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Thermocline characterisation in the Cariaco basin: A modelling study of the thermocline annual variation and its relation with winds and chlorophyll-a concentration

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ABSTRACT

The spatial and temporal evolution of the thermocline depth and width of the Cariaco basin (Venezuela) is analysed by means of a three-dimensional hydrodynamic model. The thermocline depth and width are determined through the fitting of model temperature profiles to a sigmoid function. The use of whole profiles for the fitting allows for a robust estimation of the thermocline characteristics, mainly width and depth. The fitting method is compared to the maximum gradient approach, and it is shown that, under some circumstances, the method presented in this work leads to a better characterisation of the thermocline. After assessing, through comparison with independent in situ data, the model capabilities to reproduce the Cariaco basin thermocline, the seasonal variability of this variable is analysed, and the relationship between the annual cycle of the thermocline depth, the wind field and the distribution of chlorophyll-a concentration in the basin is studied. The interior of the basin reacts to easterly winds intensification with a rising of the thermocline, resulting in a coastal upwelling response, with the consequent increase in chlorophyll-a concentration. Outside the Cariaco basin, where an open ocean, oligothrophic regime predominates, wind intensification increases mixing of the surface layers and induces therefore a deepening of the thermocline. The seasonal cycle of the thermocline variability in the Cariaco basin is therefore related to changes in the wind field. At shorter time scales (i.e. days), it is shown that other processes, such as the influence of the meandering Caribbean current, can also influence the thermocline variability. The model thermocline depth is shown to be in good agreement with the two main ventilation events that took place in the basin during the period of the simulation.

1. Introduction

The depth of the thermocline is crucial when modelling the physics of the ocean, as it largely affects the heat transfer between the ocean and the atmosphere, as well as the heat transfer between the ocean surface and deeper layers (Gill, 1982; Alexander et al., 2000). The thermocline positioning also affects the biological characteristics of the ocean such as the primary production (e.g. Muller-Karger et al., 1989; Di Lorenzo et al., 2005); it often determines the depth range at which nutrients are found, and the presence or not of phytoplankton, by establishing the separation between the warmer surface layer from deeper, cooler and nutrient-rich waters below the thermocline (Valiela, 1995). A correct characterisation of the thermocline is necessary for an accurate modellisation of the upper ocean dynamics and, in the case of coupled models, for a proper characterisation of the biomass and its location in the water column (Soetaert et al., 2001).

Upwelling-favorable winds over the coastal ocean result in a rising of isotherms, bringing the subsurface nutrient-rich waters to the surface, and inducing an increase of primary production in the surface layers, and hence of chlorophyll-a concentration. Situated in the Caribbean Sea, the Cariaco basin is affected by Trade winds and an upwelling is observed from November to May each year (Muller-Karger et al., 1989; Astor et al., 2003). In addition, rising isotherms outside of the basin might bring subsurface oxygenated water from the Caribbean Sea into the anoxic basin, because of its characteristic topography (Astor et al., 2003). A combination of in situ data, remote-sensing data and a numerical hydrodynamic model is used in this work to study the thermocline depth evolution inside and outside the Cariaco basin, and the relation of this variable with winds and chlorophyll-a concentration. The aim is to better understand how these variables are related and how the Cariaco basin is affected by the thermocline depth variability.

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A reliable method to calculate the thermocline depth in both the in situ data and the hydrodynamic model is needed. In addition, the accuracy of the hydrodynamic model in the representation of the thermocline depth needs to be assessed.

There are a number of works dealing with the calculation of the mixed layer depth. The mixed layer lies above the oceanic thermocline layer, and it is uniformly mixed due to the action of winds and solar heating. For example, Kara et al. (2000) use a threshold method in which a given increment in the temperature or density profile is identified as the position of the bottom of the mixed layer. Thomson and Fine (2003) use a split-and-merge method that approximates a specified curve using piecewise polynomial functions to find breakpoints that indicate the location of the mixed layer depth. Soetaert et al. (2001) use a fitting to a two-layer model to find the mixed layer depth in density and nitrate profiles.

On the other hand, this work describes a new technique to calculate the depth of the thermocline. Some works have previously dealt with this problem. For example, Palacios et al. (2004) and Kim and Miller (2007) use the maximum vertical temperature gradient to identify the depth of the thermocline. In this work we propose an alternative method to extract the depth and width of the thermocline from observed and modelled temperature profiles. Our approach consists in fitting individual temperature profiles to sigmoid curves, in a least-square approach. This method is similar to the one used by Steyn et al. (1999) to determine the height of the atmospheric entrainment zone (a concept equivalent to the thermocline in the ocean), and it provides not only the depth of the thermocline but also the width of this layer. The width of the thermocline layer gives information on the steepness of the temperature gradient, which in turn indicates the availability of tracers like nutrients from the subsurface layers.

Once the thermocline depth and width are known, the error between model and observations can be then analysed separately for various components: the error in the positioning of the thermocline, the error of the temperature at the thermocline depth and finally an error of the thermocline layer width. These three error measures provide information on the amount of mixing induced by the model and the transfer of heat through the surface and subsurface water layers. This information can be a useful feedback for model calibration processes: an error in the depth of the thermocline directly affects the heat transfer in the upper layers of the ocean and the atmosphere; an error in the thermocline width will have an impact in the heat transfer among surface and deeper layers, and can also affect species concentration and vertical migration in coupled biological models; finally, an error in the temperature of the thermocline might as well indicate that the heat transfer from the surface is too high, or that an overall bias is present in the model.

This work is organised as follows: the domain of study, data and numerical model used on this work are described in Section 2. Section 3 introduces the fitting method for temperature profiles and compares its accuracy with the maximum-gradient method. The model thermocline error analysis is shown in Section 4. A study of the annual variation of the thermocline depth in the Cariaco basin and its relation to wind intensity and chlorophyll-a concentration is presented in Section 5, along with a study of the ventilation events observed in the basin. The conclusions of this paper are presented in Section 6.

2. Materials

2.1. Study area

The Cariaco basin is a semi-enclosed area off the coast of Venezuela. Two shallow passages (the Centinela channel to the west and the Tortuga channel to the northeast) connect the upper 150 m of the basin to the open ocean. The basin interior, with a maximum depth of 1400 m, is therefore completely isolated from the open ocean, and the ventilation of the basin waters is done only through the upper layers. Waters deeper than 250 m are anoxic in the Cariaco basin, with very limited changes in temperature, salinity and other properties (Astor et al., 2003). A detailed description of the basin hydrography can be found in, e.g. Muller-Karger et al. (2001), Astor et al. (2003), Alvera-Azcárate et al. (2009a), Muller-Karger et al. (2010). Accurate modelling of the surface waters that connect the Cariaco basin with the open ocean is very important in order to correctly simulate the temperature, salinity and currents in the basin's interior. Moreover, a correct characterisation of the thermocline width and depth will determine if the ventilation of the basin is accurately represented by a model (i.e. if water of Caribbean origin is able to enter into the Cariaco basin). The results from a hydrodynamic model of the Cariaco basin described in Alvera-Azcárate et al. (2009a) are analysed in this work.

2.2. In situ and satellite data

A series of 35 CTD casts were taken between 15 and 19 March 2004 in the eastern part of the Cariaco basin (Fig. 1), in the framework of the carbon retention in a colored ocean (CARIACO) time series program (Muller-Karger et al., 2010). These CTD profiles are used in this work to asses the ability of a hydrodynamic model of the Cariaco basin (Alvera-Azcárate et al., 2009a) to reproduce the thermocline depth and width. The hydrodynamic model was validated in Alvera-Azcárate et al. (2009a), but no analysis of the thermocline depth was done. The CTD data available for this work are averages over 19 depth levels, with a refinement in the surface layer (11 out of the 19 depth levels are concentrated at the top 200 m of the water column). Data from monthly cruises made during 2004 at the CARIACO station ([10.5°N; 64.68°W], see location in Fig. 1) are also used. In particular, temperature and continuous dissolved oxygen profiles are used. Details on the processing of these data can be found in Astor et al. (2003). All in situ data were realised aboard the R/V Hermano Ginés, from the Fundación La Salle de Ciencias Naturales of Venezuela, and have been accessed through the project website, http://www.imars.usf.edu/CAR/.

Satellite chlorophyll-a concentration data are also used in this work. The data are obtained from the sea-viewing wide field-of-view sensor (SeaWiFS), on board the SeaStar spacecraft (http://oceancolor.gsfc.nasa.gov/), with a spatial resolution of about 11 km in the study zone. The data are 8-day composites and contain a small percentage of clouds (about 22%) that have been removed using DINEOF (data interpolating empirical orthogonal functions), an EOF-based technique to reconstruct missing data (Beckers and

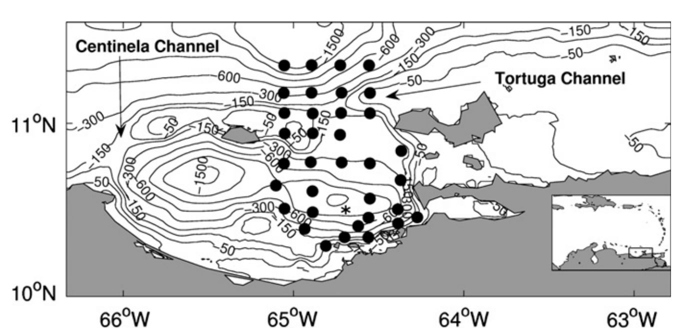

Fig. 1. The Cariaco basin. Contours show the bathymetry, and the circles show the position of the 35 CTD profiles measured in March 2004. The asterisk shows the location of the CARIACO station. The small insert map shows the location of the Cariaco basin in the Caribbean Sea.