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Marine climate on the Costa Brava (northwest Mediterranean) littoral

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ABSTRACT

The temporal variability of the climatologic and hydrographic conditions in the coastal waters of the Costa Brava (northwestern Spanish Mediterranean coast) during 1992-1993 is examined. Besides the seasonal variability typical of temperate zones, the physical and chemical properties studied markedly exhibit both short-term (daily to weekly) and interannual variability. We show this high temporal variability to be associated with three characteristic features of the Costa Brava, namely: the yearly ocurrence of a winter period with high atmospheric pressure and low sea level (locally known as *minves),* the ragged submarine topography which allows intrusion of open-sea waters onshore along the canyons, and the Mediterranean stormy rainfall regime, which induces both short- and long-term variability. The peculiar hydrographic dynamics on the Costa Brava appear to have important consequences for biological productivity, such as the phytoplankton bloom and benthic recruitment triggered during the *minves,* and the high concentrations of nutrients and resuspended sediments during storm events.

Key words: Climatology, hydrology, temporal variability, Costa Brava.

RESUMEN

Clima marino en el litoral de la Costa Brava (Mediterráneo noroccidental)

Se examina la variabilidad temporal de las condiciones climatológicas e hidrográficas en la Costa Brava (costa española mediterránea nororiental) durante los años 1992-1993. Además de la variabilidad estacional propia de las zonas templadas, las propiedades físicas y químicas estudiadas en las aguas de la Costa Brava muestran variabilidades marcadas a corto (diaria a semanal) y a largo plazo (interanual). Mostramos que esta elevada variabilidad temporal está asociada a tres rasgos característicos de la Costa Brava, en concreto el periodo invernal de altas presiones y bajos niveles del mar («minves»)*, la topografía submarina accidentada que permite la intrusión de aguas oceánicas hacia la costa por los cañones, y el régimen de lluvias tormentoso mediterráneo que conlleva variabilidad temporal a corto y largo plazo. La dinámica hidrográfica de la Costa Brava parece tener consecuencias importantes para la productividad biológica, como por ejemplo el crecimiento fitoplanctónico y el reclutamiento bentónico desencadenados durante las* «minves»*, o las altas concentraciones de nutrientes y sedimentos resuspendidos durante las tormentas.*

Palabras clave: *Climatología, hidrografía, variabilidad temporal, Costa Brava.*

INTRODUCTION

The Costa Brava is a stretch of coastline on the northwest Mediterranean that extends for about 300 km from the French border (42°27.63' N, 3° 9.11' E) to Blanes (41°40.12' N, 2°48.10' E), a town 65 km north of Barcelona (figure 1). The Costa Brava is characterised by the adjacent land being dominated by mountains rather than sedimentary basins. This mountainous nature results in a ragged topography, which extends below the shoreline into rocky, steep submarine slopes. The submarine topography of the Costa Brava is characterised by the presence of two large submarine canyons (figure 1), located in Blanes and Palamós, which have major effects on local oceanographic conditions (Masó, La Violette and Tintoré, 1990) deflecting currents and channelling transport of materials derived from land (Masó and Tintoré, 1991).

The Costa Brava has attracted substantial interest from littoral ecologists, because of the unique diversity of ecosystems (e.g. sea-grass meadows, rocky shores, macroalgal beds, marshes, etc.) it comprises, and the existence of protected (Medes Islands) and pristine (e.g. Cape Creus) areas to study. Ecological studies often require an appropriate knowledge of

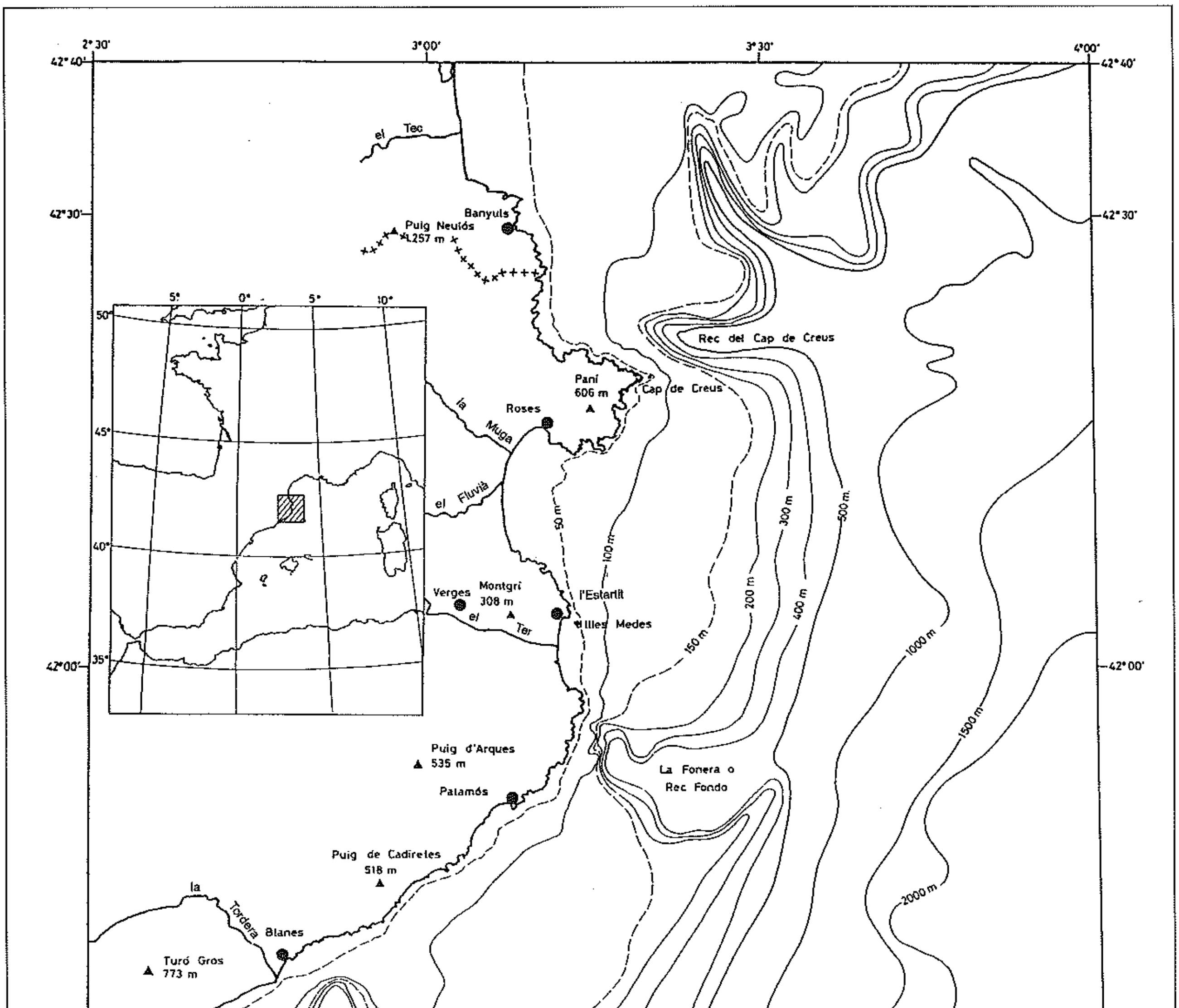

Figure 1. Location and topographic map of the Costa Brava.

the littoral climate (i.e. the environmental conditions that littoral organisms experience). However, no comprehensive description of the marine climate (physical and chemical) of the Costa Brava littoral, which would provide the appropriate framework for these ecological studies, is available as yet, and the existing information is scattered throughout the literature (e.g. Pascual and Flos, 1984; Riba *et al.*, 1979; Font, Salat and Tintoré, 1988).

Here we provide a synthetic description of the littoral climate on the Costa Brava, primarily on the basis of data collected in l'Estartit, Cape Creus, and Blanes (figure 1). Marine climate is represented by basic physical and chemical properties that regulate ecosystem dynamics, emphasising their seasonal dynamics. Hence, we report data on seasonal changes in sun irradiance and associated sea-water temperature dynamics; salinity oscillations; sea-level dynamics, with its wave, tidal, and barometric components; rainfall; water transparency; and seston and nutrient concentrations.

MATERIAL AND METHODS

The data presented is derived mostly from sampling programmes in Blanes Bay and off l'Estartit, the site of the longest data set in the Spanish Mediterranean. Surface seawater temperature and salinity off Blanes was recorded with an Aanderaa model 3210 Salinity-Temperature probe, with sampling frequencies ranging from 0.3 and 12 day^{-1}. Data on wave height off Blanes was taken from a monitoring mooring with a sampling frequency of 12 day^{-1}. Surface water samples were collected at sampling intervals ranging from daily to three-day intervals from March 1992 to February 1993, and weekly from March 1993 to March 1994. Seston

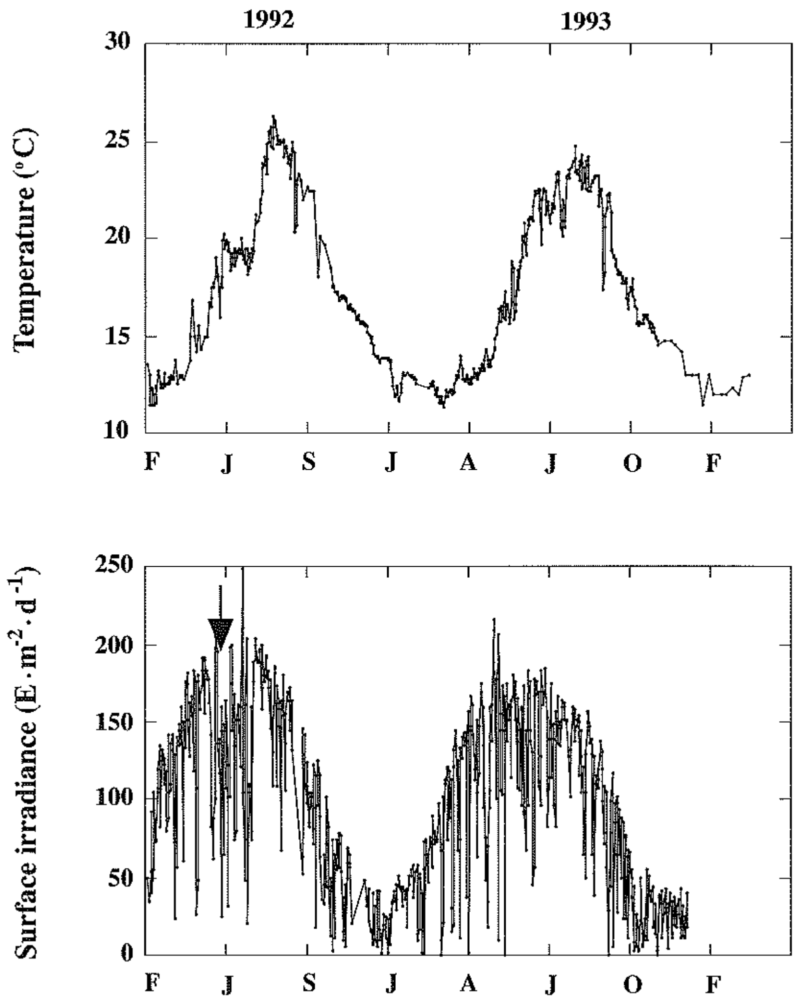

Figure 2. Annual variability of seawater temperature and surface irradiance on the Costa Brava. The arrow indicates the low irradiances associated with the period of intense storms in June 1992.

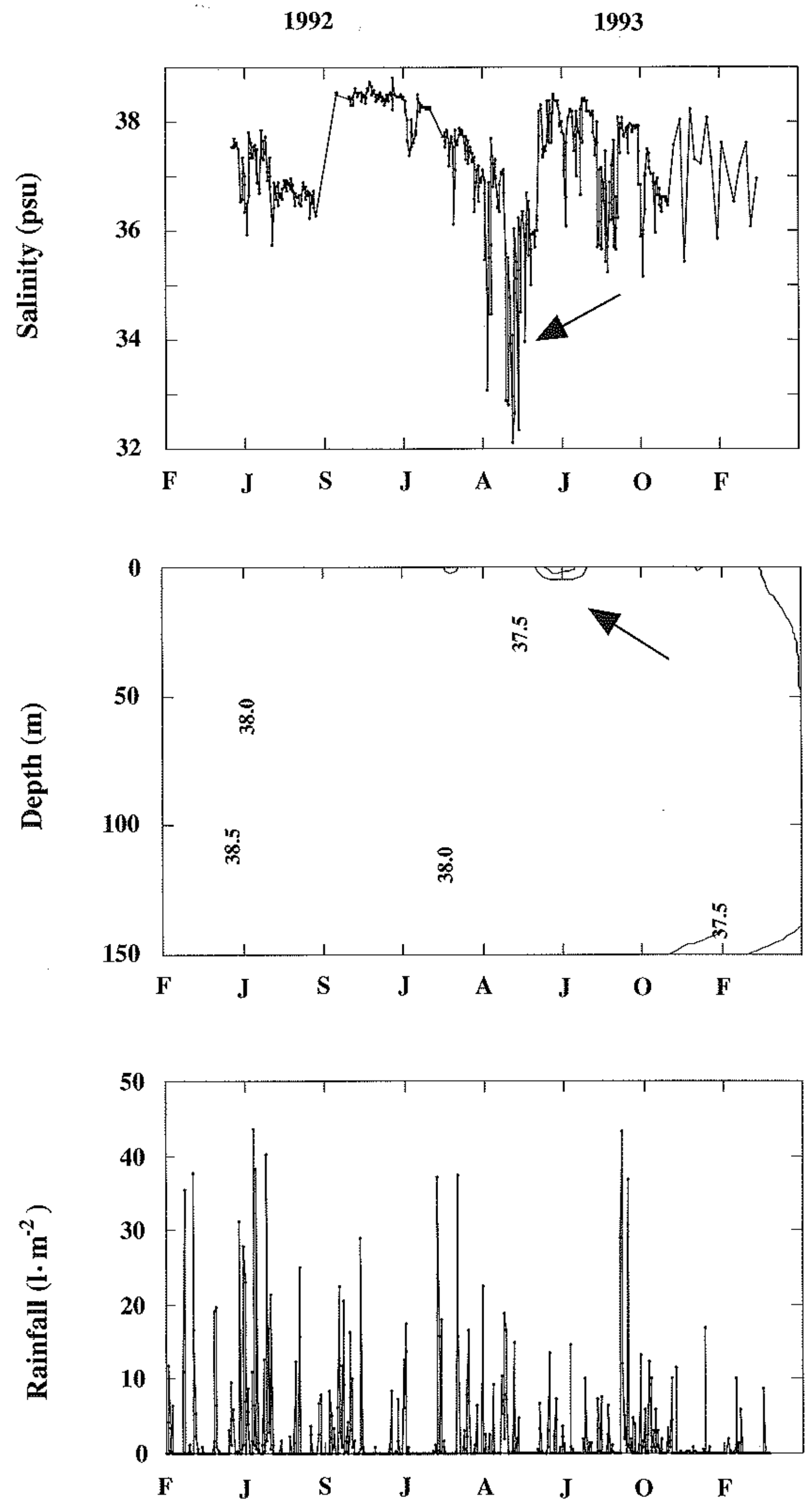

Figure 3. Annual variability of surface seawater salinity, vertical distribution of seawater salinity, and rainfall on the Costa Brava. Arrows indicate intrusions of low-salinity water derived from the Rhone River.

concentrations were determined gravimetrically on dried (24 h at 85 °C) seston samples filtered through Whatman GF/C filters (about 2l). Dissolved nutrient concentrations (nitrate, nitrite, ammonium, and phosphate) were measured on samples preserved by adding about 1 ml of a 5%

chloroform solution and frozen after shaking gently until analysis. Nutrient concentrations were analysed following the procedures described in Strickland and Parsons (1972) on an autoanalyser. Meteorological data (rainfall and atmospheric pressure) for Blanes were obtained from a meteorological station 500 m from the sampling site (Pruna, unpublished data). Complementary data on rainfall for other locations within the catchment of the Tordera River were obtained from two additional meteorological stations (El Vilar and St. Coloma de Farners, about 10 and 30 km inland from the sampling site, respectively).

Data from l'Estartit consisted of sea-level records, derived using a mareograph, transparency measurements obtained using a white Secchi disk, and salinity and temperature profiles (to 150 m), measured in water samples collected with a Nansen bottle carrying an inverted thermometer. Salinity was measured in the laboratory using a salinometer calibrated with standard seawater. These data were collected at weekly intervals from a station situated about one nautical mile off l'Estartit. Surface irradiance (daily values) was obtained from measurements of direct solar radiations at normal incidence, which were registered by a thermoelectric pyrheliometer at a meteorological station (Mas Badia station, Verges) 40 km north of Blanes.

RESULTS AND DISCUSSION

Surface seawater temperature oscillated between 11-12°C and 25-26°C, with the minimum and maximum typically occurring from late January to March, and August to September, respectively (figure 2). These temperatures are about 2°C lower

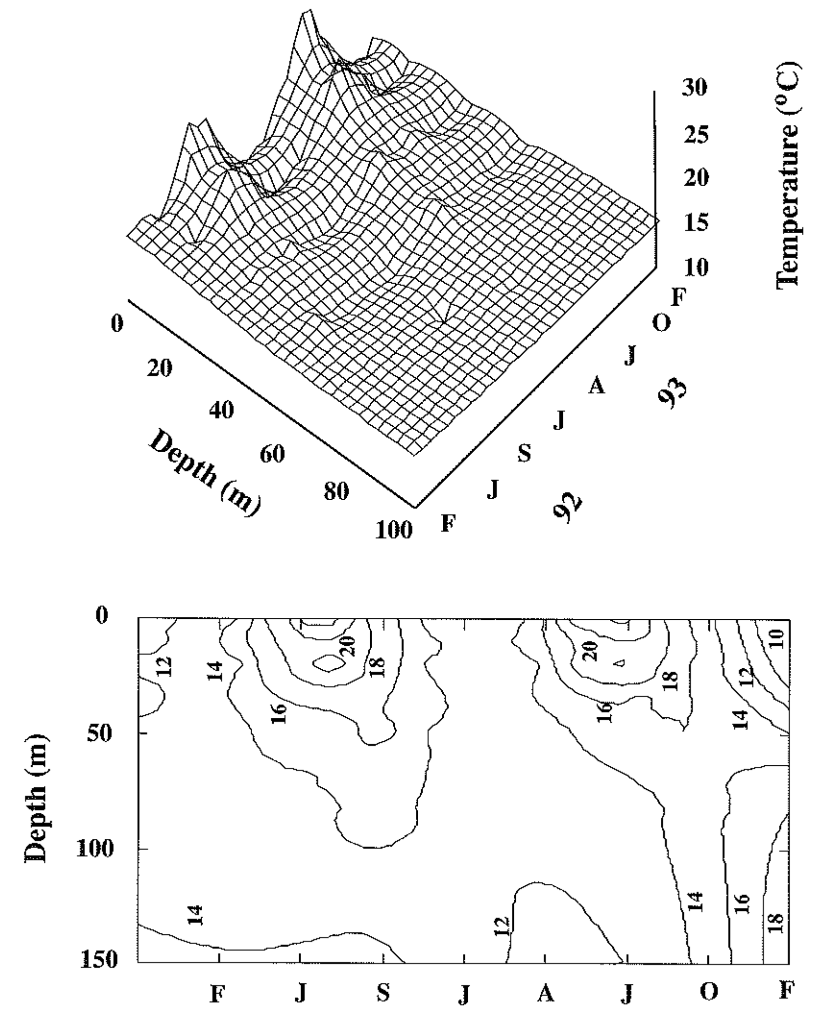

Figure 4. 3-D plot of vertical and temporal variation in seawater temperature, and the annual variability of vertical distribution of seawater temperature on the Costa Brava.

than those registered on the southern Spanish Mediterranean littoral (e.g. Zoffmann, Ramos and Rodríguez-Varela, 1985). Surface temperature patterns also exhibit considerable variability at time scales shorter than seasonal (figure 2). These fluctuations derive from several phenomena, all linked to barometric perturbations and the effect of the associated winds on vertical mixing. Still, surface temperature is much less variable than the incoming irradiance, on which it closely depends (figure 2). Extended anomalies in surface irradiance, such as the reduced irradiance associated with the storms of June 1992 (figures 2 and 3), are responsible for much of the interannual variability in surface sea temperature. Indeed, a large interannual variation in precipitation is one of the characteristics of the Mediterranean region (Pascual and Flos, 1984; Maheras, 1989).

The high irradiance in the summer period is conducive to strong stratification of the water column (figures 3 and 4), with a strong thermocline established from about mid-June to September. The vertical structure of the water column may in fact be rather complex in summer, with several thermoclines developing, between depths of about 15-20 m to about 50 m depth (figure 4), and a tendency to become deeper throughout the summer (Pascual and Flos 1984). There is also considerable interannual variability in the date of thermocline development and erosion (figures 3 and 4), associated with the large variability of storms in spring and fall, the main periods of precipitation in the Mediterranean (figures 2 and 3, *cf.* Pascual and Flos, 1984). Hence, the 1993 thermocline development on the Costa Brava preceded that in 1992 by one month (figures 2-4).

In addition to incoming irradiance, thermocline formation is greatly influenced by the invasion of the Costa Brava by water masses characterised by low salinity (down to 32 psu; figure 3), derived from discharge of snowmelt water from the Rhone River (Castellón, Salat and Masó, 1985; Masó and Duarte, 1989). The littoral of the Costa Brava is occupied by waters with salinity ranging between 37 and 38.4 psu during most of the year. These water masses are characteristic of Mediterranean coastal surface waters and open-sea surface waters, respectively (Masó and Tintoré, 1991). The occurrence of surface waters with a salinity of 38 psu and higher provides evidence of intrusions of oceanic waters into the Costa Brava littoral (Masó and Tintoré, 1991). The characteristics of the surface water masses may be severely altered during the thaw period of the Alps (late May and June), the time of peak discharge of the Rhone River into the Gulf of Lyons (Cruzado, 1985). This leads to large cells of low salinity water that are advected southward along the coast (Masó and Tintoré, 1991), forming patches of low salinity such as the strong intrusion of continental waters from the Gulf of Lyons detected in June 1983 (Castellón, Salat and Masó, 1985; La Violette, Tintoré and Font, 1990; Masó and Duarte, 1989), and that observed on the coast of Blanes in the spring of 1993 (figure 3). The presence of these low-salinity surface waters stabilises the water column, favouring solar heating of surface water and accelerating thermocline formation. This process helps to account for the much earlier (about 40 days) thermocline onset in 1993 compared with 1992, and has important effects on biota (Masó and Duarte, 1989; Sabatès and Masó, 1990).

The properties and dynamics of water masses on the Costa Brava littoral are also greatly influenced by its topography. In particular, the presence of the submarine canyons of Blanes and Palamós (figure 1) has a major effect on local circulation, the canyons acting as barriers deflecting the southward flow, favouring shelf/slope water exchange along these canyons (Masó, La Violette and Tintoré, 1990; Masó and Tintoré, 1991). The predicted vertical transport of water along the canyons (Masó and Tintoré, 1991) has significant effects on the littoral water masses when the absence of thermoclines allows the vertical motions to reach the surface waters. This is reflected in the observations, off the upper end of the canyon in Blanes, of a circadiurnal cycle in surface salinity and temperature, involving large, simultaneous changes in water-mass salinity (up to 2 psu · day^{-1}) and temperature (up to 2°C · day^{-1}) (figure 5).

There is evidence that the important effects of the submarine canyons on oceanographic processes on the Costa Brava littoral also have considerable biological implications. The altered circulation around the canyons favours penetration of oceanic waters to the coastal zone, resulting in reduced phytoplankton biomass (Masó and Duarte, 1989), and the presence of oceanic zooplankton and ichtyoplankton (Sabatès and Masó, 1990; Palomera and Olivar, this volume) in the littoral zone. Moreover, the currents induced along the canyons appear to serve as the major vehicle for transport of materials, located in nephelometric layers moving along the canyons, from land into the deep ocean (Agustí, unpublished results). This

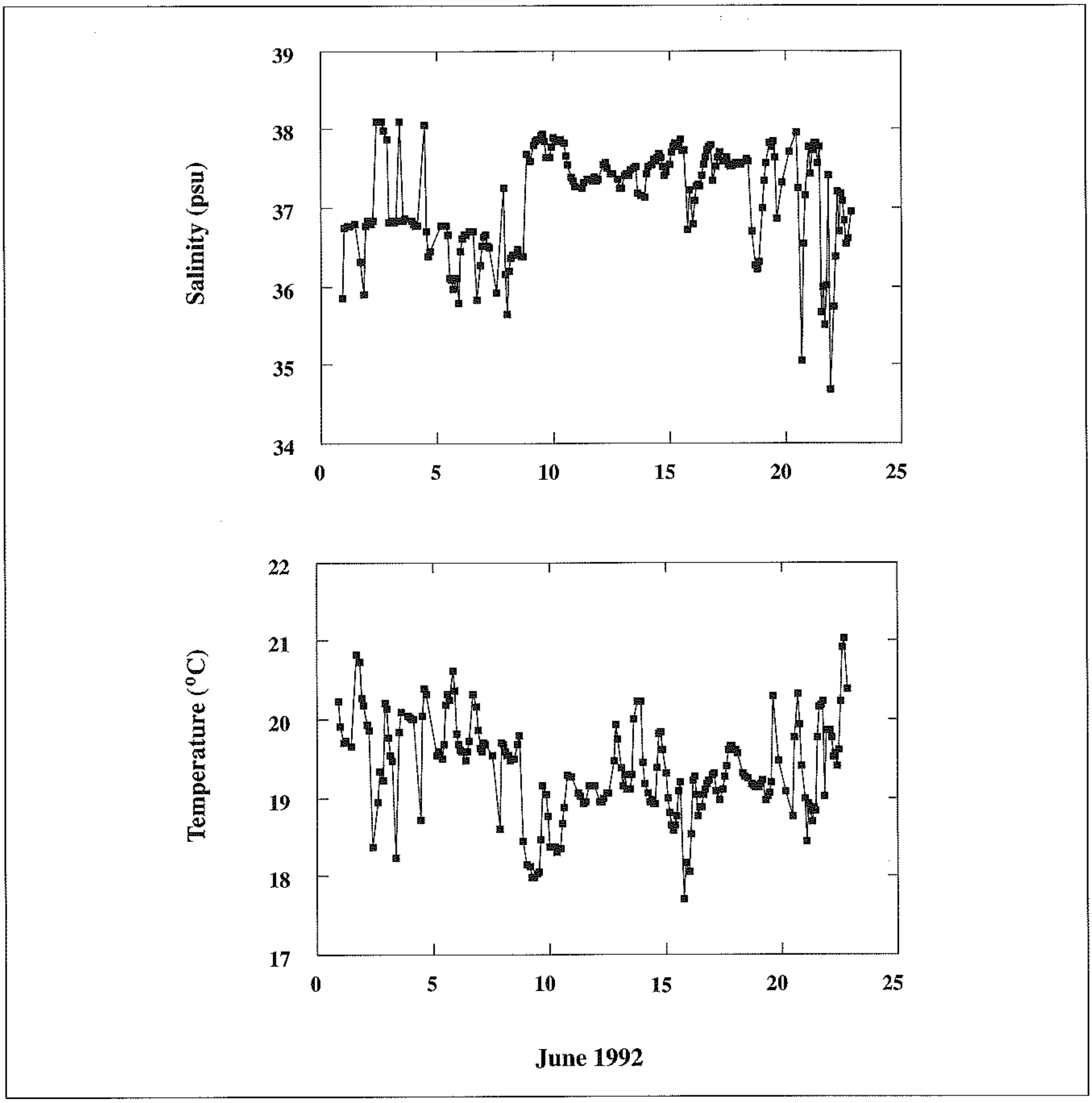

Figure 5. Circa-diurnal variability of surface seawater salinity and temperature in Blanes Bay in June 1992.

load of materials along the canyons must also account for the presence of a major fishery of deep-living prawns (*Aristeus antennatus*, Demestre and Martín, 1993) exclusively located in these canyons.

The topography of the Costa Brava is important in accounting for permanent features of the littoral climate, but cannot account for its dynamics. The physical dynamics on the Costa Brava littoral are intimately linked to changes in sea level (Hopkins, 1985). Sea-level changes show a moderate variation (annual range of daily mean sea level of about 60 cm, figure 6) when compared to littoral zones elsewhere. This variation has, however, important consequences because sea level is closely associated with marine turbulence and currents (*cf.* Hopkins, 1985). Examination of the pattern of daily mean sea level in the northwest Mediterranean shows considerable variability at both short (e.g., weeks) and seasonal time scales (figure 6). In general, sea level is highest during the fall and summer, and is lowest during a period of about 1-2 months early in the year. This winter period of low sea level is a recurrent feature to the point that it has even received a local name (*minves de Gener,* literally

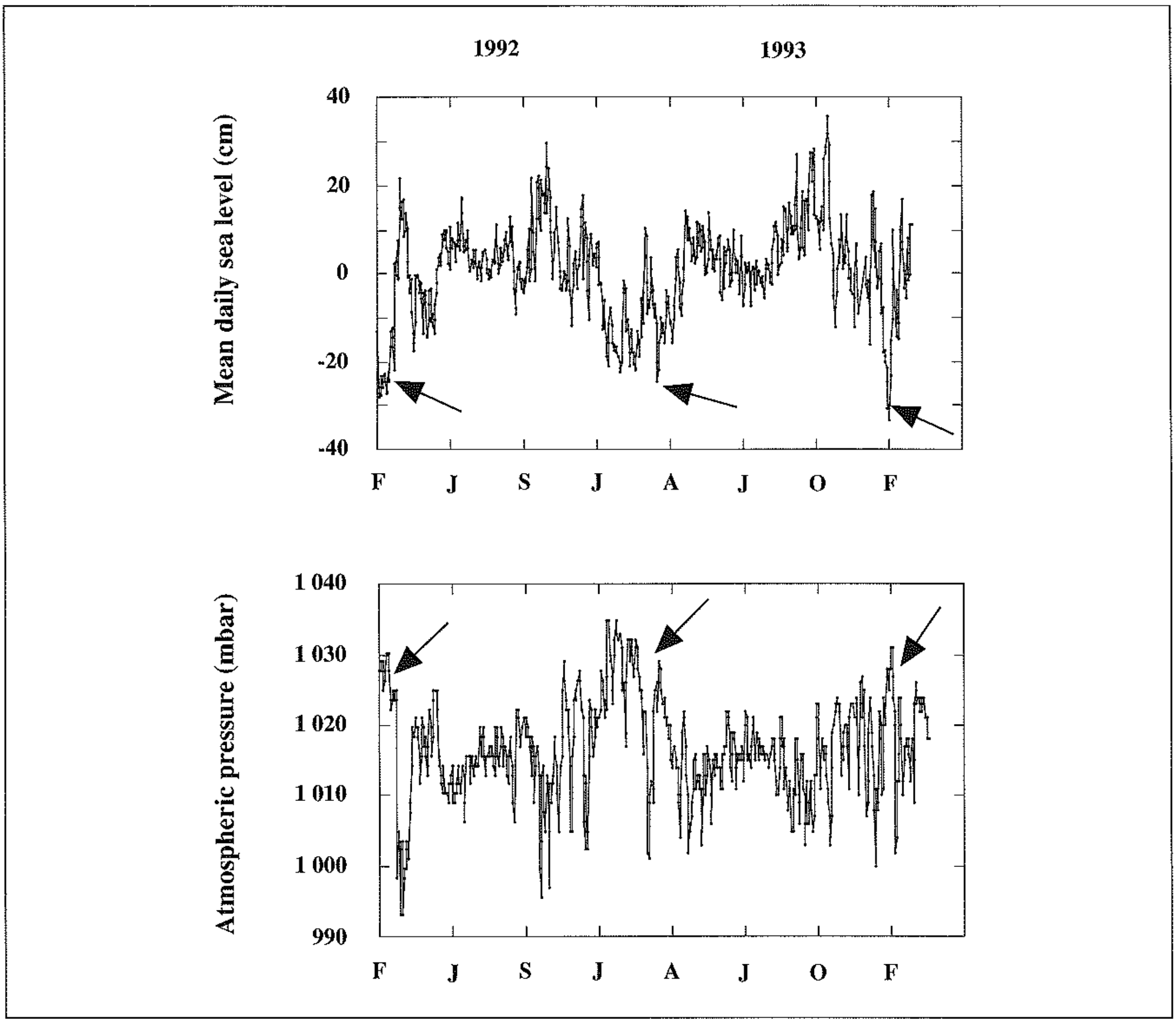

Figure 6. Annual variability of the mean daily sea level and atmospheric pressure on the Costa Brava. Arrows indicate the winter periods of low sea level (minves).

"January vanishing waters"), and is associated with a sustained period of atmospheric stability, with high atmospheric pressure and no rainfall (figures 3 and 6). This winter period of low sea level, promoted by high atmospheric stability, is perhaps the single most important event of the year for biota, for it appears to set the timing of a winter phytoplankton bloom (Mura *et al.*, this volume) and recruitment of benthic invertebrates (Pinedo, Sardá and Martín, this volume; Andreu and Duarte, this volume) and fish (Palomera and Olivar, this volume).

In addition to the clear association of mean daily sea level with atmospheric pressure (figure 6), it is also closely determined by thermal expansion (figure 7). Dial variation in surface temperature and atmospheric pressure together account for 66 % of the variation in mean daily sea level, as described by the regression equation,

$$\text{Sea level (cm)} = 1\,083 + 0.51\ (\pm\ 0.07)\ \text{Temperature (°C)} - 1.07\ (\pm\ 0.04)\ \text{Pressure (mbar)}$$
$$R^2 = 0.66,\ N = 540,\ P < 0.0001$$

which indicates that sea level increases, on the average, half a cm per degree of temperature and decreases one cm per mbar pressure. In addition to thermal expansion and atmospheric pressure, which induce variability in sea level at weekly and monthly (i.e., seasonal) time scales, sea level experiences considerable short-term (hours to seconds) variability. Short-term variability in sea level on the Costa Brava is attributable to the effect of tides, seiches, and waves. The tidal regime of the Costa

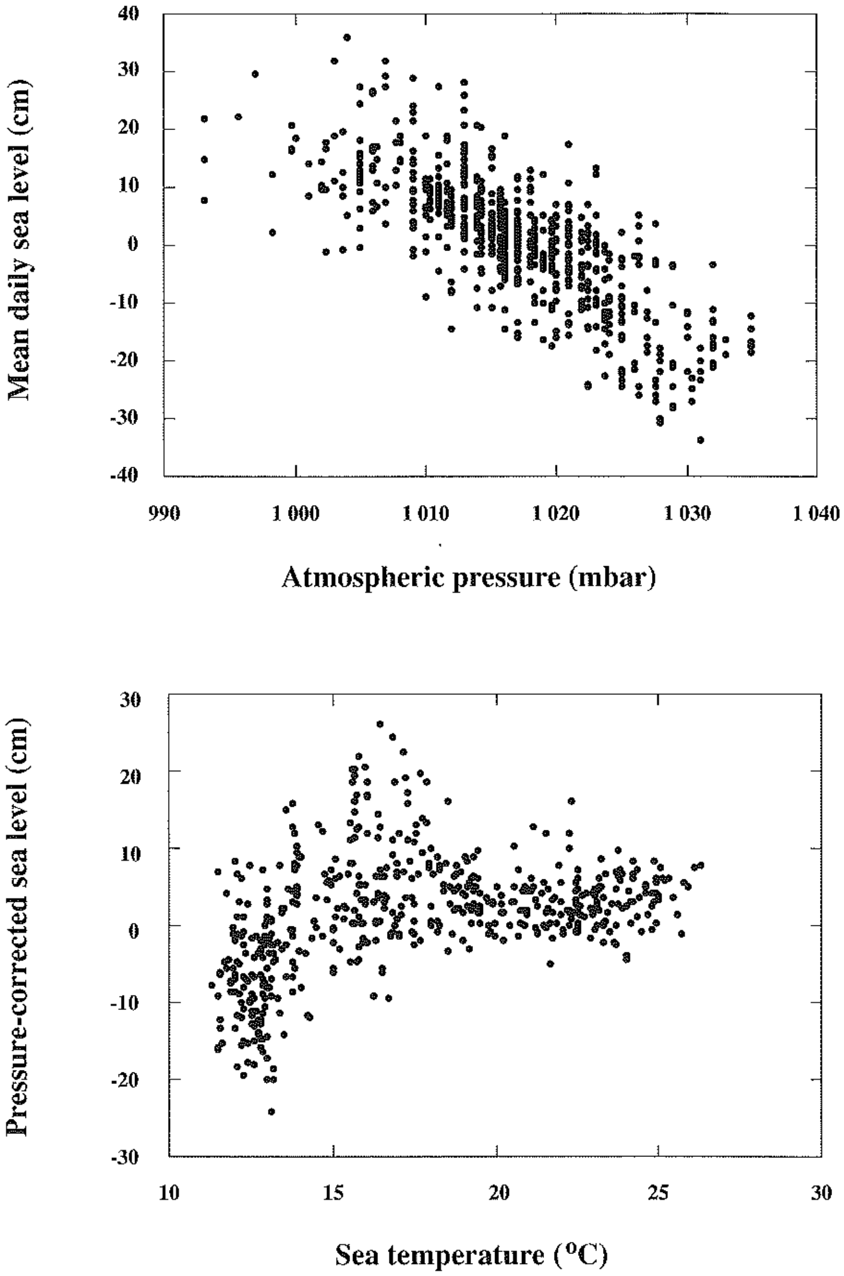

Figure 7. The relationships between the mean daily sea level and atmospheric pressure, and between the pressure-corrected sea level and sea temperature on the Costa Brava. The pressure-corrected sea level is obtained after adding the difference between the registered atmospheric pressure and 1 017 mb (the zero-pressure value for the calibration of the mareograph employed) to the sea-level value measured by the mareograph.

Brava is characterised by a low, but significant, tidal range of about 20 cm, with a semidiurnal period (i.e., two maxima and minima per day) which depends on the lunar cycle (figure 8; Pascual and Flos, 1984). Superimposed on this semidiurnal variation there are seiches, with periods of about 15 minutes (Pascual and Flos, 1984), and involving larger changes in sea level of up to 1 m (figure 8). At yet shorter time scales, there is considerable wave action (figure 9), if smaller than that on open Atlantic shores. Mean wave height (averaged over 2-h periods) ranges from very low over the summer (typically < 0.5 m over the stratified period) to substantial (>1.5 m) during the wind events that occur in the fall and winter (figure 9) in association with sudden drops in atmospheric pressure (figure 6). These short-term components are important because they, large waves in particular, can generate

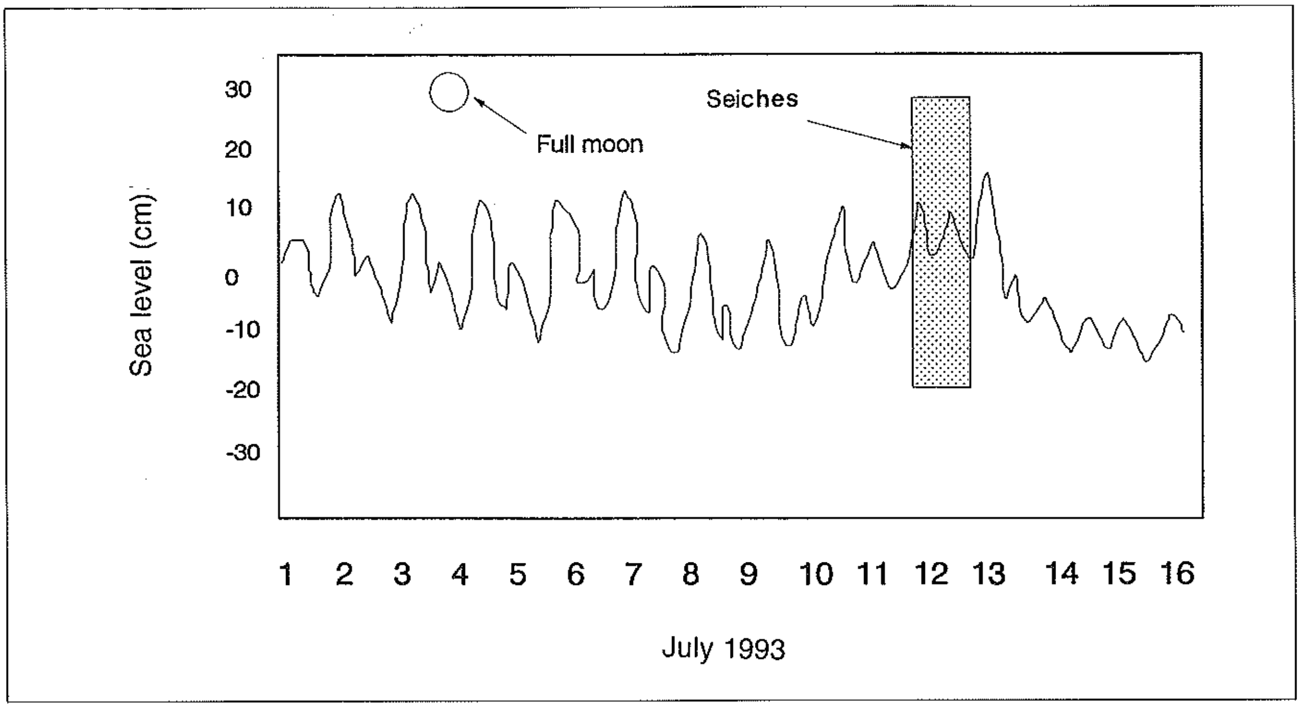

Figure 8. The tidal regime of the sea level on the Costa Brava. The dotted rectangle represents a period of seiches.

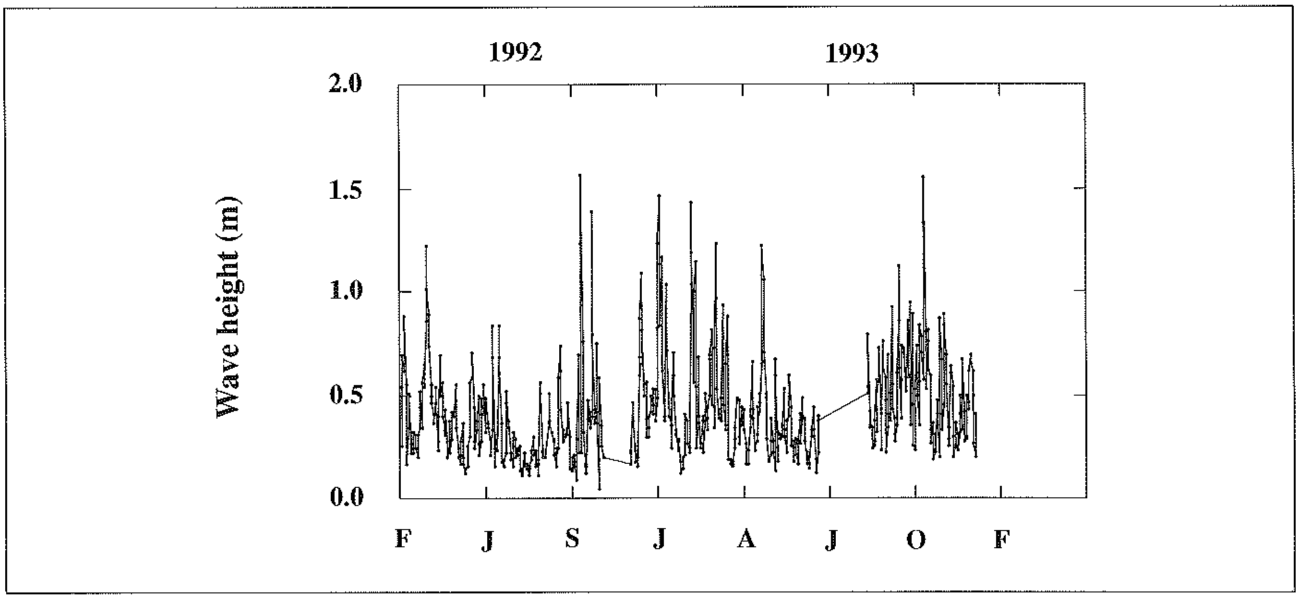

Figure 9. Annual variability of wave height on the Costa Brava.

substantial turbulence, with the associated vertical mixing and resuspension of sediments in the littoral zone, which can shade benthic primary producers (Ward, Kemp and Boynton, 1984; Sand-Jensen, 1989).

Seston concentrations show considerable variation (1.8 to 28.5 mg D.W. l^{-1}) mostly driven by wave effects (figure 10), with organic particles representing 25.7% (± 0.5), on the average, of the seston. Consequently, seston concentrations are highest during the storms in the fall and winter (figure 10), the period of highest wave action (figure 9). Transparency also fluctuates a great deal, ranging from minimal values of about 5 m to maximal values of about 30 m, which occur in summer and fall, respectively (figure 10). Seston concentrations and transparency are also greatly influenced by storm activity and the associated discharge of sediments from the Costa Brava littoral. Hence, the anomalously long period of heavy storms in May-June 1992 resulted in high seston concentrations and relatively low transparency (figure 10).

Nutrient concentrations were relatively low (average (± SE) during 1992 and 1993 in Blanes Bay = 1.18 ± 0.09 μmol · l^{-1} ammonium, 0.11 ± 0.01 μmol · l^{-1} nitrite, 0.96 ± 0.07 μmol · l^{-1} nitrate, and 0.29 ± 0.04 μmol · l^{-1} phosphate), but not so low as expected for an oligotrophic sea. The concentrations measured in Blanes, which could be thought to be influenced by inputs from the nearby population, are comparable to those measured in a pristine, undeveloped site on the northern Costa Brava (average [± SE] over 1993 in Cala Jonquet = 1.42 ± 0.08 μmol · l^{-1} ammonium, 0.12 ± 0.03 μmol · l^{-1} nitrite, 1.15 ± 0.11 μmol · l^{-1} nitrate, and 0.34 ± 0.06 μmol · l^{-1} phosphate; Vidondo, unpublished results). Nutrient concentrations were highly variable at all time scales sampled (figure 11). Phosphorus concentrations can decline to levels close to the detection limit following the winter low sea-level period, associated with the development of the largest phytoplankton bloom in the year (Mura *et al.*, this volume), and exhibit high pulses associated with storm events (figure 11). Nitrate concentrations, in contrast, remain high during winter and decline in the summer (figure 11). These patterns of nutrient concentrations may also vary substantially from year to year, particularly in relation to extreme events, such as the storm period of late spring 1992, which led to high phosphate and nitrate concentrations maintained over the summer of 1992 (figure 11). The substantial variability in nutrient concentrations observed on the Costa Brava littoral may be a general characteristic of the northwest Mediterranean littoral, as indicated by the similarly large fluctuations and the absence of a reiterated

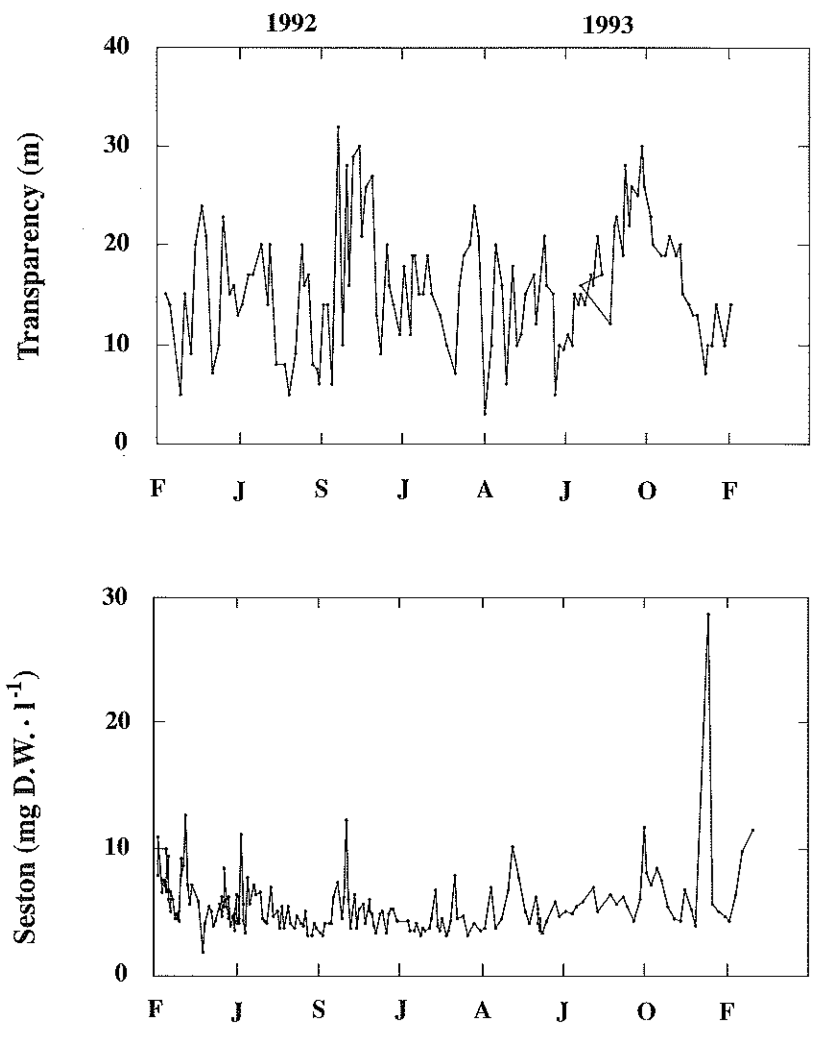

Figure 10. Annual variability of seawater transparency and seston concentration on the Costa Brava.

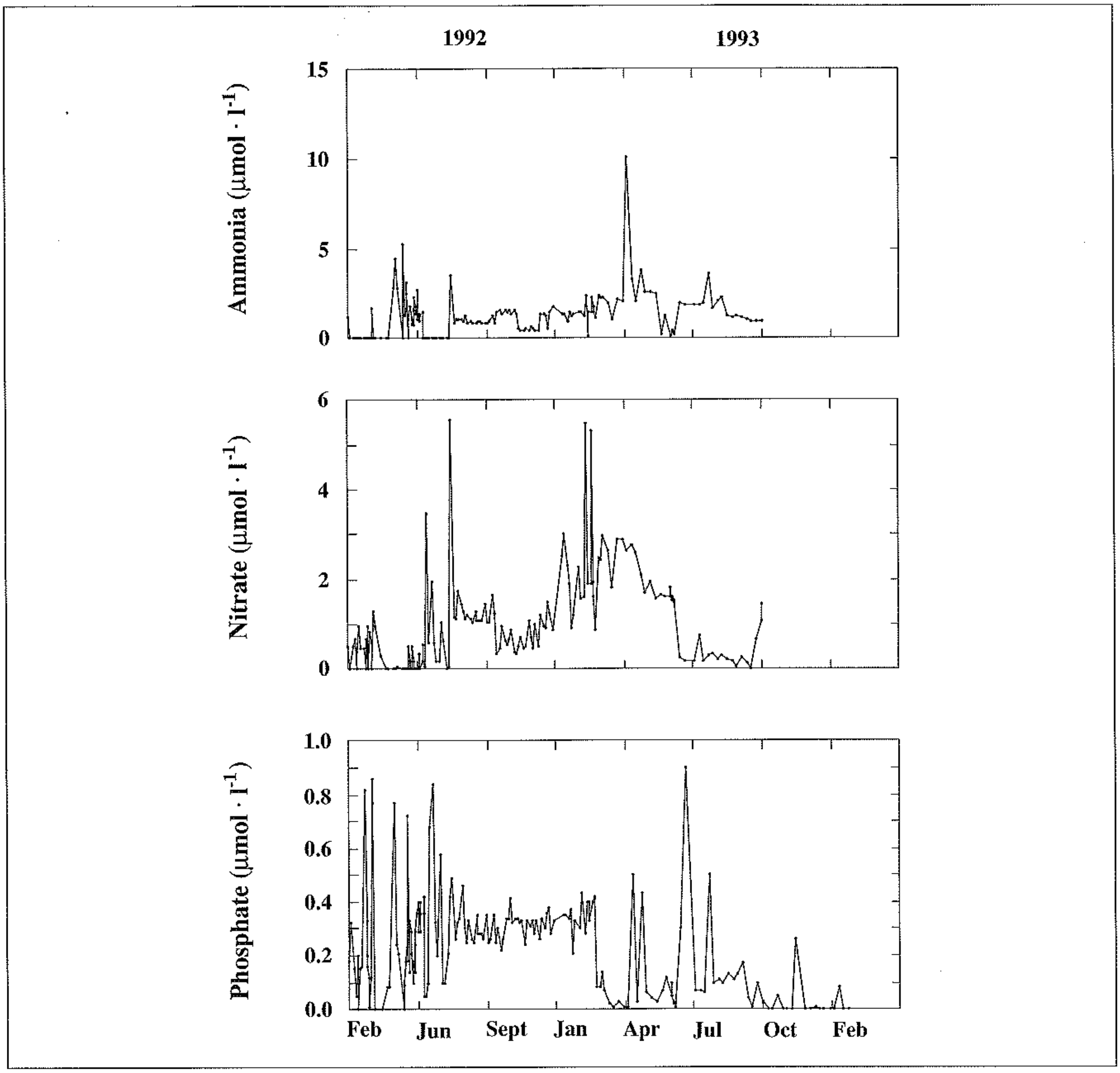

Figure 11. Annual variability of ammonium, nitrate and phosphate concentrations in Blanes Bay.

annual pattern observed elsewhere (Ferrier-Pagès and Rassoulzadegan, 1994).

In summary, the littoral climate of the Costa Brava is dominated, in addition to the seasonal forcing characteristic of the temperate zone, by three main features: (1) the steep topography of the coast, with the great impact of the submarine canyons of Blanes and Palamós on oceanographic and biological processes; (2) the recurrence of the January-February period of high atmospheric pressure and associated low sea level, which appears to be a major factor in the phenology of littoral biota (Mura *et al.*, this volume; Andreu and Duarte, this volume; Pinedo, Sardá and Martín, this volume); and (3) the stormy rainfall regime, characteristic of the Mediterranean climate, which has a major effect on water-column conditions, suspended sediments, and nutrient concentrations. The topography exerts a permanent influence on littoral climate, enhancing exchange of water masses and material transport, the winter high-pressure period acts as an important component of seasonality, and the storm occurrence generates high interannual variability. The combined effect of these three peculiar features blurs the signal imposed by thermal seasonal forcing of the temperate zone to generate a complex and variable climate that strongly constrains biological productivity on the Costa Brava littoral.

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