The Hydrological Cycle in the Mediterranean Region and Implications for the Water Budget of the Mediterranean Sea

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ABSTRACT

The hydrological cycle in the Mediterranean region is analyzed focusing on climatology and interannual to interdecadal variability, in particular long-term changes related to the well-established North Atlantic Oscillation (NAO) teleconnection. Recent atmospheric reanalyses and observational datasets are used: precipitation, evaporation, and moisture flux from 50 yr of NCEP's and 15 yr of ECMWF's reanalyses; precipitation from the Climate Prediction Center Merged Analysis of Precipitation (CMAP) and the East Anglia University Climate Research Unit (CRU) datasets; and evaporation from the University of Wisconsin—Milwaukee (UWM) Comprehensive Ocean–Atmosphere Data Set (COADS). A budget analysis is performed to study contributions to the freshwater flux into the Mediterranean Sea, including atmospheric as well as river discharge inputs. The total river discharge is derived using historical time series from Mediterranean Hydrological Cycle Observing System (MED-HYCOS) and Global Runoff Data Center (GRDC) archives.

Mediterranean-averaged precipitation during the period 1979–93 has an annual mean ranging among datasets from 331 to 477 mm yr^{-1}, with a seasonal cycle amplitude of $\sim$700 mm yr^{-1}. Evaporation is estimated in the range of 934–1176 mm yr^{-1} with a seasonal cycle amplitude of $\sim$1000 mm yr^{-1}. The excess of evaporation over precipitation gives an annual mean Mediterranean Sea water loss ranging among datasets approximately from 500 to 700 mm yr^{-1}. The annual mean river discharge is 100 mm yr^{-1}, somewhat smaller than previous estimates using similar approaches. Water loss to the atmosphere and riverine inputs combined lead to an estimated Mediterranean freshwater deficit of about 500 mm yr^{-1}, consistent with most oceanographically based estimates of the water flux from the Atlantic Ocean at the Gibraltar Strait.

On interannual to interdecadal timescales, during the period 1948–98, the Mediterranean atmospheric winter water deficit is positively correlated with the NAO and has been increasing due to the long-term positive anomalies of the NAO since the early 1970s. Precipitation, which is also significantly correlated with the NAO, appears to be mostly responsible for this since no significant correlation is found for evaporation. Over the 50-yr period the Mediterranean atmospheric water deficit increased by about 24% in the winter season, and by 9% annually. Given the pattern of the NAO-related precipitation anomalies, this change is likely to have occurred primarily north of 35°N. The results presented here suggest that in response to the changes in the freshwater flux significant variations in the characteristics of Mediterranean waters and the Gibraltar flux may also have occurred during this period, mostly driven by the influence of the NAO.

1. Introduction

Located between the midlatitude storm rainband and the Sahara Desert, the Mediterranean region experiences a profound 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 (NAO; Hurrell 1995, 1996; Rodo et al. 1997; Eshel and Farrel 2000). Past and future global climate changes affecting, for example, storm track characteristics (Arpe and Roeckner 1999), as well as changes in the land surface conditions (Reale and Shukla 2000), may be linked to significant changes of the hydrological cycle in the Mediterranean region (Be-

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thoux and Gentili 1999). These in turn may potentially impact the Atlantic thermohaline circulation by changing the characteristics of the water flux at the Gibraltar Strait (Reid 1979; Hecht et al. 1997; Johnson 1997). The Mediterranean Sea is also an important source of atmospheric moisture and the characteristics of the local water budget influence the amount of moisture that flows into northeast Africa and the Middle East (Peixoto et al. 1982; Ward 1998). Consequently, an improved knowledge of the Mediterranean hydrological cycle and its variability could yield important socioeconomic benefits to these areas.

Large-scale water budget studies have been conducted for various continental regions (Rasmusson 1968; Roads et al. 1994). Recent atmospheric reanalysis efforts by the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR; Kalnay et al. 1996), the European Centre for Medium-Range Weather Forecasts (ECMWF; Gibson et al. 1997) and the National Aeronautics and Space Administration's (NASA's) Data Assimilation Office (DAO; Schubert et al. 1993) offer the opportunity for new investigations providing a more stable platform for the analysis of long-term variability (e.g., Zeng 1999). Intercomparison of the global-scale hydrological cycle in these datasets has been conducted by Trenberth and Guillemot (1998), Stendel and Arpe (1997), and Mo and Higgins (1996). In this paper we use reanalyses, in conjunction with other observational datasets, to focus on the Mediterranean region and intercompare results on various aspects of the local hydrological cycle.

A number of studies have dealt with the Mediterranean water budget (Bethoux 1979; Peixoto et al. 1982; Bryden and Kinder 1991; Harzallah et al. 1993; Gilman and Garrett 1994; Castellari et al. 1998; Angelucci et al. 1998; Bethoux and Gentili 1999; Boukthir and Barnier 2000) and results can vary significantly among authors according to the specific methodology applied. For example, Boukthir and Barnier (2000) have recently analyzed the freshwater flux in the Mediterranean Sea using atmospheric reanalyses from ECMWF, and found that climatological means for precipitation (P) and evaporation (E) yield an $E - P$ budget of about 650 mm yr^{-1}. Bethoux and Gentili (1999) review a number of studies to reassess the Mediterranean water budget and indicate that, in consideration of the heat and salt budgets, reasonable estimates for $E - P$ fall in the range 1050–1230 mm yr^{-1}, values significantly larger than Boukthir and Barnier (2000). These discrepancies reflect the uncertainties still more generally associated with the estimates of the air–sea fluxes (WGASF 2000) and indicate that further work is necessary to obtain the climatological picture of the Mediterranean hydrological budget, useful among other things for validating global analyses and calibrating parameterizations (Gilman and Garrett 1994; Castellari et al. 1998). Most importantly, few studies concerning the Mediterranean have focused on the long-term variability of these fluxes. Bethoux et al. (1998) have discussed the observed changes in the salinity of the Mediterranean Deep Water since the 1940s and suggest that a decrease in precipitation and an increase in evaporation over the whole sea, possibly in relation to global warming, could be responsible for up to 50% of the observed salinity changes. More recently, Tsimplis and Baker (2000) suggest that the sea level drop observed in the Mediterranean Sea since 1960 could be partly related to the influence of NAO on the air–sea water fluxes. The availability of the atmospheric reanalyses in recent years have provided a new opportunity to study not only the climatology, but also the variability of the air–sea water fluxes at different timescales.

In this work, we study the hydrological cycle in the Mediterranean region and the Mediterranean Sea water budget focusing on climatology and interannual to interdecadal variability, in particular long-term changes related to the well-established NAO teleconnection. The paper is organized as follows: in section 2, we discuss the data and the methods; the analyses and the intercomparison of precipitation, evaporation, and moisture transport are dealt with in section 3a, 3b, 3c, respectively; the Mediterranean freshwater flux and its variability are analyzed in sections 4a and 4b. In section 5, we discuss our results and present our concluding remarks.

2. Data and methodology

The main components of the Mediterranean Sea hydrological cycle are shown in the schematic two-box diagram of Fig. 1. The time-varying equation for the vertically integrated atmospheric water budget is

$$\frac{dW}{dt} = E - P - D, \qquad (1)$$

where W is the total water vapor content, P is precipitation, E evaporation, and D is the vertically integrated moisture divergence:

$$D = \nabla \cdot \mathbf{Q}, \qquad \mathbf{Q} \equiv \int_0^H \mathbf{V}q\, dz.$$

Here $\mathbf{Q}$ is the vertically integrated atmospheric moisture flux ($\mathbf{V}$ is the wind, q is atmospheric specific humidity, and H is the height in meters). On an annual mean basis the 1hs of Eq. (1) can be neglected and the atmospheric water budget equation is approximately

$$E - P \simeq D. \qquad (2)$$

Here we have also neglected the analysis error (Schubert et al. 1993) that for NCEP reanalyses is at most about 25% of the annual mean D. The time-varying equation for the total Mediterranean Sea water content M is

$$\frac{dM}{dt} = G + B + R - D, \qquad (3)$$

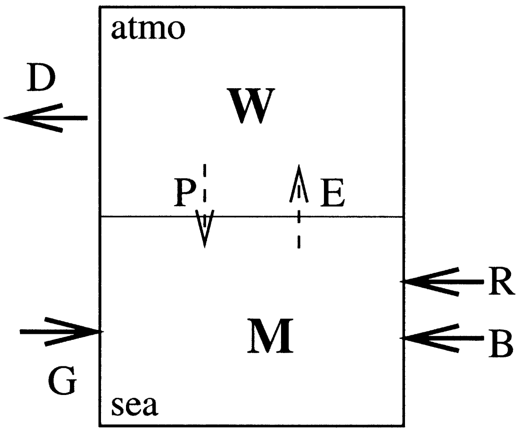


FIG. 1. A schematic two-box diagram illustrating the main components of the Mediterranean Sea hydrological cycle. *M* and *W* are the total Mediterranean atmospheric and oceanic water content, respectively. *P* is precipitation, *E* evaporation, *D* the atmospheric moisture divergence, *R* the Mediterranean river discharge, *B* and *G* are the total water fluxes from the Black Sea and the Gibraltar Strait, respectively.

where G and B are the total water inputs at the Gibraltar Strait and from the Black Sea, respectively, and R is river discharge into the Mediterranean Sea. The long-term mean of the Mediterranean water deficit (MWD) is approximately equal to the water flux at Gibraltar:

$$\mathrm{MWD} = D - R - B \simeq G. \tag{4}$$

We analyze precipitation, evaporation, and moisture flux from the ECMWF and NCEP–NCAR reanalysis projects. The NCEP–NCAR reanalysis project (hereafter NCEP; Kalnay et al. 1996) is run at T62 spectral resolution (approximately a grid size of 1.9°), with 28 sigma levels, 7 of them below 850 hPa. We use 50 yr of data, from 1948 to 1998, available at the time of this study: monthly means of precipitation and evaporation archived by the reanalysis project, and the 6-hourly data necessary to compute monthly vertically integrated moisture transport.

The ECMWF Re-Analysis project (ERA; Gibson et al. 1997) uses a horizontal resolution of T106 (approximately a grid size of 1°) with 31 hybrid levels, 6 of them below 850 hPa. It covers the period 1979–93. Monthly mean moisture transport is calculated from 6-hourly analyses, while monthly means of precipitation and evaporation are derived from twice daily 12–24-h forecasts (Stendel and Arpe 1997). Precipitation and evaporation from NCEP and ERA are compared with other observational datasets; the intercomparison of climatologies, unless otherwise stated, refers to the period 1979–93, common to all datasets. Observational datasets we use include the precipitation dataset of the East Anglia University Climate Research Unit (CRU; New et al. 2000); this is a gridded high-resolution (0.5° × 0.5°) dataset of monthly mean precipitation estimates from rain gauge measurements (land only), available from 1901 to 1996. We also use the Climate Prediction Center Merged Analysis of Precipitation (CMAP; Xie and Arkin 1996, 1997), which gives estimates of monthly mean precipitation at 2.5° × 2.5° resolution, for the period 1979–97. The ''standard'' version is used; this is a merged analysis mainly based on gauge stations over land and satellite estimates over ocean. For evaporation, reanalyses are compared with the University of Wisconsin—Milwaukee (UWM) Comprehensive Ocean–Atmosphere Data Set (COADS) from da Silva et al. (1994; hereafter UWM/COADS). This dataset provides, at a resolution of 1° × 1°, an objective global analysis of monthly mean evaporation over the oceans, for the period 1950–93, from individual observations found in COADS. We choose to analyze the ''unconstrained'' product (that is not tuned to fix the imbalances found in the global fluxes), more directly related to local ship observations.

The climatological river discharge is estimated using historical time series archived by the Mediterranean Hydrological Cycle Observing System (MED-HYCOS) and the Global Runoff Data Center (GRDC). From these datasets, all available rivers flowing into the Mediterranean Sea are taken into account: 67 rivers altogether, covering roughly 76% of the Mediterranean catchment area (Margat 1992). The time series of the major rivers (those contributing to more of the 80% of the total runoff) are at least 10 yr long, but climatologies for each river refer to whenever data were available. For a given river we consider data from the station nearest to the river mouth.

3. Components of the water cycle as depicted by various datasets

a. Precipitation

An intercomparison of climatological winter (December–February) and summer (June–August) precipitation in the Mediterranean region is presented in Figs. 2 and 3. In all seasons, the latitudinal gradient is the predominant feature of precipitation in the Mediterranean region with drier areas along the African coast and significantly wetter ones north of the Mediterranean Sea. According to CRU, winter mean precipitation along the African coast is about 350 mm yr^{-1}, with higher values toward the western part of the basin (Fig. 2); over 750 mm yr^{-1} are found in parts of France, across the Alpine region, and along the eastern rim of the basin. Other datasets are broadly consistent with CRU. For the ocean areas, these datasets indicate that on area average the western Mediterranean subbasin tends to be drier than its eastern counterpart.

During summer, the whole Mediterranean region south of 40°N is dry, receiving less than 200 mm yr^{-1} (Fig. 3). Between 40° and 44°N precipitation increases rapidly to approximately 550 mm yr^{-1}. CRU, CMAP, and ERA show local maxima of precipitation over the Alpine region and toward eastern Europe, but more

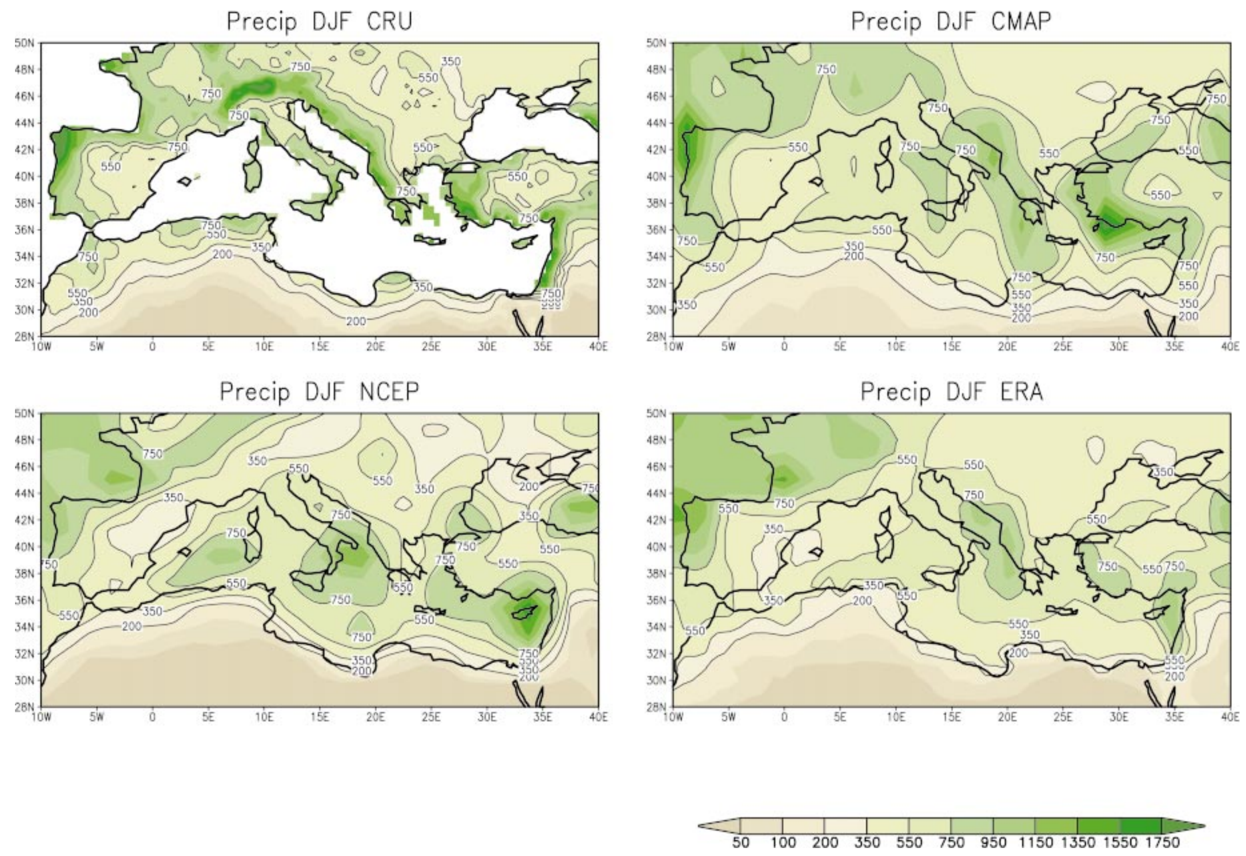


FIG. 2. Climatological winter mean precipitation in the Mediterranean area. (top left), (top right) Means derived from the CRU and CMAP datasets; (bottom left), (bottom right) means from NCEP and ERA reanalyses, respectively (period 1979–93, units mm yr^{-1}).

abundant in CRU especially over the Alps (over 1550 mm yr^{-1}). In comparison, NCEP gives considerably higher summer precipitation over central and eastern Europe, a feature already discussed by Arpe and Roeckner (1999).

Figure 4a shows the climatological seasonal cycle of area-averaged precipitation over the Mediterranean Sea derived from CMAP, ERA, and NCEP. The broad maximum suggests that the rainy season extends beyond the conventional winter season well into autumn and spring. Larger amounts occur from November to January while smaller ones occur from June to August, with a seasonal cycle having a mean amplitude among datasets of about 700 mm yr^{-1}. NCEP is similar to CMAP during autumn, while it is roughly 100 mm yr^{-1} drier during spring and early summer; ERA instead is drier than CMAP all year around by 100 mm yr^{-1} or more.

An intercomparison of the variability of Mediterranean-averaged precipitation is presented in Fig. 5a. In the left panel, we show time series of NCEP, ERA, and CMAP annual mean precipitation for the period 1979–93. Interannual fluctuations are quite consistent among datasets, and especially among reanalyses. For instance similar precipitation variations of about 150 mm yr^{-1} occurred from the wetter period around 1985 to the drier 1990. Significant interdecadal changes are seen in the longer 50-yr record by NCEP (1948–98) presented in the right panel of Fig. 5a. Mediterranean precipitation dropped from 550 mm yr^{-1} around the mid-1960s to 400 mm yr^{-1} around 1990, and there appears to be a slight recovery later in the 1990s. These variations will be discussed further in section 4b when considering the variability of the Mediterranean freshwater flux in relation to the variability of the NAO during this period.

b. Evaporation

Here we analyze evaporation from ERA and NCEP reanalyses, and compare results with values from the UWM/COADS dataset (sea points only). Mediterranean evaporation is most intense during winter (Fig. 6), primarily because of the stronger winds and drier air above; in NCEP and UWM/COADS rates of 1550 mm yr^{-1} or more are found in the eastern part of the basin. ERA tends to have lower rates everywhere and especially at sea. Over land, winter evaporation is less than 350 mm yr^{-1} in most areas for both reanalyses; higher values are found over most of the Italian peninsula, partly because of the limited resolution available to define the land–sea contrasts.

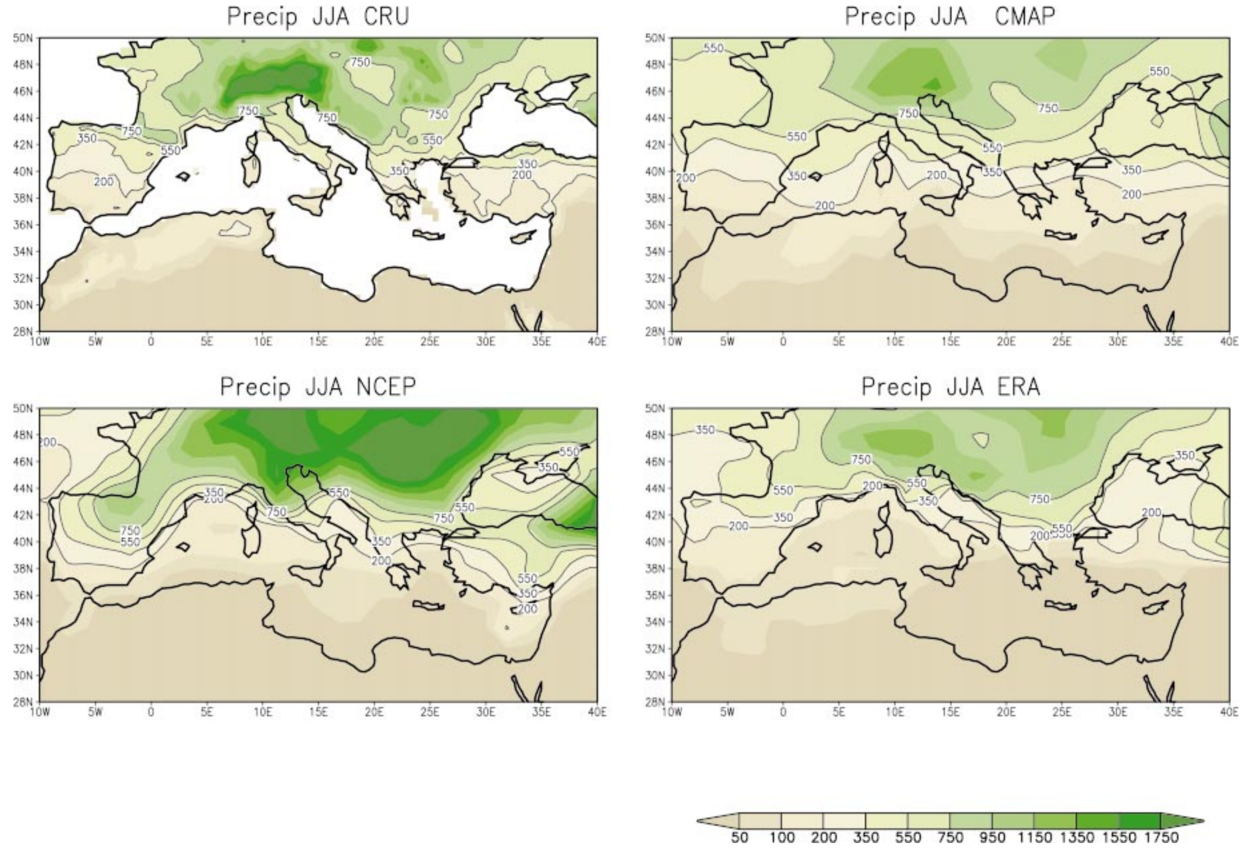


FIG. 3. Same as Fig. 2 but for summer mean precipitation.

Summer evaporation in the Mediterranean (see Fig. 7) is less than in winter, with rates smaller by 400 mm yr^{-1} or more over most of the basin. Over land, summer evaporation drops to 350 mm yr^{-1} or less inland from the African coast in both NCEP and ERA, although gradients are sharper in NCEP. Evaporation increases north of the basin, toward central eastern Europe, where ERA gives about 950 mm yr^{-1}. NCEP's rates in this region are high, reflecting a similar bias in precipitation (see section 3a).

The climatological seasonal cycle of area-averaged evaporation for the Mediterranean Sea, in Fig. 4b, has a broad maximum with higher values from October to January and smaller ones from April to June. An average of the different datasets gives a maximum of about 1500 mm yr^{-1} and a minimum of about 600 mm yr^{-1}. ERA evaporation rates are smaller than those in the other two datasets by at least 100 mm yr^{-1} throughout the year.

The time series of evaporation averaged over the Mediterranean Sea is shown in Fig. 5b. The left panel shows annual mean evaporation from NCEP, ERA, and UWM/COADS for the period 1979–93, while the right panel shows the NCEP and UWM/COADS data for 1948–98. Despite differences in the climatological mean values, interannual variations in the left panel of Fig. 5b have similar characteristics in the various datasets, and especially among reanalyses. The range of variations is about 100 mm yr^{-1}, somewhat smaller than those in precipitation rates. On decadal timescales (right panel of Fig. 5b), NCEP shows a general agreement with UWM/COADS in the first part of the record, but differs significantly in the 1980s and early 1990s. NCEP evaporation also appears to be correlated with its own precipitation on multidecadal timescales (right panel of Fig. 5a). As for precipitation, these variations will be discussed further in section 4b.

c. *Moisture transport and atmospheric water budget*

In Fig. 8 we plot the vertically integrated atmospheric water vapor flux, **Q**, and its divergence, *D*, calculated from NCEP and ERA reanalyses as described in section 2 (a 9-point smoothing has been applied to the divergence fields to eliminate some small-scale noise). The annual means are similar for both reanalyses. The moisture flux in the Mediterranean region comes mostly from the Atlantic Ocean with a southward component in the eastern part of the basin. Over the Mediterranean Sea the flux is more intense than in surrounding land regions to the north or south, and intensifies eastward, from the Iberian Peninsula into the Mediterranean. Atmospheric moisture divergence is positive almost everywhere over

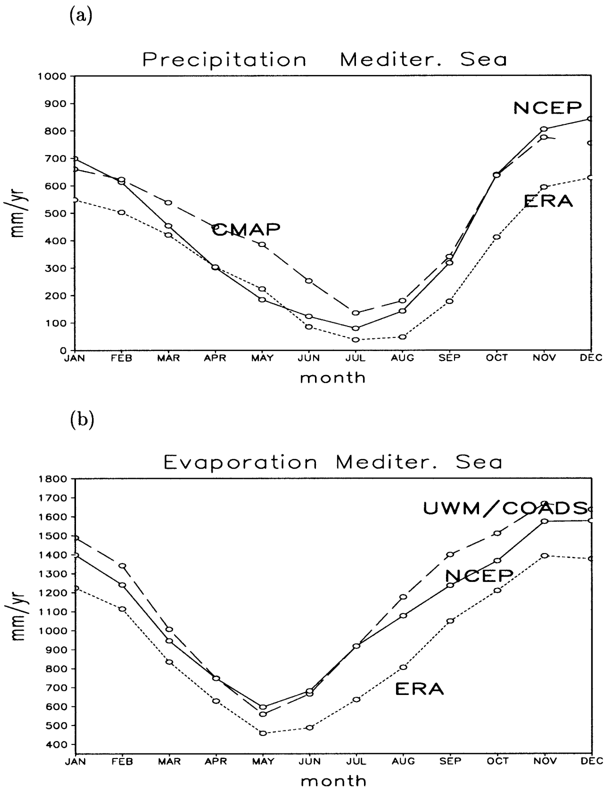


FIG. 4. Climatological seasonal cycle of area-averaged Mediterranean (a) precipitation from CMAP (long dashed line), ERA (short dashed), NCEP (solid), and (b) evaporation from UWM/COADS (long dashed), ERA (short dashed), NCEP (solid). The climatology refers to the period 1979–93.

the Mediterranean Sea, indicating a local net water flux from the ocean to the atmosphere.

During winter, the storm tracks shift southward and a westerly moisture flux brings abundant precipitation over central and southern Europe. The associated flow turns south in the vicinity of the Iberian Peninsula and picks up moisture as it passes over the Mediterranean Sea. In both reanalyses, three regions provide maximum water supply to the atmosphere: the Levantine Sea (the eastern tip of the Mediterranean), the southern Ionian Sea (between Italy and the African coast), and the Gulf of Lions (just off the French coast). In the surrounding land regions to the north of the Mediterranean basin, divergence is generally negative during this season.

During summer, the storm tracks are farther north. Along the eastern flank of the North Africa high a strong southward flow brings moisture from the eastern Mediterranean into northeast Africa and the Middle East.

As for moisture divergence, a positive sign of the budget evaporation minus precipitation ($E - P$) indicates that the atmosphere is gaining moisture from the underlying land or sea. Results for the atmospheric water budget calculations are broadly similar to the ones from moisture divergence (cf. Figs. 9 and 8). On annual mean this budget is positive over the whole Mediterranean, especially in the eastern part of the basin where evaporation exceeds precipitation by over 750 mm yr^{-1} (see Fig. 9); elsewhere at sea the water budget $E - P$ is between 350 and 750 mm yr^{-1}. In winter, precipitation exceeds evaporation in most land areas. Over the sea, the winter $E - P$ water budget is greatest in the eastern Mediterranean (750–1150 mm yr^{-1}) while more moderate elsewhere (350–750 mm yr^{-1}). During summer most of the Mediterranean region, including the land areas, have a positive $E - P$. The budget is about 350 mm yr^{-1} over land, while in the eastern Mediterranean is 750–1150 mm yr^{-1} for NCEP and 350–750 mm yr^{-1} for ERA.

4. Freshwater flux into the Mediterranean Sea

a. Climatology

The climatological seasonal cycle of the various contributions to the Mediterranean Sea freshwater budget is plotted in Fig. 10. Here we show area averages and consider only the estimates from observations: CMAP precipitation, UWM/COADS evaporation, the difference between the two ($E - P$) and the Mediterranean river discharge derived as described in section 2. The annual mean river runoff is ~100 mm yr^{-1} (8.1×10^3 $m^3\ s^{-1}$; values are converted from $m^3\ s^{-1}$ to mm yr^{-1} assuming that the Mediterranean area is $2.5 \times 10^{12}\ m^2$). Its seasonal cycle has an amplitude of about 63 mm yr^{-1}, with a broad maximum during late winter and spring, and a minimum in August. Throughout the year evaporation is the largest term in the budget, at times more than twice the precipitation. Minimum evaporation occurs in May, about two months before minimum precipitation, and this is when $E - P$ is also minimum. Owing to the timing of the different terms, this budget is maximum in autumn. Although runoff is a relatively small contribution to the Mediterranean freshwater flux, nevertheless its magnitude becomes comparable to $E - P$ during spring.

The Mediterranean Sea freshwater budget $E - P - R$, derived from the various datasets, is presented in Fig. 11a [we denominate the estimate using evaporation from UWM/COADS and precipitation from CMAP as (UWM/COADS)+CMAP]. This amounts to a freshwater deficit for the Mediterranean Sea throughout the year with a minimum in spring estimated between 100 and 300 mm yr^{-1} and a maximum during autumn between 750 and 1000 mm yr^{-1}. The UWM/COADS+CMAP budget has the largest seasonal cycle among the three datasets, with an amplitude of 940 mm yr^{-1}. The $D - R$ estimate of the freshwater deficit is presented in Fig. 11b. Results are broadly similar to those in Fig. 11a; as for $E - P - R$, the deficit from ERA is smaller than that from NCEP throughout the year.

The freshwater budget ($E - P - R$ or $D - R$) minus the contribution from the Black Sea gives the total Mediterranean water deficit (MWD). The long-term mean of

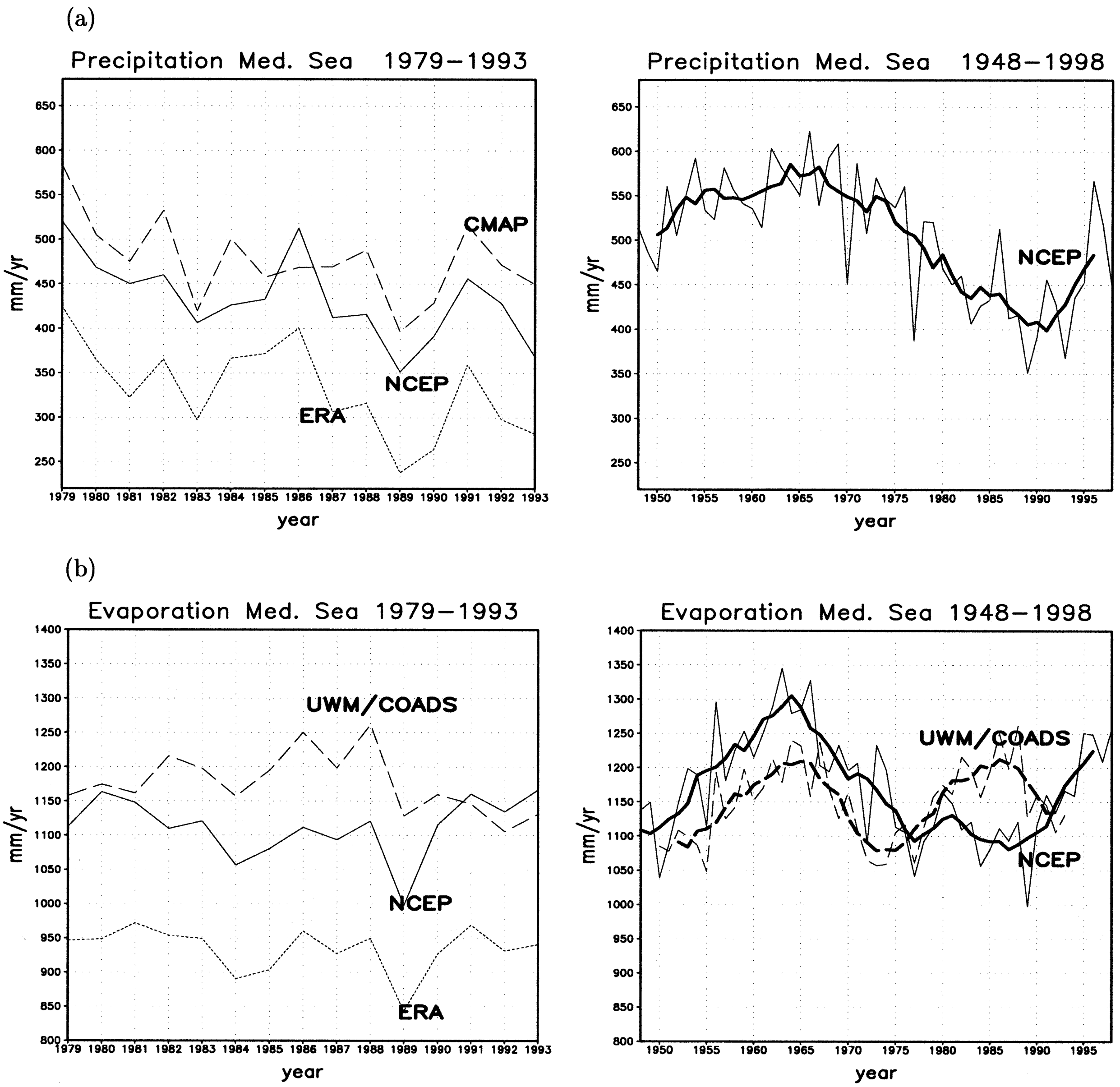


FIG. 5. Time series of area-averaged Mediterranean (a) precipitation from CMAP (long dashed line), ERA (short dashed), NCEP (solid), and (b) evaporation from UWM/COADS (long dashed), ERA (short dashed), NCEP (solid). (left) Annual means for the period 1979–93; (right) annual means for the period 1948–98 (thicker lines are 5-yr running means).

MWD should approximately be the same as the net water flux at the Gibraltar Strait [see Eq. (4) and Fig. 1]. Tables 1 and 2 summarize estimates of the climatological annual mean MWD and G, respectively, by various authors using different approaches. The G estimates derived from current measurements are typically based on a few months of observations so some caution should be exercised when comparing them to other climatological values reported in the tables. In our calculations, B is assumed to be a net inflow of about 75 mm yr^{-1} (Lacombe and Tchernia 1972) while for river discharge we use our estimate $R = 100$ mm yr^{-1}. Both Tixeront (1970) and Boukthir and Barnier (2000), also compute river discharge and obtain ~215 and ~140 mm yr^{-1}, respectively. Our estimate is closer to the latter result that was derived using a similar approach; this method is expected to give an underestimate of the actual river contribution because it neglects underground waters and considers only rivers for which measurements are available.

MWD estimates in Table 1 range from 370 to 950 mm yr^{-1}. Two of the lowest estimates (one of ours and Boukthir and Barnier 2000) use the ECMWF reanalyses, while the highest value 950 mm yr^{-1} is given by Be-

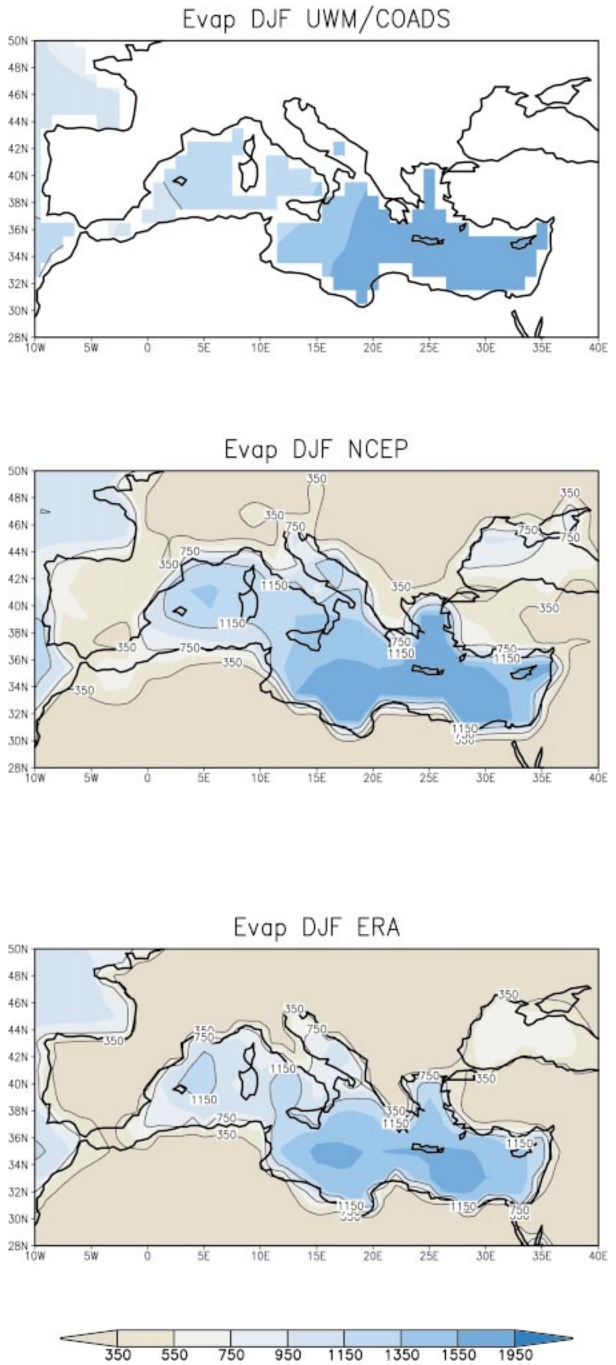


FIG. 6. Climatological winter mean evaporation in the Mediterranean area. Means from (top) UWM/COADS, (middle) NCEP, and (bottom) ERA datasets, respectively (period 1979–93, units mm yr^{-1}).

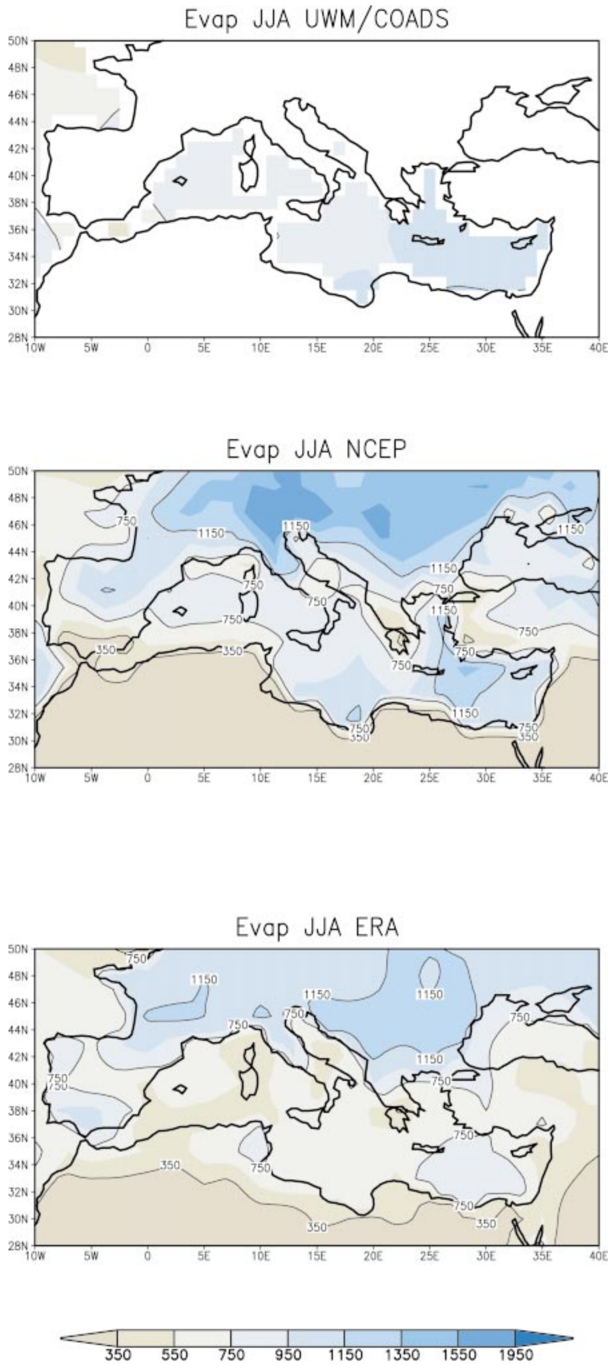
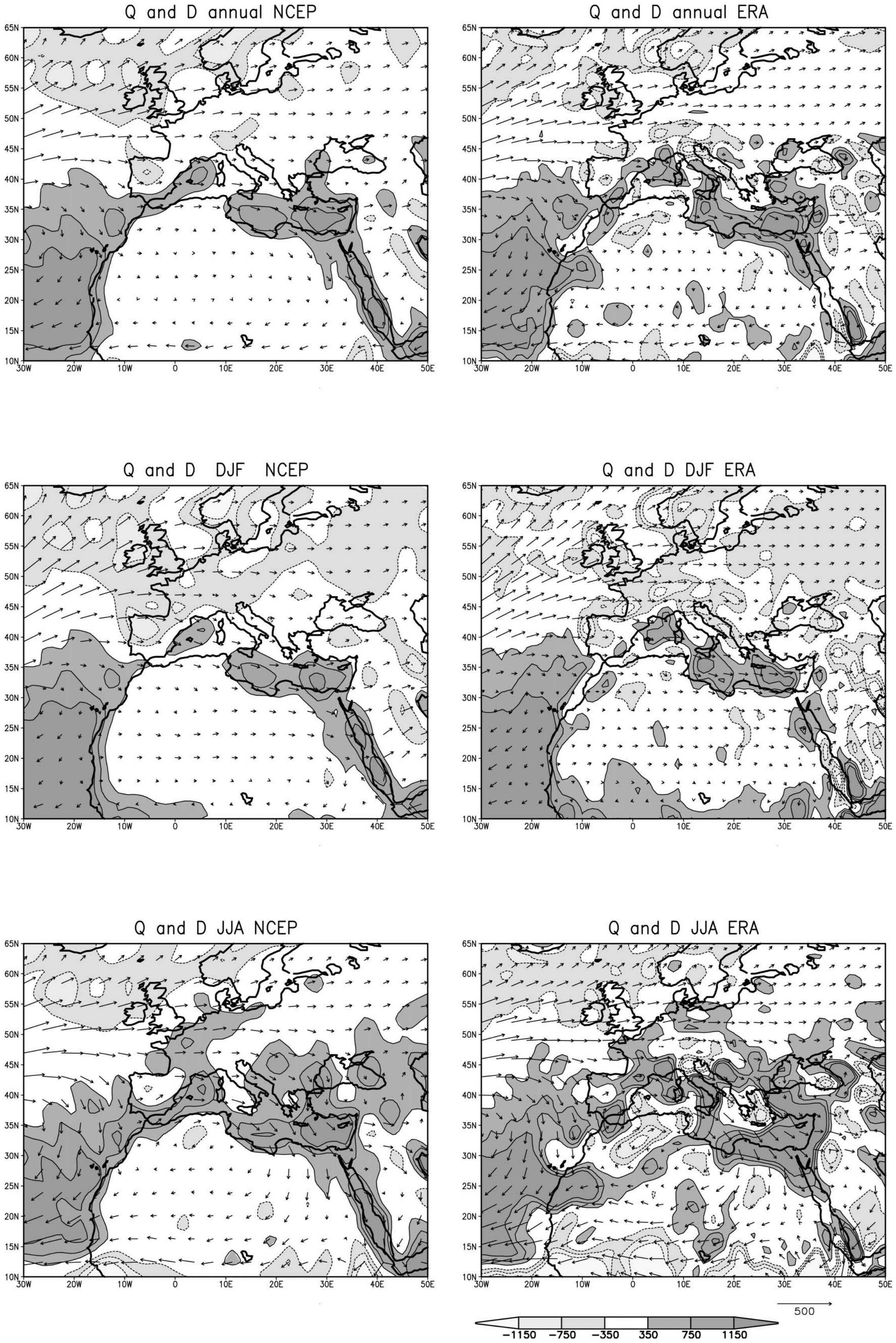


FIG. 7. Same as Fig. 6 but for summer mean evaporation.

thoux and Gentili (1999). Most of the differences between these two extremes can be attributed to the evaporation, low in ECMWF reanalyses while much higher for the latter author. The estimate by Harzallah et al. (1993), from ECMWF analyses but using moisture divergence, would actually give a more intermediate MWD if not for the higher discharge adopted by these authors. Castellari et al. (1998) derive the highest evaporation but compensate by adopting also the highest precipitation, so as to lie in the intermediate MWD range of values, approximately between 500 and 600 mm yr^{-1}. Gibraltar net flow estimates also generally fall in this range, except the 1000 mm yr^{-1} given by Bethoux (1979) and the 680 mm yr^{-1} from current measurements by Lacombe and Tchernia (1972). If compared to the


Q and D annual NCEP
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10E
20E
30E
40E
50E
500
−1150
−750
−350
350
750
1150

wide range of previous MWD estimates, the datasets we analyze give an overall converging range of values consistent with a Gibraltar flux of about 500 mm yr^{-1}.

b. Variability and trends

The time series of the 1979–93 annual mean Mediterranean atmospheric water budget from evaporation minus precipitation and moisture divergence, are shown in the left panels of Figs. 12a and 12b, respectively. For each quantity, interannual variability is similar in both the NCEP and ERA reanalyses, although the deficit in ERA is always smaller than in NCEP. During this period year-to-year variations in $E - P$ are generally about 50 mm yr^{-1} except in 1983 when a relatively abrupt change decreased the water deficit by about 100 mm yr^{-1}. Interannual variations in D are only broadly similar to the ones in $E - P$; for D the amplitude of the variations tends to be generally larger and the increasing trend much stronger than in $E - P$. The longer NCEP time series, from 1948 to 1998, for both $E - P$ and D (see right panels of Figs. 12a and 12b) show that interannual variations in the Mediterranean atmospheric water budget of over 100 mm yr^{-1} seem to have been quite frequent during this period. Important interdecadal changes of about 100 mm yr^{-1} also took place with a decrease of the Mediterranean water deficit from the early 1960s into the 1970s and an increase from the late 1970s into the 1990s.

The well-established NAO–Mediterranean teleconnection is expected to have a primary influence on Mediterranean climate especially during winter (Hurrell 1995). We now analyze NAO-related interannual to interdecadal precipitation, evaporation and moisture divergence changes, and address the implications for the variability of the Mediterranean water budget. We correlate winter mean (December–March) NAO index (Jones et al. 1997) with annual, winter, and five-winter running means (for NCEP data only) of Mediterranean precipitation, evaporation, and atmospheric water deficit ($E - P$ and D). Table 3 reports correlation coefficients as well as significance levels according to the Student's *t* test. Correlation coefficients for precipitation are negative, 99% significant for both annual and winter mean precipitation and for all datasets. For evaporation, there is a tendency for it to be anticorrelated with the winter NAO, nevertheless no significant correlation coefficients are found. The NAO affects Mediterranean precipitation as the positive (negative) phase of the oscillation induces higher (lower) than normal sea level pressure over the Azores and the western Mediterranean, causing drier (wetter) than average Mediterranean conditions (Hurrell 1995). The variability of Mediterranean winter atmospheric water deficit reflects that of precipitation, the correlation with the NAO is positive for both $E - P$ and D and the coefficients are all at least 95% significant. For the annual mean atmospheric water deficit, only ERA is significantly correlated with the winter NAO. For both precipitation and atmospheric water deficit, results are similar at interannual and interdecadal timescales.

Among the observational precipitation datasets we have considered in this work, only CRU goes back in time as much as NCEP, and can provide, at least for the land areas surrounding the Mediterranean Sea, an independent check of the variability of NCEP precipitation. The correlation between winter precipitation and the NAO index for the winter season (period 1949–96) is plotted in Fig. 13 for both NCEP and CRU datasets. The correlation patterns for NCEP precipitation are consistent with the ones from CRU over land. They indicate that winter precipitation is significantly anticorrelated with the NAO index in the northern part of the Mediterranean Basin (roughly between 35° and 45°N), while the correlation becomes nonsignificant and positive in the southern part of the basin. Figure 14 shows the precipitation anomalies resulting from the regression of precipitation with the NAO index (1949–96) for the winter season. Again, similar results are found for NCEP and CRU over land. The NCEP regression analysis also indicates that corresponding to positive NAO index anomalies, the Mediterranean Sea experiences a decrease in winter precipitation, as well as an increment in the freshwater deficit, mostly confined north of 35°N.

Figures 15a–15c show the five-winter running means for Mediterranean-averaged NCEP precipitation, evaporation, and moisture divergence, respectively, together with the winter NAO index. Decadal to interdecadal variability of the Mediterranean winter moisture divergence appears to be closely related to the NAO. In particular, the increase in Mediterranean water deficit from the 1970s to the 1990s discussed above corresponds to a switch from a low to high NAO index. Precipitation appears to be mostly responsible for this since no significant correlation with the NAO is found for evaporation. As the NAO index increases from 1970 to roughly 1993, winter precipitation decreases by about 300 mm yr^{-1}; a similar increase is also observed for moisture divergence, which implies an increase of the Mediterranean water deficit of about 300 mm yr^{-1} over approximately a 20-yr period. Considering the longer period since 1948, a linear best-fit analysis of the NCEP

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FIG. 8. Climatological atmospheric moisture flux **Q** [vectors, in kg$(ms)^{-1}$] and moisture divergence D (shaded and contours, in mm yr^{-1}). (top) Annual, (middle) winter, and (bottom) summer climatologies for the period 1979–93 from NCEP (left panels) and ERA (right panels). For clarity, **Q** vectors are plotted only at 1/3 and 1/4 of the actual data resolution for NCEP and ERA, respectively, while a nine-point smoothing has been applied to moisture divergence.

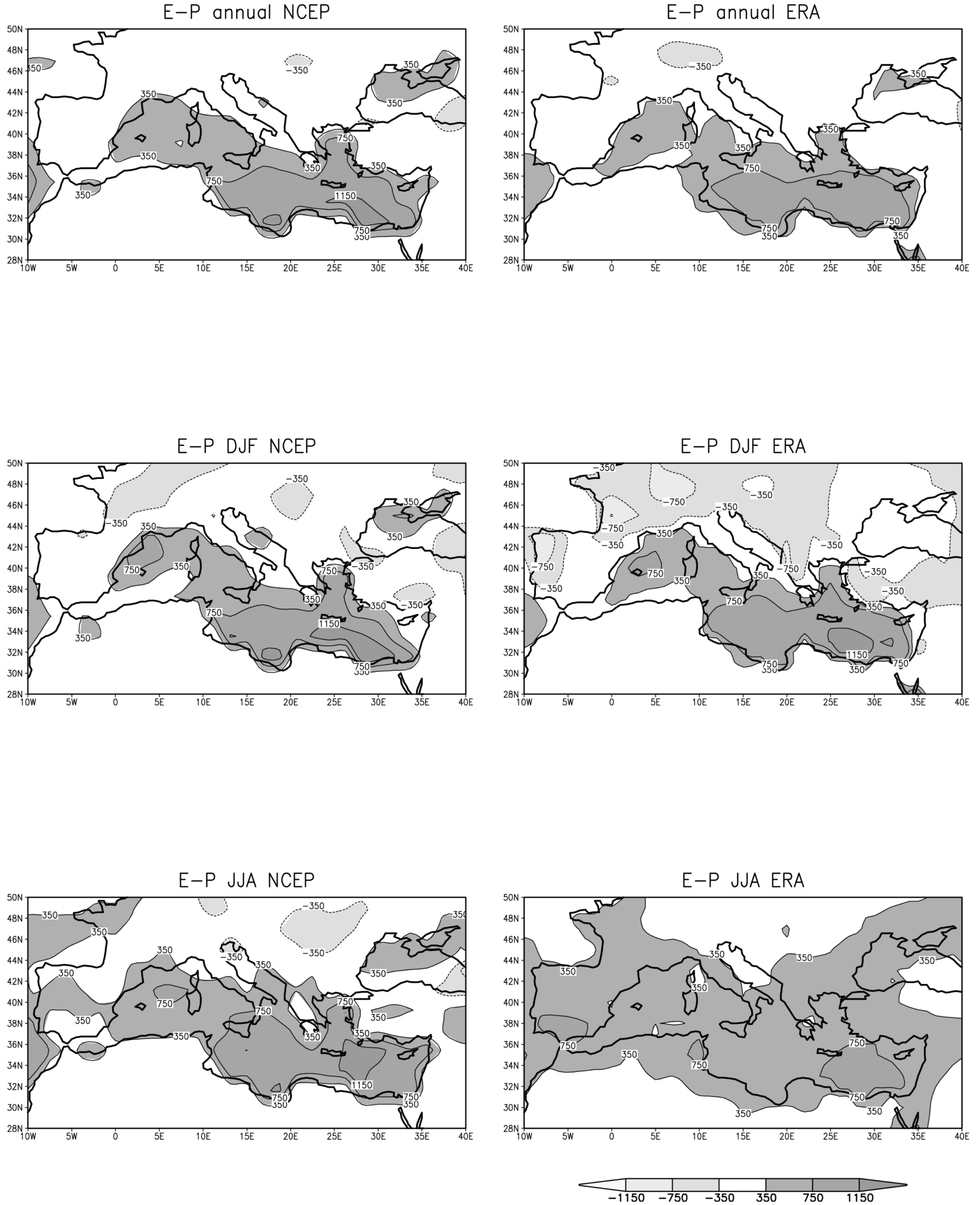

FIG. 9. Climatological atmospheric water budget (evaporation minus precipitation, mm yr⁻¹). (top) Annual, (middle) winter, and (bottom) summer climatologies for the period 1979–93 from NCEP (left panels) and ERA (right panels).

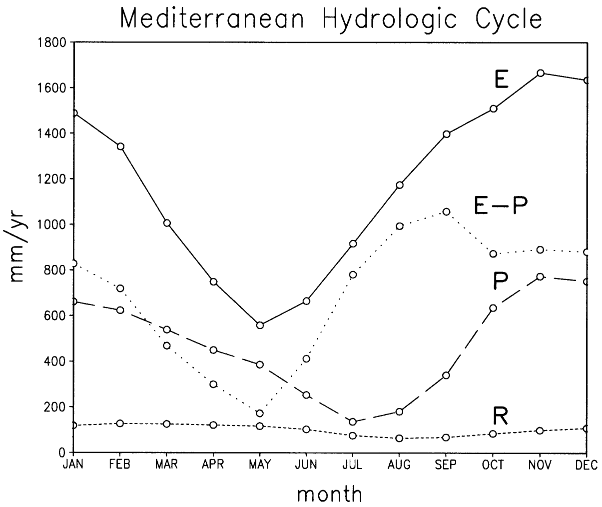

FIG. 10. Climatological area-averaged freshwater components of the Mediterranean Sea hydrological cycle (period 1979–93). Evaporation from UWM/COADS (*E*, solid line), precipitation from CMAP (*P*, long dashed), the budget ($E - P$, dotted), and our derivation of Mediterranean river discharge based on data from GRDC and MED-HYCOS archives (*R*, short dashed).

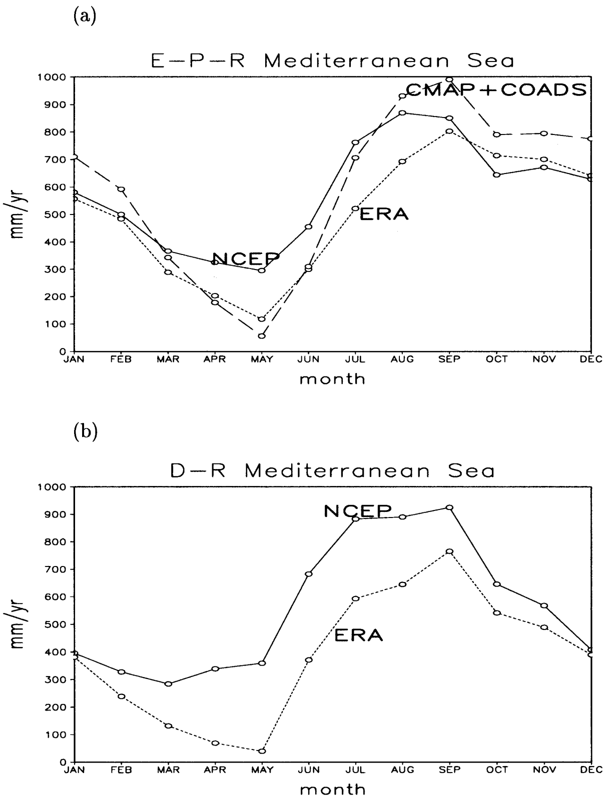

FIG. 11. Climatological seasonal cycle of area-averaged Mediterranean freshwater flux (period 1979–93). (a) Estimates from precipitation, evaporation, and river discharge. (b) Estimates from moisture divergence and river discharge. Atmospheric datasets are NCEP (solid line), ERA (short dashed), and the combination of CMAP and UWM/COADS (long dashed). River discharge is same as in Fig. 10.

data indicates that the Mediterranean winter water deficit has increased by about 24% from 1948 to 1998. A similar calculation, but for the annual mean deficit, indicates a more moderate positive trend of about 9%, which is an increase of the deficit of about 50 mm yr^{-1} over the 50-yr period.

5. Conclusions

We have presented a study of the hydrological cycle in the Mediterranean region during the last 50 years using recent atmospheric reanalyses and observational datasets. The analysis focused on climatology and in-

TABLE 1. Climatological contributions to the Mediterranean water budget as estimated by various authors. Here, *E* is evaporation, *P* is precipitation, *D* is moisture divergence, and MWD is the Mediterranean water deficit derived from the atmospheric water budget. Our estimates are calculated according to Eq. (4) with $R = 100$ mm yr^{-1}, $B = 75$ mm yr^{-1}, and using the mean of $E - P$ and *D* for reanalyses. Values have all been converted to mm yr^{-1} assuming an area for the Mediterranean Sea of 2.5×10^{12} m^2.

Authors	*E*	*P*	$E - P$	*D*	MWD	Method
Tixeront (1970)	1200	350	850		570	Obs and assumptions
Jaeger (1976)	1210	550	660			Derived from obs
Peixoto et al. (1982)				694		Derived from obs
Harzallah et al. (1993)				655	378	Analyses, ECMWF 1981–85
Gilman and Garrett (1994)	1121–1430	550[a]–700[b]	421–880		520[c]	Derived from obs
Angelucci et al. (1998)	1100	450	650			Analyses, ECMWF/NCEP
Castellari et al. (1998)	1320–1570	550[a]–700[b]	620–1020		560[c]–660[c]	Derived from obs
Bethoux and Gentili (1999)	1360–1540	310	1050–1230		780–950	Derived from obs
Boukthir and Barnier (2000)	920	326	594		391	Reanalyses, ECMWF 1979–93
This study	1171	504	667	649	483	Reanalyses, NCEP 1948–98
This study	1113	433	680	659	494	Reanalyses, NCEP 1979–93
This study	934	331	603	488	370	Reanalyses, ECMWF 1979–93
This study	1176	477	699		524	UWM/COADS, CMAP 1979–93

[a] From Jaeger (1976).
[b] From Legates and Wilmott (1990).
[c] From Bryden and Kinder (1991).

TABLE 2. Annual mean Gibraltar water flux (G) as estimated by various authors. Values have all been converted to mm yr^{-1} assuming an area for the Mediterranean Sea of 2.5×10^{12} m^2.

Authors	G	Method
Lacombe and Tchernia (1972)	680	Current obs at Gilbraltar
Bethoux (1979)	1000	Ocean potential energy budget
Bryden and Kinder (1991a)	500–600	Current obs/salt budget
Bryden and Kinder (1991b)	500–630	Ocean model simulation
Bryden et al. (1994)	520	Current obs/salt budget
Garrett (1996)	520	Modeling at Gilbraltar

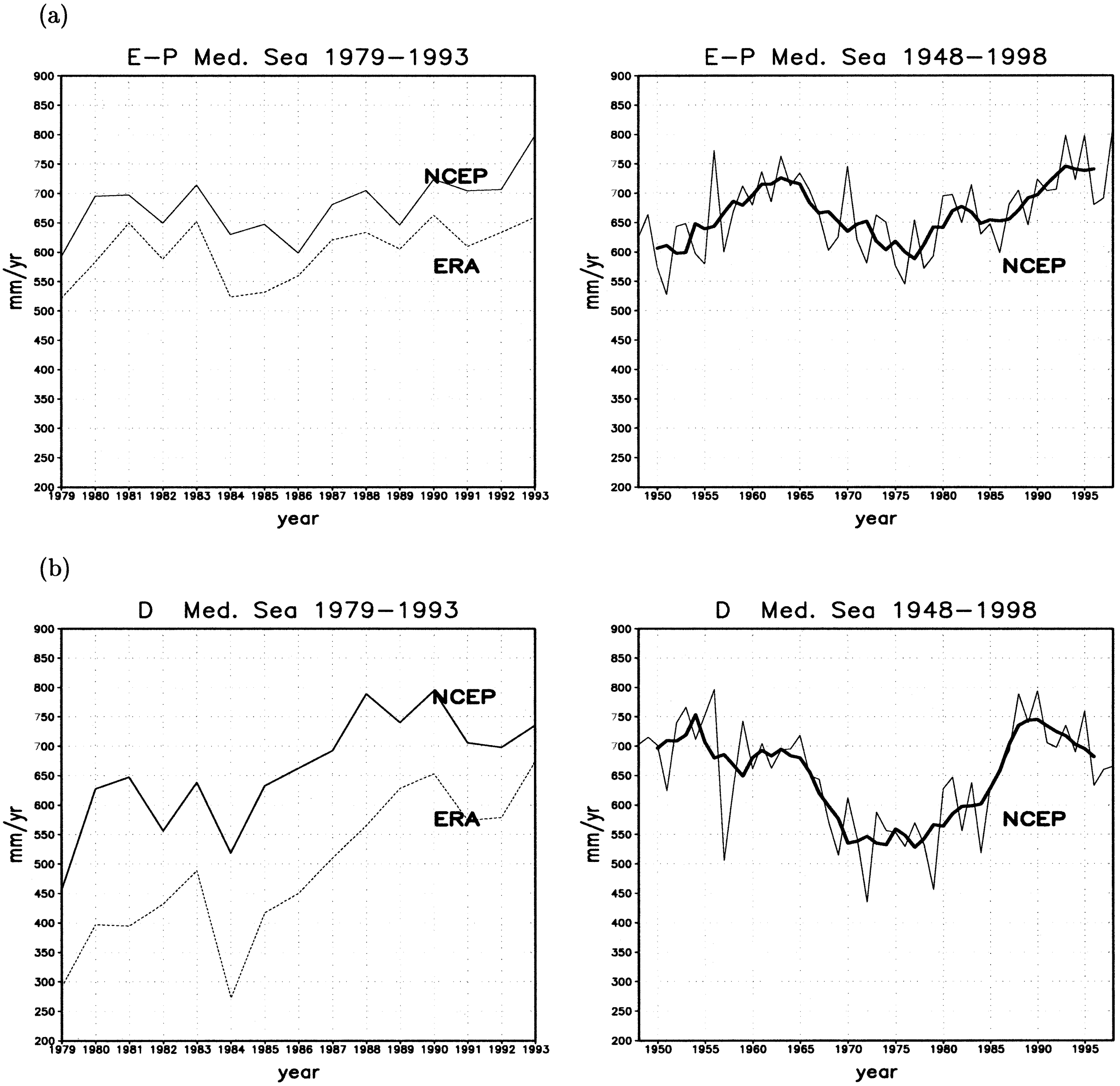

FIG. 12. Time series of area-averaged Mediterranean (a) $E - P$ and (b) D. Datasets are NCEP (solid line) and ERA (short dashed). (left) Annual means for the period 1979–93; (right) annual means for the period 1948–98 (thicker lines are 5-yr running means).

TABLE 3. Correlation between the winter (Dec–Mar) NAO index and annual, winter, and five-winter running means of Mediterranean-averaged P, E, D, and the budget $E - P$. In brackets, next to the correlation coefficients, the significance level according the Student's t test (NS is for not significant results) and the number of independent data.

Dataset	Annual means	Winter means	Five-winter means
P (NCEP 1949–98)	−0.51 (99%, 49)	−0.51 (99%, 49)	−0.84 (99%, 9)
P (ERA 1980–93)	−0.87 (99%, 13)	−0.73 (99%, 13)	
P (CMAP 1980–97)	−0.77 (99%, 17)	−0.84 (99%, 17)	
E (NCEP 1949–98)	−0.29 (NS, 49)	−0.04 (NS, 49)	−0.49 (NS, 9)
E (ERA 1980–93)	−0.45 (NS, 13)	−0.12 (NS, 13)	
D (NCEP 1949–98)	0.22 (NS, 49)	0.61 (99%, 49)	0.65 (95%, 9)
D (ERA 1980–93)	0.55 (95%, 13)	0.67 (99%, 13)	
$E - P$ (NCEP 1949–98)	0.18 (NS, 49)	0.55 (99%, 49)	0.72 (99%, 9)
$E - P$ (ERA 1980–93)	0.55 (95%, 13)	0.57 (95%, 13)	

terannual to interdecadal variability, in particular long-term changes related to the well-established NAO teleconnection. In our intercomparison, the various atmospheric datasets provided overall consistent results with differences among climatological estimates comparable to the uncertainties generally associated with precipitation and evaporation reanalyses data (20%–30%; e.g., Arpe and Roeckner 1999). More importantly,

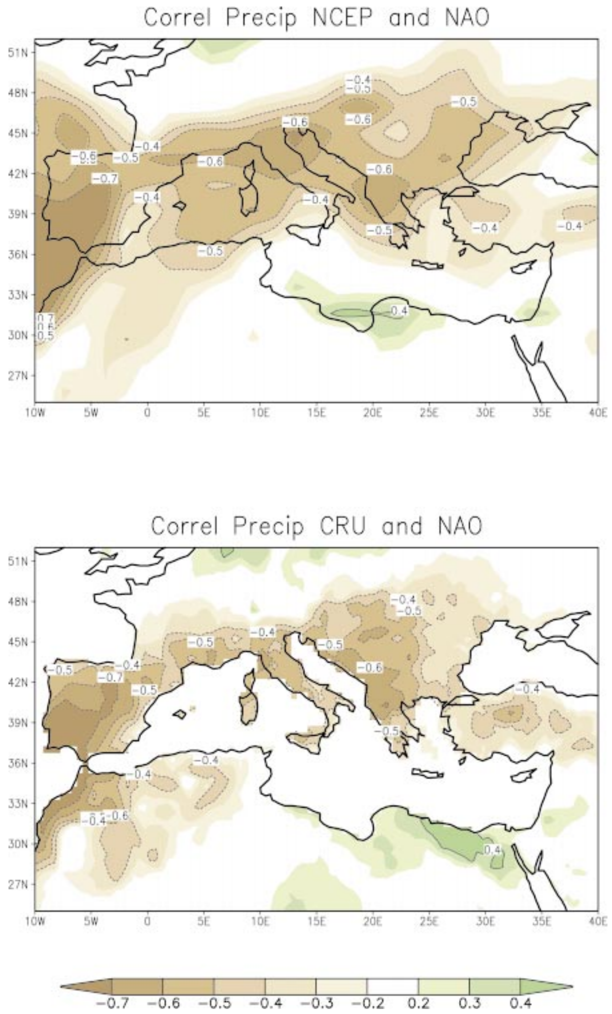

FIG. 13. Correlation between precipitation and the NAO index for the winter season (period 1949–96). (top) NCEP precipitation; (bottom) CRU precipitation. Correlation coefficients over 0.4 (absolute value) are 99% significant.

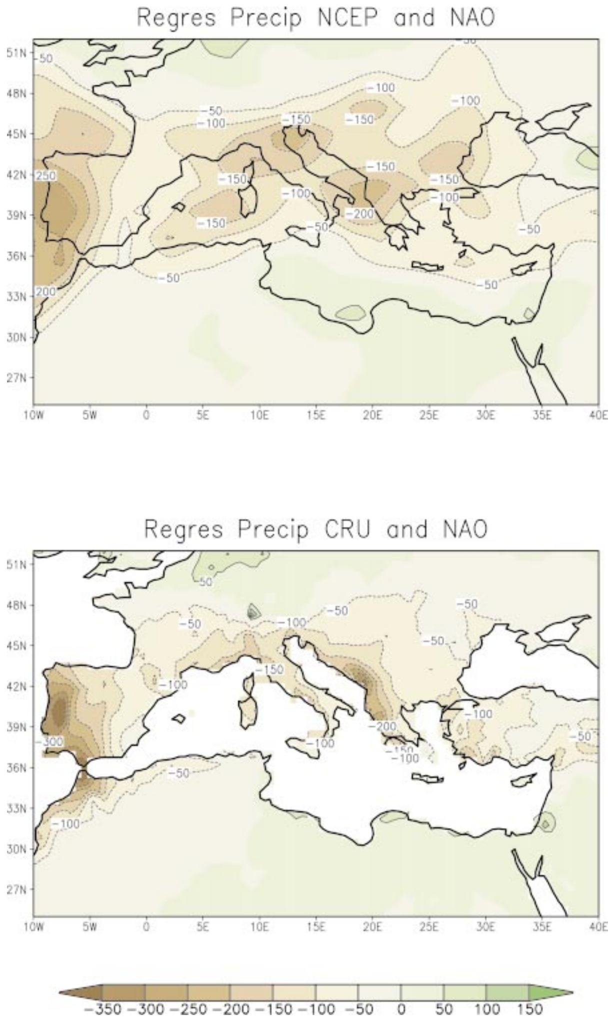

FIG. 14. Regression of precipitation with the NAO index for the winter season (period 1949–96). (top) NCEP precipitation; (bottom) CRU precipitation.

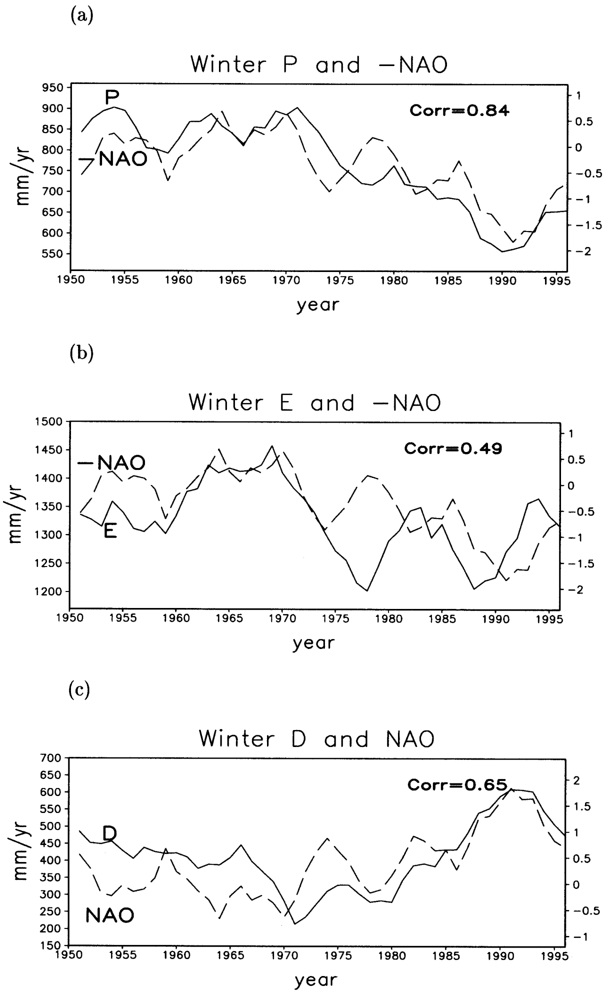

FIG. 15. Time series of five-winter (Dec–Mar) running means of the NAO index and area-averaged Mediterranean (a) precipitation, (b) evaporation, and (c) moisture divergence [note that the sign of the NAO index is reversed in (a) and (b)]. The atmospheric data is from NCEP reanalyses (solid line) while the NAO index is as in Jones et al. (1997) (long dashed). On the top right corner is the correlation coefficient for the datasets on each panel.

most of the datasets presented quite similar interannual to interdecadal variability.

Climatological contributions to the freshwater flux into the Mediterranean Sea, including atmospheric as well as river discharge inputs, were considered to derive a new estimate of the water budget for the Mediterranean Sea. Mediterranean-averaged annual mean precipitation for the period 1979–93 ranges among datasets from 331 to 477 mm yr^{-1}, with a seasonal cycle of ~700 mm yr^{-1}, maximum from November to January and minimum from June to August. Evaporation has an annual mean in the range of 934 to 1176 mm yr^{-1} with a mean seasonal cycle of ~1000 mm yr^{-1}, maximum from October to January and minimum from April to June, about two months before minimum precipitation. Both ERA and NCEP reanalyses give a broadly similar moisture flux, mostly from west to east year-round, but with a southward component during summer, from the eastern Mediterranean into northeast Africa and the Middle East.

Evaporation is the largest term in the Mediterranean freshwater budget, in fact annual precipitation is about half the evaporation and river discharge, which we estimate at about ~100 mm yr^{-1}, is less than half the precipitation. Year-round the Mediterranean has a freshwater deficit; the seasonal cycle has a maximum in autumn and a minimum in spring of magnitude similar to the interannual variability of $E - P$ or D. Comparing to the large range of values obtained by previous works concerning the Mediterranean annual mean atmospheric water deficit, we find that our results are converging to values roughly between 500 and 700 mm yr^{-1}. Among our estimates those from reanalyses probably tend to underestimate both evaporation and precipitation, as indicated by CMAP and UWM/COADS. Considering that we are also likely underestimating river discharge, our results for the overall Mediterranean freshwater deficit are consistent with a Gibraltar flux of about 500 mm yr^{-1} in agreement with the more intermediate range of MWD/G values (e.g., Bryden and Kinder 1991a,b).

The availability of long-term reanalysis data enabled us to study in detail interesting interannual to interdecadal variations in the Mediterranean hydrological cycle. For both precipitation and evaporation the interannual variations since 1979 are quite similar among datasets and especially among reanalyses. Year-to-year variations are up to ~150 mm yr^{-1} for precipitation and ~100 mm yr^{-1} for evaporation. On decadal scales NCEP precipitation shows a significant drop from the mid-1960s to the 1990s. NCEP evaporation appears correlated with its own precipitation and is in general agreement with UWM/COADS in the first part of the record since 1950, but differs significantly in the 1980s and early 1990s. The interannual variability in Mediterranean atmospheric water deficit since 1979 is also similar in NCEP and ERA reanalyses. The longer NCEP time series, from 1948 to 1998, for both $E - P$ and D show that interannual variations in the annual Mediterranean atmospheric water deficit of over 100 mm yr^{-1} are quite frequent during this period. Important interdecadal changes of about 100 mm yr^{-1} also took place with a decrease of the annual Mediterranean water deficit from the early 1960s into the 1970s and an increase from the late 1970s into the 1990s.

The interannual to interdecadal variability of the Mediterranean hydrologic cycle and the implications for the water deficit of the Mediterranean Sea were analyzed in relation to the well-established influence of the NAO on climate in this region. The variability of the Mediterranean winter atmospheric water deficit is indeed significantly related to the NAO. Precipitation appears to be mostly responsible for this since no significant correlation with the NAO is found for evaporation. As the NAO index increases from 1970 to roughly 1993, winter precipitation decreases by about 300 mm yr^{-1} and the Mediterranean water deficit increases by about 300 mm yr^{-1} over this approximately 20-yr period. Considering the longer period since 1948, a linear best-fit analysis of the NCEP data indicates that the Mediterranean winter water deficit has increased by about 24% from 1948 to 1998. A similar calculation, but for the annual mean deficit indicates a more moderate positive trend of about 9%, that is an increase of the deficit of about 50 mm yr^{-1} over the 50-yr period. The pattern of the NAO-related winter precipitation anomalies indicates that most of the decrease in Mediterranean winter precipitation as well as the increase in the freshwater deficit observed during the last 50 years are likely to have occurred north of 35°N.

On interannual to interdecadal timescales, during the period 1948–98, the Atlantic water influx through Gibraltar must have adjusted to compensate for the enhanced Mediterranean water deficit. Significant variations in the characteristics of Mediterranean waters may also have occurred, mostly driven by the influence of the NAO. The multidecadal change in the NAO has been linked to global SST variations in the Tropics (Hoerling et al. 2001), thus the type of correlation found in this analysis provides a possibility of long-term prediction for the various aspects of the Mediterranean hydrological cycle.

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