THE BOSPHORUS JET

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1. Introduction

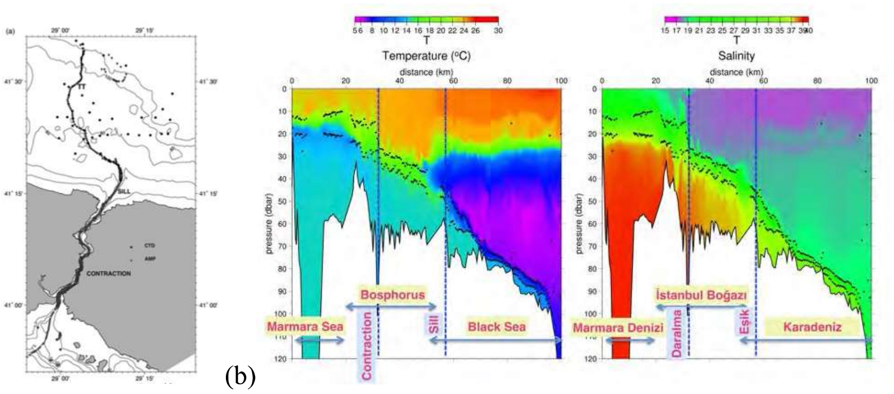
The Turkish Straits System (TSS) provides the only mechanism of communication between the Black and the Mediterranean Seas, allowing material transport between these two seas by the two-layer exchange flows. The exchange has great influence on the water mass characteristics and transport of materials with potential to alter the environmental states of the TSS and the neighbouring basins of the Mediterranean and the Black Seas.

Figure 1. MODIS aqua image of Emiliana huxleyi bloom on June 23, 2003 (http://disc.sci.gsfc.nasa.gov/oceancolor/additional/science-focus/ocean-color/marmara.shtml).

The counter flowing waters of the Black Sea and Mediterranean Sea are mixed by turbulent entrainment processes along their course through the TSS (Özsoy *et al.* 2001) and issue into the adjacent basins (Figure 1) either as surface buoyant jets (at the Bosphorus exit to the Marmara Sea and Dardanelles exit to the Aegean Sea) or bottom dense water plumes that generate gravity currents and plumes cascading into the interiors of these seas (at the Dardanelles exit to the Marmara Sea and Bosphorus exit to the Black Sea).

2. The Functioning of the Bosphorus Strait

In order to visualize the unique processes of mixing and transport within the Bosphorus Strait we provide interpretation of a unique data set that has been collected in the 1994 study of Gregg *et al.* (1999) and Gregg and Özsoy (1999, 2002). A continuous set of measurements were obtained from a free fall AMP instrument connected to the R/V BİLİM with a signal transmitting optical fiber cable. A total of 178 temperature and salinity profiles were collected along the complete path of consecutive stations (Figure 2a) extending from the Marmara Sea to the Black Sea, following the Bosphorus channel, for which the temperature and salinity are respectively displayed in Figures 2b and 2c. Details of the measurements and their interpretation can be found in Özsoy *et al.* (2001).



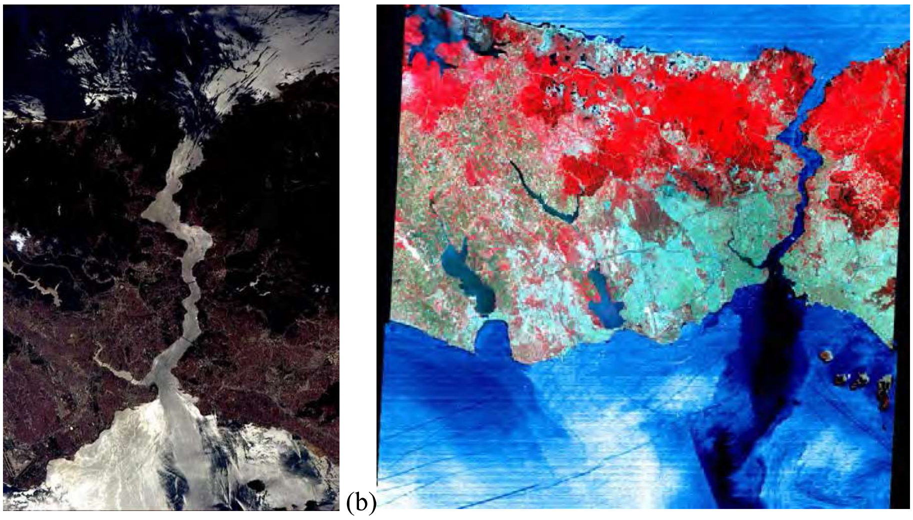
(a) (b)

Figure 2. (a) Locations of the dense profiling network and the continuous distribution of (b) temperature and (c) salinity along the Bosphorus, from Marmara Sea to the Black Sea obtained from 178 profiles. Black dots separate the upper, interfacial and lower layers estimated from salinity profiles (Özsoy *et al.* 2001).

3. The functioning of the Bosphorus Jet

Unique opportunities to visualize the detailed structure of the flows through the TSS and in the adjacent basins is also offered by space photographs, notably during the recent International Space Station observations by astronauts. Examples are provided below.

The two images in Figure 3 show features of the Bosphorus Jet. In the color image of Figure 3a, the water surface has high reflectance, showing the flow along the Bosphorus and the jet issuing to the Marmara Sea, with dark lines showing multiple small fronts and boat wakes. In the thermal image of Figure 3b colder waters are displayed in darker blue and warmer areas in light blue. The light blue of the Black Sea and Marmara waters excluding the jet area have warmer temperatures, while the dark blue area covered by the Bosphorus Jet demonstrates the turbulent mixing and entrainment process that results in the cold waters. The surface waters south of the main contraction of the Bosphorus and in the core of the Bosphorus Jet exiting to the Marmara Sea derive their cold temperatures from increased mixing and turbulent entrainment of cold water from below.



(a) (b)

Figure 3. The Bosphorus Jet as seen on the (a) 7 July 2013 high reflectance image obtained by astronaut Chris Hadfield aboard the International Space Station (https://twitter.com/Cmdr_Hadfield/status/350012636345270272/photo) and (b) 16 June 2000 ASTER image (https://asterweb.jpl.nasa.gov/gallery-detail.asp?name=Istanbul). On land, the green color shows the city area, while the remaining forested areas are shown in red false color, in this image from the beginning of the millennium.

In the Marmara Sea, a strong upper layer circulation (Beşiktepe *et al.* 1994) with a large anti-cyclonic loop with occasional smaller scale eddies is joined by the Bosphorus Jet. The Bosphorus Jet, as well as the other jets and plumes exiting on different sides of straits function to enhance vertical and horizontal mixing through turbulent entrainment processes and by the mesoscale processes of jets, jet fragments and eddies, and thereby are the main agents of basin-wide mixing processes. Their contribution to total entrainment exchanges between layers and to the total basin averaged mixing and entrainment processes have to be quantified. The local response of the jets to changes in forcing, and the further influence of eddy and jet breakdown processes on mixing are also important elements of the overall mixing. However, from the above example of the Bosphorus Jet, it is clear that the jets can play a primary role on basin-wide mixing. These fine scale processes in the end determine tracer distributions and their residence times in the respective basins.

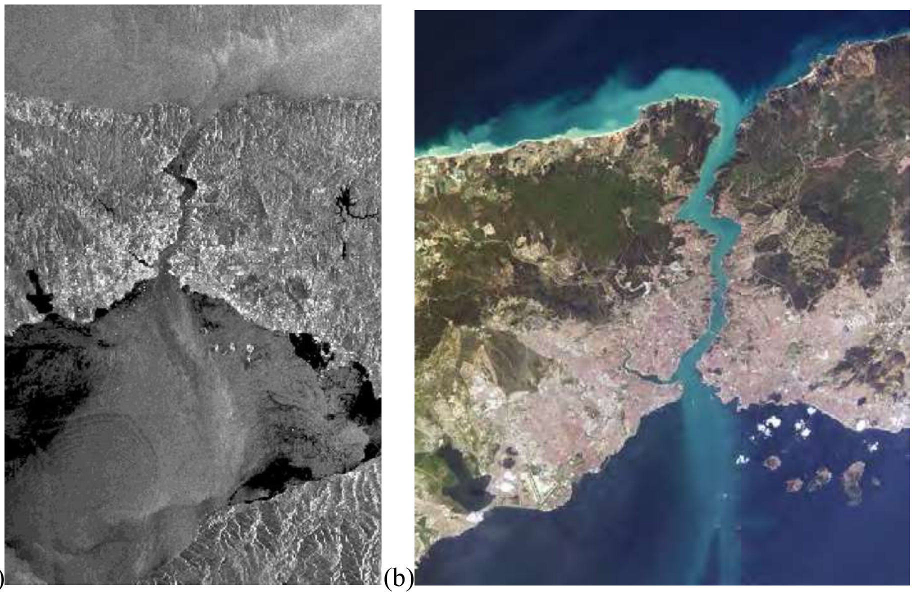
(a)  (b)

Figure 4. The Bosphorus Jet in the (a) ERS-1 SAR image of the Bosphorus Strait and the adjoining Marmara and Black Sea regions (after Özsoy *et al.* 2001) and (b) April 16, 2004 International Space Station image showing turbid coastal waters from the Black Sea transported by strong currents and later carried through the Strait into the Sea of Marmara (https://eol.jsc.nasa.gov/SearchPhotos/photo.pl?mission=ISS008&roll=E&frame=2175).

In the Synthetic Aperture Radar (SAR) image of Figure 4a, the Bosphorus Jet is made visible by the surface roughness effects detected by the satellite sensors. The Jet reaches and strikes the Bozburun Peninsula on the opposite side, where a series of internal waves have been created at the area of impingement, seen to be spreading towards the Marmara Sea, in the image.In the ISS colour image of Figure 4b, the surface flow converges toward the Black Sea mouth of the Bosphorus, superposed on the predominantly easterly currents along the Black Sea coast, then flows south through the Bosphorus Strait and exits into the Marmara Sea in the form of a jet. The transported material is shadowed past the small island on the path of the Jet.

The remarkable picture in Figure 5 shows flows of material originating from the Black Sea coast (near the planned new site of the 3rd airport of İstanbul) entering the Bosphorus and reaching the Marmara Sea in the form of a surface jet, which once more curves toward the west after striking the cape of Bozburun. In Figure 5, we recognize that the Bosphorus Jet touching the southern coast effectively isolates the polluted Gulf of İzmit area from the rest of the circulation of the Marmara Sea, thereby limiting its flushing and adversely affecting the environmental status of the Gulf.

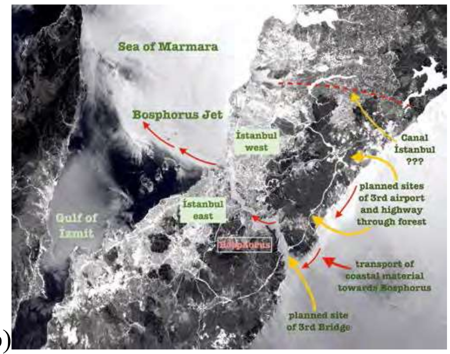
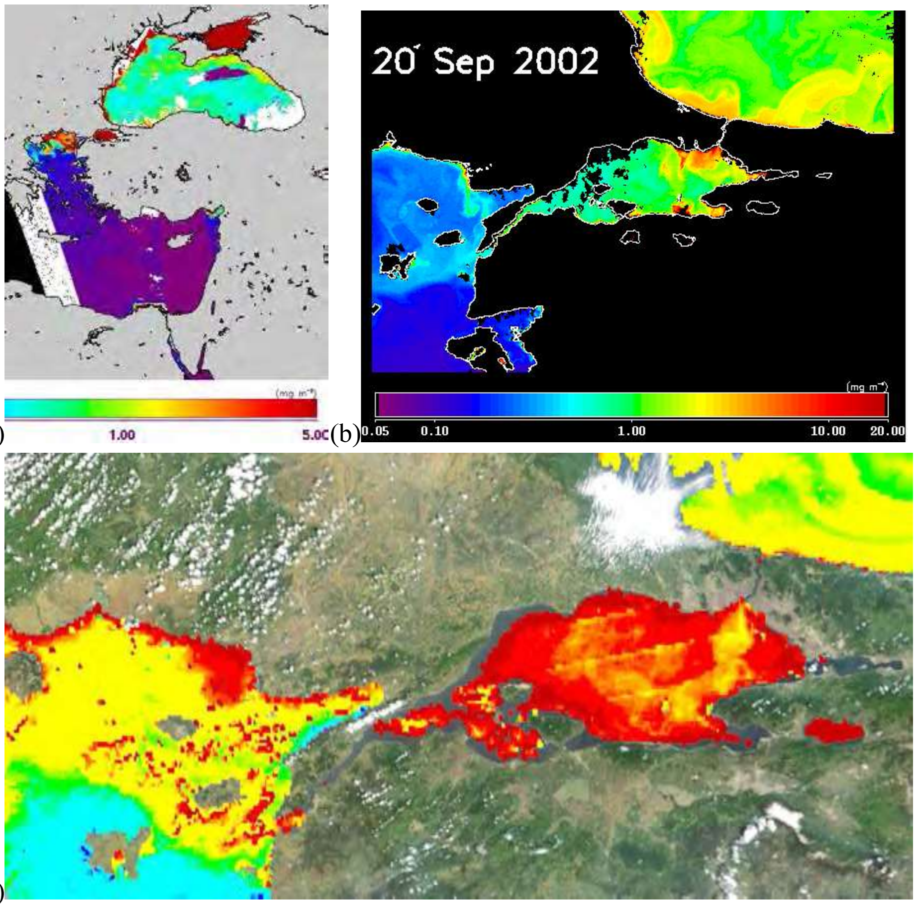
(a)  (b) 

Figure 5. Turkish Straits captured by ISS astronaut Samantha Cristoforetti on June 9, 2015 (a) color image showing transport of coastal materials first eastwards by currents in the Black Sea, later into the TSS through the Bosphorus and spread into the Marmara Sea by the Bosphorus Jet, (b) paths of currents and locations of planned "development" in the region (https://twitter.com/astrosamantha /status/608197918395400192).

4. Significance of the Bosphorus Jet for the TSS Ecosystem

The nutrient transport across the TSS (Polat and Tuğrul 1995) fuels the interactions between ecosystems of the neighboring seas. In the example of Figure 1, presented earlier, a typical phytoplankton bloom coccolith Emiliana huxleyi, well known for its turquoise blue colour illustrates a condition found in the spring season in the Marmara Sea. The observed event is part of the Marmara local primary production process and the dark colour of the current flowing in from the Bosporus into the Marmara Sea is the Black Sea water devoid of the same plankton species because its bloom in the Black Sea is a little later. Finally, the bloom locally formed in the Sea of Marmara reaches the Aegean Sea with a jet flow exiting the Dardanelles Strait.

Significant mixing occurs inside the Straits and further by surface buoyant jets upon exit to the wider sea regions from the two Straits. The surface plumes carrying relatively fresh water and chemical / biological signatures from their sources affect material cycling in the target basins not only through transport, but also as a result of efficient turbulent mixing and entrainment in the exit regions. Interfacial mixing at the straits and jet mixing near their exit regions yield the highest horizontal rates of change in properties within the TSS and largely determine the cycling of matter and biological productivity of the confined waters of the Marmara Sea; a fact emphasized earlier by Ünlüata et al. (1990) and Beşiktepe et al. (1994).



(a) (b) (c)

Figure 6. Satellite images showing the interaction of the Turkish Straits System with the neighboring seas: (a) chlorophyll distribution in ten Eastern Mediterranean and Black Sea with hot areas (red) in the Marmara Sea and Azov Sea, medium areas downstream of the Danube River along the western Black Sea shelf and in the northern Aegean downstream of the TSS, (b) chlorophyll distribution on 20 September 2002, (c) 12 May 2015 MODIS Aqua chlorophyll image showing phytoplankton blooms in Marmara Sea and the Bosphorus Jet enhancing the production by transporting nutrients to the Marmara Sea from the Black Sea.

The efficient jet induced local recycling makes this small basin a region of high productivity often far exceeding the Black Sea (Figure 6a), and incomparable to the "blue desert" of the eastern Mediterranean Sea. A similar picture of chlorophyll distribution in Figure 6b emphasizes the gradients and transport of chlorophyll from the Black Sea to the Aegean Sea in the autumn season. Finally the Bosphorus Jet transporting nutrients to the Marmara Sea buffer zone where the isolated and polluted waters of the TSS create continuous blooms as shown in Figure 6c.

High concentrations of chlorophyll were found in the TSS region in the "Ünlüata Cruises" of the SESAME European project, in continuous sampling of surface waters fed through a Turner fluorometer (Figure 7). In fact the situation was the same on cruises repeated in April and September 2008, extending from the Eastern Mediterranean to the mid-sections of the Black Sea, which showed that the highest chlorophyll concentrations of up to 3 mg/l were always found in the TSS, while the concentrations were much lower in the other regions. It seems that the Sea of Marmara is in a state of eutrophication with continuous blooms saturated with high levels of primary production and detrital material that is depriving it from being the precious marine heritage of rich marine life that it was only less than half a century ago.

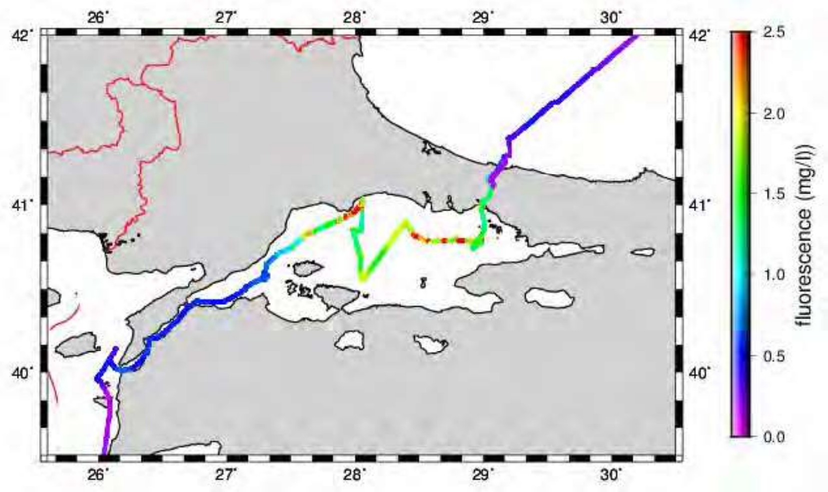


Figure 7. Chlorophyll concentration on the cruise path of the R/V BİLİM during April 2008.

Significant changes have occurred in our lifetime in the ecological status of the TSS, and mainly after the 1960's industrialization and population expansion. The eutrophic Marmara Sea waters fed by Black Sea nutrients (Polat and Tuğrul, 2005), as well as the efficient jet induced local recycling makes this small basin a region of high productivity often far exceeding the Black Sea, with increasing occurrences of mucus and harmful algae blooms (Figure 8-12). The plans for what is often inappropriately called as 'development' pose increasing risks of ecosystem crises and failures in the TSS, with implied effects on adjacent basins, as many signs of deterioration are already easily discernible.

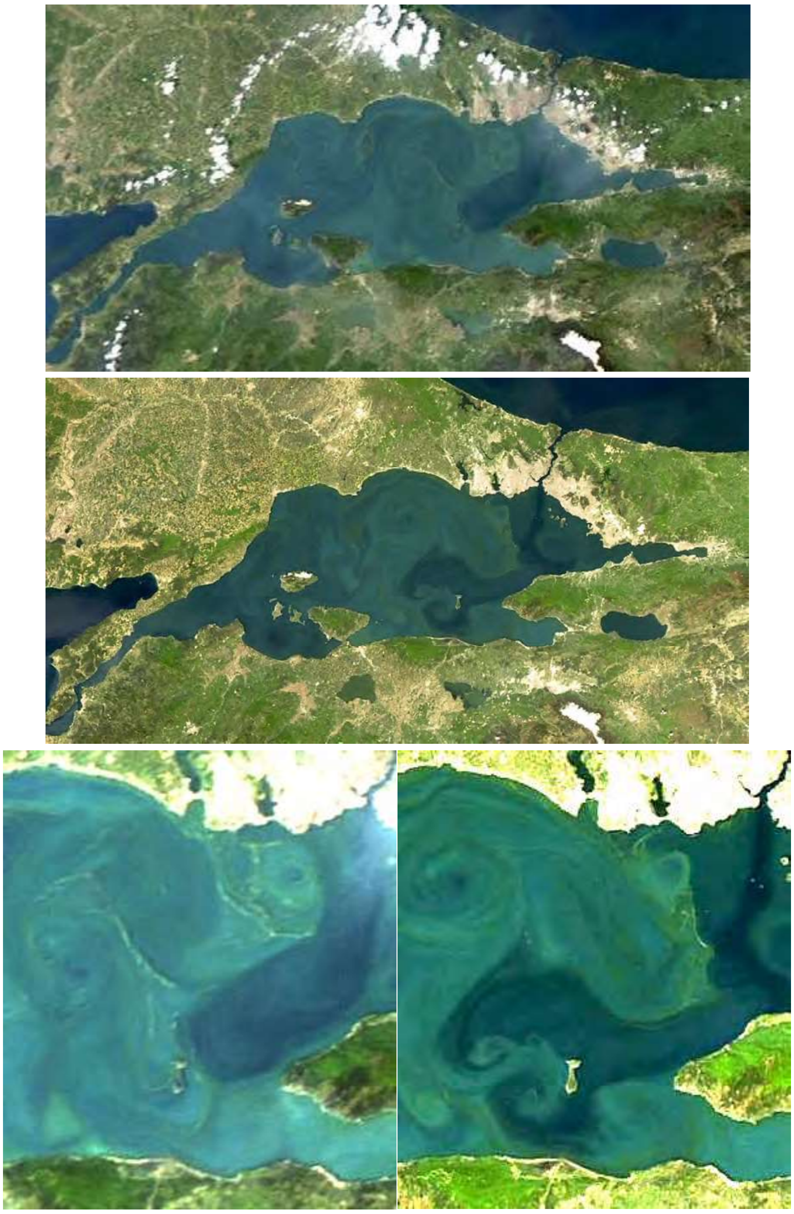


Figure 8. MODIS ocean colour images on 26-27 April 2013, showing the Bosphorus Jet (dark colour) surrounded by what looks like coccolith (green) and toxic plankton (orange) blooms. The upper two panels are the images covering the entire TSS, while the lowest panel shows enlarged images showing the Bosphorus Jet for the consecutive days of 26-27 April 2013.

MODIS Aqua images in Figure 8 show the Bosphorus Jet advancing inside the Marmara Sea, where the flow features are made visible by the ongoing coccolith bloom in the TSS. What was not immediately discerned in the satellite images is the yellowish to orange colored striations lined along circulation features such as eddies and jets, providing excellent "flow visualization", which ominously turn out to be Harmful Algae Blooms (HABs). Such blooms, indicative of the decline in the ecological status of the Marmara Sea are now increasingly observed since the last ten years. The aerial images in Figure 9 provide further evidence during exactly the same dates displayed in Figure 8, showing the actual toxic blooms that were identified for the first time in this period.

Figure 9. (a) Possible toxic plankton bloom near Tekirdağ; Milliyet, 24 April 2013 (b) from a jet flight over the Marmara Sea on 28 April 2013 (Photo: Dr. Bettina Fach, IMS-METU).

A similar event in full bloom is observed in Figure 10a, by the beautiful artwork of a visible satellite image created by the circulation of the Marmara Sea supporting a Harmful Algal Bloom, which was reported to include toxic dinoflagellates such as Prorocentrum micans and Noctiluca scintillans, made visible once again by the numerous lines aligned with the flow demonstrating the existence of numerous eddies and jet segments created by the surface flow. The image used in Figure 10a has been displayed at the 14th İstanbul Biennial entitled "Salt Water" as a piece of artwork of nature, at the same time calling attention to the very urgent state of matters regarding the marine environment of the TSS. In this figure the Bosphorus Jet is made up of various segments making up the familiar S-curve of meandering currents first advancing south from the Bosphorus, then turning east and north towards the northern coast, later to turn southwest. In between this current pattern are dispersed many small fronts and eddies where the yellowish-orange colored HAB species help to visualize the complex flow pattern. The aerial picture in Figure 10b during the same dates near the southern exit of the Bosphorus Strait on the Anatolian side shows the actual blooms in the process.

Figure 10. (a) Spiral eddies, jets and dinoflagellate blooms (red tide) in the Marmara Sea, 17 May 2015, based on an image of the NASA Earth Observatory, (http://earthobservatory.nasa.gov/IOTD/view.php?id=85947&eocn=image&eoci=related_image), (b) local aerial picture of the coastal area of the Marmara Sea south of İstanbul, showing the same bloom published in the daily journal Milliyet on 20 May 2015.
(http://www.milliyet.com.tr/marmara-iste-boyle-oluyor-gundem-2061522/).

Fish migration between the Mediterranean and Black Seas and the local production in the Marmara Sea traditionally have been positive assets of the TSS that support intense fishing activity. The excessive and uncontrolled fishing activity together with the increased pressures of pollution by the highly populated and industrialized coastal environment and intense shipping through the TSS have caused the marine life to be adversely affected. The intense phytoplankton blooms including HABs are only the symptoms of the decline in the health of the TSS by the eutrophication process that has an alarming increase in recent years.

5. Marine Transport and the TSS Environment

The TSS, deserving the highest level of environmental protection as a consequence of its natural reserves of high economical stand, is concurrently located at the convergence of major oil/natural gas marine transport routes and pipelines from the hinterlands of Black Sea and Caspian Seas to world markets. This region with rich energy resources is an important supplier of the world and specifically of the European energy demand. In order to ensure safe marine transport while still being watchful of environmental protection, the outcome of the planned project can contribute to knowledge serving the reduction of accidents and traffic regulation in a congested, environmentally sensitive zone. A secure route means lower transport prices positively affecting oil prices, henceforth increasing the competitiveness of European and local industry. The risks in the TSS have become increasingly evident by frequent cases of grounding, ramming and collisions leading to fires and spread of pollution in recent years. The danger of heavy accidents is a nightmare for the tens of millions of people living in the region.

Linking three continents, the TSS is four times busier than the Panama Canal and three times busier than Suez Canal, surpassing 150 ships/day, with about 15 ships/day carrying dangerous cargo. Some of today's vessels are up to 400,000 gross tons in size and 400 m in length, while the narrowest point the Bosphorus is only 700m wide and its navigable channels in each direction are only 200 m across. Maneuvering under currents reaching 2-3 m/s locally in the strait and exit regions can often be hazardous.

The ship traffic passing through the TSS have increased by about 10 times by numbers and by about 20 times by weight in the last 80 years since the Montreux Treaty (1936) regulating it under current international policy and law (Plant, 2000). The congested traffic makes the Turkish Straits extremely predisposed to accidents (Figure 11), mostly resulting from poor visibility, strong currents and winds. Accidents involving collisions, grounding, fires and explosions often result in oil spills severely threatening this very delicate environment and the very safety of the maritime transport itself (Tan and Otay, 1999; Örs and Yılmaz, 2003; Ulusçu *et al.* 2009; Birpınar *et al.* 2009). It is estimated that 175,000 tons of oil spilled into the TSS from major accidents during 1979-2003. Turkey has unilaterally adopted marine traffic regulations including a sensors based system of Vessel Traffic Services in 1994, for increased security of shipping in the TSS, leading to a dramatic reduction of accidents since then.

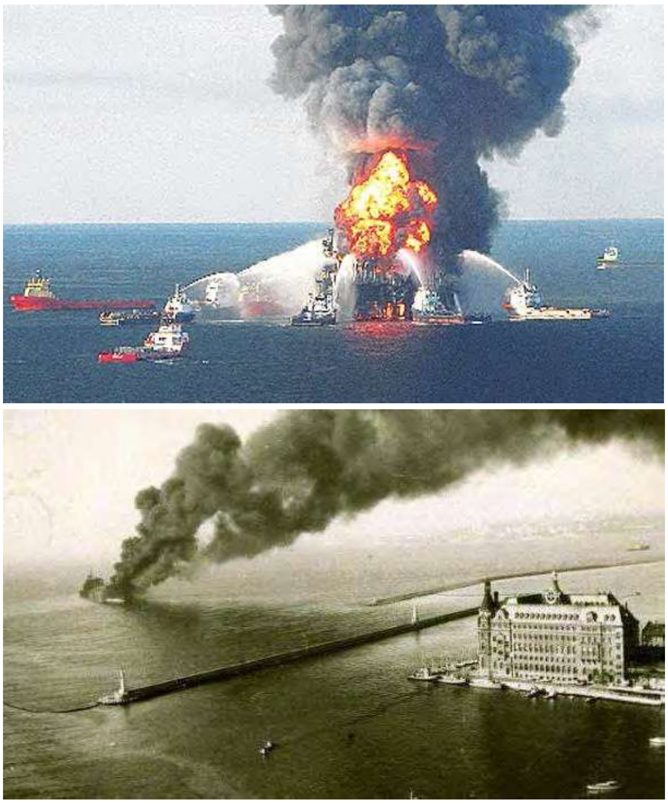


Figure 11. The Independenta (1979) tanker fire and explosion near the Marmara exit of the Bosphorus on the jet exit region, resulting in 43 deaths, with 95,000 tons of oil spilled to the marine environment and spread to the TSS.

6. Modeling Needs

The nonlinear, turbulent, strongly stratified hydrodynamics of the flow through the narrow straits has made the modeling of the TSS a grand challenge. The coupling of the adjacent basins of highly contrasting properties, in a region of extreme hydro-climatic variability can only be achieved if the entire TSS is modeled as a finely resolved integral system, accounting for steep topography, nonlinear hydraulic controls and turbulent mixing processes, as well as an active free-surface. The challenge has been taken in a number of steps, using models of increasing complexity, of the Bosphorus Strait based on ROMS (Sözer, 2013, Sözer and Özsoy, 2016), as well as those covering the entire TSS while fully resolving the narrow Bosphorus: a curvilinear grid MITgcm (Sannino *et al.* 2016) and an unstructured grid FEOM, the results of which are shown in Figure 12 (Gürses et al, 2016; this volume) currently continued to be developed.

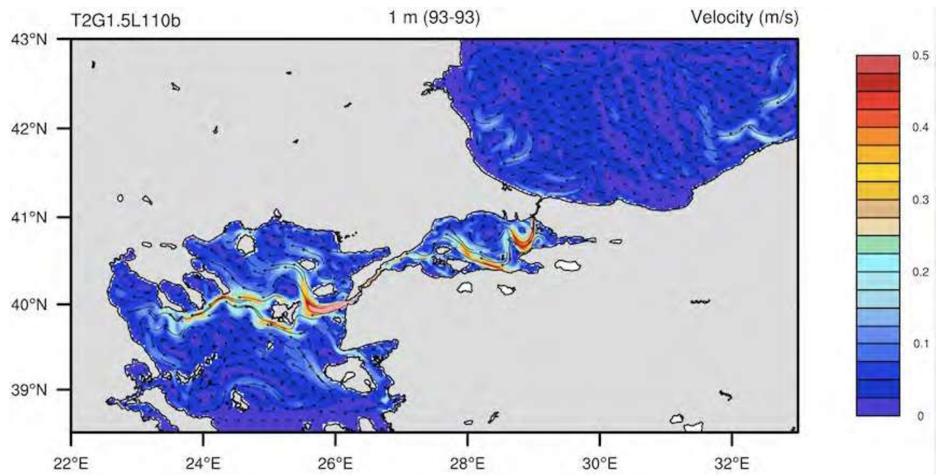


Figure 12. Surface currents generated by uniform northeasterly wind of 14 m/s in FEOM based TSS model.

The meso-scale dynamics of the two Straits and the Marmara Sea appear successfully captured by these models. The response to net barotropic volume flux, The efficient jet induced local recycling makes this small basin a region of high productivity often far exceeding the Black Sea (Figure 6a), and incomparable to the "blue desert" of the eastern Mediterranean Sea. A similar picture of chlorophyll distribution in Figure 6b emphasizes the gradients and transport of chlorophyll from the Black Sea to the Aegean Sea in the autumn season. Finally the Bosphorus Jet transporting nutrients to the Marmara Sea buffer zone where the isolated and polluted waters of the TSS create continuous blooms as shown in Figure 6c.guided by past field experiments, indicates adjustment to net flux and atmospheric conditions. The flow under mild to strong net flow evolves from an anti-cyclonic cell to an S-shaped current with a smaller anticyclone withdrawn closer to the Bosphorus. In extreme cases the lower and upper layers get blocked at the Bosphorus. The circulation pattern appears analogous to buoyancy driven flow adjacent to a river mouth.

An example of the various modeling results only sampled in Figure12 replicates the main known features of the surface currents, such as the jets issuing from the Bosphorus and Dardanelles Straits, and a number of cyclonic / anticyclonic eddies in the Marmara Sea. The most essential element to capture in the integrated modelling of the TSS circulation is the Bosphorus Jet, which as an internal forcing of the Marmara Sea determines the circulation developed by the forcing of the coupled system of adjoining seas imposed on the whole system by the flows developing out of Bosphorus Strait.

7. The Use of HF-radars

Besides being a fundamental component of ocean monitoring systems, HF radars have a broad range of applications they can provide valuable inputs by providing data on ocean surface currents, such as search and rescue operations for people and objects lost at sea, oil spill accidents, water quality monitoring, marine protected areas, marine navigation and ocean energy production. The United States has developed a HF radar network consisting of 185 coastal radars providing real-time ocean currents data to the public along its continental coasts (http://cordc.ucsd.edu/projects/mapping/maps/). In Europe, a working group consisting of Spanish and Portuguese institutions (http://www.iberoredhf.es/en/home) aims to improve the exploitation and visibility of data generated by HF radars on the coasts of the Iberian Peninsula coast. Other efforts in Europe are aiming to make the HF radar data available, as shown in a recent meeting in Lisbon (http://www.emodnet-physics.eu/hfradar/Home). Besides these, there is an international effort to build a global HF radar network of over 400 HF radar systems deployed in the worldwide (http://www.ioos.noaa.gov/globalhfr/welcome.html).

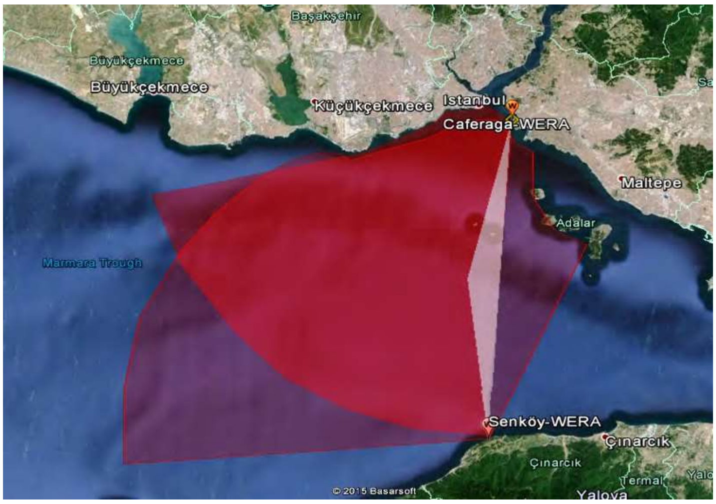


Figure 13. Proposed HF-radar deployment to cover Bosphorus outflow (red patch is where full current vectors can be recovered).

The accurate prediction of the strength orientation and three-dimensional properties of the Bosphorus Jet is of critical importance for the prediction of the Marmara Sea circulation, which develops from the jet providing the initial conditions south of the Bosphorus Strait. It is well known from experiences using integral TSS models (Sözer, 2013; Sözer and Özsoy, 2016; Sannino *et al.* 2016; Gürses *et al.* 2016) that the response times of the straits are much shorter than the basin response time, encompassing also the most unstable features of the turbulent Bosphorus Jet turbulent patches and eddies (Figures 8 and 10). Detailed information obtained by an HF Radar System on the surface currents of the Bosphorus Jet would serve as the most important element of a coastal marine observatory to be developed in the most congested traffic route of the region. Real-time and archived observations are the best assets for model validation and possible data assimilation for improved predictions. Our efforts proposing to build such an observatory for the TSS so far have not been appreciated and irresponsibly turned down by non-scientist functionaries of the establishment, leaving us the option of anticipation for the future.

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