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Anatomy of shelf–deep sea exchanges by a mesoscale eddy in the North West Black Sea as derived from remotely sensed data

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ABSTRACT

Satellite derived full resolution data on chlorophyll, water leaving radiance, sea surface temperature, as well as altimetry data are used to characterise the process of shelf–open sea exchange induced by an individual mesoscale eddy off the North West coast of the Black Sea in the summer 2005. The shelf edge front in the NW part of the Black Sea separates biologically productive and often eutrophicated shelf waters from the open sea waters. A large mesoscale eddy (diameter about 120 km) was formed away from the shelf front southwest of Crimean peninsula in the spring 2005. The eddy moved towards the shelf break and repeatedly attached itself to the shelf edge front causing its disturbance and formation of a cross-shelf jet and a Chl-a rich filament spiralling around the eddy periphery. The jet represented an important cross-shelf transport mechanism sustaining an average cross-frontal flux of shelf waters of 0.3 Sv over period of 40 days. The total transport of water in our case study was equivalent to 40% of the overall volume of water on the shelf. Formation of the filament significantly increased the length of contact between shelf and deep sea waters from 70 km at the base of filament to about 800 km along its sides, thus providing a highly efficient mixing mechanism.

1. Introduction

Recent advances in satellite systems for Ocean observation allow the investigation of delicate processes and phenomena in marine ecosystem at high spatial and temporal resolution. The goal of this paper is to use a combination of remotely sensed and in-situ data in order to reveal and quantify a physical mechanism which governs shelf–deep sea exchanges. The data for this study was collected in the Black Sea, which is a large virtually enclosed 413,490 km^2 water body with a population of about 140 million living in its 14-country, 2.5 million km^2 catchment (Shapiro, 2008).Drainage from this huge catchment has a major influence for water structure in the sea and is particularly significant for the north-western shelf, the 80,000 km^2 region that receives the discharge of Europe's second (Danube) and fourth (Dnieper) largest rivers. These rivers discharge significant amounts of nutrients and pollution affecting thousands of square kilometres of the shelf and are widely regarded as the main cause of eutrophication and the collapse of much of local ecosystem from the early 1970s (Mee, 1992). The level of eutrophication is controlled by the overall balance of sources and sinks of nutrients. Although all major sources of nutrients entering the shelf area of the Black Sea are known, it has been difficult to construct even simple nutrient mass balances because the outgoing fluxes, which are largely attributed to shelf–deep sea exchanges, are still poorly quantified.

Horizontal circulations induced by mesoscale features such as eddies and filaments are often cited as primary mechanisms of shelf–deep sea water exchanges (Mizobata et al., 2006; Moore et al., 2007). The reason is that the large scale oceanic currents, such as the basin scale Rim Current in the Black Sea, tend to flow at constant depth and become bounded by constant potential vorticity contours due to geostrophic constraints. Thanks to their smaller sizes and non-steady state nature, mesoscale eddies are able to impinge on the shelf break and further onto the outer shelf. Typically the mechanism of eddy formation and shelf–deep sea exchanges by the eddies have been associated with the classical ‘Gulf Stream Ring’ scenario where the main current generates meanders that grow, close upon themselves, and then shed eddies that spin up from the current (Morrow et al., 2004). The shelf water with high chlorophyll content incorporated into the eddies is subsequently transported away from the coast into the deep sea (Aristegui et al., 1997) where they mix their content with the ambient waters (Garcia et al., 2004). Globally, mesoscale eddies have been able to generate localised regions of elevated productivity in many nutrient-poor regions of the world ocean by transporting

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nutrients offshore from coastal, frontal or upwelling areas by either cyclonic or anticyclonic eddies (e.g. Garcon et al., 2001).

Remote sensing-based studies of the Black Sea basin have firmly documented intensive mesoscale activity in various parts of the sea (Grishin, 1994; Gawarkiewicz et al., 1999; for more references see Zatsepin et al., 2003 and references therein). In particular, mesoscale eddies have been observed in the NW Black Sea. It is thought that the formation of eddies is initiated by the baroclinic instability of the basin scale cyclonic gyre called the Rim Current or by the interaction of the main current with the protruding land mass of the Crimean peninsula (Staneva et al., 2001). Formation of the eddy southwest of Crimea, often called the Sevastopol Eddy, has been analysed using medium resolution (9 km pixel size) satellite charts of Chl-a distribution and interpreted in accordance with the classical, 'Gulf Stream Ring' scenario by Oguz et al. (2002). It has been suggested that eddies can efficiently transport "considerable amounts" of biota to the interior parts of the Black Sea, however quantitative estimates of this transport have not been established.

In this paper we use a combination of remote sensed information on ocean colour (MODIS, SeaWiFS), altimetry (JASON-1), Water Leaving Radiance (WLR MODIS) and Sea Surface Temperature (SST, AVHRR NOAA) supported by in-situ measurements of current velocity in order to identify the mechanism of shelf–deep sea exchanges associated with a mesoscale eddy observed in North-Western Black Sea during the summer 2005. The use of high resolution products (1.1 km pixel size for ocean colour, SST and WLR as opposed to 9 km) enables us to get a better insight into the details of the mesoscale processes. In the subsequent sections we describe the anatomy, dynamics and evolution of the eddy, its role in facilitating exchanges between shelf and deep sea waters, and provide quantitative estimates of the emerging cross-shelf-break fluxes.

2. Data and methods

Chlorophyll-a (Chl-a) distribution derived from ocean-colour sensors has been used successfully as a good tracer of water masses (Ginzburg et al., 2002) and surface currents (Smyth et al., 2001). In the Black Sea, there is a significant difference in Chl-a concentration between the western shelf regions and the deep part of the Black Sea, especially in the warm season. The summer mean Chl-a concentration on the western shelf could be up to an order of magnitude higher than that in the deep parts of the sea, so that higher Chl-a concentrations can be used as a reliable marker of shelf waters in the NW Black Sea (Kopelevich et al., 2002). Eddy manifestation in WLR and Chl-a is different due to the difference in the composition of species typical for shelf and open sea. For example, during June–July the main phytoplankton species in the open sea are coccolithophore (characterized by strong scattering and high WLR), whilst in the shelf area the main species are the diatoms and dinoflagellates (Vinogradov et al., 1992). As a result, shelf waters have greater values of Chl-a but a lower WLR signal. We use Chl-a data as it has proved to be a good tracer of the productive shelf waters.

For this study we selected daily charts of Chl-a concentration and SST for the period between March to September 2005. These were produced operationally by the Marine Hydrophysical Institute (MHI) Remote Sensing Department with high resolution of 1.1 × 1.1 km (http:/dvs.net.ua) which corresponds to the pixel resolution in the centre of the image of MODIS-Aqua Level-2 full resolution digital data obtained from "NASA Goddard Space Flight Center" (http://oceancolor.gsfc.nasa.gov) and the MHI data archive. Chl-a concentration was typically as low as 0.3–0.8 mg/m^3 in the deep sea and as high as 8–12 mg/m^3 in the core shelf waters. We are aware that there is debate on the accuracy of Chl-a estimates for the Black Sea from current algorithms (Oguz and Ediger, 2006) but for the purposes of this paper,

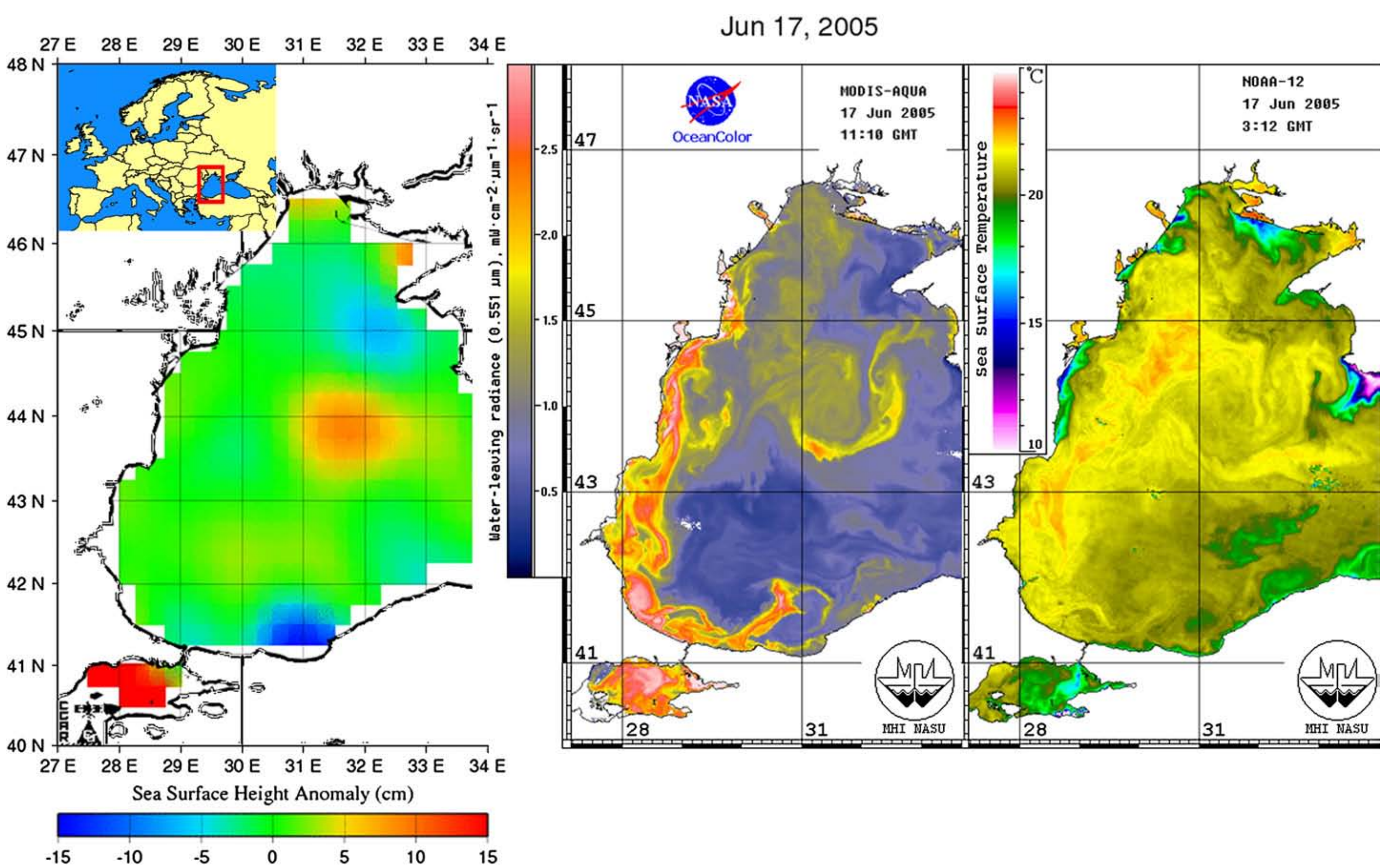

Fig. 1. Manifestation of the eddy on charts of Sea Level Anomaly (left), Water Leaving Radiance at 551 nm (mid) and Sea Surface Temperature (right) in the western part of the Black Sea on June 17, 2005.