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Numerical simulation of the interannual variability of the Mediterranean Sea upper ocean circulation

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Abstract. Numerical simulations reveal that variations in wind stress and heat fluxes can induce significant interannual fluctuations in the circulation of the upper layers of the Mediterranean. From January 1980 to November 1988, the atmosphere shows changes in the structure and magnitude of the surface winds and in the air temperatures which induce modifications in the upper ocean structure and currents. The model prediction of the interannual fluctuations of the Sicily Strait baroclinic westward volume transport is in agreement with observations and the variability is explained as a function of the wind curl forcing in the region. The current anomalies persist for many months after a Winter atmospheric anomalous disturbance has occurred over the basin. The Eastern Mediterranean basin is the area where the interannual ocean response is most pronounced.

Introduction

In recent years it has become evident that the structure of the general circulation of the Mediterranean is different from year to year. For example, the position of the Algerian current in the Western Mediterranean, described by recent climatological studies [*Brasseur et al.,* 1995] to meander in the middle of the Algerian-Provencal basin, was previously thought to be a current hugging the North African coasts and meandering in an episodic way [*Millot,* 1987]. The definite appearance of a Mersa-Matruh and Shikmona gyres in the Levantine basin after the POEM (Physical Oceanography of the Eastern Mediterranean) experiment [*Robinson et al.,* 1991], but only sporadically present in the previous literature [*Ovchinnikov and Fedoseyev,* 1965], hinted that interannual variability could have been the source of the discrepancy between the different circulation pictures drawn on the basis of episodic surveys of the basin.

The analysis of these data and other sets indicates that interannual circulation differences could not be explained if changes in external forcing are not considered. Atmospheric variability over the Mediterranean Sea is very intense at both seasonal and interannual time scales [*Garrett et al.,* 1993]. Here we want to assess if ocean changes from year to year can be explained by the atmospheric forcing variability. Since we compare principally with the POEM data, we show the Sicily transport variability and the structure of the surface general circulation as indications of interannual changes in our model simulations.

This study uses a General Circulation model for the entire Mediterranean region with new air-sea physical parameterizations to account for the crucial heat and momentum budgets at the air-sea interface [*Roussenov et al.,* 1995]. We highlight the ocean response to realistic winds and heat fluxes for a nine years period, from January 1980 to December 1988. The results show that major interannual variabilities in the flow field are related to changes in winter wind forcing over the basin.

Model design

The basic numerical formulation of the model is based upon the GFDL primitive equation model [*Cox,* 1985]. The grid resolution is set to $\frac{1}{4}^\circ \times \frac{1}{4}^\circ$ of latitude and longitude and 31 levels in the vertical. The Gibraltar Strait is open and the exchanges are predicted by the model which extends into the North Atlantic where relaxation to climatological temperature and salinity is enforced [*Roussenov et al.,* 1995]. The important aspects of the model design reside in the use of monthly mean atmospheric parameters such as air temperature, relative humidity and wind velocity at 1000 mb from the National Meteorological Centre (NMC, Washington, DC, US) analyses and monthly mean cloud cover from COADS (Comprehensive Ocean-Atmosphere Data Set). The biharmonic horizontal viscosity is $8 \times 10^{18} \frac{cm^4}{s}$ and $2.4 \times 10^{19} \frac{cm^4}{s}$ and the vertical diffusivity is $1.5 \frac{cm^2}{s}$ and $1 \frac{cm^2}{s}$ for momentum and temperature and salinity respectively, as used by *Roussenov et al.,*[1995]. Details on the forcing formulations are given by *Roussenov et al.* [1995]. An important improvement with respect to *Roussenov et al.* [1995] is the increased vertical resolution of the model and the use of clouds in the air-sea physics of the model.

The GCM was initialised with climatological data coming from a new comprehensive historical data set [*Brasseur et al.,* 1996] collected for the Mediterranean. We drive the model for 11 years with monthly mean cli-

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matological values of momentum and heat fluxes at the surface and then we start with the interannual forcing parameters. The main deficiency of the present forcing formulations is the absence of salt fluxes interannual variability, mainly due to the insufficient knowledge of precipitation values over marine areas. At the same time we believe that water fluxes interannual variability could be important in generating the observed ocean response. A trade-off was found in using a conservative salinity flux boundary condition, widely used in other GCM simulations [*Rosati et al.*, 1995]. We would like to point out that in the case of our forcing formulation the interannual variability is mainly generated by wind stress interannual changes, as shown by experiments done with and without wind stress forcing variability (not shown here).

Integrated response of the basin: the Sicily Strait transport

The Sicily Strait interannual volume transport variability is one of the manifestations of year to year changes in the basin current structures. In this section we present the analysis of the simulated Sicily volume transport and connect it to the external forcing interannual variability, giving for the first time a plausible explanation to the transport values found in *Moretti et al.* [1991].

In Fig. 1 (upper left and right panels) we show the interannual changes in the wind stress amplitude and heat fluxes at the air-sea interface of the model.The wind stress has been averaged separately in the Eastern and Western parts of the Mediterranean. The two major episodes of anomalous wind amplitude are in the Winters of 1981 and 1986, mainly in the Eastern and Western Mediterranean respectively. The absolute minimum in heat flux is reached during the Winter of 1981, corresponding to maximum heat losses especially over the Ionian basin and Levantine. The second largest peak in heat loss is associated with the Winter of 1987 which shows also large amplitude wind stress both in the Western and Eastern basins. In the Summers of 1987 and 1988 the large heat gains are due to air temperature maxima which reached values above 35° C for a few months in the Eastern Mediterranean.

In Fig. 1 (lower left panel) we show the net heat transport across the Sicily section. The time average heat transport is 1.2 $10^{13} W$ which is in very good agreement with previous calculations [*Bethoux*, 1979]. The interannual fluctuations modulate the seasonal cycle in a significant way and during the Summers of 1982 and 1987 we have the largest heat transport values. We may speculate that after $\sim 0.5-1.5$ years the strongest wind and heat loss anomalous events of the time series, the heat transport at Sicily is amplified. The corresponding average salt transport at Sicily is 7.1 $10^5 \frac{PSU\ m^3}{s}$ which balances exactly the water flux at the air-sea interface of the model over the entire Eastern Mediterranean basin (about $25 \frac{cm}{yr}$).

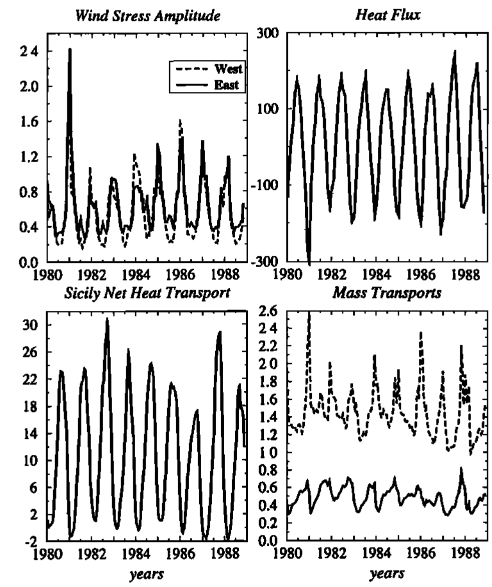

Figure 1. Area integrated quantities for the period January 1980 - November 1988. Upper left panel: Eastern and Western Mediterranean area average wind stress amplitude in $\frac{dyn}{cm^2}$. Upper right panel: Mediterranean area average net heat flux at the surface in $\frac{Watts}{m^2}$. Lower left panel: Net heat transport time series at the Sicily Strait in 10^{12} Watts. Positive values indicate eastward transport. Lower right panel: Sicily (continuous) density driven or baroclinic and total (dotted) westward volume transports. In our rigid lid model westward and eastward volume transports are equal in amplitude but opposite in sign. Units are in Sverdrup (or $10^6 \frac{m^3}{s}$).

In Fig. 1 (lower right panel) we show the westward volume transport at the same Sicily section, computed by subdividing it into baroclinic (BC) and barotropic (BT) components. Please note that the model is rigid lid so the barotropic component here is the part of the westward flow field which is independent of depth. The westward volume transport, shown in Fig. 1, is on average 1.4 Sv (1 Sv = $10^6 \frac{m^3}{s}$) which is higher than the 0.95 Sv long term average transport at Gibraltar (not shown). The interannual fluctuations in westward volume transport at Sicily are the same order of magnitude of the average transport, reaching over 2 Sv many years during Winter or late Summer. The values of westward volume transport at Sicily and Gibraltar are in rather good agreement with observations [*Manzella and La Violette*, 1990] and other transport computations [*Bethoux*, 1979]. However, recent computations of westward volume transport [*Moretti et al.*, 1993] from hydrographic measurements at Sicily showed lower transport estimates. We can explain this apparent discrepancy by showing in Fig. 1 that BC was only one third of the total transport while the rest is due to BT. The low contribution of BC is consistent with the low transport values found from temperature and salinity data [*Moretti et al.*, 1993] and thus it is evident that eastward or westward volume transport estimates from hydrogra-

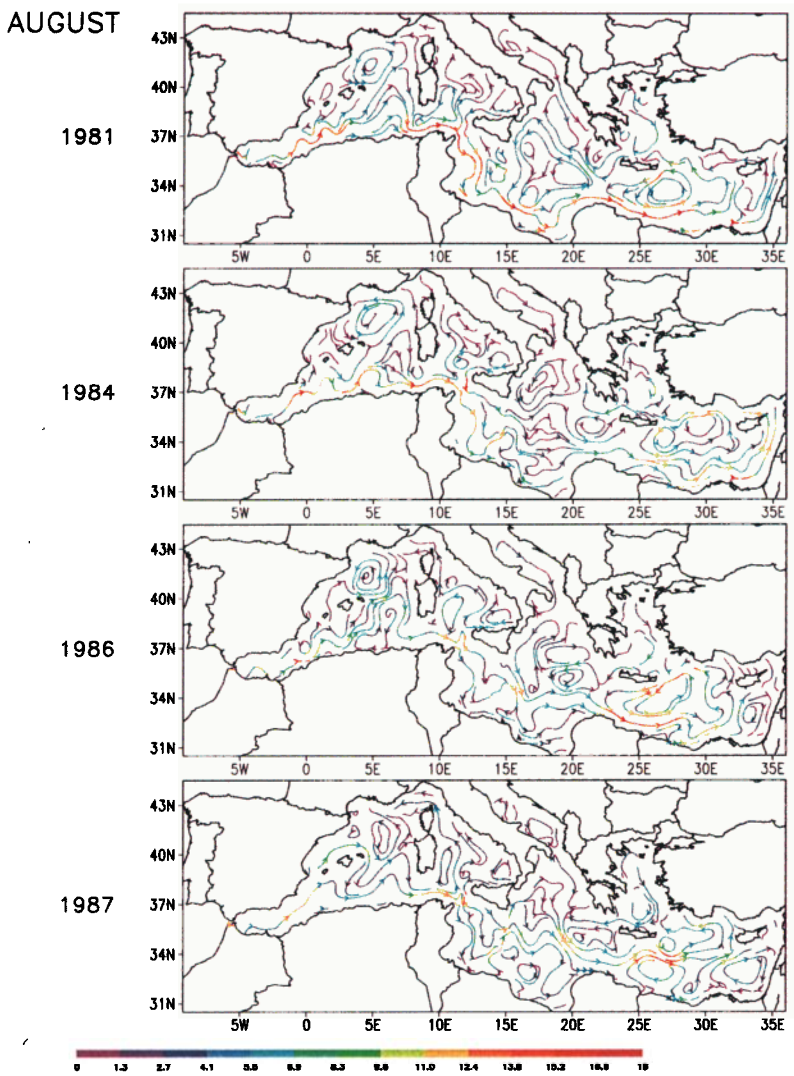

Figure 2. Near-surface streamlines of the simulated monthly averaged velocity field at 30 meters for August of years 1981, 1984, 1986, 1987. Colours indicate the magnitude of the current vectors

phy could be lower than transport values deduced from current meter measurements.

Another open and important question is the timing of maximum/minimum westward transport at the Sicily Strait. *Moretti et al.* [1991], measuring only the baroclinic westward volume transport, found that maximum values were achieved during the late Summer. The current meter estimates of transport in the Strait [*Grancini and Michelato,* 1987; *Manzella and La Violette,* 1990] have instead found maximum amplitude during Winter. The apparent paradox can be understood by looking at Fig. 1. The model simulation shows that the baroclinic and barotropic westward transport peak at different times during the year. The BC contribution has its maximum amplitude in October-November while the total transport peaks in December-January, due to the direct effect of wind fluctuations in these months.

Basin circulation structure

Previous modelling studies have established that the basin general circulation is composed of sub-basin scale gyres driven in different proportions by winds and heat fluxes [*Heburn,* 1987; *Malanotte-Rizzoli and Bergamasco,* 1989, 1991; *Pinardi and Navarra,* 1993; *Zavatarelli and Mellor,* 1995; *Roussenov et al.,* 1995] and locked or modified by topography. We now describe the simulated year to year changes in these structures and discuss the similarities with observations. In Fig. 2 we show the near-surface streamlines of the velocity field for four different August months to emphasise the summer interannual variability and to demonstrate that circulation anomalies persist at least up to six months after the winter anomalous forcing events shown in Fig. 1.

In the Western Mediterranean the interannual variability is shown by the change in the strength of the Algerian current, its meandering and branching east of the Alboran Sea. We see that in August 1987 a large fraction of the surface eastward current is displaced towards the Spanish coast and turns around the Balearic islands before forming the well known Algerian current in the southern Balearic basin. Another interesting feature of the interannual variability of this basin is the strength of the Lion Gyre and the Tyrrhenian northward current.

In the Eastern Mediterranean the changes are more dramatic and correspond to reversals of the current directions in major subportions of the basin. The outstanding change between 1986 and 1987 is the appearance of a large Mersa-Matruh Gyre (centred at about 28^oE, 33^oN) and a large scale anticyclonic circulation in the Southern Levantine basin. In 1987 the Atlantic-Ionian stream is branching northward at 35.5^oN after exiting the eastern Sicilian shelf plateau, reversing the southward flow present along the Italian coast during the previous years. Although verification with observed data is difficult, a comparison with the large scale circulation picture as deduced from POEM September 1987 data [*Robinson et al.*, 1991] is possible. The model correctly captures the northward turning of the Atlantic-Ionian Stream in the Northern Ionian, the longitudinal extension of the Rhodes gyre, the position of the Mid-Mediterranean Jet and the extension of the anticyclonic area in the south-eastern Levantine basin. The model result is unsatisfactory in the western Ionian, in the Cretan passage and the Levantine basin where the observed vigorous eddy field is absent, probably due to the coarse resolution of the model.

We want to show now that the change in strength and direction of the flow field in the Summer month of 1981 of Fig. 2 can be traced back to the anomalies in the winds and heat fluxes of the previous Winter. The ocean "memorises" the Winter conditions so that it alters the regular occurrence of the seasonal cycle in the following Summer. We examined Winter 1981 in detail because it shows the strongest anomalies in wind stress over the Ionian basin (see Fig. 1). In Fig. 2 we see that in August 1981 the overall Ionian circulation is strongly cyclonic, as well as in the Eastern Levantine. We call this a distortion of the regularly repeating seasonal cycle in the Ionian, which would have produced an eastward flowing Atlantic-Ionian Stream at 35.5° N during August (as seen for 1984 and 1986) and anticyclonic motion in the southern Ionian. In order to show that the ocean "remembers" the Winter event so that it modifies the upcoming Summer conditions, we performed several experiments with March 1981 initial condition but 1986,1987 Summer forcing. The result is that the solution in the Eastern Mediterranean does not differ from the standard August 1981 case shown, demonstrating that the memory of the ocean is set during the Winter time, distorting the upcoming Summer period circulation. On the other hand, the Western Mediterranean, even after an anomalous Winter event, shows always a relevant seasonal cycle. We conclude that in the Eastern Mediterranean the amplitude of the interannual variability can overcome the amplitude of the seasonal cycle.

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References

Bethoux J.P. Budgets of the Mediterranean Sea, Their dependence on the local climate and on the characteristics of the Atlantic waters, *Oceanologica Acta* , *10,* 157-163, 1979.

Brasseur P., Beckers J.M., Brankart J.M. and Schoenauen R., Seasonal Temperature and Salinity Fields in the Mediterranean Sea: Climatological Analyses of an Historical Data Set, Deep Sea Res., 43(2), 159-192, 1996.

Cox, M.D, An eddy resolving numerical model of the ventilated thermocline, J. Phys. Oceanogr., *15,* 1312-1324, 1985.

Garrett, C., R. Outerbridge and K.Thompson, Interannual variability in the Mediterranean heat and buoyancy fluxes, *J. Climate* , *6,* 900-910, 1993.

Grancini,G. and A.Michelato, Current structure and variability in the Strait of Sicily and adjacent area, *Annales Geophysicae* , *5,* 75-88, 1987.

Heburn, G., The dynamics of the western Mediterranean Sea: A wind forced case study, *Annales Geophysicae 5B(1),* 61-74, 1987.

Malanotte-Rizzoli P. and A.Bergamasco, The general circulation of the Eastern Mediterranean. Part I: The baratropic wind driven case, *Oceanologica Acta* , *12(4),* 335-351, 1989.

Malanotte-Rizzoli P. and A.Bergamasco, The wind and thermally driven circulation of the eastern Mediterranean Sea, II, The baroclinic case, *Dyn. Atm. Oceans* , *15,* 179-214, 1991.

Manzella, G.M.R. and P.E. La Violette, The seasonal variation of water mass content in the Western Mediterranean and its relationship with the inflows through the Straits of Gibraltar and Sicily, J. Geophys. Res., *95,* 1623-1626, 1990.

Millot, C., Circulation in the western Mediterranean Sea, *Oceanologica Acta* , *10,* 143-149, 1987.

Moretti, M., E.Sansone, G.Spezie and A.De Maio, Results of investigations in the Sicily Channel (1986-1990), *Deep Sea Res. II* , *40(6),* 1181-1192, 1993.

Ovchinnikov, I.M. and A.F.Fedoseyev, The horizontal circulation of the water of the Mediterranean Sea during the summer and winter seasons, in Basic Features of the Geological structure, Hydrological regime and Biology of the Mediterranean, edited by L.M.Fomin, pp. 185-201, Nav. Ocean. Off., Stennis Space Center, 1965.

Power, S.B. and L.A.Mysak, On the interannual variability of Arctic Sea-level pressure and sea ice, *Atmosphere-Ocean* , *30(4),* 551-577, 1992.

Robinson, A.R., M. Golnaraghi, W. G. Leslie, A. Artegiani, A. Hecht, E. Lazzoni, A. Michelato, E. Sansone, A. Theocharis, U. Unluata, Structure and variability of the Eastern Mediterranean general circulation, *Dyn. Atm. Oceans* , *15,* 215-240, 1991.

Rosati, A. R.G.Gudgel and K.Miyakoda, A decadal analysis produced from an ocean data assimilation system, *Mon. Wea. Rev.* , *123 (7),* 2206-2228, 1995.

Roussenov, V., E.Stanev, V.Artale and N.Pinardi, A seasonal model of the Mediterranean Sea general circulation, J. Geophys. Res., *100 (C7),* 13515-13538, 1995.

Zavatarelli, M., and G.L.Mellor, A numerical study of the Mediterranean Sea circulation, J. Phys. Oceanogr., *25,* 1384-1414, 1995.

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