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Identification of upwelling areas on sea surface temperature images using fuzzy clustering

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Abstract

Sixteen sea surface temperature (SST) images obtained over the coastal ocean of Portugal during the period September 1992–September 2003 were used aiming to identify automatically the areas covered by upwelling waters. Suitable high resolution colour scales were applied to the SST images in order to enhance the thermal patterns and easily identify the waters with a coastal upwelling origin. The automatic identification of the areas covered by upwelling waters was developed by the authors in a previous work, through the application of fuzzy clustering and validation indexes, and here is explored as an oceanographic application to the Portuguese coastal upwelling. The fuzzy c-means (FCM) algorithm showed to be able to find partitions that closely defined the upwelling areas and the visualization of the fuzzy c-partitions was achieved through the application of a colour scale. The Xie-Beni validation index was used to select the c-partition that best represented the stage of the upwelling event and showed an agreement with the oceanographic interpretation in 10 of the 14 SST segmented images used in this work. Two SST images without upwelling were also used in order to check the response of the algorithm to the absence of the phenomena. The computation of the matching rate between a c-partition and the two areas split by the hand-contoured upwelling boundary also allowed the evaluation of how closely the obtained segmentation reproduced the shape of the areas covered by upwelling waters. This method successfully identified the upwelling boundary regions in 10 of the 14 SST images. The values obtained for the matching rate were higher than 0.77, thus indicating the good quality of the fuzzy partitions. The segmented images with 3 or 4 clusters were the most suitable ones to reproduce the areas covered by upwelling waters, but it was also shown that, for some cases, the upwelling areas could be reasonably well reproduced by the FCM 2-partition images. While in the latter, the area covered with upwelling waters was coincident with the first cluster, in the former, the segmented image showed two clusters within the upwelling area: the first cluster coincided with the area occupied by the most recently upwelled waters near the coast, while the second cluster was coincident with the area occupied by the "older" upwelling waters with its extensions offshore, the so-called cold filaments. The FCM algorithm revealed to be a promising technique in the automatic identification of upwelling areas on SST images.

Keywords: SST images; Upwelling; Fuzzy image segmentation; Validation indices; Portugal

1. Introduction

During the summer, the coastal ocean of Portugal, located in the eastern boundary of the North Atlantic, is under the influence of northerly winds favourable to the occurrence of upwelling (Fiúza et al., 1982; Wooster et al., 1976). This phenomenon is evidenced at the surface by cold, less salty and nutrient-rich waters over the whole shelf (e.g., Coste et al., 1986; Fiúza, 1984) and by filaments of upwelled waters penetrating into the open ocean. The filaments, extending offshore hundreds of kilometres, have been observed in satellite sea surface temperature and ocean colour imagery (e.g., Fiúza, 1983; Haynes et al., 1993; Sousa & Bricaud, 1992).

Images of sea surface temperature (SST), obtained with the thermal infrared channels of the AVHRR sensor onboard

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NOAA-n satellite series, are frequently used to study the transition zone between colder upwelled waters near the coast and offshore warmer oceanic waters; these transition zones are easily identifiable because they correspond to relatively strong thermal fronts observed in satellite imagery during the upwelling events. These thermal fronts are strong enough to be identified with a suitable and expanded (high resolution) colour scale applied to the image (see Fig. 1(a)), but they are almost indiscernible when a gradient function or a high-pass filter (like a Sobel edge detection technique) is applied through satellite image processing software.

In the studies carried out for the Portuguese coastal ocean, Fiúza (1983) and Sousa (1995) concluded that the areas covered by upwelling waters which include cold filaments progressed offshore or receded shoreward in response, respectively, to intensification or weakening cycles of northerly winds. The upwelling waters have much greater concentrations of nutrients (nitrates, phosphates and silicates) than the surrounding waters, resulting in important biological production areas. The upwelling filaments reaching distances of about 200 km from the coast provide a major shelf-ocean exchange mechanism.

In the aforementioned studies, the authors contoured the positions of the outer limit of the upwelled waters in order to characterize the transition zone including the recurrent upwelling filaments. Although these contours were made by hand, which is a subjective method, they were done by experienced users (oceanographers) and based on the location of the thermal upwelling fronts which are characterized by meanders and filaments repeatedly observed in SST images obtained every summer over decades in the Portuguese coastal ocean.

One way to avoid this subjectivity is to apply automatic identification methods to identify the areas covered by upwelling waters. Nascimento et al. (2005) successfully applied fuzzy clustering (Bezdek et al., 1999) in the segmentation of sixteen SST images with upwelling events obtained in the Portuguese coastal ocean and evaluate the results by applying clustering validation indexes. In the present work, these results are further explored as an effective tool for oceanographic applications, having as an objective the development of a non-user dependent technique to be applied to a large set of satellite imagery.

The application of fuzzy clustering methods to the upwelling phenomenon is most pertinent, not for the definition of the upwelling area itself, but also for the automatic identification of the upwelling boundaries. Preliminary studies showed that most of the near-boundary points presented a degree of membership that is among the lowest membership values within the cluster. This result can be used to characterize the fuzziness associated with this problem.

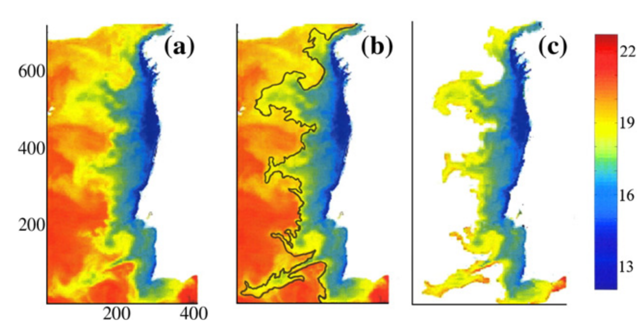

Fig. 1. (a) SST image of an upwelling event obtained on 04 August 1998 (04Aug1998/04:22); (b) upwelling boundary manually contoured; (c) upwelling areas automatically retrieved.

In this study, we used sixteen SST images obtained in the coastal ocean of Portugal, during the period September 1992–September 2003. The results of the automatic identification of the areas covered by upwelling waters validated by clustering validation criteria and presented in Nascimento et al. (2005) are here explored in order to check if they are consistent with the oceanographic knowledge of the Portuguese upwelling area.

2. Data and methodology

2.1. Data

In this study 16 AVHRR thermal infrared data sets, obtained during the period September 1992–September 2003, were used. These satellite data were received and processed at the Satellite Receiving Station of the Instituto de Oceanografia of the University of Lisbon, using the software package "TeraScan®" (SeaSpace Corporation). AVHRR data processing includes calibration, navigation (georeference adjustments), atmospheric correction, cloud detection, remapping, and sea surface temperature (SST) computation. A high resolution colour scale (192 levels) was applied to each image in order to have the best distribution of colour levels over the SST range in each image individually. This way, regions where strong colour variations occur correspond to relatively strong thermal fronts.

An individual SST image consists of 720 × 400 pixels with a spatial pixel resolution of 1.1 km × 1.1 km. Under clear sky conditions (no clouds) and no missing data during the satellite transmission, each sea pixel value is a temperature in degrees Celsius. Data over land and clouds or missed during the satellite transmission are excluded from processing and represented in white in the SST images.

Each SST image was named according to date and time of the data acquisition. For example, the image 02Sep1994/16:28 was obtained on 02 September 1994 at 16:28 UT. See Table 1 for the identification of all the SST images used in this study.

The SST images were divided into five groups according to different "upwelling situations": (Group 1) 5 cloud-free images and well-defined upwelling events; (Group 2) 4 images where upwelling was evident but with areas where there was no temperature information, due to cloud cover or noise; (Group 3) 2 images where the upwelling event was not well-defined; (Group 4) a 3-day sequence of an upwelling event with images separated by ≈ 24 h, and (Group 5) 2 images without upwelling events. Although there was no upwelling on these last two images, they were also included in this study to test the effectiveness of the fuzzy clustering algorithm for all possible situations (for example a period of very weak northerly winds or no wind at all during the summer, resulting in a total upwelling recession).