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Environmental and stock effects on the recruitment of anchovy in the Bay of Biscay : a multivariate analysis

by

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Variability in anchovy recruitment in Biscay is temptatively explained using variables from the stock and from the environment during the ichtyoplankton phase. Anchovy recruitment depends on many different processes : weight of adults and proportion of multiple spawners (age 2), river discharges, upwelling events at the coast and at the shelf break. Meteorological variables (wind, rain, temperature) are forcing effects on the sea but they are not the effective processes that govern the production in the sea. So they do not relate directly to the survival of larvae and to recruitment. In Biscay, many different physical processes are active and used by anchovy which spawns in different physical systems (river plumes, open ocean enrichment systems). Therefore we use a hydrodynamical physical model to construct environmental variables that relate directly to the physical processes that occur in the sea. Such environmental variables are thought to have a more powerfull explanatory power than general meteorological variables alone. Stock effects are parametrised by the importance in the population of year class 2 and by individual average weight. Environmental effects are physical indices derived from the physical model: vertical turbulence, stratification, upwelling, river plumes. As we have a small amount of years and a lot of variables, a step by step regression analysis (Linear Model) is used to analyse hierarchy in the explanatory power of the factors. Upwelling is the first explanatory variable with a very strong positive effect on recruitment, then comes breakdown of stratification events with a negative effect. All other variables have a smaller explanatory power on recruitment and the stock effect is found to be not significant. A model with 2 physical variables explains 80% of the recruitment variability observed in the 1987-1996.

Keywords : bio-physical coupling, recruitment, anchovy, hydrodynamics, step by step regression

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1. Introduction

Variability in anchovy recruitment in Biscay is temptatively explained using variables from the stock and from the environment during the ichtyoplankton phase. The anchovy stock in ICES area VIII is composed majorly by ages 1 and 2 (85% of the catches). Population biomass has varied since 1987 from 10 thousand to 100 thousand tonnes without trend (Fig. 1). The understanding and prediction of recruitment is of critical importance for scientific advise and fishery regulation rules. We use ICES assessments for age 1 (year n+1) as a recruitment index for year n (Fig. 1) between 1986 and 1997.

Various hypotheses have been put forward to explain the mechanisms leading to recruitment variability. Hjort (1914) suggested that first feeding was a critical period for fish larvae. Cushing (1975) noted that coincidence of peak spawning and high prey abundance from the spring phytoplankton bloom could be a major determinant of recruitment success ("match-mismatch" theory). Sinclair (1988) argued that physics predominates over food chain processes in the control of population biology (retention mechanisms, etc.). Lasker (1978) showed the negative effects of turbulence caused by strong winds on anchovy larvae feeding and survival. Marteinsdottir & Thorarinsson (1998) found that Iceland Cod recruitment depends on the age of the spawners ("maternal influence" : eggs and larvae from multiple spawners show a higher survival rate).

There are many candidate processes in Biscay that can affect anchovy recruitment : weight of adults and proportion of multiple spawners, river discards, upwelling events at the coast and at the shelf break (cf. Fig. 2 & 3), larval drift... Meteorological variables (wind, temperature, river discards) are forcing effects on the sea but they are not the effective processes that govern the production in the sea. So they do not relate directly to the survival of larvae and to recruitment. In Biscay, many different physical processes are active and used by anchovy which spawns in different physical systems (ie, river plumes, open ocean enrichment systems). Therefore we use a 3D hydrodynamical physical model (IFREMER Brest) that simulates ocean processes occuring over the Biscay french continental shelf to construct environmental variables that relate directly to the physical processes that occur in the sea.

2. Methods

More than fifty variables have been constructed to describe the variations of Gironde river plume, coastal upwelling and stratification / turbulence processes occuring between March and July on the continental shelf of SE Bay of Biscay (south to 46°5 N). Linear regressions with each set of 1, 2...7 variables are adjusted to the recruitment index. Among the "best" regressions according to the R^2 criterion (highest R^2 for a fixed number of parameters, cf. Fig. 4), we have selected the models which variables are all significant according to a Student's *t* test (Fig. 6). A "stock" variable (biomass of ages 2 and more) has also been included in these models, but it appeared not to be significatively influent.

3. Results

The variables and corresponding physical processes selected by this procedure are, in order of their explanatory power :

(1) *upwelling* index, which is the summed positive "vertical speed" over the period March-July along the Landes coast (SW France). Vertical speed corresponds to the weekly mean vertical current from the bottom to the surface (tide effects have been filtered). These upwelling events are caused by moderate and intermittent easterly to north-easterly winds (Fig. 9), which is different from Eckman-type large upwelling systems. Their influence appears always positive and especially crucial in March-May (before the peak spawning), according to the examples of the 2 best recruitment years 1991 and 1997.

(2) *destratification or high turbulence* index, which is a binary variable describing stratification breakdown events in June or July concerning the waters above the whole continental shelf. These events are obviously linked with periods of strong westerly winds (>15 m/s) in June or July (Fig. 8) and could have caused important larvae mortality (after the peak spawning) responsible for the bad recruitments in 1987, 1988 and 1990.

(3) *Stratification or river plume surface* indexes, which correspond to years with a high level of stratification caused by important to exceptionnal Gironde river outflows over the period, and that would have a possible negative impact on anchovy recruitment (especially in 1994 and 1995).

4. Discussion - Conclusion

Anchovy recruitment in the Bay of Biscay from 1986 to 1997 is thus well explained (75 %) as the result of the influences of easterly and westerly wind regimes, affecting two crucial oceanic processes for larvae (respectively weak upwelling and stratification) in their importance and/or succession in the spring and summer. Moderate eastern winds (anticyclonic regime) and Western gale winds (cyclonic regime) are exclusive. Unlike large upwelling systems governed by one wind regime, the physics in South Biscay is governed by the balance between 2 exclusive meteorological regimes which generate respectively 2 exclusive physical processes, upwelling and breakdown of stratification. Upwelling has a positive effect where as loss of stratification has a negative effect on recruitment. This situation explains why Linear Regression methodology has been appropriate in this study and why there is no dome-shaped relation of Recruitment with wind as in the « optimal envionmental window » of Cury and Roy 1989.

Borja et al. 1996 first found that the upwelling was well correlated to recruitment. They used ctach data to estimate recruitment and used a wind index for recruitment. The physical model shows that northern winds produce little upwelling along the french coast where as NE to E winds do. In this study the other difference with Borja et al. 1996 is that we have found an important impact of turbulence when they have not.

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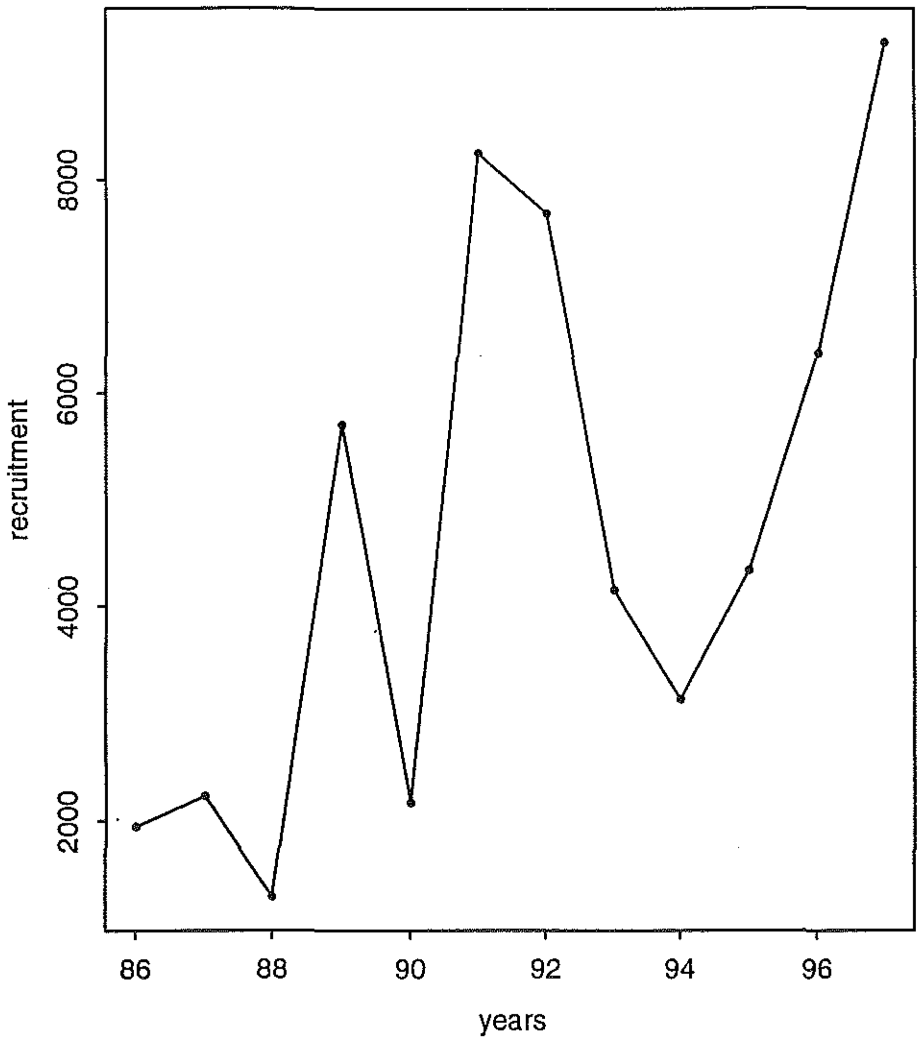
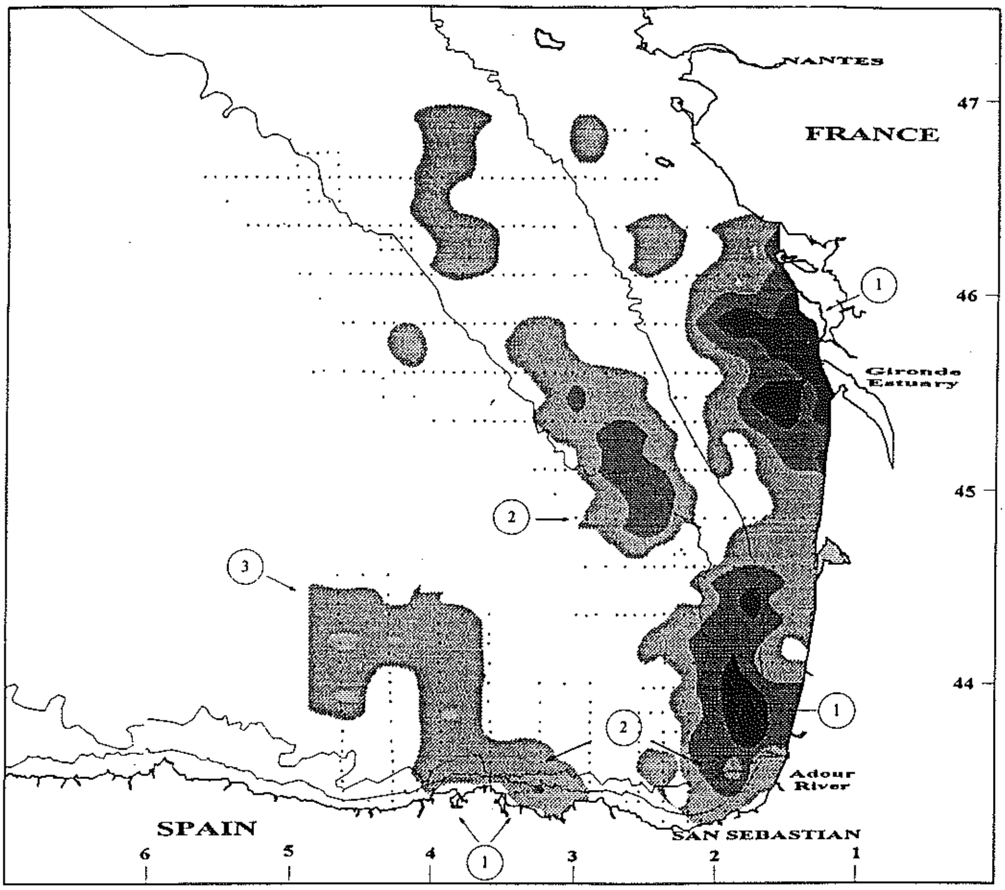
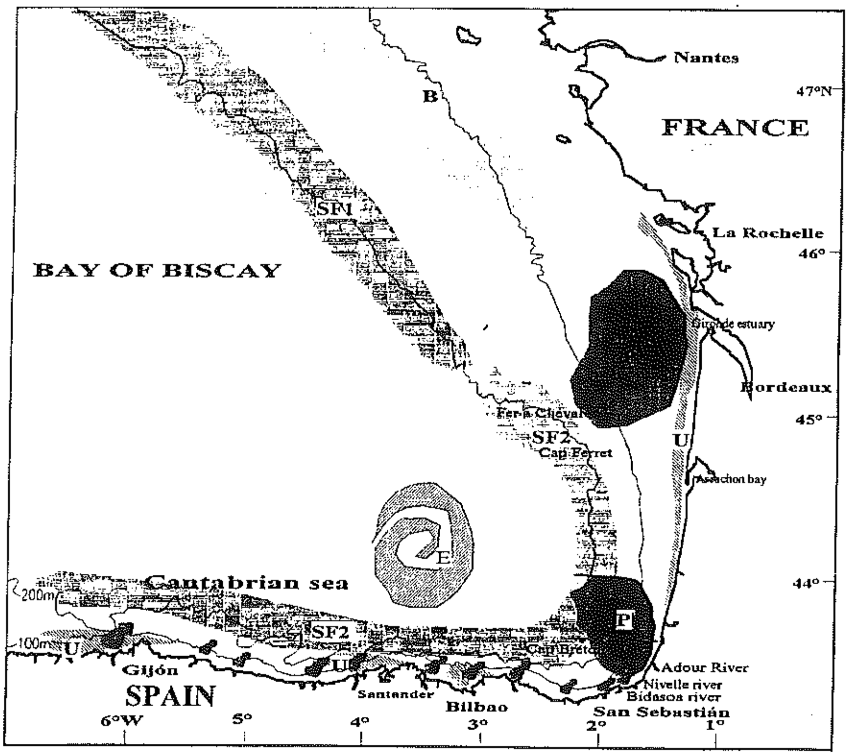


Fig. 1- Recruitment estimations for the Bay of Biscay anchovy 1986-1997 (from ICES 1998).



Bay of Biscay map showing the major spawning areas of anchovy (example corresponding to the survey of 1992 made from 16 May to 13 June) (Motos *et al.*, 1996): 1- Coastal spawning associated with the areas influenced by river plumes. 2- Shelf edge spawning areas associated with the shelf break fronts 3- Offshore spawning areas associated with oceanic eddies.

Fig. 2- in Borja et al. (1996)



Synoptic description of the main oceanographical features linked to anchovy spawning. U=Upwelling, P=River Plumes, E=Eddies, SF1 and SF2=shelf edge fronts. B='bottom cold water (<12°C) tongue'.

Fig. 3- in Motos et al. (1996)

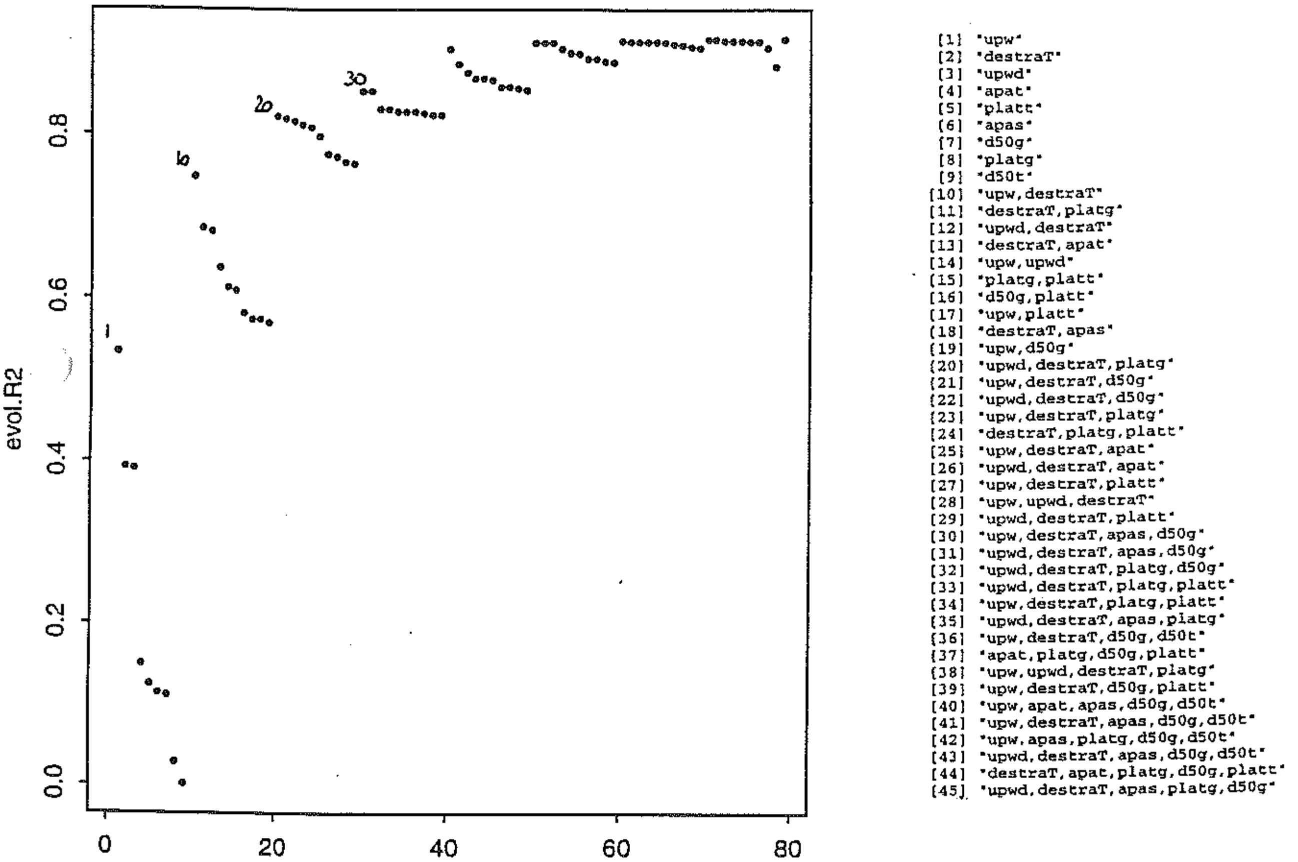


Fig. 4- The "best" models selected on the R^2 criterion. Left : R^2 of the best models with 1, 2…7 variables (in successive groups). Right : Variables of the different models shown on the figure (models are in the same order). *upw* : upwelling index from (cumulated positive vertical speed) from March to July - *destraT* : binary index for destratification events in June-July – *upwd* : upwelling index (cumulated positive vertical speed) from March to mid-May – *apat* : cumulated surface of Gironde river plume over the period March-July – *platt* : mean thermic stratification level in July – *apas* : cumulated surface of Gironde river plume south to 45°30'N over the period March-July – *d50g* : date corresponding to the time when 50 % of mean July global stratification level is reached - *platg* : mean global stratification level in July – etc.

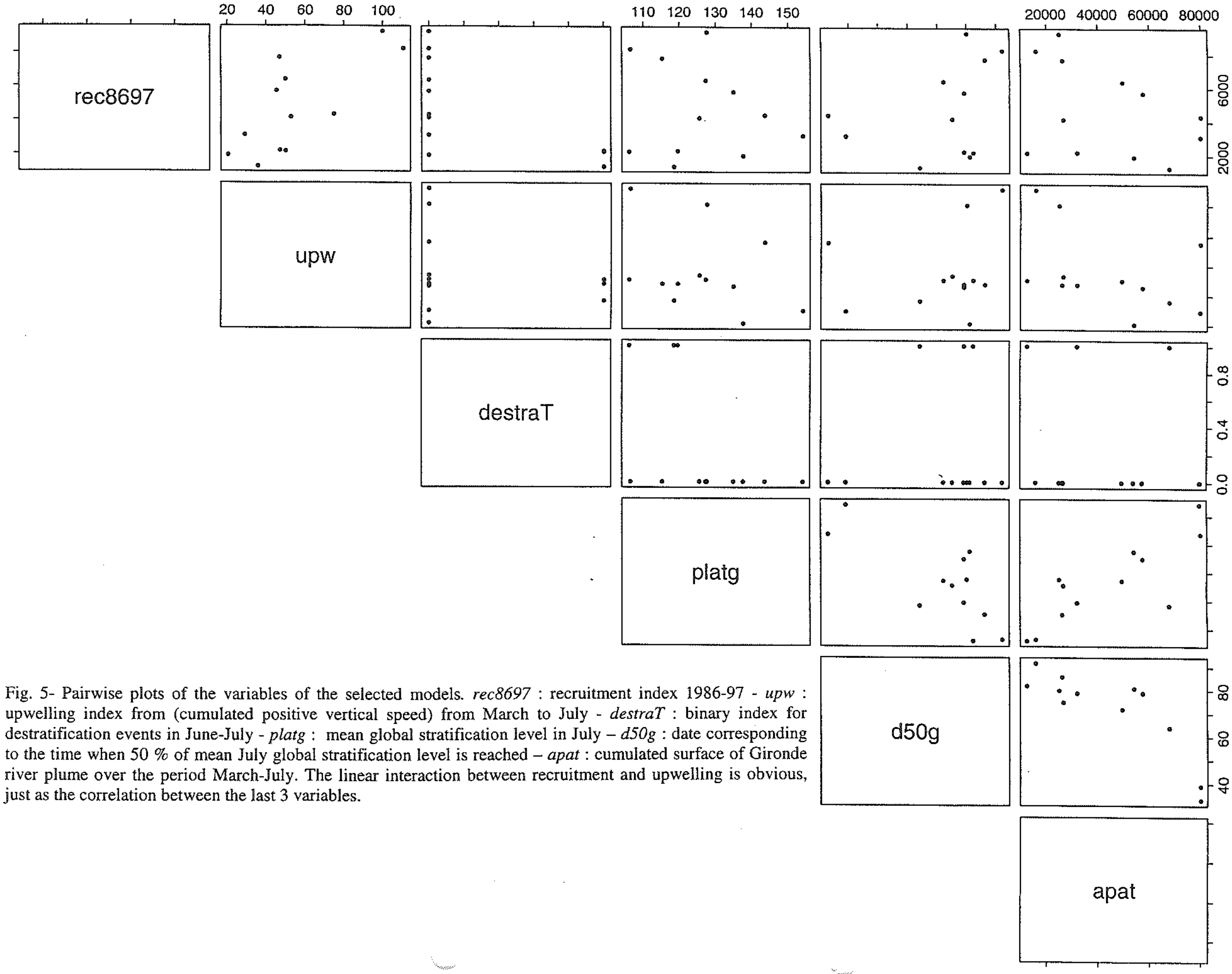


Fig. 5- Pairwise plots of the variables of the selected models. *rec8697* : recruitment index 1986-97 - *upw* : upwelling index from (cumulated positive vertical speed) from March to July - *destraT* : binary index for destratification events in June-July - *platg* : mean global stratification level in July – *d50g* : date corresponding to the time when 50 % of mean July global stratification level is reached – *apat* : cumulated surface of Gironde river plume over the period March-July. The linear interaction between recruitment and upwelling is obvious, just as the correlation between the last 3 variables.

MODEL 1 : recruitment ~ upw

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Coefficients:
                  Value Std. Error  t value  Pr(>|t|)
(Intercept)  638.4399 1326.1156    0.4814   0.6406
        upw   73.5383   21.7024    3.3885   0.0069

Residual standard error: 1944 on 10 degrees of freedom
Multiple R-Squared: 0.5345
F-statistic: 11.48 on 1 and 10 degrees of freedom, the p-value is 0.006903
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MODEL 10: recruitment ~ upw + destraT

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Coefficients:
                   Value Std. Error    t value    Pr(>|t|)
(Intercept)  2002.7891  1143.2179     1.7519     0.1137
        upw    61.7965    17.3899     3.5536     0.0062
    destraT -2856.9756  1038.2036    -2.7518     0.0224

Residual standard error: 1510 on 9 degrees of freedom
Multiple R-Squared: 0.7472
F-statistic: 13.3 on 2 and 9 degrees of freedom, the p-value is 0.002054

Correlation of Coefficients:
        (Intercept)      upw
    upw -0.8979
destraT -0.4337       0.2454
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MODEL 20 : recruitment ~ upwd + destraT + platg

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Coefficients:
                    Value   Std. Error     t value     Pr(>|t|)
(Intercept)  14897.0445    4805.5671      3.1000      0.0147
       upwd     48.1339      19.4213      2.4784      0.0382
    destraT  -4743.4952    1078.1062     -4.3998      0.0023
      platg    -86.0273      34.1645     -2.5180      0.0359

Residual standard error: 1344 on 8 degrees of freedom
Multiple R-Squared: 0.8219
F-statistic: 12.3 on 3 and 8 degrees of freedom, the p-value is 0.002295

Correlation of Coefficients:
        (Intercept)     upwd destraT
   upwd -0.4907
destraT -0.5908       0.3088
  platg -0.9837       0.3526   0.5415
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MODEL 20' : recruitment ~ upw + destraT + b2plus

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Coefficients:
                   Value Std. Error     t value    Pr(>|t|)
(Intercept)  1469.3882  1637.9072     0.8971     0.3959
        upw    62.4625    18.2420     3.4241     0.0090
    destraT -2738.1091  1114.1621    -2.4575     0.0395
     b2plus     0.0169     0.0355     0.4765     0.6465

Residual standard error: 1579 on 8 degrees of freedom
Multiple R-Squared: 0.7542
F-statistic: 8.181 on 3 and 8 degrees of freedom, the p-value is 0.008052

Correlation of Coefficients:
        (Intercept)      upw destraT
    upw -0.7059
destraT -0.4616       0.2556
 b2plus -0.6834       0.0766   0.2239
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MODEL 30 : recruitment ~ upwd + destraT + d50g + apas

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Coefficients:
                   Value Std. Error    t value    Pr(>|t|)
(Intercept) -5485.1327  4183.9603    -1.3110     0.2312
        upw    71.6477    20.1160     3.5617     0.0092
    destraT -2741.4549   956.5710    -2.8659     0.0241
       d50g    78.0562    36.0784     2.1635     0.0673
       apas     0.1601     0.1237     1.2948     0.2365

Residual standard error: 1302 on 7 degrees of freedom
Multiple R-Squared: 0.8537
F-statistic: 10.21 on 4 and 7 degrees of freedom, the p-value is 0.004774

Correlation of Coefficients:
        (Intercept)      upw destraT     d50g
    upw -0.6840
destraT -0.3335       0.4018
   d50g -0.9203       0.3880   0.1506
   apas -0.9152       0.6405   0.3154   0.7837
```

Fig. 6- Summaries of the selected models. Models 1, 10 and 20 have all significatively influent variables (on the $\Pr(>|t|)<0.05$ criterion) while models 30 and 20' (with age2+ biomass) do not.

MODEL 1 : recruitment ~ upw

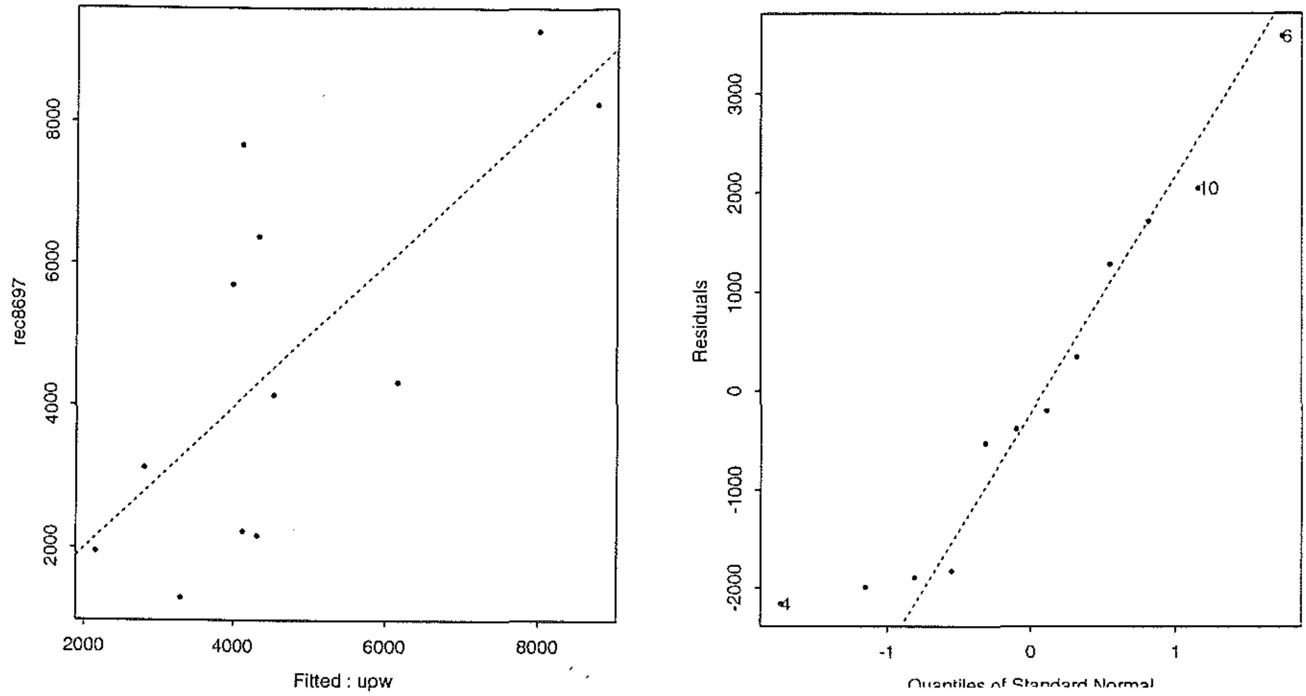
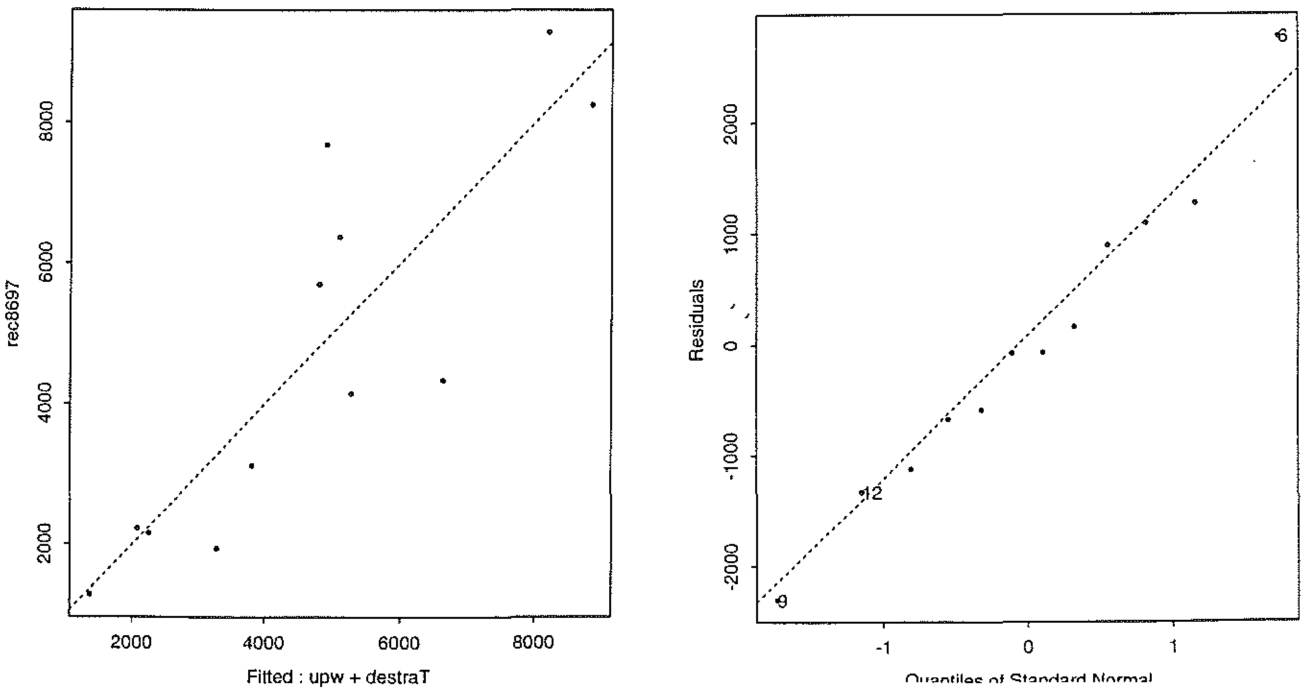
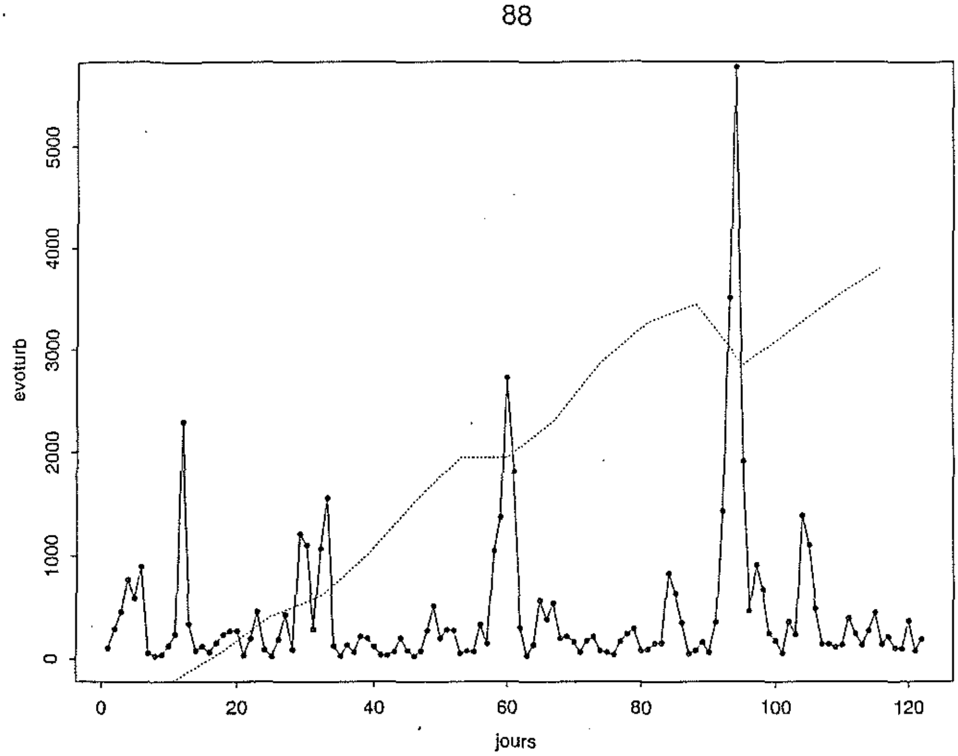


Fig. 7- Plots for models 1 and 10 : fitted versus observed values (left), quantiles of standard Normal versus residuals (right).

MODEL 10: recruitment ~ upw + destraT





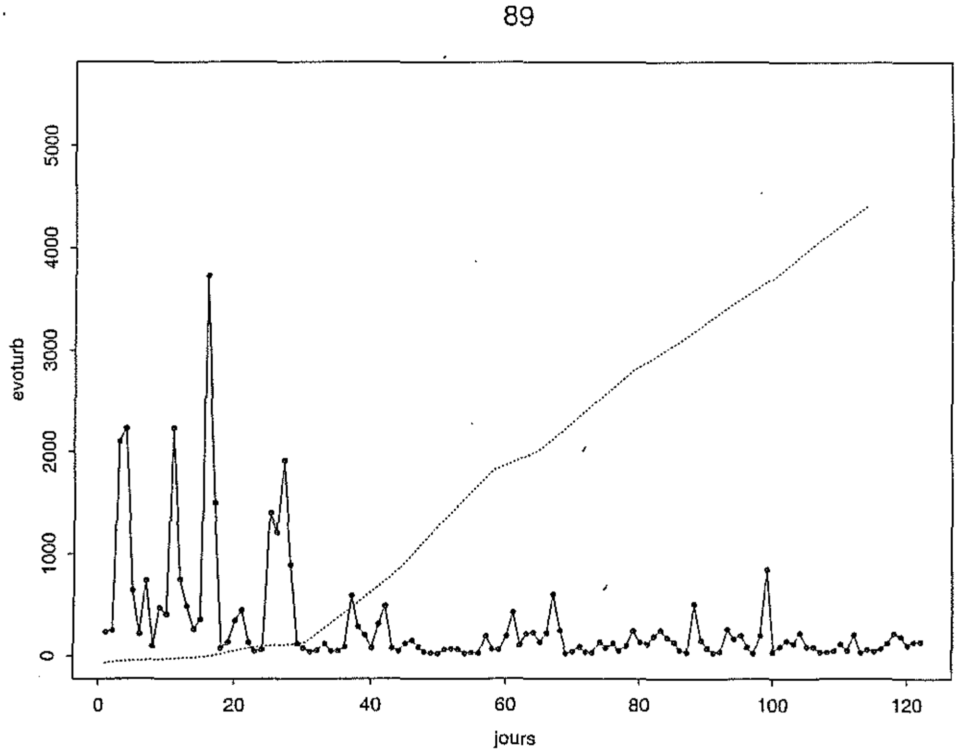
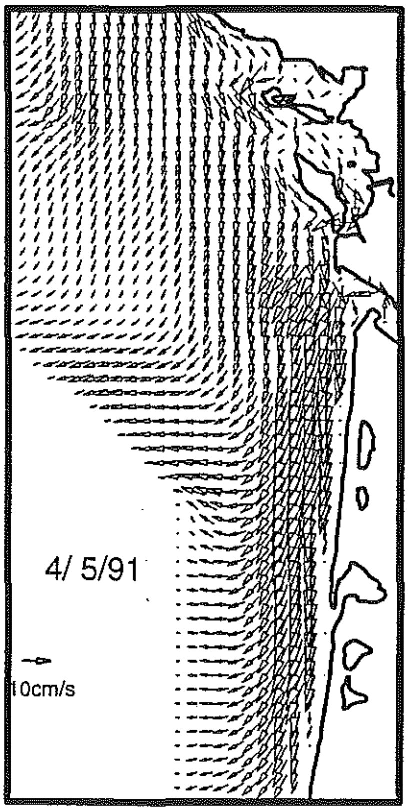
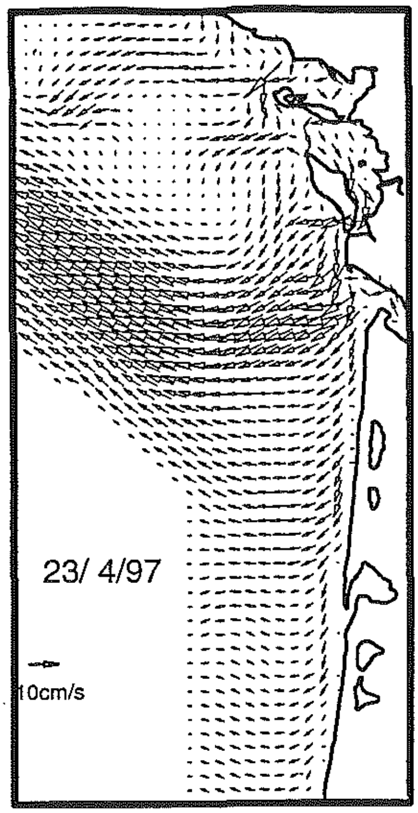


Fig. 8- The link between destratification events (decreases in the stratification dotted line) and high-intensity turbulence (daily cube of wind speed) in June and July. Time in days ("jours") from April 1st (day 0) to July 31st (day 122). 1988 shows 2 major turbulent events (from westerly winds), the second one resulting in an obvious breakdown in stratification (it is a bad recruitment year). 1989 shows weak winds in June-July and a continuous increase in stratification (it is a good recruitment year).





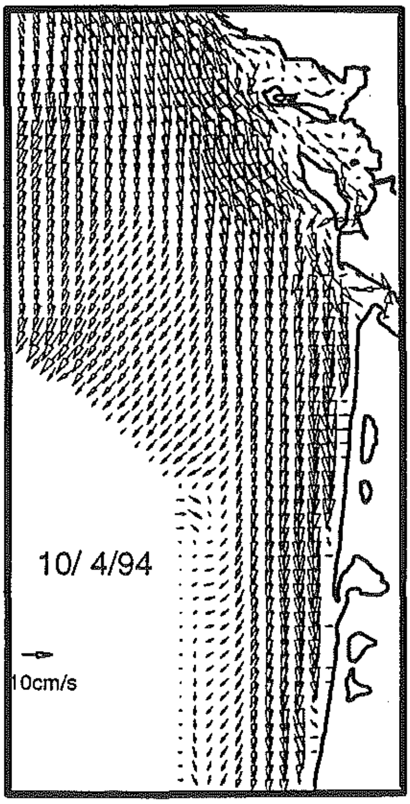


Fig. 9- Examples of simulated currents daily maps corresponding to upwelling/downwelling events on the Landes coast (SW France).

Top left (4/5/91) and top right (23/4/97) maps correspond to the 2 main types of upwelling events, produced respectively by moderate north-easterly and weak easterly winds. Bottom left (10/4/94) map corresponds to a slight downwelling situation caused by northerly winds. Strong downwelling is caused by westerlies (not illustrated).