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Seasonal and mesoscale variability of biological and chemical parameters related to the hydrodynamics of the Ibiza Channel (western Mediterranean)

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ABSTRACT

*The interactions between the hydrodynamics and the spatial distribution of nutrients (nitrates), percentage of oxygen saturation and chlorophyll-*a *concentration were studied by means of a 3-D mesoscale analysis. The data were obtained from four surveys carried out in the Ibiza Channel in November 1990, March 1991 and twice in July 1992. The comparative study of the data showed a high variability due to variations of a cyclonic eddy and a frontal system caused by the incoming modified Atlantic water, layered onto the resident water that flows out of the channel. This phenomenon determined fertilisation by upwelling, as a consequence of the surface-divergence/deep-convergence system associated with the front and the cyclonic gyre.*

Mesoscale spatial variability was closely related to hydrographic parameters. The short life of some small-scale structures can be considered independently of the season, which mainly causes vertical gradients and general circulation.

In November 1990, the relatively low chlorophyll concentrations could be related to transport and diffusion phenomena caused by the intense inflow of the Modified Atlantic Water (MAW) mass. On the other hand, in March 1991, it seems that an enclosure phenomenon was found. The material produced was accumulated in a relatively isolated cyclonic area, horizontally compressed by a northern water mass, which also obstructed the normal inflow of the MAW. This could explain the high chlorophyll concentrations observed in the cyclonic area. The comparison between the surveys carried out in early and mid-July 1992 showed how a single southward displacement of the cyclonic system could have a great impact on the intensity of nutrient inputs and the location of chlorophyll maxima. In both cases, the very high, but patchy, chlorophyll concentrations observed might have been caused by an accumulation mechanism. This mechanism could be based on a joint process involving a slight advective transport and a drop in the phytoplankton's sinking rate through the pycnocline. Also, accumulation of nutrients due to vertical compression of upwelling phenomena reaching the pycnocline may lead to some phytoplankton production near the deep chlorophyll maxima.

Key words: Hydrography, nitrates, oxygen saturation percentage, chlorophyll-*a*, Ibiza Channel, western Mediterranean.

RESUMEN

Variabilidad estacional y a mesoescala de algunos parámetros biológicos y químicos en relación con la hidrodinámica del canal de Ibiza (Mediterráneo occidental).

Este trabajo está basado en el análisis tridimensional a mesoescala de la relación entre la hidrodinámica y la distribución espacial de los nutrientes (nitratos), el porcentaje de saturación de oxígeno y la concentración de clorofila a, *de acuerdo con los resultados obtenidos en cuatro campañas llevadas a cabo en el canal de Ibiza en noviembre de 1990, marzo de 1991 y a principios y mediados de julio de 1992. El estudio comparado de estas cua-*

tro campañas muestra una fenomenología diversa y cambiante, aunque puede ser descrita como variación de un patrón básico consistente en la generación de un sistema ciclónico y un frente originado por el agua entrante en el canal, de procedencia atlántica, situada sobre el agua residente que sale a través de él. Este fenómeno determina la fertilización por afloramiento producido por el sistema divergencia superficial - convergencia profunda asociado al sistema frontal y al torbellino ciclónico.

La variabilidad espacial detectada a mesoescala está estrechamente relacionada con las distribuciones hidrográficas y la escasa duración de algunas estructuras de dimensiones reducidas. En consecuencia, este tipo de fenomenología puede ser considerada independiente de la época del año, que condiciona principalmente los gradientes verticales y la circulación general.

De acuerdo con esto, en noviembre de 1990, las concentraciones relativamente bajas de clorofila a *observadas pueden estar relacionadas con fenómenos de difusión y transporte debido a la intensidad de la corriente de agua de procedencia atlántica. Por el contrario, en la campaña efectuada en marzo de 1991, parece existir un fenómeno de confinamiento del material producido en una cuña ciclónica, que queda relativamente aislada y horizontalmente comprimida por una masa de agua situada al norte de la misma que, simultáneamente, obstaculiza el avance hacia el norte del agua de procedencia atlántica. Esto puede explicar, en parte, las elevadas concentraciones de clorofila observadas en el área ciclónica. La comparación de las campañas realizadas a primeros y mediados de julio de 1992 muestra cómo un simple desplazamiento hacia el sur del sistema ciclónico puede alterar, de manera importante, tanto los aportes de nutrientes como la distribución de los máximos de clorofila. En ambos casos las elevadas, aunque discontinuas, concentraciones de clorofila registradas pueden ser causadas por un mecanismo de acumulación que abarcaría conjuntamente procesos tales como un relativamente pequeño transporte advectivo y la disminución de la velocidad de sedimentación del fitoplancton a través de la picnoclina, así como la acumulación de nutrientes debida a la compresión vertical de los afloramientos que alcanzan la picnoclina, pudiendo permitir la producción fitoplanctónica cerca de los máximos de clorofila.*

Palabras clave: Hidrografía, nitratos, porcentaje de saturación de oxígeno, clorofila *a*, canal de Ibiza, Mediterráneo occidental.

INTRODUCTION

From 1975 to 1979, several interdisciplinary surveys were carried out in the southern and western areas of Majorca, and several studies of nutrient and phytoplankton pigment distribution were published (Deyá, 1978; Durán and Jansá, 1986).

Studies of the vertical distribution of chlorophyll-*a* have shown a clear seasonal pattern (Jansá, 1979; Durán and Jansá, 1986). Surface maxima were recorded in winter and deeper maxima in summer, with intermediate situations in spring and autumn.

The chlorophyll variation is based on the development of the thermocline, which acts as a barrier, reducing the supply of nutrients from deep water, causing a general depletion of nitrates above the thermocline. In contrast, the absence of high vertical temperature or density gradients in the cold season favours the fertilisation of surface layers by convective mixing, (sometimes affecting the entire water column), which explains the winter surface maxima. Nevertheless, high chlorophyll-*a* concentrations appear under the thermocline during the warm season.

Different mechanisms could explain the deep chlorophyll maxima (DCM): sedimentation of phytoplankton from more superficial levels, phytoplankton production near the level of the chlorophyll-*a* maximum or in layers above it and losses of chlorophyll-*a* by grazing, lysis, and bleaching in the upper layers. Cullen (1982) has presented a complete and critical discussion on the DCM. Fernández de Puelles and García-Braun (1989) hypothesised that the DCM observed in the waters off Tenerife was due to accumulation and sedimentation rather than to phytoplankton production. Takahashi and Hori (1984) suggested that the DCM observed in tropical and subtropical waters resulted from a drop in the phytoplankton's sinking rate through nutrient-enriched deep waters, based on the absence of significant differences in the primary production above and at the depth of the chlorophyll maxima (Taguchi, Ditullio and Laws, 1988). On the other hand, sedimentation mechanisms do not completely explain the high chlorophyll concentrations frequently observed at the DCM. High production rates could explain the observed chlorophyll maxima, but they would require adequate light levels and nutrient supply. Anderson (1969) suggested that an active phytoplankton adapted to low light levels should be present at the DCM. Nutrient supply could take place in the oceanic divergence regions.

The important role of the divergence phenomena and the nutrient supply associated with frontal systems in the formation of DCM was shown in the western Mediterranean by Estrada (1985) and Estrada and Margalef (1988).

More recently, a combined physical-biological model (Varela *et al.*, 1992; Varela, Cruzado and Tintoré, 1994) was able to simulate the DCM, taking into account turbulent diffusion and nutrient supply.

Estrada *et al.* (1993) found significant correlations between the depth of the nitracline and the depth of the DCM.

The seasonal pattern of vertical chlorophyll-*a* distributions can be typical of the different regions of the Mediterranean Sea. In addition, it may be a common characteristic of other seas which, until now, have been considered oligotrophic.

The aim of the present study was to obtain a more detailed view of the seasonal pattern's three-dimensional structure. Preliminary analyses of the distribution of physical, chemical and biological parameters in this project's first two surveys have been published in López-Jurado *et al.* (1992) and Jansá, Reñones and Martínez (1992).

The present paper is based on the results of four surveys carried out in November 1990, March 1991 and at the beginning and middle of July 1992. The mesoscale three-dimensional distribution of the nutrients (nitrates), percentage of oxygen saturation and chlorophyll-*a* were analysed in relation to the hydrodynamics in an attempt to carry out a comparative study of their patterns.

The Ibiza Channel (western Mediterranean Sea) has complex hydrographic conditions due to variations of the Balearic front, the instability of the Almería-Orán front and to the eddies derived from the Algerian current. Moreover, its dimensions and bathymetry make this site very suitable for mesoscale studies. For complete analysis the Ibiza Channel's hydrographic conditions, see López-Jurado, García Lafuente and Cano (1995).

MATERIAL AND METHODS

Sampling

Synoptic data were a high-priority objective of the sampling strategy. A network of 54 stations at 9-km intervals was covered in less than five days during each survey (figure 1). The sampling of both chemical and biological parameters was limited to 24 stations in the upper layer between the surface and a depth of 200 m. Seawater samples for analysis of nutrients, dissolved oxygen and chlorophyll-*a* were obtained with Niskin bottles at five standard depths (0, 25, 50, 75 and 100 m), and additionally at 150 or 200 m, depending on the season. At all stations, vertical measurements of conductivity, temperature and pressure were made from the surface to the bottom using a Neil Brown MARK III CTD in the two first surveys and a Seabird SBE-25 CTD in the others. Both instruments were calibrated to ensure precise recordings (López-Jurado, García Lafuente and Cano, 1995).

The dissolved oxygen concentration was determined on board using the Winkler method (Strickland and Parsons, 1972). The percentage of oxygen saturation was calculated according to Weiss's equations (1970). Samples for nutrient analyses were frozen at −20 °C. In the case of chlorophyll-*a*, 1.5-l water samples were filtered through

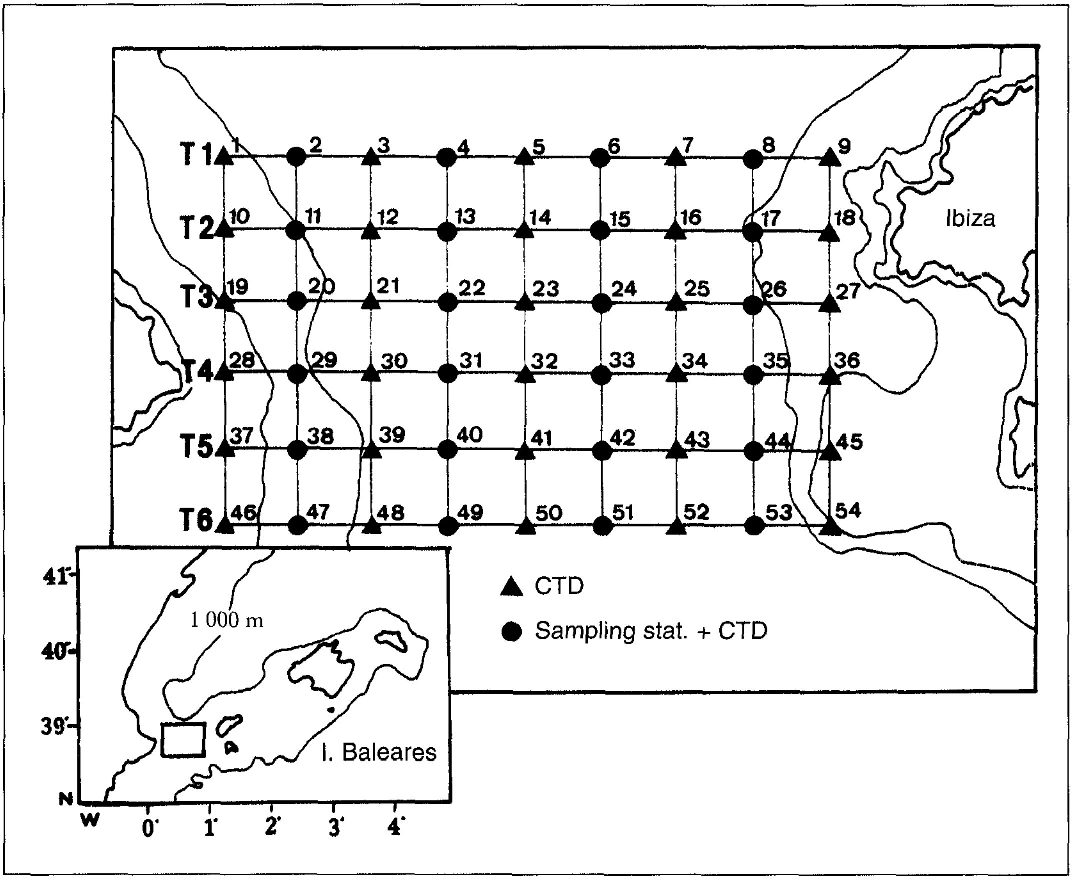

Figure 1. Location of the hydrographic and CTD stations in Ibiza Channel

a Whatman GF/C glass fibre filter which was then frozen at –20 °C.

Laboratory methods

Nutrient (nitrates) analyses were carried out using a Technicon AAII, according to Armstrong, Sterns and Strickland (1967) as modified by Grasshof (1969). Chlorophyll-*a* in 90 % acetone extracts was measured fluorometrically (Holm-Hansen *et al.*, 1965) using a calibrated Perkin-Elmer 204 spectrofluorometer. The general steps of the method followed the recommendations of Anon., 1966.

The anomalies of the dynamic height of several isobaric surfaces relative to a 600-dbar reference level were calculated from temperature and salinity distributions. For sampling stations shallower than 600 m, the anomalies were calculated by extension of the reference level from the nearest station in the same section (Montgomery, 1941).

The spatial distribution of the different parameters was shown by means of vertical west-east sections from north to south and some horizontal distribution maps. The interpolation process was made by means of an objective analysis method (Surfer for Windows software).

RESULTS

Pattern observed in November 1990

The main chlorophyll-*a* maximum (0.8 $\mu g\ l^{-1}$) was located near Ibiza at a depth of 50 m (figure 2). Nevertheless, this maxi-

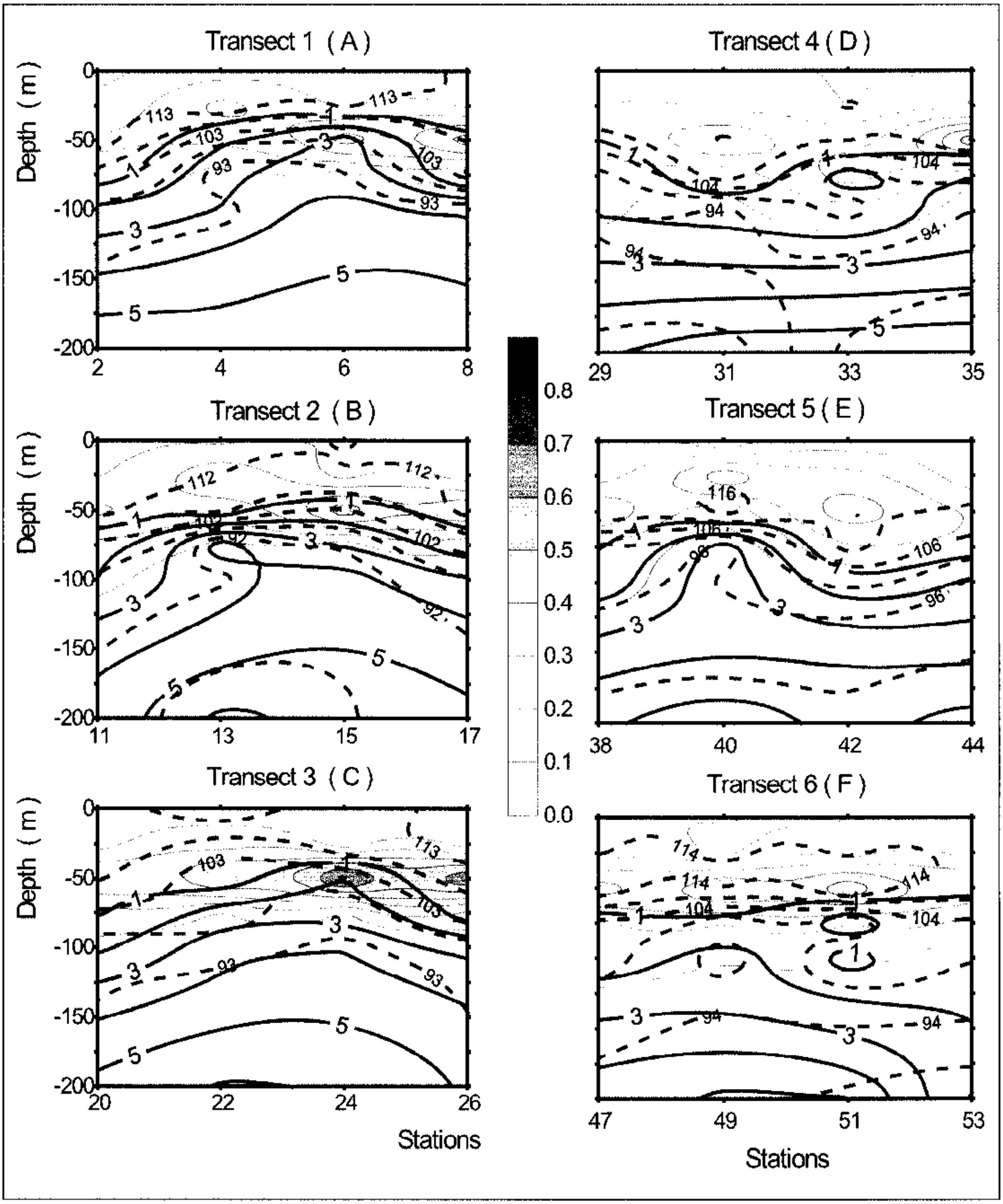

Figure 2. Vertical distribution of chlorophyll-*a* (µg l⁻¹, grey scale), nitrates (µmol l⁻¹, solid line) and percent of oxygen saturation (dashed line) at transects T1-T6 during November 1990

mum was extended at some points (stations 13 and 40) into the upper layers at a depth of 25 m (figure 2A,B,E). This pattern was connected with the distribution of nitrates. The nitracline was located either at or deeper levels than the chlorophyll-*a* maxima. A frequent inverse relationship in the distribution of nitrates and percentage of oxygen saturation was observed.

It should be noted that the chlorophyll-*a* maxima at a depth of 25 m were peripheral to the north and the south of the local nutrient maximum, although both parameters were slightly displaced to the eastern part of the cyclonic region (figure 3A).

The eastern location of the chlorophyll and nutrient maxima from the cyclonic area was more pronounced at a depth of 50 m (figure 3B). Moreover, a displacement of the chlorophyll maxima could be observed towards the east of the highest nitrate concentrations.

Observed pattern in March 1991

The phenomena recorded during this survey were quite different to those

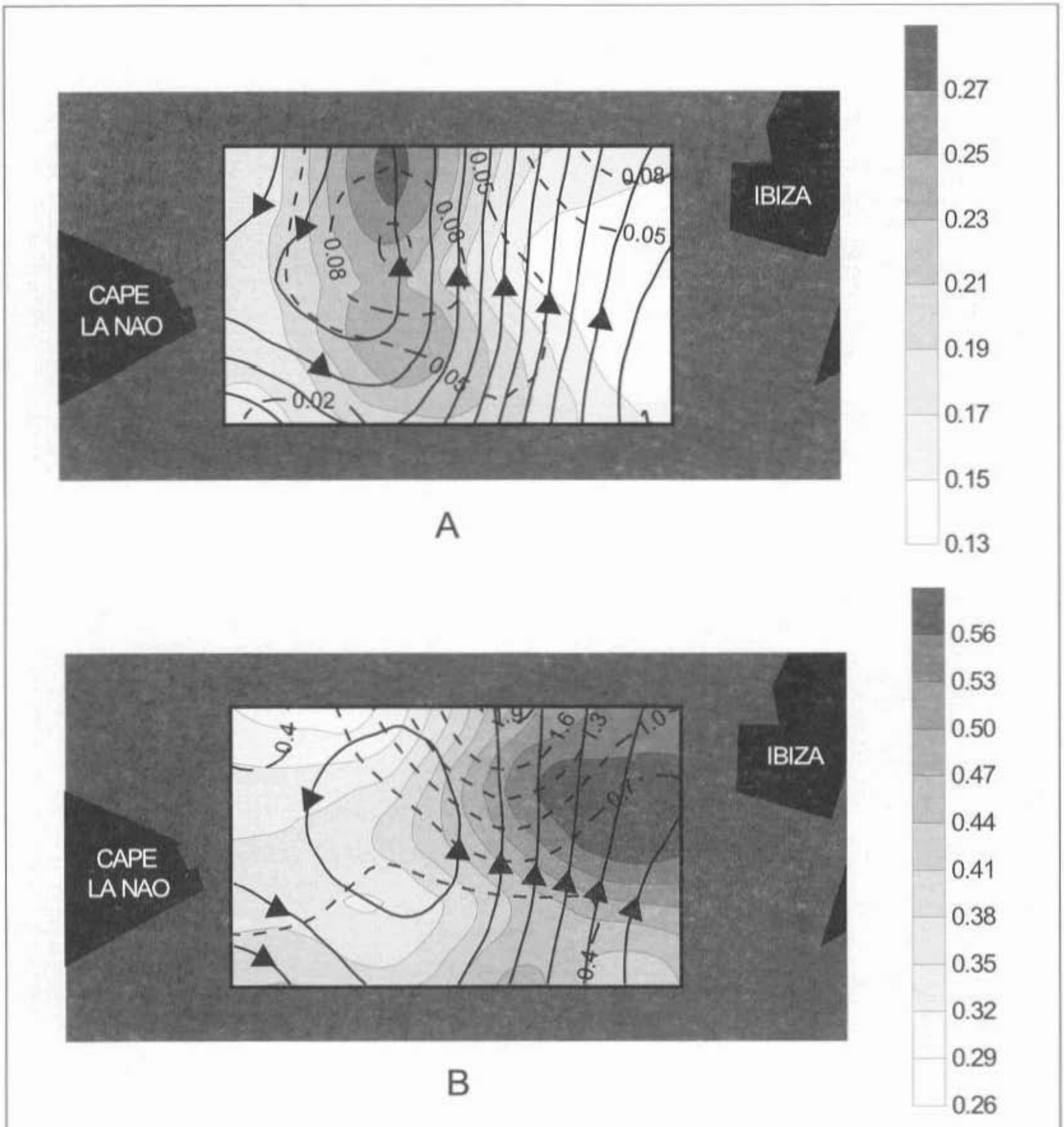

Figure 3. Horizontal distribution of chlorophyll-*a* (μg l⁻¹, grey scale) and nitrates (μmol l⁻¹, dashed line) at a depth of 25 m (A) and 50 m (B) and dynamic topographies (solid line, contour interval: 1 dyn cm; arrows indicate the direction of the flow) of 20 dbar (A) and 60 dbar (B) relative to the surface of 600 dbar during November 1990

observed in November 1990. In the vertical transects, the channel could be divided into two different parts. The northern part (transects 1, 2 and 3) showed a stratified pattern (figure 4A-C) while in the southern part (transects 4, 5 and 6) the nitrate gradients which paralleled the distribution of the percentage of oxygen saturation were very clearly and closely related to the chlorophyll-*a* maxima (figure 4D-F). These maxima, recorded at a depth of 25 m, were relatively high, reaching values around 1 and 2 µg l⁻¹. Furthermore, the horizontal distribution of these chlorophyll peaks coincides

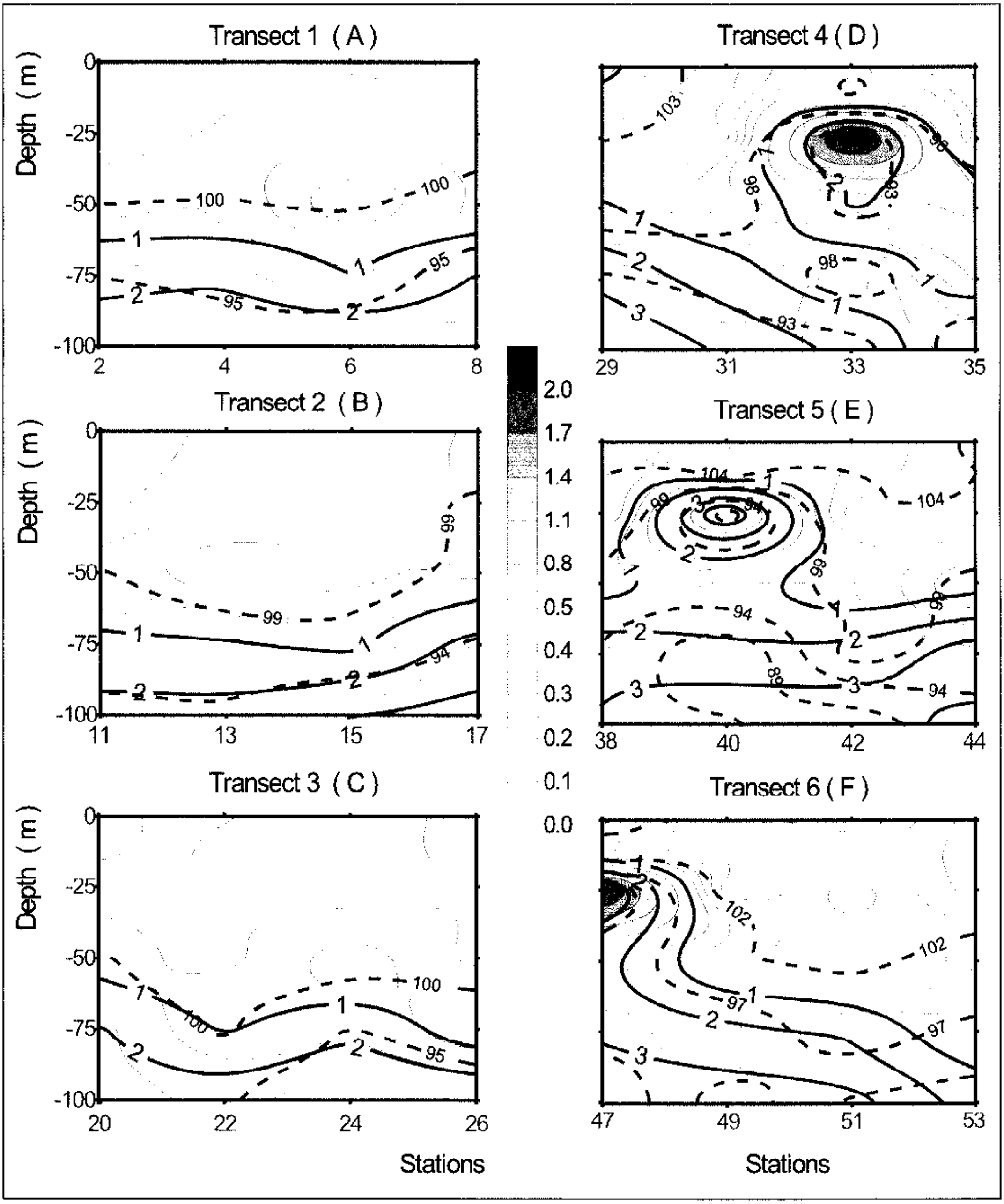

Figure 4. Vertical distribution of chlorophyll-*a* ($\mu g\ l^{-1}$, grey scale), nitrates ($\mu mol\ l^{-1}$, solid line) and percent of oxygen saturation (dashed line) at transects T1-T6 during March 1991

with very steep nitrate gradients, corresponding to dynamic topography (figure 5).

Patterns observed in July 1992

During the summer, the formation of a strong nitracline and an oxycline was detected. In the first survey, some high nitrate gradients appeared connected with very high chlorophyll concentrations at a depth of 50 m (figure 6C-E). At station 26 in particular, the chlorophyll-*a* concentration exceeded 6 $\mu g\ l^{-1}$. Taking into account all the available data from surveys carried out near the Balearic Islands (Durán and Jansá, 1986; Forteza, Martínez Taberner and Moyá, 1988), this was the highest chlorophyll value recorded in the Balearic Sea. The dynamic topography of 50 dbar relative to 600 dbar showed the existence of cyclonic circulation with general features similar to those observed during November 1990. Taking into account the horizontal distribution of the chlorophyll maxima at a depth of 50 m, it showed high chlorophyll concentrations, which could be found in the northern and southern parts of the gyre. The peak was found close to the Ibiza slope, coinciding with higher nitrate concentrations (figure 7).

Fifteen days after finishing the first survey, the whole sampling process was repeated in another survey carried out in mid-July, and the distribution pattern was quite different.

Some nitrate vertical gradients were smoothed or remained as a residual phenomenon (figure 8). The chlorophyll-*a* maxima decreased and even disappeared at some points (compare figures 8 and 6). The most remarkable aspect of the vertical distribution was the 'summer normalization' with its chlorophyll maximum at a depth of 75 m, whereas previously it was at 50 m. A high chlorophyll concentration at a depth of 50 m (station 24, figure 8C), could be explained as being a residual part of the maximum found at station 26 in the previous survey, but displaced westwards. The westward displacement with depth of chlorophyll maxima is clearly shown in figure 9A-B, and it seems to be related to the change in the direction of flow observed in the dynamic topography maps (see figures 7 and 9).

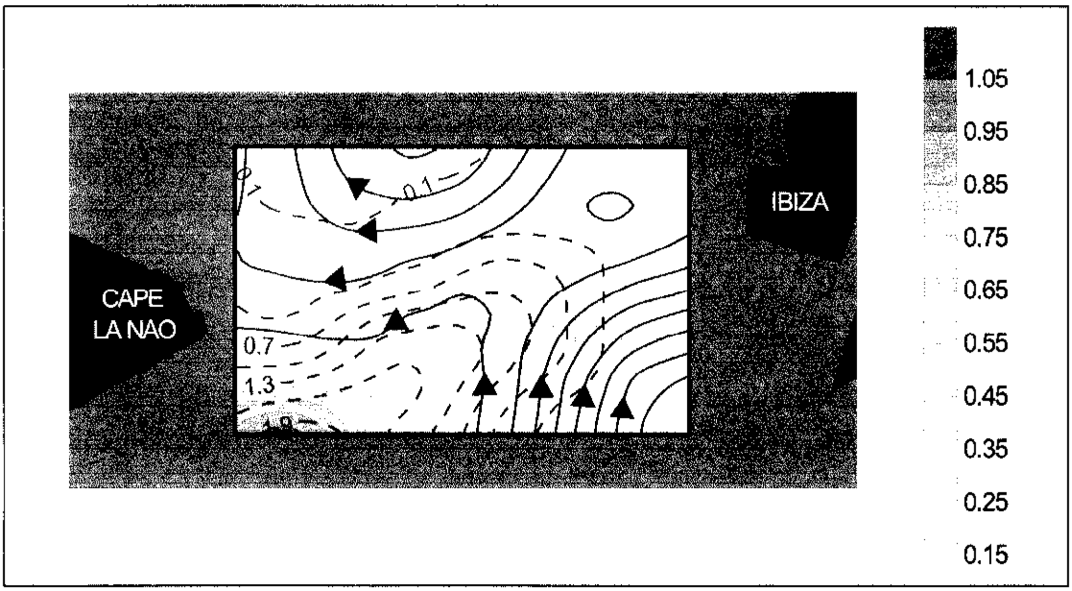

Figure 5. Horizontal distribution of chlorophyll-*a* ($\mu g\ l^{-1}$, grey scale) and nitrates ($\mu mol\ l^{-1}$, dashed line) at a depth of 25 m and dynamic topography (solid line, contour interval: 0.5 dyn cm; arrows indicate the direction of the flow) of 20 dbar surface relative to the surface of 600 dbar during March 1991

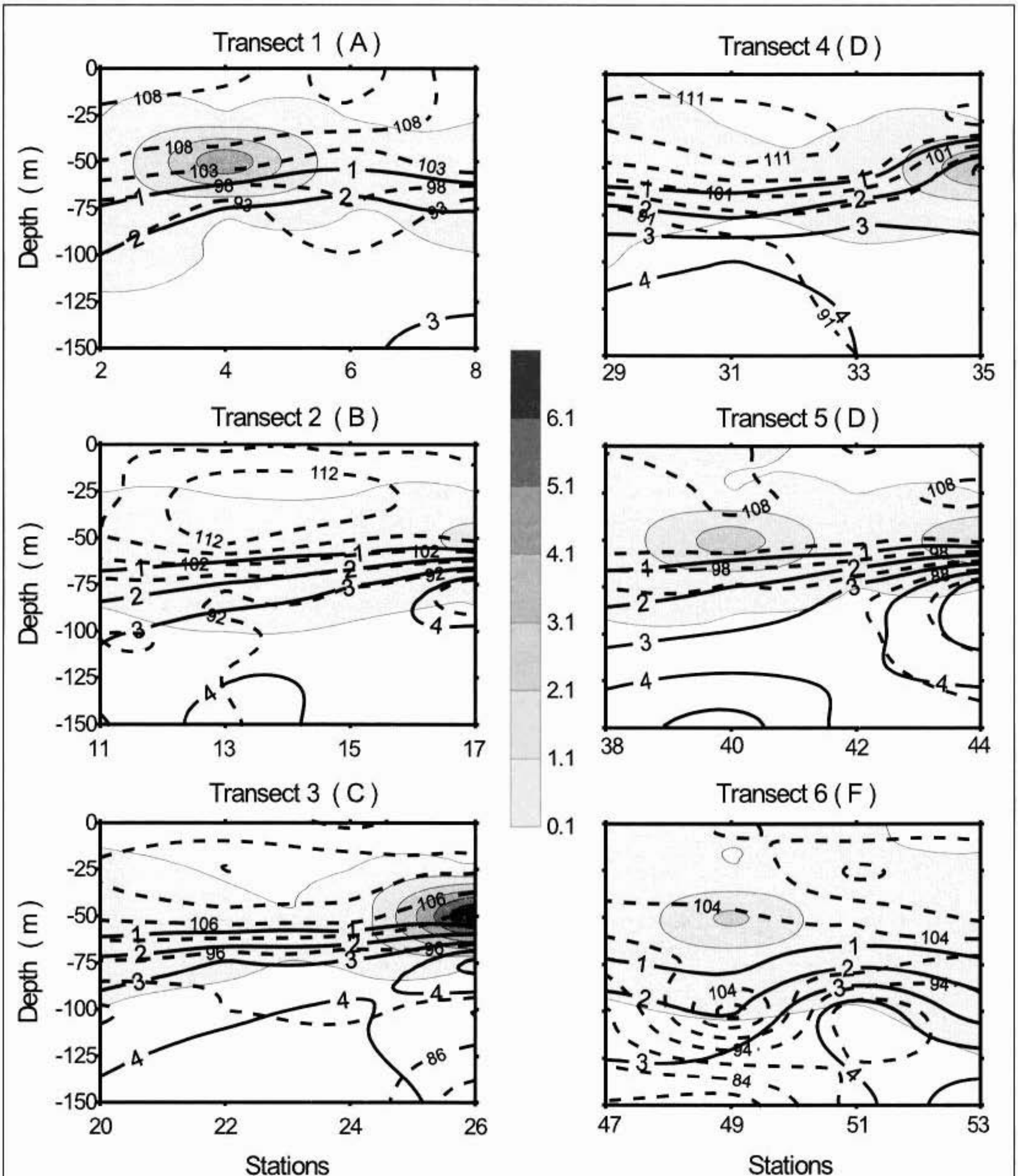

Figure 6. Vertical distribution of chlorophyll-*a* (µg l-1, grey scale), nitrates (µmol l-1, solid line) and percent of oxygen saturation (dashed line) at transects T1-T6 in early July 1992

DISCUSSION

The cyclonic region detected in the dynamic topography maps in November 1990 was generated by the northward flow of the Modified Atlantic Water (MAW) and the southward flow of Atlantic Local Water (AAL) along the topography of Cape La Nao (García Lafuente *et al.*, 1995). The juxtaposition of these two water masses created a frontal system, and a superficial divergence caused by the cyclonic eddy was compensat-

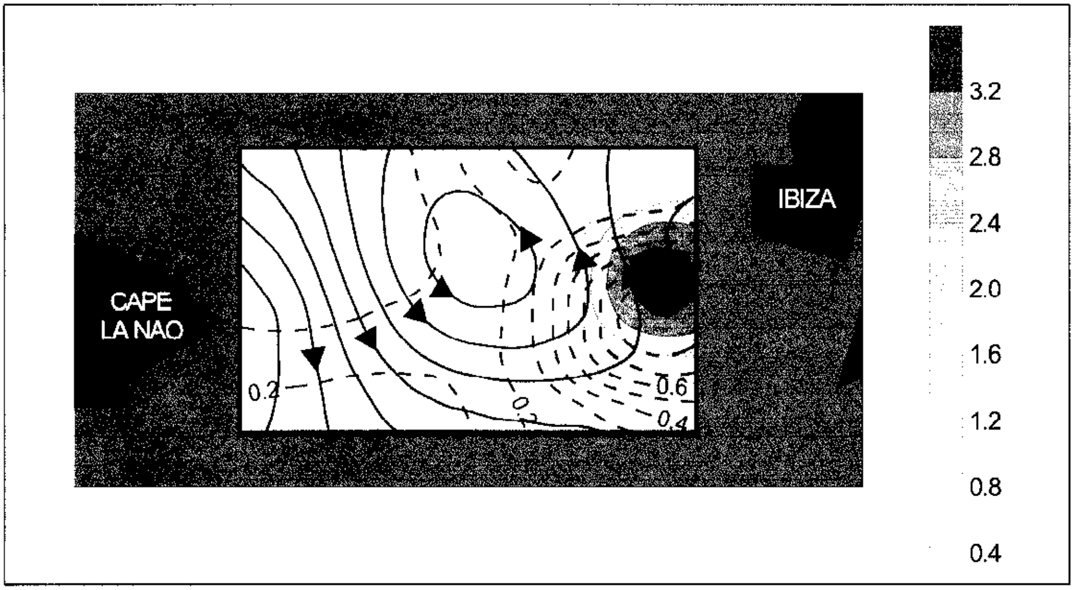

Figure 7. Horizontal distribution of chlorophyll-*a* (µg l⁻¹, grey scale) and nitrates (µmol l⁻¹, dashed line) at a depth of 50 m and dynamic topography (solid line, contour interval: 0.5 dyn cm; arrows indicate the direction of the flow) of 50 dbar surface relative to the surface of 600 dbar in early July 1992

ed by an upwelling from the deepest regions. This upward movement has been calculated recently (Pinot *et al.*, 1995) and seems to be more intense in the cyclonic region (about 4 m/day). This slow rise would take place following the isopycnal surfaces. The dynamic topography maps (figure 10A) showed a progressive horizontal enlargement of the cyclonic eddy and a simultaneous drop in the dynamic relief with depth. This resulted in a decrease of current velocities, from 39 cm s⁻¹ to 11 cm s⁻¹ (Pinot *et al.*, 1995). From these features, we can consider that the upward movement was not only acting in the core of the cyclonic gyre, but was also operating (perhaps more slowly) in the frontal region (border of the MAW current) and in the eastern part of the front. The upwelling caused the bending of the top of the pycnocline (weak but detectable in November 1990) (figure 11A). This bending was in some way favoured by the less dense MAW in the eastern part of the channel.

The distribution patterns of nitrates and the percentage of oxygen saturation (figure 2) are the result of this upward movement acting as a fertilisation mechanism. In every case, the upwelling may not be linear and may show complicated behaviour related to different factors, such as slope topography, submarine mountains, internal waves and convective mixing. In addition, other factors, e.g. nutrient consumption by phytoplankton and grazing, could explain some morphological variations, somehow masking the typical divergence pattern. Notwithstanding, the agreement between hydrographic phenomena and nitrate gradients and chlorophyll maxima detected in the mesoscale study supports the idea that the main features of chlorophyll distribution may be explained only on the basis of hydrographic fertilisation mechanisms. In fact, the model of Varela, Cruzado and Tintoré (1994) indicates that grazing or sinking are not needed in the generation of the main DCM features.

The distribution pattern observed could be considered a single phenomenon related to the superficial divergence-deep convergence described above. As mentioned previously, the chlorophyll-*a* maxima placed at a depth of 25 m (approximately 0.5 µg l⁻¹)

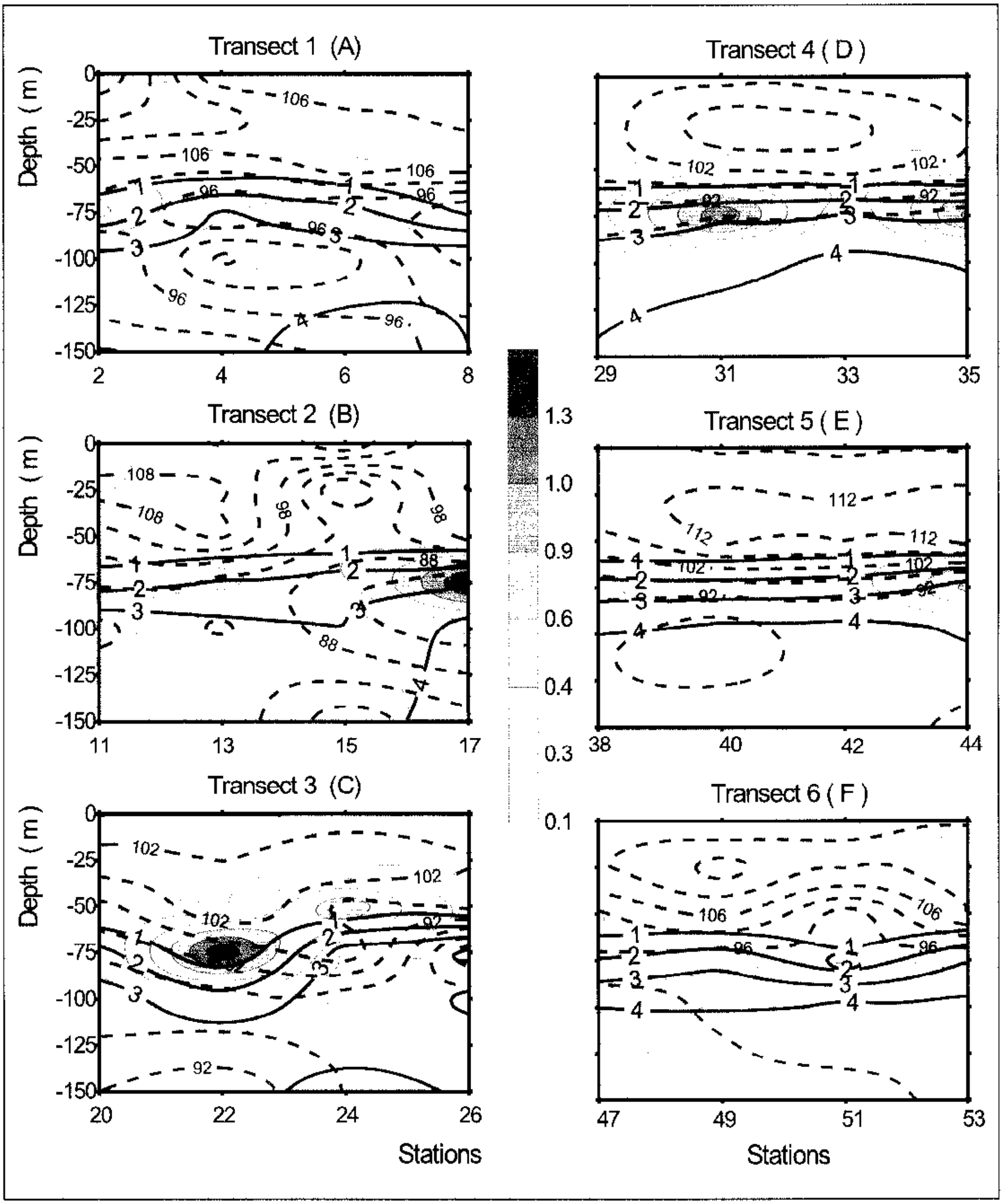

Figure 8. Vertical distribution of chlorophyll-*a* (µg l^{-1}, grey scale), nitrates (µmol l^{-1}, solid line) and percent of oxygen saturation (dashed line) at transects T1-T6 in mid-July 1992

were located slightly eastwards in the northern and southern part of the cyclonic gyre (figure 2-A). These moderate maxima may be the consequence of a local nutrient supply (figure 2B,E). However, their peripheral location in the cyclonic region was probably due to the transport from the upwelling region to areas with low momentum, where phytoplankton was accumulated. The nutrient supply was probably extended within the MAW current, although the fertilisation processes were restricted to the deeper lev-

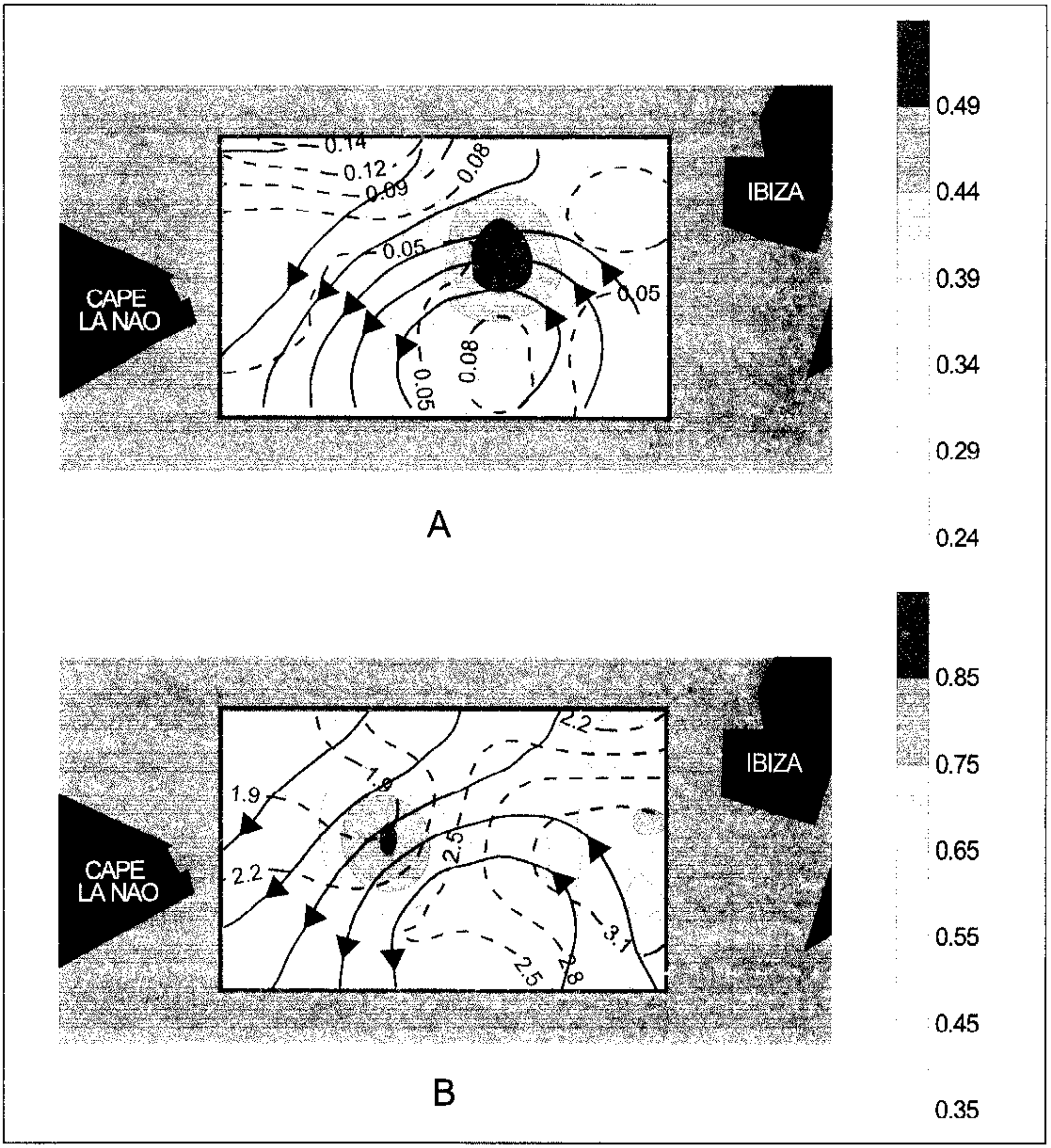

Figure 9. Horizontal distribution of chlorophyll-*a* (µg l^{-1}, grey scale) and nitrates (µmol l^{-1}, dashed line) at a depth of 50 m (A) and 75 m (B) and dynamic topographies (solid line, contour interval: 0.5 dyn cm; arrows indicates the direction of the flow) of 50 dbar (A) and 75 dbar (B) surfaces relative to the surface of 600 dbar in mid-July 1992

els and generated the chlorophyll-*a* maximum at a depth of 50 m (up to 0.8 µg l^{-1}). Possibly this was a result of the enhanced current in the upper layers and the presence of the pycnocline. Thus, the upward movement of the nutrient-rich subsurface water could not reach the shallowest levels of the Atlantic current, because the horizontal velocity component was very high and the density gradient of the MAW acted as a barrier. In the top 50-m layer the advective transport was slighter, but sufficient to distribute the phytoplankton. The increase with depth of the eastwards displacements of the chlorophyll maxima from the core of the cyclonic region can be explained by the

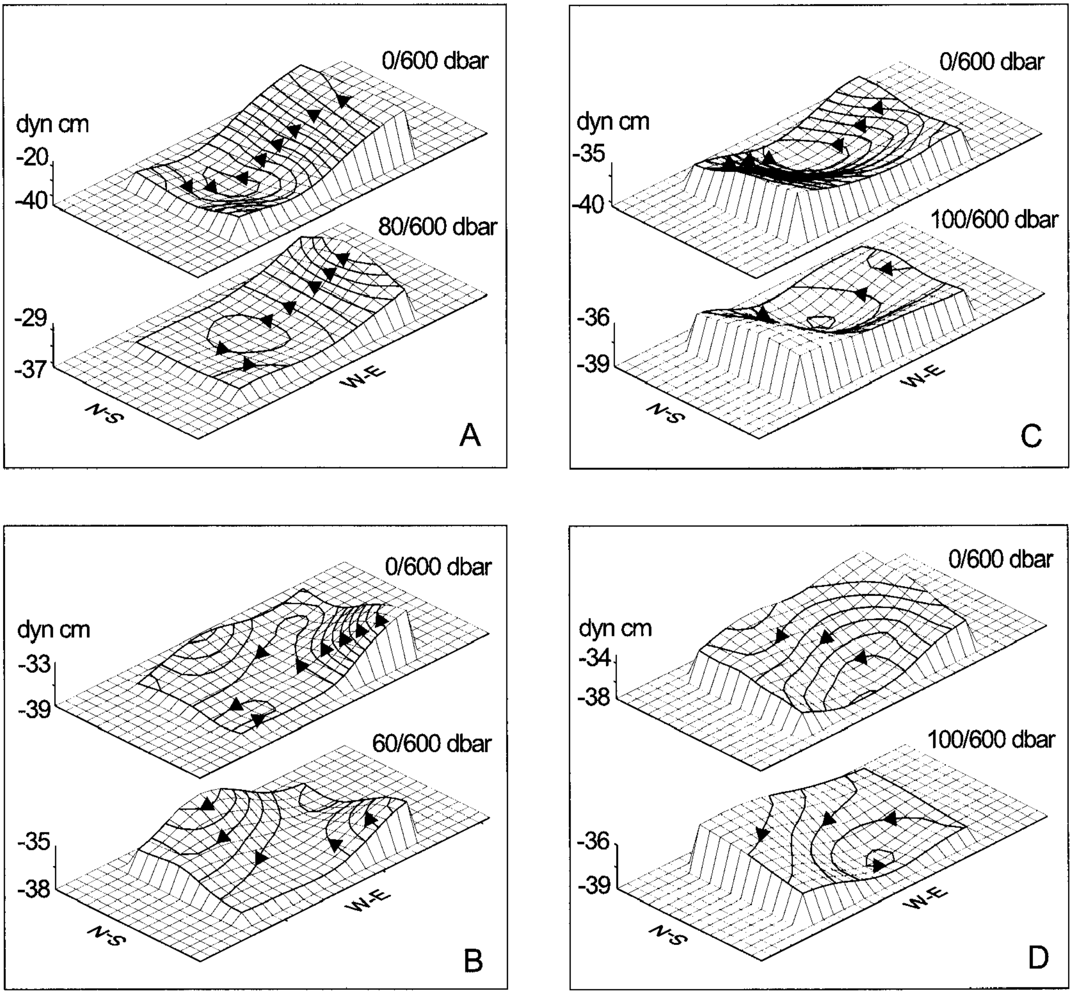

Figure 10. Anomalies of dynamic heights corresponding to different surfaces relative to 600 dbar and direction of the flow in November 1990 (A), March 1991 (B), early July 1992 (C) and mid-July 1992 (D). Contour intervals: 1 dyn cm in November and 0.5 dyn cm in the rest

Coriolis effect acting on the advective transport along the isopycnal surfaces (figure 12A).

During the survey carried out in March 1991, the MAW current was confined to the southeastern part of the channel (López-Jurado, García Lafuente and Cano, 1995), possibly due to its lower intensity or to the barrier effect of an anticyclonic gyre placed in the northern part of the channel. This phenomenon could have generated a cyclonic wedge (figure 10B) with its associated process of surface-divergence/deep-convergence and may have given rise to a southwest-northeast-oriented frontal system.

In the cyclonic region the vertical distribution of nutrients suggested an upward movement (figure 4). However, it was not clearly reflected in the topography of the isopycnal surface of s_T 28.44 kg m^{-3} (figure 11B) possibly due to the masking effect of the upward bending of the named isopycnal surface near Cape La Nao and Ibiza (it suggests the influence of the continental slope, especially when the currents are orthogonally directed towards it) (figures 10B and 11B).

The anticyclonic gyre located in the northern part of the channel and the MAW current in the eastern part caused a hori-

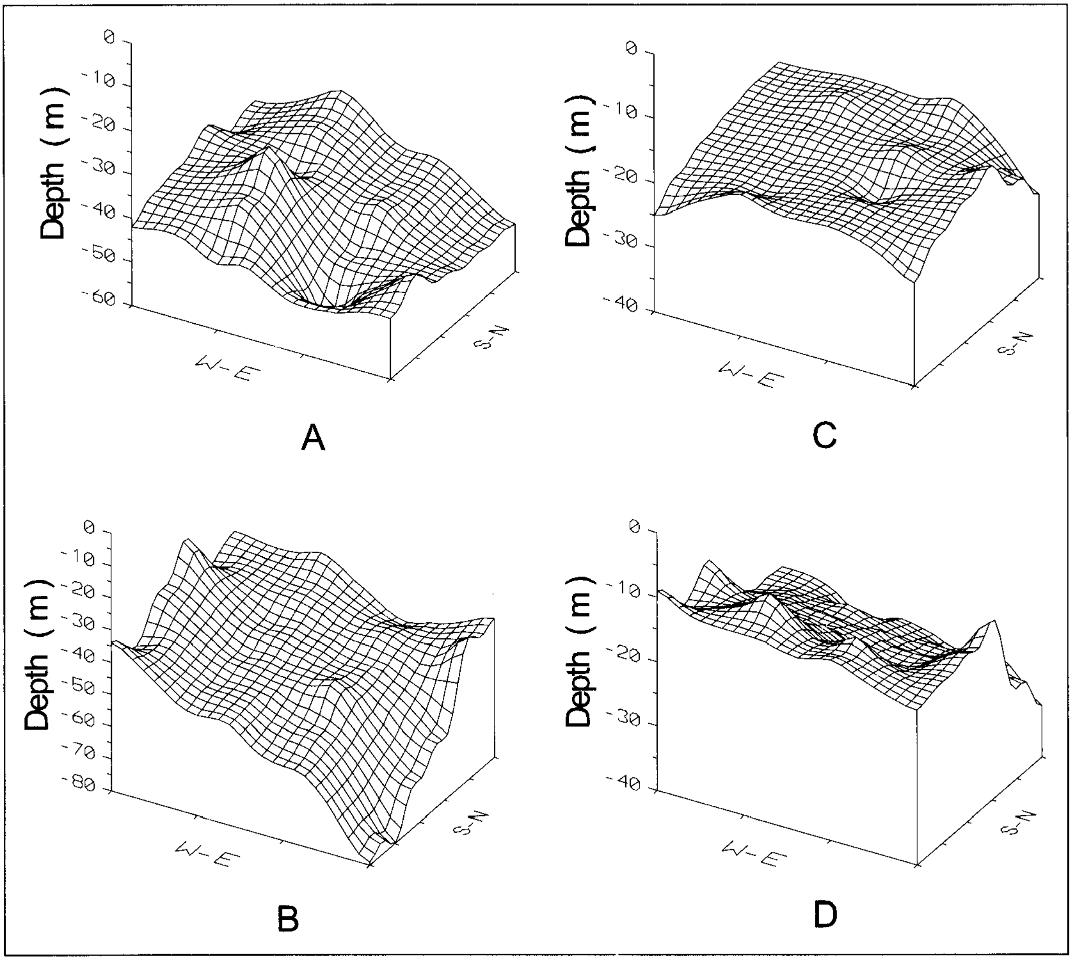

Figure 11. Depth of the top of the pycnocline in November 1990 (A), early July 1992 (C) and mid-July 1992 (D) and bathymetry of the isopycnic surface (s_T = 28.44) in March 1991 (B). Axes have been rotated 90 degrees from those in figure 10

zontal compression of the cyclonic wedge with weak velocity values (about 10 cm s^{-1}). This phenomenon greatly restricted, in the cyclonic wedge, the advective transport of phytoplankton and chemical tracers, explaining the high chlorophyll concentrations observed due to the preponderance of accumulation phenomena.

The stratification of nitrates, chlorophyll-*a* and dissolved oxygen observed in the northern part of the channel can be related to the presence of the anticyclonic gyre causing an absence of fertilisation events (figure 12C).

The vertical distribution pattern of the different variables was determined in July 1992 by thermal stratification. Here, the seasonal thermocline causes a vertical density gradient that acts as a transport barrier. Consequently, the upward movements generated below the pycnocline within the divergence regions can not reach the surface layers. Below the pycnocline upward motions steepen the vertical density gradient, causing the pycnocline to bend. The vertical compression against the pycnocline can partially explain the nitracline. The nitracline can also be caused by the nitrate uptake by phytoplankton (Varela, Cruzado and Tintoré, 1994).

In the Balearic Sea the deep chlorophyll maximum is normally around a depth of 80 m (Durán and Jansá, 1986) during the warm season. However, the chlorophyll maxima appeared only at a depth of 50 m during the first cruise. This might be due to the delayed 1992 summer (June was a relatively cool month), or to the hydrographic activity of the channel, mainly the upward movements, which would be sufficiently intense to push the pycnocline upward. This second hypothesis might be confirmed by the topography of the top of the pycnocline, which was located in a very high position (figure 11C). At the same time, it was noted that some bending near Ibiza was closely connected with the nitrate input.

The horizontal pattern observed at the beginning of July 1992 was similar to that observed in November 1990. Nevertheless, some differences were evident in a more detailed view: for instance, the cyclonic gyre was enlarged in July 1992 and the velocity of the currents (mainly in the MAW) was lower than that observed in November 1990 (from 15 cm s^{-1} at the surface to 5 cm s^{-1} at a depth of 100 m). This lower advective transport decreased phytoplankton dispersion. On the other hand, the chlorophyll maxima were located at the same 50-m level. As indicated above, the barrier effect of the seasonal pycnocline involves a vertical compression of the upward movements, and it can also restrict phytoplankton to a relatively narrow layer. The hypothetical decrease in the phytoplankton's sinking rate through the pycnocline, together with the fertilisation inputs that occur at some points, may explain (in the absence of high advective transport) not only the high chlorophyll concentrations observed but also the higher degree of spatial heterogeneity.

In a broad sense, the fertilisation mechanism probably acted in the same way during November 1990. Therefore, the upward movement generated by the cyclonic eddy took place along the isopycnal surfaces but, in this case, was enlarged and with a weaker surface-divergence/deep-convergence system. The peripheral location of the chlorophyll maxima may be explained partially as the result of an advective transport from the inner generation areas. As occurred in March 1991, another fertilisation mechanism could be taken into account: this is the upward movement that the water layers can undergo when currents are more or less orthogonally directed to the continental slope. In this sense, although the general bending of the pycnocline can be related to the upwelling associated with the cyclonic system, the more important local bending of this surface was located in the stations close to Ibiza (figure 11C) near the region of the chlorophyll maximum (figure 7).

The sinking of the chlorophyll-rich layer observed in mid-July 1992 and the drop in nutrient inputs can be interpreted on the basis of a preponderance of sedimentation over production processes. The nutrient inputs were more moderate (figure 8) and the chlorophyll concentrations were generally lower in this survey. At the same time, the depression of the pycnocline, mainly in the northern part of the channel (figure 11D), could explain the deepening of the DCM. Another important phenomenon recorded in this survey was the striking change in the horizontal distribution of nitrates and chlorophyll (figure 9). This change can be due to the advective transport. The dynamic heights and direction of the flow (figure 10D) still showed the cyclonic eddy, but it was displaced to the southern part of the channel. This was also the case with the general bending of the top of the pycnocline surface and the local nearshore Ibiza bending (figure 11D). The displacement of the cyclonic circulation established a remarkable change in the direction of the flow that acted on the different sampling stations, and this could have caused the dispersion of phytoplankton from previous accumulation regions and the generation of new patches by advective transport (figure 12B,D).

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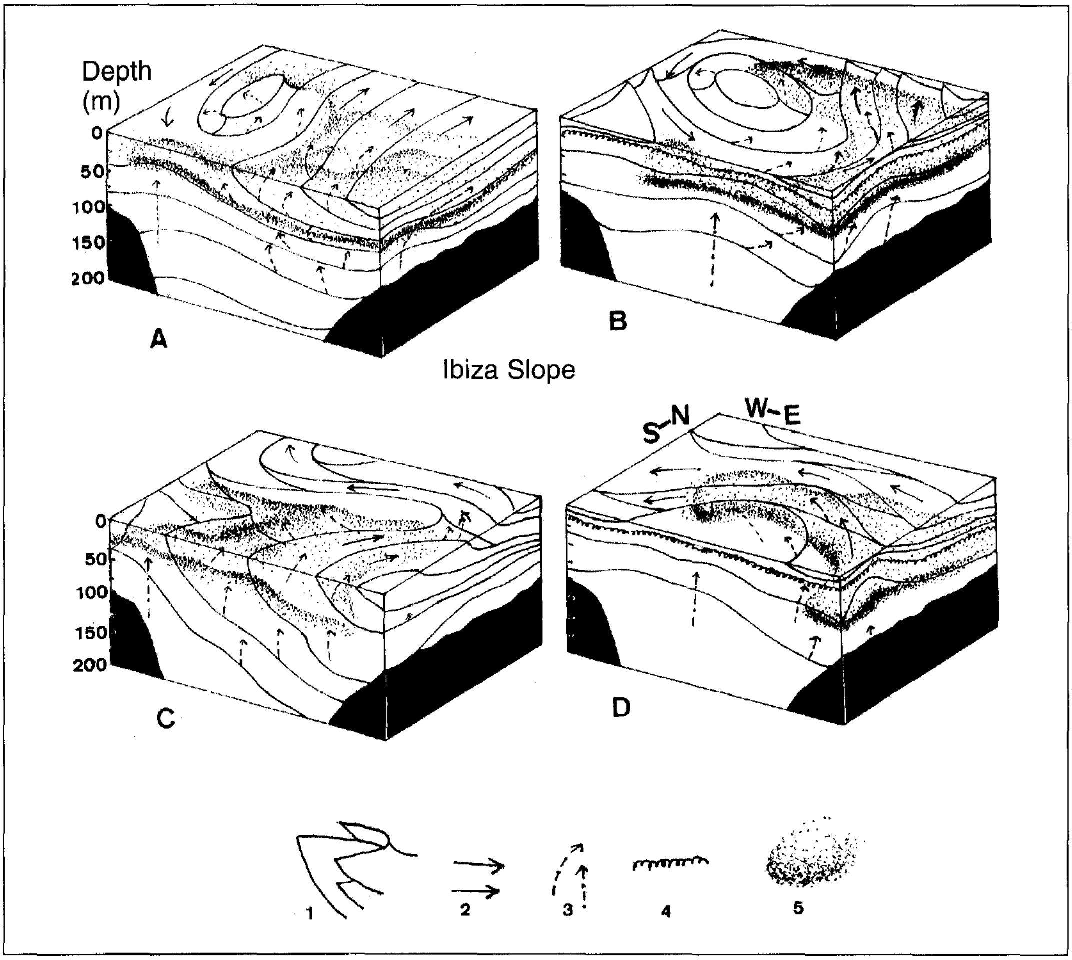

Figure 12. Interpretation of the situations observed in November 1990 (A), March 1991 (C), early July 1992 (B) and mid-July 1992 (D). (1): Approximate distribution of the isopycnic surfaces; (2): horizontal movements; (3): vertical movements and nutrient supply; (4): pycnocline; (5): chlorophyll maxima

crew members of the ships *Francisco de Paula Navarro* and *Odón de Buen*. Carlos Martínez and Olga Reñones collaborated on the preliminary studies, and Ignacio Reguera and Ricardo Casas on sampling during the cruises. María Cruz Iglesias, Dolores Oñate and Gabriel Pomar provided technical assistance in the preparation of the text and figures.

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