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Freshwater from the Bay of Biscay shelves in 2009

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ABSTRACT

In April–November 2009, surface salinity data provide a good coverage of most of the south-east Bay of Biscay and nearby Aquitaine/Armorican shelves. By late April most of the shelf, in particular south of 46°N, is covered by a fresh surface layer amounting to a fresh water volume of $49 \cdot 10^9$ m^3. At that time, a moderate amount of fresh water has spread over the Landes Plateau. By mid-June, this shelf water penetrates over the Cape Ferret Canyon north of the Landes Plateau. By mid-July, it is found west of the Landes Plateau to at least 4°W, with an estimated fresh-water content of $11–14 \cdot 10^9$ m^3. Drifters deployed on June 17 in the Cape Ferret Canyon, or later on the shelves, confirm the spreading of shelf fresh-water over the deep ocean. Lagrangian tracking using altimetric products, also confirms the transport by a quasi-stationary circulation. Operational numerical simulations (PREVIMER, IBI, HYCOM) display this spread of the freshwater, but in different areas. In particular, all have some fresh water escaping westward near the coast in the Basque region, which is not observed. Later in the summer season, the fresh water spreads westward to south-westward and along the shelf break to at least 5.5°W in late September.

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1. Introduction

In the southeastern part of the Bay of Biscay, low salinity structures are sometimes apparent on the ferrybox records from the Pride of Bilbao which crosses the southern area of the Bay of Biscay every 1–3 days and collects water from a shallow depth (Garcia-Soto and Pingree, 2009) (for example in July 2006 or April 2007). Freshwater is also advected near the sea surface to the site of the long time series Santander section over the slope that plays a role in the interannual variability of salinity in the upper layer of the water column (Somavilla et al., 2011, personal communication).

The hypothesis that we will discuss from extensive 2009 data and model simulations is that the freshwater in this part of the southeastern Bay of Biscay can originate from the Aquitaine shelf in the spring and summer with direct exchange there across the shelf break.

South of Cape Breton (just north of the Adour estuary) and west along the Basque and northern Iberic coasts, the Cantabrian shelf is often almost interrupted or narrow (O (10 km)), in particular near Cape Breton and Llanes canyons. The shelves on the French side of the Bay of Biscay north of Cape Breton present a large transition near 45°N at the Cape Ferret Canyon latitude. South of it, the shelf is a relatively narrow 50 km-wide strip with a relatively smooth shelf break and gradual slope towards the deeper Landes Plateau further offshore that extends to an immersion of 2000 m. North of it, the Aquitaine shelf gets wider than 150 km, and is gently sloping towards a sharp shelf break near the 150 m to 200 m isobaths, with a usually steep slope descending to more than 4000 m depth.

The waters of the southern French continental shelves often have a low surface salinity in spring for depths less than 100 m, as a result of winter and spring outflows from the major rivers (primarily, Gironde, Loire and Adour, with a combined flow often exceeding 4000 m^3/s during that season) (Castaing et al., 1999, update on PREVIMER web-site

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www.previmer.org). During the spring warming, over shelf depths deeper than 50 m, these surface waters get isolated from the bottom by a cold layer left from the previous winter water. The surface fresh water layer then extends usually further across the shelf, often reaching the shelf break (Castaing et al., 1999), sometimes in low salinity lenses, as a result of coastal upwelling favourable wind forcing (for example, in 1998, 1999 or 2001 (Puillat et al., 2004)). Along the Spanish coasts (Pais Vasco, Cantabria, Asturias), outflows from the small coastal rivers also cause in late winter and spring important salinity decrease near the coast (in particular in the eastern part, see summary in Valencia et al., 2004). This coastal freshening can induce a geostrophic shear towards the east near the surface along the Cantabrian shelf and to the north along the Aquitaine shelf. Upper ocean currents along the continental slope are often strong (20 cm/s), but highly variable on time scales of a week (Valencia et al., 2004), in particular as a result of changes in the winds. Similar observations pertain to the currents along the slope (or on the shelf in particular near the 100-m isobath) in the southern part of the French margin (Pingree and Le Cann, 1990; Koutsikopoulos and Le Cann, 1996; Durrieu de Madron et al., 1999).

Observations (Le Cann and Pingree, 1995), as well as high resolution numerical model outputs (2011 communications, R. Baraille with MICOM model, P. Lazure with Mars-3D model, and M. Le Hénaff with Symphonie model) suggest that this near-surface circulation veers mostly cyclonically around the slopes of the Bay of Biscay, but with a seasonal reversal from May to September, when winds are more favourable to upwelling situations, in particular along the coast of Asturias, but also for parts of the Landes area of the Aquitaine shelf. The details of an often complicated bathymetry of the slope surely play a key role in the development or absence of instabilities in the slope current. For example, the generation of swoddies, anticyclonic eddies presenting a maximum intensity in the upper thermocline (or mode water layer) might be favoured along the north flank of the Cape Ferret Canyon (Pingree and Le Cann, 1992), at least during times when the slope current is towards the north. This seasonal reversal of the currents and the circulation does not happen during all years (for example, the summers of 2004 or 2006 presented no upwelling favourable circulation; whereas upwelling-favourable winds lasted until December in 2007). Some numerical simulations also show episodes of cross-shelf exchanges (filaments, jets) during periods of current reversal in this segment of the shelf (2011 personal communications: R. Baraille with HYCOM model; M. Le Hénaff with 2004 Symphonie model simulations). In the numerical simulations, they tend to happen near the Cape Ferret canyon or over the Landes Plateau. The smoother continental slope between Cape ferret and Cape Breton (towards the offshore plateau des Landes) was also commented as potentially near-critical for the internal wave reflection of M2 tides, and therefore might lead to local intensification of near-bottom currents and therefore vertical mixing and sediment transport (Durrieu de Madron et al., 1999).

Observations from hydrological spring cruises also indicate fresh water lenses from the Gironde estuary water reaching the vicinity of the shelf break (Castaing et al., 1999; Puillat et al., 2004). The presence of occasional fresh water filaments in the area of the Landes Plateau north up to Cape Ferret Canyon is often found offshore from the shelf in late spring cruises. Fig. 1 (top panel) illustrates SSS data from a 2006 June PECH cruise on the R.V. Côtes de la Manche with a very fresh filament 15–25 km from the shelf break, and then with gradual increase above the eastern part of the Landes Plateau up to 50 km from the shelf break. Ocean colour date obtained two days later clearly indicate cross-shelf exchange in this Landes Plateau sector of the shelf break, but also further north along the northeastern wall of the Cape Ferret canyon (Fig. 1, lower panel).

The simultaneous evolution of the distribution of the freshwater over the shelf and of the fresh water spreading across the shelf break has not yet been studied. In this paper, we will discuss evidence for massive outflow of shelf water in the summer of 2009. Surface data will be used to map the evolution of the surface fresh water distribution. Profile data will be used to estimate the vertical extent of this fresh water and the percentage of the fresh water that was exported from the shelf. Evidence from drifter trajectories and back-trajectory simulations will be provided to better interpret this export.

The paper will be organised as follows. In Section 2, the different data sets are presented, as well as the tools we will use for the interpretation. In Sections 3 and 4, the data results and other data and simulations are presented respectively, which will be followed by a discussion in Section 5 and conclusions in Section 6.

2. Data

2.1. Surface salinity data sets

Surface data are routinely acquired from thermosalinographs (TSG) mounted on research vessels or ships-of-opportunities. Here, we include data from the Pride of Bilbao ferrybox (Garcia-Soto and Pingree, 2009), a ferry running every three days between Bilbao and Portsmouth. Data were checked and usually found suitable for our purpose without corrections. We also include TSG data from the French R.V. Côtes de la Manche, Thalia, Antea, Atalante, Pourquoi Pas, Thalassa, Spanish R.V. Cornide de Saavedraa and Sarmiento de Gamboa, Irish R.V. Celtic Explorer, and in August and September from the research sailing vessel Tara. The data, often obtained from the Coriolis real time web site (www.coriolis.eu.org) were checked and corrected based on comparison with water samples or CTD casts when these data were available. The TSG data are often collected at a depth of 3–4 m, and are usually associated with a temperature measured at an intake. Surface samples from the R.V. Investigador (campaigns conducted by AZTI-TECNALIA) and the R.V. Côtes d'Aquitaine were also used.

Salinity data were also provided from conductivity sensors on drifters (GLOSCAL and CAROLS projects) deployed primarily during the Gogasmos cruise on the R.V. Antea and Carols cruise on R.V. Côtes de la Manche in May–June 2009. These data recorded at depths between 15 and 45 cm were corrected from biases and validated by comparison with samples, sensor calibrations or comparison with nearby data, as was done for earlier projects (Reverdin et al., 2006). Data from a 3-m deep microcat SBE sensors located on a 3.79°W/43.84°N surface mooring maintained by IEO Santander (www.boya_agl.st.ieo.es/), and from 10-m deep microcat SBE sensors located on two surface moorings at 2.03°W/43.56°N and 2.69°W/43.64°N maintained by AZTI-Tecnalia (Rubio et al., 2010) were also included. These data should be accurate to within a few 0.01 psu (practical salinity based on conductivity as used here has no unit, and we will refer to it in practical salinity units (psu)).

We also use uppermost data from salinity profiles, in particular when they are not associated with TSG data (see next section), including CTD or bottle casts during research cruises, profile data collected by a glider, two ARGO floats and Recopesca sensors instrumented on fishing vessels gear. This uppermost depth of the casts can vary: it is typically within a few metres from the surface, but is at least 5 m down for ARGO floats. Accuracy is also variable: typically on the order of 0.01 psu, but is much worse for one cruise on the R.V. Investigador (0.1 psu), or for the Recopesca sensors (0.1 psu) (Leblond et al., 2010).

We map salinity using classical Gauss–Markov objective mapping procedure (Bretherton et al., 1976), starting from a guess field corresponding to a climatology adjusted first at the large scale to the observed salinity data (we find in particular on the Aquitaine shelf in April–June that salinity is −0.6 psu less than in climatological fields, a difference that needs to be retained in the guess field). The mapping radius of influence is 25 km to resolve the variability on the shelf, a scale that is sometimes resolved by the data distribution. Mapping is done at least once a month for data grouped during at most 20 days, and at least 10 days, to get enough coverage over

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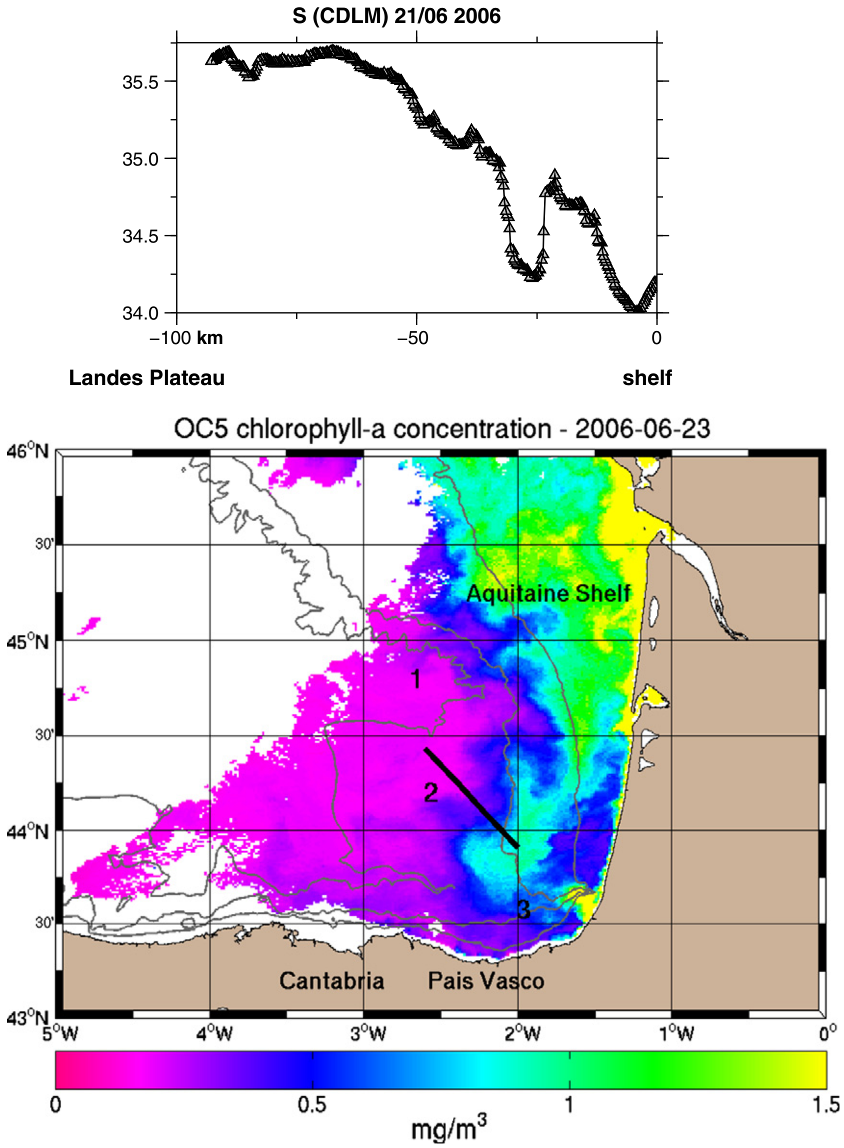

Fig. 1. Upper panel: 21 June 2006 S section from the TSG on R.V. Côtes de la Manche across the Landes Plateau (distance is from SE corner near shelf-break and is negative to the north-west; ship track on lower panel). Lower panel: Modis ocean colour map on June 23 2006 (obtained on Nausicaa at IFREMER/CERSAT). The isobaths plotted are the 100, 200 and 2000-m contours, and the labels 1, 2, and 3 are for Cape Ferret Canyon, Landes Plateau, and Cape Breton Canyon, respectively.

most of the shelf and south-eastern Bay of Biscay. For some periods, this was not satisfactorily, but otherwise the coverage is rather good, and mapping uncertainties are less than the signals featured.

2.2. Salinity profiles

We use a subset of the profile data collected on the shelf and its vicinity, to investigate fresh water content of the upper water column, in the spring, and for specific areas off the shelf in summer. This includes CTD casts during cruises GOGASMOS in May (R.V. Antea), cruises CAROLS and LEVIATHAN in June (R.V. Côtes de la Manche), ARCADINO surveys from April to August on the southern Aquitaine shelves (R.V. Côtes d'Aquitaine and Côtes de la Manche), cruises CO2ARVOR in April and July off southern Brittany and near the Loire estuary (R.V. Thalia and Côtes de la Manche), cruise PELGAS in April–May over all shelves surrounding the Bay of Biscay (R.V. Thalassa). We also included data from towed undulating profilers equipped with CTDs, both from a Scanfish during GOGASMOS in May (R.V. Antea) and ASPEX in July (sections D and E, R.V. Thalassa), and from a Seasoar during MOUTON2009 in August (section D, R.V. Atalante). Other CTD profiles are from May–October stations from the Santander (3.78°W) standard section monthly surveys and from an early August cruise on the R.V. Cornide de Saavedra, as well as from the May R.V. Investigador cruise carried by AZTI-Tecnalia. The accuracy of data of this last cruise is however much less (0.1 psu), as the temperature sensor had a 1 s time-constant, requiring special processing that results in rather smoothed profiles, removing structures of a few metres thickness.

We also incorporate salinity profile data from a coastal glider crossing most of the shelf along 45°41′N in May to mid-June (accurate to within 0.03 psu), from two autonomous ARGO floats at 5-m resolution on the outer shelf/Landes Plateau, and from Recopesca temperature/conductivity sensors on fishing gear. The Recopesca CT sensors are collecting data during descent, often to the near bottom. Sensor absolute accuracy is not better than 0.1 psu, and it may suffer from poor flow through the cell, sensors time constant and thermal mass effects. For some profiles, this results in large errors when crossing temperature gradients. Dubious profiles were not retained, and these profiles were

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mostly used to ascertain S near the surface or in unstratified deep layers, providing reasonable coverage in the shallow part of the shelf south of the Gironde estuary, as well as in southwestern Brittany near the 100-m isobath.

For each salinity profile a freshwater content is integrated by estimating $\int(35.6-S)/35.6*dz$ from the surface to the depth where the 35.60 psu isohaline is reached. This assumes that the shelf background salinity is 35.60 psu before additional freshwater from winter rain or river flow, and that the evolution is through mixing of 35.60 psu salinity water and shelf water. Subsurface southeast Bay of Biscay salinity was on the order of 35.60 to 35.62 psu in the spring of 2010, which we assume is the main source of offshore water for the southern part of the shelves. North-east Atlantic Central water with higher salinities (up to 35.7 or 35.8 psu), were found further north or west (April 2009 FORCLIM cruise), but should not contribute to the budget in this region. A 0.1 change in reference salinity typically introduces a 10% error for the shelf freshwater content. Thus, it seems reasonable to consider the 35.60 reference level for investigating the spreading of the shelf water in the southeast Bay of Biscay during summer, when it is confined in the upper 100 m. However, deeper mixing happens in November 2009 and later during the winter season, so the simplified freshwater budget does not apply in this season. Evaporation and precipitation contribute to the evolution of the shelf fresh water. For example over the shelves, assuming a 10 cm excess of evaporation over precipitation, a magnitude coherent with the May measurements on the R.V. Antea and climatology, it results in a decrease of freshwater on the order of $1.5\cdot10^{10}\,m^3$ from early May to late July (three months).

2.3. Drifters

Most drifters were deployed during the GOGASMOS, CAROLS and ARCADINO cruises. These drifters were SVP drifters usually drogued at 15 m. However, during GOGASMOS, 5 SVP drifters were drogued at 8 m, as it was found that the fresh surface layer was often shallower than 15 m near the shelf break. Those drifters were launched within 1 km of each other near the shelf break north of the Cape Ferret Canyon and were recovered on June 16–17. Four of these drifters that had retained a drogue were redeployed on June 17 along the northern slope of the Cape Ferret Canyon. Prior to June 16, they were equipped with a salinity sensor (attached Surplas float) to check salinity evolution. The ARCADINO drifters were deployed during the different ARCADINO spring cruises (Charria et al., 2013), but the drifters deployed in June are the most interesting for this investigation. They were also drogued at 15 m depth. Drogue loss was checked and we consider only portions of the trajectories when the drogue was present.

2.4. Lagrangian model

In order to explore the effect of meso-scale circulation in the southeastern Bay of Biscay in the distribution of SSS, we use an approach based on simulated Lagrangian trajectories.

Lagrangian trajectories are obtained by integrating altimetry derived surface velocities with a 4th order Runge–Kutta integrator at a fixed time step of 6 h. Altimetry velocities (gridded at 1/3° and 1 week) are interpolated linearly in space and time. Lagrangian techniques measure transport properties along the trajectories of a water parcel. By doing this, these techniques allow to take into account the temporal variability of the velocity field and the non-local transport effects resulting from the sequence of the stretching events experienced by a water parcel along its trajectory. Time-dependent stretching gives also rise to chaotic stirring, which can generate submesoscale filaments. By reproducing this mechanism, Lagrangian diagnostics applied to altimetric data have been shown to predict the geometry of chlorophyll or SST submesoscale filaments (Lehahn et al., 2007; d'Ovidio et al., 2009).

The salinity filaments induced by the mesoscale chaotic advection are reconstructed by a simple passive advection model, based on altimetry for the velocities and on the analysed SSS fields for the salinity initial distribution. In order to develop filaments, the cascade of chaotic stirring needs advection timescales corresponding to the inverse of Lyapunov exponents (a few tens of days, in this region). In the context of eddy circulation in the Irminger Sea, Després et al. (2011) find the best agreement for integration times of 30 days. Analysing here a salinity field over a smaller region, we had to set the integration time to a slightly shorter three-week window, in order not to disperse too much the interpolated salinity values. Altimetric meso-scale currents are the mapped 1/3°-resolution geostrophic currents computed from satellite sea surface height measurements and provided by Archiving, Validation, and Interpretation of Satellite Oceanography Data (AVISO) every 7-days and is based on data from mostly three satellites during the period of study, as well as a mean dynamic topography from Rio et al. (2009). This altimetric product is not expected to have skill within 25 km of the coast, or resolves eddies of scales less than 50 km (Dussurget et al., 2011).

2.5. PREVIMER, HYCOM, and IBI model simulations

Three real-time high-resolution simulations are performed daily in France with a domain including the shelves and nearby deep-ocean of the Bay of Biscay at high resolution and with realistic topography. All the models are forced by winds and atmospheric 6 or 3-hourly fields from ECMWF (European Centre for Medium-range weather forecasts) model or Arpege operational model from French Meteo-France. PREVIMER runs a Mars3D model in the Bay of Biscay sector. This is a sigma (proportional to bathymetry) coordinate model run at IFREMER with very high vertical resolution on the shelf, 4 km horizontal resolution and daily observed river run-offs (Lazure et al., 2009; Lazure and Dumas, 2008). It is forced at is open boundaries from operational psy2V3 and runs daily without any assimilation control. Mercator runs an OPA7 model at nearly 2 km resolution with a z-grid and partial steps bathymetry in the Bay of Biscay sector, which we will refer to as IBI. HYCOM (Bleck, 2002) is a mixed-coordinate model (isopycnic in the interior, z near the surface, and sigma on portions of the shelf) run by SHOM in a 3 km resolution version for the Bay of Biscay. Both IBI and Bay of Biscay HYCOM use 3-hourly forcing fields from ECMWF, are forced at their open boundaries from operational run psy2V3 of MERCATOR-Ocean, and initialised every week. For IBI, climatological river run-offs are used, and the fourth week of the simulation is retained here, to avoid the spin-up phase. Bay of Biscay HYCOM includes observed daily river run-offs.

3. Salinity data

3.1. Freshwater extension

By late April, most of the shelf, in particular south of 46°N, is covered with a very fresh surface layer (with SSS often less than 34 psu) originating from the high river outflow in winter and spring 2009, in particular from the Gironde and the Adour (Fig. 2a). This fresh surface layer expanded further throughout May (Fig. 2b–c), as there was still high river outflows in the first half of May (in particular, the Gironde) and further spreading to the outer shelf of the fresh water. At that time, it is possible to estimate a freshwater content over the shelf by vertically integrating salinity from available profiles as explained in the data section. This indicates very large values near the estuaries in narrow plume areas, but also a very large area over the shelf with fresh water content in excess of 1 m (Fig. 3). There were different surveys providing snapshots every 10–15 days that allow to map the westward propagation of the fresh water, at least between 44°N and 46°N. This fresh water layer has variable thickness, but near the shelf in early–mid May it rarely exceeds 30 m, with the freshest water within a 10–15 m

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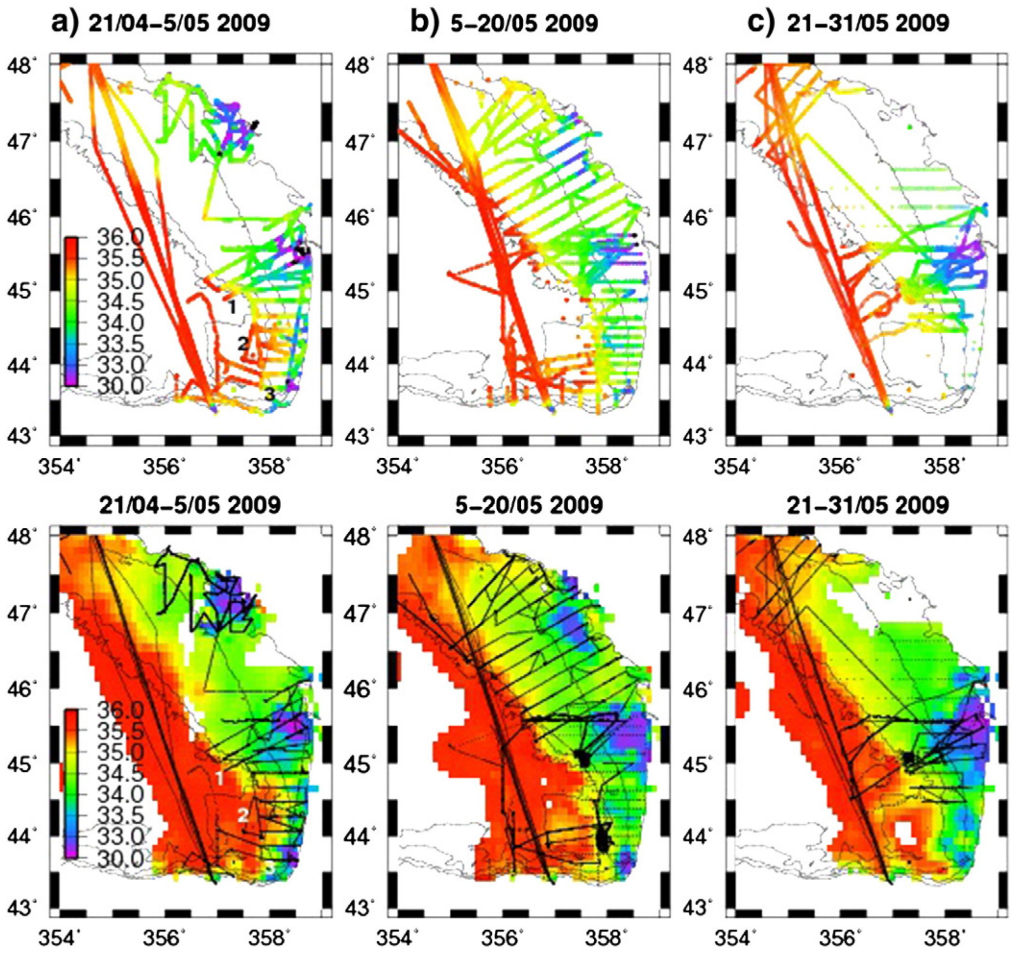

Fig. 2. SSS for three periods in late April–May. The upper panels with coloured symbols indicate the data points (colour-coded with SSS) and the lower panels present objectively mapped SSS with data points overlaid. The heavy curves are for the 200 and 2000 m isobaths. On the left panels, symbols 1, 2 and 3 refer to the Cape Ferret Canyon, the Landes Plateau and the Cape Breton Canyon, respectively. The isobaths plotted (light line) are at 100 m, 200 m and 2000 m depths.

thick layer. This freshest water reaches by early May the slope area near or south of the Cape Ferret Canyon, with SSS values between 34.2 and 34.6 and freshwater content between 0.6 and 1.0 m on three different sites in May along the shelf break (two to the North-east of Cape Ferret Canyon and one near 44°N east of the Landes Plateau).

By May 16–20, a moderate amount of fresh water has penetrated over the Landes Plateau. In some casts in the northeastern part of the plateau, the fresh water content reaches 0.6 m and there is also a low SSS patch seen offshore over the southeastern part of the Landes Plateau (near 3°W/44°N). By late May and mid-June (Fig. 4), the surface signature of this fresh water over the Landes Plateau has rescinded away from the shelf break, except maybe over its northern part (the CAROLS CTD section near 44–44.2°N did not witness fresh water offshore of the 500 m isobaths). For the first time, there are surface indications (from SSS) of fresh water penetrating north of the Landes Plateau, over the Cape Ferret Canyon, either from its eastern end near 44.7°N or along its northwest spur, west of 3°W. A CTD cast done near July 1 (Leviathan cruise) in the eastern part of the Cape Ferret Canyon indicates fresh water content exceeding 0.5 m over 3000 m depth near 2.5°W in the central part of the Canyon. This suggests by then already a large penetration of the fresh water over the deep southeast Bay of Biscay. This contrasts with the situation near 45.6°N followed by the glider which do not indicate until mid-June major fresh water penetration offshore of the shelf break. However, even at

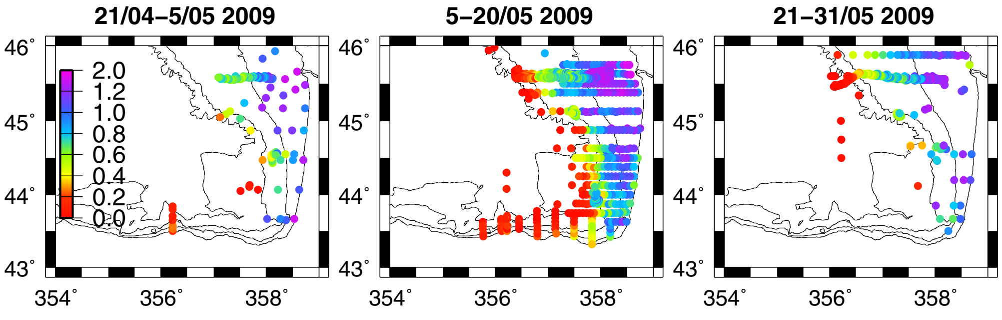

Fig. 3. Vertically-integrated fresh water contents for the same periods as Fig. 2 (in metres).

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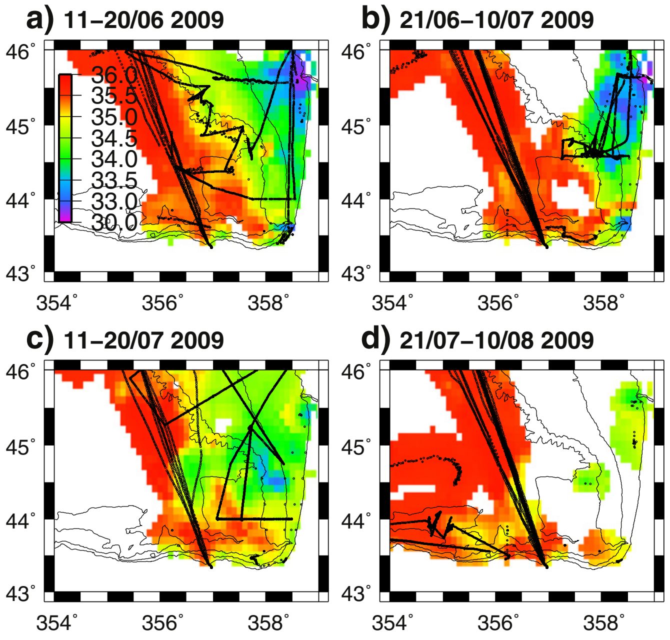

Fig. 4. SSS maps in mid-June to early August (same as lower panels on Fig. 2 with a zoom on southeastern Bay of Biscay).

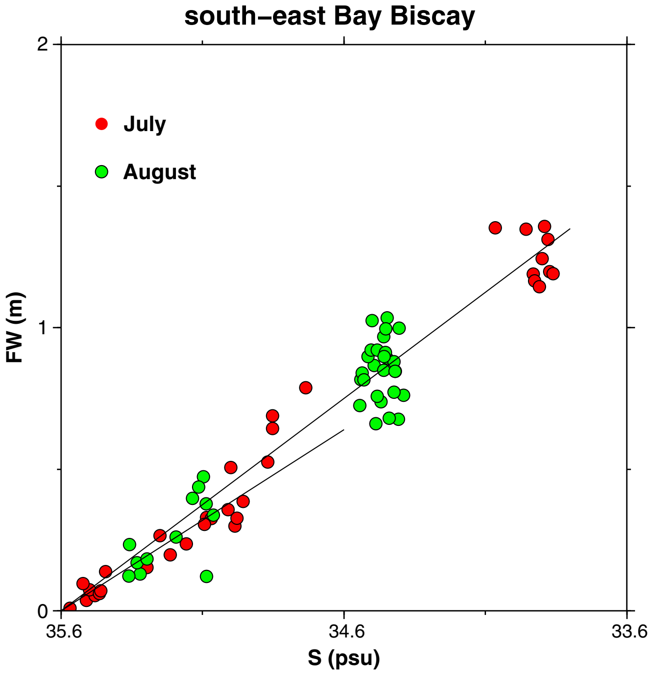

Fig. 5. The fresh water content/35.6-SSS scatter plot for CTD/seasoar/scanfish casts taken off the shelves in the south-eastern Bay of Biscay in July and August 2009. Two regression lines are presented: one taking only SSS larger than 34.6, and the other including all data.

that latitude, there was a large increase of the fresh water content west of 2.3°W over the part of the shelf deeper than 100 m from early May (0.6) to mid-June (1.0 m) (not shown).

In the mid-June survey, the surface data suggest that most of the fresh water is still contained relatively close to the shelf-break (Fig. 4a). By July 1 in the eastern Bay of Biscay, there is an indication that the fresh water is still confined east of 2.7°W (Fig. 4b). On the other hand, along the Pride of Bilbao route near 3.5°W, the fresh water started to be felt by June 27 near 44.5°N, with increasing strength until mid July. By mid-July (Fig. 4c), surface salinity of 34.08 is measured by the Pride of Bilbao west of the Landes Plateau (3.2°W) with the water with salinity less than 34.5 psu extending over a 60 km stretch of its track, whereas water salinity as low as 33.87 psu and 33.85 psu were measured further east over the Cape Ferret Canyon on July 17 and July 19. Such very low salinity was found much further inshore on the shelf by mid-June (east of 2.5°W at 45.55°N, the latitude of the Gironde estuary) and was first observed just west of the shelf Break on June 26 for the first time. This suggests a large exit of the diluted Gironde plume by late June–mid July. Interestingly, during this whole period, salinity remains much higher along the east–west shelf break off the Basque country and Canyon of Cape Breton sector, as seen by the two surface moorings there.

By late July (Fig. 4d), the surface fresh water is also felt by the mooring at 3.78°W near the 2000 m isobaths, thus over the slope, and is also observed further west, off the shelf until close to 5°W. At that time, as well as for the earlier May to July period, SSS values further east along the shelf-break and slope are higher (Basque moorings or Pride of Bilbao north of Santander), indicating that the origin of this fresh water is not through westward advection along the shelf break. Off the shelf, along the 3.78°W section, the fresh water is witnessed in CTD casts at that time with fresh water content up to 0.4 m, thus much higher than closer to shore. It is also measured by mid August on stations of a cruise at the same longitude extending further offshore (to 45°N), with comparable values of freshwater content over an almost 50 km swath of the cruise. An approximate relation for the mid-July to mid-August season between SSS and fresh water content can be derived from the different CTD profiles obtained outside of the shelves (3.78°W sections, scanfish (ASPEX) and seasoar (MOUTON2009) sections in the Cape Ferret canyon sector) (Fig. 5).

This relation can be used to convert the relatively well sampled SSS map of mid July (Fig. 4) into a freshwater content for the off-shelf sector. This assumes that the fresh water has not yet penetrated west of the Pride of Bilbao line, as suggested by the 3.78°W mooring site. Depending on how we establish the linear relationship (including or not profiles with surface freshening of 1 psu or more, or whether it is based on July or August data, regression lines on Fig. 5), the freshwater content is estimated in the range 11–14 · 10^9 m^3 in this offshore freshwater pool. Half of it is west of 2.8°W, therefore well inside the deeper areas of the southeastern part of the Bay of Biscay.

The low salinity patch is still very well defined by mid August (Fig. 6), with SSS already increasing over part of the southeastern Bay of Biscay shelves and freshest surface waters found along the slope between 44 and 45°N. Some late September data (Fig. 6) indicate that the fresh water has penetrated westwards to at least 5.5°W, with a more patchy distribution than before. As there has already been some vertical mixing, surface values are higher everywhere, and the spatial data coverage is too low in the western part (west of 3°W) to estimate a reasonable budget of the offshore fresh water (for example, the mapped maximum near 3°W/44.8°N could be an artefact of insufficient sampling). Similarly to the late August maps, the freshest water is found (except for some outflow from the Gironde) near the shelf break or offshore of it in the 44°N–45°N sector including both the Landes Plateau and the Cape Ferret Canyon. Late October data (Fig. 6) confirms this distribution, which is thus still present in the preconditioning phase of winter mixing.

4. Other data and simulations

The salinity data described in the previous section only suggest that the fresh water spreads westward from the eastern part of the Cape Ferret Canyon in June–July. To complement these in situ salinity observations, we will adopt three approaches: observed Lagrangian trajectories from drifters, back-trajectory estimates, and realistic real-time model simulations.

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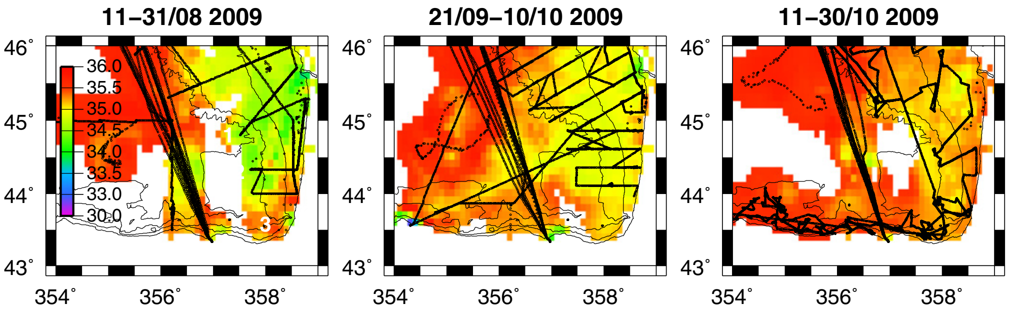

Fig. 6. August to late October SSS maps (same as Fig. 4).

4.1. Drifter trajectories

Five drifters drogued at 8 m and equipped with salinity sensors were released on the northeast side of the Cape Ferret Canyon by May 20 in salinity of 34.3. These drifters indicated a progressive increase in salinity, until they were recovered on June 16–17 in places over or west of the Cape Ferret Canyon where SSS was 34.9 to 35.2 (not shown). The change in time of SSS is indicative on one hand of the effect of evaporation and vertical mixing on surface salinity, but quite likely also of relative advection with respect to the drifter (current is sheared between 8 m and deeper water). The drifter trajectories nonetheless indicate one route by which fresh water was transported over the deep ocean. However, when 4 of these drifters (with a drogue at 15-m depth) were redeployed on June 17 at a similar site, their route brought them in the following 20 days further west/northwest mostly along the shelf break (Fig. 7). Two of those drifters then drifted to the southwest and by mid-July, they were respectively over the Landes Plateau or the western Cape Ferret Canyon. Both reached the Asturian shelf by late July, one indicating further westward trajectory on the shelf until late August. The two other drifters ended in August in the central Cape Ferret canyon area. These trajectories are suggestive of transport of shelf surface water to the interior between the northern part of the Cape Ferret Canyon and the south-eastern Bay of Biscay.

Three other drifters from the Arcadino project (Fig. 7) suggest that there would also have been a pathway for very fresh shelf water westward in the 44°N–45°N sector (Fig. 7 lower panel). This includes one drifter deployed on June 29 in the central part of the Cape Ferret Canyon (2.6°W), possibly near the western edge of the fresh water (based on the SSS map). This drifter went southward around the Landes Plateau and reached the vicinity of the southern shelf (in the western extension of the Cape Breton Canyon) in late July, and then veered to the northwest. Two drifters deployed in mid July over the shelf (water depth less than 100 m) went also westward well across the shelf break by late July, with further trajectories over the Landes Plateau/Cape Ferret Canyon sector. These trajectories indicate that the cross-shelf transport of fresh water could have continued after mid-July, at least until early August. The July 2009 period witnessed significant northerly wind, which could have favoured westward surface outflow of shelf water.

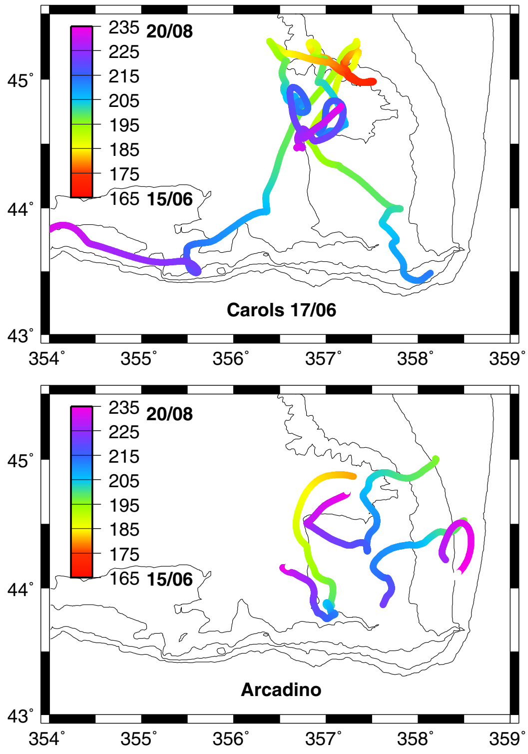

Fig. 7. Smoothed drifter trajectories (drifters drogued at 15 m depth). Upper panel, from June 17 Carols cruise deployment; lower panel from Arcadino June–July deployments. Trajectories are colour-coded with respect to date in calendar days.

4.2. Real-time numerical simulations

All simulations suggest that the Gironde fresh water plume reached the shelf Break near or just north of Cape Ferret Canyon by mid-May (Fig. 8). At that time, all simulations suggest that Adour water flows westward along the Basque country. By mid-June, both HYCOM and PREVIMER indicate fresh water spreading over the eastern part of the Cape Ferret Canyon. At that time, IBI, on the other hand, has some fresh water spreading near the western north-west end of Cape Ferret Canon, and also some water spreading northward from Cape Breton canyon area near 2.5°W. By mid-July, PREVIMER has the fresh water from Gironde spreading south to the Basque country and then west along Spain. It also covers the Landes Plateau. HYCOM has less fresh water over the Landes Plateau, but presents a westward freshwater flow along the Basque coast, with some fresh water spreading then northward near 3–3.5°W, but also some fresh water having flowed westward near 45°N from a fresh water pool in the eastern part of Cape Ferret Canyon. By then, on the other hand, IBI presents fresh water over the Landes Plateau east of 3°W. It also presents some spreading from the Cape Ferret Canyon, but instead of flowing to the west as in HYCOM, it flowed to the south or south-west, reaching the Asturian shelf-break near 4°W.

4.3. Lagrangian simulation

Part of the observed variability in SSS from mid-June to mid-July is captured by the Lagrangian back trajectories (Fig. 9). Because of trajectories originating from the coast, there are more holes on the maps than on the analysed SSS fields. This is not surprising, as we don't expect the geostrophic current analysis to be realistic in the near shore region. It is

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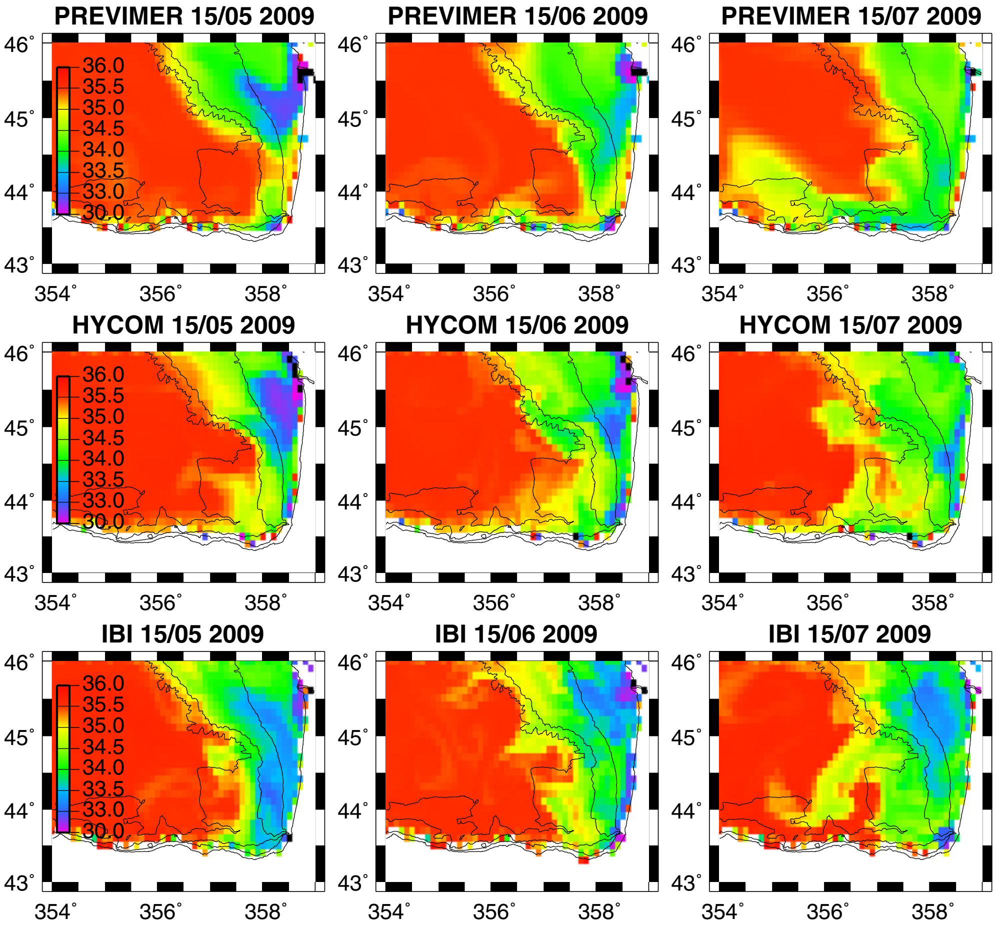

Fig. 8. SSS mapped in the south-eastern Bay of Biscay from three different numerical simulations: PREVIMER (top), HYCOM (middle) and IBI (low) on May 15, June 15 and July 15 (from left to right).

also likely that some of the missing area would be covered with rather fresh water, as water sector near the coast was also fresh in mid-June (for example near 45°N). The simulations shows a spreading of the fresh water westward near 45°N, and an invasion of higher salinity water on the shelf and the eastern Landes Plateau south of 44.5°N. Compared to the observed change, the structures are shifted somewhat to the north in the simulations. The fresh water seems to spread closer to the north edge of the Cape Ferret Canyon rather than in its centre, as observed. A large part of the fresh water also continues to the north-west, something that does not seem to be observed (although drifter trajectories were initially suggestive of such path in late June). There is, as observed, some southward flow near 3.5°W. Both features are directly associated with the altimetric current patterns which provide a direct path in this sector from the shelf to the deep ocean.

Simulations a month earlier (from late-May) do not indicate such a large penetration of fresh water off shore (not shown). However, there is some fresh water signal advected, in a larger way than what is observed. We also found that the simulation seemed rather sensitive in this area to the choice of average dynamic topography retained.

5. Discussion

The real-time numerical simulations do not do as well as the rather simplistic Lagrangian method in simulating the evolution of salinity in this region from mid-June to mid-July. Clearly, the currents near the Basque shelf break were in the opposite direction in all simulations from what is observed in the rather low-resolution altimetric analyses. The currents might also have been in the opposite direction over the

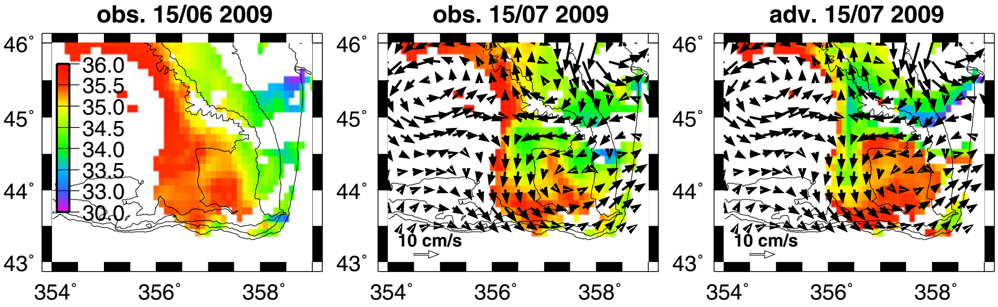

Fig. 9. Observed SSS field on June 15 (left) and July 15 (middle); SSS simulated on July 15, using the back-trajectory method initiated from the June 15 SSS field (left), with July 15 currents overlaid (scale near the bottom). Only areas filled in all fields are plotted.

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Landes Plateau. On the other hand, IBI runs which get some of their information from data assimilation of altimetry showed more realism further off-shore, as well as an overall coherence with the Lagrangian back-trajectories simulation. Both IBI and the Lagrangian simulation show some spreading to the south near 3.5°W, coherent with the altimetric currents and drifter trajectories in the sector. These Lagrangian trajectories tend also to produce some spreading northward along the shelf break of the fresh water escaping Cape Ferret Canyon, something that might have happened in an early stage (based on the drifters), but that has not lasted to mid-July (based on the salinity observations). In the Lagrangian back-trajectories simulations, this could have resulted from not having taken into account Ekman drift (that would have been mostly a westward flow in that period). It is also likely that Ekman effects are not properly taken into account in some models, that have difficulties in representing the very shallow late spring to mid-summer mixed layers (as indicated, for example, from the thickness of fresh water layers in the different July and August sections).

Drifter trajectories, as-well as simulated salinity field using back-trajectories in altimetric currents indicate an origin of the fresh water from the shelves and the importance of cross-shelf transport during late June–July in this Cape Ferret Canyon sector near 45°N. In 2009, it seems that the main mechanism is one of Ekman transport off shore of the shelf break, with the fresh water then carried by a fairly steady meso-scale geostrophic eddy circulation. Interestingly, this contrasts with high-resolution simulations (HYCOM models) indicating exchange by filamentation along the Cape Ferret shelf break in May–June (as was also found in this simulation in other years or suggested by the data presented in Fig. 1). Filamentation is more associated with evolving eddy dynamics.

The average 15 m current climatology (Charria et al., 2013) suggests that this off-shelf circulation might be an average feature for the late spring–early summer season, although in this climatology it seems to appear at 46°N and not 45°N. The very low shelf salinity observed in 2009 (in late May, the fresh water content referred to 35.6 psu amounts to $4.9 \cdot 10^{10}$ m^3) might on the other hand be the result of the large fresh water input from the rivers in January through May 2009. The combined January through May outflow from the rivers Vilaine, Loire, Gironde and Adour is $3.65 \cdot 10^{10}$ m^3, which is a large share of the shelf fresh water content, implicating that most of the fresh water has not resided for more than 5 months on the shelves (river outflows were not strong in autumn 2009), and that earlier fresh water escapes from the shelves were probably not strong, although there are indications of some fresh water, probably from the Adour, having flown westward to 3°W along the North Iberic shelves in late March–April. There was also a late spring flow of the very fresh surface water from the Gironde to the southwest towards the shelf break.

The June–July 2009 exit of the fresh water from the Aquitaine shelf towards the northern Iberic shelves did not happen by the south-east corner of the shelf close to Cape Breton Canyon. Data in other years or even in mid-March/April 2009 (Basque moorings, for example) suggest that this can also be a fresh-water path. The current data (for example from drifters or altimetry) suggest that the circulation during June–July 2009 was not favourable for this path. There are not enough data available to find how often the particular situation encountered in 2009 happens, whereas cases of Fig. 1 suggest that this happens in other years, although there are no published indications of a signal as large as in 2009 (2011 personal communication, R. Somavilla). The mechanisms involved will need to be investigated more thoroughly from interannual data sets and model simulations.

6. Conclusions

There was a very large freshwater river input in winter and spring 2009 to the Aquitaine shelf of the Bay of Biscay. This freshwater had spread to the shelf break by early May. By mid-June significant amounts of freshwater were observed along parts of the slope between 44°N and 45°N. By mid-July, a large amount of freshwater had spread at least to 4°W west of the shelves over the deep south-eastern Bay of Biscay. This amounts to roughly a quarter of the total freshwater content of the shelves. From the Arcadino trajectories and the SSS surveys, we suspect that this freshwater export from the Aquitaine shelf has continued until late July, and this could have contributed to even more of the shelf freshwater reaching the deep ocean in this sector. This export is at least as large as the changes of the Aquitaine–Armorican shelf freshwater content that would have resulted from excess evaporation or freshwater inputs, during this late spring to mid-summer period. Interestingly, this summer export was not through the southeast corner of the Bay of Biscay along the shelf break towards the northern Iberic shelves.

This 2009 off-shelf path of the fresh water is apparently not simulated numerically by the high resolution operational models, with the possible exception of the IBI run, which has a stronger guide on altimetry, at least offshore. On the other hand, all models had over the shelf a flow of diluted Gironde water to the southwest, approaching the shelf break. Investigating why the simulations failed to carry correctly the water south-westward outside of the shelves and why they presented westward flow along the Basque shelf break around the Cape Breton Canyon, will require further investigation.

The off-shelf drift of this fresh water might have consequences for larval/juvenile transport of larva initially found off the Gironde (for example for anchovies: Lavín et al., 2006). It might have also had an impact on the tuna fishery distribution of the summer 2009, which did not proceed east of 5°W (R. Somavilla, personal comm.).

Interestingly, this large amount of surface fresh-water in the summer–autumn 2009 having spread over the south-eastern Bay of Biscay, contributes to additional upper ocean stratification. During the following winter, this would thus result in shallower and fresher mixed layer depths than would have been attained without this freshwater input, although usually freshwater input plays a minor role there in winter mixed layer deepening (Somavilla et al., 2009; Somavilla et al., 2011 personal communication). This contribution, as well as the impact of anomalous heavy rainfall combined with surface cooling of a stratified surface layer will have to be investigated further from autumn 2009 and winter 2010 data, as well as numerical modelling.

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