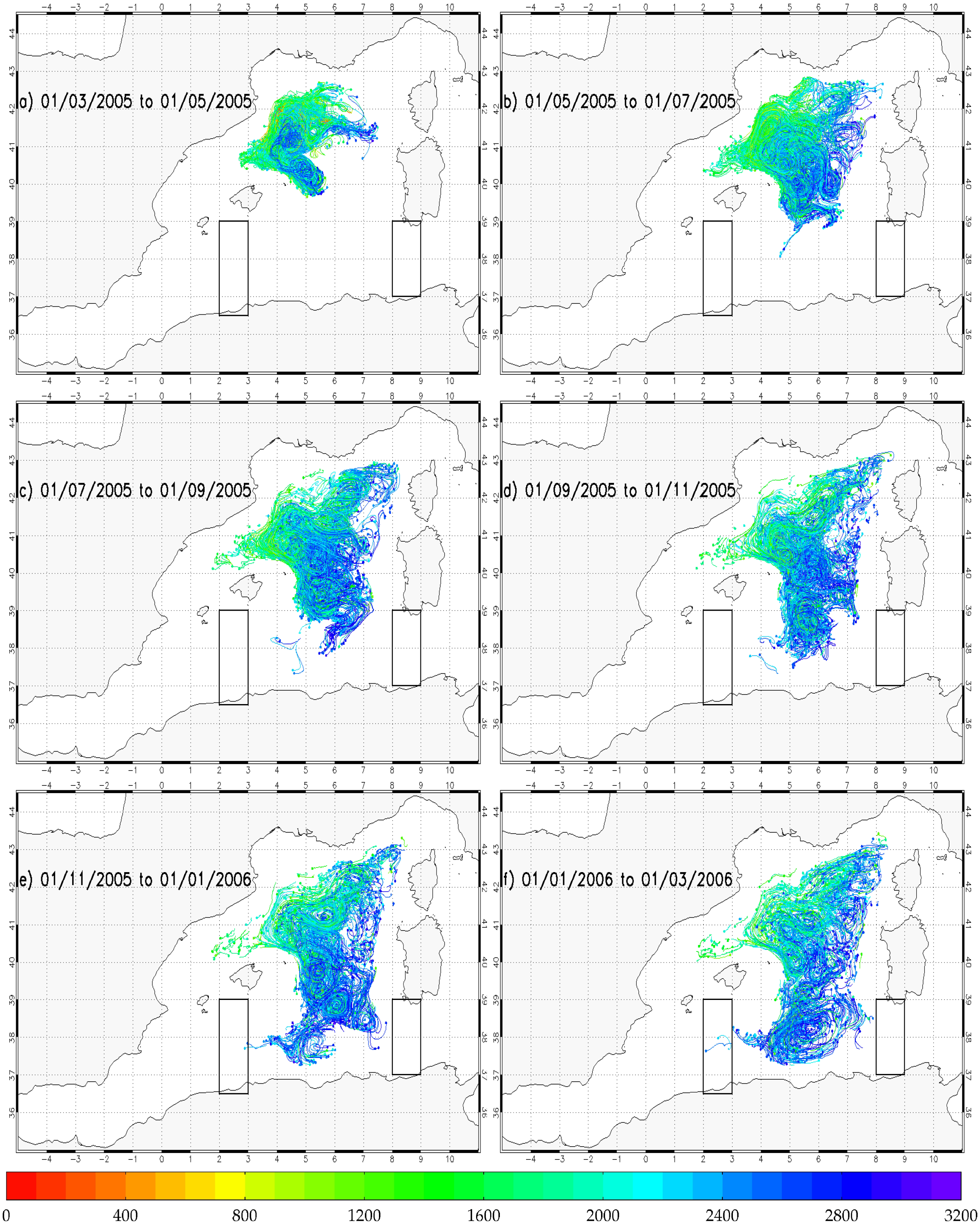

FIG. B.18 – *Trajectories deeper than 1100 m during the first year of the ARIANE simulation : (a) from the 1st March 2005 to the 1st May 2005, (b) from the 1st May 2005 to the 1st July 2005, (c) from the 1st July 2005 to the 1st September 2005, (d) from the 1st September 2005 to the 1st November 2005, (e) from the 1st November 2005 to the 1st January 2006 and (f) from the 1st January 2006 to the 1st March 2006. The colors indicates the depth (in meters) of positions and trajectories. The rectangles correspond the boxes of the θ-S diagrams of Figure B.10.*

patterns occur, they can be related to the successive deep cyclonic eddies previously identified. The recirculation due to the deep eastern Algerian gyre is also noticeable on Figure B.18f.

B.4.3.3 Discussion

A deep convection event occurs in March 2005 in the simulation. New WMDW is formed in large volume. With a noticeable signature in density, we track this water mass until the southern part of the Algero-Provencal subbasin (APsb in Figure B.1). In the simulation, the Eulerian and Lagrangian approches give different estimates of this new WMDW transport time towards the southern boundaries of the Algero-Provencal subbasin (the Channel of Sardinia and the Strait of Gibraltar). It can be assumed that the Eulerian approach includes diffusive and mixing processes whereas the Lagrangian approach gives an approximation of only the advective transport time. In the area at the western entrance of the Channel of Sardinia, changes of the deep water thermohaline characteristics appear 9 to 10 months after the convection event whereas in the ARIANE simulation, particles need more than one year to propagate towards this area. Thus, in the south-eastern part of the Algero-Provencal subbasin, new WMDW characteristics are carried faster when diffusion and mixing are taken into account than through advection only. On the contrary, particles in the ARIANE simulation arrive in the western Algerian subbasin 8 months after the convection event, while we showed that the deep thermohaline characteristics changed there 12 to 13 months after winter 2005. Thus, in the south-western part of the Algero-Provencal subbasin, advection alone carries quicker the new WMDW characteristics than when diffusion and mixing are also considered.

The main pathway of spreading for the WMDW in the southern part of the Algero-Provencal subbasin should be constrained by the bathymetry and the Coriolis force (*Millot*, 1999). It means that the current along the continental slope of the Balearic Islands is the favorite advective path for the spreading of WMDW. Thus, the effect of the main advective spreading (*i.e.* without the eddy circulation) tends to propagate WMDW towards the Strait of Gibraltar rather than towards the Channel of Sardinia. But a part of it is trapped into the eastern Algerian gyre by closed f/H isocontours constraint (*Testor et al.*, 2005b), where f is the planetary vorticity and H the water depth. On the contrary, we showed that the deep eddy circulation south of the Balearic Islands towards the center of the Algerian subbasin is able to transport WMDW characteristics to the east towards the Channel of Sardinia. Then they disappeared by mixing and diffusion in the interior of the Algerian subbasin. We can thus say that the deep eddy circulation, in comparison to the main advective path alone, accelerates the spreading of the new WMDW characteristics through diffusion and mixing towards the Channel of Sardinia and reduces the available quantity of WMDW which can reach the Strait of Gibraltar.

We identified a southwards and southeastwards direction of propagation of deep eddies carrying WMDW. This is in agreement with the findings of *Testor and Gascard* (2003) and *Testor and Gascard* (2006), who showed that numerous eddies, both anticyclonic and cyclonic, export WMDW far away from the convection area and with the same direction of propagation (southwards and southeastwards). However, as they are submesoscale features with a typical size of 5-10 km, they cannot be reproduced in our model. Nevertheless, deep cyclonic eddies with a larger size have already been observed, since *Send et al.* (1999) mentionned the observation of a large cyclonic eddy in the Algerian subbasin (near 38 °N, 6.5 °E). Concerning modelling studies, *Demirov and Pinardi* (2007) simulated a similar propagation of cyclonic eddies with a diameter of 80-100 km from the North to the South of the Algero-Provencal subbasin. With a higher resolution coastal model (horizontal resolution about 3 km), *Herrmann et al.* (2008) identified mesoscale eddies with a typical size between 25 and 50 km as responsible of one third of the export of dense water away from the convection area in the open-sea part of the

Gulf of Lions. But, as their model do not extend more south than the Minorca-Sardinia line, they were not able to quantify the further propagation in the Algerian subbasin. MED12, with an horizontal resolution between 6 and 8 km, is able to resolve the mesoscale processes, the first Rossby radius being equal in average to about 10 km in the Mediterranean Sea. Nevertheless, as ocean circulation models like MED12 are able to represent only processes whose spatial scale (diameter) is larger than 5-6 times their horizontal resolution, MED12 is able to simulate only eddies whose horizontal scale is larger than 40 km (which is probably a size between meso- and sub-meso scales). We can thus assume that increasing the horizontal resolution of our model would maybe lower the size of the mesoscale eddies involved in the deep spreading of the WMDW, and also probably improve the modelling of the deep water advection time. However, our first attempt to simulate the winter 2005 deep water formation within a 4-year simulation of the whole Mediterranean Sea at 1/36° ORCA resolution (MED36 configuration with a 2.5 km horizontal resolution) tends to moderate this assessment, as the thick barotropic cyclonic eddies we identified here with MED12 still have an horizontal extent larger than 75 km in the MED36 configuration (*Beuvier*, 2011). It will be the subject of following studies.

The volume of new WMDW formed in the simulation is estimated to be lower by about 1.5 Sv compared to what was deduced from in-situ observations. This leads to a potential loss of WMDW along its spreading pathes by mixing and diffusion relatively higher and quicker than in the reality. Moreover, the deep layers in the model are relatively thick at the Algero-Provencal subbasin floor (about 300 m thick at 2400 m depth). This explains why the deep velocity is relatively slow in the model compared to observations. Considering these two points, it can be inferred that the real transport time would be smaller than our model estimates. Indeed, we deduced from the comparison with satellite observations that it takes 2 months for surface cyclonic eddies to pass from the southern part of the Gulf of Lions towards the Algerian subbasin, and *Schroeder et al.* (2008) observed new WMDW characteristics in the Algerian subbasin 4 months after the convection event of winter 2005. Nevertheless, the model approach allows to draw a 4D picture of the deep water spreading process after the intense convection event of winter 2005, which has never been done before, to our knowledge, in a modeling study for this typical year. In particular, we showed that deep cyclonic eddies with a typical size of about 100 km wide and more than 1500 m thick, are mainly responsible of the fast WMDW spreading process. It allowed us to complete the view given by in-situ observations, which are by definition sparse in space and time.

B.5 Conclusion and outlook

In this work, we have studied the spreading of the WMDW formed in the Gulf of Lions during winter 2005 by using MED12, an eddy-resolving model of the Mediterranean Sea at $1/12°$ of horizontal resolution (6-8 km). A simulation of the 1998-2008 period has been performed, with a daily atmospheric forcing from ARPERA, a high-resolution dynamical downscaling of ECMWF products. The use of new state-of-the-art parameterizations has been validated with respect to satellite observations and gridded dataset deduced from in-situ observations. The use of a new Atlantic sea level condition allows the simulation to well reproduce the variability of the net water flux through the Strait of Gibraltar and of the SSH in the Mediterranean Sea. Then, we analysed the simulation in terms of interannual variability in the Western Mediterranean and of WMDW formation rate in 2005.

We have shown that the strong convection event of winter 2005 in the Gulf of Lions was well reproduced in the simulation. The formation of a substantial volume of WMDW with a well marked density signature allowed its tracking in the Western Mediterranean. It induced an important uplift of the isopycnal surfaces, with an amplitude in agreement with in-situ observations. We identified several deep cyclones that successively trap and carry WMDW southwards. The occurence of such cyclonic eddies is realistic with respect to satellite observations. The comparison of Eulerian and Lagrangian approaches highlights the role of these cyclones in spreading the thermohaline characteristics of the WMDW towards the Channel of Sardinia.

Some aspects in the simulation could be improved. We obtained a higher WMDW formation rate in winter 2005 than in previous modelling works, but it is still smaller than the formation rate deduced from in-situ observations. In addition, the new WMDW formed in the model is too cold and not salty enough with respect to these observations. Its southwards propagation is also too slow if directly compared with in-situ observations and indirectly with satellite observations.

Future work will thus focus on the effect of increasing the horizontal resolution (with a global Mediterranean model at $1/36\,^{\circ}$ or with embedded coastal models) on the scale of the eddies responsible for a part of the WMDW spreading. The vertical resolution of the model will also be improved, especially near the sea bottom, to better reproduce the deep water mass propagation. Atmospheric forcing at higher resolution (about 12 km, see *Herrmann et al.* (2011)), will also be used, probably allowing an enhancement of the dense water formation rate. Longer simulations (*Beuvier*, 2011) will help to have better oceanic conditions before winter 2005, as *Beuvier et al.* (2010b) and *Herrmann et al.* (2010) did, but with an eddy-permitting model, and also to assess the place of the winter 2005 deep convection event in the long-term variability of the Gulf of Lions and of the entire Mediterranean Sea.

Acknowledgments

We want first to acknowledge the three anonymous reviewers for the very usefull comments, they helped us a lot to improve the scientific quality of this work. The numerical work was supported by the Groupe de Mission Mercator Coriolis (GMMC). This work was granted access to the HPC resources of IDRIS (Institut du Développement et des Ressources en Informatique Scientifique) of the Centre National de la Recherche Scientifique (CNRS) under allocation 2010 and 2011 (project number 010227) made by Grand Equipement National de Calcul Intensif (GENCI). The financial support of J. Beuvier's Ph.D was provided by Météo-France. We thank Michel Déqué from Météo-France for running the ARPERA simulation with ARPEGE-Climate. The realisation of GLORYS1 global ocean reanalysis had the benefit of the grants that Groupe Mission Mercator Coriolis, Mercator Ocean, and INSU-CNRS attributed to the GLORYS project, and the support of the European Union FP7 via the MYOCEAN project ; computations for GLORYS1 were performed with the support of Météo-France HPC Center. We thank Bruno Levier from Mercator Océan for gathering the bathymetry products. We acknowledge the GEBCO-08 Grid, version 20081212, http ://www.gebco.net, for providing the GEBCO-08 bathymetry. The altimeter products were produced by Ssalto/Duacs and distributed by AVISO, with support from Cnes (http ://www.aviso.oceanobs.com/duacs/). This work is a contribution to the HyMeX international program on the study of the water cycle in the Mediterranean area.

Modelling the long-term variability of circulation and water masses in the Mediteranean Sea : impacts of the ocean-atmosphere exchanges

Abstract

This thesis aims at progressing on key points about the realistic reproduction of the formation and the paths of the Mediterranean water masses, and their variability. For that purpose, several regional oceanic models of the Mediterranean Sea, with different horizontal resolutions, are developped and used. A realistic configuration, representing the interannual variability of the boundary conditions of these models (atmosphere, Atlantic Ocean, rivers, Black Sea) is used to carry out long-term simulations of the Mediterranean for the last 50 years. Two rare events, characterising the decennial variability in the Mediterranean, are studied : the Eastern Mediterranean Transient (EMT) and the Western Mediterranean Transition (WMT).
The EMT is a period, at the beginning of the 1990's, during which the main site of dense water formation in the eastern Mediterreanean basin switched from the Adriatic subbasin to the Aegean subbasin. The ability of the long-term simulations to reproduce the sequence of the EMT events is first proved. Among the preconditionning and triggering elements of the EMT suggested in the literature, we show that the main factors are the intense winter fluxes over the Aegean subbasin during winters 1992 and 1993. The realism of the Cretan Deep Water (CDW) formation and propagation during the EMT is then analysed in reference and sensitivity simulations. The spreading of the CDW on the bottom of the eastern Mediterranean is only reproduced with modified atmospheric conditions.
The WMT has been starting during winter 2005 in the Gulf of Lions, during which a huge volume of Western Mediterranean Deep Water (WMDW) was formed with unusual high temperature and salinity. The simulations reproduce the intensity of the winter 2005 deep convection in the Gulf of Lions, which is due to the strong surface buoyancy loss. They also show that 100-km width deep cyclonic eddies are responsible for the fast southwards spreading of the new WMDW. Then, the long-term simulations allow to set back the WMT in the decennial variability of the north-western Mediterranean. They show that the EMT potentially doubled the volume of new WMDW formed in winter 2005 in the Gulf of Lions, but that it is not responsible for the high temperature and salinity of the new WMDW. These unusual characteristics are due to the absence of intense convection in the Gulf of Lions during the 1990's, which favours a salt and heat accumulation in the north-western Mediterranean.

Keywords : regional oceanic modelling, Mediteranean Sea, winter convection, long-term simulations, interannual and decennial variability, Eastern Mediterranean Transient, Western Mediterranean Transition.

Modélisation de la variabilité climatique de la circulation et des masses d'eau en Méditerranée : impacts des échanges océan-atmosphère

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Soutenue le 08 décembre 2011 à l'Unité de Mécanique de l'ENSTA-ParisTech
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Résumé

Cette thèse a pour but de progresser sur des points essentiels concernant le réalisme de la représentation de la formation et du trajet des masses d'eau en Mer Méditerranée, ainsi que de leur variabilité. A cet effet, plusieurs modèles océaniques régionaux de la Méditerranée, de résolutions horizontales différentes, sont développés et utilisés. Une configuration réaliste permettant de représenter la variabilité interannuelle des conditions aux limites de ces modèles (atmosphère, océan Atlantique, fleuves, mer Noire) est utilisée pour réaliser des simulations à long terme des 50 dernières années en Méditerranée. Deux événements rares, caractérisant la variabilité décennale en Méditerranée, sont étudiés : l'Eastern Mediterranean Transient (EMT) et la Western Mediterranean Transition (WMT).
L'EMT est la période, au début des années 1990, pendant laquelle le site principal de formation d'eau dense dans le bassin oriental méditerranéen est passé du sous-bassin Adriatique au sous-bassin Egée. La capacité des simulations à long terme à reproduire la séquence d'événements composant l'EMT est tout d'abord démontrée. Parmi les éléments de préconditionnement et de déclenchement de l'EMT suggérés dans la littérature, nous montrons que les facteurs essentiels sont les flux hivernaux intenses au-dessus du sous-bassin Egée pendant les hivers 1992 et 1993. Le réalisme de la formation et de la propagation de l'eau crétoise profonde (Cretan Deep Water, CDW) pendant l'EMT est ensuite analysé dans les simulations de référence et de sensibilité. La propagation de la CDW au fond de la Méditerranée orientale n'est reproduite qu'avec des conditions atmosphériques modifiées.
La WMT a commencé à l'hiver 2005 dans le Golfe du Lion, pendant lequel a été formé un volume très important d'eau profonde ouest-méditerranéenne (Western Mediterranean Deep Water, WMDW), caractérisée par une température et une salinité inhabituellement élevées. Les simulations reproduisent l'intensité de la convection profonde dans le Golfe du Lion pendant l'hiver 2005, qui est est due à la forte perte de flottabilité en surface. Elles indiquent également que des tourbillons cycloniques profonds, d'une centaine de kilomètres de diamètre, sont responsables du transport rapide de la nouvelle WMDW vers le Sud. Puis, les simulations à long terme permettent de replacer la WMT dans la variabilité décennale de la Méditerranée nord-occidentale. Elles montrent que l'EMT a potentiellement doublé le volume de nouvelle WMDW formé en 2005 dans le Golfe du Lion, mais qu'il n'est pas responsable de la température et de la salinité élevées de la nouvelle WMDW. Ces caractéristiques inhabituelles sont dues à l'absence de convection intense dans le Golfe du Lion pendant les années 1990, ce qui a favorisé l'accumulation de sel et de chaleur dans la Méditerranée nord-occidentale.

Mots-clés : modélisation océanique régionale, Méditerranée, convection hivernale, simulations longues, variabilité interannuelle et décennale, Eastern Mediterranean Transient, Western Mediterranean Transition.