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Decadal variability of net water flux at the Mediterranean Sea Gibraltar Strait

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ABSTRACT

Long-term variability of the net water flux into the Mediterranean Sea at the Gibraltar Strait over the period 1960–2009 is explored based on an approach combining multiple observational datasets and results from a regional climate model simulation. The approach includes deriving Gibraltar net inflow from the application of the Mediterranean Sea water budget equation using observationally based estimates of mass variation, evaporation, precipitation and simulated river discharge and Bosphorus Strait water fluxes. This derivation is compared with results from a simulation using the PROTHEUS regional ocean–atmosphere coupled model considering both individual water cycle terms and overall Gibraltar water flux.

Results from both methodologies point to an increase in net water flux at Gibraltar over the period 1970–2009 (0.8 +/− 0.2 mm/mo per year based on the observational approach). Simulated Gibraltar net water flux shows decadal variability during 1960–2009 including a net Gibraltar water flux decrease during 1960–1970 before the 1970–2009 increase.

Decadal variations in net evaporation at the sea-surface, such as the increase during 1970–2009, appear to drive the changes in net inflow at Gibraltar, while river runoff and net inflow at the Bosphorus Strait have a modulating effect. Mediterranean Sea mass changes are seen to be relatively small compared to water mass fluxes at the sea surface and do not show a long-term trend over 1970–2009. The Atlantic Multi-decadal Oscillation (AMO) and the North Atlantic Oscillation (NAO) are relevant indirect influences on net water flux at Gibraltar via the influence they bear on regional evaporation, precipitation and runoff.

1. Introduction

As the Mediterranean Sea is a semi-enclosed basin, connected with the open Atlantic Ocean only at the Gibraltar Strait, the fluxes of water and salt through this Strait bear a major influence on the state of the Sea with impacts on the mass, salt and energy budgets. A net water inflow at Gibraltar (G) results from incoming fresh and cool Atlantic water and outflowing warm and salty Mediterranean water. Climatologically, net inflow of water at Gibraltar primarily balances the vertical loss of water at the sea-surface (water fluxes through the Bosphorus Strait (B) and river discharge (R) also contribute to balance the surface water loss; e.g. Mariotti et al., 2002). Recent research has shown that decadal changes in net Mediterranean Sea evaporation have characterized the 1958–2006 period, with an overall increase in net evaporation resulting in a substantial increase in sea-surface water loss (Criado-Aldeanueva et al., 2010; Mariotti, 2010). An open question is whether this increased water loss has induced increases in the net water inflow at Gibraltar or whether there have been changes in Mediterranean Sea water mass. In fact, while the Mediterranean thermohaline circulation is sustained by the atmospheric forcing, its intensity is controlled by the narrow and shallow Strait of Gibraltar via hydraulic control processes (Sannino et al., 2007, 2009a). While measurements of the Mediterranean water outflow through Gibraltar have been collected over short time periods (Sanchez-Roman et al., 2009, Soto-Navarro et al., 2010), there are no long-term direct measurements of net water fluxes. Model simulations have been utilized to improve the understanding of the processes that regulate water fluxes at Gibraltar, with very high-resolution models now able to represent much of the complexity characterizing the dynamics of the Strait and simulate realistic Gibraltar flows (Sannino et al., 2009a; Sanchez-Garrido et al., 2011). It is interesting to note that a common assumption in state-of-art Mediterranean Sea models used for these studies is the "equilibrium condition" which forces the net flow at Gibraltar to strictly compensate the freshwater lost at the sea-surface (e.g. Tonani et al., 2008). Here we stress that such an assumption has still not been verified by specific observations.

Nowadays, changes in Mediterranean Sea mass are directly measured by the satellite gravimetric mission GRACE. These measurements, available over the interval 2002–2010, are usually expressed in terms of changes in equivalent water thickness, i.e. water mass

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changes per surface area (with 1 mm water column corresponding to 1 kg/m^2 if a density of 1 g/cm^3 is assumed). Mediterranean Sea water mass change values may also be derived from sea level change, provided the steric component of the sea level change can be estimated. In this case the water mass change is directly expressed as water thickness (volume). Recent studies have compared indirect estimates of Mediterranean Sea water mass derived from sea-level by way of steric-corrected satellite altimetry with those based on GRACE satellite mass retrievals. Results indicate a good agreement and a Mediterranean Sea mass increase during the last decade (Calafat et al., 2010; Fenoglio-Marc et al., 2012b).

Mediterranean sea level variability has been shown to be affected by the variability of the North Atlantic Oscillation (NAO; Hurrell et al., 2003) mainly through the impact of atmospheric sea-level pressure changes (Tsimplis and Josey, 2001). Although these results collectively suggest long-term variations in Mediterranean Sea mass and sea-level, and large-scale atmospheric influences, to our knowledge how long-term changes in fresh water fluxes may have affected Gibraltar water fluxes is yet to be explored. The level of accuracy of the satellite-based measurements calls for a re-examination of many conventional approximations often taken for granted (Greatbatch and Lu, 2001).

The goal of this work is to study the decadal variations in net water flux at the Strait of Gibraltar over the period 1960–2009 based on a combined observational-modelling approach and to indirectly explore the correctness of the "equilibrium condition" assumption made in state-of-art models. First, Gibraltar water flux is derived indirectly from the water budget equation based on observational estimates of Mediterranean Sea mass changes (from steric-corrected sea-level estimates and GRACE mass retrievals), regional precipitation and evaporation. Next, an independent estimate of the Gibraltar water flux is obtained from a numerical simulation by a regional ocean–atmosphere climate model. Lastly, potentially important factors regulating long-term Gibraltar flux changes are discussed. The paper is organized as follows: overall data and methodology are described in Section 2; results pertaining Mediterranean Sea mass and Gibraltar water flux variability are presented in Section 3; conclusions are in Section 4.

2. Methodology and data

The net water inflow through Gibraltar (G), may be estimated on the basis of the water budget equation for the Mediterranean Sea:

$$G = E–(P + R + B) + \partial M/\partial t \quad (1)$$

with E being sea-surface evaporation, P precipitation over the sea; R river discharge into the sea from the Mediterranean catchment; B net water influx from the Black Sea at the Bosphorus Strait; ∂M/∂t the rate of Mediterranean Sea water mass (M) change (see also Fenoglio-Marc et al., 2012b; Grayek et al., 2010). (Note that changes in Mediterranean Sea mass due to salinity changes are not accounted for in this water budget equation). As all quantities in Eq. (1) represent a volume variation, they can be expressed as basin-uniform sea level change in units of mm/mo, We apply Eq. (1) to derive G based on observational estimates of ∂M/∂t, E and P. ∂M/∂t may be derived as the difference of water mass-induced sea level averaged over the sea (S_{mass}) at two following time-steps (Fenoglio-Marc et al. (2007)), as well as estimated from GRACE gravity solutions. In contrast, the independent results from the model simulation are based on the model's assumption, so it is interesting to see how these results compare with the observational estimate of G and whether they can contribute to a qualitative description of long-term variability in Gibraltar water fluxes.

All the quantities in Eq. (1) are estimated indirectly (as explained in the following) and it is clearly a challenge to define long-term changes and uncertainties of any of these quantities, let alone the resulting G estimate. Nevertheless, we attempt to estimate errors of annual mass-induced sea level S_{mass} and derivated quantities, namely ∂M/∂t and G. These error estimates are based on either the root mean square (RMS) difference between the various datasets available for a given quantity, or on error propagation considering the various components contributing to a given estimated quantity (see Table 1 for a summary of data used in this study; Tables 2–5 for associated error estimates). The first method reflects the spread of the datasets, but unknown systematic errors may remain. We account for the temporal autocorrelation of a time series, by using its effective sample size based on the lag-1 autocorrelation coefficient (Santer et al., 2000). The correlation between time-series and its double-sided significance are evaluated. Linear regression is used to estimate the linear trend and its error. We further assess the trend significance by applying the t-test to the ratio between the estimated trend and its error (Fenoglio-Marc et al., 2011). In the error propagation we consider the components to be uncorrelated (Fenoglio-Marc et al., 2006, 2012b).

2.1. Mediterranean Sea water mass derivation

During August 2002–December 2009, Mediterranean water mass-induced sea level (S_{mass}) may be estimated directly from satellite-based gravity observations retrieved by the GRACE satellite mission (S^g_{mass} hereafter; Flechtner, 2007; Fenoglio-Marc et al., 2006). Note that since GRACE measures gravity, a priori mass changes detected by GRACE include both the effect of water and salt changes. Over the longer 1970–2009 period, S_{mass} may be also estimated indirectly from Eq. (2), by correcting the total sea level (S_{tot}) for its steric component (S_{ster}) so as to account only for water mass induced sea-level (S_{mass}):

$$S_{mass} = S_{tot} - S_{ster} \quad (2)$$

During 1993–2009, S_{tot} is evaluated from satellite altimetry data (S^{alti}_{tot}). For this derivation we have used along-track data of the Topex/Poseidon, Jason-1, Jason-2 and Envisat altimetry missions from the RADS database (Naeije et al., 2008) and applied the conventional geophysical corrections accounting for the ocean response to atmospheric wind and pressure forcing (atmospheric loading on the sea surface) via the Dynamic Atmospheric Correction (DAC). Grids of 0.5 degrees have been computed and used to evaluate the sea level basin average. Prior to the altimetry era, starting from 1970 S_{tot} is derived based on a reconstruction developed by Meyssignac et al. (2011) (hereafter MBMED11). Comparing the MBMED11 basin averaged reconstruction (S^{reco}_{tot}) with a

Table 1
List of data. For the seven fields used in this study : temperature (T), salinity (S), sea level (S_{tot}), mass-induced sea level (S_{mass}), evaporation (E), precipitation (P), sea level pressure (SLP) the name of the database together with its time interval, spatial and temporal resolutions are given. For the T and S fields the maximum depth and the number of levels are given in addition.

Database name	Field	Time interval	Grid	Depth (m)	Levels	Time sampling
Medar/Medatlas	T, S	1945–2002	0.2°×0.2°	4000	25	1 yr
Ishii v6.7	T, S	1945–2006	1°×1°	700	16	30 days
MFSTEP/ICBM	T, S	2000–2009	1°×1°	3850	31	30 days
GRACE	$S_{mass,}$	2002–2009	300 km			30 days
altimetry	S_{tot}	1993–2009	0.5°×0.5°			30 days
MBMED11	S_{tot}	1970–2009	0.5°×0.5°			30 days
Protheus	E	1958–2001	30 km			30 days
OAFLUX	E	1958–2009	1°×1°			30 days
Protheus	P	1958–2001	30 km			30 days
GPCP	P	1979–2009	2.5°×2.5°			30 days
REOFS	P	1960–2009	5°×5°			30 days
HadSLP	SLP	1960–2009	5°×5°			30 days