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Modeling a 200-Yr Interruption of the Holocene Sapropel S_1

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An oceanic general circulation model, previously used to simulate the conditions associated with the Holocene Sapropel S_1, is used to simulate the effects of a climate deterioration (represented as a cooling event) on the sapropelic circulation mode. The enhanced cooling (2°–3°C) induces deep convection in the Adriatic and the Gulf of Lions and intermediate water formation in the Aegean, where in all cases there had previously been only stagnant unventilated waters. The depths of ventilation (to ~1250 m) are in agreement with core data from this period. The short decadal timescales involved in modifying the sapropelic circulation suggest that such a climatic deterioration may be associated with the interruption of S_1 between 7100 and 6900 ^{14}C yr B.P., which divided the sapropel into two subunits.

Key Words: **Mediterranean Sea; Sapropel S_1; sapropel interruptions; paleomodeling; Holocene.**

INTRODUCTION

Numerous layers of black, often laminated, sediments rich in organic matter (sapropels) have been found between the normal pelagic sediments by deep-sea coring in the Mediterranean (Kullenberg, 1958). They have been found throughout the eastern Mediterranean, with upper depth limits (for the overlying water column) quoted at 700 m (Thunell *et al.*, 1984), to 300 m (Rohling and Gieskes, 1989), to as shallow as 150 m in the northern Aegean Sea (Perissoratis and Piper, 1992). Abundant and well-preserved calcareous microfossils of planktonic origin have been found in the sapropels, but they are mostly devoid of benthic fossils (Castradori, 1993; Rohling, 1994). The (1) common absence of benthic foraminifera from sapropels (azoic conditions) and (2) specific sequence of increasing dominance of progressively low-oxygen-tolerant benthic species below and into the base of sapropels suggest anoxic conditions below the specified depths (Jorissen *et al.*, 1993; Rohling, 1994; Rohling *et al.*, 1997; Jorissen, 1999).

During the warm and wet climate of the early Holocene period (Rossignol-Strick *et al.*, 1982; Mangini and Schlosser, 1986; Rossignol-Strick, 1987; Wijmstra *et al.*, 1990; Rohling and Hilgen, 1991) the most recent sapropel S_1 was deposited between about 9000 and 6000 ^{14}C yr B.P. (Jorissen *et al.*, 1993; Troelstra *et al.*, 1991; Perissoratis and Piper, 1992; Fontugne *et al.*, 1992). Oxygen isotope (δ^{18}O) records (e.g., Vergnaud-Grazzini *et al.*, 1977; Cita *et al.*, 1977; Thunell and Williams, 1989; Tang and Stott, 1993; Kallel *et al.*, 1997; Rohling and De Rijk, 1999) suggested that eastern Mediterranean surface salinities were substantially reduced at the time of the formation of S_1, relative to the present. The effect of low surface salinities would be to decrease the densities of the surface waters and hence reduce the potential for convective overturning and deep-water formation. Without abyssal ventilation, the oxygen content of the deep waters would gradually decrease as it was utilized for oxic degradation of organic matter. Consequent development of deep anoxia is thought to increase the potential for the preservation of organic matter in the sediments and is consistent with the observed absence of benthic fossils from sapropelic sediments (Rohling, 1994).

Recently, Myers *et al.* (1998) examined the conditions associated with Sapropel S_1 using a sophisticated general circulation model of the Mediterranean that had been shown to reproduce accurately the present 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 anti-estuarine circulation, albeit weakened, at the straits of both Gibraltar and Sicily. In the 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. A separate tracer model shows this isolated deep layer becoming anoxic over time (K. Stratford, R. G. Williams, and P. G. Myers, unpublished data, 1999; hereafter referred to as SWM).

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Myers *et al.* (1998) also show 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 trapping of nutrients, shoaling of the pycnocline (Myers *et al.*, 1998), and increases in productivity (SWM).

Pale-colored "interruptions" have been seen in cores that include a number of sapropels, e.g., S_1, S_6, S_8, and C_2 (Rohling *et al.*, 1993, 1997; De Rijk *et al.*, 1999). These intervals are best studied in sedimentary sequences with high accumulation rates. Rohling *et al.* (1993) showed that the interruption in the Upper Pliocene sapropel C_2 (Singa section, southern Italy) was associated with repopulation by a low-oxygen-tolerant benthic species, *Bulimina marginata,* following a benthic azoic (=persistently anoxic) interval. Variations in the planktonic foraminiferal and oxygen isotope records suggest that surface water cooling preceded this benthic repopulation, which would have favored enhanced deep-water formation. The records also suggest that the cooling associated with temporarily improved deep-water ventilation ended with the end of the benthic repopulation, after which time azoic/anoxic conditions returned.

Cores from high-sedimentation-rate areas containing the most recent sapropel, S_1, show another, more detailed, record of sapropel interruption. Rohling *et al.* (1997) noted that a number of S_1 cores throughout the eastern basin, and especially in the Adriatic, contained evidence for an interruption during sapropel formation. A detailed analysis of core IN68-9 from the southern Adriatic Sea (Rohling *et al.*, 1997) suggested a 200-yr interruption between 7100 and 6900 yr B.P. Although planktonic foraminiferal faunas suggest generally increased productivity across the sapropel interval, supporting the arguments of Pederson and Calvert (1990) that sapropel formation should be associated with increased productivity, Rohling *et al.* (1997) did not observe a link between short-term productivity variations and the deposition of S_1 into two distinct subunits. Instead, changes in SST conditions were found to be associated with changes in bottom-water oxygenation at the time of sapropel interruption. Only small temperature changes ($<2°$C) were suggested, but the Adriatic Sea may still be sufficiently sensitive to resultant changes in surface-water density that deep ventilation is induced.

Perissoratis and Piper (1992) found near-synchronous interruptions of S_1 in the northern Aegean Sea, and De Rijk *et al.* (1999) recently completed a detailed study of a core from the southeastern Aegean Sea. The latter authors again suggest that the interruption in the Aegean S_1 sapropel is associated with temperature reduction and related increased deep-water ventilation. De Rijk *et al.* (1999) correlate their record to other independent circum-Mediterranean investigations, thus relating the sapropel interruption to a period of climatic cooling and increased aridity. Both effects would act to increase surface-water density and the likelihood of convective overturn.

The above evidence suggests that the sapropelic circulation mode may be sensitive to short-term (i.e., decadal- to centennial-scale) climatic perturbations. In particular, conditions associated with improved deep-water ventilation (cooler temperatures and/or increased aridity) may lead to brief hiatuses within sapropels. Here, we aim to establish whether the sapropel mode is a stable, robust state or whether it is strongly sensitive to fluctuations in the surface buoyancy loss. We therefore use the ocean general circulation model (OGCM) of Myers *et al.* (1998) to investigate whether a small climate deterioration is able to induce deep convection and reoxegenation of the eastern Mediterranean. The model is briefly described and then we present our sapropel interruption experiments and compare them with cores that present evidence of the interruption within S_1.

NUMERICAL MODEL FORMULATION

The model used is the Modular Ocean Model-Array, a free-surface OGCM. The basic model is described in greater detail by Webb (1993). The model setup is based on the work of Haines and Wu (1995) and Wu and Haines (1996, 1998). The horizontal resolution is $0.25° \times 0.25°$ with 19 vertical levels (mainly concentrated in the upper water column to resolve the thermocline). The model parameters and setup are described in Myers *et al.* (1998).

Haney (1971) relaxation conditions are applied at the sea surface for temperature and salinity, as described in Myers *et al.* (1998). A sea-level reduction of 20 m, appropriate for the time of S_1 (Fairbanks, 1989), is considered. Although Myers *et al.* (1998) considered a number of different salinity reconstructions, we will use the intermediate reconstruction they chose as a baseline, based upon the findings of Kallel *et al.* (1997), which suggest a significant freshening of the Holocene Mediterranean and a near disappearance of the present west–east salinity gradient. We use present winds, as Myers *et al.* (1998) demonstrated that paleo winds from a Holocene atmospheric general circulation model (Dong and Valdes, 1995) show little difference from the present. As a baseline, we use present temperatures, consistent with the findings of Kallel *et al.* (1997) in the eastern basin. To this is added a cooling to represent the climatic deterioration thought to have occurred during the interruption. The cooling is applied in the Adriatic, Aegean, and northern sectors of the western basin/Gulf of Lions (i.e., in all parts of the Mediterranean that are now influenced by orographically channeled cold air flows from the continent—the Bora, Etesians, and Mistral, respectively). A small buffer region allows the cooling to be decreased incrementally away from its northern source regions. We do not apply the cooling over the entire Mediterranean because it is only in the water formation regions that surface forcing changes will make a difference to the thermohaline circulation. The magnitude of the cooling varies between experiments and will be discussed in the following section.

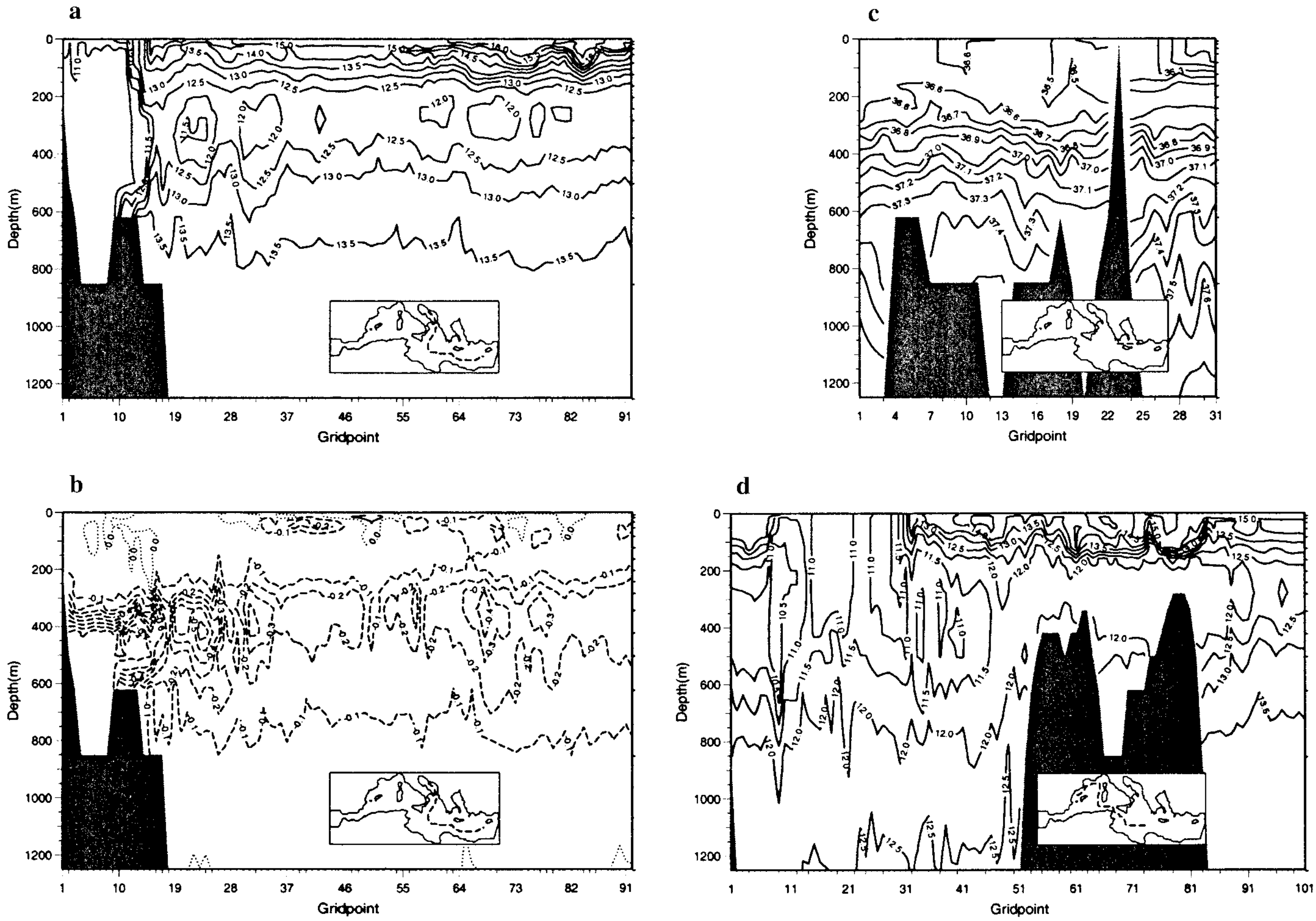

FIG. 1. Plots (with paths shown in the insets) showing the results from cooling experiment 1: (a) temperature section through the Adriatic and eastern Mediterranean for the final winter of the experiment; (b) difference plot between the end of experiment HOL1 of Myers *et al.* (1998) and the end of cooling experiment 1 for salinity in the Adriatic and eastern Mediterranean; sections (c) in the Aegean (salinity) and (d) through the Strait of Sicily, western basin, and Gulf of Lions (temperature), both for the final winter of the experiment. The contour interval is 0.5°C in a and d and 0.1°C in b and c.

SAPROPEL INTERRUPTION

In our first experiment, we apply a 2.0°C cooling to our high-latitude regions, in line with suggestions of the maximum cooling associated with this period (Rohling *et al.*, 1997; De Rijk *et al.*, 1999). The model was then integrated for 40 yr [from the end of the experiment HOL1 of Myers *et al.* (1998)], with each model year representing one "real" year, using the modified surface temperature profiles until a steady state was reached. Compared with the experiments of Myers *et al.* (1998), the enhanced cooling makes only a small difference to the overall basin circulation, but has substantial impact on the seas along the northern margin where the coolings are imposed.

The temperature drop leads to enhanced wintertime convection in the Adriatic, with penetrative sinking now to the bottom of the subbasin (Fig. 1a), compared with the 300- to 400-m depth limit in Myers *et al.* (1998). The deep Adriatic is now 2.0°C cooler and 0.7 fresher, with the resulting exported AIW now ventilating a thicker slice of the water column (as seen by the wedge of fresher water, Fig. 1b), down to ~750 m. It also penetrates much farther into the eastern basin, reaching the Levantine, as can be seen following the core along the transect path in the difference plot (Fig. 1b). It still does not penetrate the Aegean, where salinity regularly increases for depths below ~300 m (Fig. 1c). Enhanced convection also occurs in the eastern Cretan basin and southern Aegean, with sinking to 200–250 m in wintertime. The resulting Aegean water mass fills intermediate levels of the Aegean (Fig. 1c) but does not sink to depth in the Aegean Trough. The modified AIW is also exported across the Sicilian sill into the western basin, resulting in significantly greater heat transport through the Strait of Sicily, to balance the greater cooling occurring over the eastern basin. Within the western basin, cooler conditions in the Gulf of Lions lead to enhanced sinking to depths of about 500–600 m (Fig. 1d, consistent with the temperature sensitivity experiment of Myers *et al.*, 1998), although the temperature signal penetrates into the deep parts of the western basin by diffusion.

Although the enhanced cooling increases convection and intermediate water ventilation in the model, especially in the Adriatic, it does not reach significantly below 1000 m in the main eastern Mediterranean basin. We therefore repeat our previous experiment, but increase maximum cooling to 3.0°C in the northern regions. This experiment is started from the midpoint of the previous experiment and integrated for just 20 yr. Despite this short integration length, the strong cooling has time to alter significantly the water properties of much of the basin.

Again, the Adriatic completely convects in winter (not shown), producing a very cold AIW. The export of this water mass is as before. However, with even greater temperature contrasts with the existing deep waters, mixing and diffusion allow the temperature signal to penetrate to ~1250 m (Fig. 2a; note the different vertical scale). This water mass now begins to penetrate the deeper Aegean, filling it below depths of ~400 m, where it can be seen as a homogeneous water mass with salinity >37.0 (Fig. 2b). Above this depth (150–400 m), the cold and fresh core of the Aegean intermediate water exists, formed in the Cretan Sea and exported to parts of the central Levantine and Ionian. The circulation at Sicily remains anti-estuarine, however, with AIW exported to the western basin. The reason for this, in part, remains the very strong cooling and buoyancy loss within the northern regions of the eastern basin.

In both experiments, two additional 40-yr continuation experiments with the enhanced cooling removed, carried on from the end of the cooling experiments, found a return to the sapropel-type (or sapropelic circulation mode) as presented by Myers *et al.* (1998). Deep convection ceases and only intermediate water formation in the 200- to 500-m range occurs. However, the previously produced deep waters remain trapped in the deep Adriatic, Aegean, and western basin, isolated from the newly forming warmer intermediate waters. The temperature and salinity signal that had diffused into the deeper waters in the eastern basin, such as along the path of the sapropel-interruption AIW, remains. The 40-yr time frame is appropriate for the Mediterranean to respond to changes in its surface forcing (Rohling and Bryden, 1992; Bethoux and Gentili, 1996).

DISCUSSION AND SUMMARY

We have used a paleoceanographic OGCM to examine the interruptions seen in cores of the most recent sapropel, S_1. The model is that used by Myers *et al.* (1998) to examine the large-scale Mediterranean circulation during S_1 (and also the last glacial maximum). They found that the Mediterranean's circulation remained anti-estuarine at the time of S_1, although weakened, with only reduced intermediate water ventilation over a stagnant deep layer. A separate off-line experiment, with the fields from the Myers *et al.* (1998) work and a nutrient/oxygen model (SWM), showed the deep water to become sub- or anoxic over time (~400 yr, but less for localized regions such as the Adriatic and Aegean).

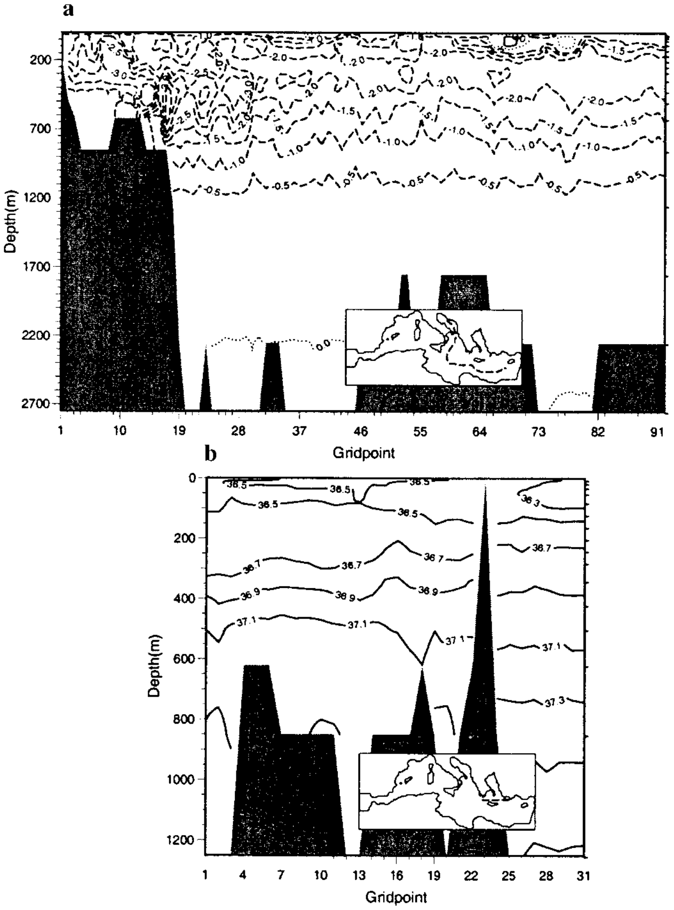

FIG. 2. Plots (with paths shown in the insets) showing the results from cooling experiment 2: (a) difference plot between the end of experiment HOL1 of Myers *et al.*, (1998) and the end of cooling experiment 2 for temperature in the Adriatic and eastern Mediterranean; (b) the salinity during the final year of the experiment in the lower Aegean. The contour interval is 0.5°C in a and 0.2°C in b. Note the difference in depth scale between a and b.

Here, we have applied coolings to the northern regions of the basin to examine the role that a possible climatic deterioration might have on the sapropelic circulation mode. In particular, we examine whether cooling is able to produce deep convection and thus reoxygenation within the basin.

Two experiments are performed, one with a 2.0°C cooling, comparable with the maximum magnitude some suggest for an event that occurred during the time of deposition of sapropel S_1, and one additional experiment with a larger, 3.0°C cooling. In both experiments, deep convection occurs within the Adriatic, with ventilation occurring all the way to the bottom of this subbasin. In the 2.0°C cooling experiment, enhanced convection also occurs in the eastern Cretan sea (to 200–250 m) and in the Gulf of Lions (to ~600 m). Adriatic intermediate water is exported extensively throughout the eastern basin, ventilat-

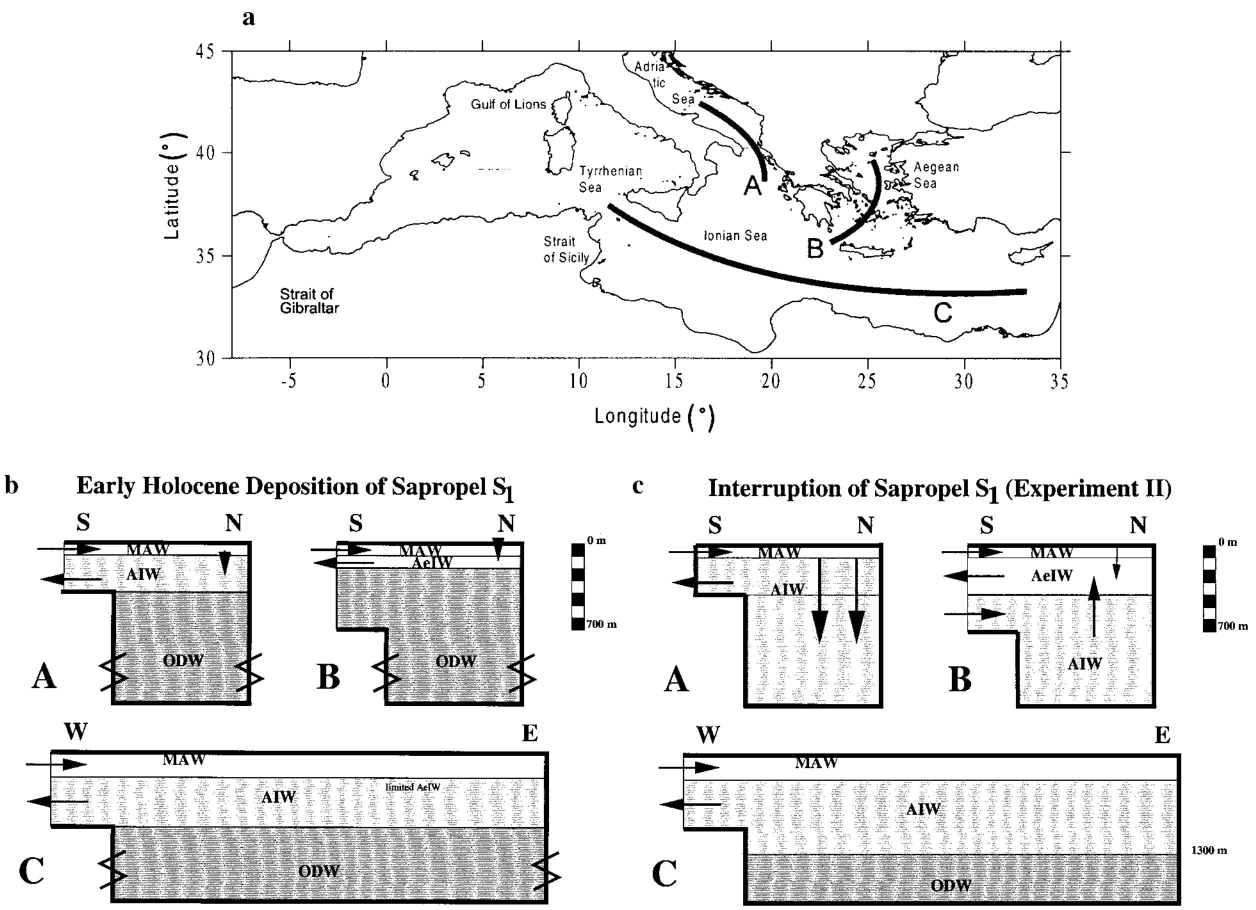

FIG. 3. Schematic diagram summarizing the results of the sapropelic modeling experiments, along sections shown in (a) for the (b) base sapropelic mode of Myers *et al.* (1998) (their experiment HOL1) and (c) cooling experiment II, as discussed in the text. The abbreviations for the water masses are AIW, Adriatic intermediate water; ODW, old deep water; AeIW, Aegean intermediate water; and MAW, modified Atlantic water.

ing down to 700 m, and also through the Strait of Sicily to the western basin. The reventilation of the Adriatic is seen in the data (Rohling *et al.*, 1997), but the depth of ventilation in the Aegean is less than that suggested by De Rijk *et al.* (1999).

With the larger 3.0°C cooling, eastern basin ventilation is enhanced in the Aegean, producing an Aegean water mass that fills the Cretan Sea above 400 m and disperses through parts of the central Levantine and Ionian. It does not sink below 400 m because enhanced formation of denser AIW now penetrates the Aegean, filling it and most of the rest of the eastern basin down to 1250 m. The changes to the eastern basin are summarized in Figure 3 and compared with the base Holocene results of Myers *et al.* (1998). Deep convection also occurs in the western basin. The depth of reventilation in the 3.0°C cooling scenario is naturally greater than that in the 2.0°C cooling scenario. However, it may be more appropriate than the 2.0°C cooling scenario since De Rijk *et al.* (1999) suggested that the ca. 2.0°C cooling was compounded by increased aridity, which would have an effect equivalent to extra cooling.

When the enhanced cooling is removed, the model, in both cases, quickly returns to its previously sapropelic circulation, with no deep-water formation and only very limited intermediate ventilation. Remnants of the deep water formed during the cooling period do remain and would only slowly dissipate by diffusive processes. Therefore, in areas affected by the changes in ventilation, some oxygen might persist through the onset of the second unit of S_1 until utilized. This would be especially true in the less-stratified western basin.

Our results suggest that a climatic deterioration, associated with enhanced cooling of a few degrees magnitude, and/or increased aridity, could temporarily enhance deep-water ventilation, even in a highly stratified sapropelic circulation mode. The effects would primarily be seen in the seas along the northern margin where convection resumes and would not likely have affected the main eastern Mediterranean basin below 1200–1300 m depth. The importance of this is that it can possibly explain interruptions in sapropels seen in cores of shallow and intermediate depths. The coincidence of the timing of these interruptions with climatic deteriorations strengthens the idea that increased convection and ventilation are related to the break in the sapropel at these times. Similarly, more intense coolings and ending of the enhanced freshwater input into the basin at the end of periods of sapropel formation (e.g., Rohling *et al.*, 1997; Targarona *et al.*, 1997; De Rijk *et al.*, 1999) would have been conducive to rapid convective overturn and complete eastern Mediterranean deep-water ventilation.

We conclude that the sapropelic circulation mode is highly sensitive to short-term (i.e., decadal- to centennial-scale) climatic perturbations. This sensitivity is most pronounced in the limited subbasins along the northern regions of the basin. Upper- and intermediate-level circulations are also affected on basin-wide scales, with a change in dispersal depths and paths for the intermediate waters. However, the basic eastern Mediterranean sapropel mode, with a weakened anti-estuarine circulation overlying a deep stagnant layer, is robust to short-term surface buoyancy fluctuations.

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