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STATE OF THE PLANET Discussions

The dynamical role of salinity content in the Mediterranean Sea

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Abstract.

The Mediterranean Sea is a semi-enclosed basin with an excess amount of evaporation compared to the water in-flux through precipitation at the surface and river runoff on the land boundaries. The deficit in the water budget is balanced by the inflow in the Straits of Gibraltar and Dardanelles connecting the Mediterranean with the less saline Atlantic Ocean and the Marmara Sea, respectively. There is evidence that the Mediterranean region will be a hotspot with the warming Earth (Tuel and El Tahir, 2020) which will possibly change the water cycle significantly, but with a large uncertainty (Cos et al., 2022). Therefore, it is inevitable to monitor the evolution of the essential ocean variables (EOVs) to respond to the associated risks and mitigate the related problems. In this work, we evaluate the evolution of the salinity content and anomaly in the Mediterranean Sea during the last decades using the Copernicus Marine Service products. The results show an increasing mean salinity with a stronger trend in the eastern basin. The spread of the products implies a larger variability in the western basin while the standard deviation is lower in the eastern side, especially in the Ionian and the Levantine basins.

Short summary.

This paper investigates the salinity content and anomaly in the Mediterranean Sea using observational and reanalysis products. The salinity content increases overall while negative salinity anomalies appear in the western basin especially around the upwelling regions. There is a large spread in the salinity estimates that reduces with the emergence of the Argo era.

1 Introduction

The Mediterranean Sea is warming (Pisano et al., 2020). It is evaporating more and more (Skliris et al., 2018; Jordà et al., 2017) with marine heat waves increasing in intensity, duration and frequency (Juza et al., 2022). The Mediterranean region is expected to be a hotspot with global warming (Tuel and El Tahir, 2020) that will likely alter the water cycle (Cos et al., 2022). Tracking the changes in the essential ocean variables (EOVs) is crucial in order to understand the impact of climate

https://doi.org/10.5194/sp-2022-11
Preprint. Discussion started: 26 September 2022

change. Two of these EOVs are linked to the ocean salinity at the surface and subsurface, which will be affected significantly by the surface heat and water fluxes. The global water cycle modulating the ocean salinity is a key element of the Earth's climate (Cheng et al., 2020). In the Mediterranean Sea, water fluxes through the land (rivers) and atmosphere (evaporation and precipitation) are balanced by two sea straits, namely Gibraltar and Dardanelles, which transport the less saline Atlantic Ocean and Black Sea waters into the basin. These density contrasts contribute to the wind driven circulation and generate a highly energetic anti-estuarine circulation (Cessi et al., 2014). The salinity of the Atlantic water entering through the Gibraltar Strait is about 36.2 psu. The salinity of the Dardanelles can vary significantly due to the strong mixing though it can be as low as 27 psu (Aydogdu et al., 2018; Sannino et al., 2017). Recently, Fedele et al. (2022) studied the characterization of the Atlantic Waters (AW) and Levantine intermediate waters (LIW) from the ARGO profiles in the last 20 years. Their conclusion is a clear salinification and warming trend which characterised both AW and LIW over the last two decades. Skliris et al. (2018) argue that the Mediterranean basin salinification is driven by changes in the regional water cycle rather than by changes in salt transports at the straits, as it is shown by the water mass transformation distribution in salinity coordinates. However, we will show that there is bigger uncertainty in the radius of influence of both the Gibraltar and Dardanelles Straits. In Section 2, the data and methods used in this study are presented. In Section 3, the results are shown and discussed, while in Section 4 the conclusions are drawn.

2 Data and method

In this study, Copernicus Marine Service global and regional reanalysis as well as observational gridded products are used to explore the role of the salinity variability in the 0-300 m depth among different estimates as well as temporal and spatial anomalies against a mean.

The Mediterranean 1/24° resolution regional reanalysis (hereinafter, MEDREA24; Escudier et al., 2021) from Copernicus Marine Service is used as a regional high-resolution product. In this work, MEDREA24 and its interim extension until the end of 2021 are included. Moreover, the 1/4° resolution Global Reanalysis Ensemble Product (hereinafter, GREP) is also used. It consists of the global reanalysis from Mercator Ocean's GLORYS2V4 (Lellouche et al., 2013), UK MetOffice's GLOSEA5v13 (MacLachlan et al., 2014) using the FOAM system (Blockley et al., 2014), CMCC C-GLORSv7 (Storto et al., 2016) and ECMWF's ORAS5 (Zuo et al., 2017). A study on the ocean heat content and steric sea level representation in the GREP ensemble can be found in Storto et al. (2019a). A more general status of the global ocean reanalysis is reviewed in Storto et al. (2019b). The period covered by the GREP is 1993-2019.

As observational products, the CORA (Szekely et al., 2019) and ARMOR3D (Guinehut et al., 2012) gridded reconstructions are adopted. Both datasets are available between 1993 and 2020.

https://doi.org/10.5194/sp-2022-11
Preprint. Discussion started: 26 September 2022

The investigation is performed in the entire Mediterranean Sea as well as in the eastern and western basins, which have very different characteristics. The salinity (S) mean is computed using formula (1) as the monthly volume (V) average of each product between 0 and 300 m depth, i.e., excluding the shelf areas close to the coast with a depth less than 300 m.

$$\overline{S} = \frac{1}{V}\iiint_V S dV \quad (1)$$

The mean of different products and their standard deviation are evaluated in the common period 1993-2019. Besides this time frame, the CORA and ARMOR3D time series are available until 2020, while the MEDREA24 time series is provided up to 2021 (last 6 months extended in interim mode).

The salinity anomalies are computed using formula (2). The difference of the salinity, S, with a reference salinity, S_{ref}, is normalised by the depth of the water column which is constant in our case with $z_2 = 300$ m and $z_1 = 0$ m.

$$S_A = \int_{z_1}^{z_2} \frac{S - S_{ref}}{z_2 - z_1} dz \quad (2)$$

Formula (2) is a modified version of the one proposed in Boyer et al. (2007) which uses the salinity as a proxy for the equivalent freshwater content. This method has been later adopted in various studies including, among the others, Holliday et al. (2020), with a density weight to account for baroclinic properties of the water column. The formulation in Boyer et al. (2007) is based on a reference salinity. As an example, mean values of a basin (Aagaard and Carmack, 1989) is a widely used choice for S_{ref} in global freshwater content calculations. However, it is argued that since a reference value can be chosen arbitrarily, this would bring ambiguity (Schauer and Losch, 2019) in computing the equivalent freshwater content. Therefore, in this study we propose to evaluate the salinity content and anomaly following formula (2) by choosing S_{ref} as a monthly climatology of each dataset itself computed from each product separately between 1993 and 2014. Furthermore, the calculations are performed in the entire Mediterranean Sea (MED) as well as in its western (WMED) and eastern (EMED) sub basins, separated at the Sicily Strait. In Fig. 1, we present the monthly variation of the S_{ref}, as an example only the one from MEDREA24, which shows a clear difference in the seasonality in the EMED and WMED, with a maximum in March and December, respectively. It is also evident that the Mediterranean monthly salinity reference shows a seasonal cycle much similar to the one of the Eastern basin (but with different magnitude) characterised by lower salinity during the summer period and larger values at the end of the year.

3 Results and Discussion

The Copernicus Marine service products described in the previous section allow the assessment of the salinity content of the Mediterranean Sea along with its anomaly and trend during the last decades.

https://doi.org/10.5194/sp-2022-11
Preprint. Discussion started: 26 September 2022

In Fig. 2, we present the time series of the mean salinity content in the first 300 m derived from the analysed products (MEDREA24 in red; GREP ensemble mean in blue; GREP ensemble members in thin light blue; CORA in dark green, ARMOR3D in light green) and their overall mean (in black) and spread (shaded grey).

In the early 90s in the entire Mediterranean Sea (Fig. 2a), there is a large spread in salinity with the observations showing a higher salinity while the reanalysis products present relatively lower salinity. This is the case until 2005. Coinciding with the global coverage of the Argo profilers in the early 2000s following the efforts in the Global Ocean Data Assimilation (GODAE) together with the Climate Variability and Predictability Programme (CLIVAR) and the Global Climate Observing System/Global Ocean Observing System (GCOS/GOOS), the spread among different products narrows. Possibly, the reanalyses are better constrained through data assimilation with this novel observation type (Johnson et al., 2022) which provides high-resolution and high-frequency temperature and salinity profiles all over the world' ocean. The maximum spread between the period 1993-2019 is in the 90's with a value of 0.096 psu and it decreases to as low as 0.009 psu by the end of 2010s. The mean salinity computed in the entire Mediterranean Sea from all products varies between approximately 38.5 and 38.6 psu with a spatiotemporal mean of 38.57 psu (Table 1). All the products show a positive trend between 1993-2019 (in parenthesis in Table 1). The trend in the mean of all products is calculated as 0.0056 psu/year.

In the western Mediterranean (Fig. 2b), the overall mean is centred around 38.16 psu with a larger spread - with a maximum and minimum of 0.172 psu and 0.026, respectively - occurring in the early 2000s. An increase of the mean salinity in 2005 is evident from all the reanalysis products and, at a lesser extent, from the CORA dataset, which may be related to the climate regime shift in the basin (Schroeder et al., 2016) corresponding to a major deep water formation event at the beginning of the Western Mediterranean Transition (Zunino et al., 2012). The trend in the entire analysed period is about 0.0049 psu/year. This is below the rate of the basin-wide trend which is larger due to the trend in the eastern basin (0.0061 psu/yr).

In the eastern Mediterranean (Fig. 2c), the overall mean is centred around 38.87 psu with a lower spread compared to the western basin with a maximum and minimum of 0.086 psu and 0.003, respectively.

Overall, for the period between 1993-2019 we note that the observational products, gridded using optimal interpolation statistical techniques, show a higher average salinity compared to the reanalysis products that are dynamically integrated and corrected through data assimilation.

For 2020, CORA and ARMOR3D products are available, and both continue to sustain the positive trend even though it is less evident in the western basin. MEDREA24 (and its interim extension) shows an increasing mean salinity until the end of 2021. All products present larger values after 2016 and a maximum in 2018.

The spatial mean, computed between 1993-2014 from all products in the first 300 m (Fig. 3a), shows a gradual increase in the salinity from west to east. Minimum salinity occurs close to river mouths, such as in the North Adriatic Sea due to the presence of several freshwater inputs such as the Po river, and on the pathways of the outflow of the Dardanelles and Gibraltar straits. The Atlantic water, modified through its route, can be traced till the eastern basin from its salinity imprint. The spread

https://doi.org/10.5194/sp-2022-11
Preprint. Discussion started: 26 September 2022

deduced from all the products (Fig. 3b) implies that they agree more, meaning lower spread, in the Levantine and Ionian Seas and to a lesser degree between the Balearic and Sardinia / Corsica islands. The spread is larger especially in the northern Aegean and Adriatic Sea and southwestern coast between the Gulf of Gabes and Gibraltar Strait. This uncertainty or mismatch in the products is possibly due to the different volume fluxes through the rivers and straits.

In Fig. 4 (a-c), we show the time series of the salinity anomaly estimates in the western (Fig. 4a), eastern (Fig. 4b) and entire (Fig. 4c) basin from each product using formula (2). We recall that the salinity reference is computed for each product per se. Moreover, the salinity anomaly map in 2021 from MEDREA24 is depicted in Fig. (4d), computed against the overall mean between 1993-2014, which is shown in Fig. (3a).

The anomalies have a larger range in the reanalysis products. There is a negative anomaly within the first decade in GREP and MEDREA24 which turns to positive first in the western Mediterranean (Fig. 4a) and followed by the eastern basin (Fig. 4b) after 2006. In the CORA and ARMOR3D, instead, there is a clear increase in the salinity anomaly in the eastern Mediterranean and the entire basin with a less evident positive trend in the western basin. We summarise the mean salinity anomalies in Table 2.

In 2021, the anomaly is mostly positive with some negative anomaly structures on the path of modified Atlantic water (Fig. 4d), Alboran Sea, upwelling favouring Balearic islands. Fedele et al. (2022) reports a positive salinity trend in the modified Atlantic and Levantine intermediate waters using 18-year long (2001-2019) Argo profiles, which in general agrees with the anomaly map to a large extent. However, we note that the spread on the pathway of the water entering from the Gibraltar strait and reaching the Levantine basin has a relatively larger spread compared to the deeper areas (see Fig. 3b).

4 Conclusions

In this study, we presented the salinity characteristics of the Mediterranean Sea deduced from various products including reanalysis and gridded observational datasets released by Copernicus Marine Service which allowed us to reach more robust outcomes. The mean salinity with its anomaly and trend is computed and analysed in the entire basin as well as in the western and eastern basins for all the datasets separately and averaged. The spatial maps of the mean and the spread of the salinity are depicted and discussed. The overall results show a salinification of the Mediterranean Sea agreeing with earlier studies (e.g., Skliris et al. 2018). The subbasin scale investigation shows negative salinity anomalies in the western basin in the upwelling regions, which may imply stronger upwelling events, and waterway following the north African coast, which may be a consequence of the freshening North Atlantic water masses (Holliday et al., 2020). There is a large spread in the salinity estimates among different products, which reduces with the introduction of the Argo profilers in the data assimilation components of the reanalysis systems. Besides the large spread, considering the reported discrepancies in the salinity measurements after 2016 (Barnoud et al., 2021), it is essential to use all available information sources for a more accurate state estimate and uncertainty quantification.

https://doi.org/10.5194/sp-2022-11
Preprint. Discussion started: 26 September 2022

Data availability

All datasets used in this article can be obtained from the Copernicus Marine Service catalogues as described in Table 3 with their names, temporal coverages, and documentation.

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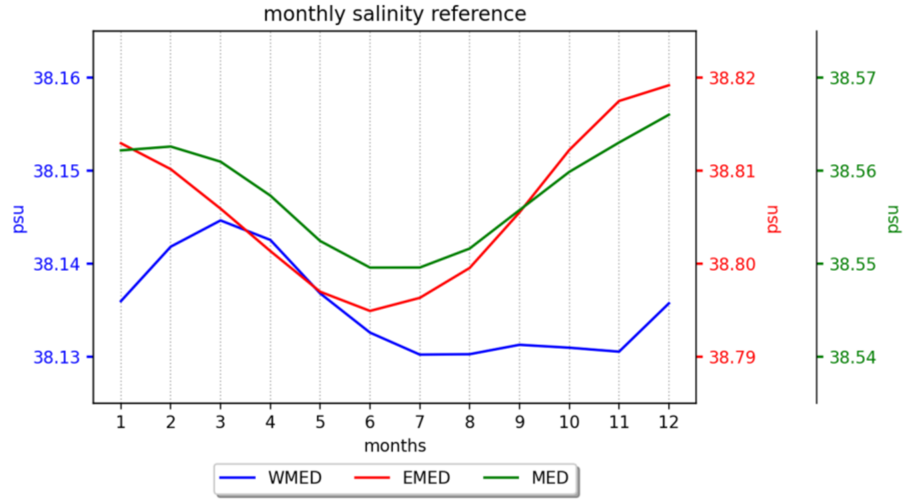

Figure 1: The monthly reference salinity S_{ref} estimates calculated from the MEDREA24 in the period 1993-2014. The green, blue, and red curves show the MED, WMED and EMED regions respectively on the corresponding vertical axis. The same calculation is done for each product separately (not shown) to evaluate formula (2) to compute salinity anomaly.

psu (psu/year)	MED	WMED	EMED
MEDREA24	38.58 (0.0070)	38.15 (0.0055)	38.83 (0.0078)
GREP	38.48 (0.0110)	38.01 (0.0111)	38.87(0.0106)
CORA	38.61 (0.0020)	38.21(0.0019)	38.84 (0.0024)
ARMOR3D	38.64 (0.0027)	38.24 (0.0020)	38.75(0.0032)
mean	38.57 (0.0056)	38.16 (0.0049)	38.87 (0.0061)

Table 1. The temporal mean salinity (in psu) and trend (in psu per year) in the 0-300 m between the common period 1993-2019 for separate products and their overall mean in *Fig. 2*.

https://doi.org/10.5194/sp-2022-11
Preprint. Discussion started: 26 September 2022

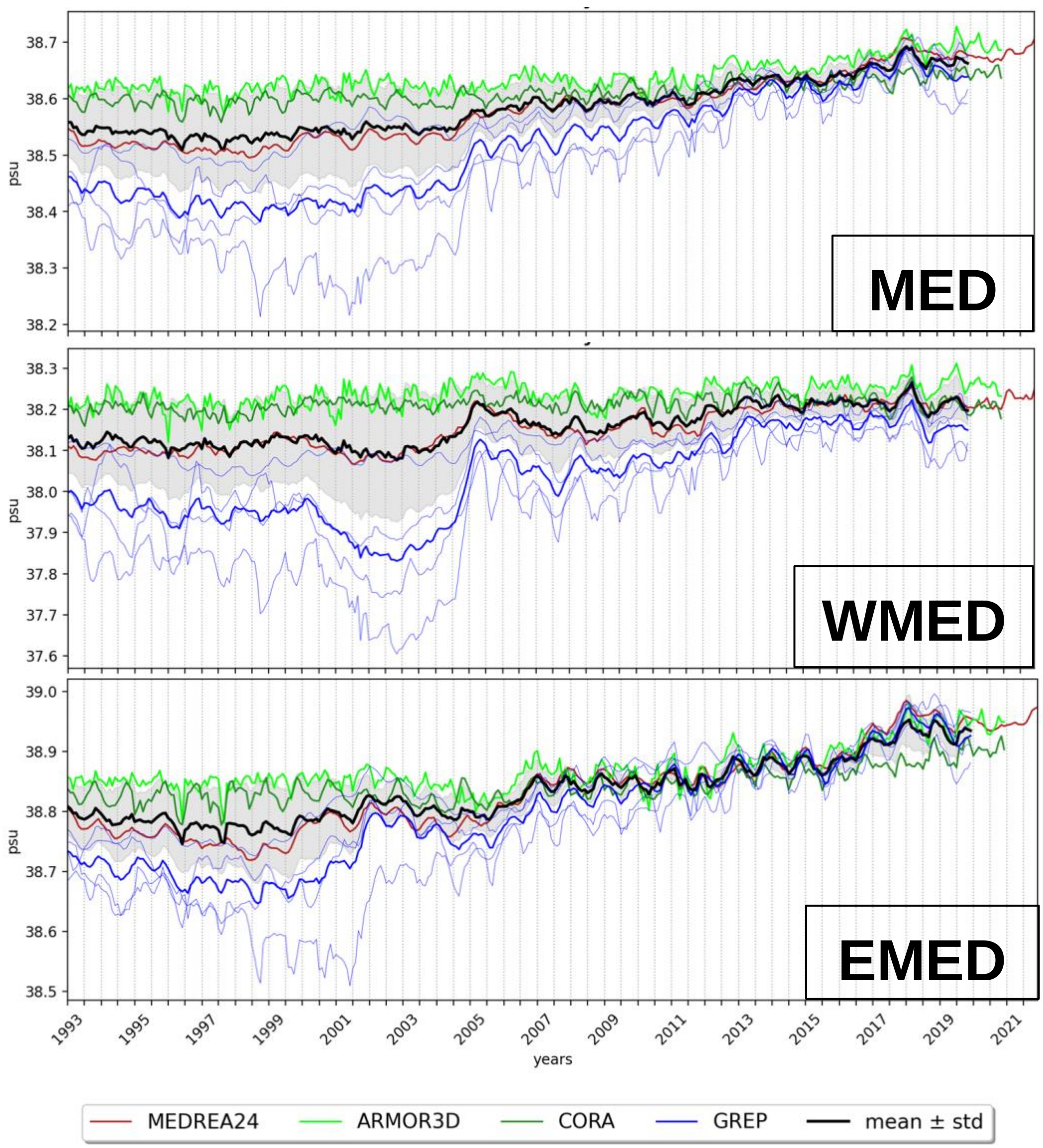

Figure 2: Time series of mean salinity in the **(a)** entire Mediterranean Sea **(b)** western Mediterranean basin and **(c)** eastern Mediterranean basin between the period 1993 and 2021 from MEDREA24, ARMOR3D, CORA and GREP. The mean of all the products is drawn in black with their standard deviation shaded around the mean. GREP ensemble members are depicted in thin blue curves. The GREP product covers the period until 2019 while the observational products CORA and ARMOR3D cover until 2020. The time series for MEDREA24 is extended until 2021 using the interim products.

https://doi.org/10.5194/sp-2022-11
Preprint. Discussion started: 26 September 2022

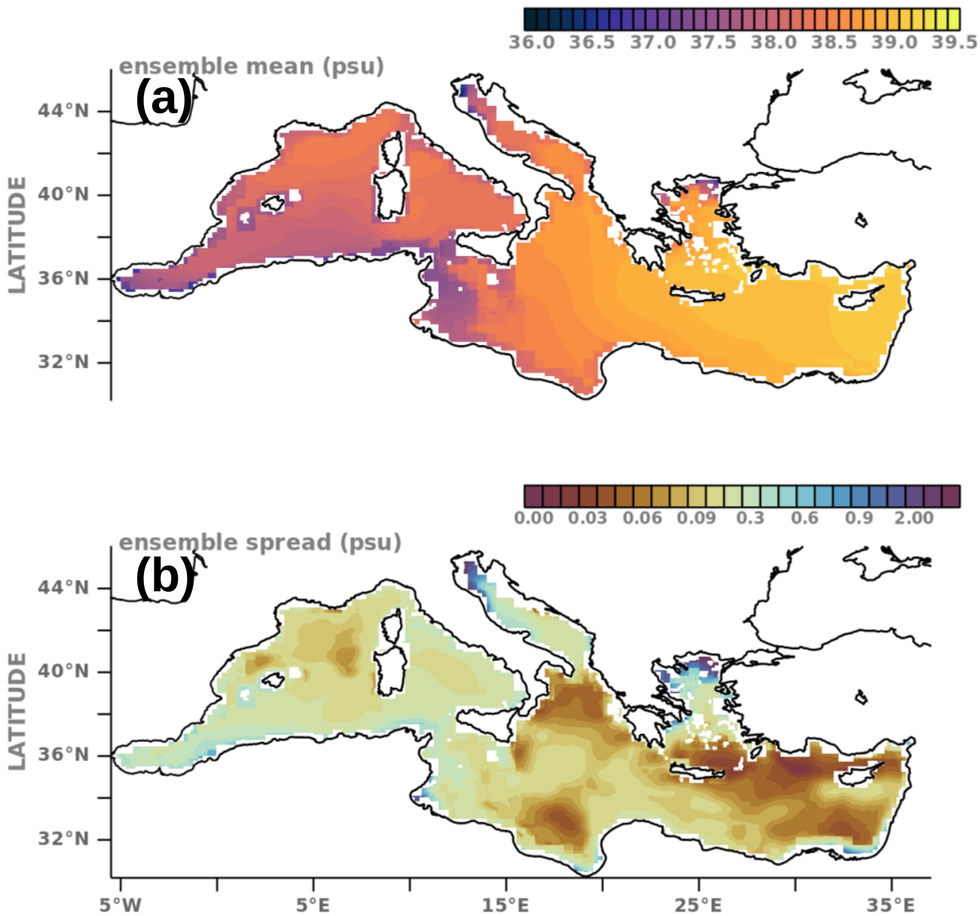

Figure 3. The maps of **(a)** mean and **(b)** spread of salinity in the period between 1993–2014 in 0-300 m. computed from the GREP ensemble mean, CORA, ARMOR3D and MEDREA24 products. We refer to the text for the information on the data products used. The analysis is performed only if the water column is deeper than 300 m. Note that in **(b)** the colour scale is not linear to show the smaller standard deviation.

psu	**MED**	**WMED**	**EMED**
MEDREA24	0.026	0.027	0.025

https://doi.org/10.5194/sp-2022-11
Preprint. Discussion started: 26 September 2022

GREP	0.042	0.056	0.034
CORA	0.001	-0.008	0.007
ARMOR3D	0.001	-0.009	0.008
mean	0.018	0.017	0.019

Table 2. The temporal mean salinity anomaly (in psu) in the 0-300 m between the common period 1993-2019 for separate products and their average in *Fig. 3*.

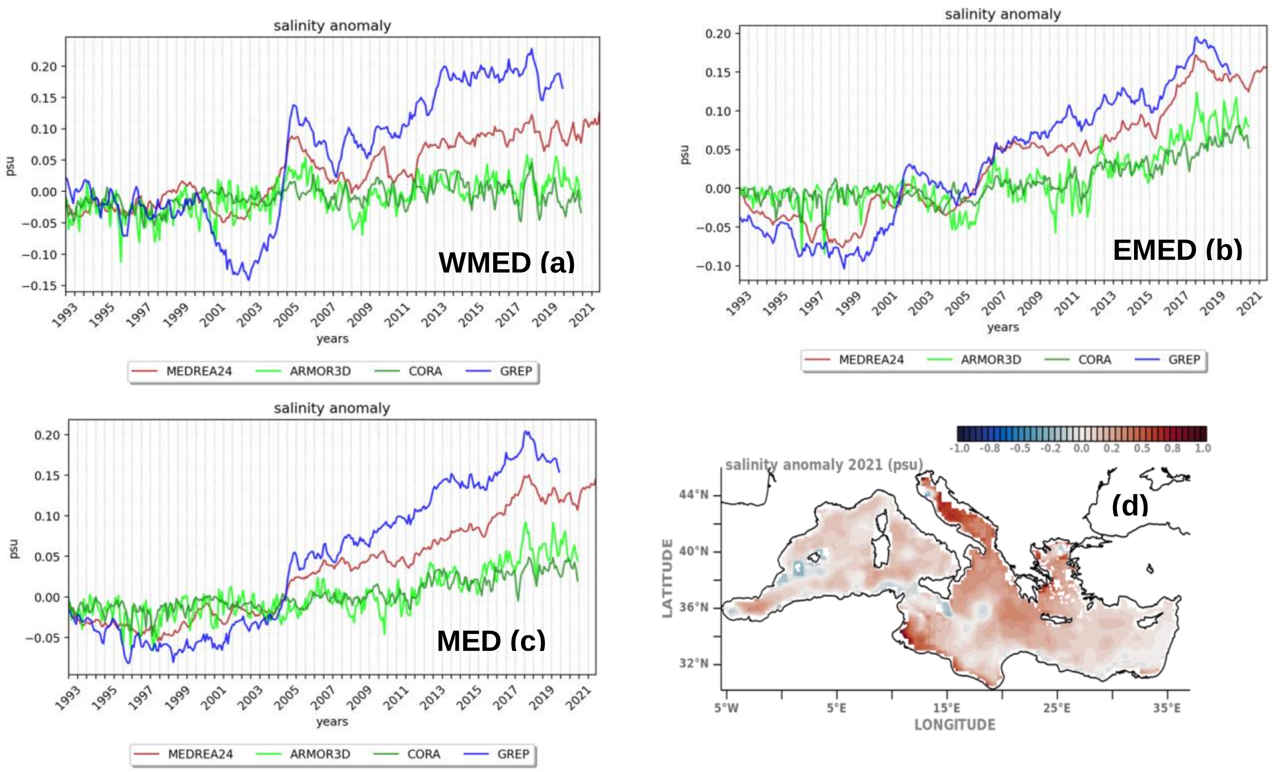

Figure 4. Time series of salinity anomaly from the MEDREA24, GREP, ARMOR3D and CORA products in the **(a)** western Mediterranean Sea **(b)** eastern Mediterranean basin and **(c)** entire Mediterranean basin computed with respect to the monthly reference salinity estimates in the corresponding area in **Fig. 1** calculated from the MEDREA24 in the period 1993-2014. The GREP products cover the period until 2019 while the observational products CORA and ARMOR3D covers until 2020.

https://doi.org/10.5194/sp-2022-11
Preprint. Discussion started: 26 September 2022

The time series for MEDREA24 is extended until 2021 using the interim products. **(d)** salinity anomaly in 2021 in the Mediterranean Sea against the mean of salinity in Fig. 3a.

	Product Name	Documentation	Time Period
Mediterranean Sea Physics Reanalysis	MEDSEA_MULTIYEAR_PHY_006_004	Product User Manual (CMEMS-MED-PUM-006-004) Quality Information Document (CMEMS-MED-QUID-006-004) https://resources.marine.copernicus.eu/product-detail/MEDSEA_MULTIYEAR_PHY_006_004/DOCUMENTATION	1987-2021
Global Ocean Ensemble Physics Reanalysis	GLOBAL_REANALYSIS_PHY_001_031	Product User Manual (CMEMS-GLO-PUM-001-031) Quality Information Document (CMEMS-GLO-QUID-001-031) https://resources.marine.copernicus.eu/product-detail/GLOBAL_REANALYSIS_PHY_001_031/DOCUMENTATION	1993-2019
Global Ocean-Delayed Mode gridded CORA-In-situ Observations objective analysis in Delayed Mode	INSITU_GLO_TS_OA_REP_OBSERVATIONS_013_002_b	Product User Manual (CMEMS-INS-PUM-013-002-ab) Quality Information Document (CMEMS-INS-QUID-013-002b) https://resources.marine.copernicus.eu/product-detail/INSITU_GLO_TS_OA_REP_OBSERVATIONS_013_002_b/DOCUMENTATION	1993-2020
Multi Observation Global Ocean 3D Temperature Salinity Height Geostrophic Current and MLD	MULTIOBS_GLO_PHY_TSUV_3D_MYNRT_015_012	Product User Manual (CMEMS-MOB-PUM-015-012) Quality Information Document (CMEMS-MOB-QUID-015-012) https://resources.marine.copernicus.eu/product-detail/MULTIOBS_GLO_PHY_TSUV_3D_MYNRT_015_012/DOCUMENTATION	1993-2020

Table 3. Products from Copernicus Marine Service used in this study.