Modelling the hydrodynamics and water quality of Madeira Island (Portugal)

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The Madeira archipelago is located in the mid-Atlantic Ocean, off the northwest coast of Africa and north of the Canary Islands (Fig. 1), between latitudes 32°22'20" and 33°7'50" and longitudes 16°16'30"W and 17°16'38"W. It is one of the autonomous regions of Portugal and an outermost region of the European Union which is distinguished by its low population density and distance from mainland Europe. Madeira is the largest (741 km^2) and most populated (~350,000 habitants) island of the archipelago. Despite its prime location, with important ecological and fishery resources, local coastal dynamics off Madeira have been little studied. Porto Santo Island is also populated (~3,000 habitants) whereas the Desertas Islands are unpopulated natural reserves.

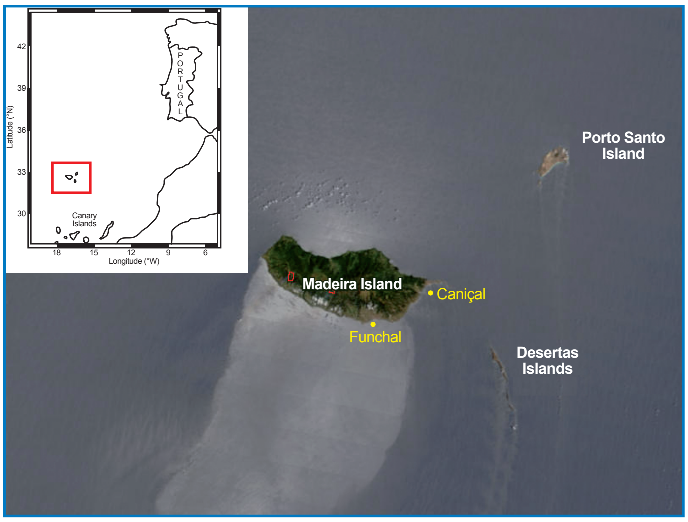

Figure 1. Satellite image of the Madeira Archipelago showing the different islands where an island wake can be observed. The location of the two IH buoys used for validation is shown in yellow (source: NASA/GSFC, MODIS Rapid Response).

The meteorological conditions in this region are mainly determined by the Azores subtropical high pressure system, responsible for the northwest trade winds (IH, 1979) with average speed values of around 20 km h^{-1}. The island topography affects the local winds due to the island mass effect, where the sheltered areas downwind result in a less mixed water column. Also the submarine oceanic crest that connects the Madeira Island to the Desertas Islands, less than 200 m deep is an obstacle to the general circulation and provokes the upwelling of colder nutrient rich waters (Fig. 5).

In the assessment of the impact of urban waste water discharges through submarine outfalls in the south coast of Madeira Island, a monitoring programme was designed that includes field surveys and modelling work, intended to explain the processes that determine water quality in these coastal waters. This study introduces some of the oceanographic features that illustrate the island mass effect phenomena and its potential importance to the increase in local biological productivity.

The sampling programme included monthly campaigns at eight stations located on the south coast of the island, in the area of influence of the submarine outfalls discharges. In each station Secchi depth was measured and vertical profiles of temperature, salinity, pH, oxygen, chlorophyll and turbidity were obtained using a YSI 6600 multi-parameter water quality sonde. Also, surface water samples were collected for determination of nutrient concentrations (nitrate, nitrite, ammonia, total nitrogen, phosphate and total phosphorus), chlorophyll, dissolved oxygen, total suspended matter, particulate organic carbon and microbiological parameters (coliforms, thermotolerant coliforms, *Escherichia coli* and *Enterococcus*). Microbiological parameters, nutrients and chlorophyll were also determined at 20 and 40 m depth. The main goal of these surveys was to characterise the environment in terms of faecal pollution and primary production, and to provide data for the model validation.

The mathematical modelling was based on a system of models, with the Mohid numerical system (Braunschweig *et al.*, 2003; http://www.mohid.com), developed at the Technical University of Lisbon, at the core. This model was used to simulate the 3D hydrodynamical and ecological processes for the period between November 2008 and October 2009. The model received local atmospheric conditions (air temperature, wind speed and direction, relative humidity, etc.) from Weather Research and Forecasting (WRF) model simulations (http://www.wrf-model.org/), salinity, temperature and hydrodynamical boundary and initial conditions from the Mercator Ocean model (Drillet *et al.*, 2005), climatological vertical distribution of oxygen and nutrients from the World Ocean Atlas 2005 (Garcia *et al.*, 2006a,b) and tidal forcing in the open boundary from the global tide model FES2004 (Lyard *et al.*, 2006).

Two different sources of bathymetry were combined: the Hydrographic Institute (IH) bathymetric survey of the southern coast of the Madeira Island performed between 2002 and 2007 which includes depths of up to 150 m (IH technical report REL.TF.GM.02/03) and the 30 second resolution global topography data from the NASA Shuttle Radar Topography Mission (Becker *et al.*, 2009), four nested grids were designed with a downscaling approach (Fig. 2). The top level grid was forced with tide dynamics and the rest of the forcing was added in the second level, the following levels received the boundary conditions from its respective superior level.

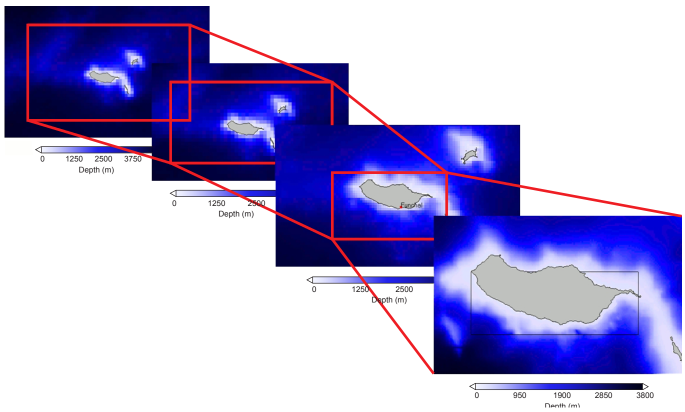

Figure 2. System of nested grids used for simulating the hydrodynamics and ecology of the Madeira Island.

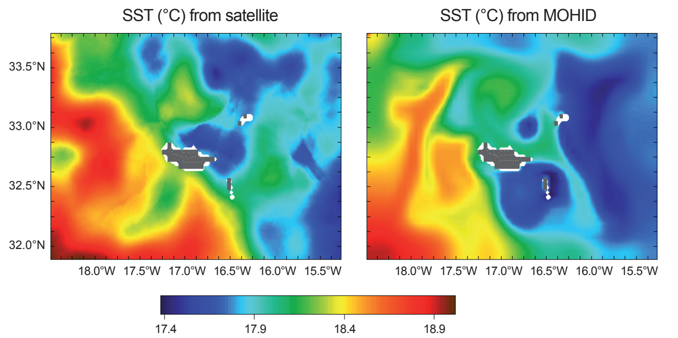

Figure 3. Surficial temperature on 27 December 2008 observed by satellite (left) and through modelling with Mohid (right) in its second nested level.

Several datasets were used to validate the hydrodynamic models. These included water level time series provided by the Ports Authority of Madeira Ltd, surficial temperatures observed by the IH buoys in Funchal and Caniçal (Fig. 1), vertical profiles observed by the Argos buoy system (http://www.argos-system.org/) and satellite observations of the horizontal variability (Fig. 3). Only some relevant validation results will be shown due to the limitation of this communication. The two stations Funchal and Caniçal also served as reference sites for comparing model results and field observations.

As was described through satellite imagery by Caldeira and Lekou (2000) and Caldeira *et al*. (2002), the island effect creates a series of meso-scale phenomena that can be observed at the water surface. The creation of island wakes on the downwind sheltered areas can be highlighted. These consist of warmer water masses with differences that can reach 3°C, and eddies or fronts and upwelling of cold waters with high primary production around the island. These phenomena can be distinguished from the satellite images as in Figure 1 where an island wake is present or in Figure 3 where a temperature front with NW-SE orientation both in the model and the remote sensing observations can be observed.

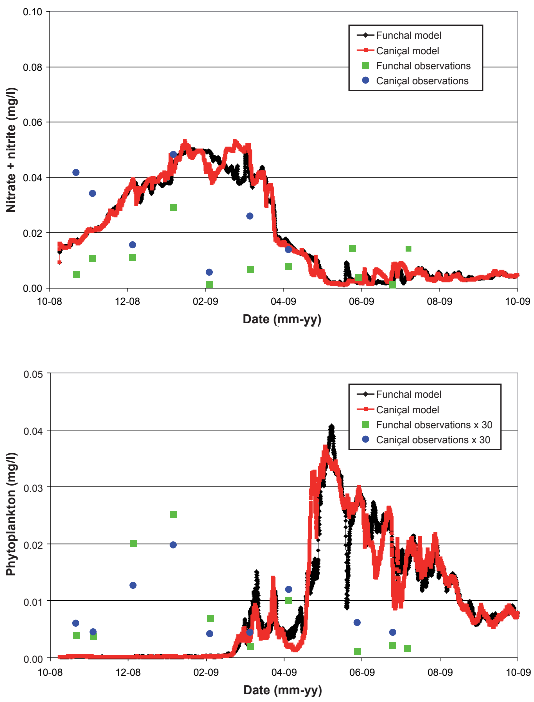

Figure 4. Model results for Funchal and Caniçal stations (black and red lines respectively) and field observations (green squares and blue circles respectively). Nitrate plus nitrite on top and phytoplankton in the bottom, in the latter case observed values have been converted from Chl a to phytoplankton using a conversion factor of 30.

Satellite image data showed an inverse relationship between temperatures and primary production in this region (not shown in theis paper). Maximum water temperatures were observed during the months of August and September coinciding with the minimum Chl *a* concentrations. Maximum values for Chl *a* were observed during spring time. Nutrient concentrations, light and optimum temperature are fundamental parameters for phytoplankton growth. From modelling results, the nutrient cycle in the Madeira archipelago waters can be divided in two phases (Fig. 4): the first phase where nutrients accumulate in the surface due to the vertical instabilities and a second phase when the water temperature and the solar radiation favour the primary production and the accumulated nutrients are consumed; this takes place during spring time. These conditions also help the formation of the pycnocline that reduces the entry of nutrients from deeper water and thus reducing the primary production. The modelling results show that our model gives a similar range of values for nutrients and primary production values, although the main phytoplankton peak starts later. One of the possible reasons is that the starting date of simulation was too close to the real start and the ecological model needs time to reach an equilibrium.

Figure 5 shows the surface horizontal distribution of phytoplankton and phosphate and the vertical distribution of phytoplankton and nitrate on 14 May 2009. The horizontal distributions show the existence of a high spatial variance associated around the islands. The vertical profiles show that these variations are due to the island topography and the current direction. The arrows indicate a general N-NE direction, due to typical trade winds, with higher velocities near the island complex formed by the Madeira and Desertas Islands. This increase also leads to an increase of nutrients on the surface accompanied by a decrease of temperature when compared with the surrounding waters due to upwelling processes. It can also be observed that upwind of the island complex the phytoplankton concentration is low and surface nutrients are exhausted. In the coastal area of the archipelago, the topography leads to higher vertical mixing in the water column that increases the nutrient concentrations in the surface and thus phytoplankton production. Maximum

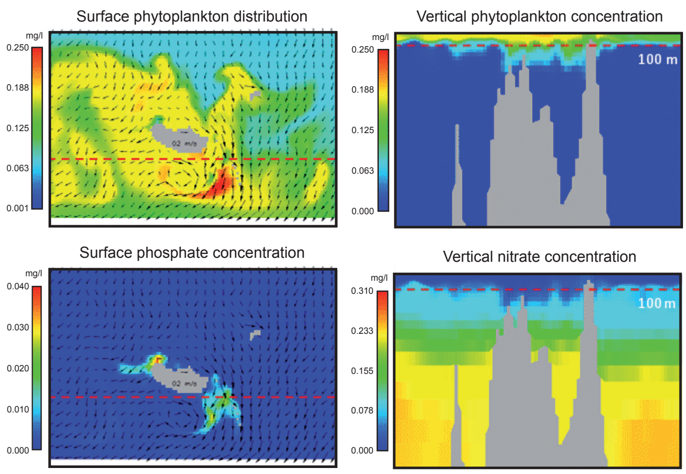

Figure 5. Ecological model results: horizontal distributions of phytoplankton (top left) and phosphate (bottom left) and vertical concentrations of phytoplankton (top right) and nitrate (bottom right).

phytoplankton concentrations are found off the coast. It can be concluded that nutrient dynamics are mainly related to meso-scale events and land-based inputs are unlikely to play a strong role in the ecological processes of the region.

The application of the model was able to simulate the main hydrodynamics and water quality processes. Coastal fronts and eddies can be regarded as important coastal features often associated with high productivity regions. Future studies on the area should concentrate on further validation of the ecological model with *in situ* and remote observations.

Acknowledgments

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