Mesoscale Dynamics and Vertical Motion in the Alborán Sea

JOAQUÍN TINTORÉ, DAMIÀ GOMIS AND SERGIO ALONSO
Departament de Física, Universitat de les Illes Balears, Palma de Mallorca, Spain

GREGORIO PARRILLA
Instituto Español de Oceanografía, Madrid, Spain

(Manuscript received 29 May 1990, in final form 17 December 1990)

ABSTRACT

The inflow of Atlantic water through the strait of Gibraltar usually exhibits a stationary wavelike pattern in the Alborán sea. We use an objective analysis technique for quantitative scale separation to investigate the interaction of scales in the region. The large scale is clearly dominated by an anticyclonic gyre. Smaller scale analysis shows the existence of several mesoscale cyclonic eddies along the northern boundary of the western Alborán sea anticyclonic gyre. The relationship between the large-scale/mesoscale variability and the induced ageostrophic vertical motion is established using the \( Q \) vector formulation. We find that on the macroscale, upward motion occurs upstream of the anticyclonic gyre (upstream of a wave crest) while downward motion takes place downstream (upstream of a trough). We also show that the vertical motion associated with the mesoscale eddies is an order of magnitude higher than the large-scale vertical motion. These patterns of large-scale and mesoscale vertical motions are confirmed by an extensive sensitivity analysis and by an independent estimate of the large-scale vertical velocity.

1. Introduction

The Mediterranean Sea is a well-known example of a semienclosed basin with a negative water budget. A two-layer flow through the strait of Gibraltar compensates for the water and salt deficit with Atlantic Water (AW, \( S < 36.5 \)) flowing in the upper layer into the Alborán sea and Mediterranean Water (MW, \( S > 37.5 \)) flowing westward below.

In the Alborán sea, several field studies have examined the circulation and dynamics associated with the incoming AW. These studies, (e.g., Gascard and Richez 1985; Parrilla and Kinder 1987) showed the incoming jet of AW usually develops into a well-defined anticyclonic gyre, although sometimes a coastal jet along the Moroccan coast has been also observed. Borsans and Garret (1989) summarized the more relevant laboratory, numerical and observational studies and, from a laboratory study, suggested the gyre/coastal jet bimodality in the western Alborán sea is related to different conditions of the bimodal flow (supercritical or subcritical) through the eastern end of the strait of Gibraltar.

In the eastern Alborán sea, Arnone et al. (1987) and Heburn and La Violette (1990) observed the presence of a second anticyclonic gyre, which was not shown in historical datasets (Lanoix 1974). This gyre usually develops near Cape Tres Forcas, reaches the Spanish coast near Almería and forms a well-defined southeastward jet south of Cape Gata (Tintoré et al. 1988).

All of these studies have given a fairly good picture of the large-scale circulation in the Alborán sea, which outlines an almost stationary wavelike pattern. However, the dynamics of the adjustment process in the Alborán sea are not yet fully understood (Wang 1987; Werner et al. 1988), and the importance of mesoscale processes remains unknown.

The aim of this work is to investigate the existence of a significant mesoscale circulation in the Alborán sea and study the relationship between the observed three-dimensional variability (large scale/mesoscale) and the vertical motion. We have applied an objective analysis technique for isolating mesoscale structures (Maddox 1980) to data collected during an intense survey in October 1986. After detailed analysis of the observations, we show the dynamic effects of several mesoscale cyclonic eddies detected along the boundary of the meandering jet and study the interaction between large-scale and mesoscale features. We then apply the \( Q \) vector quasi-ageostrophic formulation introduced by Hoskins et al. (1978) and show that the vertical motion is mainly induced by the mesoscale eddies. Finally, we perform a sensitivity study where the different approximations used are reexamined.

Corresponding author address: Dr. Joaquín Tintoré, Group of Geophysical Fluid Dynamics, Dept. de Física, Universitat de les Illes Balears, 07071 Palma de Mallorca, Spain.

© 1991 American Meteorological Society
2. Data analysis

a. The dataset

The Alborán Sea is a domain measuring roughly 300 \times 140 km^2 with typical dimensions for the diameter of the western anticyclonic gyre around 100 km. The field experiment was carried out from 29 September through 4 October 1986. The region between the strait of Gibraltar and 3^\circ W was covered (with a mean distance between stations of 18 km along-section and 45 km across-section), resulting in 48 CTD casts (Fig. 1). The sampling strategy was similar to Mooers and Robinson (1984), who discussed the requirements of high resolution sampling along tracks that are relatively coarsely separated for the definition of mesoscale features.

Since, to our knowledge, no previous mesoscale datasets exist (10 km^2 grid) no statistical base was available to use optimal interpolation (also known as “statistical analysis”, Carter and Robinson 1987). We have therefore used a simple isotropic univariate interpolation method to analyze the dataset. We have used an objective technique for mesoscale structures’ detection similar to the one described in Robinson et al. (1987). However, in our method the two model parameters are related to the physical dimensions of the scales to be separated, and the inverse problem on the analysis caused by the inhomogeneity of data points is reduced by implementing an additional step in the analysis procedure. Both the analysis technique and the correction method are described briefly in the following sections.

b. Description of the objective analysis technique

The scale separation technique developed by Doswell (1977) and Maddox (1980) is based on the filtering properties of the objective analysis scheme developed by Barnes (1964, 1973). Since the technique was already described in detail in these papers, only a brief description is given here for completeness.

A first analysis, \( f_1 \), operates as a low-pass filter, smoothing the observed data field to define the macroscale. A second analysis, \( f_2 \), with cutoff located near the smaller resolvable scale is then carried out. The normalized difference between these two low-pass filters (a band-pass filter) is assumed to account for the mesoscale signal. The total field is recovered as the sum of the macroscale and the mesoscale contributions, the short wavelength noise being filtered by the analysis. Therefore, in addition to the total analysis, two different scales are obtained, and this allows the independent analysis of each scale. This scale separation has been used successfully to isolate different subsynoptic meteorological phenomena (Maddox 1980; Gomis and Alonso 1990).

Each Barnes’ analysis consists of two steps. The gridded values \( f^0(i, j) \) are initially computed from the total N of station values \( f_n \) as

\[
f^0(i, j) = \frac{\sum_{n=1}^{N} W_n(i, j)f_n}{\sum_{n=1}^{N} W_n(i, j)}
\]

(1)

where the weight functions are

\[
W_n(i, j) = \exp[-d_n(i, j)^2/4C];
\]

(2)

\( d_n(i, j) \) is the separation distance between the grid point \((i, j)\) and the \(n\)th station, and \(C\) is an analysis parameter. Next, the first guess, \( f^0 \), is evaluated at each station and the difference \( \Delta f_n = f_n - f^0 \) is used to obtain the final values

\[
f(i, j) = f^0(i, j) + \frac{\sum_{n=1}^{N} W_n^*(i, j)\Delta f_n}{\sum_{n=1}^{N} W_n^*(i, j)}.
\]

(3)

Here the modified weight functions are

\[
W_n^*(i, j) = \exp[-d_n(i, j)^2/4CG], \quad 0 < G < 1
\]

(4)

and \(G\) is another analysis parameter. Barnes (1973) showed that the wavelength dependence of his scheme is actually a low-pass filtering with the cutoff location given as a function of the parameters \(C, G\). Therefore, we can choose the values for \(C\) and \(G\) as those giving a convenient smoothing of the original field.

The mesoscale analysis \( f_2 (i, j) \) is defined as the difference between the two low-pass analyses, \( f_1 (i, j) \) and \( f_2 (i, j) \)

\[
f_2(i, j) = r^{-1}[f_1(i, j) - f_2(i, j)]
\]

(5)

where the transmission factor of \( f_1 \) has to be greater than \( f_2 \) at all wavelengths. The factor \( r^{-1} \) is to ensure

---

Fig. 1. Distribution of stations in the Alborán sea (29 September to 4 October 1986).
a response unity at the wavelength at which the band-pass is centered (see Maddox 1980). An objective analysis of the actual field (total analysis) is obtained by adding the macroscale contribution $f_2(i,j)$ to the mesoscale contribution $f_0(i,j)$. The total field obtained differs slightly from the field $f_1(i,j)$ because of the normalization.

The choice of the convenient scale separation is an important a priori step from which the parameters $C$ and $G$ will be determined. It can be done either on the basis of theoretical constraints (characteristic scale, deformation radius) or from a previous knowledge of the structures present in the field. In our case the choice was made by combining the experience from previous studies (e.g., Gascard and Richez 1985) with the theoretical constraints of mesoscale dynamics. In the ocean, the horizontal scale of eddies is related to the Rossby internal deformation radius $R$ (depth scale multiplied by the buoyancy frequency, $N$, divided by the Coriolis parameter). In the Alborán sea, assuming a two-layer system with an upper layer 150 m thick with a mean density around 1.027 g cm$^{-3}$ and a lower layer 500 m thick with a mean density around 1.029 g cm$^{-3}$, we obtain $R = 20$ km. Mesoscale eddies in the Alborán sea would therefore have a diameter of the order of 60/80 km, though topographic interactions might considerably reduce this characteristic length (Robinson 1984). These a priori theoretical constraints agree with the observations of Gascard and Richez (1985), who detected, using surface floats, a mesoscale cyclonic eddy with a diameter around 40 km northeast of the strait. We have therefore centered the band-pass response of the filtering at a wavelength $\lambda = 90$ km (Fig. 2). Any feature with such a wavelength will be considered as a mesoscale feature.

Typical values for the diameter of the large-scale gyres are around 100 km, and we will consider macroscale features as those with wavelengths near $\lambda = 160$ km. Since the scales to be separated are not very distinct, intrinsic properties of the analysis technique do not allow a complete scale separation. Unfortunately, part of the anticyclonic gyres ($\sim 30\%$) will appear as a mesoscale contribution, but most of the large-scale wavelike pattern will remain unchanged after the low-pass filtering (see macroscale and mesoscale responses, Fig. 2).

**c. Correction method**

The data were first objectively analyzed onto a 0.1° longitude by 0.075° latitude grid (approximately 7.5 × 7.5 km$^2$ cells). However, the station points used in the analysis are far from being homogeneously distributed. This implies that the two scale contributions and, to a lesser extent the total field, can be affected by errors which depend on both the station distribution and the structures of the field themselves. In order to minimize these errors, we applied a correction method based on successive analyses (Buzzi et al. 1991), which is briefly described below.

After the first analysis is completed using the original station values, two more analyses are carried out. One of them uses as input data the grid-point values provided by the first analysis as if they were station values. The other analysis is based on the station values themselves. The differences between the results (macroscale, mesoscale and total fields), obtained from these two “parallel” analysis procedures are interpreted as the error fields due to the inhomogeneity of station density. The final analysis is then obtained after subtracting the so obtained error fields from the first analysis fields. This method assumes that the fields produced by the first analysis provide a sufficiently good approximation to the “true” field for the computation of the error due to the station distribution (see Buzzi et al. 1991).

**3. Observations**

Satellite imagery analyzed for the period 26 September to 2 October 1986 show the usual wavelike pattern (Fig. 3a,b) and indicate that the surface AW was significantly cooler than the MW (19° and 23°C, respectively). The western anticyclonic gyre was characterized by strong temperature gradients (3°C in 5 km) and a warm central region reaching 23°C. For the eastern gyre (located just east of Cape Tres Forcas, 35°30′N, 3°E), the gradients appeared to be smaller and the inner temperature lower. Figure 3a shows the western gyre was closed at its western boundary, with no apparent connection to the inflowing jet of AW (which was actually not well defined). In the eastern Alborán sea, clouds unfortunately masked almost completely the anticyclonic gyre, but the Almería–Orán front was clearly detected south of Cape Gata.

![Fig. 2. Wavelength dependence of the response provided by the analysis scheme used all along this work. The range of wavelengths retained by each of the two contributions as well as by the total field are drawn. Also the values of the parameters governing the analysis (see Maddox 1980) are listed.](image-url)
(36°40'N, 2°10'E). Four days later, Fig. 3b shows several differences: the western boundary of the western gyre appears now associated with the jet of inflowing AW while in the eastern Alborán sea, both the anticyclonic gyre and the Almería–Orán front is clearly identified.

The surface wavelike pattern depicted in satellite imagery was confirmed at depth. At shallow depths, the gyre was well defined only in the temperature and sigma-t fields, the salinity distribution being almost uniform in the upper 30 m, (Fig. 4). The highest horizontal gradients were detected at 100 m, and since temperature and salinity effects are additive, the density gradients are here very intense (1.9 sigma-t units in the eastern boundary of the anticyclonic gyre, Fig. 5). Figures 4 and 5 also show that north of Cape Tres Forcas, the western boundary of the eastern Alborán sea anticyclonic gyre is also evident. As for the western gyre, the core is characterized by higher temperature and lower salinity than surrounding water. In between the two anticyclonic gyres, a cyclonic eddy was also clearly detected. Figure 6 provides a three-dimensional picture of the main features detected. The 28.0 isopycnic surface sinks significantly upstream of the two anticyclonic gyres and rises sharply upstream of the cyclonic gyre.

The vertical structure in the two anticyclonic gyres shows significant differences (Fig. 7a,b). The western gyre is characterized by a well-mixed upper layer (40 m, 21.5°C) and lower salinity and higher temperature at all depths than the eastern one [except for the upper mixed layer of the eastern gyre, which is smaller and warmer (20 m, T > 22°C)]. The differences in the vertical structure of the two gyres can be explained in terms of the different paths followed by the two water types. The eastern gyre appears to be formed by “recent” modified AW (low temperature) mixed with MW (thus higher salinity). The western one is formed by “older” modified AW trapped in the gyre (warmer due to solar insolation).

Comparison of the vertical structure at stations 53 and 35 (Fig. 8) shows a remarkable similarity, suggesting that the cyclonic eddy was formed by recent AW advected by the surface jet around the western anticyclonic eddy. A similar process was described by La Violette (1984), who showed advection of cold small scale structures of AW around the edges of the anticyclonic eddy.

Figure 9 shows a vertical N–S section through the western gyre. The deepening of isolines related to the anticyclonic eddy is evident. Note the very strong sigma-t gradients at approximately 100 m in the central region and the steep tilting of the 37.5 isohaline (9 m

---

**FIG. 4.** Surface (10 m) temperature (a), salinity (b) and sigma-t (c) distributions.
that the winds were not favorable for upwelling at that time.

We applied the objective analysis technique to separate the macroscale and mesoscale contributions. Figure 10 shows the macroscale, mesoscale and total sigma-t distributions at 100 m. The total field shown in Fig. 10c is quite similar to Fig. 5, and this supports the applicability of this type of objective analysis. Not surprisingly the macroscale is clearly identified as the western Alborán sea anticyclonic gyre, while the mesoscale distribution depicts several cyclonic eddies in the northern area, the existence of which has been suggested by Cano (1977, 1978) and Parrilla and Kinder (1987). Despite the fact that the gradients of the mesoscale eddies are small in comparison with the large-scale gradients, the changes of curvature induced along the boundary of the gyre can give rise to significant vorticity gradients as we show below.

We have computed the dynamic topographies and geostrophic currents at 10 m with reference to 200 m for easy comparison with other studies (Lanoix 1974; Parrilla and Kinder 1987), Fig. 11a. The anticyclonic gyre is evident with inner values reaching 24 dyn cm. Except in this central region occupied by the gyre, dynamic topographies were very small. Negative values were obtained at the locations where mesoscale cyclonic eddies had been detected. Geostrophic computations (Fig. 11b) show the anticyclonic gyre had associated east–west velocities of the order of 40 cm s⁻¹ and very significant north–south velocities that reached 60 cm s⁻¹. The cyclonic gyre detected northwest of Cape Tres Forcas had velocities around 20 cm s⁻¹. Along the Spanish shelf, the effects of the mesoscale eddies shown in Fig. 7 are evident and appear as a meandering coastal westward current with a mean speed of 19 cm s⁻¹, but occasionally reaching 40 cm s⁻¹ (stations 60 and 61). The dynamic influence of the mesoscale features is therefore clearly established. However, it is important to consider that in the regions of high horizontal shear

km⁻¹), arbitrary chosen to delineate the boundary between the modified Atlantic water, MAW, and the MW. Near the Spanish coast, the upward isohalines could be an indication of the upwelling known to occur in the region. However, the meteorological conditions at the time of the cruise (not presented here) indicate

Fig. 5. Distributions of temperature (a), salinity (b) and sigma-t (c) at 100 m.

Fig. 6. Depth (m) of 28.0 isopnic.
(e.g., station 71), the nonlinear terms might be of the same order of magnitude as the Coriolis terms, and therefore geostrophic values should be considered with caution.

A better picture of the dynamic effects of the interaction between these macroscale/mesoscale features is provided by Fig. 12, where the geostrophic vorticity at 100 m is shown. The western Alborán sea anticyclonic gyre appears to consist of three smaller anticyclonic eddies. On the outside boundary of the gyre six different positive vorticity regions are found. This figure shows the important influence of small changes of the curvature within the anticyclonic gyre. Numerical values of the geostrophic vorticity obtained are very similar for the total field and the mesoscale, suggesting therefore a very significant dynamic influence of the mesoscale cyclonic gyres in the Alborán sea. In particular, the upward isohalines observed in Fig. 9 north of the anticyclonic gyre could be the result of the positive vorticity region centered around stations 72, 73.

4. Diagnosis of the three-dimensional motion

In this section we establish the relationship between the tridimensional variability and the ageostrophic vertical motion within the framework of quasi-geostrophic (QG) theory.

---

1 A similar feature was observed by one of the authors (GP) in October 1987 onboard the R/V Lynch with ADCP.
To understand the relationship between the horizontal and vertical variability we start from the quasi-geostrophic vorticity equation and the thermodynamic equation using the classical notation (Pedlosky 1987):

\[
\left( \frac{\partial}{\partial t} + v_g \cdot \nabla_h \right) \xi_g - \frac{f_0}{\rho_0} \frac{\partial}{\partial z} (\rho_0 w) = 0 \tag{6}
\]

\[
\left( \frac{\partial}{\partial t} + v_g \cdot \nabla_h \right) \frac{g}{\rho_0} \rho' - N^2 w = 0 \tag{7}
\]

where the vertical advection term has been neglected and we have also assumed that the advection of planetary vorticity is negligible compared to the advection of relative vorticity. Equation (6) indicates that according to QG theory, the relative vorticity associated with the geostrophic motion changes in response to the geostrophic advection of relative vorticity and stretching or shrinking of the strong vortex tubes associated with the planetary rotation by the ageostrophic vertical motion.

Eliminating the time derivatives between (6) and (7) and assuming that \( w \) varies with \( z \) much more rapidly than \( \rho_0 \), we obtain a diagnostic equation, known in meteorology as the Omega equation (Holton 1979, p. 137).

\[
N^2 \nabla^2 w + f_0^2 \frac{\partial^2 w}{\partial z^2} \tag{8}
\]

\[
= f_0 \frac{\partial}{\partial z} (v_g \cdot \nabla_h \xi_g) + \frac{g}{\rho_0} \nabla^2 (v_g \cdot \nabla_h \rho') \quad (8)
\]

This diagnostic equation relates the vertical velocity to the horizontal geostrophic velocity and density fields.

In the QG theory, the vertical velocity \( w \) is the velocity that maintains the thermal wind balance in the presence of variations in the horizontal advections of vorticity and density. Specifically, (8) shows that the vertical velocity is forced by the vertical derivative of vorticity advection associated with the geostrophic current, and by the horizontal Laplacian of the density advection.

We can use this equation for qualitative reasoning about the vertical motion. Since it is a Poisson type equation, we can assume that, if \( w \) is approximately sinusoidal in the three-dimensional space, when the right-hand side is negative \( w \) will be positive, i.e. upward motion. Therefore, from a given dataset, we can estimate the right-hand side and thus the sign of the vertical motion.

If we first consider the large-scale wavelike pattern (Fig. 10a) and assume the B term (differential vorticity advection term) to be dominant, we can infer the sign of the induced vertical motion. Since geostrophic velocity decreases with depth, below 150 m the vorticity advection will be very small. At the surface, strong positive vorticity advection is observed in the western boundary of the anticyclonic gyre \((-v_g \cdot \nabla_h \xi_g > 0\) and strong negative advection in the eastern part (Fig. 13a). This according to (8) implies upward motion upstream of the western anticyclonic gyre and downward motion downstream. For a qualitative discussion of the C term, we assume that the Laplacian of the density advection is proportional to minus the density advection itself. Examination of the effects of this term show the induced vertical motions are opposite to the ones induced by the differential vorticity advection (Fig. 13b). This cancellation between the two terms on the right-hand side of (8) is one of the major drawbacks of the Omega equation when used as a basis for quantitative diagnosis of geostrophic forcing.
where

\[
\mathbf{Q} = \frac{g}{\rho_0} \left( \frac{\partial u_x}{\partial x} \frac{\partial \rho'}{\partial x} + \frac{\partial v_x}{\partial x} \frac{\partial \rho'}{\partial y} + \frac{\partial u_y}{\partial y} \frac{\partial \rho'}{\partial x} + \frac{\partial v_y}{\partial y} \frac{\partial \rho'}{\partial y} \right)
\]  

(10)

The \( \mathbf{Q} \) vector can be calculated from the distributions of density and geostrophic velocity, and convergence of this vector indicates the regions where upward motion is taking place (Hoskins and Pedder 1980). We have computed the \( \mathbf{Q} \) vector and its divergence for the large-scale and for the total fields. Comparison between the two calculations will provide an estimate of the ageostrophic vertical motion associated with the mesoscale features in the Alborán sea.

Figure 14a shows the macroscale \( \mathbf{Q} \) vector and its divergence at an intermediate level (100 m). This figure indicates upward motion occurring upstream of the crest (western Alborán sea anticyclonic gyre) and downward motion taking place downstream. The differential vorticity advection is therefore the dominant term in the Omega equation (8) discussed before. This

We have therefore used the form of the Omega equation introduced by Hoskins et al. (1978; also discussed by Gill 1982, p. 543) in which this cancellation effect is avoided. This can be written as

\[
N^2 \nabla^2 \mathbf{w} + f_0 \frac{\partial^2 \mathbf{w}}{\partial z^2} = 2 \nabla \cdot \mathbf{Q}
\]  

(9)

Fig. 10. Macroscale (a), mesoscale (b) and total (c) sigma-\( \tau \) objective analysis at 100 m.

Fig. 11. (a) Objective analysis of the dynamic topography at 10 m with reference to 200 m. Units are dyn cm. (b) Geostrophic velocities at 10 m. Vector reference is 1 m s\(^{-1}\). Note the velocity distribution near the coast has to be considered with caution since there is no account for the coast in the computations.
We first study the applicability of QG theory in the Alborán sea. Quasi-geostrophic theory is applicable (providing no application is made near the slope regions) since in the Alborán sea the Rossby number is of the order of 0.02 for the large scale and 0.05 for the mesoscale. Even consideration of very different velocity and length scales yields Rossby numbers smaller than 0.1, which indicates that, indeed, QG theory can be applied to study the dynamics of the Alborán sea.

We then performed a sensitivity test to quantify the impact on the analysis of a random noise in the data. We used different noise to signal variance ratio, up to 0.01 (10% error), and found that the analyses of the noisy dataset \( \{T, S\} \) were almost identical to the original analyses. This result was actually expected since application of the objective technique is equivalent to a low-pass filtering of the data (Fig. 2). As a consequence, the analyses of derived variables (such as vorticity or divergence of \( Q \) vector) were also similar, with rms deviations of 20% for the macroscale contribution and 10% for the total and mesoscale fields.

5. Sensitivity study

We have shown that the dynamics of the Atlantic Water in the Alborán sea is strongly affected by the existence of mesoscale eddies along the boundary of the well-known large scale anticyclonic gyre and that these mesoscale eddies induce vertical motions an order of magnitude higher than the large scale gyre. In this section we present a detailed sensitivity study where the different approximations previously employed are re-examined.
higher wavelengths, however, geostrophic vorticity and vertical forcing patterns obtained were considerably weaker. This confirms that the vertical motion is forced by mesoscale features with wavelengths of the order of 90 km.

It should also be noted that as a result of the non-linearity of the operator on the left side of (9), the $Q$ vector results for the total field are not exactly the sum of the mesoscale and macroscale results. A residue exists and this residue has to be small if mesoscale vertical motions are studied. We computed this residue and found it is of the order of 20% of the mesoscale contribution. This confirms that the estimation of mesoscale vertical motion is indeed correct, i.e., that the mesoscale vertical motions strongly dominate in the Alborán sea.

It is necessary to note that applying the high order differencing required to solve (9) and (10) can introduce significant numerical errors, as well as amplify the effect of analyses errors. We have therefore carried out an extensive sensitivity study where those errors have been quantified. The evaluation of errors derived from the numerical data treatment gives expected values around 15% for the total fields and around 30% for the macroscale fields. Two different methods (finite differences and local polynomial fitting) have been used to compute the derivatives required to define the $Q$ divergence fields; results differ one from the other in the degree of smoothing, but not in the shape of the fields, therefore confirming that the dominant role of mesoscale structures cannot be explained in terms of numerical errors.

We have finally carried out another sensitivity test computing the vertical velocity for the large scale and the total fields from the time-independent thermodynamic equation (7). Comparison of these velocity patterns with the patterns of $\nabla \times Q$ allows for a discussion of the errors introduced in the application of the objective analysis technique and the $Q$ vector formulation for the description of the dynamics of the Alborán sea. Figure 15a shows a macroscale vertical motion pattern very similar to that given by the $Q$ vector formulation (Fig. 14a). Since it is well known that the large-scale gyre in the Alborán sea is stationary, this good qualitative agreement between two independent analyses of the vertical motion at macroscale suggests the $Q$ vector formulation is indeed applicable. We also found that the total field vertical velocity (Fig. 15b) is significantly higher than the macroscale vertical velocity. The same difference between the macroscale and the total field patterns was obtained with the $Q$ vector formulation and this also suggests the $Q$ vector formulation is applicable for the description of mesoscale dynamics in the Alborán sea. Note, however, that the total-field pattern in Fig. 15b differs from that obtained using $Q$ vectors. This difference can be explained by the high temporal variability associated with mesoscale features in the Alborán sea (La Violette 1984), which is of
course neglected in the computation of the vertical motion from the stationary thermodynamic equation.

6. Conclusions

We have applied an objective analysis technique for scale separation to a well-defined, almost stationary, wavelike pattern such as the Atlantic inflow in the Alborán Sea.

We have shown that the macroscale is clearly identified as the western Alborán sea anticyclonic gyre. Smaller scale analysis suggests however that this anticyclonic gyre is actually formed by three smaller anticyclonic eddies and shows also the existence of significant mesoscale cyclonic eddies along the northern boundary of the gyre.

We have studied the relationship between this large-scale/mesoscale variability and the vertical motion using the Q vector formulation. The vertical motion computed for the macroscale indicates upward motion occurs upstream of the anticyclonic gyre (upstream of a wave crest) and downward motion occurs downstream (upstream of a trough).

More importantly, we also found that the vertical motion associated with the mesoscale eddies is an order of magnitude higher than the vertical motion associated with the large-scale structure. The mechanism of formation of these mesoscale cyclonic eddies and their role in the decay of the large-scale gyre should be explored in the future. Consideration of mesoscale processes might therefore be essential for a complete understanding of the dynamics of the Atlantic inflow in the Alborán sea.

These patterns of vertical motion on the macroscale and the mesoscale have been qualitatively and quantitatively confirmed by an in-depth sensitivity analysis and also by an independent estimate of the vertical velocity.

Acknowledgments. We thank Nan Bray (Scripps Institution of Oceanography) for kindly providing the CTD data, collected under U.S. Office of Naval Research Contract N00014-85-C-0407, and Robert Grant (NOARL) and Paul E. La Violette (Mississippi State University Research Center) for processing the satellite images provided by P. Baylis (The University of Dundee). We would like to thank Brian Hoskins, Dong-Ping Wang and Francisco Werner for useful discussions. Thanks are also extensive to anonymous reviewers who pointed out the importance of a sensitivity study. We are particularly thankful to Mike Pedder who help clarifying several important aspects of the mesoscale vertical motion. We are also thankful to Eugeni Isern for help with the figures and to Gloria Ayuso for careful and expert editing of the manuscript. Partial support from, CICYT (Programa Nacional de Recursos Marinos y Acuicultura, MAR89-0550), DGICYT (PB89-0428) and from EC program MAST (0043-C) is gratefully acknowledged.

REFERENCES


