

## River Discharge into the Mediterranean Sea: Climatology and Aspects of the Observed Variability

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### ABSTRACT

River discharge across the Mediterranean catchment basin is investigated by means of an extensive dataset of historical monthly time series to represent at-best discharge into the sea. Results give an annual mean river discharge into the Mediterranean of  $8.1 \times 10^3 \text{ m}^3 \text{ s}^{-1}$ , or at most a value that should not exceed  $10.4 \times 10^3 \text{ m}^3 \text{ s}^{-1}$ . The seasonal cycle has an amplitude of  $5 \times 10^3 \text{ m}^3 \text{ s}^{-1}$ , with a dry season in midsummer and a peak flow in early spring. Dominant contributions are from Europe with a climatological annual mean of  $5.7 \times 10^3 \text{ m}^3 \text{ s}^{-1}$ . Discharge in the Adriatic Sea, the Gulf of Lion, and the Aegean Sea together account for 62% of Mediterranean discharge, which mostly occurs in the Adriatic ( $2.7 \times 10^3 \text{ m}^3 \text{ s}^{-1}$ ).

The North Atlantic Oscillation (NAO) impacts Mediterranean discharge primarily in winter, with most river discharges across the Mediterranean catchment being anticorrelated with the NAO. Related winter anomalies are about 10%–20% of the winter means. During the period 1960–90, Mediterranean winter discharge as a whole may have undergone year-to-year NAO-related variations of up to 26% of the seasonal mean, while about 17% on decadal time scales. These variations are expected to have occurred mostly in the Gulf of Lion and the Adriatic Sea, together with the Balearic Sea, where the impact of the NAO is greatest.

### 1. Introduction

River discharge is one of the five components of the Mediterranean Sea water budget, together with the net inflow of Atlantic water through the Strait of Gibraltar that from the Black Sea at the Dardanelles Strait, evaporation, and precipitation. In terms of absolute values, river discharge ( $R$ ) represents the smallest contribution to this budget. In fact, climatological annual mean discharge is less than 20% of the atmospheric water budget evaporation minus precipitation ( $E - P$ ), and the amplitude of its seasonal cycle is almost negligible with respect to the seasonal cycle of  $E - P$  (Boukthir and Barnier 2000; Mariotti et al. 2002). Evaporation largely dominates the Mediterranean water budget all year-round resulting in a general freshwater deficit.

Nevertheless, discharge together with precipitation is the only freshwater input into the basin, and during spring the two basin-integrated components  $E - P$  and  $R$  are fairly comparable. In addition, for coastal regions and Mediterranean subbasins where the major rivers discharge, freshwater input from rivers as well as its loading in nutrients and minerals are quite significant. Discharge variability, natural or anthropogenic, can play a relevant

role in modulating the characteristics of the Mediterranean environment. On decadal time scales, river discharge variations may induce a response in the Mediterranean thermohaline circulation affecting the entire basin. For instance, the occurrence of negative eastern Mediterranean freshwater anomalies, due to natural variability or to the regulation of major rivers, determines an increase in local surface water salinity. In conjunction with winter cooling, these conditions determine the formation of a more salty than usual Levantine Intermediate Water. The advection of these salinity anomalies to sensitive regions carries the potential to alter the characteristics of both the Eastern and Western Mediterranean Deep Waters (Rohling and Bryden 1992).

River discharge also heavily affects the processes governing the Mediterranean Sea's ecosystem. Zavatarelli et al. (1998) have investigated the climatological characteristics of the Adriatic Sea biogeochemical properties. They show that nutrient levels in the northern Adriatic are controlled by river inputs (not only from the Po) inducing intense phytoplankton development in winter and autumn. River discharge variability can also affect open ocean primary production influencing, as discussed earlier, the processes of dense water formation and related open ocean oxygenation rates (Bethoux and Gentili 1999). Coastal areas are especially sensitive to the direct input of nutrients and pollutants. For instance, Lefevre et al. (1997) have studied the temporal and spatial variability of primary production in the coastal

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zone nearby the Gulf of Lion. They show that half of the production occurring in the zone confined between the coast, the Liguro-Provencal current to the south and the Rhone River plume to the east, can be considered to be dependent on the input of river nutrients.

The climatology of Mediterranean river discharge depends on properties of the atmospheric water budget as well as on the geographical characteristics of the Mediterranean catchment. A great latitudinal gradient characterizes Mediterranean precipitation all year-round, with dry areas along the African coast and significantly wetter ones to the north of the Mediterranean Sea. Winter is the main rainy season in most land regions discharging into the Mediterranean Sea, while in summer regions south of 40°N are basically dry. Geographically the Mediterranean catchment is extremely heterogeneous, extending from the source of the Nile River, approximately at the equator, to the source of the Rhone River at 48°N. It consists of great valleys, such as the Nile and the Rhone valleys or the Po plain, high mountains, such as the Alps, where most of winter precipitation is in form of snow, and mountains, such as the Atlas in northeastern Africa and the Taurus in Turkey, that can capture moisture by means of orographic effects from eastward-propagating midlatitude cyclones generated in the North Atlantic Ocean and in the eastern Mediterranean Sea.

Natural river discharge variability is primarily driven by precipitation variability and the large-scale climate modes which affect the Euro-Mediterranean area, in winter and spring mainly through the North Atlantic Oscillation (NAO). The NAO exhibits negative correlation with precipitation in the Mediterranean region on interannual and longer time scales (Hurrell 1995). In particular over the past 50 yr, a significant decrease in Mediterranean precipitation has been documented in connection with the recent long-term positive phase of the NAO (Mariotti et al. 2002). Various studies (Tixeront 1970; Ovchinnikov 1974; Boukthir and Barnier 2000) have dealt with the determination of climatological river discharge into the Mediterranean Sea, using different methodologies and obtaining quite different results. Unfortunately, these results are not easily comparable, because of the differences in methods and data used. While some studies have investigated the impact of the NAO on northern European rivers (Shorthouse and Arnell 1997) or eastern Mediterranean rivers [Cullen and de Menocal (2000) and Cullen et al. (2002)], to our knowledge a comprehensive analysis of Mediterranean river discharge interannual variability in relation to the NAO still remains to be performed. In addition at decadal time scales, the impact of NAO-related precipitation variations on river discharge in this region has not been evaluated.

The aim of this work is to improve the knowledge of the climatology and natural variability of Mediterranean river discharges on interannual, and to some extent, decadal time scales. Climatological characteristics of Med-

iterranean river discharges are investigated using an extensive set of monthly river data. An estimate of the uncertainties due to unrepresented basins is also given (see section 2 for data and methodology). Climatological results are presented in section 3 decomposing discharge by continents and Mediterranean Sea subbasins. In particular the focus is on the Gulf of Lion, the Adriatic Sea, and the Aegean Sea for which data coverage is reasonably good. Interannual river discharge variability is investigated considering the relation with the NAO in various seasons. The analysis then focuses on the winter season, when interannual and decadal NAO-related discharge variations are evaluated (section 4). The variability of discharge in the Adriatic Sea and the Gulf of Lion is investigated by analyzing long time series from the Po and Rhone Rivers, the major contributors to discharge in these basins (section 5). In the last section we give a summary of results and some conclusive remarks.

## 2. Data and methodology

Historical river discharge time series used in this work are derived from the Global Runoff Data Center (GRDC) hydrological database and the Mediterranean Hydrological Cycle Observing System (Med-HYCOS) project regional database. Monthly discharge time series of 67 rivers, 24 from Med-HYCOS and 43 from GRDC are analyzed. If a given river is in both datasets, either the longest time series is used or data from the two datasets is combined to achieve maximum time coverage. For each river, data is from the station nearest the river mouth to represent at-best discharge into the sea. Generally time series for the various rivers cover different periods. However, the time series of the major rivers, which together account for more than 50% of Mediterranean discharge, overlap for more than 30 yr. The time series of rivers contributing to more than 98%, overlap for at least 6 yr. The coverage of the Mediterranean catchment achieved here includes all major rivers in Spain, France, northern and central Italy, Balcanian countries (most of these waters, however, are collected by the Danube and are consequently discharged into the Black Sea), Greece, and North Africa. Data coverage is poor for Turkey where two important rivers, Aksu and Seyhan, are missing. Data are also unavailable for some rivers in southern Italy and Libya, but only minor contributions are expected from these areas. For the Nile, the time series is that from El Ekhsase, the closest site to the river mouth, which unfortunately only covers the years from 1973 to 1984. Longer time series are available from more upstream stations but are not representative of discharge into the Mediterranean. Data from El Ekhsase instead, well represents the current state of the Nile streamflow, heavily dammed since 1964 and strongly altered not only in its mean discharge [reduced to 42% of the natural value according to Bethoux (1984)] but also in its seasonal cycle, previously char-

acterized by floods in late summer and fall (Mikhailova 2001).

Basin data for the Mediterranean catchment is from the Total Runoff Integrating Pathways dataset (TRIP; Oki and Sud 1998) at the resolution of  $0.5^\circ \times 0.5^\circ$ . TRIP data are used to visualize the catchment distribution of results as well as to estimate uncertainties (see later, this section). TRIP features 57 of the 67 rivers considered in this study. Not all river basins could be identified in TRIP, either because they are too small or because in TRIP rivers too close to each other are grouped as a single basin.

An estimate of the errors associated with unaccounted river basins can be attempted mostly based on assumptions from the work of Margat (1992). The first assumption (a) is that the conventional extension of the Mediterranean drainage area (not including the High Nile region) is approximately 1 857 000 km<sup>2</sup>. Assumption (b) is that 95% of the total discharge comes from northern Mediterranean regions (from Spain to Turkey, including islands) and only 5% from southern regions. Based on TRIP, river data used in this study are relative to a catchment area of 1 089 000 km<sup>2</sup>, that is, 59% of the conventional Mediterranean catchment; 840 000 km<sup>2</sup> in northern regions ( $A_N$ ) and 249 000 km<sup>2</sup> in southern regions ( $A_S$ ). One-fourth of the missing area is located in northern regions, the remaining in southern ones. An estimate of the represented drainage area ( $A$ ) and missing one ( $\Delta A$ ) for both northern and southern regions can be derived using TRIP data. In the hypothesis of a spatially homogeneous rate of discharge  $\rho_N = R_N/A_N$  and  $\rho_S = R_S/A_S$ , the missing contributions are  $\Delta R_{N,S} = \rho_{N,S}\Delta A_{N,S}$ . Using assumption b one can estimate the rates of discharge in terms of the actual discharge  $R$ :

$$\rho_N = 0.95 \frac{R}{A_N}, \quad \rho_S = 0.05 \frac{R}{A_S}.$$

Including information about the fraction of missing area, it is found that discharge coming from northern regions is underestimated by 19% of its actual value, while that coming from southern regions is underestimated by 3%. Consequently, the error on the climatological annual mean Mediterranean discharge should not be higher than 22% of its actual value. This value should represent an upper bound to the error given that the assumption of an homogeneous discharge rate is in fact a very conservative one (see Fig. 1, introduced in the next section, for discharge climatology). This methodology is applied throughout the paper to estimate errors on the various climatological discharge values.

In order to relate river discharge variability to precipitation anomalies, the observational precipitation dataset of the East Anglia University Climate Research Unit is used (CRU; New et al. 2000). This is a gridded high-resolution dataset ( $0.5^\circ \times 0.5^\circ$ ) of monthly mean precipitation estimates from rain gauge measurements

(land only), available from 1901 to 1996. When comparing discharge and precipitation variability, generally no lag is considered. In fact, lag is expected to be negligible when considering monthly means, for small catchments with precipitation in the form of rainfall. Most basins in the Mediterranean catchment satisfy these conditions. Even for the Po and the other alpine rivers, which are affected by snowmelt, at monthly time scales there is basically no detectable lag between precipitation and discharge. The analysis of discharge variability in relation to the NAO includes seasonal correlation and regression with the NAO index. The NAO principal component index is used here, for winter basically identical to the conventional station-based NAO index but more adequate to describe the NAO at various seasons (Hurrell et al. 2003). For this analysis, river discharge time series have at least 20 yr of data (24 rivers out of 67). A notable exclusion is that of the Nile for which only a 10-yr time series is available. The significance of the correlation results is assessed using Student's  $t$  test and only results above the 95% significance level are discussed. In order to account for the possible autocorrelation of the time series we choose the number of degrees of freedom equal to  $3N/4$ . This choice seems to be sufficiently stringent as the seasonal time series decorrelate in less than one time step.

### 3. Mediterranean river discharge climatology

#### a. Catchment distribution and Mediterranean totals

Figure 1 shows the distribution of annual, winter [December–January–February (DJF)], and summer [June–July–August (JJA)] climatological river discharge across the Mediterranean catchment (top, middle, and bottom, respectively). For mere visualization purposes, here discharge at the river mouth is artificially attributed to every point of the corresponding catchment basin if given by the TRIP dataset, otherwise only to the river mouth. Major contributions to Mediterranean discharge are from the Rhone, Po, and the Nile Rivers (about 1700, 1500, and 1200 m<sup>3</sup> s<sup>-1</sup>, respectively). Secondary, but still relevant contributions, are from the Ebro and rivers on the eastern Adriatic coast. While very little is contributed by North African rivers, other than the Nile. Winter is when most Mediterranean rivers discharge at their maximum capacity. Exceptions come from the Nile and those rivers draining the Alpine region, which reach their maximum discharge rates in spring and autumn. Such peculiarities of the seasonal cycle are further discussed in the next sections, when rivers are grouped by continents and Mediterranean Sea subbasins.

The seasonal cycle of basin-integrated Mediterranean river discharge is shown in Fig. 2. Discharge is greatest from late fall to spring, with a peak flow of about  $10 \times 10^3$  m<sup>3</sup> s<sup>-1</sup> occurring in late winter. Minimum discharge is in late summer (about  $5 \times 10^3$  m<sup>3</sup> s<sup>-1</sup>). Climatological annual mean Mediterranean discharge is 8.1

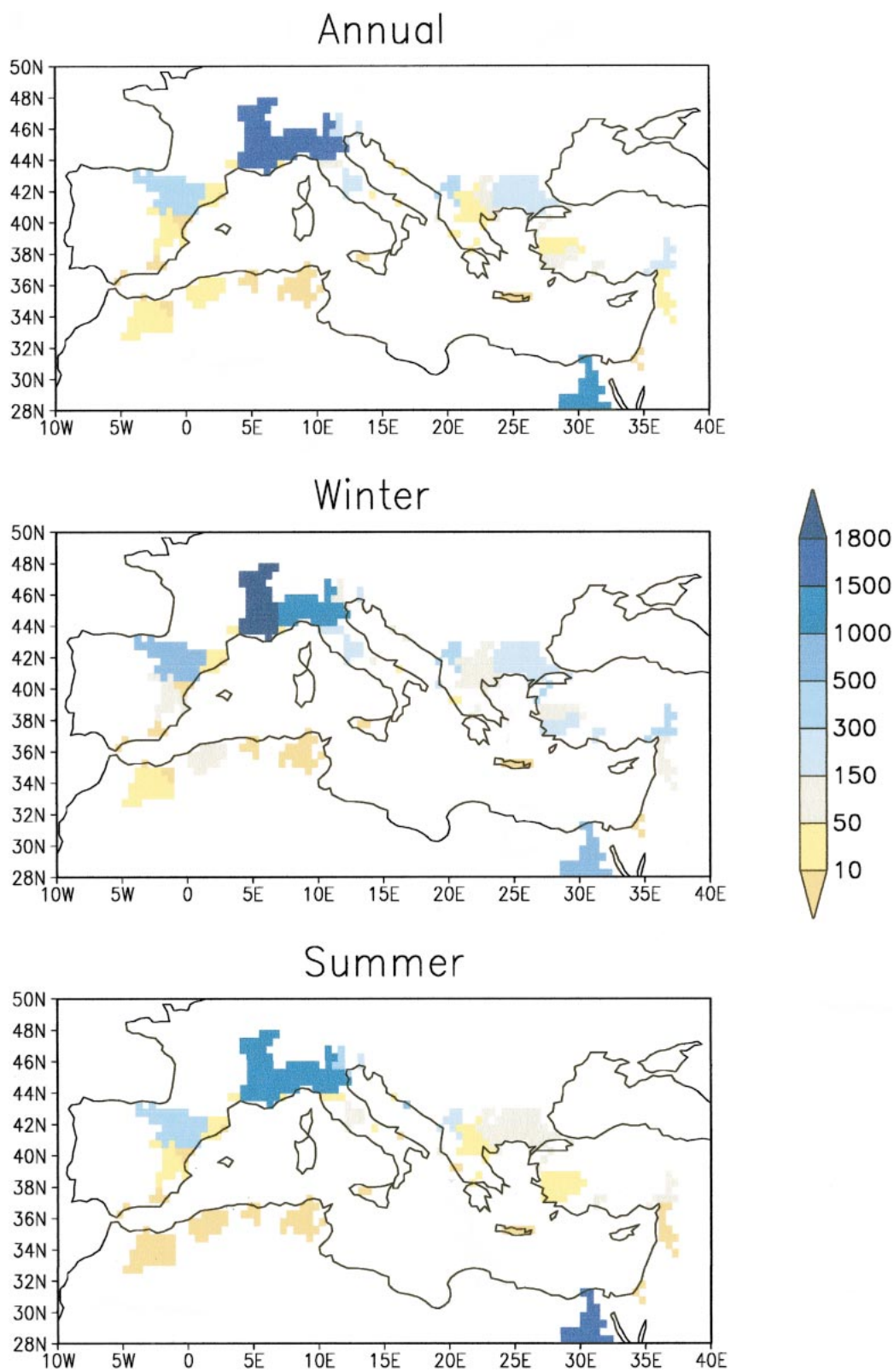


FIG. 1. Climatological river discharge across the Mediterranean catchment. (top) Annual, (middle) winter (DJF) and (bottom) summer (JJA) climatologies ( $\text{m}^3 \text{s}^{-1}$ ) respectively. For visualization purposes, discharge at the river mouth is attributed to all grid points of the corresponding river basin. Catchment data are derived from the TRIP dataset (Oki and Sud 1998).

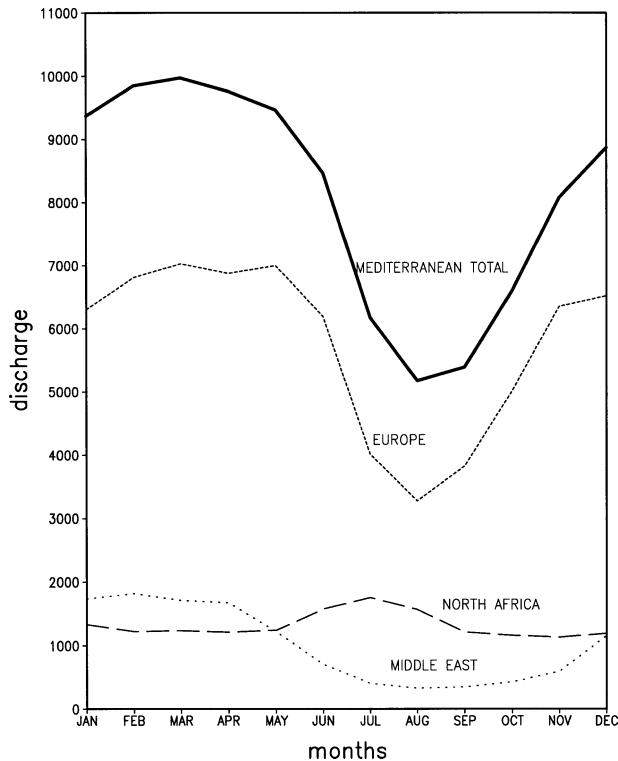


FIG. 2. Climatological seasonal cycle of total discharge into the Mediterranean Sea and its decomposition by continent of origin. Represented here is at least 78% of the actual Mediterranean totals (solid line), 76% of discharge from Europe (short dashed), 40% of that from the Middle East (dotted), and 86% of discharge from North Africa (long dashed). (Values are in  $\text{m}^3 \text{s}^{-1}$ .)

$\times 10^3 \text{ m}^3 \text{ s}^{-1}$ . Based on the considerations discussed in the previous section, setting an upper bound to possible underestimates of the mean value, Mediterranean discharge should not exceed  $10.4 \times 10^3 \text{ m}^3 \text{ s}^{-1}$ . Tixeront (1970) proposed an estimate of Mediterranean discharge principally based on rain maps and data from a few coastal stations, leading to a value of  $16 \times 10^3 \text{ m}^3 \text{ s}^{-1}$ . Ovchinnikov (1974) gave a mean annual value of  $13.6 \times 10^3 \text{ m}^3 \text{ s}^{-1}$ . While Margat (1992) obtained the same value as Tixeront, as a result of the total hydrological budget of the Mediterranean basin, including in a residual way discharge from underground waters. Boukthir and Barnier (2000) derived a value of  $11 \times 10^3 \text{ m}^3 \text{ s}^{-1}$  using time series of observed river discharge data from UNESCO. Unfortunately, because of the differences in methods and data used, all these results are not easily comparable. Nevertheless, the estimate derived here appears to be somewhat lower than most previous ones, while quite close to that of Boukthir and Barnier (2000) if the correction for the missing discharge is considered. In the derivation presented here, other errors, besides the negative bias from unrepresented catchments, may come from the fact that climatologies for the various rivers are not all for the same time period (see section 2 for more details), and in a

TABLE 1. Climatological characteristics of Mediterranean river discharge. Discharge from continents surrounding the Mediterranean Sea as well as discharge in specific Mediterranean subbasins is reported ( $R$ ) together with an upper bound for the negative bias possibly associated to these estimates ( $\Delta R$ ). The sum of all continental contributions represents the total discharge into the Mediterranean Sea. (Values are in  $10^3 \text{ m}^3 \text{ s}^{-1}$ .)

Continents	$R$	$\Delta R$	Subbasins	$R$	$\Delta R$
Europe	5.7	1.4	G. Lion	1.8	0.07
Middle East	1	0.6	Adriatic	2.7	0.6
Africa	1.4	0.2	Aegean	0.5	0.1
All	8.1	2.2	All	5	0.8

restricted number of cases, are computed from rather short time series. This error is forced by data availability and is expected to have been a factor also in other studies deriving discharge from river time series and not in any indirect manner. Table 1 summarizes climatological annual mean results from this study, also giving an upper bound to the negative bias likely to be affecting these estimates.

#### b. Discharge by continents

Together with the climatological seasonal cycle of Mediterranean integrated river discharge, Fig. 2 also displays its decomposition by continent of origin. European discharge is the main contributor, clearly determining the time behavior of the whole Mediterranean seasonal cycle. This includes discharge from the Rhone, Po, and Ebro that are the three major European rivers. European annual mean discharge is  $5.7 \times 10^3 \text{ m}^3 \text{ s}^{-1}$ ; this should represent at least 76% of the actual annual mean discharge. The seasonal cycle has a minimum of about  $3 \times 10^3 \text{ m}^3 \text{ s}^{-1}$  in mid to late summer and a broad maximum from fall to spring of about  $7 \times 10^3 \text{ m}^3 \text{ s}^{-1}$ .

The Middle Eastern seasonal cycle has an analogous time behavior, with a very broad minimum in summer, a broad maximum in winter, but a much lower annual mean discharge. Given the lack of data from a number of Turkish rivers discharging in the Levantine basin this estimate is only representing about 40% of the actual Middle Eastern contribution.

North African discharge is mainly due to the Nile River. The largest tributary of the Nile is the Blue Nile which contributes to 70% of the total Nile discharge (Hurst 1952), draining the Ethiopian Plateau where intense precipitation falls during the summer months. As a result, this is when the African contribution is at its peak (about  $1.7 \times 10^3 \text{ m}^3 \text{ s}^{-1}$ ). The annual mean, representative of the current state of the Nile, is  $1.4 \times 10^3 \text{ m}^3 \text{ s}^{-1}$ . In this estimate, the North African contribution, without the Nile, is basically negligible.

#### c. Discharge in selected Mediterranean Sea subbasins

Here, discharge is analyzed in terms of inputs to the major Mediterranean Sea subbasins. This formulation is

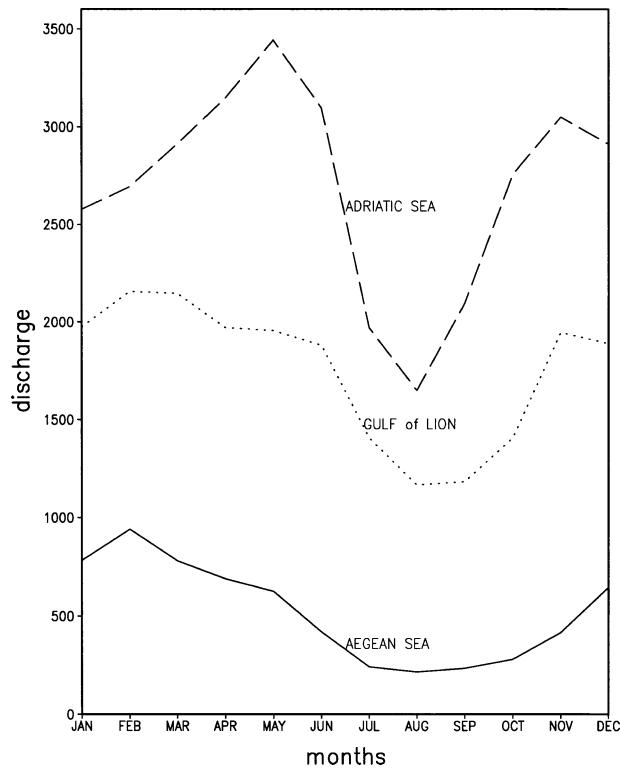


FIG. 3. Climatological seasonal cycle of discharge in selected Mediterranean subbasins. Represented here is at least 78% of discharge into the Adriatic Sea (solid line), 80% of that into the Aegean Sea (dashed), and 96% of discharge in the Gulf of Lion (dotted). (Values are in  $\text{m}^3 \text{s}^{-1}$ .)

given to allow a more direct connection with oceanic processes such as the Mediterranean thermohaline circulation and deep water formation. The climatological seasonal cycle of discharge in the Adriatic Sea, the Gulf of Lion, and the Aegean Sea is represented in Fig. 3. In this analysis all available rivers discharging in these three basins are considered, reaching a reasonably good level of representation of the climatological means (78% for the Adriatic Sea, 80% for the Aegean Sea, and 96% for the Gulf of Lion). Together, discharge received by these basins amounts to 62% of the whole discharge into the Mediterranean Sea. The rest is mostly received by the Levantine basin where the Nile River discharges together with a number of Turkish rivers. Unfortunately, given the poor data coverage for this region, the Levantine is not included in the present analysis.

Of the three Mediterranean subbasins considered, the Adriatic is the one with the greatest freshwater input (about  $2500 \text{ m}^3 \text{ s}^{-1}$  on annual basis), which is mostly due to the Po River and other alpine rivers. Discharge into this basin has a peculiar seasonal cycle with an evident minimum in summer (about  $1700 \text{ m}^3 \text{ s}^{-1}$ ) and two maxima in fall and spring (about  $3000 \text{ m}^3 \text{ s}^{-1}$ ). In the alpine region maximum precipitation occurs in fall and spring; precipitation is mostly in the form of snow during the core of the winter and into early spring. As

a result discharge from this region and in the Adriatic is greatest in fall, due to heavy rains, and in spring when both rain and snowmelt occur. According to our estimates of annual mean, 57% of discharge in the Adriatic Sea is due to the Po River alone, which reaches  $2000 \text{ m}^3 \text{ s}^{-1}$  in May and November. This is a considerable freshwater plume in the North Adriatic, at approximately  $45^\circ \text{N}$ , following a southward path along the Italian coast as surface water.

The best represented subbasin in our database is the Gulf of Lion (about  $1700 \text{ m}^3 \text{ s}^{-1}$  on annual mean), whose annual mean and seasonal cycle are dominated by the Rhone. The lack of information about the narrow region along the western French coast (see Fig. 1) is responsible for an estimated error of 4% of the total. The seasonal cycle has an amplitude of about  $1000 \text{ m}^3 \text{ s}^{-1}$ , with a minimum in late summer and a broad maximum from early winter into late spring, due to frontal activity in central Europe. It is also evident another maximum occurs in November, as happens in the Po valley at the same time. This fact allows the interpretation of this feature as a result of precipitation due to Mediterranean cyclogenesis that affects both river basins during fall.

The good coverage of the northern coasts of the Aegean Sea, enables us to represent at least 80% of discharge into this basin. Mean discharge is about  $500 \text{ m}^3 \text{ s}^{-1}$  with a broad minimum during summer and a maximum in winter.

#### 4. NAO-related discharge variability

Once the climatological seasonal cycle is subtracted from the monthly series of river data, a considerable variability still remains over a wide range of time scales. Here discharge variability is investigated in relation to the NAO and compared to the NAO-forced variability of precipitation, the component of the hydrological cycle primarily driving natural discharge variations. Figure 4 shows the seasonal correlation of discharge and the NAO index for individual Mediterranean rivers. For clarity, results for 16 rivers are plotted in this figure, the major ones available for the catchment in the dataset, out of the 24 rivers which qualify for this correlation analysis (see section 2). For each river, anomalies are computed for the four standard seasons of the year considering the seasonal mean for the period for which the river data is available. Correlations for the various rivers generally refer to different time periods, even though most of them share the period 1960–90. As a consequence, correlation values for different rivers cannot be directly compared. In all seasons and for all rivers considered in Fig. 4, correlation values are negative. During the DJF season, across the whole of the Mediterranean catchment, analyzed rivers have a significant correlation with the NAO, with values varying from  $-0.29$  for the Po River (over the period 1951–96) to  $-0.73$  for the Acheloos River. In spring [March–April–May (MAM)]

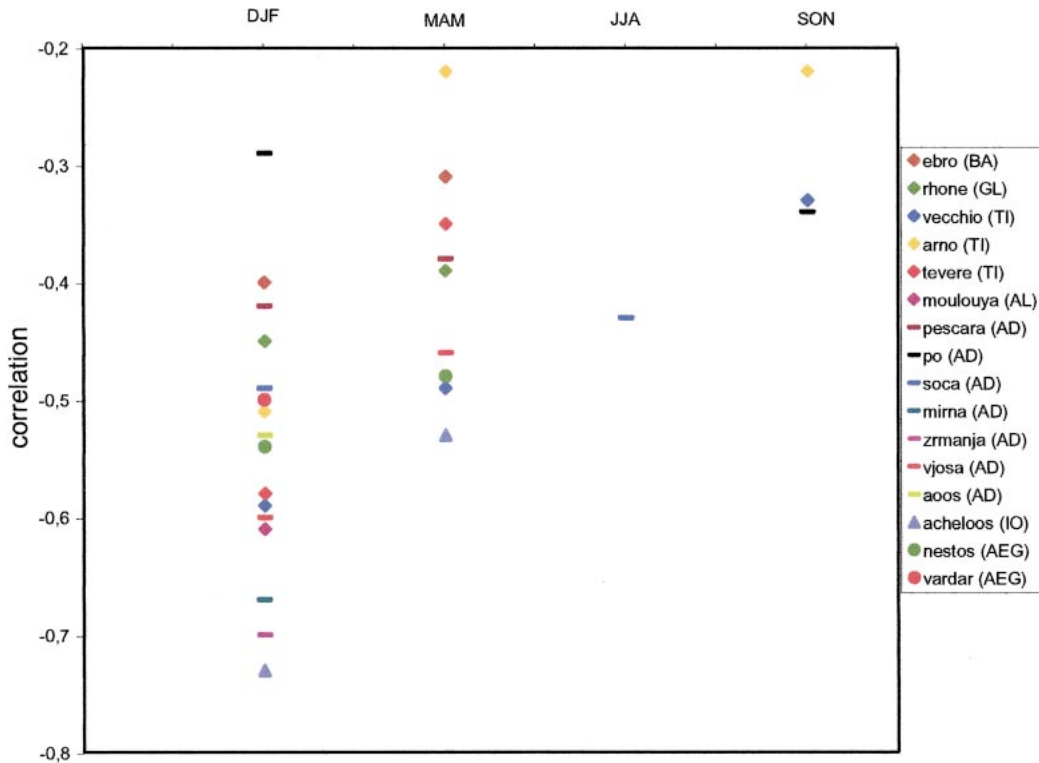


FIG. 4. Seasonal correlation of discharge from individual Mediterranean rivers and the NAO index for the four standard seasons of the year. Each symbol represents the correlation for a particular river and season, over the time period for which the data was available. All values are at least 95% significant. The shape of the symbol depicts the Mediterranean subbasin in which the river discharges: western Mediterranean (diamonds; this basin includes the Balearic Sea, the Gulf of Lion, and the Tirrenian Sea, in the legend BA, GL, and TI, respectively), Adriatic Sea (short lines; AD), Ionian Sea (triangle; IO), Aegean Sea (circles; AE), and the Alborean Sea (square; AL). The color depicts a particular river within that subbasin.

the correlation with the NAO is overall reduced, but all rivers discharging in the western Mediterranean (the Balearic Sea, Gulf of Lion, Tirrenian and Alboran Seas) and in the Ionian and Aegean Seas maintain a significant degree of correlation (major rivers are the Rhone, Ebro, and Tevere). Instead among the rivers discharging in the Adriatic Sea, only Mirna, Pescara, and Vjosa still have a significant correlation. In JJA significant correlation is found only for the Soca River (North Adriatic). Interestingly the Po River, which does not correlate with the NAO during spring, reaches its maximum correlation in autumn [September–October–November (SON)]. During SON significant correlation is also found for Arno and Vecchio. In Fig. 5, the spatial distribution of the correlation between winter discharge and the NAO across the Mediterranean catchment (all 24 rivers) is represented together with the correlation between the NAO and precipitation. Since, as discussed earlier, discharge correlation values cannot be directly compared from river to river, as a measure of the NAO impact on discharge, in this figure for a particular river, the level of confidence of the correlation is plotted, artificially assigning to it the sign of the correlation. Also for visualization purposes, this value has been assigned

to each point of the corresponding river basin, if available from TRIP, otherwise just to the river mouth. As the NAO–discharge correlation has been evaluated over periods mostly falling during 1960–90, this is also the period considered to compute the correlation of precipitation with the NAO. The patterns in Fig. 5 for discharge and precipitation are in very good agreement. The general anticorrelation found for discharge during this season is matched by negative correlation values for CRU precipitation. Also, as for precipitation, there is a tendency for positive, although barely significant, values to appear in the southern part of the Mediterranean catchment. Highest significance (99% level) is achieved for the Rhone, Ebro, Moulouya, and rivers in central Italy and along the eastern shore of the Adriatic, Ionian, and Aegean Seas. While for the Po River anticorrelation with the NAO is only significant at the 95% level.

The effect of the NAO on winter river discharge is further investigated quantifying the NAO-related anomalies by means of a linear regression analysis with the NAO index. The resulting discharge anomalies are displayed in Fig. 6 (top), and as the percent change from climatology (middle panel); for reference, similar results

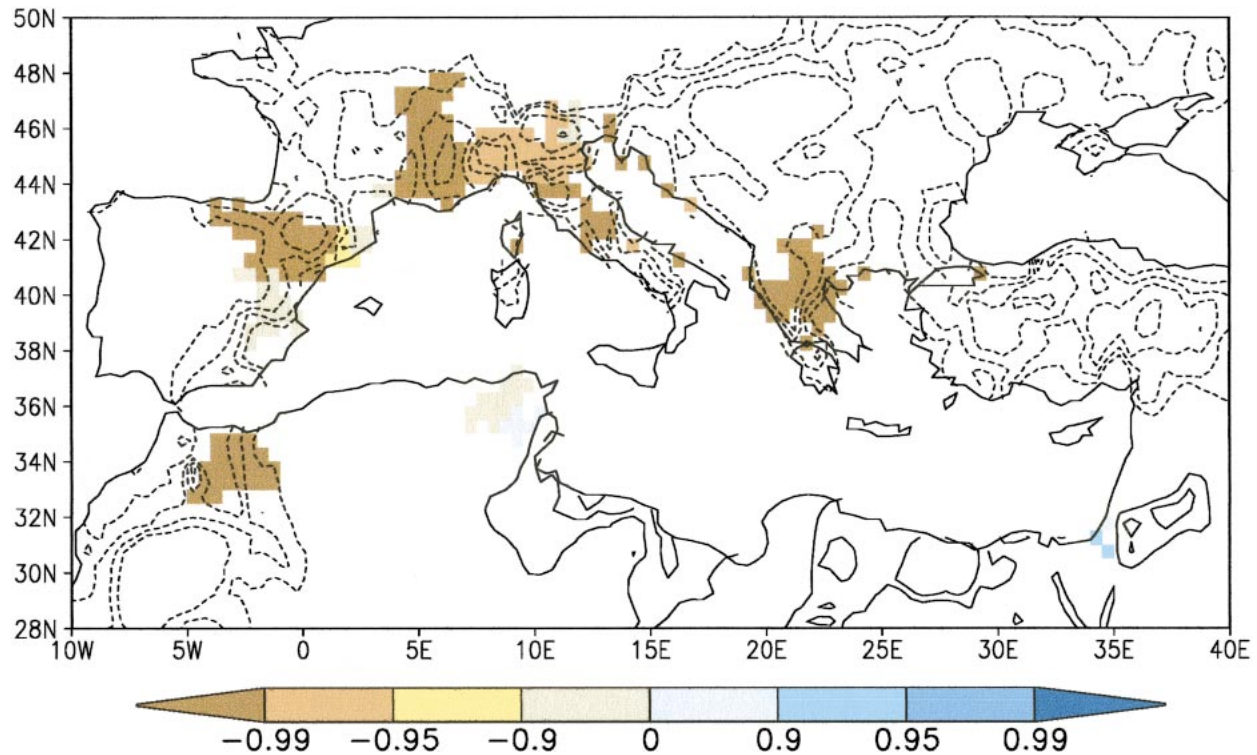


FIG. 5. Correlation of river discharge across the Mediterranean catchment and the NAO index for the winter season. The shading over a particular catchment defines the level of confidence and the sign of the correlation for discharge at the river mouth (see text). For comparison, the correlation of winter precipitation and the NAO index for the period 1960–90 is also reported. Contours represent correlation (positive: solid; negative: dashed) for absolute values greater than 0.3 (95% significant), at intervals of 0.1.

only for precipitation are also reported in Fig. 6 (bottom). In absolute terms, winter NAO-related anomalies are greatest for the Rhone, Po, and Ebro. Relative to their climatological mean, the Moulouya River in North Africa and the Llobregat River in Spain, are most affected by the NAO, with anomalies exceeding 30% of their winter mean. Also, rivers in central Italy, along the eastern Adriatic and in Greece show variations due to the NAO of up to 20% in this season. For the Po River, NAO-related variations are more modest (5%–10%) relative to the large climatological values for this river, but still considerable in absolute terms for the Mediterranean catchment. The high values found in parts of northern Africa are to be disregarded in regions where the corresponding correlation values displayed in Fig. 5 are not significant.

Under the hypothesis of a linear and stationary relationship during the investigated period, between the NAO, Mediterranean precipitation, and river discharge, one can attempt to use the results from the regression analysis to give a first estimate of the variations Mediterranean winter river discharge may have undergone as a whole in relation to observed NAO variations. Summing up all anomalous contributions derived for each river from the linear regression with the NAO index, it is found that a variation of  $-866 \text{ m}^3 \text{ s}^{-1}$  in Mediterranean winter discharge would correspond to a change

of  $+1 \sigma$  (standard deviation) in the NAO index. From year to year, observed winter NAO variations during the period 1960–90 have been of up to  $3 \sigma$ , which points to NAO-related interannual Mediterranean winter discharge changes of about  $2600 \text{ m}^3 \text{ s}^{-1}$ , that is about 26% of the seasonal mean. On decadal time scales, considering that from the early 1970s to the early 1990s the winter NAO index has undergone an increase of about  $+2 \sigma$  (see, e.g., Mariotti et al. 2002), one can speculate a corresponding long-term reduction in Mediterranean winter discharge of approximately  $1700 \text{ m}^3 \text{ s}^{-1}$ , that is about 17% of the winter mean. This change would have been located mainly in the Gulf of Lion, with a decrease of the discharge from the Rhone of about  $600 \text{ m}^3 \text{ s}^{-1}$ , and in the Adriatic and Balearic Seas with a decrease of discharge from the Po and the Ebro each by about  $250 \text{ m}^3 \text{ s}^{-1}$ .

##### 5. Variability of discharge in selected Mediterranean Sea subbasins

Given our dataset, time series representing, to a reasonable extent, discharge into Mediterranean subbasins can only be derived for the Adriatic Sea and the Gulf of Lion. For the Adriatic Sea a time series covering the period 1961–84 is constructed, representing at least 70% of the actual Adriatic discharge. In addition to the Po,



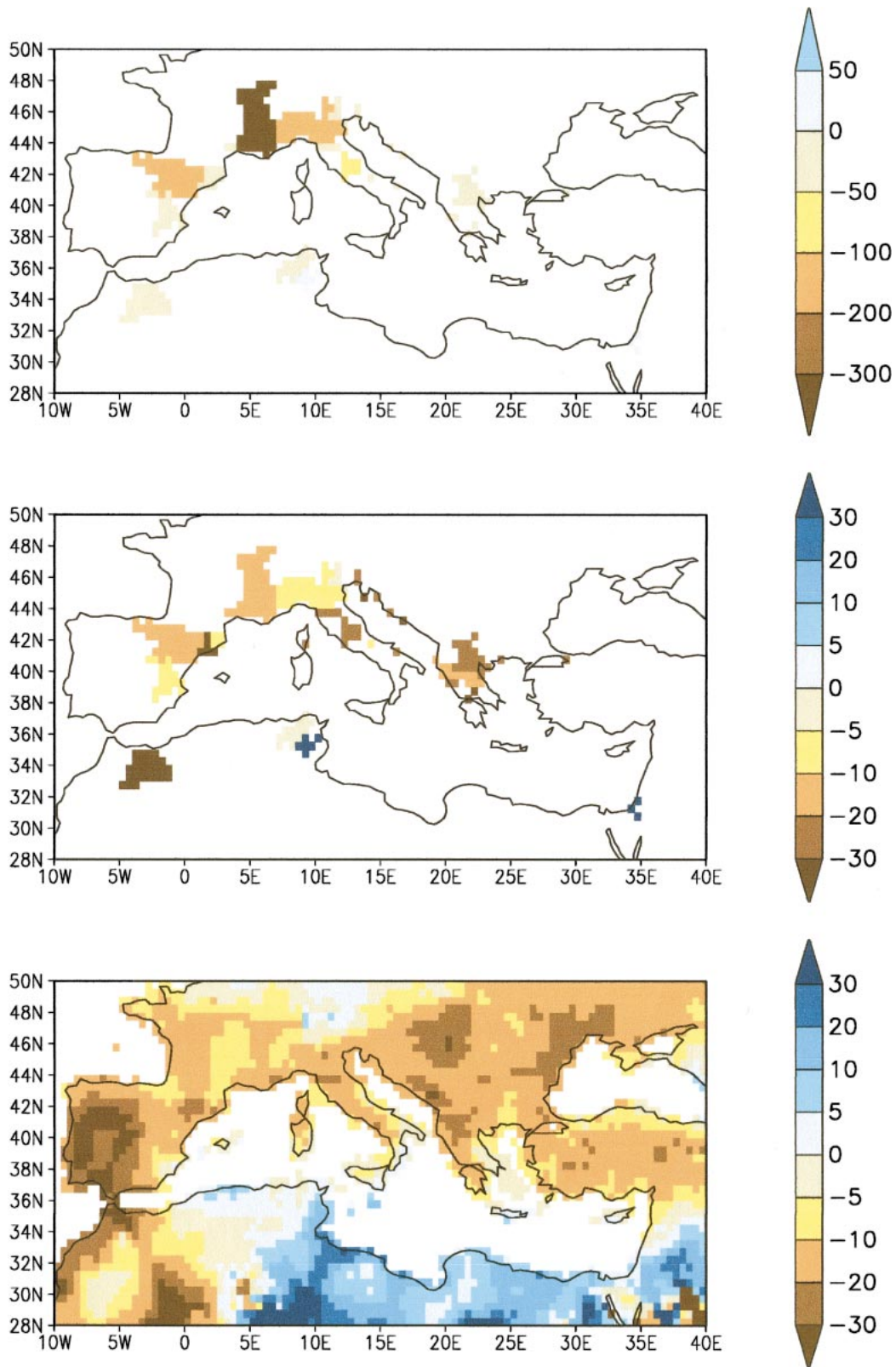


FIG. 6. Regression of river discharge across the Mediterranean catchment and the NAO index for the winter season. (top) Discharge anomalies from the regression analysis ( $\text{m}^3 \text{s}^{-1}$ ), and (middle) corresponding percent changes from climatology. (bottom) For comparison, percent changes for precipitation from a similar regression analysis.

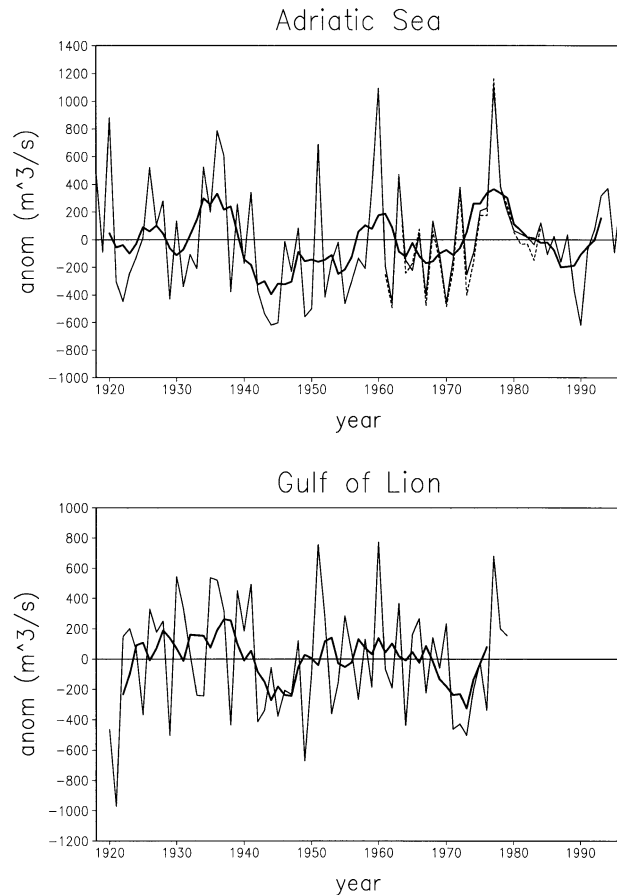


FIG. 7. Anomalous river discharge in (top) the Adriatic Sea and in (bottom) the Gulf of Lion. For the Adriatic, a reconstruction representing at least 70% of the actual annual mean discharge for the period 1961–84 (dashed line). Over the period 1918–96 the Adriatic time series is represented by that of the Po River (annual means: thin solid line; 5-yr running means: thick solid line). Discharge into the Gulf of Lion is that from the Rhone River for the period 1920–79, representing over 95% of the actual discharge (annual means: thin solid line; 5-yr running means: thick solid line).

this includes the rivers: Adige, Pescara, Cetina, Krka, Mirna, Soca, Vjosa, and Zrmanja. For the Po River at Pontelagoscuro, a very long time series is derived combining data from GRDC and Med-HYCOS to cover the period 1918–96. Annual mean anomalies for both time series are displayed in Fig. 7a together with the 5-yr running mean for the Po time series. During the period for which both the reconstruction of the Adriatic discharge and the Po River data are available, the two anomaly time series are basically identical. Year-to-year anomalies of up to  $+1100 \text{ m}^3 \text{ s}^{-1}$  in the Po discharge took place in 1960 and 1977, corresponding to variations of  $+3 \sigma$  or about 60% of the climatological annual mean Adriatic discharge. Given the similarity between the reconstructed Adriatic time series and the Po time series, these anomalies have very likely also characterized the whole Adriatic basin-integrated discharge. By the same token, decadal variations of up to  $300 \text{ m}^3 \text{ s}^{-1}$

may have characterized discharge into this basin, with a period of higher values in the mid-1930s, anomalously lower ones in the mid-1940s and an increasing trend from there into the late 1970s. Anomalies for precipitation totals for the Po River basin, derived from CRU, closely match these interannual-to-interdecadal variations (not shown).

The Rhone is the greatest contributor to discharge in the Gulf of Lion, representing roughly 95% of the actual discharge in this basin. For this river a time series from 1920 to 1979 is available at Beaucaire; annual anomalies and 5-yr running means are displayed in Fig. 7b. Discharge into the Gulf of Lion (represented by discharge from the Rhone) has undergone year-to-year variations of up to  $+800 \text{ m}^3 \text{ s}^{-1}$ , that is about  $+2\sigma$  or 45% of the annual mean discharge into the Gulf of Lion. A particularly large interannual variation occurred around 1950 from anomalously low to anomalously large values, with an overall change of over  $1200 \text{ m}^3 \text{ s}^{-1}$ . On decadal time scales, discharge into the Gulf of Lion has been above the mean (by about  $150 \text{ m}^3 \text{ s}^{-1}$ ) from the mid-1920s into the mid-1930s and from 1950 to the late 1960s. Discharge has been below the long-term mean, by about  $300 \text{ m}^3 \text{ s}^{-1}$ , in the mid-1940s and in the mid-1970s.

Correlation between the annual Po time series and the annual NAO index over the period 1918–96 is not significant, while  $-0.30$  and 99% significant for the Po winter mean (not shown). Correlation between the annual Rhone time series and the annual NAO index over the period 1920–79 is  $-0.51$ , while  $-0.45$  for the winter discharge time series (not shown), both are 99% significant. For the winter season, the correlation with the NAO is further investigated decomposing the signal in lower and higher frequencies (respectively the 5-yr means and the residual once these 5-yr means are subtracted from the original time series). For both the Po and the Rhone, the degree of correlation with the NAO is basically the same at both higher and lower frequencies, with correlation values similar to those already found for the entire signal.

## 6. Conclusions

River discharge across the Mediterranean catchment basin has been investigated by means of an extensive dataset of historical monthly time series from stations representing at-best, given the available data, discharge into the sea. Results give an annual mean river discharge into the Mediterranean of  $8.1 \times 10^3 \text{ m}^3 \text{ s}^{-1}$ , or according to our estimate of the missing contributions, a value that should not exceed  $10.4 \times 10^3 \text{ m}^3 \text{ s}^{-1}$ . Mediterranean discharge has a severe seasonal cycle of amplitude  $5 \times 10^3 \text{ m}^3 \text{ s}^{-1}$ , with a dry season in midsummer (August) and a peak flow in early spring (March). Major rivers are the Rhone, Po, and Nile Rivers, which together account for roughly half of the annual mean discharge into the sea. Of the three continents (Europe, Asia, and Africa) which discharge into the Mediterranean Sea, dom-

inant contributions are from Europe with a climatological annual mean of  $5.7 \times 10^3 \text{ m}^3 \text{ s}^{-1}$ , clearly determining the seasonal cycle for the Mediterranean totals. Discharge from the Middle East and Africa are considerably smaller ( $1 \times 10^3$  and  $1.4 \times 10^3 \text{ m}^3 \text{ s}^{-1}$ , respectively), although the Middle Eastern contribution, which is likely severely underestimated, could be as much as  $1.6 \times 10^3 \text{ m}^3 \text{ s}^{-1}$ .

Discharge in the Adriatic Sea, the Gulf of Lion, and the Aegean Sea (those basins for which a reasonably good level of representation exists) together account for 62% of the whole discharge into the Mediterranean Sea which mostly occurs in the Adriatic ( $2.7 \times 10^3 \text{ m}^3 \text{ s}^{-1}$ ). According to our estimates, 57% of discharge in the Adriatic Sea is due to the Po River, which at its peak flow, in spring and fall, represents a considerable freshwater plume of about  $2 \times 10^3 \text{ m}^3 \text{ s}^{-1}$  at approximately  $45^\circ\text{N}$ , following a southward path along the Italian coast as surface water.

Interannual discharge variability has been investigated in relation to the NAO, the major large-scale climatic mode known to affect Mediterranean precipitation. The effect of the NAO on Mediterranean discharge is primarily in winter, but also in spring. In these seasons all rivers across the Mediterranean catchment, with the exception of a few rivers toward the southeastern part of the basin, are anticorrelated with the NAO index. This closely reflects the impact of the NAO on precipitation variability, the main driver of natural discharge variations. NAO-related discharge anomalies have been quantified by means of a linear regression analysis. In winter the NAO accounts for discharge changes of up to 30% for western Mediterranean rivers in Spain and northern Africa. Rivers in central Italy, along the eastern Adriatic and in Greece show variations due to the NAO of up to 20% in this season; 5%–10% for the Po River.

An estimate of the variations winter Mediterranean river discharge may have undergone as a whole in relation to observed NAO variations has been attempted based on the additional hypothesis of a stationary relationship between the NAO and river discharge during the investigated period. Year-to-year NAO-related Mediterranean winter discharge variations during the period 1960–90 may have been up to  $2600 \text{ m}^3 \text{ s}^{-1}$ , that is about 26% of the seasonal mean. On decadal time scales, considering that from the early 1970s to the early 1990s the NAO index has gone on a long-term positive phase, an NAO-related reduction in Mediterranean winter discharge of approximately  $1700 \text{ m}^3 \text{ s}^{-1}$  may have occurred, that is about 17% of the winter mean. This would be about one order of magnitude smaller than the NAO impact on the Mediterranean Sea atmospheric water budget (Mariotti et al. 2002).

At Mediterranean Sea subbasin scales, observed interannual discharge variations for the Po River during the twentieth century have been up to 60% of the climatological long-term mean, and are likely representative of Adriatic discharge anomalies. For the Rhone

River, basically representing discharge into the Gulf of Lion, interannual variations have been up to 45% of the mean. During the same period, decadal changes in the Po and Rhone annual mean discharge have been up to 20% and 17% of their respective long-term mean. For these two major rivers, winter discharge anomalies during the twentieth century significantly correlate with the NAO at both interannual and decadal time scales. Considering the whole Mediterranean Sea, the Gulf of Lion and the Adriatic Sea, together with the Balearic Sea, is where the impact of the NAO on winter discharge is expected to have been greatest.

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