Water and energy budgets over the Mediterranean Sea and differences between East and West Mediterranean basins

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Abstract

The global water cycle is experiencing significant changes as a consequence of climate change. A specific area which is more sensitive to changes in the water cycle is the Mediterranean region. The Mediterranean Sea is an important source of atmospheric moisture. An improved knowledge of the Mediterranean hydrological cycle and its variability is a compelling issue and could yield important socioeconomic benefits. Preliminary results of the investigation of the main components of the water cycle budget over the Mediterranean Sea are here presented.

1. Introduction

The Mediterranean Sea (MS) is a semi-enclosed basin, surrounded by complex orography: the Eurasian and the African continents (protected from oceanic air masses) and connected to the Atlantic Ocean through the Gibraltar Strait. Located between the mid-latitude storm rain-band and the Sahara desert, the Mediterranean region experiences a profound seasonal cycle, with wet-cold winters and dry-warm summers (Peixoto et al. 1982). Occasionally long drought periods occur during summer.

Climate variability over the Mediterranean region has been shown to be driven by several major climate modes, such as the El Nino-Southern Oscillation (ENSO), the North Atlantic Oscillation (NAO), and African and Asian monsoons (e.g., Brönnimann et al. 2007, Basharin et al. 2003, Hurrell et al. 2003, Mariotti et al. 2002, Ziv et al. 2004, Rowell 2003, Rodwell and Hoskins, 2001; Mariotti et al. 2003), with the NAO as the dominant mode of winter climate variability in the North Atlantic region, which influences the precipitation patterns over Euro-Mediterranean region (Hurrell 1995, 1996; Rodo et al. 1997; Eshel and Farrel 2000).

All the past and future global climate changes may be linked to significant changes of the hydrological cycle in the Mediterranean region (Bethoux and Gentili 1999, Giorgi 2006). These in turn may potentially impact the Atlantic thermohaline circulation by changing the characteristics of the water flux at the Gibraltar Strait (Hecht et al. 1997).

The MS itself is an important source of moisture for the atmosphere since local evaporation largely exceeds precipitation in all seasons. The characteristics of the local water budget influence the amount of moisture available for the surrounding land regions, especially one that flows into northeast Africa and the Middle-East (Peixoto et al. 1982; Ward 1998).

A number of studies have investigated different aspects of the Mediterranean water cycle and of its components. To mention only the most recent ones: present and past precipitation and temperature variability, large scale dynamics and trends (Xoplaki, et al. 2004), summer air temperature variability and its connection to the large scale atmospheric circulation and sea surface temperatures (SSTs; Xoplaki, et al. 2003), the energy and water budgets of the MS (Pinardi and Masetti 2000), climatology and aspects
of the observed variability of the river discharge into the Mediterranean Sea (Struglia et al. 2004). Several characteristics of the Mediterranean climate variability (Lionello et al. 2006) and ocean processes for the Mediterranean (Robinson and Malanotte-Rizzoli 1994) have been reviewed.

However, there are many uncertainties, including observations of the main hydrological components and estimates of air-sea fluxes. Mechanisms and physical processes regulating the variations of the hydrological cycle and the atmosphere-ocean relationships are poorly understood and explained. The availability of atmospheric re-analyses and satellite data in recent years, as well as longer observational datasets, provides a new opportunity to study not only the climatology, but also the variability of the water cycle air-sea water fluxes at different spatial and temporal scales.

This work constitutes a preliminary analysis of some of the elements of the hydrological cycle over the MS, including variables describing the ocean-atmosphere relationship. This project is part of my doctoral work, which aims at a further and more in-depth analysis and investigation of the following issues:

- Documentation of the climatological characteristics of the hydrological cycle and the thermohaline circulation components over the MS with new and most recent data (observations, reanalyses, remote sensed);
- Assessment of different estimates of evaporation and relationship with salinity;
- Analysis of the temporal (e.g., trends, periodicities) and spatial (e.g., recurrent modes) variations of these components and their anomalies, with a particular focus on the variability of the “evaporation minus precipitation” (E-P) difference, and the study of the tendency of the Mediterranean toward drying or wetting;
- Analysis of the origin and evolution of the feedbacks of E-P with the atmospheric and oceanic circulations at intraseasonal and interannual scales in the East and West Mediterranean basins individually;
- Investigation of the connections between E-P and surface salinity over the Mediterranean.

2. Data and Analysis Techniques

Part of this work concerned data collection and preparation, especially the homogenization of the formats, in view of the long-term objectives.

- Atmospheric circulation and surface variables come from the European Centre for Medium-Range Weather Forecasts (ECMWF) reanalysis (ERA-40) monthly data from 1958 through 2001, archived on a 2.5° longitude x 2.5° latitude horizontal grid, and at 23 vertical isobaric levels from 1000-hPa to 1-hPa.
- Precipitation is taken from GPCP (monthly values during 1979-2004), CMAP (observational-only data at monthly scale during 1979-2006), and CRU land-only observations (during 1979-2001). GPCP and CMAP are available on a 2.5° x 2.5° grid and CRU on a 0.5°x0.5° grid.
Latent and sensible heat fluxes over the oceans from the Objectively Analyzed Air-Sea Fluxes for the Global Oceans (OAFlux). Collected data cover the period 1981-2002 at monthly scale, on a 1°x1° grid.

Surface winds over the oceans at monthly resolution from QuikSCAT during 1999-2006 and available on a 1°x1° grid.

Radiation data from the ISCCP D2 dataset during 1984-2004. Downloaded data are at monthly scale on a 2.5°x2.5° grid.

River runoff climatological (1807-1991) monthly data come from the Global Runoff Data Center (GRDC)/University of New Hampshire.

Ocean temperature and salinity data were collected from the Simple Ocean Data Assimilation (SODA) reanalyses, version 1.4.2. Data are available at monthly resolution, from 1958-2001, on a 0.5°x0.5° grid and at 40 levels. MEDAR MEDATLAS ocean temperature and salinity climatological data (on a 0.2°x0.2° grid and 25 vertical levels) were also used.

SST monthly data were also downloaded from the Hadley Centre (during 1901-2003) and Reynolds (from 1981-2005). Both datasets are on a 1°x1° grid resolution.

Monthly climatological salinity values were collected from Levitus (1994, 1°x1°, 19 vertical levels) and the World Ocean Atlas (2005, 1°x1°, 24 vertical levels).

The period from 1979 to 2001 was used in the analysis, unless data cover different time periods.

All data were masked out over the MS when computing time series of area-averaged values. East and West Mediterranean basins were also identified and uniquely divided based on geographical, topographical and climatological features recognized during the analysis. The division crosses the Sicily Strait area, from Tunisia to Greece.

3. Results

3.1 Climatologies

The seasonal climatology (1958-2001) of precipitation (P, not shown) from ERA-40 shows the known general characteristics of the Mediterranean climate: wet winters and dry summers. In comparison with GPCP, precipitation from ERA-40 shows lower values in all four seasons. In general, direct measurements of precipitation over the sea are complex and rare. Given the low-resolution of these data, differences between datasets over the sea could be questionable.

The seasonal climatological (1958-2001) evaporation (E, not shown) from ERA-40 shows that E significantly exceeds P over the Mediterranean Sea through all seasons, especially in summer. Evaporation is a leading term of the water budget variability. Unfortunately, very few direct measurements are available, and the low resolution and poor quality of current data of evaporation gives low confidence in the reanalysis estimations (accounting for the lack of closure of water budget in reanalyses).
Figure 1 shows the 1958-2001 climatology of E-P from ERA-40 for all four seasons. E-P is always positive over the MS, and reaches the highest (lowest) value during fall (spring) in the East and West Mediterranean. This contrasts with the timing of maximum and minimum values of P and E individually. As E increases, P and river discharge (R) into the Mediterranean decrease, showing strong impact of the climate change over the Mediterranean region. There are large uncertainties of absolute values for E-P estimates (Somot and Prieur, 2007).

Figure 2 shows the climatological (1979-2001) 1000-300hPa vertically integrated moisture flux and convergence from ERA-40 for all 4 seasons (brown color showing divergence area, and green color showing convergence area). Strongest divergence is present during summer, especially over the Eastern Mediterranean, corresponding to the descending branch of the Hadley cell. More northward westerlies are associated with a lower mean sea level pressure over the MS. Convergence is strongest during winter, under the influence of the more southward westerlies associated with a higher mean sea level pressure (weaker center displaced southward with respect to summer) and higher precipitation over the MS.

The atmosphere interacts with the ocean through the exchange of heat, fresh water, and momentum at the air-sea interface. The air-sea heat exchange includes a number of processes: solar radiation, longwave radiation, sensible heat transfer by conduction and convection, and latent heat release by evaporation of sea surface water. The amount of heat exchange resulting from these radiative and turbulent heat transfer processes is the air-sea heat flux.

Figure 3a shows the climatological (1984-2004) total net radiation (SWd-SWu+LWd-LWu) from ISCCP for all seasons, and Figure 3b shows the area-average over the MS. The annual cycle of the total net radiation is clearly modulated by the elevation of the sun on the horizon (SWd). However, higher values are present over the MS with respect to the surrounding land mass from spring to fall due to its low albedo, and there are noticeable differences in net radiation values between the East and West Mediterranean basins. Looking at intermediate seasons, MAM has remarkably higher values than SON.

Figure 4 displays the spatial distribution of climatological (1981-2002) sensible heat flux (Fig 4a) and latent heat flux (Fig. 4b) from OAFlux for all 4 seasons. The area-averaged cycles are represented in Fig. 4c and 4d, respectively. Both sensible and latent heat fluxes have maximum values in winter due mainly to the contribution from the East Mediterranean basin. The East basin has higher latent heat flux with respect to the western side year-round. Minimum sensible heat flux is reached in summer and the variations in this period are quite modest. On the opposite, latent heat flux clearly decreases until May and rapidly increases afterward until the absolute maximum in November. Examining the land–sea contrast (using ERA-40 data), during winter the land has negative values of sensible heat flux due to the cooler land with respect to the overlying air (so the flux is downward). The opposite is true for the sensible heat flux over the MS. Latent heat flux has maximum in winter over the MS because of the air with low specific humidity which favors evaporation associated with strongest surface winds.
The minimum of latent heat flux in May is associated with the weakest surface winds which negatively affect the flux.

Figure 5a (taken from Caniaux, 2007; Matsoukas et al. 2005) reviews different estimates of the heat budget over the MS and it shows the predominance of solar and latent heat fluxes. Large differences in the estimates from different sources exist and support the need for further and deeper research.

3.2 Annual cycles

This section discusses the monthly variations of the components of the hydrological cycle averaged over the MS.

When looking at the Mediterranean water budget, atmosphere-land-sea interaction is a very important issue, and the regional water cycle plays an important role within the global water cycle.

The annual cycle of total river runoff from GRDC (1958-2001; not shown) masked out along the Mediterranean coastline shows a minimum discharge into the MS of 1000 mm/month in August-September, and a maximum of 20000 mm/month in January. There are uncertainties in these estimates. River runoff fluxes have local and large-scale impact on the MS hydrology, and will be included in calculating the ocean water budget in the future.

Figure 5b (taken from Caniaux, 2007) reviews several estimates of E, P and E-P over the MS. Large discrepancies are evident for each parameter according to the methods or data used.

Figure 6 shows the climatological (1979–2001) annual cycle of the components of the atmospheric water budget from ERA-40 area-averaged over the whole MS (Fig. 6a), the East Mediterranean (Fig. 6b), and the West Mediterranean (Fig. 6c). The tendency of the total column water content has been neglected (and usually this is a very good approximation at monthly or longer time scales). Divergence and E-P should balance each other if ERA-40 has a closed budget. With respect to the whole MS, during summer divergence predominates over E-P, while the opposite occurs in all other months. Minimum difference occurs in the intermediate seasons. Similar variations are recognized over the East Mediterranean with higher values of all components, especially divergence. The West Mediterranean is more balanced with lower values of all components. The difference between E-P and divergence is always positive and variations are in phase.

In order to better understand the ocean-atmosphere relationship, the analysis of the variation of oceanic parameters with different data comparison follows.

Figure 7a displays the climatological (1979–2001) annual cycle of sea surface temperature, with a clear maximum value in August (lagging the maximum incoming
radiation by one month due to the thermal inertia of water) and minimum in February. The three datasets have similar variations, although in summer MEDATLAS is lower by about 0.5°C. The East Mediterranean (Fig. 7b) is much warmer (2-3°C) than the West Mediterranean (Fig 7c) during winter, while the maximum values during summer are very similar. Hadley’s surface temperature very well compares to the 5-m depth sea temperature from SODA, showing small temperature variations in the sea surface layer.

The comparison of surface salinity in Fig. 7d shows some differences between displayed data, with the highest values from WOA, and smallest values from SODA (not shown). Salinity has two maxima and two minima, lagging evaporation (see Fig. 6a) by one month. The East Mediterranean 5-m depth salinity (Fig. 7e) shows small differences in the variations, but has significantly higher values than salinity in the West Mediterranean (Fig. 7f).

### 3.3 Time series of anomalies and trends

The time series of the anomalies of seasonal averages of P, E and E-P are first examined. The time series of P (not shown) has the largest anomalies during winter, with mostly positive anomalies until 1988, followed by a prolonged period of negative anomalies in the late 1980s and the early 1990s. Anomalies have smaller amplitudes in other seasons and are within ±0.4 mm/day. The time series of E (not shown) has also the largest anomalies during winter. The intercomparison of data shows that ERA-40 has always smaller variations and values than other data (GPCP and CMAP for precipitation, OAFlux for evaporation). In general, evaporation from OAFlux shows a positive trend in all seasons, stronger and spatially wider than ERA-40. Figure 8 shows the time series of E-P anomalies. Winter has the largest variations and a clear positive trend. Early 1990s were a dry period (with E bigger than P). The last decade shows a positive trend and positive anomalies of E-P.

Most Mediterranean charts and graphs in pervious studies were done in the winter. This is because winter in the Mediterranean has the most extreme properties. Intense cooling and unusually high evaporation due to the cold, dry continental winds increase the surface mass and encourage vertical mixing, leaving the Eastern basin very uniform in salinity and pretty uniform in temperature. Current research examining the circulation within the Mediterranean (Manca, et al. 2003), gives the result of extended dry spell and exceptionally cold winters over the Aegean Sea in late 1980s with a consequence of altered the thermohaline circulation of the Eastern Mediterranean through the mid-1990s.

Considering the interannual variability of the Mediterranean Sea upper ocean circulation (Pinardi et al. 1997) some results for SST and salinity follows.

Figure 9a displays the time series of seasonally-averaged standardized anomalies of Hadley’s SST over the MS. The most important features are a period of colder temperatures in the first two decades of the last century, several decades characterized by
generally warmer temperatures between 1930’s and 1970’s, a colder period in the 1970’s and early 1980’s, followed by a strong warming of SST continuing now.

SODA’s salinity at 5m depth (Fig. 9b) shows two long periods characterized by opposite anomalies of salinity: a “fresh” period (1986-1992) and a salty one (from 1992 up to now).

Geographical maps of seasonal trends of E-P, temperature and salinity at 5m depth are shown in Figs. 10, 11 and 12, respectively. All fields show positive trends during all seasons over most of the MS, with strongest values during winter and especially in the East Mediterranean. The trends of E-P in observations (OAFlux-GPCP) are more positive than in reanalysis (ERA-40).

3.4 Correlations

Figure 13 shows the point-wise contemporaneous correlations between GPCP precipitation and Hadley’s SST. In general, a negative correlation between the seasonal-mean SST and precipitation anomalies may indicate that the atmosphere affects SST more than SST affects the atmosphere; conversely, a positive correlation means the ocean plays a major role in determining the atmospheric response (Wang et al. 2005). In the Mediterranean, the East Mediterranean basin reveals a strong positive correlation during summer, slowly decaying in fall. This suggests that the East Mediterranean could play an important role on the atmospheric variability, at least regionally.

To further investigate the ocean-atmosphere relationship, correlations between OAFlux evaporation and SODA salinity have been computed (Fig. 14). Correlations are in general positive through all seasons, especially during fall in the East Mediterranean, where the strongest coupling between ocean and atmosphere is presumably in action.

4. Conclusions

The Mediterranean Sea is an important point for the study of the hydrological cycle, both at regional and global scale, because of its links with the large-scale atmospheric and oceanic circulation.

This work aimed at a better and comprehensive view of the climatological characteristics and variability of the components of the atmospheric hydrological cycle and thermohaline properties over the Mediterranean Sea with the use of new data and by focusing on the whole annual cycle.

The evolution of the anomalies in last few decades shows strong signal of recent climate change with corresponding positive trends. The relative importance of salinity in the context of understanding the ocean-atmosphere feedback mechanisms is more stressed here.
As outlined in the introduction, this work will be extended in the next months following the issues described above. The future work, benefiting from better-quality data, will provide not only a description of the fields depicting the variations of water cycle, but also a deeper investigation into the mechanisms and the interconnections between ocean and atmosphere over the East and West Mediterranean.

References


Figure 1. Climatology of E-P (mm/day) from ERA-40 (1958-2001) for December-February (DJF, top left), March-May (MAM; top right), June-August (JJA, bottom left), and September-November (SON, bottom right).
Figure 2. Climatology of vertically integrated moisture flux (1000-300 hPa) and convergence (brown=divergence, green=convergence, mm/day) from ERA-40 (1979-2001) for December-February (DJF, top left), March-May (MAM; top right), June-August (JJA, bottom left), and September-November (SON, bottom right).
Figure 3. a) Climatology of total net radiation at the surface (SWd-SWu+LWd-LWu) in (W/m²) from ISCCP (1984-2004) for all 4 seasons, and b) climatological (1984-2004) annual cycle of total net radiation from ISCCP area-averaged over the Mediterranean Sea.
Figure 4. Climatology of a) Sensible Heat (SH) flux and b) Latent Heat (LH) flux in (W/m²) from OAFlux (1981-2002) for all 4 seasons, and climatological annual cycle of c) SH flux from OAFlux (red line) and ERA-40 (blue line), and d) LH flux OAFlux (1981-2002) (green line) and ERA-40 (1979-2001) (orange line) in (W/m²).
Figure 5. Table of a) heat budget (modified from Matsukas et al, JGR 2005) and b) water budget (modified from Mariotti et al, JC 2002).
Figure 6. Climatological (1979–2001) annual cycle of the atmospheric water budget components: evaporation=\(E\) (red line), precipitation=\(P\) (blue line), \(E-P\) (orange line), and vertically integrated moisture flux divergence=\(\text{VIMF}\) (green line) in (mm/day) from ERA-40 area-averaged over a) the whole Mediterranean Sea, b) the East Mediterranean, and c) the West Mediterranean.
Figure 7. Climatological (1979–2001) annual cycle of a) sea temperature in deg C (Hadley – red line, Reynolds – green line, MEDATLAS – blue line) at the surface area-averaged over the whole Mediterranean Sea; b) temperature (Hadley at the surface – red line, SODA at 5m depth – orange line) area-averaged over the East Mediterranean Sea, and c) the West Mediterranean Sea; annual cycle of salinity (Levitus – red line, World Ocean Atlas – green line, MEDATLAS – blue line) in psu at the surface area-averaged over d) the whole Mediterranean Sea; salinity (SODA – orange line) at 5m depth over e) the East Mediterranean Sea, and f) the West Mediterranean Sea.
Figure 8. Seasonally-averaged time series of E-P anomalies (mm/day) from OAFlux evaporation - CMAP precipitation (green line), OAFlux evaporation – GPCP precipitation (blue line), and E-P from ERA-40 (orange line) for a period 1981-2001, for a) DJF, b) MAM, c) JJA, and d) SON (0.43 is the 95% significance level of the correlation coefficient).
Figure 9. Time series of seasonally-averaged standardized anomalies of a) Hadley’s SST (1901-2003) with 11-year running mean (black line), and b) SODA’s salinity (1979-2001) at 5m depth with a 5-year running mean (black line).
Figure 10. Seasonal trends of OAFlux evaporation – GPCP precipitation (top) and E-P from ERA-40 (bottom) in (mm/day/year) during 1981-2001 for a) DJF, b) MAM, c) JJA, and d) SON.
Figure 11. Seasonal trends of SODA’s temperature (C/year) at 5m depth during 1979-2001 for a) DJF, b) MAM, c) JJA, and d) SON.
Figure 12. Seasonal trends of SODA’s salinity (0.1*psu/year) at 5m depth during 1979-2001 for a) DJF, b) MAM, c) JJA, and d) SON.
Figure 13. Point-wise simultaneous correlations between GPCP and Hadley SST, based on monthly data, for the period 1979-1999, for a) DJF, b) MAM, c) JJA, and d) SON (the 95% significance level corresponds to the a correlation coefficient of 0.25).
Figure 14. Point-wise simultaneous correlations between OAFlux evaporation and SODA salinity, based on monthly data, for the period 1981-2001, for a) DJF, b) MAM, c) JJA, and d) SON (the 95% significance level corresponds to the a correlation coefficient of 0.25).