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Chapter 16

Satellite-derived flow characteristics of the Caspian Sea

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Abstract. Mesoscale dynamics of the Caspian Sea are analyzed with satellite data to capture rapid submesoscale motions not sufficiently resolved by in-situ measurements. A combination of Sea-viewing Wide Field-of-view Sensor (SeaWiFS) ocean color data and Advanced Very-High Resolution Radiometer (AVHRR) sea surface temperature (SST) measurements provide a novel evaluation of marine biogeochemical and physical processes and their forcing mechanisms. The main feature of the Caspian Sea is higher pigment concentration with respect to other basins in the Mediterranean region. SeaWiFS detects riverine sediments introduced into the Caspian Sea by the Ural, Terek, Volga, and other rivers, and planktonic flora created in the Caspian Sea by nutrient-rich river runoff. The influence of river flow into the north-northwestern shelf area is especially evident after springtime flooding. Runoff from the Volga River has a major impact on the biomass in the northern Caspian Sea. Eddies and river plumes in coastal waters transport materials and momentum into the Caspian's northern and middle basins. In winter, the cyclonic (counterclockwise) circulation leads to much higher SST in the eastern part of the Caspian than in the west. In summer, wind-induced upwelling yields a pronounced decrease in temperature and higher biomass in the upper layer of the eastern Caspian Sea. In spring, cold water is formed over the entire northern Caspian Sea.

1. Introduction

The new capability to measure the ocean surface at high spatial wavenumber with imaging sensors onboard satellites has motivated detailed observations of complex oceanic processes. Although the temperature of the ocean skin (about 20 micrometers) measured by infrared sensors, such as the National Oceanic and Atmospheric Administration (NOAA) Advanced Very-High Resolution Radiometer (AVHRR), is frequently used to identify surface flow features, diurnal solar heating, evaporation, and other factors temporarily mask the true value of surface temperature, adversely affecting correlations with the ocean's underlying dynamical features (Deschamps and Frouin 1984). Thus, the sea surface temperature (SST) pattern does not necessarily correspond to the ocean current pattern. In addition, the heat stored by the surface mixed layer can be uniform in relatively large areas of the ocean, and therefore many flow features may have a color signature, even when they do not appear on infrared imagery (Ahlnas et al. 1987).

The Sea-viewing Wide Field-of-view Sensor (SeaWiFS) on the SeaStar satellite collects data from a depth range (approximately a few tens of meters) comparable to the attenuation distance of visible light in the ocean and may give a better indication of surface circulation than AVHRR SST. SeaWiFS is a modern instrument designed to assess biological productivity in large areas of the ocean. However, phytoplankton pigments are not constant tracers and often contain "nutrient enrichment" effects produced by vertical mixing, density discontinuities, or upwelling of nutrients into the euphotic zone for plankton growth (Yentsch 1984). Regions of increased fertility are typically the boundaries of ocean currents or eddies. Observations of spatial distributions of plankton and suspended matter, which are usually concentrated in shelf waters, reveal circulation patterns and interactions between waters on the shelf and over the deep sea. Consequently, the combination of SST and ocean color images is very useful for studying ocean conditions.

Satellite data are used to identify a number of important dynamical processes in the Caspian Sea. Wind-induced upwelling events occur along the eastern periphery of the Caspian Sea. Significant amounts of fresh water, nutrients, and sediments enter the Caspian Sea from the Volga, Ural, and Terek Rivers. Riverine input is advected along the coast by a boundary current, which interacts with coastline and bathymetry to produce eddies, and is being partially injected into the sea's interior as a result of turbulent exchanges. Satellite data have proven useful in similar environments where rapid changes and turbulent features cannot be sufficiently resolved by in-situ data (Sur et al. 1994, 1996, 1997).

Cloud-free NOAA AVHRR SST and SeaStar SeaWiFS ocean color images are used to infer regional flow dynamics of the Caspian Sea. All image processing was done at the Institute of Marine Sciences, Middle East Technical University, and at the Institute of Marine Sciences and Management, University of Istanbul.

2. Oceanography of the Caspian Sea

The Caspian Sea is the world's largest inland water body with no outlet to the ocean. Its surface area and volume are about 4×10^5 km^2 and 7.8×10^4 km^3. The north-south

length is about 1200 km and the east-west width is approximately 310 km. The Caspian Sea is divided into the northern, middle, and southern parts (Figure 1). The northern part is very shallow, averaging about 5–6 m in depth; its maximum depth is 20 m. The 788-m maximum depth of the middle Caspian Sea is located in the Derbent Depression near the western coast. The western slope of this depression is much steeper than the eastern slope. The southern Caspian Sea is separated from the middle by the Apsheron Ridge, which is the continuation of the Apsheron Peninsula. Water depths along the ridge are less than 180 m. The deepest part of the southern Caspian Sea is 1025 m (Voropayev 1997) and is located east of the Kura River delta. Several ridges rising to 500 m occur in the southern depression. Kara Bogaz Gol, a large gulf on the eastern shore, is an extensive evaporite basin that is below the level of the Caspian Sea.

The salinity range of the Caspian Sea is 3–13 practical salinity units (psu), increasing from north to south. Temperature almost totally determines the density stratification because the salinity of the Caspian Sea is relatively homogeneous. The Volga River supplies 82% of the annual volume of inflow to the Caspian Sea. Riverine water accounts for about 80% of the annual water input. Because the Volga supplies about 65% of all water to the Caspian, sea level variations are highly dependent on Volga River discharge, which peaks in May–June, when about 35% of the annual flow occurs (Figure 2).

The Caspian Sea surface circulation consists of cyclonic (counterclockwise) eddies in the southern, middle, and northern regions (Terziev et al. 1992) (Figure 3). The mesoscale eddy features have a seasonal evolution (Trukhchev et al. 1995; Rashit et al. 1999). Caspian Sea currents are considered to be mainly wind-generated. The northern Caspian Sea has strong easterly winds in autumn and winter, and weak southerly winds in summer. The middle and southern Caspian Sea has northerly-northwesterly winds during summer, with easterly-southeasterly winds in winter. Currents on the northern shallow shelf are especially influenced by wind (Bondarenko 1993) and, in addition, are strongly influenced by the spatial gradient of buoyancy produced by river discharge. The inflows of the Volga and Ural Rivers are responsible for the southwestward-southward current in the near-delta region. In the coastal regions of the middle and southern Caspian Sea, currents correlate with wind direction and are typically toward the northwest, north, southeast, and south. Easterly currents are also observed near the east coast. Along the western coast of the middle Caspian Sea, the prevailing currents are southeastward and southward. Other types of currents, such as baroclinic currents and seiches, also play an important role in local circulation patterns. In summer, upwelling occurs along the eastern coast of the middle Caspian Sea (Kosarev and Yablonskaya 1994).

Sea level has had large fluctuations this century to impact two key natural resources: oil and natural gas, and caviar-producing sturgeon. In the early 1930s, the Caspian's sea level began to decline, dropping 3 m by the mid-1970s. However, beginning in 1978, sea level began to rise, increasing about 2.5 m in the past 20 years. Flooding in the coastal

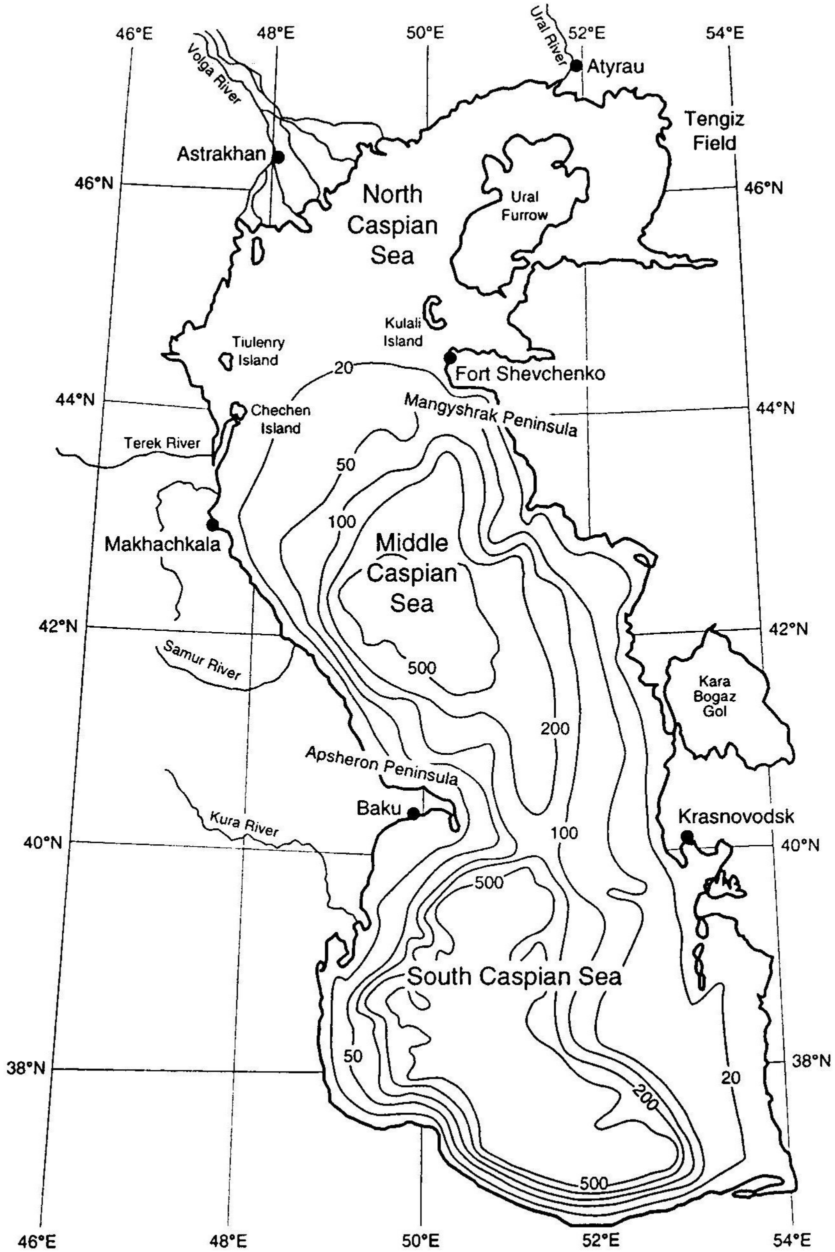

Figure 1. Bathymetry and location map of the Caspian Sea (depth in meters).

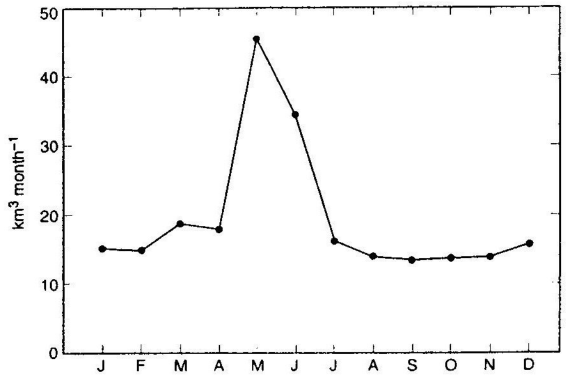

Figure 2. Long-term measurements of monthly average Volga River discharge (after Baidin and Kosarev 1986).

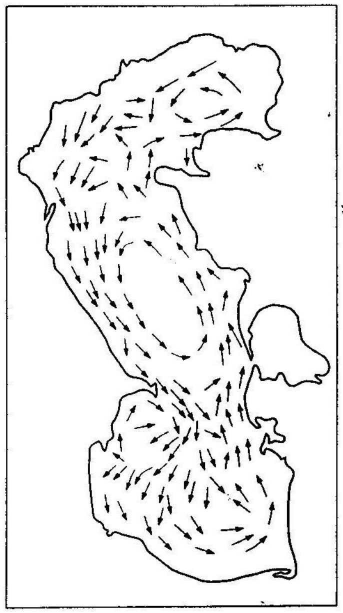

Figure 3. Sea surface currents of the Caspian Sea based on indirect methods of current measurement (floats, bottles, etc.) (after Lednev 1943).

zone damaged buildings, roads, beaches, oil wells, and much farm land. A higher sea level of the Caspian could lead to an increase in environmental problems for the sea's ecosystems as more and more oil is washed into the sea (Glantz and Zonn 1997).

3. Results

There are significant SST differences between the northern and southern regions. In winter the SST gradient is about 0.8°C per degree latitude; in summer the SST is uniform from south to north. Ice forms in mid-November, lasting 5–6 months (Rodionov 1994), and covers almost the entire shallow northern Caspian Sea. During severe winters, shallow bays freeze and shorelines are icy along the eastern coast. Along the western coast, drifting ice is found as far south as the Apsheron Peninsula.

Cold water flows southward along the west coast and warm water intrudes northward from the southern Caspian to the middle Caspian in the cyclonic system of water circulation (Figure 4a). The zonal width of the southward intrusion of cold water along the western continental shelf decreases towards the south (Figure 4a), and is parallel to the decreasing width of the shelf. The offshore boundary of cold water follows a constant depth contour between 20 and 50 m along the entire western shelf of the middle Caspian Sea. Blending of cold and warm waters proceeds along the coast to the Apsheron Ridge, where cold water mixes efficiently with warm water. The cold water tongue diminishes

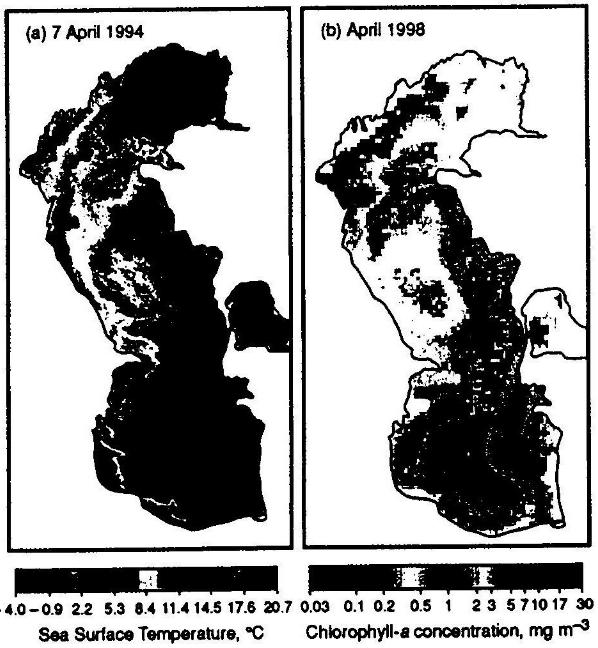

Figure 4. Development of flow along the northwestern and western coasts of the Caspian Sea shown in (a) AVHRR SST on 7 April 1994 and (b) monthly mean SeaWiFS chlorophyll-*a* concentration.

beyond the Apsheron Peninsula. In addition, the cyclonic circulation in the middle Caspian Sea shows marked differences in SST between the eastern and western parts (Figure 4a).

High phytoplankton concentration was linked to the southward transport of cold nutrient-rich water from the northwest shelf (Figure 4b). When the cold water reaches the coastline north of the Apsheron Peninsula, it flows eastward, becomes partially separated from the coast, and is then trapped in an elongated cyclonic (counterclockwise) eddy over the deepest region of the middle Caspian Sea. This meridionally stretched cyclonic eddy is in agreement with the circulation pattern shown in Figure 3. SeaWiFS data (Figure 4b) shows a spectacular phytoplankton bloom within this eddy. The nutrients to drive the phytoplankton production associated with the eddy originate from river discharges in the northern region. River water forms the trophic regimes in the northern part of the sea, which are the main areas for juvenile sturgeon. The increase in biological productivity, specifically the blue-green algae *Cyanophyta*, develops in summer after the Volga River discharge is at its peak and spreads over half of the northern Caspian Sea.

Southward winds along the east coast of the Caspian Sea produce persistent upwelling of cold water in summer. Cold-water patches initially form as eddies (Figure 5a), and a week later (Figure 5b) the eddies have been stretched in the offshore direction, taking the

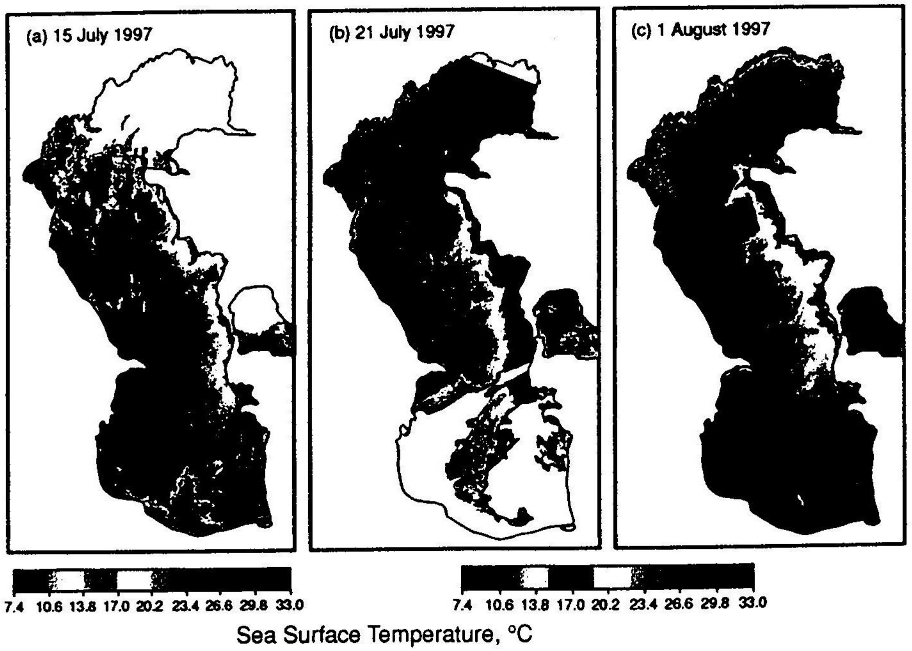

Figure 5. AVHRR SST on (a) 15 July, (b) 21 July, and (c) 1 August 1997.

form of filaments. Growing filaments extend offshore (Figure 5c). Nutrients injected by coastal upwelling into the euphotic zone result in higher phytoplankton biomass and productivity along the eastern coast.

4. Summary and Conclusions

A limited study of satellite imagery indicates a cyclonic flow pattern in the Caspian Sea. Effects of the Volga River along the western coast of the northern and middle Caspian Sea were identified. Riverine materials are transposed by the coastal current and distributed along the coast and across the frontal region by turbulent motions. Flow separation caused by the Apsheron Peninsula is also evident, and influences transport as well as vertical motion along the coast. Southward wind stress along the eastern coast produces upwelling, giving rise to seasonal changes in phytoplankton concentrations along the eastern coast. The observed flow patterns were similar to those occurring when sea level was lower (Figure 3), suggesting that sea level rise in the past 20 years has not affected flow patterns.

The large size of the Caspian Sea requires spaceborne sensors to monitor SST, phytoplankton pigment concentration, wind vectors, and other variables at adequate time and space scales to identify environmental conditions. Most environmental processes in the Caspian Sea are strongly influenced by interactions between the current and coastal boundaries, freshwater runoff, and bottom topography. Atmospheric forcing by wind and by heat and fresh water fluxes is very important and leads to distinct effects on both surface and deep-sea phenomena. Scientific questions about natural and anthropogenic variations of inland-drainage seas (e.g., Caspian, Great Salt Lake, Chad Lake) require remote-sensing data for comparative studies.

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