

## **Modelling the seasonal variability of the general circulation of the Mediterranean Sea: monthly vs daily forcing.**

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### **Abstract**

Within the framework of the Mediterranean models evaluation experiment, a Princeton Ocean Model (POM) of the Mediterranean has been developed in University of Athens. It has a horizontal resolution of 0.25 degrees in longitude and latitude and 32 levels in vertical. Here we report the results for year 15 of two perpetual experiments with monthly and daily meteorological forcing accordingly. For the first integration with monthly mean forcing, the model was ran with restoring boundary conditions for both temperature and salinity and monthly climatological momentum fluxes derived from ECMWF daily means averaged for the period 1986-1992. For the second integration the model was forced using ECMWF daily mean heat, evaporation and momentum flux fields for 1988 (which is considered a typical year). In addition, precipitation data were taken from Jaeger's monthly climatology and E-P flux was additionally corrected using a smooth relaxation to monthly SSS climatology. The main features of the Mediterranean Sea general circulation are reproduced satisfactory in both experiments (i.e. Algerian current and its anticyclones, Gulf of Lions Gyre, Tyrrhenian cyclonic circulation, positioning of the MMJ, Rhodes gyre). Seasonal changes are evident within the Tyrrhenian and the Ionian basin as expected. The annual surface heat flux averages to  $6 \text{ Wm}^{-2}$  for the monthly forcing run and to  $2 \text{ Wm}^{-2}$  for the daily forcing run. The positive budget results in a continuous increase of the mean temperature field which is more evident in the first integration. The E-P budget for both experiments is  $\sim 0.4 \text{ myr}^{-1}$ , however the salinity field reaches equilibrium much faster in the daily forcing run. Although the model is skillful in reproducing the seasonal variability of the general circulation, it is not able to form the deep waters of the basin mainly due to the weakness of the surface heat and salinity fluxes. While the amplitude of the heat flux field is improved with the daily forcing run, again the model is unable to produce the deep waters of the WMED (Gulf of Lions) and only a shallow convection occurs during March. On the other hand the LIW formation process and its spreading is more realistic particularly in the second experiment. Finally, the transports through the major straits remain similar for both runs (Gibraltar 1.2 / 1.1 Sv, Sicily 2 / 2.4 Sv, Otranto 0.4 / 0.4 Sv).



**INTERNATIONAL CONFERENCE  
COASTAL & OCEAN MODELLING  
MALTA: 12-14 November 1998**

## Introduction

Although the Mediterranean Sea is considered a regional basin, the presence there of almost all the important physical oceanographic processes with the additional simplicity of the well controlled fluxes due to its semi-enclosed nature, renders the basin a scale model for oceanographers. Thus, considerable effort has been put up to day, in order to understand, explain and emulate the observed structures and their driving mechanisms. As a result, a fair number of Mediterranean general circulation models exist (e.g. Roussenov *et al.* 1995, Zavatarelli and Mellor 1995, Horton *et al.* 1997, Wu and Haines 1998). In University of Athens and within the framework of MEDMEX programme, a POM model (Blumberg and Mellor 1987) of the Mediterranean has been developed (Drakopoulos and Lascaratos 1998). In this work we present the results of two distinct integrations of this model, one with climatological monthly forcing (MF) and the other with daily (DF).

## Model setup

The horizontal grid was set with a resolution of 0.25 in longitude and latitude given by  $-9.5+0.25i$ ,  $i=1,182$ , and  $30+0.25j$ ,  $j=1,63$ . In the vertical, 32 sigma levels were chosen having variable resolution being finer near the surface and the bottom. The model's bathymetry was interpolated from the  $1/12^\circ$  topography supplied by Harvard University for depths below 500 m and from the topography supplied by Princeton University for depths above 200 m. In between, a linear weighting of the two data sets was used (e.g. Beckers *et al.*, 1996). The Gibraltar Strait is located sixteen grid boxes to the east of the model's sole open boundary in the Atlantic Ocean. Right on the boundary and during each time step, the temperature and salinity is prescribed to the seasonal climatology from MED4 dataset, the latest gridded dataset provided by the Mediterranean Ocean Data Base -MODB (Brasseur, 1995). The internal normal velocities on the boundary were governed by a Sommerfeld radiation condition. The vertical mixing coefficients were calculated with the scheme developed by Mellor and Yamada (1982) and the horizontal diffusivity terms by the Smagorinsky algorithm (Smagorinsky 1963).

The wind stress was obtained from ECMWF data covering the period 1986-1992. The forcing is based on monthly values derived from averaging daily means (Beckers *et al.*, 1996). The top layer temperature and salinity were relaxed with a restoring coefficient of  $1 \text{ (mday)}^{-1}$  to MED4 monthly climatology. The order of magnitude of this value is similar to the ones used in other models (i.e. Tziperman and Bryan 1993, Roussenov *et al.* 1995). In the location of the Atlantic box, the applied surface forcing was linearly varied from zero the full value right on the strait location. For the second integration with daily forcing, the model setup was practically the same with the one used for the MF run. In addition, T-S profiles within the Atlantic box were relaxed to climatology. Daily ECMWF momentum and heat fluxes for year 1988 (which is considered a typical year) were used to drive the model. For this integration, precipitation data were taken from Jaeger's monthly climatology (Jaeger, 1976). E-P fluxes due to errors in evaporation and precipitation fields were additionally corrected using a smooth relaxation to MODB monthly SSS climatology.

## Results

In both experiments the model was diagnostically spun up from initial winter conditions for three days in order to establish a horizontal flow field, and after that it was integrated for 15 years. The kinetic energy reached equilibrium after 50 months of integration. In Figure 1 the evolution of the mean temperature and salinity fields for both experiments is depicted. For the MF experiment the

volume average potential temperature for the whole basin reached 14.5 °C after 15 years of integration. The increase rate of the basin was 0.05 °C $y^{-1}$ , rate slightly higher in eastern basin. The nature of the drift is logarithmic and indicative of an increase of the heat content of the basin. Both subbasins have minimum temperature during late March and early April and maximum during October. The average basin salinity for year 15, is 38.49 psu. The salinity tendency of the basin is to decrease, and it is dictated by the western basin trend. This is a consequence of the combination of excessive fresh Atlantic water inflow through the Gibraltar strait and inadequate evaporation through the surface. In contrast, the eastern basin has a weak tendency for salinity increase. The different behaviour of the two sub-basins has been also reported in the results of other modeling efforts. With the daily forcing integration, the rate of heat content increase is lower. The basin average temperature is only 14 °C after 15 years of integration and corresponds to a rate of 0.02 °C $y^{-1}$ . The salinity field also behaves better. Again the basin loses salt, however the rate is much lower and reaches equilibrium after 15 years of integration (38.58 psu). Similarly with the first integration, the eastern subbasin gains salt while the western is freshening. In nature, Mediterranean loses on the average about 5 Wm $^{-2}$  from the surface and has an excess of evaporation over precipitation of about  $\sim 0.6$  myr $^{-1}$  (e.g. Garrett et al. 1993, Bryden et al. 1996). Regarding these surface fluxes, the monthly forcing run results in a 6 Wm $^{-2}$  heat gain, most of it in eastern subbasin, while the daily forcing run has a more moderate gain of 2 Wm $^{-2}$ . The peak to peak amplitude of the cycle is much realistic with the daily forcing run being dictated by the ECMWF forcing. The amplitude of the surface salt fluxes are similar for both experiments,  $\sim 0.4$  myr $^{-1}$ , however the daily forcing integration gives a more realistic spatial distribution, again, due to the prescribed surface forcing. All the above parameters are tabulated in Table 1.

The surface flow field (30 m) is presented in Figure 2 for February (winter) and Figure 3 for August (summer). Both integrations have an overall similar behaviour although the MF run appears to be more energetic in the western subbasin and the DF run in the eastern. During winter in the western subbasin a meandering strong current propagates along the Algerian coast. When it reaches the East coast of Sardinia it bifurcates, and a section heads up in the Tyrrhenian cyclonically where through the Strait of Corsica enters in the North Balearic and creates a strong Ligurian-Provencal Current. This current eventually reaches the Alboran Sea. The Lyons Gyre is well formed. The circulation of waters of Atlantic origin is in a good agreement with the picture presented by Millot, (1987) which is based on *in situ* measurements. The only departure from that picture is the tendency of the Ligurian-Provencal Current in the DF experiment to circumscribe the Balearic Islands anticyclonically. The major section of Atlantic waters that enters the eastern Mediterranean evolves in the Ionian Current and rejoins the North African coast near the Cretan passage. There forms the Mid Mediterranean Jet which after reaching the coast of Israel heads northward to create the Asia Minor current. Adjacent to the main body of the Mid Mediterranean Jet the Rhodes and Mersa-Matruh Gyres are present. In the southern Adriatic, the well known cyclonic gyre is formed only in the MF integration. Moreover the flow in the central Ionian for this run is more or less cyclonic. Again this circulation is in a good agreement with that reviewed by Robinson *et al.* (1991). During summer, the Algerian Current in certain regions moves away from the African coast in the southern Balearic basin and at one point bifurcates with one section heading northward. The other section, after passing Sardinia bifurcates again with one section entering the Tyrrhenian while the main stream enters east Mediterranean through Sicily Strait. In the Gulf of Lions, there is a well defined Ligurian-Provencal current. The flow now in the Tyrrhenian Sea is clearly anticyclonic in both integrations. The Ionian current is strongly meandering, creating cyclones and anticyclones and the circulation in the Ionian Sea for the MF integration shifts to anticyclonic.

At the depth of 330 m (not shown here) where intermediate water flows, the exported East Mediterranean waters enter Tyrrhenian and following a cyclonic path reach Corsica. One section

propagates through Corsica Strait, the other flows around Corsica and Sardinia and rejoins the former at the Lyons Gyre location. Then they flow north of the Balearic Islands to exit eventually through Gibraltar Strait. This picture again is in a good agreement with that presented by Millot, (1987). In eastern basin, the Mersa-Matruh and Rhodes Gyre are present separated by the meandering Mid Mediterranean Jet.

Deep and intermediate water masses are formed during winter through different processes, which are difficult to be reproduced in a coarse resolution climatologically forced model. However, the integration with daily forcing was able to form the levantine intermediate waters (LIW) realistically. This water mass is believed to be formed in the Rhodes Gyre area and is located at depths of about 300-500 m. It has a core salinity of 39 psu, temperature around 15.5 °C and density of 29.05 (Lascaratos *et al.*, 1993). In the MF integration, during March and early April, intermediate water is formed at Rhodes Gyre and the surrounding area. Its potential density is no more than 28.6 (salinity 38.85 psu and temperature 16.6 °C). This is a result of not enough buoyancy loss in the formation area. Formation occurs down to 320 m at the doming area of the cyclone. In the contrary, the DF run is able to produce LIW with a realistic density of 29.05 (salinity 38.9 psu and temperature 14.8 °C) during March at a depth of 350 m. In the Western Mediterranean and in the area of Lyons Gyre, another characteristic water mass is formed, the West Mediterranean Deep Water (WMDW). This water mass is formed through open ocean deep convection during winter extreme cooling episodes and spreads in the deepest parts of the western basin. Such process is difficult to be reproduced by hydrostatic models forced with climatological surface boundary conditions. Although it was anticipated that the DF run will be able to emulate better this process, only a transient water mass was formed at the dome of Lyons Gyre, and at a depth of about 500 m even when the wind stress was increased by 50%.

The straits play an important role in controlling both the general and the thermohaline circulation in the Mediterranean. The overall flow of the basin is controlled via the Strait of Gibraltar, which acts as a valve for the inflow of Atlantic and outflow of Mediterranean waters. According to the model, the volume transport of each layer is about 1.1 – 1.2 Sv and with an almost absent seasonal cycle. From field measurements this value should be around 0.7 to 1.3 Sv depending on the reference (e.g. Bryden *et al.*, 1996). Although the net transport is mainly controlled by the buoyancy loss in the basin, the local width of the strait should have an effect on the transport. The Sicily Strait controls the exchange between the two subbasins. The monthly integration indicates a volume transport of 2.0 Sv and the daily 2.4 Sv. A strong seasonal signal is present with maximum exchange from November till February as is observed by most in situ measurements e.g. Manzella *et al.* (1988), Astraldi *et al.* (1996). In these references the quoted transport value ranges from 1.2 to 3 Sv. For the Otranto Strait, the model implies an annual exchange of 0.4 Sv, while it has been reported an observed value of about 0.3 Sv. Maximum exchange is during October.

## Conclusions

Both integrations were able to reproduce the basic known features of the general circulation of the Mediterranean Sea. Seasonal changes are evident within the Tyrrhenian and the Ionian basins. The daily forcing fails to produce deep waters as was initially anticipated. On the other hand the LIW formation process is realistic.

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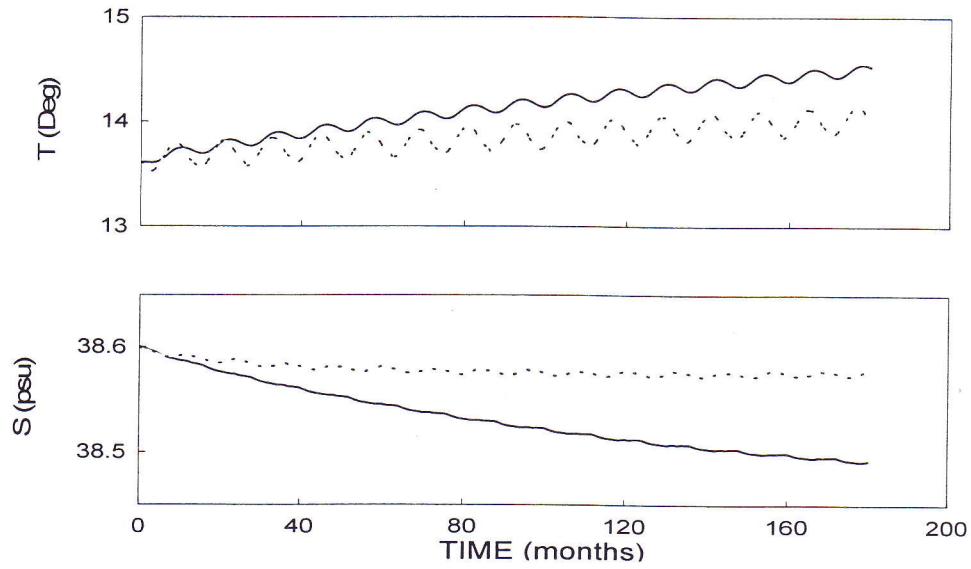
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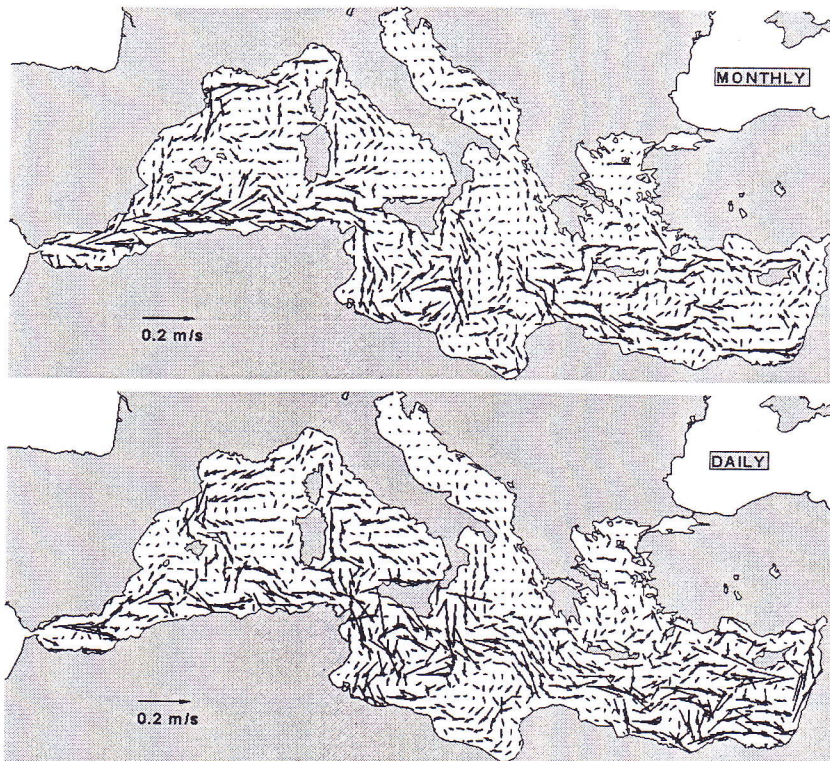
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## FIGURES



**Figure 1:** Evolution of (a) volume integrated temperature and (b) volume integrated salinity for both experiments. With the solid line is the monthly forcing experiment and with dashed the daily.

FEBRUARY YEAR 15 (30m)



**Figure 2:** Surface winter circulation for monthly and daily forcing integration.

AUGUST YEAR 15 (30m)

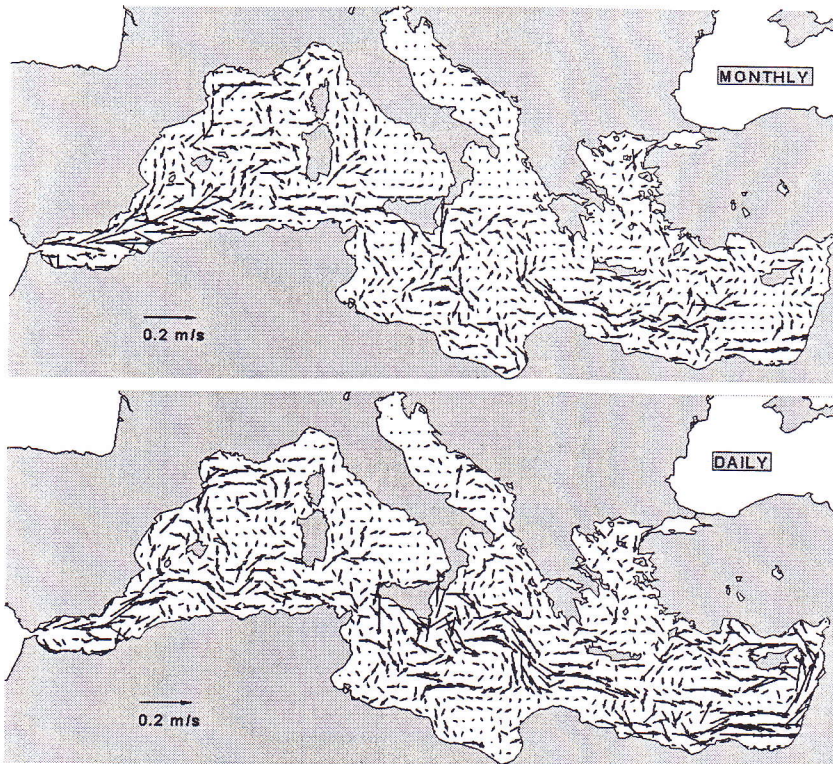


Figure 3: Same as in Figure 2 but for summer conditions.

## TABLES

**Table 1:** Comparison of assorted model parameters for the two experiments.

YEAR 15 PARAMETERS	MONTHLY FORCING	DAILY FORCING
TOTAL TEMPERATURE ( $^{\circ}\text{C}$ )	14.49	14.02
TOTAL SALINITY (psu)	38.49	38.58
HEAT FLUX ( $\text{Wm}^{-2}$ )	5.8	2.0
E-P ( $\text{myr}^{-1}$ )	0.4	0.4
GIBRALTAR TRANSP. (Sv)	1.2	1.1
SICILY TRANSP. (Sv)	2.0	2.4