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# The eastern Mediterranean climate at times of sapropel formation: a review

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**Abstract**

Sapropel formation in the eastern Mediterranean coincided closely with minima in the precession index. Such minima occur approximately every 21 000 years. At such times perihelion falls within Northern Hemisphere summer. Minima in the precession index are characterized by intensified Indian Ocean (summer) SW monsoonal circulation, which enhanced discharge of the river Nile into the eastern Mediterranean. However, by compiling paleoclimatological data from the literature, the influence of the monsoon is shown to have reached only as far as the southern Sinai Desert. Therefore, it does not account for contemporary humid phases in the northern borderlands of the eastern Mediterranean, which seem to have been characterized mainly by increased summer precipitation. We argue that increased (summer) precipitation along the northern borderlands of the eastern Mediterranean, at times of sapropel formation, was probably due to increased activity of Mediterranean (summer) depressions. Forming predominantly in the western Mediterranean and tracking eastwards, such depressions tend to lower the excess of evaporation from the eastern Mediterranean relative to that from the western basin. Picking up additional moisture along their eastward path, such depressions also redistribute freshwater within the complex eastern Mediterranean water balance. The increase in runoff and the related flux of nutrients and continental organic matter that resulted from the increased precipitation on the northern borderlands of the eastern Mediterranean, at times of sapropel formation, presumably provided a substantial addition to that which entered the eastern Mediterranean via the Nile.

## Introduction

### *Present-day climatic conditions in the eastern Mediterranean*

At present, the Mediterranean region forms a transition between the central and northern parts of Europe that remain under the influence of the westerlies for the entire year, and the deserts of North Africa which lie within the zone of the subtropical high pressure belt (Boucher 1975). In summer, the subtropical belt of high pressure is displaced to the north and most of the Mediterranean, especially the southeastern part, experiences drought. Polar front depressions may reach the western Mediterranean, but towards the east they become less frequent and they only exceptionally penetrate the eastern Mediterranean. Even when they do, there is little precipitation (Furlan 1977). During winter, the greatest activity of the polar front and the associated depressions occurs over the Mediterranean, especially over the southeastern part and the southern Balkan Peninsula. Accordingly, the frequency and amount of precipitation are highest there in winter (Mariolopoulos 1961, Furlan 1977).

Although cyclones may enter the Mediterranean from the Atlantic, the majority develops within the Mediterranean basin itself in preferred areas of cyclogenesis (Rumney 1968). They tend to be steered by the upper winds and move roughly eastwards (Trewartha 1966, Rumney 1968, Griffiths 1972, Boucher 1975, Furlan 1977). Cyclogenesis is much more frequent over the western Mediterranean than over the eastern basin, the activity being highest in the Gulf of Genoa (Trewartha 1966, Rumney 1968, Cantu 1977) and extending across the Plain of Lombardy to the northern Adriatic (Cantu 1977, Furlan 1977). Although a large number of depressions forms in the western Mediterranean, their central pressures are considerably higher than those of the massive Atlantic storms. Mediterranean depressions should be regarded as secondary depressions, which are often related to much larger disturbances north of the Alps (Trewartha 1966, Boucher 1975). During winter, the Cyprus area becomes a significant centre of cyclogenesis as well (Trewartha 1966, Rumney 1968, Boucher 1975, Furlan 1977).

In present-day summers, a branch of the Asiatic depression (monsoon low) east of the northeastern Mediterranean invokes steady northwesterly winds over the southeastern Mediterranean (Goldsmith & Sofer 1983). This branch consists of an essentially thermal low, centred over the Iranian Plateau, and the resultant (dry) winds with a marked northerly component are known as the 'Etesians' (Mariolopoulos 1961, Furlan 1977). The steady Etesians are characteristic of the summer circulation across southeastern Europe down to the Levantine area, and respond to the generally counterclockwise circulation around the dominant monsoon low. A secondary depression often develops over Cyprus in summer, augmenting the larger circulation (Rumney 1968).

The summer dryness, a present-day characteristic of the climate in most of the eastern Mediterranean, presumably developed in the Late Pliocene in response to the climatic modifications invoked by the uplift of the Tibetan Plateau. Uplift simulations by Ruddiman & Kutzbach (1989) show a change in the lower-level winds from westerly to northeasterly in the western limb of an intensified low-level cyclonic flow around the Tibetan Plateau, and in the eastern limb of the intensified North Atlantic subtropical high. Increased subsidence east of the elevated plateau also appeared to be of importance. Both a slight increase in winter wetness and a greater and significant increase in summer dryness developed due to the Tibetan Plateau uplift (Ruddiman & Kutzbach 1989).

## *Evidence of past climatic variations*

Miocene to Recent sedimentary sequences show that the eastern Mediterranean's oceanographic (and climatic) conditions have been subject to considerable variations. Numerous brownish to black coloured beds are intercalated. These beds are relatively enriched in organic carbon and often well laminated, and are named sapropels.

Sapropels have been deposited in dysoxic to anoxic bottom waters, which allowed the preservation of organic matter in the sediments and caused the (near) absence of benthic fauna. Bottom water oxygen depletion may occur due to restricted deep water ventilation, due to a large flux of marine organic matter from the euphotic zone and/or continental organic matter via river run-off, or due to a combination of these processes.

Many workers argued that restricted deep water ventilation was the principal mechanism invoking sapropel formation. This restriction would be due to lowered salinities or higher temperatures at the sites of deep water formation, resulting in a more stable stratification which, in turn, inhibits large-scale convection. However, sapropels are known to have developed during pleniglacials as well as during interglacials, which suggests that warming was not the major agent invoking more stable stratification in the eastern Mediterranean. On the contrary, increased freshwater fluxes from various sources, at times of sapropel formation, have been positively identified (Rossignol-Strick et al. 1982, Shaw & Evans 1984, Rossignol-Strick 1985, Cramp et al. 1988, Zachariasse et al. in prep.). Moreover, low $\delta^{18}O$ values within sapropels (see Fig. 1) strongly suggest generally lowered surface water salinities at that time (a.o. Cita et al. 1977, Vergnaud-Grazzini et al. 1977, Williams et al. 1978, Mangini & Schlosser 1986). Increased river run-off into the basin would not only lower the salinities, but it would also enhance the input of river-borne nutrients and continental organic matter.

A new model for sapropel formation, combining increased productivity with decreased deep water production and a more detailed assessment of the eastern Mediterranean's vertical density-structure, has been proposed by Rohling & Gieskes (1989). In that model, increased freshwater fluxes into the basin resulted in a shoaling of the density gradient (pycnocline) between the Mediterranean Intermediate Water (MIW) and the surface water, to a depth within the euphotic layer. Thus, a Deep Chlorophyll Maximum (DCM) could develop, between the top of the pycnocline and the base of the euphotic layer, as reflected by the planktonic foraminiferal record. At the same time, the nutrient concentration in the eastern Mediterranean would have been increased as a result of increased riverine fluxes, favouring increased marine organic production.

Rossignol-Strick (1985) coupled the temporal occurrence of sapropels to an orbitally forced monsoonal index, and concluded that sapropel formation was invoked by Nile floods, which are related to monsoonal rains over eastern tropical Africa. In a later paper, Rossignol-Strick (1987) concluded that Eurasian river run-off, regulated by the 'local' eastern Mediterranean climate, also contributed to the excess freshwater input which triggered sapropel formation. Furthermore, she concluded that increases in humidity in the Northern Borderlands of the Eastern Mediterranean (NBEM), at times of sapropel formation, were due in large part to precipitation in the summer season.

In this paper, we will discuss atmospheric circulation patterns that may have increased (summer) precipitation in the NBEM during sapropel formation. We end with a discussion of the major implications with respect to the Mediterranean freshwater budget and the formation of sapropels.

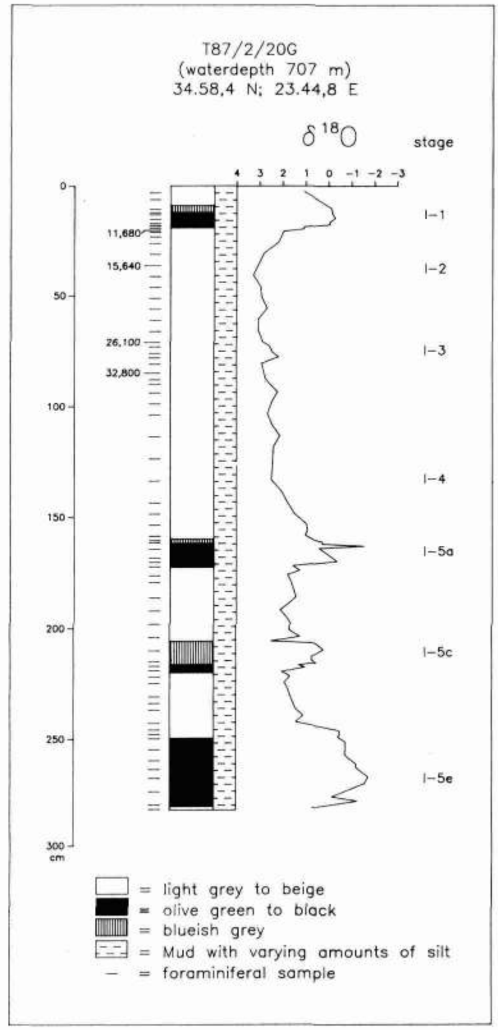
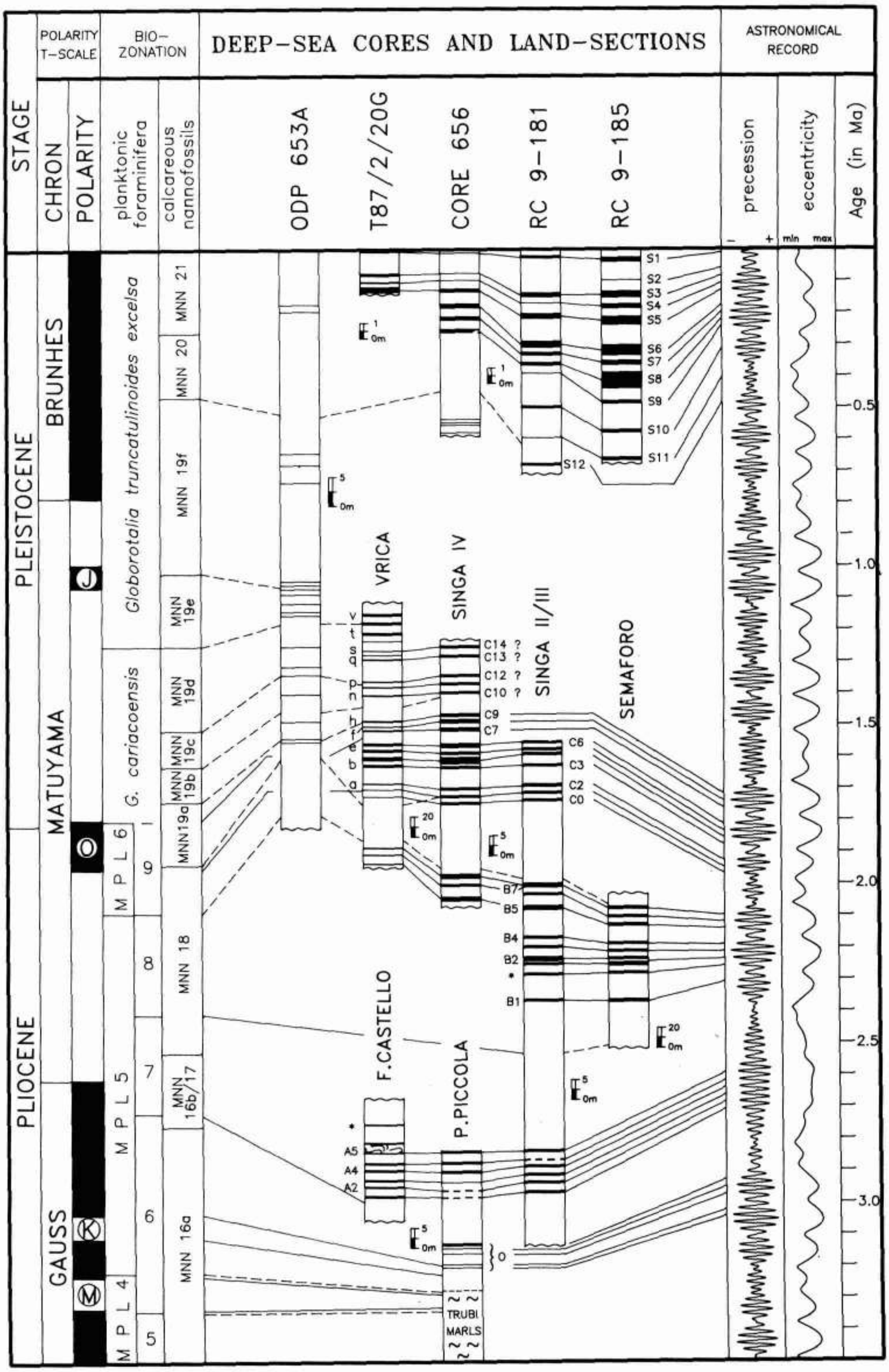



*Fig. 1.* Highly detailed record of $\delta^{18}O$ values versus lithology in core T87/2/20G from the Crete perimeter (Rohling & Gieskes 1989). Oxygen isotopic stages are indicated on the right hand side of the graph. Note the prominently low $\delta^{18}O$ values at the sapropelic levels (= black + hatched). The analyses were performed on the carbonaceous tests of the planktonic foraminiferal species *Globigerinoides ruber*. Small numbers at the left side of the core refer to AMS $^{14}C$ datings.

## The temporal occurrence of sapropels

It would seem most promising to try and unravel the climatic and oceanographic changes that initiated the formation of the youngest sapropel – the early Holocene $S_1$ sapropel – since its time of formation falls well within the age range covered by the AMS $^{14}C$ dating method. This dating method


STAGE
POLARITY T-SCALE
CHRON
POLARITY
BIO-ZONATION
planktonic foraminifera
calcareous nannofossils
DEEP-SEA CORES AND LAND-SECTIONS
ODP 653A
T87/2/20G
CORE 656
RC 9-181
RC 9-185
ASTRONOMICAL RECORD
precession
eccentricity
min max
Age (in Ma)
PLEISTOCENE
PLIOCENE
BRUNHES
MATUYAMA
GAUSS
Globorotalia truncatulinoides excelsa
G. cariacoensis
MPL 6
MPL 5
MPL 4
MNN 21
MNN 20
MNN 19f
MNN 19e
MNN 19d
MNN 19c
MNN 19b
MNN19a
MNN 18
MNN 16b/17
MNN 16a
VRICA
SINGA IV
SINGA II/III
SEMAFORO
F.CASTELLO
P.PICCOLA
TRUBI MARLS
S1
S2
S3
S4
S5
S6
S7
S8
S9
S10
S11
S12
C14 ?
C13 ?
C12 ?
C10 ?
C9
C7
C6
C3
C2
C0
B7
B5
B4
B2
B1
A5
A4
A2
0.5
1.0
1.5
2.0
2.5
3.0

enables detailed correlation of changes in both the marine and the continental environment, within about the last 40 000 years.

The $S_1$ sapropel, with its age range between approximately 9 000 and 6 000 BP (see Fig. 1), however, has been deposited at about the Holocene warm Climatic Optimum, which followed the last major retreat of the Northern Hemisphere continental ice sheets. As stated before, such a coincidence with a warm Climatic Optimum is not typical for all sapropels, since they have been deposited also during glacials. Therefore, ice-cap geography cannot be considered as the dominant factor controlling the climatic initiation of sapropel formation.

Rossignol-Strick (1985) was the first to elaborate a relation between sapropel formation and orbital forcing. She calculated a monsoonal index from the caloric Northern Hemisphere insolation in tropical latitudes, and argued that sapropels were deposited at times of intense (northern) summer monsoons, since they coincided in time with maxima of the monsoonal index.

Hilgen (in press) demonstrated that sapropel formation coincided closely with minima in the precession index, which occur approximately every 21 000 years. A minimum in the precession index implies that perihelion falls within Northern Hemisphere summer, assuring greater Northern Hemisphere insolation in summer and less in winter. Consequently, the seasonal contrast on the Northern Hemisphere would be significantly increased. Since the heat capacity of water is much larger than that of land, the seasonal temperature contrast of the sea surface would be much less amplified than that of the land surface; according to Kutzbach & Guetter (1986) the range of the former would be about one-fifth of the latter. Consequently, land-sea temperature differences would be considerably larger at times of a precession-minimum than they are today. The relation between sapropel formation and precession minima is most obvious when considering Quaternary sapropels, which have been accurately placed in a time-stratigraphic framework (Rossignol-Strick 1985, Prell & Kutzbach 1987, Hilgen in press). Hilgen (in press) argued that the relation existed also throughout the Pliocene (Fig. 2). We emphasize that there seems to be a systematic phase-lag, the precession minima preceeding sapropel formation by approximately 2 000 to 3 000 years. As yet, there is no ready explanation for these lags.

Summarizing; ice-cap geography has differed considerably between individual phases of sapropel formation, and we should be careful not to overestimate its influence on the climatic constraints for sapropel formation. The correlation between minima in the precession index and the formation of sapropels suggests that orbital forcing is the major agent controlling the atmospheric circulation patterns which result in sapropel formation. On the Northern Hemisphere, the orbital configuration at times of sapropel development invoked increased seasonal and land-sea temperature contrasts and, consequently, enhanced (summer) monsoonal circulation.

## Discussion

In the literature, several models have been introduced that deal with geologically recorded wet

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*Fig. 2.* (modified after Hilgen, in press). Calibration of Plio-Pleistocene sapropels in Mediterranean land-based sections and deep-sea cores to the astronomical record. This was established by correlating first the late Pliocene sapropels to the astronomical record, using oxygen isotope stage boundaries for calibration. The established phase-relations (individual sapropels correlate with 21 ka precession minima and sapropel-clusters with 100 and 400 ka eccentricity maxima) were subsequently employed to astronomically calibrate the late Pliocene-early Pleistocene sapropels. For further details, the reader is referred to Hilgen (in press). Note that eccentricity modulates the amplitude of precession variations in 100 and 400 ka cycles. Also shown is the correlation to the (resultant) astronomically calibrated Geomagnetic Polarity Time Scale of Shackleton et al. (in press) and Hilgen (in press), based on first order magnetostratigraphic records. Solid lines mark lithostratigraphic, magnetostratigraphic and astronomical correlations, dashed lines mark biostratigraphic correlations. Biozonations used are those of Cita (1975) and Spaak (1983) for the planktonic foraminifera, and Raffi & Rio (1979) for the calcareous nannofossils.

phases in the Sahel, Magreb, central Sahara, Near East, eastern tropical Africa and the eastern Mediterranean countries in general. We will discuss the three major existing models with respect to literature-based information on the climate at times of sapropel formation. Futhermore, we will argue whether the prominent southeastern Black Sea precipitation system may have expanded towards the Aegean Sea at times of sapropel formation, a possibility which has not been discussed previously.

*Monsoonal intensifications*

Using the Community Climate Model (CCM) of the National Center for Atmospheric Research (NCAR), Kutzbach & Street-Perrott (1985) and Kutzbach & Guetter (1986) simulated an orbitally produced precipitation maximum from 12 000 to 6 000 BP, concentrated between 0° and 30° latitude in the Northern Hemisphere (see also COHMAP Members 1988). This precipitation maximum was due to increased vigour of the summer monsoon, in response to the increased heating of the Northern Hemisphere continental interiors when perihelion fell in northern summer (Kutzbach 1985). Also using the CCM, Prell & Kutzbach (1987) studied the monsoon variability over the past 150 000 years. They concluded that monsoonal strength and monsoonal precipitation were positively correlated to precession-caused peaks in the Northern Hemisphere summer radiation, over this interval of time.

Rossignol-Strick (1985) coupled the temporal occurrence of sapropels in the eastern Mediterranean to a monsoonal index, calculated from the caloric Northern Hemisphere insolation in tropical latitudes for the last 465 000 years. This insolation is controlled by variations of the orbital parameters, of which the precession cycle dominates at low latitudes. Peak values of the monsoonal index would relate to periods of intensified summer monsoons. Rossignol-Strick et al. (1982) and Rossignol-Strick (1985) reasoned that enhanced monsoonal precipitation, especially over the northern Ethiopian highlands, caused heavy Nile floods to reach the eastern Mediterranean some 35° of latitude north of the catchment area. Sapropel formation would then be triggered by the increased, high-nutrient, Nile discharge.

This hypothesis, considering Nile discharge as the exclusive cause of sapropel formation (Rossignol-Strick et al. 1982, Rossignol-Strick 1985) was rejected by Jenkins & Williams (1984) on the basis of a study of oxygen isotope records. Moreover, based on an oxygen isotopic study, Gudjonsson & Van der Zwaan (1985) concluded that European rivers, rather than the Nile, supplied the freshwater which caused anomalously low $\delta^{18}O$ values of foraminifera in Sicilian Pliocene sapropels.

Turkish and Greek rivers (Shaw & Evans 1984, Cramp et al. 1988, Zachariasse et al. in prep.) showed increased discharge rates at times of sapropel formation. Rossignol-Strick (1987) concluded that increases of humidity and winter mildness in the Northern Borderlands of the Eastern Mediterranean (NBEM) prevailed during sapropel formation, according to a revised interpretation of fossil pollen assemblages from northeastern Greece. Therefore, she adjusted her earlier theory by stating that, in addition to Nile flooding, precipitation in the NBEM played an important role in the initiation of sapropel formation. The oak pollen increases in northeastern Greece, which coincided with sapropel formation, would be primarily due to increased precipitation in the summer season (Rossignol-Strick 1987). A similar increase in summer precipitation at times of sapropel formation was reconstructed from Macedonian pollen records by Wijmstra et al. (1990).

As argued above, there must be a mechanism controlling the humidity in the NBEM, which operates in phase with (or as part of) the Northern Hemisphere summer monsoon. Furthermore, the increased humidity in the NBEM during sapropel formation appeared to be largely due to increased precipitation in summer. Combined, this might suggest that the humidity in the NBEM should be interpreted as monsoonal precipitation, implying temporal expansion of the Indian Ocean's summer (SW) monsoon into the eastern Mediterranean.

The results from numerical climate simulations, summarized by the COHMAP Members (1988), show that the area receiving monsoonal precipitation had indeed expanded at 9 000 BP, compared to the present, reaching across tropical Africa – as far north as the Lybico-Egyptian desert – via the Arabian Peninsula, Pakistan and India into southeastern Asia and northwards into the Hoang Ho province of China. According to these simulations, however, the monsoonal precipitation did not reach into the eastern Mediterranean. According to Sarnthein (1978), the monsoonal summer rains of Africa reached their most northerly position at $>30°$ N in Lybia and the Atlas Mountains around 6 000 BP.

Studying fluorescent bands in fossil corals, Klein et al. (1990) concluded that during the mid Holocene, as well as during other Quaternary periods of reef growth at high sea-level stands, a wet climate prevailed in the Sinai Desert, possibly with a summer rainfall regime. Klein et al. (1990) considered their observations as evidence for northward extension of the monsoon over the Sinai region. This seems to match with the numerically simulated northernmost extension of significant monsoonal precipitation in that region (COHMAP Members 1988). However, Prell & Kutzbach (1987) showed that the precession related intensifications of the summer monsoon were much less pronounced during glacials than during interglacials.

Goodfriend (1988) reconstructed a mid Holocene wet phase in the northern Negev desert (Israel), between 6 000 and 4 000 BP. He argued that the moisture increase in the Negev resulted from a southward shift of the rainfall isohyet pattern, rather than from an overall increase of rainfall throughout the southern Levant. Similarly, Goodfriend & Magaritz (1988) argued that strong north-south rainfall gradients, as today, existed during the wet phases in the northern Negev which occurred during globally warmer periods within the last glacial. These wet phases, at about 13 000 BP, 28 000 BP and 37 000 BP resulted in the formation of paleosols in the northern Negev. Goodfriend & Magaritz (1988) concluded that the source area of the precipitation was in the north or northwest, and that the periods were not the result of northward penetration of monsoonal rains from the Indian Ocean. Therefore, during wet phases in the Northern Negev, both during interglacials (Goodfriend 1988) and during glacials (Goodfriend & Magaritz 1988), the moisture seems to have originated mainly in the north or northwest.

Summarizing, sapropel formation coincided with intensified (summer) monsoonal circulation, which invoked increased discharge of the river Nile, In addition, however, increased (summer) precipitation rates have been recorded in the NBEM. Data from the Levant provide a means to study the northernmost extention of the monsoonal precipitation system. During interglacial wet phases, significant monsoonal precipitation reached the Sinai in summer. Meanwhile, the Negev desert benefited from a substantial moisture supply from the north to northwest. At glacial times, the summer monsoon failed to reach as far as the Sinai. On the contrary, the northerly to northwesterly moisture flux towards the northern Negev did prevail during glacial (interstadial) wet phases. The principal moisture source for the Negev seems to have been the Mediterranean rather than the Indian Ocean, during interglacial as well as glacial (interstadial) wet phases. This implies that the temporal (summer) humidity in the NBEM may not be explained by intrusions of the (summer) monsoonal precipitation regime into the eastern Mediterranean.

*Secondary depression tracks*

Lamb (1966, 1969, 1977) reconstructed the climate of medieval times, also called the Little Climatic Optimum. According to Lamb (1977), the temperatures in this period regained values approaching those of the Holocene Climatic Optimum. Also, he stated that the medieval circum-Mediterranean climate was more humid than at present, with greater rainfall in the Mediterranean and Near East and bigger, more frequent stream flow in the wadis of the African and Arabian deserts. At medieval times, the westerly track of cyclones (depression track) over the Atlantic had shifted considerably northwards, as far as 65–70° N (Lamb 1969, 1977) or 60–65° N (Flohn 1981c). As a consequence, a secondary depression-track could have developed across the Mediterranean, according to Lamb (1966, 1969, 1977).

In his reconstructions of medieval climate, Lamb indicated a secondary depression track in summer only east of Italy, in contrast to that in winter which he drew across the entire Mediterranean. Unfortunately, Lamb did not really explain what process would have invoked the summer depression track east of Italy. He suggested, however, that the medieval summers were characterized by a cold mid-tropospheric trough with its axis from the Barentz Sea down to the central Mediterranean. In such a configuration, the flow of cold air from the northwest favours cyclogenesis over the western Mediterranean, especially over the Gulf of Genoa (cf. Boucher 1975). The resultant Mediterranean depressions would have moved eastwards, which may explain the medieval summer depression track which Lamb suggested east of Italy.

Lamb's reconstruction of the medieval climate does suggest increased precipitation in the eastern Mediterranean, also along the northern limits of the basin. Therefore, accepting the medieval climate as an analogue to that around 9 000 BP would provide a means to explain the increased humidity in the NBEM during the formation of sapropel $S_1$. However, it remains doubtful whether we may really compare the two periods, since whatever external forcing may have acted upon the medieval climate, it certainly was not identical to that around 9 000 BP which was dominated by the summer perihelion. Consequently, the circulational response may also have differed significantly. Nevertheless, in the 9 000 BP simulations of Kutzbach & Guetter (1986), the subpolar jet in summer was found further north over the Atlantic Ocean (up to about 70° N) than at present. This suggests that the main depression track was displaced to the north as well, during the summers around 9 000 BP, much as it was at medieval times according to Lamb (1966, 1969, 1977).

*Saharan depressions*

Flohn (1981a) argued that a moist period affected northern Africa between 10 000 and 5 000 BP. He also stated that this moist phase was interrupted around 8 000 BP, for several centuries, in the western and central Sahara, whereas it was not interrupted in East Africa and the Middle East. Flohn (1981a) suggested a relation between the first moist period and the occurrence of a warm Climatic Optimum in the Southern Hemisphere around 9 500 BP, while Scandinavia was still ice-covered. He argued that the second moist period – when Scandinavia was free of ice – was due to a quasi-permanent secondary mid-tropospheric trough, reaching across Central Europe into the western Sahara and caused by the extended remnants of the Laurentide Ice.

In another paper (Flohn 1981b), Flohn discussed teleconnections between the Sahelian and the western and eastern Mediterranean climates. He stated that a major connection was due to the occurrence of Saharan depressions, which form within the tropical belt of easterly waves, cross the desert with heavy sandstorms, and develop convective rainstorms when approaching the moist air of the Mediterranean. Crane (1981) stated that a marked increase of such depressions would have occurred during the moist North African periods. Flohn (1981b) suggested that the Saharan depression mechanism would especially influence the Mediterranean rainfall in winter.

Flohn's mechanism of Saharan depressions cannot explain the increased humidity in the NBEM, since the influence of this mechanism is restricted to areas more to the south. Also, the humidity in the NBEM appeared to be substantially due to summer rains, whereas Flohn (1981b) suggested that the Saharan depression mechanism would especially influence the Mediterranean rainfall in winter. Moreover, we found no substantial evidence in favour of increased Saharan depression activity around 9 000 BP in the numerical simulations of Kutzbach & Guetter (1986) and Kutzbach & Gallimore (1988).

*Expansion of the summer precipitation regime of the southeastern Black Sea towards the eastern Mediterranean?*

At present, a distinct summer precipitation system exists along the southeastern coast of the Black Sea, only 1 000 km east of the Aegean Sea. Although we have found no account in the literature as to whether this regime could have temporarily expanded westward to influence the NBEM, we think that this possiblity should not be discarded without discussion.

Detailed descriptions of the climate around the eastern Mediterranean show that the Batumi region, southeast of the Black Sea, receives year-round precipitation and lacks a dry season (Trewartha 1966, Lydolph 1977). Annual precipitation in the Batumi region amounts over 2 500 mm $yr^{-1}$ (Grasshoff 1975, Lydolph 1977). According to Trewartha (1966), the summer rainfall in this area is due to: 1) the fact that the Etesians are still more humid than further south and have not yet attained their genuinely stable characteristics, 2) cyclonic storms which, in these latitudes north of 40° N, are still active even in summer, especially along tracks entering the Black Sea, 3) humidification of the northwesterly air flow by the Black Sea itself, so that moderate precipitation develops when the air is forced upwards by highlands or convectional systems. Both types of upward forcing exist in the vicinity of the Caucasus mountains. The former due to topography, and the latter since (especially) the Armenian Plateau induces a local low pressure system in summer due to thermal effects (Lydolph 1977). Processes similar to those causing summer precipitation in the Batumi region invoke the summer precipitation along the southern coast of the Caspian Sea (Trewartha 1966).

Although the heaviest precipitation in the Batumi region originates from summertime thunderstorms, the winter maximum – associated with cyclonic storms moving in from the west – is generally considered to be the more characteristic feature of the Black Sea-Caucasus-Caspian Sea rainfall regime (Trewartha 1966, Lydolph 1977). Descriptively, the classical 'Mediterranean climate', characterized by wet winters and dry summers, is modified by substantial summer rains in the Batumi region to a so called 'humid subtropical climate' (Trewartha 1966). The summer rains appear to be largely due to uplift of the moistened air in the vicinity of the Caucasus mountains (cf. Rumney 1968). Because of its dependance on topography, we envisage that the Batumi region's summer precipitation regime may not have expanded far enough to the west to cover the NBEM, as a response to insolation changes through times with about present-day topography.

*Evaluation*

The above considerations allow some restriction as to the origin of the increased humidity – largely summer precipitation – in the NBEM, at times of sapropel formation. In the present paper, we argue that neither Saharan depressions, nor westward expansions of the southeastern Black Sea's summer precipitation regime, would form a likely mechanism to invoke summer precipitation in the NBEM. Furthermore, we concluded that the temporal humidity in the NBEM may not be explained by intrusions of the monsoonal precipitation regime into the eastern Mediterranean.

It appears that the increases of summer precipitation in the NBEM simply reflect increased activity of summer depressions, which track eastwards across the Mediterranean. In addition, we emphasize that the (normal) winter precipitation in the NBEM was probably enhanced as well (Wijmstra et al. 1990). Therefore, we think that Lamb's reconstruction of the medieval climate may serve as a proxy for the climatic configuration during sapropel formation.

## Implications for sapropel formation

As argued in the Introduction, Mediterranean depressions should be regarded as secondary depressions, which are often related to much larger disturbances north of the Alps. Cyclogenesis is most common in the western Mediterranean, especially in the Gulf of Genoa. A significant part of the moisture is collected in these formation areas, while more moisture may be picked up along the track eastwards. At present, summer depressions from the western Mediterranean are being notably reinforced when they cross the Aegean Sea (Trewartha 1966). The summer precipitation in the NBEM will, therefore, constitute 1) in part, a lowering of the excess evaporation from the eastern Mediterranean relative to that from the western basin, and 2) in part, a redistribution of freshwater within the complex eastern Mediterranean water balance.

The lowering of excess evaporation from the eastern Mediterranean relative to that from the western basin would decrease the contrast between the water budgets of these two basins. Consequently, the exchange of watermasses between the two basins across the Strait of Sicily may have been decreased, which would increase the residence time of water in the eastern Mediterranean.

Also, we have concluded that sapropel formation occurred at times of minima in the precession index and, therefore, coincided in time with intensifications of the Indian Ocean's summer (SW) monsoon. Such intensifications enhanced freshwater fluxes into the eastern Mediterranean, via the river Nile. Hence, the increased activity of Mediterranean depressions resulted in a greater flux of moisture of western origin, superimposed on an increased (monsoonal) moisture flux from the southeast.

The relative 'freshening' of the eastern basin due to increased summer and winter precipitation in the NBEM, in addition to that invoked by monsoonal intensification, may have invoked a decrease in the density difference between the surface and intermediate water masses, as compared to that at present. This would result in the processes described by Rohling & Gieskes (1989). Meanwhile, increased precipitation on the NBEM would, via the resulting increase of runoff, have enhanced the flux of river-borne nutrients, from the adjacent land into the basin. Again, this process adds to the effect of monsoonal intensification, which augmented the flux of nutrients via the Nile.

## Conclusions

Orbital forcing of the climate seems to control the formation of sapropels in the eastern Mediterranean. More specifically, the cycle of precession appears to be dominant. Furthermore, sapropels have been deposited both during interglacials and during glacials. Combined, this suggests that increased seasonal and land-sea temperature contrasts are more important, for the climatic changes initiating sapropel formation, than average warm (interglacial) or cool (glacial) conditions.

Rossignol-Strick's (1985) monsoonal theory fitted the requirement of being orbitally forced. Moreover, the coupling of monsoonal precipitation to orbital forcing has been confirmed by the numerical climate simulations of Kutzbach & Street-Perrott (1985), Kutzbach & Guetter (1986), Prell & Kutzbach (1987), Kutzbach & Gallimore (1988) and the COHMAP Members (1988). The Nile flood scenario as proposed by Rossignol-Strick (1985), however, did not account for humidity in the NBEM, as she concluded herself in a later paper (Rossignol-Strick 1987). Neither did the numerical simulations, but this was not noticed since – for some reason – the COHMAP Members (1988) interpreted the 9000 BP paleoclimatic data from Greece and Turkey as indicative of conditions drier than present. Obviously, we disagree with this interpretation.

Rossignol-Strick (1987) and Wijmstra et al. (1990) stressed that the humid phases in the NBEM contain evidence of increased summer precipitation. Also, the (normal) winter precipitation seems to have been increased (Wijmstra et al. 1990). Since substantial summer precipitation would be the major deviation from the present-day climate, we focused on the mechanisms that may have invoked it. We conclude that the most likely mechanism consists of increased activity of Mediterranean summer depressions, the moisture sources being both the western Mediterranean Sea and the eastern Mediterranean Sea itself.

Sapropels were formed at times of distinct minima in the precession index. Such periods are characterized by intensified (summer) monsoons, which resulted in increased discharge of freshwater and nutrients via the Nile. The coeval increases of yearly precipitation in the NBEM also increased the fluxes of freshwater and river-borne nutrients, which added to the fluxes from the river Nile.

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