evolution of the structures suggest nonlinear interactions with the wind forcing, with local values of divergence exceeding the Coriolis parameter f, indicating significant submesoscale vertical velocity in the water column. The results show that the simplified paradigm of Ekman transport and induced coastal upwelling/downwelling can be significantly altered by the presence of submesoscale. The specific mechanisms of interaction, as well as the role of high resolution inhomogeneity in the wind magnitude and direction (Zatsepin et al. 2019) need further investigation.

Results also show that small scale ocean weather strongly modifies horizontal and vertical transport, suggesting a potential impact on the biological response. Unfortunately, though, no glider biogeochemical data are available during the event, so that the ecosystem response cannot be directly evaluated. The study indicates the importance of further investigating data from multi-platform observations such as water column information from gliders or fixed buoys within the HFR coverage. Further investigations are also planned to assess the generality of the results as a function of ocean state, wind conditions and seasonality.

Acknowledgements

This work is supported by the JERICO-NEXT and JERICO-S3 projects under the European Union's Horizon 2020 research and innovation programme with grant agreement no. 654410 and no. 871153, respectively. Investigation on submesoscale dynamics in the Mediterranean Sea is also supported by the Office of Naval Research (ONR) through the CALYPSO Departmental Research Initiative (Grant N000141613130).

Section 4.9. Drifter observations and Lagrangian tracking of the 2018 easterly wind event in the North Sea

Authors: M. Ricker, E. V. Stanev, T. H. Badewien, H. Freund, J. Meyerjürgens, J.-O. Wolff, O. Zielinski

Statement of main outcome: Persistent easterly winds in spring 2018 reversed the circulation in the North Sea for more than a month. This reversal has been documented by GPS-drifter observations, as well as by the stranding positions of wooden drifters released along the German North Sea coast. The latter information came from members of the public, the majority of which are likely to be non-scientists. It provided a valuable contribution to the GPS-drifter experiment and demonstrates an excellent example of the usefulness of citizen science. Lagrangian numerical experiments were also performed and helped explain and quantify the anomalous transport and the reversal of the circulation at the sea surface and in deeper layers. It has been shown that the CMEMS surface current products agree well with drifter observations, even under extreme wind conditions, which adds to their credibility.

Products used

Ref. No.	Product name & type	Documentation
4.9.1	NORTHWESTSHELF_ANALYSIS_FORECAST_PHYS_004_001_b Model analysis and forecast	PUM: https://marine.copernicus.eu/documents/PUM/CMEMS-NWS-PUM-004-001.pdf QUID: https://marine.copernicus.eu/documents/QUID/CMEMS-NWS-QUID-004-001-b.pdf
4.9.2	NORTHWESTSHELF_ANALYSIS_FORECAST_WAV_004_012 Model analysis and forecast	PUM: https://marine.copernicus.eu/documents/PUM/CMEMS-NWS-PUM-004-012.pdf QUID: https://marine.copernicus.eu/documents/QUID/CMEMS-NWS-QUID-004-012.pdf
4.9.3	Wooden drifters Observations	http://portal.macroplastics.de/index.php?page=drifter-meldung
4.9.4	GPS drifters Observations	Data: Stanev et al. (2019) (Drifter 1) Technical description: Meyerjürgens et al. (2019)

4.9.1. Introduction

The present research was motivated by observations made during the project 'Macroplastics Pollution in the Southern North Sea' (http://www.macroplastics.de/), one aim of which was to study the propagation pathways of marine litter in the North Sea (e.g. Stanev et al. 2019). It describes the response of the circulation in the North Sea to non-typical atmospheric situations in 2018 and the validation of available CMEMS surface and Stokes drift velocities against observations from drifters during extreme weather conditions. Data of two drifter types have been used: 1. GPS drifters providing temporally highly resolved trajectories (Meyerjürgens et al. 2019) and 2. Wooden drifters providing a large amount of beaching positions and emphasising the benefits of citizen science (Garcia-Soto et al. 2017).

The sense of circulation in the North Sea is overall anti-clockwise (Mathis et al. 2015), which is illustrated in Figure 4.9.1 by the annual mean surface currents during 2018 computed using the Copernicus product for the European North West shelf (product ref. 4.9.1). Earlier research on the wind effects focused mostly on the annual mean circulation, on the circulation patterns resulting from wind blowing from different directions and with varying magnitudes, or on the coupled wind-tidal variability (Maier-Reimer 1977; Backhaus 1989; Otto et al. 1990; Sündermann and Pohlmann 2011; Jacob and Stanev 2017). However, not much is known about the role of extreme, or specific, wind conditions (e.g. untypical change of wind-direction, very strong magnitudes, persistence of anomalous conditions for a

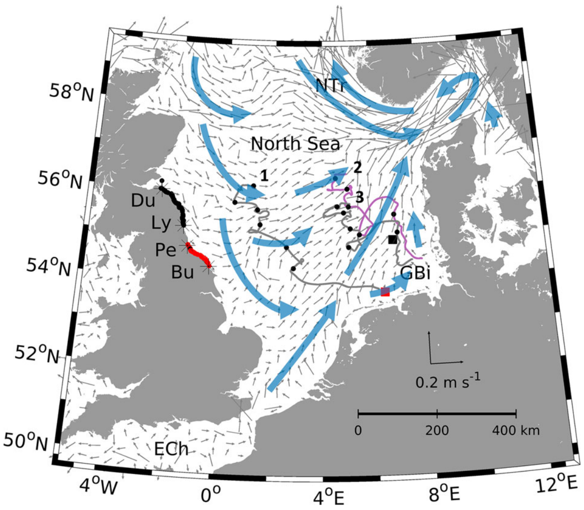

Figure 4.9.1. Mean surface currents (grey vectors) in 2018 in the area of the North Sea plotted on a grid with a resolution of ~30 km (product ref.: 4.9.1). Superimposed are schematic current patterns (blue arrows). The squares indicate the locations (red: Borkum Riffgrund, black: Sylter Außenriff) where wooden drifters have been released. The respective beaching locations between the towns (stars) Dunbar (Du), Lynemouth (Ly), Peterlee (Pe) and Burniston (Bu) are shown with smaller black and red symbols where the colour of the beaching locations relates to the colour of the release points. Grey/purple lines: the trajectories of three GPS drifters in 10-day intervals (black dots) from 24.02.2018 to 25.04.2018. The trajectories start in the German Bight and end at their respective numbers. ECh: English Channel, GBi: German Bight and NTr: Norwegian Trench.

long time), neither about the associated changes of the general circulation in the North Sea. To enable reliable future studies of the influence of extreme wind events on the North Sea circulation, the validation of the numerical models during such events is inevitable.

The North Sea is a shallow shelf sea with an average depth of ~90 m. Large areas of it are shallower than 30 m, and the whole water column there can be directly impacted by wind forcing as the upper Ekman layer can reach the bottom. The response to variable winds can thus change the circulation down to the bottom in a very short time (about one inertial period, i.e. about 15 h in this region). Short-periodic reversals are not untypical in this sea, because the circulation is essentially dominated by daily and semi-daily tidal periodicity. Whether pronounced reversals of the circulation could persist for very long times, is not well known. If they do, this would suggest a long-range displacement and mixing of large bodies of water. An improved knowledge on the non-typical transformations of the North Sea circulation is needed also for trajectory forecasts and many related activities, e.g. search and rescue operations (Röhrs et al. 2012), propagation of fish eggs, larvae and marine litter (Christensen et al. 2007; van der Molen et al. 2007; Gutow et al. 2018), or for optimising the use of the marine environment and preserving its environmental status (Emeis et al. 2015).

In the present study, we analyse the propagation pathways of surface water using surface drifters, which are advected by the Lagrangian current that includes the wave-induced Stokes drift, as well as the direct wind drag. Lagrangian tracking using data from an operational model is also performed.

4.9.2. Methods

The research methods are based on observations of three GPS and wooden drifters, as well as Lagrangian tracking. A total of 1600 wooden drifters (Schöneich-Argent et al. 2019; Stanev et al. 2019) were released during the research cruise HE503 of the RV Heincke (Figure 4.9.2). The first 800 wooden drifters were released on 24.02.2018 in the southern North Sea at approximately 53.11° N, 6.42° E

(a) (b)

Figure 4.9.2. 1600 wooden drifters were released on 24.02.2018 and 27.02.2018 during the research cruise HE503 of the RV Heincke (Figure 4.9.1). (a) The wooden drifter (message in English is on the back side: 'Help us understand the distribution of marine litter! Please report the number and position of this drifter to the University of Oldenburg'). (b) Floating drifters after the deployment at Borkum Riffgrund.

(Borkum Riffgrund, red square in Figure 4.9.1) which is situated northwest of the Dollart, i.e. in the Ems estuary. The second release of 800 wooden drifters was conducted on 27.02.2018 at approximately 54.97° N, 6.79° E (Sylter Außenriff, black square in Figure 4.9.1).

The wooden drifters are cut from solid, FSC-certified spruce wood, and measure 10 × 12 cm and 2 to 4 cm in height, respectively. Finders are asked to report the drifters via the project website (Aden and Stephan 2017). Hence, a message in German and English as well as a unique identification number are branded on either side (Figure 4.9.2a). Each report contains information on the drifter ID, the location and time of finding, as well as any additional comments that the finder may want to leave. More technical details and further information about stranding are given in Stanev et al. (2019).

GPS drifters (Meyerjürgens et al. 2019) have a cylindrical shaped housing (500 mm in length) made of polyvinyl chloride (PVC), which is divided into two parts (Figure 4.9.3). The upper part (140 mm in diameter) holds the positioning and transmission unit. The lower part (90 mm in diameter) contains a battery pack which powers the GPS transmitter, yielding an average battery life span of 4 months by transmitting the positions at an interval of 10 min. Four drag-producing cruciform wings are mounted directly to the lower part of the housing to reduce the direct windslip-induced motion to the drifter. Positions of the drifter were sampled with an accuracy of ~2.5 m.

Start and end positions and times are the only information known for the wooden drifters (Figure 4.9.1). The GPS drifter also provides the trajectory, but does not fully describe the circulation over the entire North Sea. Therefore, for the period of drifter observations, data from the CMEMS numerical model for the European Northwest Shelf (product ref. 4.9.1), which is based on version 3.9 of NEMO (Madec 2008) have been additionally used (see also O'Dea et al. 2012). The second set of data from operational modelling included Stokes drift velocities (product ref. 4.9.2). These are produced from the North-West European Shelf Wave Analysis and Forecast system using the WAVEWATCH III model (version 4.18; The WAVEWATCH III Development Group 2016).

Particle tracking was used to analyse the transport in the studied area and to support the observations from the GPS and wooden drifters. The model, which is known as OpenDrift (Dagestad et al. 2018), uses a 2nd-order Runge-Kutta scheme. Experiments were carried out 'offline' using data from the circulation and wave model, as well as 10 m winds. The horizontal diffusion is accounted for as described in Stanev et al. (2019). The calibration of the tracking model (weights of currents, Stokes drift and wind drag) using drifter observations is also described in their work.

4.9.3. Wooden drifters

Wooden drifters (product ref. 4.9.3) released within a distance of 40–120 km to the German coastline stranded at the east coast of England and Scotland (Figure 4.9.1). In total, 782 validated drifter reports (out of 1600 released drifters) were recorded between the time of deployment and 05.06.2018. All these reports were made along the British northeast coast (Figure 4.9.1). This is contrary to the 'canonic' circulation scheme described above. A simple explanation for this finding could be that easterlies persisted for a relatively long time after the release of the drifters. These events are known as the 'Beast from the East', a phrase used to describe cold conditions in the UK caused by easterly winds from the continent. The general wind direction

(a) (b)

Figure 4.9.3. One of the GPS drifters (a) and their deployment (b) during the RV Heincke cruise HE503 at Borkum Riffgrund (Meyerjürgens et al. 2019).

was mostly towards the west with peak values of up to 22.6 m s^{-1}. The time period 19.02.2018 to 15.04.2018 exhibited the strongest easterlies. Ocean surface velocities responded to the wind speeds which resulted in a general westward ocean surface circulation accompanied by westward Stokes drift velocities.

The calibration of wind drag for the wooden drifters was conducted by comparing the simulated stranding

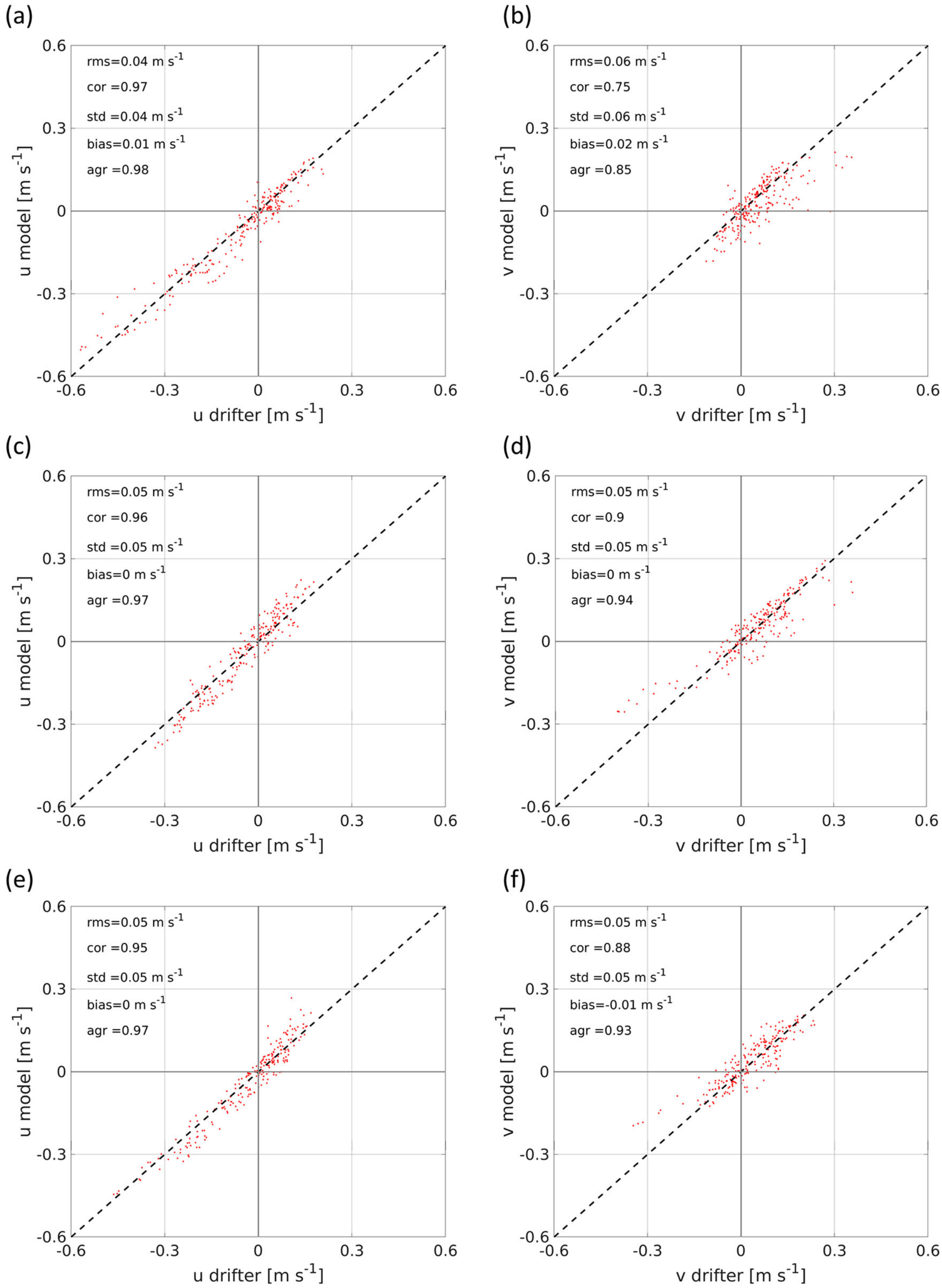

Figure 4.9.4. Validation of model surface currents against observations from GPS drifters. Top, middle and bottom panels correspond to drifters 1, 2, and 3, respectively. Left panels: zonal velocity component (u), right panels: meridional velocity component (v). The dashed line is the diagonal and the optimal location of the dots.

positions with the real ones and finding the appropriate coefficient for which the difference between stranding positions of real and simulated drifters was minimal. The additional contribution of the wind to the current and Stokes drift is estimated at ∼2.5%. The pathways of simulated wooden drifters (see their stranding positions in Figure 4.9.1) demonstrated that their movement is dominated by several strong eastward wind events followed by several stagnation periods. The stranding positions of model drifters with characteristics of the wooden drifters from the two releases coincided almost perfectly with the observations (Stanev et al. 2019).

4.9.4. GPS drifters

The trajectories of the three grey/purple (grey solid lines in Figure 4.9.1) complement the propagation patterns of floating objects (product ref. 4.9.4). The strong easterly wind conditions resulted in a substantial westward displacement, opposite to the canonic pattern. During the two months considered here, the drifters travelled 790, 722, and 668 km, respectively.

The experiments with Lagrangian tracking showed that the GPS drifter can be considered to be primarily driven by the Eulerian currents and Stokes drift. The influence of wind on the simulated drifters was found to be ∼0.3% of the 10 m winds. This result is in very good accordance with Meyerjürgens et al. (2019) who determined a direct wind drag of 0.27% from the drifter surfaces above and below water.

A validation experiment is presented in the following by comparing the observed and modelled data. Surface velocity was computed using observed positions and times of GPS drifters. For each observed location and time, model data was extracted and compared with observations by linear interpolation. Besides the root mean square error (*rms*), linear correlation (*cor*), standard deviation (*std*) and *bias*, the skill of the calibrated Lagrangian model was also estimated by the index of agreement (*agr*)

$$agr = 1 - \frac{\sum_{i=1}^{n}(P_i - O_i)^2}{\sum_{i=1}^{n}(|P_i - \bar{O}| + |O_i - \bar{O}|)^2},$$

where n is the number of observations (index i) of the observed (O) or model (P) data and the overbar is the temporal mean (Willmott 1981). The *agr* was 0.98/0.85, 0.97/0.94, and 0.97/0.93 for the zonal/meridional velocity component, respectively, of which the latter is slightly worse. Seeding experiments over the entire model area with particles having the characteristics of the GPS drifters showed that many of the particles covered distances of more than 400 km, which is ∼2/3 of the zonal extension of the North Sea. The results of validation of surface currents from the operational model against observations (Figure 4.9.4) are shown separately for the zonal (left panels) and meridional velocity (right panels) components. Statistics of agreement between observed and modelled data (Eulerian currents, Stokes drift and wind) are shown in each panel for the respective dataset. The conclusion is, that the model gives accurate estimates of surface currents even for these extreme wind conditions. For comparison, during regular westerly winds, Ricker and Stanev (2020) found similar statistics for the German Bight and Johnson et al. (2007) for the world ocean. However, even in deeper water Stokes drift cannot be neglected during extreme wind events. Further analyses reveal, that the model performance in terms of velocity direction is almost the same for westerly and reversed wind conditions emphasising the good model performance. This validation experiment is of great value, because so far not many direct observations exist over large areas in the North Sea.

4.9.5. Conclusions

Drifter releases were conducted in early 2018 in German waters using three drifters equipped with Global Positioning System devices, as well as 1600 wooden drifters. Some of the wooden drifters stranded in different coastal areas, a large number of them on the UK coast. These unique observations appeared successful, because individuals finding the stranded objects gave their valuable feedback about the position and time of drifter findings. This public participation in scientific research further demonstrated the usefulness of citizen science.

An anomalous propagation of the drifters was observed. Some of them reached the British coast in just a few weeks. Using observed and numerically simulated drifters allowed us to calibrate the Lagrangian model in a way to adequately resolve the wind drag. This further enabled us to reconstruct the propagation pathways during the period of strong easterlies in early 2018.

The agreement between direct observations of surface currents and the CMEMS products demonstrates that the modelled data are of good quality. Furthermore, it can be concluded that the model replicates ocean dynamics well even under extreme weather conditions.

Acknowledgements

The authors are grateful to all people finding and reporting wooden drifters. Data from CMEMS portal for the European Northwest Shelf have been used. This work was carried out within the project ‘Macroplastics

Pollution in the Southern North Sea – Sources, Pathways and Abatement Strategies' (grant no. ZN3176), funded by the Ministry of Science and Culture of the German Federal State of Lower Saxony. DFKI acknowledges financial support by the MWK through 'Niedersachsen Vorab' (ZN3480).

Section 4.10. Coastal ocean variability related to the most extreme Ebro River discharge over the last 15 years

Authors: Inmaculada Ruiz-Parrado, Ana Genua-Olmedo, Emma Reyes, Baptiste Mourre, Paz Rotllán, Pablo Lorente, Marcos García-Sotillo, Joaquín Tintoré

Statement of main outcomes: Extreme rivers discharges contribute to enhance the shelf/open ocean fronts and the associated currents, being also one of the crucial factors controlling sediment supply and dispersal, impacting in turn water quality in highly sensitive environments. The most extreme Ebro river freshwater discharge event recorded over the past 15 years was observed in April 2018 at the Tortosa gauge in the Western Mediterranean. This freshwater-pulse discharge had a high impact on the surface current patterns which was captured by many different observational sources provided by the Copernicus Marine Environment Monitoring Services (CMEMS hereinafter): three-site High Frequency Radars (HF Radar, hereinafter) around the Ebro delta (CMEMS In Situ TAC) and satellite-derived surface Chlorophyll-*a* (CMEMS Ocean Color TAC) as well as satellite-derived suspended matter (Sentinel 2-ESA). Furthermore, the intercomparison of various simulations from CMEMS Monitoring Forecasting Centres (CMEMS MFCs) and other regional ocean models with increased resolutions highlighted the advantages of downscaling and the importance of implementing realistic runoff forcing to properly represent the river plume and its impacts on the coastal circulation.

Products used

Ref No.	Product name & type	Documentation
4.10.1	OCEANCOLOUR_MED_CHL_L4_NRT_OBSERVATIONS_009_041	PUM: https://resources.marine.copernicus.eu/documents/PUM/CMEMS-OC-PUM-009-ALL.pdf QUID: https://resources.marine.copernicus.eu/documents/QUID/CMEMS-OC-QUID-009-038to045-071-073-078-079-095-096.pdf
4.10.2	INSITU_MED_NRT_OBSERVATIONS_013_035	PUM: https://resources.marine.copernicus.eu/documents/PUM/CMEMS-INS-PUM-013.pdf QUID: https://resources.marine.copernicus.eu/documents/QUID/CMEMS-INS-QUID-013-030-036.pdf
4.10.3	GLOBAL_ANALYSIS_FORECAST_PHY_001_024	PUM: https://resources.marine.copernicus.eu/documents/PUM/CMEMS-GLO-PUM-001-024.pdf QUID: https://resources.marine.copernicus.eu/documents/QUID/CMEMS-GLO-QUID-001-024.pdf
4.10.4	IBI_ANALYSIS_FORECAST_PHYS_005_001	PUM: https://resources.marine.copernicus.eu/documents/PUM/CMEMS-IBI-PUM-005-001.pdf QUID: https://resources.marine.copernicus.eu/documents/QUID/CMEMS-IBI-QUID-005-001.pdf
4.10.5	MEDSEA_ANALYSIS_FORECAST_PHY_006_013	PUM: https://resources.marine.copernicus.eu/documents/PUM/CMEMS-MED-PUM-006-013.pdf QUID: https://resources.marine.copernicus.eu/documents/QUID/CMEMS-MED-QUID-006-013.pdf
4.10.6	ESA-Copernicus Sentinel 2A	WEB: https://sentinels.copernicus.eu/web/sentinel/missions/sentinel-2/data-products
4.10.7	INSITU_GLO_UV_NRT_OBSERVATIONS_013_048	PUM: https://resources.marine.copernicus.eu/documents/PUM/CMEMS-INS-PUM-013-048.pdf QUID: https://resources.marine.copernicus.eu/documents/QUID/CMEMS-INS-QUID-013-048.pdf Data source: HF Radar Ebro: http://opendap.puertos.es/thredds/catalog/radar_local_deltaebro/catalog.html
4.10.8	A027 Tortosa River gauge	WEB: http://www.saihebro.com/saihebro/index.php?url=/datos/ficha/estacion:A027
4.10.9	Western Mediterranean Operational Model (WMOP)	WEB: http://www.socib.es/?seccion=modelling&facility=forecast_system_description REFERENCES: http://socib.es/?seccion=modelling&facility=research
4.10.10	Ebro River basin and tributaries (Ebro Hydrographic Confederation)	WEB: http://iber.chebro.es/geoportal/
4.10.11	2010 CORINE (the Coordination of Information on the Environment programme initiated by the EU) Habitats distribution maps in the Ebro Delta (Department of Planning and Sustainability of the Generalitat de Catalunya)	WEB: https://territori.gencat.cat/ca/01_departament/12_cartografia_i_toponimia/bases_cartografiques/medi_ambient_i_sostenibilitat/bases_miramon/territori/29_habitats_1_5000_perfulls/ REFERENCES: https://land.copernicus.eu/user-corner/technical-library/tech40add.pdf
4.10.12	Sistema de Apoyo Meteorológico y Oceanográfico de la Autoridad Portuaria (SAMOA)	REFERENCES: https://upcommons.upc.edu/bitstream/handle/2117/116102/21977687.pdf;jsessionid=F3CEFB5D06F92BA3CD4F4F890295A95F?sequence=3

The coastal ocean, here defined as the region extending from the coast to the continental shelf break, is a highly variable environment that provides direct benefits to society, being subject to continental, atmospheric and ocean forcings. In this context, CMEMS models and in-situ data products, as well as other complementary datasets, have been used to characterise the impact of an extreme river discharge on the local shelf circulation. The area of interest is the Western Mediterranean Sea