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ΜΕΤΑΠΤΥΧΙΑΚΗ ΕΡΓΑΣΙΑ

"Inferring Mediterranean Sea water cycle changes from 3-D salinity changes"

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Abstract

Uncertainties and lack of direct observations of the water cycle, led the development of a new method to estimate water cycle change from salinity change, based on the water mass transformation theory[1]. Studying the water mass transformation distribution in salinity coordinates allowed us to estimate changes of the Mediterranean water cycle. Our study shows an increase in net evaporation of 8% - 25% over the period of 1955-2014, associated with strong basin-scale and multi-decadal salinification. Direct analysis of the water cycle parameters showed an increase in Evaporation, combined with a decrease in River run off and small trends in Precipitation, while also showing a strong intensification of the water cycle of 7% - 30% for the same period. Water mass transformation distribution in salinity coordinates suggests that the Mediterranean basin salinification is driven by changes in the regional water cycle rather than changes in salt transports at the straits, most likely linked to global climate changes.

Περίληψη

Αβεβαιότητες, έλλειψη και κακή χωρική και χρονική κάλυψη δεδομένων του υδρολογικού κύκλου (Εξάτμιση, Βροχόπτωση, Εισροές ποταμιών), οδήγησαν στην δημιουργία μιας νέας μεθοδολογίας, βασιζόμενη στην θεωρία μετασχηματισμού μάζων νερού (Water mass transformation theory)[1]. Η ανάλυση της κατανομής της αλατότητας και των ρυθμών μετασχηματισμού μαζών νερού μας δίνει την δυνατότητα να υπολογίσουμε της αλλαγές του υδρολογικού κύκλου, δηλαδή τους μηχανισμούς μεταβολής της αλατότητας. Η ανάλυση έδειξε αύξηση του υδρολογικού ισοζυγίου (E-P-R) της τάξης 8% - 25% για την περίοδο 1955-2014, συνδεόμενη με μια σημαντική αύξηση της αλατότητας σε κλίμακα λεκάνης και σε υπερ- δεκαετή χρονική κλίμακα. Η απευθείας ανάλυση των παραμέτρων του υδρολογικού κύκλου επίσης δείχνει αύξηση στον υδρολογικό κύκλο της τάξης του 7% - 30%, οφειλόμενη κυρίως στην ισχυρή αυξητική τάση της εξάτμισης σε συνδυασμό με την αρνητική τάση στις ποτάμιες εισροές και μικρές τάσεις στην βροχόπτωση. Ο μετασχηματισμός των μαζών νερού υποδεικνύει ότι παρατηρούμενη αύξηση της αλατότητας της Μεσογείου να οφείλετε σε αλλαγές του υδρολογικού της Μεσογείου που πιθανόν να συνδέονται με αποτελέσματα της κλιματικής αλλαγής και όχι σε αλλαγές στην μεταφορά αλατιού μέσω των στενών (Γιβραλτάρ, Δαρδανέλια).

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1. Introduction

1.1. Geography

The Mediterranean Sea is a semi enclosed basin, almost completely enclosed by land: on the north by Southern Europe and Anatolia, on the south by North Africa, and on the east by the Levant. Mediterranean waters are covering an area of approximate 2,500,000 km^2 and a volume of 3,750,000 km^3, the average depth of the basin is about 1,500m and the deepest parts are reaching down to 5,267m. The Mediterranean is formed by two principal sub-basins (the Western and the Eastern Mediterranean) which are connected by the Sicily Strait. Both the Eastern and the Western Mediterranean, in their turn, enclose several regional seas that are also separated by straits and channels. The Mediterranean is connected to the Atlantic Ocean only through the Gibraltar strait (~15km width), through the Dardanelles strait to the Black Sea and through the artificial Suez Canal to the Red Sea, build in 1869.

1.2. Hydrology

The Gibraltar strait plays a major role in the Med overturning circulation, in fact Atlantic inflow water is counterbalancing the Mediterranean water deficit caused by the intense Evaporation which overcomes Precipitation and River Run off in the basin. Thus, the Med Sea is characterized as an Evaporation (concentration) Basin. The water deficit and the high salinity produced due to Evaporation, drives an inverse estuarine circulation in the Strait of Gibraltar, created by the density contrast between the highly Saline Mediterranean waters (38.4 pss) and the relative fresh Atlantic Water (AW ~ 36.2 pss) (Bethoux and Gentili, 1999), the total water budget is balanced through the water fluxes at the Gibraltar Strait (Atlantic Water (AW) inflow: 0.72-0.92 Sv & Mediterranean Overflow Water (MOW) outflow: 0.68-0.88Sv) and Dardanelles strait (Black Sea Water (BSW) inflow: 0.039 Sv & North Aegean Sea (NAS) outflow: 0.030 Sv, (Tanhua, 2013). The AW entering the Mediterranean flows as Modified Atlantic Water (MAW) at the surface throughout the whole basin, gaining salinity and density. In the Levantine sea through high evaporation the Levantine Intermediate Water (LIW) is formed, creating the main component of the intermediate layer thermohaline circulation (200-600m) branch returning to the Atlantic Ocean. LIW plays a major role in the formation of the Eastern Mediterranean Deep Water (EMDW) and the Western Mediterranean Deep Water (WMDW). Aside of the active deep overturning circulation, the Mediterranean has a shallow circulation cell and a complex upper layer circulation with several permanent and quasi permanent eddies. The intermediate water exiting the strait of Gibraltar has a significand and direct impact on the Atlantic Ocean, influencing its oceanographic conditions and the global overturning circulation due to the input of dense and

Saline waters. Due to small exchange of properties with the world ocean and the internal transformation processes, the Mediterranean has often been suggested as an “laboratory” of a “mini-ocean”, representing processes taking place in larger scale in the world oceans (Bergamasco and Malanotte-Rizzoli, 2010). Furthermore the Gibraltar strait plays a crucial role in maintaining the hydraulic control(Rohling and Bryden, 1992) which in fact seems to control the steady state of the Mediterranean, controlling the strength of the in-outflow so that changes in forcing will be mitigated through the netflow and the system will return to steady state condition.

Physical parameters of the Mediterranean Sea show significand trends over the last century. Many studies have shown a clear positive trend in the Mediterranean salinity and Temperature trend since the 1950s, which are consistent with the amplification of the global ocean water cycle (Borghini et al., 2014, Rohling and Bryden, 1992, Bethoux and Gentili, 1999, Rixen et al., 2005, Vargas-Yáñez et al., 2010, Skliris et al., 2014, Schroeder et al., 2016a), more in detail, (Skliris et al., 2014) showed that the deep Mediterranean layers (below 1000m)exhibited the strongest salinity gain of the World Ocean, with the effects carried by the Mediterranean Overflow Waters (MOW) reaching the intermediate depths (1000-1500m) of the subtropical North Atlantic (Curry et al., 2003, Skliris et al., 2014, Potter and Lozier, 2004).

The increasing salinity trends have been widely observed by the scientific community and are consistent with the observed changes in the various parameters of the water cycle, mostly attributed to the increase of Evaporation driven by surface warming over the last decades (Mariotti et al., 2002, Skliris et al., 2012, Romanou et al., 2010) combined with a decrease in Precipitation observed from 1960s to 1990s and mainly associated with the North Atlantic Oscillation (NAO) (Krahmann and Schott, 1998, Mariotti et al., 2002, Mariotti, 2010, Tsimplis and Josey, 2001) and a reduction of river runoff(R) attributed to climate change and river damming of Mediterranean river (Rohling and Bryden, 1992, Skliris and Lascaratos, 2004, Ludwig et al., 2009, Skliris et al., 2007). According to (Borghini et al., 2014) the deep waters of the western Mediterranean Sea have underwent a trend of 0.015 and 0.04 deg. C per decade in Salinity and Temperature, respectively over the last 40 years. The scientific community is not yet sure which are the main drivers for the observed changes, some support that the global warming causes intense heating and evaporation (Bethoux and Gentili, 1999, Krahmann and Schott, 1998), others support that the trend is caused due to the changing properties (Increasing Salinity and Temperature) of the Atlantic Water (Millot, 2007), some other relate the changes to changes in air–sea fluxes related to variability in the North Atlantic Oscillation (Rixen et al., 2005) and some (Rohling and Bryden, 1992) attribute the increases to hydraulic control requirements associated with the changing water budget due to the damming of rivers, particularly the Nile River. (Nof, 1979) first suggested that the steady-state water balance for the Mediterranean was considerably disrupted by the damming of the Nile River during the 1960s. Considering the damming of the Nile River inflow, (Nof, 1979) estimated a change to the overall freshwater budget of the

Mediterranean Sea equal to an increase in net evaporation of 13 cm year^{-1}. Using hydraulic control theory to model the changes in Gibraltar exchange associated with a 10% increase in net evaporation, (Rohling and Bryden, 1992). A model study by (Skliris and Lascaratos, 2004) compared Mediterranean thermohaline circulations with and without Nile River discharge. They showed that removing the Nile River discharge caused the salinity of the Mediterranean to increase by about 0.04 over a timescale of 40 years. It gets clear that the determination of the exact forcing and driving mechanisms of the Mediterranean Sea are hard to understand, thus is hard to exactly determine which of the above driver is causing the observed changes. It can be said though that all parameters play a crucial role and none can be left outside when investigating the changes.

1.3. Water cycle of the Mediterranean, effects of climate change

The Mediterranean water cycle is a complex and dynamical component of Europe's and global climate, affected strongly by global climate shifts, teleconnections and anthropogenic forcing. It is well known that the Mediterranean sea is not in a steady state over time, deep water sites are shifting over time, creating a dynamic and complex system, obtained Salinity and Temperature trends are strong (Borghini et al., 2014, Schroeder et al., 2010) suggesting changes in the water cycle. Located between the mid-latitude storm rain band and the Sahara Desert, the Mediterranean region has an intense seasonal cycle, with wet-cold winters and dry-warm summers (Peixoto et al., 1982). The hydrological cycle is especially sensitive to the timing and the location of the winter storms as they move into the region. Interannual climate variability is closely related to the variability in the Atlantic sector such as the North Atlantic Oscillation (Mariotti et al., 2002). Past and future global climate variability can affect many components of the water cycle (storms, land surface conditions) (Arpe and Roeckner, 1999). Changes in the hydrological cycle may in fact impact the Atlantic thermohaline circulation by changing the characteristics of the water flux at the Gibraltar Strait (Reid, 1979).

It is shown that the Mediterranean is a hot spot for climate change (Giorgi, 2006, Lionello and Scarascia, 2017), therefore broadly affected by the global changing climate, with the effects being already visible and measurable in most parts of the world and the Mediterranean. As mentioned before it is widely accepted that the Mediterranean Sea hydrological properties have already changed significantly showing a surface warming and a strong salinification over the last 50-60 years (Adloff et al., 2015). Future projections agree that this trend will continue for at least a century. (Adloff et al., 2015) found with numerical modelling that for the 2070–2099 period compared to 1961–1990, the sea surface temperature anomalies will range from +1.73 to +2.97 °C and the SSS anomalies will spread from +0.48 to +0.89. In most of the cases, they found that the future Mediterranean thermohaline circulation (MTHC) tends to reach a situation similar to the eastern Mediterranean Transient, similar findings are provided by (Gualdi et al., 2013) and show a substantial warming (almost 1.5°C in winter and almost 2°C in summer) and a significant decrease of precipitation (about 5%) which might affect the region in the 2021–50 period compared to the reference period (1961–1990), in an A1B[2] emission scenario. However, locally the changes might be even larger. The projected surface net heat loss decreases in the projected period, leading to a weaker cooling of the Mediterranean Sea by the atmosphere. In contrast, the water budget appears to increase in the next decades, leading the Mediterranean Sea to lose more water through its surface than in the past. Furthermore, according to the CIRCE projections, the climate change might induce a mean steric sea level rise that ranges between +7 and +12 cm (2021–50). The fact that the Mediterranean Sea but also the broader Mediterranean region seems to be already affected by the changing climate, makes it clear that there is great need in exactly understanding the driving mechanisms, to proper measure the changes and estimate future changes. The water cycle is major parameter directly affected by a changing climate, affecting directly Evaporation, Precipitation, River run off which in fact affect human welfare directly and thus is of great socio-economic interest.

Unfortunately, uncertainty in directly estimating changes in the water cycle remains a long-standing problem. Changes in the hydrological cycle are notoriously hard to measure, with the lack of robust estimates of rainfall and evaporation over the ocean (and their concomitant latent heating/cooling) being of particular concern (Zika et al., 2015, Trenberth et al., 2007, Schanze et al., 2010). There are also major problems when assessing the global hydrological cycle and its variability from reanalysis products, which often violate basic physical constraints and are inconsistent with observational estimates (Trenberth et al., 2011).

1.4. Scientific questions

In this study, we will investigate the changes of the Mediterranean fresh water cycle. The approach will be separated in two methodologies, the first will be based on the analysis of surface

[2] The A1 storyline and scenario family describes a future world of very rapid economic growth, global population that peaks in mid-century and declines thereafter, and the rapid introduction of new and more efficient technologies. Major underlying themes are convergence among regions, capacity building and increased cultural and social interactions, with a substantial reduction in regional differences in per capita income. The A1 scenario family develops into three groups that describe alternative directions of technological change in the energy system. The three A1 groups are distinguished by their technological emphasis: fossil intensive (A1FI), non-fossil energy sources (A1T), or a balance across all sources (A1B) (where balanced is defined as not relying too heavily on one particular energy source, on the assumption that similar improvement rates apply to all energy supply and end-use technologies). [source: IPCC].

fresh water fluxes and the second on the indirect estimation of the water cycle through the water mass transformation theory, which we hope will give us a view of the changing water cycle through the more robust 3D Salinity observations. Finally, we will try to direct the observed changes to their driving mechanisms.

2. Methodology *(Data Used / Methods of Analysis)*

2.1. Data Used

A broad variety of available hydrographic and air sea fresh water fluxes data sets where used in this approach, in order to detect robust multi-decadal climatic trends in salinity and the water cycle, time-series should span significantly longer than a few decades to filter out most of natural climate multi-decadal oscillations. Therefore, all our analysis is undertaken on time periods greater than 30 years, in the following lines we are presenting the data sets used and their specific characteristics. Multi-decadal salinity and temperature changes in the Mediterranean Sea are investigated here using two 'in-situ' and one reanalysis dataset which are currently available:

2.1.1. MEDATLAS

The Medatlas data base which consists of all available data delivered by 150 laboratories from 33 Countries, representing a total of 286,426 Sea temperature and 118,509 Salinity stations (vertical profiles), all original in-situ data, was quality checked (QC) according to the common protocol based on the international IOC, ICES and EC/MAST recommendations, with automatic (objective) and visual (subjective) checks. The data management structure was distributed between four Regional Data Centres (RDC) and one coordinating and Global Assembling Centre (GAC). Each National Oceanographic Data Centre (NODC) or Designated National Agencies (DNA) of the participating countries sent his data set to the corresponding RDC for regional expertise. The data have been gathered and checked for quality in the RDC, and then sent to the GAC which finalise the last quality and duplicate checks. Finally a selection of all the "Good" data was interpolated to pre-defined standard levels has been sent to the Analysis Centre (AC) for climatologies computation, spanning the period of 1945 - 2002 and existing of an 0.2°×0.2° horizontal grid and a vertical grid of 25 levels created by a variational inverse model (Rixen et al., 2000)

2.1.2. EN.4.2.0.

The UK Met Office Hadley Centre Enhanced Ocean Data Assimilation and Climate prediction (ENACT) archive version EN.4.2.0. The data set runs from 1900 to present and is based on subsurface ocean temperature and salinity profile data obtained from the WOD09, GTSPP, Argo, and ASBO collections. All data were first compared to identify and remove duplicates. They were then subjected to a series of quality control procedures and quality flags assigned. These included three new checks introduced in this version of the data set. The first of these checked the depth at the location of each profile in the ETOP01 relief data set to confirm that it lies in the ocean. The second ensured that depths increase monotonically throughout each profile and rejected levels that appeared erroneous. The third implemented automatically a check that might be done by a human operator. It compared sequences of salinity profiles recorded by an Argo float to find errors. The profile data are output into monthly NetCDF files and are made available for research and private study from http://www.metoffice.gov.uk/hadobs. In this study, we used the objectively-analysed monthly dataset covering the 1950-2015 period, at 1° × 1° horizontal grid and a vertical grid of 42 levels (Good et al., 2013), from which we only analyzed the part covering the Mediterranean Sea. Due to the fact that the grid has a low horizontal resolution the Mediterranean basin volume is not well represented, (i.e. the actual volume is considerably overestimated), which was solved by interpolating the EN.4.2.0 data onto the 1/16° × 1/16° horizontal grid of the NextData project which we will analyze below.

2.1.3. NextData project

The MEDSEA_REANALYSIS_PHY_006_009 data set, provided through the NextData project, which is part of the Copernicus Marine Service Information (CMEMS) an initiative of the European Union. The 60 years reanalysis has been produced by combining, every day, the output of the ocean model, forced by atmospheric surface fluxes and relaxed to SST, and quality controlled ocean observations. The hydrodynamics are supplied by the Nucleos for European Modelling of the Ocean (NEMO) with a variational data assimilation schema (OceanVar) thanks to which salinity and temperature profiles and satellite Sea Level Anomaly along track data are jointly assimilated to estimate the initial conditions for numerical ocean model. The model horizontal grid resolution in 1/16˚ (ca. 6-7 km) and the unevenly spaced vertical levels are 72. The system is based upon the operational configuration of the prototype Copernicus Marine Service (MyOcean) models. The Ocean General Circulation Model (OGCM) codes are NEMO-OPA version 3.2 and 3.4, developed and maintained by the NEMO consortium. The model is primitive equation in spherical coordinates implemented in the Mediterranean at 1/16° x 1/16° horizontal resolution and 72 unevenly spaced vertical levels (Oddo et al., 2009). It is nested in the Atlantic within the monthly mean climatological fields computed from ten years of daily output of the 1/4° x 1/4° degrees global model (Drévillon et al., 2008). The model uses vertical partial cells in order to have better representation of the flow over steep topography. The model is forced by momentum, heat and water fluxes computed by bulk formulae adapted to the Mediterranean case, using AMIP data (Cherchi and Navarra, 2007). Heat flux is corrected proportionally to the difference between the model and observed SST (Pinardi et al., 2015) with a relaxation coefficient equal to -60 $Wm^{-2}\ K^{-1}$, corresponding to about 2.5 day time-scale over a depth of 3 m. The choice of use

Met Office Hadley Centre SST dataset (HadSST1) for the production of 60 years reanalysis is consistent with the idea to use AMIP-type experiments since AMIP were obtained from ECHAM4 model forced by HadSST1. The dataset consists of monthly SST on regular grid of 1°x1° starting from 1870 (Rayner et al., 2003). Water balance is computed as evaporation minus precipitation and runoff. The evaporation is derived from the latent heat flux while the precipitation and the runoff are provided by monthly mean datasets. Precipitation is taken from the Climate Prediction Centre Merged Analysis of Precipitation (CMAP) Data (Xie and Arkin, 1997). Runoff is taken instead from the Global Runoff Data Centre dataset (Fekete et al., 1999) for the Ebro, Nile and Rhone and the dataset from Raicich (Raicich, 1996) for the Adriatic rivers (Po, Vjosë, Seman and Bojana). The Dardanelles inflow is parameterized as a river, and the climatological net inflow rates are taken from (Kourafalou and Barbopoulos, 2003). The model is combined with a three-dimensional variational assimilation scheme called OceanVar (Dobricic and Pinardi, 2008). The evolving part of temperature and salinity background error covariances is represented by seasonal varying Empirical Orthogonal Functions (EOFs), divided in 13 sub regions of the Mediterranean Sea (Dobricic et al., 2005), calculated from the temporal variability of parameters in a historical model simulation. The mean dynamic topography used to assimilate sea surface height measurements by altimeter satellites has been computed by (Dobricic et al., 2005). Altimeter data and in-situ temperature and salinity vertical profiles are jointly assimilated to estimate the initial conditions for numerical ocean model. The SLA data consist of sea level anomalies referred to a 7-year average (1993-1999) and combine information from different missions (Topex/Poseidon, ERS-1 and ERS-2, Envisat, Jason1 and Jason2), intercalibrated with respect to a reference mission, which is currently Jason2. The temporal coverage depends on the duration of the mission starting from 1992. The in-situ temperature and salinity vertical profiles are collected from different instrumental data types, such as CTDs, XBTs, MBTs, bottles, ARGO, and sources: MFSPP (Mediterranean ocean Forecasting System Pilot Project), MFSTEP (Mediterranean ocean Forecasting System Toward Environmental Prediction), SeaDataNet, MEDAR-MEDATLAS and MyOcean in-situ TAC (Thematic Assembly Centre)

2.1.4. Air sea fresh water fluxes

Two atmospheric reanalysis-based E-125 P datasets are used covering the 1950-2010 period: the NCEP/NCAR Reanalysis 1 spanning 1948-present (Kistler et al., 2001) and the 20th century reanalysis (20CRv2), spanning 1871-present (Compo et al., 2011). Moreover, a hybrid E-P product, partially based on observational/satellite-derived data, is also used here to compare with the two re-analysis products over a shorter common period (1979-2010). Evaporation is provided by the Objectively Analyzed air-sea Fluxes (OAFlux) dataset (http://rda.ucar.edu/datasets/ds260.1/) , that blends NCEP and ERA-40 reanalysis products with satellite surface meteorology through an objective synthesis (monthly mean data on a 1°×1° grid, available from 1958), while P is obtained from the Global Precipitation Climatology Project (GPCP v2.2, http://rda.ucar.edu/datasets/ds728.2/, monthly mean data on a 2.5°×2.5° grid, available from 1979). Total Mediterranean river runoff climatological mean (0.011 Sv) and change (0.0027 Sv) over the considered period are taken from the observational study of (Ludwig et al., 2009).

We also used fresh water flux data from next data project, in fact we used the respective data to the hydrology datasets used in this approach, which was computed by the OGCM (Ocean General Circulation Model) by the NEMO-OPA (Nucleus for European Modelling of the Ocean-Ocean Parallelise) code version 3.2 (Madec et al 2008). This code is developed and maintained by the NEMO-consortium. This is a primitive equation model in spherical coordinates. NEMO has been implemented in the Mediterranean at 1/16deg. x 1/16deg. horizontal resolution and 72 unevenly spaced vertical levels (Oddo et al., 2009). The model is located in the Mediterranean Basin and also extend into the Atlantic in order to better resolve the exchanges with the Atlantic Ocean at the Strait of Gibraltar. The NEMO model is nested, in the Atlantic, within the monthly mean climatological fields computed from ten years of daily output of the 1/4° x 1/4° degrees global model (Drévillon et al., 2008). The model uses vertical partial cells to fit the bottom depth shape. The model is forced by momentum, water and heat fluxes interactively computed by bulk formulae using the 12-h, 1.125° horizontal-resolution AMIP fields (Cherchi and Navarra, 2007) and the model predicted surface temperatures. The water balance is computed as Evaporation minus Precipitation and Runoff. The **evaporation** is derived from the latent heat flux while **precipitation** and the **runoff** are provided by monthly mean datasets: the Climate Prediction Centre Merged Analysis of Precipitation (CMAP) Data (Xie and Arkin, 1997), the Global Runoff Data Centre dataset (Fekete et al., 1999) for the Ebro, Nile and Rhone and the dataset from Raicich (Raicich, 1996) for the Adriatic rivers (Po, Vjosë, Seman and Bojana). The Dardanelles inflow is parameterized as a river and the climatological net inflow rates are taken from (Kourafalou and Barbopoulos, 2003). The data assimilation system is an updated version of the OCEANVAR scheme developed by Dobricic and Pinardi (Dobricic and Pinardi, 2008). The assimilated data include: sea level anomaly, sea surface temperature, in situ temperature profiles by VOS XBTs (Voluntary Observing Ship-eXpandable Bathythermograph), in situ temperature and salinity profiles by argo floats, and in situ temperature and salinity profiles from CTD (Conductivity-Temperature-Depth). Met Office Hadley Centre SST data set (HadSST1) (Rayner et al., 2003) is used for the correction of surface heat fluxes with the relaxation constant of 60 W/m2K1.

2.2. Methods

In this study, we will use two different methodologies of studying the water cycle of the Mediterranean Sea. Therefore, we will first analyze directly the available air sea fresh water data sets by creating spatial trend maps out of monthly averaged data sets for the Mediterranean Sea, furthermore we created E-P and E-P-R maps, the analysis of various data sets and the comparison with others studies gave as a first insight of the Mediterranean water cycle, further more we analyzed the E-P-R patterns in Salinity space, referencing the spatial patterns to the Salinity distributions, which in fact was the overall goal of this study. With the ocean receiving over 80% of the total global rainfall (Schanze et al. 2010), oceanic observations of salinity offer a unique opportunity in terms of measuring the integrated effect of changes in the hydrological cycle (Trenberth et al., 2007). Only recently, however, has the observational network expanded to the point where the mean state and trends in upper-ocean salinity can be robustly estimated. This is thanks to historical and ongoing ship-based hydrographic measurements and now the Argo observing programs, allowing the quantification of the global salinity change. Our approach is based on the water mass transformation theory (Walin, 1977, Zika et al., 2015) which allows us to attribute the fresh water fluxes and their changes over time to the changes in 3D salinity distributions. To archive this, we construct monthly anomaly time series for all datasets by subtracting the mean seasonal cycle from the monthly data at each grid point. Annual anomalies are then constructed from the monthly anomalies, allowing us to compute linear trends in salinity and E-P over 1950-2010. Based on the salinity trends we then calculate the change in the volumetric salinity distribution over this period in order to infer changes in the water cycle. Following the water mass transformation theory (Walin, 1977), the movement of an individual water parcel in salinity coordinates is given by:

$$\frac{DS}{Dt} = S_o\,(E - P - R) + \nabla . K \nabla S \qquad (1)$$

Where S_0 is the mean ocean salinity and K is a positive definite diffusion tensor. A fluid parcel changes its salinity, S, through surface freshwater flux (*E-P-R*) and mixing. The total movement of water across an isohaline surface is the integral of both right-hand terms of (1):

$$\frac{dV}{dt} = \int \int \int \delta(S - S')\,(S_o\,(P + R - E) - \nabla . K \nabla S)dxdydz \qquad (2)$$

Where $V(S)$ is a volume of water bound by isohaline $S=S'$ and δ is a dirac delta function. Equation (2) states that the change in the volume of water dV/dt (i.e. the water mass transformation rate) is set by $P+R-E$ (i.e. the water cycle) and mixing. If we integrate (2) in salinity space we get the total displacement of freshwater:

$$\int_0^{S\prime} \frac{dV}{dt} dS = \int \int \int \Pi(S - S')\, (S_o\, (P + R - E) - \nabla . K\nabla S) dxdydz \qquad (3)$$

Where $\Pi(S\text{-}S')$ is a step function ($\Pi=0$ for $S<S'$ and $\Pi=1$ for $S>S'$). If we assume that changes in mixing and changes in net transports through the Gibraltar and Dardanelles straits are negligible over the considered period then the left-hand side of (3) will provide an estimate of the water cycle change.

$$\int_0^{S\prime} \frac{dV}{dt} dS = \int \int \int \Pi(S - S')\, (S_o\, (P + R - E) - \nabla . K\nabla S) dxdydz + \iint \Pi(S - S')u_G dydz + \Pi(S - S')u_D dydz \qquad (4)$$

Where u_G and u_D are the current velocities at the Gibraltar and Dardanelles straits, respectively, since the Reanalysis data sets handles the Dardanelles straits as a river, we ignore it in the equation since its included in the River runoff. Following equation (4) we may then infer the change in Mediterranean net evaporation if changes in net transports at the straits and salt mixing can be estimated over the considered period.

In other words, we create salinity steps (bins) to which we correspond the respective volume of water, so we create a distribution of water in salinity coordinates, allowing us to have a first insight of the patterns, after creating the distributions of the beginning and end of our considered periods we can have a view of the change, by subtracting the 'past' distribution from the more recent we create the volumetric change in salinity coordinates. If we integrate this distribution we will find the Transformation rate of the water volume. The last step is to integrate again the distribution of the Transformation rate, giving every Salinity bin and flux its overall weight, the output will show us the Accumulated fresh water transport in salinity coordinates.

3. Results

In this chapter we present our findings, first we will try to present the most important driving forces of the Mediterranean water cycle and how they might vary over time. Secondly, we will present separately the components of the Mediterranean water cycle, based on observational and reanalysis data sets (Evaporation-Precipitation-River run off). In the next step we will combine all data and present the observed changes in the water cycle over various periods. Finally, we will present the changes of the Mediterranean water cycle observed from the analysis of 3D salinity fields using the water mass transformation framework.

3.1. Components of the Mediterranean water cycle

The Mediterranean is well known for its intense Evaporation, which is largely exceeding

Table 1: Mediterranean basin averaged precipitation and evaporation trends, delivered from various data sets and spanning for the periods of 1950-2010 & 1979-2010.

	E trend (1950-2010)	E trend (1979-2010)	P trend (1950-2010)	P trend (1979-2010)
20CRv2	**0,0212**	**0,0212**	**-0,0974**	**-0,0229**
NCEP/NCAR	**0,0138**	**0,1547**	**-0,0614**	**0,1337**
CORE2	**nan**	**0,1723**	**nan**	**0,0097**
NCEP/DOE	**nan**	**0,2518**	**nan**	**0,1268**
ERA-Interim	**nan**	**0,0788**	**nan**	**0,0181**
OAFLUX-GPCP	**nan**	**0,0957**	**nan**	**-0,008**

Precipitation and River run off. This pattern seems to get reinforced due to strong positive Evaporation trends combined with smaller or even negative Precipitation and River run off trends. The Analysis of various data sets in this study (20CRv2, NCEP/NCAR, OAFlux, ERA-Interim) for the period of 1950-2015 confirms previous findings. In table 1 we present the analyzed E, P

Table 2: Mediterranean basin averaged evaporation minus precipitation (E-P) trends and means, delivered from various data sets and spanning for the periods of 1950-2010 & 1979-2010.

E-P mean & trend averaged over the total Mediterranean surface

1950-2010	Mean (m/yr)	Trend (m/yr)	1950-2010	Mean (Sv)	Trend (Sv)
20C	0.57	0.117	20C	0.045	0.0093
NCEP1	0.54	0.075	NCEP1	0.042	0.0059

1979-2010	Mean (m/yr)	Trend (m/yr)	1979-2010	Mean (Sv)	Trend (Sv)
20C	0.6	0.05	20C	0.048	0.004
NCEP1	0.56	0.021	NCEP1	0.044	0.0017
OAFLUX	0.53	0.3	OAFLUX	0.042	0.0238
NCEP2	0.85	0.12	NCEP2	0.067	0.0095
ERA-INTERIM	0.74	0.06	ERA-INTERIM	0.0587	0.0048
COREI	0.7	0.16	COREI	0.055	0.0127

data for two periods (1950-2010, 1979-2010), with the second period being chosen due to the developing Satellite era, which started providing more data. Results are consistent with observational studies indicating a long-term Evaporation increase driven by the rapid warming of the Mediterranean surface during the last decades implying an increase of latent heat loss (Skliris et al., 2012) from the late 1960s to mid-1990s mainly attributed to an increasingly positive phase of the North Atlantic Oscillation (Mariotti et al., 2002). There seem to be major differences between the two periods, which can partly be explained due to the different data sources, the uncertainties associated with satellite data and the sparse sampling of the above parameters. Even though all data sets show a consistent positive trend in Evaporation, the trend in Precipitation is not consistent in sign, showing much smaller trends, which again can be attributed to the lack of observation combined to the difficulty of accurate observations. Even though, we can say with high confidence that the water cycle has changed and continues to change rapidly, with the Mediterranean becoming on average a dryer region. Furthermore, one will expect a positive effect on the Salinity distribution over the given region.

On table 2 we present the averaged E-P climatological means and trends for the Mediterranean Sea, climatological mean E-P flux over the whole Mediterranean surface (~2.5

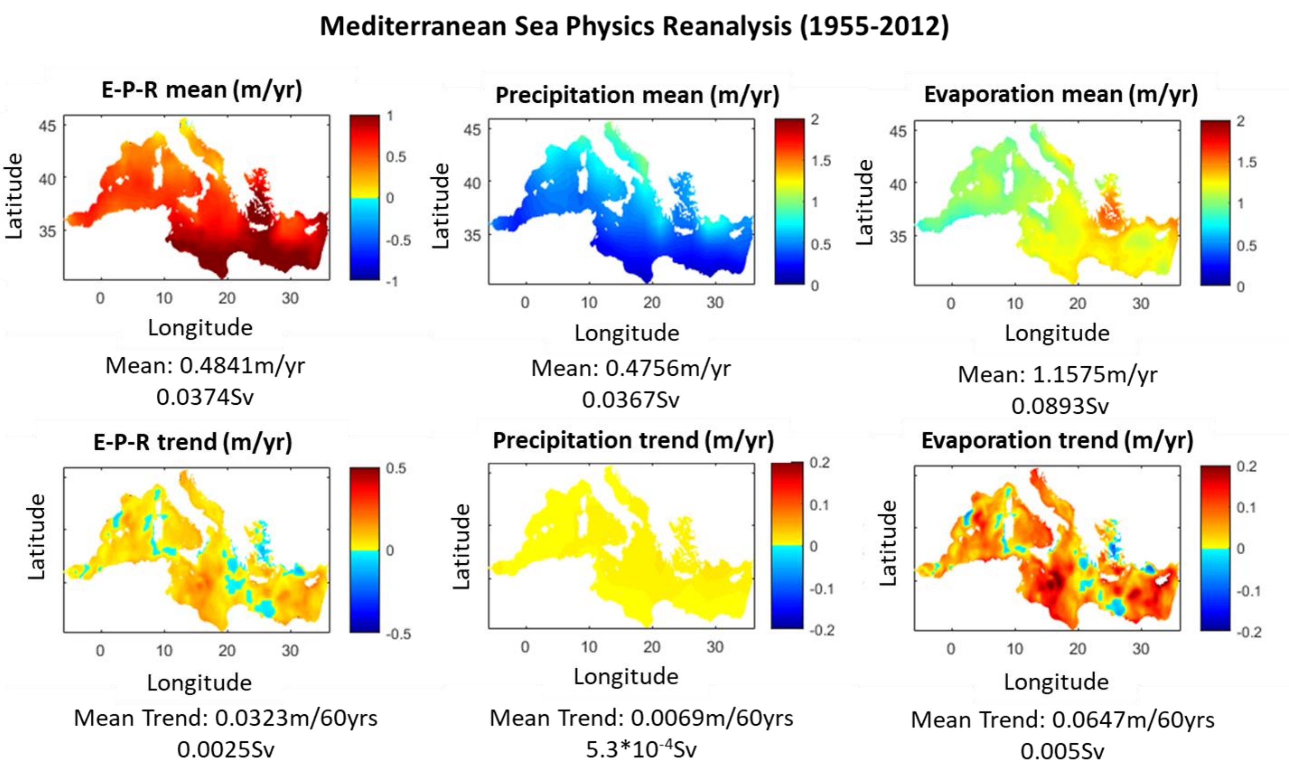

Figure 1: Fresh water cycle components of the Mediterranean Sea, delivered by the physics reanalysis data set (NextData project) and for the period of 1955-2012. Upper left: E-P-R mean flux per year, Upper middle and Right: Precipitation and Evaporation mean flux per year, bellow figures show the respective trends of the water cycle.

10^{12} m^2) amounts to 0.045 Sv (Sverdrup, 1 Sv = 10^6 m^3/s) for 20CRv2 and 0.042 Sv for NCEP/NCAR, with a mean change of 0.0093Sv and 0.0059 Sv respectively, which stands for total change of

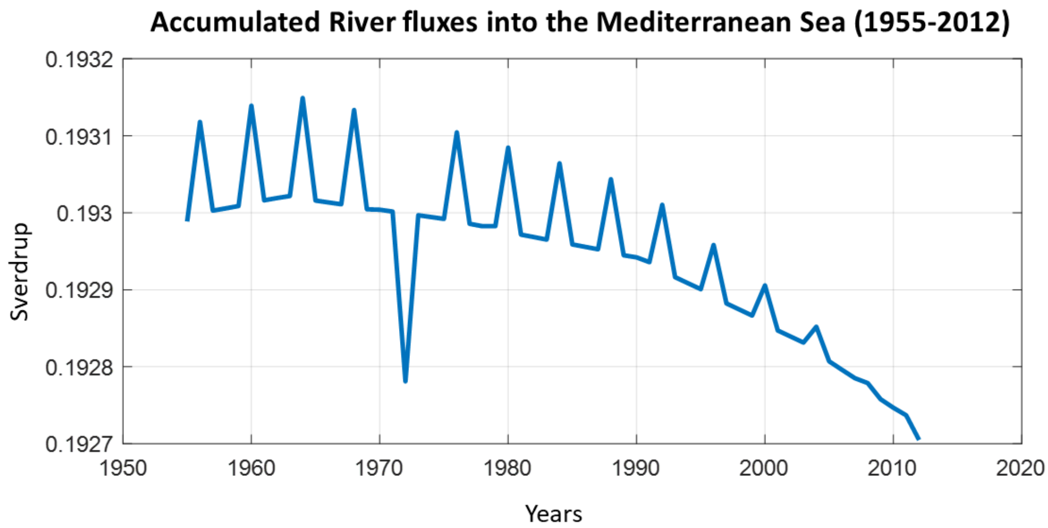

Figure 2: Accumulated River fluxes into the Mediterranean Sea, estimated from the physics reanalysis data set (NextData project) and for the period of 1955-2012, values are in Sverdrup ($10^6 m^3/s$). Dardanelles in-outflow is parameterized as a river in the data set.

~21% and 14% respectively over the period of 1950-2010. These values are close to previous estimates of 0.040-0.056 Sv (Mariotti et al., 2002). Adding the total mean river discharge (1960-2000) from (Ludwig et al., 2009) of ~0.01 Sv we get a mean net E-P-R flux of 0.035-0.032Sv. Based on the linear trends, net E-P change over 1950-2010 amounts to 0.0059 Sv for NCEP/NCAR and 0.0093 Sv for 20CRv2, respectively. Adding a decrease of total river discharge of ~0.0031 Sv over this period (Ludwig et al., 2009) we get a net E-P-R change ranging 0.009-0.0124Sv. This indicates a quite large increase in net evaporation of the basin of ~24-32% over the last 60 years.

The Mediterranean Sea physics reanalysis data set shows a similar pattern and values in the surface fresh water fluxes as one can obtain in (Figure 1). Over the period of 1955-2012 there seems to be a broad scale increasing trend in Evaporation, which combined with minimal positive trend in Precipitation and a small negative trend in river run off is leading to a positive trend of E-P-R (increasing net evaporation). This data set in fact indicates a change of 0.0025Sv in E-P-R, which amounts to an increase of ~6.7% in the mean water cycle (net evaporation).

3.2. Salinity Changes

Over the period 1950-2014 the Mediterranean Sea seem to have changed its Salinity properties significantly, affected by local changes in forcing combined with global changes. It gets clear from figure 3, that for the common period (1955-2014) of the two data sets the

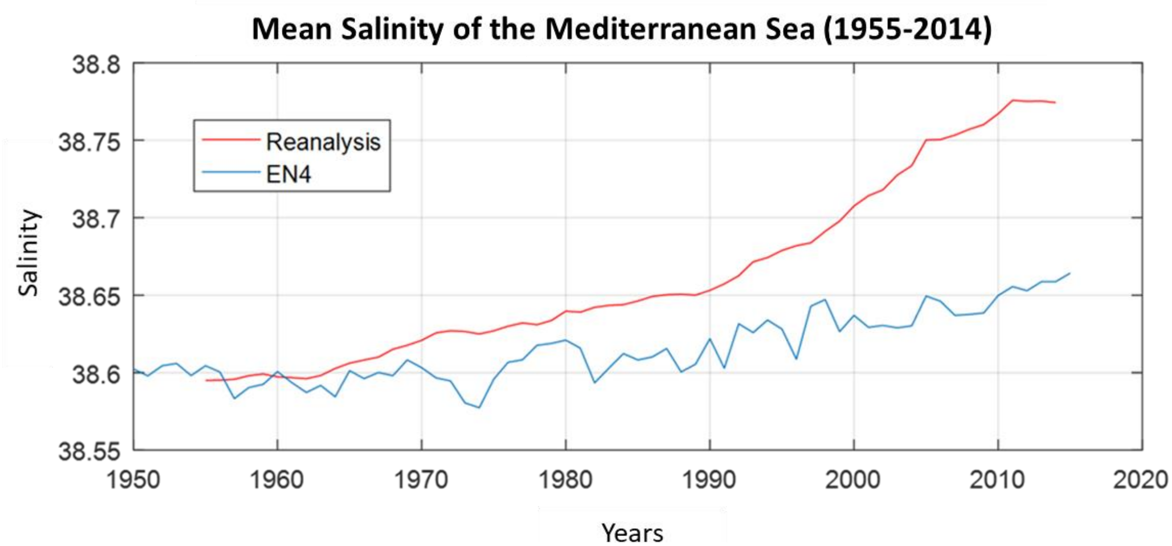

Figure 3: Volume averaged Salinity of the Mediterranean Sea, calculated from both EN4 (blue line) & Reanalysis (red line) datasets.

Mediterranean shows a consistent positive trend which indicates a nearly broad scale salinification of the basin. The surface layer (0-150m) shows a clear positive trend in EN4 and Reanalysis (0.11 and 0.21 pss/60yrs respectively), with some small negative trends, mainly encountered in the Adriatic Sea and the North Aegean, (which could be explained by increases

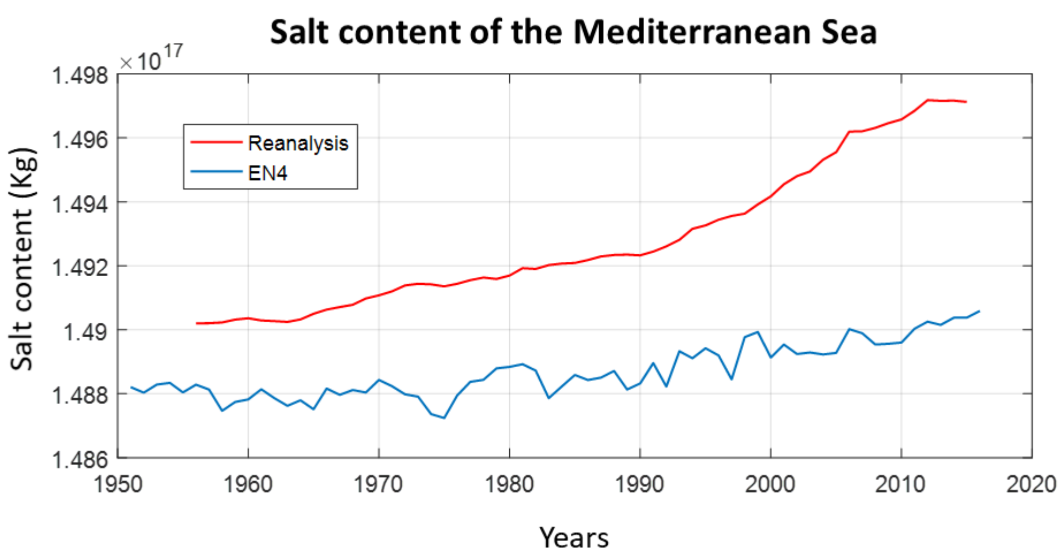

Figure 4: Yearly Accumulated Salt content of the Mediterranean Sea, calculated for both EN4 (blue line) & Reanalysis (red line) datasets.

of river runoff into the Adriatic Sea, and of the fresher Black Sea Water outflow through the Dardanelles Straits, respectively. It is to mention that the reanalysis data set shows a trend nearly twice as big as the En4 data for the same period. The intermediate layer (150-600) shows a clear but small positive trend in both Reanalysis and EN4, with the Reanalysis showing a small freshening in the central Aegean and Ionian Seas, the surface layer in the EN4 data set shows a slightly bigger trend of 0.071/60yrs compared to 0.061/60yrs of the Reanalysis. Finally, the Bottom layer shows a clear positive trend in both data sets, with the Reanalysis data showing a quadruple trend in salinity (0.22/60yrs vs 0.055/60yrs), the clear positive trend in the Bottom layer gives us a more robust proof of the Mediterranean Salinification, which seems to be broad

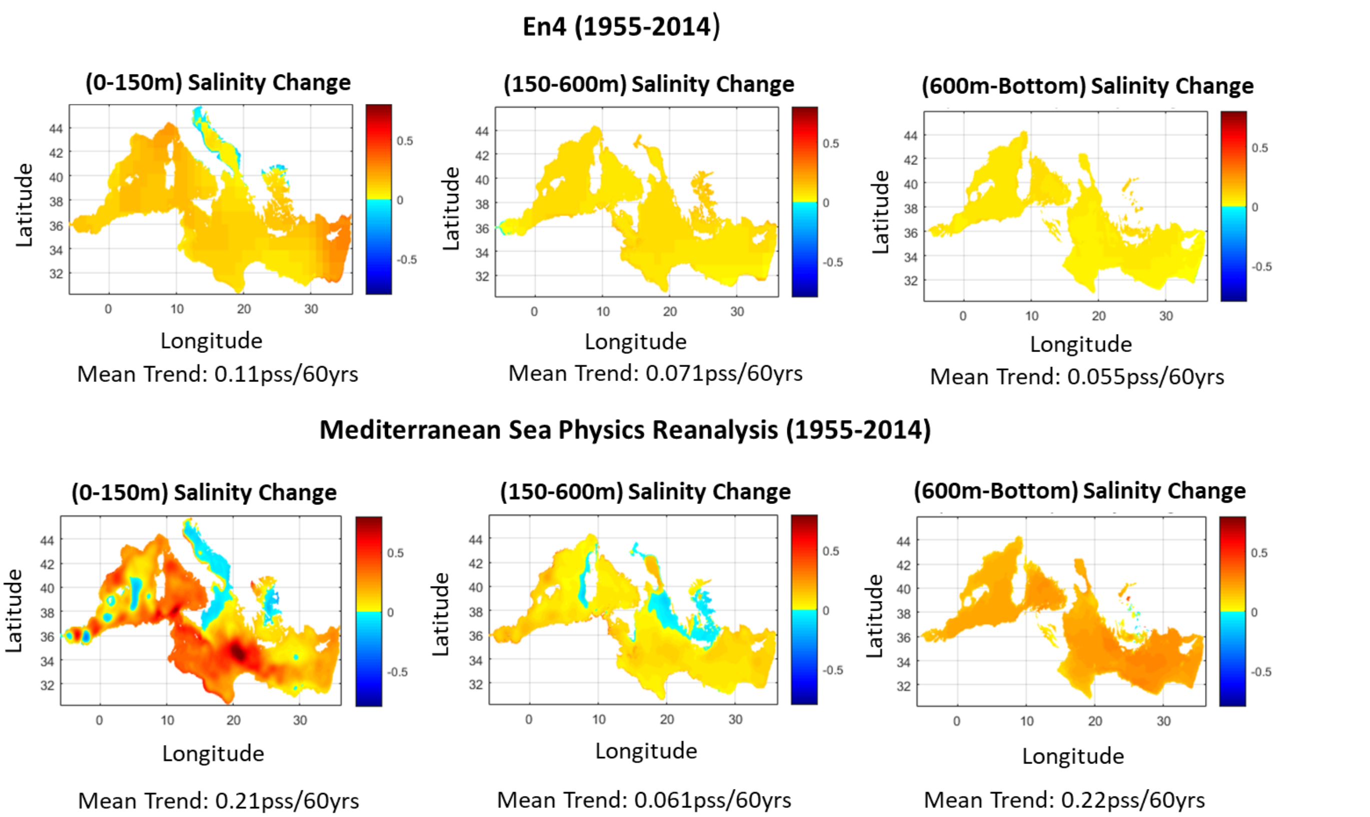

Figure 5: Salinity trends for the period of 1955-2014, delivered by two data sets EN4 top (observational) and Mediterranean Sea Physics bottom(Reanalysis). The maps are a result of the volume averaged trend for the various depth layers.

scale and multi-decadal with a volume average trend of 0.18pss/60yrs for the Reanalysis data set and 0.065pss/60yrs (Same period) for the EN4 data set.

3.3 Temperature Changes

Observed variability in Mediterranean Sea Temperature seems to differ significantly in all data sets. As seen in figure 6 there are large differences in the Temperature anomalies over the years, which also is shown in the Trend maps (Figure 7). Figure 6 shows that the differences between EN4 and Reanalysis grow after 1990's, where EN4 shows an abrupt increase in

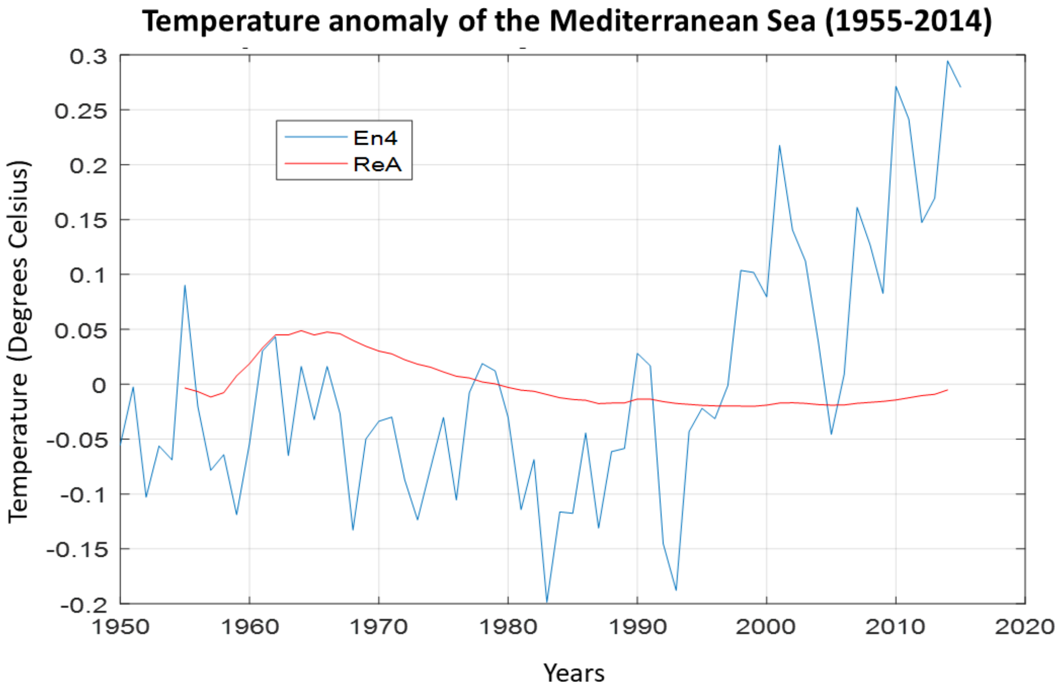

Figure 6: Basin wide Temperature anomaly of the Mediterranean Sea, red line shows the development of temperature provided by the Reanalysis data set (1955-2014) and the blue line shows the temperature provided by the EN4 data set (1950-2015).

Mediterranean Sea temperature, whilst the Reanalysis shows no significant trend. If one analyses the different depth layers of the Med Sea as shown in figure 7 one will again notice the differences in both data sets and layers. The surface layer (0-150m) shows in both data sets a broad-scale warming of ~0.35 ºC/60yrs, in addition the Intermediate layer (150-600m) which shows cooling of ~-0.44 ºC/60yrs in the Reanalysis data and a small warming of ~0.084 ºC/60yrs in EN4, finally the Bottom layer (600m-Bottom) shows again a small cooling in Reanalysis of about ~ 0.03 ºC/60yrs and warming of about ~0.12 ºC/60yrs in EN4. The volume averaged trend of the data sets for the Period of 1955-2014 is 0.14 ºC/60yrs and -0.08 ºC/60yrs for EN4 and Reanalysis respectively, specific trends for different periods are presented in Table 3. From the analysis, we note an important difference when comparing the two in-situ data sets (Medatlas-En4) with the Reanalysis, the difference was also notable in the Salinity fields and trends but only small and not in sign. While when looking at the temperature fields, the data sets show opposite trends in the volume average mean trend. This in fact is very strange since most researchers agree on a warming trend of the Mediterranean region and Sea, it is interesting though that this trend is

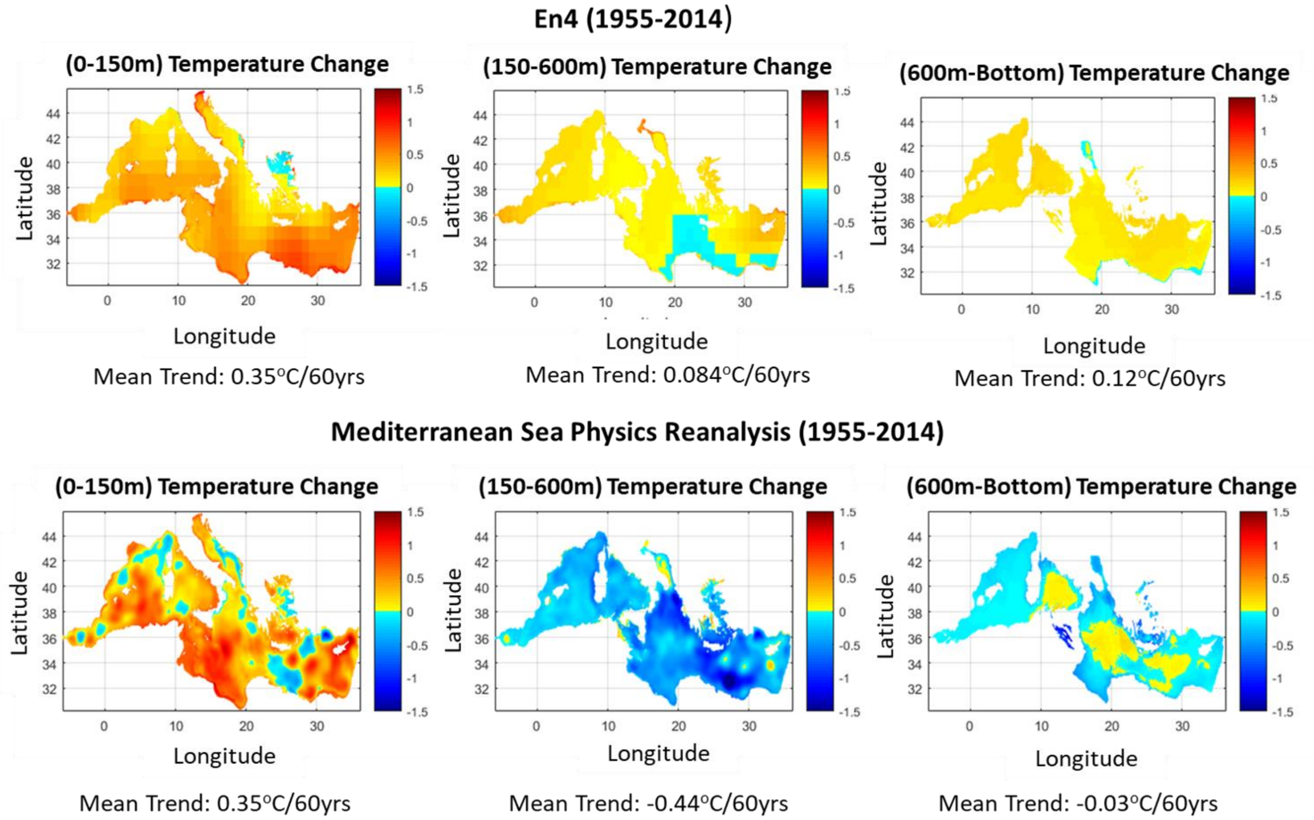

Figure 7: Temperature trends for the period of 1955-2014, delivered by two data sets EN4 top (observational) and Mediterranean Sea Physics bottom(Reanalysis). The maps are a result of the volume averaged trend for the various depth layers (degrees Celsius).

only present in the surface layer of the Reanalysis data set, which is presented as well in EN4 and Medatlas, it is notable that also in the In-situ data sets there is a clear reduction in Temperature trends when looking at greater depths, which in fact is not presented in the Salinity Trends.

Table 3: Volume averaged temperature trends calculated for various periods.

	T trend (1955-2014)	T trend (1979-2014)	T trend (1955-2002)
EN4	0.14 °C/60yrs		0.047°C/48yrs
REANALYSIS	-0.08 °C/60yrs	-0.09°C/36yrs	-0.057°C/48yrs
MEDATLAS			0.012°C/48yrs

3.4. Water mass transformation framework

As mentioned above, the ocean can be considered as a 'rain gauge' reflecting the changes of the above atmosphere, thus the Water mass transformation Theory allows us to estimate changes of the water cycle by studying changes in the 3D salinity distribution (Zika et al. 2015). Changes in Salinity Distributions are forced mainly by the water cycle (Fresh water fluxes), changes in volume fluxes (Salt fluxes) and salt mixing. Water mass transformation in salinity space is estimated by three data sets (Medatlas, EN4, Reanalysis). Using the described methodology of water mass transformation framework (Zika et al., 2015, Walin, 1977). The volumetric distribution in salinity space shows two significant peaks representing the two Mediterranean

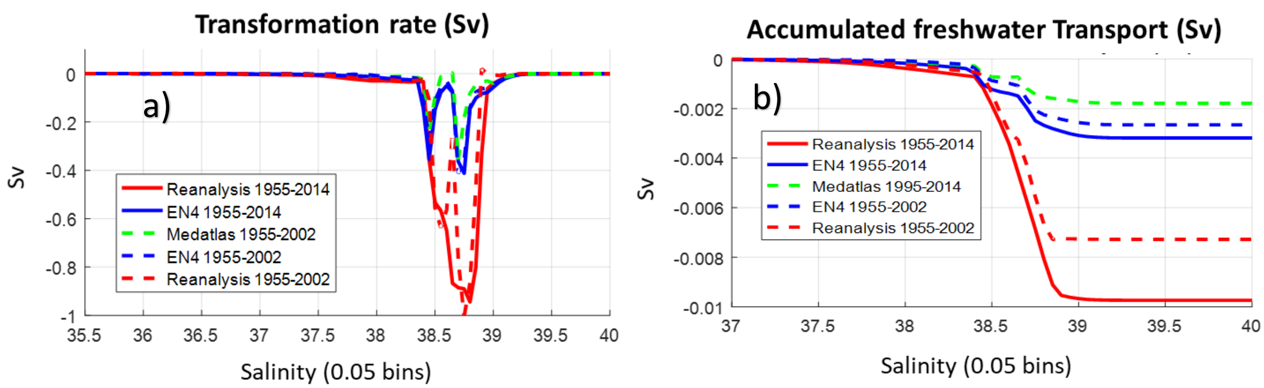

Figure 8: Panel (a) shows the transformation rate in Sverdrup of the Mediterranean Sea in Salinity coordinates and for various periods and Data sets. Panel (b) shows the Accumulated fresh water transport in salinity space.

sub-basins (WMED & EMED) with peaks at around 38.4 and 38.7, respectively [figure. 9. a, d]. The observed change between the two periods (1955-2014) is clearly visible in both data sets, with the EN4 showing a smaller displacement towards higher salinities (~38.5 & ~38.75) and the Reanalysis showing a much higher displacement towards higher salinities (~38.7 & ~38.85), showing as expected a high salinification of the Mediterranean Sea, which gets also clear from the water mass transformation rate [figure. 8.a & 9.c], showing almost everywhere negative values, indicating a fresh water transport from more Saline to less Saline water throughout the basin. Indicating that salty waters are becoming even more salty. The two data sets show some differences, with the EN4 peaking at the two sup-basins at about -0,4Sv and the Reanalysis showing a much higher transformation rate throughout the basin with peaks at about -0.9Sv. It is to mention that both data sets show a high transformation rate at a salinity range of about 38.3-39.4, with the highest rates at about 38.7 (Reanalysis), indicating that the transformation is occurring in the waters of the central and East Mediterranean and not in the Inflowing MAW, which is an indicator that the observed changes are mostly attributed to internal processes of the Mediterranean rather that changes in the Volume fluxes. The total accumulated isohaline freshwater displacement over 1955-2014 calculated through equations [1-3] is -0.0032 Sv in EN4 and -0.0097 Sv in Reanalysis more than three time higher [figure.8.b & 9.a]. If we consider no

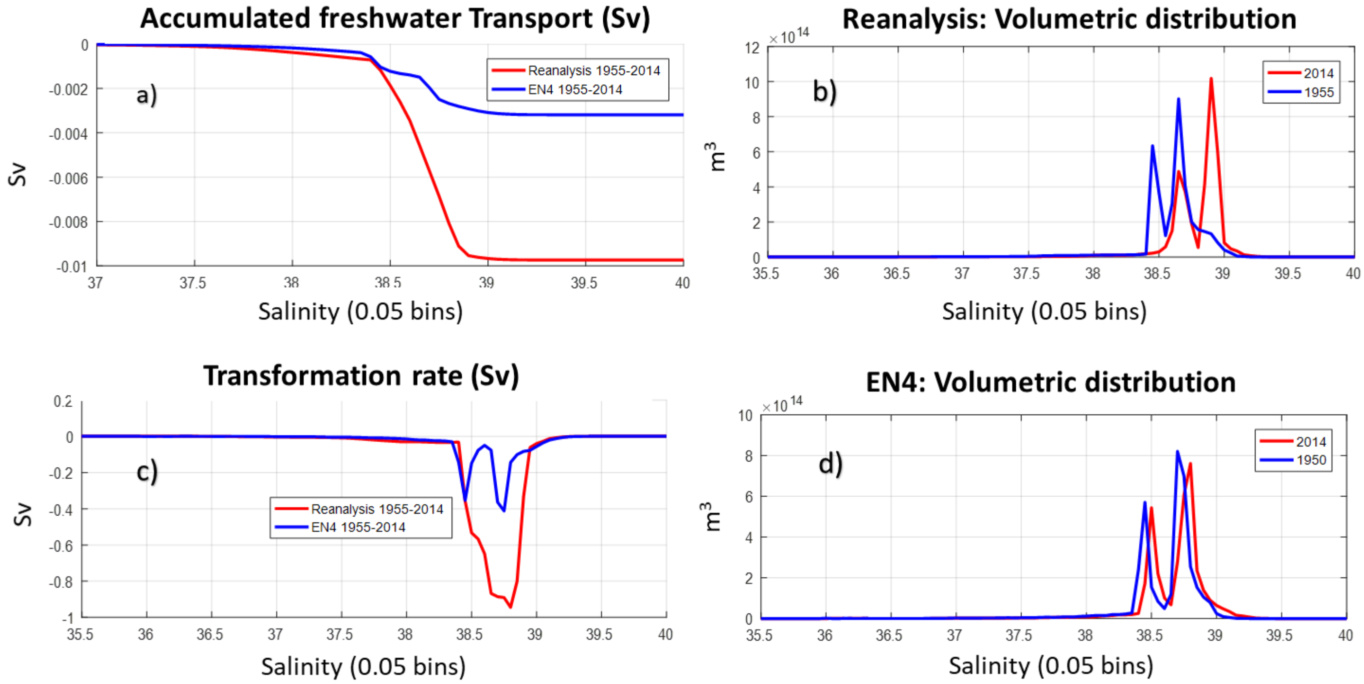

Figure 9: Panel a) shows the accumulated freshwater transport in Sverdrup, for both EN4 and Reanalysis for the period 1955-2014. Panel b & d show the volumetric distribution in Salinity space for reanalysis and EN4 respectively, red lines show the distribution for 2014 and blue line shows the 1955 distribution. Panel c) shows the transformation rate, which is the accumulated change (1955-2014) for both for EN4(Blue) and Reanalysis (Red).

changes in the net salt flux through the straits over the given period and negligible salt mixing we can estimate that a net Evaporation increase of (~0.0032Sv & 0.0097 Sv) over 1955-2014 for EN4 and Reanalysis respectively. Therefore, if we consider the climatological mean net Evaporation (E-P-R) over the Mediterranean Sea surface of 0.0386Sv provided from the Reanalysis data set for surface fresh water. The change calculated through the transformation theory of (~0.0032Sv & 0.0097Sv) would stand for a net evaporation increase of 8% and 25% for EN4 and Reanalysis respectively, meaning that we observe an intensification of 8% & 25% of the water cycle over the given period.

3.5. Fluxes at the Gibraltar strait

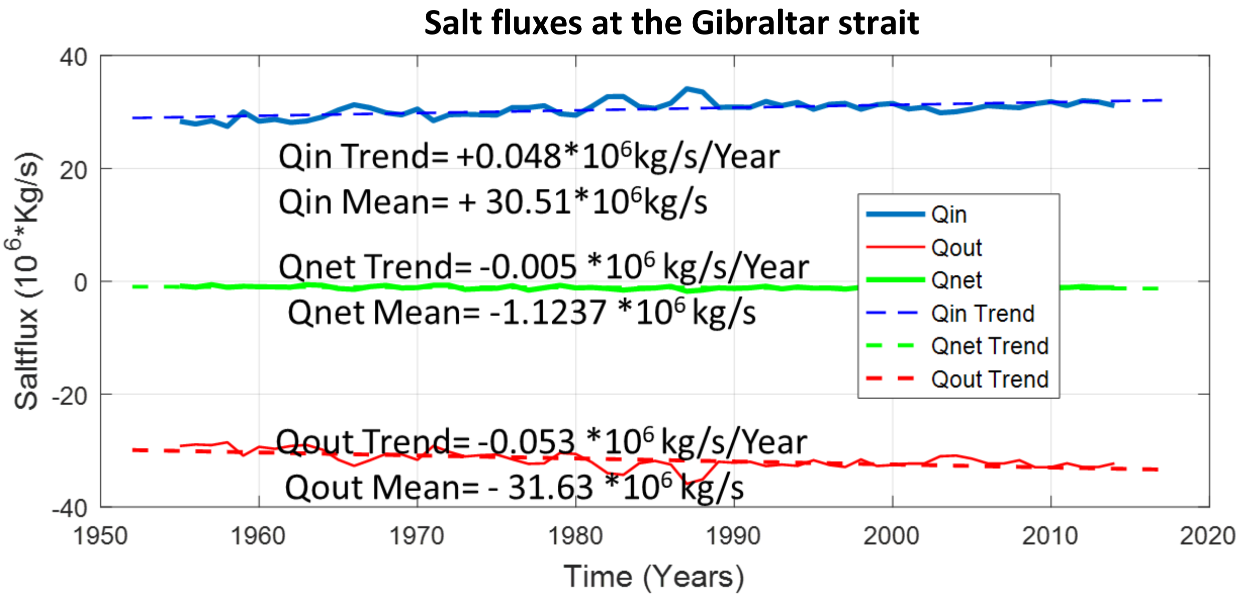

Figure 10: Salt fluxes at the Gibraltar straits calculated from the reanalysis data set. Blue solid line shows the mean yearly Salt flux into the Mediterranean Sea, while the dashed line shows the linear trend, respectively the green line shows the net Salt flux and the Red line the salt outflux.

The Gibraltar strait plays a major role in the dynamics of the Mediterranean Sea, preventing the later from drying out. The anti-estuarine circulation driven by the excessive net evaporation forces more water to enter the Mediterranean than the water exiting the same time through the strait. At the same time, more Salt is outflowing the Gibraltar than entering. These balances play a major role in our methodology. Therefore, we calculated the salt fluxes and volume fluxes over time, provided by the reanalysis data set. We calculated a total volume transport of +0.0208Sv with a minimal positive trend of 0.001Sv/60years, consisting of an inflow of 0.8241Sv with a trend of 0.079Sv/60years and an outflow of -0.8033Sv with a trend of -0.078Sv/60years (figure 11). Salt fluxes are shown in figure 10, the net Salt flux is $-1.1237*10^6$kg/s with a trend of 0.29 $*10^6$kg/s/60years and a salt content change due to exchange at the Gibraltar equal to $-0.88*10^{13}$ kg for the period 1955-2012, with the negative sign showing that the net transport forces a total salt lost into the Atlantic Ocean, while the positive sign in the volume flux indicates a net flow towards the Mediterranean, balancing the net evaporation loss. It is to notice that while there isn't a significant trend in the net Volume flux, there is a significant trend in net salt flux showing again that more salt is outflowing the Mediterranean every year.

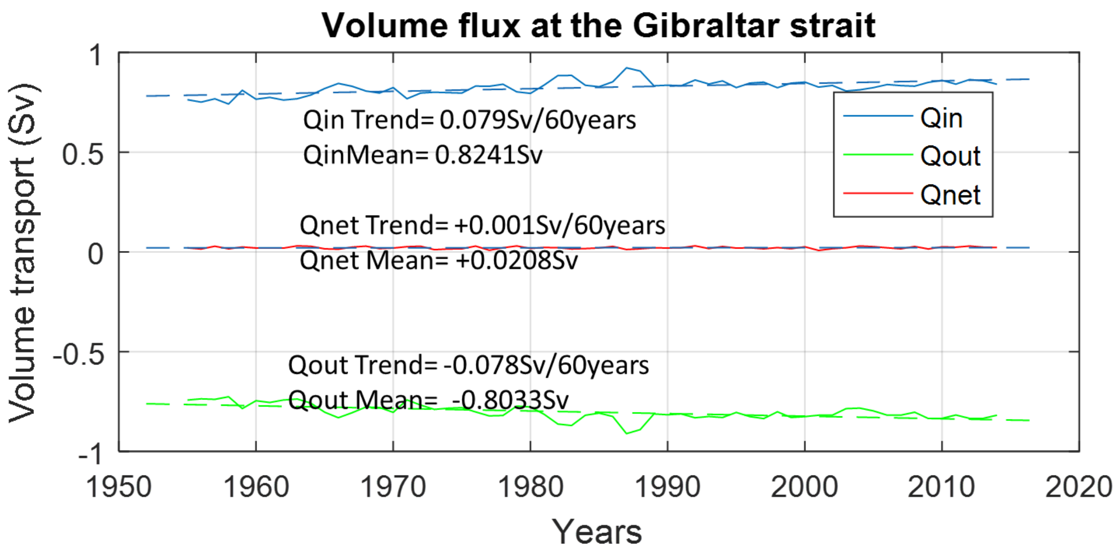

Figure 11: Volume fluxes at the Gibraltar straits calculated from the reanalysis data set. Blue solid line shows the yearly averaged Volume flux into the Mediterranean Sea, while the dashed line shows the linear trend, respectively the green line shows the net Volume flux and the Red line the volume outflux.

3.6. Salt mixing

The global ocean water cycle amplifies in a warming climate accentuating the contrast between Precipitation and Evaporation dominated areas, stretching in this way the volumetric distribution of Salinity (i.e. salty regions become saltier and fresh regions become fresher). This in turn leads to enhanced salt diffusion fluxes between isohaline water masses (Zika et al., 2015, Skliris et al., 2016). Therefore, it is expected that Mixing is weakening the signal of the water cycle amplification when looking at the Salinity distribution, because mixing will always transport salt from the more saline areas to the less saline areas, thus decreasing the width of the volumetric distribution of Salinity. The Mediterranean Sea in particular is an Evaporation dominated area, transforming its water masses towards higher salinities almost throughout the basin. In all datasets considered here the whole volumetric distribution is displaced towards higher salinities (see figure. 9d). However, if saltier waters become saltier at a higher rate than the less salty waters then the width of volumetric distribution will again increase leading to increased salt mixing between isohaline volumes. Although this is clearly evidenced between the relatively fresh MAW and the very salty upper layer waters of EMED showing larger salinification rates, this is not the case for the deep parts of the two sub-basins, where the salinification rate is relatively larger in the less salty waters of WMED than in the saltier EMED waters. In addition, one may argue that the increased salinification of the basin may reduce stratification through the density increase, thus further enhancing diffusive fluxes. Significant salinity-driven density increases are observed in the WMDW over the last decade associated with the Western Mediterranean

Transient (Schroeder et al., 2016b). However, salinification and warming trends over the second half of the 20th century are shown to be almost density compensated in both the WMDW (Bethoux and Gentili, 1999) and in the MOW within the Northeast Atlantic subtropical region (Potter and Lozier, 2004), suggesting no significant long-term changes in Mediterranean Sea stratification.

3.7 Salt budget

The increase of E-P-R over the Mediterranean surface produces an increase in salt content, which in case of a steady state balance can be calculated from the approximate salt equation:

$$DV = \frac{V(basin) \cdot (S_1 - S_2)}{S_2} \quad (5)$$

Where DV is the extra volume of fresh water extracted from the Mediterranean Sea due to the E-P-R flux increase (assuming negligible net flux changes at the straits):

$$DV = \sum_{1955}^{2012} change[E - P - R]\,(m^3) \quad (6)$$

V(basin) is the volume of the Mediterranean Sea, S_1 is the basin averaged salinity in 1955 and S_2 the increased salinity in 2012 due to the net evaporation increase. If we solve for S_2 :

$$S_{2=}\frac{S_1 \cdot V(basin)}{(DV + V(basin))} \quad (7)$$

S_1 equals to 38.595, DV = -4.6246*10^{12} m^3, and the Mediterranean volume calculated from the model 3-D grid equals to V(basin)= 3.7557484*$10^{15}$$m^3$. This gives us an increased basin average salinity S_2 of 38.6426, that is considerably lower than the actual basin average salinity of 2012 obtained from the data of 38.7743. We can calculate the salt budget of the Mediterranean Sea for the given period of 1955-2012, by considering the different processes adding or subtracting salt from the basin. The total basin salt content change may be attributed to changes in the Gibraltar salt fluxes and changes in the net evaporation:

$$Salt_{change} = Saltflux_{change}(Gibraltar) + S_{change(E-P-R)},$$

Where: $Salt_{change} = S_{trend(1955-2012)} \cdot \rho \cdot V(basin) = 6.912 \cdot 10^{14} kg,$

$$Saltflux_{change} = Volumeflux(Gibraltar) \cdot Salinity \cdot \rho \cdot time\ (1955 - 2012) \\ = -0.88 \cdot 10^{13}\ \text{kg}\ ,$$

$$Salt_{change(E-P-R)} = \rho \cdot V(basin) \cdot \left(S_{2012(E-P-R)} - S_{1955}\right)$$
$$= 1029kgm^{-3} \cdot 3.755748 \cdot 10^{15} m^3 \cdot (38.6426 \frac{gr}{kg} - 38.595 \frac{gr}{kg}) \cdot \frac{1kg}{1000gr}$$
$$= \ 1.839 \cdot 10^{14} \text{ kg},$$

where ρ is the basin average density (=1029kg/m^3) and $S_{2012(E-P-R)}$ is calculated from Eq. 7.

Results show that net evaporation change is the dominant contributor to salinity change. However, the net evaporation increase alone cannot explain the actual salt content increase of the basin indicating that the Mediterranean is far from a steady state.

4. Conclusions

By analyzing various types of data sets we aimed to assure a more robust proof of the effects of climate variability and climate change on the Mediterranean Sea. Due to uncertainties, sparse spatial-temporal resolution and lack of in-situ available data, we made as mentioned before, a double approach, applying two methodologies for studying the variabilities of the Mediterranean water cycle. Our first approach, based on the analysis of the actual parameters of the water cycle, such as evaporation, precipitation and river run off fluxes, available in reanalysis data sets. These data sets gave us a first insight of the water cycle, unfortunately this data sets are connected with large uncertainties due to sparse sampling (prior to Satellite Era) and inconsistency between observations and modelled data (Trenberth et al., 2011, Schanze et al., 2010, Skliris et al., 2014). Therefore, we wanted to evaluate our results via another method, the water mass transformation framework, allowing us to calculate changes of the water cycle by analyzing changes in the Salinity distribution. In fact, for oceanic regions, Salinity measurements are more consistent, with a better spatial and temporal resolution, leading to less uncertainty. In theory, the water mass transformation theory should give us a more robust proof of its main driving mechanisms (Water cycle). In practice, the method is also connected with some major problems, while studying the Mediterranean Sea, one need to consider that it is not a closed system, but connected through the Gibraltar and the Dardanelles to the Atlantic Ocean and the Black sea respectively. Therefore, exchanging various physical properties which are hard to measure on a large time scale.

The analysis of air sea fresh water fluxes delivered from various data sets showed a clear intensification of the water cycle, indicating a large increase of net Evaporation mainly caused by an increasing trend in Evaporation, combined with a small decreasing trend in River run off and a rather small trend in Precipitation, observed over the last few decades. Reanalysis data sets NCEP/NCAR and 20CRv2 show an increase of the water cycle of about 20-30% over the period 1950-2010, while the higher resolution reanalysis product (Mediterranean Sea Physics) shows only a change of about 7% in E-P-R. On the other hand, our salinity based analysis showed an intensification of 8% (EN4) & 25% (Reanalysis) of the water cycle over the period of 1955-2014, with these values slightly underestimating the water cycle change since they are not considering the net salt transport out of the Mediterranean through the Gibraltar strait. However, the latter is negligible when compared to the E-P-R flux change, standing only for an underestimation of 0.006% and it is therefore not considered.

While the reanalysis data sets of NCEP/NCAR and 20CRv2 show a large change of more than 20% in the water cycle, considerably higher with respect to that inferred from the salinity observed change provided from Medatlas and EN4, for the same period. This could be partly explained by the overestimation of fresh water cycle, often connected to the related data sets. In contrast, one would assume that the Reanalysis data set, which in fact runs a coupled Ocean – Atmosphere model, combined with in-situ data would give us comparable results when using both methods, which would allow us to attribute the observed differences to the various mechanisms causing uncertainties in the water transformation framework, such as salt mixing and salt fluxes. Since salt fluxes are provided by the data set we would have a good insight of the contribution of salt mixing. Unfortunately, although still agreeing on strong intensification of the water cycle both methods show large differences. The observed differences between the two results might be caused due to abrupt changes which bring our system far from a steady state, not allowing us to use the salt approximation equation properly, or due to inconsistency in the ocean re-analysis outputs, which could affect our salt content change estimations. These issues should be considered and improved in future approaches, which would allow us to accurately estimate changes in the water cycle only through Salinity observations.

This study together with many others clearly shows that observed global climate change has a huge impact on the Mediterranean region (Sarigu and Montaldo, 2017, Adloff et al., 2015, Bethoux and Gentili, 1999, Krahmann and Schott, 1998), which in fact is a very vulnerable region to climate change impacts and considered as a hot spot for undergoing and future climate changes (Giorgi, 2006, Lionello and Scarascia, 2017). Understanding and evaluating the changes of the Mediterranean water cycle is a key issue for the welfare, survival and evolution of the region. The dynamics of the fresh water cycle does not only affect the mentioned physical parameters of the Mediterranean Sea, but more importantly control the balances of ground and fresh water supply for the nature. This study along with many other studies provides a robust proof of the fast-changing water cycle of the Mediterranean Sea, an increase of net Evaporation, meaning the region is becoming dryer. Future projections showing further increases in net Evaporation, rising salt and Temperature trends (Borghini et al., 2014, Adloff et al., 2015, Schroeder et al., 2010, Gualdi et al., 2013) . Future studies should provide more detailed future scenarios for the various regions of the Mediterranean, providing stakeholders and law makers the right tools for mitigating present and future climate changes.

5. References

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6. Appendix

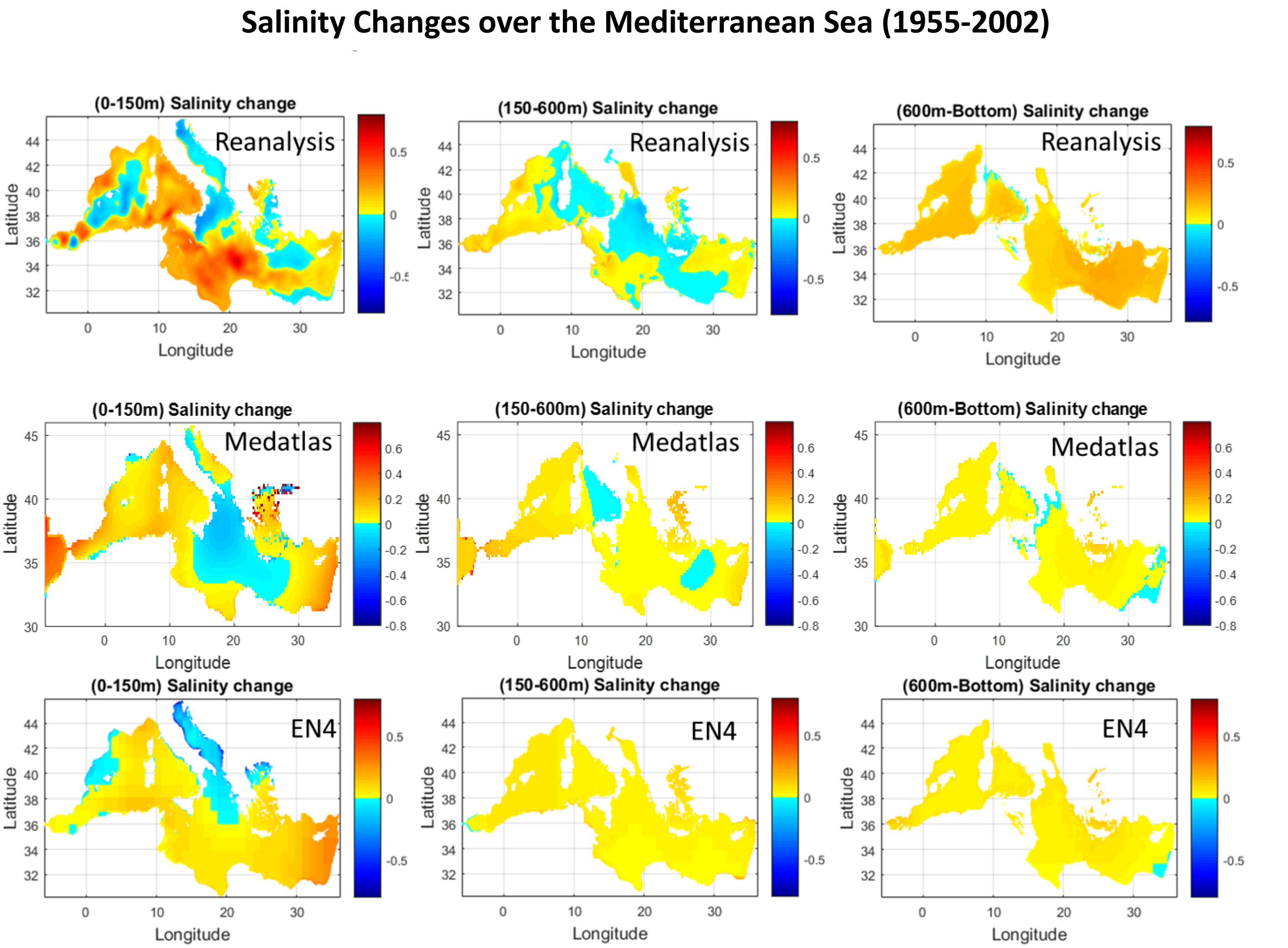

Figure A1: Salinity trends of the Mediterranean Sea, derived from three data sets (Reanalysis, Medatlas and En4), over the same period (1955-2002).

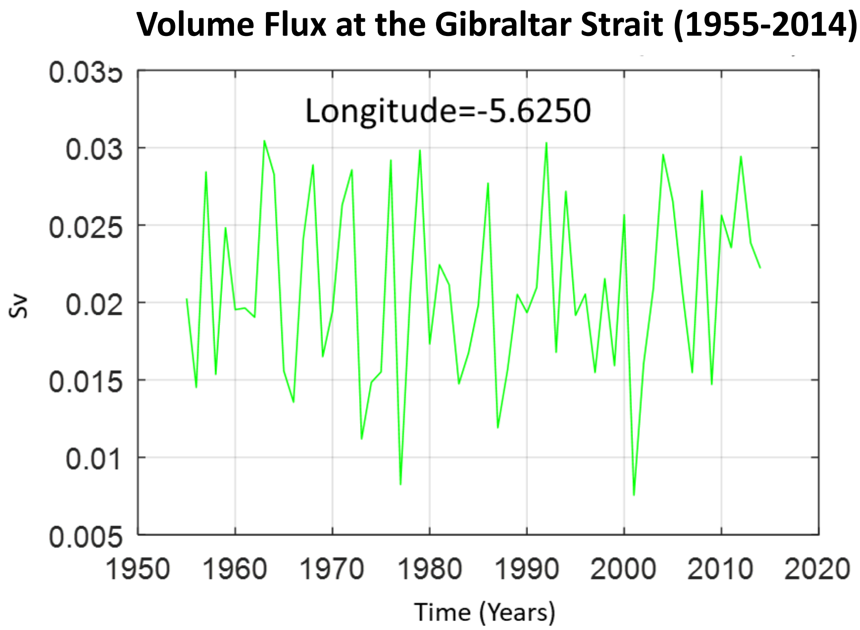

Figure A2: Net Volume flux at the Gibraltar strait, calculated from the Reanalysis data set (Next data project).

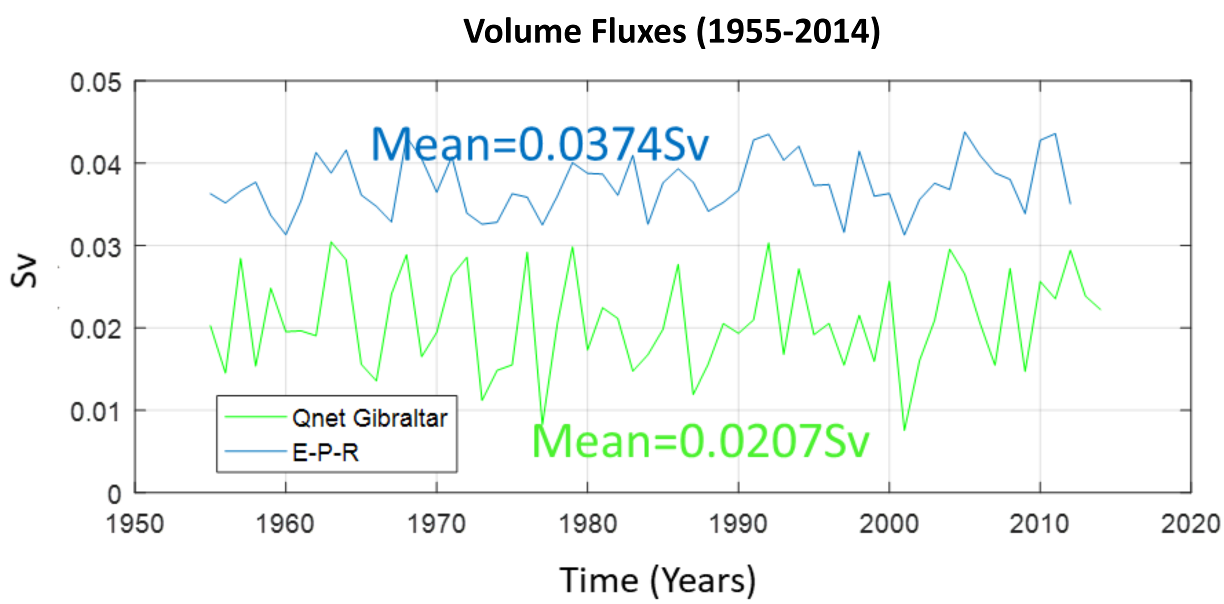

Figure A3: Net Volume flux at the Gibraltar strait (Green line), compared to the Accumulated E-P-R flux, both calculated from the Reanalysis data set (Next data project).

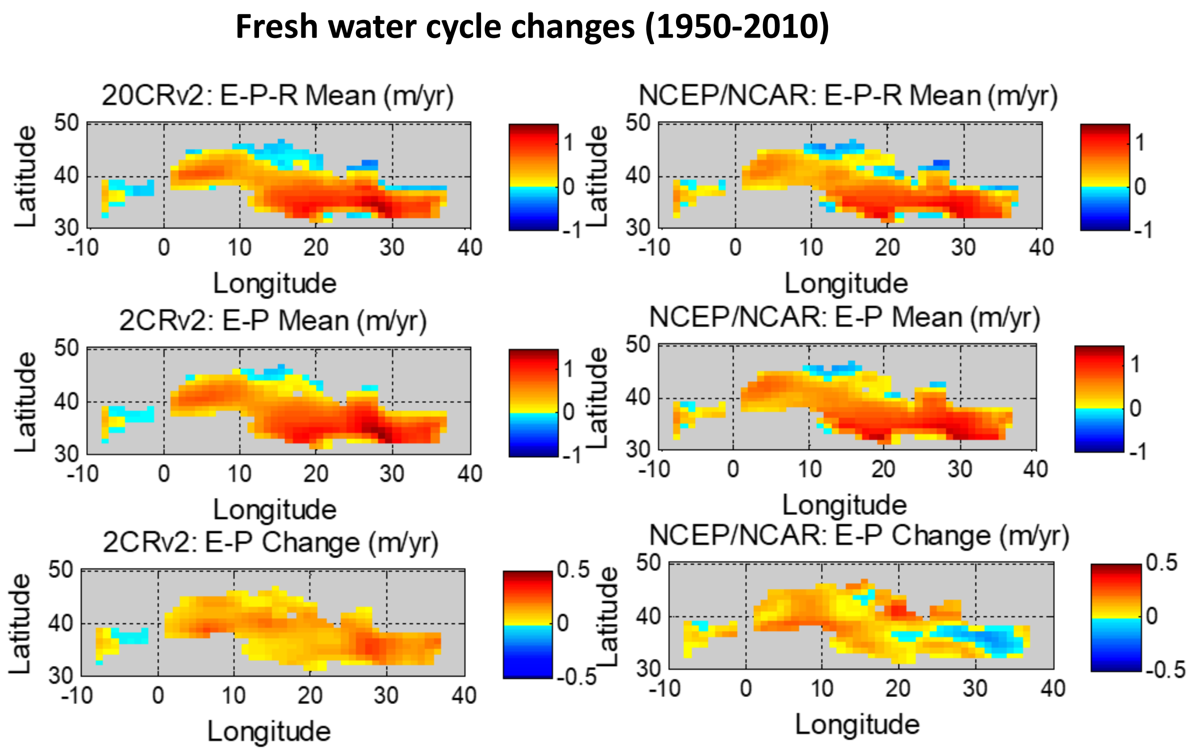

Figure A4: Mean and trend calculated for both 20CRv2 and NCEP/NCAR data sets over the period 1950-2010, over the Mediterranean basin.

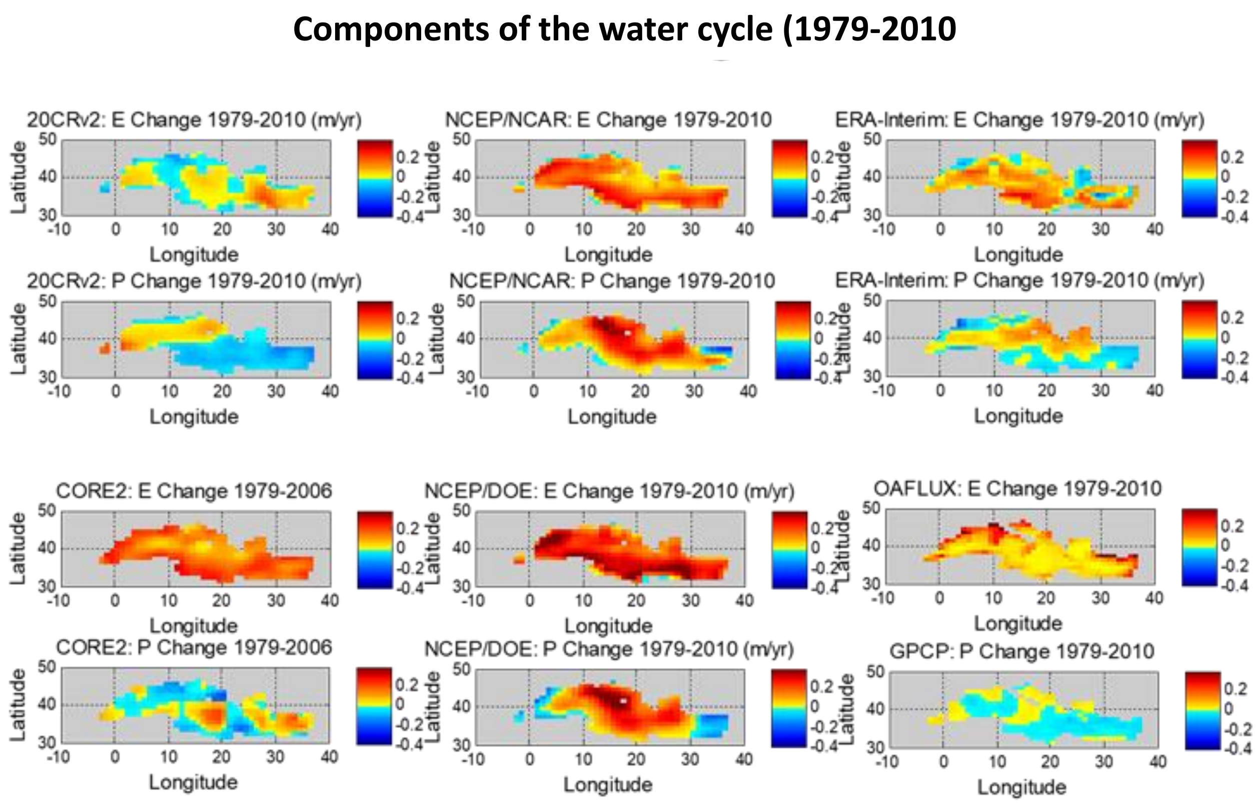

Figure A5: Components of the fresh water cycle of the Mediterranean Sea, direct comparison of Precipitation and Evaporation trends of various available data set, calculated for the period 1979-2010.