OCEANOGRAPHY OF THE BAY OF BISCAY.
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P. Petitgas (eds.)

SCIENTIA MARINA, 70S1
June 2006, 7-14, Barcelona (Spain)
ISSN: 0214-8358

Analysis of salinity measurements near islands on the French continental shelf of the Bay of Biscay

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SUMMARY: The Bay of Biscay is characterised by large fresh water inputs from two major rivers, the Loire and the Gironde, with a mean discharge of about 900 m^3/s. To describe the spatial and temporal variability of the Loire and Gironde plumes, continuous salinity measurements were made at 4 locations on French coastal islands over periods lasting at least two years. These islands are located at a distance from the large local gradients linked to local inputs. Whereas sea surface salinity in the centre of the Bay of Biscay is 35.6, salinities at the coast vary between about 35 in summer to occasionally less than 30 in late winter or in spring. Minimum salinities do not occur at the same time along the coast, indicating a strong spatial gradient. Near the Loire and Gironde estuaries, a strong temporal correlation between discharges and salinity variation appears. Far from the estuaries, some drops in salinity seem to be correlated with a change of wind regime. In summer, a general decrease from north to south is found along the coast and may be linked to northwesterly wind conditions, which drive surface water to SW of the bay. These data constitute the first set of time series of salinity. They will be pursued to assess the interannual variability which is presumed to be high because of the large variability in river discharges and wind regimes.

Keywords: hydrology, salinity, seasonal variability, river plume, continental shelf, Bay of Biscay.

RESUMEN: ANÁLISIS DE MEDIDAS DE SALINIDAD CERCA DE ISLAS DE LA PLATAFORMA CONTINENTAL FRANCESA DEL GOLFO DE VIZCAYA. – El golfo de Vizcaya se caracteriza por los importantes aportes de agua dulce que recibe de dos grandes ríos, Loira y Garona, de un caudal medio de 900m3/s. Para medir la variabilidad espacial y temporal de estas plumas, se han realizado medidas continuas de salinidad en 4 puntos situados en sendas islas de la costa francesa durante períodos mínimos de dos años. Estas islas están alejadas de los fuertes gradientes relacionados con aportes locales. Mientras que la salinidad en la superficie del mar en el centro del golfo es de 35.6, en la costa oscila entre 35 en verano y menos de 30 en ciertos momentos al final del invierno o durante la primavera. Los mínimos de salinidad no se dan simultáneamente a lo largo de toda la costa, lo que indica un fuerte gradiente espacial. Cerca de los estuarios, ciertas disminuciones de salinidad parecen estar correlacionadas con cambios en los regímenes de viento. En verano se observa una disminución general desde el norte hacia el sur a lo largo de la costa y que puede estar relacionada con unas condiciones de viento del noroeste que conduce el agua de la superficie hacia el sudoeste del golfo. Estos datos constituyen el primer conjunto de series temporales de salinidad cuyo estudio se continuará para evaluar la variabilidad interanual que se supone elevada debido a la fuerte variabilidad de las descargas de los ríos y de los regímenes de viento.

Palabras clave: hidrología, salinidad, variabilidad estacional, plumas de ríos, plataforma continental, Golfo de Vizcaya.

INTRODUCTION

The Bay of Biscay (Fig. 1) opens in the west onto the NE Atlantic Ocean. In the oceanic domain, surface waters called BBCW (Bay of Biscay Central Waters) are characterised by a salinity of 35.6 (Tréguer *et al.*, 1979; Botas *et al.*, 1989). Below the surface waters, maximum salinity was identified at a depth of about 1000 m. These waters come from the Mediterranean, with a salinity of about 35.8-35.9 (Le Floch, 1969; Botas *et al.*, 1989).

On the continental shelf, salinity is more variable, resulting from the mixing of sea water and fresh water inputs from rivers. These river inputs are significant in the Bay of Biscay. Table 1 summarises the main fresh water discharges in the Bay. They mainly come from the Loire and Gironde rivers, whose average annual flow rates are about 900 m^3/s. The vertically stratified river plumes they induce are one of the major features of Bay of Biscay hydrodynamics (Kousikopoulos and Le Cann, 1996). Density gradients induced by drops in salinity create geostrophic dynamics, which tend to push the plumes poleward (Lazure and Jegou, 1998). The wind's influence creates more complex circulation patterns showing high seasonal and interannual variability.

Salinity measurements in the Bay of Biscay have been patchy. They have been taken on occasional cruises, but rarely cover the entire bay and are hardly ever synoptic.

walls. Two kinds of measurements were made. The first consisted in varying the temperatures from 20°C to 0°C with a 5°C step after a stable state at 20°C for one night. In the second one, the bath was maintained at 15°C and salinity varied from 35 to 3 (PSS 78). After each measurement, a water sample was taken and then measured for salinity by the GUILDLINE salinometer gauged with an IAPSO standard sea water ampoule. Once calibrated, the probes can give salinity measurements to ± 0.1 between 28 and 35.

Throughout the in situ experience, the probes were regularly changed and checked in laboratory reference baths.

In order to obtain extensive time series of at least one year at a reasonable cost, the measurement devices were not moored at sea. The risk of losing these moorings due to either trawls or the often rough sea conditions in the Bay of Biscay seemed too high. Moreover, there is a considerable problem with biological fouling in the coastal area, meaning that the conductivity sensor must be cleaned regularly (every two weeks on average, from spring to autumn) to avoid any alteration in the quality of measurements. Setting up offshore probes would have limited the need for such regular maintenance, but sufficiently frequent access to them by boat was not available.

Considering all these constraints, the probes were set up along the coast on already existing supports (quay, fish pond and fisheries). The major drawback of this solution is that the probe is uncovered at low tide. The period of measurement loss around low tide varied, depending on the tidal range. But this lack of measurements did not penalise our results, since our aim was to describe salinity gradients on a large scale.

Probe sites were chosen on French coastal islands because they were located away from the large local gradients linked to local inputs. These are small islands, sharing the features of having no large catchment areas and few fresh water discharges. Four sites were chosen with respect to their geographical location on the coast, their accessibility, and the possibility of setting up the measurement devices under optimal safety conditions. The distribution of probes along the Atlantic coastline is shown in Figure 1. The northernmost one was set up on an island in the Glénan archipelago, the next northernmost was to the north of Belle-Ile, on the Isle of Houat, about 40 km from the Loire estuary. The third probe was attached to a jetty west of Yeu Island located south of the Loire estuary at a distance of about 50 km. The fourth probe was set up to the north of Oléron Island. This probe was the closest to the Gironde estuary (about 50 km).

TABLE 2 . – Position of probes, dates and duration of records.

Position Latitude, longitude	Start date (mm/dd/yyyy)	End date (mm/dd/yyyy)	Usable days
Glénan 47°40'N, 4°00'W	04/06/2000	04/17/2003	1005
Houat 47°24'N, 2°58'W	02/09/2001	02/26/2003	576
Yeu 46°41'N, 2°20'W	04/06/2000	01/30/2003	795
Oleron 46°25'N, 1°30'W	02/21/2000	01/04/2003	839

Measurements were acquired on each site with a 30 minute sampling step. Lengths of recordings varied, and there were gaps generally due to functional problems with the equipment. Table 2 summarises the dates of records which could be exploited.

Two data processing methods were tried out with the aim of retaining a single daily value. These were calculating the mean salinity over a period of immersion and saving the maximum daily values. Both processing methods provided very close values, with the exception of a few days showing a very sharp drop in salinity before the probe was uncovered. Since those readings could have affected the mean value, it was decided to use the second method, i.e. keeping only the maximum value.

As suggested by a referee, the behaviour of the probe could be problematic when it is uncovered. Salt particles could be deposited on the electrodes during sunny days and could lead to an overestimation of the daily maximum salinity. To evaluate this spurious effect, time series were re-analysed to detect when maximum salinity occurred in the first measurements after the probe had been recovered.

At the Glenan site, over the whole time series, the probe was in the air on average during 14 measurements, or 7 hours a day (the time step being 30'). This means that it was under water for 17 hours (34 measurements). Assuming that the maximum salinity could occur on each measurement with the same probability, the probability that the maximum would occur on the first measurement after the water recovered the probe was 1/34, i.e. 3%. In fact it occurs 7% of the time, denoting a probable effect of drying.

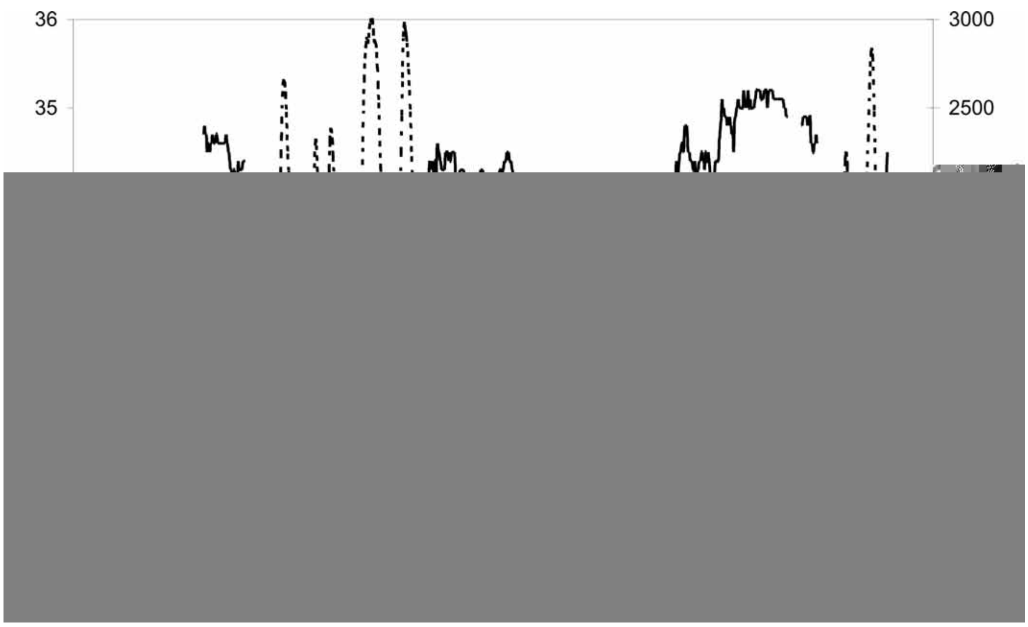

FIG. 2. – Time series of mean salinity (solid line) and averaged Loire and Gironde runoffs (dotted line).

At Houat, the probe spent 43% of the time in the air on average, the probability that the maximum would occur just after drying was 4% and observations showed that the maximum occurred 5% of the time just after drying. At Yeu, these percentages were respectively 2% and 15% and at Oléron 3% and 7%.

Some uncertain points were identified by this method. So, when the maximum occurred on the first observation after re-cover, it was rejected and the maximum was chosen from amongst the other observations.

RESULTS

Mean and standard deviation

Figure 2 shows the arithmetic mean of salinities (solid line) for the 4 sites when at least 3 probes were operating. Each year, the salinity maximum occurred in summer and in early autumn. During that period, salinity reached 34.7 in 2000, 34.5 in 2001 and 35.2 in 2002. These values are significantly lower than the Bay of Biscay Central Waters salinity (35.6). Mean calculated salinities decreased in winter and spring, reaching a minimum of 31.2 in March 2000 and April 2001. This value corresponds to 12% of fresh water. During the autumn 2000 and winter of 2001, salinity fluctuated between 31.2 and 33.8, with characteristic time periods of about 25 days. During autumn 2001 and winter 2002, the minimum averaged salinities remained above 32.6.

Figure 2 also displays the average of the Loire and Gironde discharges (dotted line). These two major rivers have nearly the same outflows. They were at the minimum in late summer, when the average runoff decreases to around 220 m^3/s each year. A high year-to-year variability appears in the maximum. The average floods exceeded 2500 m^3/s in 2001 and 2003 whereas they hardly reached 1500 m^3/s in 2002.

Measurement characteristics by site

Figure 3 shows the salinity measured at each site. In the Glénan Islands (Fig. 3a), salinity was particularly stable. Between June and December 2000, it ranged from 34.8 to 35. During the winter of 2000-2001, the salinity reached the minimum for the time series, at a reading of 30 on 26 December 2000. Generally speaking, for this site, salinity fluctuated between 32 and 34.5 during the winter period. However, a maximum of 34.8 was reached on 7 February 2001 and it exceeded 35 during the first two weeks of February 2003.

On Houat Island (Fig. 3b), three minima around 28.3 were obtained in February and in late March 2001 and then in March 2003. Between these two values, salinity generally remained above 32. The maximum of 35.2 was reached in August 2002.

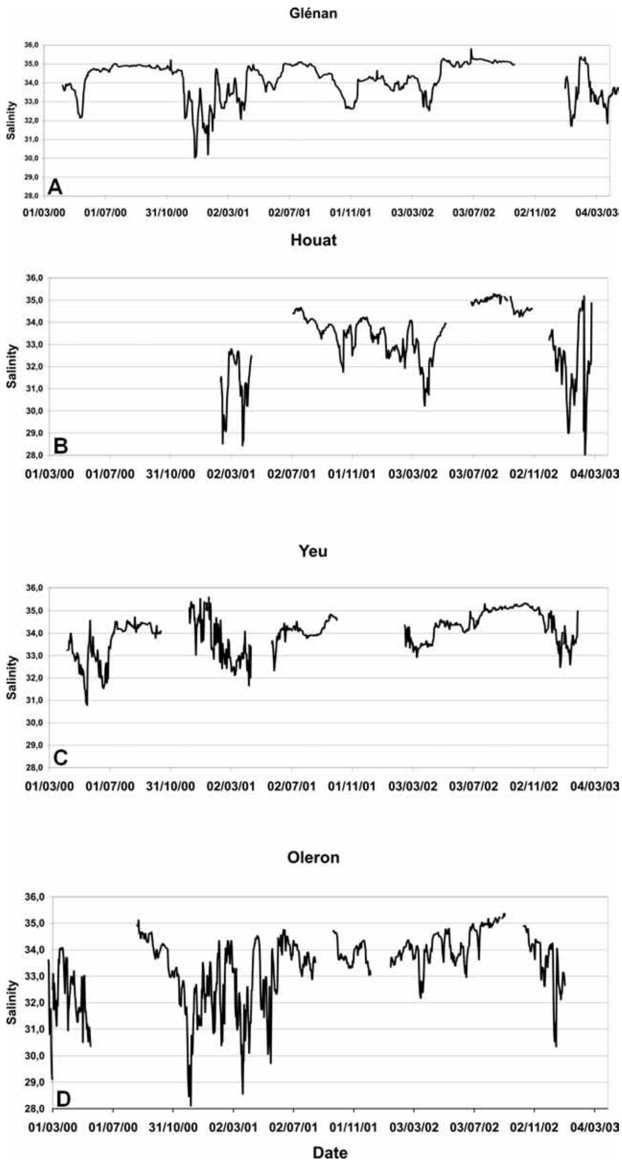

FIG. 3. – Salinity time series at the 4 locations: Glenan (a), Houat (b), Yeu (c), Oleron (d).

On Yeu Island (Fig. 3c), salinity time series showed significant, high frequency variability. The seasonal signal was less pronounced than at the other stations. The minimum of 30.8 was reached on 16 May 2000. In the summer and early autumn of 2000 and 2001, salinities fluctuated between 34 and 34.5, whereas in summer 2002 they were over 35.

On Oléron Island (Fig. 3d) the salinities showed the largest range of variability of the four probes. As in the other sites, the winter and spring 2001 showed high fluctuation, with salinities lower than 29 at the beginning of December 2000 and March 2001. In late summer 2002 the salinity reached the maximum for the time series: 35.3 on 3 September.

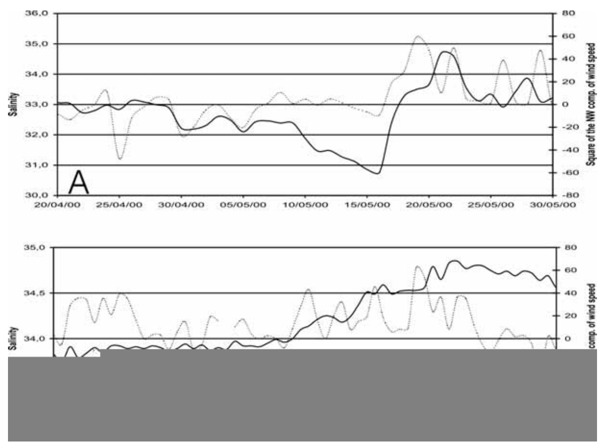

FIG. 4. – Time series of salinity at Yeu Island (solid line). Square of the NW component of the wind speed at Belle Ile (dotted line): positive values indicate a NW wind, negative values a SE wind.

DISCUSSION

Salinity recordings along the coast revealed high variability on different time scales. Since the sampling method took only the highest daily salinity reading, the variability due to the tide (hourly time scale) is not provided by this study. However, high frequency variability induced by tides resulted in local salinity gradients (on the scale of a tidal excursion, i.e. a few km. in length), which is beyond the scope of this paper.

Variability on a monthly scale

Sharp variations in salinity over periods ranging from a week to a month appear to be mostly linked to the wind regime and flow rates of the Loire and Gironde rivers. The wind's action on salinity is exercised either through horizontal transport of river plumes, or by vertical upwelling/downwelling transport. Correlations between changes in the wind regime and salinity variations can be observed. For instance, at Yeu Island, a sharp rise in salinity of 3 was observed between 16 and 21 May 2000 (Fig. 4a) and a progressive rise was observed during September 2001 (Fig. 4b). These increases in salinity correspond to periods of wind from the NW, which provides a component that favours the creation of upwelling.

In Figure 4, the square of the NW component of the wind (dotted line) which was proportional to the wind stress was plotted with salinity (solid line). In late April and early May 2000 (Fig. 4a), the negative wind speed indicated that the wind

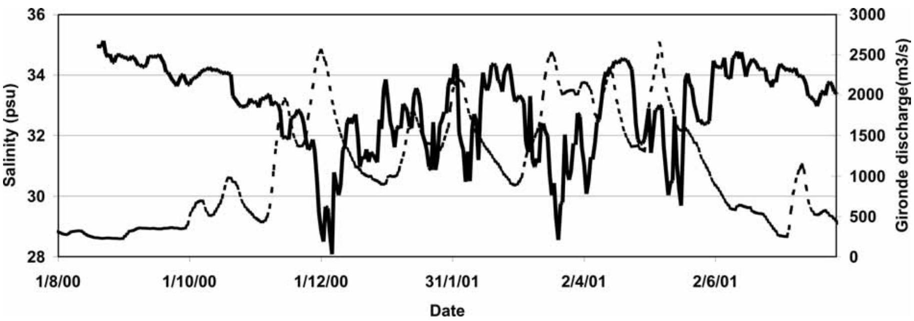

FIG. 5. – Salinity time series at Oleron (solid line) and Gironde outflows (dotted line).

was instead from the SE. In this case the wind corresponded to a decrease in salinity. When the wind was upwelling-favourable (on the 16 May), a sharp increase in salinity occurred, but this point alone does not make it possible to distinguish the potential influence of horizontal advection or of an upwelling of salty bottom water. In late summer 2001 (Fig. 4b), the same event occurred but with a different time scale. The continuous increase of 1 for one month is associated with a positive NW component of the wind. This feature is typical of late summer.

Near estuaries, the variability of river inputs appears to be the main factor in salinity variations. Figure 5 shows the salinity measured at Oléron Island (solid line) and the flow rate of the Gironde river smoothed (dotted line) over one week. The negative correlation between Gironde flow rates and salinity at Oléron Island is very clear. There was a lag of about 5 to 10 days between the maximum flow rate and the local salinity minimum. The fluctuations with the highest frequency are linked to the wind, whose direction varied considerably during this period, modifying the transit time between the Gironde estuary and the north of Oléron Island. Therefore, we can estimate that the transit speed between the mouth of the estuary approximately 40 km away and the measurement point fluctuated from 3 to 7 cm/s. These values are on the same order of magnitude as those calculated by the numerical model (Lazure and Jégou 1998).

This series of measurements also illustrates the influence of Gironde waters on the origin of waters entering the Marenne Oléron basin. This basin is indeed subject to a residual tidal current flowing from north to south (Heral and al, 1982; Boutier and al 2000). Therefore, the water entering here contained a large proportion of Gironde river water ranging from 3% (34.5) to 20% (28).

Seasonal variability

As seen in Figure 2, the salinities have a significant seasonal component. The rise in salinity in late spring is the direct result of lower river flow rates (Loire, Gironde and other rivers). Figure 6 gives salinities for the 4 sites during the summer of 2001. A north-south gradient is clearly visible. The highest salinities during this period were observed in the Glénan Islands with an average of 35, whereas the lowest ones were observed at Oléron with an average of about 33.5. This drop in salinity can be interpreted as an accumulation of low-salinity waters in the southern bay under the effect of winds.

Figure 7 illustrates this hypothesis. Surface salinities were measured by CTD in September 2001 on the shelf (Modycot 2001-2 cruise). The decrease in salinities moving southward can be clearly distinguished. In the Bay of Biscay, the seasonal wind cycle is characterised by two seasonal regimes, one in autumn and winter when the wind blows from the

FIG. 6. – Salinity time series at 4 locations in summer 2001.

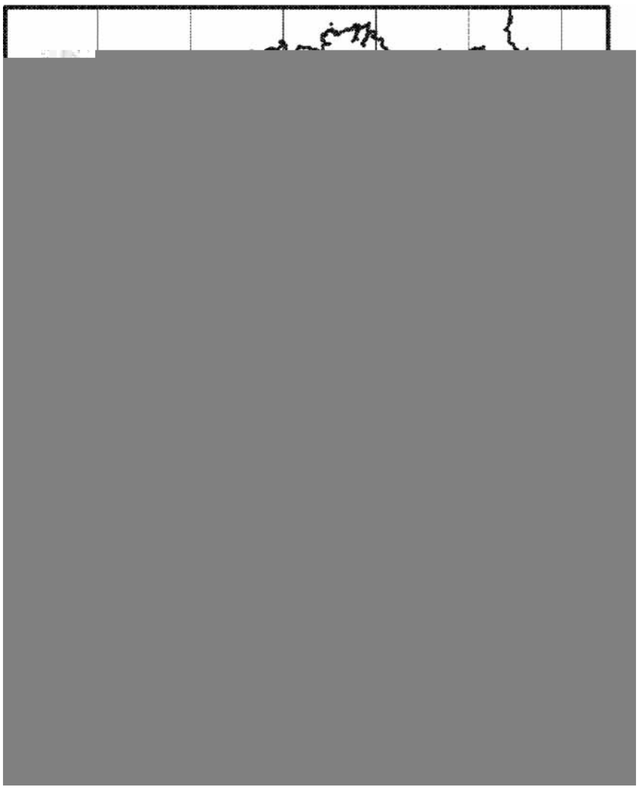

FIG. 7. – Surface salinity measured during the Modycot 01-2 cruise.

SW and one in spring and summer with winds from the NW sector (Pingree and Le Cann 1990). Since the NW wind is upwelling-favourable, it tends to push the low-salinity surface waters southwards and towards the open sea. Observations along the Spanish coast of low-salinity water arriving in summer from the north (Botas *et al.*, 1989; Lavin *et al.*, 1998; Gil *et al.*, 2001) confirm this hypothesis. These results are also consistent with simulations of the fate of Loire and Gironde river plumes in spring and summer (Lazure and Jégou, 1998). In summer, the Adour plume is presumed to have a weak effect because the river outflow is lowest, but in spring, high discharges may contribute to the general decrease of surface salinity in the southern part of the Bay of Biscay.

As shown by Gil *et al.* (2002), continental runoff from the French shelf may determine the distribution of water masses of the eastern Cantabrian Sea in May and the transport of biological material. Spreading of low salinity water lenses was related to high values of the biomass abundance and distribution.

However, contrary to observations from the Spanish coast, winter salinities did not correspond to the presence of a poleward current advecting more saline water (Botas *et al.*, 1989; Lavin *et al.*, 1998; Valencia *et al.*, 2003). Taking account of the widening of the continental shelf, no evidence of a warm, high-salinity poleward current appeared through analysis of salinity recordings near French coasts. Furthermore, the presence of large river plumes at the estuary mouths hides any possible increase in salinities induced by an inflow of ocean water from offshore.

CONCLUSION

Continuous measurement of salinity on different sites is rather complicated to implement, especially due to maintenance problems. All the same, the measurements presented here enabled us to highlight how salinities change along a large part of the French coast. Salinities drop in winter and spring because of high flow rates and they increase in summer and autumn during the low water period. Short-term variations in wind contribute to changes in the direction and circulation of plumes and induce high frequency variability. However, other factors of variability must be studied, such as spatial variability of wind, instability in gravity circulation, and flood effects.

These measurements offer the advantage of obtaining simultaneous salinity time series from the north and south of the continental shelf. This made it possible to highlight the seasonal variability of salinity and confirm that low-salinity waters accumulate in the south of the Bay of Biscay in summer.

Using these analyses, the measurement series will be compared with the results of the MARS 3D hydrodynamic model for the Atlantic shelf (Lazure and Jegou, 1998; Jegou *et al.*, 2000) to validate its surface salinity calculations and their changes over time.

ACKNOWLEDGEMENTS

The authors are very grateful to all those who contributed to the success of this measurement network: Mr. Castric, a fisherman in the Glénan Islands, the municipalities of Houat and Yeu islands, Mr. Morisset and the St Denis d'Oléron heritage conservation association, Ifremer's coastal laboratories and the Ifremer/Brest Metrology Laboratory. We thank the CMO (French Military Oceanographic

Centre) for the Modycot surveys. The French national HYDRO data base and Bordeaux Port Authority for rivers runoff data. We are also grateful for the comments of the reviewers and for the linguistic assistance of Janet Heard Carnot.

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Received June 28, 2002. Accepted November 24, 2004.