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Inter-annual/decadal variability of north Aegean Sea hydrodynamics over 1960-2000

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Abstract

Results from a high-resolution hindcast model experiment, supported by available observations, reveal an increasing salinity trend in the north Aegean during the Eastern Mediterranean Transient (EMT) period, largely controlled by increases in the flow rate and salinity of water masses of Levantine origin entering the domain through the Myconos-Ikaria strait as a response to an acceleration of the Aegean thermohaline cell. Changes in the Dardanelles inflow (increasing salinity) and in the surface freshwater flux (increasing Evaporation-Precipitation), although both contributing to a higher salt content of the basin during the EMT, play a minor role in the inter-annual/decadal variability of the freshwater budget. A long-term decreasing temperature trend is observed from the 1960s to the early 1990s. It is superimposed on the salinity-preconditioning phase over the 1980s and early 1990s. Both signals are, concomitantly, favouring conditions for intense Dense Water Formation (DWF) in the north Aegean Sea. In addition, the northward displacement of the Black Sea Water front over the EMT, leads to the expansion of convective cells towards the north and to higher formation rates associated with both colder and saltier surface waters.

Keywords: North Aegean Sea, Thermohaline forcing, Dardanelles strait, Dense Water Formation, Eastern Mediterranean Transient.

Introduction

The north Aegean Sea is known to have a complex thermohaline and wind driven circulation. Its circulation complexity arises from several factors, including the strong topographic and coastal influences, the atmospheric forcing and internal dynamic processes. The topography includes many sea-bed features comprising a succession of deep valleys, ridges and localized pits (Fig. 1). A series of straits of high relief and sill depths between the Aegean sub-basins and the adjacent seas have a pronounced impact on the prevailing flows.

The most important feature of the circulation pattern is the surface inflow of the brackish, low density Black Sea Water (BSW) from the Dardanelles strait (Zodiatis, 1994; Zodiatis *et al*., 1996; Zervakis *et al*., 2000). The Dardanelles outflow consists of generally cold waters and very low salinity at the range of 24-35 close to the Dardanelles mouth. This allows the outflow to be detected in satellite imagery mainly during winter, as summer wind-induced upwelling masks BSW surface temperature signal (Zodiatis *et al*., 1996; Zervakis & Georgopoulos, 2002; Skliris *et al.,* 2010). A bifurcation is often observed east of Limnos Island, with the northern branch of the current contributing to a permanent anticyclone around the island of Samothraki (Zervakis & Georgopoulos, 2002). BSW creates a strong thermohaline front with the saline Levantine Surface Water (LSW) that enters the north Aegean through the wide Myconos-Ikaria strait (Fig. 1), with salinities usually greater than 39. The position of the front fluctuates around the island of Limnos, generating strong currents controlling the circulation in the North Aegean (Zodiatis, 1994). Following a general cyclonic circulation path, BSW flows westward and exits the north Aegean following the Evia jet along the eastern coast of Evia Island (Lykousis *et al*., 2002; Velaoras & Lascaratos, 2010; Gerin *et al*., 2014).

The most active dynamic circulation features are the mesoscale cyclonic and anticyclonic eddies and boundary currents. Although most of them present strong seasonality, features such as the cyclonic eddies in the Chios basin, the Evian current and the anticyclonic circulation around Samothraki Island are robust. The north Aegean deep water masses are characterized by very high densities (i.e. higher than 29.2 kg.m^{-3}). Those very dense water masses are formed on the north Aegean shelves, mainly the Limnos-Lesvos plateau and in the Skyros and Chios basins (Fig. 1) (Velaoras & Lascaratos, 2005; Gertman *et al*., 2006; Vervatis *et al*., 2011). Deep water formation processes and changes in the thermohaline properties of the north Aegean Sea were discussed by many authors investigating the Eastern Mediterranean Transient

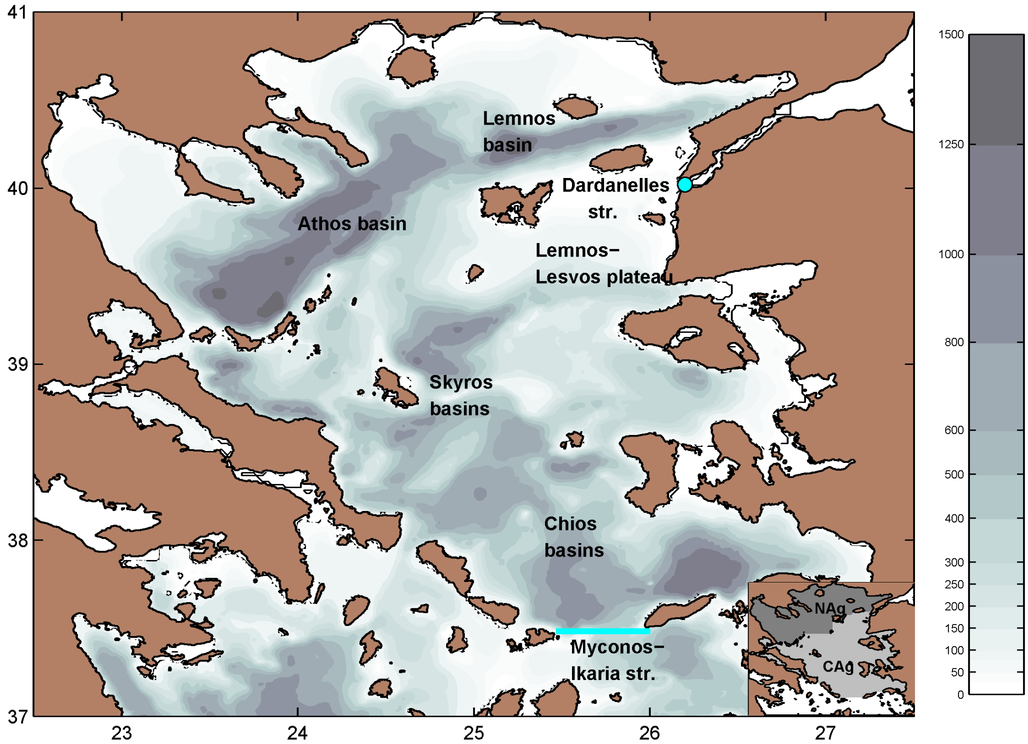

Fig. 1: Map of the north Aegean Sea. Different regions cited in the text are highlighted inside the map (see lower right corner); dark grey area: Northern Aegean (NAg), light grey area: Central Aegean (CAg), cyan dot: Dardanelles mouth, cyan line: Myconos-Ikaria strait.

(EMT) (Roether *et al*., 1996; Theocharis *et al*., 1999; Zervakis *et al*., 2000; Gertman *et al*., 2006; Vervatis *et al*., 2013). During the EMT (over roughly 1987-1994), the main source of Eastern Mediterranean Deep Water (EMDW) shifts from the Adriatic to the Aegean Sea. Large amounts of very dense Aegean Sea waters spread out through the Cretan arc straits and simultaneously uplift the old EMDW of Adriatic origin. This dramatic climatic event was mainly attributed to extreme winter surface cooling events in the early 1990s and regional circulation changes inducing a large salinity increase in the Aegean Sea (e.g. Lascaratos *et al*., 1999; Malanotte-Rizzoli *et al*., 1999; Theocharis *et al*., 1999) whilst the reduction of BSW over the same period was also noted as being an important factor controlling deep water formation events in the north Aegean (Zervakis *et al*., 2000).

The objective of the present paper is to investigate the inter-annual/decadal variability of north Aegean Sea hydrodynamics (1960-2000) in relation to the atmospheric and lateral thermohaline forcing. The dynamic processes driving changes in the thermohaline properties of the north Aegean due to surface and lateral inputs are analyzed through a high-resolution model hindcast simulation, whereas various observational databases are used to validate the model results. The significance of the BSW frontal position and its role in exposing or suppressing areas of Dense Water Formation (DWF) in the north Aegean during the EMT are also discussed. The paper is organized as follows: in the "Data and Methods" section the modelling and observational datasets are presented; in the "Results and Discussion" section the basic findings of this study are analyzed; in the "Conclusions" section the work is summarized and linked to recent studies related to eastern Mediterranean dynamics.

Data and Methods

Model and observational datasets are used to investigate the long-term variability of the thermohaline properties and dynamics of the north Aegean Sea over 1960-2000. The extracted datasets are used to interpret north Aegean temperature and salinity inter-annual variations, exchanges with the adjacent seas, and changes in thermohaline circulation patterns.

Model results of the ALERMO high-resolution (1/30°) eddy resolving hindcast experiment (1960-2000) in the eastern Mediterranean (Vervatis *et al*., 2013) are analyzed herein for the north Aegean Sea. In this hindcast experiment, the ALERMO is one-way nested to the coarse OPAMED model, the Mediterranean limited area 8.1 version of the OGCM OPA model (Madec *et al*., 1998) with resolution 1/8 of a degree, described in details in Somot (2005) and Somot *et al*. (2006). The model is coupled with the ARPERA atmospheric dataset, a dynamic downscale of the ERA40 reanalysis (Hermann & Somot, 2008). The Dardanelles strait is introduced in the AL-

ERMO configuration as an open boundary, described in detail in Vervatis *et al*. (2013). Since there is no available long-term observational data for the Dardanelles strait, a "perpetual" seasonal cycle was introduced at the strait (Fig. 2, upper panels). The most well-known parameters from the literature are the inflow/outflow/net water fluxes at the Dardanelles strait. The net water flux rate in previous observational/modelling studies has been estimated at ~300 km^3/year (~0.01 Sv) (Ünlüata *et al*., 1990; Korres *et al*., 2002; Nittis *et al*., 2003; Kourafalou & Tsiaras, 2007; Skliris *et al*., 2007; Tzali *et al*., 2010). In the modelling study, an upper 25 m layer inflow of BSW and a bottom layer outflow are prescribed with sinusoidal seasonal modulations. The monthly Θ-S characteristics are derived from Kourafalou *et al*. (2004), based on the Beşiktepe *et al*. (1994) observational study. For both inflow/outflow rates the maximum value is reached in mid-July and the minimum in mid-January. Since the BSW inflow is an important factor which adds to the thermohaline forcing in the northern Aegean, the seasonal cycle allows winter variations that are important to determine the formation rates of the region. Furthermore, during the summer period, mesoscale activity is more pronounced, due to the increasing BSW inflow, compared with a mean annual flow of the same annual rate. The interannual variability of the BSW Θ-S properties is implicitly introduced from the coarse OPAMED model (Somot *et al*., 2006), through a salinity/temperature surface relaxation (Fig. 2e). More details about the ALERMO 1960-2000 hindcast simulation may be found in Vervatis *et al*. (2013).

Volume averaged salinity and temperature variations produced by the model are validated using the MEDATLAS II database (MEDAR Group, 2002; Rixen *et al*., 2005). This is a yearly 3D-dataset consisting of quality checked temperature and salinity profiles in the Mediterranean from 1945 to 2002 interpolated onto a 0.2°×0.2° horizontal grid by a Variational Inverse Model (VIM) (Brankart & Brasseur, 1998).

Two observational datasets, a satellite-derived and an in-situ-derived dataset, are used to validate the model SST variability. The construction of the satellite-derived SST data for the north Aegean Sea considered herein is based on a re-analysis of the AVHRR Pathfinder (version 5.0) SST time series of the Mediterranean Sea (Marullo *et al*., 2007). The 1985-2000 spatiotemporal dataset for the north Aegean Sea consists of optimally interpolated declouded monthly SST maps at a 1/16° resolution-grid (~6 km), provided by the Gruppo Oceanografia da Satellite (GOS) of the CNR - ISAC (Istituto di Scienze dell'Atmosfera e del Clima) (http://gos.ifa.rm.cnr.it). Marullo *et al*. (2007) validated the optimally interpolated Pathfinder SST dataset for the Mediterranean Sea using in-situ data from 1985 to 2005, and found a mean bias of less than 0.1 K with a root mean square error of about 0.5 K, whilst they showed that errors were weakly dependent on season and did not drift with time.

A longer SST time series but with much lower horizontal resolution is also constructed based on in-situ data obtained from the International Comprehensive Ocean Atmosphere Data Set (ICOADS) (Woodruff *et al*., 2008).

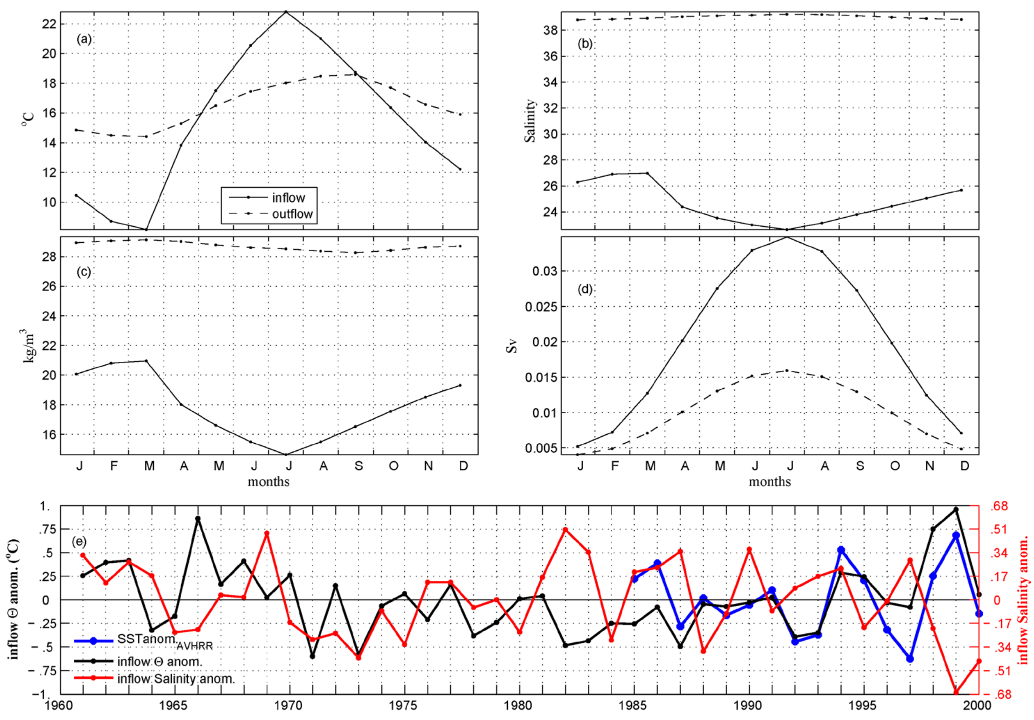

Fig. 2: (a) Theta °C, (b) salinity, (c) potential density kg.m^{-3} and (d) model monthly inflow/outflow rates Sv at the Dardanelles strait; (e) model Θ/S annual anomaly (1961-2000; black/red lines) of the Dardanelles inflow and SST °C anomaly (1985-2000; blue line) derived from the AVHRR Pathfinder re-analysis.

A 2°x2° dataset covering the north Aegean Sea is created using the ICOADS SST raw data for the period 1950-2000, provided by the National Center for Atmospheric Research (NCAR) (http://icoads.noaa.gov). Due to the much lower spatial resolution and observations density of the ICOADS-derived SST dataset (i.e. the total number of observations is at least one order of magnitude lower as compared with the satellite-derived SST dataset) and due to the pronounced SST spatial gradients within the Aegean Sea, in order to minimize biases in the calculation of the basin-average annual mean SST the following procedure is adopted: Before calculating annual basin-scale spatial averages, monthly values are first computed for each grid cell, using a threshold-criterion of at least 3 available observations per month. For the few temporal gaps encountered in the monthly time series (i.e. when the monthly 3 values threshold-criterion was not met in a grid cell), the monthly value of that year for the specific grid cell is obtained by linear temporal interpolation using the monthly values of the adjacent years for the same grid-cell. In addition, due to the complicated coastline and the numerous islands of the Aegean Sea, the proportion of sea and land in each grid point is also taken into account (i.e. using a sea/land weighted value) when calculating the north Aegean basin average SST.

Results and Discussion

As shown in the observational and model-derived temperature and salinity annual mean time series (Fig. 2 and 3), the model reproduces quite well the inter-annual variability of the north Aegean Sea thermohaline properties as well as the SST variability of BSW intrusion. Focusing on the model skills, a high correlation coefficient is calculated for the SSTs, exceeding in both observational datasets (ICOADS, AVHRR) 0.90 (statistically significant at a 95% confidence interval). In addition, the ALERMO Θ/S average properties are correlated with the MEDATLAS II database (Fig. 3), by about 0.87 for temperature and to a lesser extent for salinity, i.e. by about 0.60; both being statistically significant at a 95% confidence interval. In absolute values, the ALERMO presents lower SSTs compared with the aforementioned databases (Fig. 3). The ALERMO SST is biased on average by about -0.2 °C compared with the high resolution AVHRR satellite dataset and by about -0.5 °C with the coarse ICOADS dataset. In addition, the water column average Θ is biased by approximately -0.3 °C, whilst the ALERMO salinity as a mean value does not show any noticeable bias with respect to MEDATLAS II. The ALERMO presents a significant lesser Θ/S variability compared with the MEDATLAS II dataset. This fact, along with the Θ bias, is probably due to significant under-sam-

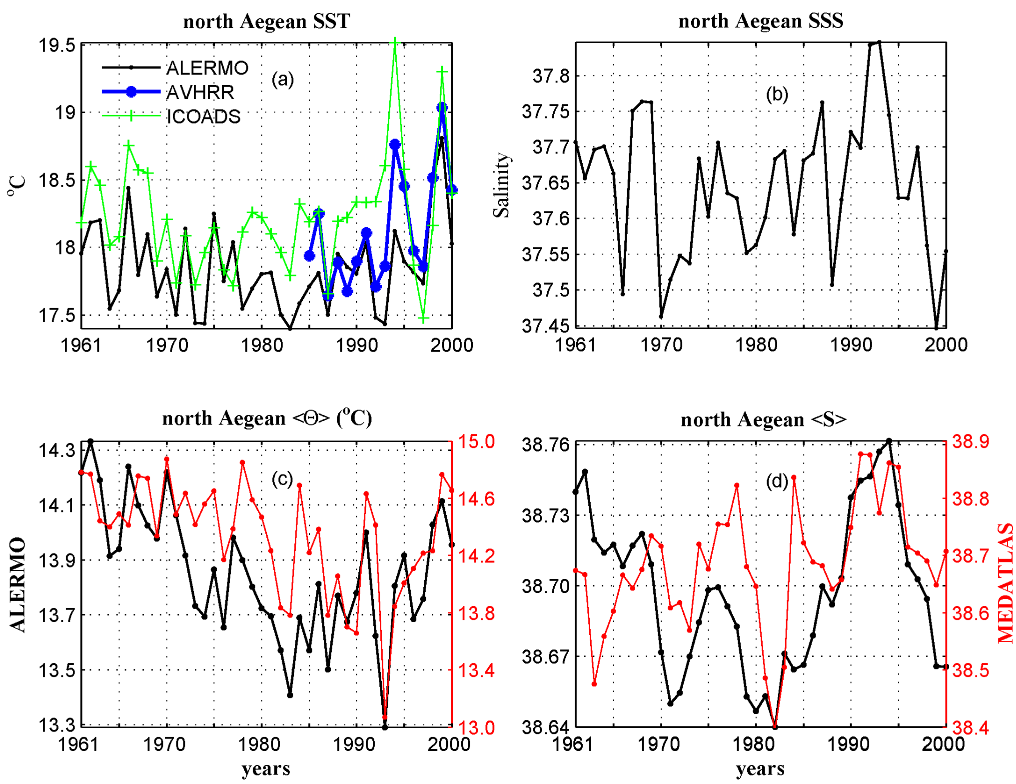

Fig. 3: Model north Aegean annual thermohaline properties (black lines); (a) superimposed annual SST °C observational datasets (blue/green lines) AVHRR, ICOADS, (b) model SSS, (c) water column average Θ (°C) from ALERMO and MEDATLAS II (red line) (d) water column average salinity from ALERMO and MEDATLAS II (red line).

pling in the MEDATLAS II (Rixen *et al*., 2005), which is in particular true for the north Aegean region. In addition, the large SST and Θ biases could also be attributed partially to the ARPERA high resolution forcing (Hermann & Somot, 2008; Josey *et al*., 2011) and partially to the eddy resolving character of the model, since eddies are known to interact with convection in DWF key regions such as the north Aegean.

Changes occurring in the thermohaline properties and circulation patterns of the north Aegean Sea are driven by the variability of the wind forcing and the thermohaline forcing applied on the surface and lateral boundaries of the region. The atmospheric data shows important interannual variability in the heat, freshwater and wind components (Fig. 4). The north Aegean experienced periods of very low temperatures and strong heat loss during the mid-1970s early 1980s (Fig. 4), followed by a long period of dry conditions in the 1980s and early 1990s. During the latter period, significant changes are also observed for the north Aegean wind pattern variability, leading to an increase of anticyclonicity and wind stress (Fig. 4). Temperature variations (Fig. 3), both in the model and in the observations, show a strong cooling trend roughly from the early 1960s to the early 1990s both at the surface and for the volume averaged north Aegean basin, creating a long-term preconditioning of this region for the subsequent DWF processes. This long-term temperature-related preconditioning seems to be superimposed on the well-documented salt preconditioning of the Aegean Sea from the early 1980s to the early 1990s. Both signals are, concomitantly, favouring conditions for intense DWF in the north Aegean Sea. This cooling trend also coincides with a prolonged period of increasing positive NAO index, favouring cooler conditions over the eastern Medi-

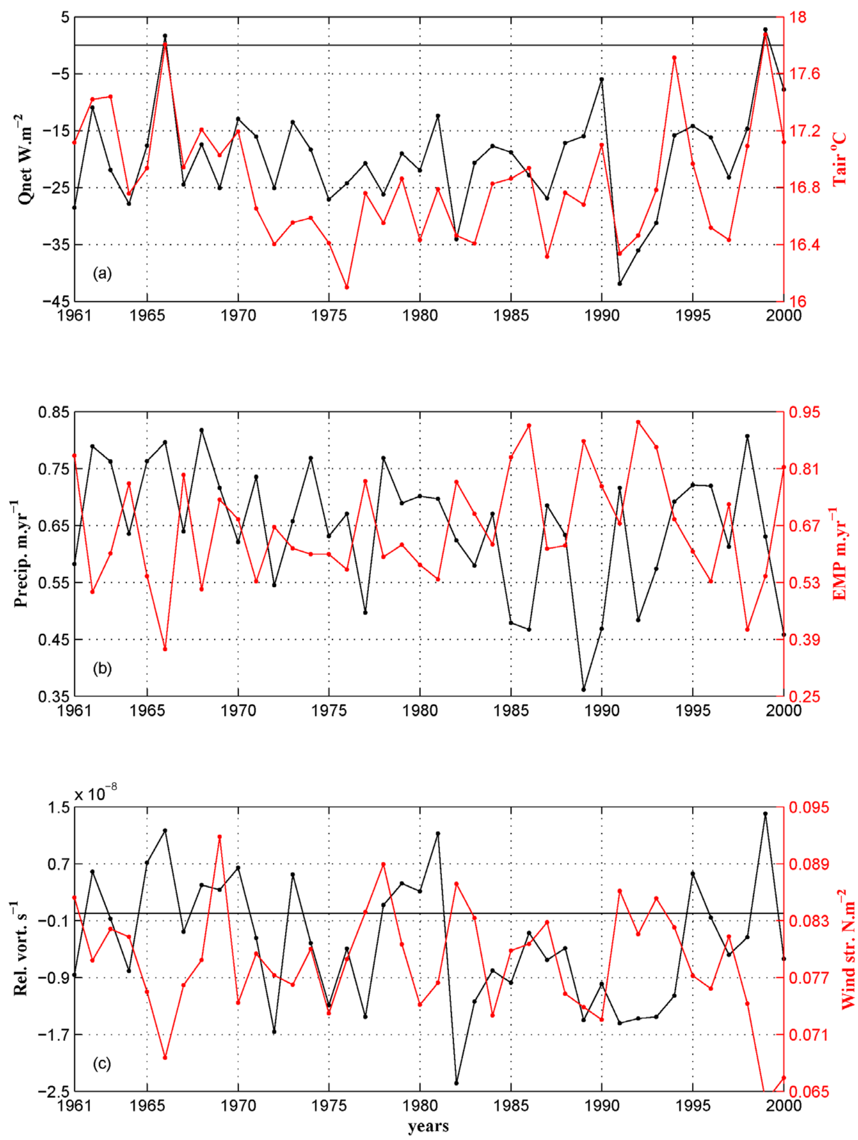

Fig. 4: Model north Aegean atmospheric forcing: (a) net heat flux Qnet (W.m^{-2}; negative/positive values denote loss/gain for the ocean; zero line is drawn) and air temperature Tair (°C), (b) precipitation (m.yr^{-1}) and Evaporation-Precipitation (m.yr^{-1}), (c) wind relative vorticity (s^{-1}; zero line is drawn) and wind stress (N.m^{-2}).

terranean basin (Skliris *et al*., 2011, 2012). It is interesting to note that just after the EMT a long-term strong warming trend is initiated in the Aegean Sea associated with a long-term broad-scale warming signal and a decadal scale variability signal linked to NAO (Skliris *et al*., 2012). From the mid-1990s onwards with the abrupt shift of NAO from a high positive to a weakly positive/negative NAO phase (inducing a warming effect in the eastern Mediterranean) the superposition of the two signals may have resulted in accelerated surface warming of the Aegean Sea with potential strong implications for DWF processes. The absence of episodes similar to EMT over the last 2 decades in the Aegean Sea, although intense anomalous winter cooling events did occur (Androulidakis *et al*., 2012), may be partially explained by long-term increasing stratification due to surface warming in this region. In addition, a concurrent strong salinity decrease is observed after 1995 (Fig. 3), which reduced the Aegean's DWF efficiency and led to a long-term (1995-2007) decay phase for the EMT (Gačić *et al*., 2011; Krokos *et al*., 2014; Theocharis *et al*., 2014).

During the EMT period, the Aegean Sea undergoes a combination of intense heat loss, dry conditions, increased wind stress and evaporation (e.g. Roether *et al*., 1996; Theocharis *et al*., 1999; Klein *et al*., 1999; Lascaratos *et al*., 1999; Vervatis *et al*., 2013). Vervatis *et al*. (2013) showed that while long-term trends of surface and lateral exchanges are preconditioning the changes in Aegean stratification, it is the extreme heat loss pulses, related to the variability of the wind field that is controlling the formation processes by abruptly lowering the buoyancy content. In particular, during the extreme cold winters of 1987 and 1993 (discussed extensively in the literature, e.g. Lagouvardos *et al*., 1998; Zervakis *et al*., 2000) short-term atmospheric heat loss reaching 1000 W.m^{-2} (Fig. 5), modulated the long-term changes in north-Aegean stratification. However, the Mixed Layer Depth (MLD) in the northern areas of the Aegean Sea seems to be constrained by the presence of the BSW surface layer (Fig. 5). Vervatis *et al*. (2013) demonstrated that during the EMT the largest part of the extreme dense water formation actually occurred in the central Aegean region (CAg in Fig. 1) whereas the northern part of the domain (NAg in Fig. 1) had a rather small contribution.

A large inter-annual variability and positive anomalies observed in salinity at the Dardanelles exit during the 1980s and early 1990s (Fig. 2e), are indicative of a possible lateral thermohaline forcing increasing surface salinity in the north Aegean (Fig. 3), in accordance with Zervakis *et al*. (2000). During the EMT, Evaporation Minus Precipitation (EMP) also increases in the north Aegean Sea mainly due to a decreasing precipitation trend (Fig. 4). However, the most important source of heat and salt flux in the north Aegean is through the wide Myconos-Ikaria strait (Fig.1), where the warm/saline Levantine origin water masses enter the region (Fig. 6). The net flow (Sv) variability in the Myconos-Ikaria strait is one order of magnitude larger than both the variability in the EMP flux and the flow rate in the Dardanelles strait (see Fig. 2 and Fig. 6) whilst the gross inflow/outflow rates (not shown here) are two orders of magnitude larger. Therefore, variations in salinity are largely determined by the

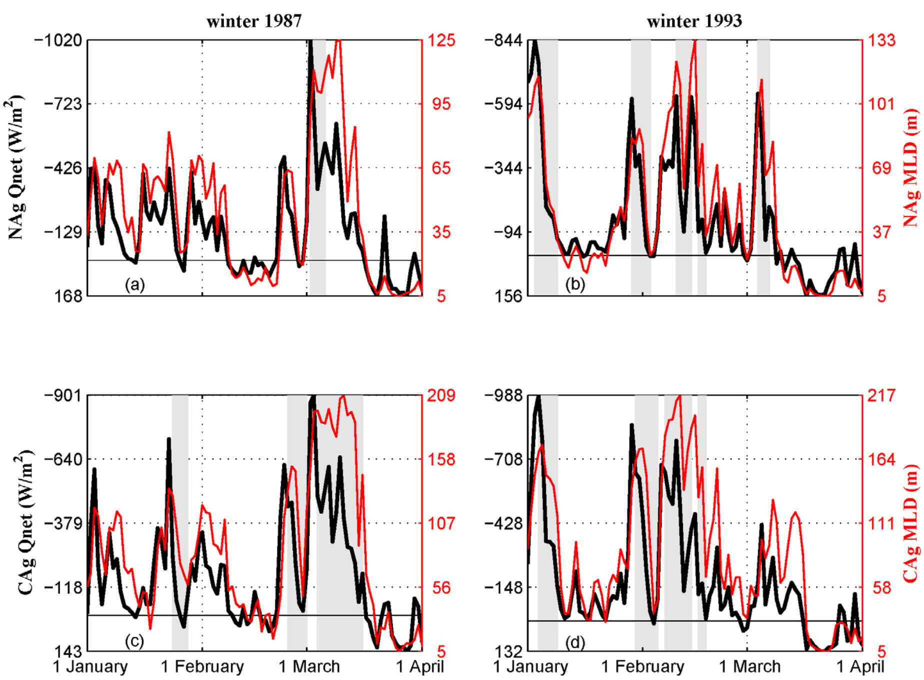

Fig. 5: Model daily time series for NAg (a, b) and CAg (c, d) (see also Fig. 1) of the net heat flux Qnet (black lines) and the Mixed Layer Depth (MLD) (red lines), during the winters of 1987 (a, c) and 1993 (b, d). The MLD is calculated using a threshold value for the vertical diffusion coefficient of 4 cm^2.s^{-1}. Negative/positive values denote loss/gain for the ocean (zero line is drawn).

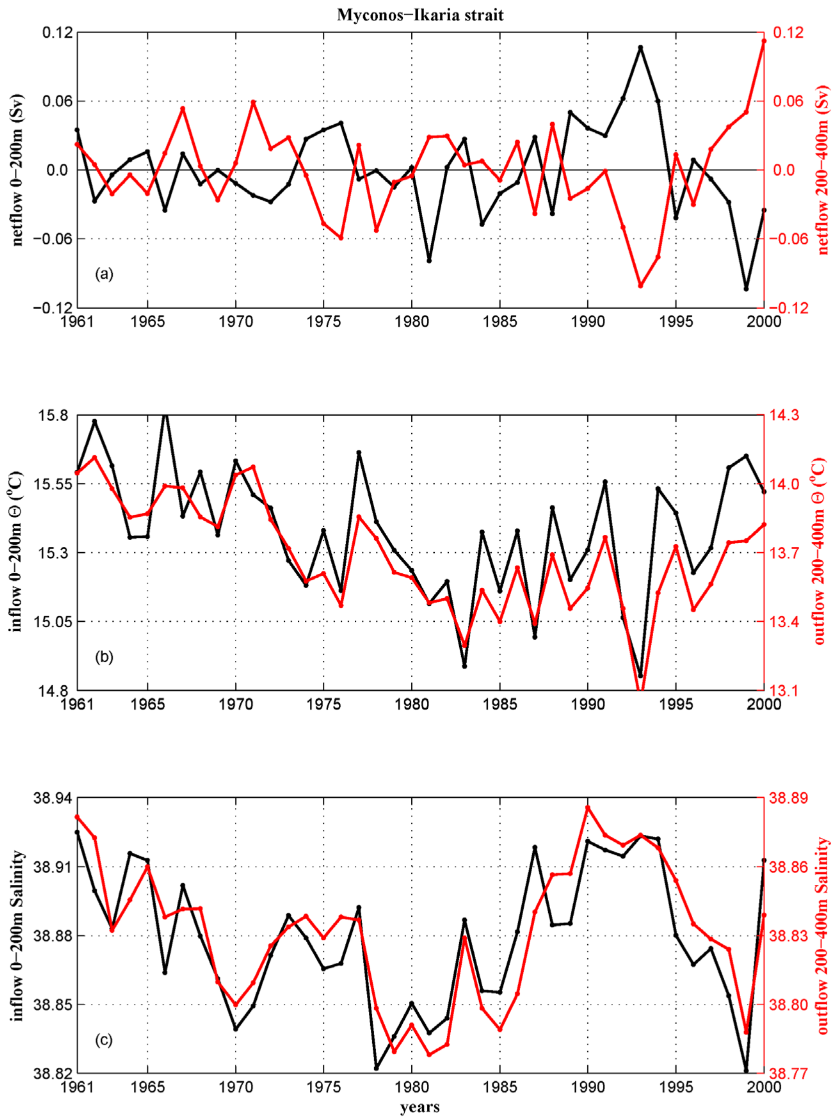

Fig. 6: Myconos-Ikaria strait upper layer 0-200m (black line) and lower layer 200-400m (red line): (a) net fluxes in Sv; inflow/outflow Θ(°C); inflow/outflow Salinity. Negative (positive) values in net fluxes denote loss (gain) for the north Aegean Sea.

intrusion of the Levantine origin water masses and to a much lesser extent by changes in the Dardanelles input or the surface freshwater flux. Prior and during the EMT phase, the salinity increase in the north Aegean is linked to a significant increasing trend observed in the salinity of the upper layers at the Myconos-Ikaria strait (Fig. 6). In particular, a trend of about 0.01 $psu.yr^{-1}$ is observed in the upper 200 m layer in the Myconos-Ikaria strait over 1982-1993 (Fig. 6), whereas a slightly lesser increasing trend is also observed in north Aegean volume averaged salinity (9.10^{-3} psu yr^{-1}) over the same period (Fig. 3).

During the EMT period, temperature variability in the north Aegean (Fig. 3) follows the abrupt heat loss pulses of the very cold winters (mainly in 1987, 1992 and 1993, see Fig. 4 and 5). Fig. 6 also depicts increasing negative values for the net flow through the lower layers of the Myconos-Ikaria strait during the EMT period. The water mass of the outflow through the lower layers of the strait has significantly lower temperature than the intruding LSW, due to DWF processes occurring in the north Aegean. The salinity in the two aforementioned layers is similar, although entrainment during the large outflow period may lower salinity values. The positive net flow in the upper 200 m layer is approximately compensated by the outflow of the lower layer 200-400 m (Fig. 6). A residual net flow closing the north Aegean budget is introduced in other minor straits connecting the north and south Aegean regions (i.e. Kafireas strait, eastern and western straits of Myconos-Ikaria strait, not shown here), as well as the Dardanelles input, the rivers included in ALERMO and the surface freshwater fluxes. As clearly shown in Fig. 6, during the EMT period both flows increase significantly as a response to an acceleration of the Aegean thermohaline cell, triggered by intense formation events (Velaoras & Lascaratos, 2005, 2010; Gertman *et al*., 2006; Vervatis *et al*., 2011) and possibly by wind stress intensification (Kontoyiannis *et al*., 1999; Nittis *et al*., 2003).

The densest water masses in the Aegean Sea are formed in the north-central regions, through open ocean and shelf convection processes. Prominent formation areas are the Chios basin and the Limnos-Lesvos plateau. In contrast, Limnos, and in some cases the Athos and Skyros basins are occupied by surface less saline BSW. This water mass enhances north Aegean stratification and acts as an insulation lid for the air-sea fluxes. Thus, the position of the BSW front during winter is crucial for exposing areas of possible convective processes. We focus on winters prior and during the EMT period (1980s and early 1990s), when salinity increases via lateral preconditioning and EMT prevails as the most prominent event over 1960-2000. Circulation pattern variability (Fig. 7) shows permanent or semi-permanent structures, such as the cyclonic circulation pattern in the Chios basin and the northern anticyclonic circulation pattern of BSW (i.e. Samothraki anticyclone). Results highlight that the position of the BSW front is displaced further north during the intense cold winters of the EMT period (in particular during 1987, 1992 and 1993, in agreement with Theocharis & Georgopoulos, 1993) in comparison with the pre-EMT period. Thus, convective cells can expand to a larger domain thus increasing the possibility of higher formation rates during the EMT period. The displacement of the BSW frontal position to the north, marked by the salinity isoline of 38.3 (Fig. 7), coincided with significant lower surface temperatures, marked by the temperature isoline of 13.5 °C (Fig. 7), due to intense atmospheric forcing. The area between the two aforementioned isolines is favourable for the existence of convective processes in the north Aegean and the production of dense water masses with low temperature and high salinity characteristics.

Conclusions

Based on a high-resolution hindcast model experiment results, supported by available observations, we revealed a strong inter-annual and decadal variability of north Aegean Sea thermohaline properties over 1960-2000. Results demonstrate that the north Aegean significant salinity increase during the EMT period is largely controlled by increases in the flow rate and salinity of Levantine origin water masses entering the domain mainly through the Myconos-Ikaria strait as a response to an acceleration of the Aegean thermohaline cell. On the other hand changes in the Dardanelles inflow (increasing salinity) and in the surface freshwater flux (increasing EMP), although both contribute to a higher salt content of the basin over the EMT, play a minor role in the interannual/decadal variability of the freshwater budget.

A long-term decreasing temperature trend is observed from the 1960s to the early 1990s associated with a prolonged period of increasing positive NAO, favouring cooler conditions over this region. This cooling phase is superimposed on the salinity-preconditioning phase over the 1980s and early 1990s with both signals concomitantly favouring conditions for intense DWF in the north Aegean Sea.

Another important feature derived from the model re-

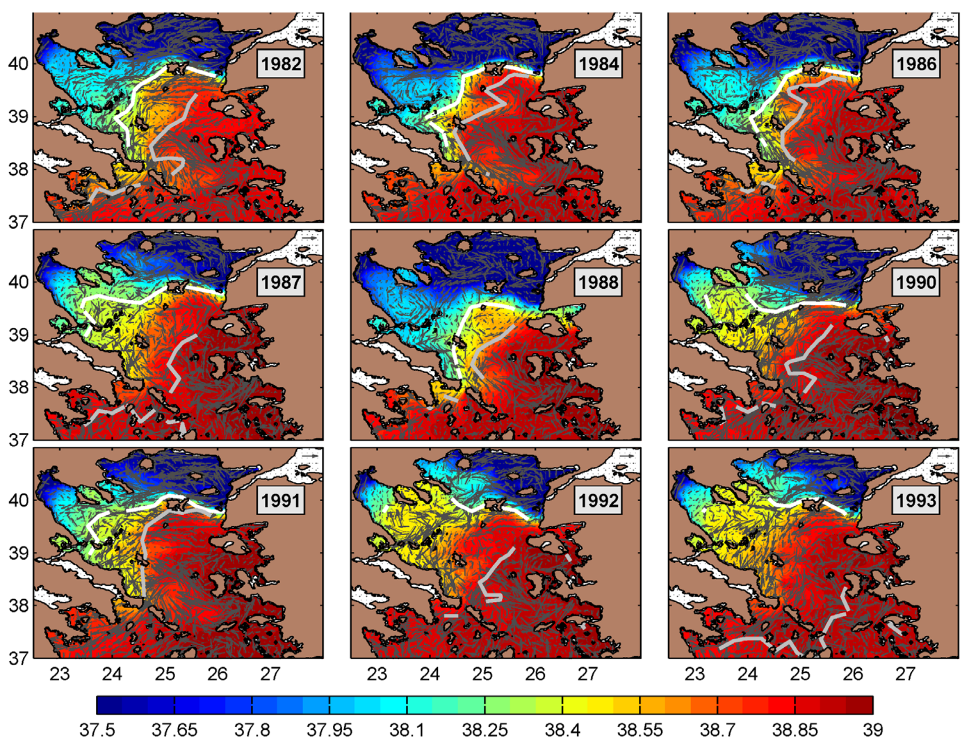

Fig. 7: Mean winter (JFM) north Aegean Sea Surface Salinity (SSS) prior and during the EMT. The salinity isoline of 38.3 (white line) and SST isoline of 13.5°C (grey line) are also depicted. Velocity vectors are scaled in 0.1 m.s^{-1}.

sults is the northward displacement of the BSW front during the anomalous cold winters of the EMT period. The changes in the BSW circulation pattern are related to the increased anticyclonicity of the wind, reduced inflow of BSW and increased inflow of Levantine origin water masses. The three mechanisms introduced in the model, are driving the BSW displacement and the expansion of convective cells towards the north, whereas high DWF rates are associated with both colder and saltier surface waters.

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References

Androulidakis, Y.S., Kourafalou, V.H., Krestenitis, Y.N., Zervakis, V., 2012. Variability of deep water mass characteristics in the North Aegean Sea: The role of lateral inputs and atmospheric conditions. *Deep Sea Research, Part I, Oceanographic Research Papers*, 67, 55-72.

Beşiktepe, S.T., Sur, H.I, Özsoy, E., Latif, M.A., Oluz, T. *et al*., 1994. The circulation and hydrography of the Marmara Sea. *Progress in Oceanography*, 34, 285-334.

Brankart, J.M., Brasseur, P., 1998. The general circulation in the Mediterranean Sea: A climatological approach. *Journal of Marine Systems*, 18, 41-70.

Gačić, M., Civitarese G., Eusebi Borzelli, G.L., Kovačević, V., Poulain P.-M. *et al*., 2011. On the relationship between the decadal oscillations of the northern Ionian Sea and the salinity distributions in the eastern Mediterranean. *Journal of Geophysical Research*, 116, C12002, doi: 10.1029/2011JC007280.

Gerin, R., Kourafalou, V., Poulain, P.-M., Beşiktepe, S., 2014. Influence of Dardanelles outflow induced thermal fronts and winds on drifter trajectories in the Aegean Sea. *Mediterranean Marine Science* 15 (2), 239-249.

Gertman, I.F., Pinardi, N., Popov, Y., Hecht, A., 2006. Aegean Sea water masses during the early stages of the Eastern Mediterranean Climatic Transient (1988-1990). *Journal of Physical Oceanography* 36, 1841-1859.

Herrmann, M.J., Somot, S., 2008. Relevance of ERA40 dynamical downscaling for modeling deep convection in the Mediterranean Sea. *Geophysical Research Letters*, 35, L04607, doi:10.1029/2007GL032442.

Josey, S.A., Somot, S., Tsimplis, M., 2011. Impacts of atmospheric modes of variability on Mediterranean Sea surface heat exchange. *Journal of Geophysical Research*, 116, C02032, doi:10.1029/2010JC006685.

Klein, B., Roether, W., Manca, B.B., Bregant, D., Beitzel, V. *et al*., 1999. The large deep water transient in the Eastern Mediterranean. *Deep-Sea Research* 46, 371-414.

Kontoyiannis, H., Theocharis, A., Balopoulos, E., Kioroglou, S., Papadopoulos, V. *et al*., 1999. Water fluxes through the Cretan Arc Straits, Eastern Mediterranean Sea: March 1994-June 1995. *Progress in Oceanography*, 44, 511-529.

Korres, G., Lascaratos, A., Hatziapostolou, E., Katsafados, P., 2002. Towards an ocean forecasting system for the Aegean Sea. *Global Atmosphere-Ocean System*, 8, 191-218.

Kourafalou, V.H., Tsiaras, K.P., 2007. A nested circulation model for the North Aegean Sea. *Ocean Science*, 3, 1-16.

Kourafalou, V., Savvidis, Y., Krestenitis, Y., Koutitas, C., 2004. Modeling Studies on the Processes that Influence Matter Transfer in the Gulf of Thermaikos (NW Aegean). *Continental Shelf Research*, 24 (2), 203-222.

Krokos, G., Velaoras, D., Korres, G., Perivoliotis, L., Theocharis, A., 2014. On the continuous functioning of an internal mechanism that drives the Eastern Mediterranean thermohaline circulation: The recent activation of the Aegean Sea as a dense water source area. *Journal of Marine Systems*, 129, 484-489.

Lagouvardos, K., Kotroni, V., Kallos, G., 1998. An extreme cold surge over the Greek Peninsula. *Quarterly Journal of the Royal Meteorological Society*, 124, 2299-2327.

Lascaratos, A., Roether, W., Nittis, K., Klein, B., 1999. Recent changes in deep water formation and spreading in the eastern Mediterranean Sea: a review. *Progress in Oceanography* 44, 5-36.

Lykousis, V., Chronis, G., Tselepidis, A., Price, N.B., Theocharis, A. *et al*., 2002. Major outputs of the recent multidisciplinary biogeochemical researches undertaken in the Aegean Sea. *Journal of Marine Systems*, 33-34, 313-334.

Madec, G., Delecluse, M., Imbard, M., Levy, C., 1998. OPA 8.1 Ocean General Circulation Model reference manual. *Note Pôle Model*., 11. Inst. Pierre-Simon Laplace des Sci. de l'Environ., Paris, France, 91 pp.

Marullo, S., Buongiorno Nardelli, B., Guarracino, M., Santoleri, R., 2007. Observing the Mediterranean Sea from space: 21 years of Pathfinder-AVHRR Sea Surface Temperatures (1985 to 2005): Re-analysis and validation. *Ocean Science,* 3, 299-310.

MEDAR Group 2002. *Mediterranean and Black Sea database of temperature, salinity and biogeochemical parameters climatological atlas*. IFREMER, Brest, 4 CDROM.

Malanotte-Rizzoli, P., Manca, B.B., Ribera D' Alcala, M., Theocharis, A., Brenner, S. *et al*., 1999. The Eastern Mediterranean in the 80s and in the 90s: the big transition in the intermediate and deep circulations. *Dynamics of Atmosphere and Oceans,* 29, 365-395.

Nittis, K., Lascaratos, A., Theocharis, A., 2003. Dense water formation in the Aegean Sea: numerical simulations during the Eastern Mediterranean Transient. *Journal of Geophysical Research* 108, 8120.

Rixen, M., Beckers, J.-M., Levitus, S., Antonov, J., Boyer, T. *et al*., 2005. The Western Mediterranean Deep Water: A proxy for climate change. *Geophysical Research Letters,* 32, L12608, doi:10.1029/2005GL022702.

Roether, W., Manca, B.B., Klein, B., Bregant, D., Georgopoulos, D. *et al*., 1996. Recent changes in eastern Mediterranean deep waters. *Science*, 271, 333-335.

Skliris, N., Sofianos, S., Lascaratos, A., 2007. Hydrological changes in the Mediterranean Sea in relation to changes in the freshwater budget: a numerical modelling study. *Journal of Marine Systems*, 65, 400-416.

Skliris, N., Mantziafou, A., Sofianos, S., Ganasos, T., 2010. Satellite-derived variability of the Aegean Sea ecohydrodynamics. *Continental Shelf Research,* 30, 403-418.

Skliris, N., Sofianos, S., Gkanasos, A., Axaopoulos, P., Mantziafou A. *et al*., 2011. Long-term sea surface temperature variability in the Aegean Sea. *Advances in Oceanography and Limnology*, 2(2), 125-139.

Skliris, N., Sofianos, S., Gkanasos, A., Mantziafou, A., Vervatis, V. *et al*., 2012. Decadal scale variability of sea surface temperature in the Mediterranean Sea in relation to atmospheric variability. *Ocean Dynamics*, 62*,* 13-30.

Somot, S., 2005. *Modélisation climatique du bassin méditerranéen: Variabilité et scénarios de changement climatique*. Ph.D. thesis. Spec. Phys. du Clim., Univ. de Toulouse III Paul Sabatier, Toulouse, France, 333 pp.

Somot, S., Sevault, F., Déqué, M., 2006. Transient climate change scenario simulation of the Mediterranean Sea for the twenty-first century using a high-resolution ocean circulation model. *Climate Dynamics*, 27, 851-879.

Theocharis, A., Georgopoulos, D., 1993. Dense water formation over the Samothraki and Limnos plateau in the north Aegean Sea (Eastern Mediterranean Sea). *Continental Shelf Research*, 13, 8/9, 910-939.

Theocharis, A., Krokos, G., Velaoras, D., Korres, G., 2014. An Internal Mechanism Driving the Alternation of the Eastern Mediterranean Dense/Deep Water Sources. In *The Mediterranean Sea: Temporal Variability and Spatial Patterns*. Borzelli, G.L.E., Gačić, M., Lionello, P., Malanotte-Rizzoli, P. (Eds). John Wiley & Sons, Inc., Oxford. doi:10.1002/9781118847572.ch8.

Theocharis, A., Nittis, K., Kontoyiannis, H., Papageorgiou, E., Balopoulos, E., 1999. Climatic changes in the Aegean Sea influence the Eastern Mediterranean thermohaline circulation (1986-1997). *Geophysical Research Letters*, 26, 1617-1620.

Tzali, M., Sofianos, S., Mantziafou, A., Skliris, N., 2010. Modelling the impact of Black Sea water inflow on the North Aegean Sea hydrodynamics. *Ocean Dynamics*, 60 (3), 585-596.

Ünlüata U., Oğuz, T., Latif, M.A., Oszoy, E., 1990. On the physical oceanography of Turkish Straits. p. 25-60. In: *The physical oceanography of sea straits*. Pratt, L.J. (Ed.). Kluwer, Netherlands.

Velaoras, D., Lascaratos, A., 2005. Deep Water mass characteristics and Interannual Variability in the Northern and Central Aegean Sea. *Journal of Marine Systems,* 53, 59-85.

Velaoras, D., Lascaratos, A., 2010. North-Central Aegean Sea surface and intermediate water masses and their role in triggering the Eastern Mediterranean Transient. *Journal of Marine Systems,* 83, 58-66.

Vervatis, V.D., Sofianos, S.S., Theocharis, A., 2011. Distribution of the thermohaline characteristics in the Aegean Sea related to water mass formation processes (2005–2006 winter surveys). *Journal of Geophysical Research*, 116, C09034, doi:10.1029/2010JC006868.

Vervatis, V.D., Sofianos, S.S., Skliris, N., Somot, S., Lascaratos, A. *et al*., 2013. Mechanisms controlling the thermohaline circulation pattern variability in the Aegean-Levantine region. A hindcast simulation (1960-2000) with an eddy resolving model. *Deep-Sea Research, Part I, Oceanographic Research Papers*, 74, 82-97.

Woodruff, S.D., Diaz, H.F., Kent, E.C., Reynolds, R.W., Worley, S.J., 2008. The evolving SST record from ICOADS, in Climate Variability and Extremes during the Past 100 Years. *Advances in Global Change Research, Springer*, 33, 65-83.

Zervakis, V., Georgopoulos, D., 2002. Hydrology and Circulation in the North Aegean (eastern Mediterranean) throughout 1997–1998. *Mediterranean Marine Science, 3 (1), 5-19.*

Zervakis, V., Georgopoulos, D., Drakopoulos, P.G., 2000. The role of the North Aegean in triggering the recent Eastern Mediterranean climatic changes. *Journal of Geophysical Research*, 105, 26103-26116.

Zodiatis, G., 1994. Advection of the Black Sea water in the North Aegean Sea. *The Global Atmosphere and Ocean System*, 2, 41-60.

Zodiatis, G., Alexandri, S., Pavlakis, P., Jonsson, L., Kallos, G. *et al*., 1996. Tentative study of flow patterns in the North Aegean Sea using NOAA-AVHRR images and 2D model simulation. *Annales Geophysicae*, 14, 1221-1231.