A REVIEW OF WATER FLUXES ACROSS THE TURKISH STRAITS SYSTEM

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1. Inroduction

The exchange flow at the Bosphorus is determined by the water budget of the Black Sea. The conservation of mass for the Black Sea requires that the net water flux through the Strait is balanced by the rate of mean sea level change and the other water imports / exports. It is therefore important to establish the annual and seasonal average water flux to and from the Black Sea through the Bosphorus. A critical review of the available data and estimates of the fluxes have been given by Ünlüata *et al.* (1990). In the present report, we review the existing sources of information for an updated understanding of the exchange.

Long term measurements of volume fluxes are essential for the calculation of the seasonal export rates of nutrients and organic carbon in the straits. The nutrient fluxes coming from the Black Sea by upper layer flow in winter is about at least 2-3 times greater than in the autumn due to changes in both nutrient concentrations and volume fluxes (Polat and Tuğrul 1995; Tuğrul *et al.* 2002).

In reality the inter-basin exchange through the TSS is sensitive to conditions in the adjacent basins (changes in the net water flux entering the Black Sea, as well as sea-water density, atmospheric forcing and sea-level difference), and on the average, has to balance the net annual water budget of the coupled system. Because the ratio of runoff to basin volume is much larger for the Black Sea compared to the Mediterranean, TSS water exchange is more sensitive to changes in Black Sea river runoff. With a catchment area five times as large as the sea surface area, the Black Sea amplifies global climate signals (Stanev and Peneva 2002).

Measurements to date seem to indicate that the mean values of fluxes through the TSS are difficult to establish with certainty. This is because the mean values are actually masked by the great variability observed in currents on daily to inter-annual time scales, the typical experiment duration possibly being too short to establish statistics.

2. Flux Estimates Based on Mass Balance

By making use of the average salinity measured at the Straits and the water fluxes of the Black and Marmara Seas, the annual average fluxes are computed from the Knudsen relations expressing a steady state mass balance of the TSS. Climatological estimates of the TSS have been given in Ünlüata *et al.* (1990), Beşiktepe *et al.* (1993, 1994), Tuğrul *et al.* (2002), as reviewed in Schroeder *et al.* (2012) and Jordà *et al.* (2016), Mavropoulou *et al.* (2016) and others. These computations show greater fluxes at the Dardanelles relative to the Bosphorus, and large entrainment fluxes across the halocline throughout the TSS (Figure 1).

The annual average upper and lower layer fluxes of the Bosphorus respectively were estimated as 650 and 325 km3/y (20500 and 10300 m3/s) in the above references, in agreement with the long-term salt budget of the Black Sea requiring an approximate ratio of ~2 between the output and input mass fluxes (Özsoy and Ünlüata 1997). The mean net flux of water exiting the Black Sea is therefore estimated to be about 325 km3/y (10300 m3/s).

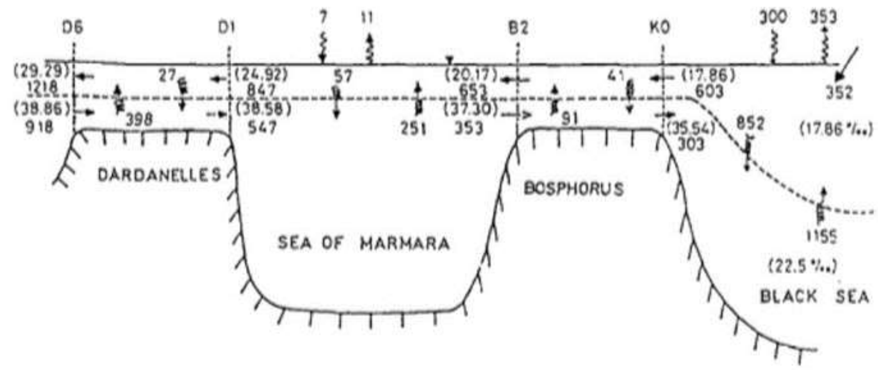


Figure 1. Volume fluxes of the Turkish Straits System in units of km3/y (1km3/ y = 31.7m3/s), after Beşiktepe *et al.* (1994). Numbers in parentheses are average salinity values used in the computations.

There are also large transports of water between the layers by turbulent entrainment processes. In the Bosphorus, about 25% of the Mediterranean water influx is entrained into the upper layer, and about 7% of the Black Sea water is entrained into the lower layer flow. The computations show that 45% of the Aegean inflow is entrained into the upper layer in the Dardanelles; a further 45% of the amount reaching the Marmara Sea is lost to the upper layer by basin-wide entrainment.

The exchange flows of the TSS, observed at the Bosphorus, are found to increase in the spring and early summer, and weaken markedly in the autumn (within a margin of about Sea40% of the annual mean) in r

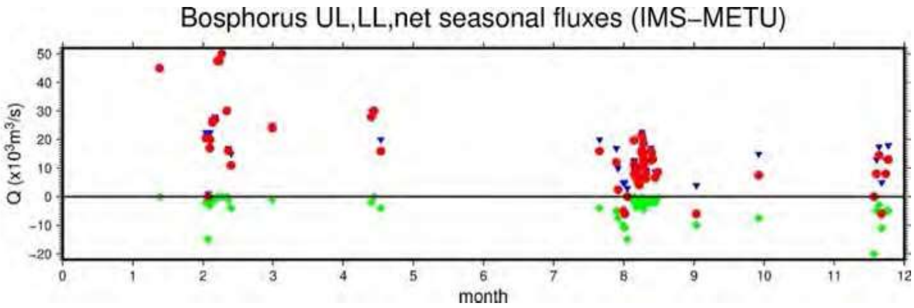
(Tuğrul *et al.* 2002). Indirect estimates (Stanev and Peneva 2002) indicate seasonal anomalies which are hard to validate and compare with estimates by Tuğrul *et al.* (2002) obtained from realistic seasonal mass budgets on the one hand and fluxes inferred from indirect methods on the other.

3. ADCP Flux Measurements

Direct measurements of fluxes are performed by taking transects across the strait with the research vessel recording the current measurements in real-time obtained by a vessel-mounted ADCP. There are losses of data in the shallow zones adjacent to the coast, and for about 15% of the total depth near the surface and the bottom. The current profile data are extended by a constant value upwards to the surface and a linear extrapolation to zero velocity at the bottom from the nearest reliable data in the profile in each case. The methodology has been used first by (Özsoy *et al.* 1996, 1998) and later by Altıok and Kayışoğlu (2015) to compute fluxes at the Bosphorus Strait.

The first set of fluxes computed from ship mounted ADCP measurements in the Bosphorus (Özsoy *et al.* (1996, 1998) shown in Figure2a revealed measured maxima of about Q1 = 1600 km3/y (50000 m3/s) and Q2 = 630 km3/y (20000 m3/s) for the upper and lower layers respectively, including blocked cases, indicating instantaneous fluxes 2-3 times larger than the annual mean. Despite large scatter in data due to sampling, average values of Q1 = 540 km3/y (17000 m3/s) and Q2 = 115 km3/y (3500 m3/s) were computed, the latter value possibly being underestimated as a result of data loss near the bottom. Maderich and Konstantinov (2002) have compared these data with their simple model. Accordingly, blocking of either the upper or lower layer flows were indicated for net flux exceeding Q = -580 km3/y (18500 m3/s) or Q = 800 km3/y (25000 m3/s) in the respective directions.

These measurements have shown the same seasonal trends as the mass budget calculations, although the measurements were clustered at certain times of the year not sufficiently sampling the seasonal cycle. Yet it is clearly seen in Figure 2b that the winter and spring fluxes are larger than during the summer and autumn. A number of upper and lower layer blocking cases are evident in Figures 2a and 2b, where the corresponding fluxes vanish, not only in winter and spring months but also in summer.



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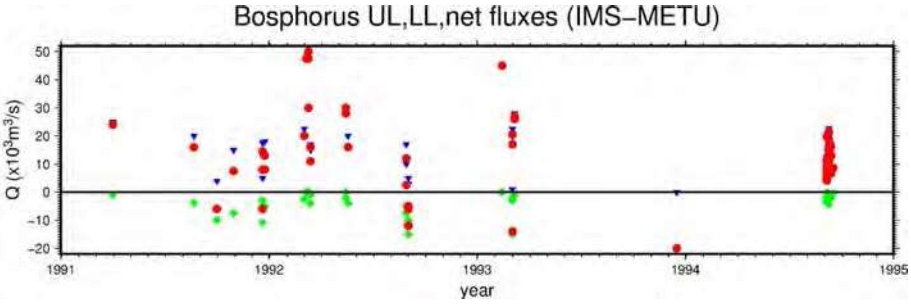

(b)

Figure 2. Fluxes computed from ADCP measurements in the Bosphorus during 1991-1994 by the IMS-METU, (a) time variations during the same period and (b) seasonal variations. Averages for the upper-layer (blue inverted triangles), lower-layer (green diamonds) and net (red dots) fluxes have been computed such that positive fluxes are associated with the upper layer.

A 10-year monthly measurements campaign has been carried out by Altıok and Kayışoğlu (2015) to monitor the Bosphorus fluxes at the two ends of the Strait using vessel-mounted ADCP measurements obtained on sections across the Strait. The time series of the monthly upper layer volume flux measurements at stations B3 at the southern end and station K0 at the northern end of the strait exhibited a wide range of variability (Figure 3a). The larger variability occurs in the upper layer fluxes, while the lower layer is less variable.

During the 1999-2010 campaign, the maximum values of measured upper-layer volume fluxes were 38560 m3 s-1 at the southern section of the strait and 33313 m3 s-1 at the northern section of the strait. Often the very small values of fluxes (<10 km3 y-1 or 330 m3 s-1 which is negligible) are considered as blocking cases for the upper layer. In the southern section of the strait, the upper layer flow blockage was observed more frequently than the upper reaches. In addition to the October 2003 upper layer blocking case investigated earlier by Altıok *et al.* (2014), other cases of blockage occurred also in October 2002 and March 2006. In October 2002 and 2003, the upper and lower layers and a thick interfacial layer was observed to flow north altogether. In these events the limited increase of salinity in the northern part of the strait suggested transient blocking that did not reach the north. In March 2006, the upper layer blockage was observed to reach the northern exit of the strait as well, and the corresponding volume flux was the overall minimum for this section.

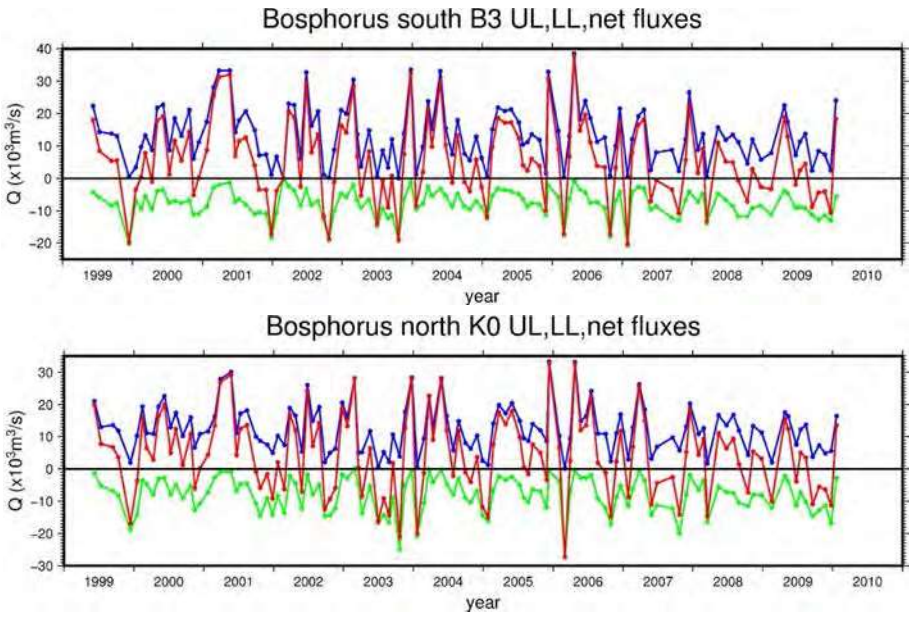

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Figure 3. Fluxes computed from monthly ADCP measurements at stations B3 and K0 respectively at the southern and northern ends of the Bosphorus during 1999-2010 by the IMSM-IU. Time-series at (a) station B3 and (b) station K0. The upper-layer (blue), lower-layer (green) and net (red) fluxes have been computed such that positive fluxes are associated with the upper layer flowing south.

The maxima of the monthly lower layer volume fluxes at both ends of the strait were 27460 m3s-1 (866 km3y-1) and 20750 m3s-1 (654 km3y-1), respectively. The low values (<1000 m3s-1) of the lower layer volume fluxes indicate lower layer blockage or near blockage, while the higher volume fluxes (>13,000 m3s-1) of the lower layer typically indicate the upper layer blockage. In fact, the maximum values of the volume fluxes at the two ends of the strait were observed in March 2006 when the upper layer volume fluxes were very low at the two ends of the strait. During the upper layer blockage, the volume fluxes of the lower layer were greater than 13,000 m3s-1 (~400 km3y-1) and/or the lower layer salinity values were less than 34 in January 2000, December 2001 and January 2002, as well as February 2002, April 2003 and March 2006.

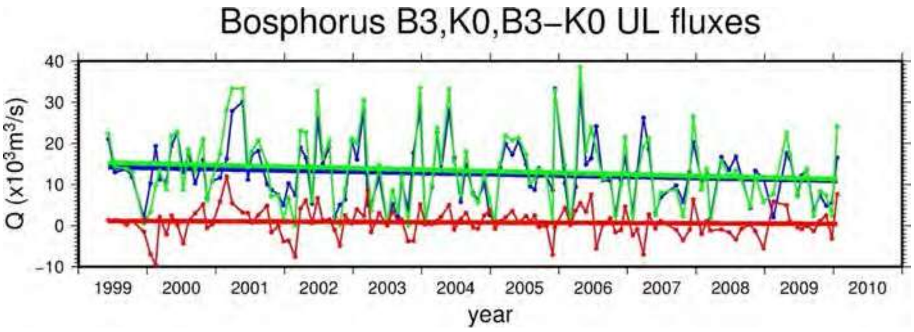
The details of a lower layer blockage at the northern exit of the strait in February 2003 has been described by Altıok *et al.* (2014). Cases of diminished volume flux (<1000 m3s-1 30 km3y-1) occurred in the March-May periods of 2001, 2002, 2004, 2006, 2007, as well as in December 2003 and 2005. In all of these dates, the lower layer temperature and salinity values reflected the Mediterranean water, that is, they showed salinity values greater than 35 and temperature values ranging between 13.5-15 °C.

The average volume fluxes computed from the long-term campaign of monthly measurements by Altıok and Kayışoğlu (2015) established a relatively better basis for statistical evaluations, despite the extreme variability observed in the Strait. The means and trends of volume fluxes calculated for stations B3, K0 and also the difference B3-K0 are given in Table 1, and the time series for the layer and net fluxes with calculated trends are given in Figure 4. The results of the measurements produced mean upper, lower layer and net fluxes of 12540, 8100, 4440 m3/s at the northern exit (K0) of the Bosphorus Strait and 13310, 7900, 5420 m3/s respectively at the southern exit (B3) of the Strait. The increase of the upper layer flux from the upper layer flux from north to south and the increase of the lower layer flux from south to north are as expected, the result of entrainment fluxes for which mass flux estimates were given in the above sections and in Figure 1. In fact, based on estimates provided in Figure 1, one should expect larger differences, which may be obliterated by the approximations used in the computations and the essential data losses. On the other hand, the net flux should be absolutely conserved between the two ends of the Strait, in an average sense. This expected behavior however is only approximately fulfilled by the observations since upper, lower layer and net flux differences in B3-K0 are respectively found to be 770, 210 and 980 m3/s, as a result of instrumental and methodological inaccuracies that are involved in the measurements.

Table 1. Means and trends of volume fluxes of Bosphorus Strait (positive values of the means imply southward flow)

Section	Upper layer		Lower layer		Net (total)	
	Mean (m^3/s)	Trend ($m^3/s/y$)	Mean (m^3/s)	Trend ($m^3/s/y$)	Mean (m^3/s)	Trend ($m^3/s/y$)
B3	13314	-373	-7896	-110	5417	-484
K0	12543	-306	-8101	-191	4442	-497
B3-K0	771	-67	205	80	976	13

The trends of the monthly volume fluxes are also given in Table 1. Accordingly, both the upper layer volume flux showed negative linear trends. The upper layer trend average of the two stations is about ~350 m3s-1y-1 (10 km3y-2), while the lower layer average is ~150 m3s-1y-1 (5 km3y-2). Over the 10-year period of the measurements, it appears that the upper layer volume flux decreased by about ~100 km3/y and the lower layer volume flux increased by about ~50 km3/y. These significant changes could be related to the climatic changes in precipitation, river runoff and evaporation of the Black Sea.



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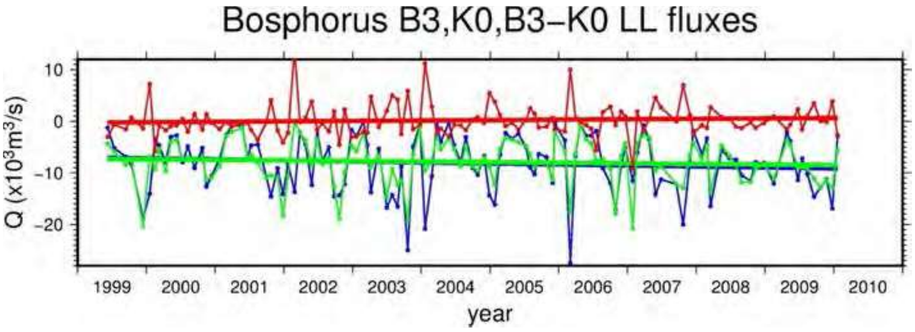

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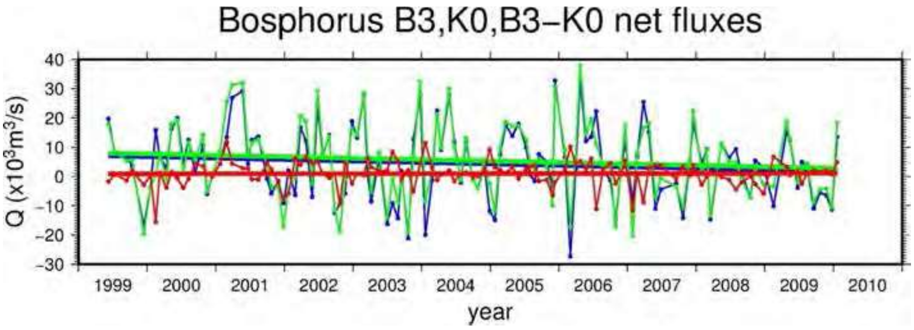

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Figure 4. Upper, lower layer and net fluxes and their differences computed from monthly ADCP measurements at stations B3 and K0 respectively at the southern and northern ends of the Bosphorus during 1999-2010 by the IMSM-IU. Time-series at (a) station B3 and (b) station K0, and (c) the difference B3-K0. The upper-layer (blue), lower-layer (green) and net (red) fluxes have been computed such that positive fluxes are associated with the upper layer flowing south.

The seasonal variations of the fluxes measured through the 10-year program of the IMSM-IU at the northern (K0) and southern (B3) sections of the Bosphorus are shown in Figure 5. There are significant seasonal variations in both layer fluxes, influencing the seasonal variations of the net flux. Although the seasonal signal is very clear in these measurements, the extremely dynamic behavior of the Bosphorus Strait influenced by its internal hydraulics as well as the remote atmospheric and oceanic events in the

Mediterranean and Black Seas are hidden in the seasonal plots. The upper layer volume flux is typically very high in the late spring and early summer months (May, June and July). In addition to the spring and early summer increases in fluxes related to the increased river discharges in the Black Sea, the other time when extreme fluxes are observed is the winter months starting with December. In general, the higher upper layer flux values are observed during the lower layer blockage events of the spring and winter months (December and February-May). The lower layer appears relatively more steady and less influenced by the seasonal variations.

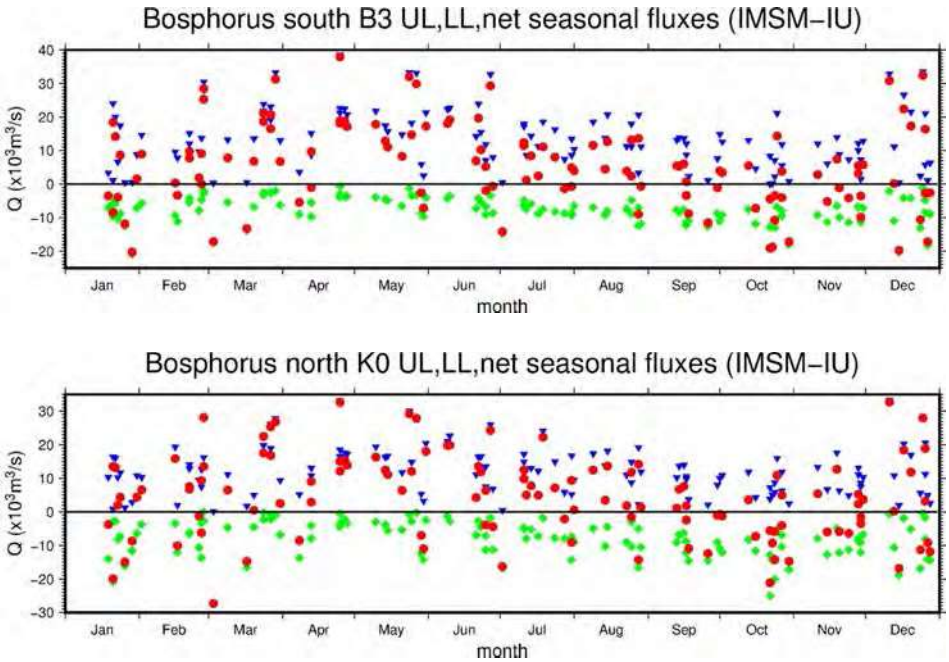


Figure 5. Seasonal variations of the upper (blue, inverted triangles), lower (green, diamonds) layer and net (red, circles) volume fluxes at sections B3 and K0 respectively at the southern and northern exits of the Bosphorus Strait.

The summary of all past flux estimates, based on historical as well as mass balance calculations and those obtained from vessel-mounted ADCP measurements presented in the above sections are parametrically replotted in Figure 6, with the net flux in the abscissa and the upper and lower layer fluxes in the ordinates. The net flux, a measure of currents integrated across the whole section, is actually the main forcing of the strait, while the layer fluxes represent the response. There appear clear relationships between primary flux variables confirmed by different sets of measurements, although a lot of scatter in the data is also present as a result of the deficiencies in measurement instruments and flux estimation methodologies. It is also evident from Figure 6 that either the upper or the lower layer currents are blocked beyond certain limiting values of the net flux.

Approximate limits for the net current to block the upper and lower layers respectively are -20000 m3/s (630 km3/y) and 30000 km3/s (950 km3/y) according to the results from all measurements reported above. These limits are consistent with modelling results of Sözer and Özsoy (2016) and Sannino *et al.* (2016) evaluated in the latter, though not presented here.

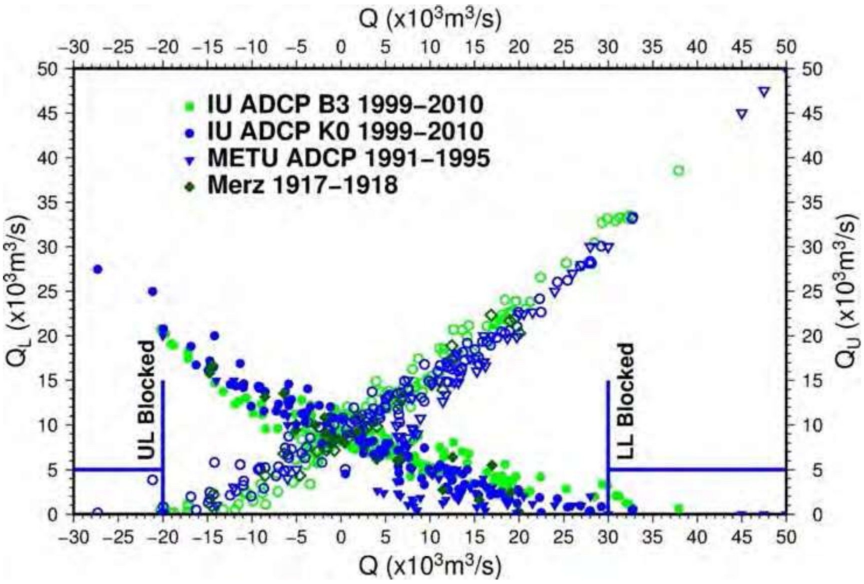


Figure 6. Upper and lower layer fluxes as a function of the net flux in the Bosphorus Strait. The sign convention in this figure sets both the upper layer and the lower layer fluxes to have positive values in their respective general flow directions.

4. Continuous Flux Measurements

More recent volume flux estimates based on continuous current measurements at the Bosphorus and Dardanelles Straits are documented in a series of papers presented by Jarosz *et al.* (2011a,b, 2012, 2013) and Book *et al.* (2014).

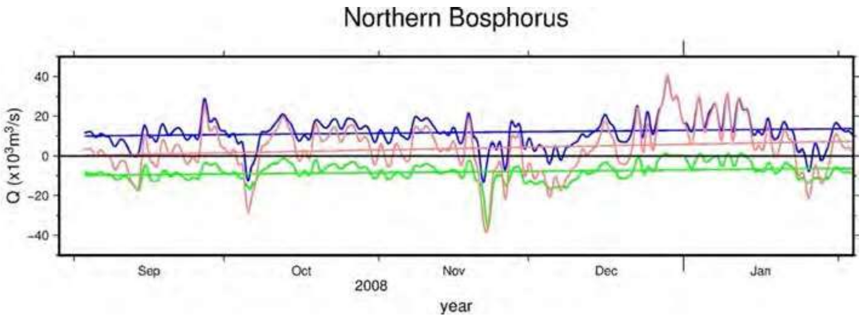
The monitoring of the currents have been based on pairs of moorings containing acoustic Doppler current profilers (ADCPs) deployed at each end of the Bosphorus Strait as a part of the United States Naval Research Laboratory's "Exchange Processes in Ocean Straits (EPOS)" project, and the deployments facilitated by the joint program TSS-08 of the NATO Undersea Research Center(NURC) and the Turkish Navy Navigation, Hydrography and Oceanography Office (NHO). The continuous measurements by moored instruments at the two ends of the Bosphorus covered about six months, while the same at the Dardanelles covered more than a year during the 2008-2009 period. We evaluate these data with respect to layer and mean fluxes which have been shared by the experimental group, although the full data set has not been shared to date.

Time series of the measured volume fluxes are shown in Figure 7, with trends represented by the straight lines. While a great amount of variability is observed in both straits, the Dardanelles time series shows much greater variability over a longer period of measurement. A greater winter-time variability is also evident in the Dardanelles time-series. Comparing the two ends of each strait, the differences are larger in the Dardanelles as compared to the Bosphorus.

The Bosphorus Strait also displays more regular motions as compared to the Dardanelles. The upper layer of the Bosphorus responds to various forcing factors both local and remote, to vary around a mean positive (southward) flux only interrupted during typical 'Orkoz' or upper layer blocking events, which often end up with the currents being totally reversed to flow north. On the other hand, the lower layer is more steady and when lower-layer blocking events occur the flow is completely stopped in the lower layer. The relatively steady pattern in the Bosphorus in fact suggests strong hydraulic control at the northern sill especially stabilizing the lower layer. During some strong upper layer blocking events, the lower layer currents towards the Black Sea are considerably increased to differ strongly from the otherwise steady pattern. One of these strong events occurred in late November 2008 when an 'explosive storm' passed over the region with a large drop in barometric pressure and strong southerly winds on November 21, as documented by Book *et al.* (2014).

Comparing with the Bosphorus, both layers of the Dardanelles Strait are more variable. However, one is forced to observe some basic differences in behavior. For instance, the upper layer blocking occurs several times in the winter period, but the currents do not reverse direction as much, staying positive most of the time. On the contrary, the lower layer of the Dardanelles Strait fluctuates much dissimilar to the steady behavior of the Bosphorus lower layer. In the southern Dardanelles, the lower layer appears to be intermittently blocked for long periods in winter, while the lower layer flux at the northern (Marmara) side fluctuates in negative and positive directions, continuing to flow towards the Aegean Sea during blocking events detected in the Aegean side, showing the inertia of the flow possibly compensated by the large upward entrainment.

Furthermore, comparing the Dardanelles and Bosphorus records on the same time period, a great degree of similarity exists in the time series, especially for the stronger events related to the dynamic response pattern of the entire TSS.



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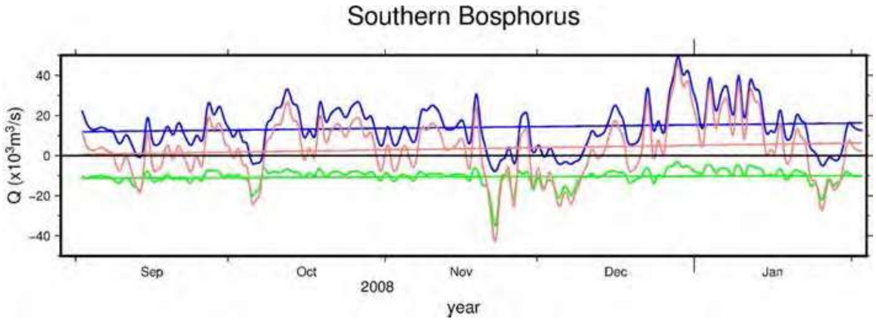

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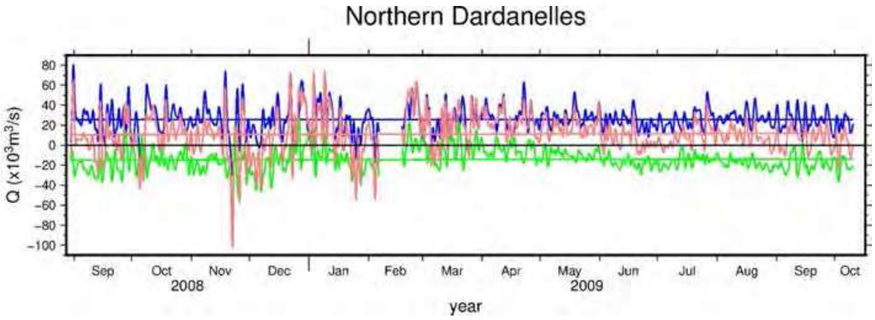

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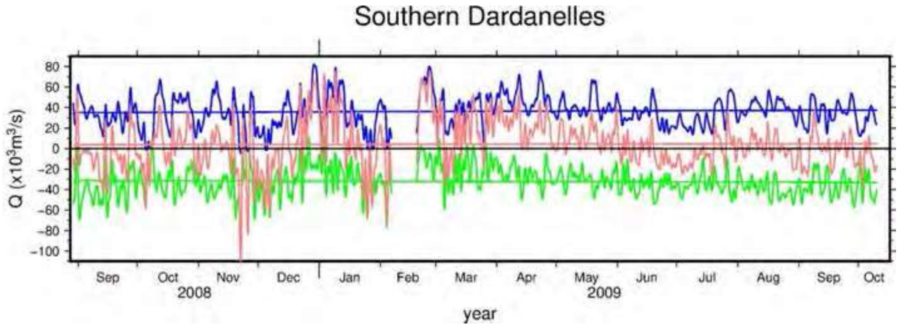

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Figure 7. Upper (blue), lower (green) layer and net (red) flux time-series at the (a) northern (and (b) southern ends of the Bosphorus Strait, (c) northern and (d) southern ends of the Dardanelles Strait, based on measurements of the NURC TSS-08 campaign. Fluxes are positive in the southward direction. Straight lines indicate trends.

The mean upper, lower layer and net (total) volume fluxes at the two ends of the straits obtained from the continuous measurement campaign and their differences between these two ends of each strait are given in Table 2. Mean values of the upper, lower layers and the total flux respectively were found to be 11900, 8000, 3900 m3/s in the northern Bosphorus, and 14100, 10600, 3500 m3/s in the southern Bosphorus (Jarosz *et al.* 2011b). Based on similar but year-long data, the upper, lower layer and total (net) fluxes were 25600, 14500, 11100 m3/s in the eastern (Marmara) section and 36300, 31100, 4200 m3/s in the western (Aegean) section of the Dardanelles Strait (Jarosz *et al.* 2013). The reason for the relatively low net fluxes compared to other measurements is a result of the measurement period covering mainly the late summer season when river inputs to the Black Sea are usually at a minimum level. The mean flux increases towards the winter, as demonstrated by the analyzed trend in Figure 7a.

Table 2. Mean Layer and Net fluxes at the Bosphorus and Dardanelles Straits and Flux Differences between two ends of each strait (positive sign implies southward flow)

Layer	**Bosphorus**		**Difference**	**Dardanelles**		**Difference**
	South (m^3/s)	North ($m^3/s/$)	South-North (m^3/s)	South (m^3/s)	North ($m^3/s/$)	South-North (m^3/s)
Upper	14071	11875	2217	36329	25560	10844
Lower	-10564	-8018	-2559	-32129	-14473	-17673
Net	3508	3857	-342	4200	11087	-6829

These measurements have confirmed the great variability in fluxes, but more importantly showed noticeable differences of the net fluxes between the two ends of the Straits. For instance, the net flux respectively at the southern and northern ends of the Bosphorus are 3500 and 3900 m3/s with south-north difference of -342 m3/s, while the same for the Dardanelles are 4200 and 11200 m3/s with a difference of -6829 m3/s. The difference of net fluxes for the Bosphorus may be acceptable in view of the accuracy of the measurement and computation, though the net flux difference for the Dardanelles is quite larger, on the same order as the mean fluxes, pointing to the inefficiency of the experiment design to measure fluxes in the much wider sections of the strait. With differences of net flux between sections obtained to be on the order of or even larger than the mean value of the net fluxes, it is very difficult to explain the disparity by sources/sinks of water between sections, as they are scarce in the region.

On the other hand, the sense of the change in upper and lower layer volume fluxes between the two ends of the straits seems to be consistent with the estimates given in Figure1. The difference of the upper layer fluxes is positive in a southward direction and for the lower layer it is negative in the southward direction, which implies upward entrainment fluxes. The upward entrainment is reasonable for the Bosphorus, being about the same in both the upper and lower layers, with an average 2300 m3/s, accounting for about 18-24 % of the entering fluxes at the two ends. On the other hand, the upper and lower layer upward entrainment estimates for the Dardanelles Strait differ much between 10800 m3/s and 17700 m3/s with an unreasonable difference of 6800 m3/s between them. This would indicate the ratio of the upward entrainment to entering fluxes to be about 42-55 %.

The measurements essentially confirm in orders of magnitude the results of the earlier measurements and provide essential and detailed characterization of the multiple scales of motion in the TSS. However, this independent evaluation of the Jarosz data set clearly shows that net fluxes computed at four different locations, i.e. the two ends of the two straits, especially for the wider Dardanelles Strait fail to give comparable results between themselves, e.g. the average net flux magnitudes of the time series are very different between different sections, although the average net fluxes should in fact be strictly identical between different sections, in view of the continuity equation of fluid dynamics, unless a significant volume of water is added by external sources such as precipitation minus evaporation.

Time series of the differences in upper, lower layer and net fluxes computed between pairs of sections respectively are shown in Figure 8-10, where the upper panels (Figure 8-10a) represent differences between south and north sides of the Dardanelles, the middle one (Figure 8-10b) corresponds to the same for the Bosphorus, and the lower one (Figure 8-10c) to the difference between the Marmara sides of the Dardanelles and Bosphorus Straits. Time series filtered with a time window of 150 hr (~17d) are also shown. The mean values of time series are indicated by the horizontal lines.

It is clearly shown that large differences exist between the two ends of the Dardanelles and Marmara segments, while these differences are smaller for the Bosphorus sections.

The upper layer fluxes compared in Figure 8 indicate differences in all four sections which explicable both because of the entrainment fluxes between layers and the surface fluxes by atmospheric or land-based sources. The larger differences are between the two ends of the Dardanelles and the Marmara Sea segments, and smaller for the Bosphorus which is shorter. On the other hand, it is significant that the lower layer fluxes compared in Figure 9 indicate comparable magnitudes between the two ends of the Bosphorus and Marmara segments, the mean lower layer fluxes between the two ends of the Dardanelles are larger, the difference being on the same order as the mean inferred from all sections. The means of the Marmara and Bosphorus lower layers are consistent because there could not be too great effects of downward entrainment as the upper layer is faster, and there could not be any external water sources as well. Therefore the Dardanelles measurements are possibly less internally consistent.

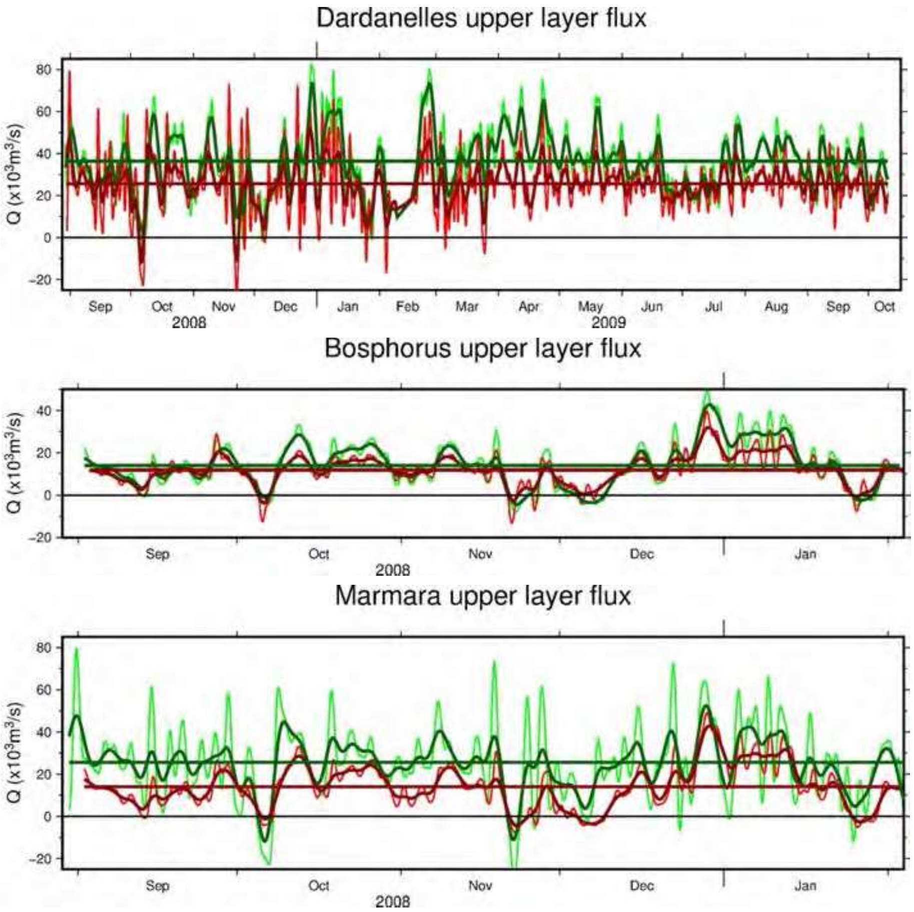

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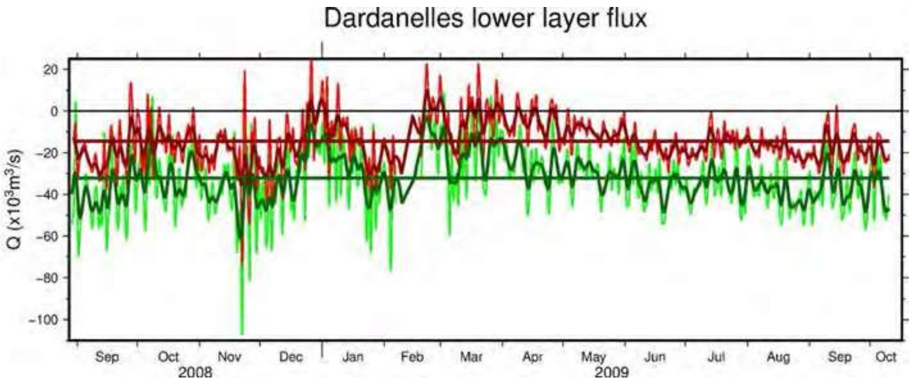
Figure 8. Time series and means of the upper layer fluxes for segments of the TSS compared at pairs of southern (green) and northern (red) sections, based on measurements of the NURC TSS-08 campaign. The superposed darker lines of the same colour show time series filtered with a time window of 150 hr. Fluxes are positive in the southward direction. Straight lines indicate mean values of the original time series.



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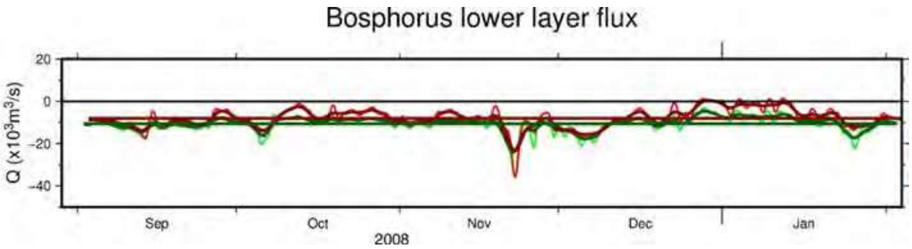

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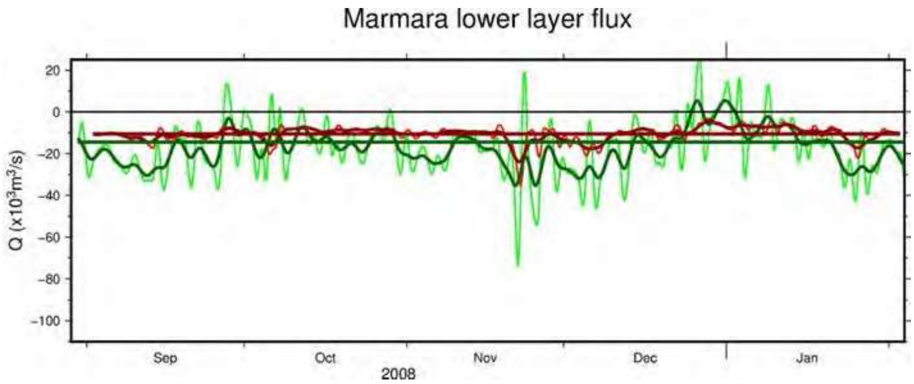
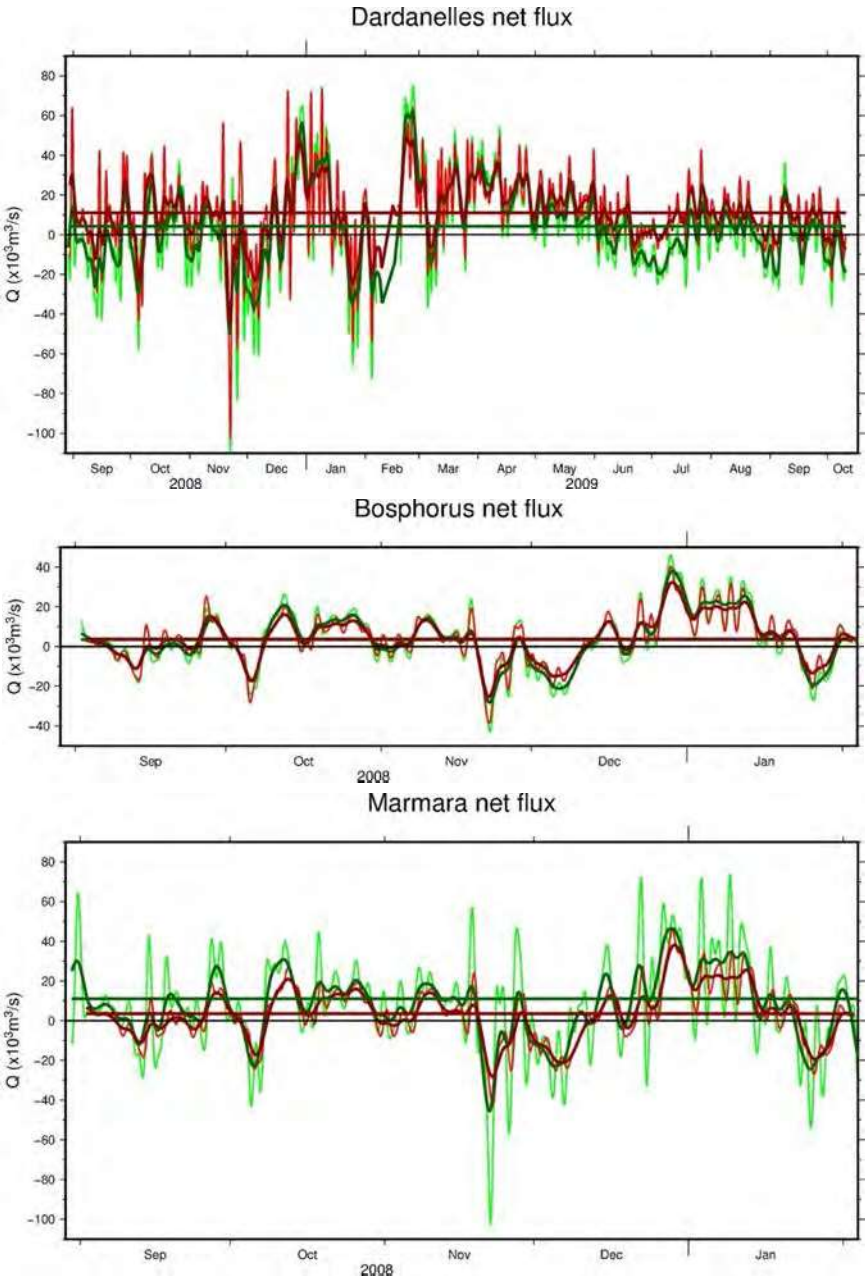


(c)

Figure 9. Time series and means of the lower layer fluxes for segments of the TSS compared at pairs of southern (green) and northern (red) sections, based on measurements of the NURC TSS-08 campaign. The superposed darker lines of the same colour show time series filtered with a time window of 150 hr. Fluxes are positive in the southward direction. Straight lines indicate mean values of the original time series.



(a)

(b)

(c)

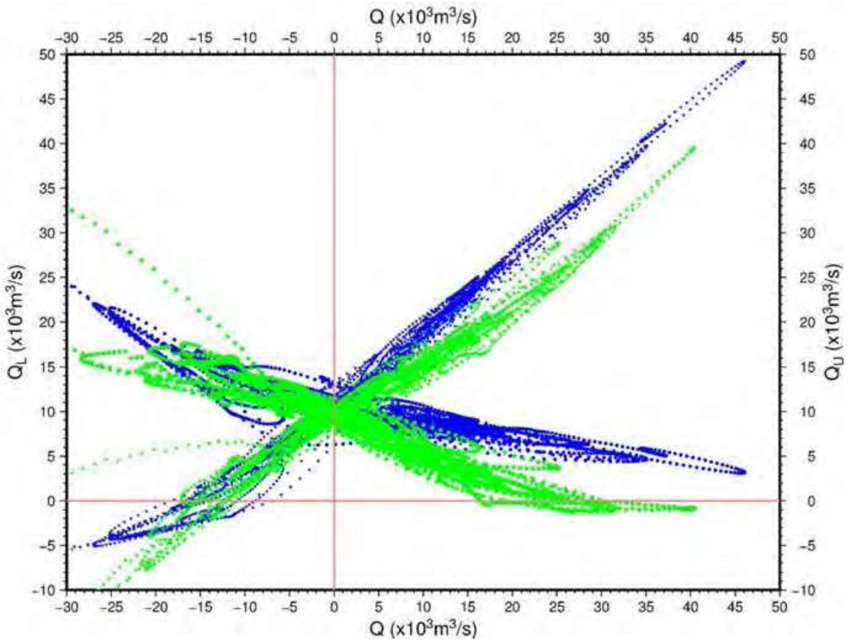
Figure 10. Time series and means of the net (total) fluxes for segments of the TSS compared at pairs of southern (green) and northern (red) sections, based on measurements of the NURC TSS-08 campaign. The superposed darker lines of the same colour show time series filtered with a time window of 150 hr. Fluxes are positive in the southward direction. Straight lines indicate mean values of the original time series.

The net fluxes at two ends are compared in Figure 10 for the Dardanelles, Bosphorus and Marmara segments, all of which are showing positive net fluxes towards the Aegean Sea. The agreement of the net flux is better for the Bosphorus compared to the Dardanelles, which once again shows a greater level of difference. In fact the greatest difference is displayed in the net fluxes between the two ends of the Marmara segment, which could be explained both by external water fluxes, but not by entrainment from the lower layer, because the lower layer differences in Figure 9c were not that large. It seems that the larger error in the Dardanelles measurements are associated with the section at the exit to the Marmara Sea.

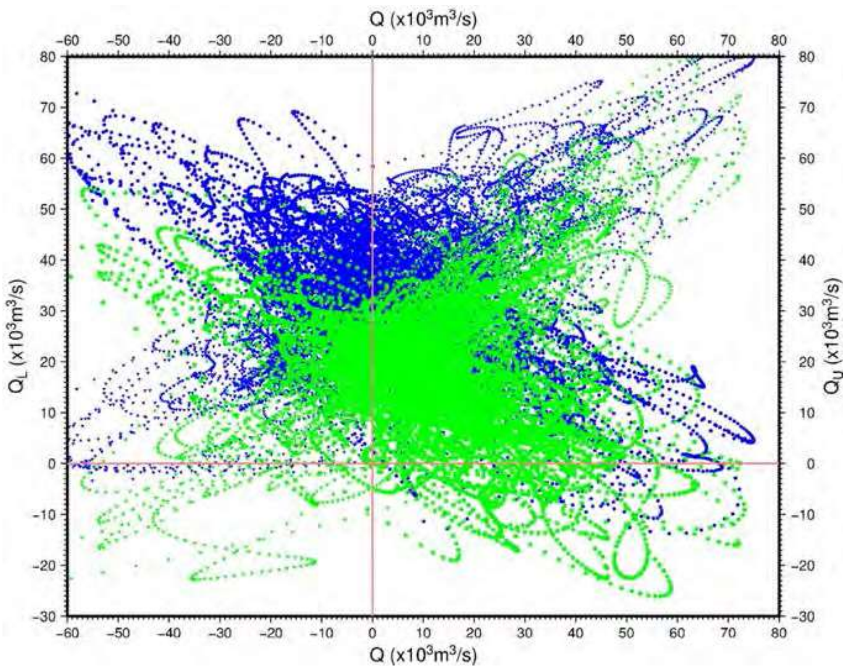
Finally, we make parametric plots of the EPOS/NURC flux time series data in Figure 11, in a similar manner we have done for the other experimental data in Figure 6. While the data presented in Figure 6 have random sampling times, these time-series data are based on continuous sampling obtained from moored instruments at strategic sections of the TSS. Therefore they represent the dynamic response of the TSS. In Figure 11a we plot the characteristics of the two ends of the Bosphorus Strait, while in Figure 11b we do the same for the Dardanelles Strait.

It is in fact not very surprising that the response of the Bosphorus Strait differs in appearance from the Dardanelles Strait. What is surprising is that the response in the Bosphorus Strait follows a very clear pattern as compared to the response in the Dardanelles Strait, considering that the time-series represent a dynamical response of a system. We would normally expect a parametric dependence fluxes in a statistical sense by plotting time averaged or randomly sampled characteristics, and that is what was done in Figure 6. In Figure 11 summarizing the dynamic responses of the two straits, one would therefore expect a large scatter about some mean values, and this is more apparent in Fig11b relative to Figure 11a. In fact, if we consider these figures to be similar to phase diagrams of a nonlinear dynamical system, then the phase trajectory of the Bosphorus follows a regular pattern, while the phase trajectory of the Dardanelles is more irregular.

We believe the regular behavior observed at the Bosphorus (Figure 11a) is due to the strict hydraulic controls at the two or more sections of the strait constituting a “maximal exchange” response, while the relatively less orderly behavior of the Dardanelles (Figure 11b) indicating greater freedom in its response because of the “sub-maximal” nature of the control existing only at the Nara Pass. The differences of response between the two ends of either strait in Figure 11 are due to the difference in upper and lower layer fluxes between the two ends as remarked earlier, resulting from either entrainment processes transporting material between layers or external effects of evaporation, precipitation and runoff. Letting alone the external sources, which should have limited influence during the rapid transit of upper layer waters through the straits, the generally greater flux found at the southern sections indicate entrainment to be directed towards the upper layer.



(a)



(b)

Figure 11. Correlograms of upper and lower (green) layer fluxes with the net flux time series for the (a) Bosphorus and (b) Dardanelles Straits. The blue dots are for the southern end and the green dots are for the northern end sections for both straits.

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References

Altıok, H. and M. Kayışoğlu 2015. Seasonal and interannual variability of water exchange in the Strait of Istanbul. *Medit. Mar. Sci.* 16(3): 636-647.

Altıok, H., Aslan, A., Övez, S., Demirel, N., Yüksek, A., Kıratlı, N., Taş, S., Müftüoğlu, A.E., Sur, H.I. and E. Okuş 2014. Influence of the extreme conditions on the water quality and material exchange flux in the Strait of Istanbul. *Journal of Marine Systems* 139: 204-216.

Beşiktepe, Ş., Özsoy, E. and Ü. Ünlüata 1993. Filling of the Marmara Sea by the Dardanelles lower layer inflow. *Deep-Sea Res.* 40: 1815-1838.

Beşiktepe, Ş., Sur, H.İ., Özsoy, E., Latif, M.A., Oğuz, T. and Ü. Ünlüata 1994. The circulation and hydrography of the Marmara Sea. *Prog. Oceanogr.* 34: 285-334.

Book, J.W., Jarosz, E., Chiggiato, J. and Ş. Beşiktepe 2014. The oceanic response of the Turkish Straits System to an extreme drop in atmospheric pressure. *J. Geophys. Res.* 119: 3629-3644.

Jarosz, E., Teague, W.J., Book, J.W. and Ş. Beşiktepe 2011a. On flow variability in the Bosphorus Strait. *J. Geophys. Res.* 116: C08038. doi:10.1029/2010JC006861.

Jarosz, E., Teague, W.J., Book, J.W. and Ş. Beşiktepe 2011b. Observed volume fluxes in the Bosphorus Strait. *Geophys. Res. Lett.* 38: L21608. doi:10.1029/2011 GL049557.

Jarosz, E., Teague, W.J., Book, J.W. and Ş.T. Beşiktepe 2012. Observations on the characteristics of the exchange flow in the Dardanelles Strait. *J. Geophys. Res.* 117: C11012. doi:10.1029/2012JC008348.

Jarosz, E., Teague, W.J. Book, J.W. and S.T. Besiktepe 2013. Observed volume fluxes and mixing in the Dardanelles Strait. *J. Geophys. Res. Oceans* 118: 5007-5021.

Jordà, G., Von Schuckmann, K., Josey, S.A., Caniaux, G., García-Lafuente, J., Sammartino, S., Özsoy, E., Polcher, J., Notarstefano, G., Poulain, P.M., Adloff, F., Salat, J., Naranjo, C., Schroeder, K., Chiggiato, J., Sannino, G. and D. Macías 2016. The Mediterranean Sea heat and mass budgets: estimates, uncertainties and perspectives (submitted for publication in Progress in *Oceanography*).

Maderich, V. and S. Konstantinov 2002. Seasonal dynamics of the system Sea-Strait: Black Sea–Bosphorus case study. *Estuarine, Coastal and Shelf Science* 55: 183-196.

Mavropoulou, A.M., Mantziafou, A., Jarosz, E. and S. Sofianos 2016. *Ocean Dynamics* 66: 195.

Özsoy, E., Latif, M.A., Sur, H.İ. and Y. Goryachkin 1996. A review of the exchange flow regimes and mixing in the Bosphorus Strait. In: F. Briand (Ed) Mediterranean Tributary Seas, Bulletin de l'Institut Oceéanographique, Monaco, Special Number 17, CIESM Science Series No. 2, Monaco.

Özsoy, E. and Ü. Ünlüata 1997. Oceanography of the Black Sea: A review of some recent results. *Earth Sci. Rev.* 42(4): 231-272.

Özsoy, E., Latif, M.A., Beşiktepe, S., Çetin, N., Gregg, N., Belokopytov, V., Goryachkin, Y. and V. Diaconu 1998. The Bosphorus Strait: exchange fluxes, currents and sea-level changes. In: L. Ivanov, T. Oğuz (Ed) Ecosystem Modeling as a Management Tool for the Black Sea, NATO Science Series 2: Environmental Security 47. Kluwer Academic Publishers, Dordrecht. (1): 367 pp + (2): 385 pp.

Polat, Ç. and S. Tuğrul 1995. Nutrient and organic carbon exchanges between the Black and Marmara Seas through the Bosphorus Strait. *Cont. Shelf Res.* 15(9): 1115-1132.

Sannino, G., Sözer, A. and E. Özsoy 2016. A high-resolution modeling study of the Turkish Straits System (submitted for publication in *Ocean Dynamics*).

Schroeder, K., Garcìa-Lafuente, J., Josey, S.A., Artale, V., Nardelli, B.B., Carrillo, A., Gačić, M., Gasparini, G.P., Herrmann, M., Lionello, P., Ludwig, W., Millot, C., Özsoy, E., Pisacane, G., Sánchez-Garrido, J.C., Sannino, G., Santoleri, R., Somot, S., Struglia, M., Stanev, E., Taupier-Letage, I., Tsimplis, M.N., Vargas-Yáñez, M., Zervakis, V. and G. Zodiatis 2012. Chapter 3: Circulation of the Mediterranean Sea and its Variability. In: P. Lionello (Ed) The Climate of the Mediterranean Region - From the past to the future, Elsevier, 592 pp.

Sözer. A. and E. Özsoy 2016. Modeling of the Bosphorus exchange flow dynamics (submitted for publication in *Ocean Dynamics*).

Stanev, E.V. and E.L. Peneva 2002. Regional sea level response to global climatic change: Black Sea examples. *Global and Planetary Change* 32: 33-47.

Tuğrul, S., Yılmaz, A., Beşiktepe, Ş. and İ. Salihoğlu 2002. Seasonal variation of nutrients in the exchange flows between the Black and Marmara Seas through the Bosphorus Strait. In: A. Yılmaz (Ed) Oceanography of the Eastern Mediterranean and Black Sea, TÜBİTAK Publisher, 424-428 pp.

Ünlüata, Ü., Oğuz, T., Latif, M.A. and E. Özsoy 1990. On the physical oceanography of the Turkish Straits In: L.J. Pratt (Ed) The Physical Oceanography of Sea Straits NATO/ASI Series, Kluwer, Dordrecht, 25-60 pp.