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RESEARCH ARTICLE

Blocking of the upper layer flow in the Çanakkale (Dardanelles) Strait and its influence on fish catches

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Abstract

Migrating fish are challenged by a series of physical barriers as they pass through the Turkish Straits System (TSS) such as the strong mixing zones and blocking of water transport in the Straits. The possible influence of the Çanakkale (Dardanelles) Strait blocking on fish migration is investigated. For this purpose, a numerical ocean model of the TSS has been implemented to predict transports of water at the Çanakkale (Dardanelles) Strait. Results are used to investigate the relationship between the blocking events and wind stress magnitude and direction in the North Aegean Sea. The analysis showed that upper layer blocking occurs when the wind stress magnitude exceeds a certain threshold in the 0-70° sector. Inter-annual time-series of upper layer blocking events deduced from wind stress for the 1979-2013 periods was used as proxy variable found to be highly correlated with the fish catch in the Aegean Sea and the Black Sea.

Keywords: Çanakkale Strait, blocking events, Aegean Sea, fish catch

Introduction

Living organisms make up part of the material passively or actively transported between the Black Sea and the Mediterranean Sea through the Turkish Straits System (TSS). For example, phytoplankton originating from the Black Sea are carried by currents and finally injected into the Aegean Sea after passing through the Marmara Sea (Tarkan 2000; Kovalev *et al.* 2001). Similarly, zooplankton of Black Sea origin has been found in the Aegean Sea (Moraitou-Apostolopoulou 1976). The TSS is also a very important barrier as well as a corridor of acclimatization for migrating fish (Öztürk and Öztürk 1996). Every fall season, many fish migrate from the cold Black Sea to the warm Aegean Sea waters, passing through the TSS and return later, respectively referred to as 'katavasya' and 'anavasya', and may choose the areas on their route for spawning (Deveciyan 2006; Ertan 2010). It is known that commercially important fishes such as horse mackerel, bonito, bluefish and sardine migrate from the Black Sea to the Aegean Sea. Bluefish migrates in spring to the Black Sea, and returns back to the Mediterranean in early autumn (Ceyhan *et al.* 2007). Beside small fish, marine mammals could also migrate from the Black Sea to the very south of the Aegean Sea. Rosel *et al.* (2003) have analyzed the DNA of two harbour porpoises, *Phocoena phocoena*, found in the north Aegean Sea, concluding that their genetic signature is indicative of their Black Sea origin. Tonay and Dede (2013) reported the same species stranded on the southern Aegean Sea coast.

Although it is widely known that temperature is the critical environmental factor that controls the timing of migration, in this study we emphasize the influence of oceanic processes associated with currents, mixing and blocking of the flow on the migration of small fishes through the TSS. The importance of the Istanbul Strait (Bosphorus) as a biological corridor was studied by Öztürk and Öztürk (1996). There are two important obstacles for migrating species on their way from one basin to another: firstly the influence of mixing processes in the narrow Istanbul and Çanakkale Straits (Özsoy *et al*. 2001) and secondly the strong temperature and salinity gradients and turbulence in the TSS inducing physical and physiological stresses on fish passing along the colonization route of the TSS (Oğuz and Öztürk 2011; Keskin 2012). Although there are many accounts of the migrations in popular fishing literature, we are not aware of any scientific study on the seasonal or inter-annual effects of the strait's currents on the migration dynamics and associated changes in the abundance and biodiversity of fishes.

The Çanakkale (Dardanelles) Strait constitutes a two-layer system. The relatively less saline water (with salinity of around 25-29 ‰ in the Marmara Sea) originating from the Black Sea enters the North Aegean Sea (NAS) as a buoyant upper layer outflow (Black Sea Water, BSW) affecting water properties of the region (Androulidakis *et al.* 2012a). The Mediterranean Sea water with a salinity of around 38.9 ‰ enters the Marmara Sea in the lower layer inflow at the Çanakkale (Dardanelles) Strait (Beşiktepe *et al.* 1993). Based on results of a circulation model, Androulidakis and Kourafalou (2011) have shown the strong influence of the buoyant outflow of the Çanakkale plume on the NAS circulation. The impact of the BSW outflow on the NAS and further on the Eastern Mediterranean Transient (EMT) has been investigated by Zervakis *et al.* (2000) and Androulidakis *et al.* (2012b).

The water transport to the Aegean Sea through the Çanakkale (Dardanelles) Strait may come to a halt or even become reversed in instances when the upper layer flow becomes blocked, as indicated by the measurements of Jarosz (2012). In similarity to the İstanbul (Bosphorus) Strait where blocking of either the lower or the upper layer is well known (Oğuz *et al.* 1990; Latif *et al.* 1991; Özsoy *et al.* 1996; Özsoy *et al.* 1998), Even when complete blocking is achieved by adverse wind forcing, the flow may be retarded or its influence spreading into the Aegean Sea may be limited. Modeling studies of buoyant plumes (Whitney and Garvine 2006; Choi and Wilkin 2007) indicate that upwelling favorable winds result in offshore spreading of the plume, while downwelling favorable winds compress it against the coast.

The blocking has consequences on fish migration since the physical barriers (Oğuz and Öztürk 2011), turbulent mixing and occasional flow blocking at the narrow Nara Pass poses a challenge for fish navigating their way through the Çanakkale (Dardanelles) Strait. Jarosz *et al.* (2012) estimated the time series of volume fluxes from velocity measurements obtained from moorings at the two ends of the Çanakkale (Dardanelles) Strait. They showed that the upper layer flow variability is coherent with the local atmospheric forcing and concluded that strong winds are responsible for blockages and/or reversals of the upper layer flow. The variability of the water transport and its pathway in the TSS is also very important for the "health" of the ecosystem (Polat and Tuğrul 1995).

In this study, we investigate the influence of the inter-annual variability (1979-2013) of the Çanakkale (Dardanelles) Strait upper layer flows in connection with the wind stress variations and demonstrate the possible role of blocking events on fish catch in the Aegean and the Black Seas.

Materials and Methods

A numerical ocean circulation model (HYbrid Coordinate Ocean Model, HYCOM, Bleck 2002) successfully used in different regions of the world (Kara *et al.* 2005; Gündüz and Özsoy 2014) and recently developed to study the hydrodynamics of the TSS region is used to calculate water transport through the Çanakkale (Dardanelles) Strait. The model domain shown in Figure 1 includes the Marmara Sea, the İstanbul (Bosphorus) Strait, and the Çanakkale (Dardanelles) Strait, and the neighboring western Black Sea and North Aegean Sea.

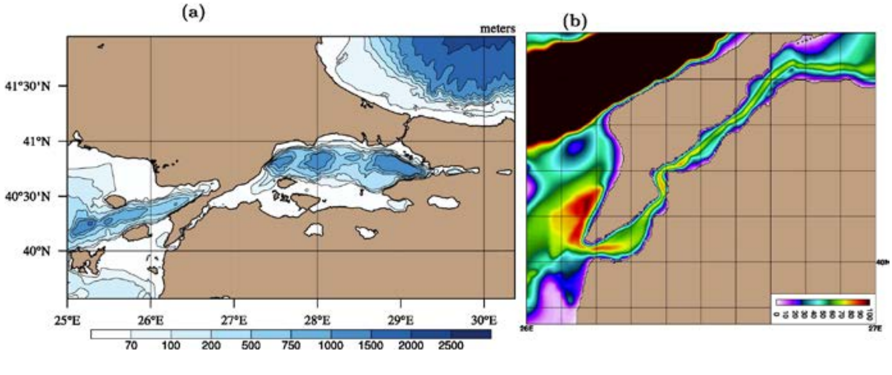

Figure 1. (a) HYCOM-TSS model domain and bathymetry (m).
(b) Zoomed bathymetry of the Çanakkale (Dardanelles) Strait

The model has 1/225° horizontal resolution, which approximately corresponds to a grid spacing of around 400 m. The model has 10 vertical levels, four being z-levels near the surface and the remaining ones bounding isopycnal layers. Spatially varying isopycnal target densities used by the model were set to values in the range of 11 to 28.6 in the Marmara Sea. The minimum thickness of the z-levels was set to 1.5 m, and the maximum thickness was set to 15 m. Vertical mixing is parameterized by the Price-Weller-Pinkel dynamical instability model. The model has been initialized by using in-situ CTD data obtained in September 2008 in the framework of the NATO TSS Project, with selected temperature and salinity profiles from each basin to represent the Black Sea, the Marmara Sea and the Aegean Sea conditions. The seawater properties at the open boundaries, which in this case were treated as closed ones, were relaxed to the World Ocean Atlas (WOA09) temperature and salinity climatology. The model was integrated for 11 months, from September 2008 to July 2009.

The zonal and meridional components of the wind stress were obtained from European Centre for Medium-Range Weather Forecasts (ECMWF) Interim Re-Analysis (ERA-Interim, Dee *et al.* 2011) with 0.75° horizontal resolution and three hourly time interval. The closest grid point of the atmospheric model to the Çanakkale (Dardanelles) Strait was used as station data utilized in the analysis.

The annual fish catch data for the Black Sea, the Marmara Sea and the Aegean Sea were obtained from the Turkish Statistical Institute (TSI, http://www.turkstat.gov.tr) database. It is widely known that the data set has some problems associated with the collection method. Erdoğan *et al.* (2005) have summarized the problems of accuracy of the data by comparing them with the other countries' statistics. It should be emphasized that we restrict our analysis to the annual mean values of TSI data for comparison with our results.

Results

BSW transport in the Çanakkale (*Dardanelles*) *Strait*

The two-layer exchange flow at the Çanakkale (Dardanelles) Strait with currents flowing in opposite directions and a buoyant outflow jet in the North Aegean Sea is well represented in the model. Model generated zonal velocity at a section near the southern end of the strait averaged over the whole model integration period is shown in Figure 2. The upper layer velocity (negative, toward to the Aegean Sea) reaches up to 0.6 m/s in the upper 15-20 m. The maximum zonal velocity (positive, towards the Marmara Sea) is around 0.25 m/s at the core of the lower layer flow.

During exceptional conditions in winter, the upper layer flow is often blocked. By using satellite derived Sea Surface Temperature (SST) data, these blocking events can be detected since the relatively colder temperature of the BSW arriving in the NAS can be differentiated from the ambient Aegean Sea water at the exit region of the Çanakkale (Dardanelles) Strait, when there is sufficient outflow, as clearly seen for instance in Figures 3a, b, c, showing surface water with temperature of around 10° C moving west or north-west after exiting from the Strait.

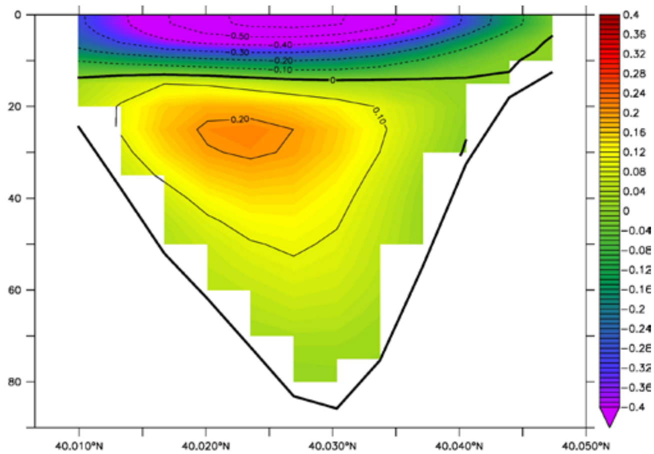

Figure 2. Model generated zonal velocity (m/s) at the southern mouth of the Çanakkale (Dardanelles) Strait averaged over the whole model integration period. Positive values are toward to east and negative values are toward to west.

Often when the Çanakkale outflow into the Aegean Sea is well established, wind stress variations of moderate magnitude do not seem to be able to retard and block the outflow, except when southwesterly winds influence the Strait, corresponding to the cases in Figures 3d, e, f when only warmer surface water of the Aegean Sea is observed at the mouth of the Strait and in some cases seems to enter the Strait. A rule-of-thumb estimate arrived at by examining the wind stress components and such cases of blocking from satellite observations suggest blocking to occur for strong southwesterly winds with wind-stress at the Çanakkale (Dardanelles) Strait mouth exceeds a value of 0.5 N/m^2.

The upper layer water transport of the Çanakkale (Dardanelles) Strait calculated from the model integration in Figure 4 shows strong daily variations in the range 0-900 km^3/yr. The upper layer blocking events (vanishing water transport, marked by red lines in Figure 4) typically last for a couple of days. They occur especially in winter months, not observed after March within the studied period. Although the model calculated transport seems to underestimate the variability of the observed transport, we rely on the estimation of blocking days for the purpose of this study.

The distribution of zonal velocity (for the same section as Figure 2) during selected upper layer blocking days are shown in Figure 5, the, halting (b) and reversal of the upper layer flow (a,c) Examining salinity for the same dates (not shown) indicates increased values during the blocking period due to mixing and Aegean Sea waters backing up into the Strait.

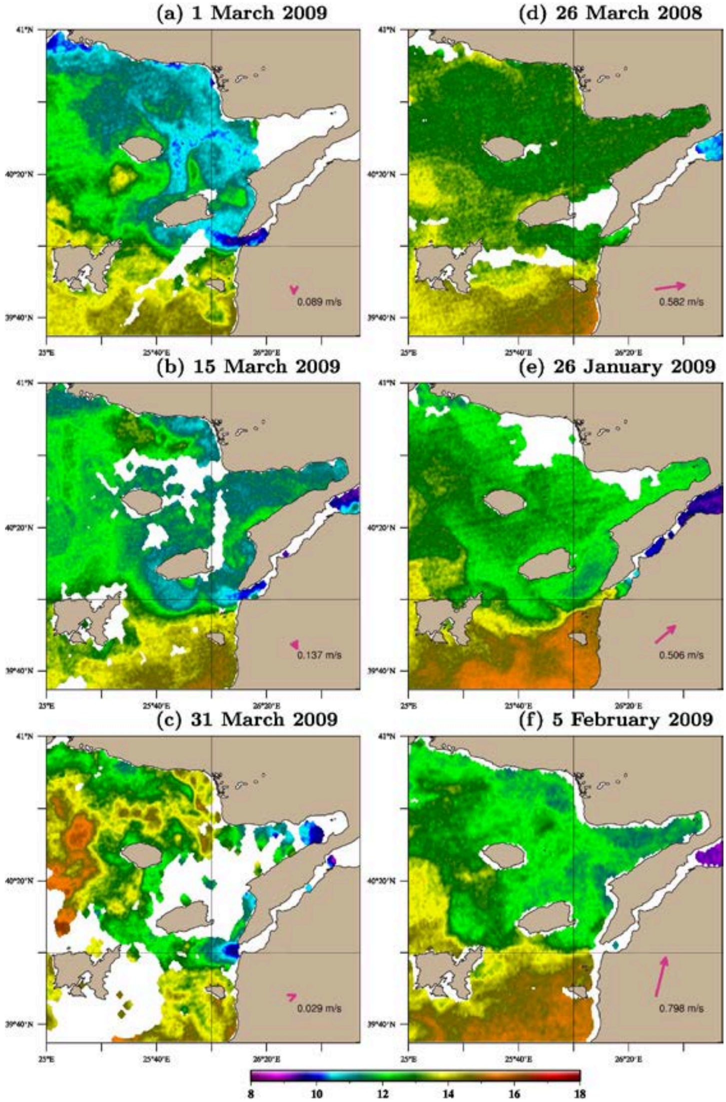

Figure 3. Sea surface temperature (SST) derived from MODIS-Aqua; on the left hand side for the dates (a) 1 March 2009. (b) 15 March 2009 (c) 31 March 2009, when outflow is clearly detected, on the right hand side for the dates (d) 26 January 2009 (e) 5 February 2009 (f) 28 March 2009, when outflow is suppressed, possibly due to blocking. The direction and magnitude of the daily average wind stress for each case is shown in the lower right corner of the figures.

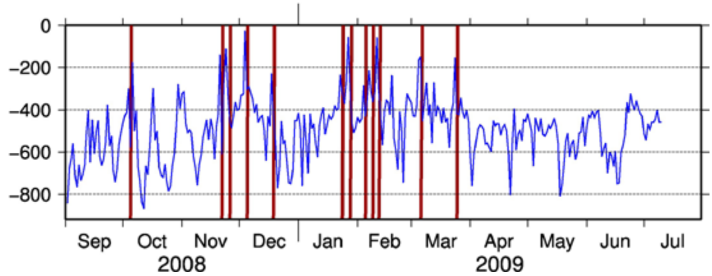

Figure 4. Daily upper-layer water transport km 3 /yr at the southern end of the Çanakkale (Dardanelles) Strait. The red lines shows the days when there is a blocking.

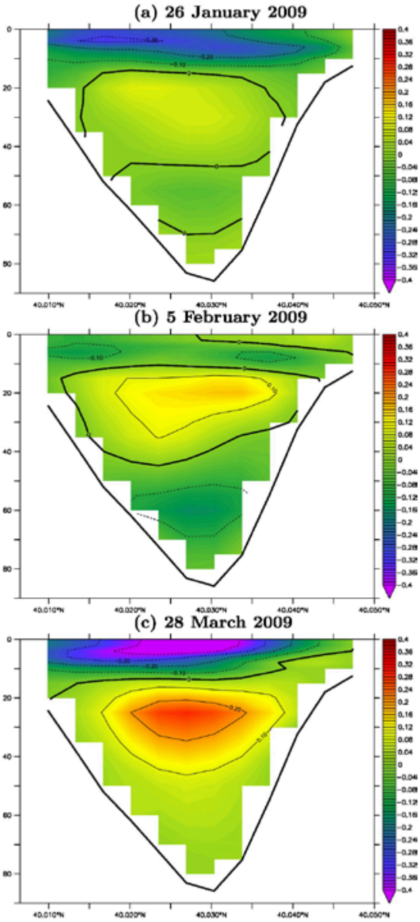

Figure 5. Zonal velocity transects at the mouth of the Çanakkale (Dardanelles) Strait during the tree upper layer blocking events. (a) 26 January (b) 5 February (c) 28 March 2009

Connection between upper layer blocking and wind stress

Figure 6 shows the magnitude, zonal and meridional components of wind stress at the southern mouth of the Çanakkale (Dardanelles) Strait, based on the ERA-Interim Atmospheric Re-Analysis product. The blocking days corresponding to red lines in Figure 4 are also shown. It is clear from the figure that the blocking events occur when both the meridional and the zonal components of velocity are positive, pointing to the northeast, in the 0-70° sector. We therefore choose wind direction as the first necessary condition for the occurrence of the blocking. As a second condition, a threshold value is selected as the magnitude of wind stress arbitrarily increased by 50%, since adding 1.5 times the annual mean components to annual wind-stress did not seem to change the conditions for blocking. In summary, two conditions were specified for a blocking event to occur: the wind stress magnitude being greater than the annual threshold value and the vector direction being within the sector 0-70°.

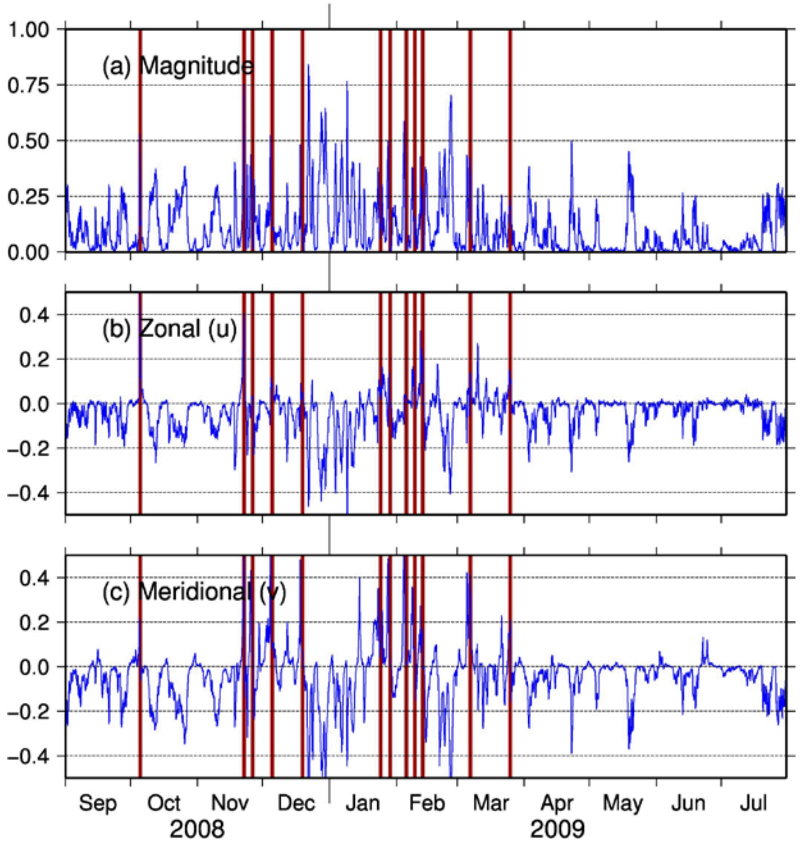

Figure 6. (a) Magnitude (b) zonal and (c) meridional component of the wind stress N/m^2 at the exit region of the Çanakkale (Dardanelles) Strait from the ECMWF-ERA-Int Atmospheric Re-Analysis. The red lines shows the days when there is a blocking.

Inter-annual variability of the number of the upper layer blocking and its connection with the fish catch

Based on the above criteria, the blocking events were counted for each month by using three hourly wind stress data over the available atmospheric model data period (1979-2013), as shown in Figure 7. In general, the blocking events are indicated to take place mostly in the winter months when the winds are stronger. On the average, about ten blocking events occur each month over the winter. The maximum number of blocking events would have occurred in December 2010.

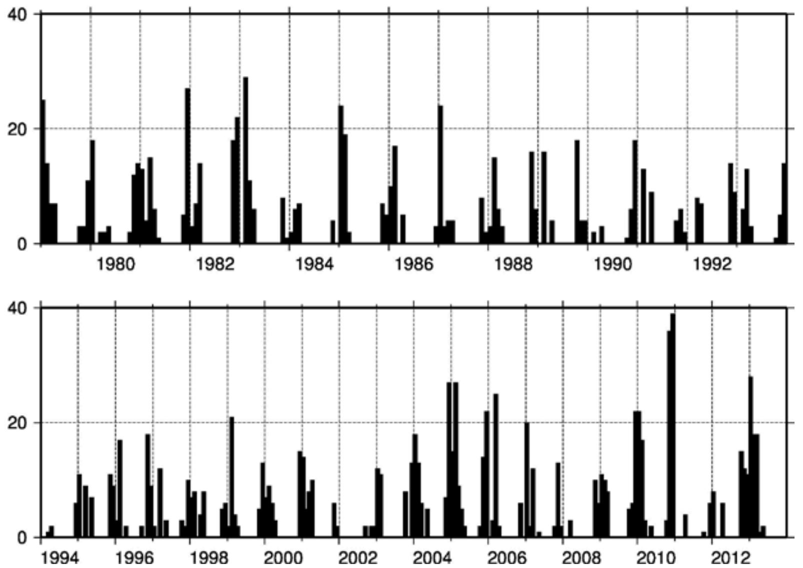

Figure 7. Monthly mean number of upper layer blocking events deduced from 3 hourly data for 1979-2013

In this study, we aim to show the importance of currents in the Çanakkale (Dardanelles) Strait which forms a physical barrier for the fish migration route. The idea is simple, if there is no water exchange between the Marmara Sea and the North Aegean Sea, fish, which are actually active swimmers sensitive to the environment, cannot take advantage of the currents to pass through the Strait and this affects the fishing activities in the downstream NAS area.

Figure 8 shows the correspondence between time series of the number of upper layer blocking events and total fish catch in the Aegean Sea in tons, for two commercial fish species bluefish and horse mackerel. Not much evidence of blocking events is seen in the late 1980's and early 1990's, when actually fishing data were not available to us. Starting with the year 1998 significant variations with increased incidence of blocking events are observed, with the maximum number of blocking events found in 1999. The dramatic second big drop in the amount of fish catch for all species happened in 2005, after a period of increased catch in between, which agrees well with the variation of transport without major blocking events. There are also some indications of delayed response in fish catch suggesting buffering or memory effects of the TSS, in addition to side effects that may have something to do with applying annual averages to scant data. Delays of about one year are seen in the recovery of bluefish and mackerel catches following the severe blocking case in 1999, and in mackerel catch following the next blocking period in 2009. It can also be observed that the bluefish catch fails to recover after the 2005 blocking case, which uniformly affected all studied fish classes, while mackerel recovered and did well in the periods following the major blocking periods. It should also be noted with some caution that the fish schools for the selected fish types arriving at the Çanakkale (Dardanelles) Strait originate from the Black Sea and the TSS, therefore are dependent on the changes in environment and stocks at origin.

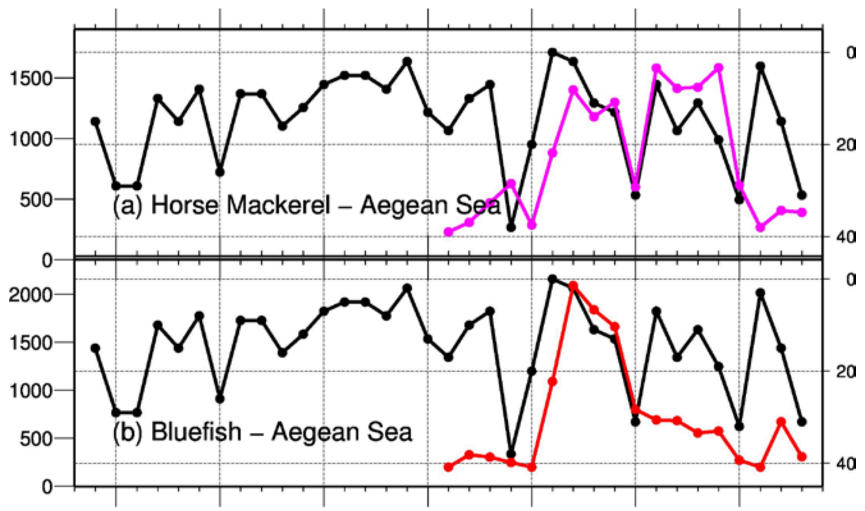

Figure 8. Annual mean number of blocking events (black line, right axis) and fish catches in tons (colored line, left axis) in the Aegean Sea for (a) Horse mackerel (b) Bluefish

Since similar blocking events may happen in the Istanbul (Bosphorus) Strait simultaneously, there should also be some indication in the fishing activities in the Black Sea. The behavior of the mackerel is also very interesting in the western part of the Black Sea. When there is a blocking in the Çanakkale (Dardanelles) Strait, higher amount of catch is observed in this basin. As shown in Figure 9, the blocking events have its maximum in 1999 and 2000. Maximum mackerel catch in the Black Sea is also seen at these particular years. The second big catch happened in 2005 and it is also a blocking year. After this year the catch amount is almost zero. However there is another small amount of catch in 2010, this year also coincide with the blocking year.

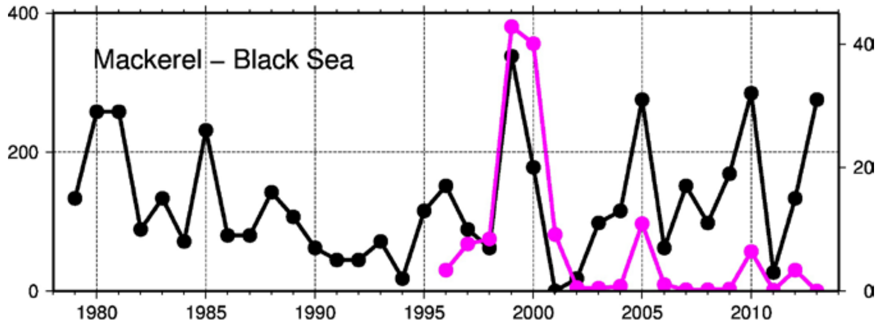

Figure 9. Annual mean number of blocking events (black line, right axis) and fish catches in tons (magenta, left axis) in the Black Sea for mackerel

Conclusions

A possible connection between the blocking of the Çanakkale (Dardanelles) Strait upper layer flow and fish catches in the Aegean Sea and the Black Sea was investigated. It was shown that the direction and magnitude of the wind stress over the southern end of the Çanakkale (Dardanelles) Strait strongly influence the upper layer blocking. A time series was constructed based on this relationship enabling the investigation of the inter-annual variability of the upper layer blocking in the Strait. The blocking of the upper layer water transport should affect the fishes passing through the Strait. It was shown that while the fish catches in the Aegean Sea is directly correlated with the upper layer blocking events; there is a reverse relationship between the fish catches in the Black Sea and blocking events.

It should be emphasized that other factors affecting the above mentioned correlations such as the variability of available fishing boats, the advance in instruments for fishing and the accuracy of the fish catch data from TUIK needs further investigations. While the wind observations used in this study are 3 hourly intervals, the fish catch data has annual mean value. In a further study, fish catch could be obtained more frequently (such as daily) by conducting field measurements, and then the daily comparison of catch data and blocking events may provide more valuable information about the availability of the fishes to the fishermen operating in the North Aegean Sea. This will help to reduce the cost and time for the fish catch activities.

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