Spatial and Temporal Dynamics of the Upwelling off Senegal and Mauritania: Local Change and Trend

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Abstract

A specific processing chain applied to the infrared data of the Météosat series satellites has been elaborated. The high repetitiveness of the observations allows to obtain 5 days synthesis SST maps over West Africa at a 6 km resolution. The resulting data set precisely describes the spatio-temporal dynamic of the coastal upwelling, from Mauritania to Guinea (21°N-9°N), since 1984. The study area is dominated by the seasonal coastal upwelling which displays important interannual variations. The study of the superficial thermal field structure enables to link the mean position of the upwelled water to the topography of the continental shelf. Continuous monitoring of SST along the shelf allows the spatial estimation of an upwelling index and to characterize the seasonal dynamic of the upwelling via parameters such as the intensity and the duration of the seasonal transition phase and its seasonal lags. The example of an anomalous migration of *Sardina pilchardus* in Senegal leads to the hypothesis that neither the mean seasonal intensity nor the precocity of the upwelling is sufficient to initiate an abnormal southward migration and that the seasonal transition leads may be a key parameter in this process.

RÉSUMÉ

L'élaboration d'une chaîne de traitement spécifique aux données infrarouge thermique des satellites de la série METEOSAT a été réalisée. L'abondance des données satellitales liées à la répétitivité des observations permet d'accéder à une résolution de 5 jours et 6 km, soit très en deçà des méthodes d'investigation utilisables en routine en océanographie côtière. La description spatio-temporelle précise et régulière de l'upwelling côtier de la Mauritanie à la Guinée est ainsi accessible depuis 1984. La zone étudiée est soumise à la très forte saisonnalité de l'upwelling côtier, lequel présente aussi de fortes anomalies interannuelles. La connaissance de la structure des champs thermiques superficiels permet de relier la position moyenne des zones de remontée à la topographie du plateau continental. La détermination de la TSM sur une bande continue centrée sur le maximum de résurgence permet le calcul d'indices d'upwelling spatialisés et de caractériser la dynamique saisonnière de l'upwelling à travers des paramètres tels que : intensité et durée mais aussi décalages saisonniers et progressivité des transitions saisonnières. A partir de l'exemple de *Sardina pilchardus* au Sénégal, on émet l'hypothèse que ni l'intensité saisonnière moyenne, ni la précocité de l'upwelling ne permettent d'expliquer à eux seuls certaines migrations exceptionnelles de cette espèce, mais que la dynamique des transitions saisonnières semble également déterminante.

INTRODUCTION

Remote sensing of sea surface provides synoptic and repetitive overviews, especially for large scale monitoring of climatic parameters. At a lower space and time scale, satellite infrared imagery allows satisfactory observation of coastal areas. Due to their low cloud coverage, coastal upwelling areas may be particularly well monitored via sea surface temperature (SST) mapping, at a time and a space scale adapted to their particularly high dynamic. A specific data processing chain has been developed from METEOSAT infrared data and ships of opportunity data (Citeau and Demarcq, 1990; Demarcq and Citeau, 1995) and tested in West African upwellings.

The upwelling zone studied extends from North Mauritania to Guinea and corresponds to the seasonal zonal displacement of the trade winds along the western African coast. Directly depending on this dynamic, the seasonal variability of the SST reaches 14°C (Rébert, 1983), and is one of the largest in the world. The high pressure regime of the northern anticyclone which governs NE trades leads to weaker cloudiness (and permits better remote sensed observations of SST) during the cold season (October to June, depending on the latitude).

The enrichment of these coastal areas depends on both intensity and variability of the corresponding upwellings. Important fluctuations of pelagic fishes population abundance and particularly of *Sardinella* species, a major resource for Senegal, have been recorded, in spite of the ability of these species to tolerate some environmental fluctuations (Fréon, 1988; Cury and Fontana, 1988). The irregular presence of species depending of geographically neighboring stocks (as for *Sardina pilchardus*) is noticeable and may also be related to environmental fluctuations.

1. The specific data processing for SST retrieval from Meteosat infrared imagery

In terms of radiometric and spatial resolution, the accuracy permitted by geostationary satellites (0.5°C and 5 x 5 km subsatellite in the case of METEOSAT infra-red channel) is lower than the accuracy currently obtained from polar orbital satellites (0.12°C and 1 km for NOAA/AVHRR). Nevertheless, this lowest resolution is not really a constraint, even in coastal areas, if compared with the size of the oceanic structures observed at sea level, on the one hand, and with the strong thermal gradients encountered, on the other hand. On the contrary, the regularity of the earth scan provided by METEOSAT allows a simpler processing for geometric corrections, while its repetitiveness (every 30 minutes) allows improvements in discriminating the sea from clouds.

1.1. Pre-processing

Data pre-processing takes advantage of the half-hourly availability of earth scans by METEOSAT. Each satellite view of the earth is classically calibrated (transformation of the energy emitted by the earth to temperature by inversion of Planck's Law). An extraction of the working area is then performed and the image is geometrically corrected to a linear latitude and longitude projection.

In tropical areas, the infra-red radiance measured by the satellite sensor is systematically lower than the infra-red rariance emitted by the sea surface (except in the presence of suspended dusts), due to cold atmospheric water vapor. Consequently, by assuming that the SST is constant over 24 hours, the 48 images of the day are combined into a new image synthesis, retaining for each pixel the 'warmest' one of the time series.

Cloud cover in west Africa may strongly vary during one day, especially when the trade winds are weak. The efficiency of the 'maximum temperature method' is shown for 27 days, from 5 to 31 May 1991 (Fig. 1) by comparing the instantaneous cloud cover at 12h00 GMT (generally low cloud cover) and the daily synthesis index. The advantage of the repetitiveness of observations by a geostationary orbit appears clearly.

This important benefit in term of usable pixels for SST retrieval will also determine the performance of the sea-cloud discrimination, the major step of the processing in SST restitution.

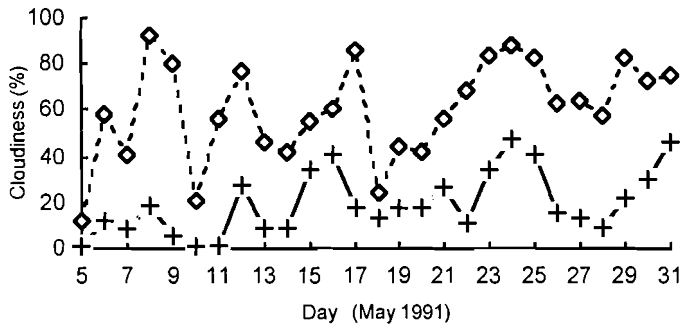

Fig. 1: Reduction of the cloud cover (%) on the daily thermal synthesis (solid line; crosses) compared to the instantaneous cloud cover (dotted line; open dots) at 12h00 GMT.

1.2. Sea-cloud discrimination

In remote sensing processing, sea-cloud discriminations are very often based on visible/infra-red comparisons. Nevertheless, this technique has some constraints. The major one for acquisition and processing is the large amount of data required, five times more in the case of METEOSAT. Furthermore, some low level clouds are strongly absorbent in the IR channel and remains transparent in the VIS one. The visible/infrared algorithm is then unusable.

The method we developed for sea-cloud discrimination is based on a comparison of a daily synthesis with the 'most probable' real SST field. This field is provided either from a climatology of SST or, more often, from a previously processed SST field. For adequate masking, this reference situation is chosen as close as possible to the daily synthesis, in terms of upwelling spatial extent.

A comparison of the radiative temperature synthesis (Fig. 2a) with this reference is then performed and the values with temperature deviation greater than a definite threshold (around 3°C according to the similarities of both fields) are considered to refer to clouds, and are masked (in black on Fig. 2b).

1.3. Atmospheric correction and SST restitution

The above resulting temperature field remains affected by atmospheric absorption, mainly due to the atmospherical water vapor. In tropical area, the apparent thermal absorption generally lies between 2°C (trade wind region) and 5°C or more (equatorial region).

According to the previous pre-processing steps (maximum temperature synthesis), and considering the difficulty to obtain direct information on atmosphere structure compatible with space and time resolution of the SST fields (6 km and 5 days in our case) the most adequate way to correct this temperature field from the atmospheric absorption is to use an exogenous source of SST data. The ships of opportunity data disseminated by the Global Transmission System (GTS) in the 'SHIP' meteorological messages (including SST, wind, air temperature, etc.) and synthesized in

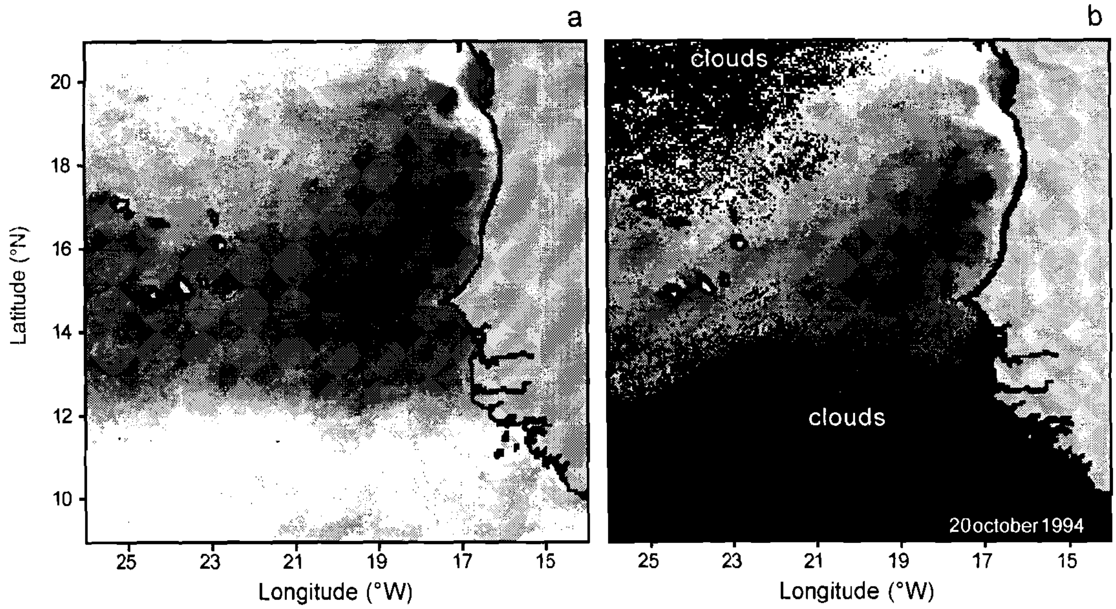

Fig. 2: Raw daily infrared synthesis on October 20, 1994 (a) and after cloud masking (b) in the beginning of the cold season. The SST decrease from dark grey to white while the cloudy area is displayed in black.

the COADS database (Roy and Mendelssohn,1994, this vol.) are rather convenient for this, by providing an adequate density of SST measurements, especially in Mauritanian and Senegalese areas (Fig. 3). Note that Figure 3a corresponds to the satellite situation displayed in Figure 2 and that SHIP data would not allow to detect the presence of the coastal upwelling in South Mauritania and North Senegal.

Because of their generally irregular spatial distribution, their poor sampling of the coastal area, (especially damaging during the beginning and the end of the upwelling season) and their relatively high instrumental noise, the usefulness of the SHIP *in-situ* data for precisely describing the SST field in coastal upwelling areas is generally very low.

The suspect SHIP data are first eliminated from the original data set, initially by comparison with a global SST climatology i.e., the Reynolds monthly SST climatology (Reynolds, 1982) or with our own climatology, preliminary computed from 1984 to 1989 (Demarcq and Citeau, 1995). Only values whose departure from the climatology is greater than 5°C are removed given the strong SST anomalies that are encountered in this upwelling area.

Despite the above limitations, the SHIP data provide a very satisfying estimation of the residual atmospheric absorption field. The latter is obtained by coupling ship data with the uncorrected satellite data (Fig. 2b) in order to give corrected SST field: the field of 'atmospheric correction' is then computed as the statistical departures of the satellite synthesis from the *in-situ* SHIP SSTs. An example of atmospheric field and the resulting corrected satellite SST field is displayed on Figure 4.

Standard SST processing was applied on a temporal basis of 5 days from 1984 to 1995. During the upwelling season off Senegal and Mauritania (from October to June), approximately 90% of the daily METEOSAT infrared synthesis can be used. This percentage is in fact seasonally variable, and depends on the mean coastal nebulosity, which is inversely proportional to trade wind intensity.

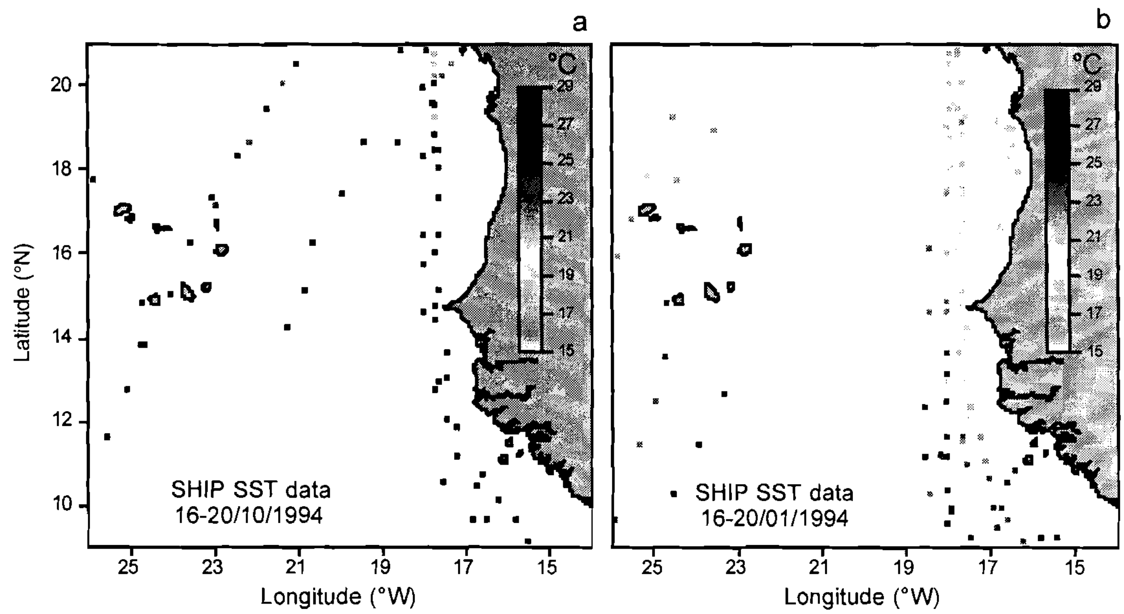

Fig. 3: Typical examples of "SHIP" data distribution offshore Mauritania and Senegal during 5-days periods at the beginning (a) and in the middle (b) of the upwelling season.

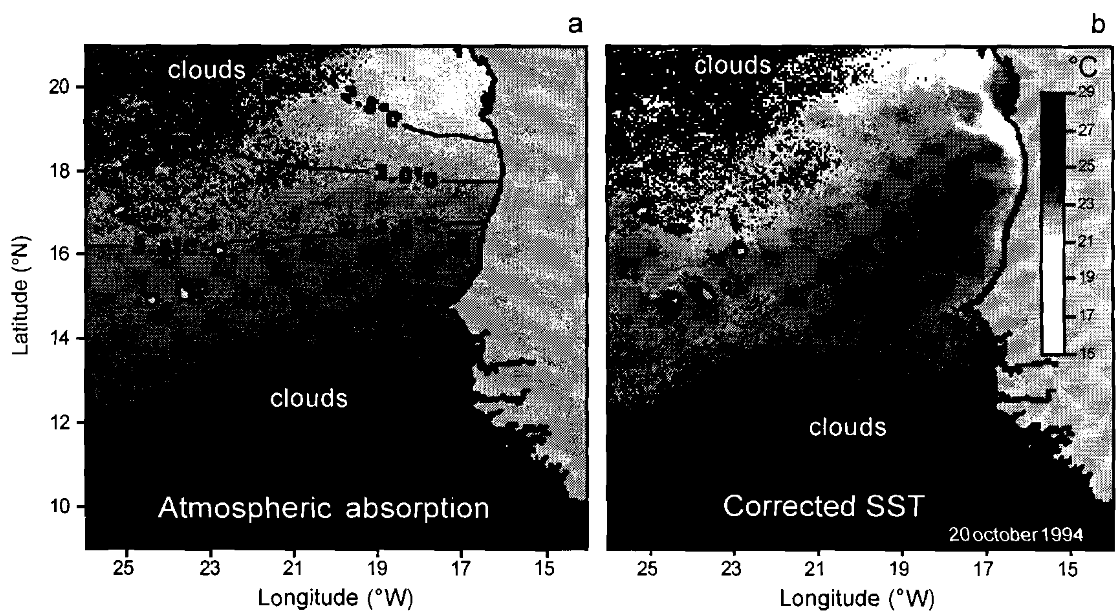

Fig. 4: Example of atmospheric absorption field (a) on 20 October 1994 (beginning of the upwelling season) and the resulting corrected satellite SST field (b).

For each daily synthesis, the cloudy area is masked and a radiative temperature field is calculated by a 5 day period. This field is then atmospherically corrected by adjusting the raw temperature values with the corrected SHIP SST measurements as described above.

2. Computation of coastal upwelling indexes from SST fields off Mauritania and Senegal

The upwelling structures observed off Mauritania and Senegal from October to June are representative of a complex spatial dynamic, characterized by several local SST minima, mainly depending on wind direction and local bathymetry. The SST contrast with offshore waters depends mainly on the history of the upwelling in the preceding few weeks and tends to decrease during weak upwelling episodes. Superficial upwelling filaments moving offshore are frequently observed and reveal the concentrating effect of the shelf topography.

Figure 5 displays some commonly observed features. The main differences in SST field are linked to the large scale wind field variation, in both intensity and direction. According to Ekman's theory (Ekman, 1905), upwelling is maximum along coast lines parallel to the wind. The localization of this maximum varies according to wind direction and is particularly visible during the beginning of an upwelling event (see for example Figure 5a, b). During more intense phase of the trade winds, the cooling extent is continuous along the coast line, from 21°N to 10°N approximately (Fig. 5c). The southern most extent occurs around March, according to the most southern latitudinal position of the ITCZ/trades system which occurs in February and March (Citeau *et al.*, 1989).

The localization of the maximum flow of upwelled waters at the sea surface can be defined by a continuous area of minimum SST. This area is relatively fixed and closely linked to the local bathymetry (Fig. 6). SST at these locations is related to the instantaneous response of the upwelling system to wind forcing. This local spatio-temporal signal does not reflect the dilution effects due to past upwelling events that would be reflected in the mean SST calculated on a larger space scale.

An SST based upwelling index is calculated by differencing the local SST ('SSTsat') located at the minimum SST line (see Fig. 6) and a reference offshore temperature at the same latitude, to avoid taking into account large scale SST anomalies due to planetary climatic anomalies, not reflected in coastal areas. This reference temperature is chosen as the climatic SST temperature (and not the current offshore SST), calculated from 1984 to 1994 in the tropical Atlantic from a routinely elaborated product calculated from METEOSAT and SHIP data (Demarcq and Citeau, 1995; Demarcq and Suisse de Sainte-Claire, 1995).

According to Jacques and Tréguer (1986), the upwelled water off Mauritania and Senegal is essentially composed of SACW (South Atlantic Central Water). Regular coastal measurements in several oceanographic stations in Senegal (Roy *et al.*, 1985) show that the extreme coldest events correspond to very stable values of SST between 14.0°C and 14.5 °C. In this case, the salinity of the upwelled water (between 35.4‰ and 35.5‰) confirms its SACW origin.

According to the Ekman's theory and oceanographic coastal measurements off Senegal, the departure of the SST (measured as close as possible to its arrival location at the sea surface) from its minimum value (pure SACW) is

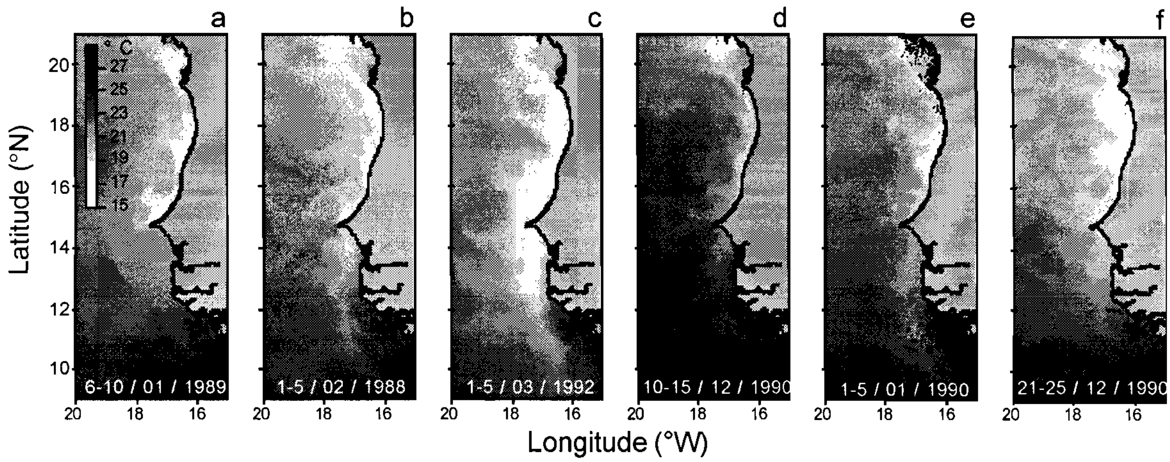

Fig. 5: Commonly observed superficial SST fields during the upwelling season off Mauritania and Senegal. The SST decrease from black (27°C) to white (17°C) for all images. Numerous filaments of upwelled waters moving offshore are clearly visible.

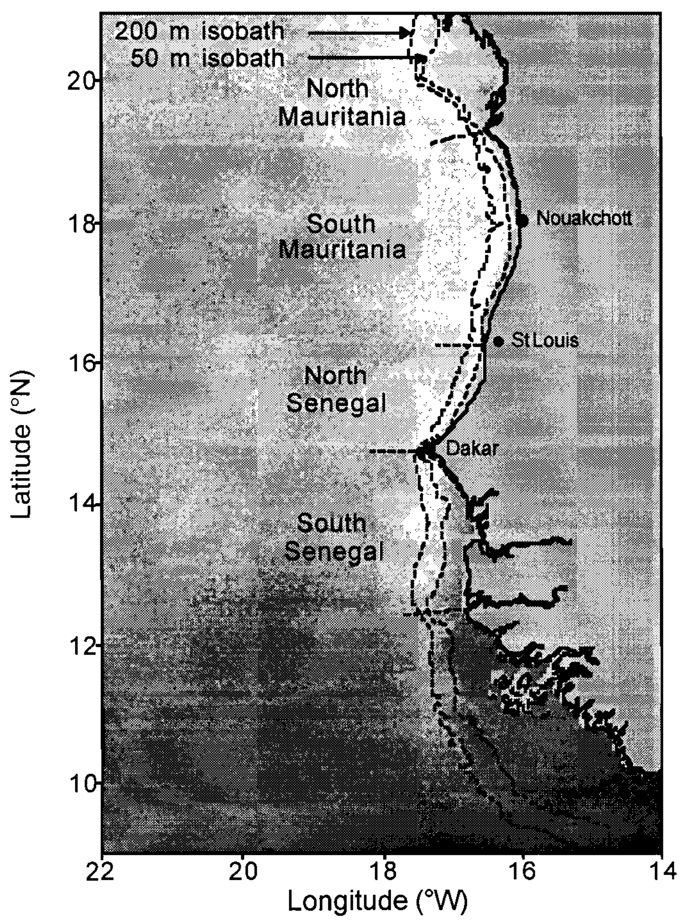

Fig. 6: Localization of the maximum flow of upwelled waters at the surface in relation to the local bathymetry and localization of coastal areas for upwelling index computation.

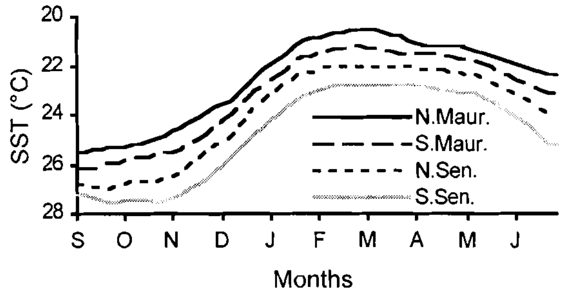

Fig. 7: Offshore SST (SSTmax [lat,month]) at 23°W off Mauritania and Senegal, calculated for the upwelling season of the years 1984-94 from satellite climatology.

directly linked to the upwelling flow. On the other hand, the maximum SST recorded from oceanographic coastal measurements in upwelling season during very weak upwelling phases varies seasonally, and converges towards the offshore SST at the same latitude, where the upwelling influence is negligible (because of the dilution of the upwelled water due to wind-generated turbulence).

The minimum value of SST expected at the upwelling centers, noted SSTmin, is the temperature of SACW as it reaches the surface. The maximum temperature, noted SSTmax, is chosen as the offshore climatic SST recorded at 23°W. Figure 7 displays this mean seasonal signal, calculated from the satellite climatology elaborated for the 1984-1994 period, from North Mauritania to South Senegal. This offshore signal is representative of the mean offshore upwelling influence. For a given year, it reflects the mean 'seasonal past' of the upwelling in the coastal area, but not its current intensity.

As reported in the time series of coastal oceanographic measurements of wind and SST, the seasonal variation of the observed value of SSTsat reflects the fact that, for a definite level of wind forcing, SST cooling is greater at the beginning or at the end of the upwelling season in a relatively warm environment than during the middle of the season in colder surrounding waters (Teisson, 1982). This makes it possible to compare the upwelling intensity during the whole season. The main difference with the Ekman index is the spatio-temporal integrating effect intrinsically linked to an SST based index and clearly displayed in Figure 8.

Important discrepancies remain between these two parameters (Fig. 8) partly due to the spotty sampling of the ship data close to the coast (especially in the south Mauritania region), because of the ship route locations (see Fig. 3). This fact is clearly shown across the differences in mean SST separately calculated from SHIP data (by objective analysis) and from satellite data over the same coastal area (Fig. 9). This difference leads to a severe under-estimation of upwelling extent and intensity calculated from the SHIP data. This under-estimation is high at the beginning of the upwelling season (when the offshore extent of the upwelling is generally weak, see for example Fig. 4 and 5d). In addition this under-estimation is different from one year to another, depending on the variability in the distribution of SHIP data.

From these observations, a relative SST-based upwelling index, ('SSTI') was calculated from the deviations of the locally observed SST from their extreme theoretical values, respectively fixed and seasonally varying.

To take into account the effect of the spatial dilution of the upwelled waters at the surface mixed layer, the SSTI may

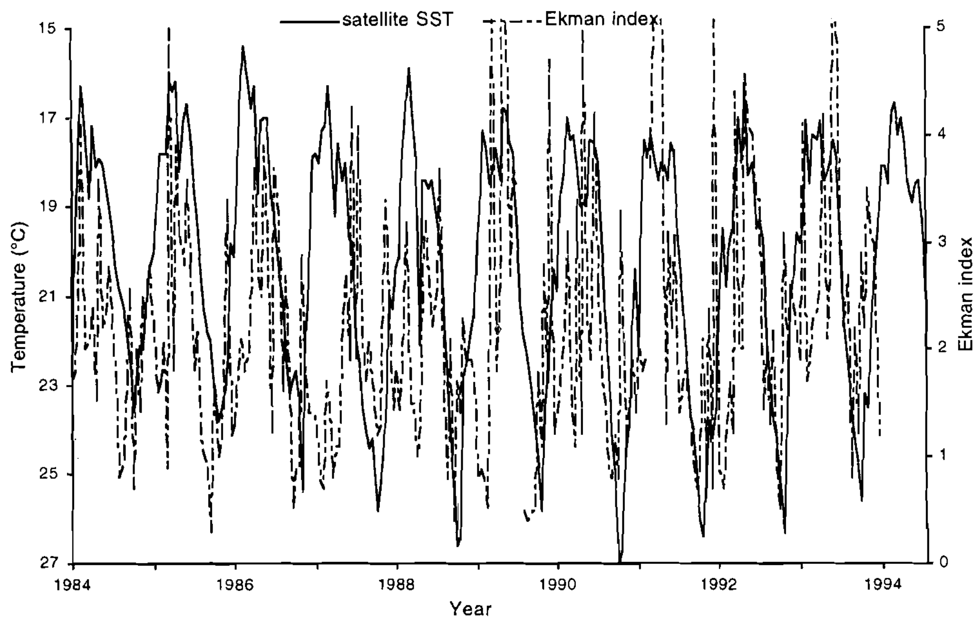

Fig. 8: Direct comparison of Ekman index and satellite SST (°C).

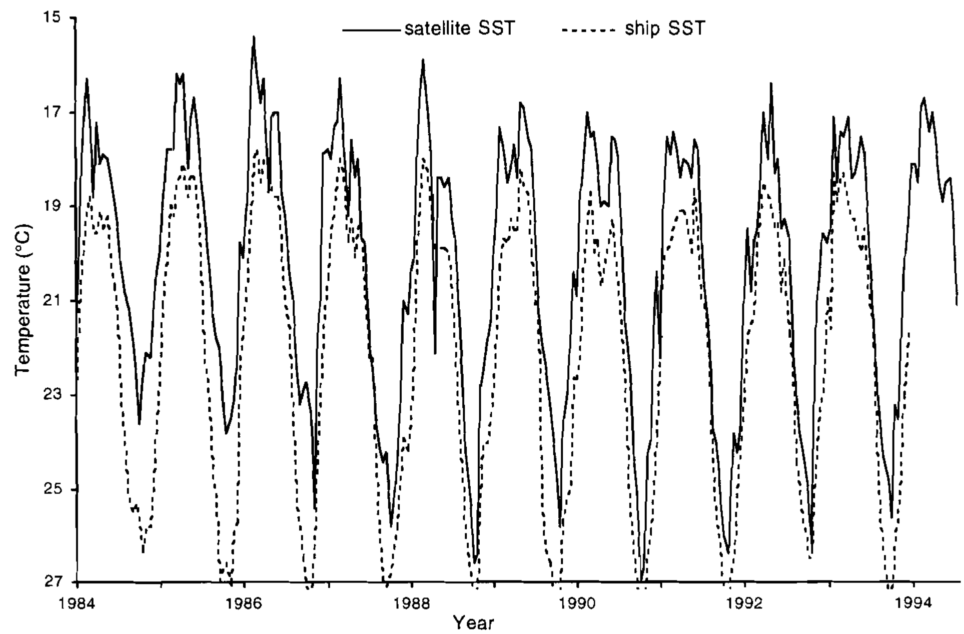

Fig. 9: Simple SST-based index calculated from SHIP data only (dotted line) and from the satellite product (solid line) in the south Mauritania region.

be expressed by the relation:

$$SSTI = (SST_{sat} - SST_{max}[lat,month]) / (SST_{min} - SST_{max}[lat,month])$$

Figure 10 shows the upwelling dynamic calculated using this index for 4 areas (see also Fig. 6) from North Mauritania to South Senegal for the 1984-1993 period. The 5-days time scale reproduces the short term dynamic of the upwelling intensity. Major bias (other than a systematic one) seem improbable, considering the large amount of input data and the processing homogeneity of the time series.

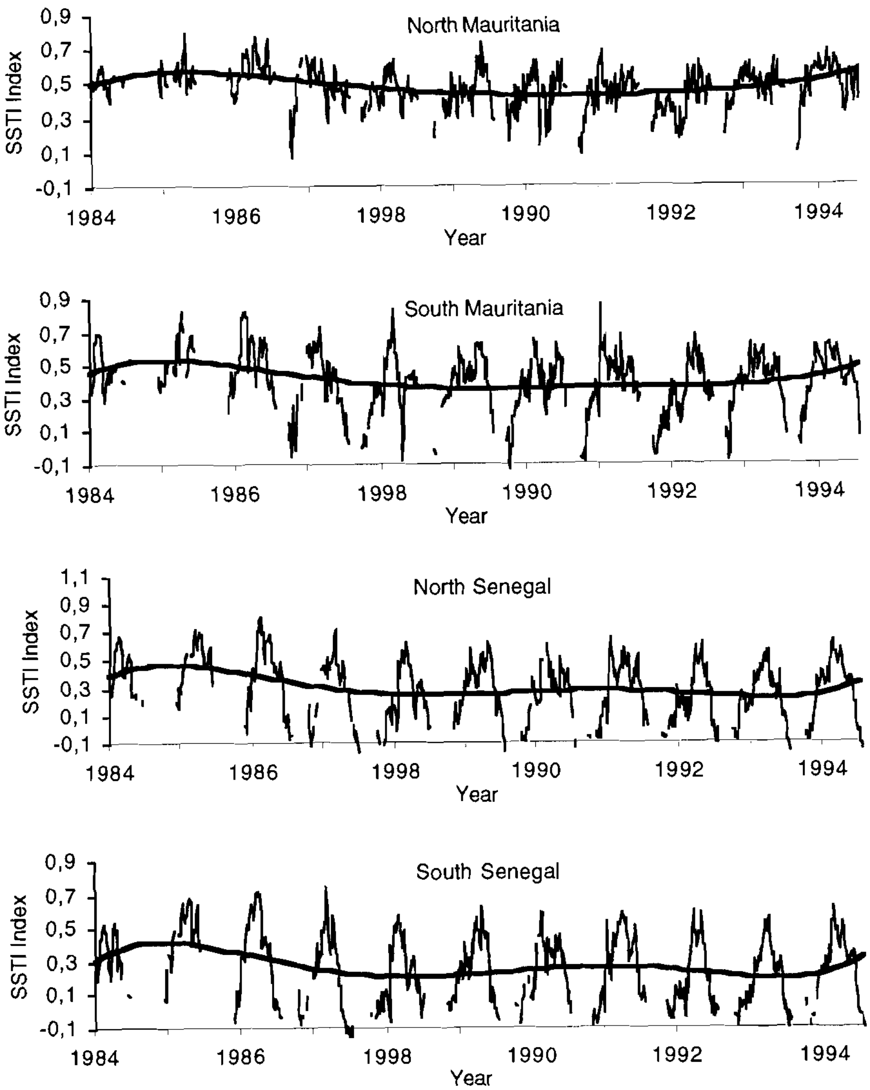

Fig. 10: SSTI index calculated from North Mauritania to South Senegal from 1984 to 1993.

3. Trends and relevant parameters in upwelling dynamic

The very high seasonal upwelling dynamic off West Africa is clearly shown through the SST-based upwelling index from 1984 to 1993 (Fig. 10) and is indirectly confirmed by the short scale spatial dynamics seen across the series of daily satellite images which suggest a daily response to the wind forcing, according to previous coastal measurements of SST.

Relative bias seems avoided in such SST satellite product, and no linear trend is obvious in term of upwelling intensity change considering a period of 11 years. Nevertheless, groups of 'cold' and 'warm' years are exhibited when a polynomial adjustment of 5th degree is used (Fig. 10, heavy lines). The years 1984 and 1985 are the coldest of the time series and 1988, 1989 and 1992 the warmest. It is interesting to note that 1985 was a warm year in the tropical Atlantic, due to the impact of the 1982-83 El Niño, and that the intensification of the coastal upwelling off Mauritania may be a local effect of this warming.

The general similarity of the short term trends of SSTI is obvious for the four areas (Fig. 11). An interesting observation is the case of the 89/90 and 90/91 cold seasons, for which an inversion of the trends is observed, from warm years in North Mauritania to cold years in South Senegal. The very regular North-South gradient of this phenomenon allows to reject the hypothesis of a processing artifact and to think that a temporary change in the zonal trade wind fields for this years did occur. This observation expresses a decline of the normal decreasing zonal gradient of the upwelling-favorable component of the trade winds, from Mauritania to Senegal. The temporal evolution of the SSTI (Fig. 11) shows that a strengthening in the trade winds in this region is sometimes in phase (in the case of the 85-90 period) and sometimes in opposing phase (in the case of the 90-94 period). It has been shown in this region that the intensity of the zonal gradient between the north of Mauritania and the Senegal enhances the migratory response of several migratory species (Cury and Roy, 1988; Binet, 1988; Binet this vol.).

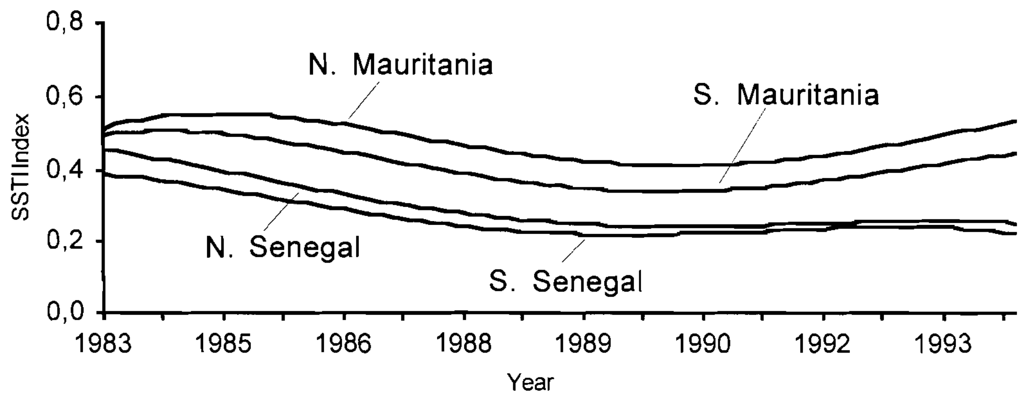

Fig. 11: Zonal structure of SSTI trends from North Mauritania to South Senegal (1984-93).

Long term changes in upwelling intensity have been examined from 1964 to 1993 from SHIP data. Both Ekman CUI (Fig. 12) and SST (Fig. 13) show a weak increase of upwelling intensity. This increase seems coherent with the other long-term observations in trade wind intensity (Bakun, 1990, 1992). Nevertheless, reducing potential impact on coastal fish populations to the unique long term trend due to the global warming would be restrictive, as it can be shown that the amplitude of the medium-term interannual variations are several times greater (or inverse) than the global warming amplitude. Also, the upwelling intensity off Senegal measured from remote sensed data presents a weak decrease in the trade winds for the 84-93 period (see Fig. 10).

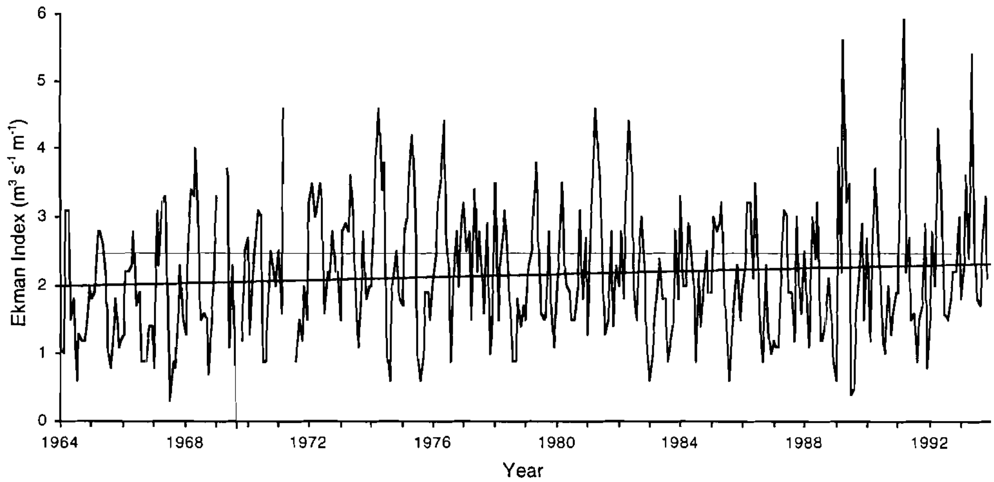

Fig. 12: Ekman CUI calculated from SHIP data in the Mauritania region, from 1964 to 1992.

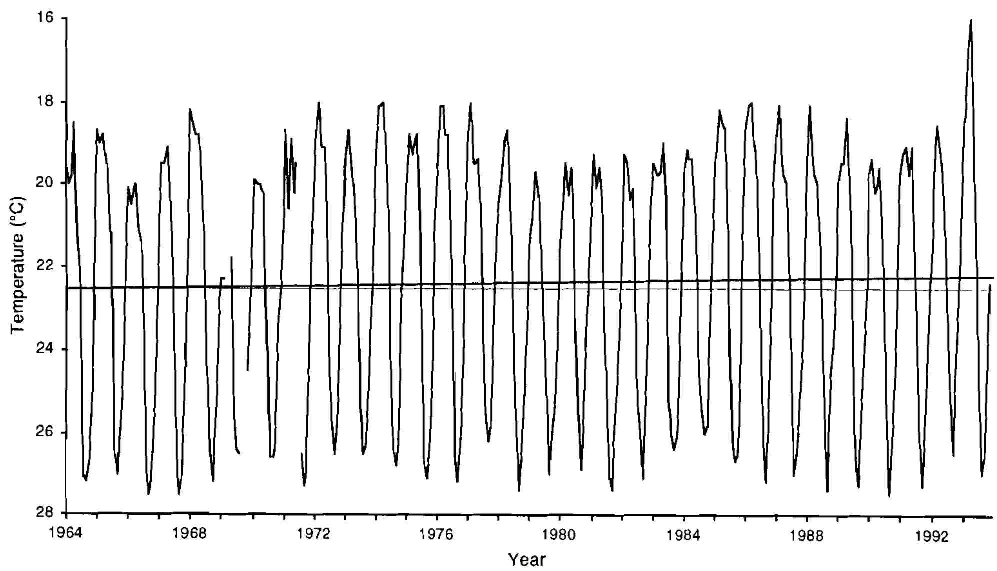

Fig. 13: SST from SHIP data in Mauritania region from 1964 to 1993.

Also, reducing upwelling dynamic to its mean intensity term would be restrictive, as it is obvious that many parameters are required to describe the upwelling dynamic at the different space and time scales involved. Among these, the duration of the upwelling season seems to be a very complementary parameter since no relation can be shown among upwelling intensity, season duration and seasonal timing, whether one uses satellite data or coastal oceanographic measurements (Portolano, 1986).

Similarly, the importance of timing of the hydrological transition on the local fisheries has been shown in Mauritania (Chavance *et al.*, 1991). In other upwelling regions, e.g., in Côte-d'Ivoire, the trend in upwelling season duration appears to have played a major role in the recovery of the *Sardinella aurita* fishery during the last years (Pezennec and Bard, 1992).

4. AN APPLICATION TO THE UNDERSTANDING OF THE SARDINE MIGRATION OFF SENEGAL

A very exceptional seasonal migration of *Sardina pilchardus* (Walb.) occured in Senegal at the end of 1993 (Binet, this vol.; I. Sow, pers. comm.), and represents the main event of the 93-94 fishing cold season for the local small-scale fishery. It seems interesting to examine some possible environmental causes for this anomaly, based on the dynamic of the upwelling seasonality observed from satellite data.

Sardina pilchardus is a pelagic species whose southern occurence (and the associated fishery) in West Africa was extended gradually from north Morocco in the 1920s, to South Morocco and North Mauritania around the 1950s (Belvèze, 1984). The southern extent of the fishery was estimated at 18°N in 1973 (Domanovsky and Barkova, 1981), while specimens where occasionally fished in Senegal in 1974 (Conand, 1975) and 1976 (Fréon, 1988). This species supports important fisheries in Morocco since the 1950s, the main period of southern extension of the species. The microphageous/phytoplanctonic regime of this species enables its development in strong upwelling ecosystems, as off Morocco and Mauritania, where the food web is short and dominated by phytoplanctonic production (Binet, 1991).

The long-term trade winds' increase from 1964 was related to the sardine fishery changes from 26°N to 14°N by Binet (this vol.). The dynamic of the upwelling as depicted from satellite observation from 1984 to 1994 is synthesized in a latitude/time diagram (Fig. 15), Binet's hypothesis.

Satellite observations show that the 1985-86 upwelling season was one of the coldest in term of both mean upwelling intensity and duration. These mean characteristics are confirmed by the SHIP observations, especially for the duration parameter (Fig. 14), while the satellite data shows that the cooling was particularly sudden and uniform from 20°N to 15°N (Cape Vert).

On the contrary, the 1992-93 cold season was characterized by a weak upwelling, associated with a remarkable regularity in the seasonal southward cooling.

We hypothesize that this progressive dynamic – induced by the same regularly zonal propagation of the trade winds – may have an 'attractive' effect on the seasonal migration amplitude of *Sardina pilchardus*, by reducing the natural barrier caused by the spatio-temporal discontinuities of SST it usually encounters. The 19-20°N upwelling discontinuity due to the local upwelling unfavorable coast line orientation (Fig. 5 and Fig. 6) may constitute a thermal barrier to the southward

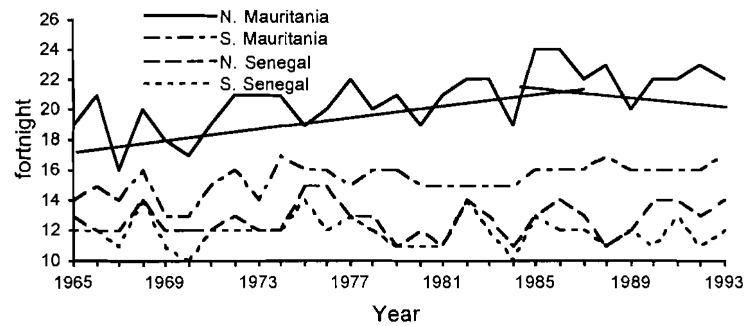

Fig. 14: Cold season duration from North Mauritania to South Senegal calculated from SHIP data for the 1965-1993 period.

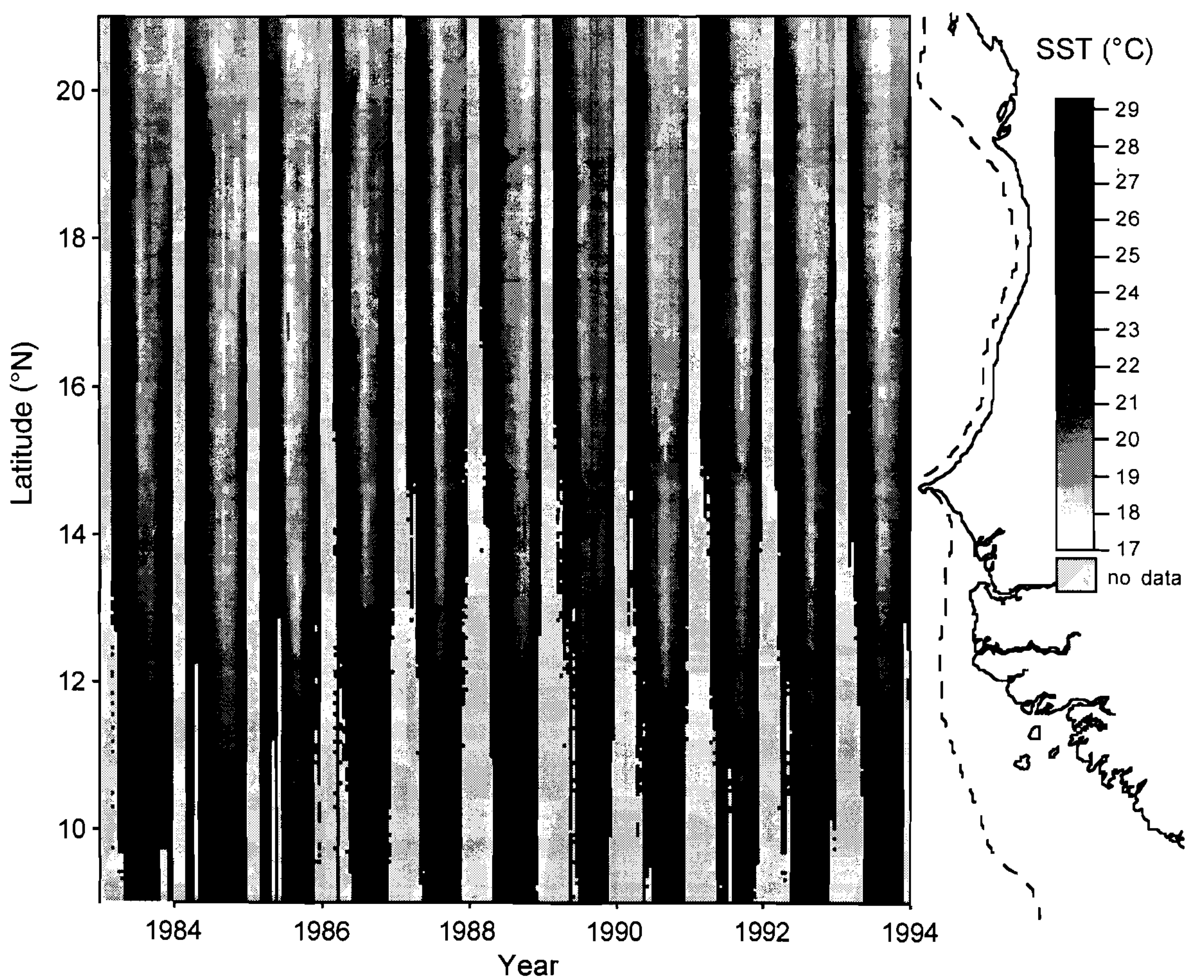

Fig. 15: Spatio-temporal dynamic of SST off West Africa, computed from satellite data for the 1984-1994 period.

migration of *S. pilchardus*. This discontinuity, very well evidenced by satellite observations (Demarcq and Citeau, 1995), reinforces the annual mean thermal gradient around 20°N and may be related to the estimated southern limit of *S. pilchardus*, which fluctuates around 18°N to 21°N since the 1970s.

Thus, the dynamic of the seasonal southward cooling seems to be one of the key parameters that affects the large amplitude seasonal migration of *S. pilchardus*. Thus, Binet's hypothesis appear validated.

Conclusion

Calculation of an SST based coastal upwelling index from satellite data made it possible to describe the short-term dynamic of the coastal upwellings off West Africa. Parameters such as mean upwelling intensity, long-term, trends, short-term, variability, SST zonal gradient, duration of the upwelling season, trends in seasonal variations and spatio-temporal modalities of seasonal transitions must be taken into account to understand the key processes that govern the biological cycles of fish species of economical importance in coastal upwelling areas. This is particularly true regarding the seasonal migrations of small pelagic species in upwelling areas,which are affected by long-term environmental variations and exceptional seasonal conditions. These changes may be considered responsible for the major species substitutions and alternation generally observed in upwelling regions, independently of the effects of fishing effort.

The processed data set shows that the informative potential of precise spatial and temporal remote sensed information would be of great interest for wider areas (such as the whole West African coast). Comparative studies should be conducted to analyze the impact of local environmental anomalies on biological processes in similar coastal upwelling ecosystems.

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