Trends and Variability of Environmental Time Series along the Senegalese Coast

ITAF DEME-GNINGUE

Centre de Recherches Océanographiques
de Dakar-Thiaroye (CRODT)
BP 2241
Dakar
SENEGAL

ABSTRACT

The variability and trends of some environmental time series measured on the Senegalese coast are presented. Since the 1980s, wind speeds are increasing and since 1988, sea surface temperatures are decreasing. Nitrates, which are related to temperature, fluctuate notably during the upwelling periods. Salinity varies depending on many factors such as rainfalls which occur during the hot season. Phosphates and chlorophyll are also variable according to seasons and years. Seasonal variations predominate for the majority of the studied parameters.

RÉSUMÉ

La variabilité et les tendances observées dans certaines séries temporelles d'environnement mesurées sur les côtes sénégalaises sont présentées. Depuis les années quatre-vingt, les vitesses des vents augmentent et, depuis 1988, les températures de surface de l'océan diminuent. Les nitrates, qui sont liés à la température, fluctuent de façon notable pendant les périodes d'upwelling. La salinité varie en fonction de nombreux facteurs, comme les pluies qui ont lieu durant la saison chaude. Les phosphates et la chlorophylle sont aussi variables selon les saisons et les années. Les aspects saisonniers sont prédominants pour la plupart des paramètres étudiés.

Author deceased the 27th of october 1997

Introduction

The environment of the Senegalese coast has been studied in different ways: on the one hand, sea surveys are undertaken at various times of the year; on the other hand samples are regularly taken off the coast. They constitute time series used for a routine monitoring of the hydro-climate.

Others methods such as the monitoring of sea surface temperatures by remote sensing and by ships of opportunity are others means of studying the environment.

Data have been processed in different studies (Berrit, 1962; Rossignol and Aboussouan, 1965; Rébert, 1978; Gallardo, 1981; Portolano, 1981; Teisson, 1982; Rébert, 1983; Touré, 1983). They have permitted to understand the hydrology of the Senegalese coast. The morphological contrast between the north and the south of Cap-Vert and the seasonal contrast, mainly due to the winds, are the main characteristics of the coast. Moreover, the temporal series collected from the coastal stations have shown other phenomena such as a North-South shift of the upwelling phenomenon on the fringe of the coast. Indeed the upwelling lasts longer in the South than in the North and seems to start sooner in the South (Teisson, 1982). However, because of the importance of the upwelling in the enrichment of the Senegalese waters, most of those works tend to study parameters such as temperature or wind. The other parameters, such as salinity and nutrient salts have so far attracted very little attention.

The aim of this note is to determine the variability and trend of the various parameters monitored from coastal stations. The wind will be also considered because of its impact on the dynamic of the upwelling.

1. Material and methods

1.1. Choice and distribution of stations

The first coastal stations along the Senegalese coastline have been established in the 1950s. Rightaway, it appeared that the Senegalese coast should be divided into three zones (the Grande Côte in the North, the Cap-Vert area and the Petite Côte in the South). Thus, stations were established such as to cover these three sectors. From North to South, we have stations at Saint-Louis, Kayar, Yoff, Thiaroye, Gorée and Mbour (Fig. 1). They have progressively been established and consequently time series are available from ten to twenty years.

These stations were established to monitor the hydrology of the marine zone regularly, and at a low cost. The Cap-Vert stations, like all the others, were located such as to monitor the littoral. These stations, however, benefit from the proximity of the CRODT laboratory whose team of technicians can carry out on the spot sampling. This makes it possible to sample nutrient salts and phytoplankton in addition to the physical parameters.

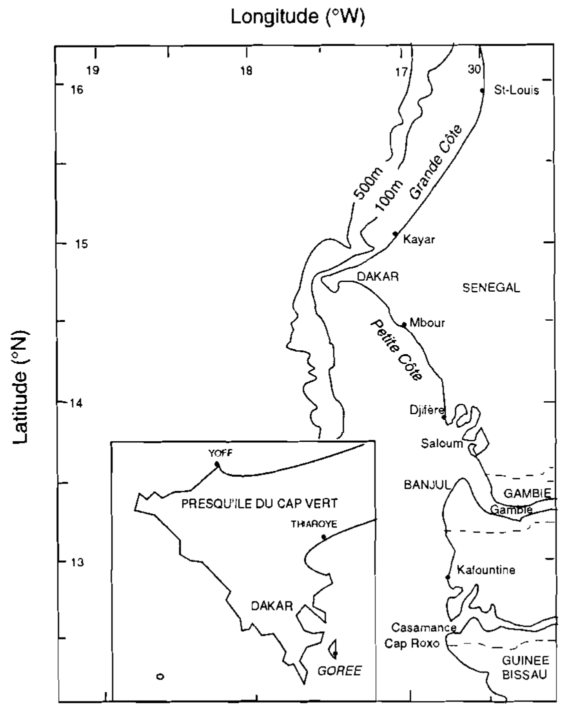


Fig. 1: Location of coastal stations (dots) off Senegal.

1.2. Frequency and mode of the sampling

Sampling at coastal stations is done with buckets. The temperature and salinity data are collected daily. Subsamples are collected in 200 ml glass bottles for salinity and 250 ml for chlorophyll measurements; for nitrates and phosphates, 50 ml bottles are used. The nutrient salt samples are taken weekly from two of the three Cap-Vert stations, i.e., from Gorée and Yoff. Thiaroye station is too polluted for these parameters to reflect what really happens in the open sea. Chlorophyll samples are taken every day at Yoff and Thiaroye and every week at Gorée. The time series of nutrient salts are very short (they only cover the last three years), whereas the salinity and temperature series cover all the stations for periods of up to thirty years. The wind data are gathered every three hours and come from the Dakar-Yoff meteorological station. These data have been collected for about thirty years.

1.3. Method

Temperatures are measured with a precision of 1/10th of a degree Celsius, using a mercury thermometer; a digital salinometer is used in the laboratory to determine salinity. The nutrient salt samples are kept at a cold temperature in chloroform as soon as they are taken. Estimation of nutrient salt levels is done using the method of Strickland and

Parsons (1972). Chlorophyll levels are estimated using a Turner 111 fluometer; when the chlorophyll concentration was very high, a Bausch-Lomb 2000 spectrophotometer was used.

2. RESULTS

2.1. Temperature

The temperature daily data show that there is little variability from one day to the next, except for the cold season, during which diurnal fluctuations of over 1°C are sometimes observed. The monthly mean temperature measured in one station for all the years vary according to seasons. The length of the cold season is variable and depends on the station considered.

At Mbour, the variations around the monthly median were relatively weak from 1959 to 1992 particularly during the hot season. The strongest fluctuation is observed in February. The cold season (below 24°C) goes from November to mid May and the minimum temperature is about 19°C. On the 'Grande Côte' along the north part of the coast, as well as at Cap-Vert, we observed higher variations at the beginning and at the end of the cold season, and during the transitional season (from October to December and from April to June). The minimum temperature are about 16°C at Saint-Louis and 17°C at Yoff. A progressive warming can be observed as one moves southward. During the hot season, the dispersion of the temperatures is higher in this zone than in Mbour. The cold season seems shorter than in Mbour and lasts from December to mid April. At any given station, the temperature gaps between the cold and hot seasons are very high (over 10°C). The highest difference is about 15°C. We also note that the annual mean temperature increases from North to South, that is from Saint-Louis to Mbour. This North-South tendency is, however, disturbed by the station of Thiaroye, which record lower temperature than at Yoff and Kayar. At all stations, the annual mean temperature (Fig. 2) clearly show periods of low temperatures from 1974 to 1977 and from 1985-1986. From 1988 on, a decrease is noticed which continues until 1991. In 1992, the temperatures increased again. The annual average temperatures are relatively high and vary from 1964 to 1970.

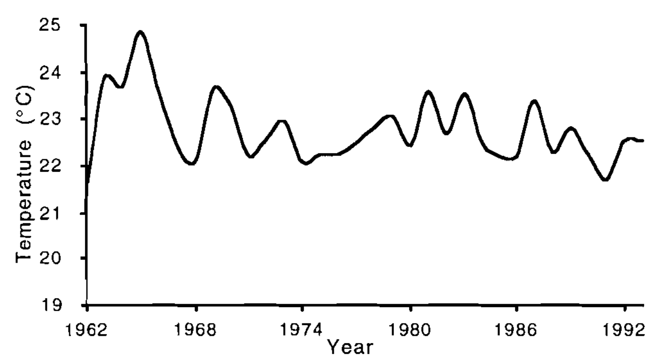


Fig. 2: Annual mean temperatures from 1962 to 1992 for coastal stations off Senegal.

2.2. Salinity

The daily salinities show a relatively important variability (up to 1‰). The evolution of monthly mean salinity is relatively stable between January and May, increases in June and reaches its maximum in July. Between August and September, a minimum of salinity is observed and the gaps between minimum and maximum salinity are smaller in the Cap-Vert stations, particularly during the cold season. They are important in Mbour and Saint-Louis. No North-South trend is noticed however. On the other hand, the decrease of average salinity is sharper and lasts longer at Saint-Louis than at the other stations. Between March and April, a slight decrease of salinity is observed at the stations of Mbour and Saint-Louis, whereas at Kayar and at Cap-Vert, this phenomenon does not occur. In fact, at Cap-Vert, between January and June, the salinity is hardly variable, but stays between 35 and 36‰. The seasonal variability of salinity is weaker than that of temperature. However, a clear prevalence of the average salinities occurs between September and December.

The annual average of the salinities shows that at Cap-Vert (Fig.4, Yoff and Thiaroye), from one station to the other, the salinity does not vary. On the Grande Côte, during the 1960s and 1970s, salinities increased from Saint-Louis to Kayar and became stable from the 1980s (Fig. 4). In the same way until 1983, the salinities at Mbour became closer to those at Saint-Louis (Fig.4). The annual mean for salinities at all stations (Fig.3), shows a progressive increase from the 1970s, and a maximum is observed in 1987.

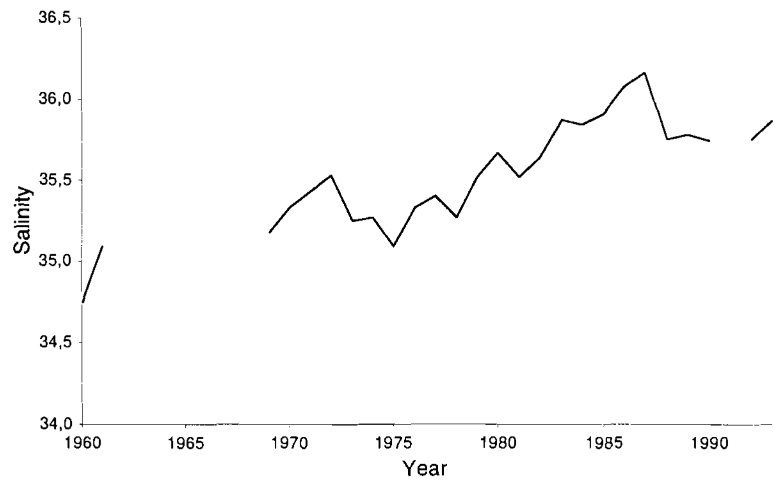


Fig. 3: Annual mean salinity at coastal stations off Senegal.

2.3. Winds

Analyses of wind data from the Senegalese coast have been presented by Rébert (1978), Portolano (1986), Roy (1989) and Roy (1992). Monthly wind mean speed (Fig. 5a) shows a progressive increase between January and April. From May, there is a decrease which reaches the minimum of August-September. The fluctuations of speed around the median are strong all throughout the year, the maxima and minima always being constant. The gap in relation to the median slightly diminishes from mid-June to mid-August. August has the highest extreme values and rather high average speeds.

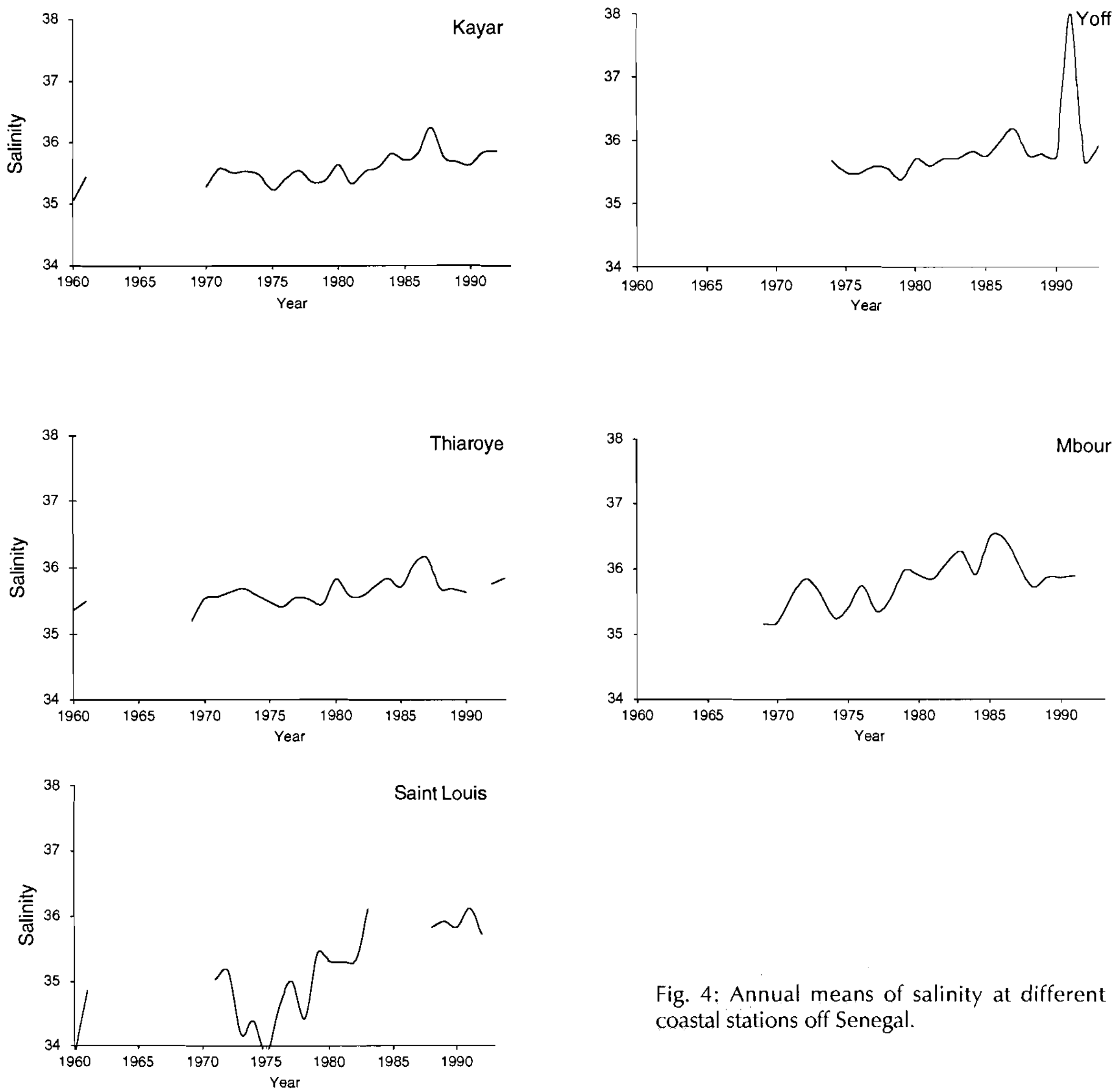


Fig. 4: Annual means of salinity at different coastal stations off Senegal.

The evolution of mean annual wind speed between 1964 and 1992 is presented in Fig. 5b. Note the peak in the early 1970s and the increase in the late 1980s - early 1990s.

2.3.1- The upwelling index

The Senegalese coastal upwelling strength can be determined using the normal component of the Ekman transport (Teisson, 1982). Because the orientation of the coast is different north and south of Cap-Vert, an upwelling index has been calculated for each of these areas using wind data from 1964 to 1991. This index is calculated using the equation :

$$IUC = rCd * V_2/2 * g * \sin(j) \qquad (1)$$

where:

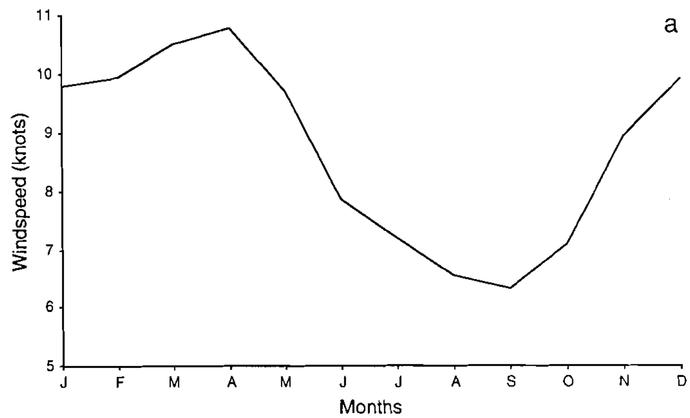
r= air density;

Cd= rugosity coefficient;

V_2= square parallel to the coast wind component;

g = earth rotation angular speed;

j = latitude.



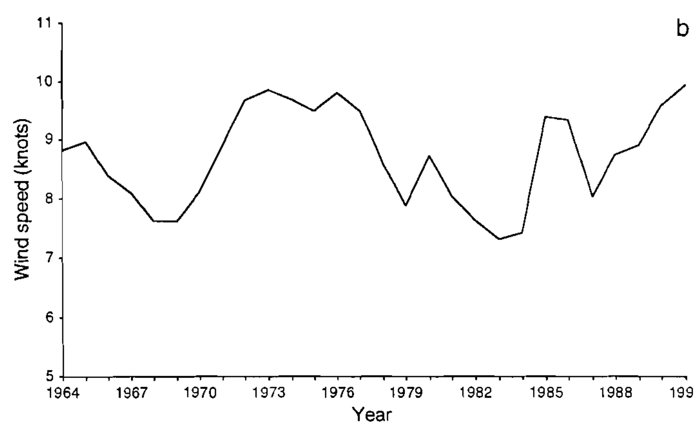


Fig. 5: Wind speed (in knots)
a) montly means; b) annual means.

This index depends, among other things, on wind intensity (Bakun, 1973). The monthly means of the upwelling index for all years 1964-1991 (Fig. 6a) show a strong variability. In June - September, the variability is weaker. In the southern zone, the monthly mean index is positive throughout the year (between 1.50 and 0.10), whereas in the North it is equal to zero or becomes negative in June - September. South of Cap-Vert, the mean index increases from January to April and from September to December. In the North, the peak is reached between March and April. Moreover, the mean indices observed in the South are higher than those in the North. The mean upwelling indices (Fig. 6b) show a period of strong upwelling from 1972 to 1977. The index was strong in 1985 and has been growing since 1988. The mean index was higher in the South during those years. However, it varies in the same way in the two zones. The upwelling indices calculated from wind data collected at sea by trade ships (Roy, 1992) are higher than those calculated from data collected at Yoff. They show that from 1971, the index started to increase and reached a peak in 1973. Starting from 1975, the index leveled off and remained high in the North as well as in the South. The North-South difference is relatively weak but the index is generally higher in the South.

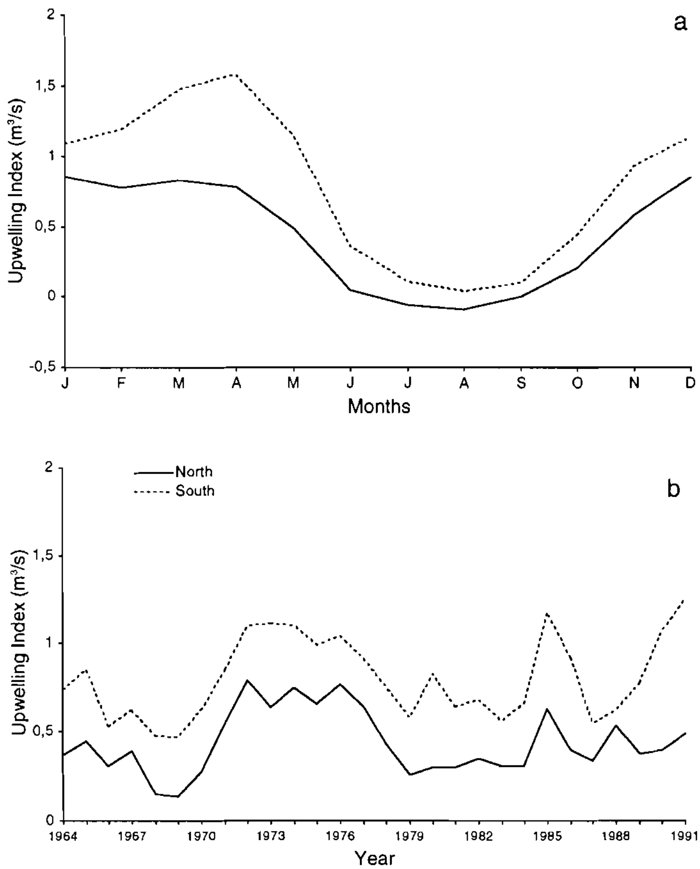


Fig. 6: Upwelling index (m^3/s) a) monthly mean for the areas north and south of Cap-Vert, Senegal; b) annual means.

2.4. Nitrate

Monthly mean nitrate (Fig. 7) increases from January to reach a peak in May. At Gorée the values get close to zero from August whereas at Yoff, the concentrations are generally higher. Monthly means show that maxima as well as concentrations vary from one year to another. At Gorée (Fig. 7a) concentrations measured between January and May 1991 are generally higher than those measured during the other years. The peak is reached in April and May. In 1992 the maximum at Gorée was measured in April and concentrations, although weak starting from June, were still noticeable throughout the rest of the year. They were generally higher than those of 1993. In 1993 the highest nitrate concentrations were measured in February at Gorée and were nearly zero between July and October. At Yoff (Fig. 7b) in 1991, nitrates reached a peak in June whereas in 1992 and 1993, this peak was observed in March and February respectively. The average concentrations measured in 1991 are generally higher than those of the other two years, and those of 1992 are higher than those of 1993 which become null between July and October. The variability around the mean is higher during the cold season and can reach 80% of the mean. The inter-annual variability is also rather marked at each station.

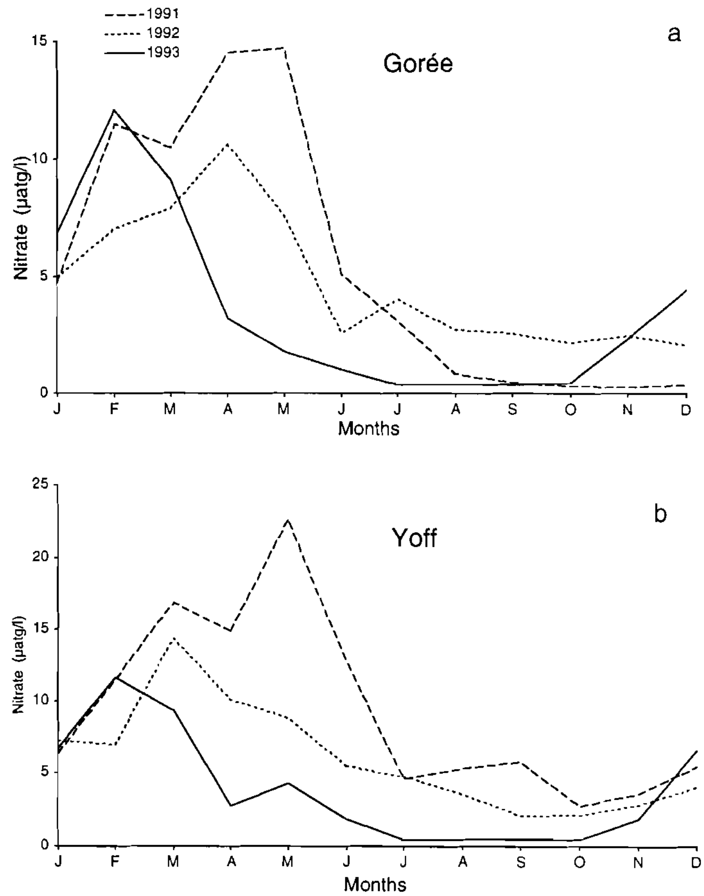


Fig. 7: Monthly means of nitrates in 1991, 1992 and 1993
a) at Gorée; b) at Yoff.

2.5. Phosphates

Monthly mean phosphate (Fig. 8) shows an increase in average values during the cold season, with a peak in March. Concentrations are lower from July to December, and the minimum occurs in August. Concentrations are higher at Gorée than at Yoff. The monthly means for each year and station show that while in Gorée (Fig 8a) the highest concentrations occurred from January to May in 1991 and 1993; in 1992, they occurred from August to November. Peaks were observed in February for the year 1993, in March for 1991 and in September for 1992. At Yoff (Fig. 8b), the highest phosphate concentrations were measured in May 1991, February 1993 and September 1992. At these two stations the measured concentrations were generally higher during the 1991 cold season. The variability around the mean is relatively high during the cold season; It can reach 36% of the mean, while the concentrations are lower and less variable during the hot season.

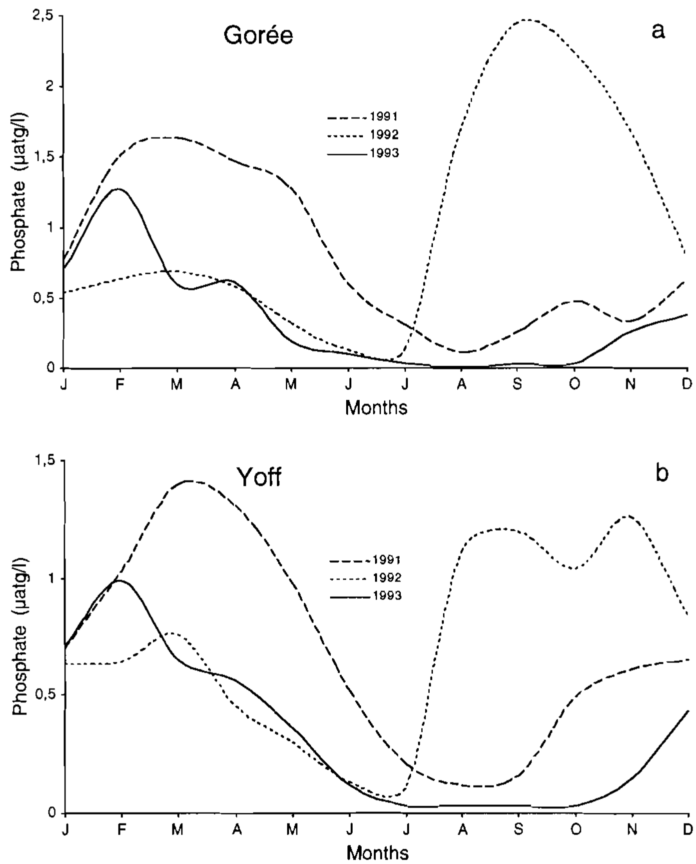


Fig. 8: Monthly means of phosphates in 1991, 1992 and 1993
a) at Gorée; b) at Yoff.

2.6. Chlorophyll

At the three stations of the Cap-Vert, monthly mean chlorophyll (Fig. 9), shows a great seasonal variability. In fact, two periods can be seen: from January to June, when high concentrations of chlorophyll can be measured at all stations; and from July to December when chlorophyll concentrations are extremely low. The highest peak for chlorophyll is measured in May at the various stations except at Thiaroye where a higher second peak appears as early as February.

At Yoff and at Gorée, chlorophyll concentrations are rather close and lower than at Thiaroye.

The evolution of the monthly means per station and per year shows that :
- at Gorée (Fig. 9a), there were higher concentrations in 1993, with a peak in May. In 1991 and 1992, the peaks were

reached in May. A secondary peak occurred, however, in July 1992 and an important decrease of concentrations appeared from September; in 1991 this decrease occurred as early as July;

- at Yoff (Fig. 9b), chlorophyll concentrations were higher in 1993 than in the other years and, unlike the general mean the maximum was reached in July. In 1992, the maximum chlorophyll occurred in February, whereas in 1991 it was in May;
- at Thiaroye (Fig. 9c), the concentrations are higher than at the other stations. In 1991 the maximum was measured in May, while in 1992 two peaks were observed in April and June.

The intra-seasonal variation is generally stronger during the cold season and the inter-annual variability is high particularly at Thiaroye.

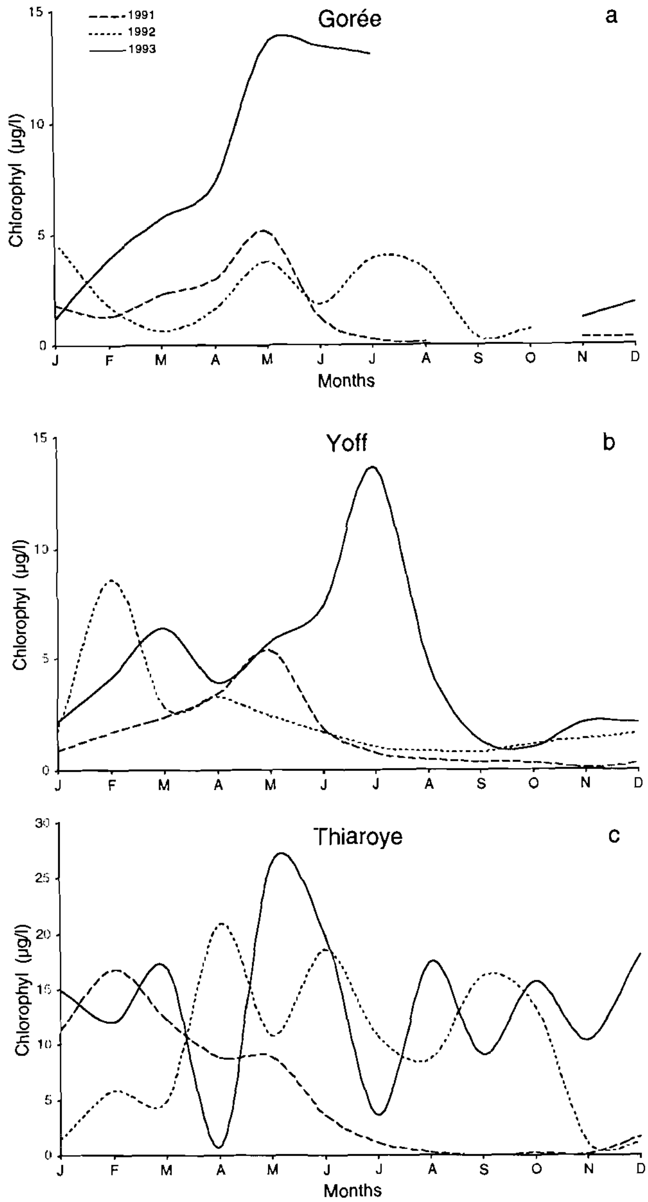


Fig. 9: Monthly chlorophyll concentration (µg/l) in 1991, 1992 and 1993 a) at Thiaroye; b) at Yoff; c) at Thiaroye.

Discussion

Comparisons show that during the period 1964-1991, temperature and wind speed varied inversely through time. According to coastal upwelling indices, the upwelling has generally been weaker north of Cap-Vert according to the two wind data sources (Yoff station and ships of opportunity). However, the temperatures at Mbour and Saint-Louis recorded opposite signals. This may be explained by the fact that on the southern coast, the upwelling is situated at the same level as the continental slope, whereas in the northern zone, the upwelling takes place near the coast (Deme-Gningue *et al.*, 1990). Thus, lower temperatures are measured in this zone when the indices show that the upwelling is stronger on the southern coast.

The fact that the variation of temperatures is weaker at Mbour than near Saint-Louis and Yoff may be due to the remoteness of the upwelling sources in this area, compared to the two other areas. Towards south of Cap-Vert, the gradual increase of minimum temperatures may also be explained by this phenomenon; this confirms results obtained during the CIRSEN survey (Deme-Gningue *et al.*, 1990). The fact that temperatures recorded at Thiaroye and Gorée are lower than those measured at Yoff and Kayar stations, further north, may be explained by the orientation of the coast in that area and to a local phenomenon that concerns only the bay of Gorée (Teisson, 1982).

An analysis of seasonal variability of salinity, based on the division between the upwelling season and the hot (rainy) season is not very conclusive because, during the rainy season there is a period of strong decrease of salinities which increase rapidly afterward. The decrease in salinity at stations Thiaroye and Yoff from August to September and up to mid-October may be due to the arrival of the Guinean waters (Toure, 1983; Rébert, 1983). The fact that the rain water draining system is more dense at Thiaroye and Yoff than at Goree may explain why the salinity is higher at Gorée. In the same way, changes in rain patterns may be the cause for the gradual increase of salinities since the 1970s.

The concentrations of nutrient salts and phytoplankton biomass at coastal stations appears to be closely linked to the temperatures measured at those sites. In fact, a temperature-nitrate relation (T-NO3) can be clearly observed at Cap-Vert stations, and also at Yoff and Gorée. It is represented by a steep straight line which tends to later stabilize. In 1991 the straight line was between 15 and 21°C, with a more gentle inclination at those stations. According to those observations, the T-NO3 relation is not variable in space in a given year, and its shape is the same through time. Indeed, nitrates decrease quickly as temperatures increase and this up to a certain level which may vary from one year to another. We can also note that the 1991 upwelling was stronger than the 1992 one, as the temperatures were clearly lower in 1991. It seems that the gradient of the line T-NO3 is more gentle when the upwelling is weaker, and thus the threshold temperature increases.

The variability of the gradient of the T-NO3 relation may be linked to the evolution of the threshold temperature of the straight part of the curve, which may explain the gradient. Thus, variability, which according to Oudot and Roy (1991) and Bakun (1986) expresses the biological mechanisms of the ecosystem, only reflect the speed at which the waters are brought up to the surface. The gradient is more gentle when the speed is low. In fact, we can refer to the explanation of Rébert (1983) concerning upwelling waters which can be relatively warm and still rich in nutrient. According to Rébert (1983) the thermal response of the ocean in relation to wind variations should be around 2.5 days. Thus, a hypothesis which may explain this phenomenon is that the distance between the station and the source of the upcoming would cause a warming up of the waters before they reach the coast. This, combined with the proximity of the continent and the shallowness of the waters are factors which may explain the characteristics of our observations.

The evolution of temperatures and chlorophyll through 1991 shows that apart from Thiaroye station, the trade winds period is the richest in chlorophyll. At Yoff, as well as at Gorée, the chlorophyll peak is observed in May, whereas minimal temperatures are measured in February-March. On the opposite, at Thiaroye, the chlorophyll maximum is observed in November, a month of abnormally high upwelling index for the period considered. The temperature-chlorophyll relation (T-CHL) in 1991 at Thiaroye station looks like those of T-NO3. The threshold of the line would be at 22°C. For 1992 the relation T-CHL is different from that observed in 1991. A definite form which links the two parameters cannot be identified at any of the stations. The 1992 observation on the T-CHL relation conforms better to the T-CHL relation theories, because temperature is not the explanatory factor for chlorophyll concentrations. The year 1991 is not a typical case. The shape of the 1991 chlorophyll-temperature curve, which is the same as the shape of the T-NO3 curve at Thiaroye is best explained by the presence, at that station, of macrophytes whose chlorophyll, mixed with that of the phytoplankton, could influence the relationship (Dème-Gningue *et al.*, 1990). The chlorophyll-nitrate relation (CHL-NO3) is less simple than the one between temperatures and nitrates because nitrate is not the only important parameter for the development of phytoplankton. In 1991 and 1992, chlorophyll increased with nitrates to reach about 10 µg/l of nitrate and then decreased. This threshold, which was constant for 1991 and 1992 at Yoff and at Gorée may be variable depending on conditions of light and water stability. The work done at Cap-Vert stations permits to analyze the variability of the T-NO3 relation. It always has the same shape of a line whose slope varies from one year to the next. On the other hand the relation between the upwelling, the presence of nutritient salts and the development of phytoplankton is determined by nitrate increase coupled with temperature decreases. The threshold of this relation corresponds to the lull of winds and the start of the increase of chlorophyll concentration.

The correlation between the different parameters studied are significant only for temperature and nitrate. Nitrates and temperatures have a negative correlation which is weaker on a monthly basis than on a seasonal basis. On the contrary, the correlation between the station and the various parameters are all very weak. The nitrates concentrations at Yoff are on average higher than at Gorée. This can be explained by the location and physical environment of these stations. The station of Yoff is closer to the shore and further North.

References cited

Bakun A. 1973. Coastal upwelling indices, west coast of North America, 1946-1971. *U.S. Dept. Commer. NOAA Tech. Rep. NMFS SSRF*, 671, 103 p.

Bakun A. 1986. Definition of environmental variability affecting biological processes in large marine ecosystems. *In*: K. Sherman and L.M. Alexander (eds.). *Variability and management of large marine ecosystems*. AAAS selected symposium, 99:89-108.

Berrit G.R. 1962. Contribution à la connaissance des variations saisonnières dans le golfe de Guinée. Observations de surface le long des lignes de navigation. II. Etude régionale. *Cah. Océanogr. COEC*, 14 (9): 633-643.

Dème-Gningue I., C. Roy and D. Touré. 1990. Variabilité spatio-temporelle de la température, des nitrates et de la chlorophylle devant les côtes sénégalaises. *Doc. scient. CRODT*, 122.

Gallardo Y. 1981. On two marine ecosystem of Senegal, separated by a peninsula. *In*: J.C.J. Nihoul (ed.). 12th. Int. Liège Colloquium on Ocean Hydro-dynamics, Liège (Belgium), 1980. *Eco-hydro-dynamics*. Elsevier, Oceanogr. Sér., 32: 141-154.

Portolano P. 1981. *Contribution à l'étude de l'hydroclimat des côtes sénégalaises*. Rapp. interne CRODT/ORSTOM, vol. 1 (Texte), 68 p. vol. 2 (Fig.), 61p.

Portolano P. 1986. Analyses des séries vent-températures de la mer en surface des côtes sénégalaises. *Océanog. trop.*, ORSTOM, 21 (2): 205-227.

Oudot C. and C. Roy. 1991. Les sels nutritifs au voisinage de Dakar: cycle annuel moyen et variabilité inter-annuelle. *In:* P. Cury P. and C. Roy (eds.). *Pêcheries ouest-africaines: variabilité, instabilité, changement.* ORSTOM, Paris: 80-89.

Rébert J.P. 1978. Variabilité des conditions de surface dans l'upwelling ouest-africain. Comm. 100. Symposium sur le courant des Canaries: Upwelling et ressources vivantes. *Doc. scient. CRODT*, 67, 27p.

Rébert J. P. 1983. Hydrologie et dynamique des eaux du plateau continental sénégalais. *Doc. scient. CRODT*, 89, 99p.

Rossignol M. and M.T. Aboussouan. 1965. *Hydrologie marine côtière de la presqu'île du Cap-Vert. Contribution à l'étude de la productivité des eaux.* Publ. prov. ORSTOM. 2° partie, 166 p.

Roy C. 1989. Fluctuation des vents et variabilité de l'upwelling devant les côtes du Sénégal. *Oceanologica Acta*, 12 (4): 361-369.

Roy C. 1992. *Réponses des stocks de poissons pélagiques à la dynamique des upwellings en Afrique de l'ouest: analyse et modélisation.* Thèse de doctorat. Editions ORSTOM, coll. Etudes et Thèses, Paris.

Strickland J.D.H. and T.R. Parsons. 1972. *A practical handbook of seawater analysis.* Fish. Res. Board of Canada Ottawa, 167, 2nd ed.

Teisson C. 1982. Application de la théorie d'Ekman à l'étude des courants et des remontées d'eau profondes le long des côtes sénégalaises. *Doc. scient. CRODT*, 106, 79 p.

Touré D. 1983. Contribution à l'étude de l'upwelling de la baie de Gorée (Dakar, Sénégal) et de ses conséquences sur le développement de la biomasse phytoplanctonique. *Doc scient. CRODT*, 93, 186p.