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Climatic forcing on hydrography of a Mediterranean bay (Alfacs Bay)

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ABSTRACT

Time series of meteorological and hydrographic variables were analyzed using Huang's Empirical Mode Decomposition (EMD) to ascertain the relationships among climatic forcings and the hydrographic behavior in an estuarine bay. The EMD method allowed us to separate the different characteristic oscillation patterns (or modes) of a 14 year-long time series of weekly hydrographic (water temperature and salinity) and meteorological (air temperature, pressure, wind and precipitation) data from Alfacs Bay (Ebre delta, NW Mediterranean). In order to explore the relations between couples of oscillation modes from different series, we developed a correlation index based on the phase differences between these modes. Common characteristic modes in the studied series are a seasonal pattern and an inter-annual oscillation. The comparison between series of meteorological and hydrographic variables shows significant correlations of two modes (of 1 year and 2–3 year periods, respectively) of water temperature with the corresponding two modes of air temperature and air pressure. There were also significant positive correlations between wind speed and water temperature. The use of EMD allowed to discover a strong connection between stratification and the use of irrigation channels in the bay; in addition, with the help of this method we can propose a common meteorological forcing mechanism for the observed patterns of variability. Those findings would have been impossible to guess by use of classical Fourier methods, and gives a demonstration of the power of EMD in climatic series analysis.

1. Introduction

The Alfacs Bay is a semi-enclosed estuary placed at the South of the Ebre river delta (NW of Mediterranean Sea 40°40′N, 0°40′E, Fig. 1). The bay is separated from the Mediterranean Sea by a 5 km long, 300 m wide sand barrier that leaves a 2500 m wide opening between the bay and the open sea (Camp, 1994). Several irrigation channels discharge into the bay, which does not directly receive river water. The total area of Alfacs Bay is about $49 \times 10^6\,m^2$ with a mean depth of 3.13 m; the maximum depth is 6.5 m at the center of the bay. This geometry encloses a total volume of water of $153 \times 10^6\,m^3$.

Alfacs Bay is not only of scientific interest from the physical and ecological points of view, but is also very important for the economy of the region due to its fish and shellfish aquaculture. Studies on the ecology of the bay have been published by Camp (1994), Vidal and Morgui (1995), Vidal et al. (1997), Garces et al. (1997, 1999) and Vila et al. (2001). However, information on the temporal patterns of variability of the physical environment in Alfacs Bay is scarce.

Due to the low impact of tidal forcing, factors like temperature or salinity differences are relatively more important in Mediterranean bays than in other places with larger tidal amplitudes (Weisberg and Zheng, 2006; Li et al., 2005; Gutierrez et al., 2006). Based on short-term hydrographic surveys, two basic states have been proposed as characteristic of the estuarine system of Alfacs Bay (Camp and Delgado, 1987; Camp, 1994). One, a transient state lasting for a short period (2–5 days), usually subsequent to storm events that destroy the estuarine dynamics and mix the water column. The other, a steady state, present during almost all the year, with the typical hydrodynamics of a slightly stratified estuary. In turn, the steady state presents two main periods controlled by the discharge of the irrigation channels, an 'open channel' period (more stratified water column) and a 'closed channel' one (less stratified water column). Here we analyze the physical variability of Alfacs bay, based on 14 year-long weekly time series of meteorological and hydrographical variables.

Our objectives are first, to assess the temporal variability patterns of the meteorological and hydrographical variables considered here and second, to test the hypothesis that meteorological forcing influences hydrographic properties of the bay

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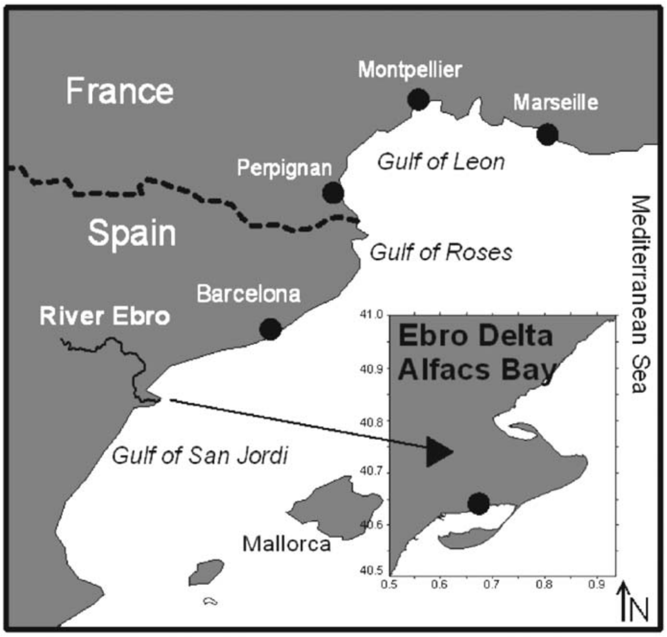

Fig. 1. Situation and geometry of Alfacs bay (From Garcés).

waters. A possible approach to these goals implies the analysis of the time series of the studied variables and the explicit decomposition of these series as a sum of oscillating modes. Although it does not give causal evidence, similarity among particular oscillation modes from two different variables may suggest either a mechanistic relationship between these variables or a common response to physical forcing acting upon both of them. In this context, the classical Fourier transform method does not work well, mainly due to the requirement of stationarity, with the difficulty of effectively filtering out the trend component of the signal, and to the requirement of time-independent frequencies. What is needed is a processing method able to mark the starting and finishing instants of non-periodic events in an objective way, so that these events can be clearly separated from the periods in which the system presents a stationary 'mean' behavior. In addition, the method should resolve oscillatory patterns of different frequencies in a flexible way, allowing these frequencies to evolve with time. Thus it should provide an instantaneous frequency associated with each time point.

Empirical Mode Decomposition (EMD) (Huang et al., 1998, 2003; Wu and Huang, 2004), an objective method recently devised to study time series, satisfies the requirements formulated above. The EMD method produces a linear decomposition of a series in a number of non-linear modes of time-depending frequency, called Intrinsic Mode Functions (IMF), within an objectively defined frequency range. The method is based on the time scale dependent local variability of the data, giving a precise meaning to local frequencies and removing spurious harmonics (typical in Fourier analysis, Bloomfield, 2000), in order to represent non-linear and non-stationary signals (Coughlin and Tung, 2004). In this paper, we will apply the EMD method to the series of hydrographical and meteorological variables of Alfacs Bay. We will use an amplitude-based threshold and the Hilbert–Huang spectrum (HHS) of each variable (Huang et al., 1998) to ascertain the relative importance of its oscillating modes. The relations among the main IMFs coming from the different series will be studied in order to decide which IMFs appear to be specific to a given variable and which ones appear in several of them and can be interpreted in terms of a common underlying physical cause (such as seasonal patterns or longer-term climatic oscillations). Finally, we will discuss the results.

2. Materials and methods

The IMFs obtained by the EMD method represent partial Hilbert transforms of the signal and possess properties such as smoothness in both frequency and amplitude modulation (Huang et al., 1998). The essence of the method is to empirically identify oscillatory modes in the data by means of their local extrema. The decomposition is based on three assumptions (Huang et al., 1998, 2003; Wu and Huang, 2004): (1) the signal has at least two extrema—one maximum and one minimum; (2) the characteristic local time scale is defined by the time interval between two consecutive extrema; and (3) if the data are totally free of extrema but contain only inflection points, then the characteristic local time scales can be obtained by the integration of the components. To obtain a valid IMF an iterative process called sifting (Huang et al., 1998) is applied. This iterative process works as follows: after obtaining the extrema of the signal, two envelopes for these extrema (one for maxima and other for minima) are defined using spline interpolation (upper and lower envelopes). The mean of the two envelopes is denoted by m_1, and the difference between the data and m_1 is the first oscillatory component, c_1, i.e.: $X(t) - m_1 = c_1$. By repeating this process i times (obtaining the new envelopes and their mean, and then subtracting it from the data) we obtain c_i. The iterative process will stop according two criteria reported in Huang et al. (1998, 2003) and the resulting decomposition is the EMD.

Some applications of the EMD method are reported in Huang et al. (2003), Wu and Huang (2004) and Flandrin et al. (2004). Recently the EMD method has been employed for many different datasets such as cardiorespiratory synchronization (Wu and Hu, 2006), ozone records (Jánosi and Müller, 2006), precipitation variability related with El Niño (El-Askary et al., 2004), analysis of North Atlantic oscillation (Hu and Wu, 2004), analysis of solar insolation (Lin and Wang, 2006), space-time rainfall analysis (Sinclair and Pegram, 2005), ice-cover analysis (Gloersen and Huang, 2003), and analysis of temperature under global warming (Molla et al., 2006). For this work we have used a MatLab implementation of the algorithm, provided by Patrick Flandrin and collaborators (Rilling et al., 2003). The code can be retrieved at the following URL: http://perso.ens-lyon.fr/patrick.flandrin/emd.html. A new application of the EMD method to compare two time series using the phase differences between their respective modes will be developed in this paper.

The hydrographic series under study are surface and bottom (1 and 5 m depth) water temperature and salinity (Figs. 2a and b), sampled weekly at the central point of the bay between 1990 and 2004, and an associated stratification index, defined as the Brunt–Väisäla frequency (Fig. 2c). The meteorological data included weekly air temperature and barometric pressure (Figs. 3a and b), obtained between 1990 and 2004 at the Roquetes (Tortosa) station of the National Institute of Meteorology, distant 10 km from the bay, and weekly wind (Figs. 3c and d) and precipitation anomaly (which is the cumulative sum of the precipitation data once the mean precipitation is subtracted, Fig. 3e) measured between 1994 and 2004 at the St. Carles meteorological station (MeteoCat), placed on the North coast of Alfacs Bay. We used also stratospheric temperature data from the ERA-40 Re-Analysis Atlas of the European Centre for Medium-Range Weather Forecasts