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Climate variability and deep water mass characteristics in the Aegean Sea

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ABSTRACT

The main objective of this study is to investigate the variability of the thermohaline characteristics of the deep-water masses in the Aegean Sea and the possible impact of the regional atmospheric forcing variability by analyzing the available oceanographic and atmospheric datasets for the period of 1960–2012. During this period the variability of the deep water characteristics of the Aegean sub-basins is found to be very large as well as the diversity of the deep water characteristics among the sub-basins. The Central Aegean seems to play the key role in the Aegean deep water formation processes. Due to its small size, the Aegean Sea surface responds rapidly to the meteorological changes and/or the variability of the lateral fluxes and this variability propagates in the thermohaline characteristics of the deep water masses of the basin through deep water formation processes. There are many episodes characterized by a tight coupling of the atmosphere and the ocean during the examined period, with the Eastern Mediterranean Transient (EMT) being the most prominent case. We suggest that deep water formation is triggered mostly by the combination of preconditioning during early winter and/or previous winters together with the number of subsequent extreme events during present winter and not only by the total amount of the extreme heat loss winter days.

1. Introduction

The Aegean Sea is a semi-enclosed basin located in the northeastern Mediterranean Sea covering an area of 240,000 km^2. The Aegean Sea communicates with the Ionian and Levantine basins through the Straits of the Cretan Arc and with the Black Sea through the Dardanelles Strait (Fig. 1). The total volume of the Aegean Sea is about 75,000 km^3 (Gertman et al, 2006; Vervatis, 2013) and the coastal and offshore topography is irregular and complex. The complexity of the shoreline and bottom topography is associated with the presence of a great number of islands (over 3000 islands and islets are present in the Aegean Sea) and in consequence the bottom topography is characterized by an alternation of shelves, sills and deep depressions. The Aegean Sea constitutes of three major basins; the North Aegean, with maximum depths up to 1500 m; the Chios Basin in the central part, with maximum depth of 1100 m; and the Cretan Sea in the south, the largest basin, with maximum depth of 2500 m. The above major basins are connected through channels shallower than 400 m. The exchange fluxes through the straits are not well known, especially at the intermediate and deep layers (Zervakis et al., 2003).

The annual evaporation exceeds the sum of precipitation and river runoff over the Aegean Sea, but the water balance is positive if we take into account the low salinity Black Sea Water (BSW) inflowing in the Aegean Sea. The annual net heat flux is estimated at - 26 W/m^2 (Poulos et al., 1997) and

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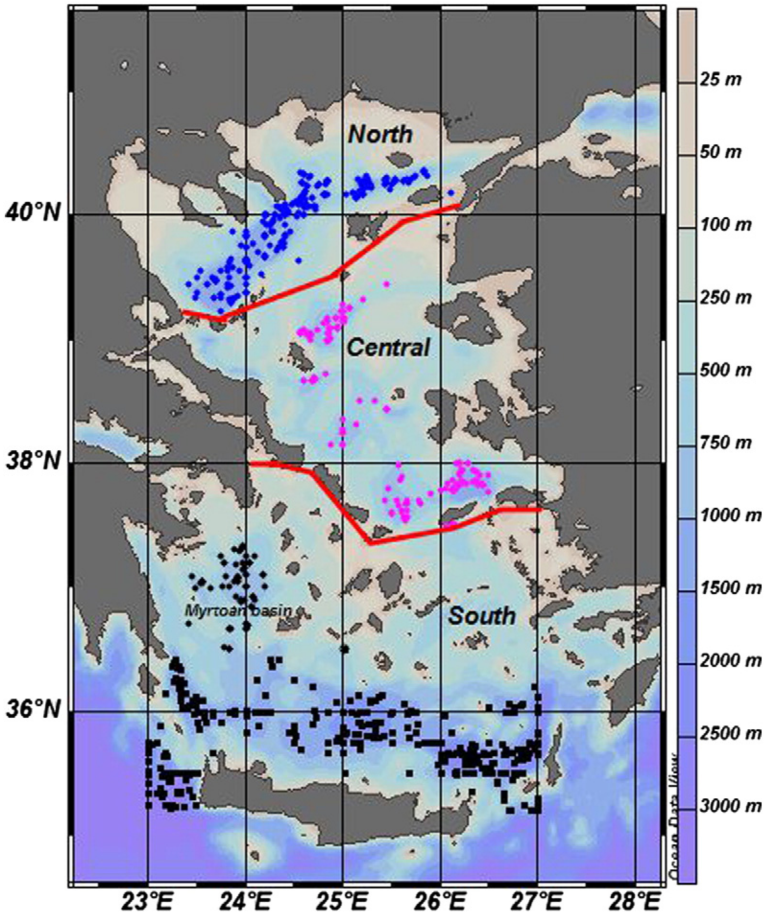

Fig. 1. Stations in the Aegean Sea with depth greater than 700 m (dots in blue and magenta for the North and Central Aegean) and 1000 m (southern Aegean—black dots). The South Aegean includes the Myrtoan Sea where depth greater than 700 m was selected.

consequently the Aegean Sea surface heat losses are balanced by the advection of warmer water masses through its open boundaries, mainly by the inflow of warm Levantine waters at the surface and intermediate layers. During summer (July–August) and winter (December–February) strong winds from northern directions blow over the Aegean Sea. These northerly winds bring relatively cool continental air from the region of southern Russia and the Caspian Sea, contributing to the decrease of surface temperature and the moderation of summer heat that lead to surface buoyancy loss (Poulos et al., 1997). Papadopoulos et al. (2012a, 2012b) and Josey et al. (2011) found a remarkable coupling between events of extreme surface cooling and the large-scale sea level pressure (SLP) configuration in the Mediterranean Sea. The patterns favoring abnormal heat loss are associated with the transfer of cold and dry air masses over the Mediterranean basin. In particular, SLP anomalies, related primarily to the East Atlantic/West Russian (EA/WR) pattern, are a prominent regulating factor of the air–sea heat fluxes over the Aegean Sea region especially during the cold season of the year.

The overall Eastern Mediterranean thermohaline circulation is driven by the air–sea buoyancy losses at the sea surface (Wüst, 1961). The classical pattern of the circulation in the Eastern Mediterranean is characterized by an inflow, through the Strait of Sicily, of low-salinity surface Atlantic Water (AW), by the formation of warm and of high-salinity intermediate waters in the Levantine Sea (LIW) and the Cretan Sea (CIW—Cretan Intermediate Water) during February and March, under the influence of dry and cold continental air masses (Bruce and Charnock, 1965; Lacombe and Tchernia, 1972; Georgopoulos et al., 1989) and by the production of Eastern Mediterranean Deep Water (EMDW) in the Adriatic Sea in the form of self and open sea convection. The warm, saline Levantine Surface Waters (LSW) can also be detected in most of the regions of the eastern Mediterranean (Lacombe and Tchernia, 1960). The intermediate layers between the LIW (200–500) and the EMDW (700–1600 m) are occupied by the Transitional Mediterranean Water (TMW) and are considered to be a transitional water mass (Pollak, 1951) with S and Θ lower than those of LIW (Theocharis et al., 1999a).

The circulation pattern of the Aegean Sea has been described analytically in the past through a series of observational and modeling studies and it can be summarized as follows. The northeastern region of the Aegean is characterized by the intrusion of the low salinity (24.0–35.0) surface Black Sea Water (BSW) through the Dardanelles Straits (Theocharis and Georgopoulos, 1993). BSW mainly follows the cyclonic general circulation of the Aegean (Ovchinnikov et al., 1976) reaching the western Cyclades region (Zodiatis, 1994; Zodiatis et al., 1996; Zervakis et al., 2005). Levantine Surface Waters (LSW) enter the Aegean through the eastern Straits of the Cretan Arc with salinities greater than 39.0 and create a strong thermohaline front in the North–Central Aegean with the fresher BSW. Another water mass that influences the salt balance in the Aegean Sea is the Atlantic Water (AW) that enters through the Straits of the Cretan Arc (Hopkins, 1978) and it can be identified by a subsurface salinity minimum (38.68–38.90) (Lacombe et al., 1958). Finally, LIW enters the Aegean through the Straits of the Cretan Arc, where it can be transformed by convective processes to become a slightly denser water mass (Theocharis et al., 1999b; Astraldi et al., 1999).

Dense water formation at the surface is related to the buoyancy flux, which is determined by the heat and freshwater fluxes between the atmosphere and the sea. The sinking of the dense surface water to the intermediate and the deep layers is also connected with the stability of the stratification of the water column. Papadopoulos et al. (2012b) underline that intermediate and deep water formation is directly related to extreme winter heat loss events.

Eastern Mediterranean deep waters are formed in winter mainly in the southern Adriatic Sea, contributed by a smaller amount formed in the northern part of the basin. After exiting the Adriatic Sea, the dense water spreads to the bottom of the Eastern Mediterranean basin (Wüst, 1961; Schlitzer et al., 1991; Stratford and Haines, 2000). The Aegean Sea was recognized as a source of dense waters (Nielsen, 1912), but not dense enough to contribute to the EMDW (Pollak, 1951; Wüst, 1961; Schlitzer et al, 1991). Dense water formation sites in the Aegean Sea have been identified through observations and analysis from the early '60s (Lacombe and Tchernia, 1960; Plakhin, 1971, 1972; Georgopoulos et al., 1989). Moreover, observations in the early '90s revealed that the Aegean Sea could also constitute a dominant source of EMDW (Roether et al., 1996, 2007; Klein et al., 1999; Lascaratos et al., 1999; Malanotte-Rizzoli et al., 2003; Rupolo et al., 2003). The shelves in the north Aegean (Theocharis and Georgopoulos, 1993) were considered as sites where dense water formation (DWF) may take place. Other major sites of DWF were considered to be the Cyclades plateau, for shelf formation, and the Cretan Sea, for open-sea deep convection (Miller, 1963; Lascaratos, 1992, 1993; Zodiatis, 1991; Velaoras and Lascaratos, 2005; Gertman et al., 2006). Zervakis et al. (2004) mentioned that open-sea convection may occur also in the North Aegean depending on the preconditioning and mesoscale phenomena. The dense water originated in the South Aegean outflowed through the Cretan Straits (Zodiatis, 1992, 1993a, 1993b). Recent data collected in the Cretan Sea have revealed that in March 1986 there was intermediate water (down to 250 m) formation (Georgopoulos et al., 1989), and in March 1987 deep convective mixing led to the homogenization of the water column down to 700 m (Zodiatis, 1991).

Owing to the different processes of the DWF and also due to the complicated geography and topography in the Aegean sub-basins, their deep water thermohaline characteristics differ. Thus, the deep water characteristics of the South Aegean (Cretan Sea) vary from those of the Central Aegean and those of the North Aegean (Androulidakis et al., 2012; Gertman et al., 2006; Velaoras and Lascaratos, 2005; Theocharis and Georgopoulos, 1993). Lacombe et al. (1958) observed through measurements that deep waters in Chios basin (Central Aegean) are warmer and slightly saltier than those in the North Aegean. Deep waters in the South Aegean are warmer and saltier (and lighter) than those in North–Central Aegean. Zodiatis (1991) suggested that in the western part of Cretan Sea appears denser deep water than those in eastern part, since the former is slightly saltier than the latter. Significant changes of water masses in the period from 1987 to 1993 have led to the outflow of dense water from the Aegean Sea, better known as the Eastern Mediterranean Transient (EMT) (Klein et al., 1999; Lascaratos et al., 1999; Manca et al., 2003; Kress et al., 2003), with long lasting effects in the Eastern Mediterranean deep waters till the present (Özsoy et al., 2013).

During the period of the EMT, the dense Cretan Deep Water was formed in the Aegean Sea and later on exited the Aegean and occupied the deep layers of the Eastern Mediterranean, with 3 times greater formation rate (1Sv) than the previous Eastern Mediterranean Deep Water formed in the Adriatic Sea (Roether et al., 1996). Zodiatis (1993) suggested that the main outflow of the Cretan Sea obtained through the Kasos and Elafonisos straits. The outflow of CDW towards the Levantine and Ionian basins affected the stratification of the water column since it sank, occupied the abyssal part of the basins and uplifted the existing lighter EMDW. This resulted in the inflow of the lower salinity TMW in the Aegean Sea that replaced the dense waters contributing to the termination of the climatic event. The TMW is a mixture of LIW and old EMDW with its core around 750 m, which enters from the adjacent Levantine basin through Kassos strait (1000 m) at the sill depth (Theocharis et al., 2006).

The EMT has affected the conveyor belt of the Eastern Mediterranean. The newly formed dense water of Aegean origin that replaced 20% of the EMDW (Roether et al., 1996), caused great changes in the deep layers of the Eastern Mediterranean and thus to the whole water column. Appropriate deep water formation conditions are observed at the central and eastern parts of the Aegean Sea, where the highest surface water salinity occurs due to the surface and intermediate inflow from the Levantine basin. The coincidence of high salinity surface waters, intense winter atmospheric forcing and relatively weak stratification makes this area favorable for dense water formation processes (Vervatis et al., 2011, 2013). Roether et al. (2007) suggested that the Aegean Sea is a more effective source of deep water than the Adriatic Sea since it produces deep waters of greater density and volume.

The EMT event has gradually decayed, indicating a transitional character of the changes observed (Theocharis et al., 2002). After 2003 the Adriatic Sea is again considered as the major source of deep water in the Eastern Mediterranean. Hainbucher et al. (2006) and Rubino and Hainbucher (2007) suggested that these new Adriatic deep waters are saltier and warmer than previously observed. It is not yet clear if the EMT is the consequence of a unique coincidence of regional climatic factors or a part of the internal and/or external variability.

Many studies aimed at clarifying the mechanisms underlying this climatic anomaly and many scenarios were suggested, such as the Nile damming (Boscolo and Bryden, 2001; Skliris and Lascaratos, 2004), the Black Sea outflow reduction

(Zervakis et al., 2004), extreme winter heat losses (Josey, 2003; Wu et al., 2000; Theocharis et al., 1999a), change in wind-driven circulation (Samuel et al., 1999), the blocking mechanism of the Atlantic Water in the Ionian Sea (Malanotte-Rizzoli et al., 1999; Gertman et al., 2006; Borzelli et al., 2009), the changes in the Levantine Intermediate Water (LIW) circulation (Malanotte-Rizzoli et al., 1999) and changes in the freshwater flux, linked with the North Atlantic Oscillation (NAO) (Tsimplis and Josey, 2001). Related to that, Nastos and Zerefos (2009) suggested that since 1980 the higher NAO led to anomalies in precipitation over the Mediterranean.

The presence of a strong regional climatic event of the thermohaline circulation in the Eastern Mediterranean disrupts the picture of a robust circulation pattern and generates several questions on the sensitivity of the regional thermohaline circulation and the characteristics of the deep waters associated with it. These questions are more pertinent in an area characterized by strong atmospheric variability (Giorgi, 2006) that is enhanced by the proximity of important natural and anthropogenic aerosol sources (Esteve et al., 2014). How sensitive is the formation of dense waters in the Aegean Sea and what is the role of the local atmospheric forcing? How important are the extreme events, related to abnormal buoyancy loss of the ocean during the winter formation period? What is the relative importance of surface air–sea buoyancy fluxes compared to the horizontal advection of seawater characteristics? The main purpose of the paper is to investigate a potential correlation between the deep water formation and the climate variability taking also into account the variability of the extreme atmospheric events. The study is structured as follows: in Section 2 the data sets used and the methodology followed are presented. The analysis of the data is presented in Section 3 and finally, the discussion and conclusions are presented in Section 4.

2. Data and methodology

In order to study the impact of the long-term variability of the winter atmospheric forcing on the inter-annual changes in the thermohaline features of the deep water in Aegean Sea, two data sets are used. Temperature and salinity profiles for the Eastern Mediterranean (1912–2010) are provided from ISRAMAR, the Israel Marine Data Center, National Institute of Oceanography of the IOLR, Israel (Özsoy et al., 2013). The data set was enhanced with data for the Eastern Mediterranean Sea for the period 2000–2012 obtained from the National Oceanographic Data Center ("WOD05" database – http://www.nodc.noaa.gov/OC5/WOD05/pr_wod05.html). Concerning the quality control of the data set, the quality flags of the thermohaline properties in each profile are checked and only acceptable values are taken into account. As already mentioned in Section 1, the deep water thermohaline characteristics of the South Aegean (Cretan Sea) differ from those of the Central and those of the North Aegean. To investigate the variability of the deep-water thermohaline characteristics, the Aegean Sea has been divided in three sub-basins (Fig. 1) for a spatio-temporal analysis of the variability of deep water masses in the Aegean. Different limits of depth have been chosen as representative of the deeper layers for each sub-basin. Thus, for the northern section and the central section of the Aegean data at depths below 700 m are segregated. Concerning the southern part of the Aegean, data below the isobaths of 1000 m were selected for further analysis (with the exception of the Myrtoan basin where we selected the limit of 700 m). For the examined period (1960–2012) the number of stations deeper than 700 m in the North and Central Aegean is 377 and 197 respectively and the number of stations deeper than 1000 m in the South Aegean is 693.

The annual mean deep water salinity, potential temperature and sigma-theta (referenced to the surface) for the 3 sub-basins are calculated and represented in the time-series plots in Fig. 2. The error bars in this figure display the 95% confidence interval of the estimated mean properties. The computation of the confidence intervals is based on Student's *t*-test (Emery and Thomson, 2001) and indicates how reliable the data points are in respect to the number of observations and the variance of the sample. The higher the confidence interval, the less accurate is the data point. Years with low statistical significance (data points with large confidence interval) were not included.

Direct measurements of atmospheric parameters, especially over the sea, are difficult to obtain for such a long period. For this reason, daily mean atmospheric data for the period 1961–2011 are provided by the NEMOMED8 simulation for the Mediterranean basin (Sevault et al., 2009; Herrmann and Somot, 2008). The atmospheric and oceanographic parameters and fluxes examined in the framework of the present study concern the domain of the Aegean Sea and its sub-basins (north, central and south Aegean Sea) and consist of the net heat flux (W/m^2), sea surface temperature (SST, °C), sea surface salinity, freshwater flux (in m/y, evaporation minus precipitation, $E - P$).

Deep water formation processes occur mostly in winter under anomalously high heat loss (extreme events) and also under late-winter buoyancy loss events. In order to find such extreme events in the atmospheric data, the daily values of heat loss for the period of January to March of each year are calculated and presented in Fig. 3. There is no clear definition in literature of what is an extreme event of heat loss in the Aegean Sea. Instead, we computed the number of winter days (January to March) with heat loss greater than 350 W/m^2, – twice the standard deviation of the average winter heat loss (2σ, corresponding to 5% of the winter heat loss variation) – and will hereafter be referred as *extreme days*. Each year of the examined period is therefore characterized by the sum of the extreme days (Fig. 4).

The buoyancy flux ($m^2\,s^{-3}$) for the winter months (January to March) is calculated using the heat and fresh water fluxes (Fig. 5) by the following equation:

$$B = -c_w^{-1}\, g\,\alpha\, Q\,\rho^{-1} + g\beta(E{-}P)S$$

where $\alpha = \rho^{-1}\partial\rho/\partial T$ and $\beta = \rho^{-1}\partial\rho/\partial S$ are the thermal and saline expansion coefficients respectively, c_w is the specific heat capacity of water (3990 J kg^{-1} K^{-1}), g is the gravitational acceleration (9.81 m s^{-2}), ρ is the reference density for the Aegean (1028 kg m^{-3}), S is the sea surface salinity, Q (W/m^2) is the net heat flux, $E - P$ is the net freshwater flux (m s^{-1}). Positive values of buoyancy flux ($B > 0$) correspond to buoyancy loss from the ocean at the sea surface that causes an increase in the density of the surface waters, thus contributing in the transformation of the surface water thermohaline characteristics and the possibility of dense

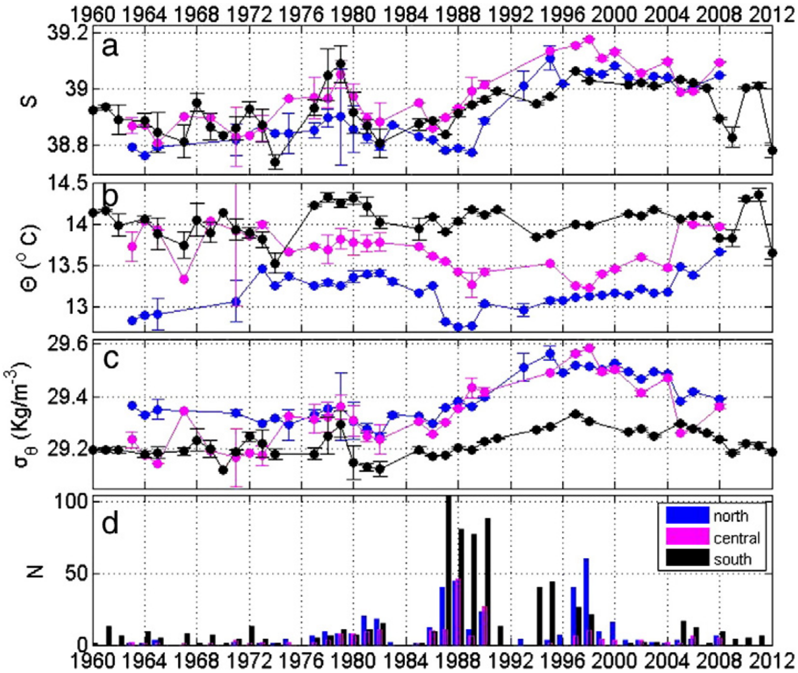

Fig. 2. Time-series of annual mean (a) salinity, (b) potential temperature, (c) sigma-theta and (d) number of stations in the sub-basins of Aegean Sea for depth greater than 700 m (northern-central Aegean) and 1000 m (southern Aegean).

water formation. Negative buoyancy fluxes (B < 0) reflect buoyancy gain at the surface, which makes the stratification of the water column more stable, and consequently the formation of deep water less likely.

3. Data analysis

3.1. Deep water variability

In this section we study the variability of the deep water hydrographic characteristics in the sub-basins of the Aegean Sea (North Aegean, Central Aegean, and South Aegean). The annual mean thermohaline properties of the water masses in these deep basins of the Aegean show large variability during the years. The time series of the annual mean salinity (S), potential temperature (Θ) and potential density (σ_θ) of the deep water masses in the three sub-basins of the Aegean Sea are depicted in Fig. 2.

The salinity time series (Fig. 2a) reveals significant inter-annual to decadal variability in all three sub-basins. In the North Aegean Sea at depths greater than 700 m, the salinity time series presents small variability until the late '80s while

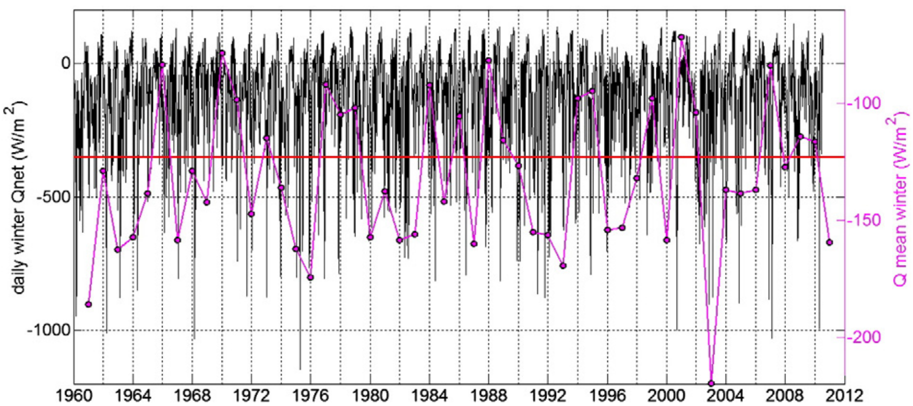

Fig. 3. Daily winter heat loss (black line, in W/m^2) and mean winter heat loss (magenta line) for the Aegean Sea. Each circle corresponds to the end of the winter.

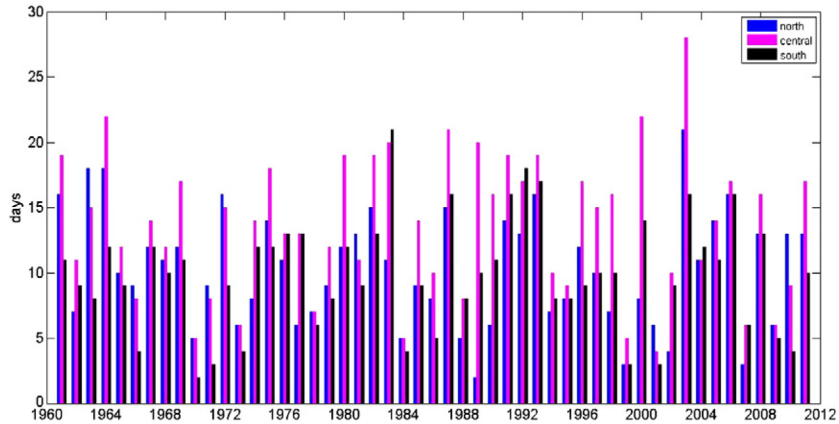

Fig. 4. Number of days with winter heat loss greater than 350 W/m^2 for the North (bars in blue), Central (bars in magenta) and South (bars in black) Aegean (*extreme events*).

after 1990 this variability becomes much higher. On the contrary the time series of the salinity in the Central (depths below 700 m) and South Aegean (depths below 1000 m) shows great variability during the whole examined period. Continuous increase of salinity is observed during the '70s and the years 1987–1993 (EMT onset), with the latter period standing as the most significant, since it reaches the maximum value of the whole period under examination in all three sub-basins. In detail, the increase of salinity in the South, Central and North Aegean during the '70s is approximately 0.4, 0.1 and 0.05 respectively and on the EMT the increase is of the order of 0.3 in all three. It is remarkable that the mean salinity of the pre-EMT period (until late '80s) is 38.9 in the South and Central Aegean and 38.8 in the North, while the EMT and post-EMT mean values are set at 39 in the South and North Aegean and in the Central are set at 39.1. This shift in the salinity of the deep water in the Aegean is mainly due to the newly formed deep water mass in the basin during the EMT onset period, which is characterized by higher salinity than the previous deep water mass. After the EMT onset period, the salinity maintains the high values and only after 2004 there seems to be a slight decrease, but with values higher than the pre-EMT ones. The time series of salinity in the sub-basins of the Aegean presents high correlation among each other. The correlation between the North and Central Aegean is 89%, between the North and South Aegean is 69% and between the South and Central Aegean is 73%.

The time series of the annual mean potential temperature of the deep water masses in Fig. 2b verifies that the deep sub-basins of the Aegean Sea have different characteristics something that was not clearly shown in the time series of salinity. The annual mean potential temperature of the deep waters in the North Aegean is always lower than the values of the Central and South Aegean during the examined period and it ranges from 12.8 to 13.7 °C. In the northern-central basin the most prominent cooling events occurred after the mid 1980's,

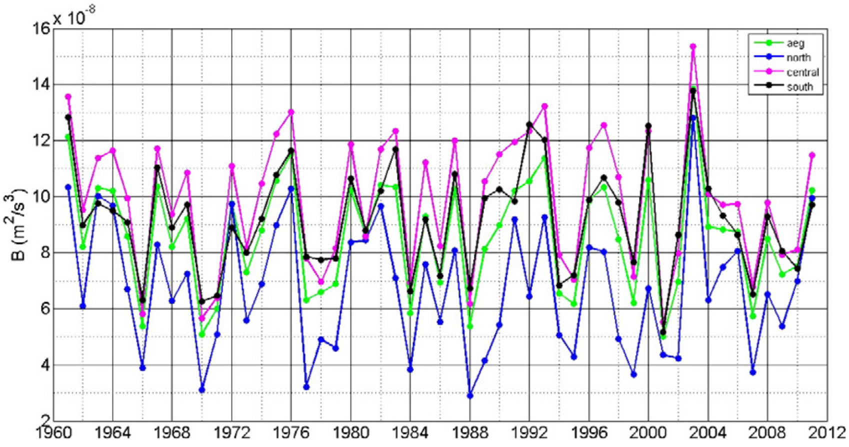

Fig. 5. Winter buoyancy flux (in m^2/s^3) of the North (line in blue), Central (line in magenta) and South (line in black) Aegean. Averages are made for each winter period (January to March). The green line represents the overall winter heat loss of the Aegean. B > 0 corresponds to buoyancy loss from the ocean at the sea surface and B < 0 reflects buoyancy gain at the surface.

when the salinity increase was accompanied by large changes in the temperature characteristics, resulting in extreme density values associated with the EMT (Theocharis et al., 1999). During the post-EMT period (1993–2008) the deep water temperature increases with a rate of 0.04 °C per year in the North and 0.06 °C per year in the Central Aegean. In the South Aegean the temperature of the deep water also shows a positive trend (+0.04 °C per year) which lasts only until 2001. The period of 2006–2012 is characterized by two strong cooling events (2008–2009 and 2012) and by a significant increase (2010–2011). The temperature of the deep water at the end of the examined period reaches the maximum values of the whole period. Although the correlation between the time series of the potential temperature between the north and the central part is fairly high ($r = 0.64$, $p \ll 0.05$) there is insignificant negative correlation between both the North and the Central Aegean with the South Aegean ($r = -0.01$, $p = 0.72$ and $r = -0.07$, $p = 0.33$ respectively). The higher correlation coefficient between the North and Central Aegean is mostly related to the connection of the basins and the associated sensitivity to atmospheric forcing. Furthermore, the coupling of the Central–South Aegean deep layers is complicated, due to entrainment phenomena, underlined from the greater densities in Chios than in Cretan Basin, during the first stages of the EMT (Vervatis et al., 2011).

For the whole examined period the density of the deep water in the Aegean (Fig. 2c) mostly follows the variability of the salinity having a strong correlation coefficient greater than 80%. It may also be observed in Fig. 2c that the density of the deep water shows greater variability in the northern-central Aegean (of 0.4 kg m^{-3}) than in the South (range of 0.3 kg m^{-3}). Central Aegean deep water density follows South Aegean deep water density until the end of 70s while later on it follows North Aegean deep water density until the end of the examined period, as it is evident that the EMT event caused the most significant changes in the northern-central Aegean. During the EMT, density in the sub-basins characterized by a steady increase (more intense in the northern-central Aegean) leads to maximum values of density. This rising trend of density is followed by an annual reduction in all three sub-basins (−0.01 kg m^{-3} per year in the North and South Aegean and of the order −0.02 kg m^{-3} per year in the Central). In the northern-central Aegean, where the greatest changes are observed, density during the post-EMT era despite the negative trend remains high and only after 2005 that it tends to acquire the pre-EMT values.

We may note that deep layers in the sub-basins of the Aegean during the post-EMT period are characterized by an increasing trend of temperature and decreasing trends both in salinity and density. Velaoras and Lascaratos (2005) suggested that the thermohaline properties of deep water after 1993 slowly change to a warm and less salty condition due to the interaction with the intermediate layer. Also, Zervakis et al. (2003) mentioned that the density of the trapped deep water in the depressions of northern-central Aegean slowly decreases due to an internal wave braking mechanism.

The evolution of deep water characteristics of the Aegean Sea can also be affected by the very complicated topography. Vervatis et al. (2011) suggested that the effect of topography on deep water mass renewal can explain the density differences between the depressions in the North and Central Aegean. In Central Aegean, the V-shaped Chios basin allows the replacement of the deep water masses by thermohaline circulation cell. In contrast, basins in North Aegean are very abrupt with a shallow shelf favorable for replenishment by abrupt pulses of deep water formation on shelf regions.

3.2. Air–sea fluxes variability

The Aegean Sea undergoes important surface buoyancy losses each winter with great variability in the range of $0.4–1.5 \times 10^{-7}$ m^2/s^3 and that the central region is subjected to higher values of buoyancy loss (Fig. 5). During the EMT onset period (1988–1993) the winter buoyancy loss continuously increases and this leads to an increasing destabilization of water column and thus to favorable conditions for deep-water formation. There are also other periods of larger than normal winter buoyancy loss, such as 1963–64, 1975–1976 and 1982–83. Maximum buoyancy loss of the examined period is observed in 2003, when an increase of more than 7×10^{-8} m^2/s^3 occurs in comparison to the previous winter.

The winter heat flux time series (Fig. 6) shows important variability from year to year (up to 150 W/m^2) with minimum values in 2003 and follows closely the variability of the

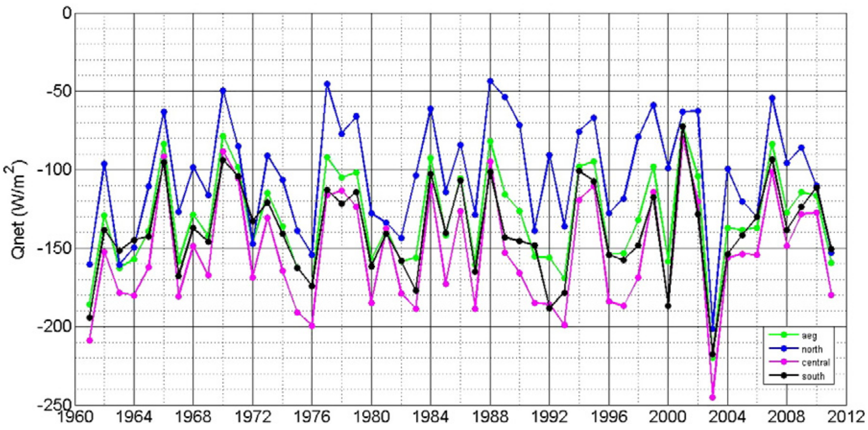

Fig. 6. Winter heat flux (in W/m^2) of the North (line in blue), Central (line in magenta) and South (line in black) Aegean. The green line represents the overall winter heat loss of the Aegean.

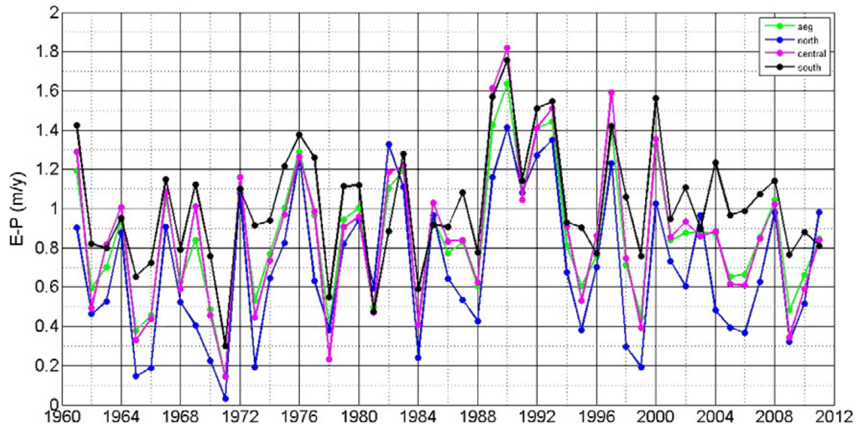

Fig. 7. Winter net freshwater loss (E − P, in m/y) of the North (line in blue), Central (line in magenta) and South (line in black) Aegean. The green line represents the overall winter heat loss of the Aegean.

buoyancy loss time series (correlation coefficient greater than 90%). It presents periods of enhanced heat loss similar to those of the buoyancy loss, namely in 1973–76, 1988–93 (EMT onset period), 2001–2003, without any important trend throughout the examined period. Very intense variability can be seen in the daily winter heat flux from the sea surface in the Aegean (Fig. 3). The greatest values of heat loss are observed during February and the maximum winter heat gain is observed in the end of March, while extreme heat loss events may happen throughout winter. It is noteworthy that the EMT period is not characterized by abnormal episodes of extreme heat loss but rather by more frequent episodes of moderate intensity (e.g. during the years 1991–1993).

Since deep-water formation processes are expected to relate to episodic winter heat loss events (extreme days, defined in Section 2) we investigate their connection to deep-water characteristics. In Fig. 4, where the number of days of abnormal heat loss is presented, it is evident that winter periods with large number of extreme days in the Aegean are observed mainly in the central Aegean. Some of these years and/or periods are related to changes in the deep-water characteristics (e.g. 1983, 1992–93) while others (e.g. 1964, 1987 and 2003) seem to impact the deep water temperature of the following year (e.g. 1965, 1988 and 2004). The latter can be related to the sparse sampling in space and time that makes impossible to detect the changes at the time they take place but rather when the signal has propagated and spread around the basin. The influence of the extreme events can be also masked by the complex combination of other processes, as it will be discussed in Section 3.3.

The time-series of the winter net surface fresh water flux ($E - P$ in Fig. 7) has a mean value of about 0.8 m/y, at the pre-EMT period, while in the EMT onset period (1989–1993) the mean surface fresh water flux is increased to 1.4 m/y with a decreasing trend afterwards. If we compare the winter surface freshwater flux evolution with the winter buoyancy flux, we observe similar patterns during the first half of the period (correlation coefficient around 70% until late 80s) while significant differences are present during the second part of the record where the correlation coefficient jumps to 50% (with the most significant difference observed in the year 2003). This implies that during the last part of the record the buoyancy flux variability is mainly determined by the heat flux variability showing an extraordinary high degree of correlation ($r = 0.90$).

The winter sea surface temperature variability (Fig. 8) presents similar patterns in regions of the Aegean (the

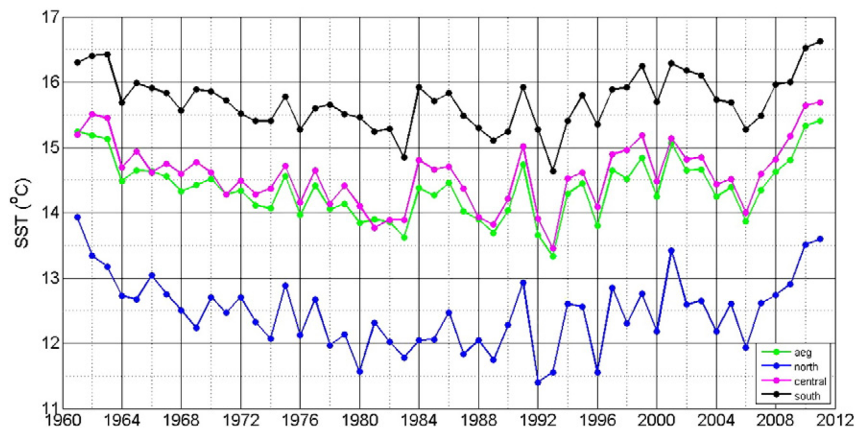

Fig. 8. Winter sea surface temperature (°C) of the North (line in blue), Central (line in magenta) and South (line in black) Aegean. The green line represents the overall winter heat loss of the Aegean.

correlation coefficient between the sub-basins is greater than 85%), showing a decreasing trend from 1961 up to the mid 80s (-0.06 °C year^{-1}) (pre-EMT), high year to year variability during the EMT onset period and an increasing trend ($+0.05$ °C year^{-1}) at the end of the examined period (1993–2012). An exceptional feature is the fact that sea surface temperature variability remains rather small until early 80s becoming much larger later on. A drop of 2 °C is observed from winter 1991 to winters 1992–1993, an indication of dramatic changes in the area. Skliris et al. (2011) found a small SST decreasing trend in the Aegean Sea from the late 1960s to the early 1990s followed by an acceleration of the warming rate in the Aegean Sea until 2008.

Surface salinity (Fig. 9) differs greatly among the three sub-basins and exhibits important variability throughout the examined period in all 3 sub-basins. High sea surface salinity (Fig. 9) is recorded during the winter periods of the years 1962–65, 1972–76 and 1990–94 with higher values in the two first periods. In the northern-Aegean it rises again and continuously after 1997 until the end of the period, when it almost reaches the EMT onset period levels. Similarly in the Central and South Aegean, the salinity increase is mostly obvious after 2005 until the end of the examined period.

3.3. The relation between the surface forcing and the deep-water characteristics

Comparing atmospheric forcing data (derived from NEMOMED8 reanalysis) with deep-water characteristics (derived from direct observations) is not always straightforward and the interpretation of the results can be difficult. These difficulties are enhanced by the different spatial and temporal data distribution of the two sets. However, some indications of their possible coupling and the scales of variability associated with this can produce interesting conclusions. The following study is focused on the winter seasons with the highest number of extreme days, since deep-water formation is expected to occur during high frequency heat loss events. We next review the behavior of the deep water of the sub-basins within the Aegean Sea and the potential connection with the variability of the atmospheric forcing.

In the North Aegean, during the period 1963–1964 a significant number of extreme days (Fig. 4) are recorded together with high winter buoyancy loss (Fig. 5) and high sea surface salinity (Fig. 9). However, the winter freshwater loss (Fig. 7) has moderate values. The fact that there is a small decrease in salinity and density in deep waters in 1964 indicates that freshwater fluxes could act as a suppressive factor in the deep water formation processes. Nevertheless the low number of deep stations during the '60s does not allow reaching more accurate conclusions.

In the North and Central Aegean, during the years 1973–1976 we observe a large number of extreme days (Fig. 4) that peak up in 1976 with winter buoyancy loss greater than those observed in the previous period (Fig. 5), together with high values of winter freshwater loss (Fig. 7) and sea surface salinity. In 1979 there is a high salinity event, in the deep layer of the Aegean, reaching its maximum following by a small decrease of temperature (1977–1979). Due to the lack of oceanographic data during this period we may conclude that this extreme atmospheric forcing led to anomalous density values in the deep water in north and central Aegean (sigma-theta values around 29.4 kg/m^3) mainly due to an increase in salinity. Vervatis (2013) suggested that the northern-central Aegean was a dense water formation area during the mid-1970s under intense heat loss and also Josey (2003) observed highest production rates in the mid-1970s. The northern-central Aegean local forcing mechanisms seem to play an important role in the deep-water formation events.

The 1980–1982 period, in North Aegean, is characterized by a large number of extreme days (Fig. 4) and high heat loss that peak up in 1982, together with high values of winter freshwater loss (Fig. 7), but the sea surface salinity (Fig. 9) demonstrates quite low values. In this period we can observe an increase in temperature and a decrease in salinity of the deep water that lead in a decrease in density. According to (Beuvier et al., 2008) there is an increased BSW inflow at the specific period (1975–1980), which could hinder the deep water formation processes (through insulation of the water

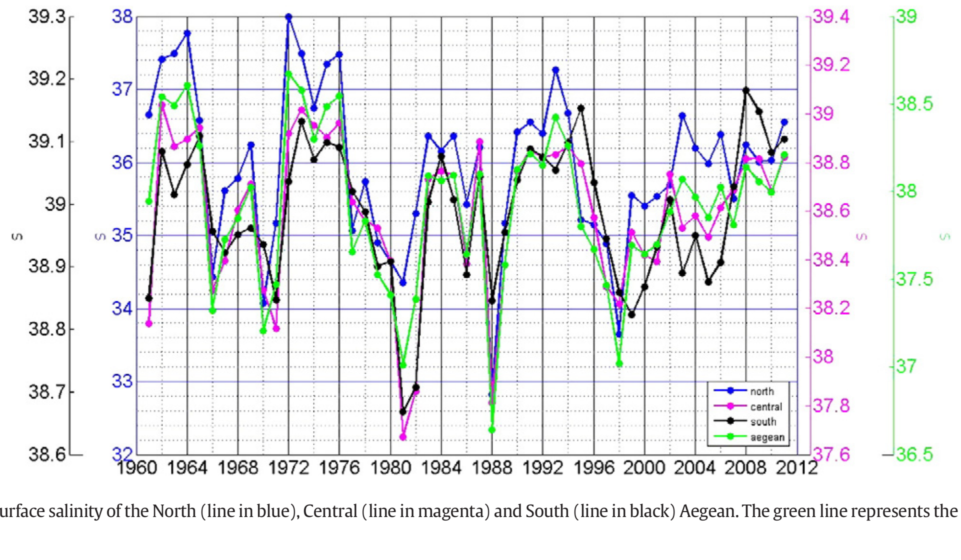

Fig. 9. Winter sea surface salinity of the North (line in blue), Central (line in magenta) and South (line in black) Aegean. The green line represents the overall winter heat loss of the Aegean.

column by a fresh and buoyant layer at the sea surface) in the Northern Aegean Sea (Tsimplis et al., 2006).

During the next period (1987–1993) that is characterized as the onset of the EMT climatic event, the most dramatic changes are taking place. These years are characterized by a large number of extreme days (Fig. 4) with winter buoyancy loss greater than those observed in the previous period, together with high values of winter freshwater loss (Fig. 7). Greater variability of the surface forcing (Figs. 5 and 6) is mostly observed in the Central and South Aegean. Additionally, the mean winter surface temperature in 1993 reaches its minimum in all three regions (Fig. 8). Continuous increase of the salinity in the deep layers (Fig. 2a), together with cooling events with concurrent increasing in density are observed in the sub-basins from the late 80s to mid 90s. It is interesting that the maximum values of salinity and density of the deep water in the central Aegean occur in 1998 (Fig. 2a,c) with a concurrent cooling event. During the period 1996–1999 there is a large number of extreme days in the central Aegean (Fig. 4) followed by high values of winter buoyancy loss, winter freshwater loss and heat loss (Figs. 5, 6 and 7). It is noteworthy that although the time series of salinity in the south Aegean shows an increasing trend during 1987–1991 its maximum occurs in 1997. This is also evident in the time series of density with a gradual increase observed in late 80s until 1997 showing a possible connection between central and south Aegean deep layers (Gertman et al., 2006). According to Roether et al. (2007) Aegean dense outflow continued until at least 1998.

It seems that it is not solely the number of the extreme heat loss days that plays the most crucial role in deep-water formation. It is rather the combination of preconditioning during early winter together with the number of subsequent extreme events (days) during winter that does not allow the re-stabilization of the stratification in the dense water formation area. Moreover, a number of events during consecutive winters may weaken the overall stratification of deep water formation areas. This provides a preconditioning mechanism for the following winter deep water formation processes, as suggested by Mantziafou et al. (2008). The number of the extreme events during the EMT period is large in comparison to other periods such as especially during 1991–1993. Thus, the extreme atmospheric changes have a significant effect to deep-water formation in the Aegean Sea during the EMT onset period (Theocharis et al., 1999; Sofianos et al., 2013). Beuvier et al. (2010) estimated that the annual formation rates of dense water in the Aegean Sea during the period of 1972-1976 were significantly high but two times lower than the rates during the onset of the EMT.

During the following period (1994–95) the atmospheric changes seem to have an impact on the thermohaline properties of the deep water. The reduction of winter surface salinity and winter buoyancy loss combined with a small number of extreme days (Figs. 4, 5 and 9) resulted in the increase of temperature and in the decrease of both salinity and density of the deep water in the northern-central Aegean (Fig. 2a,c).

In 2003 the number of extreme days (Fig. 4), the winter buoyancy loss (Fig. 5) and the annual mean winter heat loss (Fig. 6) reach the maximum values in the examined period. The winters of 2003 and 2008 are considered to be potential

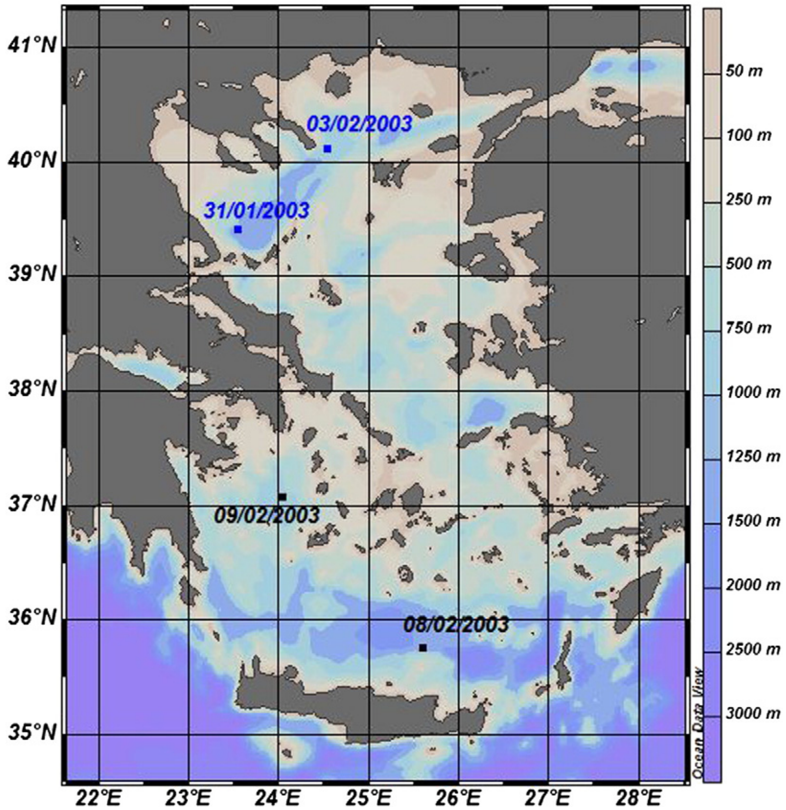

Fig. 10. Location of deep stations in 2003.

periods of deep water formation for the Northern Aegean basin (Zervakis et al., 2009). The changes in the deep-water characteristics is recorded during the next year, when there is a rise both in salinity and density in the northern-central Aegean. This could probably be due to the uneven distribution of observational data. The observations in 2003 are mainly located in the Southern Aegean and in particular in the Cretan Sea (Fig. 10) and any formation event that occurred in north or central part of the Aegean would have been recorded with a time lag. Additionally, the rest of the observations in 2003 located in the northern-central Aegean dated in January and early February, thus they are indicative of processes that took place during the previous year.

From the previous analysis, we suggest that the abnormal atmospheric forcing in the Aegean Sea has a superior impact in the North and mainly in the Central Aegean. On the other hand, the South Aegean appears greatly influenced by the Eastern Mediterranean circulation rather than the atmospheric forcing.

4. Summary and conclusions

One of the most complete data set for the Eastern Mediterranean (Özsoy et al., 2013, enriched with NODC data) for the period 1960–2012 is used and compared with daily mean atmospheric data for the period 1961–2011 provided by the NEMOMED8 simulation for the Mediterranean basin (Sevault et al., 2009; Herrmann and Somot, 2008) in order to study interannual to decadal variability in deep water characteristics of the Aegean sub-basins and how this is connected to the atmospheric variability. The deep waters of the Aegean Sea sub-basins present great sensitivity to various forcings, exhibited by the large interannual variability of their characteristics. This variability is linked with the relatively small size and the complex topography of the entire basin, that lead to rapid response to atmospheric forcing, together with the strong variability of the atmospheric forcing and the lateral advection of seawater properties from adjacent basins.

The most outstanding event is the EMT that provoked the formation of the densest waters of the examined period, but other events, characterized by the presence of high-density deep water, occurred before and after the event, especially during the mid and late 1970's. It is remarkable that the event that happened during the 70s shows greater variability in the South Aegean comparing with the EMT event, which is more intense in the northern-central Aegean. After the EMT the densities remain in high levels until 2004 and then decrease to the pre-EMT values, indicating that no extreme density deep waters are forming in the Aegean after 2004.

The diversity of the northern-central and the South Aegean is evident through the time series analysis of the deep water thermohaline characteristics. The salinity time series of the deep water in the sub-basins of the Aegean shows a good correlation. On the other hand the variability of the potential temperature reveals the poor connection between the South and northern-central Aegean ($r \approx -0.05$) and the strong connection between the North and the Central Aegean ($r \approx 0.50$). From the foregoing, it is evident that the direct exchange of water masses between the southern and the northern Aegean is confined to the surface and at intermediate depths, while the deep basins of these two regions do not communicate directly with each other. The atmospheric forcing variability, including extreme events, also shows strong interannual variability. The winter mean surface heat flux has a range of over 100 W/m^2 (with very large daily and synoptic variability), while the winter mean surface freshwater flux has a range of more than 1 m/year. This large variability can be very important for the heat and fresh water budgets of a small basin, leading to abrupt changes in the stratification and the thermohaline characteristics of the whole water column. Although deep-water characteristics are achieved through complicated phenomena related to the dense-water formation processes, the combination of strong atmospheric forcing, small size and complicated topography make the Aegean Sea thermohaline circulation pattern very sensitive.

There are obvious correlations between the atmospheric forcing and the deep-water characteristics, especially during periods or years with extreme buoyancy loss, related to strong heat loss and/or freshwater loss. It is evident that until the late 80s both heat and salt fluxes are important for determining the buoyancy flux, while at the end of the examined period the buoyancy is determined mainly from the heat fluxes.

The role of the extreme events in the dense-water formation and the characteristics of the deep waters is not very straightforward. Although their effect is important during several periods/years, it is the sequence and timing of the extreme events that seem to determine their impact in the whole process. The present study suggests that the impact of extreme events in the deep water formation processes in the North–Central Aegean is more intense than in the south.

Although the variability of the deep-water characteristics is greatly influenced by the lateral fluxes at the open boundaries of the basin we have excluded the related discussion in this paper, keeping such analyses for future studies. However, the comparison of the variability of the thermohaline characteristics of the deep water within the Aegean sub-basins with the variability of the atmospheric forcing indicates that the deep-water appears to be strongly influenced by the inflow of BSW and by waters of Levantine origin.

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