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Inter-annual variability and long term predictability of exchanges through the Strait of Gibraltar

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ABSTRACT

Inter-annual variability of calculated barotropic (*netflow*) and simulated baroclinic (*inflow* and *outflow*) exchanges through the Strait of Gibraltar is analyzed and their response to the main modes of atmospheric variability is investigated. Time series of the outflow obtained by high resolution simulations and estimated from *in-situ* Acoustic Doppler Current Profiler (ADCP) current measurements are compared. The time coefficients (TC) of the leading empirical orthogonal function (EOF) modes that describe zonal atmospheric circulation in the vicinity of the Strait (1st and 3rd of Sea-Level Pressure (SLP) and 1st of the wind) show significant covariance with the inflow and outflow. Based on these analyses, a regression model between these SLP TCs and outflow of the Mediterranean Water was developed. This regression outflow time series was compared with estimates based on current meter observations and the predictability and reconstruction of past exchange variability based on atmospheric pressure fields are discussed. The simple regression model seems to reproduce the outflow evolution fairly reasonably, with the exception of the year 2008, which is apparently anomalous without available physical explanation yet.

The exchange time series show a reduced inter-annual variability (less than 1%, 2.6% and 3.1% of total 2-day variability, for netflow, inflow and outflow, respectively). From a statistical point of view no clear long-term tendencies were revealed. Anomalously high baroclinic fluxes are reported for the years of 2000–2001 that are coincident with strong impact on the Alboran Sea ecosystem. The origin of the anomalous flow is associated with a strong negative anomaly (~−9 hPa) in atmospheric pressure fields settled north of Iberian Peninsula and extending over the central Atlantic, favoring an increased zonal circulation in winter 2000/2001. These low pressure fields forced intense and durable westerly winds in the Gulf of Cadiz–Alboran system. The signal of this anomaly is also seen in time coefficients of the most significant EOF modes.

The predictability of the exchanges for future climate is discussed.

1. Introduction

On subinertial time-scales, the netflow through the Strait of Gibraltar (Q_t) is a response to various processes occurring within the Mediterranean Sea basin: evaporation (*E*), precipitation (*P*), river discharge (*R*), and sea level atmospheric pressure (*SLP*) fluctuation. The first three components in the form of *E-P-R* is the so called "*net evaporation*" (Bryden et al., 1994) that drives the netflow through the Strait on seasonal to inter-annual time-scales. On shorter periods (from a few days to a few months) the flow is mainly forced by atmospheric pressure fluctuations (*e.g.*, Candela et al., 1989; Candela, 1991; García-Lafuente et al., 2002b). The flux through the Dardanelles Strait connecting the Mediterranean basin with the Black Sea is an additional variable of the Mediterranean Sea mass (volume) balance equation. Although its annual mean (Kanarska and Maderich, 2008) is on the order of the river contribution, nevertheless it was not considered because its seasonal cycle is not well defined yet (*i.e.*, simulated cycle exists, but observational one is not established).

This large dependency of the netflow on external (atmospheric) variables enables its study on long time-scales based on atmospheric data and reanalysis, as well as its prediction for future climate scenarios. Estimates of mean netflow and of its longer term variability based on different methods are presented in the literature: long term current and salinity observations in the Strait (Bryden et al., 1994), hydrological balance of the Mediterranean Sea (*e.g.*, Mariotti et al., 2002; Soto-Navarro et al., 2010), hydrological balance and sea level variations from altimetry measurements (Fenoglio-Marc et al., 2006), using Mediterranean Sea level only (Gomis et al., 2006). The latter study was also used for netflow reconstruction since 1659.

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However, the netflow on longer time-scales is just a small part of the baroclinic exchanges through the Strait. The large density difference between the Mediterranean and the Atlantic basins drives a baroclinic exchange with an inflow (Q_i) in the upper layer and an outflow in depth (Q_o) with magnitudes of the order of 0.8 Sv (1 Sv = 10^6 m^3/s) about one order of magnitude — up to 20 times larger than the netflow estimates (*e.g.*, Bryden et al., 1994; Soto-Navarro et al., 2010; García-Lafuente et al., 2011).

This baroclinic exchange, on the other hand, is extremely difficult to measure and estimate, and the number of longer term studies is very small (Kinder and Bryden, 1987; Candela, 2001; García-Lafuente et al., 2002a; Sánchez-Román et al., 2009; Soto-Navarro et al., 2010).

In this study we analyze a 20-year estimate of low-frequency (at inter-annual scales) baroclinic and barotropic exchanges. Barotropic flow was calculated based on the "*net evaporation*" of the Mediterranean Sea and forced by atmospheric pressure fluctuations over the Sea using the analytical model of Candela (Candela, 1991). Baroclinic exchanges were obtained with high resolution (grid size of about 2 km with 32 σ-levels) numerical simulations using the Regional Oceanic Modeling System (ROMS, Shchepetkin and McWilliams, 2005). The model was forced with the Weather Research and Forecasting (WRF) simulations with a spatial resolution of about 9 km. The detailed description of how the original time series were produced, and their seasonal cycle is presented in Peliz et al. (2013). WRF simulations are described in Soares et al. (2012).

The main objectives are to understand the inter-annual changes in the inflow/outflow transports and their link to the main modes of regional atmospheric variability, to explain the main anomalies (like the "*2001 Anomaly*", see *e.g.*, Ruiz et al., 2013) and investigate the predictability of such anomalous events in particular, and exchanges through the Strait in general.

The paper is organized as follows. First, we give a brief description of the data used. Then, we analyze the inter-annual variability of exchanges based on Peliz et al. (2013) results. This part starts by describing the input for the model: netflow and their main contributors (evaporation, precipitation, SLP); after that, the analysis of model outputs (inflow and outflow) is presented. For the latter we have observational results, so both outflows are compared using a simple statistic. Then we analyze the variability of the forcing winds and SLPs based on EOF decomposition. Finally, we compare the exchange evolution with the time coefficients (TCs) of the main driving factors and analyze predictability of the flows through the Strait of Gibraltar.

2. Data and methods

2.1. Exchange data

2.1.1. Netflow

The netflow (Q_t, Fig. 1) through the Strait of Gibraltar in simulations of Peliz et al. (2013) was calculated based on "*net evaporation*" (assuming equilibrium condition, *i.e.*, volume conservation) and forced by atmospheric pressure fluctuations over the Mediterranean Sea using the analytical model of Candela (1991). As it was stated in the previous section, the exchange with the Black Sea was neglected. The final form of the equation is $Q_t = Q_{E\text{-}P} - Q_R + Q_{SLP}$, where $Q_{E\text{-}P} = -(E - P)$ is a flow due to *E-P* balance, Q_R — river discharge and Q_{SLP} is a barotropic flow in the Strait due to atmospheric pressure fluctuations. The validity of the equilibrium condition is discussed in Section 4.

The netflow was calculated using ERA (*Extended ReAnalysis*)-Interim data (Dee et al., 2011) produced by the European Centre for Medium-Range Weather Forecasts (ECMWF): evaporation and precipitation (3 h accumulated fields), instantaneous SLP fields over the Mediterranean Sea (6 h interval on a spatial grid of 1.5° × 1.5°); and the river contributions from Struglia et al. (2004). Over the Mediterranean Sea SLP fields were used to calculate barotropic fluxes through the Strait due to atmospheric pressure fluctuations. For the river input component

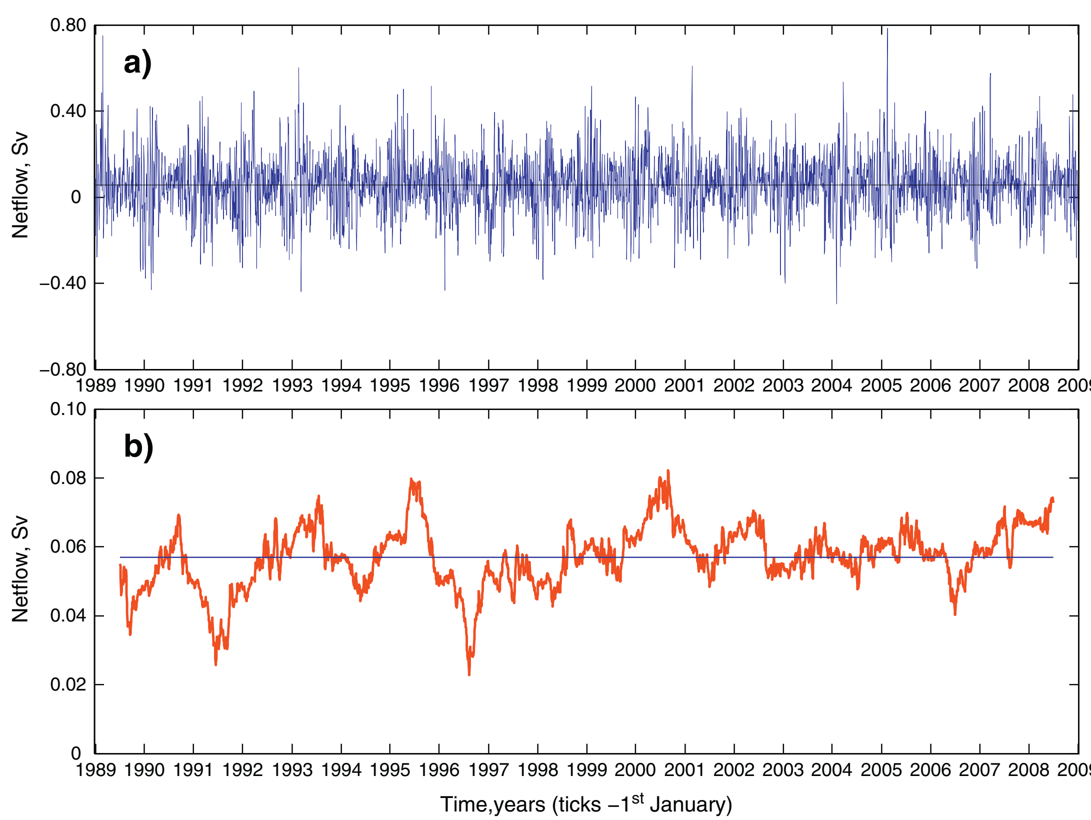

Fig. 1. Time series of the netflow through the Strait of Gibraltar: a) 2-day averaged (blue) and its mean value (black), b) one-year running averaged (red), and its mean value (blue).