The seasonality of mesoscale motion in the Northern Current of the western Mediterranean: several years of evidence

North-western Mediterranean
Circulation
Mesoscale dynamics
Seasonal variability
Current measurements

Méditerranée nord-ouest
Circulation
Dynamique à moyenne échelle
Variabilité saisonnière
Courantométrie

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ABSTRACT

The Liguro-Provenço-Catalan or Northern Current, which contours the continental slope of the north-western Mediterranean Sea, has been described as a permanent flow affected by important variability at different scales. Many observations indicate a higher flux in winter than in summer, while the occurrence of mesoscale events appears to be a common characteristic. The opportunity of examining several years of current meter data at a location close to the inner border of the Northern Current has definitively demonstrated the existence of a seasonality in the mesoscale variability. Although the records do not concern the core of this current, the consistency of the several characteristics we have determined with results found by other authors in the Ligurian Sea allows us to consider them as representative of its general trends. Three current meters moored at 15, 50 and 100 m depth from an oil drilling ring near the shelf break off the Ebro delta, with a considerable coverage from mid-1987 to mid-1992, provide a clear image of the current behaviour. The general flow is along-slope and presents occasional disruptions for periods of several days, described here as mesoscale events. Most of the motion we have recorded displays a marked barotropic character. The intensity of the current is relatively low, increasing suddenly in autumn at the three levels monitored, in a manner that appears not to be connected to the local wind regime. One of the most relevant pieces of information contained in the whole current data set concerns the repeated presence of clockwise rotations in a near-inertial frequency, even at 100 m. The principal objective of the present study was to investigate any seasonal signal in the appearance and characteristics of the mesoscale motion. The main observed feature in a low-passed time series below the thermocline, namely a rapid and strong autumn increase in mesoscale activity, is shown to be consistently present, with very small inter-annual temporal variability. This maximum of mesoscale activity is followed by a rapid decrease in winter and then by a continuous decline until the end of the summer. A complete characterization of the mesoscale motion in the Northern Current, including its origin and interaction with the main flow, requires extensive experimental and numerical work. Our results have demonstrated that this motion displays a clear seasonal cycle and provided evidence that the recorded mesoscale activity is linked far more to the shelf/slope front evolution than to local wind variability.

RÉSUMÉ

Variabilité saisonnière à moyenne échelle du courant nord de la Méditerranée occidentale.

Le courant Liguro-Provençal-Catalan ou courant nord suit la pente continentale du nord-ouest de la mer Méditerranée. Il a été décrit comme un flux permanent marqué par une variabilité importante à différentes échelles. De nombreuses observations indiquent un courant plus important en hiver qu'en été, avec des phénomènes à moyenne échelle caractéristiques. L'analyse de plusieurs années de données de courantométrie en un point situé à la limite intérieure du courant nord a mis en évidence le caractère saisonnier de la variabilité à moyenne échelle. Bien que les enregistrements ne portent pas sur le courant principal, nos résultats sont en bon accord avec ceux d'autres auteurs dans la mer Ligure ; ils peuvent donc être considérés comme représentatifs des tendances générales du courant nord. Trois courantomètres ont été mouillés à 15, 50 et 100 m de profondeur sur une plate-forme pétrolière à la bordure du plateau continental, au large du delta de l'Ebre. Les enregistrements acquis de mai 1987 à avril 1992 donnent une image très claire de l'évolution du courant. Le flux général suit le talus avec quelques inversions de sens sur des périodes de plusieurs jours, décrites ici comme fluctuations à moyenne échelle. La plupart des variations enregistrées présentent un caractère barotrope marqué. L'intensité du courant est relativement faible et augmente brusquement en automne aux trois profondeurs considérées, indépendemment du régime des vents locaux. Dans l'ensemble des données de courantométrie, l'une des informations les plus remarquables est la présence d'oscillations quasi-inertielles jusqu'à 100 m. L'objectif du présent travail est la recherche d'un signal saisonnier dans l'apparition et les caractéristiques du mouvement à moyenne échelle. Les séries temporelles filtrées audessous de la thermocline montrent une augmentation rapide et forte de l'activité à moyenne échelle, chaque année en automne. Le maximum de l'activité à moyenne échelle est suivi par une diminution rapide en hiver et plus lente ensuite, jusqu'à atteindre un minimum vers la fin de l'été. Pour décrire complètement la variabilité à moyenne échelle du courant nord, incluant son origine et son interaction avec le courant moyen, il faut un travail expérimental et numérique plus étendu. Nos résultats démontrent que ce mouvement suit un cycle saisonnier très marqué et mettent en évidence que l'activité à moyenne échelle est liée plus étroitement à l'évolution du front plateau/talus qu'à la variabilité du vent local.

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INTRODUCTION

The Liguro-Provenço-Catalan or Northern Current contours the continental slope of the north-western Mediterranean Sea from the Gulf of Genoa at least as far as the Gulf of Valencia (Millot, 1987). It has been described as a permanent flow affected by important variability at different scales. Many observations provide evidence of a higher flux in winter than in summer (Béthoux *et al.*, 1982), while the occurrence of mesoscale events appears to be a common characteristic (Millot, 1991).

The existence of this current and its behaviour, partially linked to winter thermohaline forcing (Madec *et al.*, 1991; Astraldi and Gasparini, 1992), is one of the major features of the circulation in the western Mediterranean. An accurate computation of the Northern Current fluxes and their spatial and temporal evolution is of fundamental importance for a correct modelling of the circulation in the different sub-basins of the western Mediterranean. García-Ladona and Djenidi (1991), with a reduced-gravity model of the Catalan Sea (Balearic Basin), showed how sensitive the regional circulation is to the different boundary conditions, in terms of flux and spatial structure of the along-slope jet. Computation of transports in the Balearic channels with high horizontal resolution CTD data (García-Ladona, 1990; Pinot, 1994) clearly indicates the high variability and complex interactions to be found between the inflow of Modified Atlantic Water and the along-slope Northern Current in its final sector (Salat, 1995).

In the Liguro-Provençal Basin, this current has been studied for a considerable time (Béthoux *et al.*, 1982, 1988) and its variability carefully analysed from specific experiments (Sammari *et al.*, 1995; Albérola *et al.*, 1995). Downstream from the Gulf of Lions, the continental shelf is narrow (less than 25 km) and intersected by several submarine canyons (Canals *et al.*, 1982). The along-slope Northern Current, after being affected by the complex circulation regime that dominates the wide Gulf shelf (Millot, 1990; Salat *et al.*, 1990), penetrates the Balearic Basin with a flux of 1-1.5 Sv (Font *et al.*, 1988). The fresh water from the Rhône river and other continental discharges reinforces the corresponding shelf/slope front and feeds a plume of cool water that is entrained by the current and can easily be traced in satellite thermographs up to the entrance of the Gulf of Valencia (La Violette *et al.*, 1990).

This is a classical shelf/slope front, separating low salinity shelf water from the more saline offshore water. The front is present all year round in the upper 300 m, mostly characterized by the salinity gradients, and usually lies (at the surface) over the 1000 m isobath. Temperature gradients are usually weak and can escape satellite detection due to the formation of a sub-basin wide upper mixed layer in summer (López *et al.*, 1994). In the Balearic Basin there are no predominant winds and the wind-driven circulation may therefore be considered as a transient circulation superimposed on the mainly thermohaline circulation.

Along the slope of the narrow shelf of the Catalan Sea, the current jet has been clearly identified in vessel-mounted ADCP records (Castellón *et al.*, 1990). Surveys with CTD, surface drifters and infrared imagery have revealed the occurrence of energetic mesoscale eddies and filaments in the frontal area (Wang *et al.*, 1988; La Violette *et al.*, 1990; Tintoré *et al.*, 1990). Current-meter records disclose the presence of seasonal and shorter period changes that are not directly related to local winds (Font, 1990). Topography appears to induce modifications in the general south-westward current through the effect of submarine canyons (Masó *et al.*, 1990) or changes in slope direction (Font *et al.*, 1990). High spatial and temporal heterogeneity has been found in phytoplankton biomass related to circulation variability (Masó and Duarte, 1989), as well as anomalous larval fish distributions associated with frontal mesoscale events (Sabatés and Masó, 1992). The progression of the current to the southwest is accompanied by a weakened flow and increased variability, giving rise to a complex circulation pattern and interactions with incoming southern waters near the Balearic Islands (see García-Ladona *et al.*, 1994, for a review).

In one site at the shelf break of this region, the Barcelona-based Institut de Ciències del Mar (CSIC) has been performing current measurements over a five-year period that includes the period of the PRIMO 0 experiment (see Millot, 1995). Here we present an analysis of the seasonal and mesoscale variability of these data, carried out as part of the EUROMODEL/MAST project.

DATA SET: EBRO SHELF BREAK 1987-1992

When reaching the Gulf of Valencia, and coincident with the location of the Ebro river delta, the continental shelf widens to 40-60 km and the horizontal direction of the slope changes suddenly by about 70° from WSW to S (Fig. 1). Just in this area, the existence of the REPSOL EXPLORACION company oil-drilling platform "Casablanca", situated near the shelf break 35 km off the Ebro delta, has permitted the safe deployment of current meters for long periods. The location (40°43'4" N, 1°21'34" E, 165 m depth) is

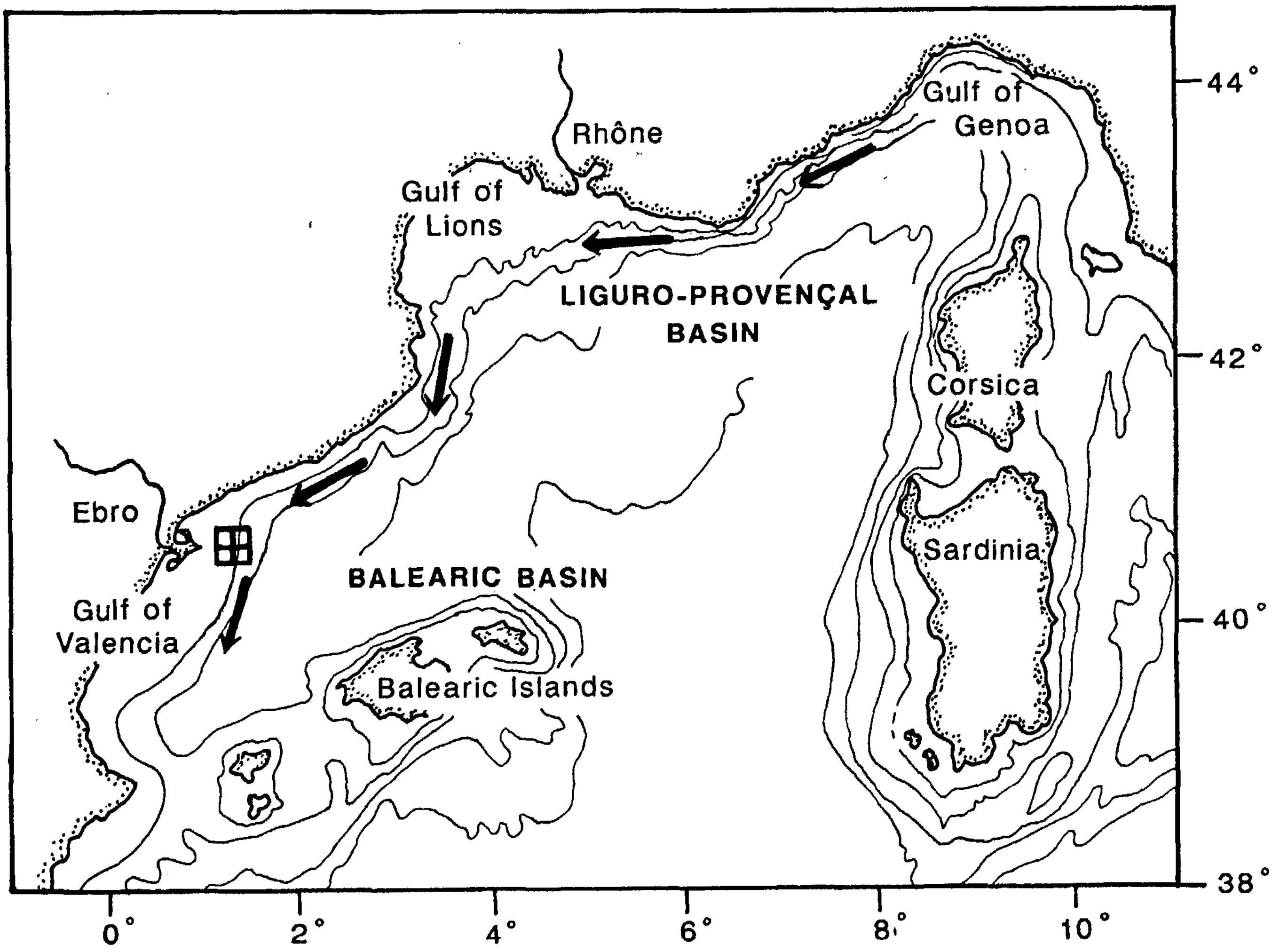


Figure 1

The Northern Current along the continental slope of the north-western Mediterranean and location of the "Casablanca" mooring.

10-15 km inshore from the core of the current, as determined by geostrophic calculations. Fig. 2 shows salinity and geostrophic velocity vertical distributions from a cruise in June 1987 (Salat *et al.*, 1992) in a cross-shore high horizontal resolution section along 40°41' N, *i.e.* less than 4 km to the south of the platform. Results from an initial survey in 1982-84 (Font *et al.*, 1990) indicated that, under different seasonal conditions, the velocities recorded at this point are mainly driven by the along-slope current. Those results, and other data collected at neighbouring sites (Font, 1983), indicated that the local wind has a minimal effect on the general circulation (Font, 1990). The records obtained over a lengthy period at the "Casablanca" station can be used in studies of the long-term variability of the characteristics of the Northern Current.

From May 1987 to April 1992, with some gaps, three current meters were maintained there at depths of 15, 50 and 100 m with a sampling interval of 30 min. Servicing of the instruments (Aanderaa RCM 4S and RCM 7) was carried out nearly every two months. In a first technical report, Navarro (1990) presented the data for the period May 1987 - December 1989, where 85 % of reliable records were recovered. For the remaining 2.5 years only 58 % of the complete three-level coverage is available, due to partial deployments or failures in some instruments.

Meteorological data were at first manually obtained every 12 or 6 hours on the platform; from March 1990 an automatic weather station was operating with an hourly recording interval. From May 1991 to July 1992, a thermistor chain with 11 sensors in the 5-60 m range was also deployed, and a complementary set of seven current meters was moored 250 m to the north from July until October 1991. Unfortunately, three of these instruments were lost by accident.

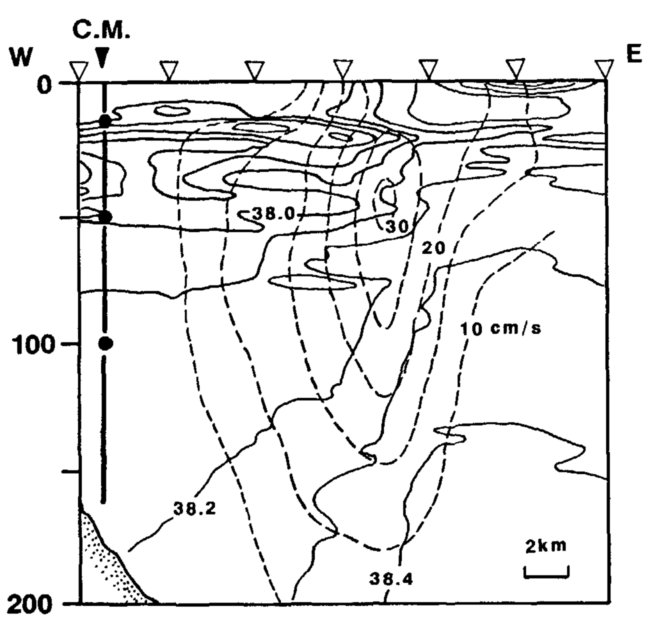


Figure 2

Salinity (at 0.1 psu intervals) and geostrophic velocity (at 5 cm/s intervals) in a cross-shore section (7 CTD casts 4 km apart) south of "Casablanca" in June 1987. The position of the three current meters relative to the current is indicated.

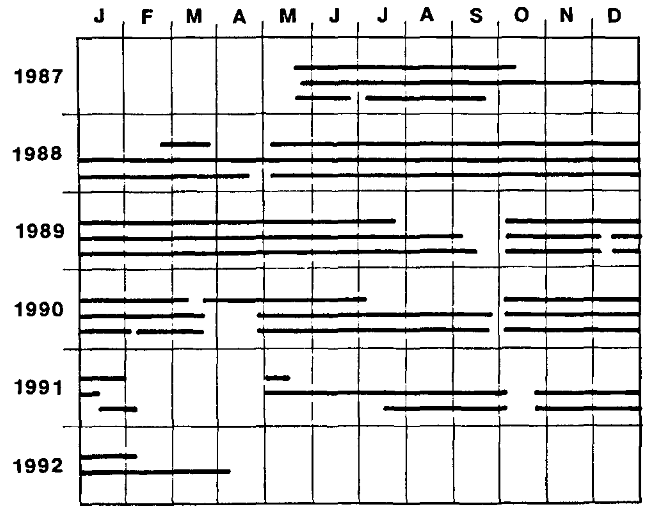


Figure 3

Time coverage of current records for the 15, 50 and 100 m levels from 1987 to 1992.

Fig. 3 summarizes the temporal data coverage for the three main levels during the five years of current measurements. From the deployment of the thermistor chain (May 1991) the recording interval was set at one hour and the current meter at 15 m removed. For a coherent analysis all the data were interpolated and subsampled at exact hours.

SEASONALITY OF THE NORTHERN CURRENT

As is usual in the region, temperature data indicate the existence of two well-differentiated hydrographic seasons: vertically homogeneous from December to April and stratified from June-July to September-October, with two intermediate transition periods centring on May and November. For our study we have defined four three-month seasons: winter (full homogeneity beginning in January); spring (heating and mixed upper layer formation); summer (full two layer stratification); and autumn (cooling and vertical mixing). An example of the temporal evolution of the vertical thermal structure can be observed through the data recorded in 1991-92 by the thermistor chain. Fig. 4 corresponds to the first deployment, May to October 1991, and original values have been low-passed with a 72 h filter.

The three levels of velocity records indicate a clear trend of the current to the S-SW. The deep current meter shows a more evident alignment with local isobaths, while the upper directions can be slightly deviated to the continental shelf. In fact, slope water has been repeatedly observed (Font *et al.*, 1987, 1990) to be upwelled over the shelf north and east of the Ebro delta, due to the steep change in slope orientation. Fig. 5 comprises a progressive vector diagram of the longest uninterrupted data record: current at 50 m from 25 May 1987 to 4 September 1989. The

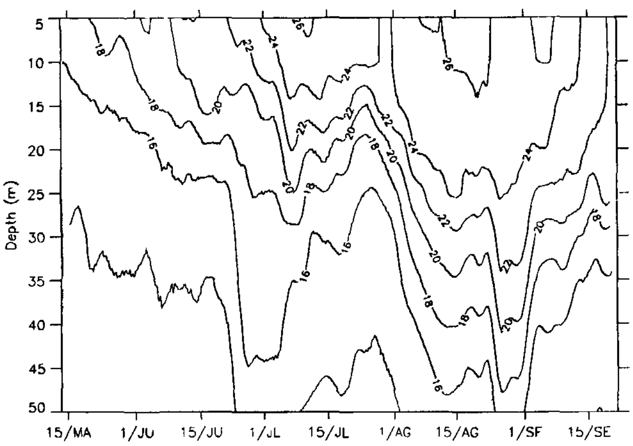


Figure 4

Temporal evolution of the vertical thermal structure in "Casablanca" from 14 May 1991 to 5 October 1991 as recorded by the thermistor chain. Low-passed (72 h filter) data in °C.

Northern Current is manifested as the general south-westwards displacement, while several-day disruptions and shorter-period clockwise oscillations are also usual features. The effective mean speed, calculated as the total virtual displacement in the 51.5 months of this record length, is of the order of 5 cm/s.

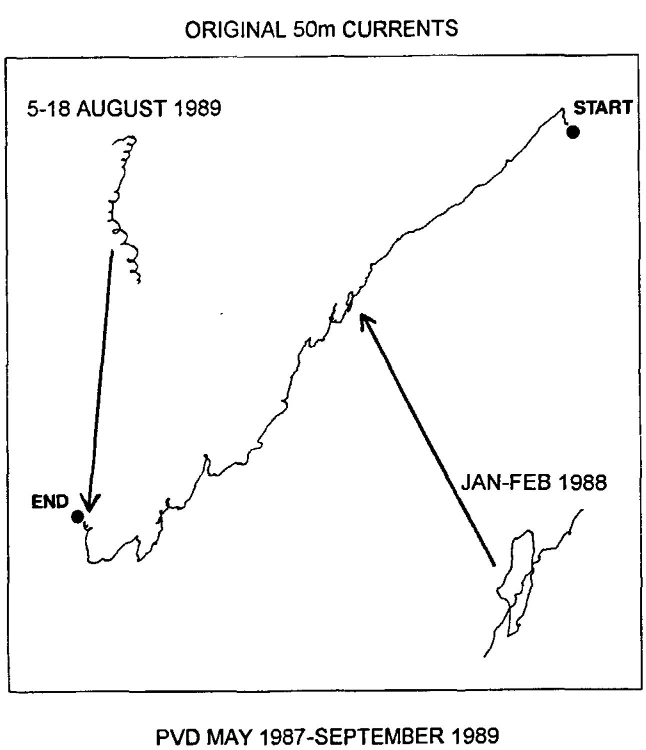


Figure 5

Progressive vector diagram of the original current records at 50 m from 29 May 1987 to 4 September 1989. The periods of January-February 1988 and 5 to 18 August 1989 are enlarged.

Seasonal mean velocities are weak, with large standard deviations. Maximum values for these seasonal averages are of the order of 10-15 cm/s at the two upper levels in autumn. It should be recalled that, besides the measures being taken at the periphery of the frontal current, the jet in this region is in general clearly weaker than in the Ligurian Sea, where the most detailed information exists for the Northern Current (see Albérola *et al.* in this issue). Ship surveys in spring in the area of the Ebro shelf and slope, and in other locations of the Catalan Sea, indicate core velocities in the jet of the order of 25-30 cm/s (Castellón *et al.*, 1990), while in winter they can reach 40 cm/s off Barcelona (Castellón *et al.*, 1991).

To observe the seasonal variation of the long-period characteristics, the current and wind records have been low-passed with a 7-days Lanczos filter. Fig. 6 shows the filtered intensity subsampled every 24 h for the wind and the three current-meters throughout the experiment. The most striking feature that appears in the whole data set is an important and quite sudden increase in current speed that occurs every year in autumn at the three levels. From mean values of less than 10 cm/s, the current intensity increases to 40 cm/s at 15 and 50 m and 30 cm/s at 100 m. During winter, the velocity decreases and the minimum values are reached in summer, with seasonal averages of 2-6 cm/s at 15 m. The occurrence of strong winds is a regional characteristic during the cold season, beginning from October-November (Font, 1990). However, a careful examination of the wind and current time series (*e.g.* Fig. 7) shows that these two intensity growths, in wind and in current, do not necessarily occur at the same time and, as a consequence, one should expect an explanation other than just local wind forcing for the current intensification. Even a shoreward displacement of the shelf/slope front could contribute to this intensification.

An analysis with 7-day filtered records was also used by Astraldi and Gasparini (1992) for three years of current

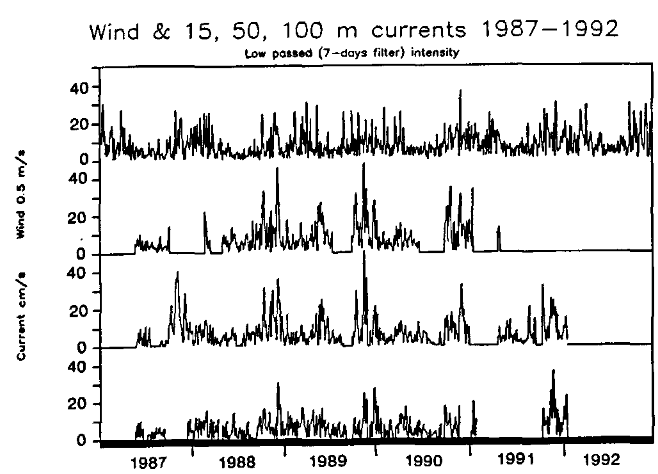


Figure 6

*Wind (in m/s * 0.5) and current intensity (in cm/s) at 15, 50 and 100 m for the whole data set. Time series have been low-passed by a 7-day filter and subsampled every 24 hours.*

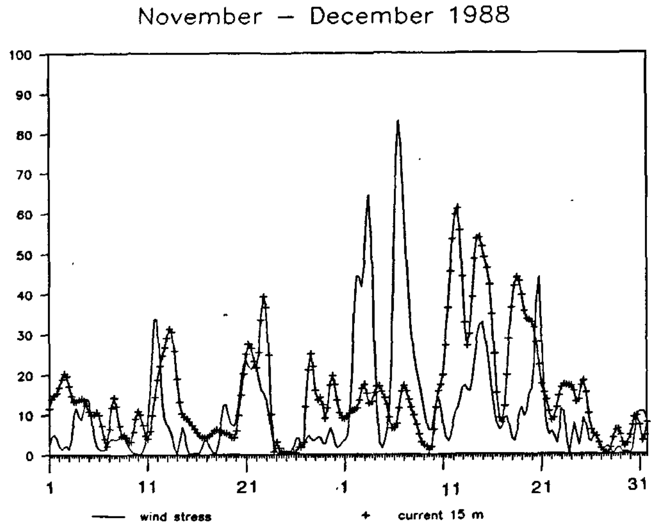


Figure 7

*Wind stress (in m^2/s^2 * 0.2) and current intensity at 15 m (in cm/s) from 1 November to 31 December 1988. Time series have been low-passed by a 33 h filter and subsampled every 6 hours.*

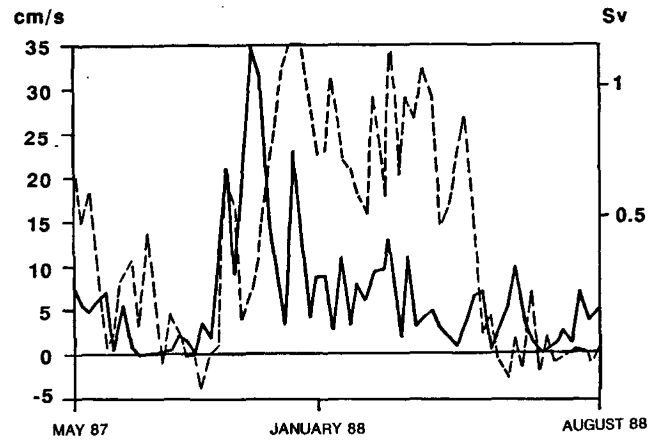


Figure 8

Current intensity at "Casablanca" 50 m (in cm/s, full line) and transport at the Corsican Channel (in Sv, dashed line) from May 1987 to August 1988. Values are at one-week intervals.

data in the Corsican Channel. They found a seasonal signal with a sudden increase by December-January, high intensities during the cold season and a progressive decline until very weak values are reached by summer and autumn. This evolution was well correlated with the air-sea heat flux in the Liguro-Provençal basin (measured in the Gulf of Lions); consequently, the authors inferred that a unique circulation pattern, mostly driven by atmospheric-climatic conditions, involves this northern part of the western Mediterranean. The similarity between the seasonal modulation of the intensity at the beginning (Corsican Channel) and near the end (Ebro shelf break) of the Northern Current is highly remarkable. However, our data display a more pronounced intensity variability during its maximum period, a rapid decrease of the signal during winter and a secondary maximum in late spring (very marked in 1989 and 1990, Fig. 6). Unfortunately, few direct comparisons between both sets of data are possible due to different temporal coverage. Contemporaneous measurements from spring 1987 to summer 1988 (Fig. 8) suggest, after a quasi-simultaneous increase in November, a considerable interruption of the flow at the "Casablanca" station in winter and a later unification of both regimes in May. Astraldi and Gasparini (1992) showed that the mean winter-spring transport crossing the Corsican Channel closely corresponds to the mean value of the upper-layer volume involved in the deep water formation processes as calculated by Béthoux (1980). Since these winter processes take place mainly in the northern part of the Liguro-Provençal basin, *i.e.* between both measuring sites, the flow interruption observed at "Casablanca" could be related to this "trapping" of the Northern Current water during winter. Font (1987) has suggested that this could also be the reason for a similar seasonal behaviour observed in the characteristics of the intermediate water along the Catalan Sea. Steep changes in mean sea level (lowering of the order of 20 cm in 1-2 months) have been observed to occur repeatedly in early winter along the Spanish Mediterranean coast, and a tentative explanation for this, after removing atmospheric effects, has been offered in the form of density modifications produced by the winter dense water formation process (Hernández, 1991).

Vector spectra of different periods of the original time series have been performed. By analysing 5 months of data relating to either homogeneous (December-April) or stratified (June-October) conditions, we can obtain the spectral characteristics of the two main seasons with considerable resolution. A band width of 0.0027 CPH allows a net separation of the inertial (local period 18.4 h) and diurnal peaks, and gives 17-20 degrees of freedom. The principal feature in all the spectra (not shown) is the dominance of the low-frequency fluctuations, with a remarkable contribution of inertial motion, especially during the stratified season in the uppermost instrument. The series at 15 m in summer are the only ones in which less than 50 % of the total energy corresponds to variance at periods longer than 3 days. The component ellipses of the most energetic bands are very eccentric, and oriented in the range of 210-260°. Most of the ellipses are rotating clockwise.

MESOSCALE VARIABILITY

As indicated in the introduction, mesoscale dynamics plays a key role in the western Mediterranean, where large-scale circulation cannot be understood without reference to smaller scale variability. In the high-frequency limit of the mesoscale band, inertial variability can be very significant.

The presence of inertial motion and its seasonal evolution is one of the relevant observations in our data set. Previous current measurements in the area (Font, 1983, 1990) had always evidenced the dominance of inertial energy in the summer power spectra of surface currents. But even below the thermocline, a significant part of the energy is sometimes observed to be in the near inertial range. Near the coast, or in the vicinity of a large-scale current, the interaction between inertial oscillations and the mean field can give rise to very significant, although transient, horizontal and vertical shears that can have also important biological effects. In the Mediterranean, due to the discontinuous nature of the wind forcing, the weakness of the mean currents and the variable topography, inertial motion appears to be very significant.

Following verification of the existence of clear seasonal characteristics in the whole data set, a shorter period of uninterrupted records for the three levels was chosen for further analysis: May 88 - July 1989. To observe the year-round evolution of the contribution of the different frequency bands, consecutive spectra have been calculated for series of three months of data shifted one week at a time, until the whole period was covered. From the resulting series of 52 spectra, the evolution of some characteristic bands (7.7 d, 3 d, 24 h and 18.4 h) has been plotted to compare the relative negative, positive and total power throughout the year (Fig. 9). The 7.7 d period band is always dominant, except in spring at 15 m when it can be equalled or surpassed by the contribution of the inertial band. It is followed by the 3 d band that, unlike the 7.7 d band, has a positive polarization during its highest values, in autumn. The inertial band makes a noticeable contribution, even at 100 m and especially in summer (Fig. 10). The power of the 24 h band, although sometimes forming a distinguishable peak, is very small, as are all the components with periods near 12 h. This confirms that tides are almost irrelevant in the area.

By analysing the evolution in time of the near-inertial components, a spreading and shifting of the inertial energy to neighbouring bands is observed, due to the interaction of the inertial oscillations with the main flow. But in some periods (autumn and winter) this effect, which usually shifts the peak to higher frequencies, appears to force the shifting to lower frequencies. This should be attributed to the interaction with a negative vorticity flow (right-hand side of the jet) that has to be more manifest when the jet has highest core speeds and the negative vorticity is consequently increased. This lower frequency shift at the "Casablanca" station can be used to sense remotely the

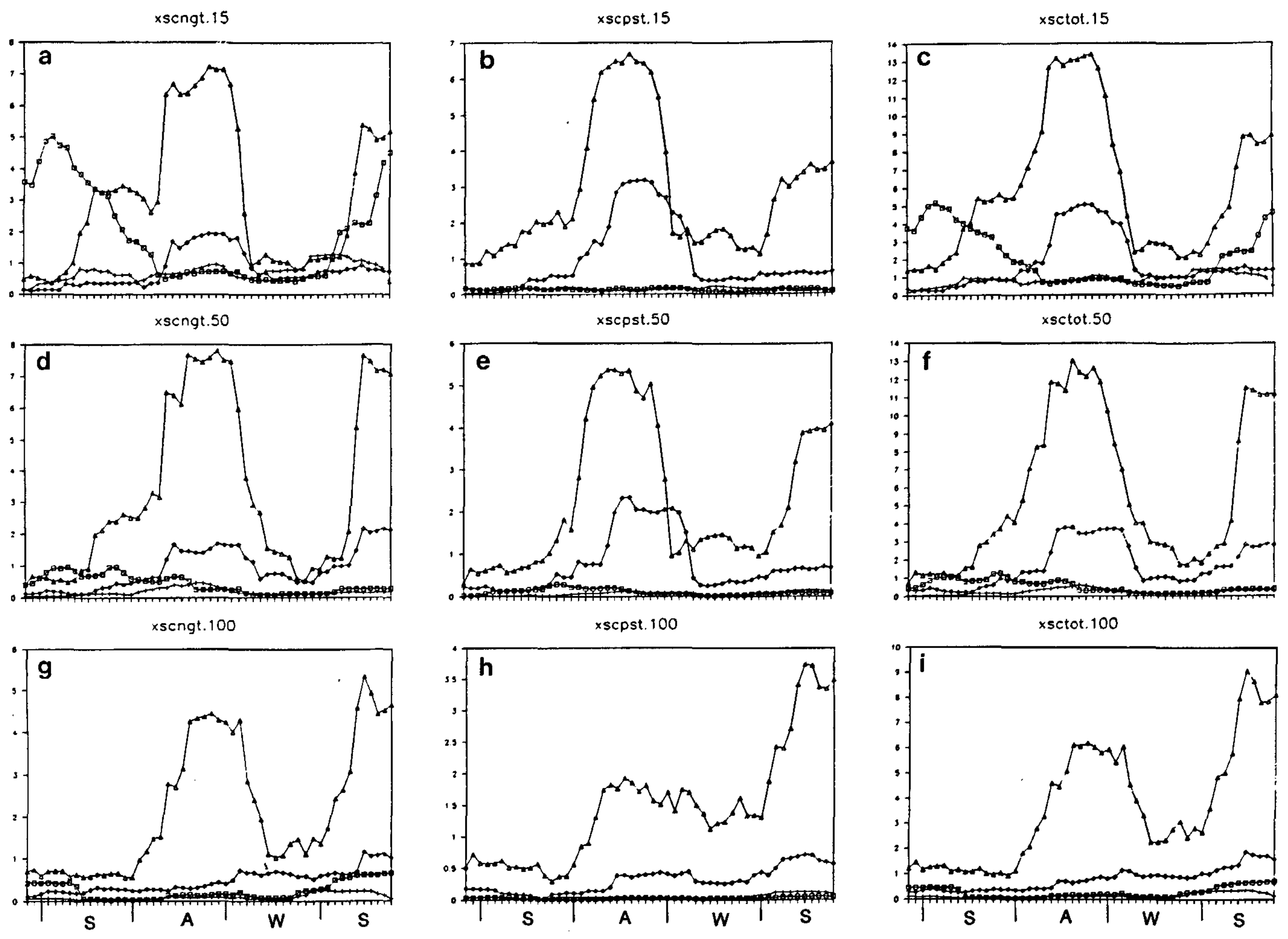


Figure 9

Weekly evolution of 4 spectral bands (□ inertial, + 24 hours, ◇ 3 days and Δ 7.7 days) for 3 months data series centred from mid-June 1988 to mid-June 1989 (in relative units): 15 m clockwise (a), 15 m anticlockwise (b), 15 m total (c), 50 m clockwise (d), 50 m anticlockwise (e), 50 m total (f), 100 m clockwise (g), 100 m anticlockwise (h), 100 m total (i).

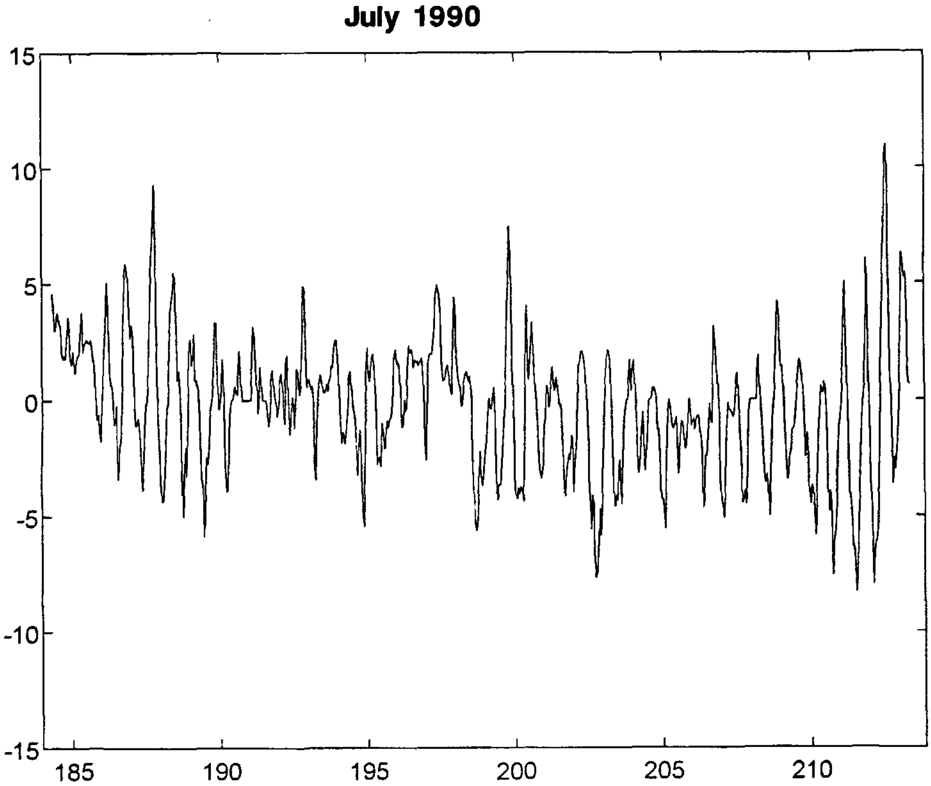
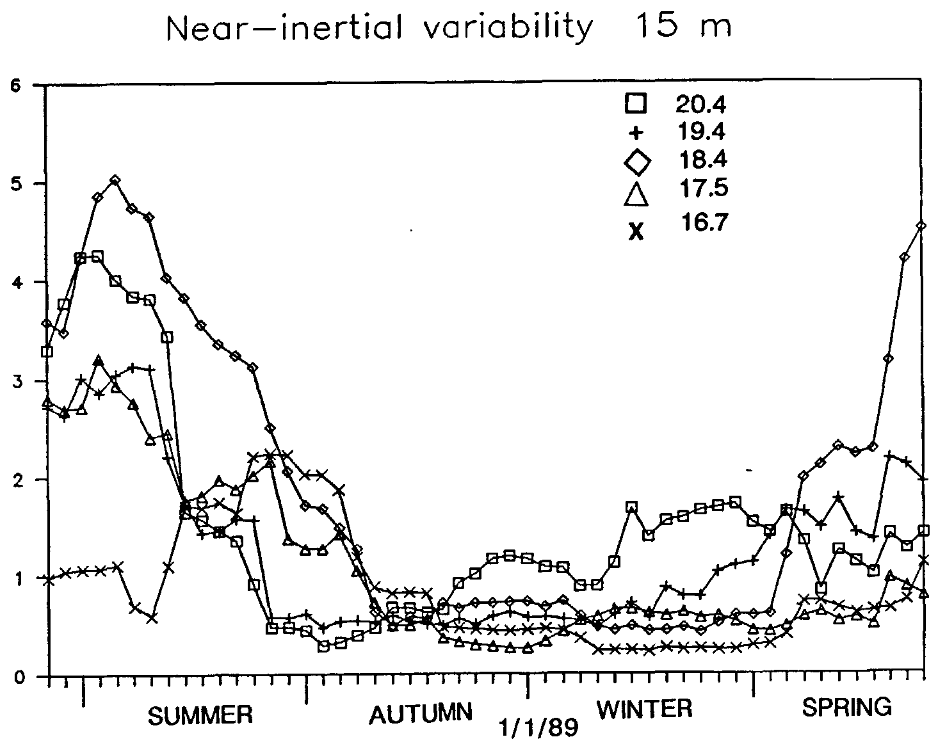


Figure 10

Inertial oscillations present at the 100 m original data series (cross-shore component) during July 1990. Units are cm/s and Julian days.

Figure 11

Weekly evolution of 5 near-inertial spectral bands (20.4, 19.4, 18.4, 17.5 and 16.7 h periods) for the 15 m currents from mid-June 1988 to mid-June 1989 (relative units).



along-slope current. Fig. 11 presents the time series, for the above mentioned period, of five near-inertial 15 m spectral bands. The 18.4 h inertial peak is distinguishable in spring and summer, while during the cold season (with lower near-inertial energy) the maximum is clearly shifted to the 20.4 h period band, *i.e.* it shows the influence of a stronger mean flow.

A general characteristic of our original data set is the occurrence of current inversions in the southward along-slope flow: velocities have been recorded to be northward for periods that can reach up to 20 days. These could be related to the passage of mesoscale structures (eddies, filaments) located at this point on the border of the along-slope jet, although it is not possible to verify this with just a single mooring. It should be noted that most of the time the inversions are present simultaneously in the records of the three levels. This barotropic character of the fluctuations in the 100 m of water column is always present when a strong signal is detected in the data set.

Fig. 12 shows the vector series of the 33 h low-passed currents (to eliminate the diurnal and higher frequency variability) and subsampled at 6 h intervals, at the three levels during spring 1989. This was a period with unusual intense motion (*see* Fig. 6). General current inversions can be observed from 7 to 24 May and from 16 June to 9 July. An infrared satellite image of 26 June 1989 (Fig. 13) allows us to interpret the second current inversion as being related to an anticyclonic eddy developed in the continental side of the cold (white) water plume that is progressing south-westwards along the slope off the Ebro delta. The clockwise rotation of the current vectors at the beginning of the inversion fits with the passage of an anticyclonic event, while the subsequent persistence of the current to the north for almost three weeks would be consistent with the large diameter of the eddy, of the order of 50 km.

One of the aims of the current-meter survey at the "Casablanca" station was to identify the occurrence of mesoscale events as perturbations of the general circulation in periods from 3 to 20 days, to observe their vertical structure and the seasonal evolution of their appearance and intensity.

Albérola *et al.* (1995), in their analysis of the Northern Current variability in the Ligurian Sea during the 1990-91 winter, pointed out the existence of a layer from 60 (their common uppermost measurements) to 150 m where the currents were vertically similar whatever the location of the mooring, inside or outside the along-slope jet. Intense winter mesoscale events were observed simultaneously in the whole width of the current and at least as deep as this 100 m vertically coherent layer.

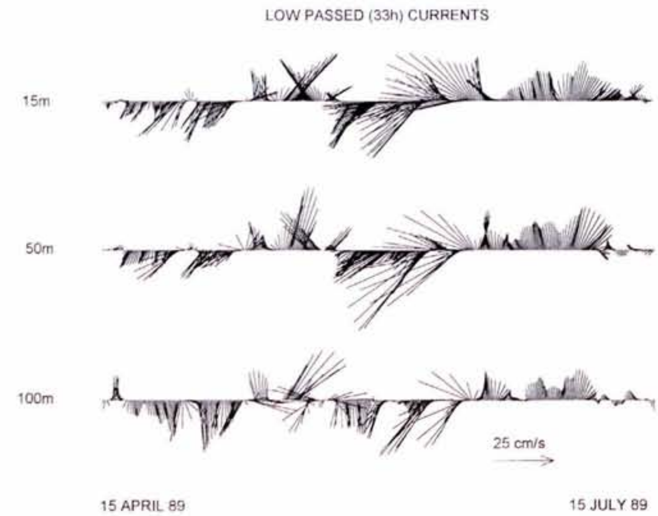


Figure 12

Low-passed (33 h filter) current vector series from 15 April 1989 to 15 July 1989 subsampled every 6 h.

An Empirical Orthogonal Functions analysis of the two components of our three uninterrupted 1988-89 low-passed series in seasonal periods (Table 1) quantifies the barotropicity of the current fluctuations, as stated above. A first mode always explains more than 75 % of the variance of the three series. Maximum values are in winter (99 - 94 % of the variance) while the role of the second mode is relevant in summer and autumn, when it accounts for more than 20 % of the variability at 100 m. The vertical co-oscillation appears to be a major component of the current variability, with only a slight decoupling between an upper and a lower layer when the seasonal thermocline is well established.

Figure 13

Infrared image (channel 4 AVHRR NOAA 11) at 13.30 GMT on 26 June 1989. Processed at the University of Dundee.

Table 1

Percentage of variance explained by the three Empirical Orthogonal Modes in seasonal analysis for the U and V components of the currents measured during one year: July 1988 to June 1989.

	Spring		Summer		Autumn		Winter		
	U	V	U	V	U	V	U	V	
1st	92	89	99	98	90	87	98	95	15 m
	93	94	93	85	90	85	99	97	50 m
	90	87	73	81	85	75	96	94	100 m
2nd	8	9	1	2	10	4	1	4	15 m
	3	0	6	14	10	1	0	0	50 m
	5	11	22	10	0	24	4	5	100 m
3rd	0	2	0	0	0	9	1	1	15 m
	4	6	1	1	0	14	1	2	50 m
	6	2	5	8	14	0	0	0	100 m

As a consequence, we decided to construct one 33 h low-passed time series, using the 50 m records when available (the longest series), complemented by 100 m currents and even by 15 m during 37 days in March-April 1990 under vertical homogeneous conditions. This reconstructed low-passed series (Fig. 14), which we assume to be representative of the fluctuations of the current in "Casablanca", covers 92 % of the five-year period and has been used to analyse the seasonal evolution of the mesoscale motion.

Taupier-Letage and Millot (1986) examined one year of current meter data in different locations of the Ligurian Sea and quantified the mesoscale activity at several depths by computing the variance of low-passed (36 h) currents in periods of 20 days. In the region of the Northern Current they found a marked seasonality, with a stormy period (high mesoscale activity) between December and May, reaching a maximum in February-March, and a quiet period during the rest of the year. A similar activity index was used by Sammari *et al.* (1995) and Albérola *et al.* (1995) with current measurements in the Northern Current off Nice from May to December 1985 and December 1990 to May 1991, respectively. Both papers computed the variance of the low-passed currents, at 100 m or different averages in the surface layer, by periods of 30 days. The results confirmed the seasonality of the mesoscale activity: a rapid increase in autumn up to a maximum in February (200 cm^2/s^2 in the centre of the current), followed by a rapid decrease in March and a smoothed continuous lowering from April till September, when the minimum is reached (10-45 cm^2/s^2 depending on the location).

To evaluate the temporal evolution of the current fluctuations in our reconstructed series, we computed the same index of mesoscale activity: the mean of the variance of the two components of the velocity vector calculated in 30-day periods, shifted one week at a time for the whole set of data. By reproducing the same calculation as that done by previous authors for a long series lasting several years, and at a different point of the Northern Current (some 750 km downstream), we expected to discern any repeated seasonality in the characteristics of mesoscale motion in the NW Mediterranean circulation.

Fig. 15 presents the weekly evolution of this index for the 1987-1992 measurements. Each year, one can observe a rapid increase in mesoscale activity in October with maximum values reached in December, except in 1987 when they were reached early in November. In 1991 the increase begins few weeks earlier. Although the initial trend is always the same, the maximum intensity can vary from 210 cm2/s2 in 1988 and 1989 to less than 100 in 1990. January is characterized by a dramatic fall in activity, followed by an irregular trend in the direction of lower values until the end of the summer.

A remarkable anomaly is observed in 1989, when very high values are found in late spring (more than 110 cm^2/s^2 in June), although in fact every year appears to present a secondary maximum by June-July. The vector series always indicates large current inversions during this season, apparently in relation to the occurrence of intense mesoscale events (Figs. 12, 13). One example of this was also observed by Wang *et al.* (1988), who tracked for several days in June 1986 a rapidly evolving filament a few kilometres south of "Casablanca".

When comparing this seasonal behaviour with the measurements in the Ligurian Sea, a general agreement can be found in the rapid increase in early autumn, the rapid decrease in winter and the continuous lowering until the

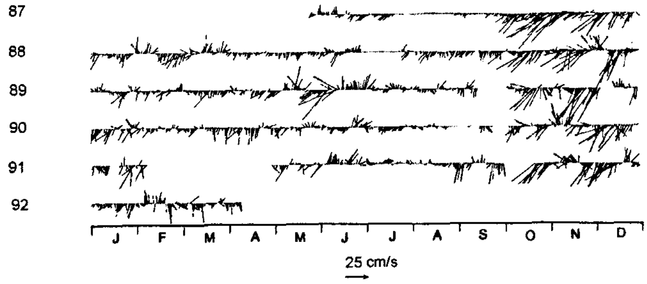


Figure 14

Reconstructed low-passed vector series (50-100 m) for the whole set of data May 1987 - April 1992.

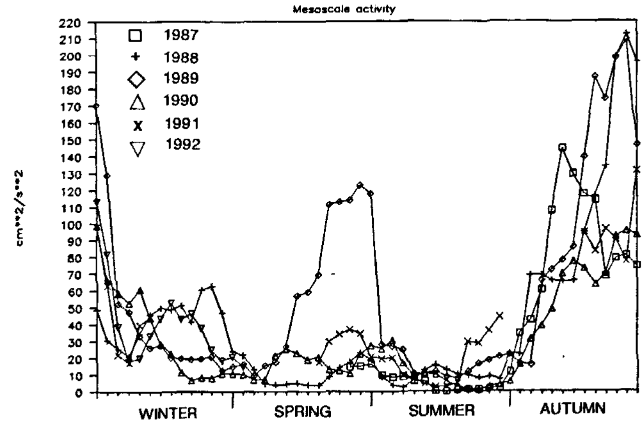


Figure 15

Reconstructed low-passed series: weekly evolution of the mesoscale activity index for natural years (1987 to 1992).

end of summer. However, the most remarkable difference is that our winter maximum and the subsequent rapid decrease take place earlier than in the upstream current measurements. It should be recalled that the "Casablanca" mooring was clearly on the inner side of the current, while the analysed data in the Ligurian Sea were collected at several locations always within 10 km of the core of the jet. The results of Albérola *et al.* (1995) show a time lag in the peak of the mesoscale activity depending on the position of the mooring: it occurs earlier (end of January) at the shoreward point and progressively later as one approaches the centre of the Ligurian Sea, as has also been confirmed in simultaneous measurements done by Astraldi and Gasparini (not published). A tendency towards an open-sea propagation of the mesoscale activity, already observed by Taupier-Letage and Millot (1986), could be responsible for the maximum activity in our data series being recorded by the end of December, one month before the measurements done closer to the jet.

A second distinct characteristic of the mesoscale activity in "Casablanca" is that it is linked to current intensity. Fig. 16 shows the weekly evolution of the current intensity monthly averages calculated from the reconstructed low-passed series. The intensity rise described in the previous section is simultaneous with the increase of mesoscale activity, and the same occurs with the decrease in January, although the lowering in intensity is smoother than in mesoscale activity. It can also be observed that the anomalous high activity in June 1989 occurred with unusually large current intensity. This general intensity-activity correlation does not seem to be present in the inner region of the Northern Current in the Ligurian Sea, since either an increase in intensity is not clearly manifested (Taupier-Letage and Millot, 1986; Sammari et al., 1995) or the mesoscale activity is rapidly decreasing (March) when the intensity is still reaching its maximum values (Albérola *et al.*, 1995).

Fig. 17 presents the weekly evolution at 50 m of the different spectral bands ranging in the mesoscale, for the special period in 1988-1989 shown in Fig. 9. The autumn peak is strongly highlighted due to the contribution of the lower frequency band, while for the rest of the mesoscale bands there

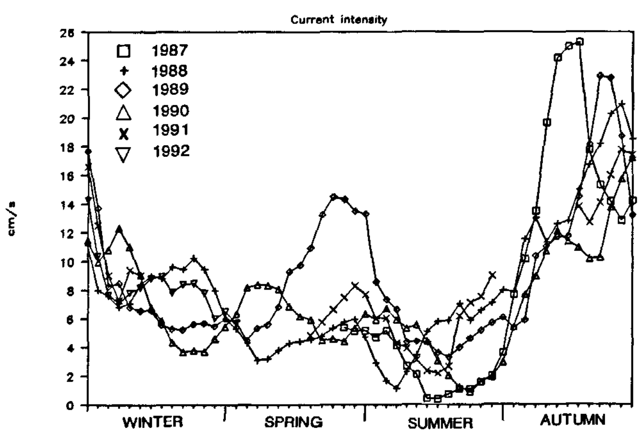


Figure 16

Reconstructed low-passed series: weekly evolution of the monthly mean current intensity for natural years (1987 to 1992).

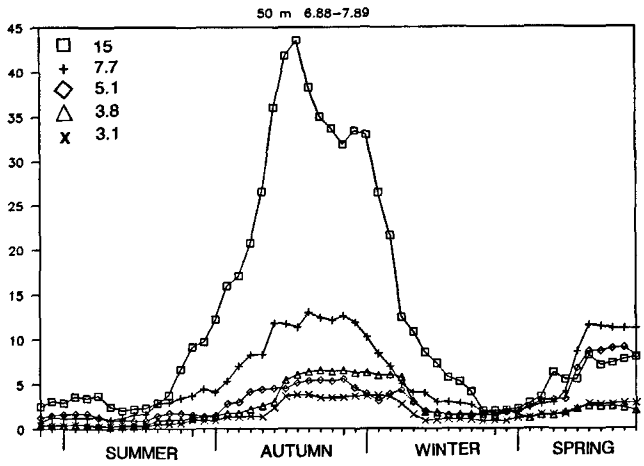


Figure 17

Weekly evolution of mesoscale spectral bands (15, 7.7, 5.1, 3.8 and 3.1 days) at 50 m from mid-June 1988 to mid-June 1989 (relative units).

is no significant difference in the energy during the autumn maximum and the maximum in June 1989. This can indicate that the highest mesoscale activity that occurs every year in autumn is mainly due to fluctuations at larger periods (more than 10 days) than the activity recorded in late spring (3- 10 days). The existence of more rapid but less energetic fluctuations in spring than in winter was also mentioned by the two recent Ligurian Sea papers, associating fluctuations at 10-20 days with current pulses and fluctuations at 3-6 days with meanders.

A careful examination of current, wind and hydrographic data is required to identify clearly the nature of this mesoscale activity. As discussed in the section on the seasonality of the Northern Current, the local wind does not appear to play a key role. Correlation coefficients between wind and currents at 15 m have been computed, and found to be less than 0.5 for periods longer than 3 days. The 1987-92 full set of data contains several examples of mesoscale events with intrusion of offshore water into the "Casablanca" area (evidenced by the temperature records) that have a temporal evolution completely disconnected from the wind variability.

SUMMARY AND CONCLUSIONS

The opportunity of examining several years of current meter data for a point close to the inner border of the Northern Current has definitively revealed the existence of a seasonality in the mesoscale variability. Although the records do not concern the core of the current, the consistency of the several characteristics we have found with findings by other authors concerning the Ligurian Sea, more than 700 km upstream, allow us to consider them as representative of the general trends throughout the Northern Current.

Three current meters moored at 15, 50 and 100 m depth from an oil drilling ring near the shelf break off the Ebro delta, with a considerable coverage from mid-1987 to mid-1992, give a clear image of the current behaviour. The general flow is along-slope, the main characteristic of the Northern Current, and presents occasional disruptions for periods of several days that we have described as mesoscale events. Most of the motion recorded displays a marked barotropic character, as has been quantified by EOF analysis.

The intensity of the current is relatively low, and increases suddenly in autumn at the three levels, in a manner that appears not to be connected to the local wind regime. This increase occurs every year and is similar to what happens in the Corsican Channel (Astraldi and Gasparini, 1992), probably indicating a link with the general seasonal driving mechanism in the entire north-western Mediterranean. However, our records present higher temporal variability in this maximum current intensity, as well as a quite rapid decrease during winter that could be related to upstream processes of dense water formation.

One of the most relevant elements of information contained in the whole current data set relates to the presence of clockwise rotations in a near-inertial frequency. This inertial motion also depicts a seasonal evolution, with maximum occurrence in the upper layer level during the stratified season, shown to be repeatedly present even at 100 m. The enhancing of inertial motions in the lower layers can be due to the vertical transfer of energy by means of internal waves with near-inertial frequencies. This has been demonstrated in the cases of rapidly-moving storms (Gill, 1984; Kundu, 1986) and also in presence of a coastal boundary, where after wind pulses a wave-front is generated on the coast and propagates offshore with near-inertial frequency (Kundu *et al.*, 1983; Tintoré *et al.*, 1995). These inertial oscillations in and below the thermocline are very often observed in the Mediterranean, where they are as intense as the mean flows (Millot and Crépon, 1981; Salat *et al.*, 1992; Font, 1990). In our analysis we have also observed a shift of the inertial frequency and a spreading of the energy towards the near-inertial bands, which is a clear evidence of interactions between inertial motions and a mean current where the frequency is shifted by the vorticity field (*e.g.* Kunze and Sanford, 1984).

The principal objective of the present study was to investigate any seasonal signal in the appearance and characteristics of mesoscale motion. The main observed feature in a low-passed time series below the thermocline, a rapid and strong autumn increase in mesoscale activity, is found to be always present and with very small inter-annual variability as to its temporal location. It should be stressed that this increase has been identified as occurring in early October in four consecutive years. A common property in our data series, coherent with other observations in the Ligurian Sea (Albérola *et al.*, 1995; Sammari *et al.*, 1995) is that the maximum of mesoscale activity is followed by a rapid decrease in winter and then by a continuous decline until the end of the summer. We cannot obtain results on spatial variability, but the evolution in time of mesoscale activity we have recorded, and the location of our sampling site with respect to the core of the current, are consistent with an offshore spreading of mesoscale motion such as has been identified in the Ligurian Sea.

A complete characterization of the mesoscale motion in the Northern Current, including its origin and interaction with the main flow, requires extensive experimental and numerical work. Our results have demonstrated that this motion displays a clear seasonal cycle and provided considerable evidence that the recorded mesoscale activity is linked much more to the shelf/slope front evolution than to local wind variability.

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