SEA LEVEL AND FIXED ADCP MEASUREMENTS FROM TURKISH STRAITS SYSTEM DURING 2008-2011

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1. Introduction

The Turkish Straits System (TSS) is a unique channel system between the Black Sea and the Mediterranean Sea, which plays key role in exchanging water and materials through the Dardanelles (DS) and Bosphorus Straits (Ünlüata *et al.* 1990). The channel system is vital for both the Black and the Mediterranean Seas, since the TSS is sensitive to climatic changes and contrasts (Özsoy 1998). It is also capable of driving environmental changes in the adjacent basins disproportionate to its relative size (Özsoy *et al.* 2001). Mass balance estimates of the fluxes through the system and dynamical factors leading from daily to inter-annual variability in the currents have been reviewed in the past literature (Ünlüata *et al.* 1990; Latif *et al.* 1991; Özsoy *et al.* 1996; Özsoy *et al.* 1998; Gregg *et al.* 1999; Gregg and Özsoy 2002).

The main objective of the present study is to obtain long-term surface atmospheric and ocean data in an attempt to understand and quantify regional climatic variability in the Turkish Straits System as well as assess the effects of such variability on the Mediterranean-Black Sea coupling through the Turkish Straits System. We provide some salient results here, while the full details can be found in Tutsak *et al.* (2010) and Tutsak (2012).

2. Materials and Methods

2.1. Datasets

Measurements from 6 coastal stations located in the Turkish Strait System were obtained between January 2008 and December 2011. The coastal stations are in Gökçeada (Aegean Sea), Erdek, Marmara Ereğlisi and Yalova (Marmara Sea), Şile and İgneada (Black Sea). These stations were installed within the framework of the Turkish Meteorology and Oceanography Network of Excellence (MOMA) project in order to observe sea level and meteorological parameters, namely; atmospheric pressure, air temperature, air humidity, wind velocity and wind direction. In addition to these parameters, current profile data were collected at Baltalimanı (Bosphorus) between 2008 and 2011 using ADCP instrument deployed at 70m depth connected to the shore with a cable for data acquisition. The MOMA project has been described by Özsoy *et al.* (2009).

3. Results and Discussion

3.1. Sea level

The seasonal variations of monthly mean sea level at all stations, based on a common datum, are plotted in Figure 1. The seasonal maximum of sea level in the Mediterranean occurs in the period July-August, while the lowest sea level occurs in the period March-April, with a difference of 17 cm between the lowest and highest monthly value in the Mediterranean. A great amount of this variation is attributable to the seasonal steric affect that is the thermal expansion of sea water. On the other hand, this situation is not valid for the Turkish Straits System and especially in the Black Sea where the lowest monthly mean sea level values are found in autumn whereas the highest occurs in March-April. As for Marmara Sea, the highest monthly sea level is seen in June and the lowest means are observed in the autumn season.

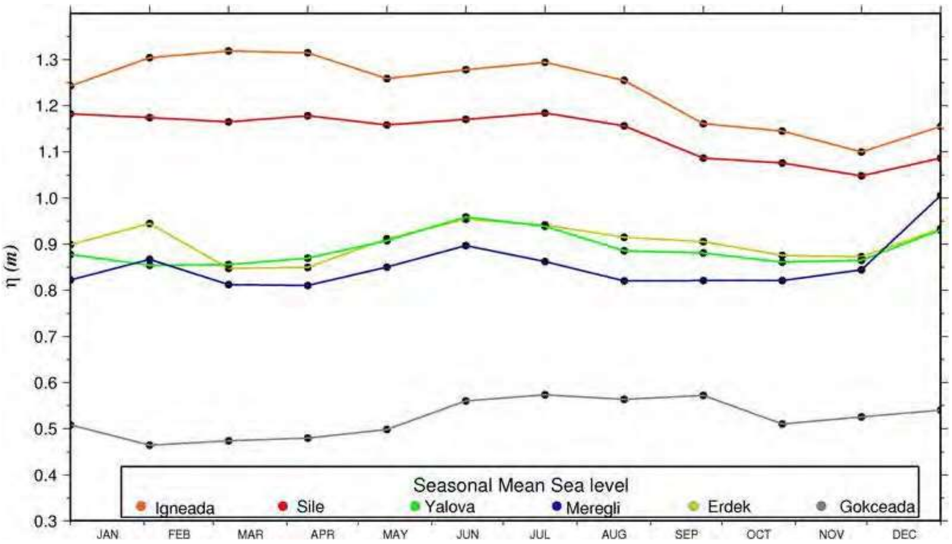

Figure 1. Monthly mean average sea level at TSS stations between 2008 and 2011.

With respect to inter-annual variability, the annual mean sea level in 2010 is higher than other years at all stations. In the Mediterranean Sea there is about 4.5 cm difference between 2010 and other years such that the annual mean of 2009 and 2011 is almost same in the Mediterranean. In the Marmara Sea, the mean of 2010 is greater, by 10.2 cm from 2009 and by 13.5 cm from 2011, respectively. Lastly, the mean of Black Sea in 2010 is 12.3 cm and 14.8 larger than 2009 and 2011, respectively. The year 2008 is not taken into account on annual scale due to the low data coverage during this year. On the other hand, the records indicate abnormal sea level rise in the year 2010, especially in the Black Sea.

The possible relationship of the increased sea level to the North Atlantic Oscillation (NAO) is examined in Figure2, indicating mostly negative NAO index during 2010, when the sea level is at its maximum. The NAO index measures pressure differences of air masses between Azore high and Iceland low. Positive winter NAO index often results in the arrival of cold and dry air masses to southern Europe and the Black Sea region by strong northwesterly winds whereas the negative winter NAO brings milder winters with warmer air temperatures and more wet atmospheric conditions transported over the Black Sea from the southwest (Hurrell *et al.* 2003). Stanev (2002) has shown the coincidence of maxima in river runoff with the negative extremes in the NAO index, based on several decades of observations. We infer that the possible reason for the increased sea level in 2010 could be related to increased runoff, since our records do not indicate abnormal changes in the mean atmospheric pressure and winds.

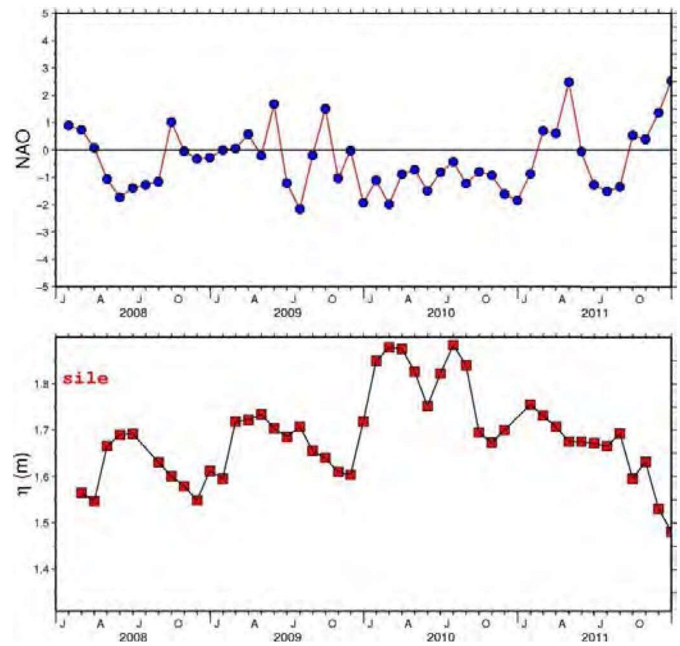

Figure 2. North Atlantic Oscillation monthly index (upper panel); Şile monthly sea level from 2008 to 2011 (lower panel).

3.1.2. Case studies of short term sea level variations

We display only few cases of temporal variations of significant events in this paper, one of which is displayed in Figure 3 for the Yalova Station in the Marmara Sea. Persistent northeast winds during 15-18 February 2008 (days 46-49) with wind velocity reaching about 17 m/s are observed to result in about 50 cm decrease in the sea level.

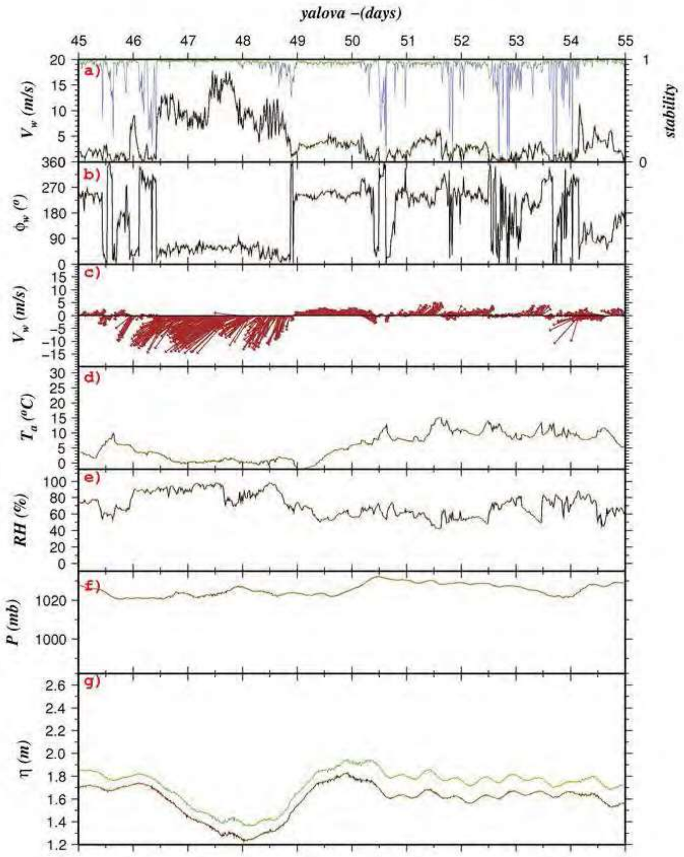

Figure 3. Time-series at Yalova station during 14-24 February 2008 (days 45-55) for (a) wind speed (upper part: wind vector stability), (b) wind direction (measured from east), (c) wind vector, (d) air temperature, (e) relative humidity,
(f) barometric pressure and (g) sea level (with and without barometric pressure adjustment).

At the same time in Figure 3, it is noted that the sustained winds causing a sea level drop during 15-18 February 2008 are not associated with a passing storm as no significant drop is detected in the barometric pressure signal. This is an event when unidirectional steady winds sustained from the northeast has resulted in the free surface piling up towards the west in the Marmara Sea and dropping at Yalova in the east.

In comparison to the above description of the effects of steady winds, the events during 20-30 November 2008 (days 325-355) at Yalova in the Marmara Sea (Figure 4) show some contrasts in behavior under combined effects of atmospheric pressure and winds created by passing storms. There is approximately 50 cm increase in the sea level at the Yalova station during 20-23 November 2008 (day 325-328), when a very intense storm center passed the region, during which the atmospheric pressure dropped very rapidly from 1015 mbar to 982 mbar and southwest winds with 8 m/s velocity prevailed.

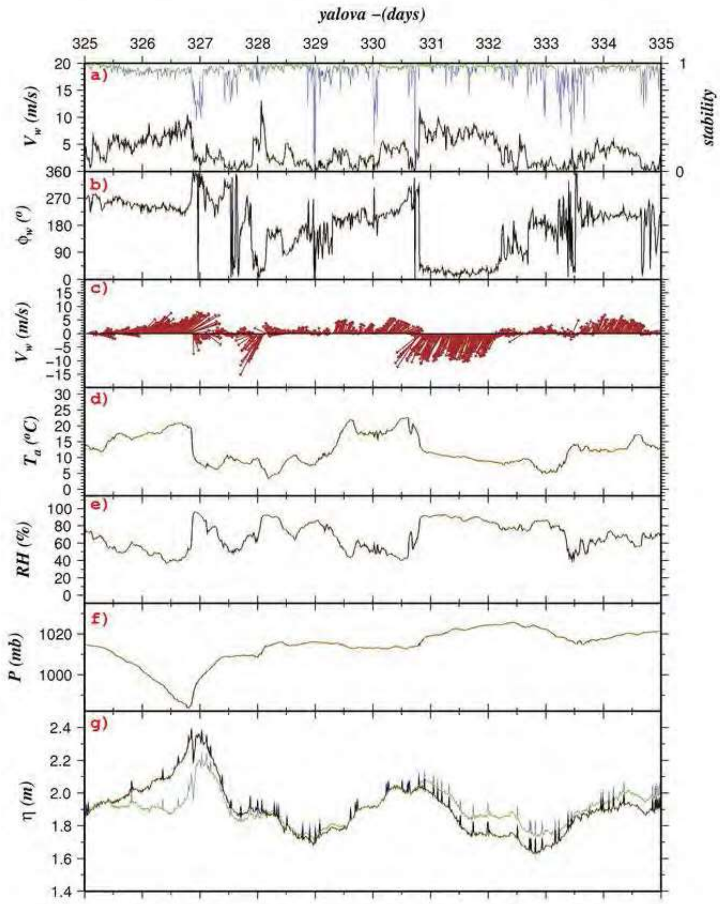

Figure 4. Time-series at Yalova station during 20-30 November 2008 (days 325-355) for (a) wind speed (upper part: wind vector stability), (b) wind direction (measured from east), (c) wind vector, (d) air temperature, (e) relative humidity, (f) barometric pressure and (g) sea level (with and without barometric pressure adjustment).

In this event of 20-23 November 2008 (day 325-327), the southwesterly wind forcing of the approaching storm and the strong pressure drop at the cyclone center are responsible for the notable increase in sea-level at Yalova. The event, characterized by an "explosive" cyclone, has been studied by Book *et al.* (2014) who conclude that the response of the TSS has been dominated by a variable pressure distribution across the straits and the Marmara Sea, which has forced not only a sharp sea-level response, but also an internal sloshing of the two-layer density stratified volume of the Marmara Sea, with large fluxes through the Straits. Many examples of wind and barometric pressure effects on sea-level are also observed for storms of lesser amplitude.

Cross-correlation between sea level with atmospheric pressure and wind components at Yalova station are given in Figure 5. There is negative correlation between sea level and barometric pressure for time lags of up to one day, and at no lag due to inverse barometer effect, which however should differ from what is usually assumed in the open ocean. The east-west wind component shows strong positive correlation with sea level, while correlation is not found with the north-south wind component. This suggests that the piling up of the water towards the east is effective during westerly winds at Yalova which is at the eastern end of the elongated Marmara Sea.

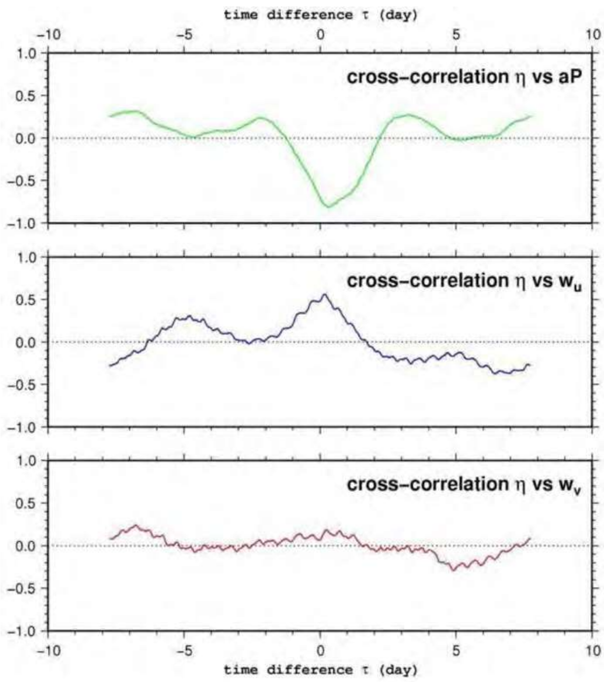

Figure 5. Cross-correlation between sea level and atmospheric pressure (upper panel); sea level and east-west wind component (middle panel); sea level and north-south wind component (lower panel) at Yalova station.

3.2. ADCP Data

The measurements of current profiles at Baltalimanı on the Boshorus has been carried out by a fixed ADCP installed at 70 m depth. Although a uniform section of the Bosphorus exists in this locality and the instrument has been placed close to the deepest point on the section, the channel is narrow in the deeper section and with the loss of data near the bottom by the ADCP methodology relying on Doppler shifts of acoustic signals in currents, there is usually a loss of few meters at the bottom, further increased by reverberation effects in the v-shaped narrow bottom channel geometry. Therefore, our current measurements in the lower layer may not be representative of the total lower layer currents and fluxes computed from them, due to these measurement problems. Instead we present results for the upper layer, which has been better sampled.

The time series for the upper layer current measurements obtained by the ADCP moored in the Bosphorus and the sea level difference across the Bosphorus, between the Black Sea station Şile and the Marmara Sea station Yalova during 2008-2011 are shown in Figure 6.

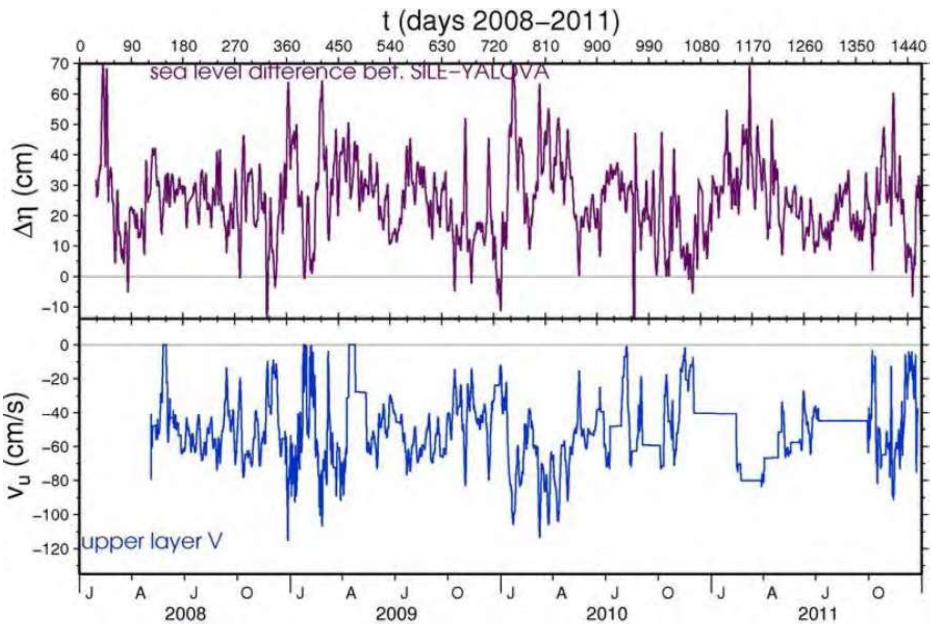

Figure 6. Time series of sea level difference Şile-Yalova (upper panel) and the depth average of the upper layer velocity component in the north-south direction at Baltalimanı in the Bosphorus (lower panel).

Despite some gaps in the current data due to non-operational states of the remotely controlled instrument caused by site problems such as electricity cuts and cable repair, the measurements have been continued over a total period of about four years. Comparison of the current data with the sea level difference indicates significant relations between them, with negative currents towards the Marmara Sea increasing at times of higher sea level difference and decreasing when the sea level difference decreases. When the sea level difference becomes very small, zero or negative, the upper layer is blocked, with velocity decreasing to small values or becoming zero.

Summary information on the monthly values of depth averaged upper layer velocity in the north-south direction (positive to the north) is given in Table 1. In March and April, the highest means of upper layer current are found, with a range 0.1 to 0.2 m/s greater than the other monthly means (Table 1). The maximum velocity in upper layer occurs during winter and early spring. The standard deviations of means indicate high temporal variability of the upper layer flow. The annual mean of the upper layer current for the years 2008, 2009 and 2010 are found respectively as -0.515 m/s, -0.507 m/s and -0.552 m/s. Although one is tempted to exclude the annual mean of 2011 due to low data coverage during this year, a mean value of 0.483 m/s is still calculated. The mean value of -0.552 m/s for the year 2010 was in fact distinctively high compared with the other years.

Table 1. Monthly average values of the depth averaged Bosphorus upper layer current velocity in the north-south direction (m/s). Positive value is to the north.

Month	Number of samples	Mean Current (m/s)	Standard Deviation (m/s)	Range (m/s)
January	16987	-0.46	0.30	-1.75 – 0.07
February	15738	-0.52	0.31	-1.75 – 0.07
March	12954	-0.68	0.23	-1.65 – 0.04
April	8938	-0.62	0.32	-1.5 – 0
May	9232	-0.47	0.27	-1.1 – 0.03
June	9598	-0.47	0.20	-1.17 – 0
July	7411	-0.56	0.17	-1.16 – 0.11
August	7504	-0.54	0.19	-1.13 – 0.05
September	5892	-0.51	0.18	-1.21 – 0.03
October	15364	-0.48	0.22	-1.23 – 0.1
November	15945	-0.49	0.24	-1.25 – 0.08
December	12886	-0.41	0.30	-1.65 – 0.11

3.2.1 Upper layer Volume flux

Quantifying the volume flux from vertical profiles obtained at a single location from the bottom-mounted ADCP in the Bosphorus is challenging since the measurements do not provide information on the horizontal distribution of currents. It is assumed that the upper layer velocity and the upper layer thickness is the same along the cross-section, and integrated over the vertically variable width of the channel, possibly resulting in underestimation or overestimation of the upper layer flux. The original 15 min time series and the 3-day low pass filtered version are shown in Figure 7, in the same way as the earlier Figure 6 is obtained.

The original time series calculated from 15 min sampled currents in Figure 7 actually shows great variability, the details of which cannot be fully displayed in this compressed figure. The extreme variability of the upper layer currents on short term is such that fluctuations in volume transport are often two or three times greater than the mean values. Both very high negative values (towards the Marmara Sea) outside the limits of display and zero or positive values (towards the Black Sea), the latter occurring during "Orkoz" events, are found in the original time series. By applying a low pass filter a lot of the variability is removed to show the essential features on scales longer than 3 days, but at the cost of simplifying the original variability showing many extreme but frequent conditions of both very high fluxes and the occurrences of short term upper layer blocking events.

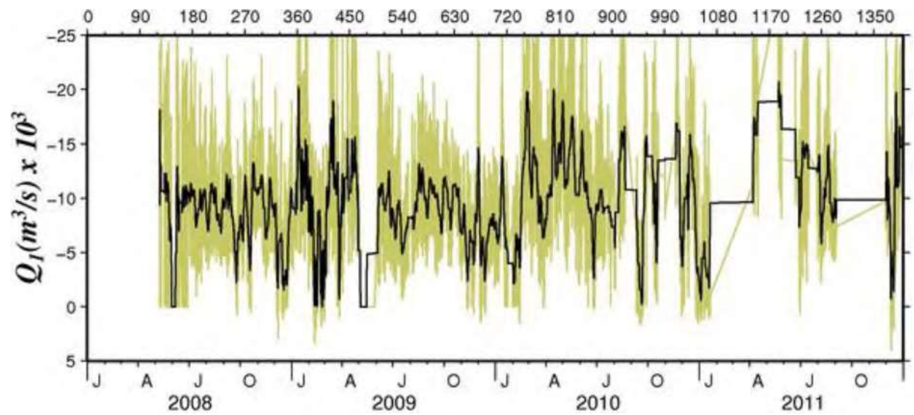

Figure 7. Time series of the upper layer volume flux during the study period (yellow=15 minutes data, black= 3-day low pass filtered data)

A summary of the calculated monthly mean upper layer fluxes is given in Table 2. Based on these results, the largest transport in the upper layer appears to occur in the spring and early summer, especially in March whereas the lowest transport in the upper layer takes place in the fall and winter. The annual mean of upper layer volume flux in the years 2008, 2009 and 2010, respectively are -9028 m^3/s, -8549 m^3/s and -10341 m^3/s. We note once again that the upper layer volume flux for 2010 is larger compared with other years.

Table 2. Monthly average values of the depth averaged Bosphorus upper layer volume flux in the north-south direction (m^3/s). Positive value is to the north.

Month	Number of samples	Mean Volume flux (m^3/s)	Standard Deviation (m^3/s)	Range (m^3/s)
January	16987	-7608	5208	-49407 – 3373
February	15738	-8894	5603	-46887 – 1884
March	12954	-11605	4478	-51175 – 1081
April	8938	-10931	6006	-41491 – 0
May	9232	-9306	5626	-28457 – 680
June	9598	-9525	4439	-28960 – 0
July	7411	-10413	3712	-28241 – 792
August	7504	-9577	3715	-24496 – 1689
September	5892	-8900	3258	-26492 – 849
October	15364	-9641	4979	-29761 – 4014
November	15945	-10234	5611	-32640 – 3076
December	12886	-7570	5527	-41441 – 2314

3.3. Bosphorus Upper Layer Current versus Sea Level Difference between Marmara and Black Seas

The sea level difference between the Black Sea and the Marmara Sea with ancillary data such as atmospheric pressure, atmospheric pressure and wind velocity are examined using data from coastal stations. The sea level difference between the Black Sea and The Marmara Sea based on the the measurements at Yalova and Şile coastal stations over the study period varied from -14 cm to 71 cm with a mean of 26 cm. The sea level difference between the Black Sea and the Marmara often responds to the winds over the region. The northerly winds increase the sea level north of Bosphorus, while the while southerly winds do the reverse by increasing sea level south of the Bosphorus. Since the wind setup is enhanced in shallower regions, increasing inversely with the water depth, it is not surprising to observe that the sea level change due to the wind setup in the South of the Bosphorus, in the shallower Marmara Sea is relatively greater than in the north of Bosphorus, in the Black Sea. The barometric pressure difference between the two seas at stations at the two ends of the Bosphorus varies at most by about 3 mbar, which is not enough to create the observed total changes in sea level differences. However, the barometric pressure averaged over the Black and the Mediterranean Seas area should be great enough to be one of the drivers of the exchange.

The present results for the sea level difference between the Marmara Sea and the Black Sea are different from previous observations reported by others. The average annual sea level difference between the ends of Bosphorus was estimated as 35 cm by Gunnerson and Özturgut (1974), as 33 cm by Çeçen *et al.* (1981). Büyükay (1989) found the annual average sea level difference to be 28 cm in 1985, 29 cm in 1896, and 13 cm in 1987. These observations suggest that the average mean sea level difference is typically about 30 cm. The average 26 cm obtained in this study is smaller than these estimates but coincide better with the Büyükay (1989) results.

Time series of Bosphorus averaged upper layer current and sea level differences (Figure 6) indicate that upper current of Bosphorus responds to the sea level differences. An increase of the sea level difference results in accelerating the upper layer current. A linear regression with the least squares approach between sea level difference and upper layer current results in the plot of Figure 8. Although a linear relationship seems to exist, large scatter in the data indicates a more complex dynamic response to be in action.

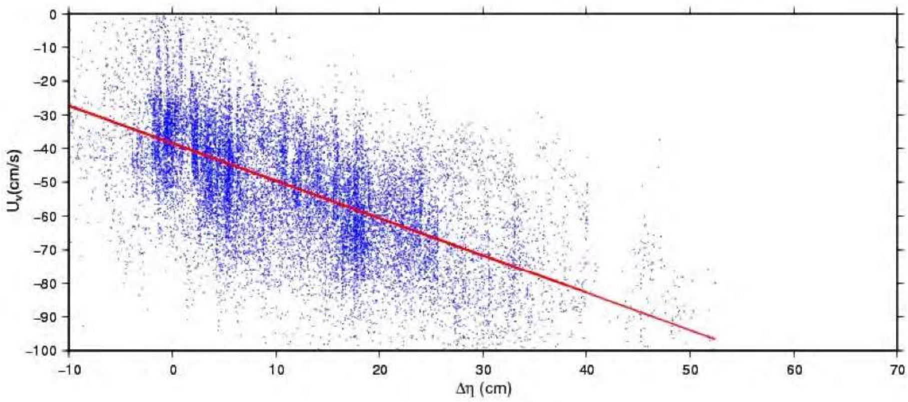

Figure 8. The north-south velocity component of the Bosphorus upper layer current versus sea level differences between Şile and Yalova stations.

Time series of the bottom-mounted ADCP currents at Baltalimanı, sea level, wind velocity and barometric pressure presented in Figures 9 and 10 for selected monthly periods illustrate typical response of the Bosphorus as a function of environmental conditions.

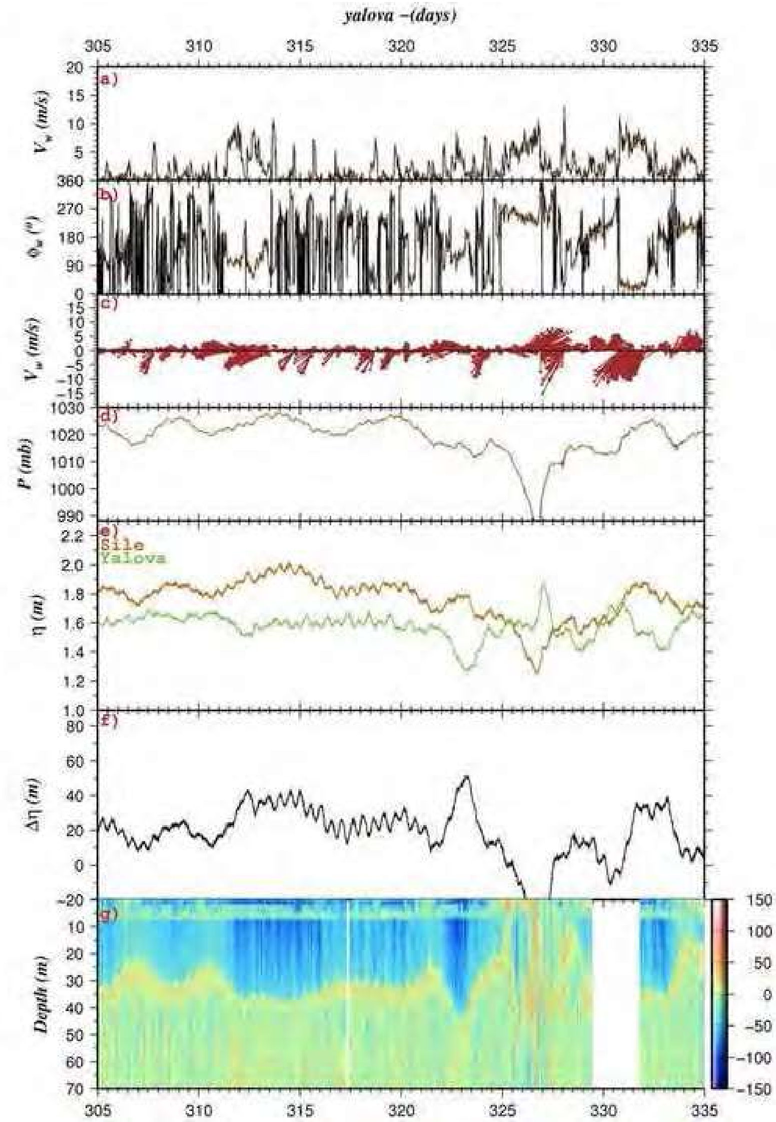

Figure 9. Time series of 01-30 November 2008 (days 305-335) for (a) wind speed, (b) wind direction (measured from east), (c) wind vector and (d) barometric pressure at the Yalova station, (e) inverse barometer corrected sea level at Şile (red) and Yalova (green) stations (f) their differences Şile-Yalova, (g) the magnitude and sense of ADCP currents in the north-south direction (north is positive) at Baltalimanı.

During the initial part of the record in Figure 9, rather steady currents of 0.5-1.0 m/s are observed in the upper 30m under calm weather conditions. The sudden drop of barometric pressure (30 mb in about 30 hr) of an atmospheric disturbance creates temporary reversals in flow direction and subsequent oscillations. The oscillatory and mixing effects created by this particular storm have been likened to a "meteorological bomb" (Book *et al.* 2010), based on an extensive set of measurements by Jarosz *et al.* (2011). Interestingly, the sea level rises in the Marmara Sea and falls in the Black Sea in response to the southwesterly winds of the storm, resulting in a negative sea-level difference of about 40 cm with the Marmara Sea being higher than the Black Sea, as opposed to the positive difference of about 10-50 cm earlier.

Our observations of ADCP currents in Figure 9 indicate complete flow reversal at the whole depth of the Bosphorus during 20-24 November 2008 (days 325-328), subject to oscillations. The fact that the whole Bosphorus flowing towards the Black Sea must have completely altered the outflow of dense water referred to as the "Medierranean Effluent" in the Black Sea exit region studied by Özsoy *et al.* (2001) and others. Book *et al.* (2014) point to the greatly increased outflow in the same occasion and Falina *et al.* (2016) find the anomalous intrusions of the resultant transport in the intermediate depths travelling to remote areas of the Black Sea.

According to the ADCP data records, upper layer blockage events lasting for one or two days are seen starting on 13 September, 5 October, 21 November, 5 December of 2008, 25 January, 5 February, 13 October, 12 November of 2009, 01 January, 07 January, 11 January, 17 May, 30 November of 2010 and 7 October, 4 December and 10 December of 2011. The effect of southerly winds on blockage events of Orkoz are clearly documented. Sometimes different local wind conditions are observed simultaneously at both ends of Bosphorus. In such case, the differences between wind setup at each end of Bosphorus govern the exchange flow. According to this study, the blockage events are observed when the sea level difference between two ends are almost equalized and the results demonstrate that the upper layer flow returns to the usual state as soon as blocking conditions vanish. The water column profile indicates that the depth average upper layer current speed can vary between 0.2 m/s and 0.5 m/s during Orkoz. In spring and summer the blockage events aren't observed. This is possibly caused by the weak southerly winds and the increase of the sea level in Black Sea idue to the river input during that period.

Sustained northerly winds in January 2010 (Figure 10), following an initial period of reversals in the first days, result in the sea level difference building up to about 1m, with currents of up to 2 m/s covering the entire depth, leading to blocking of the lower layer currents. This is a very strong case of lower layer blocking observed in the ADCP data and also confirmed by sea level observatins.

The lower layer blockage is also observed on 29 December of 2008, 22 February of 2009 and 22 January, 3 February, 8 March, 8 April, 27 April of 2010. In terms of duration of events, the lower layer blockages typically last longer than the upper layer blockages, but it can be noted that the lower layer blockages were observed to occur less frequently than upper layer blockages during this study. In addition, lower layer blockage events are often accompanied by a sea level difference greater than 60 cm.

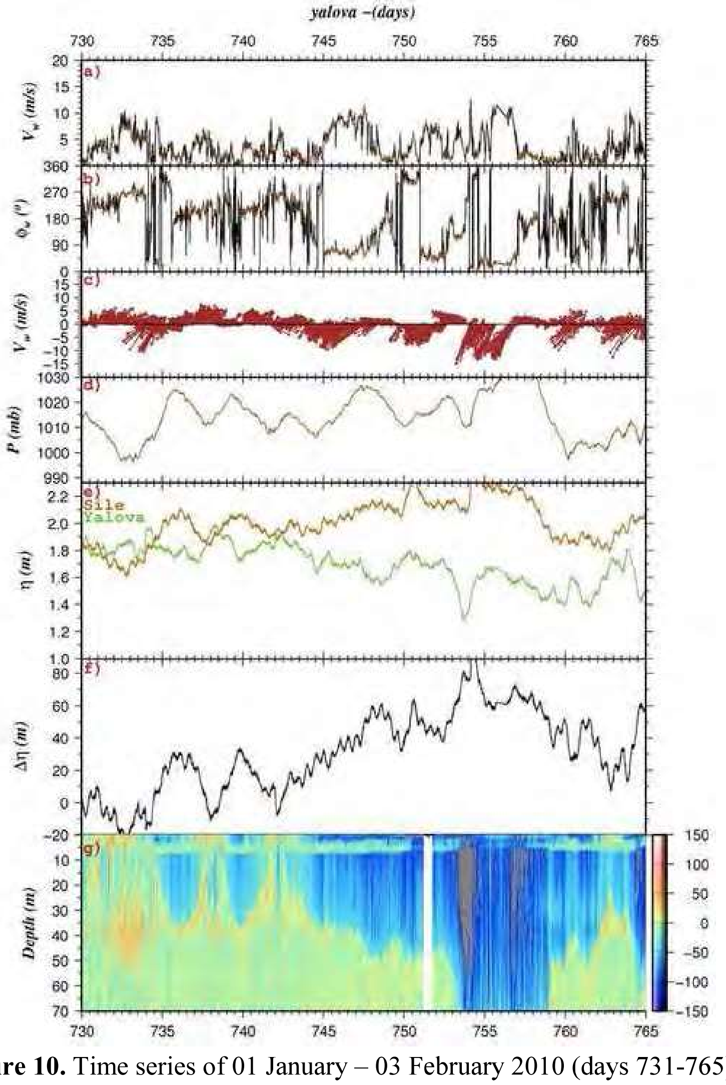

Figure 10. Time series of 01 January – 03 February 2010 (days 731-765) for (a) wind speed, (b) wind direction (measured from east), (c) wind vector and (d) barometric pressure at the Yalova station, (e) inverse barometer corrected sea level at Şile (red) and Yalova (green) stations (f) their differences Şile-Yalova, (g) the magnitude and sense of ADCP currents in the north-south direction (north is positive) at Baltalimanı.

4. Conclusions

Time series of meteorological and marine data analyzed in this study allow characterization of motion time scales. The sea level is highly variable in the Turkish Strait System. In addition to diurnal and semidiurnal oscillations in sea level, the analyses reveal oscillations varying from several days to weeks owing to winds and barometric pressure differences, although there is very limited penetration of tidal oscillations. The response to atmospheric pressure in either the Black Sea or the TSS cannot be characterized as an inverted barometer response at all. On the other hand, in the Marmara Sea, both atmospheric pressure and winds affect sea level. Annual mean sea level difference between the Black and Marmara Sea is found to be around 26 cm during the study period. However, during upper layer blockage events often the sea level difference vanishes, while the sea level differences of up to 1 m can occur during lower layer blockages. The blockage events are mainly associated with meteorological events such as wind and atmospheric pressure, as well as the net through-flow which is a function of the hydrological situation. The lower layer blockages usually occur in spring due to the increasing of sea level in Black Sea whereas the upper layer blockage events occur in winter due to the southwesterly winds.

Acknowledgments

The authors acknowledge that this study has been made possible by TÜBİTAK project 105G029, alias MOMA, which was one of the first projects assigned by the Public Research and Development Group (KAMAG) in the 2005-2008 period. One only wishes that this initiative could have been continued its development in a follow-up project. We thank the scientific and technical personnel and captains of the IMS-METU for the extensive efforts they have spent for the field work and at the laboratories. The professional expertise and efforts of the director Amil Turgay and the technical divers of the Derin Dalgıçlık Ltd. company in the installation and replacement of the cabled ADCP system at a deep location in the Bosphorus enabled successful completion of marine operations, while Ejder Varol and Selçuk Karamağara of İdealteknoloji Ltd. company participated in instrument deployment and operation. We also thank the various government organizations that were either part of the project or contributed to it, among them the Ministry of Environment, Undersecretariat of Marine Affairs, Office for Navigation, Hydrography and Oceanography and the General Command of Mapping and their technical personnel who took part in this project.

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