# Estimation of the Atlantic inflow through the Strait of Gibraltar from climatological and in situ data

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[1] Atmospheric data from reanalysis, satellite, and experimental observations have been combined to calculate a four-year time series of the Atlantic inflow through the Strait of Gibraltar. The net flow through the strait, estimated from the Mediterranean water budget, and the Mediterranean outflow, estimated from currentmeter observations in Espartel sill (western Strait of Gibraltar) from October 2004 to January 2009, made it possible to estimate the Atlantic inflow as the sum of both of them. The obtained mean net flow is 0.038 ± 0.007 Sv, with a seasonal cycle of 0.042 ± 0.018 Sv annual amplitude and maximum in September. The Mediterranean outflow shows a seasonal signal with annual amplitude of 0.027 ± 0.015 Sv peaking in April (in absolute value), and a mean value of −0.78 ± 0.05 Sv. The resulting Atlantic inflow has a mean value of 0.81 ± 0.06 Sv and a seasonal cycle with annual amplitude of 0.034 ± 0.011 Sv, peaking in September, and high interannual variability. The inflow seasonal cycle is the result of a barotropic forcing associated with the cycle of the net flow, driven by the evaporative cycle, and a baroclinic forcing linked to the seasonal cycle of the reduced gravity that drives the exchange.

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## 1. Introduction

[2] The Strait of Gibraltar is a system of sills and narrows about 60 km long and 20 km wide, with a minimum width of less than 14 km in the Tarifa narrow section (TN) and a minimum depth of 290 m in the Camarinal sill (CS), located west of Tarifa (Figure 1).

[3] As the only connection between the world's oceans and the Mediterranean Sea, the Strait plays an important role in its water, salt, and heat budgets [*Bunker et al.*, 1982; *Garrett et al.*, 1993; *Bethoux and Gentili*, 1999; *Mariotti et al.*, 2002; *Ruiz et al.*, 2008] (Criado-Aldeanueva et al., Seasonal and interannual variability of surface heat and freshwater fluxes in the Mediterranean Sea: Budgets and exchange through the Strait of Gibraltar, submitted, 2010). The semienclosed nature of the Mediterranean basin and the fact that, on a yearly base, the spatially averaged evaporation exceeds precipitation and river discharge, makes the Mediterranean a concentration basin where the fresh water deficit is compensated by a net flow of Atlantic water entering through the Strait. This feature allows indirect net flow estimation based on the conservation equation

$$\frac{dV}{dt} = S_f \frac{d\xi_M}{dt} = P - E + R + B + Q_0, \quad (1)$$

where $dV/dt$, is the volume temporal variation, $S_f$ is the Mediterranean surface (~$2.5 \cdot 10^6$ km$^2$), and $\xi_M$ the mass-induced sea level anomaly. The right-hand side terms are the different contributions to the budget: precipitation, $P$, evaporation, $E$, river discharge, $R$, the exchange with the Black Sea through the Turkish Straits, $B$, and the net flow through the Strait of Gibraltar, $Q_0$. The net flow constitutes a long-term barotropic signal resulting from the difference between the Atlantic inflow, $Q_1$, and the Mediterranean outflow, $Q_2$, that do not cancel each other on monthly time scales. This seasonal input of mass-excess into the Mediterranean Sea is neither canceled out by the evaporative cycle at short time scales, giving rise to a seasonal cycle of mass content in the Mediterranean, which adds on the steric one due to temperature and salinity variations.

[4] Many authors have estimated the net flow obtaining similar results (Table 1). *Boukthir and Barnier* [2000] and *Mariotti et al.* [2002] using the mass conservation with different approaches calculate a long-term mean of 0.031 and 0.039 Sv (1 Sv = $10^6$ m$^3$/s) from data of the European Centre for Medium-Range Weather Forecasts (ECMWF) and of the National Centers for Environmental Prediction

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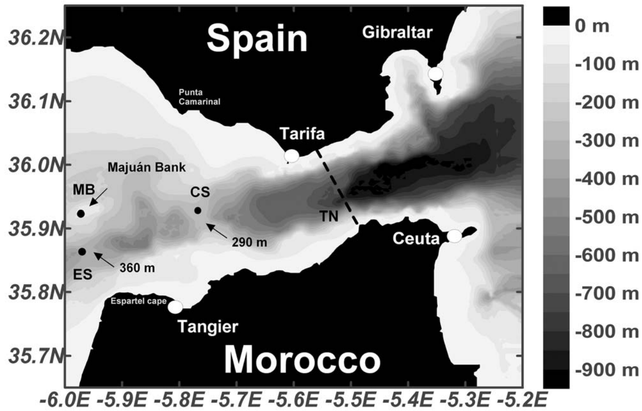


**Figure 1.** Bathymetric map of the Strait of Gibraltar showing the main topographic features. CS and ES indicate the location of the sills of Camarinal and Espartel, respectively. MB is the submarine ridge of Majuan bank, and TN is the Tarifa Narrows.

(NCEP), respectively, although *Boukthir and Barnier* [2000] pointed out that evaporation is probably underestimated in the ECMWF data. For the seasonality of the net flow, *García et al.* [2006] reported an annual amplitude of 0.029 Sv peaking in January while *Fenoglio-Marc et al.* [2006] find an annual amplitude of 0.057 Sv peaking in September both using gravimetry observations (Gravity Recovery and Climate Experiment (GRACE) Mission). Direct estimations from current measurements vary between an annual amplitude of 0.04 Sv as found by *Bryden et al.* [1994] and *Candela* [2001], and 0.044 Sv peaking in September (semiannual of 0.035 Sv peaking in July) as found by *García-Lafuente et al.* [2002a].

[5] Both the inflow and the outflow fluctuate at different timescales, the most noticeable being the semidiurnal, followed by the meteorological, seasonal, and interannual variations [*García-Lafuente et al.*, 2002b, 2007]. Seasonal variability of the exchanged flows has been studied using different approaches [*Bryden et al.*, 1994; *Candela*, 2001; *García-Lafuente et al.*, 2002a, 2007] obtaining results of about 0.10 Sv annual amplitude for the inflow, peaking in late summer, and from 0.03 to 0.14 Sv for the outflow peaking in late winter-early spring. Even though the more reliable source is in situ observations, these results must be considered cautiously due to the difficulties of computing the interface depth between the Mediterranean and Atlantic layers and from pointwise velocity observation.

[6] From the hydraulic viewpoint, the exchange state depends on the existence of one or two hydraulic controls in the strait [*Farmer and Armi*, 1986; *Bormans et al.*, 1986; *Bryden et al.*, 1994; *García-Lafuente et al.*, 2002a]. A first case is the maximal exchange regime, which occurs when the flow is controlled either at CS or at Espartel sill (ES in Figure 1) and at TN [*Farmer and Armi*, 1986]. In this situation, the region between the controls is isolated with respect to the neighbor basins, and, thus, any variation in the inflow (outflow) is reflected in the outflow (inflow) so both flows are phase locked, which means that an increase (decrease) of one of them produce a decrease (increase) of the other one [*García-Lafuente et al.*, 2002a]. A second case is the submaximal exchange in which the TN control is lost and the flow is now affected by changes in the Mediterranean since it is now possible for a signal to travel through the strait into the Atlantic Ocean [*Bormans et al.*, 1986; *García-Lafuente et al.*, 2002a]. This situation allows for independent variations of the flows.

[7] This work focuses on the inflow seasonality, which has been less studied by other authors. A net flow estimation based on the mass budget, combined with Acoustic Doppler current profiler (ADCP) observations at ES, from October 2004 to January 2009, has indirectly provided us a long time series of Atlantic inflow that allows a reliable estimation of its seasonal cycle. The paper is organized as follows: section 2 describes the data and methodology; in section 3 the main results are presented and discussed. Finally, section 4 summarizes the conclusions.

## 2. Data and Methodology

[8] Several datasets have been used to evaluate the different contributions to the Mediterranean budget in equation (1). Evaporation and precipitation have been retrieved from NCEP [*Kalnay et al.*, 1996], which is run at T62 spectral resolution (a grid size of approximately 1.9° × 1.9°) with 28 sigma levels. Monthly means from January 1948 to January 2009 have been used to describe the seasonal cycle and daily means from October 2004 to January 2009 for the inflow computation.

[9] The mass contribution of the sea level anomaly has been computed combining the Archiving Validation and Interpretation of Satellite Oceanographic (AVISO) total sea level anomaly data with the estimation of the steric contribution from the Jet Propulsion Laboratory (JPL) Estimating

**Table 1.** Estimations of the Net Flow Through the Strait of Gibraltar from Different Authors[a]

| Author | Methodology | $Q_0$ (Sv) |
|---|---|---|
| *Bethoux* [1979] | Energy budget | 0.079 |
| *Bryden et al.* [1994] | Current observations/salinity budget | 0.041 |
| *Boukthir and Barnier* [2000] | Hydrologic budget | 0.031 |
| *Candela* [2001] | Current observations | 0.040 |
| *Mariotti et al.* [2002] | Hydrologic budget | 0.039 |
| *García-Lafuente et al.* [2002a] | Current observations | $A_a$ = 0.044 Max. in September<br>$A_s$ = 0.035 Max. in July |
| *García et al.* [2006] | Gravimetry/hydrologic budget | $A_a$ = 0.029 Max. In January |
| *Fenoglio-Marc et al.* [2006] | Gravimetry/hydrologic budget | $A_a$ = 0.057 Max. in September |
| This study | Hydrologic budget | $A_a$ = 0.042 Max. in September $A_s$ = 0.011 Max. in April |

[a] $A_a$ and $A_s$ denote annual and semiannual amplitudes, respectively.

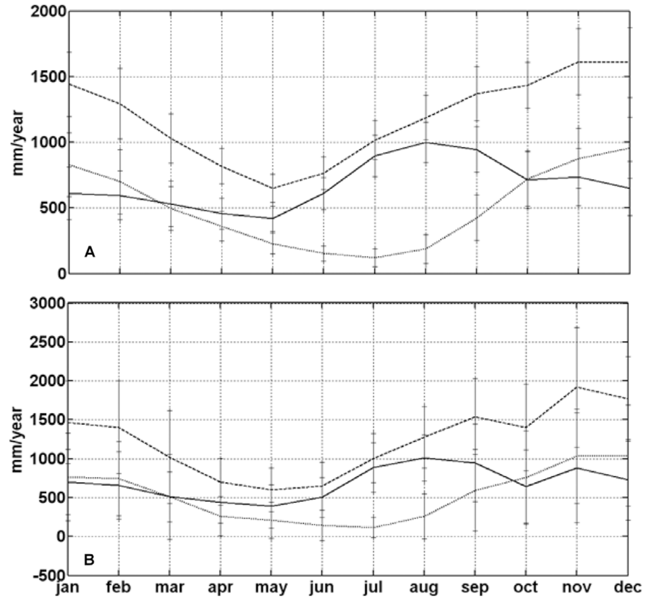


**Figure 2.** (a) Climatological monthly averaged seasonal cycle of evaporation (*E*, dashed line), precipitation (*P*, dotted line), and $E - P$ (solid line). The cycle is computed averaging the NCEP monthly means from 1948 to January 2009. (b) Climatological monthly averaged seasonal cycle of evaporation (*E*, dashed line), precipitation (*P*, dotted line), and $E - P$ (solid line) computed from the daily values from October 2004 to January 2009, the period when the measures at ES are available. Vertical bars are the standard deviation.

the Circulation and Climate of the Ocean (ECCO) model salinity and temperature profiles.

[10] The AVISO merged product is a combination of different satellite mission (T/P, ERS-1/2, GFO, ENVISAT, and JASON 1) and consists in altimetry measurements with a spatial resolution in the Mediterranean region of 1/8° × 1/8° and a weekly time resolution covering the period 1992 to 2009. All standard geophysical and environmental corrections have been applied by AVISO processing algorithms [*AVISO*, 1996].

[11] The ECCO model profiles have a spatial resolution of 1° × 1°, 46 depth levels with 10 m interval for the first 150 m and a 10 day temporal resolution covering the same period as the AVISO data. The simulation uses NCEP/COADS (Comprehensive Ocean-Atmosphere Data Sets) as forcing. The steric contribution to the sea level anomaly has been calculated according to

$$\xi_S = -\frac{1}{\rho_0}\int_{-H}^{0} \left.\frac{\partial\rho(S,T,P)}{\partial T}\right|_{T,P=cte} \cdot T^{'}(z)dz + \frac{1}{\rho_0}\int_{-H}^{0} \left.\frac{\partial\rho(S,T,P)}{\partial S}\right|_{S,P=cte} \cdot S^{'}(z)dz \qquad (2)$$

where $T'(z)$ and $S'(z)$ are temperature and salinity anomalies that refer to their climatological mean value, $\rho_0$ represents a reference density, and *H* is the bottom depth.

[12] The total sea level anomaly is the sum of the mass and steric contributions so that the mass contribution can be obtained as the difference between the total anomaly and the steric one, $\xi_M = \xi_T - \xi_S$. This assumption is arguable because both contributions are very difficult to separate out, but recent studies based on gravimetry techniques have shown a good agreement between direct estimation and the indirect approach [*Fenoglio-Marc et al.*, 2006; *García et al.*, 2006; *Criado-Aldeanueva et al.*, 2008].

[13] In situ velocity observations, used to estimate the outflow through the Strait of Gibraltar, were collected at a station located in the southern channel of ES (35°51.70′N, 5°58.60′W at 360 m depth in the framework of the Spanish-funded INGRES projects). This station is equipped with an up-looking ADCP settled 15 m above the seafloor, a pointwise current meter and an autonomous conductivity-temperature probe at 8 and 5 m above the seafloor, respectively. It provides 3-D current velocity records every 30 minutes throughout the water column. It was first installed in September 2004 and is still acquiring information. Data from October 2004 to January 2009 have been used in this work.

[14] To focus on seasonal variations, a third-order low-pass Butterworth filter with band pass and stop frequencies $f_1 = 2.496 \cdot 10^{-2}$ cpd and $f_2 = 4.992 \cdot 10^{-2}$ cpd has been applied to the time series used in the inflow estimation. Climatological and altimetry data were previously spatially averaged and all data were finally interpolated to a 10 day time interval using cubic splines.

[15] ADCP velocity data are the shortest time series and restrict the inflow estimation to the period October 2004 to January 2009. However, the seasonal cycle analysis of the different components of the water budget has been performed with the full time series, by least-squares fitting them to the following function:

$$y(t) = y_0 + mt + A_a\cos(\omega_a - \varphi_a) + A_s\cos(\omega_s - \varphi_s), \qquad (3)$$

which includes annual, $\omega_a$, and semiannual, $\omega_s$, frequencies.

## 3. Results and Discussion

[16] To estimate the Atlantic inflow, we first need to characterize the several contributions of the Mediterranean water budget (equation (1)). The main terms (*E*, *P* and $\frac{d\xi_M}{dt}$) are analyzed from the different climatological datasets mentioned in section 2. River runoff and Black Sea net flow data (*R* and *B* in equation (1)) have been obtained from the literature.

[17] Figure 2a displays the climatological monthly averaged seasonal cycle of evaporation (*E*), precipitation (*P*), and $E - P$. Evaporation has a climatological mean of 1186 ± 27 mm/year, with a seasonal cycle of 964 ± 19 mm/year range (peak-to-peak), maximum in November and minimum in May. Precipitation seasonal cycle, with 506 ± 24 mm/year mean, follows the evaporative cycle in about two months with maximum in December, the minimum in July, and a range of 838 ± 29 mm/year. Evaporation is more than twice precipitation during all the year, producing both a climatological mean of freshwater deficit ($E - P$) of 680 ± 18 mm/year and a seasonal cycle of 582 ± 21 mm/year range, with a maximum in August and a minimum in May. Similar results have been reported by several authors analyzing different datasets: *Boukthir and Barnier* [2000], *Mariotti et al.* [2002] and, more recently, *Mariotti* [2009]

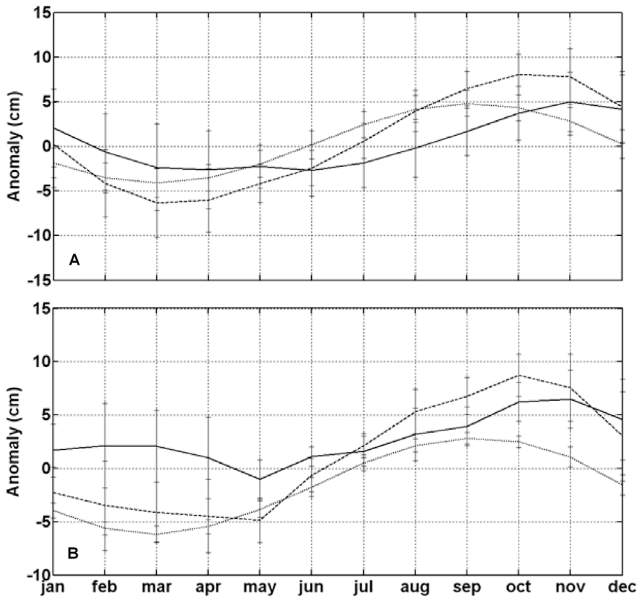


**Figure 3.** (a) Climatological monthly averaged seasonal cycle of the total sea level anomaly (dashed line), the steric (dotted line) and the mass (solid line) contribution. (b) Climatological monthly averaged seasonal cycle of the total sea level anomaly (dashed line), the steric (dotted line) and the mass (solid line) contribution computed from the daily values from October 2004 to January 2009, the period when the measures at ES are available. Vertical bars are the standard deviation.

who analyze various experimental and reanalysis datasets, and Criado-Aldeanueva et al. (Seasonal and interannual variability of surface heat and freshwater fluxes in the Mediterranean Sea: Budgets and exchange through the Strait of Gibraltar, submitted, 2010). There are not significant variations if the period from October 2004 to January 2009 (when outflow data are available) is considered for the cycle computation. The $E - P$ range changes to 625 ± 23 mm/year, while the maximum and minimum remain in the same months. The most noticeable change is the appearance of a local maximum in November (Figure 2b).

[18] The seasonal cycle of the total sea level anomaly, the steric and the mass contributions are shown in Figure 3. The total anomaly has an annual amplitude of 7.0 ± 2.1 cm peaking in October and the steric contribution, with an amplitude of 4.1 ± 0.8 cm, reaches its maximum in September, about two months later than the sea surface temperature, in good agreement with previous results [*Cazenave et al.*, 2002; *Fenoglio-Marc*, 2002; *Criado-Aldeanueva et al.*, 2008], and three months later than the sea heat content [*Ruíz et al.*, 2008] (Criado-Aldeanueva et al., Seasonal and interannual variability of surface heat and freshwater fluxes in the Mediterranean Sea: Budgets and exchange through the Strait of Gibraltar, submitted, 2010). Subtracting both terms, a seasonal cycle of 4.1 ± 1.2 cm amplitude and maximum in November is obtained for the mass contribution, almost the same as the 4.3 cm obtained using gravimetry by *Fenoglio-Marc et al.* [2006], and slightly lower than the 5.5 cm obtained, using the same technique, by *García et al.* [2006]. *Criado-Aldeanueva et al.* [2008] made an exhaustive analysis of 14 years (1992–2005) of the same satellite data used here reporting similar results. The period from October 2004 to January 2009 is considered the annual amplitude of the mass signal decrease to 3.0 ± 1.1 cm due to the increase of the steric contribution amplitude to 4.6 ± 0.9 and the decrease of the total anomaly amplitude to 6.8 ± 1.8 cm (Figure 3b).

[19] Several studies have dealt with the determination of climatological river discharge into the Mediterranean Sea using diverse methodologies with different results. *Boukthir and Barnier* [2000] analyzed data from *UNESCO* [*Vörösmarty et al.*, 1996] for the period 1974–1994 and reported a climatological mean of $11 \cdot 10^3$ m$^3$/s with an annual cycle of $6.5 \cdot 10^3$ m$^3$/s range peaking in April, 30% lower than the estimates of *Tixeront* [1970] ($16 \cdot 10^3$ m$^3$/s) based on rain maps and data from a few coastal stations, *Ovchinnikov* [1974] ($13.6 \cdot 10^3$ m$^3$/s) or *Margat* [1992], who gives the same value than *Tixeront* [1970]. *Struglia et al.* [2004] analyze data from Global Runoff Data Center (GRDC) and the Mediterranean Hydrological Cycle Observing System (med-HYCOS) and report and an annual mean climatological value of $8.1 \cdot 10^3$ m$^3$/s ($10.4 \cdot 10^3$ m$^3$/s at most, setting an upper bound to possible underestimates), with a annual range of $5 \cdot 10^3$ m$^3$/s and maximum in March. This last value is close to that of *Boukthir and Barnier* [2000] and will be adopted for our calculations. In any case, the contribution of the river discharge is less than 20% of the most important $E - P$ so the uncertainty of ~40% in $R$ represent and incertitude of about 6% in the right-hand side of equation (1).

[20] The Black Sea contribution has also been extensively studied, with results that range from $5.8 \cdot 10^3$ m$^3$/s of *Bethoux and Gentili* [1999] from hydrological budget in the Aegean Sea to $9.6 \cdot 10^3$ m$^3$/s of *Liu et al.* [2009] from numerical simulation (a value close to those of *Unluata et al.* [1990] and *Bektepe et al.* [1994]). *Kanarska and Maderich* [2008] from a 3-D model obtain mean annual values of $38.8 \cdot 10^3$ m$^3$/s for the upper layer (entering the Mediterranean) and $30.0 \cdot 10^3$ m$^3$/s for the lower layer (flowing out the Mediterranean) which means a mean net inflow of $8.8 \cdot 10^3$ m$^3$/s. These authors compute a seasonal cycle of $8 \cdot 10^3$ m$^3$/s peaking in late February, that will be adopted for our calculations. The contribution of the Black Sea is also less than 20% of the $E - P$ deficit, comparable to the river runoff.

[21] The analysis of all components of the water budget leads to the estimation of the net flow through the Strait of Gibraltar. Figure 4a displays the different contributions of equation (1) (except $R$ and $B$) and the resulting net flow ($Q_0$), which has a climatological mean of 0.038 ± 0.007 Sv, an annual amplitude of 0.042 ± 0.018 Sv peaking in September and a semi-annual amplitude of 0.011 ± 0.009 Sv peaking in mid April. Results reported by different authors using the same or different methodologies are presented in Table 1. Our indirect estimation is quite similar to those reported by *Bryden et al.* [1994], *Candela* [2001], and *García-Lafuente et al.* [2002a], based on direct current measurements, and also to those based on water budgets of *Boukthir and Barnier* [2000] and *Mariotti et al.* [2002]. The climatological monthly averaged seasonal cycle of $Q_0$ (Figure 4b) confirms this result and shows a net flow almost constant during winter and spring, with a local maximum in

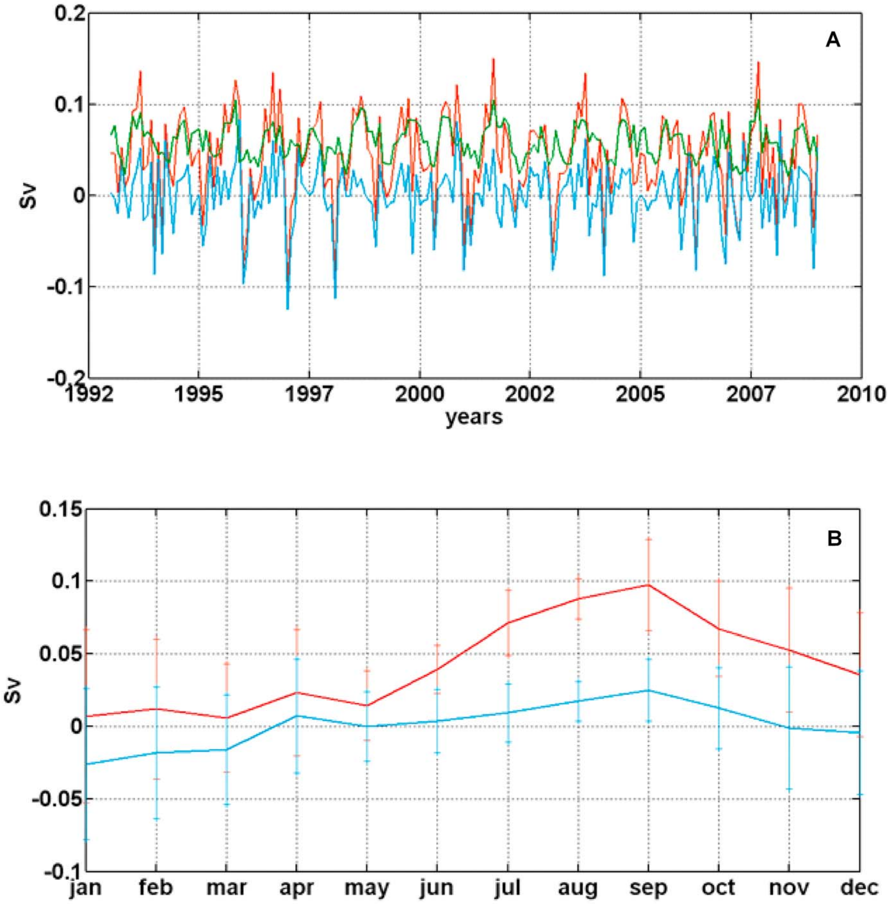


**Figure 4.** (a) Time series of the net flow through the Strait of Gibraltar (red), evaporation (green), and volume time-variation (*dV/dt*, blue) used in the computation (*R* and *B* are not shown). (b) Climatological monthly averaged seasonal cycle $Q_0$ and *dV/dt* (not canceled for the evaporative cycle on monthly basis). Vertical bars are the monthly standard deviation of each distribution.

April, then increasing in May to reach its maximum in late summer. The $Q_0$ annual amplitude is the response to the seasonal cycles of $E - P$ (Figure 2) and *dV/dt* (Figure 4b), while the semiannual amplitude could be related to the wind stress cycle as pointed by *García-Lafuente et al.* [2002a].

[22] The Mediterranean outflow has been computed from in situ ADCP velocity data collected in ES according to

$$Q_2(t) = \int_b^{h(t)} \langle u(z,t) \rangle W(z) dz, \qquad (4)$$

where $\langle u(z,t) \rangle$ is the along-strait velocity, previously filtered to remove tidal and subinertial variability (periods lower than 21 days) and subsampled to 10 days temporal resolution; *W(z)* is the channel width at depth *z*; and *h(t)* is the time-dependent depth of the surface of zero low-passed velocity (interface). More details about this procedure can be found in *García-Lafuente et al.* [2002a] and *Sánchez-Román et al.* [2009].

[23] This transport computation presents two inconvenient characteristics: it has implicitly assumed that the single velocity profile at ES is representative of the entire channel section ignoring the cross-channel structure of the flow. Moreover, only the southern main channel of the Espartel section is considered (south of Majuan Bank, MB in Figure 1), so Mediterranean water outflowing through the small, secondary northern channel is neglected. *Sánchez-Román et al.* [2009] used an improved version of the CEPOM numerical model developed by the Ocean Modelling Unit of ENEA to complement the observations and correct the flow estimations. Model outputs provide information to assess the accuracy of the outflow estimations from observations at a single station and shows that when the cross-strait structure of the velocity field is taken into account, the flow computed from a single station must be reduced around 22% due to lateral friction. The model also indicates that the fraction of the outflow through the northern channel of ES is around 18% of the total outflow. Both corrections have been incorporated to outflow estimations in equation (4).

[24] Figure 5a displays the time series of the outflow, Figure 5b shows the interface depth at ES, and Figure 5c presents the inflow. The resulting mean value for the Mediterranean outflow after all corrections is $-0.78 \pm 0.05$ Sv, similar to the $-0.75$ found by *Sánchez-Román et al.* [2009] from data between October 2004 and September 2007. The seasonal cycle of the outflow has an annual amplitude of $0.027 \pm 0.015$ Sv and a semiannual amplitude

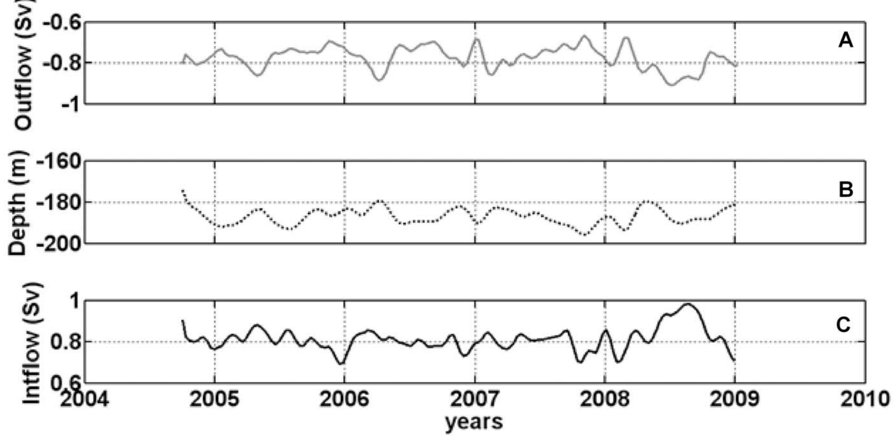


**Figure 5.** Time series of the low-passed outflow (a) and the interface depth (b) at ES for the period October 2004 through January 2009. (c) Inflow computed as the difference between the net barotropic flow $Q_0$ and the outflow during the same period.

of 0.017 ± 0.009 Sv, with maxima (in absolute values) in April and September, respectively. The monthly averaged seasonal cycle (Figure 6a) shows a steep outflow increase from November to April probably linked to the replenishment of the deep western Alboran Sea with Western Mediterranean Deep Water (WMDW) formed during winter convection in the Gulf of Lions [*Garcia-Lafuente et al.*, 2007, 2009]. From April onward the outflow decreases until the minimum of November (−0.75 ± 0.05 Sv).

[25] *Bryden et al.* [1994] and *García-Lafuente et al.* [2002a] obtained similar annual amplitudes, but they peaked in late winter from velocity data collected in 1985–1986 and October 1995 to May 1996. *Candela* [2001], using observations from November 1994 to September 1996, situates the maximum in early spring with an amplitude of 0.14 Sv, higher than our estimations. However, it must be taken into account that these time series are not long enough to neatly define the seasonality of the exchanged flows through the Strait. *García-Lafuente et al.* [2007] analyzed two years of recent $Q_2$ measurements, collected in ES between October 2004 and October 2006, and situate the maximum in April, in good agreement with our findings, with annual amplitude of 0.05 Sv and semiannual amplitudes of 0.03 Sv.

[26] The estimated inflow, computed as $Q_1 = Q_0 + |Q_2|$ (Figure 5c), has a mean value of 0.81 ± 0.06 Sv, with annual amplitude of 0.034 ± 0.011 Sv and a semiannual amplitude of 0.022 ± 0.014 Sv peaking in August and April, respectively. The monthly averaged seasonal cycle (Figure 6c) also shows a maximum in late summer (August–September). The results are greatly influenced by the high anomaly of the year 2008, suggesting the necessity for longer time series to define the seasonality. Both the fitted signal and the monthly averaged cycle are in good agreement with previous works [*Bryden et al.*, 1994; *Candela*, 2001; *García-Lafuente et al.*, 2002a]; however, these authors found a higher value for the annual amplitude: 0.14 Sv in *Bryden et al.* [1994] and 0.10 in *García-Lafuente et al.* [2002a]. Similarly to the outflow our longer time series are thought to provide a more reliable seasonal cycle.

[27] The maximum outflow found in April is not coupled with a minimum in the inflow, and the outflow minimum is found in late autumn while the maximum inflow occurs in summer (Figures 5 and 6). The fact that the inflow and outflow are not phase-locked suggests a situation of submaximal exchange with a unique hydraulic control either at CS or, more probably, at ES [*García-Lafuente et al.*, 2002a].

[28] The peak of the inflow in summer can be explained by two different mechanisms. The first one is barotropic in nature and follows the cycle of $Q_0$ which in turn is driven basically by the $E - P$ cycle (Figures 2 and 4a). A positive (toward the Mediterranean Sea) $Q_0$ is achieved by an increase of the inflow and a decrease of the outflow accompanied by a sinking of the interface. A second mechanism, baroclinic in nature, is the seasonal cycle of the density difference $\Delta\rho$ between the inflowing and outflowing waters. Inflow and outflow velocities are proportional to $(\Delta\rho)^{1/2}$ (actually, they are proportional to $g'^{1/2}$, $g'$ being the reduced gravity defined as $g' = g\Delta\rho/\rho_0$) so that when $\Delta\rho$ is at its maximum the velocities, and hence the flows, will also be. The outflow is not directly affected by air-sea exchanges, thus its density can be assumed to be constant. However, the inflow density is affected by the seasonal cycle of heat flux, also reflected in the steric anomaly that peaks in summer

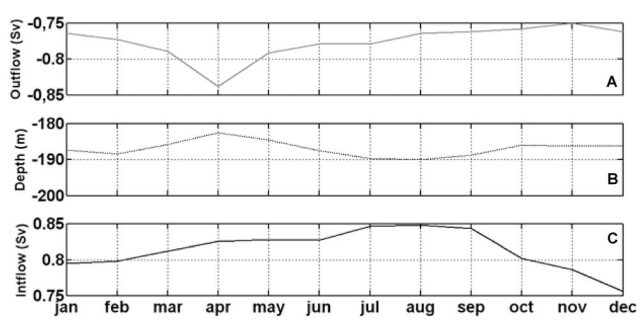


**Figure 6.** Climatological monthly averaged seasonal cycle of (a) the outflow, (b) the interface depth, and (c) the inflow. The interface is deeper (shallower) when the inflow (outflow) is maximum (see text for details).

[*Cazenave et al.*, 2002; *Criado-Aldeanueva et al.*, 2008; *Ruíz et al.*, 2008] and diminishes the upper layer density, increasing $\Delta\rho$ and inducing maximum inflow and outflow in this season. While both mechanisms act in the same direction to increase the inflow in summer, they do oppositely in the outflow, thus canceling its expected summer maximum. The only well-defined signal in the outflow is the April maximum whose origin has been already commented.

## 4. Summary and Conclusions

[29] The seasonal variability of the Atlantic inflow through the Strait of Gibraltar has been characterized by a combination of indirect net flow estimation based on the Mediterranean water budget, described from reanalysis, satellite and model data, and direct outflow measurements at ES from October 2004 to January 2009, collected in the framework of the Spanish-funded INGRES projects.

[30] The barotropic net flow signal, $Q_0$, depends on the $E - P$ seasonal cycle, with 582 ± 21 mm/year range and maximum in August, and on the mass-induced sea level signal, with a seasonal cycle of 4.1 ± 1.2 cm amplitude peaking in November. The river discharge and the Mediterranean–Black Sea exchange have been included in the budget, although their contributions to the water budget are less than 20%. A mean value of 0.038 ± 0.007 Sv and a seasonal cycle with annual amplitude of 0.042 ± 0.018 Sv and maximum in September have been obtained for the net flow.

[31] A mean value of −0.78 ± 0.05 Sv with an annual amplitude of 0.027 ± 0.015 Sv and a semiannual amplitude of 0.017 ± 0.009 Sv, peaking in April and September, respectively, have been obtained for the Mediterranean outflow from more than 4 years of direct current measurements. As a result, we have estimated a mean Atlantic inflow of 0.81 ± 0.06 Sv with an annual amplitude of 0.034 ± 0.011 Sv peaking in August and a semiannual amplitude of 0.022 ± 0.014 Sv peaking in April. The series is subject to noticeable interannual variability, and the higher 2008 outflow anomaly may bias the resulting seasonal cycle. Longer time series that are presently being collected are necessary to improve the determination of the seasonal cycle.

[32] The behavior of the exchanged flows and the interface depth between the Mediterranean and Atlantic layers suggests a submaximal regime in the strait that is reflected by the unlocked phase fluctuation of inflow and outflow. The main contribution to the inflow seasonal signal comes from the barotropic signal, $Q_0$, which follows the $E - P$ seasonal cycle and leads to a maximum inflow in late summer. A second baroclinic mechanism is the seasonal change of the reduced gravity, $g'$, due to the changes of the surface layer density produced by the seasonal cycle of heat fluxes, that peaks in summer, thus contributing to the inflow maximum. It enhances the inflow summer maximum and fades out the expected summer signal of the outflow, which only exhibits a pronounced maximum in late winter/early spring.

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## References

AVISO (1996), *AVISO User Handbook: Merged TOPEX/POSEIDON Products*, 201 pp. Available at www.aviso.oceanobs.com/donnees/tools/hdbk._gdrm.pdf.

Bektepe, S., H. Sur, E. Ozsoy, M. Latif, T. Oguz, and U. Unluata (1994), The circulation and hydrography of the Marmara Sea, *Prog. Oceanogr.*, *34*(4), 285–334.

Bethoux, J. P. (1979), Budgets of the Mediterranean Sea: Their dependence on the global climate and on the characteristics of the Atlantic waters, *Oceanol. Acta*, *2*, 105–119.

Bethoux, J. P., and B. Gentili (1999), Functioning of the Mediterranean Sea: Past and present changes related to freshwater input and climatic changes, *J. Mar. Syst.*, *20*, 33–47.

Bormans, M., C. Garrett, and K. R. Thompson (1986), Seasonal variability of the surface inflow through the Strait of Gibraltar, *Oceanol. Acta*, *9*, 403–414.

Boukthir, M., and B. Barnier (2000), Seasonal and inter-annual variations in the surface freshwater flux in the Mediterranean Sea from the ECMWF re-analysis project, *J. Mar. Syst.*, *24*, 343–354.

Bryden, H. L., J. Candela, and T. H. Kinder (1994), Exchange through the Strait of Gibraltar, *Prog. Oceanogr.*, *33*, 201–248.

Bunker, A. F., H. Charnock, and R. A. Goldsmith (1982), A note on the heat balance of the Mediterranean and Red Seas, *J. Mar. Res.*, *40*, 73–84 Suppl.

Candela, J. (2001), Mediterranean water and global circulation, in *Ocean Circulation and Climate*, edited by G. Siedler, J. Church, and J. Gould, pp. 419–429, Academic Press, San Diego.

Cazenave, A., P. Bonnefond, F. Mercier, K. Dominh, and V. Toumazou (2002), Sea level variations in the Mediterranean Sea and Black Sea from satellite altimetry and tide gauges, *Global Planet. Change*, *34*, 59–86.

Criado-Aldeanueva, F., J. Del Río Vera, and J. García-Lafuente (2008), Steric and mass induced sea level trends from 14 years altimetry data, *Global Planet. Change*, *60*, 563–575.

Farmer, D., and L. Armi (1986). The internal hydraulics of the Strait of Gibraltar and associated sills and narrows, *Oceanol. Acta*, *8*, 37–46.

Fenoglio-Marc, L. (2002), Long-term sea level change in the Mediterranean Sea from multi-satellite altimetry and tide gauges, *Phys. Chem. Earth*, *27*, 1419–1431.

Fenoglio-Marc, L., J. Kusche, and M. Becker (2006), Mass variation in the Mediterranean Sea from GRACE and its validation by altimetry, steric and hydrologic fields, *Geophys. Res. Lett.*, *33*, L19606, doi:10.1029/2006GL026851.

García, D., B. F. Chao, J. Del Río, I. Vigo, and J. García Lafuente (2006). On the steric and mass-induced contributions to the annual sea level variations in the Mediterranean Sea, *J. Geophys. Res.*, *111*, C09030, doi:10.1029/2005JC002956.

García Lafuente, J., J. Delgado, J. M. Vargas, M. Vargas, F. Plaza, and T. Sarhan (2002a), Low-frequency variability of the exchanged flows through the Strait of Gibraltar during CANIGO, *Deep Sea Res. II*, *49*, 4051–4067.

García Lafuente, J., E. Alvarez Fanjul, J. M. Vargas, and A. W. Ratsimandresy (2002b), Subinertial variability in the flow through the Strait of Gibraltar, *J. Geophys. Res.*, *107*(C10), 3168, doi:10.1029/2001JC001104.

Garcíal-Lafuente, J., A. Sánchez-Román, G. Díaz del Río, G. Sannino, and J. C. Sánchez-Garrido (2007), Recent observation of seasonal variability of the Mediterranean outflow in the Strait of Gibraltar, *J. Geophys. Res.*, *112*, C10005, doi:10.1029/2006JC003992.

García-Lafuente, J., J. Delgado, A. Sánchez-Román, J. Soto, L. Carracedo, and G. Díaz del Río (2009), Interannual variability of the Mediterranean outflow observed in Espartel sill, Western Strait of Gibraltar, *J. Geophys. Res.*, *114*, C10018, doi:10.1029/2009JC005496.

Garrett, C., R. Outerbridge, and K. Thompson (1993), Interannual variability in Mediterranean heat and buoyancy fluxes, *J. Clim.*, *6*, 900–910.

Kalnay, E., et al. (1996), The NCEP/NCAR 40-year reanalysis project, *Bull. Amer. Meteor. Soc.*, *77*, 437–471.

Kanarska, Y., and V. Maderich (2008), Modelling of seasonal exchange flows through the Dardanelles Strait, *Estuarine, Coastal Shelf Sci.*, *79*, 449–458.

Liu, K. K., et al. (eds.) (2009), *Carbon and Nutrients Fluxes in Continental Margins*, Global Change–The IGBP Series, Springer, Berlin.

Margat, J. (1992), *L'Eau dans le Bassin Mediterraneen: Situation et Perspective*, Les Fascicules du Plan Bleu, No. 6, 196 pp., Economica, Paris.

Mariotti, A., N. Zeng, and K. M. Lau (2002), The hydrological cycle in the Mediterranean region and implications for the water budget of the Mediterranean Sea, *J. Clim.*, *15*, 1674–1690.

Mariotti, A. (2009), Recent changes in the Mediterranean water cycle: A pathway toward long-term regional hydroclimatic change? *J. Clim.*, *23*, 1513–1525.
Ovchinnikov, I. M. (1974), On the water balance of the Mediterranean Sea, *Oceanology*, *14*, 198–202.
Ruiz, S., D. Gomis M. G. Sotillo, and S. A. Josey (2008), Characterization of surface heat fluxes in the Mediterranean Sea from a 44-year high-resolution atmospheric data set, *Global Planet. Change*, *63*, 256–274.
Sanchez-Román, A., G. Sannino, J. García-Lafuente, A. Carillo, and F. Criado-Aldeanueva (2009), Transport estimates at the western section of the Strait of Gibraltar: A combined experimental and numerical modeling study, *J. Geophys. Res.*, *114*, C06002, doi:10.1029/2008JC005023.
Struglia, M. V., A. Mariotti, and A. Filograsso (2004), River discharge into the Mediterranean Sea: Climatology and aspect of the observed variability, *J. Clim.*, *17*, 4740–4751.
Tixeront, J. (1970), Le bilan hydrologique de la Mer Noire et de la Mer Mediterranee, *Cah. Oceanogr.*, *3*, 227–237.
Unluata, U., T. Orguz, M. A. Latif, and E. Ozsoy (1990), On the physical oceanography of the Turkish Straits, in *The Physical Oceanography of Sea Straits*, NATO ASI Series, edited by L. J. Pratt, pp. 25–60, Kluwer, Dordrecht.
Vörösmarty, C. J., B. Fekete, and B. A. Tucker (1996), River discharge Database, Version 1.0 (RivDIS v1.0), Vols 0–6, *A Contribution to IHP-V Theme 1; Technical Documents in Hydrology Series*, UNESCO, Paris.

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