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Inter-annual variability of exchange processes at the outer Black Sea shelf

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The advection of cold water below the surface mixed layer has a significant role in shaping the properties of the Cold Intermediate Layer (CIL) in the Black Sea, and thus the horizontal redistribution of nutrients. The minimal temperature of the CIL in the southwest deep region of the sea in summer was shown to be lower than the winter surface temperature at the same location, indicating the horizontal advective nature of CIL formation in the area (Kolesnikov, 1953). In addition to advection in the deep area of the sea, the transport of cold waters from the northwest Black Sea shelf across the shelf break in winter was shown to contribute to the formation of the CIL (Filippov, 1968; Staneva and Stanev, 1997). However less is known of the exchanges between the CIL waters and the outer shelf areas in summer, when a surface mixed layer and the underlying seasonal thermocline are formed. Ivanov *et al.* (1997) suggested that the cross frontal exchange within the CIL is strongly inhibited, so that CIL waters formed in the deep sea (i.e. offshore of the Rim Current) do not replenish the CIL waters onshore of the Rim Current (also known as near-bottom shelf waters, or BSW), due to strong cross frontal gradients in potential vorticity (PV). To the contrary, Shapiro *et al.* (2011) analysed in-situ observations over the period of 1950-2001 and showed a high correlation between the CIL temperatures in the open sea and outer shelf. However, the statistical methods alone were not able to clearly establish the relation between the cause and the consequences.

In this study we use a 3D numerical model of the Black Sea (NEMO-SHELF-BLS) to quantify the exchange of CIL waters between the open sea and the outer northwest Black Sea shelf and to assess its significance for the replenishment of BSW on the outer shelf. The model has a resolution of 1/16º latitude × 1/12º longitude and 33 levels in the vertical. In order to represent near-bottom processes better, the model uses a hybrid vertical discretisation (s-on-top-of-z) and other improved parameters of the model set-up as in Shapiro *et al.* (2013). The model was run for the period from 1979 to 2012 with water discharges from 8 main rivers, exchanges through Bosporus and meteo forcing from the Drakkar Forcing Set 5.2 (Brodeau et al, 2010). The model was spun-up from climatological temperature and salinity in January using a semi-diagnostic adjustment method. Each annual simulation started from the same initial state on 1 January without data assimilation. The data for the warm period from 1 May to 31 October of each year were used for the following analysis.

The model has been validated against in-situ (based on 77867 stations) and night-time satellite monthly mean SST observations. The model also captures well the major features seen on snapshot satellite images. A simulated daily climatology was created by averaging the temperature values over the 34-year simulation. Anomalies were calculated as the deviations of the snapshot temperatures from their climatological values. The correlation between the temperature anomalies of BSW on the outer shelf and those in the CIL waters in the deep sea were computed as well as water transports between these water masses across the shelf break. The BSW on the outer shelf are defined as the waters between the density level σ_θ=14.2 kg m^3 (i.e. the bottom of the surface mixed layer) and the seabed (max z=150 m at the shelf break). The corresponding data from open sea CIL waters in the northwest part of the deep Black Sea were taken from the depth range between σ_θ=14.2 and z=150 m.

The computed Pierson correlation between summer temperatures of BSW and the deep sea CIL is R = 0.90. This significant correlation is in agreement with the analysis from observational data of Shapiro *et al.* (2011). In order to reveal a physical link between the BSW and CIL, the in-out transports of water with σ_θ $\geq$14.2 across the shelf break were computed for each day and then averaged over the warm periods of each year. Over the 34 year time span, the on-shelf and off-shelf transports between the CIL and BSW fluctuate in the range of 0.22 to 0.45 Sv, with the maximum values in 1996 and the minimum in 1990. The net cross-shelf transport is small, approximately 0.03 Sv, due to volume conservation, and is directed off-shore due to river discharges. The years with high values of transport correspond to the situation when a ‘channel’ of constant PV connecting the BSW and CIL exists, forming a conduit for the waters to move across the shelf break. In the years of reduced transport, there was a PV ‘barrier’, i.e. a band of significant PV gradient along the shelf break, which inhibits exchanges. The efficiency of the exchange can be represented by the average renewal time of BSW, which is defined as the ratio of BSW

volume to the onshore transport. This value, as well as the volumes and the transports vary over the 34 years. The renewal time is within the range between 18 to 42 days. The short renewal time (31 days on average) compared to the seasonal time scales, suggests an efficient exchange between bottom waters on the outer shelf and the CIL in the deep sea during the warm season.

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