PALEOCEANOGRAPHY, VOL. 17, NO. 1, 1009, 10.1029/2000PA000613, 2002

Flux-forced simulations of the paleocirculation of the Mediterranean

Paul G. Myers[1]

Department of Physics and Physical Oceanography, Memorial University of Newfoundland, St. John's, Newfoundland, Canada

Received 30 November 2000; accepted 24 September 2001; published 28 February 2002.

[1] A series of experiments with an ocean general circulation model of the Mediterranean forced by artificial (but realistic) surface fluxes of heat and freshwater are performed. The model has a stable thermohaline circulation under the baseline fluxes. Small decreases in excess evaporation (8%) produce a linear weakening of the thermohaline circulation with less water formation and smaller strait transports. Levantine Intermediate Water production is shown to be very sensitive to additional freshwater input. The dominant circulation mode in "wetter" climates is one with Adriatic Intermediate Water formation and dispersal, leading to ventilation of intermediate depths of the basin. Although the deep layers are not ventilated, stratification is generally weak. As the excess evaporation decreases, stratification increases. A 60–80% decrease leads to conditions closest to those suggested for sapropel S_1, with a west-east salinity gradient of half of today. *INDEX TERMS:* 4267 Oceanography: General: Paleoceanography; 4255 Oceanography: General: Numerical modeling; 4243 Oceanography: General: Marginal and semienclosed seas; *KEYWORDS:* Mediterranean, sapropels, paleofluxes, Holocene, ocean circulation

1. Introduction

[2] The Mediterranean is a small marginal sea located between Europe and Africa. *Garrett et al.* [1993] noted significant interannual variability in the fluxes over the Mediterranean. The surface fluxes acting on the basin have also varied considerably over longer timescales, as seen in the paleoclimatic record. Significant changes in the surface temperature field of up to 12°C occurred since the Last Glacial Maximum (LGM) [*Bigg*, 1995; *Paterne et al.*, 1998; *Rohling et al.*, 1998; *Rohling and De Rijk*, 1999]. Salinity changes include large increases in the eastern basin salinity during the LGM [e.g., *Thunell and Williams*, 1989; *Rohling and De Rijk*, 1999], although there is some controversy surrounding the size of the increase [*Bigg*, 1995]. The geological record also includes numerous examples of sapropels (sediment layers with enhanced organic carbon content), which are generally associated with moist and humid conditions, low salinities (a decrease of up to 4.0 psu is suggested for the most recent sapropel, S_1 [*Kallel et al.*, 1997]) and stagnant anoxic bottom waters [e.g., *Rohling*, 1994], although exceptions exist [*Rohling and Hilgen*, 1991]. The low salinities have been related to increased precipitation [*Rohling and Hilgen*, 1991], enhanced Nile runoff [*Rossignol-Strick et al.*, 1982; *Rossignol-Strick*, 1985], and Black Sea discharge [*Olausson*, 1961; *Lane-Serff et al.*, 1997]. Note that these causes are all similar to those suggested for the present-day changes in the Mediterranean [*Bethoux and Gentili*, 1996; *Rohling and Bryden*, 1992] but work in the opposite direction.

[3] G. Korres and A. Lascaratos (personal communication, 1999) used a series of 6 by 4 and 2 by 2 box models to study the stability of the thermohaline cells of the Mediterranean. They found that while the present thermohaline circulation is sensitive to variations in the surface forcing and can undergo weakening, the main east-west Levantine Intermediate Water (LIW) cell is stable. They also found that under different forcings (such as for Holocene conditions) the circulation has at least two stable states, with the imposition of a strong seasonal cycle on the surface forcing leading to the favoring of one state or the other.

[4] Recently, *Myers et al.* [1998b] examined the conditions associated with sapropel S_1 with a sophisticated general circulation model of the Mediterranean that had been shown to accurately reproduce the present-day circulation of the basin. They showed, irrespective of the salinity, temperature, and/or wind reconstruction used for the period, that the basin retained its present-day anti-estuarine circulation, albeit weakened, at both the Straits of Gibraltar and Sicily. In their simulation, deep water formation ceases, leaving a deep stagnant layer below 400–500 m in the eastern basin and 100–150 m in the Aegean. *Myers et al.* [1998b] also showed that intermediate water formation ceases in the Levantine and is replaced by water of an Adriatic source, Adriatic Intermediate Water (AIW). The AIW is exported to the western basin and also flows eastward into the Levantine, where it shows a basin-wide general upwelling associated with a trapping of nutrients, a shoaling of the pycnocline [*Myers et al.*, 1998b], and increases in productivity [*Stratford et al.*, 2000].

[5] One limitation of the study of *Myers et al.* [1998b] was their usage of restoring boundary conditions based upon a series of reconstructions of the surface salinity and temperature fields of the time. Although guaranteeing that the simulated surface fields would approach the reconstructions, this choice of boundary conditions is less realistic than prescribed fluxes. Fluxes are more appropriate for paleosimulations because in general, ideas on changes in fluxes are probably better known than detailed fields of sea surface properties. As well, the use of fluxes allows the basin's surface properties to freely evolve so as to be compared to reconstructions from cores or to suggest approximate size change in fluxes needed to produce reconstructed changes.

[6] *Myers and Haines* [2000] recently produced a version of their Mediterranean model that can be forced purely by surface fluxes without any restoring to observed quantities. Previous applications under surface fluxes showed that the freer surface boundary conditions enhanced internal variability and suggested the existence of multiple equilibria in the basin's thermohaline circulation [*Myers and Haines*, 2002]. Here we modify the basin's surface freshwater fluxes to study the stability of the paleo-Mediterranean's circulation. We consider the case of decreases in

[1] Now at Department of Earth and Atmospheric Sciences, University of Alberta, Edmonton, Alberta, Canada.

0883-8305/02/2000PA000613

Table 1. Annual Mean Surface Heat and Freshwater Fluxes Diagnosed From the Final 15 Years of an Initial Model Spin-up Under Restoring Boundary Conditions[a]

	Heat Flux, W m^{-2}	$E - P - R$, cm yr^{-2}
MED	−5.8	76
WMED	−7.1	94
EMED	−5.1	66
ADR	−41	−20

[a] The regional abbreviations are MED, basin average; WMED, the western Mediterranean; EMED, the eastern Mediterranean (including the Adriatic and Aegean); ADR, the Adriatic. *E*, evaporation; *P*, precipitation; *R*, runoff.

excess evaporation, as was suggested to occur during the Holocene. The model and its spin-up is described in section 2. The results are presented in section 3. A discussion is given in section 4 and we conclude in section 5.

2. Model and Spin-Up

[7] The model used is the Modular Ocean Model-Array (MOMA), a Bryan-Cox-Semtner type ocean general circulation model (OGCM) using the *Killworth et al.* [1991] free surface scheme. The tracer advection schemes are modified to include the *Gent and McWilliams* [1990] eddy parameterization and a flux-limiting scheme [*Stratford*, 2000] based on the work of *Thuburn* [1996]. The basic model is described in greater detail by *Webb* [1993] and has been used in the Mediterranean to study changes in the basin's thermohaline circulation, both for the present [*Myers et al.*, 1998a; *Myers and Haines*, 2000] and for past climates [*Myers et al.*, 1998b; *Myers and Rohling*, 2000].

[8] The model setup is based on the work of *Haines and Wu* [1995] and *Wu and Haines* [1996, 1998]. Basin resolution is $0.25° \times 0.25°$ with 19 vertical levels (mainly concentrated in the upper part of the water column to resolve the thermocline). The horizontal biharmonic viscosity coefficient is $A_h = 1.5 \times 10^{18}$ cm^4 s^{-1}. The vertical momentum diffusion is $A_v = 1.5$ cm^2 s^{-1}. The Gent and McWilliams thickness diffusion parameter is 2.0×10^5 cm^2 s^{-1} and the maximum (reciprocal) slope of isopycnals is 100.0. Convective adjustment is performed using the complete convection scheme of *Rahmstorf* [1993]. To handle the exchanges with the Atlantic, a small box is added outside of Gibraltar, where the temperature and salinity are relaxed on a 1 day timescale to the climatological values of *Levitus* [1982]. Wind stress data are based upon a monthly 7 year climatology (1986–1992) from the European Centre for Medium-Range Weather Forecasting (ECMWF). The use of present-day winds has been previously shown to not significantly modify simulations of the Holocene Mediterranean [*Myers et al.*, 1998b].

[9] To produce the initial baseline Mediterranean experiment, the following procedure was used. The model was initially spun up from rest using relaxation conditions. Both the initial and relaxation conditions were derived from the Mediterranean Oceanic Database (MODB), MED5 [*Brasseur et al.*, 1996]. The model was then integrated for 100 years until a steady state was reached. Monthly surface fluxes were diagnosed over the last 15 years of integration. Following this, all relaxation was removed, and the model was forced with the diagnosed surface fluxes for an initial 100 years. The model remained stable under the fluxes, although variability was enhanced. This experiment, the end of which is used as the starting point for the flux modification experiments, is described in detail by *Myers and Haines* [2000]. The diagnosed fluxes have been discussed previously [*Myers and Haines*, 2000, 2002] and have been shown to compare very well with observational estimates on the basin and sub-basin scale. The annual mean fluxes are given in Table 1.

[10] In all the following experiments (except where specified otherwise) the fluxes are modified in a very basic and straightforward manner. For each model grid point and each month they are multiplied by the change in excess evaporation desired (i.e., a decrease in excess evaporation by 20% implies that the base derived fluxes are multiplied by 0.80). This changes the basin's net freshwater flux (and similarly for each subbasin) without changing the structure of the fluxes. Although clearly a simplification, there is some justification for this. Changes in evaporation, precipitation, and runoff are mainly governed by atmospheric conditions, and on atmospheric spatial scales, the Mediterranean is very small, and thus it is not unreasonable to suppose similar conditions will apply over the entire basin. Heat fluxes have not been changed so as to concentrate on the freshwater fluxes, the main driving force for the basin's thermohaline circulation.

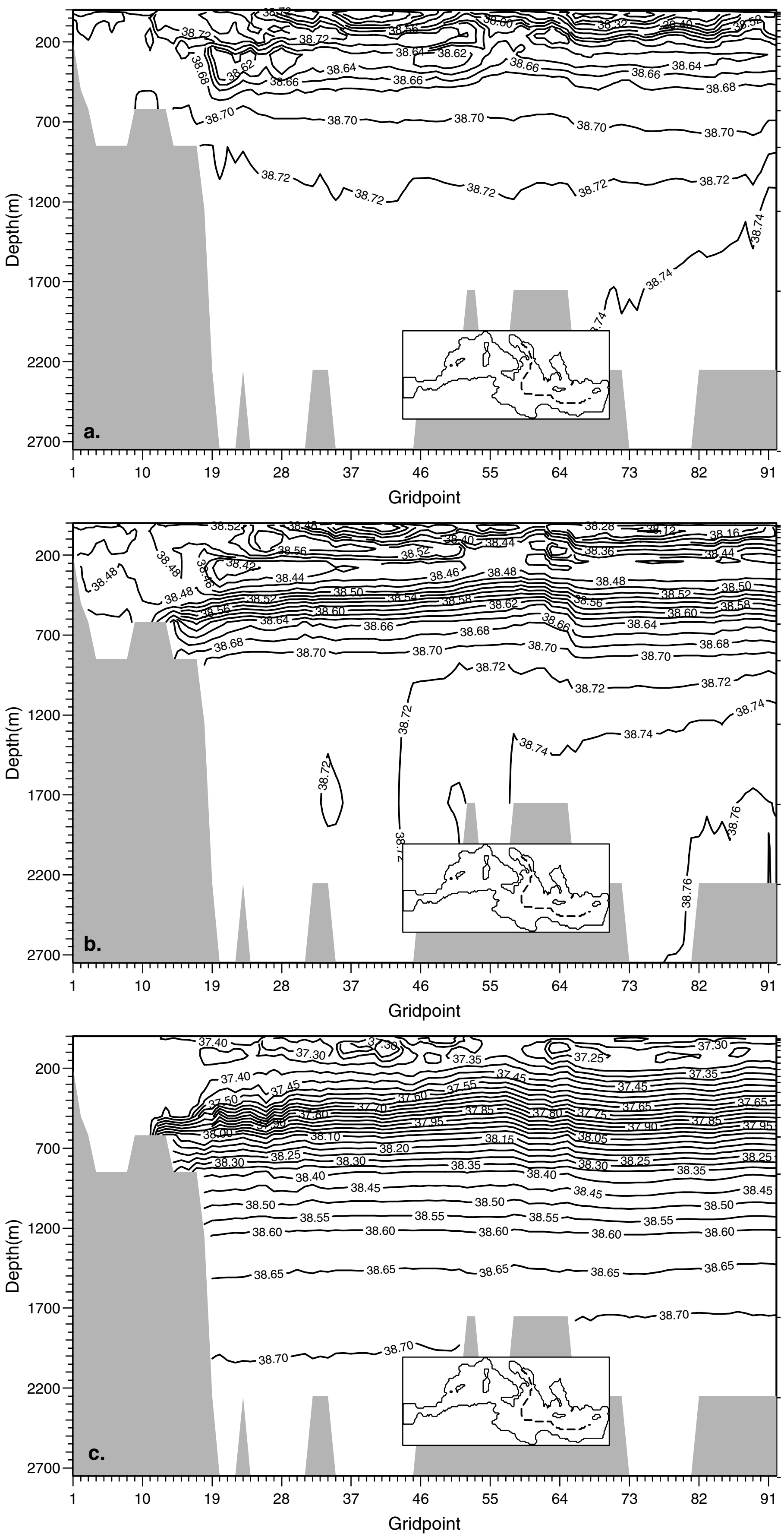
3. Decreased Excess Evaporation

[11] We begin our experiments on the role of decreasing the excess evaporation over the basin with a small 8% decrease. This matches in size the largest stable increase *Myers and Haines* [2001] were able to impose. The model is integrated for 100 years from the end of BASELINE. The circulation changes in a linear fashion (Table 2). With fresher surface waters, convection has decreased in intensity. LIW formation has ceased with a decrease in the supply of salty Modified Atlantic Water (MAW) to the Levantine. Limited convection occurs in the Aegean, while without the LIW, wintertime cooling in the northern Ionian leads to the formation of a cold, fresh, intermediate water mass in that area. Adriatic deep con-

Table 2. Summary of the Experiments Performed, Showing the Changes in Basin Average Salinity, Surface Salinity, and Transports at Gibraltar and Changes in Basin Overturning Strengths[a]

Experiment	Year	Basin Average *S*, psu	Gibraltar Volume Transport, Sv	Gibraltar Freshwater Transport, Sv	Surface *S*, psu	Zonal Overturning Strength, Sv	Eastern Deep Water Formation, Sv	Western Deep Water Formation, Sv
BASELINE	100	38.53	1.59	0.059	38.19	1.4	0.3	0.2
−8%	100	38.47	1.43	0.053	38.07	1.3	0.1	0.1
−20%	80	38.43	1.52	0.048	37.96	1.3	0.0	0.0
−40%	80	38.33	1.36	0.036	37.75	1.2	0.0	0.0
−60%	80	38.22	1.18	0.019	37.53	1.0	0.0	0.0
−80%	80	38.04	0.89	0.017	37.13	0.9	0.0	0.0
PREASWAN	100	38.51	1.49	0.056	38.15	1.4	0.2	0.2
HOLNILE	100	38.48	1.50	0.052	38.10	1.3	0.1	0.1

[a] The year column indicates the year of integration for each experiment that the calculated values are for. All results are annual averages.


a.
b.
c.
Depth(m)
200
700
1200
1700
2200
2700
1
10
19
28
37
46
55
64
73
82
91
Gridpoint
38.72
38.70
38.74
38.68
38.66
38.64
38.62
38.76
38.48
38.44
38.46
38.50
38.52
38.56
38.58
38.60
38.54
37.30
37.35
37.40
37.45
37.50
37.55
37.60
37.65
37.70
37.75
37.80
37.85
37.90
37.95
38.00
38.05
38.10
38.15
38.20
38.25
38.30
38.35
38.40
38.45
38.50
38.55
38.60
38.65
38.70

vection still occurs, but without the preconditioning from LIW import, the water no longer sinks to the bottom as EMDW after overflowing the sill at Otranto, instead occupying an intermediate layer down to 1000–1500 m (Figure 1). The loss of salt from the LIW also weakens convection in the Gulf of Lions, limiting it to a maximum of 1200 m. Although there is no deep convection occurring, the stratification in the deep waters is very weak (and would thus be easy to penetrate in an extreme winter).

[12] Similar behavior occurs when the excess evaporation is reduced by 20% (from BASELINE). Convection has been significantly reduced. Although the Adriatic still overturns in winter, the outflow now only ventilates the upper 750 m of the eastern basin (Figure 1b). The only other significant water mass in the eastern basin is a shallow Aegean intermediate water that flows into the Ionian between 100 and 150 m. Western convection is also limited to the top 500–600 m. The other main difference with the 8% reduction experiment is that the stratification between the intermediate and deep waters has significantly increased, making it unlikely that even extreme winter events during cold years would produce convection that was able to ventilate the deep waters. This circulation pattern now resembles that suggested for the sapropel S_1 by *Myers et al.* [1998b], outside of the Adriatic (Figure 2b). As well, the reconstructed salinity is very similar to that calculated for S_1 in a $\delta^{18}O$ validated box model by *Rohling* [1999]. It is also, surprisingly, very similar to the collapsed state found after 200 years by *Myers and Haines* [2002] in their +25% experiment.

[13] To reduce the computational time needed for our experiments, all of the remaining reduced flux experiments were started from the end of the previous one (i.e., 40% reduction experiment was started from the end of the 20% experiment, etc.) and then integrated for 80 years. With each successive reduction in excess evaporation, the basin-averaged properties, the depth of convection, and circulation strength continue to drop (Table 2), but only at certain levels do changes in the circulation character occur. With a reduction in the excess evaporation by 60%, Adriatic deep convection finally ceases, with wintertime sinking in this basin now limited to 400–600 m. By the time the excess evaporation has reached only 20% of present, only a very weak and sluggish thermohaline circulation remains (Figures 1c and 2c). Surface salinities have dropped to an average of 37.1 psu (36.8 psu and 37.3 psu in the western and eastern basins, respectively).

[14] The experiments so far have only looked at large-scale basin-wide changes in the excess evaporation, assumed to be produced by atmospheric changes, although changes will affect runoff as most of the rivers in the Mediterranean's catchment are fairly short and will be affected by similar climatic conditions as over the basin. The two exceptions to this, both of which have been postulated to have significant effects, are the Nile and the discharge through the Black Sea. Here the effect of explicitly including one of these "point" sources, the Nile, is considered.

[15] Runoff presently from the Nile is very low due to the Aswan High Dam, which has reduced the Nile discharge from $\sim$60 km^3 yr^{-1} to $\sim$4 km^3 yr^{-1} [*Hurst*, 1957]. The net effect of this on the Mediterranean is to reduce the overall freshwater supply by 2.5 cm yr^{-1}, a 3.3% reduction. Applying this excess freshwater to the model in the region of the mouth of the Nile Delta (6 model grid boxes), the model was integrated for 100 years from the end of BASELINE. This is called experiment PREASWAN. The input of additional freshwater to the Levantine slightly reduces the salinity of the LIW (from 38.96 to 38.91 psu). This leads to less salt being provided as a preconditioner in the convection zones of the Adriatic and Gulf of Lions and thus a weakening of the deep convection cells (Table 2). Locally, the added freshwater input can be seen as a tongue of decreased salinity water along the Israeli coast. However, the changes to the integrated basin properties (Table 2) are small, consistent with the small change in the overall freshwater balance.

[16] Next, Nile runoff is enhanced to 2.5 times the pre-Aswan values to represent its discharge of heavy monsoonal rains over East Africa during the Holocene optimum [*Rossignol-Strick et al.*, 1982; *Rossignol-Strick*, 1985]. Again, an integration for 100 years from the end of BASELINE is performed, with this experiment called HOLNILE. The net reduction to the overall excess evaporation is just over 8% of present but again applied only across the mouth of the Nile Delta. The overall basin behavior is very similar to that in the uniform 8% reduction experiment (Table 2). Some of the structure is different (i.e., the Nile discharge can be seen as a distinct low-salinity tongue flowing up along the Israeli coast to feed into the Asia Minor Current to the east of Cyprus, with the overall eastern basin SSS dropping by 0.15 psu), but the end results are similar. LIW production is stopped by a freshwater cap of Nile discharge that reaches the Rhodes Gyre. Without added salt, eastern and western convection becomes purely temperature driven and significantly shallower (maximum 1500 m).

[17] Worth noting here, in all experiments, is that with a drop in the effective excess evaporation, the freshwater flux transport into the basin through the Strait of Gibraltar no longer balances the surface fluxes, producing an excess inflow of freshwater and a drop in the basin average salinities. However, as the changes in the basin are felt in the outflow at Gibraltar, the freshwater influx through the strait decreases to a level that balances the loss at the surface from the decreased excess evaporation. The timescale for this to occur is less than one century in all cases.

4. Discussion

[18] This work provides some insight into collapsed circulation modes that could be associated with unventilated bottom waters and sapropel formation. As shown in the box model studies of Korres and Lascaratos (personal communication, 1999), while the main east-west LIW cell is stable (although subject to weakening) even with significant changes in the buoyancy budget, the secondary cells in each subbasin are highly sensitive to buoyancy changes. Even a small 8% decrease in excess evaporation stops convection from penetrating below 1500 m (albeit with weak stratification that could be easily penetrated during extreme winters), and a 20% or greater decrease leads to only intermediate water ventilation outside the Adriatic. Pycnocline shoaling also occurs in all decreased excess evaporation experiments, which may lead to productivity enhancements [*Rohling*, 1994].

[19] *Mangini and Schlosser* [1986] suggested a 0.2 psu freshening in the Adriatic would be enough to cause stratification of water masses and enhance sapropel formation. While we concur that such a small change will enhance stratification (although a larger 0.35 psu decrease is needed to actually stop Adriatic deep convection in the model as temperature-driven convection still occurs in this subbasin), the resulting circulation is not just a shoaling of the present mode. LIW formation ceases in all such experiments, showing its sensitivity to a climate amelioration (i.e., warmer or more humid conditions), as its formation is highly dependent on the input of salty MAW formed by evaporation [*Myers and Haines*, 2000]. Instead, the dominant mode for "wet" climates is AIW

Figure 1. (opposite) Transect of the annually averaged salinity through the eastern Mediterranean and the Adriatic (path shown in the inset) for the end of the (a) −8% experiment; (b) −20% experiment, and (c) −80% experiment. The contour interval is 0.02 psu in Figures 1a and 1b and 0.05 psu in Figure 1c.

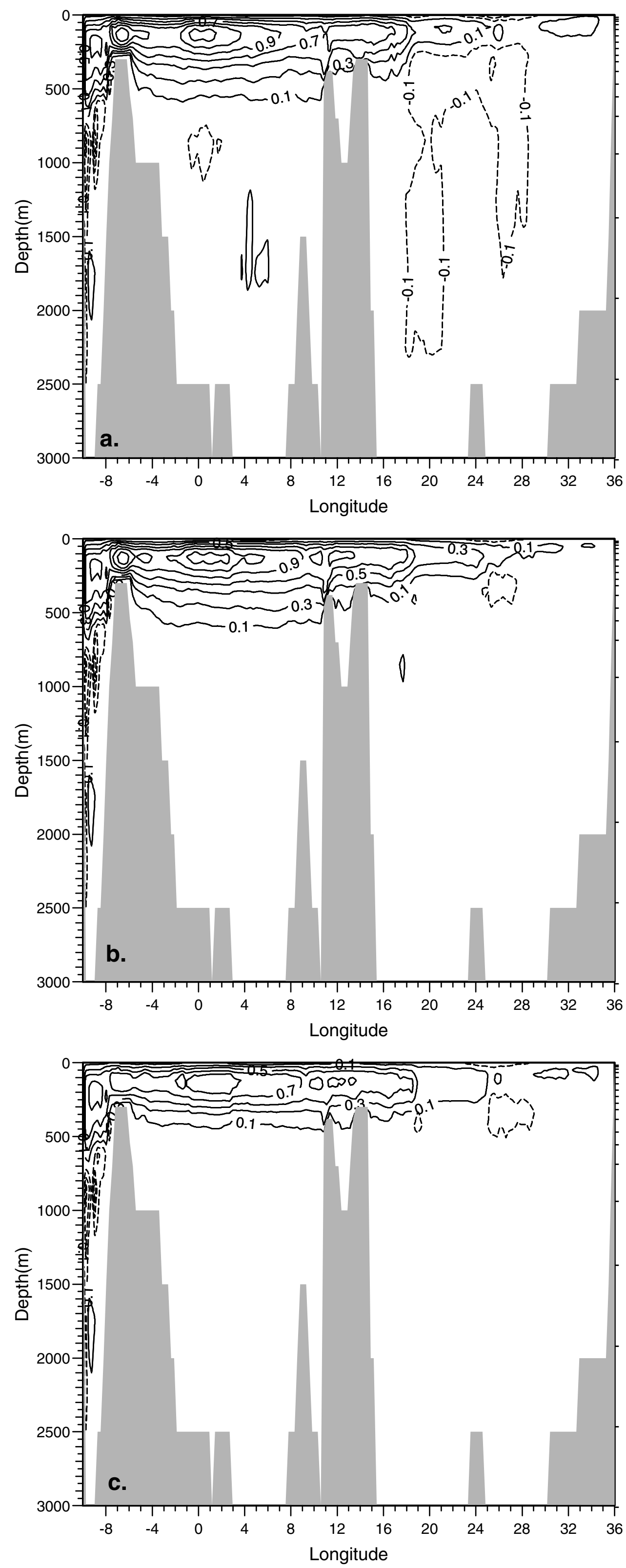


Figure 2. Annually averaged zonal stream function for the Mediterranean from the end of the (a) −8% experiment, (b) −20% experiment, and (c) −80% experiment. The contour interval is 0.2 Sv.

formation, as found for S_1 by *Myers et al.* [1998b], which ventilates both the upper parts of the eastern basin and overflows the Strait of Sicily to feed the western basin. Although the Adriatic does receive significant freshwater input from the Po and other rivers [*Artegiani et al.*, 1997], its cool winter temperatures allow for wintertime convection. The sensitivity of LIW formation supports the hypothesis of *Emeis et al.* [2000] that water formation may have shifted westward ∼2000 years prior to the onset of the formation of S_1 and then only collapsed when a significant density decrease occurred in the Ionian and Adriatic (probably associated with even less excess evaporation and also possibly warming).

[20] There is a breakdown of convection in the western basin, although the stratification is always less than in the east. This would suggest that conditions for sapropel formation may also exist in this subbasin, even though only limited examples have been found [*Rohling*, 1994; *Bethoux and Pierre*, 1999]. However, differences in productivity (i.e., less nutrient input [*Bethoux et al.*, 1998]) and climate may explain the lack of sapropels present in the western basin. With the main deep water formation region (Gulf of Lions) farther north and subject to cold katabatic winds [*Thetis Group*, 1994], wintertime temperatures have been colder there since at least the end of the Last Glacial Maximum [*Kallel et al.*, 1997]. This may have produced enough wintertime convection to prevent sapropel formation. As well, the weaker stratification in the western basin would leave the deep water subject to periodic ventilation from occasional extreme winters or extended cold periods [*Myers and Rohling*, 2000].

[21] The 60 or 80% reduction experiments are probably the ones that come closest to simulating the conditions at the time of S_1. All told, the 80% experiment represents a 540 year integration where the excess evaporation over the basin was slowly decreased in stages until reaching only 20% of today's. As stated in Table 2, the basin average surface salinity has dropped to 37.1 psu (and 36.8 psu and 37.3 psu in the western and eastern basins, respectively) in the 80% experiment and 37.5 psu (37.0 psu and 37.8 psu in the west and east, respectively) in the 60% experiment. A basin-averaged salinity of 37.1 psu for S_1 is consistent with the r = 0.8 experiment by *Rohling* [1999] using a $\delta^{18}O$ validated box model (although Rohling found that salinity associated with only a 65% reduction in excess evaporation). This value of 37.1 psu is slightly saltier than the oxygen isotope-based reconstructions of *Kallel et al.* [1997] and *Emeis et al.* [2000], whose results may be biased (to lower salinities) by treating the $S : \delta^{18}O$ relationship as temporally invariant [*Rohling and Bigg*, 1998]. The reduced west-east SSS gradient (about half of today) is in agreement with *Rohling and De Rijk* [1999]. However, with no explicit enhanced Nile outflow included in the model, one might expect the simulated Levantine salinities to be slightly too high.

[22] The local freshwater source experiments suggest that although different sources for extra freshwater may play a role in determining the short-term basin behavior, in the long-term it is the overall budget changes that are significant on the large scale (local effects will still depend on the sources). The basin will also respond and equilibrate to any external flux change, through changing the properties of the transports at Gibraltar, with a timescale of less than one century (shorter for the upper water column). What this means is that enhancing one aspect of the freshwater flux into the basin (say the Nile discharge or the Black Sea outflow) over a long period of time (1–2000 years) is not enough on its own to produce the very large salinity decreases reconstructed for S_1 or other older sapropels because of the compensation in the inflow fluxes that will occur at the Strait of Gibraltar (unless similar salinity decreases are occurring in the Atlantic). Although the discharge from the Nile and the Black Sea may have been important in providing a freshwater layer to cap convection (although general reductions in excess evaporation

could also have had similar effects) and in providing additional nutrients for sapropel productivity [*Rohling and Hilgen*, 1991], these sources cannot by themselves explain the low salinities associated with S_1.

[23] As discussed above, it is postulated that the overall decrease in excess evaporation for the Mediterranean at the time of S_1 was between 60 and 80%. Considering today's excess evaporation is ~75.0 cm yr^{-1} [*Gilman and Garrett*, 1994], an extra 54–64 cm yr^{-1} of freshwater input needs to be explained. The extra discharge from the Holocene Nile as compared to today's dammed river could explain 6–7 cm yr^{-1}. Estimated runoff from the recently connected Black Sea would suggest an additional influx of 15–30 cm yr^{-1}. That still leaves an additional 17–43 cm yr^{-1} that must be explained by local atmospheric changes producing less evaporation, more precipitation, and more runoff from the local (non-Nile) rivers bordering the Mediterranean. This is consistent with previous suggestions by *Rohling and Hilgen* [1991].

5. Summary

[24] An ocean general circulation model of the Mediterranean is forced by surface fluxes of heat and freshwater. The baseline fluxes are obtained for a long restoring experiment that accurately simulates the circulation and hydrography of the basin. The diagnosed fluxes also compare favorably with a number of observational flux estimates. The model circulation remained steady when forced by the diagnosed fluxes with increased internal variability [*Myers and Haines*, 2000]. The diagnosed fluxes were then modified (in a simple basin-averaged sense) to simulate changes to the excess evaporation associated with the basin.

[25] The excess evaporation was decreased from 8 to 80% of today to simulate conditions during more humid past times, including times that would be associated with sapropel formation. Even small decreases in excess evaporation weakened deep convection in the eastern and western basins, while LIW production is shown to be very sensitive to additional fresh water input. The dominant circulation mode in wetter climates is one with Adriatic Intermediate Water formation that then ventilates much of the intermediate depths of the basin, similar to that found during S_1 by *Myers et al.* [1998b]. Reductions of 20% or more of the excess evaporation leave stagnant unventilated deep waters, with the stratification always weaker in the western basin. A 60–80% decrease in excess evaporation comes closest to reproducing the salinity conditions reconstructed for S_1 [*Kallel et al.*, 1997; *Rohling and De Rijk*, 1999], with an west-east salinity gradient of about half of today's.

[26] **Acknowledgments.** I would like to thank Keith Haines, Eelco Rohling, Kevin Stratford, Stephan Matthiesen, and others in the CLIVAMP project for helpful discussions. This work was funded by the EU MAST CLIVAMP program under contract number MAS3-CT95-0043 and also by an NSERC operating grant to P.G.M.

References

Artegiani, A., D. Bregant, E. Paschini, N. Pinardi, F. Raicich, and A. Russo, The Adriatic Sea general circulation, part I, Air-sea interactions and water mass structure, *J. Phys. Oceanogr.*, *27*, 1492–1514, 1997.

Bethoux, J.-P., and B. Gentili, The Mediterranean-Sea, coastal and deep sea signatures of climatic and environmental-changes, *J. Mar. Syst.*, *7*, 383–394, 1996.

Bethoux, J.-P., and C. Pierre, Mediterranean functioning and sapropel formation: Respective influences of climate and hydrological changes in the Atlantic and the Mediterranean, *Mar. Geol.*, *153*, 29–39, 1999.

Bethoux, J.-P., P. Morin, C. Chaumery, O. Connan, B. Gentili, and D. Ruiz-Pino, Nutrients in the Mediterranean Sea, mass balance and statistical analysis of concentrations with respect to environmental change, *Mar. Chem.*, *63*, 155–169, 1998.

Bigg, G. R., Aridity of the Mediterranean Sea at the Last Glacial Maximum: A reinterpretation of the $\delta^{18}O$ record, *Paleoceanography*, *10*, 283–290, 1995.

Brasseur, P., J. M. Beckers, J. M. Brankart, and R. Schoenauen, Seasonal temperature and salinity fields in the Mediterranean Sea: Climatological analyses of a historical data set, *Deep Sea Res.*, *43*, 159–192, 1996.

Emeis, K., U. Struck, H. Schulz, R. Rosenburg, S. Bernasconi, T. Sakamoto, and F. Martinez-Ruiz, Temperature and salinity of Mediterranean Sea surface waters over the last 16,000 years: Constraints on the physical environment of S_1 based on stable oxygen isotopes and alkenone unsaturation ratios, *Palaeogeogr. Palaeoclimatol. Palaeoecol.*, *158*, 259–280, 2000.

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

Gent, P. R., and J. C. McWilliams, Isopycnal mixing in ocean circulation models, *J. Phys. Oceanogr.*, *20*, 150–155, 1990.

Gilman, C., and C. Garrett, Heat flux parameterizations for the Mediterranean Sea: The role of atmospheric aerosols and constraints from the water budget, *J. Geophys. Res.*, *99*, 5119–5134, 1994.

Haines, K., and P. Wu, A modelling study of the thermohaline circulation of the Mediterranean Sea: Water formation and dispersal, *Oceanol. Acta*, *18*, 401–417, 1995.

Hurst, H. E., *The Nile: A General Account of the River and Utilization of its Waters*, 2nd ed., Constable, London, 1957.

Kallel, N., M. Paterne, J.-C. Duplessy, C. Vergnaud-Grazzini, C. Pujol, L. Labeyrie, M. Arnold, M. Fontugne, and C. Pierre, Enhanced rainfall in the Mediterranean region during the last sapropel event, *Oceanol. Acta*, *20*, 697–712, 1997.

Killworth, P. D., D. Stainforth, D. J. Webb, and S. M. Paterson, The development of a free-surface Bryan-Cox-Semtner ocean model, *J. Phys. Oceanogr.*, *21*, 1333–1348, 1991.

Lane-Serff, G., E. J. Rohling, H. L. Bryden, and H. Charnock, Postglacial connection of the Black Sea to the Mediterranean and its relation to the timing of sapropel formation, *Paleoceanography*, *12*, 169–174, 1997.

Levitus, S., *Climatological Atlas of the World Ocean*, *Tech. Rep. 13*, Natl. Oceanic and Atmos. Admin., Silver Spring, Md., 1982.

Mangini, A., and P. Schlosser, The formation of eastern Mediterranean sapropels, *Mar. Geol.*, *72*, 115–124, 1986.

Myers, P. G., and K. Haines, Seasonal and interannual variability in a model of the Mediterranean under derived flux forcing, *J. Phys. Oceanogr.*, *30*, 1069–1082, 2000.

Myers, P. G., and K. Haines, Stability of the Mediterranean's thermohaline circulation under modified surface evaporative fluxes, *J. Geophys. Res.*, 10.1029/2000JC000550 in press, 2002.

Myers, P. G., and E. J. Rohling, Modelling a 200-year interruption of the holocene sapropel S_1, *Quat. Res.*, *53*, 98–104, 2000.

Myers, P. G., K. Haines, and S. Josey, On the importance of the choice of wind stress forcing to the modelling of the Mediterranean Sea circulation, *J. Geophys. Res.*, *103*, 15,729–15,749, 1998a.

Myers, P. G., K. Haines, and E. J. Rohling, Modelling the paleo-circulation of the Mediterranean: The Last Glacial Maximum and the Holocene with emphasis on the formation of sapropel S_1, *Paleoceanography*, *13*, 586–606, 1998b.

Olausson, E., Studies of deep sea cores, *Rep. Swed. Deep Sea Exped. 1947–1948*, *8*, 336–391, 1961.

Paterne, M., J.-C. Duplessy, N. Kallel, and L. Labeyrie, Clivamp Last Glacial Maximum sea surface salinities and temperatures, *Tech. Rep. CLIVAMP-MAS3-CT95-0043*, Cent. des Faibles Radioactivites, Gif-sur-Yvette, France, 1998.

Rahmstorf, S., A fast and complete convection scheme for ocean models, *Ocean Modell.*, *101*, 9–11, 1993.

Rohling, E. J., Review and new aspects concerning the formation of eastern Mediterranean sapropels, *Mar. Geol.*, *122*, 1–28, 1994.

Rohling, E. J., Environmental control of Mediterranean salinity and $\delta^{18}O$, *Paleoceanography*, *14*, 706–715, 1999.

Rohling, E. J., and G. R. Bigg, Paleosalinity and $\delta^{18}O$: A critical assessment, *J. Geophys. Res.*, *103*, 1307–1318, 1998.

Rohling, E. J., and H. L. Bryden, Man-induced salinity and temperature increases in Western Mediterranean Deep Water, *J. Geophys. Res.*, *97*, 11,191–11,198, 1992.

Rohling, E. J., and S. De Rijk, Holocene climate optimum and Last Glacial Maximum in the

Mediterranean: The marine oxygen isotope record, *Mar. Geol.*, *153*, 57–75, 1999.

Rohling, E. J., and F. J. Hilgen, The eastern Mediterranean climate at times of sapropel formation: A review, *Geol. Mijnbouw*, *70*, 253–264, 1991.

Rohling, E. J., S. De Rijk, A. Hayes, D. Kroon, W. J. Zachariasse, and D. Eisma, Abrupt cold spells in the NW Mediterranean, *Paleoceanography*, *13*, 316–322, 1998.

Rossignol-Strick, M., Mediterranean Quaternary sapropels, an immediate response of the African monsoon to variations in insolation, *Palaeogeogr. Palaeoclimatol. Palaeoecol.*, *49*, 237–263, 1985.

Rossignol-Strick, M., W. Nesteroff, P. Olive, and C. Vergnaud-Grazzini, After the deluge, Mediterranean stagnation and sapropel formation, *Nature*, *295*, 105–110, 1982.

Stratford, K., A note on the implementation of flux-limited advection for tracers in an ocean circulation model, *J. Atmos. Oceanic Technol.*, *16*, 1284–1290, 2000.

Stratford, K., R. G. Williams, and P. G. Myers, The impact of the circulation on sapropel formation in the eastern Mediterranean, *Global Biogeochem. Cycles*, *14*, 683–695, 2000.

Thetis Group, Open-ocean deep convection explored in the Mediterranean, *Eos Trans. AGU*, *75*, 217, 219–221, 1994.

Thuburn, J., Multidimensional flux-limited advection schemes, *J. Comput. Phys.*, *123*, 74–83, 1996.

Thunell, R. C., and D. F. Williams, Glacial-holocene salinity changes in the Mediterranean Sea: Hydrographic and depositional effects, *Nature*, *338*, 493–496, 1989.

Webb, D. J., An ocean model code for array processor computers, *Tech. Rep. 324*, Inst. of Oceanogr. Sci., Wormley, UK, 1993.

Wu, P., and K. Haines, Modelling the dispersal of Levantine Intermediate Water and its role in Mediterranean Deep Water formation, *J. Geophys. Res.*, *101*, 6591–6607, 1996.

Wu, P., and K. Haines, The general circulation of the Mediterranean Sea from a 100-year simulation, *J. Geophys. Res.*, *103*, 1121–1135, 1998.

P. G. Myers, Department of Earth and Atmospheric Sciences, 1-26 Earth Sciences Building, University of Alberta, Edmonton, Alberta, Canada T6G 2E3.