Estudio numérico de la pluma del río Duero y de la dinámica de la costa oeste de la Península Ibérica

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INTRODUCTION

The plume of a river is the visible part of an important amount of physical, chemical, and biological processes that take place when the river joins with the ocean

The river plumes are one of the most important pathways that drive terrestrial materials, like sediment, nutrients and pollutants, to the sea

The dynamic of a buoyant flow produced by a river discharge is a mixture between waves, wind fields, turbulent mixing, rotation, buoyancy and mesoscale circulation

The mixing between the riverine and oceanic waters can induce instabilities, which can generate bulges, filaments, and buoyant currents over the continental shelf. Offshore, the buoyant riverine water could form a front with the oceanic waters, often related with the occurrence of current-jets, eddies and strong mixing. They can have a large range of scales, persisting from hours to years

Parts on the structure of a river plume:

•The coastal current

•The offshore bulge

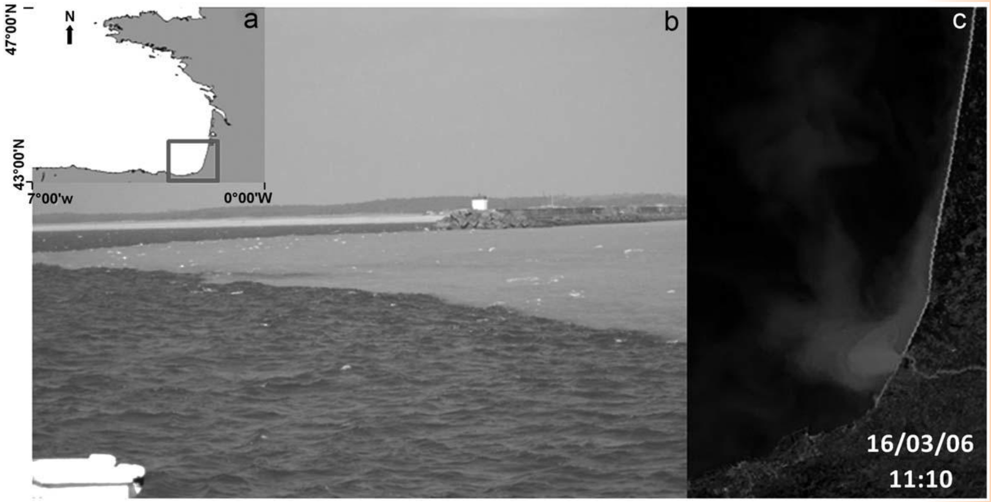


Figure:
The Adour River plume (South West of France) viewed from (b) a field picture and (c) MODIS-Aqua 1-km imagery

(from: Petus, C., G. Chust, F. Gohin, D. Doxaran, J.M. Froidefond and Y. Sagarminaga (2010): Estimating turbidity and total suspended matter in the Adour River plume (South Bay of Biscay) using MODIS 250-m imagery. Continental Shelf Research: 30, 379–392)

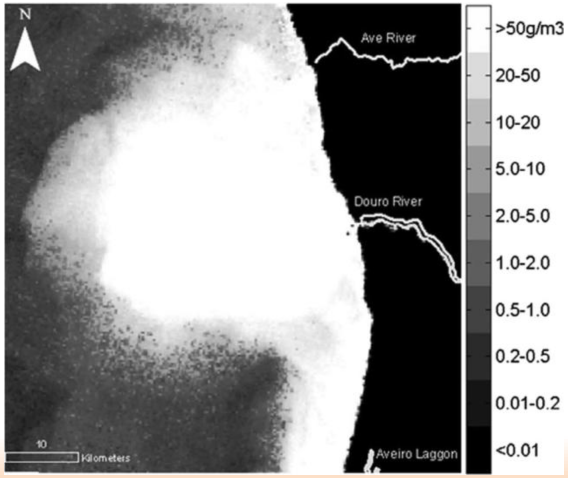


Figure:
Total suspended matter concentration for the Douro River retrieved from MERIS scene (March 8, 2003)

(from: Teodoro, A.C., H. Gonçalves, F. Veloso-Gomes and J. A. Gonçalves (2009): Modeling of the Douro River Plume Size, Obtained Through Image Segmentation of MERIS Data. IEEE Geoscience and remote sensing letters, 6, 1)

GEOGRAPHYCAL SETTING

The Douro River is located on the west coast of the Iberian Peninsula

It reaches to the Atlantic Ocean on an urban estuary surrounded by Porto and Gaia

The estuary is limited upstream by the Crestuma dam which controls the freshwater discharge

The daily averaged freshwater discharge of the River Douro can range from very low values (even zero) up to more than 13 000 m3/s

It is subjected to a strong inter-annual variability between dry and rainy years with normal pattern of caudal variability: mayor values in winter and the minor in summer

The 70 % of the annual precipitation in this region is concentrated between October and May, with maximum values in December, January and February and the minimum ones in July, August and September

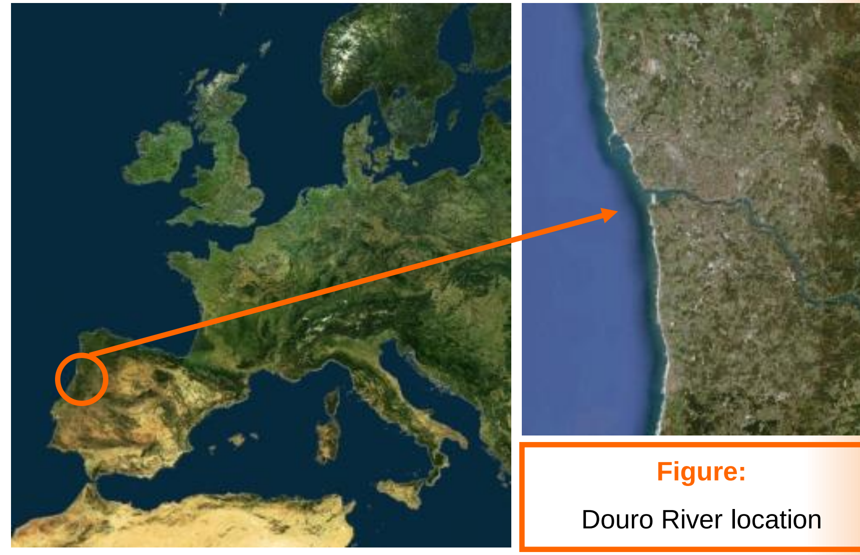


Figure:

Douro River location

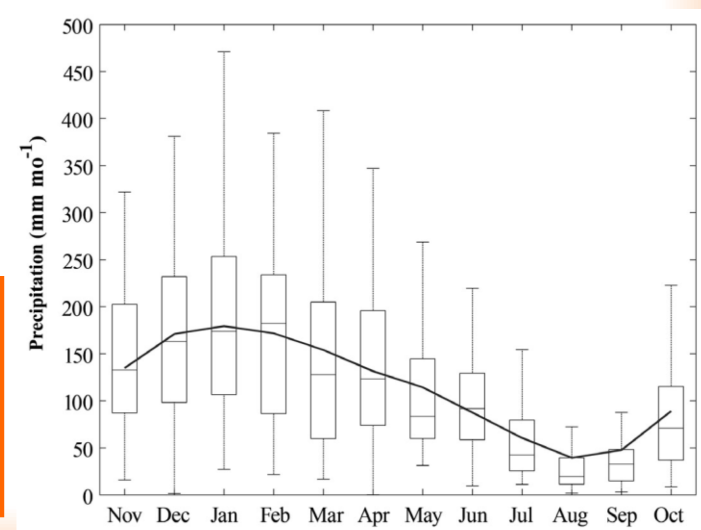


Figure:

Annual hydrologic cycle variability for the monthly average precipitation from 1961–2006 (Galicia and North Portugal)

(from: Gómez-Gesteira, M, L. Gimeno, M. deCastro, M. N. Lorenzo, I. Alvarez, R. Nieto, J. J. Taboada, A. J. C. Crespo, A. M. Ramos, I. Iglesias, J. L. GómezGesteira, F. E. Santo, D. Barriopedro, I. F. Trigo (2011): The state of climate in NW Iberia. Climate Research, 48: 109–144)

GEOGRAPHYCAL SETTING

The wind has a principal influence on the river plumes and on the coastal currents, forcing the shelf circulation

The predominant winds are the ones that present northerly and north-westerly directions.

The regional weather is mediated by the Azores Anticyclone (northerly and north-westerly winds), most frequent in any month of the year with maxima occurring during the summer months.

The southerly, south-westerly and westerly winds have their maxima during autumn and winter months.

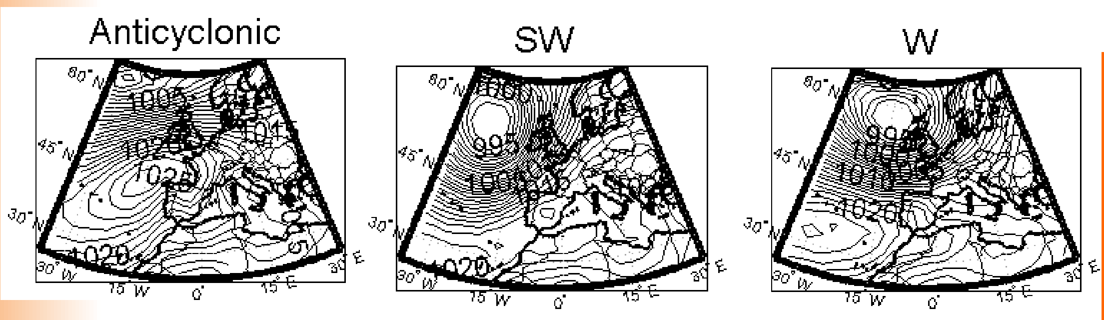
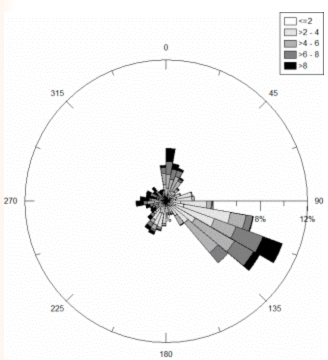
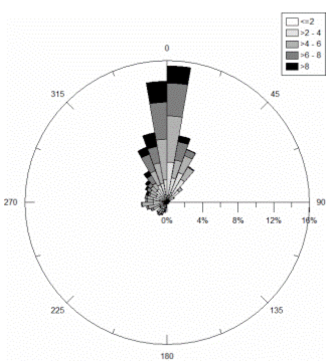


Figure:
Annual average SLP fields characteristic of the 3 common weather types on the study area

(from Lorenzo, M. N., J. J. Taboada and L. Gimeno (2007): Links between circulation weather types and teleconnection patterns and their influence on precipitation patterns in Galicia (NW Spain). International Journal of Climatology DOI: 10.1002/joc.1646)



Southern winds example



Northern winds example

An analisys of the most characteristic winds on the region (meteorological station at Ferrel, Peniche) reveals that the most frequent winds are the ones with norterly and southesterly components

GEOGRAPHYCAL SETTING

The Northwestern Iberian coast presents prominent capes, promontories and submarine canyons, which produce hydrodynamic features like filaments and eddies

The continental shelf is less than 20 km-wide south of Lisbon, 50–55 km-wide between Lisbon and Aveiro, and 30–40 km-wide between Aveiro and Galicia

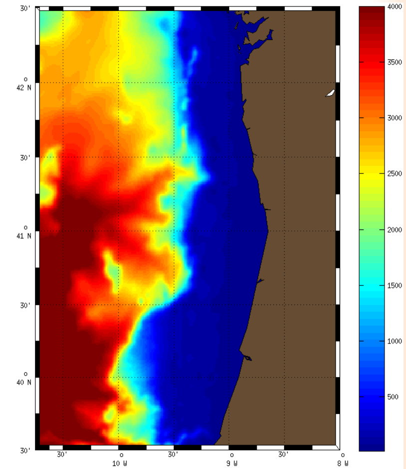


Figure:
Bathymetry (m) of the region under study

Upwelling:

- The west coast of the Iberian Peninsula is a region with frequently upwelling phenomenon
- The year period with more probability of suffers upwelling events and higher Ekman transport is between June and December, particularly in summer
- Fall-winter upwelling events exist if northerly winds blowing at shelf are present.

The WIBP:

- The Western Iberian Buoyant Plume (WIBP) is a recurrent buoyant plume which is present from autumn to spring with a strong influence on the shelf circulation
- It is formed by the rivers that reach to the Atlantic Ocean on the west coast of the Iberian Peninsula (The Galician Rias, and the rivers Minho, Mondego, Lima, Vouga and Tejo)
- It is extended along the coast over the inner shelf forming a front with the warmer more-saline surface waters
- Increases the stratification of the water column and produces a vertical retention mechanism that keeps the biological material inshore
- The interaction between the WIBP and the IPC creates shear at the surface producing favorable conditions for retention on the shelf break and constraining the offshore transport

Figure:
N: number of times that a month is under the most upwelling-favourable conditions (1985-2005)

(from: deCastro, M, M. Gómez-Gesteira, M. N. Lorenzo, I. Alvarez, A. J. C. Crespo (2008): Influence of atmospheric modes on coastal upwelling along the western coast of the Iberian Peninsula, 1985 to 2005. Climate Research, 36: 169–179)

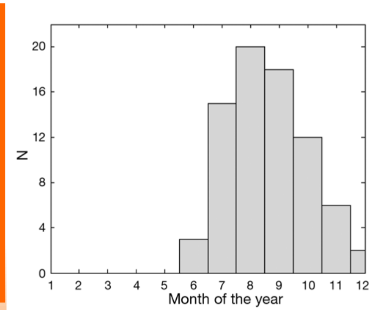
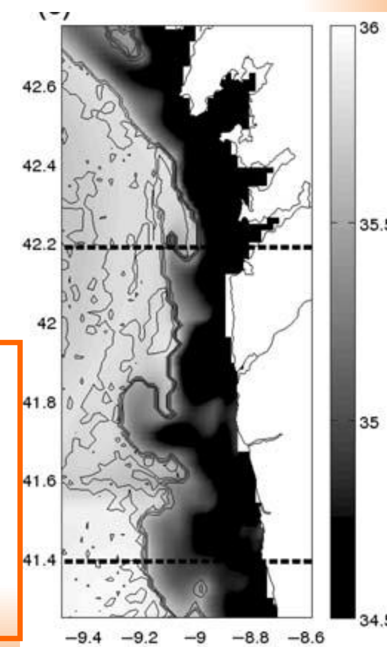


Figure:
The WIBP. Surface salinity on 6 December with contours of MLD

(from: Otero, P., M. Ruiz-Villareal and A. Peliz (2009): River plume fronts off NW Iberia from satellite observations and model data. ICES Journal of Marine Science, 66: 1853–1864)



GEOGRAPHYCAL SETTING

Satellite analysis:

•The Landsat, Modis and SeaWFiS imagery show the Douro river plume

• The Douro river can be considered as one of the main sources of suspended particles, dissolved and detrital material, chlorophyll and inorganic carbon in the NW Iberian Shelf

Figure:
Landsat 20-03-2000

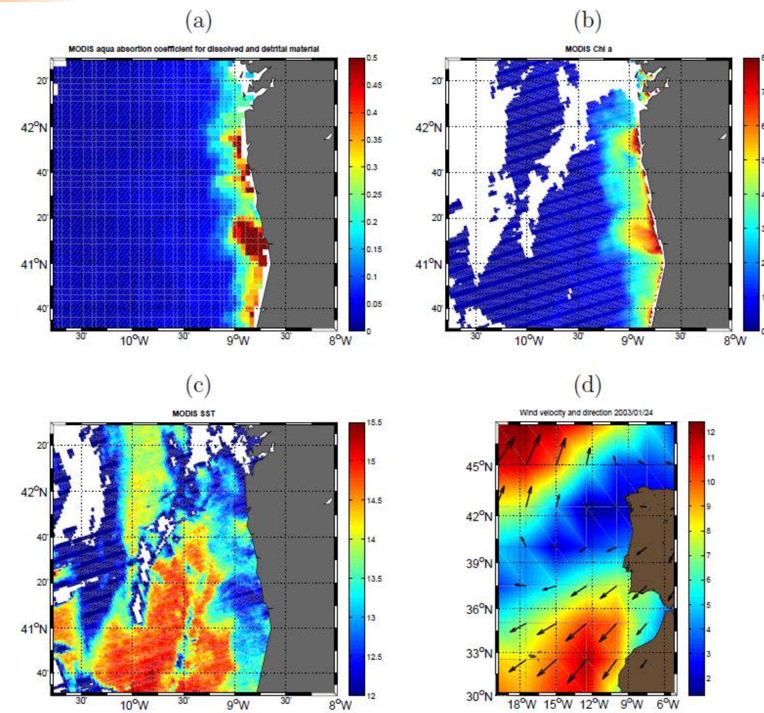


Figure 4: (a) MODIS 8 day-composite absorption coefficient for dissolved and detrital material (1/m), (b) MODIS chlorophyll concentration (mg/m^3), (c) MODIS SST (°C) and (d) NCEP reanalysis wind, for 24/Jan/2003.

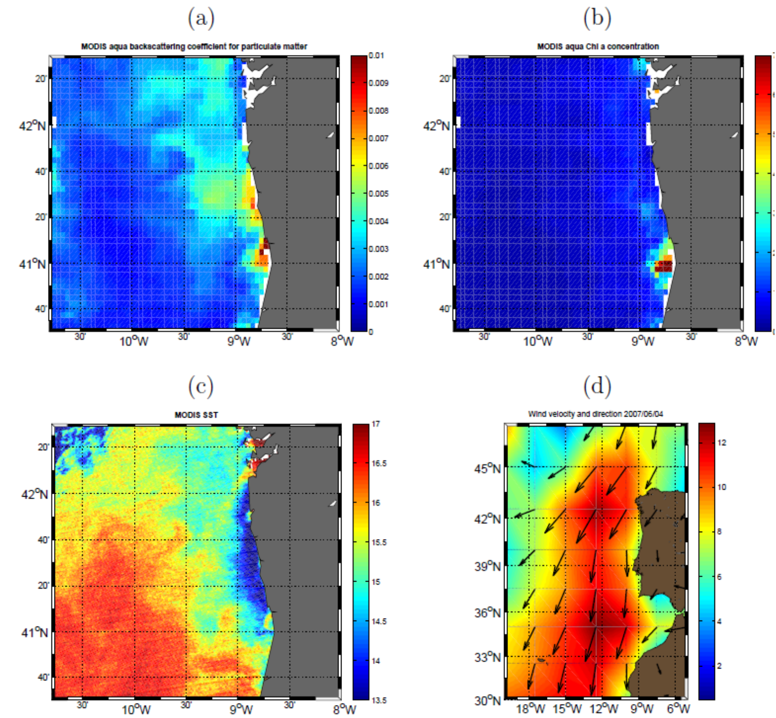


Figure 5: (a) MODIS 8 day-composite backscattering coefficient particulate matter (1/m), (b) MODIS 8 day-composite chlorophyll concentration (mg/m^3), (c) MODIS SST (°C) and (d) NCEP reanalysis wind, for 04/Jun/2007.

Figure:
Landsat 01-04-2001

MODEL CONFIGURATION

- The ROMS-AGRIF was used to reproduce the scenarios of plume generation, retention and dispersion.
- Some of the principal model characteristics for the monthly and one year simulations include:
    - Grid:
        - Longitude = 10.75º W – 8º W
        - Latitude = 39.5º N – 42.5º N
        - 35 vertical levels
        - Resolution: 1/80 (~1 km)
    - Minimal depth at the coast of 17 m
    - Data:
        - Bathymetry: Gebco (~ 800 m resolution)
        - Climatological temperature and salinity: World Ocean Atlas climatology
        - Atmospheric fluxes (heat and water): COADS
        - Tidal forcing: OSU tidal data inversion
- Particularly, for the extreme simulation the minimal depth at the coast is 50 m

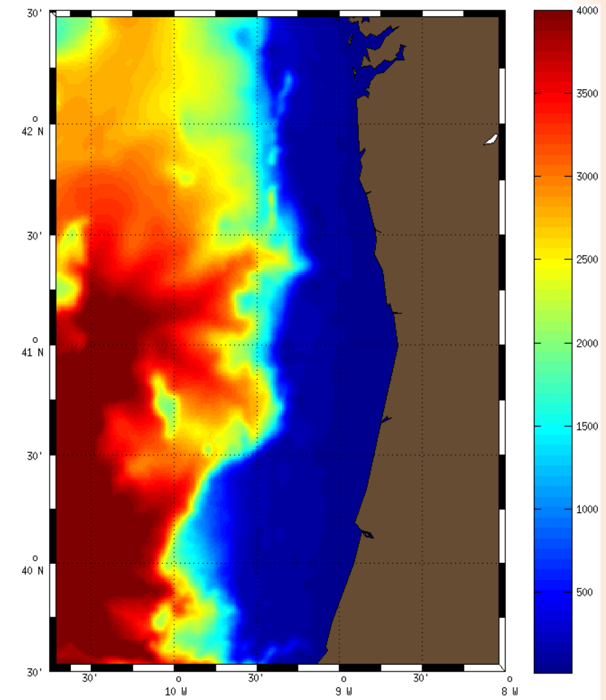
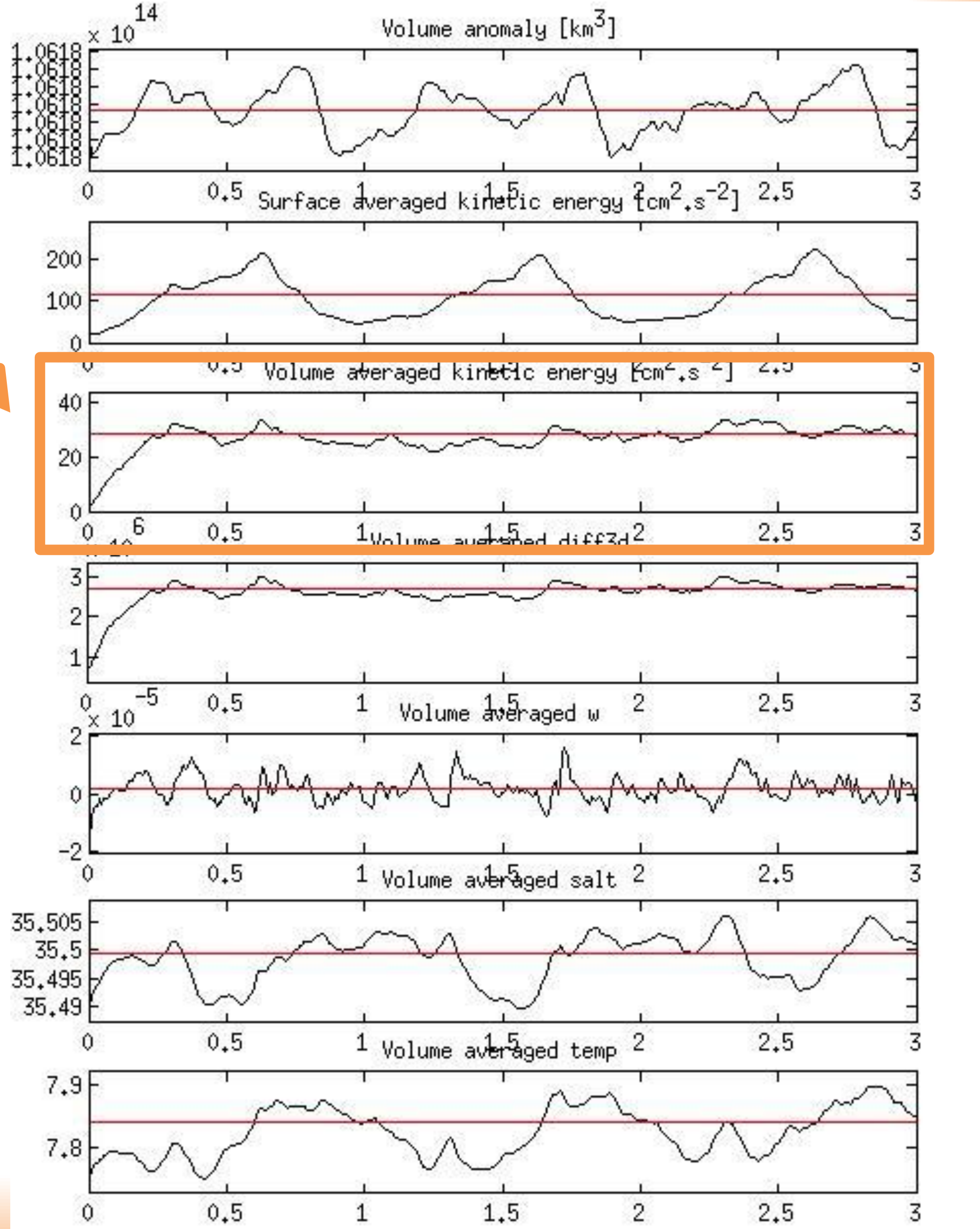


Figure:
Bathymetry (m) of the region under study

MODEL CONFIGURATION

- Other conditions
  - 3 years spin-up simulation until the volume averaged kinetic energy stabilized +1 month simulation to performed the tide ramping
  - The river flux was added on a point source on the Douro River location. The river fluxes are climatic averages at the Crestuma dam SNIRH station (EDP) between Jan/1986–Jan/2012



- Three kind of simulations were performed:
  - Schematic winds simulations
  - Multi-year climatological simulation
  - Extreme event

MODEL CONFIGURATION

- **Schematic winds simulations:**
  - 1 month-long simulations
  - January climatic initial conditions at the open ocean lateral boundaries (North, South and West boundaries)
  - River water: 5ºC and 0 psu
  - Prescribed homogeneous wind velocity and direction (see table)

Scenario	Wind direction	Wind velocity (m/s)	River flow value (m^3/s)
A1	North	Strong: 12	High: 1000
A2	South	Strong: 12	High: 1000
B1	North	Weak: 1	High: 1000
B2	South	Weak: 1	High: 1000
C1	North	Strong: 12	Low: 100
C2	South	Strong: 12	Low: 100
D1	North	Weak: 1	Low: 100
D2	South	Weak: 1	Low: 100
E1	No wind	No wind	High: 1000
E2	No wind	No wind	Low: 100

Table:
Schematic wind scenarios

MODEL CONFIGURATION

- **Multi-year climatological simulation:**
  - 3 year-long climatological simulation
  - Riverine water salinity was kept null. Its temperature and flow rate changed monthly (see table)
  - Due to the lack of freely available data for the region, the monthly temperature values were taken from previous hydrological studies

Month	River flux (m3/s)	River temperature (ºC)
1	1083	7
2	855	8
3	762	9
4	522	10
5	402	12
6	272	15
7	165	18
8	101	20
9	160	18
10	273	14
11	473	12
12	862	10

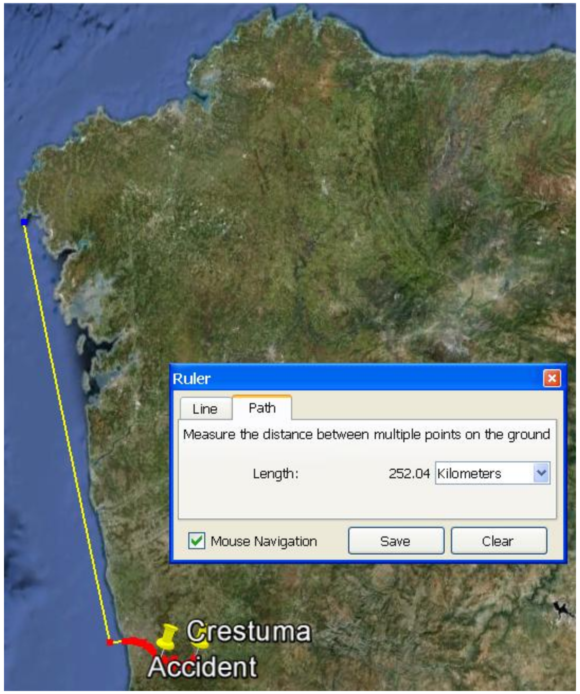
Table:
One year simulation river conditions

MODEL CONFIGURATION

Data	Douro flow at Crestuma (m3/s)
01/03/01	1267.12
02/03/01	2385.72
03/03/01	4403.05
04/03/01	**7004.12**
05/03/01	8901.06
06/03/01	7458.72
07/03/01	8591.72
08/03/01	**6440.89**
09/03/01	**6391.29**
10/03/01	**7646.20**
11/03/01	4053.11
12/03/01	3592.27
13/03/01	4144.83

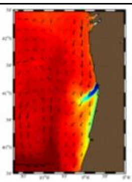
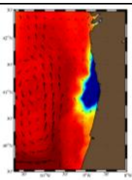
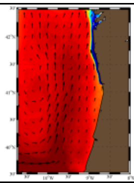
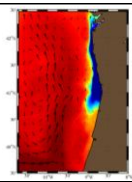
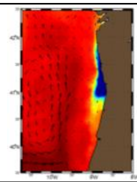
Accident

Bodys in Galicia



- **Extreme simulation:**
  - One month simulation for March 2001
  - Mean river flow: 8000 m^3/s
  - River water temperature: 9 ºC
  - River water salinity: 0
  - Real Quickscat winds
- **Why March 2001?**
  - Entre os Ríos accident: On 4/3/2001 the Hintze Ribeiro bridge broken (45 km upstream) and carry a bus and three cars.
  - Between the 7 and 10/3/2001 some corpses and car debris were found along the Galician coast, about 200 km north from the Douro river mouth
  - Meteorological conditions:
    - Strong southerly wind component
    - Strong rainfall (high river flow)

SCHEMATIC WINDS SIMULATIONS RESULTS

River flow	1000 m^3/s				
Wind direction	Northern Wind		Southern Wind		No wind
Scenario Wind velocity	A1 12 m/s	B1 1 m/s	A2 12 m/s	B2 1 m/s	E1
Salinity and current vectors					
					

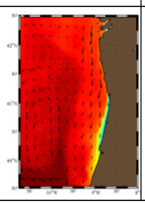
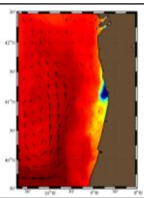
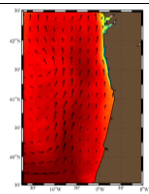
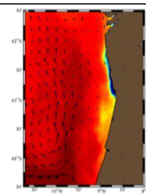
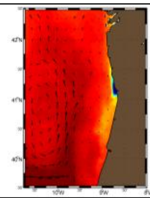
River flow	100 m^3/s				
Wind direction	Northern Wind		Southern Wind		No wind
Scenario Wind velocity	C1 12 m/s	D1 1 m/s	C2 12 m/s	D2 1 m/s	E2
Salinity and current vectors					
					

Table: Mean salinity (PSU) and current vectors (m/s) of the one month simulations

The schematic wind case studies were carried out with and without tidal forcing, and with and without bottom friction.

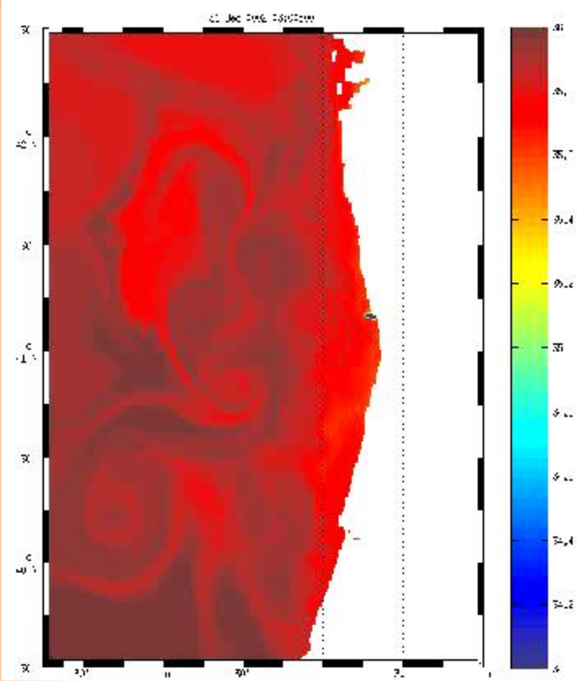
- Effect of tides: reduction of its offshore expansion and a deeper vertical mixing (narrower and deeper plumes)
- Bottom friction: In absence of friction, plumes present smaller bulges and shorter (or nonexistent) coastal currents

Remarks on the salinity/current vector plots:

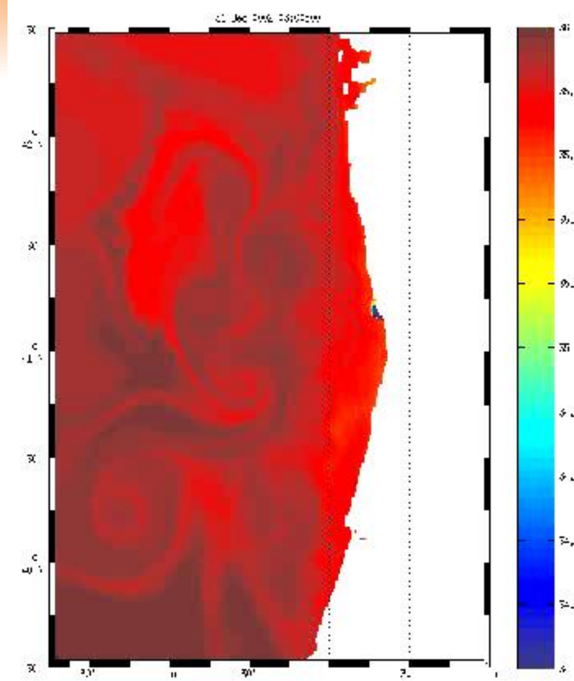
- In the absence of wind the plume developed bulges and weak coastal currents (poleward)
- Strong response to the wind
- River plumes propagate in the same direction of the wind near the coast
- Coastal currents are stronger when strong winds are combined with intense river outflows
- Plumes formed in strong wind conditions form jet-like features. Weak plumes subjected to stronger horizontal advection are allowed to expand

- Weaker winds induce the generation of a wider plume bulge at the river-mouth (B1, B2, D1, D2) crossing the continental shelf with strong river outflow (B1 ,B2)
- Strong wind (A1, A2, C1, C2) produces smaller or inexistent bulges are smaller or inexistent.
- Southerly winds: Plumes traveling poleward with an alongshore feature (A2, B2, C2,D2). Douro river water in the Galician Rías (A2, B2,C2)
- Northerly winds (A1, B1, C1, D1): Plume with a southwesterly component that crosses the continental shelf and an alongshore current which moves southward.

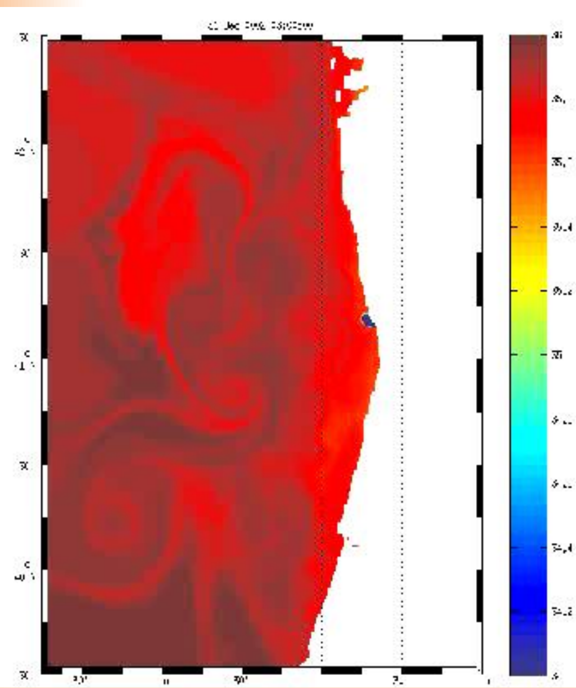
SCHEMATIC WINDS SIMULATIONS RESULTS



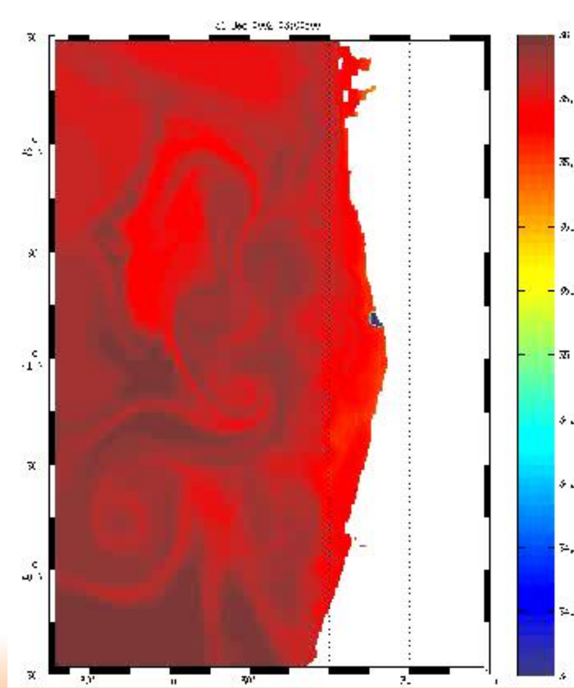
A1



A2

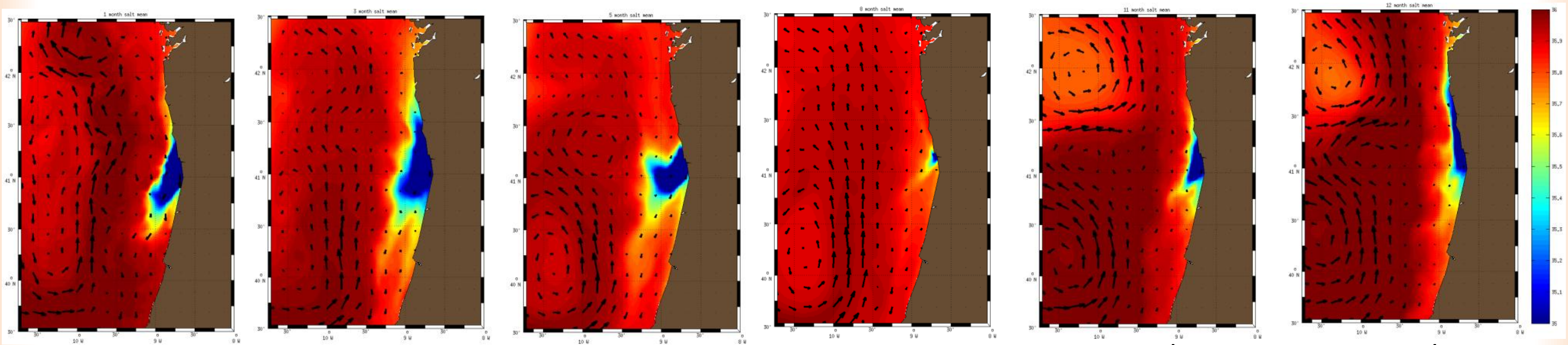


B1



B2

MULTI-YEAR CLIMATOLOGICAL SIMULATION RESULTS

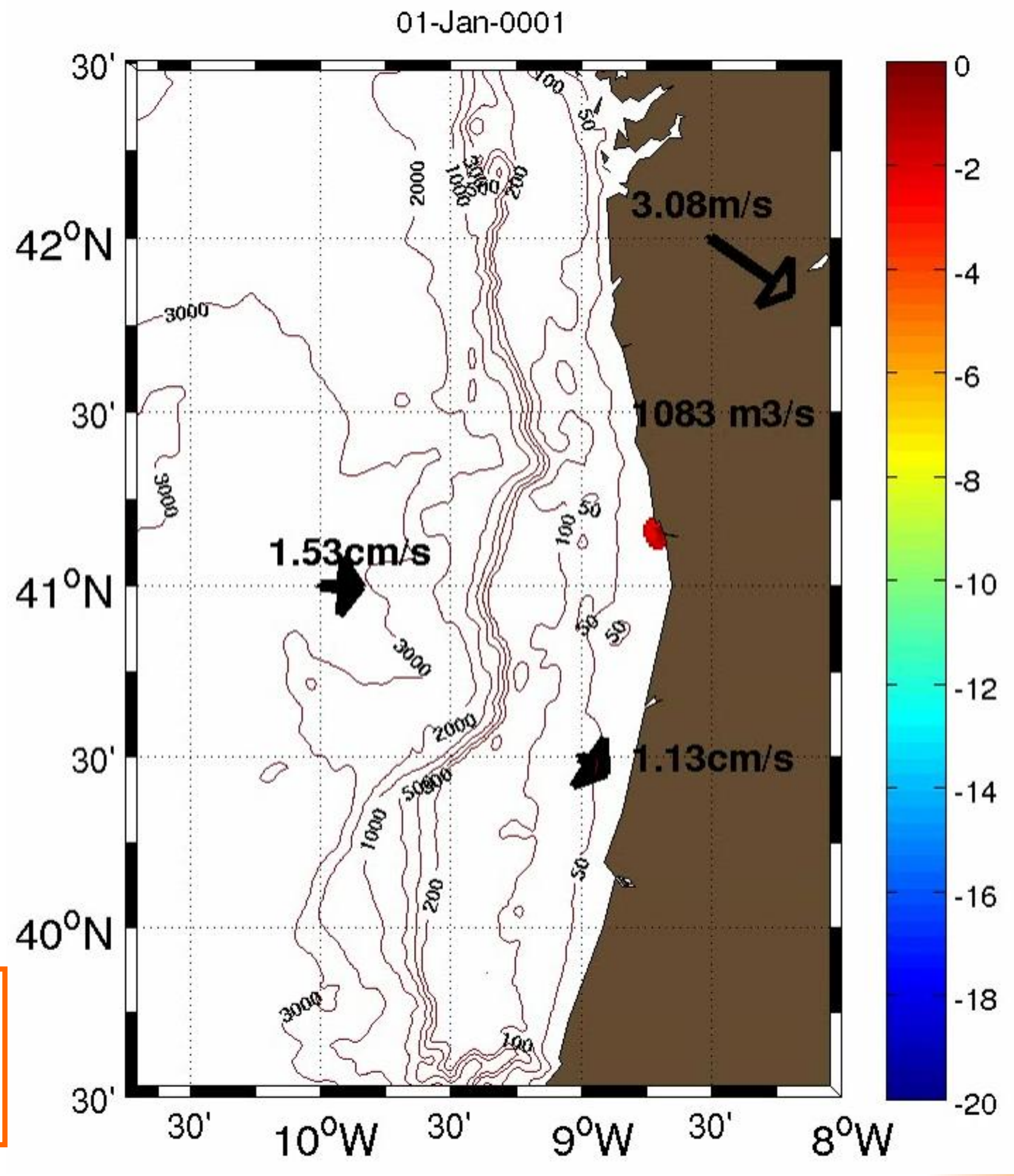


January	March	May	August	November	December
~1050 m^3/s	~750 m^3/s	~400 m^3/s	~100 m^3/s	~450 m^3/s	~850 m^3/s

- Mean horizontal salinity plots
  - High flow allows the develop of a jet like plume that evolved on a south-west direction
  - On October and November the plume evolved to north and west and on December to the north
- The climatic wind had a north component for most months except for October, November and December, which veers westward and southward.
- The wind strength varied between 2 and 8 m/s, thus the coastal current also assumed lower values than the ones observed for the schematic wind study

MULTI-YEAR CLIMATOLOGICAL SIMULATION RESULTS

- The depth of the plume was calculated
- It was defined as the depth at which the maximum value of the vertical salinity gradient is reached
- To avoid the deep water salinity gradient, any water body with a salinity above 35.7, and deeper than 100 m, was excluded
- An animated representation of the plume depth shows that, contrary to what was expected from the results of the schematic wind scenarios, the Douro plume is not as reactive to the wind as it is to the coastal (alongshore) current



Video: Plume depth from the multi-year climatological simulation. The values over the sea (from west to east) represent offshore and inshore current velocity (cm/s) and direction. The values over the land (from north to south) are the wind velocity (m/s) and direction, and the river flow rate (m3/s).

MULTI-YEAR CLIMATOLOGICAL SIMULATION RESULTS

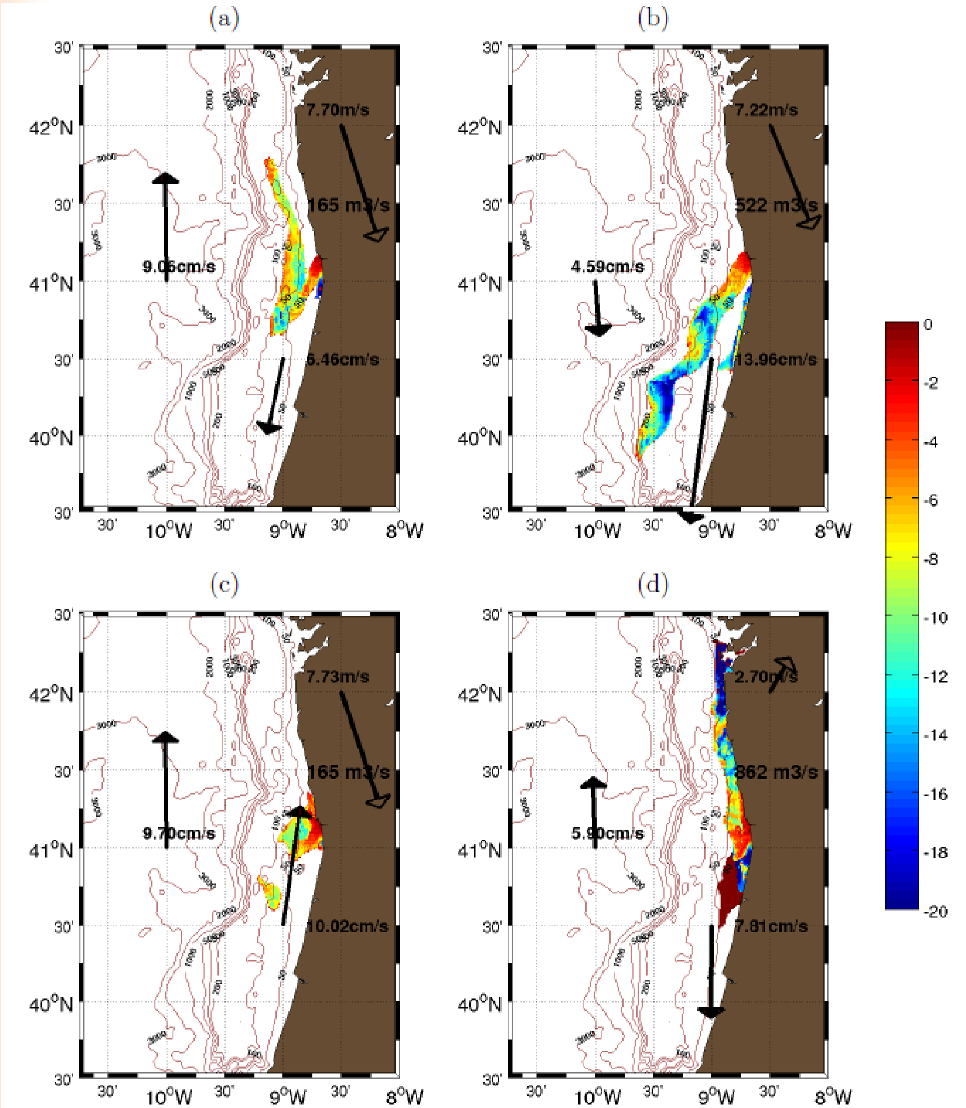


Figure: Plume depth snapshots from the multi-year climatological simulations. The values over the sea (from west to east) represent offshore and inshore current velocity (cm/s) and direction. The values over the land (from north to south) are the wind velocity (m/s) and direction, and the river flow rate (m3/s).

- The wind has an important influence on the plume dispersion (Figures a and b)
- But the wind and the plume induced current propagate in opposite directions when the offshore (geostrophic) current is at its highest strength and propagating opposite to the wind (Figure c)
- Surface offshore currents propagate in opposite direction to their coastal counterpart (Figure d) however, when a strong offshore current is formed it veers the inshore current to travel against the wind (Figure c).
- A wide variety of plume scenarios were observed
    - Jetlike feature (Figure b), which rarely crosses the continental shelf except in certain situations
    - Flapping filament features that eventually break into patches (Figure c)
    - Bifurcations or changes on the plume direction at the river mouth, with jets protruding to the north and to the south simultaneously (Figure a)

MULTI-YEAR CLIMATOLOGICAL SIMULATION RESULTS

Several structures:

- Mesoscale eddies offshore: Interact with inshore waters, advecting plume waters across the shelf (Figure: 9-day sequence eddy formation)
- Filaments
- Patches

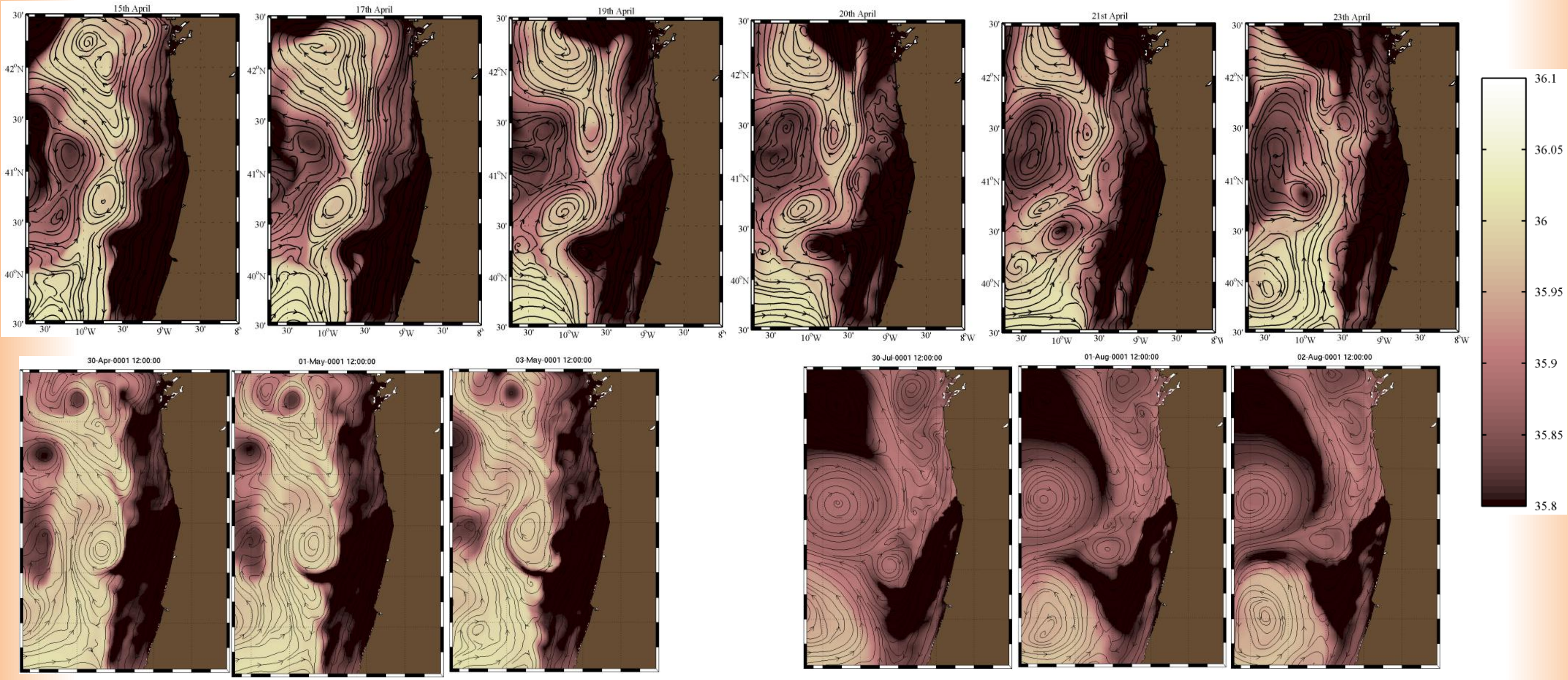


Figure:

Salinity snapshots plots + flow lines

EXTREME SIMULATION RESULTS

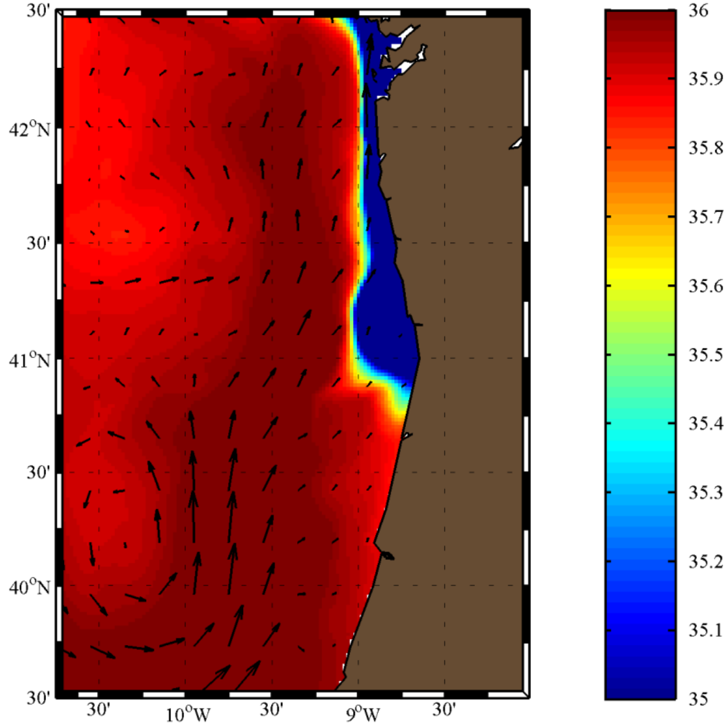


Figure:

Salt mean (with mean current vectors)

The currents travel from the south to the north and the plume reached Galicia with a big amount of water.

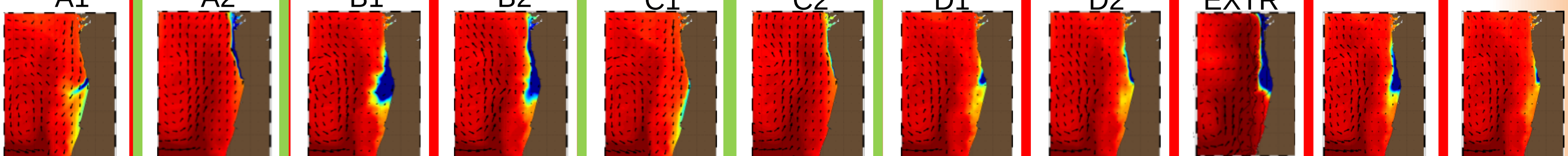
The plume is essentially wind-driven, so, the wind pushed the Douro River water to the north.

The mixing between river and ocean waters was weak, generating a buoyant surface conveyor-belt-like current transporting materials northward

PLUMES CLASSIFICATION

- **Chao parameter:**
  - Classifies the plumes according to the ratio between the maximum width of the plume bulge and the width of the coastal current.
  - If that ratio falls bellow 1.7, the plume is classified as subcritical, otherwise it is classified as supercritical.
  - A very wide plume, with a width about four times the Rossby deformation radius, is classified as diffusive.
- **Kourafalou parameter:**
  - λ = L/LC, where L is the seaward extent of the bulge (offshore distance from the river mouth) and LC is the width of the coastal current.
  - A fully developed plume
    - Supercritical: λ > 1
    - Subcritical: λ < 1
    - Diffusive: λ ~ 1

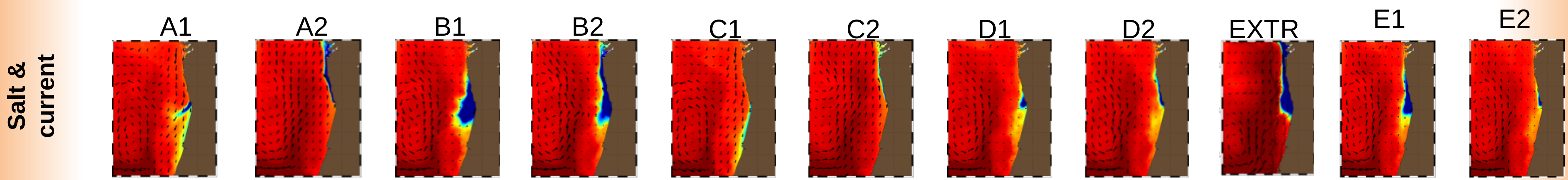
Salt & current



	A1	A2	B1	B2	C1	C2	D1	D2	EXTR	E1	E2
Bulge width	~40 km	No bulge	~45 km	~30 km	No bulge	No bulge	~24 km	~25 km	~30 km	~30 km	~10 km
Coastal current width	~15 km	~10 km	~14 km	~15 km	~5 km	~10 km	~5 km	~10 km	~15 km	~10 km	~5 km
λ	λ<1 But, supercritical	λ<1 Subcritical	λ>1 Supercritical	λ>1 Supercritical	λ<1 Subcritical	λ<1 Subcritical	λ>1 Supercritical	λ>1 Supercritical	λ>1 Supercritical	λ>1 Supercritical	λ>1 Supercritical

PLUMES CLASSIFICATION

- **The Rossby deformation radius, Rd:**
  - The length scale at which the rotational effects, due to the Coriolis force, become as important as buoyancy
  - It will be used to determine to what extent the plume structure is affected by the planetary rotation and to confirm whether the obtained plumes are diffusive
  - The calculated Rd values imply that the plumes were affected by the planetary rotation.
  - Show large values for the supercritical plumes coincident with the formation of a wide coastal current whose width is comparable with the Rd value
  - The plumes are not diffusive



	A1	A2	B1	B2	C1	C2	D1	D2	EXTR	E1	E2
Rb bulge	8 – 7 km	10 – 11 km	10 – 9 km	12 km	4 – 3 km	3 – 2 km	5 km	5 km	23 km	8-6 km	5 km

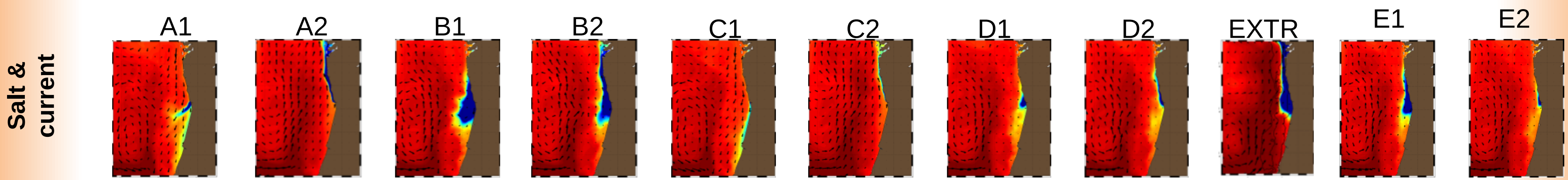
PLUMES CLASSIFICATION

- **Kelvin number, Ke:**
  - Ratio between the local plume width and the Rossby deformation radius.
  - Ke ≪ 1, the effect of the Coriolis force on the plume will be weak and the advection due to momentum is strong
  - Ke ≫ 1, the Coriolis force effect is strong while advection is weak.
  - The supercritical plumes are subject to an important influence of the Coriolis force
  - The subcritical plumes have a stronger effect of advection on their evolution
- **The Richardson number, Ri:**
  - To study the water column stability and the stratification
  - Ri = 20: Upper limit for the occurrence of turbulent mixing
  - Ri > 20: mixing becomes negligible
  - Ri < 20: the stratification weakens
  - Ri < 2: mixing is fully developed.
  - 2 < Ri < 20: Criterion to evaluate the vertical stability.
  - The highest Ri number values were obtained for the supercritical plumes with fully developed bulge (B1, B2, D1, D2, E1, E2 and extreme event)
  - The lowest Ri number values were obtained for the subcritical plumes (A2, C1 and C2)
  - With lesser river water, the wind can induce a more efficient mixing of the plume in the coastal waters, so the wind acted herein as the main forcing mechanism for the vertical mixing of the plume

Case	Ke	Classification	Ri	
			Bulge	Costal current
A1	5.6	Supercritical	4	4
A2	0.45	Subcritical	—	< 2
B1	4.8	Supercritical	> 20	7–8
B2	2.7	Supercritical	> 20	6–8
C1	0	Subcritical	—	< 2
C2	0	Subcritical	—	< 2
D1	4.8	Supercritical	> 20	7–8
D2	4.8	Supercritical	> 20	> 20
E1	3.3	Supercritical	> 20	7–9
E2	2.4	Supercritical	> 20	> 20
EE	1.8	Supercritical	> 20	6–8

PLUMES CLASSIFICATION

- **The Froude number, Fr:**
  - The leading edge of a coastal gravity current moves with a front Froude number of about unity
  - Fr < 1 the flow is considered in a subcritical state => the coastal front moves slower than the ambient flow, whereas
  - Fr > 1 the flow is considered in a supercritical state and the front would move faster than a coastal gravity current
  - The small values obtained (bellow one for all the Scenarios) => the front, i.e. the plume, is expected to move slower than the coastal current, allowing for the development of instabilities, which generate meanders, filament structures, etc
  - The scenarios with the widest bulges are those with the largest Froude numbers, => they are prone to instabilities that might quickly disperse them



	A1	A2	B1	B2	C1	C2	D1	D2	EXTR	E1	E2
Fr	~0.12 on the Douro Between 0.08-0.04 north 0.04 on coastal current	~0.14 on the Douro Between 0.14-0.07 on coastal current	~0.12 on the Douro ~0.05 at the south of the river	~0.11 on the Douro 0.05 on coastal current	~0.08 on the Douro Between 0.07-0.04 at north of the river ~0.05 on coastal current	Between 0.08-0.02 at Douro and coastal current ~0.05 at south river	~0.04 at the Douro	Between 0.03-0.02 at Douro and coastal current	~0.08 at the Douro Between 0.06-0.03 on coastal current	~0.1 at the Douro ~0.04 at the south of the river	~0.03 at the Douro

CONCLUSIONS

- The Douro river plume shows the normally structure of bulge and coastal current
- It was obtained subcritical and supercritical Douro plumes, some of them with pronounced coastal bulges, forming part of an alongshore current and/or crossing the shelf with and without the influence of offshore eddies and filaments
- The schematic wind case studies suggest that the Douro river plume is wind-driven
- Southerly winds push the river water to the north
- The high surface salinity on the plume regions during strong wind events suggests that the wind enhances the vertical mixing
- Upwelling favourable winds induce plumes with a narrow coastal current
- The influence of the Coriolis force is mitigated by a strong wind forcing
- Although the wind can play a dominant role in controlling the vertical mixing and the alongshore distribution of the Douro river plume over the continental shelf, offshore eddies and filaments are also responsible for the cross-shore transport, through the horizontal advection of plume waters.
- Analysis of the Rossby deformation radius and of the Kelvin number confirm that the Douro supercritical plumes are strongly affected by the planetary rotation.
- The supercritical plumes coincided with the coastal current maximum widths
- Douro river plumes are not diffusive.
- The values obtained for the densimetric Richardson number showed that the supercritical plumes are less mixed than the subcritical ones.

Estudio numérico de la pluma del río Duero y de la dinámica de la costa oeste de la Península Ibérica

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