Temporal evolution of the water mass properties during the Eastern Mediterranean transient (EMT) in the Aegean Sea

Erdem Sayın\(^1\) and Şükri T. Beşiktepe\(^2\)

Received 5 August 2009; revised 26 May 2010; accepted 2 June 2010; published 12 October 2010.

[1] We present time series of temperature and salinity of the Aegean Sea using the data sets for the period from 1991 to 1996 from 15 oceanographic cruises to depict the temporal variability of the water masses of the Aegean Sea. This period covers an interesting large-scale change in the thermohaline circulation in the Eastern Mediterranean and the Aegean Sea. This change is known as the Eastern Mediterranean transient (EMT) and was first described during early 1990s. Our analysis reveals that very dense water formation in the Central Aegean Sea is partially due to the anomalous decrease in winter atmospheric temperature although this alone cannot completely account for the formation of the dense water. A synchronous increase in surface salinity accompanied by low temperature values in the winter months is also necessary for the EMT event to occur.


1. Introduction

[2] The Adriatic Sea has historically been considered as the main contributor to the Eastern Mediterranean Deep Water (EMDW). However, in the early 1990s, it was observed that dense Aegean water was also flowing into the Eastern Mediterranean [Roether et al., 1996]. This resulted in a drastic change in the thermohaline circulation of the Eastern Mediterranean, named as the Eastern Mediterranean transient (EMT).

[1] The EMT is an interesting phenomenon worthy of further investigation. This new source for the EMDW is of significance for regional oceanography. There is clear evidence of how local atmospheric conditions can cause large changes in the marine environment. Following the first observation of the EMT [Roether et al., 1996] number of studies [Klein et al., 1999; Lascaratos et al., 1999; Theocharis et al., 1999a; Malanotte-Rizzoli et al. [1999] have pointed out that the EMT event clearly started before 1991. Some studies asserted that the EMT started in the years between 1987 and 1990 [Schlitzer et al., 1991; Theocharis et al., 1999a]. Gertman et al. [2006] reported that EMDW already began overflowing the sills of the Kassos and Antikithira Straits as early as during the winter of 1988. EMT event is relaxed by about 1995 [Theocharis et al., 2002].

[4] The exact mechanism for the EMT is not completely known. It is known that there is a connection between the EMT and the increasing density of water from the Aegean Sea. The deep waters of the Aegean Sea became saltier between the years 1987 and 1991 [Lascaratos et al., 1999] and then cooled from 1991 to 1995 [Velaoras and Lascaratos, 2005]. The causes concerning the increasing density of the Aegean Sea water include the following:

1. increased winter convection and the resulting dense water formation due to cooling events in 1987 and 1993 [Theocharis et al., 1999b; Lascaratos et al., 1999].

2. Low water outflow from the Black Sea, thereby enhancing air-sea interactions and increasing salinity [Zervakis et al., 2000]. Zervakis et al. [2000] identified two events of massive dense water production in the North Aegean in 1987 and 1992–1993 and further suggested that a reduction of the buoyancy input through the Dardanelles could have played a role in triggering the event in the North
Aegean by decreasing the surface salinity of the Marmara Sea in the winter 1987.

3. forming of cyclonic circulation in the Central Aegean Sea, bringing dense and cold intermediate water to near the surface resulting in a decrease in surface water temperature. In a modeling work by Nittis et al. [2003], open sea convection was identified as a mechanism for the deep water formation, where cyclonic circulation favors this mechanism in the Skyros and Chios basins. Winter mixing exacerbates cyclonic circulation [Zervakis et al., 2004].

4. upwelling processes in the Saros and Baba Cape regions cause dense coastal water to form and the water is carried to the Central Aegean Sea by the strong northerly winds [Sayin et al., 2010].

5. dense water cascade occurs from the colder coastal area of the Eastern Aegean during winter. A denser saltwater cascade occurs as a result of excess evaporation from coastal area in summertime.

The objective of this paper was to complement these descriptions and further identify regions in the Aegean Sea where abrupt increase in density were observed. To achieve this, we present time series of temperature and salinity of the Aegean Sea during 1991–1996 to describe the temporal evolution of the water mass properties before, during, and after the EMT in the selected regions of the Aegean Sea. Section 2 presents a description of the data used. Section 3 presents detailed analysis of the temporal evolutions of the water mass properties, and section 4 presents our conclusions.

2. Data

Monitoring studies in the Aegean Sea have been carried out by the Institute of Marine Sciences and Technology of Dokuz Eylül University with R/V K. Piri Reis since 1991. The conductivity, temperature, and depth (CTD) data were collected during 15 cruises from summer 1991 to fall 1996 (Table 1) using a Sea Bird CTD (911plus). The Sea Bird CTD sensors were calibrated by the Northwest Regional Calibration Center (operating under contract to NOAA) once a year. We relied on the manufacturer’s published specifications for the accuracy of measurements, and we have assumed the accuracy of our data to be within ±0.001°C and ±0.0003 S/m. The locations of some CTD stations vary from cruise to cruise within the boxes shown in Figure 1.

3. Temporal Evolution of the Water Mass Properties

The temporal evolution of the water mass characteristics was identified for different parts of the Aegean Sea.

Table 1. Data Summary

<table>
<thead>
<tr>
<th>Cruise Name</th>
<th>Cruise Period</th>
<th>Number of Stations</th>
<th>Area Coverage</th>
</tr>
</thead>
<tbody>
<tr>
<td>EY91</td>
<td>04.07-27.08 1991</td>
<td>208</td>
<td>From Marmara Sea to Levantine Sea</td>
</tr>
<tr>
<td>EB92</td>
<td>13.04-03.06 1992</td>
<td>147</td>
<td>From Marmara Sea to Levantine Sea</td>
</tr>
<tr>
<td>EG92</td>
<td>15.09-08.11 1992</td>
<td>151</td>
<td>From Marmara Sea to Levantine Sea</td>
</tr>
<tr>
<td>EK93</td>
<td>18.01-21.02 1993</td>
<td>57</td>
<td>From Marmara Sea to Chios Basin</td>
</tr>
<tr>
<td>EB93</td>
<td>04.05-23.05 1993</td>
<td>38</td>
<td>From Saros to South Aegean</td>
</tr>
<tr>
<td>EG93</td>
<td>29.09-09.11 1993</td>
<td>35</td>
<td>From Saros to South Aegean</td>
</tr>
<tr>
<td>EY94</td>
<td>31.07-04.08 1994</td>
<td>34</td>
<td>From Saros to South Aegean</td>
</tr>
<tr>
<td>EG94</td>
<td>11.11-08.12 1994</td>
<td>26</td>
<td>From Saros to South Aegean</td>
</tr>
<tr>
<td>EB95</td>
<td>18.04-21.05 1995</td>
<td>29</td>
<td>From Saros to South Aegean</td>
</tr>
<tr>
<td>EY95</td>
<td>08.08-28.08 1995</td>
<td>22</td>
<td>From Saros to Gökova Bay</td>
</tr>
<tr>
<td>EG95</td>
<td>08.11-18.11 1995</td>
<td>41</td>
<td>From Gökçeada Isl. to South Aegean</td>
</tr>
<tr>
<td>EB96</td>
<td>19.03-11.04 1996</td>
<td>45</td>
<td>From Saros to South Aegean</td>
</tr>
<tr>
<td>EY96</td>
<td>05.06-05.07 1996</td>
<td>56</td>
<td>From Saros to South Aegean</td>
</tr>
<tr>
<td>EG96</td>
<td>14.10-05.11 1996</td>
<td>45</td>
<td>From Saros to South Aegean</td>
</tr>
<tr>
<td>EK98</td>
<td>17.01-26.02 1998</td>
<td>19</td>
<td>From Dardanelles exit to South Aegean</td>
</tr>
</tbody>
</table>

*All cruises were carried out in the Eastern Aegean Sea. There are variations from cruise to cruise, a point of view of area coverage. For cruise period, read, for example, 04.07-27.08 1991, as 4 July to 27 August 1991.*

Figure 1. The Aegean Sea topography (reproduced from the GEBCO gridded bathymetric data sets). Contour intervals in meters 200, 500, 1000, 2000, 3000. Geographical locations and topographic features mentioned in the text are also shown. The boxes belong to the regions that the observed CTD data were analyzed: Saros, Limnos North, Limnos South, and South Aegean.
This was accomplished by averaging profiles of temperature and salinity from each cruise in four different regions. These regions are Saros, Limnos North, Limnos South, and Levantine as shown in Figure 1. The lowering depths of the profiles varies from cruise to cruise.

[13] The selection of these regions is not causal. Each selected region has well-known characteristics. The Saros Region is chosen to represent northern shallow area under the influence of the strong northerly winds, which cause an upwelling along the Turkish coast. The regions to the north and south of Limnos Island are selected for comparison of the water masses in the North Aegean Sea with the water masses in Central Aegean Sea. Gertman et al. [2006] found that the Central Aegean Basin is the site of the formation of Aegean Intermediate Water. The last region, the South Aegean, was selected to compare which types of water masses exist in the eastern part of the Cretan Sea during the EMT.

[14] The penetration of Levantine Waters into the Aegean Sea can reach even to the vicinity of the Saros Bay in winter and spring, causing an associated increase in the salinity of the Aegean. These waters together with Dardanelles Jet, entering from the Black Sea, enhance the mesoscale cyclonic circulation occurring south of Limnos Island and in the Chios Basin [Sayin et al., 2010]. In particular, the cyclonic gyre in the south of Limnos carries very dense water in its core. It is found that the central basin and the Lesvos-Limnos Plateau, in particular, are the main regions where dense water mass formation occurs.

[15] Upwelling is another process that makes the surface water of this region denser. The upwelling takes place mainly in the Saros area and Baba Cape region. The dense upwelling water is carried to the Lesvos-Limnos Plateau and to the Central Aegean Sea with the help of northerly winds especially in summer [Sayin et al., 2010]. The surface temperature is further lowered by open sea convection, resulting in denser surface water. Outcropping of isopycnals is very likely.

[16] We will describe the evolution of the water mass characteristics in each region starting from the northernmost box. From summer 1991 to spring 1993, less saline and relatively cold water was present in the upper layer of Saros Bay (Figure 2). Density increases in the upper layers because of the decreasing in temperature, and isopycnals 29.1–29.3 start to shoal by up to 250 m until the end of spring 1993. The high value of 29.2 ρσ density was observed at the depth of 40 m in spring 1993. Such a high density was not observed so close to the surface layer again until spring 1996. Although high salinities were observed in the 50–200 m range from 1993 to the end of observations in 1996, higher temperatures between late 1993 and end 1994 resulted in lower densities. Although a very cold winter occurred in 2002, the isopycnals 29.2 and 29.3 stayed below 250 and 400 m depths, respectively, deeper than the isopycnal levels in 1993 (data not shown). The reason for the low densities was the presence of a less saline water mass occupying the depths in the upper water column. After analyzing the time series of Saros data, it can be concluded that the Saros Region is not the site where very dense water formation occurs.

[17] Low temperatures play a similarly important role in increased densities to the north of Limnos Island, which is quite close to Saros (Figure 3). Increased densities can be observed in the subsurface water between 1991 and 1993. After spring 1993 warmer, saline water fills the subsurface layers from 50 to 200 m, and the layer above 50 m increases markedly in temperature. It is known that the exchange between the Levantine and Aegean Sea reached a maximum in the years 1994 and 1995 [Kontoyiannis et al., 1999; Theocharis et al., 1999b]. The density of the water is not as dense as before fall 1993 because of the warming and stratification of density was weak (or even unstable) between depths of 100–200 m. In a second cold period (1996), the density returns to the same values as seen before spring 1992 in the north of the Limnos Island.

[18] The area south of Limnos Island is an area where the Central Aegean gyre occurs (Figure 4). The Limnos South data show that a large amount of dense water formed in the cold period especially during the winters of 1992 and 1993. The difference in the depths of the isopycnals between south and north is due to the influence of upwelling water in the Central Aegean gyre (as mentioned before in this section). The highest densities observed in 1993 were followed by lower densities in 1994 and 1995 because of the increased temperatures. This increase in temperature was caused by Levantine surface waters bringing warm water mass to the area of Limnos just below the Black Sea water.

[19] The Black Sea water, entering through the Dardanelles, forms a thin surface layer that insulates the subsurface layer from the air mass over it in the North Aegean Sea. In the period after the influx of Levantine waters filled the subsurface layers of Central Aegean Sea, the Black Sea water can be seen at the surface as a thin layer (25 m thickness) (Figure 3). High density levels can no longer be seen at the surface and subsurface after the penetration of the Black Sea water into the area. Similar patterns are also found in the west of the Lesvos Island (Figure 4) and in the offshore side of Çandarlı Basin (data not shown). During the cold winters, the winter convection process is the main mechanism for the dense water formation in the Aegean Sea. The increasing salinity in the Central Aegean, especially in the subsurface layer, is mainly due to the penetration of Levantine waters into the area.

[20] The winter convection is a seasonally occurring phenomenon that could have brought the high salinity levels near surface as observed in spring 1992 and 1993 (Figure 5). The winters of 1992 and 1993 were very cold. Cyclonic eddy dynamics raise the isopycnals [Sayin et al., 2010]. The temperature values near surface were similar to the values in spring 1992 and 1996 that indicate the winters were cold. However, 28.5 isopycnal did not surface in spring 1996. The reasons could be

[21] - absence of cyclonic eddy movements in the area
[22] - existence of modified Atlantic water (MAW) (with temperature 16°C–18°C and salinity less than 38.7) at the surface as a thin layer (25 m).
[23] Levantine surface water (LSW) filled the surface layer with the water mass containing high salinity and high temperature during summer 1996. It overlays the less saline MAW and is separated from MAW by a strong halocline. In the subsurface layer greater than 70 m, the Levantine Intermediate Water (LIW) is identified by its salinity maximum. The underlying water mass is transient Mediterran-
Figure 2. Temporal evaluations of temperature, salinity, and density fields of Saros Region starting from summer 1991 up to fall 1996. The areas in white represent where data were not collected.
Figure 3. Temporal evaluations of temperature, salinity, and density fields of northern part of the Limnos Island starting from summer 1991 up to summer 1996. The areas in white represent where data were not collected.
Figure 4. Temporal evaluations of temperature, salinity, and density fields of south of the Limnos Island starting from summer 1991 up to fall 1996. The areas in white represent where data were not collected.
Figure 5. Temporal evolutions of temperature, salinity, and density fields of the region close to Levantine starting from summer 1991 up to winter 2002. The areas in white represent where data were not collected.
nean water (TMW) that is detectable in the layer approximately 300 m with the salinity slightly less than 39.0. TMW originates in the Levantine and Ionian basins [Balopoulos et al., 1999; Theocharis et al., 1999a]. This water mass enters the south Aegean through the Cretan Arc Straits to balance the water budget [Zervakis et al., 2004]. TMW mass is detected in the deepest observations starting from fall 1992 to spring 1995 in the Cretan Sea approximately at the depth of 250–600 m. On the other hand, the southern Aegean Sea is populated by cyclonic gyres (dipole), two anticyclonic eddies, and other smaller-scale structures variable in space and time [Theocharis et al., 1999a]. When the cyclonic gyres were enhanced during the EMT, isopycnals rose closer to the surface. This coincided with the 1992 and 1993 cold winter conditions resulting in surface cooling and mixing sufficient to cause deep convection. Kontoyiannis et al. [2005] noticed that the TMW volume that inflows into the Cretan Sea showed an overall decrease from June 1997 to May 1997, and Roether et al. [2007] mentioned that fresh TMW replaced higher-salinity waters transferred downward; by 1998, the salinities had recovered toward the 1991–1992 values. In our case, TMW 29.2 \( \sigma_o \) isopycnal shoaled from 300 to 150 m up to fall 1994 and then deepened to more than 400 m or beyond our deepest observations in parallel to the increase in the volume of warm and salty LSW in the upper layers of water column.

4. Conclusions

[24] A large volume of Aegean Sea deep water started to flow into the Levantine deep basin over the sills of the Cretan Arc after 1990, with increased activity in 1993, 1994, and 1995 as a result of dense water formation during cold winters in 1992 and 1993. A compensating flow of lighter Levantine surface and intermediate water took place into the Aegean Sea. This warm and saline Levantine water even reached the North Aegean Sea to fill the entire basin. This exchange of water masses in the Central Aegean Sea constitutes a major component of the Eastern Mediterranean transient.

[25] Some mechanisms that enable the increased density in the Aegean Sea, at the start of the EMT, especially in the Central Aegean Sea are as follows, beginning with the most important:

[26] The strong winter convection processes occurring in the cold winters (e.g., 1992 and 1993) resulted in the increase of surface density.

[27] The surface waters (Black Sea Water (BSW) in the North Aegean Sea and MAW in the Cretan Sea) decrease air-sea interactions and set the conditions for the diminishing thickness of BSW that triggers the deep water formation processes in the North Aegean Sea [Zervakis et al., 2000].

[28] Cold and dense water elevated in the cores of cyclonic water movements in Central Aegean Sea and in the Cretan Sea.

[29] The water column in the core of the Central Aegean Gyre was homogenized by the strong winter convection processes forming a chimney type shape and increasing the air-sea interaction.

[30] The high salt content of Levantine waters relative to Aegean Sea surface waters allowed the formation of the dense water in the core of the Central Aegean Gyre. The Black Sea water and the Levantine surface water generally form a protective buoyant stabilizing surface layer in the North Aegean and Cretan basin respectively that prevent deep convection, but it is breached during extreme conditions in the North Aegean. The observations showed the strong cooling of 1993–1994 that despite the BSW layer produces deep density increase and the replacement of the upper water masses by LSW and LIW in the following years. A lesser event is seen in 1996.

[31] Acknowledgments. The data presented here are collected by the R/V K. Piri Reis of the Institute of Marine Sciences and Technology during 1991–1996 within the projects sponsored by Japan International Cooperation Agency, Control of Pollution in the Mediterranean, and Turkish Scientific and Technical Research Council (as part of National Monitoring Programs). The crew of the R/V K. Piri Reis for their assistance during the fieldwork are highly appreciated. Thanks to Kim McCoy and Lillian Gassie for critical reading of the earlier version of the manuscript. Suggestions and comments from Eric Des Barton and two anonymous reviewers helped to improve this manuscript.

References


Theocharis, A., K. Nittis, H. Kontoyiannis, E. Papageorgiou, and E. Balopoulos (1999b), Climatic changes in the Aegean Sea influence...


E. Sayın, Institute of Marine Sciences and Technology, Dokuz Eylül University, Baku Bulvari, No 100, Inciraltı, 35340 Izmir, Turkey. (erdem.sayin@deu.edu.tr)

Ş. T. Beşiktepe, NATO Undersea Research Center, viale San Bartolomeo, 400 La Spezia, 19126, Italy. (besiktepe@nurc.nato.int)