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The Influence of Topography on Wind-induced Hydrodynamics in Cullera Bay

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ABSTRACT

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Cullera Bay is an example of a multi-source polluted coastal environment. The water quality in the bay is highly affected by pressure from major agricultural and industrial activities in the river basin. Fresh water is taken from the river and later returned, loaded with pesticides and fertilizers. Partially treated wastewater from riverbank towns and industries is discharged into the lower reaches of the river. This mechanism contributes to river pollution. The dramatic increase in Cullera's population during the summer tourist season and the limited capacity of the local water treatment plant also make it difficult to dispose of domestic wastewater, some of which is discharged untreated into the river or directly into the sea through a marine outfall. This freshwater input from the Júcar River and the marine outfall produces a highly polluted estuarine plume in the coastal region (with significant salinity gradients and complex spatial patterns), which is highly influenced by the hydrodynamics of the bay. Because of the discharge from the Júcar River, the sewage from the marine outfall and the particular geomorphological features of Cullera Bay, this plume may play a significant role in defining and supporting different aspects of the socioeconomic environment in neighboring areas, especially those related to water quality. However, the mean water quality in the bay does not depend only on the surface circulation pattern but also on the overall marine circulation in the water body, where the local bathymetry has more relative influence. Therefore, it is important to have the tools and capabilities needed to monitor and characterize the actual pollutant dispersion drivers (wind and hydrodynamics) to assess their influence at local and regional levels. This paper presents the characterization of the wind field and circulation pattern in Cullera Bay using data acquired during seven field campaigns. The analysis shows that there is strong seasonal behavior in the wind field, ranging from daily breeze patterns to persistent offshore winds. Although the wind field varies greatly throughout the year, the overall pattern mainly consists of daily breezes. However, the hydrodynamic field has proved to be very complex and, with a few exceptions, poorly correlated with the wind-field pattern. This poor correlation may be due to a nonhomogeneous wind field in Cullera Bay caused by a nearby mountainous barrier. Despite the complexity of the hydrodynamic field in each campaign, the overall analysis of the nearshore current pattern shows a strong "boundary condition" influence that mainly follows the isobaths rather than the wind field. The influence of the topography on the wind and currents may have significant implications for quantifying the relative importance of pollutant sources that harm the quality of the water in Cullera Bay.

ADDITIONAL INDEX WORDS: *Near shore circulation, field campaigns, estuary, Mediterranean Sea.*

INTRODUCTION

Water is considered polluted when it is adversely affected by the addition of large amounts of materials and becomes unfit for its intended use. These materials can be delivered to the water body directly (point source) or through environmental changes, like fertilizers carried into a stream by rain in the form of runoff (nonpoint source). Excessive levels of nutrients in coastal waters may overstimulate the growth of aquatic plants and algae, which increases the risk of the waterway becoming blocked and reduces the penetration of light to deeper waters. Moreover, when organic material breaks down, bacterial decomposition processes use up the dissolved oxygen, which is extremely harmful to aquatic organisms, as it affects their ability to breathe. Many organisms of this type may die when the dissolved-oxygen level drops below a critical threshold (2 to 5 parts per million) and disrupts the food chain.

Another major source of pollution is the uncontrolled input of pathogen microorganisms, mainly bacteria, viruses and protozoa. This type of pollution is especially risky to human health, as it can cause typhoid fever, dysentery, respiratory and skin diseases, etc. Most pollutants enter coastal waters from one of the following sources: (i) urban wastewater (untreated sewage, storm drains, septic tanks, *etc.*), (ii) agriculture (runoff from farms, etc.) and (iii) industry (KRANTZ and KIFFERSTEIN, 2004).

When polluted or eutrophic fresh water (emanating from outfalls or estuaries) reaches the sea, it becomes a well-defined plume over a wide coastal region. Like estuaries, freshwater plumes are highly dynamic regions with significant salinity gradients and complex spatial patterns (SIERRA *et al.*, 2002). They play a significant role in defining and supporting different aspects of the socioeconomic environment in neighboring areas. The water quality of a coastal area is directly related to the efficiency of the mixing processes of the highly polluted (and/or eutrophic) continental/urban wastewaters and the deeper offshore waters. The mixing processes that govern the water quality in coastal waters are mainly driven by the tidal range (when present) and the coastal circulation caused by the transfer of momentum from the wind to the upper layers of the coastal water body. Wave-induced circulation may be very important, but only in a relatively narrow stretch very close to the shoreline.

Therefore, it is important to have the necessary tools and capabilities to monitor the freshwater plume and predict its behavior in order to assess its influence at local and regional levels. Thus, the characterization of wind-induced hydrodynamics in the nearshore zone is important in understanding the mixing and dilution processes of nutrients and pollutants in coastal waters.

Cullera Bay is a typical multi-source polluted coastal environment. Its waters receive discharges from the Júcar River and from a shallow marine outfall. The water quality in the bay is strongly affected by the pressure exerted on the river basin by agriculture and industry. Fresh water is taken from the river and later returned, loaded with pesticides and fertilizers. Partially treated wastewater from riverbank towns and industries is discharged into the lower reaches of the river. This mechanism contributes to river pollution.

The dramatic increase in Cullera's population during the summer tourist season and the limited capacity of the local water treatment plant also make it difficult to dispose of domestic wastewater, some of which is discharged untreated into the river or directly into the sea through the marine outfall. As a result of the nutrient input from both sources, the bay is usually eutrophic (GONZÁLEZ DEL RÍO, 1986; SOLER *et al.*, 1988). This harms the quality of its waters and causes constant concern regarding important economic sectors such as tourism and fisheries. The freshwater discharge from the river and the marine outfall, combined with the shallowness of the bay (which allows benthonic nutrients to be released into the water column), causes major environmental problems related to the quality of the bay's waters. Because Cullera Bay is semi-enclosed, it is susceptible to pollution and poor water quality. These problems can jeopardize local fishing and tourism industries, since high levels of microbiological pollution may represent a public-health risk. This paper aims to provide a better understanding of the wind-induced circulation in Cullera Bay and the influence of the topography on the currents. The overall aim of this project is to analyze the spatial and temporal distributions of salinity, nutrients and chlorophyll-*a* in Cullera Bay for one year.

STUDY AREA

Cullera Bay and the Júcar River Estuary, located on the Spanish Mediterranean coast (0°13′ → 0°15′ W and 39°08′ → 39°12′ N), is a shallow basin with a maximum depth of around 10 m (Figure 1). Cullera Cape, a rocky mass that protrudes into the sea, limits the bay to the north, whereas the south end of the bay is open. It is a microtidal environment in which the net river and marine outfall discharges are highly dependent on the season of the year. The dynamics in the bay mainly depend on local sea and weather conditions.

Particulate matter carried by the river and the marine outfall continues to play a role in relevant physical and biochemical processes in the sea beyond the river mouth. During northerly wind events, the northern part of this semi-enclosed area is seriously affected by the detritus discharged by the river and the marine outfall. A large orographic feature (Monte de Oro) is located north of the Júcar River and the landscape is flat to the south of the river.

FIELD CAMPAIGNS

To improve the knowledge of the natural processes related to water quality in Cullera Bay, nine field campaigns were carried out (as a part of the European ECOSUD project) from June 2002 to July 2003 (Table 1). Water quality parameters were measured under different forcing conditions and wastewater-discharge scenarios.

The field campaigns included five different kinds of measurements:

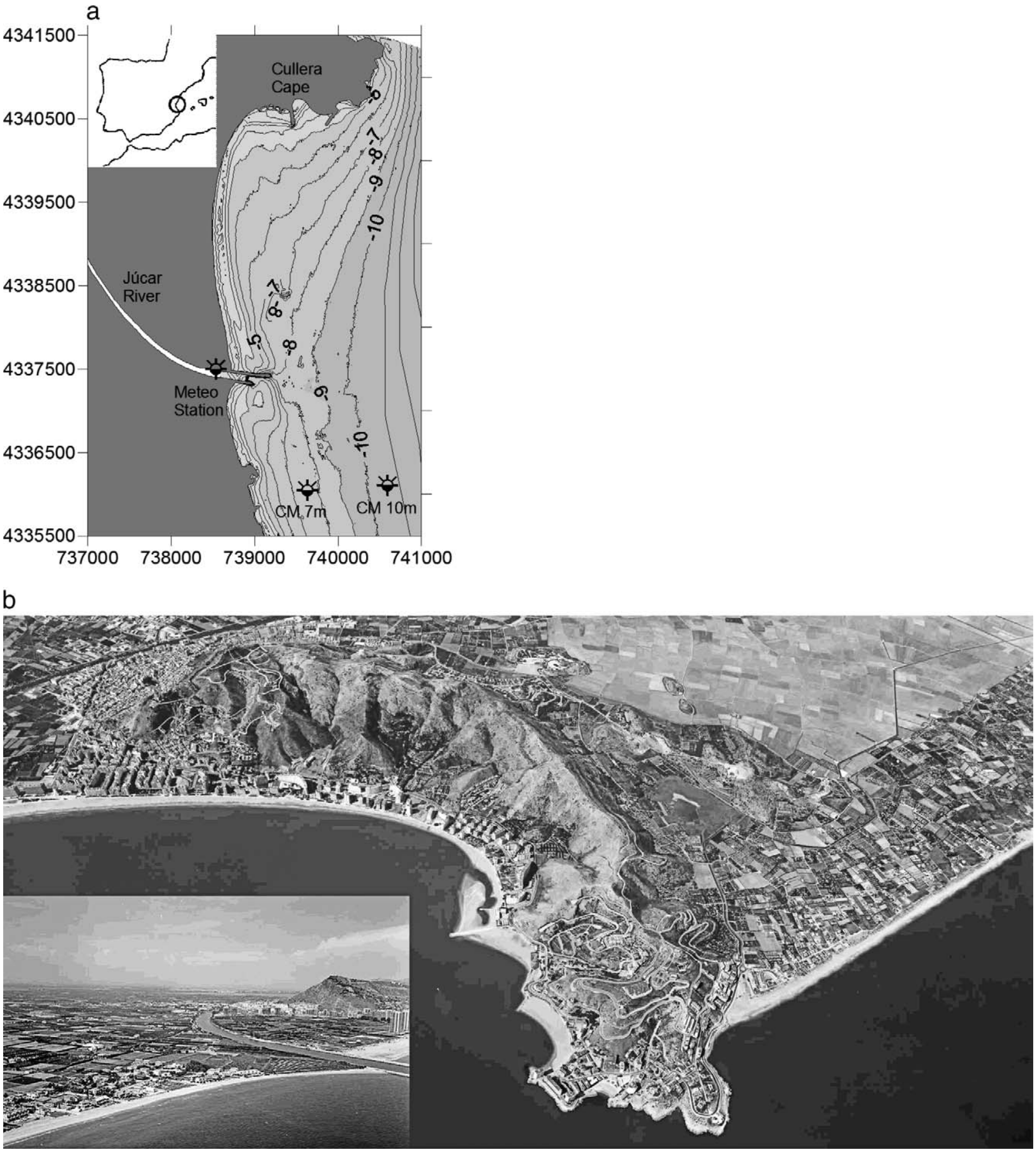
(i) Profiles of water-quality parameters (CTD and a multi-parameter probe).
(ii) Water sampling (for salinity, chloride, suspended solids, chlorophyll-*a,* ammonium, nitrate, nitrite, soluble reactive phosphorous, total dissolved phosphorous, total phosphorous and silicate). In some samples, biological oxygen demand and bacterial pathogens—total and fecal coliforms and fecal streptococci—were also analyzed.
(iii) Sediment samples (cores collected by scuba diving and dredging). The parameters measured were sediment oxygen demand, organic matter, total nitrogen and total phosphorous.
(iv) River flow velocity was measured with an ADP current meter at the river mouth and 2 km upstream. The circulation field was measured with moored current meters at depths of 7 and 10 meters (Figure 1). These currentmeters (CM 7 and CM 10 hereinafter) were moored at a relative depth of ($z/h \approx 1/3$), where h is the total depth and z the elevation above the bottom.
(v) Wind conditions. Speed and direction were used to calculate wind stresses as a driving mechanism for the marine currents.

The wind field and marine currents were not measured in ECOSUD 2 and ECOSUD 4.

RESULTS

River Flow

The waters of the Júcar River have high levels of nutrient concentration due to intensive agricultural exploitation in the river's drainage basin and the discharge of partially treated domestic and industrial wastewater from upstream towns. The river and the marine outfall of Cullera are the main sources of nutrient input into Cullera Bay. The Júcar River



Figures 1a and b. Cullera Bay bathymetry [UTM coordinates] and orographic features. The meteorological station is located near the river. The current meters at depths of 7 and 10 m (CM 7 m and CM 10 m respectively) were moored south of the river mouth.

has a typical Mediterranean flow pattern, with higher flows from October to May and lower rates during the summer.

The statistical analysis of the low river flow from 1911 to 1997 shows that the mean daily flow rate was under 5 m^3/s 53% of the time and only exceeds 20 m^3/s 12% of the time. The maximum monthly average flow rate, about 16 m^3/s, typically occurs in February while the minimum flow rate, about 4 m^3/s, occurs in July and August, the driest months (MÖSSO,

Table 1. *Field campaigns at the Júcar Estuary and Cullera Bay (* no wind or current measurements).*

Campaign	Dates
ECOSUD 1	June 20–25, 2002
ECOSUD 2*	July 9, 2002
ECOSUD 3	July 24–27, 2002
ECOSUD 4*	August 5–6, 2002
ECOSUD 5	September 4–5, 2002
ECOSUD 6	November 20–21, 2002
ECOSUD 7	February 8–9, 2003
ECOSUD 8	April 23–24, 2003
ECOSUD 9	July 22–23, 2003

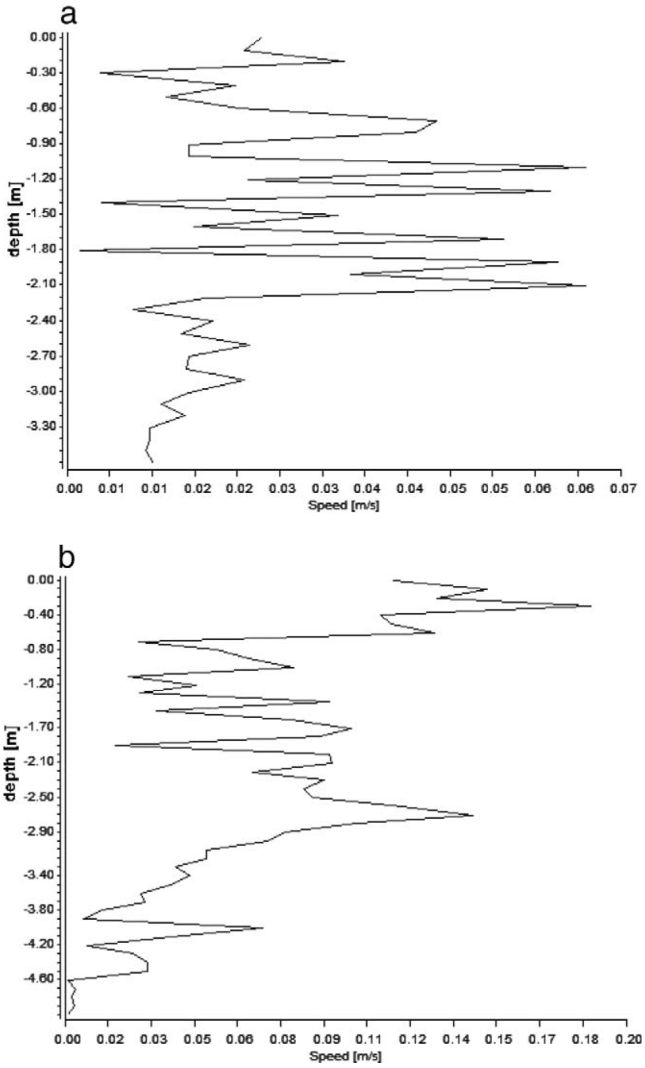


Figure 2. River flow velocity measurements at the weir (top) and river mouth (bottom) respectively.

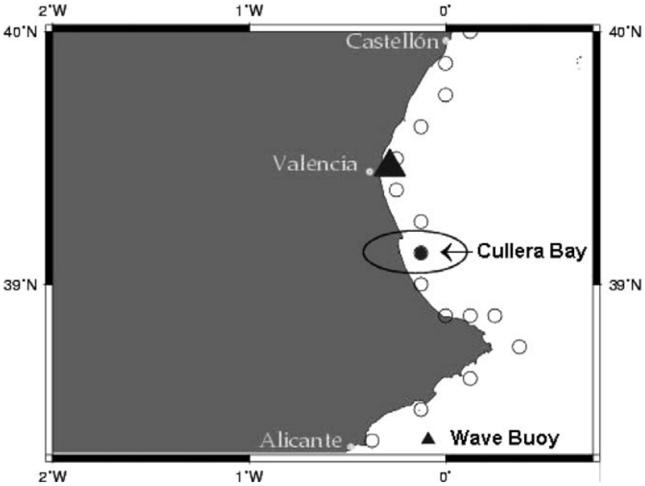


Figure 3. Location of WANA point 2047033, close to Cullera Bay (from Puertos del Estado).

2003; MESTRES *et al.*, 2006). As expected with these river flow values, the velocity measured at the river stations (weir, approximately 2 km upstream from the river mouth) and at the river mouth are extremely low (Figure 2). At the weir, the maximum and mean values are 6.0 cm/s and 2.4 cm/s respectively. At the river mouth, the maximum and mean values are 20.0 cm/s and 6.3 cm/s respectively. Thus, the influence of the river's momentum on the overall hydrodynamics in Cullera Bay is negligible (except during extreme flooding events).

Waves

No wave measurements were taken during the ECOSUD field campaigns. To assess the role of waves in the general circulation pattern in Cullera Bay, the wave field was estimated using the wave forecast system of *Puertos del Estado* (the Spanish port authority), which uses the WAM and WAVEWATCH models, and the wind field provided by the National Meteorological Institute of Spain. The wave forecast was for WANA point 2047033 [4334657.984, 748545.309 UTM], approximately 10 km from the Júcar River mouth (Figure 3). These data indicate that in 2002 the significant wave height exceeded 1 m 10.8% of the time (40 days) and 1.5 m only 3.7% of the time (14 days). Since most of the incoming waves were from the NE (23%) and ENE (15%), Cullera Cape shelters the bay against this wave action. Other major contributions (Figure 4a) are from the E (10%), ESE (9%), SE (7%) and NNE (5%). In 2003, the significant wave height exceeded 1 m 20% of the time (73 days) and 1.5 m only 9% of the time (32 days). Most of the incoming waves came from the NE (30%) and ENE (18%), with additional contributions (Figure 4b) from the E (12%), ESE (9%), SE (6%) and NNE (4%).

These data suggest that waves play a secondary role in the general circulation pattern in Cullera Bay and are only important in a narrow zone, close to the shoreline.

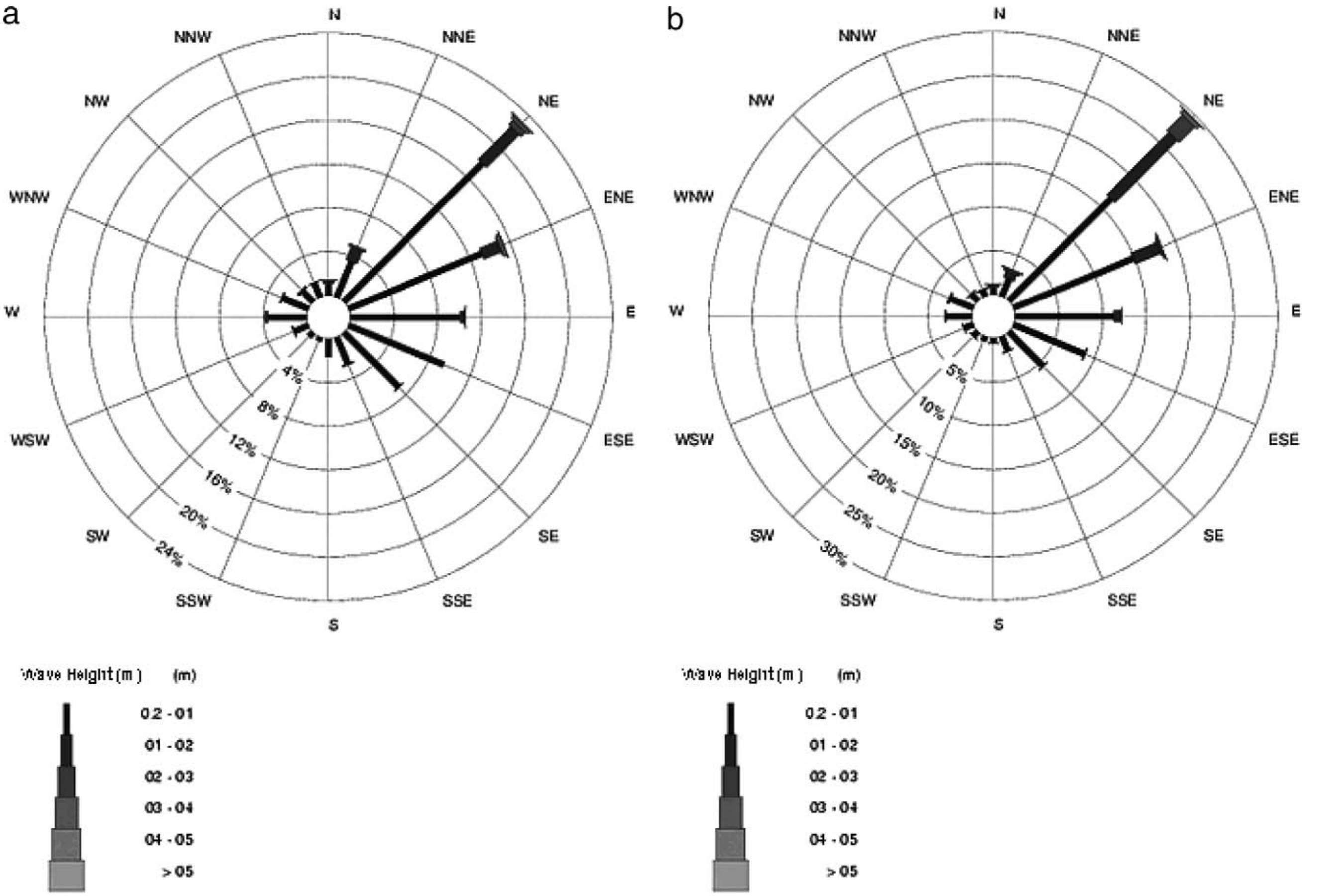


Figure 4. Wave height close to Cullera Bay (from Puertos del Estado) in 2002 and 2003 respectively.

Wind Field

This analysis suggests that the hydrodynamics in Cullera Bay are wind-induced (Mösso *et al.*, 2003; González del Río, 1986; Soler *et al.*, 1988). Therefore, wind speed and direction must be characterized. During the ECOSUD field campaigns, the wind field was measured by an Aanderaa meteorological station located near the river mouth (738534.41 longitude, 4337501.6 latitude [UTM] in Figure 1) approximately 3 m above the mean sea level. The wind velocity classes considered are based on the Beaufort scale in m/s. The wind field measurements showed marked seasonal behavior. During the ECOSUD 1 field campaign, the wind blew mainly from the SE, ESE and E, with maximum and mean velocities of 4.0 m/s and 2.38 m/s, with 72.7% of the measurements between 1.5 and 3.3 m/s. The virtual net displacement was 74.863 km towards the WNW (293°) in 11 h.

In ECOSUD 3, the wind field consisted of daily breezes (Figure 5) blowing during the day from the ESE (3.3 to 7.9 m/s) and at night mainly from the NW and WNW (0.2 to 3.3 m/s).

The mean wind velocity was 2.74 m/s and the net displacement was 269.07 km towards the WNW (288°) in 47.08 h. This wind field is representative of the average wind behavior (as discussed below).

During ECOSUD 5, the wind field was quite similar to that observed in ECOSUD 3, with daily breeze behavior. The maximum gusts were measured during the day (3.3 to 7.9 m/s) from the ESE and E. At night, the wind mainly blew from the opposite quadrant, *i.e.*, WNW and W (0.2 to 3.3 m/s). The main difference between the wind data for ECOSUD 3 and ECOSUD 5 was a non-negligible contribution from the NE (approximately 15.5% of the measurements had gusts of 1.5 to 3.3 m/s). The mean velocity was 2.74 m/s and the net displacement was 174.756 km towards 270° in 38.92 h.

ECOSUD 6 presented atypical behavior (Figure 6), which was not observed in the other field campaigns. The wind field blew constantly from the W, WNW and WSW, reaching velocities of 10.5 m/s. The mean velocity was 2.74 m/s. The net displacement was 541.838 km towards 89° in 60.67 h.

As in ECOSUD 6, the wind field measured during ECOSUD 7 had a strong land-to-sea component, mainly from the W, WNW and WSW, but also a non-negligible contribution from the NW, SW and E and NE. The main difference from ECOSUD 6 was the speed of the gusts, since the mean wind velocity was 0.83 m/s. Only 3.1% of the measurements re-

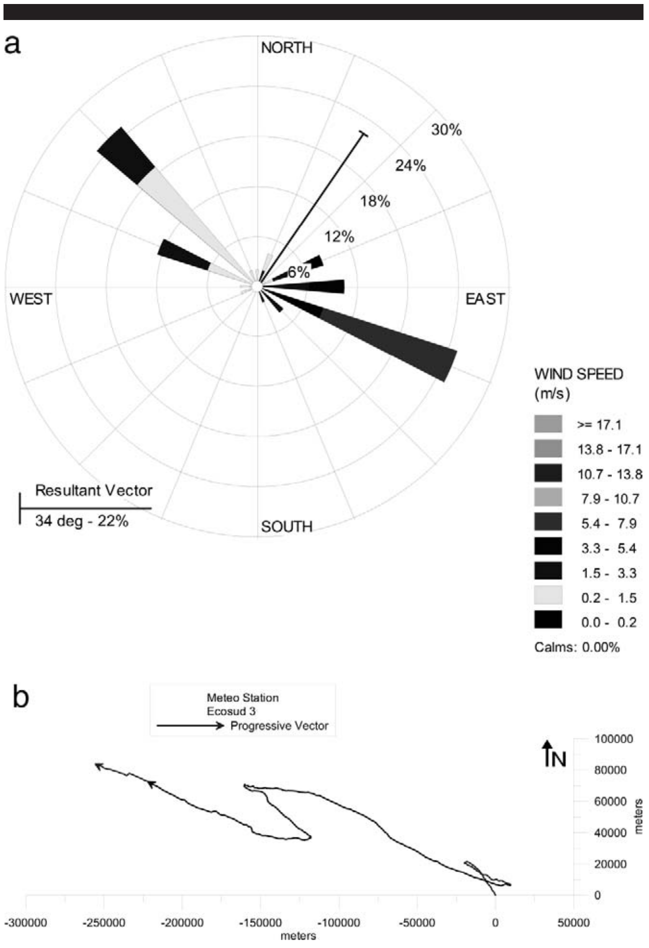


Figure 5. ECOSUD 3 wind field.

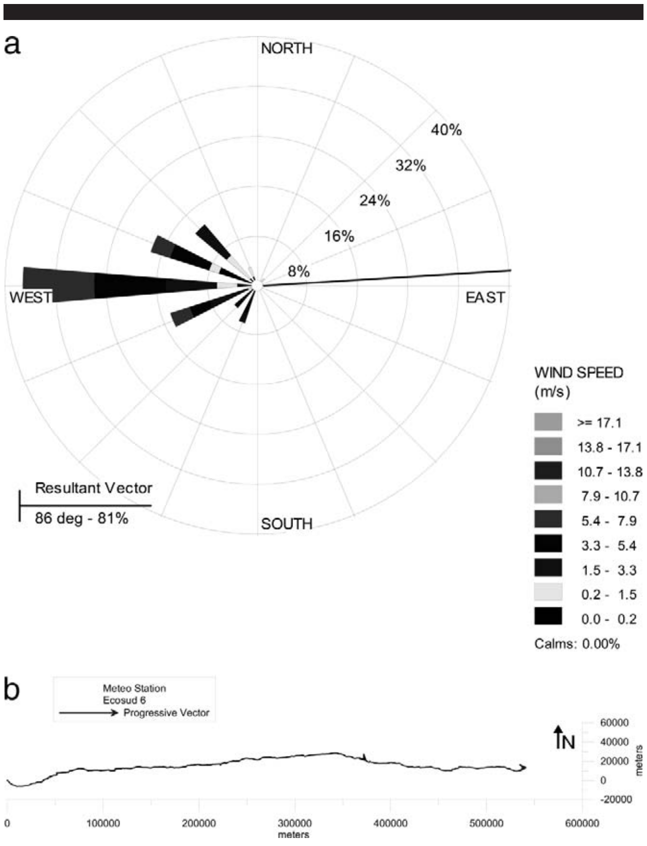


Figure 6. ECOSUD 6 wind field.

corded velocities between 3.3 and 5.9 m/s, whereas 40% of the velocities were between 0.0 and 0.2 m/s, 38.5% were between 0.2 and 1.5 m/s and 18.5% were between 1.5 and 3.5 m/s. The net displacement was 78.537 km towards 123° in 64.33 h.

During ECOSUD 8, the wind field presented daily breeze behavior, except for a short period (approximately 15 h) in which the wind rolled from WNW to NW. Most of the velocities measured (89.9%) were between 0.2 and 3.3 m/s, with a mean velocity of 2.56 m/s. The net displacement was 117.022 km towards 235° in 88.17 h.

In ECOSUD 9, although daily breeze behavior was present, the highest velocities were from the offshore wind (ENE, E and ESE) recorded during the day (up to 48.6% were between 1.5 and 3.3 m/s), with a mean velocity of 15.13 m/s. The net displacement was 188.204 km towards 243° in 70.67 h.

Hydrodynamic Field

Current measurements revealed the complexity of the hydrodynamic field in Cullera Bay.

The shoreline is oriented almost N-NNW to S-SSE, but the bathymetry is quite irregular. The mean slope of the beaches south of the river mouth is 0.0070, for the beaches north of the river mouth it is 0.0061, for the beaches close to the cape it is 0.0051 and at Cullera Cape it is 0.0229. Taking into account the geomorphological features of Cullera Bay—the mountains form a barrier to the wind and the cape acts as a barrier to the currents (Figure 1)—and the fact that the wind field is the main hydrodynamic driver, a strong topographic influence on the circulation pattern in the bay was expected.

The hydrodynamic field measured during ECOSUD 1—the only campaign in which the wind measurements were smaller than the current measurements—had strong S and SE components (Figure 7). Both current meters measured similar velocities, although slightly higher for the deeper current meter (as expected, since the bottom influence is greater in shallower water columns). The mean velocity at CM7 was 6.19 cm/s, obtained from a 31.83 h time series, with a net displacement of 5.304 km towards the SSE (163°). At CM10, the mean velocity was 6.68 cm/s, obtained from a 31.17 h time series, with a net displacement of 5.687 km towards the SSE (159°).

The behavior of the hydrodynamic field observed during ECOSUD 3 was the opposite to that of ECOSUD 1. Of all the campaigns (Figure 8), this one had the most clearly defined northward pattern (more so for the deeper current meter). The mean velocity at CM7 was 4.5 cm/s, obtained from a 31.5 h time series, with a virtual net displacement of 4.073 km towards the N (5°). The mean velocity at CM10 was 6.98 cm/

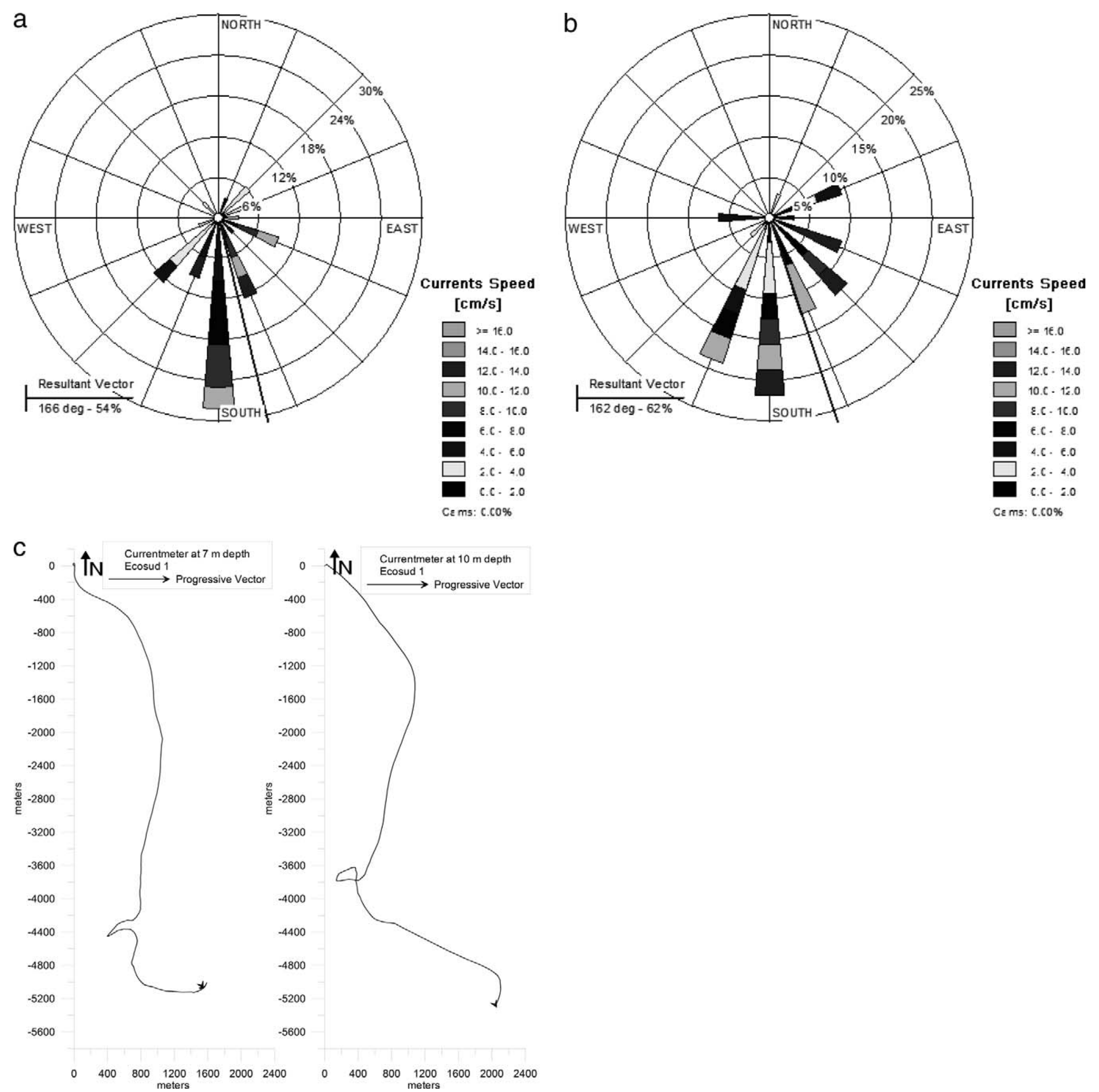


Figure 7. ECOSUD 1 hydrodynamic field.

s, obtained from a 31.83 h time series, with a virtual net displacement of 7.199 km towards the N (359°).

The currents measured during ECOSUD 5 presented a main N component, although a non-negligible E component was present at the beginning and end of the measurements (with an incipient reverse in the virtual trajectory at the end of the progressive vector). The mean velocity at CM7 was 7.25 cm/s, obtained from a 12.17 h time series, with a virtual net displacement of 2.778 km towards the NNE (21°). The mean velocity at CM10 was 12.32 cm/s, obtained from a 12.17 h time series, with a virtual net displacement of 4.190 km towards the NE (39.5°).

The hydrodynamic measurements from ECOSUD 6 had by far the most irregular and unsteady pattern (Figure 9). The velocity at CM7 had NNW, S and NNE components, while CM10 mainly had NW, NNW, WNW and W components. Because of these distributions, the progressive vectors had a very irregular path, with a major reversal in the current at

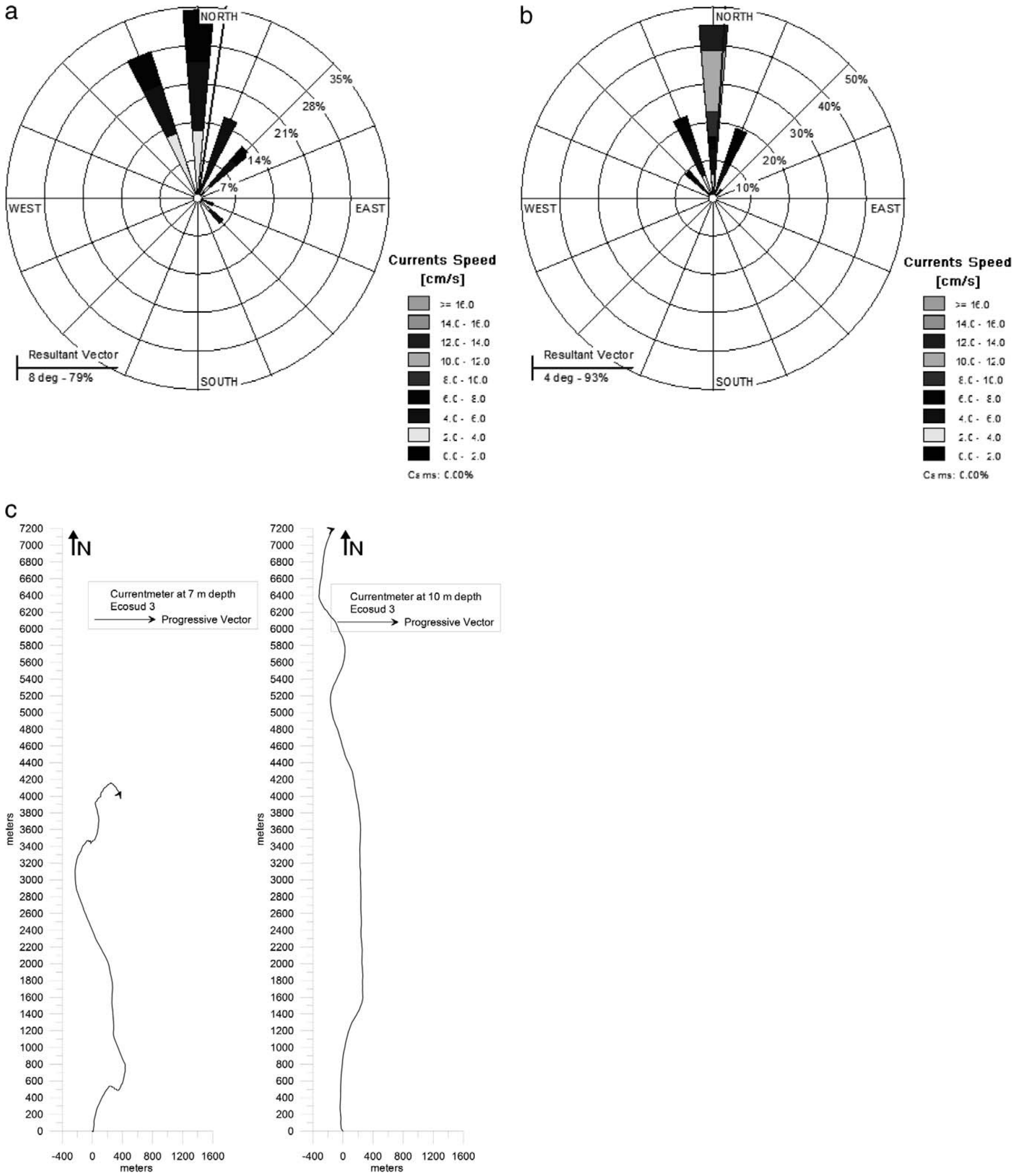


Figure 8. ECOSUD 3 hydrodynamic field.

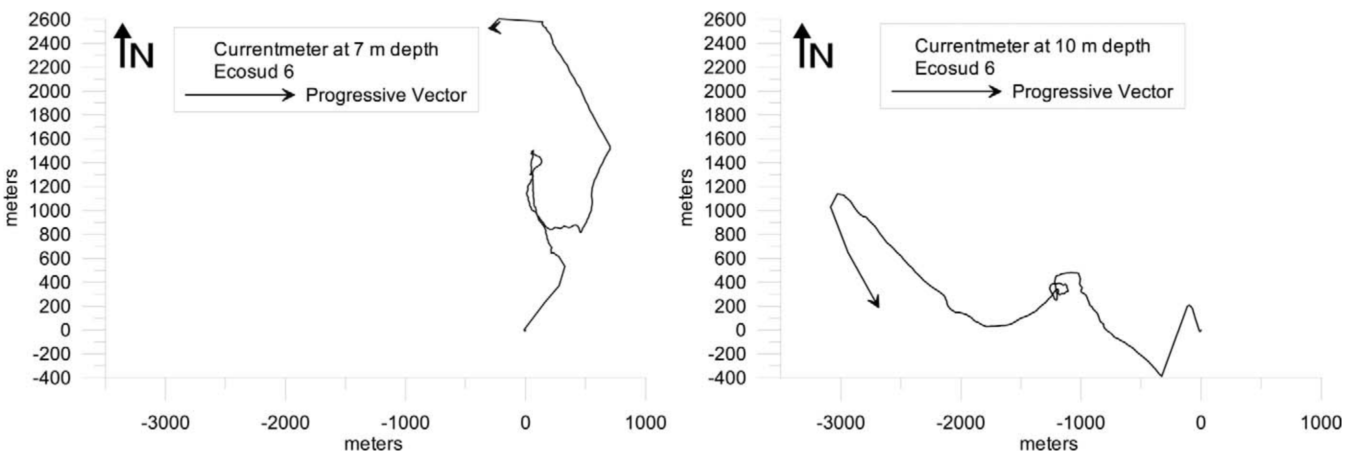


Figure 9. ECOSUD 6 hydrodynamic field.

CM7 and even a knot-type eddy in the current at CM10. The mean velocity at CM7 was 4.89 cm/s, obtained from a 34.33 h time series, with a net virtual displacement of 2.543 km towards the N (353°). The mean velocity at CM10 was 4.23 cm/s, obtained from a 34.33 h time series, with a net virtual displacement of 2.699 km towards the W (274°). It is interesting to highlight that the most "erratic" hydrodynamics corresponded to the steadiest wind (Figure 6).

The hydrodynamic field observed in ECOSUD 7 was quite intense. For the current meter at 7 m depth, most of the higher-speed gusts (38% of the measurements above 16 cm/s) had SSW, S, SW and SSE components, and those with lower velocities (from 10 to 14 cm/s) had N and NNE components. At CM10, the current was clearly directed southward (a S component 38% of the time and a SSW component 11% of the time). This velocity distribution shows a recirculation trend in the hydrodynamic field (Figure 10). The mean velocity at CM7 was 13.82 cm/s, obtained from a 31.17 h time series, with a net displacement of 5.352 km towards the SSW (208°). The mean velocity at CM10 was 11.06 cm/s, obtained from a 31.92 h time series, with a net displacement of 3.861 km towards the SSE (164°). In this field campaign, the current field at CM7 was more intense than the currents measured at CM10.

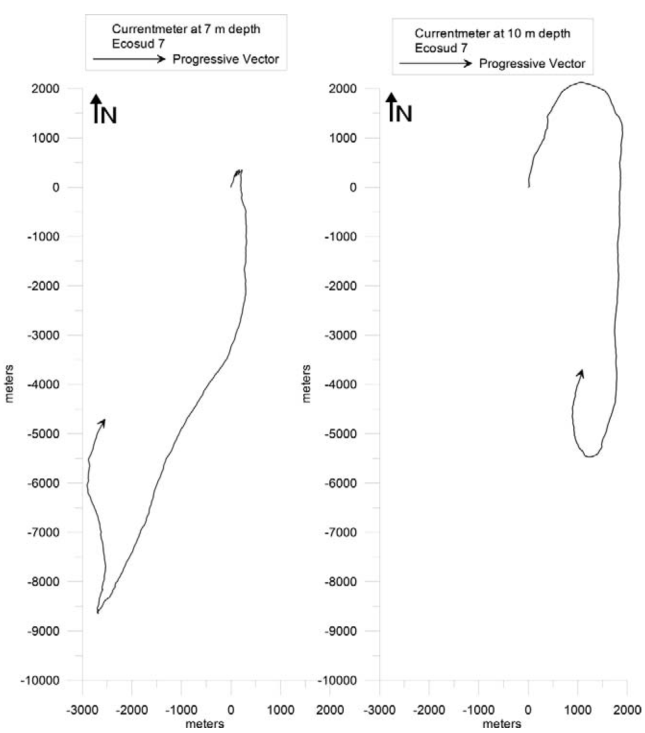


Figure 10. ECOSUD 7 hydrodynamic field.

The hydrodynamic field observed in ECOSUD 8, as in ECOSUD 7, was quite intense and showed a similar recirculation trend (Figure 11). The currents measured at CM7 had two main components. They showed strong NW, NNW and WNW components with velocities between 12 and 16 cm/s 43% of the time and showed strong S and SSW components with gusts over 16 cm/s 25% of the time. The current measured at CM10 showed strong N-S behavior (51% of the measurements) but with some SSW, W, WNW and NNW components. Despite punctual differences in the velocity distributions, the virtual path of the two currents is very similar (again higher at CM7). The mean velocity at CM7 was 13.80 cm/s, obtained from a 33.75 h time series, with a net displacement of 6.396 km towards the W (263°). The mean velocity at CM10 was 11.23 cm/s, obtained from a 33.83 h time series, with a net displacement of 2.567 km towards the WSW (240°).

Finally, the hydrodynamic field observed in ECOSUD 9 was only measured at CM7 because the current meter moored at CM10 failed. The main velocity component (48%) was NNW with smaller contributions towards the NW (10%), S (10%) and N (7%). The mean velocity was 15.13 cm/s, obtained from a 34.75 h time series, with a net displacement of 17.855 km towards the NNW (329°). The current was only disrupted by two momentary eddies (Figure 12).

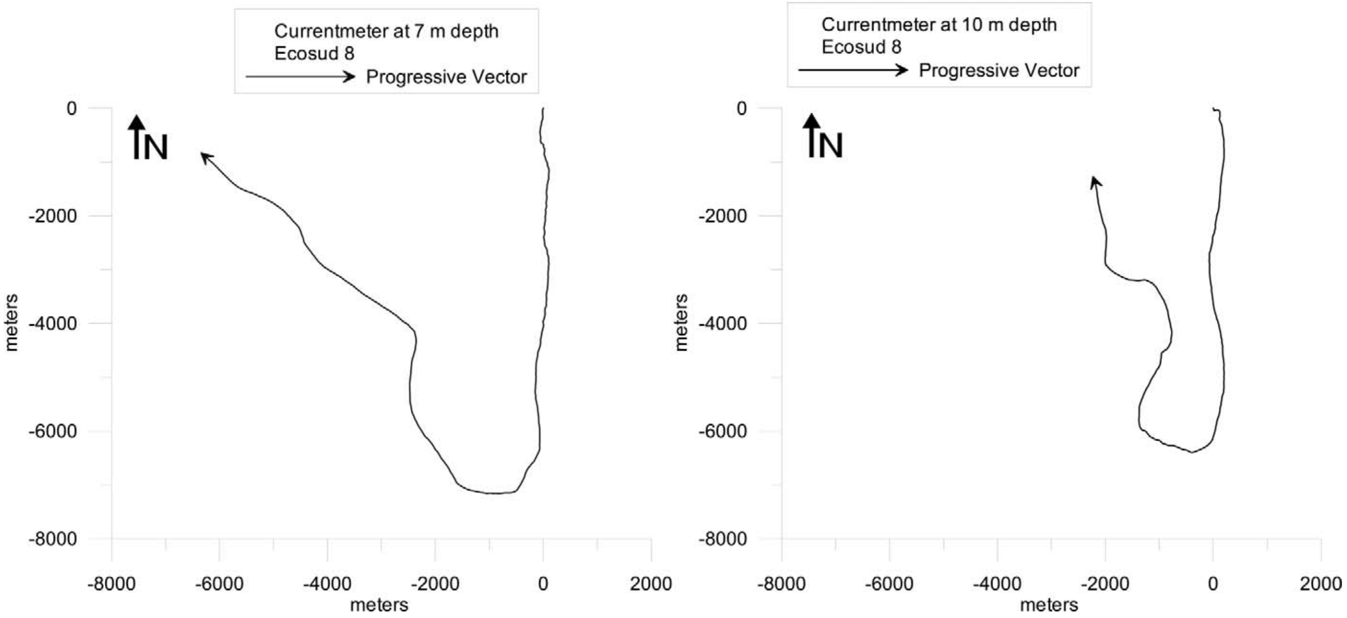


Figure 11. ECOSUD 8 hydrodynamic field.

OVERALL EXPERIMENTAL RESULTS

Wind Field

The overall analysis of the wind field shows that the wind blows mainly from three directions in Cullera Bay (Figure 13). The first two correspond to daily breeze behavior, where 48% of the measurements were offshore winds from the W (especially persistent in ECOSUD 6), WNW, NW and WSW.

The complementary wind (35%) generally blows at higher velocities, mainly from the ESE, E, SE and ENE. The third main direction is from the NE (7%). This behavior is clearly seen in ECOSUD 3, 5, 7, 8 and 9. The remaining 10% of the time, the wind blows from the N, NNE (especially in ECOSUD 7, 8 and 9), SW and SSW. These directions are mentioned in order of importance (% of the total measurements). There were almost no southerly winds.

The overall frequency distribution of wind velocity classes shows 14.2% for calm, 31.3% for light air, 36.8% for a light breeze, 10.9% for a gentle breeze, 6% for a moderate breeze, 0.3% for a fresh breeze and 0.5% for a gale. The overall average velocity (for seven field campaigns) is 2.29 m/s, which corresponds to a light breeze.

By field campaign, the lowest and highest mean velocities correspond to ECOSUD 7 with 0.83 m/s and ECOSUD 5 and 6 with 2.74 m/s respectively. The lowest and highest velocity standard deviations correspond to ECOSUD 1 with 0.850 m/s and ECOSUD 6 with 2.339 m/s respectively. The lowest and highest combined (velocity and direction) dispersion values—the ratio between the net distance and the gross distance of the progressive vector—correspond to ECOSUD 8 with 0.213 and ECOSUD 6 with 0.929 respectively.

Hydrodynamic Field

The overall analysis of the hydrodynamic field shows that the main velocity of the currents at CM7 have strong NNW (22%) and S (19%) components with minor contributions from N (13%), SSW (9%), NNE (9%) and NW (7%) components (Figure 14). The main velocity components of the currents at CM10 are N (19%) and S (16%), with minor contributions from NNW (10%), NNE (9%) and SSW (8%) components.

The overall frequency distribution of current velocity classes at CM7 shows that 3% of the currents were under 2 cm/s, 17.4% ranged from 2 to 4 cm/s, 15.7% ranged from 4 to 6 cm/s, 7.4% ranged from 6 to 8 cm/s, 4.3% ranged from 8 to 10 cm/s, 12.6% ranged from 10 to 12 cm/s, 15.7% ranged from 12 to 14 cm/s, 7% ranged from 14 to 16 cm/s and 17% were over 16 cm/s.

The overall average velocity (for seven field campaigns) is 10.02 cm/s (9.17 cm/s without considering ECOSUD 9). Only ECOSUD 6 and ECOSUD 8 had a distribution similar to the overall distribution.

By field campaign, the lowest and highest mean velocities correspond to ECOSUD 3 with 4.5 cm/s and ECOSUD 9 with 15.13 cm/s respectively. The lowest and highest velocity standard deviations correspond to ECOSUD 3 with 1.365 cm/s and ECOSUD 5 with 10.382 cm/s respectively. The lowest and highest combined (velocity and direction) dispersion values correspond to ECOSUD 7 with 0.354 and ECOSUD 3 with 0.795 respectively.

The overall analysis of the hydrodynamic field shows that main velocity components of the currents at CM10 have strong N (19%) and S (16%) components, with minor contributions from NNW (10%), NNE (9%), SSW (8%), NW (7%) and W (6%) components (Figure 15).

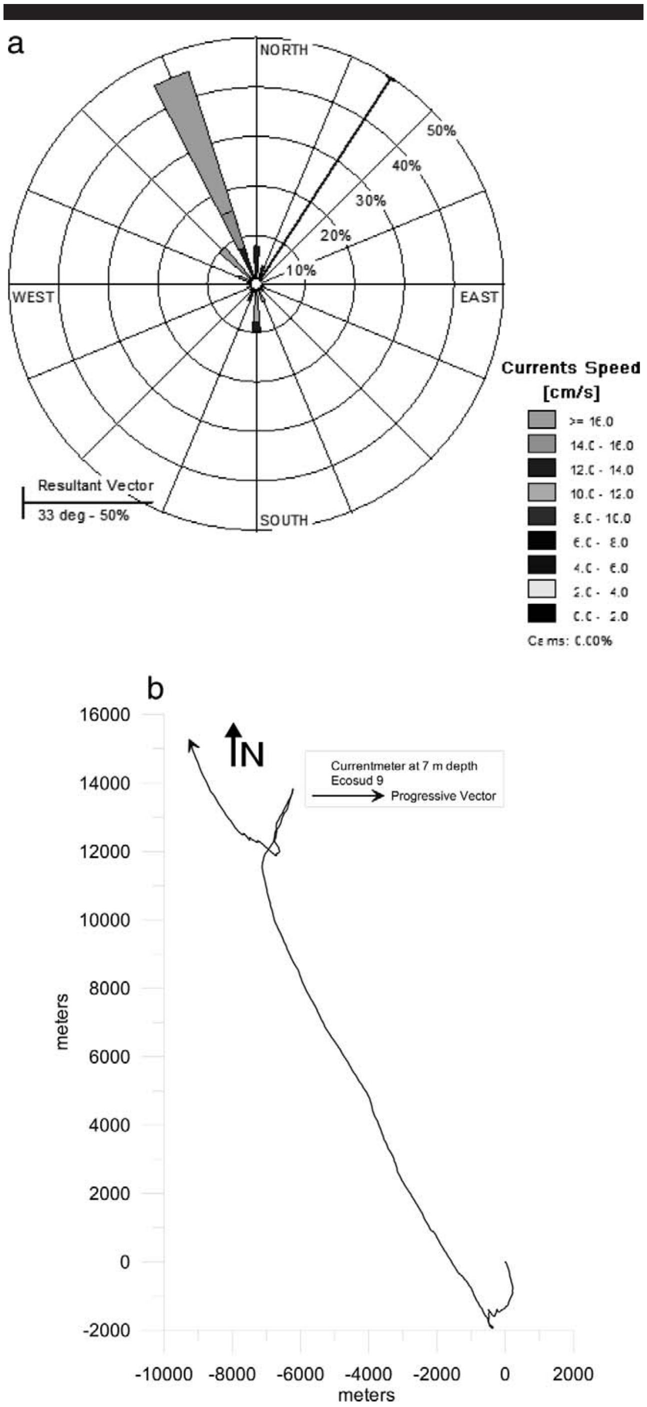


Figure 12. ECOSUD 9 hydrodynamic field.

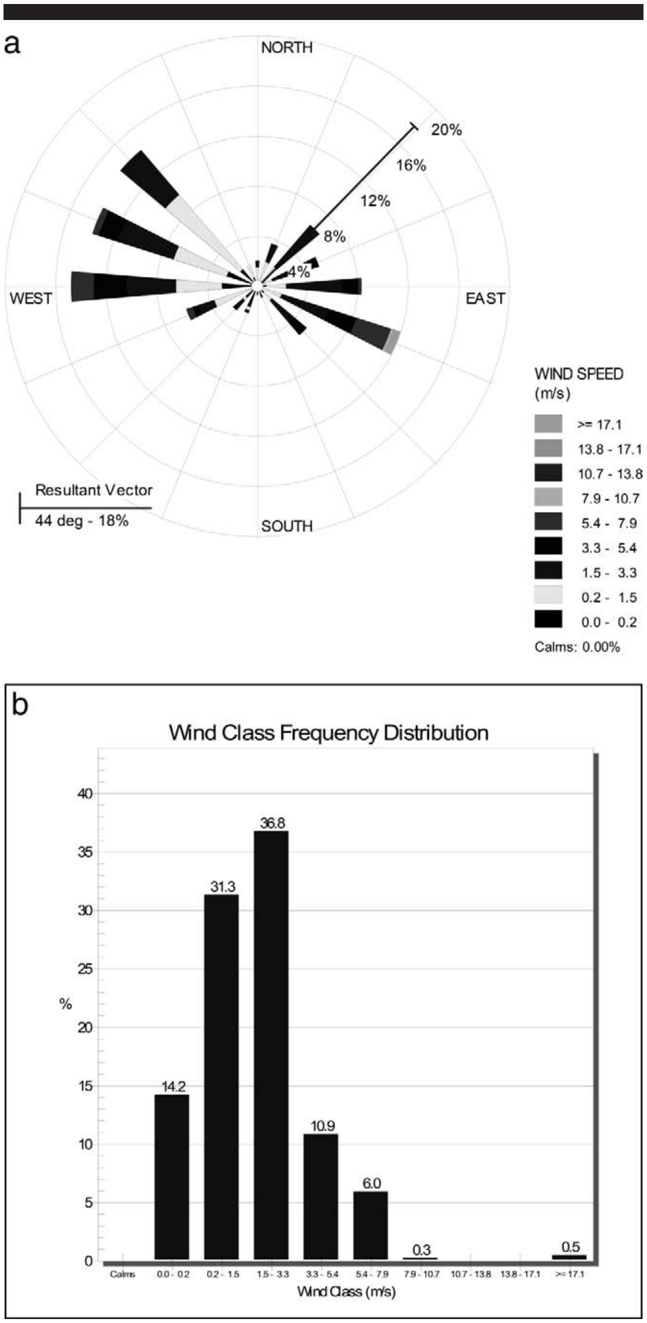


Figure 13. ECOSUD overall wind field.

The frequency distribution of current velocity classes shows that 3.9% of the currents were under 2 cm/s, 16.2% ranged from 2 to 4 cm/s, 14.0% ranged from 4 to 6 cm/s, 12.3% ranged from 6 to 8 cm/s, 19.6% ranged from 8 to 10 cm/s, 15.6% ranged from 10 to 12 cm/s, 10.6% ranged from 12 to 14 cm/s, 5.6% ranged from 14 to 16 cm/s and 2.2% were over 16 cm/s. The overall average velocity (for six field campaigns) is 8.36 cm/s. Only ECOSUD 8 showed a distribution similar to the overall distribution.

By field campaign, the lowest and highest mean velocities correspond to ECOSUD 6 with 4.23 cm/s and ECOSUD 5 with 12.32 cm/s respectively. The lowest and highest velocity standard deviations correspond to ECOSUD 8 with 2.102 cm/s and ECOSUD 5 with 21.199 cm/s respectively. The lowest and highest combined (velocity and direction) dispersion values correspond to ECOSUD 8 with 0.190 and ECOSUD 3 with 0.956 respectively.

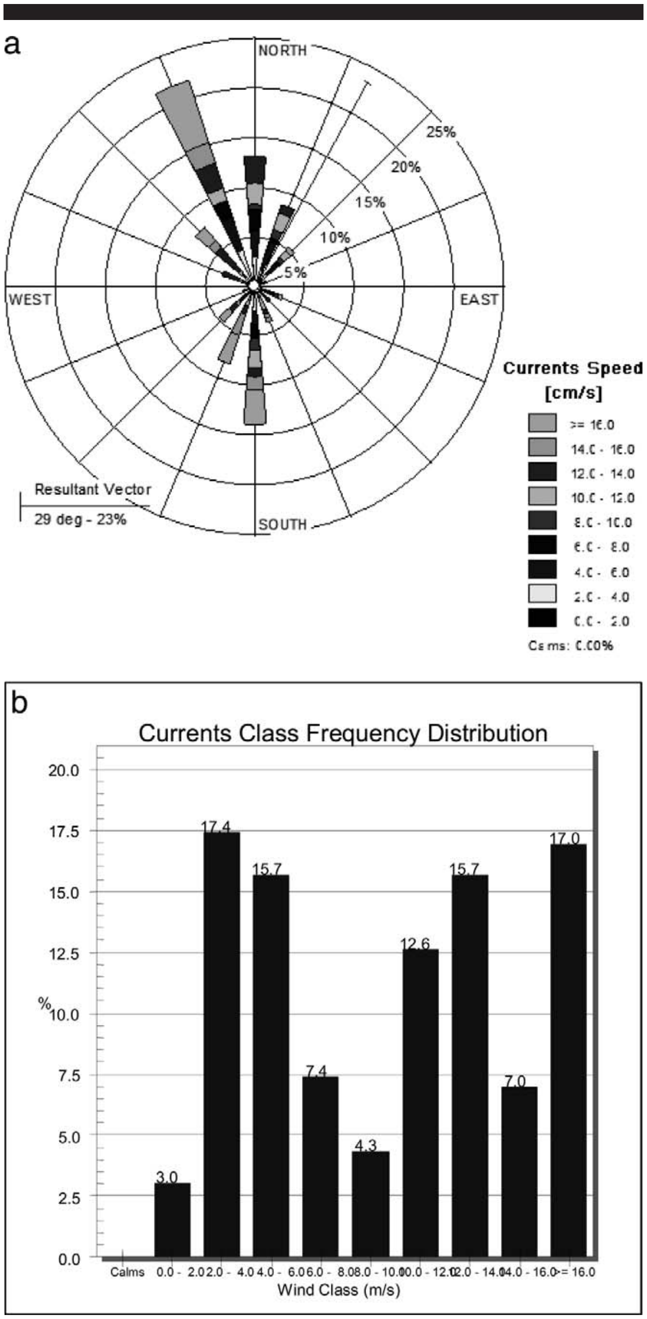


Figure 14. ECOSUD overall hydrodynamic field at 7 m depth.

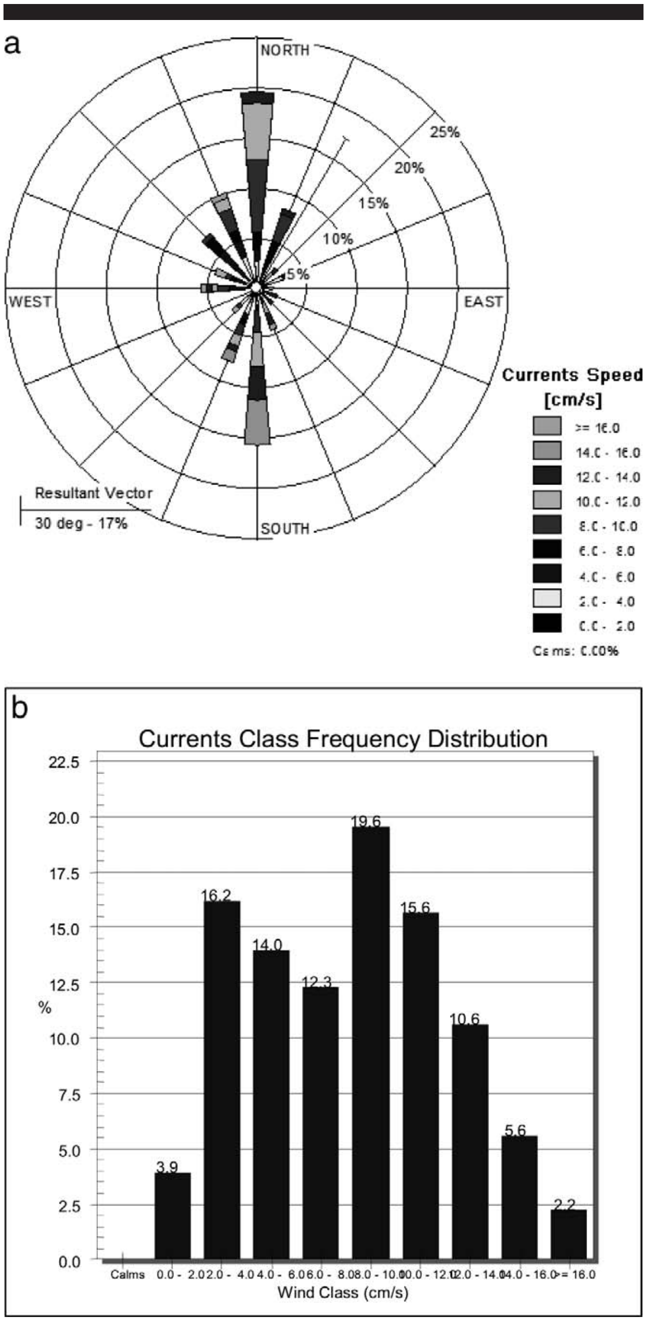


Figure 15. ECOSUD overall hydrodynamic field at 10 m depth.

DISCUSSION AND CONCLUSIONS

Topography

Cullera Bay is a semi-enclosed bay with very particular morphological features. This stretch of coast is a very flat plain on the southern bank of the Júcar River. However, a prominent mountainous feature (Monte de Oro) protrudes into the sea in the form of a cape at the northern end of the bay. Cullera Cape has a strong influence on the local wind field, local hydrodynamics, pollutant transport and water quality in the bay (MESTRES *et al.*, 2007; SÁNCHEZ-ARCILLA *et al.*, 2007).

Waves

The wind, not the waves, is the main hydrodynamic driver due to the topographic nature of Cullera Bay, and it is particularly important to the surface-layer pattern of the nearshore currents and the behavior of the freshwater plumes (discussed below). Cullera Bay is located on the Gulf of Valencia, which has a tidal range of approximately 30 cm (spring tide) and a limited fetch (the islands of Mallorca, Cabrera and Ibiza are only 230, 273 and 135 km off the coast of the bay, respectively). Therefore, tides and waves are relatively unimportant compared to the wind. Moreover, the predicted wave field for 2002–2003 showed that the significant wave height exceeded 1 m 15.5% of the time and 1.5 m only 2.2% of the time during this two-year period. Most of the higher incoming waves were from the NNE (4.5%), NE (25.6%) and ENE (16.5%), which highlights how Cullera Cape shelters the bay.

Wind Field

The wind field in Cullera Bay was measured close to the river mouth. It is highly variable (on a time scale of hours to days) and shows seasonal behavior. Nevertheless, the overall analysis of the wind field (on the mesoscale) shows that the main wind components occur as daily breezes. The offshore winds are mainly from the W, NNW and NW while the onshore winds are mainly from the ESE, E and SE. Due to the geomorphological features of Cullera Bay, the wind field in the bay is far from homogeneous. Cullera's mountain acts as a barrier to the offshore wind, which causes the wind to go around the mountain and tunnel through the river basin. In these conditions, once the wind field enters the bay (over the watershed) it may be deflected towards the N, which enhances the surface currents and the related freshwater plume transport towards the cape.

Hydrodynamic Field

Like the wind field, the hydrodynamic field in Cullera is very complex. The currents were measured close to the bottom and, with a few exceptions, they showed no correlation at all with wind direction and magnitude. In fact, the most erratic current pattern, with significant N and W components, occurred with the most steady offshore wind field (from the W) in ECOSUD 7 (Figures 6 and 9). The N component can be explained by the expected deflection of the wind field towards the N (barrier effect of the mountain), as mentioned above.

The steady W wind component induces a surface circulation pattern towards the E. The westward component near the bottom in the measured currents can be explained by the compensating flow (mass continuity) related to the eastward surface circulation. The lack of correlation between the observed wind field and the resulting circulation near the bottom shows that wind-induced hydrodynamics are very complex and must be explained by a 3D approach, since an "area" (2DH) or "profile" (2DV) approach appears insufficient. However, the salinity gradients on the surface watershed show that the surface circulation and the wind field are correlated (Cupul *et al.*, 2006). Despite the variability and complexity of the hydrodynamic field at local time scales (hours to days), the overall analysis of the measurements (on the mesoscale) shows that the main current components follow the isobaths where the current meters were moored. The main components of the currents measured at a depth of 7 m were NNW, N and S. The NNW component is consistent with the shoreline orientation. The main components of the currents measured at 10 m depth were clearly N and S, which is consistent with the isobath orientation.

There are almost no W, E, WSW or ENE components at CM7 (Figure 14) and no WSW or E components at CM10 (Figure 15). The lack of cross-shore velocity components of the wind-induced circulation therefore strengthens the hypothesis that the topography influences the nearshore circulation pattern.

These field observations show that, on the mesoscale, the wind has a strong daily breeze behavior while the current field shows a strong "boundary condition" influence by the shoreline. The transport of pollutants that enter Cullera Bay through the river mouth (in the form of a river plume) is mainly driven by the wind field, while the pollutants that enter through the marine outfall are mainly longshore transported along the recreational beaches (since mixing is expected throughout the water column). Thus, the marine outfall may have a greater impact on water quality degradation in Cullera Bay than the river outflow.

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