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VARIABILITY OF COASTAL UPWELLING AND CROSS-SHELF TRANSPORT OFF THE NORTHWEST AFRICAN COAST

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ABSTRACT

Satellite images, wind data and a hydrodynamic model have used for studying the seasonal variability of coastal upwelling along the Northwest African coast. Upwelling indices have been derived from the satellite data of sea surface temperature and from the wind data using classical Ekman theory over a period from 1981 to 1989. The seasonal variability of coastal upwelling is discussed from the 2 data sets. In both data sets appear quasi-permanent upwelling in an area north of Cape Blanc. A hydrodynamic model is used for a specific analysis of the cross-shelf transport in that area for 3 different periods in 1983 and 1984 and the model results are compared to Ekman theory.

1 INTRODUCTION

At the Joint Research Centre of the Commission of the European Communities remote sensing data and hydrodynamic models have been used since 1985 for studying the coastal upwelling system along the Northwest African coast. Initial emphasis has been on understanding the spatial and temporal variability of coastal upwelling, as well as understanding single processes and events, Van Camp *et al.* (1991), Mittelstaedt (1991), Gabric *et al.* (1993), Hoepffner *et al.* (1992), Schrimpf *et al.* (1992), Nykjær and Van Camp (1992, 1993). Remote sensing data are used initially in these studies, since some of the changes in physical and biological characteristics of the surface waters caused by coastal upwelling can be measured relatively easy from satellite sensors. This is particularly true with regard to the sea surface temperature (SST) which can be mapped at regular intervals using infrared sensors but also the changes in the biological state of the surface waters following the injection of nutrients into the euphotic zone can be measured as a change in ocean colour which in turn can be related to the phytoplankton pigment concentration. Hydrodynamic models play an important role in the interpretation of satellite data, since appropriate models permit a detailed analysis of parameters which cannot be derived from remote sensing data, such as the horizontal flow field, the turbulence characteristics in the surface mixed layer and the bottom friction layer, the vertical structure of the water column and subsurface parameters.

The aim of this paper is to summarise the analysis of seasonal variability of coastal upwelling based on upwelling indices derived from satellite data and meteorological data. Furthermore, the attention is directed to the area of quasi-permanent upwelling north of Cape Blanc where a more detailed analysis of the cross-shelf transport is carried out using a hydrodynamic model and the result of the model is confronted with an analysis based on classical Ekman theory, Ekman (1905).

2 SEASONAL VARIABILITY OF COASTAL UPWELLING

Seasonal variability of coastal upwelling has been studied from satellite and meteorological data. 3400 images from the NOAA series of satellites carrying the Advanced Very High Resolution Radiometer (AVHRR) have been processed into maps of SST covering the period from July 1981 to August 1989. The processed images include data acquired from NOAA-7, NOAA-9 and NOAA-11. Only daytime images are available. Thus all images are midday or late afternoon observations. Satellite data calibration and calculation of brightness temperatures has been done following Lauritson *et al.* (1979) and Kidwell (1988). The SST is calculated using a split window algorithm as described by Castagné *et al.* (1986). To eliminate the influence of clouds the approach of "maximum value compositing" (MVC) has been adapted here. Over a given time period all images are stacked on top of each other and a new image is created which for each location retains the warmest value found at the same location in all the images over the time period. Different tests carried out using periods of 5 days, 10 days and 1 month revealed that 10 days were a sufficient period for achieving full geographical coverage with an acceptable minimum influence of clouds.

To focus the attention on coastal upwelling, an SST upwelling index has been derived from the 10-day MVC's. The index is calculated as the zonal temperature difference between midshelf temperature and the temperature 500 km further offshore at the same latitude. The SST upwelling index is derived from 40°N to 4°N throughout the time period where satellite data is available. Finally, in order to examine seasonal variability, a mean annual upwelling index is calculated and presented in figure 1.a.

Wind data have been made available from the European Centre for Medium-Range Weather Forecasts, UK. The wind field is derived by means of an analysis of meteorological observations and a 6-hour forecast obtained with a numerical model. The winds used in this study are given at 12 UTC for each day in the period from September 1982 to June 1991. The winds are given at 10 m height on a spatial grid of 1.875 degrees latitude and longitude before May 1985 and 1.125 degrees after May 1985. In order to focus the attention on coastal upwelling and to reduce the volume of data, an upwelling index defined as being the Ekman transport perpendicular to the midshelf line has been extracted from the wind data set. Stations along the coast are selected from the wind field, interpolated to the resolution of the satellite images primarily for easier comparison to satellite data and the upwelling index calculated for these selected stations. The upwelling index will be referred to as the Ekman upwelling index. Like the SST upwelling index a mean annual upwelling index has been calculated and is presented here as figure 1.b.

The mean annual upwelling indices in figure 1.a and 1.b have been compared to similar upwelling indices calculated from in-situ data and presented in Speth and Detlefsen (1982) and Wooster *et al.* (1979).

The patterns shown in figure 1.a are in good agreement with the patterns of zonal temperature differences presented by Speth and Detlefsen (1982) and Wooster et al. (1979). The absolute values are however not in agreement, since the satellite index displays much lower dynamic range than the in-situ measurements.: This difference may be due to different measurement techniques and the processing applied to the satellite data i.e. the maximum value over 10 days as compared to instantaneous thermometer readings. Furthermore, there are differences in geographic positions from which the coastal and offshore temperatures are calculated. In particular, the index used by Wooster *et al.* (1979) used offshore temperatures in the mid-Atlantic, while the SST upwelling index is calculated as a difference between midshelf temperatures and temperatures 500 km further offshore. However, the large scale distribution of the SST upwelling index depicts the major seasonal variability. South of 20°N a strong seasonal signal is dominant with upwelling occurring during winter. Between 20°N and 26°N upwelling is persistent throughout the year with maximum intensities during May and June and between September and December. Further north between 30°N and 32°N upwelling is strongest in summer between August and September. North of 32°N upwelling is not evident along the African coast but the Portuguese summer upwelling north of

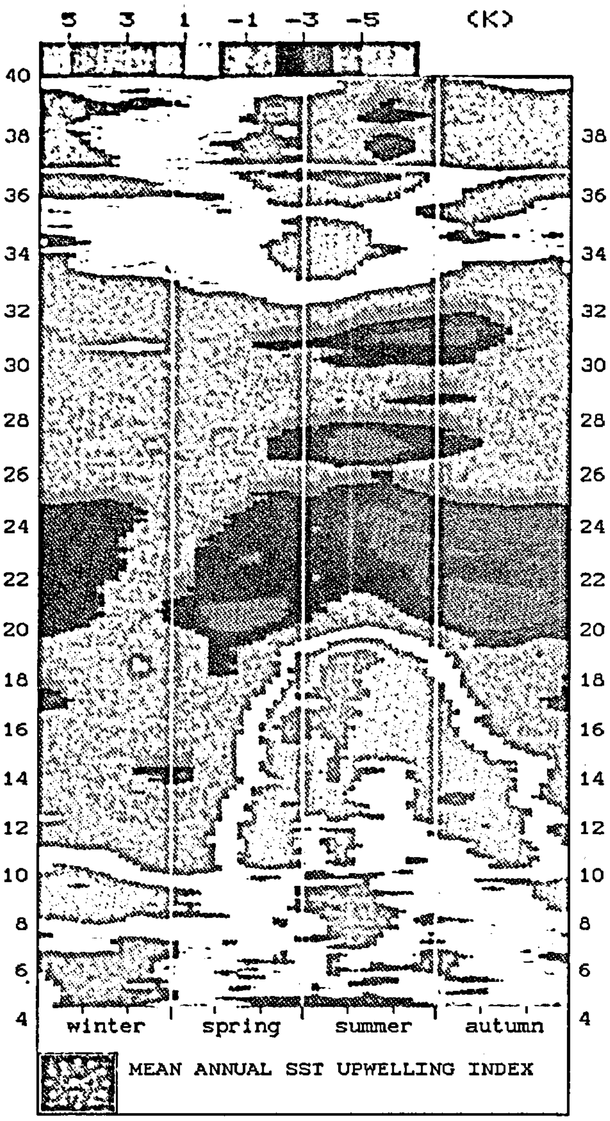


Figure 1.a. Mean annual SST upwelling index

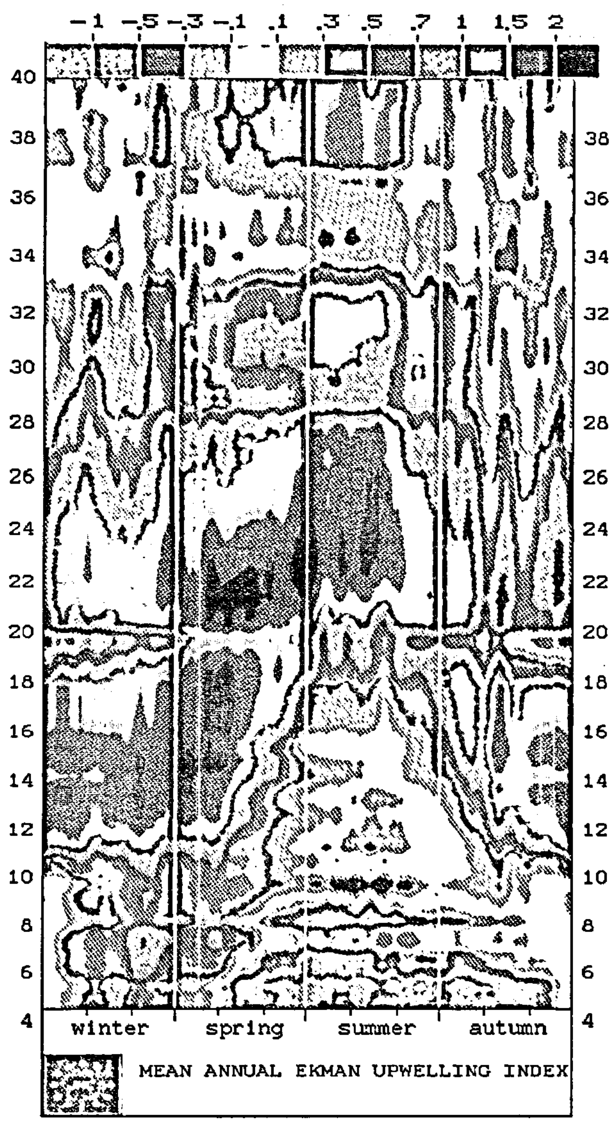


Figure 1.b. Mean annual Ekman upwelling index ($m^3 s^{-1}$ per meter coastline)

37°N can be identified. A major discrepancy between SST upwelling index and in-situ temperature upwelling index is found between 26°N and 28°N during August and September where upwelling is strong in the satellite index but absent in the in-situ based index. A plausible explanation could be that the latter is based on merchant ship measurements and the main shipping routes at 26°N-28°N pass by the Canary Islands and not along the coast, hence no data would be available.

At large scale the Ekman upwelling index, figure 1.b, compares well with the SST upwelling index in figure 1.a. The discrepancies just south of Cape Blanc at 19°N are more likely due to differences in data processing than actual differences in wind fields. The seasonality south of Cape Blanc is consistent in both indices, but north of Cape Blanc up to 25°N there are major differences. The SST index demonstrates strong upwelling throughout the year with two major peaks in May/June and October/November. The same double peak cannot be found in the Ekman index. Further north at the location of major capes along the coast the SST index is high, for instance at

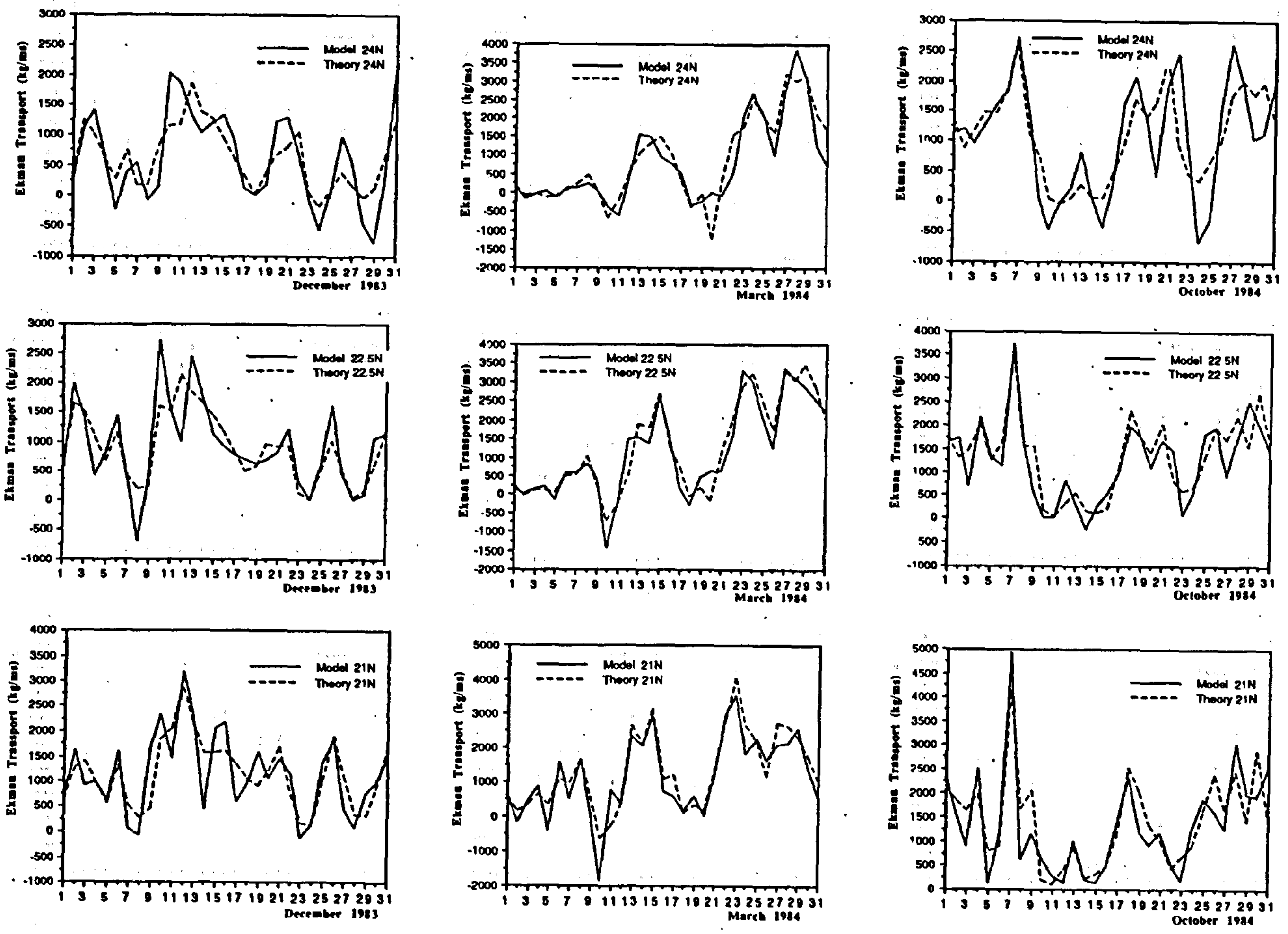
Cape Yubi at 27°N and Cape Ghir at 31°N. Apparently, the intensification of coastal upwelling in the vicinity of capes cannot be explained by simple Ekman theory.

3 MODELLING OF CROSS-SHELF TRANSPORT

The almost permanent coastal upwelling throughout the year in the Cape Blanc area between 20°N and 25°N seen in the upwelling indices in figure 1, has stimulated the interest of improving the knowledge of transport pattern, in particular the offshore volume transport in that area. The classical Ekman theory which has been use for producing figure 1.b is known to be limited by a) assumption of infinite depth, b) steady state solution and steady wind and c) no thermohaline effects. These limitations may hide important aspects of the transport patterns and mechanisms. In order to improve the basic Ekman theory a hydrodynamic model has therefore been used for examining the offshore transport. The time period which is investigated is during 3 distinct upwelling events in December 1983, March 1984 and October 1984. The offshore transport during these periods is estimated from classical Ekman theory and confronted with the transport from the hydrodynamic model. The version of the model used for this study may be described in general non-mathematical terms as a 3-D prognostic, baroclinic model based on the primitive equations, the hydrostatic approximation and the Boussinesq assumption with respect to the effect of variable density. Baroclinic effects have been computed using separate transport equations for heat and salinity. Vertical transport by turbulence is computed with the turbulent kinetic energy obtained from a solution of the corresponding transport equation and with the mixing length derived from the application of well known parameterization principles. Turbulence damping by density stratification is taken into account. A detailed description of the mathematical model and the applied numerical methods is given in Eifler and Schrimpf (1992). The model was forced by the daily wind field from ECMWF. The model computes the cross-shelf velocity $v(z)$ normal to the 200 m isobath, and then integrates over the computed mixed layer depth to estimate the net cross-shelf volume transport. The vertical discretization chosen divides the upper layer of the water column into layers of 2 m thickness in order to obtain the accurate estimate of the vertical dimension of the mixed layer. The layer thickness is increased continously downwards where the bottom layer thickness is about 200 m. To describe the different shelf geometries north of the Cape Blanc region, the computations have been carried out along 3 distinctly different cross-shelf sections at 21°N, 22.5°N and 24°N.

Ekman cross-shelf transports and model cross-shelf transports for the 3 periods studied are shown in figure 2.

The model predictions for December 1983, figure 2.a, suggest that the transport was directed offshore for most of the month and intensified between December 10 and December 16 with a peak of 3200 kg $m^{-1}s^{-1}$ at December 12 at 21°N. The winds relaxed from 4-5 days from December 21 which resulted in onshore flow during this period. The meridional gradient of the Ekman transport, with peak values highest at 21°N would cause a clockwise steering of material transported offshore. In general, the model predicts a greater range in Ekman transport than the simple Ekman theory. Contrasting to December 1983, the situation during March 1984, figure 2.b, was more variable with little offshore transport during the first 10 days of the month. A short period from March 13 to March 16 was followed by wind relaxation until March 20 when the winds intensified, particularly in the northern part of the study window and continued for the rest of the month. October 1984, figure 2.c, was characterized by moderate to strong Ekman transports for the first 10 days, with particularly high values at 21°N on October 7. A period of relaxation followed until October 17, when winds increased with moderate to strong offshore transport at all latitudes for the remainder of the month.



2.a 2.b 2.c

Figure 2. Model calculated and theoretical values of Ekman cross-shelf transport at 21°N, 22.5°N and 24°N for (a) December 1983, (b) March 1984 and (c) October 1984. Positive values are off-shore transport.

4 CONCLUSION

The upwelling indices used for examining seasonal variabilities of coastal upwelling agree well at the large-scale, while discrepancies between the 2 indices can be found in the vicinity of major capes. A mathematical model has been confronted with classical Ekman theory in calculating cross-shelf transports in the area north of Cape Blanc where upwelling seems to be a quasi-permanent feature. It appears, that most of the net cross-shelf transport can be sufficiently well described by simple Ekman theory in that area confirming the understanding of coastal upwelling as an essentially wind driven phenomenon. However, Ekman theory does not reflect the effects of more complex shelf and coastline geometries and additionally cannot provide the information on the turbulence characteristics in the surface mixed layer and in the bottom friction layer which is of vital importance for bio-geochemical studies. Hence, it is believed that hydrodynamic models are indispensable for more detailed analysis of underlying hydromechamins also in view of an improved interpretation and application remotely sensed data.

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