On the role of Black Sea Waters in controlling the North Aegean buoyancy fluxes

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Abstract

Understanding the processes that control the buoyancy fluxes of the Aegean Sea is important for various reasons.
First, the Aegean is directly connected with the Black Sea and acts as a buffer between two contrasting thermohaline systems, a concentration and a dilution basin (the Mediterranean vs the Black Sea), receiving and filtering the variability and changes of a much broader geographical area.
Second, the Aegean is capable to produce large amounts of very dense water, having temporarily been the major originator of Eastern Mediterranean Deep Water (EMDW). These processes are controlled by buoyancy fluxes, both through oceanic advection and atmospheric exchanges.
In this work we examine the characteristics and variability of heat, freshwater and the overall buoyancy air-sea fluxes, focusing on the potential role of the interaction with the Black Sea.

A thirty-year-long simulation (1985-2015) of the whole Eastern Mediterranean / Black Sea system, forced by ERA-Interim data **[1]**, was used to estimate and analyze the seasonal and interannual variability of the buoyancy fluxes in the North Aegean.
The climatological mean buoyancy flux over the North Aegean has been estimated to be about -10×10^{-6} kg m^{-1} s^{-3} (loss to the atmosphere). However, this atmospheric loss appears to be modified (reduced), by the presence of Black Sea Water (BSW). Over the eastern Aegean area, which is not directly affected by BSW, the buoyancy loss is much higher, i.e. about -30×10^{-6} kg m^{-1} s^{-3} **[2]**.
In general, the heat loss of the Aegean Sea to the atmosphere is much higher than all neighboring seas, including the Adriatic, the dominant dense-water formation site for the Eastern Mediterranean. Our analysis reveals that the thin surface layer of modified BSW acts as a moderator of the buoyancy loss from the upper water column. This layer not only absorbs the air-sea fluxes (acting as an effective insulator regarding dense-water formation processes), but also moderates or even reverses the buoyancy fluxes over its path. Moreover, Multivariate EOF analysis shows that this buoyancy loss can be connected to deeper pycnocline depth anomalies (as an indicator of vertical mixing/convection), that the Aegean Sea hosts the greatest interannual variability of buoyancy flux in the eastern Mediterranean, and that latent and sensible heat are the major components of this variability.

Thus, in addition to the significant lateral buoyancy input to the basin by the Black Sea inflow, an additional mechanism of reduction of winter heat losses to the atmosphere contributes to the control of dense water formation processes.

Research Questions

a) What is the influence of Black Sea Waters on the spatial and temporal patterns of buoyancy flux over the Aegean Sea?

b) How is the vertical distribution of the water column affected as a consequence of this surface forcing by buoyancy fluxes?

Description & Methodology

For the calculation of buoyancy fluxes over the Aegean Sea, output from the 30-year hindcast simulation of the Eastern Mediterranean - Black Sea systems (EMBS) **[1]**, is used. Monthly averages of surface heat fluxes are used to calculate the net heat flux:

$$Q_{NET} = Q_{SW} + Q_{LW} + Q_{latent} + Q_{sensible} \qquad (1)$$

and in conjunction with monthly averages of fresh water fluxes, the total monthly surface buoyancy flux is calculated, as well as its thermal and haline constituents:

$$F_B = \underbrace{\frac{1}{C_p}\, g\, a\, Q_{NET}}_{\text{thermal component, } F_B^T} - \underbrace{g\, \beta\, (E-P)\, S}_{\text{haline component, } F_B^S} \qquad (2)$$

It is evident from these equations that the thermal component F_B^T of the surface buoyancy flux can be further decomposed into a short-wave, a long-wave, a latent heat and a sensible heat component by replacing Q_{NET} by the corresponding heat flux (i.e. Q_{SW}, Q_{LW}, Q_{latent} or $Q_{sensible}$). This property is exploited in the final part of the analysis (Fig. 7).
The total surface buoyancy flux F_B as calculated by Eq. 2, time-averaged for the 30-year period, can be seen in Figure 1.

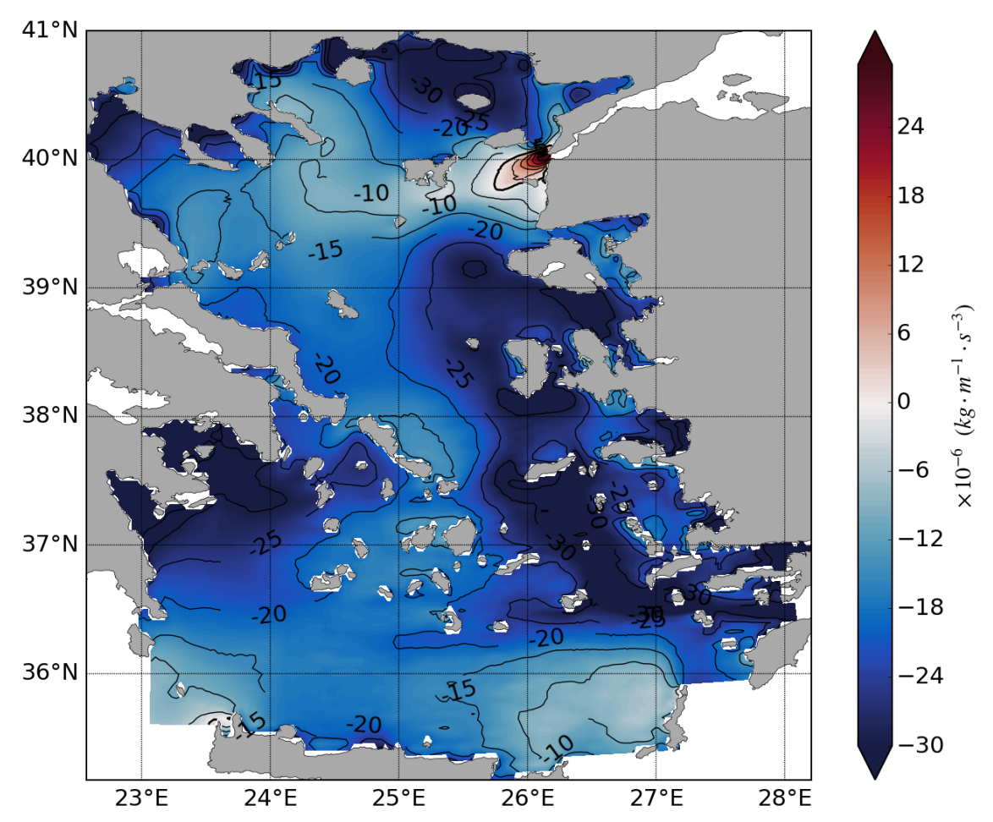


*Figure 1: Total surface buoyancy flux over the Aegean Sea, as simulated by EMBS, averaged for the period 1985-2015 (from **[2]**).*

It is clear from Figure 1, that buoyancy loss over the eastern part of the Aegean Sea which is not directly affected by the Black Sea Waters (BSW), is around three times higher than the western and northern part of the basin (which is directly influenced by BSW). Moreover, near the Dardanelles exit the input of cold/less saline surface waters results in a reversal of the buoyancy flux sign, demonstrating the role of the BSW as a modifier of the air-sea fluxes and deep-water formation processes.
A decomposition of the seasonally-averaged buoyancy flux into a thermal and a haline component (Fig. 2), shows that the thermal component is between five and ten times larger than the haline component overall.

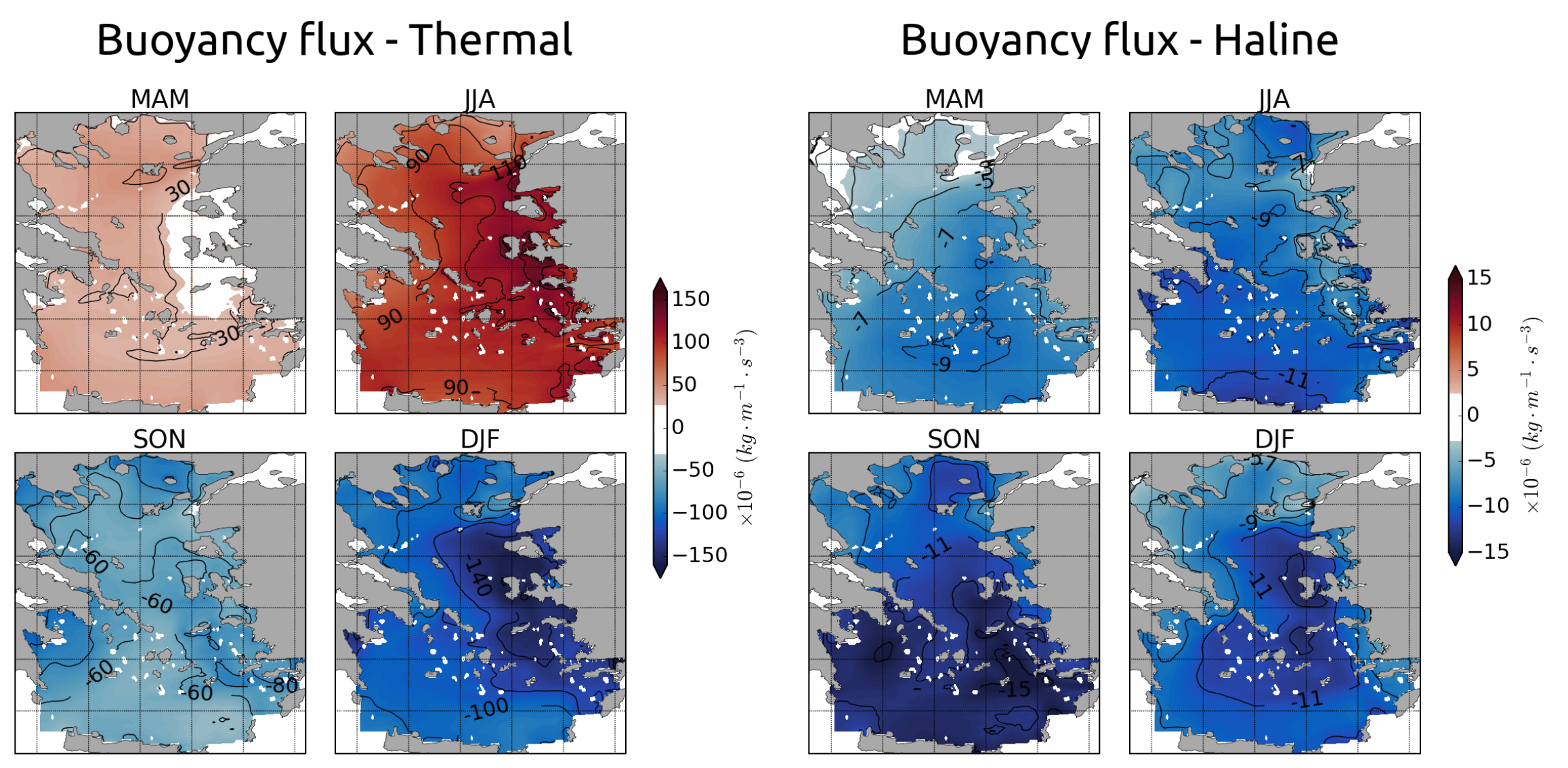
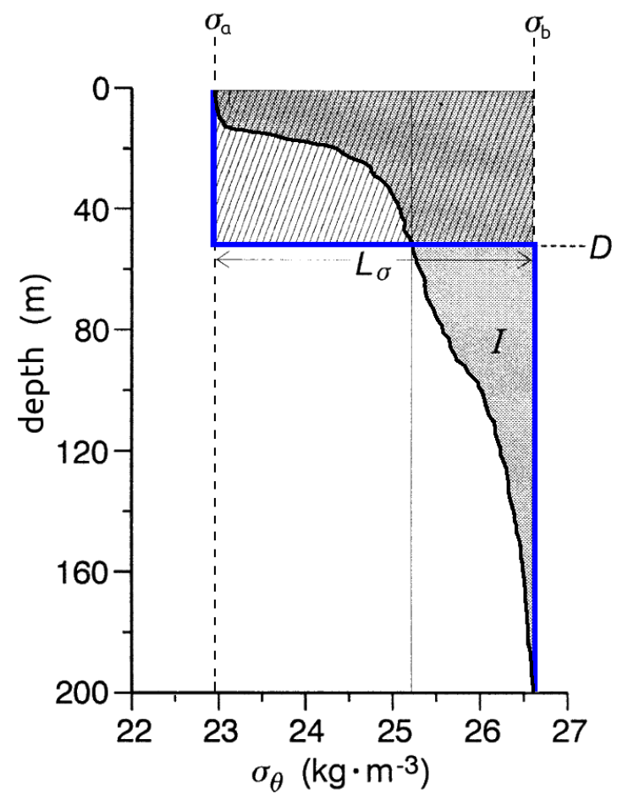


*Figure 2: Seasonally-averaged surface buoyancy fluxes over the Aegean Sea, as simulated by EMBS. Shown separately for the thermal (left) and haline (right) buoyancy flux components (from **[2]**).*

As can be deduced from Figure 2, the high buoyancy loss overall in the eastern part of the Aegean Sea (Fig. 1), can be mostly attributed to winter-time cooling (heat loss) of the surface waters, in combination with increased evaporation and higher salinity (potentially due to northward advection of Levantine waters).



$$D = \frac{\int_0^{z_b} z N_b^2(z)\, dz}{\int_0^{z_b} N_b^2(z)\, dz} = \frac{\int_{z_a}^{z_b} (\sigma_{\theta b} - \sigma_\theta)\, dz}{\sigma_{\theta b} - \sigma_{\theta a}}$$

*Figure 3: Schematic of the integral-depth-scale method for estimating the depth of the pycnocline D (Adopted from **[3]**). This method selects the depth D such, that given a density profile with surface and bottom densities σ_a and σ_b respectively, the original profile (black line) is transformed to an equivalent profile with a step from σ_a to σ_b at depth D (blue line), which preserves the total density integrated over the whole water column.*

In order to better understand the role of the BSW input on the buoyancy fluxes and the water column, as well as estimate the contribution of each of the buoyancy flux components on the total variability, Multivariate Empirical Orthogonal Function (MEOF) analysis is performed on monthly anomalies of total surface buoyancy flux, and pycnocline depth (estimated as described in Figure 3). The pycnocline depth is used as a measure of the effect of surface buoyancy fluxes on convection and mixing. Finaly, the individual thermal constituents along with the haline component are also examined in the last part of the analysis.

Results

Mutlivariate EOF analysis of two variables, namely total surface buoyancy flux anomaly and pycnocline depth anomaly, demonstrates that a large part of the combined variability of these variables in the Eastern Mediterranean, lies within the Aegean Sea (Fig. 4). The largest variability of buoyancy flux is observed in the central and south Aegean and is connected to the largest variability of pycnocline depth being in the north Cretan Sea and Cyclades (Myrtoan Sea). Peaks of buoyancy loss coincide with deeper pycnocline depths, as demonstrated in the corresponding Principal Component time-series. This behaviour occurs during the cold months of years that are known to have produced dense waters (e.g. 1987, 1992, 1993, 2012, etc.).

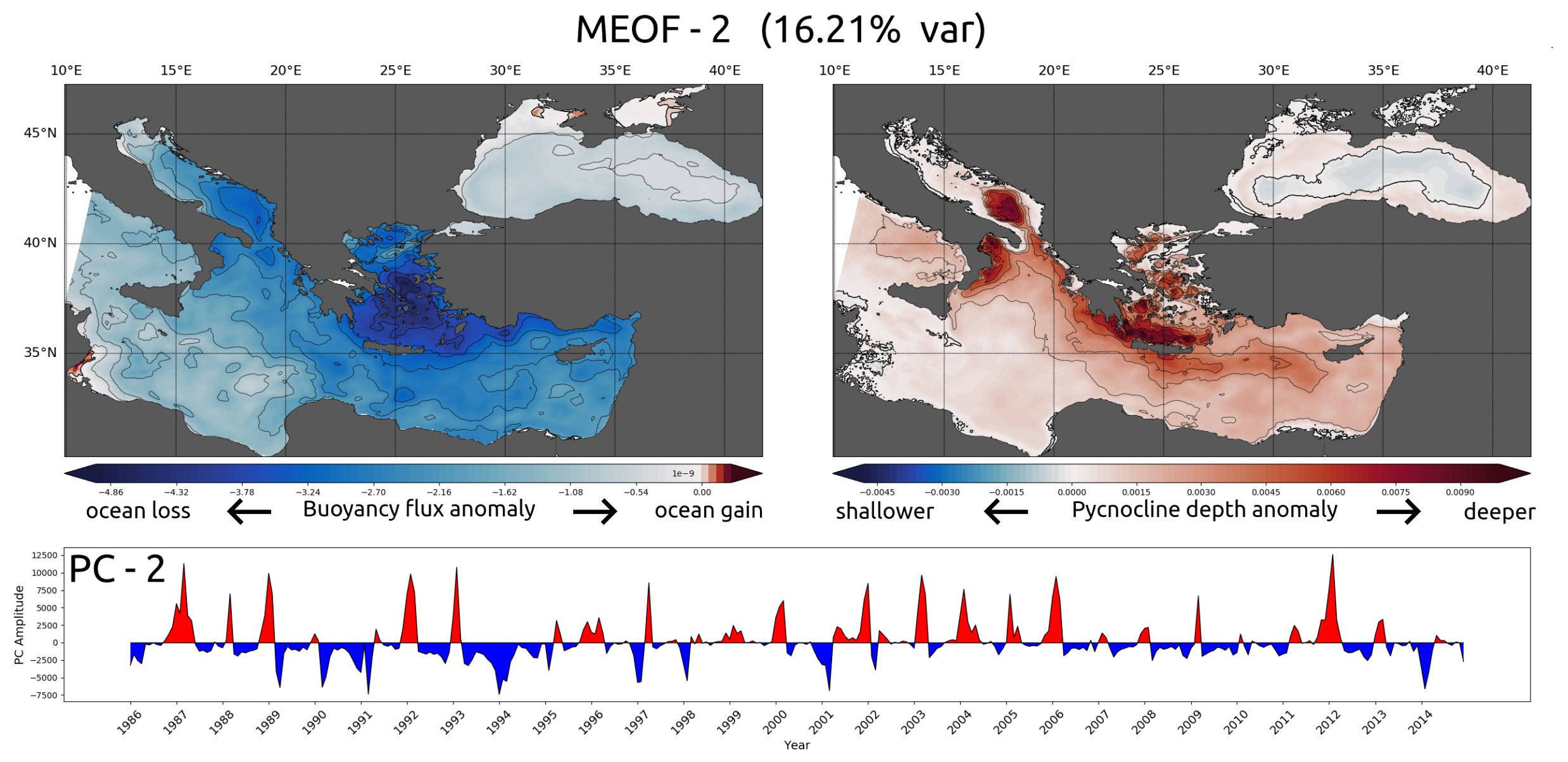


Figure 4: Second Multivariate-EOF mode explaining around 16% of the combined buoyancy-flux-anomaly / pycnocline-depth-anomaly variance. Eigenvectors for the two variables (top maps) and timeseries of the eigenvalue -or Principal Component (bottom).

The fourth MEOF mode for the Mediterranean Sea, reveals a dipole pattern between the eastern and the western parts of the basin, reversing every around 10 years and coinciding with the BiOS oscillation (Fig. 5). The pattern describes a reversal in buoyancy flux anomaly sign between the Aegean and the Ionian Seas, and coincides with a reversal in pycnocline depth anomaly, especially between the Aegean and the Adriatic Seas, and demonstrates the reported reversal between the two basins as potential sites for dense water formation.

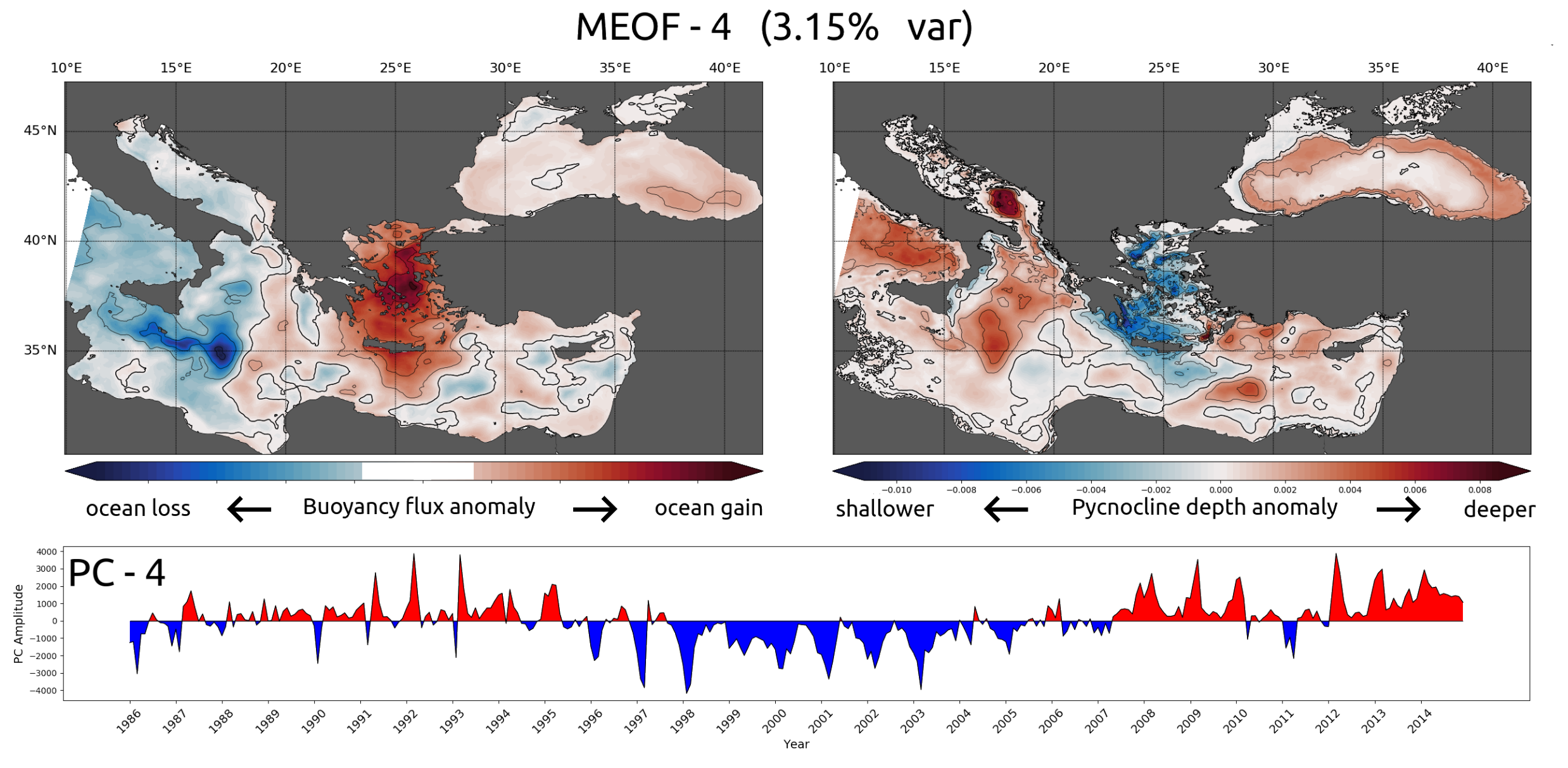


Figure 5: Same as in Fig. 4, for the fourth Multivariate EOF mode, explaining around 3% of the combined buoyancy-flux-anomaly / pycnocline-depth-anomaly variance.

When the same analysis is performed on the Aegean Sea alone (excluding the rest of the Mediterranean basin), this behaviour is observed already in the first MEOF mode, accounting to ~38% of the total variance of combined buoyancy flux anomaly and pycnocline depth anomaly (Fig. 6). The Cretan Sea, the Myrtoon Sea, the Chios and Skyros basins, and to some extent the Athos and Limnos basins, are all places of anomalously deep pycnoclines, coinciding with anomalously high surface buoyancy loss.

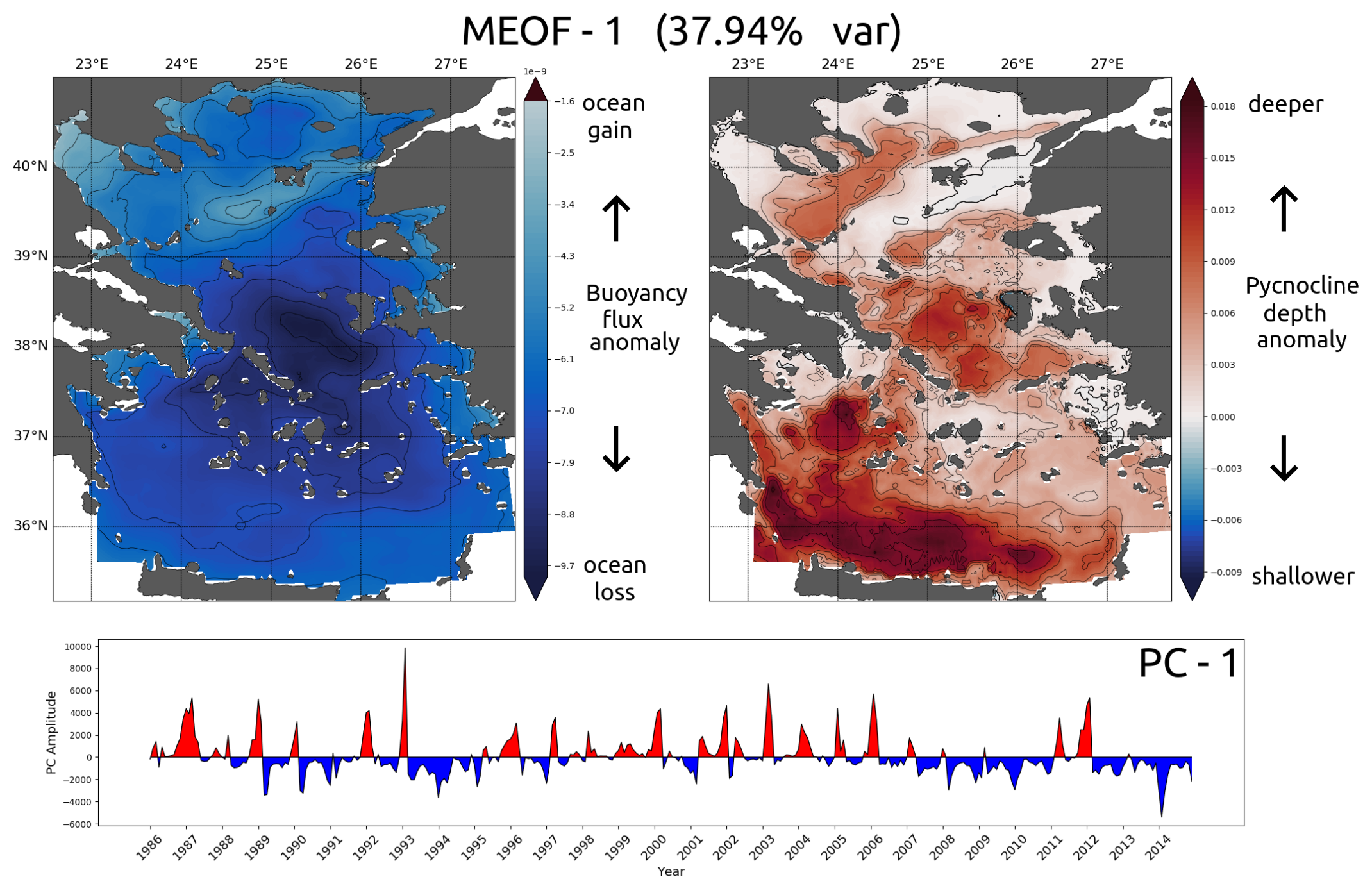


Figure 6: Same as in Fig. 4, for the first Multivariate EOF mode, explaining around 38% of the combined buoyancy-flux-anomaly / pycnocline-depth-anomaly variance. In this case the analysis was performed only for the Aegean Sea, for the 1985-2015 period.

MEOF performed on six variables shows an indistinguishable eigenvalue from the two-variable MEOF, with an identical eigenvector (PC) for the pycnocline depth anomaly (Fig. 7). However, the thermal and haline components of the buoyancy flux can now be ranked according to their contribution to the total buoyancy flux variance, with latent heat contributing the most, and the shortwave component contributing the least (i.e. Latent heat > Sensible heat > Long-wave > Haline > Short-wave).

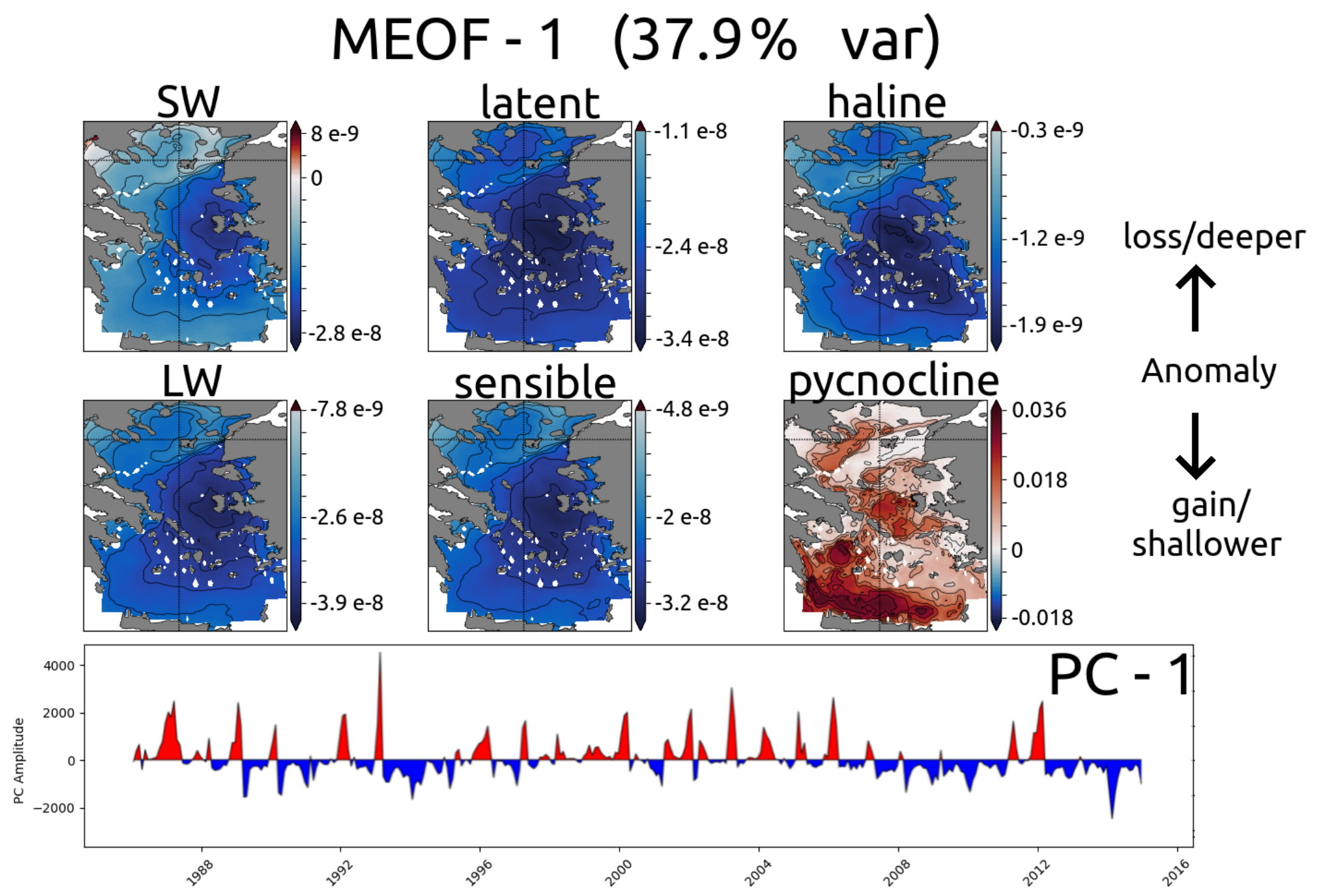


Figure 7: Same as in Fig. 6, for the first Multivariate EOF mode. In this case the analysis has been expanded to six variables and decomposes the buoyancy flux into the four thermal components anomaly and the haline component, and includes the pycnocline depth (see also the methodology section). The result explains around 38% of the orthogonaly combined variance of these six variables, for the 1985-2015 period.

Conclusions

a) Excess surface buoyancy losses in the Aegean Sea, are correlated to deeper pycnocline depths, pointing to convection.
b) The BiOS oscillation can be observed in the combined surface buoyancy fluxes and pycnocline depth anomalies.
c) The latent heat component is the main contributor of variability to the surface buoyancy fluxes, while the short-wave radiation component is the smallest contributor.

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