



HAL
open science

Poleward along-shore current pulses on the inner shelf of the Bay of Biscay

M. Kersale, Louis Marie, B. Le Cann, A. Serpette, C. Lathuiliere, A. Le Boyer, A. Rubio, Pascal Lazure

► To cite this version:

M. Kersale, Louis Marie, B. Le Cann, A. Serpette, C. Lathuiliere, et al.. Poleward along-shore current pulses on the inner shelf of the Bay of Biscay. *Estuarine, Coastal and Shelf Science*, 2016, 179, pp.155-171. 10.1016/j.ecss.2015.11.018 . hal-04200727

HAL Id: hal-04200727

<https://hal.science/hal-04200727>

Submitted on 5 Jan 2024

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Poleward along-shore current pulses on the inner shelf of the Bay of Biscay

Kersalé M. ^{1,*}, Marié Louis ², Le Cann B. ¹, Serpette A. ³, Lathuilière C. ³, Le Boyer A. ³, Rubio A. ⁴, Lazure Pascal ⁵

¹ Laboratoire de Physique des Océans, UMR 6523 CNRS-Ifremer-IRD-UBO, Université de Bretagne Occidentale, Brest, France

² Laboratoire de Physique des Océans, UMR 6523 CNRS-Ifremer-IRD-UBO, Ifremer, Centre de Bretagne, Plouzané, France

³ Division HOM, Service Hydrographique et Océanographique de la Marine, Brest, France

⁴ AZTI-Marine Research, Herrera Kaia, Portualdea z/g, 20110, Pasaia, Spain

⁵ Ifremer, Dyneco, BP70, Plouzané, France

* Corresponding author : Marion Kersalé, email address : marion.kersale@univ-brest.fr

Abstract :

We analyzed strong events of coastal poleward along-shore currents above 10 cm s⁻¹ and up to more than 50 cm s⁻¹ on the inner shelf (50-80 m depth) of the Bay of Biscay (BoB) from the Spanish coast to the Brittany coast. We used data from four acoustic Doppler current profilers (ADCPs) deployed from July 2009 to August 2011. The goal of this study was to analyze current variability at meso- and subinertial scales and their generation mechanisms. These currents occurred all year long and were classified into three types. Events occurring principally in the southern part of the BoB were classified as southern events. Bay-scale events were defined when strong poleward currents were detected over all the shelf, typically stronger on the Spanish and the southern Brittany shelves. Strong events were characterized by depth averaged current velocities over 40 cm s⁻¹ in the southern part of the BoB. At short time lags, the along-shore currents were clearly related to along-shore wind stress at upstream locations. An explanation is provided for longer time lags in terms of coastal trapped wave (CTW) dynamics. The first CTW mode phase speeds were in agreement with the propagation speeds of the fastest events (> 5 m s⁻¹), while inner shelf modes could explain the slowest events (~ 1-3 m s⁻¹). The cross-shelf density gradient and the extension of the IPC were also associated with strong coastal poleward along-shore currents. The duration of the events, the vertical structure of the currents and the associated coastal trapped waves were studied in relation with the stratification.

Keywords : Coastal Jets, ADCP, Shelf circulation, Wind forcing, Coastal Trapped Waves, Bay of Biscay

1. Introduction

Eastern boundary current systems are characterized by the generation of strong and intermittent poleward currents [7]. In many cases, these poleward flows are surface intensified and encompass the shelf. Several mechanisms have been suggested for their generation. A number of local forcings can be identified such as buoyancy, wind and rectification of coastal trapped waves (CTWs). Considering the frequent occurrence of such poleward currents flowing against prevailing equatorward winds, larger-scale, non-local forcing mechanisms, that may be mediated by CTWs, have been proposed and classified by [27]. These authors show that an along-shore surface slope or an offshore pressure gradient can also generate these flows. The establishment of these pressure gradients can be due to regional wind stress and meridional density gradients, known as the joint effect of baroclinicity and relief [JEBAR, 29], and can be modified by along-slope topography.

Studies of those dynamical processes which govern continental shelves have been reported along the U.S. west coast [e.g. recently in 34, 70, 47, 50] and along the Mexican west coast [17]. The continental shelf north of San Francisco [Coastal Ocean Dynamics Experiment - CODE, 4], the Western Florida shelf [45] and the central west coast of India [2] have been also proposed as typical regions of poleward flows. The most recent studies, described above, were based on experimental results from high-frequency (HF) radar systems or multi-year

1
2
3
4
5
6
7
8
9 Acoustic Doppler current profilers (ADCPs) measurements. The Australian
10 Coastal Experiment [ACE, 20], conducted in the coastal waters of New South
11 Wales (east coast of Australia) with a three main lines array of current meters,
12
13
14
25 was the most ambitious early observational study aimed specifically at coastally
15 trapped waves. The data obtained allowed a detailed examination of the dy-
16 namics of flow on the continental shelf and slope and in particular a description
17 of coastal trapped wave modes propagating within the coastal waveguide.
18

19
20 Despite its complex topography, the Bay of Biscay (BoB - Figure 1), located
21
22
30 at mid-latitudes in the north-eastern Atlantic, off western Europe, exhibits the
23 classical current system found in eastern boundary regions, with poleward flow
24 on the shelf and slope [53, 35, 37]. The BoB, area of interest in this study, is
25 characterized by three main parts (Figure 1): an abyssal plain, a continental
26 slope and a northward widening continental shelf (~ 20 km at 3°W - Spanish
27 shelf, ~ 60 km at 44°N - Aquitaine shelf, ~ 150 km at 47°N - Armorican shelf).
35

31 The North Atlantic circulation over the abyssal plain has been relatively well
32 studied in several works [53, 52, 66, 14, 12]. The averaged, anticyclonic, circu-
33 lation is characterized by weak values ($1-2$ cm s^{-1}) but larger velocities due to
34 mesoscale dynamics [51] are observed, such as anticyclonic eddies [54].
35

36
37
38
39
40
41
42
43
44
45
46
47
48
49
40 Along the slope, the currents are characterized by a cyclonic circulation with
higher mean velocities, $5-10$ cm s^{-1} [55]. These currents exhibit a strong season-
ality. The along-slope circulation is marked by the occurrence of an intensified
poleward surface flow (Iberian Poleward Current - IPC) in autumn and winter
north of the Iberian Peninsula. Stronger over the upper part of the slope, the
signature of the IPC, a warm and saline current, has been described in different
studies [21, 54, 57, 63]. This eastward current can reach velocities over 70 cm s^{-1}
and can extend to the Aquitaine and Armorican upper slopes [43, 22].

50 The general features of the circulation on the shelf have been described. [12]
51 suggest a link between the northern Spanish shelf circulation and the one of the
52 Aquitaine shelf similar to the continuity of the slope current from Spanish to
53 Celtic slopes [55]. Several studies have been undertaken to describe the main
54 ocean processes affecting the Spanish shelf and slope circulation [25, 65, 19, 59,
55
56
57
58

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

1]. A detailed description of the dominant surface current patterns observed by HF radars in the southeast corner of the BoB has been proposed by [63, 62] in relation to seasonal, mesoscale and high-frequency variability. Over the French shelves, weak values with residual sub-tidal currents of about 3 cm s^{-1} have been measured [53, 41]. [12] have shown a strong seasonality of the surface current direction: equatorward in spring and summer, and poleward in winter and autumn. These changes are driven by the seasonal variation of wind [53, 55]. At smaller spatial scales, the freshwater discharges induce also a significant circulation over the inner shelf, especially in the Gironde and Loire plumes [39, 40, 16]. On the northern Armorican shelf, a cold pool of water (12°C) centered between 60 m and 120 m depths is present from spring to autumn. This pool of dense water, called “bourelet froid” [for “cold pool”, 68], is associated with surface cyclonic circulation [12].

Influenced by large-scale oceanic basin circulation and by local forcings, such as seasonal wind regimes and important river discharges, the BoB shelf circulation is frequently affected by the occurrence of poleward flows. These poleward flows appear as intermittent and locally variable currents, defined as pulses, and have been reported during different seasons in the BoB. On a weekly scale, the shelf is associated with strong surface currents near the coast in the northern part of the domain in winter and strong currents affecting the whole water column in the southern part of the domain in autumn [41]. Indeed, poleward flows on the shelf exist all year long, with stronger intensity in autumn-winter than in spring-summer [12]. From October to March, marked weekly poleward currents (up to 15 cm s^{-1}) are observed over the Aquitaine shelf.

A summer poleward coastal event of up to 32 cm s^{-1} during 22 days along the Aquitaine shelf was investigated using ADCP and drifting buoys measurements by [3]. One possible mechanism of this event was reported and linked to westerlies, along-shore wind events inducing downwelling conditions along the Spanish coast. This downwelling induces an along-shore pressure gradient and can generate CTW and Kelvin waves [3]. [38] described an autumn poleward

1
2
3
4
5
6
7
8
9 current over the Armorican shelf up to 20 cm s^{-1} . The mechanism of this event
10
11 85 was linked by the authors to the breakdown of stratification at this season, in-
12
13 ducing strong cross-shore density gradients. In both cases (summer and autumn
14
15 events), a bottom front is generated and, following the thermal wind balance, a
16
17 surface intensified poleward density driven current is generated.

18
19 90 Due to intense fishing activity, long-term moorings have rarely been deployed
20
21 over the shelf, even if an understanding of the shelf dynamics and its seasonality
22
23 is crucial for many studies, *e.g.* on vertical distribution of phytoplankton [15],
24
25 dispersion of harmful algal blooms [56] or seabed morphodynamics [46].

26
27 95 To improve our knowledge of the shelf circulation of the BoB, the objective of the
28
29 ASPEX project was to observe the shelf and upper continental slope circulation
30
31 through the water column over large spatial and temporal ranges. The aim of
32
33 the present project was to analyze the dynamical characteristics and generation
34
35 processes of along-shore poleward flow events lasting several days, over a two-
36
37 year period (July 2009 to August 2011), using high temporal resolution mooring
38
39 data at different locations along the Spanish and French shelves. This current
40
41 100 variability was investigated at time scales greater than one day (with periods
42
43 longer than the local Coriolis and diurnal tides periods). Each specific event
44
45 was identified and classified according to common features. This classification is
46
47 provided as a first step in the understanding of the generation processes of along-
48
49 shore poleward flow events in such complex area, due to contorted topography,
50
51 105 changes of coast orientation and coexistence of different forcings.

42 43 44 45 **2. Data and Methods**

46
47
48 This study was conducted within the framework of the ASPEX project, an
49
50 experimental component of the EPIGRAM project (Études Physiques Intégrées
51
52 en Gascogne et Région Atlantique-Manche). The ASPEX project was based on
53
54 110 the deployment of twelve moorings, for two consecutive years, from July 2009
55
56 to August 2011 (hereafter named ASPEX period) on the BoB 60 m, 130 m and
57
58 450 m isobaths, along three cross-shelf sections [41]. Since our main focus was
59
60
61
62
63
64
65

1
2
3
4
5
6
7
8
9 on the shelf dynamics, we used only the three current-meter moorings deployed
10 over the inner shelf: *ASPEX1* from the Penmarc'h section (hereafter named
11 *M4*), *ASPEX4* for the Loire section (hereafter named *M3*) and *ASPEX7*
115 *M2*), north of the Capbreton Canyon, at 44°N (Figure 1). All
12 the moorings were bottom mounted and equipped with RDI WorkHorse ADCPs
13 operating at 300 kHz and a SBE37 Microcat T/S/P recorder. Moorings were
14 deployed twice (July 2009 and August 2010) for approximately one year period
15 each [41, , table 1]. The ADCP were gimbal-mounted on frames at 71 m depth
16 for *M4*, 47-52 m depth for *M3* and 54 m depth for *M2*. The sampling period
17 was 30 s. The readers are referred to [41] for more details about the characteris-
18 tics of the recorded data and data processing. The collected data were averaged
19 over 20 min periods and tidally filtered. We used the “120i913” filter designed
20 by [64]. This filter has a 1.4 days cut-off period and a steep response curve. In
21 the following we define the along-shore direction as the one of the major axis
22 of the depth-averaged and filtered currents variance ellipse [48]. The tidally fil-
23 tered currents were projected onto these along-shore and cross-shore directions.
24 These are defined positive poleward and positive onshore.
25
26
27
28
29
30
31
32
33
34
35

36 In order to achieve a wider coverage of the area, we also used data from
37 a downward-looking WorkHorse ADCP operating at 300 kHz located at 7.5 m
38 depth on a buoy operated by AZTI on an open sea test infrastructure with 79 m
39 water depth (Biscay Marine Energy Platform-BIMEP). This ADCP (hereafter
40 named *M1*, Figure 1) covered the ASPEX period with a sampling period of
41 1 hour. The same processing of the data (tide filtering and projection) was
42 applied. For the raw *M1* data, beam amplitude, beam correlation magnitudes
43 and vertical velocity errors were used for the data processing and quality tests,
44 following [6]. Then, standard procedures were applied to perform a quality con-
45 trol [67]. Additional inaccuracies could be expected due to the horizontal drift
46 of the surface buoy where the ADCP was mounted. Using data from a GPS
47 fixed on similar moorings existing over the upper slope in the study area, [59]
48 estimated these to be under 4 cm s⁻¹.
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

The characteristics of the ADCP data used in this study are summarized in

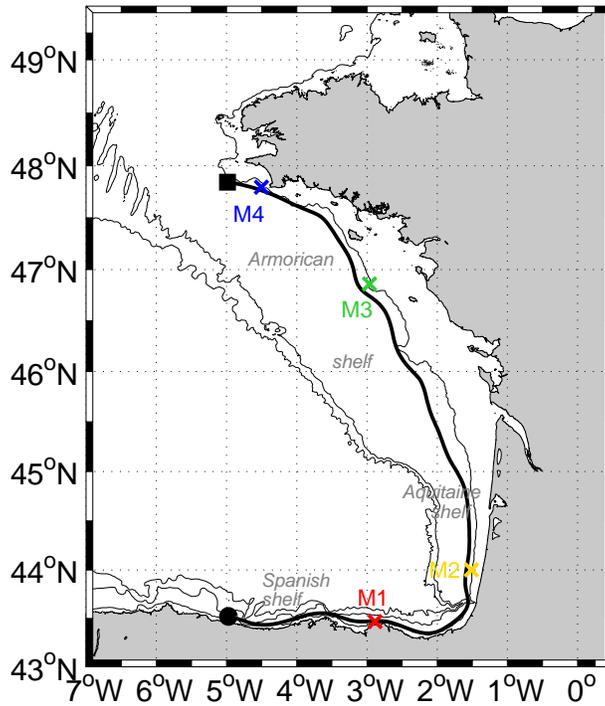


Figure 1: Study area and moorings position. The thick black line denotes the positions along the 100 m isobath section where the component of the wind stress is calculated and projected. The black dot (black square) represent the beginning (end) of the 100 m isobath section used for wind stress plots. Thin black lines indicate the 60, 130 and 450 isobaths.

Table 1.

145 The set of records presented hereafter were all low-passed currents (*i.e.* filtering out inertial and tides up to diurnal species using the Thompson filter mentioned above). Description of the different along-shore current events will be given, with a classification into three main types. All the events were characterized at *M1* by depth averaged poleward current velocities larger than
 150 14 cm s^{-1} and standard deviations greater than 8 cm s^{-1} within the period of the events. Events occurring principally at *M1* and *M2* will be classified as “southern events”. These events will be characterized by depth averaged poleward current velocities larger than 10 cm s^{-1} at *M1* and *M2*. These events corresponded approximately to the 10% of the total time series. We will refer to “bay-scale events” when along-shore current event extends toward the north
 155

Table 1: Moorings characteristics.

		ASPEX 1	ASPEX 4	ASPEX 7	BIMEP
		<i>M4</i>	<i>M3</i>	<i>M2</i>	<i>M1</i>
	Latitude (N)	47° 48'	46° 52'	44°	43° 28'
	Longitude (W)	-4° 30'	-2° 58'	-1° 31'	-2° 53'
	Cell Size (m)	2	2	2	10
	Sampling period (s)	30	30	30	3600
2009-2010	Water depth (m)	71	52	54	79
	Start	2009/07/13	2009/07/15	2009/07/19	2009/07/13
	End	2010/05/13	2010/06/29	2010/06/29	2010/07/01
2010-2011	Water depth (m)	71	47	54	79
	Start	2010/08/31	2010/09/02	2010/09/05	2010/08/31
	End	2011/08/07	2011/08/09	2011/08/10	2011/08/13

and when poleward currents are larger than 10 cm s^{-1} both in the southern and northern parts of the BoB (approximately 10% of the total time series). We used *M1* and *M4* for evaluating this type of events. When no data was available at *M1* during this type of events, we used instead data from *M2*. Finally, “strong events” will be characterized by poleward current velocities larger than 40 cm s^{-1} at *M1* and *M2* (corresponding approximately to 1% of the total time series). The start (end) time of all three types of events was set up when the poleward current velocities increase over (decrease under) 10 cm s^{-1} .

To understand the dynamics of the BoB circulation, we compared the current velocities and the wind data over the two years of measurements. This comparison was investigated using wind data from the 1 hour outputs of AROME atmospheric circulation model [61], with a spatial resolution of 2.5 km . During January 2010, wind data was not available in the AROME model. We used instead the data from the 3 hours outputs of ALADIN model [28], with a spatial resolution of 7.5 km . AROME and ALADIN are both meteorological analysis and forecast models from Météo-France over the Western Europe. Wind speeds were used to estimate wind stress values using a quadratic formula that relates the wind speed at 10 m above the sea surface to a stress value through the use of a neutral drag coefficient [36]. The model outputs were extracted every

1
2
3
4
5
6
7
8
9 175 6 h along the 100 m isobath every 10 km, starting from 5°W (Figure 1). The
10 projection of the wind speed components and the calculation of the along-shore
11 and cross-shore wind stress were made along this line. Wind stress components
12 are defined as positive poleward and positive onshore.
13
14

15 In addition, satellite sea surface imagery was analyzed to give an overview of
16
17 180 the dynamics in the area. Sea Surface Temperature (SST) was derived from the
18 Moderate-resolution Imaging Spectroradiometer (MODIS) radiometer on board
19 the NASA Terra and Aqua satellite platforms (<http://oceandata.sci.gsfc.nasa.gov/MODISA/>).
20 Weekly (8 day) MODIS SST composite products were used at 4.63 km spatial
21 resolution. To characterize the stratification of the water column, hourly SST
22
23 185 time series, at the nearest point of each mooring, from the geostationary Spin-
24 ning Enhanced Visible and Infrared Imager (SEVIRI, <http://www.osi-saf.org/>)
25 were compared to the bottom temperature records from the SBE recorder. This
26 comparison gave us the opportunity to detect thermal inversions, sustained by
27 haline stratification, with colder waters in the surface layer. Particular atten-
28
29 190 tion is paid to the presence of stratification (thermal or haline) because it influ-
30 ences the vertical structure of the poleward current events and the generation
31 of CTWs.
32
33
34
35
36
37
38

39 3. The events

40
41 Eighteen events of poleward currents were identified from 15 July 2009 to
42
43 195 30 June 2010 (Table 2) and twenty events from 1 September 2010 to 7 August
44 2011 (Table 3). The specific characteristics of the different events (hereafter
45 named as #EN, being N a number assigned in chronological order) for these
46 two periods are described in detail in Appendix A1.1 and Appendix A1.2 re-
47 spectively.
48
49

50 51 52 200 3.1. Southern events

53
54 During thirteen southern events, with a typical duration of 2-9 days, along-
55 shore currents were most intense on the north Spanish shelf (*M1*), up to 43.5 cm s^{-1}
56
57
58

Table 2: Summary for the 2009/2010 period - Pulses characteristics: Type and name of the events, maximum of depth-averaged poleward along-shore currents [cm s^{-1}] at each mooring, dates, duration (in days, d) and number of pulses.

Type	Name	M1	M2	M3	M4	Dates	Duration	Pulses
	#E1	25.7	16.0	3.4	13.7	23-30/07/09	7.3 d	2
	#E2	18.2	15.1	4.0	14.6	02-06/08/09	4.5 d	1
	#E5	15.2	5.2	7.3	13.5	21-24/10/09	2.1 d	1
	#E7	21.5	8.6	12.4	20.8	11-17/11/09	5.4 d	2
<i>Bay-scale</i>	#E9	35.4	8.2	3.7	18.4	29/11-05/12/09	5.7 d	2
<i>events</i>	#E11	No data	11.8	13.2	14.9	21-24/12/09	3.3 d	1
	#E12	No data	16.2	11.6	18.5	28/12-05/01/10	8.4 d	4
	#E13	31.8	No data	4.6	12.4	05-11/02/10	6.0 d	2
	#E14	29.3	16.7	19.6	22.0	17/02-04/03/10	14.8 d	4
	#E15	35.4	7.7	9.3	14.6	19-29/03/10	10.1 d	4
	#E3	29.2	10.0	-8.0	-7.0	03-07/09/09	4.3 d	1
	#E4	27.9	16.8	-9.7	-2.6	19-24/09/09	4.8 d	1
<i>Southern</i>	#E8	29.9	14.7	1.5	-14.8	21-24/11/09	2.2 d	1
<i>events</i>	#E10	20.7	10.9	-3.3	6.1	07-09/12/09	2.3 d	1
	#E16	43.5	17.2	4.7	5.6	29/03-02/04/10	3.5 d	1
	#E17	37.3	18.1	2.0	No data	11-20/05/10	8.6 d	1
<i>Strong</i>	#E6	54.9	55.3	5.7	0.0	31/10-10/11/09	10.1 d	3
<i>events</i>	#E18	50.2	47.3	16.9	No data	10-22/06/10	11.9 d	2

and on the Aquitaine shelf ($M2$), up to 26.4 cm s^{-1} (Tables 2, 3). The temporal evolution of the currents at $M1$ and $M2$ followed the same tendency, with poleward along-shore currents larger than 10 cm s^{-1} . During these events, equatorward or weak poleward pulses were recorded at $M3$ and $M4$. We selected #E4 and #E17 as the most representative events of this type.

During #E4, occurring between 19 September and 24 September 2009, the intensity of the along-shore currents reached 27.9 cm s^{-1} on the Spanish shelf and 16.8 cm s^{-1} on the Aquitaine shelf (Figure 2-a). Along-shore currents at $M3$ and $M4$ were oriented equatorward during this event. This event, and more generally during the periods from July to October 2009 and from September to October 2010, was characterized by currents typically more intense in the first 30 m of the water column (Figure 2-d). This depth corresponded to the depth of

Table 3: Summary for the 2010/2011 period - Pulses characteristics: Type and name of the events, maximum of depth-averaged poleward along-shore currents [cm s^{-1}] at each mooring, dates, duration (in days, d) and number of pulses.

Type	Name	M1	M2	M3	M4	Dates	Duration	Pulses
	#E23	45.8	15.6	13.8	24.3	28/10-04/11/10	6.8 d	2
	#E25	37.6	21.2	18.9	19.2	13-21/11/10	7.9 d	3
	#E26	No data	20.7	15.5	19.2	05-09/12/10	3.7 d	2
<i>Bay-scale events</i>	#E28	18.4	6.8	12.3	16.6	27-31/01/11	4.1 d	2
	#E29	27.0	8.7	15.1	28.6	08-20/02/11	11.5 d	5
	#E30	54.5	17.8	6.0	13.5	21-24/02/11	2.5 d	1
	#E31	34.1	9.3	0.1	12.4	15-19/03/11	4.1 d	1
	#E32	21.9	10.0	7.0	11.9	27/03-04/04/11	7.8 d	3
	#E33	20.2	8	2.1	13.6	20-28/04/11	8.5 d	2
	#E34	24.4	9.1	6.4	11.5	06-13/05/11	6.5 d	2
<i>Southern events</i>	#E19	33.8	12.3	4.3	6.4	04-13/09/10	8.9 d	2
	#E20	28.7	16.0	1.3	2.2	22-28/09/10	5.1 d	2
	#E22	21.4	15.2	-0.4	-2.0	24-26/10/10	2.1 d	1
	#E27	30.1	10.0	5.0	5.9	11-19/01/11	8.4 d	4
	#E35	28.4	15.1	2.2	2.8	13-21/06/11	8.7 d	2
	#E36	15.1	12.8	0.8	1.0	13-15/07/11	1.9 d	1
	#E38	16.2	26.4	7.0	8.8	25-30/07/11	4.1 d	2
<i>Strong events</i>	#E21	65.7	45.5	21.2	27.9	02-17/10/10	14.8 d	4
	#E24	61.3	42.9	12.6	13.9	07-11/11/10	3.5 d	1
	#E37	48.0	44.9	4.2	3.5	17-23/07/11	7.1 d	3

215 the seasonal thermocline, which was estimated with ScanFish sections in mid-July 2009 (data not shown). The mean temperature evidenced the presence of a thermal stratification with surface temperature around 15-20°C and bottom temperature between 12-13°C (Figure 2-b). During #E4, along-shore currents were associated with an increase of bottom temperature of 1°C at M2 (Figure 2-
220 b). This event was associated with strong values of along-shore components of the wind stress (up to 0.2 Pa, Figure 2-c). Positive values were recorded along the Spanish coast (first 300 km along the 100 m isobath, Figure 1) and negative values along the French coast.

#E17, occurring mid-May 2009 (11-20 May 2010), was classified as a *southern event*, as it appeared mainly at M1 and M2. The intensity of the depth-

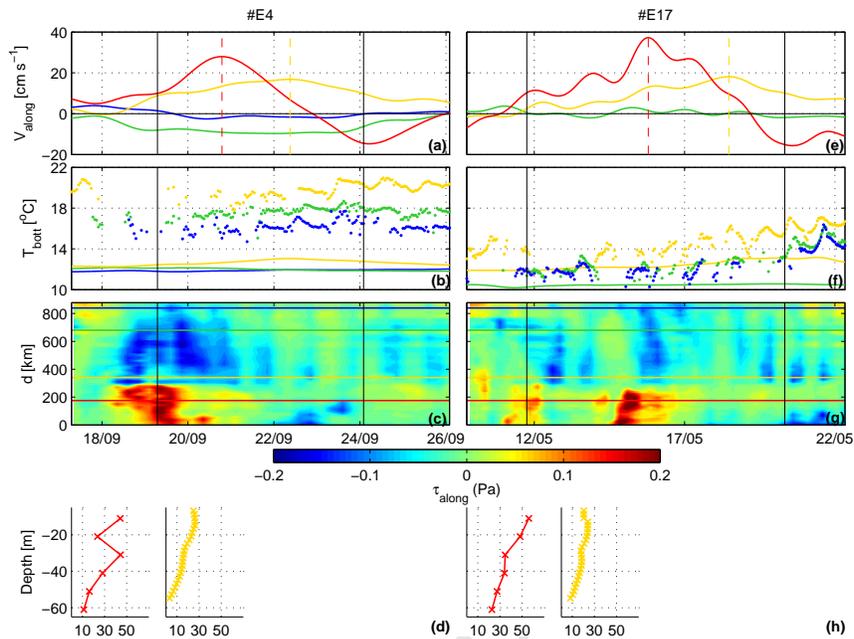


Figure 2: *Southern events*. #E4: left column; #E17: right column. (a,e) Temporal evolution of the depth-averaged along-shore component of the current velocity [cm s⁻¹] at M1 (red line), M2 (yellow line), M3 (green line) and M4 (blue line). For all the figures, the color code is the same and the vertical black solid lines represent the beginning and the end of the poleward event recorded. (b,f) The solid lines represent the temporal evolution of the bottom temperature [°C]. Dots represent the surface temperature [°C] from SEVIRI images. (c,g) Temporal evolution with distance [km] along the 100 m isobath (cf Figure 1) of the along-shore component of the wind stress [Pa] from the AROME model. The horizontal lines represent the along-shore distances where the moorings are positioned. (d,h) Vertical profile of the along-shore component of the current velocity [cm s⁻¹] for the maximum of the poleward event recorded at M1 and M2 (vertical dotted lines-a,e).

averaged along-shore current was stronger on the Spanish shelf, up to 37.3 cm s⁻¹, than on the Aquitaine shelf, up to 18.1 cm s⁻¹ (Figure 2-e). Weak intensity poleward pulses were recorded at M3 and no data was available at M4 during this event. The water column was relatively well mixed until #E17 (Figure 2-f), when the establishment of a thermal stratification was observed in mid-May (increase of surface temperature from 14 to 17°C). The mean bottom temperature

230

1
2
3
4
5
6
7
8
9 increased slowly from 12°C to 13°C at $M2$. The core of the events encom-
10 passed the first 30 m of the water column at $M1$ and $M2$ (Figures 2-h). The
11 along-shore wind stress along the coast was similar to that of #E4, with positive
12 values recorded along the Spanish coast and negative values along the French
13 coast (Figure 2-g). Similarly, #E33 occurring mid-April 2010 was simultaneous
14 235 with the establishment of a thermal stratification.
15
16
17
18

19 3.2. Bay-scale events

20
21 Twenty events were classified as *bay-scale events* as poleward along-shore
22 currents at $M1$ and $M4$ are larger than 10 cm s⁻¹ (Tables 2, 3). These events
23 240 had a typical duration between 2-15 days, with intense along-shore currents
24 on the north Spanish shelf, between 15.2-54.5 cm s⁻¹. On the French coast,
25 these events were marked at $M4$ with a maximum depth-averaged along-shore
26 component between 11.5-28.6 cm s⁻¹. The currents at $M2$ and $M3$, followed
27 generally the same temporal evolution as the current at $M4$ with weaker along-
28 shore currents (0-21.1 cm s⁻¹). We selected #E34 as the most representative
29 event of this type. #E30 was also studied as its characteristics were different
30 from the other *bay-scale events*.
31 245

32
33 #E34 (6-13 May 2010), a characteristic *bay-scale event*, occurred during the
34 establishment of the spring thermal stratification. During this event, along-shore
35 250 currents were intense on the north Spanish shelf (24.4 cm s⁻¹, Figure 3-a). On
36 the French coast, this event was marked at $M4$ with a maximum depth-averaged
37 along-shore component of 11.5 cm s⁻¹. The signal exhibited three consecutive
38 pulses. The currents at $M2$ and $M3$, had generally the same temporal evo-
39 lution with weaker along-shore currents (6.4-9.1 cm s⁻¹). The mean surface
40 temperature was equal to 15°C and the bottom temperature at values between
41 11-13°C (Figure 3-b). With this thermal stratification, the core of the events
42 encompassed the first 30 m-40 m of the water column (Figure 3-d). The wind
43 was highly variable in the bay during this period (Figure 3-c). The pulses were
44 associated with a succession of short bursts of wind with positive along-shore
45 wind stress values along the French coast and negative values along the Spanish
46 coast.
47 255
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

one.

#E30, with a duration of 2.5 days (21-24 February 2011) was characterized by strong poleward along-shore currents at $M1$ (54.5 cm s^{-1} , Figure 3-e). The temporal evolution of the depth-averaged along-shore component of the current velocity at the four moorings followed the same tendency, even if lower velocities were recorded at $M2$ (17.8 cm s^{-1}), $M3$ (6 cm s^{-1}) and $M4$ (13.5 cm s^{-1}). This event was generated during a period of intense IPC episode mentioned by [63]. During this event, the water column was relatively well mixed and the currents relatively uniform vertically for $M1$, $M2$ and $M3$ (Figures 3-f,h). During winter, it is common to observe a vertical thermal inversion in the northern part of the BoB (Figure 3-f). During this haline stratification, the event was reduced to the top 30 m of the water column at $M4$ (Figure 3-h). Strong wind stress was observed during this event, with positive wind stress over the Spanish shelf and negative values over the French shelf (Figure 3-g).

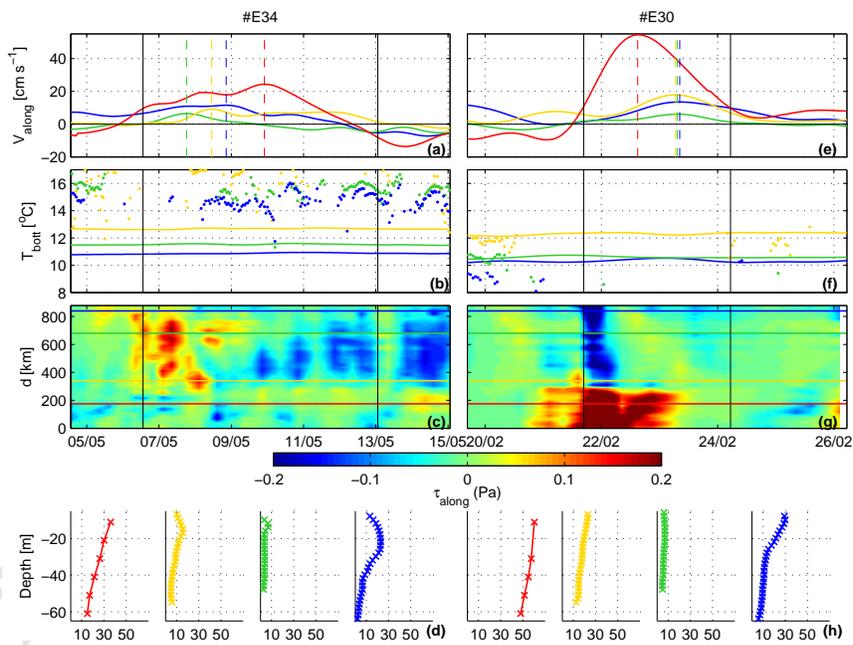


Figure 3: *Bay-scale events*. Same as Figure 2 for #E34: left column; #E30: right column.

3.3. Strong events

Finally, we distinguished five *strong events*, with along-shore poleward currents at $M1$ and $M2$ larger than 40 cm s^{-1} (Tables 2, 3). Three events in autumn (#E6, #E21 and #E24) and two events in summer (#E18 and #E37) exhibited an intense poleward current at $M1$ and $M2$ with an overall maximum depth-averaged along-shore velocity of 65.7 and 55.3 cm s^{-1} respectively, and durations between 3-15 days. The currents at $M3$ and $M4$ were also poleward but much weaker (0 - 27.9 cm s^{-1}). We selected events #E6 for autumn season and #E18 for summer season as the most representative events of this type.

#E6 was identified during November 2009 (31 October - 10 November 2009), when a strong poleward current started increasing, until reaching a maximum depth-averaged along-shore velocity of 54.9 cm s^{-1} at $M1$ and 55.3 cm s^{-1} at $M2$ (Figure 4-a). It was generated during a period of intense IPC [63]. This event was not apparent at $M3$ and $M4$, characterized by weak poleward or equatorward currents. During #E6, an increase of along-shore current velocity, over the first 60 m of the water column along with a slight decrease of the intensity near the bottom (Figure 4-d), were associated with an increase of bottom temperature of 2 - 3°C at $M2$, which marked the end of the vertical stratification (Figure 4-b). An intense and extended wind blowing during 7 days was observed during this event (Figure 4-c). Strong along-shore positive wind stress values were identified along the Spanish coast and strong negative values along the French coast. Similarly, for the 2010-2011 period, #E24 with the same properties marked the end of the vertical stratification.

The second selected *strong event* (#E18) was observed at $M1$, $M2$ and $M3$ between 10 June and 22 June 2010 (Figure 4-e). On 9 June, a strong poleward current started increasing, until reaching a maximum depth-averaged along-shore velocity of 50.2 cm s^{-1} at $M1$ and 16.9 cm s^{-1} at $M3$ on 12 June. More than five days later (on 18 June), an intense poleward current was recorded at $M2$ (47.3 cm s^{-1}). No data was available at $M4$. The core of the event encompassed the first 50 m of the water column (Figure 4-h). Associated with the sharply rising along-shore current velocity of #E18, a marked increase in bottom

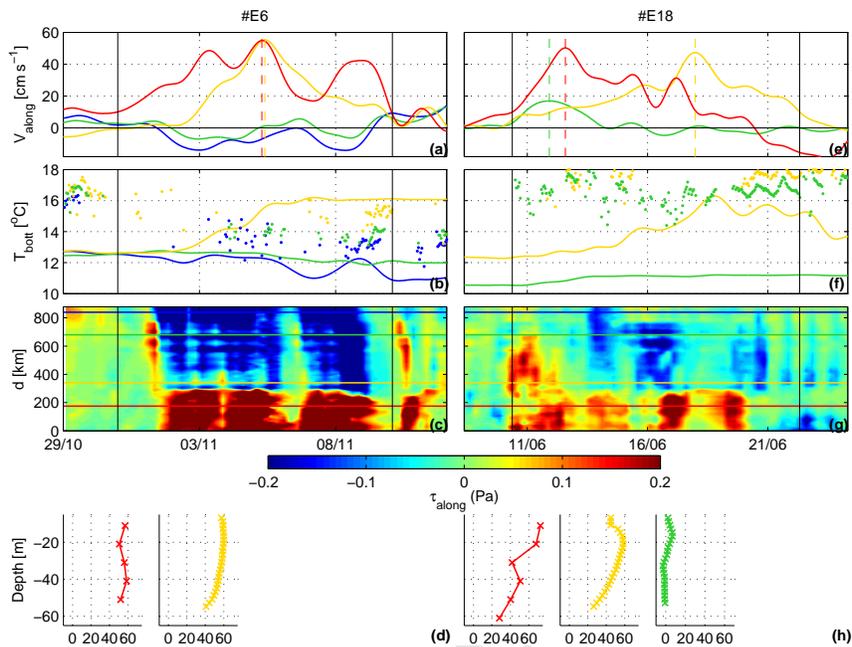


Figure 4: *Strong events*. Same as Figure 2 for #E6: left column; #E18: right column.

temperature, from 12°C to 16°C, was recorded on 18 June at *M2* (Figure 4-f). In contrast to #E6, in mid-June, during the decay of #E18, the poleward currents weakened and a quick temporal restoration of cold bottom temperature was observed. During this event, a succession of short wind bursts was observed during ten days over the 100 m isobath (Figure 4-g). A positive along-shore wind stress extended along the French coast was observed at the beginning of the event, simultaneous to the event at *M3*. As for the 2009-2010 period, the same characteristics are observed for the *strong event* of 2010 (#E37).

4. Discussion

Time series of current velocity and wind intensity allow for a detailed assessment of the variability over the continental shelf over different time scales. Data from the four moorings provide a large amount of informations for the study of the large-scale and local forcings involved in the BoB shelf circulation. The

1
2
3
4
5
6
7
8
9 simultaneous influence of different forcing scales adds complexity to studying
10 shelf circulation. Nevertheless, the large number of events and their replication
11 from year to year allows us to identify and separate the forcings for each type
12 of event previously identified.
13
14

15 To begin this inventory, the global and regional climate during ASPEX period
16
17 325 can be analyzed in a wider context of climatological variations. An analysis of
18 the dynamics associated with each event is then proposed, after which the wind
19 stress-to-current impulse response function is estimated. Finally, the propaga-
20 tion behavior is analyzed in terms of CTWs.
21
22
23

24 *4.1. Global and regional climate during ASPEX period (2009-2011)*

25
26 330 The studies of [32], [30, 31], [26] allow us to put the ASPEX period in a
27 climatological context. The station-based index of the North Atlantic Oscilla-
28 tion (NAO) can also be an indicator of the climate compared to other years
29 (Table 4).
30
31

32 The three summer seasons were relatively warmer and wetter than the long-term
33
34 335 average over most of Europe. Summers 2009 and 2011 exhibited a sustained
35 significant decrease in the NAO index (in the five lowest summer NAO index
36 since 1990). Spring seasons were drier than previous years. While autumn was
37 warmer than average almost everywhere, during winter 2009/2010, cold con-
38 ditions coincided with a record negative winter NAO index. The NAO index
39
40

41 340 turned negative in mid December 2009 and remained negative for the rest of the
42 winter. Winter 2010/2011 began unusually early and much colder than average
43 in much of Europe, with the second coldest December since 1850. During both
44 winters, cold conditions coincided with a record negative winter NAO index.

45
46
47 This global climate analysis showed us that the seasonality characteristics during
48
49 345 the ASPEX period were similar, but anomalous relative to long-term weather
50 conditions.
51
52

53 *4.2. Inventory of associated dynamics for each type of events*

54
55 Figures 5-a,b,c illustrate a schematic of three typical events (events #E4,
56 #E34 and #E6) described in the previous section superimposed to 8-day com-
57
58

Table 4: Monthly NAO index during the ASPEX period from "The Climate Data Guide: Hurrell NAO Index (station-based)." Retrieved in December 2014 from <https://climatedataguide.ucar.edu/>.

	Jan.	Feb.	Mar.	April	May	June	July	August	Sept.	Oct.	Nov.	Dec.
2009							-2.0	2.2	1.4	-2.2	2.1	-4.6
2010	-1.9	-3.6	-1.5	-2.5	-0.8	-0.3	1.7	-1.9	-0.2	-0.8	-1.5	-5.6
2011	-1.3	1.9	0.4	2.1	1.8	-0.8	0.3	-1.4				

350 positive images of SST. The 8-day composite images of SST were the closest in time to the events. For #E6 (figure 5-c), due to cloud coverage, the event occurred two weeks before the composite images of SST.

- *Southern events* (Figure 5-a) were characterized by a typical duration of 2-9 days. During these events, strong poleward along-shore currents were identified at *M1* and *M2*. Equatorward or weak poleward pulses were recorded at *M3* and *M4* during this type of event. These events were associated with westerly wind in the south and variable northerly wind in the north. This type of forcing was also observed during the particular *bay-scale event* #E30. The SST images showed warmer water in the BoB, with colder water along the French coast and in front of the southern Brittany peninsula.

- During *bay-scale events* (Figure 5-b), strong along-shore currents were predominantly poleward at *M1*, *M2* and *M4*. Poleward events of along-shore currents were also present at *M3* but with lower velocity. The widening of the shelf is expected to be associated with a decrease of the current velocity (discussed below). The SST images showed a water mass, which is warmer than the ambient waters, flowing north along the French coast. Wind direction varied quickly during this type of event with lower wind stress values along the Spanish coast. Along the French coast, these events were associated with northerly wind between *M2* and *M3* and southerly wind between *M3* and *M4*. This indicates a weak driving influence of the winds on the local circulation for this type of event. This also strongly suggests that some other mechanisms are able to force

1
2
3
4
5
6
7
8
9 the main part of the circulation (discussed below). As shown by [41], these other
10 mechanisms may be the driving up to 40% of the observed circulation which
11 could not be explained by local wind forcing.

12
13
14 375 - *Strong events* (Figure 5-c) appeared during the period of measurements. The
15 poleward flow at *M1* and *M2* was very marked during #E6 *strong event* for
16 more than 10 days. #E6 was apparent at *M3* with weak poleward currents and
17 at *M4* with equatorward currents. Strong and persistent westerly wind events
18 were present over the whole bay. The SST image showed also the propagation
19
20
21 380 of a warmer water mass along the French coast. An upwelling front off the
22 southern Brittany peninsula was also present.

23
24 The *strong events* occurred during autumn seasons (#E6, #E21 and #E24)
25 and during summer seasons (#E18 and #E37). During the autumn season,
26 along-shore currents velocity were associated with an increase of bottom tem-
27
28
29
30 385 perature of 2-3°C (Figure 4-b). A low temporal decrease of bottom temperature
31 was observed during the season. This evolution can be associated with cooling
32 and destratification and is characterized by a slow temporal restoration of cold
33 bottom temperature. An hypothesis proposed by [38] is that, during these pe-
34 riods, the stratification breakdown gives rise to a surface and a bottom front.
35
36
37 390 Then, according to the thermal wind balance, a poleward surface current is gener-
38 erated. During the summer season, strong poleward along-shore currents were
39 identified at all moorings during more than ten days (Figure 4-e). For the two
40 strong events in summer, a strong burst of northwesterly wind was observed in
41 the BoB. [3] showed that northwesterly winds can drive, during period of high
42 stratification, downwelling circulation along the Spanish coast. Their study con-
43
44
45 395 cluded that this downwelling triggers the poleward currents along the French
46 coast. The same type of event occurred during ASPEX period with the same
47 order of current velocity and bottom temperature increase. In fact, these *strong*
48 *events* seem associated with wind forcing only and are characterized by a quick
49
50
51
52
53 400 temporal restoration of cold bottom temperature (Figure 4-f).

54
55 It should be noted that intense IPC was observed [63] for different events (#E6,
56 #E30) which can accelerate the poleward current in the southern part of the
57
58

1
2
3
4
5
6
7
8
9 BoB. In winter, the southward component of the wind stress relaxes or even
10 changes sign, allowing the extension of this surface warm poleward current in
11 the southern part of the BoB.
12 405

13
14 Another important forcing of the along-shore current in the upper layer is the
15 Gironde and Loire plumes [39, 40, 16]. This low-salinity surface water body fed
16 by winter-intensified run-off from several rivers is affected by the Coriolis effect
17 and flows toward the pole. The cross-shelf density gradient, as a consequence
18 and flows toward the pole. The cross-shelf density gradient, as a consequence
19 of the freshwater runoff can also drive this poleward current. During these
20 410 events, southwesterly winds reinforce this poleward propagation. This forcing
21 seems more important near $M4$, where the vertical shear is enhanced at 30-40 m
22 depth (Figure 3-h).

23
24 In stratified conditions, the duration of these events for more than one week
25 is an important feature. An explanation may involve the vertical shear. In-
26 415 deed, [11] showed that an equilibrium can be reached due to the effect of the
27 shear, which induces a decrease of bottom velocity, hence of bottom stress. As
28 bottom stress nearly vanishes, this could favor the persistence and extension of
29 downstream poleward jets.
30
31
32
33
34
35
36

37 4.3. Estimation of the wind stress-to-current impulse response function 38 420

39 The coincidence of current events and strong wind forcing is demonstrated
40 in the above description and Figures 2, 3, 4, suggesting wind as a significant
41 forcing of the BoB shelf currents system. As an example, Figure 6 presents the
42 lagged cross-correlation between the depth-averaged along-shore component of
43 the current velocity at $M2$ and the along-shore and cross-shore components of
44 425 wind stress at all locations of the 100 m isobath illustrated in Figure 1. As
45 said before, wind stress components are defined as positive poleward along-
46 shore and positive onshore. These graphs show that the along-shore current
47 at $M2$ is strongly correlated with the along-shore wind stress (eastward) along
48 the Spanish coast, and strongly correlated with onshore wind stress along the
49 French coast. Care must however be taken not to over-interpret these graphs
50 in terms of forcing mechanisms for the currents: it is for example well known
51
52
53 430
54
55
56
57
58
59
60
61
62
63
64
65

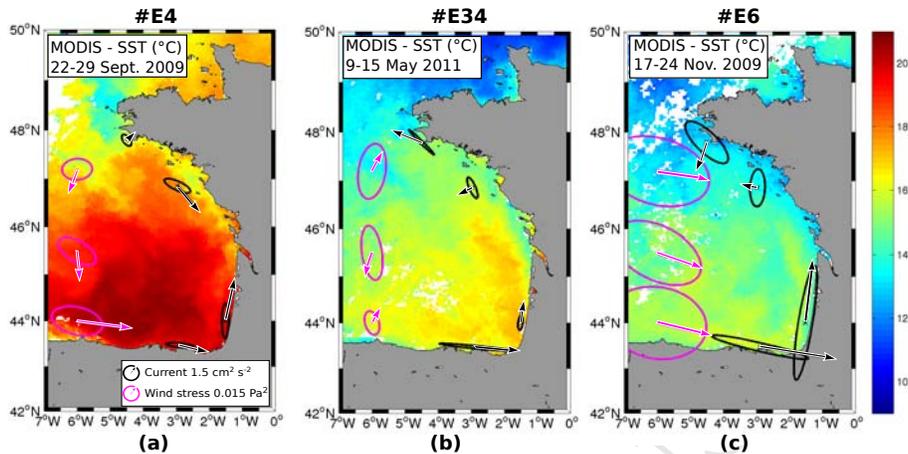


Figure 5: 8-day composite images of SST (data from MODIS) for three typical events (a: *Southern event*, b: *Bay-scale event*, c: *Strong event*). The arrows show the time-depth-averaged currents (black) and wind velocities (magenta) during each type of events with their associated variance ellipses. The wind velocities and variances were calculated along the 100 m isobath between $M1$ and $M2$ in the south, between $M2$ and $M3$ in the middle, and between $M3$ and $M4$ in the north. For clarity, they are reported along the 6°W meridian.

that, due to the usual wind direction during strong wind episodes in the area, along-shore wind stress (eastward) along the Spanish coast is strongly correlated with onshore wind stress on the French shelf. A causality relationship between any of these wind stress features and the current thus mechanically induces a strong correlation of the current with both wind stress signals. In much the same way, temporal correlations of the wind stress components are likely to induce correlations with the along-shore current at larger time lags than the intrinsic temporal response of the shelf currents system actually contains, and in particular for time lags for which causality can be excluded (*i.e.* correlation of current with wind stress at positive time lags).

The wind stress components spatial and temporal correlations, however, though non trivial, can be estimated from the wind stress data themselves. Using proper methodology, one expects that the effects discussed above could be predicted, and that a dynamical characterization of the system devoid of their influence could be designed. A first step in this direction, used to discriminate the in-

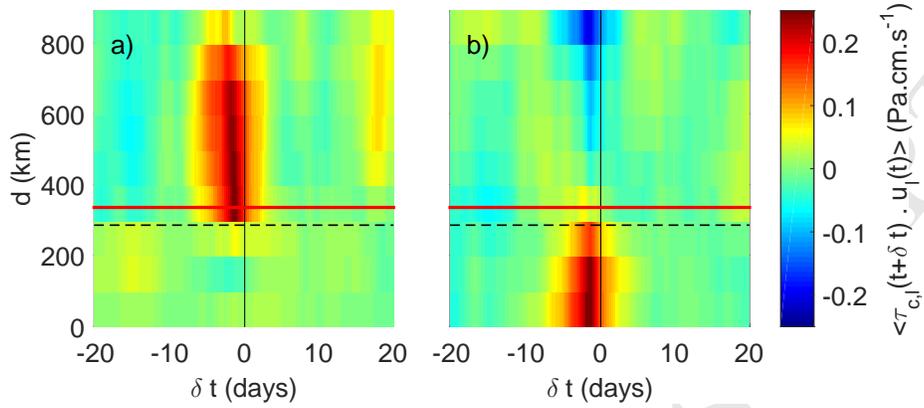


Figure 6: Lagged cross-correlations between the depth-averaged along-shore component of the current velocity at $M2$ and the cross-shore (a) and along-shore (b) components of wind stress, along the 100 m isobath illustrated in Figure 1. The thick red line marks the location of the mooring. The thick dashed lines marks the approximate location of the coastline orientation change. A thin black line marks zero lag. For negative time lags, wind stress is considered at earlier instants than along-shore current.

fluences of cross- and along-shore wind stress components is described in [18], elaborating on the work of [33]. We present here a first concept to extend the approach to the study of cases in which the influence of wind at different locations and not just different instants, is to be analyzed.

In a linear setting, it seems reasonable to model the contribution of wind forcing inside the study domain to currents at mooring m as:

$$u_m(t) = \sum_{d=c,l} \int_{coast} ds \int_{-\infty}^0 d\delta t K_m^d(s, \delta t) \tau^d(s, t + \delta t), \quad (1)$$

where the ds integral corresponds to summing contributions originating at all points of the 100 m isobath illustrated in Figure 1, the $d\delta t$ integration corresponds to summing contributions forced by wind at all locations and at all prior instants, and the summation runs on the two wind stress components. Forcing due to both along-shore ($d = l$) and cross-shore ($d = c$) wind stress components are considered. The two impulse response kernels K_m^c and K_m^l represent the intrinsic response of the currents system, and are independent of the statistical characteristics of the wind forcing. The method we have used to estimate the

impulse response functions, which is basically a time-domain implementation of methods described in chapter 7 of [5], is described in Appendix A.

Figure 7 shows as an example the impulse response functions computed for the along-shore (Figure 7-a) and the cross-shore (Figure 7-b) components of wind stress. One can clearly observe large differences with the lagged correlations

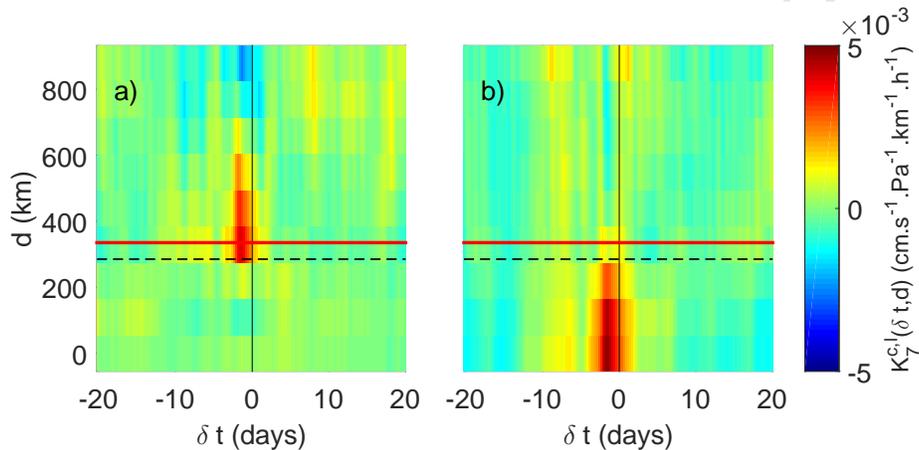


Figure 7: M_2 current impulse response functions for (a) cross-shore and (b) along-shore wind stress along the 100 m isobath illustrated in Figure 1. The thick red line marks the location of the mooring. The thick dashed lines marks the approximate location of the coastline orientation change. A thin black lines mark zero lag. For negative time lags, wind stress is considered at earlier instants than along-shore current.

of Figure 6: clearly, the largest observed response is to along-shore wind stress along the Spanish coast. The large correlation with onshore wind stress on the French shelf has almost completely disappeared, meaning this feature can in fact be entirely explained by the wind stress components correlations. In fact, the response to wind forcing over the French shelf seems altogether very weak, showing a strong influence of remote forcing from upstream locations on the along-shore currents of the southern part of the French shelf. The dynamical response of the continental shelf circulation to variable upstream along-shore winds [24, 23] or to a localized storm [10] have been already explored in terms of CTW theory.

The impulse response functions (not shown) have been computed for the other

moorings. In summary:

- The dominance of along-shore wind stress response over cross-shore wind stress response is a generic feature observed for all locations. All locations also show a dominant influence of short time lags, of the order of 1 to 2 days.
- Along-shore currents at $M4$ are influenced by along-shore wind stress at all locations on the French shelf and, to a lesser extent, the Spanish shelf.
- Along-shore currents at $M3$ are influenced by along-shore wind stress at all locations on the French shelf, but show little influence on the Spanish shelf. Two reasons can justify this observation. Firstly, [42] showed that tides are strongly amplified in the central part of the Armorican shelf. This larger tide at $M3$ induces larger bottom friction and thus, an offshore displacement of the along-shore current amplitude maxima [8]. This latter author has shown that the along-shore current can be trapped entirely on the slope under the effect of relative large bottom stress. This fact, joined to theoretical study of [69] which addressed the larger (smaller) velocity amplitude, in terms of shelf wave theory, due to the convergence (divergence) of depth contours, leads us to suggest that the influence of remote forcing from upstream locations on the along-shore currents have less influence at $M3$.
- Along-shore currents at $M1$ show a strong influence of wind at upstream locations, which rapidly reduces past the mooring location, and becomes negligible past the coastline orientation change.
- Both $M4$ and $M1$ show signs of influence of along-shore winds on the French shelf at longer time lags, of the order of 2 to 3 days. Though this does not seem unexpected at $M4$, the equatorward propagation of this signal to $M1$ can not be explained by the shelf waves discussed in Section 4.4.

4.4. Propagation events in term of CTWs dynamics

Figure 8 summarizes the velocity characteristics of the pulse events. Along-shore phase speed [m s^{-1}] between $M1$ and $M2$, $M2$ and $M3$, and $M2$ and $M4$ are computed using a time-lagged cross-correlation function of paired time sequences [9, *xcorr* function in Matlab]. This method builds a first time-

lag. We extended the time windows by this time-lag to be sure to catch all the event. The second time, the function estimates the time-varying correlations (with coefficient higher than 0.7) between the two signals used to compute the along-shore phase speed. Stratified and unstratified periods are distinguished (resp: Figure 8-a and Figure 8-b). During the stratified period, phase velocities are less than 4.3 m s^{-1} , and can be as low as 0.4 m s^{-1} (event #E18 with a maximal current speed $\sim 0.5 \text{ m s}^{-1}$). During the unstratified period, phase speeds are much faster and can reach 12.5 m s^{-1} .

We have seen previously that event #E30 has different characteristics from the other *bay-scale events*. Here, phase velocity is larger than 80 m s^{-1} with a maximal current speed $\sim 0.2 \text{ m s}^{-1}$. This event is an outlier and will not be considered.

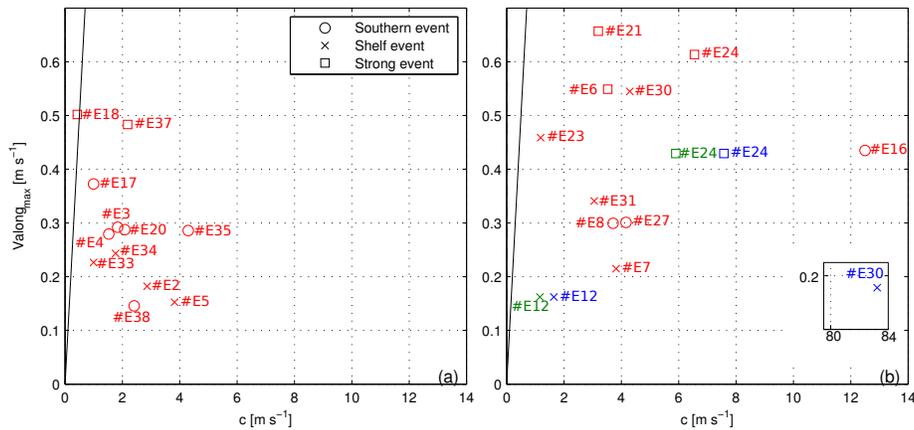


Figure 8: Maxima of vertically integrated along-shore current speed [m s^{-1}] as a function of along-shore phase speed [m s^{-1}] of these maxima, between $M1$ and $M2$ (in red), $M2$ and $M3$ (in green) and $M2$ and $M4$ (in blue) during stratified (a) and unstratified (b) periods. For completeness, we add a zoom for an extreme event (b). The black line represents the linear function $c = V_{along_{max}}$.

Like [3], we seek explanation of these propagation features in term of CTWs. Properties of CTWs were computed for typical BoB cross shelf and slope topographies and stratifications, using the Matlab codes of [8]. The first mode phase speeds range from $3\text{-}4 \text{ m s}^{-1}$ (offshore northern Spanish coast) to 9-

1
2
3
4
5
6
7
8
9
10
11 525 plain the fastest events propagations during both stratified and unstratified
12 conditions. As for slowest phase propagations (less than $2\text{-}3\text{ m s}^{-1}$), they may
13 be explained by shelf restricted modes, which range from 0.7 m s^{-1} (north-
14 ern Spanish shelf) to $\sim 2.5\text{ m s}^{-1}$ (French shelf at its widest) for the first mode
15 phase speed (restricted to the shelf). It is particularly interesting to note that
16
17
18
19 530 the computed along-shore velocity (not shown) is almost barotropic, whether
20 in stratified or unstratified periods. This is in line with the weak value of the
21 shelf Burger number $S = NH/fL$ (N : Brunt-Väisälä frequency, H : shelf depth,
22 f : Coriolis frequency, L : shelf width), which ranges from $\sim 0.01\text{-}0.1$ (winter) to
23 $0.03\text{-}0.2$ (summer). [13], through scale analysis, show that the response of a wide
24 shelf to synoptic wind fluctuations is barotropic with $S^2 \ll 1$ and restricted to
25
26 535 the shelf with more restrictive condition ($S \ll 1$).
27
28

29
30
31
32
33
34
35 540 non-linear effects are certainly affecting these simple results, notably through
36 dispersion effects. For instance, for event #E24, the along-shore currents show
37 poleward propagating signals with phase speeds of 6.5 m s^{-1} between $M1$ and
38 $M2$, 5.9 m s^{-1} between $M2$ and $M3$ and 7.6 m s^{-1} up to the Penmarc'h section
39
40 (Figure 8-b).
41

42 545 It has been shown that the presence of persistent currents (as the IPC) can
43 strongly modify the CTWs by increasing the wave frequency as the current
44 propagates in the same direction as CTWs. In addition, if the mean current is
45 sheared, the wave structure and dispersion characteristic will be strongly modi-
46 fied in the unstratified limit of barotropic shelf waves [49]. The decreasing speed
47
48
49
50 550 of the propagating signals may also result from scattering of CTWs into higher
51 modes due to curvature of shoreline and bathymetry [71, 72]. Moreover, the
52 scattering process may be strongly modified in the presence of a mean current.
53
54
55
56
57
58
59
60
61
62
63
64
65

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

555 may completely eliminate the backward propagating modes [73, 74]. Stratification increases the free-wave phase speeds and may eliminate the backward propagating modes [72]. [75] extended these ideas to fully nonlinear dynamics where mesoscale flows have been linked to adjustment of current over topographic features. As also shown by [58], the topographic variations of the coastline can transform CTWs into non-linear waves or an eddy train. These non-linear effects may also be significant in this study for high current and low phase propagation speeds (e.g. #E18), with Froude numbers ($Fr = V_{along}/c$, V_{along} : along-shore current speed, c : along-shore phase speed) close to unity.

5. Conclusion

565 The low-passed along-shore currents, observed from four locations throughout the water column, were used to describe the circulation of the shelf over the Bay of Biscay and its temporal evolution. The nearly two-year time series provided a large amount of data over a large domain for the study of the large-scale and local forcings involved in this circulation. As a first approach, the large number of events and their repeated occurrence from year to year allowed us to separate events into distinct types. This required a description and a characterization over time of the events. Based on this inventory, we showed that three kinds of events occurred, which we defined as *southern events*, *bay-scale events* and *strong events*. In all cases, the low-passed along-shore currents revealed strong coastal poleward currents. The simultaneous influence of different forcing scales adds complexity to distinguish the ones generating or influencing the shelf circulation.

We showed however that the dynamics at the moorings in the south is clearly controlled by the along-shore wind stress along the Spanish coast at short time lags, of the order of 1 to 2 days. Further north, along-shore currents at $M3$ and $M4$ are influenced by along-shore wind stress at all locations on the French shelf with the same time lag.

Taken together, these elements shed some light on the contrasting characteristics

1
2
3
4
5
6
7
8
9 of *southern events* and *bay-scale events*. Currents at *M3* and *M4* are influenced
10
11 585 in opposite ways by wind forcing along the Spanish and French coasts. In con-
12
13 trast, currents at *M1* and *M2* are only forced by wind stress along the Spanish
14
15 coast. In the case of *southern events*, westerly winds blow in the south of the
16
17 BoB, the response at *M1* and *M2* is strong, while variable northerly or north-
18
19 590 westerly winds blow in the north, the response to local forcing at *M3* and *M4*
20
21 counteracts the remotely induced response, leading to a weak total response. In
22
23 the case of *bay-scale events*, southwesterly winds blow along the French coast,
24
25 with a weak wind along the Spanish one. The response at *M4* and *M3* is thus
26
27 dominant, and the response at *M1* and *M2* is highly variable. The case of *strong*
28
29 *events* seems qualitatively different, in the sense that these events are associated
30
31 595 to high values of the Froude number, thus likely to be significantly influenced
32
33 by non-linear effects. The bottom temperature signature at *M2* moreover hints
34
35 to a possible role of the density anomaly of the advected water mass in its self-
36
37 propagation.

38
39 The analysis further demonstrated some influence of along-shore winds at longer
40
41 600 time lags, of the order of 2 to 3 days. The propagation velocities observed lend
42
43 consistency to the hypothesis of remote forcing through CTW propagation. In-
44
45 deed, the fastest events propagations could be explained by the first mode of
46
47 CTWs, while the slower phase propagation could be explained by barotropic
48
49 shelf restricted modes. These propagating signals could be also affected by
50
51 605 scattering of CTWs .

52
53 The duration of the events, more than 10 days in stratified conditions, could
54
55 be linked to the decrease of bottom stress due to the decreases of horizontal
56
57 velocity with depth. The poleward pulses were also strongly affected by the
58
59 extension of the IPC in the BoB. Finally, autumn seasons are marked by the
60
61 610 breakdown of stratification, which had been shown in a previous study and the
62
63 present work to be a triggering mechanism of strong poleward currents. Al-
64
65 though previous experiments have described poleward currents over the shelf of
66
67 the BoB, many questions still remain on the components of these currents vari-
68
69 ability at meso- and subinertial scales and their generation mechanisms. This

1
2
3
4
5
6
7
8
9 615 analysis will be the main goal of forthcoming numerical experiments. Planned
10 model runs will help us to estimate how these currents propagate and to study
11 the possible connections between the ASPEX moorings, including the ones on
12 the outer-shelf and the upper-slope. It is even more important to investigate
13 these coastal currents in light of their strong impact on the ecosystem as the
14
15 transport of toxic water masses, larvae, biogenic particles, and pollutants in the
16
17 620 along-shore direction or the retention of them in the cross-shore direction.
18
19
20
21
22
23

24 6. Acknowledgments

25
26 The ASPEX project was part of the EPIGRAM project supported by the
27 Agence Nationale de la Recherche [French National Research Agency] (Grant
28 ANR-08-BLAN-0330-01) and CNRS/INSU national programme LEFE/IDAO.
29 625 This work is part of the research program PROTEVS funded by DGA and
30 conducted by SHOM, the French Navy Hydrographic and Oceanographic In-
31 stitute. Marion Kersalé acknowledges support from the SHOM via a post-
32 doctoral fellowship. Special thanks go to the institutes that provided the data
33 for this study: IFREMER and Météo-France. Users can access the data, avail-
34 able at the LPO Laboratory, from the PI of the ASPEX Project, L. Marié
35 (Louis.Marie@ifremer.fr). The authors would also like to thank the captains
36 and crews of R/Vs Côtes de la Manche, Thalassa and Suroît. We are warmly
37 grateful to the technical staff who worked on the preparation, deployment and
38
39 630 the recovery of the instruments. The authors thank Julien Mader and Marie-
40 Noelle Bouin for precious help, comments and useful discussions. We thank
41 the Basque Energy Agency for the data from the Metocean buoy of the Biscay
42 Marine Energy Platform (BIMEP), which gave us access to an unique database
43 for analyze and understand our results. We also thank Patrice Bellec for help
44
45 635 in processing climatological hydrographic databases. Finally, we thank the two
46 reviewers of this manuscript for their constructive comments.
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

Appendix A. Inventory of all events

Appendix A.1. 2009-2010 period

Figure A1-a shows the intensity of the depth-averaged along-shore currents from 15 July 2009 to 30 June 2010. Eighteen events of poleward currents were identified during this period. The specific characteristics of the different events are described in Table 2.

Ten events are classified as *bay-scale events*. Four events (#E7, #E9, #E11 and #E12) were generated during episodes of intense Iberian Poleward Current (IPC), listed by [63]. It must also be emphasized that storm Xynthia occurred during event #E14 [44]. During *bay-scale events*, the wind was highly variable in the bay (Figure A1-b). Generally, the events were associated with a succession of short bursts of wind with positive wind stress values along the French coast. During six events, with a typical duration of 2-8 days, along-shore currents were more intense on the north Spanish shelf and on the Aquitaine shelf. These *southern events* were associated with strong values of along-shore components of the wind stress (up to 0.2 Pa, Figure A1-b). Positive wind stress values are recorded along the Spanish coast (first 300 km along the 100 m isobath) and negative wind stress values along the French coast.

Two *strong events* (#E6 and #E18) were identified during November 2009 and June 2010 (Figure A1-a). Strong positive wind stress values were identified along the Spanish coast and strong negative wind stress values along the French coast (Figure A1-b). Succession of intense short bursts or extended wind was observed during these events.

The first part of record (from July to October) was characterized by the presence of a thermal stratification and by currents typically more intense in the first 45 m of the water column (Figure A2). During this period, equatorward currents at *M3* (Figure A2-c) were detected in the first 40 m of the water column. This depth corresponded to the depth of the seasonal thermocline, which was estimated with ScanFish sections in mid-July 2009 (data not shown). During event #E6, an increase of along-shore currents velocity, over the first 60 m

1
2
3
4
5
6
7
8
9 of the water column with a slight decrease of the intensity near the bottom,
10 was associated with an increase of bottom temperature of 2-3°C at *M2*, which
11 marked the end of the vertical stratification (Figure A2-f). After that, a slow
12 decrease of bottom temperature was observed between October to April. This
13 675 decrease of bottom temperature was observed between October to April. This
14 period was characterized by currents relatively uniform vertically for *M1*, *M2*
15 and *M3* (Figures A2-c,e,g). 21 January was marked by a thermal inversion in the
16 northern part of the BoB (Figure A2-b). The pulses at *M4*, occurring after this
17 inversion, showed intense currents down to 30 m depth (Figure A2-a). The water
18 column was relatively well mixed until event #E17, when the establishment of a
19 680 thermal stratification was observed in mid-May (increase of surface temperature
20 from 14 to 18°C). The mean bottom temperature increased linearly from 12°C
21 to 13°C. In contrast, event #E18 was associated with an increase of the bottom
22 temperature up to 4°C at *M2*, while surface temperature remained constant at
23 18°C (Figure A2-f). In mid-June, during the decay of event #E18, the poleward
24 currents weakened and a quick temporal restoration of cold bottom temperature
25 was observed.
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

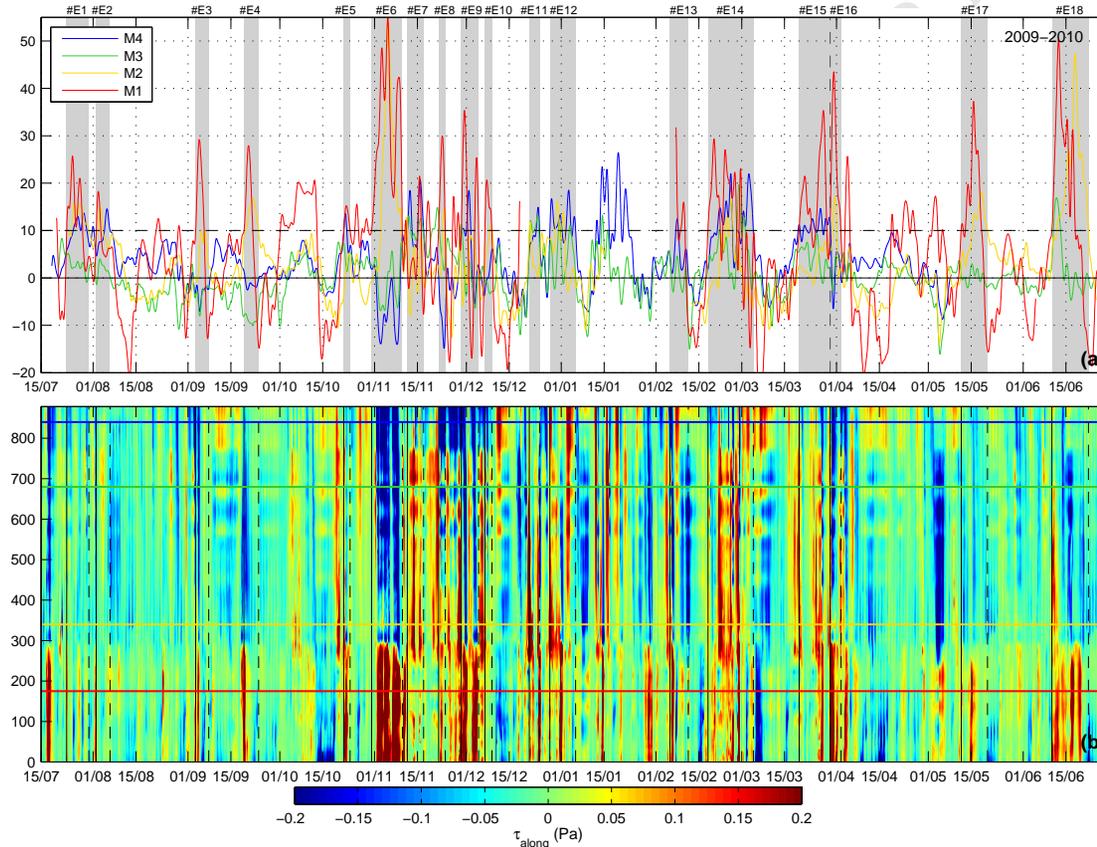


Figure A1: (a) Temporal evolution of the depth-averaged along-shore component of the current velocity [cm s^{-1}] at M1, M2, M3 and M4 for the 2009/2010 period. The shaded areas show the poleward events recorded. (b) Temporal evolution with distance [km] along the 100 m isobath of the along-shore component of the wind stress [Pa] from the AROME model. The horizontal lines represent the distances where the moorings are positioned. The vertical solid (dotted) lines represent the beginning (end) of the poleward events recorded.

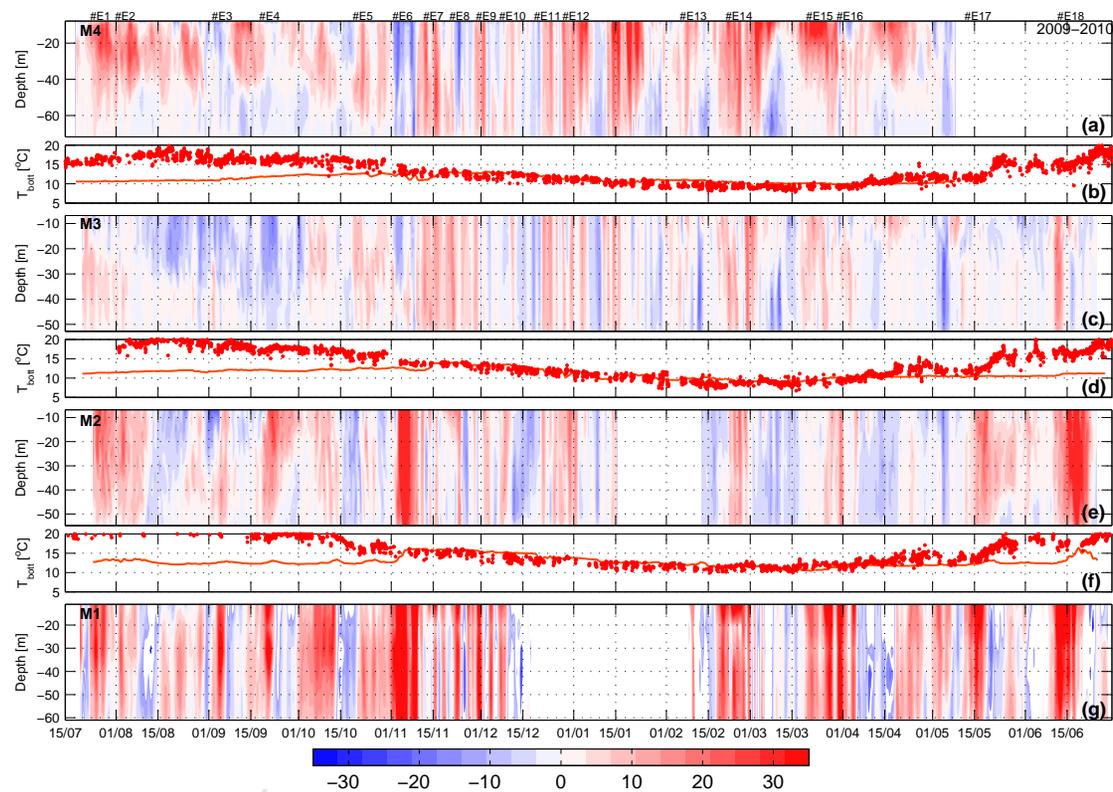


Figure A2: Temporal evolution with depth of the along-shore component of the current velocity [cm s^{-1}] at M4 (a), M3 (c), M2 (e) and M1 (g) for the 2009/2010 period. The red lines represent the temporal evolution of the bottom temperature [$^{\circ}\text{C}$] recorded at ASPEx moorings (b: M4, d: M3, f: M2). Red dots represent the surface temperature [$^{\circ}\text{C}$] from SEVIRI images.

Appendix A.2. 2010-2011 period

Twenty events of poleward currents were identified from 1 September 2010 to 7 August 2011 (Figure A3-a). The specific characteristics of the different events are described in Table 3.

Seven events could be classified as *southern events* (Figure A3-a). The wind stress along the coast is similar to that of *southern events* of 2009-2010 (Figure A3-b). The events were associated with high positive values of along-shore components of the wind stress along the Spanish coast and average negative value along the French coast.

Ten events were identified as *bay-scale events*. Generally, the observed wind stress values are dominated by along-shore with a succession of several wind bursts along the French coast (Figure A3-b). For events #E23, #E25, #E29, #E32 and #E33, strong positive values of along-shore components of the wind stress were also observed along the Spanish coast. For events #E30 and #E31, the wind stress along the coast is more similar to that of *southern events* with positive wind stress over the Spanish shelf and negative values over the French shelf.

As for the period 2009-2010, we can distinguish three *strong events*, with a duration between 3-15 days. Two events in October-November 2010 (events #E21 and #E24) and one at the end of July 2011 (event #E37). Succession of intense short bursts or extended wind was also observed during these events. During event #E21, positive wind stress values were recorded along the Spanish coast while more variable wind was present along the French coast.

The first part of this time series (from September to October) was characterized by the presence of a thermal stratification and by currents typically more intense in the first 45 m of the water column (Figures A4-a,e,g). During events #E21, #E22, #E23 and #E24, along-shore currents were associated with an increase of bottom temperature of 2-3°C (Figures A4-b,d,f). Event #E24 marked the end of the vertical stratification (Figure A2-f). A slow temporal decrease of bottom temperature was observed after this event, as in 2009-2010. This period was characterized by currents relatively uniform vertically (Figures A2-a,c,e,g).

1
2
3
4
5
6
7
8
9 January 7 was marked by a thermal inversion in the northern part of the BoB
10 (Figure A4-b). After this inversion, the events were reduced to the top 40 m
11 of the water column at *M4*. The water column was relatively well mixed until
12 mid-April. The establishment of a thermal stratification was observed by the
13 increase of surface temperature from 12 to 18°C and a bottom temperature
14 around 12°C from mid-April to June. The establishment of a thermal stratifi-
15 cation occurred earlier than in 2010. With the thermal stratification, the core
16 of the events encompassed only the first 10-40 m of the water column at *M4*
17 (Figures A4-a). Associated with the sharply rising along-shore current veloc-
18 ity of event #E37, an increase in bottom temperature from 13°C to 18°C was
19 recorded on 18 July at *M2* (Figure A4-f). As for the *strong event* of 2010 (event
20 #E18), a strong increase of bottom temperature (up to 4°C) was recorded.
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

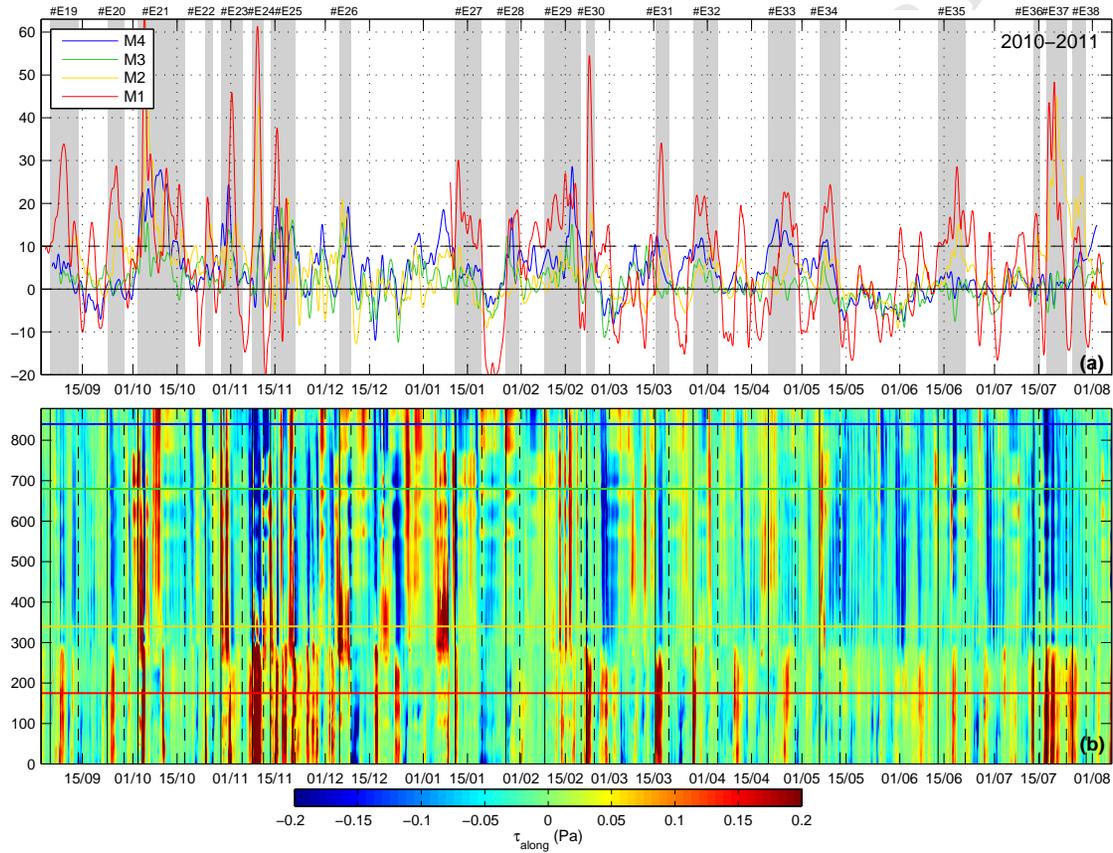


Figure A3: Same as Figure A1 for the 2010/2011 period.

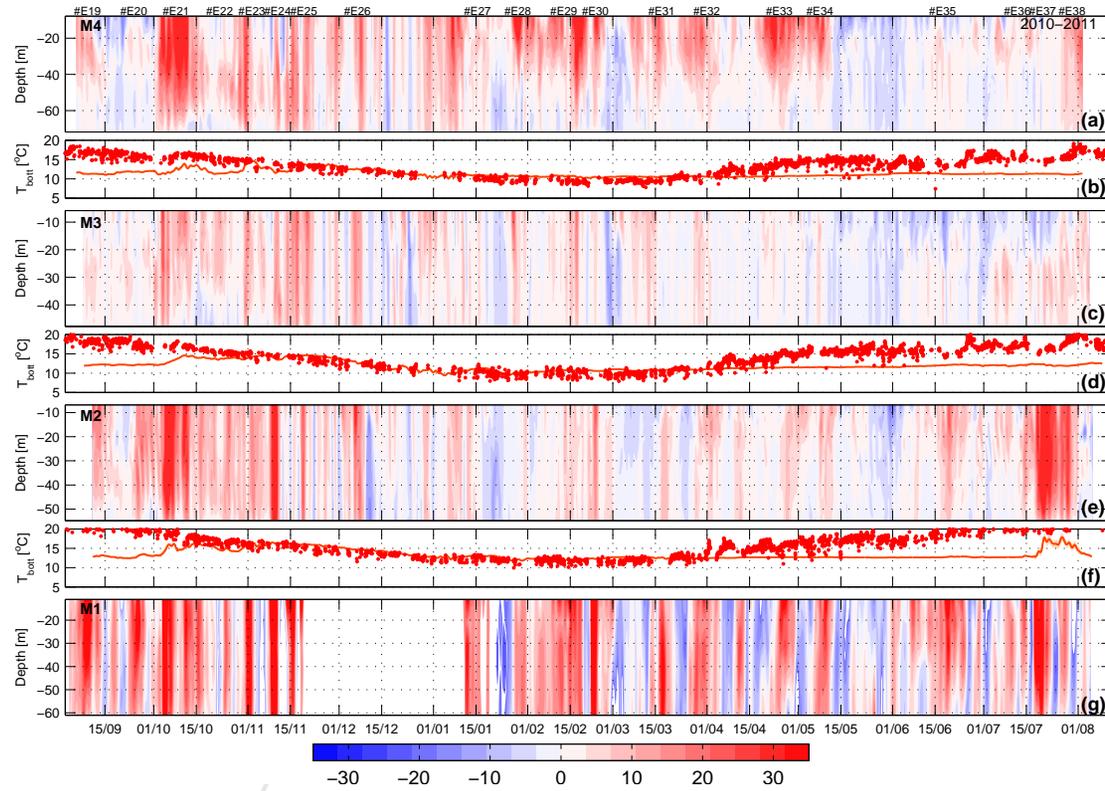


Figure A4: Same as Figure A2 for the 2010/2011 period.

Appendix B. Wind stress-to-current impulse response function estimation

In order to estimate the two impulse response functions, we have chosen to use a least-squares criterion, *i.e.* we use as defining criterion for $K_m^{l,c}$ that they minimize the prediction error:

$$E(K_m^{l,c}) = \int_t \left[u_m(t) - \sum_{d=c,l} \int_{coast} ds \int_{-\infty}^0 d\delta t K_m^d(s, \delta t) \tau^d(s, t + \delta t) \right]^2 dt \quad (\text{B.1})$$

This error function does not involve time or space derivatives of the kernels. Differentiating straightforwardly $E(K_m^{l,c})$ with respect to the values of the kernels at all locations and all instants, and requesting all derivatives to be zero yields the following integral equations for $K_m^{l,c}$:

$$\begin{aligned} \int_t \tau^c(s, t + \delta t) \sum_{d=c,l} \int_{s', \delta t'} K_m^d(s', \delta t') \tau^d(s', t + \delta t') ds' d\delta t' dt &= \int_t \tau^c(s, t + \delta t) u_m(t) dt \\ \int_t \tau^l(s, t + \delta t) \sum_{d=c,l} \int_{s', \delta t'} K_m^d(s', \delta t') \tau^d(s', t + \delta t') ds' d\delta t' dt &= \int_t \tau^l(s, t + \delta t) u_m(t) dt \end{aligned} \quad (\text{B.2})$$

One recognizes in these equations the lagged cross-correlations between the wind stress components, and their cross-correlations with the current at the mooring location.

Introducing the notations:

$$\begin{aligned} C^{dd'}(s, s'; \delta t - \delta t') &= \int_t \tau^d(s, t + \delta t) \tau^{d'}(s', t + \delta t') \\ C^{dm}(s; \delta t) &= \int_t \tau^d(s, t + \delta t) u_m(t) dt \end{aligned} \quad (\text{B.3})$$

the equations can be transformed to:

$$\begin{aligned} \sum_{d=c,l} \int_{s', \delta t'} C^{cd}(s, s'; \delta t - \delta t') K_m^d(s', \delta t') ds' d\delta t' &= C^{cm}(s; \delta t) \\ \sum_{d=c,l} \int_{s', \delta t'} C^{ld}(s, s'; \delta t - \delta t') K_m^d(s', \delta t') ds' d\delta t' &= C^{lm}(s; \delta t) \end{aligned} \quad (\text{B.4})$$

Basically, what is required is that the modeled signal have the same lagged cross-correlation with the wind stress components as the original one. Introducing in these equations cross-correlation functions of the form

$$C^{dd'}(s, s', \delta t - \delta t') = \delta_{dd'} \delta(s - s') \delta(\delta t - \delta t'), \quad (\text{B.5})$$

1
2
3
4
5
6
7
8
9 one easily sees that $K_m^d(s, \delta t)$ is actually the lagged cross-correlation one would
10 obtained between wind stress and current, if the wind stress components were
11 uncorrelated, and delta-correlated in time and space. Recovering the kernels
12 750 can be considered a way to abstract the statistical characteristics of the input
13 variables from their observed cross-correlation with the output variable.
14

15 These equations can be straightforwardly discretized. Solving their discrete
16 analog, however, requires the inversion of a fairly large matrix, and tends to
17 755 enhance small-scale noise from the imperfect data. We have thus practically
18 performed this operation by projection of the right-hand-side on the eigenmodes
19 of the matrix associated to its 100 largest eigenvalues, computed using the
20 Arnoldi method [60].
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

References

- 1
2
3
4
5
6
7
8
9
- 10
- 11 760 [1] Alvarez, I., Gomez-Gesteira, M., deCastro, M., Carvalho, D., 2014. Com-
12 parison of different wind products and buoy wind data with seasonality and
13 interannual climate variability in the southern Bay of Biscay (2000-2009).
14 Deep-Sea Res. II 106, 38 – 48. doi:10.1016/j.dsr2.2013.09.028.
15
16
17
- 18 [2] Amol, P., Shankar, D., Aparna, S., Shenoi, S., Fernando, V., Shetye, S.,
19 765 Mukherjee, A., Agarvadekar, Y., Khalap, S., Satelkar, N., 2012. Obser-
20 vational evidence from direct current measurements for propagation of re-
21 motely forced waves on the shelf off the west coast of India. J. Geophys. Res.
22 117. doi:10.1029/2011JC007606.
23
24
25
- 26 [3] Batifoulier, F., Lazure, P., Bonneton, P., 2012. Poleward coastal jets
27 induced by westerlies in the Bay of Biscay. J. Geophys. Res. 117.
28 770 doi:10.1029/2011JC007658.
29
30
31
- 32 [4] Beardsley, R.C., Lentz, S.J., 1987. The Coastal Ocean Dynamics Ex-
33 periment collection: An introduction. J. Geophys. Res. 92, 1455–1463.
34 doi:10.1029/JC092iC02p01455.
35
36
- 37 775 [5] Bendat, J.S., Piersol, A.G., 2011. Random data: analysis and measurement
38 procedures. volume 729. John Wiley & Sons.
39
40
- 41 [6] Bender, L., DiMarco, S., 2008. Quality control and analysis of acoustic
42 Doppler current profiler data collected on offshore platforms of the Gulf of
43 Mexico, OCS Study MMS 2008-XXX. U.S. Dept. of the Interior, Minerals
44 Mgmt. Service, Gulf of Mexico OCS Region, New Orleans, LA (2008) 63
45 780 pp. .
46
47
48
- 49 [7] Brink, K., Robinson, A., eds., 1998. The global coastal ocean: Processes
50 and Methods. volume 10. New York, John Wiley & Sons.
51
52
- 53 [8] Brink, K.H., 2006. Coastal-trapped waves with fi-
54 nite bottom friction. Dyn. Atmos. Oceans 41, 172–190.
55 785 doi:10.1016/j.dynatmoce.2006.05.001.
56
57
58

- 1
2
3
4
5
6
7
8
9 [9] Buck, J., Daniel, M., Singer, A., 2nd Ed., 2002. Computer Explorations
10 in Signals and Systems Using MATLAB. volume 10. Prentice Hall, Upper
11 Saddle River, N.J.
12
13
14
15 790 [10] Carton, J., 1984. Coastal circulation caused by an
16 isolated storm. *J. Phys. Oceanogr.* 14, 114–124.
17 doi:10.1175/1520-0485(1984)014<0114:CCCBAI>2.0.CO;2.
18
19
20 [11] Chapman, D.C., Lentz, S.J., 1997. Adjustment of stratified
21 flow over a sloping bottom*. *J. Phys. Oceanogr.* 27, 340–356.
22 795 doi:10.1175/1520-0485(1997)027<0340:AOSFOA>2.0.CO;2.
23
24
25 [12] Charria, G., Lazure, P., Le Cann, B., Serpette, A., Reverdin, G., Louazel,
26 S., Batifoulier, F., Dumas, F., Pichon, A., Morel, Y., 2013. Surface layer cir-
27 culation derived from Lagrangian drifters in the Bay of Biscay. *J. Mar. Sys.*
28 109-110, S60–S76. doi:10.1016/j.jmarsys.2011.09.015.
29
30
31
32 800 [13] Clarke, A.J., Brink, K., 1985. The response of stratified, fric-
33 tional flow of shelf and slope waters to fluctuating large-scale,
34 low-frequency wind forcing. *J. Phys. Oceanogr.* 15, 439–453.
35 doi:10.1175/1520-0485(1985)015<0439:TROSFF>2.0.CO;2.
36
37
38
39 [14] Colas, F., 2003. Circulation et dispersion Lagrangiennes en Atlantique
40 Nord-Est. Ph.D. thesis. Université de Bretagne Occidentale, Brest, France.
41 805
42
43 [15] Farrell, H., Gentien, P., Fernand, L., Lazure, P., Lunven, M., Youenou,
44 A., Reguera, B., Raine, R., 2014. Vertical and horizontal controls of a
45 haptophyte thin layer in the Bay of Biscay, France. *Deep-Sea Res. II* 101,
46 80–94. doi:10.1016/j.dsr2.2013.10.008.
47
48
49
50 810 [16] Ferrer, L., Fontán, A., Mader, J., Chust, G., González, M., Valen-
51 cia, V., Uriarte, A., Collins, M., 2009. Low-salinity plumes in the
52 oceanic region of the Basque Country. *Cont. Shelf Res.* 29, 970–984.
53 doi:10.1016/j.csr.2008.12.014.
54
55
56
57
58
59
60
61
62
63
64
65

- 1
2
3
4
5
6
7
8
9 [17] Flores-Vidal, X., Durazo, R., Zavala-Sansón, L., Flament, P., Chavanne,
10 C., Ocampo-Torres, F., Reyes-Hernández, C., 2014. Evidence of inertially
815 generated coastal-trapped waves in the eastern tropical Pacific. *J. Geo-*
11 *phys. Res.* 119, 3121–3133. doi:10.1002/2013JC009118.
12
13
14
15
16 [18] Fontán, A., Cornuelle, B., 2015. Anisotropic response of surface circu-
17 lation to wind forcing, as inferred from high-frequency radar currents
18 in the southeastern Bay of Biscay. *J. Geophys. Res.* 120, 2945–2957.
820 doi:10.1002/2014JC010671.
19
20
21
22
23 [19] Fontán, A., González, M., Wells, N., Collins, M., Mader, J., Ferrer, L.,
24 Esnaola, G., Uriarte, A., 2009. Tidal and wind-induced circulation within
25 the Southeastern limit of the Bay of Biscay: Pasaia Bay, Basque Coast.
26 *Cont. Shelf Res.* 29, 998–1007. doi:10.1016/j.csr.2008.12.013.
27
825
28
29
30 [20] Freeland, H., Boland, F., Church, J., Clarke, A., Forbes, A., Huyer, A.,
31 Smith, R., Thompson, R., White, N., 1986. The Australian Coastal Ex-
32 periment: A search for coastal-trapped waves. *J. Phys. Oceanogr.* 16,
33 1230–1249. doi:10.1175/1520-0485(1986)016<1230:TACEAS>2.0.CO;2.
34
35
36
37 [21] Frouin, R., Fiúza, A.F., Ambar, I., Boyd, T.J., 1990. Observations of
38 a poleward surface current off the coasts of Portugal and Spain during
39 winter. *J. Geophys. Res.* 95, 679–691. doi:10.1029/JC095iC01p00679.
40
41
42 [22] Garcia-Soto, C., Pingree, R.D., 2012. Atlantic Multidecadal Oscillation
43 (AMO) and sea surface temperature in the Bay of Biscay and adjacent re-
44 gions. *Journal of the Marine Biological Association of the United Kingdom*
45 92, 213–234. doi:10.1017/S0025315410002134.
46
835
47
48
49 [23] Gill, A., Clarke, A., 1974. Wind-induced upwelling, coastal currents and
50 sea-level changes. *Deep Sea Research and Oceanographic Abstracts* 21,
51 325–345. doi:10.1016/0011-7471(74)90038-2.
52
53
54
55 [24] Gill, A., Schumann, E., 1974. The generation of long
840

shelf waves by the wind. *J. Phys. Oceanogr.* 4, 83–90.
doi:10.1175/1520-0485(1974)004<0083:TGOLSW>2.0.CO;2.

- [25] Gonzalez-Pola, C., Ruiz-Villarreal, M., Lavin, A., Cabanas, J., Alvarez-Fanjul, E., 2005. A subtropical water intrusion spring-event in the shelf-slope of the south-western Bay of Biscay after strong wind-forcing pulses. *Journal of Atmospheric & Ocean Science* 10, 343–359. doi:10.1080/17417530601129148.
- [26] Hanna, E., Cropper, T.E., Jones, P.D., Scaife, A.A., Allan, R., 2015. Recent seasonal asymmetric changes in the NAO (a marked summer decline and increased winter variability) and associated changes in the AO and Greenland Blocking Index. *International Journal of Climatology* 35, 2540–2554. doi:10.1002/joc.4157.
- [27] Hill, A.E., Hickey, B.M., Shillington, F.A., Strub, P.T., Brink, K.H., Barton, E.D., Thomas, A.C., 1998. Eastern ocean boundaries. *The sea* 11, 29–68.
- [28] Horányi, A., Ihász, I., Radnóti, G., 1996. ARPEGE/ALADIN: A numerical weather prediction model for Central-Europe with the participation of the Hungarian Meteorological Service. *Időjárás* 100, 277–301.
- [29] Huthnance, J., 1984. Slope currents and "JEBAR". *J. Phys. Oceanogr.* 14, 795–810. doi:10.1175/1520-0485(1984)014<0795:SCA>2.0.CO;2.
- [30] Kennedy, J., Morice, C., Parker, D., 2011. Global and regional climate in 2010. *Weather* 66, 188–194. doi:10.1002/wea.820.
- [31] Kennedy, J., Morice, C., Parker, D., 2012. Global and regional climate in 2011. *Weather* 67, 212–218. doi:10.1002/wea.1945.
- [32] Kennedy, J., Parker, D., 2010. Global and regional climate in 2009. *Weather* 65, 244–250. doi:10.1002/wea.635.

- 1
2
3
4
5
6
7
8
9 [33] Kim, S.Y., Cornuelle, B.D., Terrill, E.J., 2009. Anisotropic response of
10 surface currents to the wind in a coastal region. *J. Phys. Oceanogr.* 39,
11 1512–1533. doi:10.1175/2009JP04013.1.
12
13
14
15 870 [34] Kim, S.Y., Cornuelle, B.D., Terrill, E.J., Jones, B., Washburn, L., Moline,
16 M.A., Paduan, J.D., Garfield, N., Largier, J.L., Crawford, G., et al., 2013.
17 Poleward propagating subinertial alongshore surface currents off the US
18 West Coast. *J. Geophys. Res.* 118, 6791–6806. doi:10.1002/jgrc.20400.
19
20
21 [35] Koutsikopoulos, C., Le Cann, B., 1996. Physical processes and hydrological
22 structures related to the Bay of Biscay anchovy. *Scientia Marina* 60, 9–19.
23 875
24
25 [36] Large, W., Pond, S., 1981. Open ocean momentum flux measure-
26 ments in moderate to strong winds. *J. Phys. Oceanogr.* 11, 324–336.
27 doi:10.1175/1520-0485(1981)011<0324:OOMFMI>2.0.CO;2.
28
29
30
31 [37] Lavin, A., Valdes, L., Sanchez, F., Abaunza, P., Forest, A., Boucher, J.,
32 Lazure, P., Jegou, A., 2006. The Bay of Biscay: the encountering of the
33 880 ocean and the shelf. *The sea* 14, 933–1001.
34
35
36 [38] Lazure, P., Dumas, F., Vrignaud, C., 2008. Circulation on the Ar-
37 morican shelf (Bay of Biscay) in autumn. *J. Mar. Sys.* 72, 218–237.
38 doi:10.1016/j.jmarsys.2007.09.011.
39
40
41 [39] Lazure, P., Jégou, A.M., 1998. 3D modelling of seasonal evolution of Loire
42 885 and Gironde plumes on Biscay Bay continental shelf. *Oceanol. Acta* 21,
43 165–177. doi:10.1016/S0399-1784(98)80006-6.
44
45
46 [40] Lazure, P., Jegou, A.M., Kerdreux, M., 2006. Analysis of salinity measure-
47 ments near islands on the French continental shelf of the Bay of Biscay.
48 *Scientia Marina* 70, 7–14.
49 890
50
51 [41] Le Boyer, A., Charria, G., Le Cann, B., Lazure, P., Marié, L., 2013. Circu-
52 lation on the shelf and the upper slope of the Bay of Biscay. *Cont. Shelf Res.*
53 55, 97–107. doi:10.1016/j.csr.2013.01.006.
54
55
56
57
58
59
60
61
62
63
64
65

- 1
2
3
4
5
6
7
8
9 [42] Le Cann, B., 1990. Barotropic tidal dynamics of the Bay of Bis-
10 cay shelf: observations, numerical modelling and physical interpretation.
11 895 Cont. Shelf Res. 10, 723–758. doi:10.1016/0278-4343(90)90008-A.
12
13
14 [43] Le Cann, B., Serpette, A., 2009. Intense warm and saline upper
15 ocean inflow in the southern Bay of Biscay in autumn–winter 2006–2007.
16 Cont. Shelf Res. 29, 1014–1025. doi:10.1016/j.csr.2008.11.015.
17
18
19 [44] Liberato, M., Pinto, J., Trigo, R., Ludwig, P., Ordóñez, P., Yuen, D.,
20 900 Trigo, I., 2013. Explosive development of winter storm Xynthia over the
21 subtropical North Atlantic Ocean. Natural Hazards and Earth System
22 Science 13, 2239–2251. doi:10.5194/nhess-13-2239-2013.
23
24
25 [45] Maksimova, E.V., Clarke, A.J., 2013. Multiyear Subinertial and Sea-
26 sonal Eulerian Current Observations near the Florida Big Bend Coast.
27 905 J. Phys. Oceanogr. 43, 1691–1709. doi:10.1175/JPO-D-12-0135.1.
28
29
30 [46] Mazières, A., Gillet, H., Idier, D., Mulder, T., Garlan, T., Mal-
31 let, C., Marieu, V., Hanquiez, V., 2015. Dynamics of inner-shelf,
32 multi-scale bedforms off the south Aquitaine coast over three decades
33 (southeast bay of Biscay, France). Cont. Shelf Res. 92, 23 – 36.
34 910 doi:10.1016/j.csr.2014.11.002.
35
36
37 [47] Melton, C., Washburn, L., Gotschalk, C., 2009. Wind relaxations and
38 poleward flow events in a coastal upwelling system on the central California
39 coast. J. Geophys. Res. 114. doi:10.1029/2009JC005397.
40
41
42 [48] Morrow, R., Coleman, R., Church, J., Chelton, D., 1994. Sur-
43 face eddy momentum flux and velocity variances in the Southern
44 Ocean from Geosat altimetry. J. Phys. Oceanogr. 24, 2050–2071.
45 915 doi:10.1175/1520-0485(1994)024<2050:SEMFAV>2.0.CO;2.
46
47
48 [49] Narayanan, S., Webster, I., 1987. Coastally trapped waves in the pres-
49 ence of a barotropic shelf edge jet. J. Geophys. Res. 92, 9494–9502.
50 920 doi:10.1029/JC092iC09p09494.
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

- 1
2
3
4
5
6
7
8
9 [50] Noble, M.A., Ryan, H.F., Wiberg, P.L., 2002. The dynamics of subtidal poleward flows over a narrow continental shelf, Palos Verdes, {CA} .
10 Cont. Shelf Res. 22, 923 – 944. doi:10.1016/S0278-4343(01)00112-1.
11
12
13
14
15 925 [51] Paillet, J., 1999. Central water vortices of the eastern North Atlantic. J. Phys. Oceanogr. 29, 2487–2503.
16 doi:10.1175/1520-0485(1999)029<2487:CWVOTE>2.0.CO;2.
17
18
19
20 [52] Pingree, R., 1993. Flow of surface waters to the west of the british
21 isles and in the Bay of Biscay. Deep-Sea Res. II 40, 369–388.
22 doi:10.1016/0967-0645(93)90022-F.
23 930
24
25 [53] Pingree, R., Le Cann, B., 1989. Celtic and Armorican slope
26 and shelf residual currents. Prog. Oceanogr. 23, 303–338.
27 doi:10.1016/0079-6611(89)90003-7.
28
29
30
31 [54] Pingree, R., Le Cann, B., 1992. Three anticyclonic Slope Water Oceanic eD-
32 DIES (SWODDIES) in the southern Bay of Biscay in 1990. Deep-Sea Res. I
33 935 39, 1147–1175. doi:10.1016/0198-0149(92)90062-X.
34
35
36 [55] Pingree, R.D., Le Cann, B., 1990. Structure, strength and season-
37 ality of the slope currents in the Bay of Biscay region. Journal of
38 the Marine Biological Association of the United Kingdom 70, 857–885.
39 doi:10.1017/S0025315400059117.
40 940
41
42
43 [56] Raine, R., Berdalet, E., McManus, M., Yamazaki, H., 2014. Harm-
44 ful algal blooms in stratified systems. Deep-Sea Res. II 101, 1–3.
45 doi:10.1016/j.dsr2.2014.01.005.
46
47
48
49 [57] Relvas, P., Barton, E.D., Dubert, J., Oliveira, P.B., Peliz, A., Da Silva,
50 945 J., Santos, A.M.P., 2007. Physical oceanography of the western Iberia
51 ecosystem: latest views and challenges. Prog. Oceanogr. 74, 149–173.
52 doi:10.1016/j.pocean.2007.04.021.
53
54
55
56
57
58
59
60
61
62
63
64
65

- 1
2
3
4
5
6
7
8
9 [58] Rodney, J., Johnson, E., 2014. Meanders and eddies from topographic
10 transformation of coastal-trapped waves. *J. Phys. Oceanogr.* 44, 1133–
11 1150. doi:10.1175/JPO-D-12-0224.1.
12 950
- 13
14 [59] Rubio, A., Fontán, A., Lazure, P., Gonzalez, M., Valencia, V., Ferrer,
15 L., Mader, J., Hernández, C., 2013. Seasonal to tidal variability of
16 currents and temperature in waters of the continental slope, southeast-
17 ern Bay of Biscay. *J. Mar. Sys.* 109 – 110, Supplement, S121 – S133.
18 doi:10.1016/j.jmarsys.2012.01.004. XII International Symposium on
19 955 doi:10.1016/j.jmarsys.2012.01.004. XII International Symposium on
20 Oceanography of the Bay of Biscay.
21
22
23
24 [60] Saad, Y., 1992. Numerical methods for large eigenvalue problems. volume
25 158. SIAM.
26
27
28 [61] Seity, Y., Brousseau, P., Malardel, S., Hello, G., Bénard, P., Bouttier, F.,
29 960 Lac, C., Masson, V., 2011. The AROME-France convective-scale opera-
30 tional model. *Mon. Wea. Rev.* 139, 976–991. doi:10.1175/2010MWR3425.1.
31
32
33
34 [62] Solabarrieta, L., Rubio, A., Cárdenas, M., Castanedo, S., Esnaola, G.,
35 Méndez, F.J., Medina, R., Ferrer, L., 2015. Probabilistic relationships be-
36 tween wind and surface water circulation patterns in the SE Bay of Biscay.
37 *Ocean Dynam.* XX, XX–XX. doi:10.1007/s10236-015-0871-5.
38 965
39
40
41 [63] Solabarrieta, L., Rubio, A., Castanedo, S., Medina, R., Charria, G.,
42 Hernández, C., 2014. Surface water circulation patterns in the southeastern
43 Bay of Biscay: New evidences from HF radar data. *Cont. Shelf Res.* 74,
44 60–76. doi:10.1016/j.csr.2013.11.022.
45
46
47
48 970 [64] Thompson, R.O., 1983. Low-pass filters to suppress iner-
49 tial and tidal frequencies. *J. Phys. Oceanogr.* 13, 1077–1083.
50 doi:10.1175/1520-0485(1983)013<1077:LPFTSI>2.0.CO;2.
51
52
53 [65] Torres, R., Barton, E.D., 2006. Onset and development of the Iberian
54 poleward flow along the Galician coast. *Cont. Shelf Res.* 26, 1134–1153.
55 975 doi:10.1016/j.csr.2006.03.009.
56
57
58
59
60
61
62
63
64
65

- 1
2
3
4
5
6
7
8
9 [66] Van Aken, H.M., 2002. Surface currents in the Bay of Biscay as observed
10 with drifters between 1995 and 1999. *Deep-Sea Res. I* 49, 1071–1086.
11 doi:10.1016/S0967-0637(02)00017-1.
12
13
14 [67] de la Villéon, L.P., Coatanoan, C., Edwards, M., Karstensen, J., Cardin,
15 V., 2005. In-situ real-time data quality control. *Marine Environment and*
16 980 *Security for the European Area-Integrated Project*, document id. WP03-
17 IFR-UMAN-001-01A .
18
19
20
21 [68] Vincent, A., Kurc, G., 1969. Hydrologie, variations saisonnières de la
22 situation thermique du Golfe de Gascogne en 1967. *Rev. Trav. Inst. Pêches*
23 985 *marit.* 33, 79–96.
24
25
26 [69] Wang, D.P., 1980. Diffraction of continental shelf waves by ir-
27 regular alongshore geometry. *J. Phys. Oceanogr.* 10, 1187–1199.
28 doi:10.1175/1520-0485(1980)010<1187:DOCSWB>2.0.CO;2.
29
30
31
32 [70] Washburn, L., Fewings, M.R., Melton, C., Gotschalk, C., 2011. The prop-
33 990 agating response of coastal circulation due to wind relaxations along the
34 central California coast. *J. Geophys. Res.* 116. doi:10.1029/2011JC007502.
35
36
37 [71] Wilkin, J.L., Chapman, D.C., 1987. Scattering of continental shelf
38 waves at a discontinuity in shelf width. *J. Phys. Oceanogr.* 17, 713–724.
39 doi:10.1175/1520-0485(1987)017<0713:SOCSWA>2.0.CO;2.
40
41
42 [72] Wilkin, J.L., Chapman, D.C., 1990. Scattering of Coastal-Trapped Waves
43 995 by Irregularities in Coastline and Topography. *J. Phys. Oceanogr.* 20, 396–
44 421. doi:10.1175/1520-0485(1990)020<0396:SOCTWB>2.0.CO;2.
45
46
47 [73] Yankovsky, A.E., Chapman, D.C., 1995. Generation of mesoscale flows
48 over the shelf and slope by shelf wave scattering in the presence of
49 a stable, sheared mean current. *J. Geophys. Res.* 100, 6725–6742.
50 1000 doi:10.1029/94JC03339.
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65

1
2
3
4
5
6
7
8
9 [74] Yankovsky, A.E., Chapman, D.C., 1996. Scattering of shelf waves by
10 a spatially varying mean current. *J. Geophys. Res.* 101, 3479–3487.
11 doi:10.1029/95JC02991.
12

13
14 1005 [75] Yankovsky, A.E., Chapman, D.C., 1997. Anticyclonic eddies trapped on
15 the continental shelf by topographic irregularities. *J. Geophys. Res.* 102,
16 5625–5639. doi:10.1029/96JC03452.
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65