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Variability of the large scale general circulation of the Mediterranean Sea from observations and modelling: a review

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Abstract

In this paper we present an overview of the most recent findings about the Mediterranean Sea present-day circulation structure. Both historical observations and numerical model simulations are presented, outlining the differences and agreement. The model simulations are presented for both an eddy resolving and a coarse resolution numerical model and the results are intercompared. The importance of the mesoscales in modifying the large scale flow field is elucidated. The critical point is the discovery of the large amplitude interannual variability of the circulation and water mass structure associated with the anomalies of atmospheric forcing over the basin. The seasonal variability can be strictly related to changes in heat and momentum fluxes, while the interannual variability has a component which is related to the mesoscale field. The latter is very intense in the Algerian Current region and Levantine basin but different in structure in the two regions. Results are shown, which confirm the importance of wind driving in establishing the kinetic energy of the flow field, by comparing the current transport at the Strait of Corsica with observations. In conclusion, the essential characteristics of the present-day circulation are associated with the atmospheric forcing and the basin topographic structure. Results from palaeoceanographic simulations for the last 20 000 years show that changing the atmospheric forcing can cause large changes in the circulation structure which may have affected sapropel formation.

Keywords: Atlantic water; Levantine intermediate water; Mediterranean sea

1. Introduction

The present-day large scale general circulation in the Mediterranean Sea has been studied and modelled over the past 15 years through a series of observational programs and numerical modelling studies. The observational programs (Physical Oceanography of the Eastern Mediterranean, POEM Group, 1992, Western Mediterranean Circulation Experiment, WMCE, La Violette, 1990; MTP, 1997) have collected accurate and intercalibrated data sets. By combining these with newly developed data bases of historical observations (Brankart and Brasseur, 1998) a modern reconstruction of the climatological circulation of the basin, as well as its long term variability in several particularly important regions of the basin, has been developed.

A revisited but classical circulation picture for the entire Mediterranean basin is drawn in Fig. 1, showing three major meridional and zonal vertical circulation belts. The first, an open zonal vertical circulation belt, is shallow (0–500 m) and associated with the inflow of Atlantic Water (AW) at

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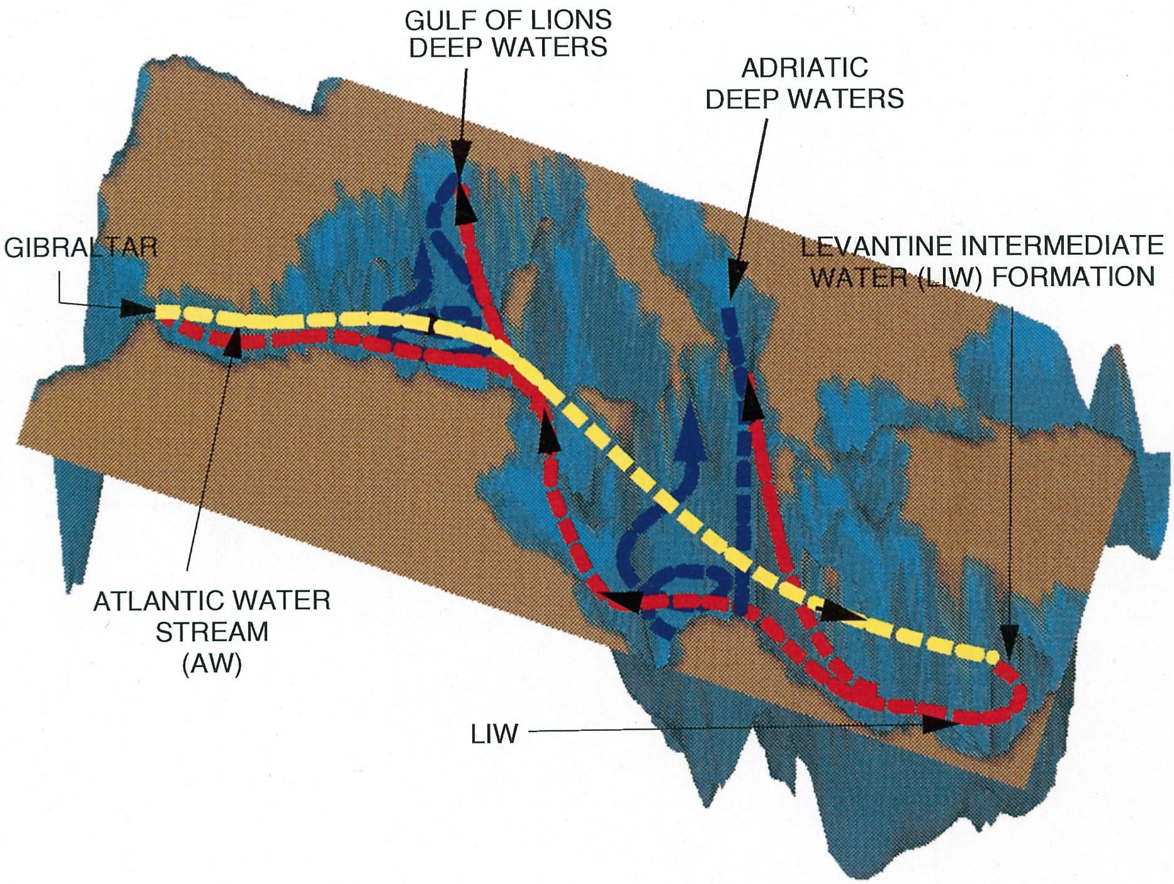


Fig. 1. The schematic of the thermohaline circulation in the basin with the major conveyor belt systems indicated by dashed lines with different colour. The yellow indicates the AW stream which is the surface manifestation of the zonal conveyor belt of the Mediterranean. The red indicates the mid-depth LIW recirculation branch of the zonal thermohaline circulation. The blue lines indicate the meridional cells induced by deep waters. LIW branching from the zonal conveyor belt connects meridional and zonal conveyor belts.

Gibraltar, which is transformed into Levantine Intermediate Water (LIW) in the Eastern Mediterranean. The LIW is an important component of the flow exiting from Gibraltar, even if components of the Western Mediterranean deep waters also contribute to the bulk of the outflowing water masses. The others are meridional cells, similar to the North Atlantic meridional overturning circulation, driven by deep water mass formation processes occurring in the Northern Mediterranean areas, such as the Gulf of Lions and the Adriatic (Schlitzer et al., 1991). The deep water formation in such areas is affected, if not controlled, by LIW present before formation events, as shown by Wu and Haines (1996). Thus the meridional and zonal cells are interconnected and the Eastern and Western Mediterranean meridional overturning cells can communicate even if on long timescales. The zonal cell is thought to have a decadal timescale (Williams and Stratford, 1998), while the meridional overturning cell has a multidecadal timescale (50–80 years). From a centennial integration of a general circulation model (GCM), Wu and Haines (1998) found that the LIW zonal overturning cell sustains the meridional cells contributing to the salt budget of the newly formed deep waters in the Adriatic and Gulf of Lions areas. This is probably the same mechanism which connects the Mediterranean salt tongue in the Atlantic to the maintenance of the North Atlantic overturning circulation, as found recently by Hecht et al. (1996). Recently, Roether et al. (1996) found that the Aegean Sea provided deep waters for the abyssal Ionian basin. Thus, the current picture of a single meridional cell emanating from the Southern Adriatic area may change in the future, considering also the Aegean as a site for deep water outflow and renewal for the Eastern Mediterranean. However, at the moment, the degree of impact of the Aegean source on the long term mean meridional conveyor belt represented in Fig. 1 is unclear.

The horizontal circulation structure is summarized in Fig. 2a for the surface and Fig. 2b for the intermediate depths. The surface basin circulation is dominated, in the northern part of both western and eastern basins, by large scale permanent cyclonic gyres. In the south-western Mediterranean and in the middle of the eastern basin, the circulation is characterised by a jet-like current both boundary intensified (Algerian Current) and free (Atlantic Ionian Stream and Mid-Mediterranean Jet). The south-eastern basin is dominated by anticyclonic large scale gyres. The named gyres in the literature are described in Fig. 2a. The intermediate depth circulation (Fig. 2b) in contrast emanates from the Rhodes gyre, the formation area of LIW (Lascaratos et al., 1993) and several branchings occur during a general westward and northward spreading of the waters. Particularly important is the path toward the Adriatic and Gulf of Lions areas which brings LIW in the deep convection areas, preconditioning the dense water formation processes as explained above and summarised in Fig. 1.

Important new discoveries have been made concerning the large amplitude time variability of the flow field at the seasonal and interannual timescales. Aspects of the seasonal variability involve: (1) the surface water mass formation cycle (Hecht et al., 1988); (2) the seasonal reversal of currents in different portions of the basin (Tziperman and Malanotte-Rizzoli, 1991); (3) the strength of the mesoscale flow field (Ayoub et al., 1998); and (4) the winter deep and intermediate convection sites in the Gulf of Lions area (Leaman and Shott, 1991), the Adriatic Sea (Artegiani et al., 1997a,b) and the Rhodes Gyre (Lascaratos et al., 1993). Aspects of interannual variability concern: (1) the intermediate and deep water mass formation rates (Nittis and Lascaratos, 1998; Castellari et al., 1999); (2) the large variations in volume transport between basins at the Straits (Astraldi et al., 1995); (3) the sudden switches in the deep water mass formation areas for the Eastern Mediterranean (Roether et al., 1996); (4) the changes in the flow direction in several regions (Hecht et al., 1988; Nittis et al., 1993; Artale et al., 1994; Pinardi et al., 1997); and (5) the abrupt changes in LIW characteristics (Hecht, 1992).

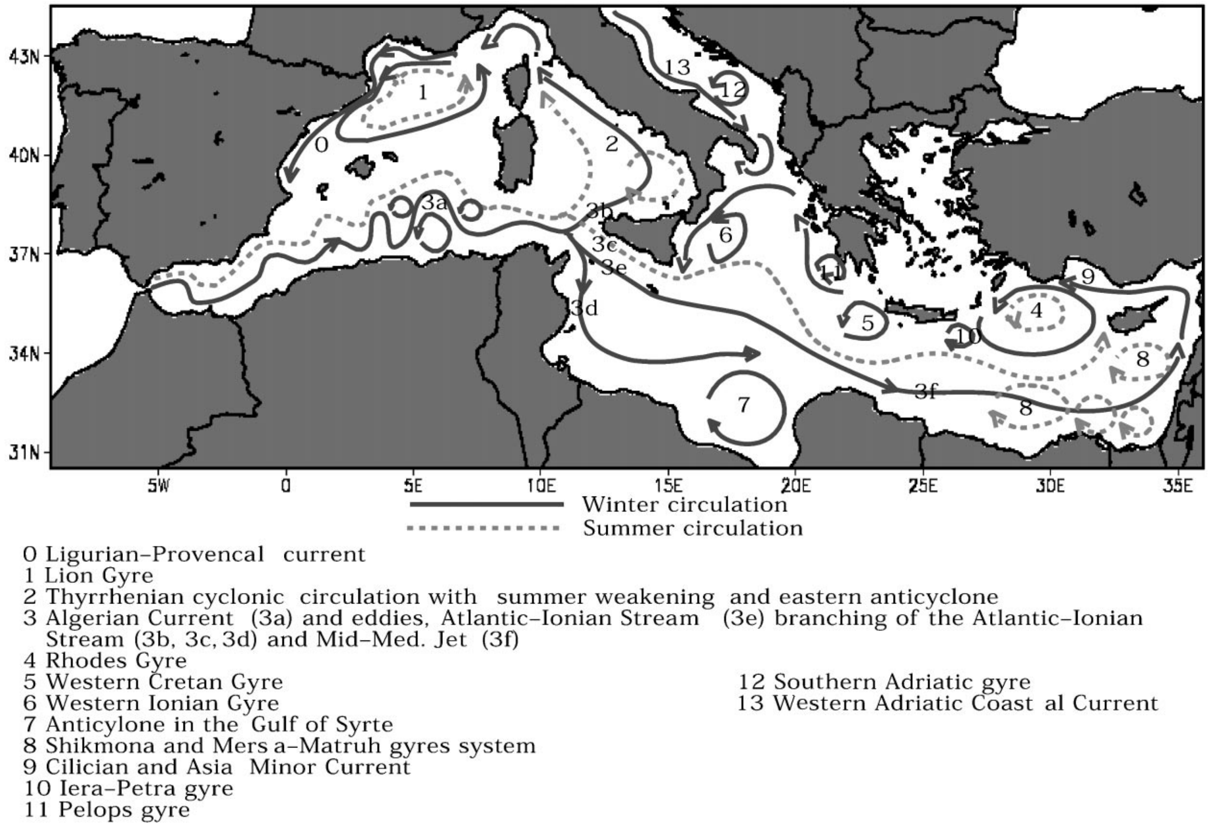
In this paper, we will overview these recent discoveries and show comparisons between simulated and observed circulation structures. We will summarise the results which show the role of atmospheric forcing in determining the seasonal and interannual variability of the basin. On the other hand, we will show evidence that the internal nonlinear dynamics of the general circulation give rise to an intense mesoscale eddy field, which substantially modifies the large scale flow pattern and its water mass characteristics.

While seasonal variations are fairly predictably related to seasonal changes in the meteorological conditions, as we will show later, the interannual variations are more difficult to explain since several mechanisms may contribute strongly. These are:

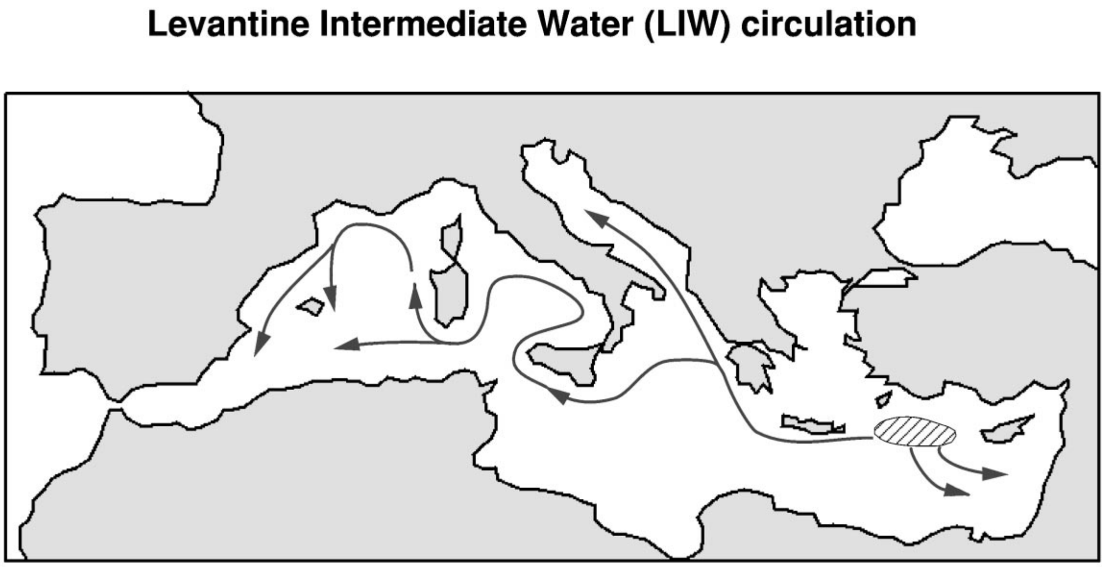
(1) Anomalies in the external atmospheric forcing that have an immediate effect on the ocean circulation through anomalous fluxes of momentum heat and freshwater, which modify vertical mixing depths, particularly in winter.

(2) Meteorological anomalies that have a delayed effect on circulation by modifying surface and intermediate water dispersal paths which in turn modify the hydrography for subsequent winter water formation events, as illustrated in the recent work by both Korres et al. (1999a,b), Myers et al. (1998a) and Samuel et al. (1999).

(3) The internal nonlinear ocean dynamics, such as the unstable mesoscale eddy field, that produces a chaotic element to the redistribution of water masses. As noted in (2), any anomalies in water dispersal can have delayed and remote affects on the circulation in other parts of the basins. A



(a)



(b)

Fig. 2. (a) The schematic of major basin current and gyres systems and their seasonal variability. Names of recognized features are given below the figure. (b) LIW dispersal pathways as synthetised from recent modelling and observational studies.

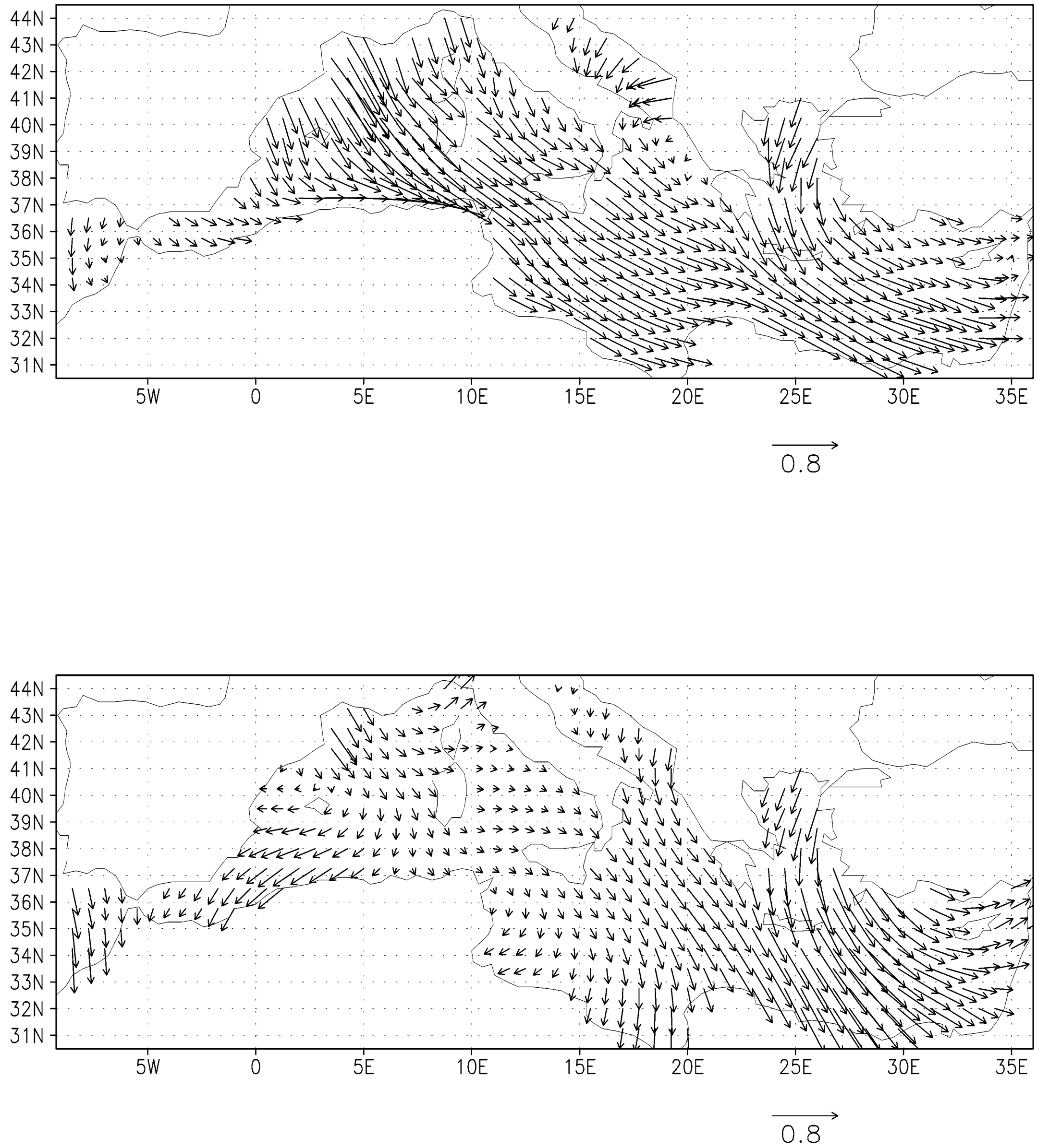


Fig. 3. Climatological wind stress field for January (upper panel) and July (lower panel) from 1979–1993 ECMWF re-analysis daily mean wind stresses. Units are dyne cm^2 and reference arrow is below panels.

recent example of this is seen in the work of Myers et al. (1998a).

(4) Apart from altering water mass dispersal, eddies can modify the wind driven gyres by extracting potential energy or converting kinetic energy between scales in different parts of the wind driven gyres themselves.

(5) For the Mediterranean, interannual variations in the Gibraltar Strait inflow could also be important (especially for the Western basin circula-

tion) but very little data on the longer term Gibraltar exchanges are available.

We will examine recent results concerning the external atmospheric forcing and the internal dynamical redistribution processes in order to understand the reasons for the interannual variability in the basin.

In Section 2 we present the amplitude of the seasonal cycle, in Section 3 the interannual variability caused by the atmospheric forcing and in Section 4 the interannual variability due to internal nonlinear dynamics. We conclude in Section 5 with an outline of solved and partially open problems in the understanding of the Mediterranean Sea circulation.

2. Seasonal variability

The seasonal variability of the surface water mass properties and the large scale circulation is strongly related to the amplitude of the seasonal cycle in the external forcing of the circulation, as shown by many recent modelling studies (Malanotte-Rizzoli and Bergamasco, 1991; Pinardi and Navarra, 1993; Roussenov et al., 1995; Zavatarelli and Mellor, 1995; Wu and Haines, 1996). Overall the climatological seasonal structure of the circulation and water masses can be explained by the space-time structure of the meteorological forcing over the basin. The structure of the wind stress over the basin is shown in Fig. 3. The general direction is westerly during winter with a stronger northerly component during late summer over the Eastern Mediterranean. As Kendrew (1938) defined in his treatise: "The Mediterranean regions are between the Westerlies and the Trade winds; owing to the seasonal swing of the pressure belts of the globe they are dominated by the former in winter and the latter in summer". The surface atmospheric flow field is characterised by subregional wind regimes which are strongly dependent upon the interaction of the Westerlies with the local orography during winter and the land-sea temperature contrast during summer. The two important wind regimes are

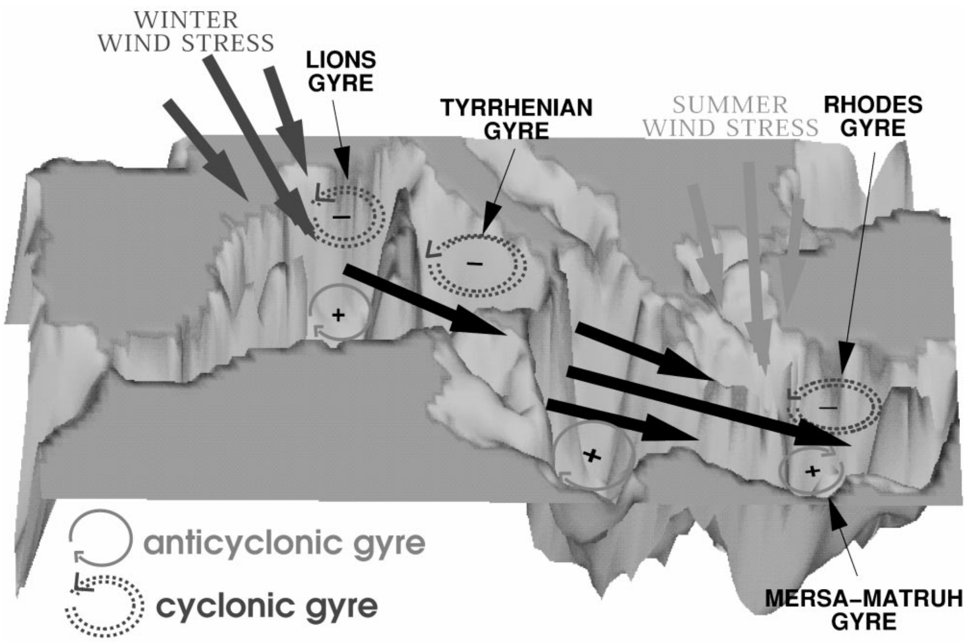


Fig. 4. Schematic of the wind driven circulation picture for winter time conditions. The thick arrows indicate schematically the direction of the surface wind stress field during winter and below the Sverdrup-induced wind driven gyres are drawn, consistently with the vorticity input from the two sides of the jet.

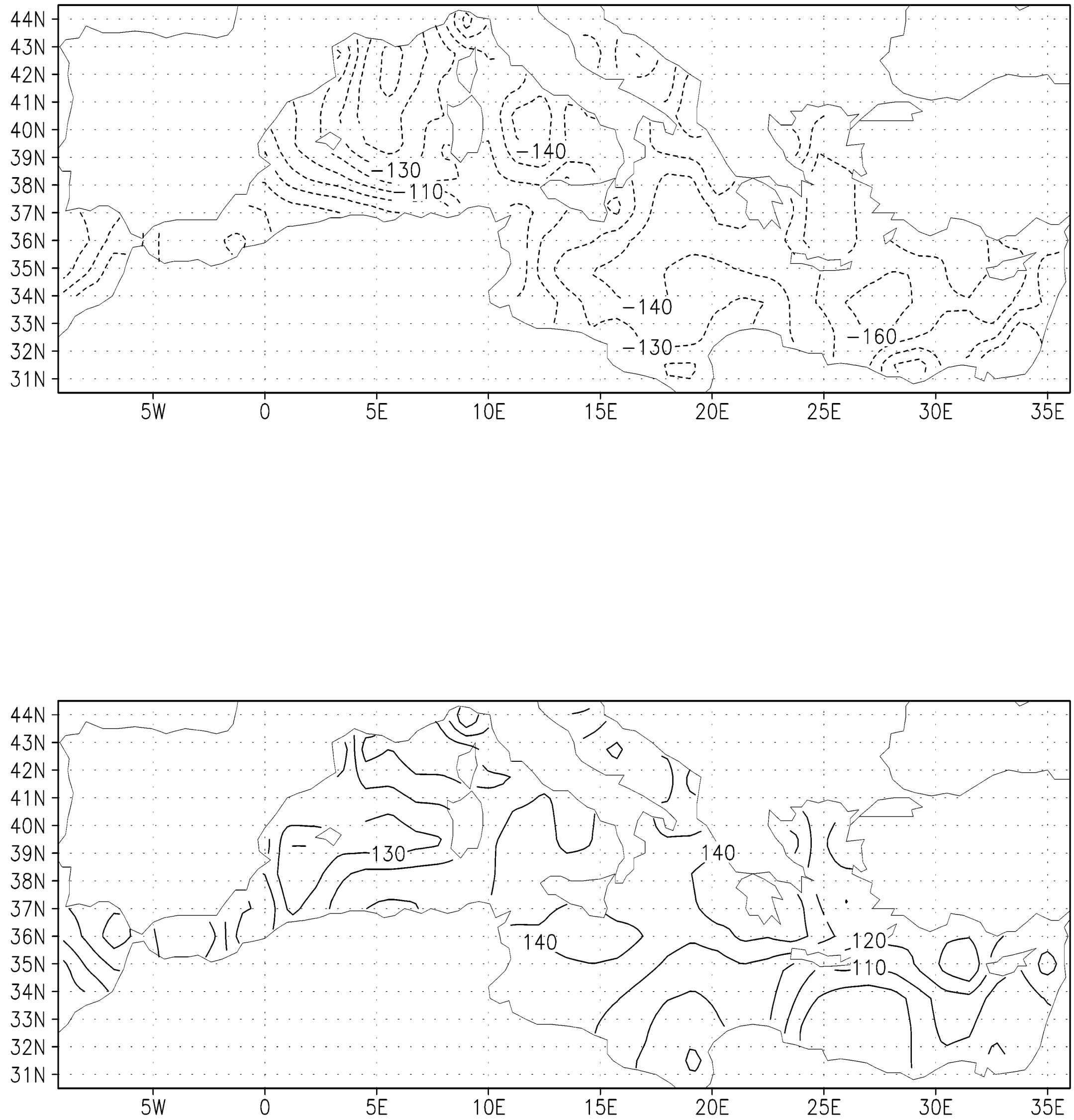


Fig. 5. Climatological Surface heat flux in W m^{-2} for January (upper panel) and July (lower panel). The climatology has been computed from heat flux daily mean values from 1979–1993 ECMWF re-analysis data.

called the Mistral westerly jet during winter and the Etesian North-easterly jet during the summer. The curl of the wind stress (Pinardi and Navarra, 1993; Molcard et al., 1998a) associated with the wind stress of Fig. 3 is such that the induced vorticity in the ocean is cyclonic on the eastern flank of the two above mentioned jets and anticyclonic on the western side. In classical wind driven circulation solutions (Pedlosky, 1987) this wind stress curl may produce ocean cyclonic gyres on the eastern side of the jet, looking downstream, and anticyclonic ones on the other, as represented schematically in Fig. 4. This interpretation of wind induced gyres in the Mediterranean Sea circulation has been formulated by the numerical simulations of Pinardi and Navarra (1993) and Molcard

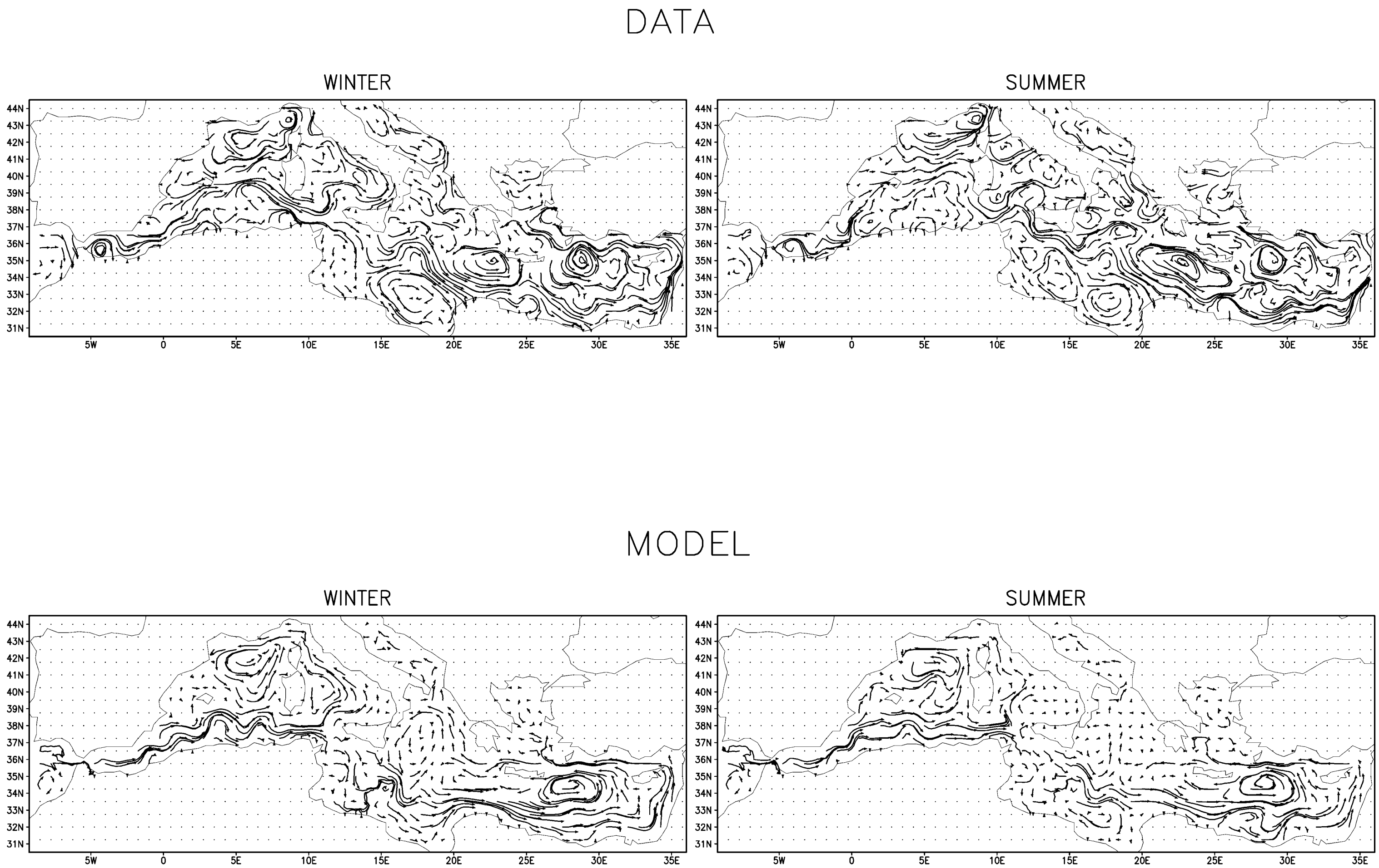


Fig. 6. Model–data intercomparison for winter (Jan–Feb–Mar) and Summer (Jun–Jul–Aug) seasons. (a) Velocity field at 30 m. The ‘DATA’ panels are from Brankart and Brasseur (1998) computed velocity from historical data base and the ‘MODEL’ panels are the climatological average of the fifteenth year of PE4 perpetual year model. The currents are indicated by particle trajectories assumed the eulerian velocity field to be constant for 30 days. (b) Dynamic height field at 30 m with respect to a 450 m reference level. The ‘DATA’ panels are from climatological temperature and salinity profiles of Brankart and Brasseur (1998). The ‘MODEL’ panels are computed from climatological average of temperature and salinity profiles of the fifteenth year of PE4 perpetual year model.

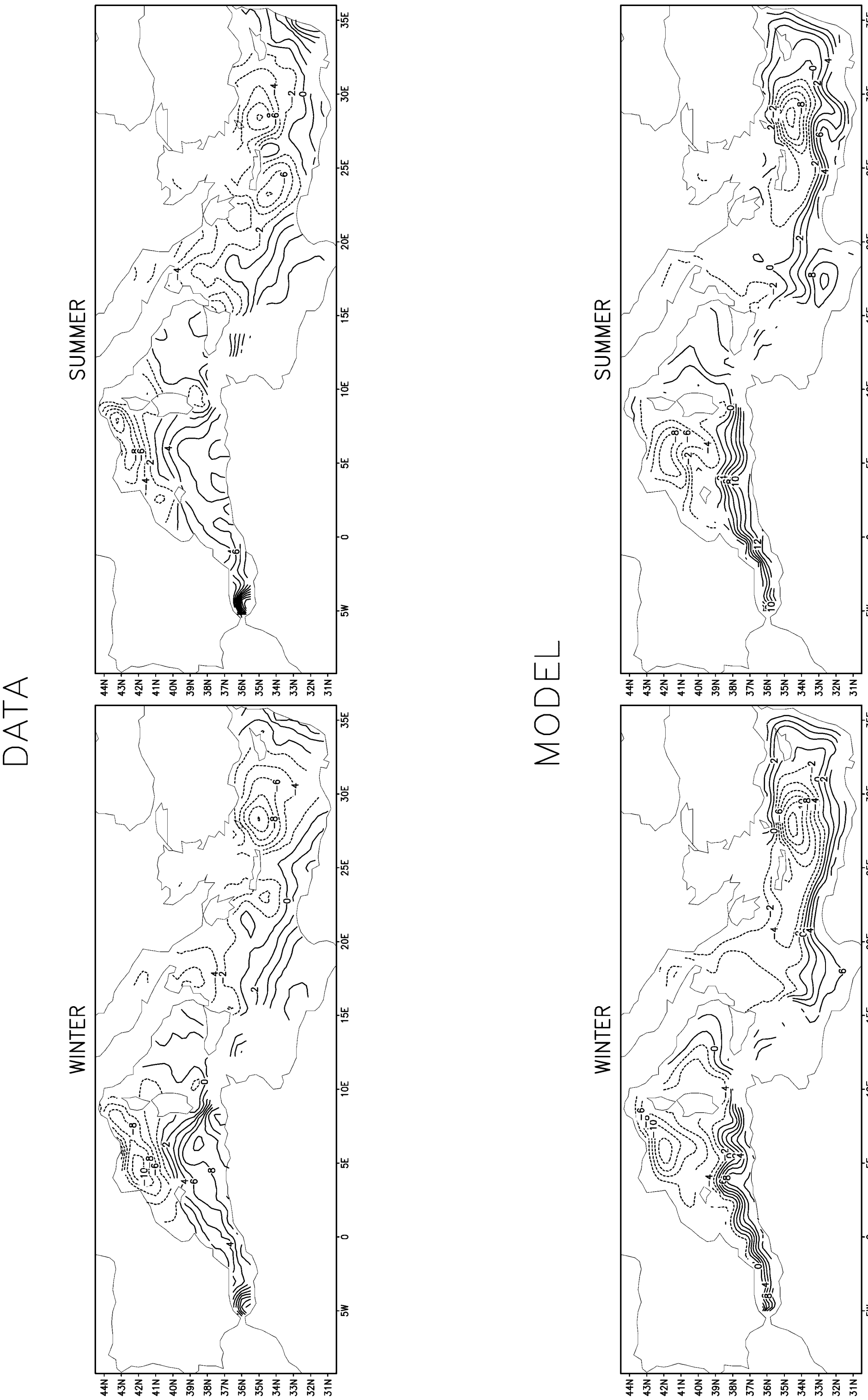


Fig. 6. (*continued*)

(1998b). The realistic simulations consider also the modifications of these gyres due to the local topography, the coastline geometry and the viscous boundary layers. The wind stress curl, the topography and the viscous effects are the same order of magnitude effects in the potential vorticity balance (Pinardi and Navarra, 1993).

The climatological surface heat flux fields are shown in Fig. 5, where we see the well known high heat loss during winter which overwhelms the summer heat gains, producing the net negative heat budget of ca. $-7\ \mathrm{W\,m^{-2}}$ on an annual basis (Garrett et al., 1993; Castellari et al., 1998). This heat flux budget would by itself justify the anti-estuarine character of the thermohaline circulation shown in Fig. 1. The evaporation minus precipitation budget of the Mediterranean is also positive, on an annual basis, and thus helps to drive the thermohaline circulation described above.

The heat and momentum fluxes illustrated here will be used to force hydrodynamic numerical models which will give the atmospherically forced solutions to the general circulation problem. The simulations shown in this paper are produced by a GCM developed by Pinardi et al. (1997) and Korres et al. (1999a). This GCM integrates the three-dimensional hydrodynamic equations in the Boussinesq, hydrostatic and incompressible approximation. The model is in spherical coordinates and it has been implemented in the Mediterranean Sea starting from the Modular Ocean Model (Pacanowski et al., 1991). Two versions of the model have been used in this paper. The first, called PE4, has a coarse resolution with $0.25^\circ \times 0.25^\circ$ horizontal grid spacing. The second, called PE8, has higher resolution with $0.125^\circ \times 0.125^\circ$ horizontal grid spacing. Both PE4 and PE8 have 31 unevenly spaced fixed vertical levels and realistic bottom topography. The PE4 model does not resolve the mesoscale variability or eddy space scale of the circulation, while PE8 does, being the Rossby radius of deformation of ca. 10 km (Grilli and Pinardi, 1998). The subgrid scale parametrizations consider a biharmonic viscosity and diffusivity with constant coefficients and harmonic vertical viscosity and mixing with constant coefficients. The atmospheric forcing is imposed at the model air-sea interface in two different ways: the first considers the wind stress and the heat fluxes to be on a ‘perpetual year cycle’, for example, the atmosphere repeats the seasonal cycle every year of model integration. The second uses the daily averaged momentum and heat fluxes from the European Centre for Medium range Weather Forecast (ECMWF, Reading, UK) analyses from January 1979 to December 1993. The salt flux is, in both cases, imposed to be equivalent to a relaxation to monthly mean surface salinity, as described in detail by Korres et al. (1999a). In the following, we call these two basic simulations the perpetual year PE4 and the interannual PE4 experiments. In Fig. 6 we see the comparison between the perpetual year PE4 simulated winter circulation and the climatological mapping of historical data (Brankart and Brasseur, 1998). The broad scale cyclonic structure of the surface circulation is intensified at the sub-basin scale, forming gyres in different areas, such as: (1) near Rhodes, in the far east; (2) in the southern Adriatic; and (3) in the Gulf of Lions in the west. The Algerian current is well reproduced by the model as well as the Atlantic–Ionian stream (see Fig. 2) system up to the Mid-Mediterranean jet. In the southern Mediterranean areas anticyclonic motion prevails. Thus we conclude that the seasonal structure of the circulation can be reasonably reproduced by the GCM forced by the atmospheric seasonal cycles in heat and momentum fluxes.

Even if this comparison with data is encouraging, we have to note that the amplitude of the winter circulation is underestimated by the model, especially in the Ionian Sea. Furthermore, some gyres are almost absent (see the Western Cretan cyclonic gyre) and the location of others may be a few degrees shifted with respect to the observed climatology. This may be due to the idealised perpetual year forcing used and/or to the bottom topography representation of the model. The Algerian current representation in the data suffers from data scarcity in that region and the high mesoscale variability present there. Thus, in this region, the comparison with the model results should be thought to be qualitative only.

In conclusion, it is evident that the seasonally varying atmospheric forcing, over a coarse resolution model such as PE4, is capable of reproducing some of the salient features of the general circulation. The seasonal variability is then largely connected to the structure and time dependency of the atmospheric forcing over the basin.

3. Atmospheric interannual variability and ocean response

Interannual variability in the atmospheric momentum and heat fluxes have been studied in detail in the past few years (Garrett et al., 1993; Castellari et al., 1998; Angelucci et al., 1998; Maggiore et al., 1998; Castellari et al., 1999). In Fig. 7 we show the basin averaged ECMWF re-analysis wind stress amplitude and heat flux values from 1979 to 1993. This is, in our opinion, the best and most consistent data set for the given period of time. The momentum flux of Fig. 7 varies in amplitude by as much as twice from winter to summer. Over the period 1979–1993, the wind stress shows large winter anomalies with an absolute maximum in 1981 and other anomalies of the order of 30–50% above or below the climatological seasonal cycle amplitude in several other years. In conclusion, the momentum flux shows large anomalous wind stress episodes and interannual variations of the order of 0.2 dyne cm^{-2} with a temporal period of 5–8 years, which are not well resolved by our time series. The heat flux over the whole basin varies on interannual and decadal timescales with annual mean heat flux changes of the order of few W m^{-2} from year to year. In Fig. 7 the heat flux from 1979 to 1993 shows opposite sign anomalies with respect to the seasonal cycle of several 100 W m^{-2} in winter and summer occurring every 2–3 years. As for the momentum fluxes, there are episodes of large heat loss events (1981 and 1992) superimposed on interannual and decadal frequencies. The absence of reliable precipitation data does not allow for a comprehensive study of the water fluxes, which are also thought to vary on the same timescales.

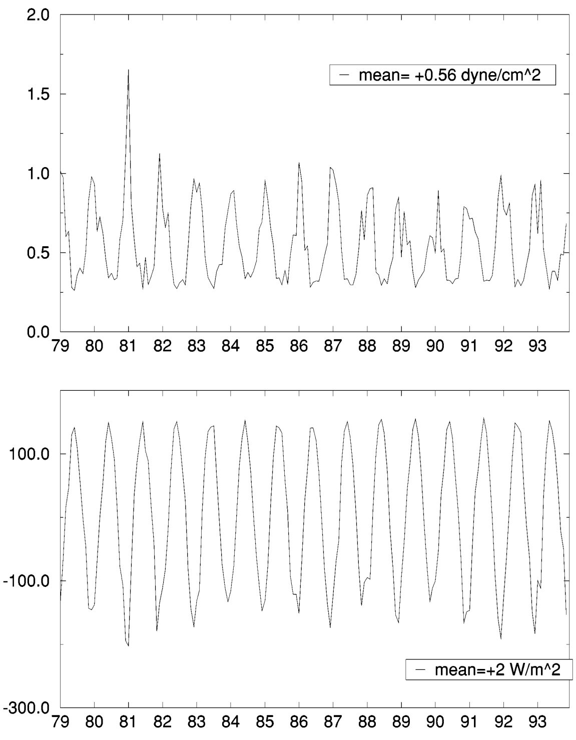


Fig. 7. Basin average values of surface forcing for interannual model run. Upper panel, monthly mean wind stress forcing from ECMWF re-analysis fields. Units are dyne cm^{-2} Lower panel, monthly mean surface heat flux budgets from ECMWF re-analysis surface fields. Units are W m^{-2}. The time series means are shown in the text boxes on each figure.

Another result emerging from the recent air–sea interaction studies is that the heat and momentum flux anomalies are large in different subregions of the basin and have maximum amplitude in the regions where the maxima of heat gain or loss are present in the seasonal cycle (Fig. 5). Another interesting observation is that interannual fluctuations are locked to the seasonal cycle for both momentum and heat fluxes. The winter anomalies are the largest, and, thus, we expect the ocean response to be extremely sensitive to the winter seasons atmospheric forcing. Furthermore, the ocean looses almost entirely its stratification during winter, thus allowing an active connection between forcing and subsurface layers (Korres et al., 1999a)

These observational air–sea interaction studies have prepared the ground for general circulation modelling studies which investigate the GCM ocean response to the interannually varying atmospheric forcing conditions (Pinardi et al., 1997, Korres et al., 1999a,b). In Fig. 8 we show the changes in the structure of the 30 m currents for

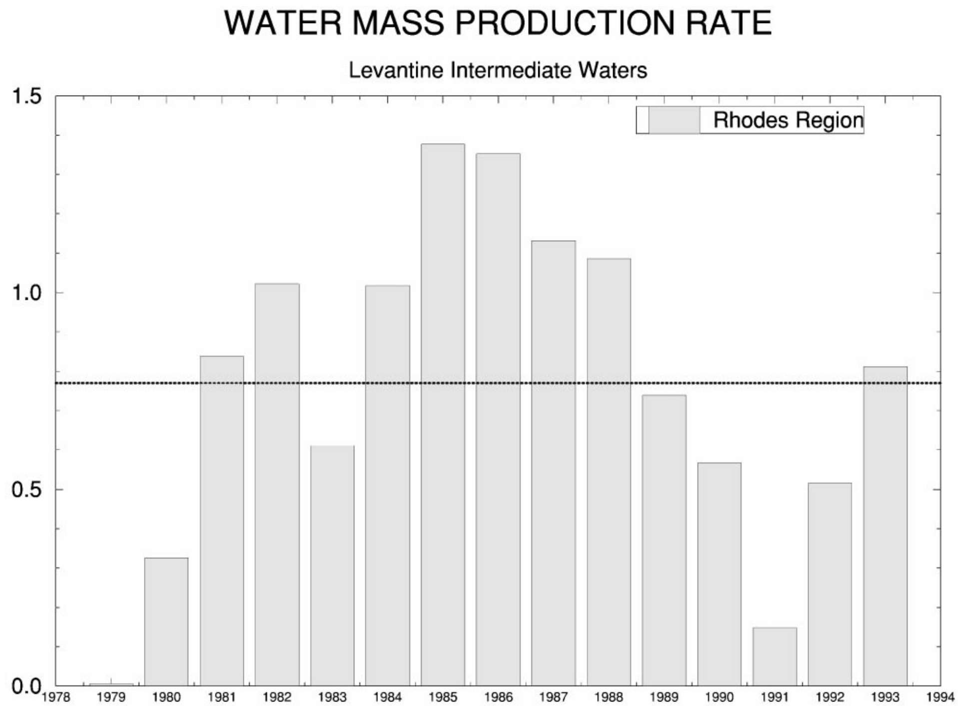


Fig. 9. The water mass production rate in the Rhodes gyre region as a function of years for the PE4 interannual experiment. The water volume is determined by the volume of water found between isopycnals 28.85 and 29.1 in the region of the Rhodes gyre and it is subsequently divided by on a yearly timescale.

the interannual PE4 model simulation. This model simulation used the fluxes shown in Fig. 7. It is evident that the Lions and Rhodes gyres change in structure and strength, the Algerian current and the Atlantic–Ionian stream shift their average axis position every year. Since the model still has a coarse resolution and relatively high horizontal viscosity, the changes are entirely due to the changed atmospheric conditions. The basic result emerging from these studies is that climatic variations in atmospheric forcing are driving substantial changes in the basin-wide large scale currents.

Another interesting contrast to note in Fig. 8 is that qualitatively the interannual circulation anomalies are larger in the Eastern than in the Western Mediterranean (Korres et al., 1999a). In the western basin, the seasonal cycle is so strong that circulation anomalies generated in the earlier seasons are more rapidly forgotten by the flow. This is related to the strong influence of the inflow at Gibraltar on the circulation in the west and the different basin extension which produces large pools of deep mixed layers in the Eastern but not Western Mediterranean area (Korres et al., 1999a).

The interannual variability of the water mass formation rate is an important parameter to monitor in order to quantify the degree of changes occurring in the thermohaline structure of the basin from year to year. In Fig. 9 we show the calculated LIW production rate for the period 1979–1993 using the PE4 interannual simulation. The average formation rate is 0.77 Sv, which is slightly lower than the 1 Sv average formation rate deduced from other data but not inconsistent with

Fig. 8. Dynamic height field at 30 m with respect to 450 m reference level in centimetres, indicated by colours. Superimposed is the 30 m velocity field highlighted by 20 days particle trajectories. The fields shown are the yearly mean for 1985, 1987, 1990 and 1992 years of the PE4 model run with interannual daily atmospheric forcing.

it. The interannual variability is very large ranging from a minimum of 0.1 Sv in 1991 and a maximum of 1.4 Sv in 1985–1986. Thus, the amplitude of the interannual variability of the formation rate is larger than the average value, indicating that the vertical water mass structure in the upper thermocline is varying in terms of volume of water renewed every year. We should note that the amount of water formed each year is not directly related to the net heat loss in the whole basin. If we look in fact at the winter heat loss of Fig. 7 in 1985 and 1986, we see that the net heat loss is at a minimum when LIW production is at a maximum. However, in the Rhodes gyre area, the net heat loss is larger (not shown) but, in any case, not enough to explain the augmented formation rate. This is due to the fact that the ocean horizontal and vertical structure at the initial stage, before the winter cooling, determines in large proportion the amount of water formed. This preconditioning to formation may take several years and is part of the ocean memory mechanism.

In the past years, modelling studies have tried to elucidate the role played separately by the wind stress and the heat flux forcing. Water flux anomalies are not known with sufficient accuracy, and they have not been as yet considered. The wind stress variability is found to be the main driving force of the general circulation variabilities on the interannual timescale. Korres et al. (1999a) shows that >50% of the basin currents kinetic energy is due to wind work and that wind amplitude drives the conversion between kinetic energy and available potential energy of the large scale flow field. The effects of wind stress changes on the circulation go from reversal of currents in the Ionian Sea (Pinardi et al., 1997) to transport changes in the Straits.

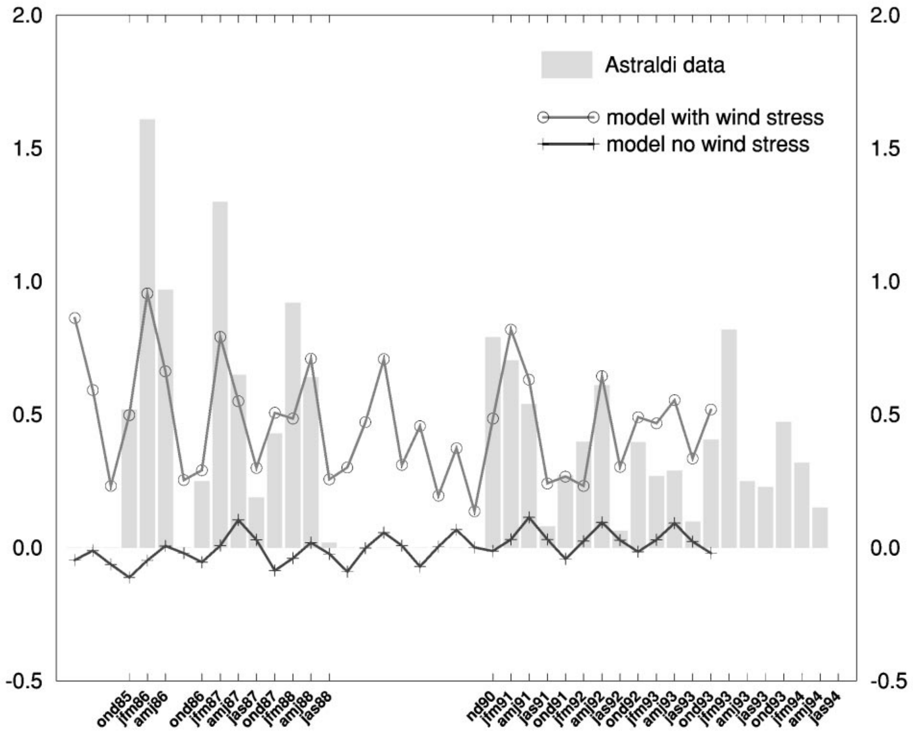


Fig. 10. Simulated and observed total volume transport across the Strait of Corsica, located between the Corsica Island and the Italian Peninsula in the North-Western Mediterranean. The values are 3 months seasonal averages from current meters located in the Corsica Strait from Autumn 1985 to Autumn 1994 (courtesy of M. Astraldi). ○, The interannual PE4 model results and the crosses the interannual PE4 forced only by buoyancy fluxes and zero wind stress.

In Fig. 10, we show the comparison between the simulated transport at the Corsica channel, in the north-western Mediterranean, and long term current meter observations (Astraldi et al., 1995). The model reproduces the phase of the seasonal cycle and some of the interannual fluctuations, even if it is at a smaller amplitude. If we do not use the wind stress forcing, the Strait transport is greatly reduced and the phasing of the transport with respect to the data is changed. This is another demonstration that the wind stress is controlling the average energy content of the large scale circulation in the basin.

Recent studies (Myers et al., 1998b) have also shown that the wind stress has changed in curl and amplitude between the years 1980–1988 and 1988–1993. Such changes can by itself provoke a change in circulation which may effect deep and intermediate water formation events.

4. Internal dynamics and mesoscale variability

The internal dynamical redistribution process hypothesis for the explanation of some of the interannual variability of the general circulation is more difficult to investigate since it requires high resolution modelling which cannot easily be done at the whole basin scale. Nevertheless, some important model results have emerged in the past few years which will be summarised below.

The mesoscale variability of the basin could be an important part of the interannual signal in the Mediterranean since the small Rossby radius of deformation produces slow phase speeds for the Rossby waves in the basin, thus possibly producing a longer lived eddy field. Furthermore, observations indicate that dimensions of eddy-like features, such as the Iera-Pietra or the Shikmona eddy (Robinson et al., 1991; Brenner, 1993), can grow with time thus hinting at the presence of an active mechanism of quasi-geostrophic turbulence cascade of energy from smaller to larger scales.

The Rossby radius of deformation is found to vary from 5 to 12 km in the whole Mediterranean and for the different seasons (Grilli and Pinardi, 1998). This value is ten to four times smaller than the equivalent Rossby radius in the North Atlantic at the same latitudes. The Rossby radius sets the scales at which important energy redistribution processes occur in the highly time dependent mesoscale fields and locks the scale of the synoptic variability to 25–60 km. The mesoscale eddy field was confirmed to be at this scale by mesoscale surveys in the past decade (Robinson et al., 1987; Paschini et al., 1993). On the other hand, the importance of the nonlinear dynamics in the ocean is inversely proportional to the horizontal scale of the flow field. Normally the importance of mesoscale eddies and nonlinear advective terms is represented by the ratio of the Coriolis force term with respect to nonlinear advective terms in the momentum equations. Such a ratio is called the β Rossby number, defined by:

$$\beta = \frac{\beta_0 L^2}{U_0}, \tag{1}$$

where β_0 is the β plane parameter for the central basin latitude, θ_0, L is the horizontal scale and U_0 the velocity scale. A small β Rossby number indicates the importance of nonlinear dynamics with respect to linear planetary wave dynamics in the region below the mixed layer. If L = 10 km and $U = 10$ cm s^{-1} in the Mediterranean, $\beta = 0.4$. For the North Atlantic, $L = 50$ km and $\beta = 7$. Thus in the Mediterranean, the mesoscale eddy field is supposed to be dominated by strong nonlinear interactions which will determine energy cascading from small to large scales. Preliminary modelling studies have confirmed that nonlinear energy cascades are an active mechanism in the Levantine basin (Robinson et al., 1992).

Modelling studies have shown that the Algerian current eddy field and ring-like features emanating from the current (Millot, 1991) are mainly connected to hydrodynamic instability of the AW jet entering Gibraltar (Herbaut et al., 1996). For the Levantine basin, mesoscale eddies are found to grow at the rim of the Rhodes gyre (Milliff and Robinson, 1992), along the southern side of the Antalya peninsula and in the South Eastern Levantine basin (Robinson and Golnaraghi, 1993). The Mid-Mediterranean jet could detach eddies by mixed barotropic/baroclinic instabilities (Golnaraghi, 1993) and gyre-like structures

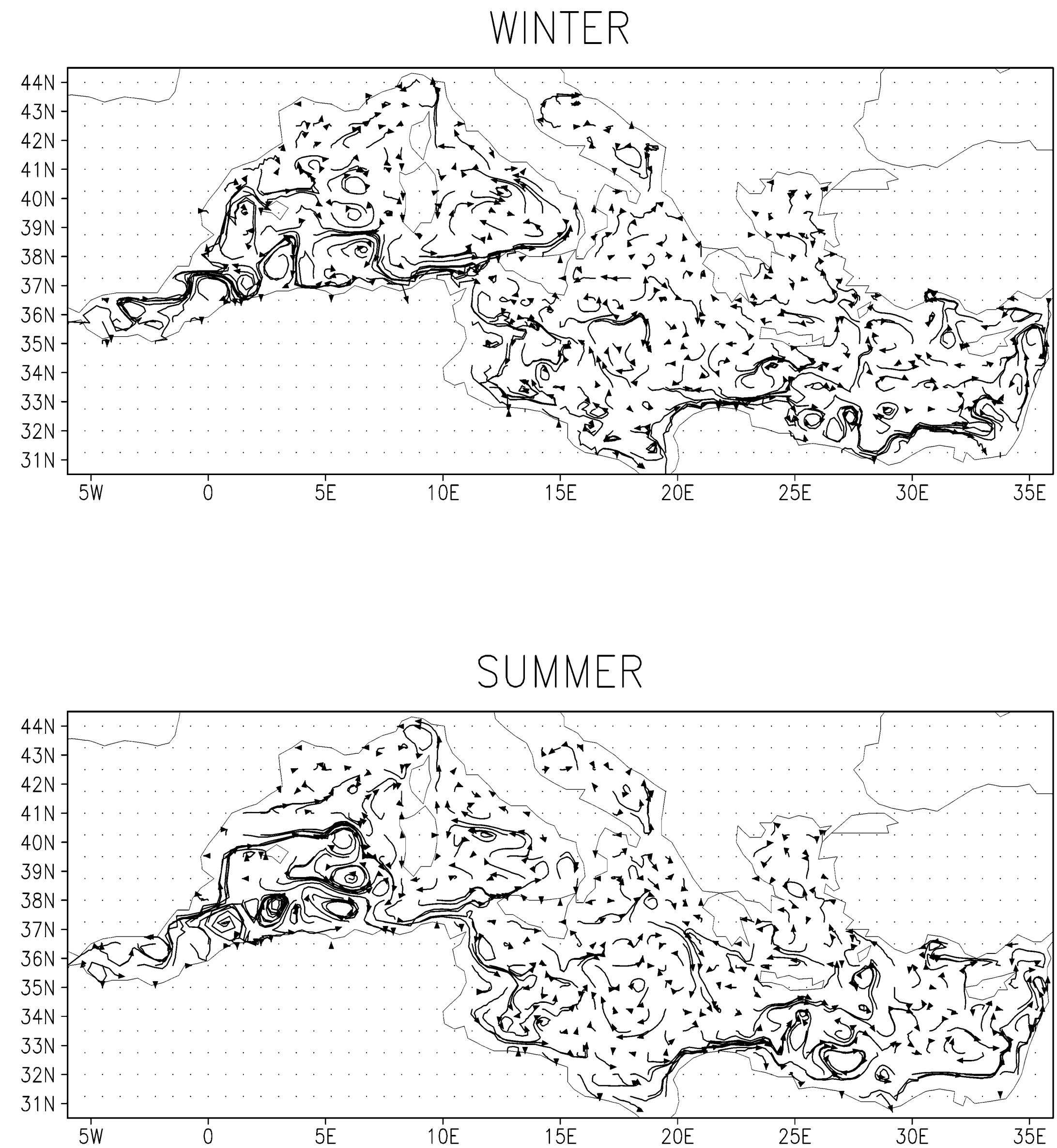


Fig. 11. PE8 perpetual year model simulation: (a) winter (upper panel) and summer (lower panel) 3 months average of 30 m currents from the 12 year of integration to be compared to the low resolution experiment results of Fig. 6a. (b) Winter (upper panel) and summer (lower panel) average of dynamic height at 30 m with respect to 450 m in centimetres.

(Pelops, Mersa-Matruh, Shikmona and Rhodes gyres) develop into multi-lobal eddy centres which are components of the mesoscale eddy field of the region.

In Fig. 11 we show the seasonal circulation computed from the PE8 perpetual year simulation. The model was run for 12 years and then the seasonal average computed. The 30 m currents (Fig. 11a) are now much more eddy-like then in Fig. 6a for the non-eddy resolving case. However, the seasonal variability, manifested by changes of the mean position of the Tyrrhenian current or the

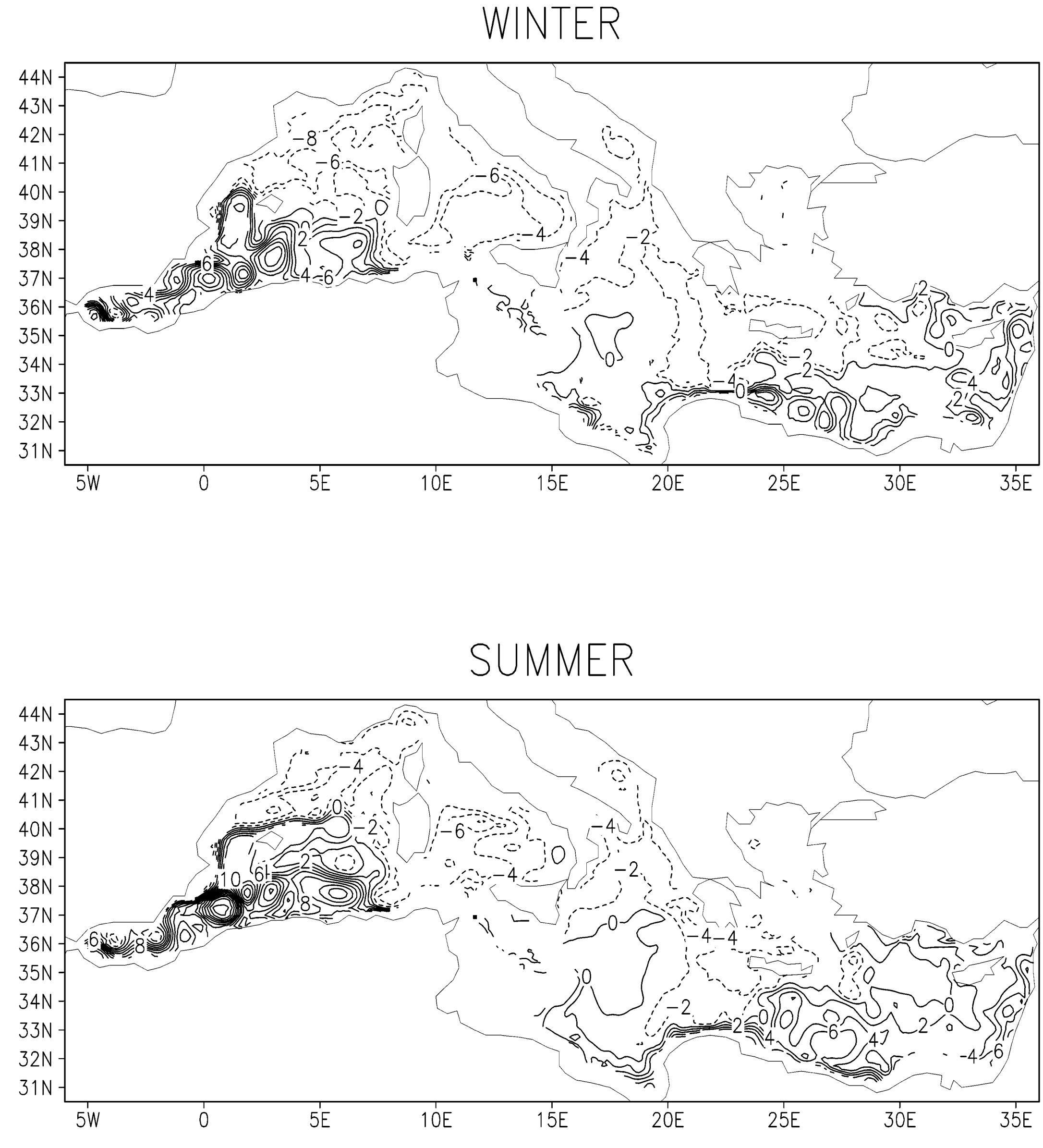


Fig. 11. (*continued*)

Atlantic–Ionian stream position, is still evident. The noticeable difference between Figs. 6a and 11a is the absence in PE8 of a well defined Ligurian–Provencal current and the Ionian–Atlantic stream. The latter is now represented by jets and segments in the deeper part of the Ionian basin. The Mid-Mediterranean jet is well defined only in summer, while the Rhodes gyre is composed of many sub-system eddy-like gyres. The dynamic height in Fig. 11b is more similar to the low resolution picture of Fig. 6b with the northern part of the Mediterranean basin occupied by cyclonic motion and southern part by anticyclonic gyres and eddies. The high resolution runs show that the eddy dynamics in the basin is extremely active and the scale of the eddy field seems also to decrease going eastward. The Rhodes gyre and the Mersa-Matruh/Shikmona gyre system are interspaced by a vigorous mesoscale field. This is in agreement with the overall findings of the POEM experiment in the 1985–1988 years (POEM Group, 1992).

The most recent studies on the merged Topex/Poseidon and ERS-1 surface dynamic topography (Ayoub et al., 1998) have confirmed the large signal of the eddies in different portions of the subbasin. Eddy kinetic energy is defined from sea level anomalies computed from the surface topography for the period 1992–1996. In Fig. 12 we show the observed and simulated surface eddy current amplitude. The model is capable of generating the scales and amplitudes of the eddy signals comparable to observations although with major discrepancies exist, such as the mesoscale signal in the Iera–Petra region. Furthermore, the Algerian current variability seem to be slightly larger than the observed, probably due to the Gibraltar boundary condition.

From the point of view of water masses, the mesoscale eddies have been demonstrated to be a basic mechanism during both formation of deep and intermediate waters (Jones and Marshall, 1993; Nittis and Lascaratos, 1998) and their dispersal processes. Modelling studies (Haines and Wu, 1995; Wu and Haines, 1996) have assessed the crucial role played by eddies in the dispersal of LIW, from the formation areas to all parts of the Eastern and into the Western Mediterranean, specifically the Gulf of Lions area. The mesoscale eddies formed at the rim of the deep convection area in the Gulf of Lions (Madec et al., 1991; Send et al., 1995; Jones and Marshall, 1997) flux heat into the convection area thus controlling the duration of convection and its depth.

These are all pieces of the puzzle which will produce in the future a comprehensive understanding of interannual variability, generated both by external atmospheric forcing and internal nonlinear dynamics of the mesoscale eddy field.

5. Conclusions

In this paper, we have reviewed some of the most recent research results on our understanding of the general circulation variability at the seasonal and interannual timescales. On one hand, the Mediterranean seasonal variability is understood as the ocean response to external buoyancy and wind forcing variability which produces the large seasonal water mass production cycles and the periodic changes in flow structure. The seasonal climatology simulated by the model compares reasonably well with the climatology estimated from the historical data sets. The permanent cyclonic gyres in the Lions and Rhodes areas are reproduced as well as the Atlantic–Ionian and Mid Mediterranean jets separating the anticyclonic southern areas from the northern part.

For the interannual variability, many unresolved questions remain. First, it has been found that the basin response to interannual fluctuations in wind and heat fluxes is large both in circulation structures and LIW production rates. It is clear that atmospheric forcing variability can drive changes in current flow structures and direction. The modelling results indicate that the wind stress amplitude is responsible for a major portion of volume transport at the Straits. Heat flux variability is, however, a very important forcing of the circulation being responsible for water mass production variability in the intermediate and deep layers. The water flux boundary condition in our model does not seem to play a very important role at interannual timescales when compared to momentum and heat fluxes.

Recent work (Wu et al., 1999) has shown that simply heat flux forcing variability can explain large water mass formation interannual changes, without considering explicitly salt flux changes. It may be argued that salinity flux changes are important for decadal and multidecadal timescales which have not been considered yet in our simulations. Myers et al. (1998b) have shown in fact that, in the Sapropel S1 period, the reconstructed surface salinity changes interpreted from palaeorecords, generated a different thermocline structure in the basin on a multidecadal timescale. Sub-basin-like gyres were however preserved and anti-estuarine thermohaline circulation of the kind shown in Fig. 1 was maintained even if with consistent changes in the meridional cells.

In this paper, we have also shown and reviewed the smaller space and temporal timescale of the variability emerging from the nonlinear dynamics

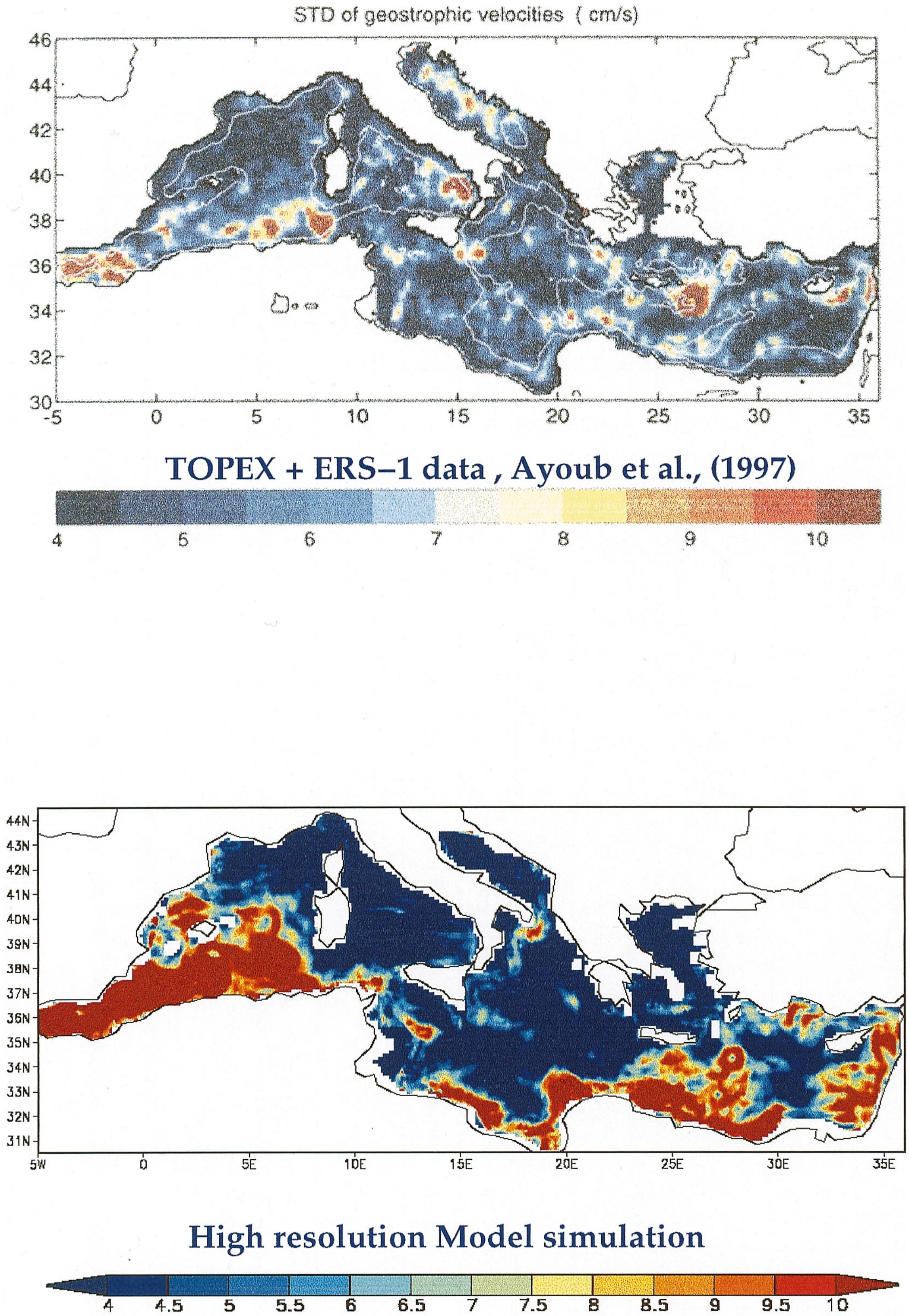


Fig. 12. Upper panel, standard deviation of surface currents computed from analyses of combined Topex/Poseidon and ERS-1 sea level anomalies (Ayoub et al., 1998). Lower panel, standard deviation of 30 m currents from the PE8 perpetual year simulation. The colour bars are shown below each panel.

of the large scale basin currents. We have tried to show evidence that the internal dynamical processes connected to the mesoscale dynamics are very pervasive and different vorticity sources for the instabilities exist in the sub-basins, from the entering AW jet in the Algerian basin to the instability of free or boundary jets, like the Mid-Mediterranean jet or the Asia Minor current. The observations suggest that the eddy field contributes to the large interannual response but modelling studies have not been done yet to connect mesoscale variability to the atmospheric forcing variability. Work is underway along these lines which will allow in the future to demonstrate the interplay between external forcing mechanisms and internal dynamical processes.

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