Modeling the Oceanic Circulation in the Area of the Strait of Sicily: The Remotely Forced Dynamics

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(Manuscript received 5 January 2000, in final form 23 June 2000)

ABSTRACT

In order to describe aspects of the baroclinic dynamics in the region of the Strait of Sicily a high-resolution multilayer numerical model has been implemented in a central Mediterranean region including the Tyrrhenian and the Ionian Seas. Three layers have been considered representing water of Atlantic origin (MAW), the Levantine Intermediate Water (LIW), and deep water of the Mediterranean. Quasi-stationary circulations representing the local manifestation of the large-scale Mediterranean conveyor belt are obtained [after an adjustment time of O(2 months)] by imposing steady fluxes along the remote open boundaries, in the absence of meteorological forcings. These circulations can be interpreted as possible dynamic scenarios of the seasonal variability in the Strait of Sicily.

In the numerical simulations an inflow of MAW and an outflow of LIW through the Strait of Sardinia, an outflow of MAW and an inflow of LIW through the Ionian boundary, and an outflow of MAW through the Corsica channel are imposed, resulting in a vanishing total net transport in each layer. For realistic values of these transports the model captures the main features of the observed circulation, such as (i) the separation of the Algerian Current into two branches, one directed toward the Tyrrhenian Sea and the other entering the strait; (ii) a secondary bifurcation of MAW within the strait giving rise to a southward-moving current that follows the Tunisian continental slope and to a current that flows southeastward along the southern Sicilian coast and then northward along the southern Italian coasts (the so-called Atlantic–Ionian Stream); (iii) a bifurcation of LIW at the strait level leading to a main current directed toward the Strait of Sardinia and to a weaker current that, after having crossed the strait, bends eastward and enters the Tyrrhenian Sea.

Sensitivity experiments carried out by imposing different boundary fluxes have shed light on the functioning of the MAW and LIW bifurcations. First of all, for a given net transport of MAW and LIW through the strait (imposed indirectly by the boundary fluxes), the ratio R_{maw} between the transport of MAW entering the Tyrrhenian Sea and that entering the strait is found to be virtually independent of the boundary-imposed Algerian Current transport. It is, on the contrary, determined by a local dynamic control, which selects the value $R_{maw} \approx 0.43$ for a net MAW/LIW strait transport of ± 1 Sv, in excellent agreement with observations. Second, for decreasing baroclinic transports the ratio R_{maw} is found to decrease up to the limiting value $R_{maw} \approx 0.2$ (corresponding to the linear regime) for transports $< O(0.1$ Sv). Finally, R_{maw} is found to be very sensitive to the barotropic transport T through the strait, whereas the corresponding ratio for the LIW, R_{liw}, is virtually independent of T. For $T = -0.5$ Sv, $R_{maw} \approx 1.1$ while for $T = +0.5$ Sv, R_{maw} decreases by one order of magnitude: $R_{maw} \approx 0.1$. In other words, a weakening of the LIW (or a strengthening of the MAW) net transport through the strait reduces the relative intensity of the Tyrrhenian branch of MAW, and vice versa. On the other hand, for values of T within the same range one always finds $R_{liw} \approx -0.3$. It thus appears that the local control exerted by the topography through the LIW potential vorticity budget forces the transport of the Tyrrhenian branch of LIW to be always $\sim$1/3 of that directed toward the Strait of Sardinia.

1. Introduction

Sea straits are peculiar areas of the World Ocean as they represent a shallow connection of small spatial extension between different oceanic regions. This often implies that some gross oceanographic features of the neighboring zones can exert a deep influence on the strait dynamics. In particular, as far as the Mediterranean Sea is concerned, large-scale variabilities such as fluctuations in the Levantine Intermediate Water (LIW) formation or in the Atlantic Water inflow and transformations are expected to affect strongly the water transport through the Strait of Sicily (Fig. 1). Hence, establishing some relationship between dynamical characteristics of the Strait of Sicily and physical and

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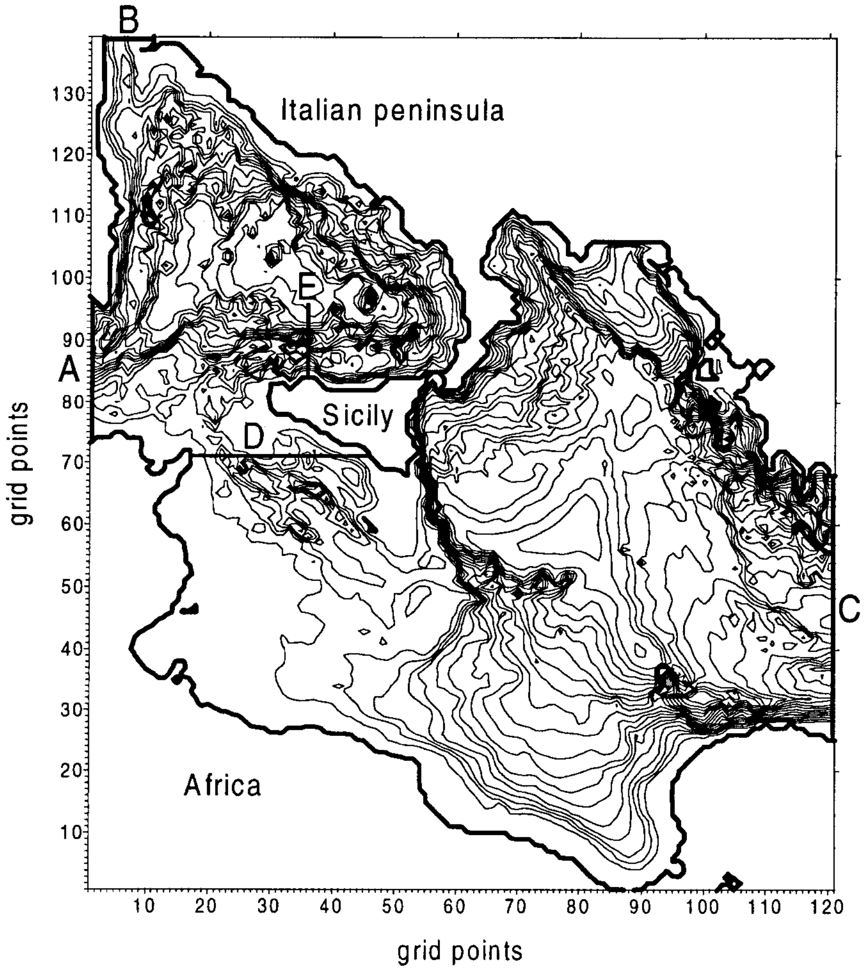

FIG. 1. The domain of integration and the bottom topography. Steady boundary conditions are imposed along sections **A**, **B**, and **C**. Transports are computed along sections **D** and **E**.

dynamical processes taking place in the Mediterranean basin could allow one to infer the occurrence of the latter from the analysis of signals measured in the strait. This can be achieved by means of numerical models through process-oriented studies, such as the one developed in this paper.

The forcings that determine the dynamics of the Mediterranean Sea are the momentum, sensible and latent heat fluxes at the air–sea interface, the river runoff, and the exchange flow through the Strait of Gibraltar. The resulting general circulation has the form of a complex conveyor belt, shaped by various mechanisms such as deep and intermediate water mass formation, dense water overflows, baroclinic instabilities, etc., yielding variabilities that range from the superinertial to the interannual scale (e.g., Ovchinnikov 1966; Béthoux 1980; Millot 1987; Robinson et al. 1991; Tziperman and Malanotte-Rizzoli 1991; Malanotte-Rizzoli and Bergamasco 1991; Astraldi and Gasparini 1992; Roussenov et al. 1995; Herbaut et al. 1996; Zavatarelli and Mellor 1995; Pinardi et al. 1997; Millot 1999). For a small region such as the Strait of Sicily and adjacent zones the forcings can be tentatively classified according to whether they induce directly a strong local manifestation but they are not able to determine ''remotely'' a strong local dynamics or, on the contrary, they induce directly a weak local manifestation but they are able to determine remotely a strong local dynamics through the action of currents produced on a larger scale. According to this distinction we classify the forcings as either *local* or *remote*. In this framework the wind appears to exert mainly a local influence. For instance, in a sensitivity numerical experiment Pierini and Simioli (1998) showed that the purely wind-driven circulations induced by realistic winds in the Western and Eastern Mediterannean subbasins are virtually uncoupled. On the other hand there is experimental evidence that in the Strait of Sicily a strong correlation between the local winds and fluctuations in the LIW transport may occur (M. Astraldi and G. P. Gasparini 1999, personal communication).

On the contrary the general thermohaline structure and the baroclinic currents associated to the MAW and

LIW exchange flow in the Strait of Sicily are only weakly determined by local heat and momentum fluxes, as these oceanographic features mainly result from the action of surface fluxes acting on a basin scale (in addition to the mass fluxes at Gibraltar). In other words the exchange flow present in the Strait of may be considered as the local response to a *remote* forcing, which can be modeled by prescribing currents along open sections delimiting the area of interest.

The aim of this paper is to investigate the baroclinic dynamics in the Strait of Sicily as induced merely by boundary transports representing, as discussed above, possible effects of remote, global-scale forcings. Motions generated locally by the atmospheric forcing and by instability mechanisms will be therefore neglected in this study. In order to achieve this goal, a high-resolution multilayer numerical model has been implemented in a central Mediterranean region including the Tyrrhenian and Ionian Seas (Fig. 1). Three layers have been considered representing water of Atlantic origin (MAW), the Levantine Intermediate Water (LIW) and deep water of the Mediterranean. In the simulations steady transports are imposed along the open boundaries with the aim of producing quasi-stationary circulation patterns that can be interpreted as possible dynamic scenarios of the seasonal variability of the circulation in the Strait of Sicily. An inflow of MAW and an outflow of LIW through the Strait of Sardinia, an outflow of MAW and an inflow of LIW through the Ionian boundary, and an outflow of MAW through the Corsica channel are prescribed, resulting in a vanishing total net transport in each layer. After an initial adjustment time lasting about 2 months a very slow evolution of the system follows. We therefore select the quasi-stationary states mentioned above just after the adjustment phase.

The paper is organized as follows. In section 2 the mathematical model, the numerical setup, and the boundary conditions are discussed in detail. In section 3 a first, basic numerical experiment is presented in which the imposition of boundary conditions inspired by experimental observations allows us to obtain circulation patterns in the surface and intermediate layers, in good agreement with what is generally known on the basis of experimental results. Moreover information is obtained about the shape of boundary and topographically controlled jets in regions not sufficiently studied experimentally. In the same section the adjustment phase is discussed and a numerical experiment is presented showing the weak sensitivity of the response to variations of the spatial structure of the boundary transports. In the remainder of the paper sensitivity experiments are presented aimed at obtaining a deeper understanding on the functioning of the main MAW and LIW bifurcations (this problem is, in fact, of particular interest as far as the role played by the Strait of Sicily in controlling the exchange flow between the two main Mediterranean subbasins is concerned). In section 4 the sensitivity of the MAW and LIW bifurcations to variations in the strength of the Algerian Current imposed at the western boundary (section 4a) and to variations of the baroclinic transports (section 4b) is analyzed in the case of vanishing barotropic transport across the strait. In section 5 the case of nonvanishing net transport across the strait is considered, and the sensitivity of the bifurcations to variations of the barotropic transport across the strait is analyzed. Finally in section 6 conclusions are drawn and future perspectives are outlined.

2. The mathematical model and the numerical setup

The complex hydrology of the Mediterranean Sea, and in particular that of the region of the Strait of Sicily, has been the subject of several experimental investigations (e.g., Ovchinnikov 1966; Millot 1987; Manzella et al. 1988; Astraldi et al. 1996; Moretti et al. 1993; Malanotte-Rizzoli et al. 1997; Millot 1999). Below a surface layer of water of Atlantic origin, modified along its path from Gibraltar (MAW), lies an intermediate layer of higher salinity water orignated in the Levantine Basin (LIW). Deep waters of different origin occupy the deepest layers: in the western basin one can distinguish between Western Mediterranean Deep Water and Tyrrhenian dense water (TDW), both originating in the Gulf of Lions, while in the eastern basin deep waters formed in the Adriatic Sea are present. In addition, several transitional water masses can be identified. A very refined representation of the hydrology of the region of the strait would therefore require in principle a model with a high vertical resolution, but the lack of sufficient experimental information on the synoptic distribution of water massess would make such a sophisticated mathematical approach subject to a high degree of arbitrariness. On the other hand, it is out of the question that two main water masses can be identified (MAW and LIW), which not only have well-defined hydrological characteristics near the strait but yield also very different dynamical features; for example, they flow in opposite directions in the Strait of Sicily.

In view of these considerations a layer model with a very limited number of layers appears to be particularly suitable for analyzing dynamical features of the Mediterranean Sea in this location, especially if the aim is to perform process-oriented studies, as is the case for the present research. Therefore the model we have used for the description of the dynamics in the area of the Strait of Sicily is a three-layer model (Rubino 1994) for the MAW, the LIW, and for a mean deep water of the central Mediterranean. The equations on which the model is based are the nonlinear, hydrostatic, shallow-water equations on a β plane, which include interface and bottom friction as well as horizontal eddy viscosity. In the following we denote the vertically averaged velocity and transport vectors by $\mathbf{u}_i$ and $\mathbf{U}_i = \mathbf{u}h_i$ ($i = 1, 2, 3$), respectively. The subscripts $i = 1$, $i = 2$, and $i = 3$ refer to the upper, the intermediate, and the lower layer respectively. For the upper layer, the momentum and the continuity equations read:

$$\frac{\partial \mathbf{U}_1}{\partial t} + \boldsymbol{\nabla}\cdot(\mathbf{u}_1 \times \mathbf{U}_1) + \mathbf{F}\cdot\mathbf{U}_1 = -gh_1\boldsymbol{\nabla}\eta_1 - \frac{\kappa_1}{\rho_1}(\mathbf{u}_1 - \mathbf{u}_2)|\mathbf{u}_1 - \mathbf{u}_2| + A_h h_1 \nabla_h^2 \mathbf{u}_1, \quad (1)$$

$$\frac{\partial h_1}{\partial t} + \boldsymbol{\nabla}\cdot\mathbf{U}_1 = 0, \quad (2)$$

for the intermediate layer they read:

$$\frac{\partial \mathbf{U}_2}{\partial t} + \boldsymbol{\nabla}\cdot(\mathbf{u}_2 \times \mathbf{U}_2) + \mathbf{F}\cdot\mathbf{U}_2 = -g\frac{\rho_1}{\rho_2}h_2\boldsymbol{\nabla}\eta_1 - g\frac{\rho_2 - \rho_1}{\rho_2}h_2\boldsymbol{\nabla}\eta_2 + \frac{\kappa_1}{\rho_2}(\mathbf{u}_1 - \mathbf{u}_2)|\mathbf{u}_1 - \mathbf{u}_2| - \frac{\kappa_2}{\rho_2}(\mathbf{u}_2 - \mathbf{u}_3)|\mathbf{u}_2 - \mathbf{u}_3| + A_h h_2 \nabla_h^2 \mathbf{u}_2, \quad (3)$$

$$\frac{\partial h_2}{\partial t} + \boldsymbol{\nabla}\cdot\mathbf{U}_2 = 0, \quad (4)$$

and for the bottom layer they read:

$$\frac{\partial \mathbf{U}_3}{\partial t} + \boldsymbol{\nabla}\cdot(\mathbf{u}_3 \times \mathbf{U}_3) + \mathbf{F}\cdot\mathbf{U}_3 = -g\frac{\rho_1}{\rho_3}h_3\boldsymbol{\nabla}\eta_1 - g\frac{\rho_2 - \rho_1}{\rho_3}h_3\boldsymbol{\nabla}\eta_2 - g\frac{\rho_3 - \rho_2}{\rho_3}h_3\boldsymbol{\nabla}\eta_3 + \frac{\kappa_2}{\rho_3}(\mathbf{u}_2 - \mathbf{u}_3)|\mathbf{u}_2 - \mathbf{u}_3| - \frac{\kappa_3}{\rho_3}\mathbf{u}_3|\mathbf{u}_3| + A_h h_3 \nabla_h^2 \mathbf{u}_3, \quad (5)$$

$$\frac{\partial h_3}{\partial t} + \boldsymbol{\nabla}\cdot\mathbf{U}_3 = 0, \quad (6)$$

where

$$\mathbf{F} = \begin{pmatrix} 0 & -f \\ f & 0 \end{pmatrix},$$

$f = f_0 + \beta y$ is the Coriolis parameter (f_0 represents the value of the Coriolis parameter in a central position of the model domain and β its variation along the meridional coordinate y); h_1, h_2, and h_3 are the thicknesses of the upper, intermediate, and lower layer respectively; η_1 is the sea surface displacement; η_2 and η_3 the distances of the upper and intermediate interface from the undisturbed sea surface; ρ_1, ρ_2, and ρ_3 are the water densities in the upper, intermediate, and lower layer respectively, g is the acceleration of gravity; κ_1, κ_2, and κ_3 are the two interface and the bottom friction coefficients respectively; and A_h the horizontal eddy viscosity coefficient. The densities, friction, and eddy viscosity coefficients are assumed to be constant. Equations (1)–(6) are discretized on a staggered Arakawa C grid and the initial–boundary value problem with vanishing initial conditions is solved by means of an explicit numerical scheme, where the advective terms are computed through a directional upstream algorithm [for further details see Brandt et al. (1997)]. The grid and time steps are $\Delta x = \Delta y = 10$ km, $\Delta t = 30$ s, $A_h = 200$ m^2 s^{-1}, $\kappa_1 = \kappa_2 = 0.1$ kg m^{-3}, and $\kappa_3 = 3$ kg m^{-3}. The densities and layer thicknesses are taken as typical mean values for the region (e.g., Malanotte-Rizzoli et al. 1997): $\rho_1 = 1027.80$ kg m^{-3}, $\rho_2 = 1029.10$ kg m^{-3}, $\rho_3 = 1029.18$ kg m^{-3}, and the undisturbed interfaces are $\eta_1 = 0$ m, $\eta_2 = 150$ m, and $\eta_3 = 800$ m. Finally, the bottom topography used derives from the digital bathymetric map of the oceans of Smith and Sandwell (1997).

As explained in the introduction, here we want to analyze the mean thermohaline circulation disregarding both the flow produced locally by the atmospheric forcing and the mesoscale motions produced locally by instability mechanisms. In order to do so, no momentum or heat fluxes are imposed at the sea surface, but boundary conditions representing the large-scale thermohaline circulation are imposed along the boundaries **A**, **B**, and **C** of Fig. 1. These boundary conditions were proved to be a valid tool for inducing, remotely, water transports in the Strait of Sicily by Pierini (1996), who applied and tested them for even more complex (strongly time-dependent) boundary transports. The same boundary conditions were also applied to study the flow induced in a semienclosed sea by a large-scale circulation (Commodari and Pierini 1999; Gravili et al. 2000). In the present case, steady transports in each boundary point are prescribed for each layer. Moreover, along the closed boundaries a free-slip condition for the velocity is applied.

Finally, as the complex hydrodynamics of the Strait of Sicily can lead to a local surfacing of the intermediate and/or lower layer as well as to a change in the extension of the regions where these layers are present, in our model a special technique for the numerical treatment of movable lateral boundaries is implemented, which allows for the description of localized water layers. Further details about this numerical technique are given in Brandt et al. (1997).

3. The basic numerical experiment

In order to investigate aspects of the hydrodynamics in the region of the Strait of Sicily, we integrate our numerical model in a domain (Fig. 1) that includes the area of the Strait of Sicily but also adjacent seas such as the Tyrrhenian and Ionian Seas, which—in our framework—serve as realistic buffer zones. Time-indepen-

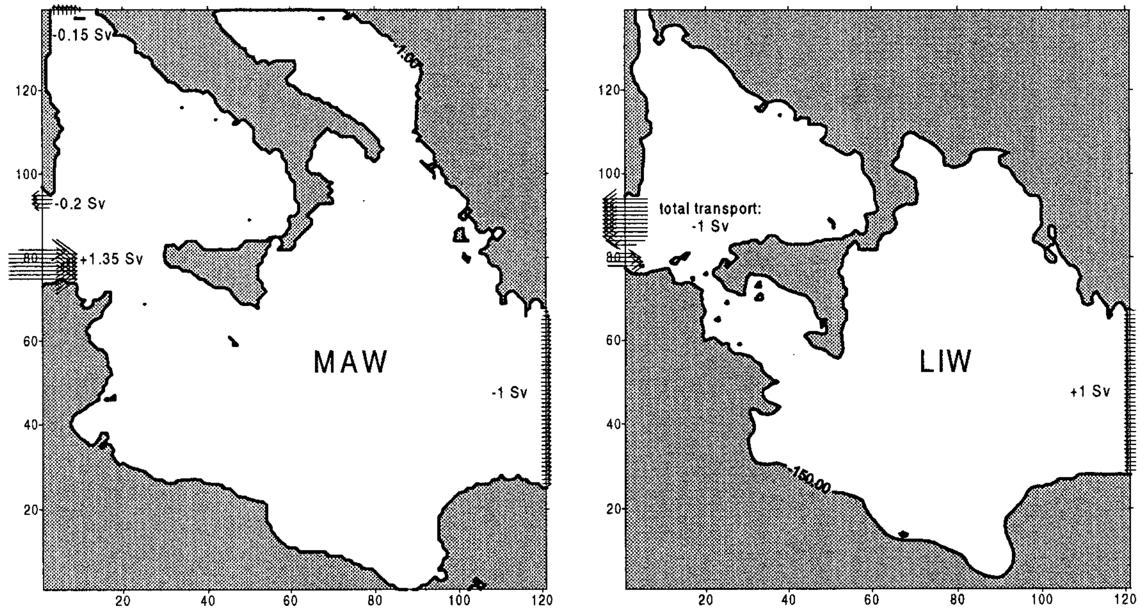

FIG. 2. Boundary conditions imposed in the expt A for the MAW and LIW layers.

dent boundary transports are imposed along the Sardinian and Corsica straits and along a boundary located in the Ionian Sea (lines **A**, **B**, and **C** of Fig. 1, respectively). Open boundaries (from now on we denote as ''open'' those boundaries where transports are prescribed) should lie far enough from the region of interest so that side effects do not affect the circulation there (see the discussion of expt A′ at the end of this section). Moreover, such open boundaries should correspond, when possible, to ''natural'' channels, where experimental data may be available to suggest realistic currents. The Straits of Sardinia and Corsica meet both these requirements. In our case, however, there is no open boundary that satisfies the last condition on the east. We then close the domain of integration with the boundary **C** of Fig. 1, which is certainly far enough from the Strait of Sicily so that the circulation near the strait is not affected by the structure of the flow near this boundary. Naturally the flow patterns generated near this fictitious eastern boundary cannot be considered as indicative of realistic circulation features. The imposition of constant-in-time boundary conditions is motivated by the hypothesis—whose validity will be checked below—that in such a case, after a rapid adjustment, a dissipative system such as ours approaches a slowly varying state (e.g., a state varying over a timescale longer than the seasonal one), whose evolution is presumably controlled by dissipative mechanisms. If this is indeed the case, then each response obtained during the slowly varying phase and corresponding to a given transport of MAW and LIW through the strait can be interpreted as a possible dynamic scenario of the seasonal variability.

In view of all this, in the present section we study the solution of the initial–boundary value problem given by (1)–(6) with the boundary conditions shown in Fig. 2, which represent one of the possible realistic choices of transports in each layer. We will use this particular example (which we denote as expt A) in order to analyze in detail the main features of the adjustment process since we have found that they are common to all the numerical experiments performed. In the next sections the response to different transports will be considered in sensitivity studies. In the present case (Fig. 2) the total net inflow of MAW (LIW) across the Sardinia and Corsica straits of $+1$ (-1) Sv and the corresponding net outflow of $+1$ (-1) Sv at the eastern open boundary **C** imply that—in a slowly varying situation—the total MAW (LIW) transport through the Strait of Sicily should also be close to $+1$ (-1) Sv, which corresponds to a locally observed mean value (e.g., Manzella et al. 1988; Millot 1999; Astraldi et al. 1996, 1999). As the layers of deep waters of the Tyrrhenian and Ionian Seas are disconnected, we decided to impose zero transport along the open boundaries of the deep layer since the abyssal circulation in the Ionian and the Tyrrhenian seas does not affect substantially the dynamics in the area of the Strait of Sicily. As far as the spatial variation of the boundary transports is concerned, through the Strait of Sardinia a shear is introduced in the MAW flux in order to model, in the southern part, a schematic Algerian Current and, in the northern part, a weaker MAW outflow (e.g., Ovchinnikov 1966). Always in the Strait of Sardinia a shear is introduced in the LIW transport as well: the outflow is limited in the central and northern part while in the south, along the African coasts, an inflow is imposed (Millot 1999; Onken and Sellschopp 1998). At the eastern boundary (section **C**) constant-in-

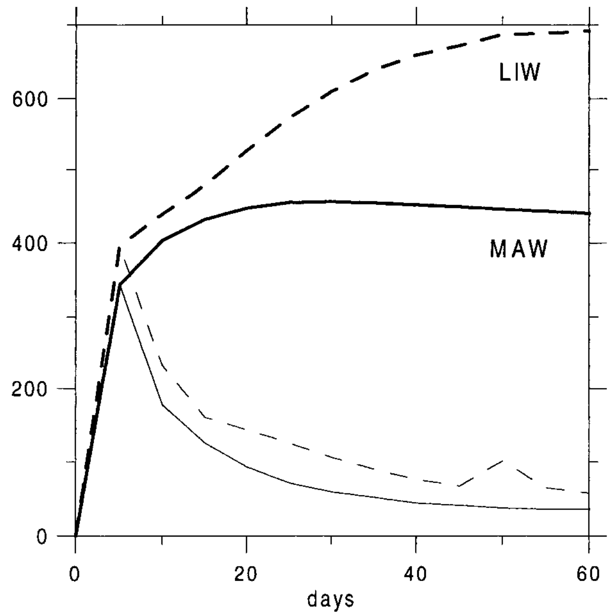

FIG. 3. Functions $Q(t)$ and $D(t)$ (see sec. 3) for expt A. Thick lines: functions Q; thin lines: function D. Solid lines: MAW; dashed lines: LIW.

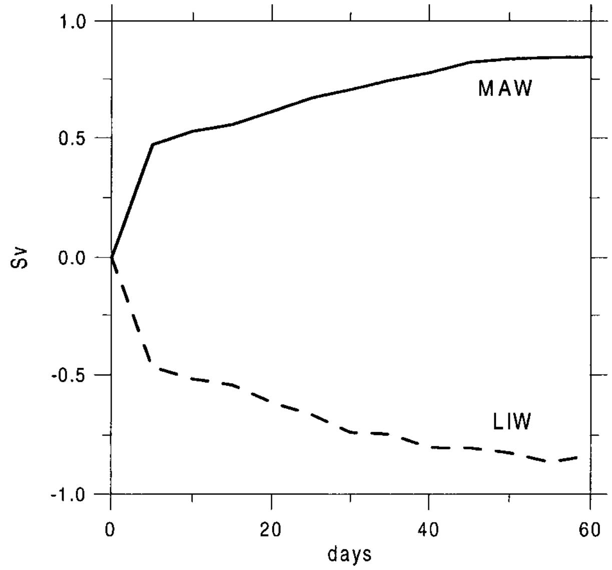

FIG. 4. Transports (in Sv) for expt A of MAW (solid line) and LIW (dashed line) through section **D** of Fig. 1.

space transports are imposed for both MAW and LIW, as the local circulation is not known in detail. At the end of this section we will analyze, with the help of an ad hoc numerical experiment (A′), the sensitivity of the interior response to changes in the spatial distribution of the boundary transports.

We now pass to study the time variation of the solution. We want to analyze in a compact way the variability following two different approaches. In the first one we study the positive-definite functions $D_i(t)$ defined as follows:

$$D_i(t) = \left\{\iint |\mathbf{U}_i(\mathbf{x}, t + dt) - \mathbf{U}_i(\mathbf{x}, t)|^2\, dx\, dy\right\}^{1/2},$$

where $i = 1, 2, 3$ denotes the layer and the integral is computed over the whole domain. These functions give a measure of the velocity of variation of the solution as averaged over the basin so that, for instance, a hypothetical steady state would be reached in the limit $D_i = 0$. Figure 3 shows D_i as a function of time for experiment A for successive 5-day increments. After a rapid variation of the solution starting from the initial condition the tendency is clearly toward a decrease of the variability. In the same figure the functions

$$Q_i(t) = \left\{\iint |\mathbf{U}_i(\mathbf{x}, t)|^2\, dx\, dy\right\}^{1/2}$$

are also reported. They can be taken as a measure (for each layer) of the change the system has experienced from the initial vanishing transports. Again, if an exact steady state were attained, then in that limit Q_i = const (but the converse is not necessarily true). Also the functions Q_i show (Fig. 3) a very rapid variation lasting 10–20 days and later the tendency toward a slowly varying state, which is reached after ~1 month for the surface layer and after ~2 months for the intermediate layer. The second approach makes use of the net transports q_i through section **D** of Fig. 1 that divides the domain in two disjointed parts. In the limiting case in which the response is exactly steady the q_i should equal the boundary transports. In our case we expect the q_i to approach that limit after the times evaluated from Fig. 3. This is, in fact, what Fig. 4 shows: at $t = 2$ months the transports differ from 1 Sv (Sv $\equiv 10^6$ m^3 s^{-1}) by less than 20% in both layers. Therefore these two "integrated" means of monitoring the evolution of the system lead to the same conclusion. In general, the initial rapid variation is related to the process of closure of the various coastal and topographic flows that originate from the western and eastern boundaries and is controlled by Kelvin and double Kelvin wave propagation (Herbaut et al. 1998). Such flows merge at $t = 20$–30 days, after which time the average variation becomes smaller. This can be recognized in Fig. 5 where the transient state for the MAW is shown in four different snapshots. Later, at $t \approx 2$ months a slowly varying state is attained. As a consequence, in the following we will choose all our fields at $t = 60$ days as representative of the response to a particular choice of the boundary transports.

Figures 6a–c show the transports of experiment A for the upper, the intermediate, and the deep layer respectively. The MAW circulation at the strait level appears to be a complex combination of circulation patterns characterized, in particular, by a series of bifurcations. The MAW entering the Strait of Sardinia is clearly coupled dynamically to the LIW, as it feels the bottom

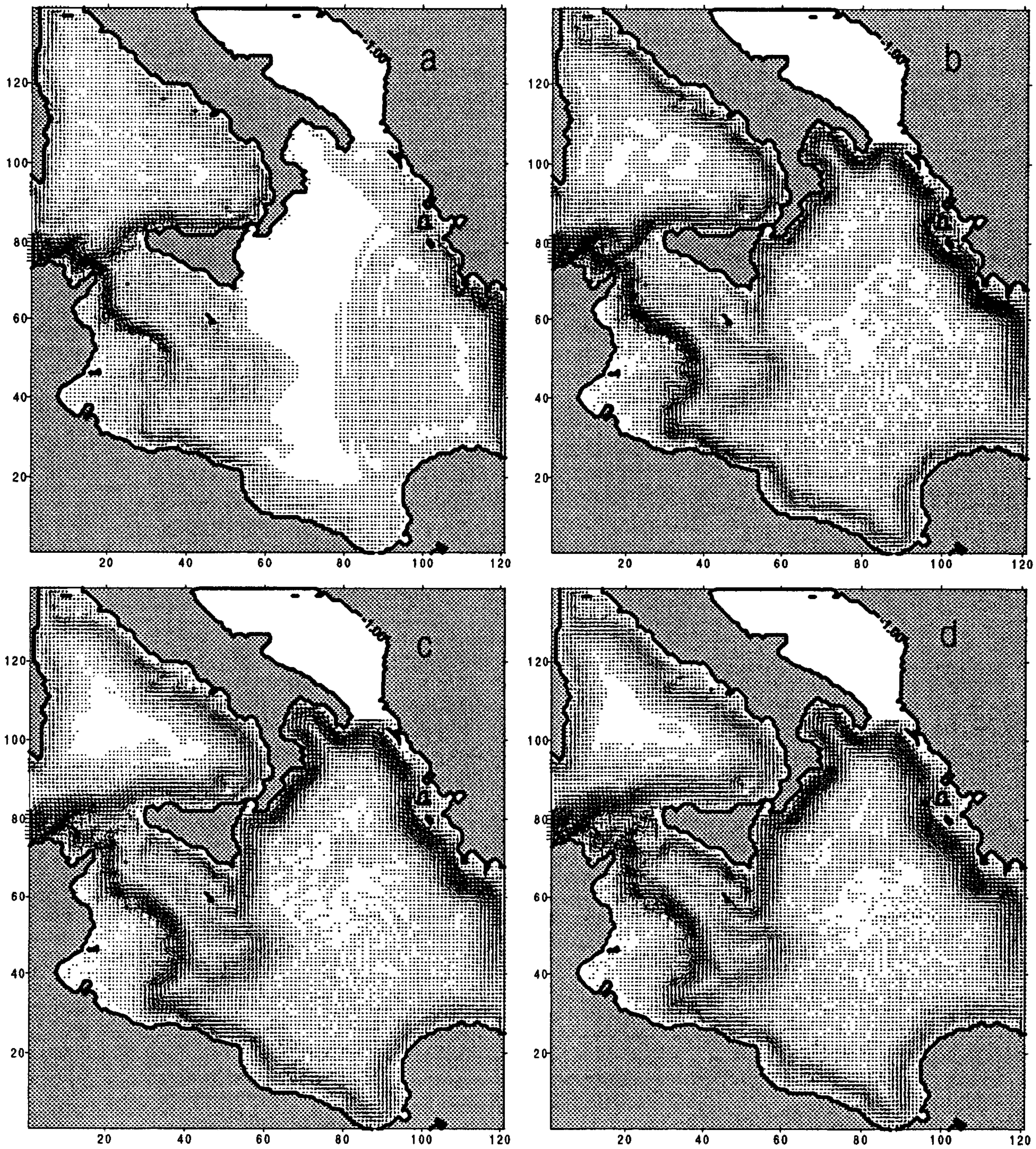

FIG. 5. Snapshots of the MAW flow for expt A at times t = 5 days (a), t = 20 days (b), t = 35 days (c) and t = 50 days (d).

control by following the strong topographic slope north of Tunisia. A weaker branch of MAW flows closer to the African coasts and, after passing Cape Bon, continues to flow southward along the Tunisian continental slope. The main stream of MAW experiences another bifurcation west of Sicily: a branch flows along the northern Sicilian coasts toward the Italian peninsula in the form of a broad current (which discharges part of its transport through the Strait of Corsica and the remaining part through the Strait of Sardinia), while a second branch turns southward and joins the weaker stream described above to produce a strong, narrow jet in correspondence to the deepest part of the strait. Here the flow undergoes a further bifurcation: a main part flows southward following the Tunisian continental slope while a weaker branch (about half the first one in

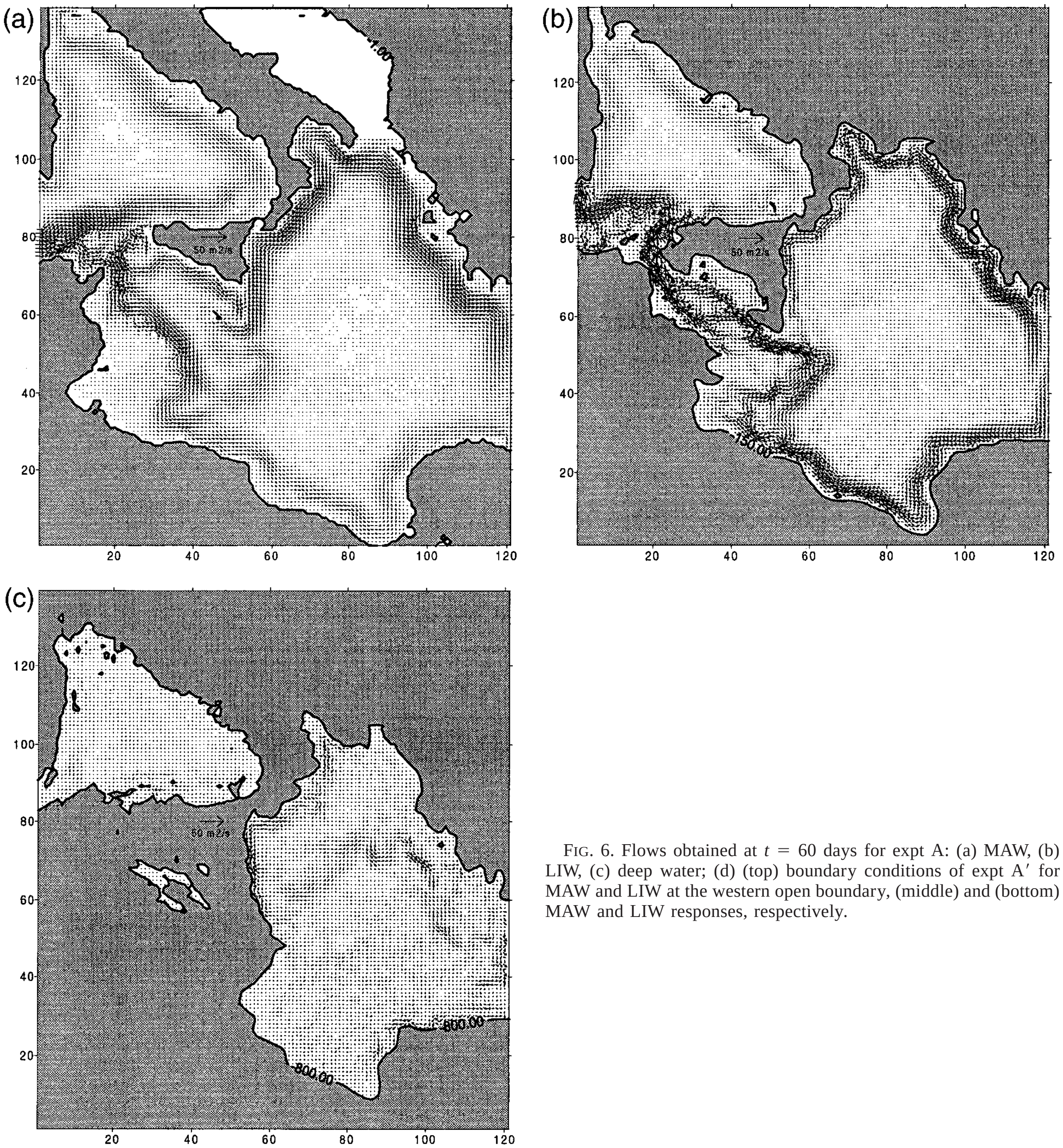

FIG. 6. Flows obtained at $t = 60$ days for expt A: (a) MAW, (b) LIW, (c) deep water; (d) (top) boundary conditions of expt A′ for MAW and LIW at the western open boundary, (middle) and (bottom) MAW and LIW responses, respectively.

transport) forms the so-called Atlantic–Ionian Stream (AIS: e.g., Malanotte-Rizzoli at al. 1997). It follows the edge of Adventure Bank (the shallow region southwest of Sicily), then flows southeastward following the southern Sicilian coasts and, after having interacted with the Malta plateau, enters the Ionian Sea flowing northward along the eastern Sicilian coasts. This scenario is in good agreement with the main features of the AIS as inferred by recent hydrological data (e.g., Malanotte-Rizzoli et al. 1997). Recent acoustic Doppler current profiler measurements also confirm this behavior (Brandt et al. 1999). Lagrangian trajectories obtained by using surface drifters recently released in the Strait of Sicily (P. Poulain and E. Zambianchi 1999, personal communication) are evidence of a strong mesoscale activity, which is not described by the present model, but also mean features that have a counterpart in the present numerical simulation, in particular as far as the AIS is concerned.

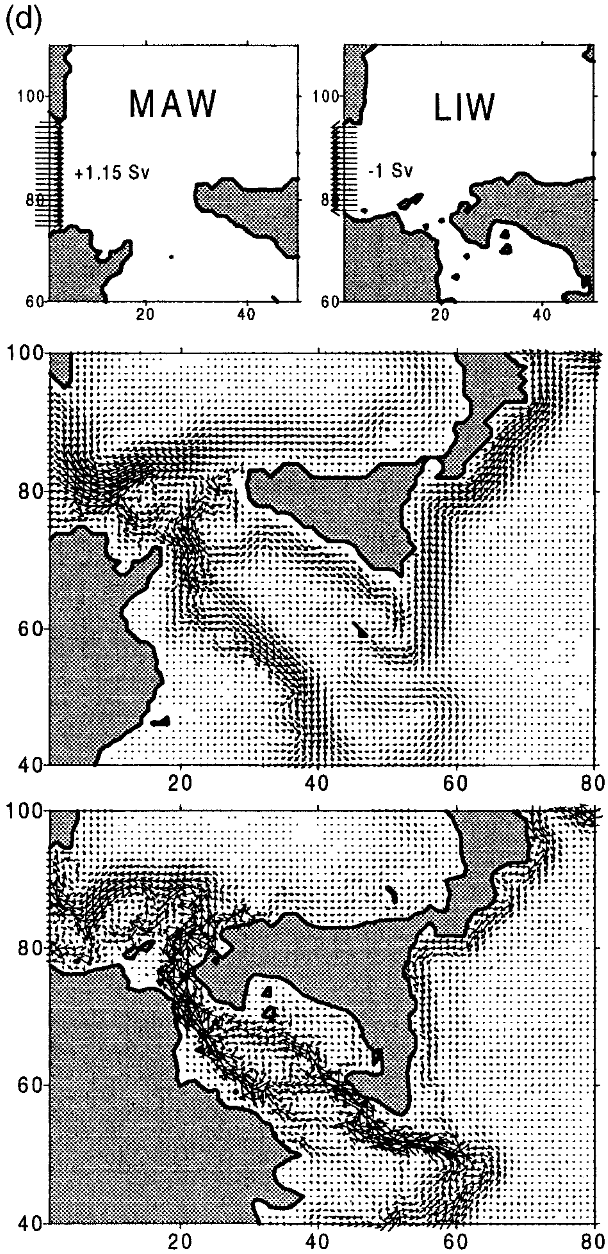

FIG. 6. (*Continued*)

Also the LIW flow presents a succession of bifurcations. A strong narrow jet approaches Malta, then divides into two veins that join together again at the strait sills. After this passage the flow continues northward until it experiences a further bifurcation: a weak vein follows the northern Sicilian coast while a main jet overshoots farther north, following a complex meandering pattern clearly determined by the bottom topography, until the flow finds its way through the Strait of Sardinia. The circulation of the deep layer is much less significant since in this model it acts as a virtually passive layer.

We conclude this section by presenting a numerical experiment (A′) aimed at showing the weak sensitivity of the response to variations of the spatial structure of the boundary transports. The approach adopted by Pierini (1996) and applied in this study is based on the assumption that the circulation in the area of the strait is determined by the open boundary conditions mainly through their gross features, such as the total transports at the open boundaries (and in turn across the strait), but not by their fine structure. The circulation patterns should, on the contrary, be shaped basically by the interaction of the induced mean flows with coasts and bottom topography. If it were not so, then the flows shown in Figs. 6a–c would still provide interesting dynamic information but they would be strictly associated to the specific boundary conditions of Fig. 2, which, though inspired by experimental observations, have some degree of arbitrariness. Moreover, it is important to check that the regions near the open boundaries, where inevitably the flow is largely determined by the details of the imposed boundary conditions, are sufficiently far from the area under investigation. Experiment A′ provides answers to both of these problems.

Experiment A′ differs from experiment A only in that the boundary transports of MAW and LIW through the Strait of Sardinia section are meridionally constant (Fig. 6d, upper panels), while their net transports through the open boundary (1.15 Sv for MAW and 1 Sv for LIW) are the same as for experiment A. If one compares the induced MAW and LIW flows of this experiment (Fig. 6d central and lower panels respectively) with those of experiment A (Figs. 6a,b) it appears evident that, apart from a region adjacent to the open boundary, very weak differences are present. The reason for this behavior is to be accounted for by the control that the topography exerts on both the MAW and LIW flows. As far as the eastern open boundary is concerned, this is so much farther away from the Strait of Sicily than the western open boundary that we expect the flow in the region of interest to be even less dependent on the spatial details of the boundary transport imposed there. This is, in fact, what results from numerical experiments not shown, in which different meridional structures are imposed assuming the same net transport across the open boundary: the response near the strait never changes appreciably.

Therefore we can conclude that the interior evolution is determined by the boundary conditions mainly through the net transports they induce in the strait and only weakly by the spatial details of their structure. Moreover it results that the area of interest is sufficiently far from the open boundaries. This allows us to impose the boundary transports with some degree of arbitrariness in their spatial structure. On the other hand, we will see at the end of section 4a that an important parameter characterizing the MAW bifurcation at the strait level agrees better with experimental results if the realistic boundary conditions of Fig. 2 (expt A) are applied instead of the less realistic ones of Fig. 6d (upper panels; expt A′). So, a degree of realism in the spatial structure of the boundary conditions does produce an appreciably more realistic response.

4. The main MAW and LIW bifurcations: Vanishing barotropic transport through the strait

In the basic numerical experiment described in the preceding section several bifurcations of both MAW and LIW were identified. Here we want to analyze in particular: (i) the bifurcation of MAW that distributes the Algerian Current into two parts, one crossing the strait and another entering the Tyrrhenian Sea; (ii) the bifurcation of LIW that distributes the intermediate water crossing the strait into two parts, one flowing directly toward the Strait of Sardinia via a meandering pattern and another entering the Tyrrhenian Sea. We denote these partitions as *main* bifurcations since they play a major role in the overall water budget, but we should bear in mind that the one distributing the MAW is composed of two minor bifurcations, as described in section 3. In order to monitor the flow separation we compute the MAW and LIW transports through line **D** (i.e., across the Strait of Sicily) and through line **E** (i.e., entering the Tyrrhenian Sea). We pass to discuss separately the cases of vanishing (this section) and nonvanishing (section 5) barotropic transport through the strait.

a. Sensitivity to the Algerian Current transport

In the basic numerical experiment described in section 3 (expt A) a zero barotropic (i.e., depth integrated) transport through the strait was remotely imposed by prescribing a ± 1 Sv for the MAW and LIW transports respectively. In experiment A the Algerian Current (denoted AC) was imposed as a MAW boundary jet of 1.35 Sv (see Fig. 2). From Fig. 6a (see also Fig. 7a, middle panel, for a zoom) it can be evinced that the MAW transport entering the Tyrrhenian Sea north of Sicily is, asymptotically, the difference between the imposed AC transport (1.35 Sv) and the remotely induced transport through the strait (1 Sv). This transport (0.35 Sv) is then discharged partly through the Corsica channel (0.15 Sv) and partly in the northern section of the Strait of Sardinia (0.2 Sv).

However, is this the case for any AC transport? Let us decrease it to 1.1 Sv leaving all the other transports unchanged except the MAW transport in the northern part of the Strait of Sardinia (-0.05 Sv) and through the Corsica Channel (-0.05 SV), which are now scaled so as to keep the transport through the strait equal to 1 Sv like in the previous experiment (we denote this numerical experiment as B1, see Table 1). One might expect that, again, asymptotically, the MAW entering the Tyrrhenian Sea north of Sicily is merely the difference between the imposed AC transport (1.1 Sv) and the transport flowing through the strait (1 Sv). On the contrary, as shown in Fig. 7a (upper panel) a cyclonic recirculation in the Tyrrhenian Sea is induced in such a way that the MAW entering the Tyrrhenian is sensibly larger than the expected value of 0.1 Sv. On the other hand, if the AC transport is increased to 1.6 Sv, again leaving the transport through the strait unchanged [the MAW transport in the northern part of the Strait of Sardinia is now -0.3 Sv and the one through the Corsica channel -0.3 SV (we denote this numerical experiment as B2, see Table 1)], then (Fig. 7a, lower panel) part of the AC near the western boundary flows directly toward the northern Strait of Sardinia, in such a way that the MAW entering the Tyrrhenian is sensibly smaller than the expected value $1.6 - 1 = 0.6$ Sv. In other words, the Strait of Sicily controls the MAW bifurcation whose structure cannot, therefore, be determined remotely by imposing given transports along the open boundaries.

The question is now: How strong is such a control? An interesting answer is provided by Fig. 7b. The MAW transports through the strait (i.e., across line **D**) in the experiments A, B1, and B2 all tend, as expected, to the same remotely imposed value (see Fig. 4 and relative discussion). What is more surprising is that also the transports entering the Tyrrhenian Sea (i.e., across line E of Fig. 1) tend to a common value equal to $\sim$0.35 Sv. This transport value is not imposed remotely, as discussed above, but rather selected by the dynamical system. Let us define the ratio $R_{\rm maw}$ as follows:

$$R_{\rm maw} = \frac{\text{MAW transport entering the Tyrrhenian}}{\text{MAW transport crossing the strait}}, \quad (7)$$

where the transports are computed along lines **D** and **E** of Fig. 1. Here $R_{\rm maw}$ characterizes quantitatively the structure of the main MAW bifurcation and is shown in Fig. 8a. The same final value $R_{\rm maw} \approx 0.43$ is obtained for experiments A, B1, and B2, which is therefore independent of the boundary-imposed AC transport and corresponds to a vanishing barotropic transport and to an $\sim\pm 1$ Sv baroclinic transport through the strait. It is interesting to notice that this value is in excellent agreement with water budget estimates computed by Béthoux (1980) in the framework of a climatological approach, which implies an almost vanishing barotropic transport through the strait, as in the case discussed in this subsection. On the basis of surface water budgets in various areas of the Mediterranean Sea estimated by Béthoux (1980), a ratio between the two transports $R \approx 0.46$ can be obtained, indeed in very good agreement with our value obtained numerically.

For experiment A′ (which differs from expt A only in that the boundary transports of MAW and LIW through the Strait of Sardinia are constant in latitude while their net transports are the same) one gets $R_{\rm maw} \approx 0.37$, whose agreement with the experimental value is still good, but not as good as for experiment A. Thus, although the comparison between experiments A and A′ (sec. 3) put in evidence the weak sensitivity of the response to variations of the spatial structure of the

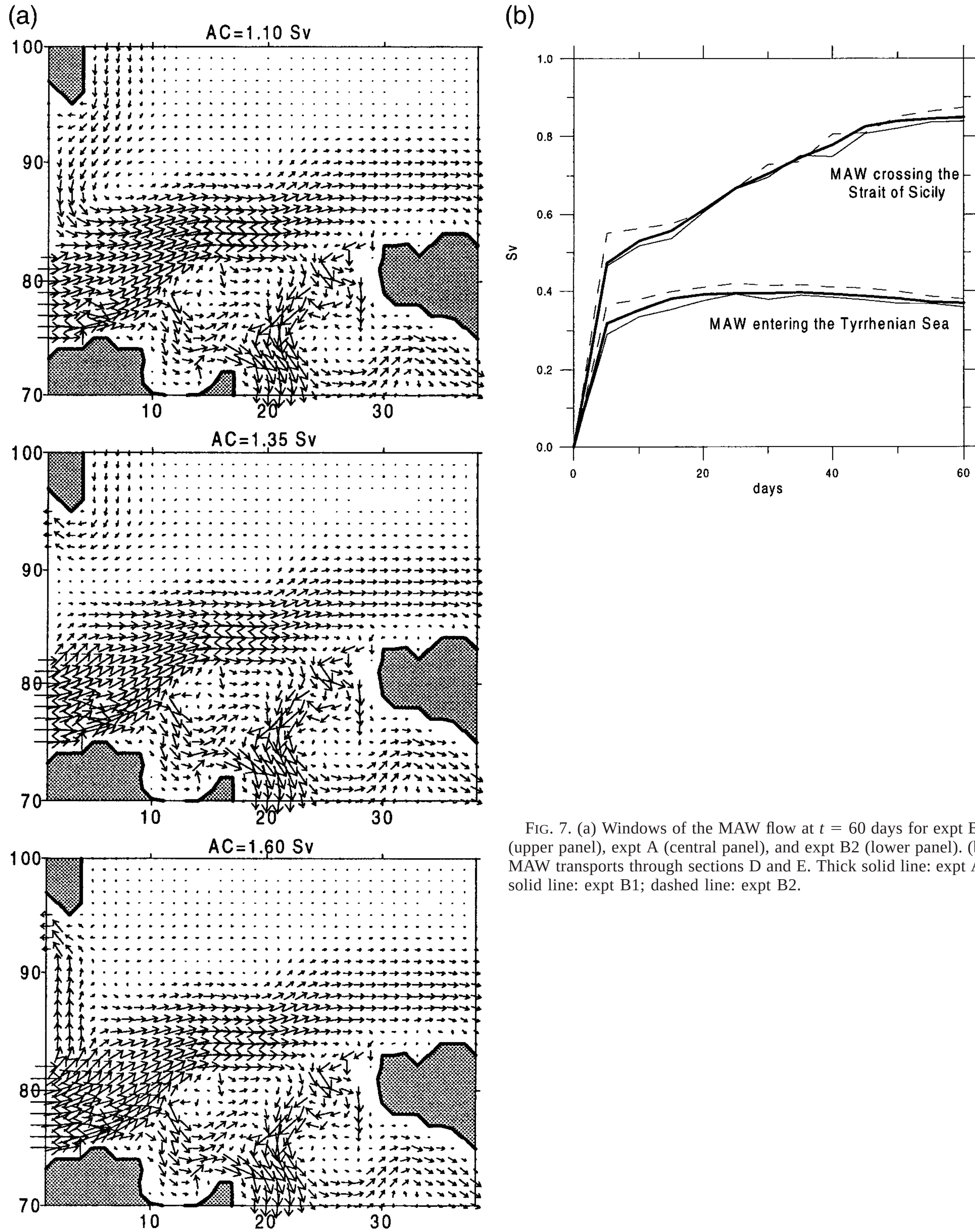

FIG. 7. (a) Windows of the MAW flow at t = 60 days for expt B1 (upper panel), expt A (central panel), and expt B2 (lower panel). (b) MAW transports through sections D and E. Thick solid line: expt A; solid line: expt B1; dashed line: expt B2.

TABLE 1. The boundary conditions for the basic numerical experiment A are reported in Fig. 2. The other experiments are characterized here by their differences with respect to experiment A (AC, NS, and CC stand for Algerian Current, Northern Sardinian Strait, and Corsica Channel MAW transports, respectively; BT: barotropic transport.)

Expt	Characteristics
B1	AC = 1.10 Sv; NS = −0.05 Sv; CC = −0.05 Sv (AC + NS + CC = 1 Sv, like in expt A).
B2	AC = 1.60 Sv; NS = −0.30 Sv; CC = −0.30 Sv (AC + NS + CC = 1 Sv, like in Expt A).
A′	Boundary transports through the Strait of Sardinia constant in latitude.
C1	All transports scaled by the factor $r = 0.5$.
C2	All transports scaled by the factor $r = 0.25$.
C3	All transports scaled by the factor $r = 0.125$.
D1	All MAW transports scaled by the factor $r = 0.5$ (BT = −0.5 Sv).
D2	All LIW transports scaled by the factor $r = 0.5$ (BT = +0.5 Sv).

boundary transports, the value of R_{maw} show that a degree of realism in the spatial variation of the boundary conditions does produce an appreciably more realistic response.

Finally, Fig. 8b shows the value of R_{liw}, which is analogous to R_{maw} for the LIW layer, and we can notice that again the final value is not sensitive to the value of the AC transport, although this is less surprising since no changes in the intermediate layer are imposed.

b. Sensitivity to variations of the baroclinic transports through the strait

The numerical experiments B1 and B2 have revealed the existence of a control that the Strait of Sicily exerts on the main MAW bifurcation in the case in which the MAW and LIW transports through the strait are +1 Sv and −1 Sv respectively. If for such realistic transport values the nonlinear advective terms in the equations of motion were negligible, a scaling of all the boundary fluxes through a common coefficient would lead to an equal scaling of the response and would, in particular, leave the ratios R_{maw} and R_{liw} unaltered. If, on the contrary, the nonlinear advective terms were not negligible, these ratios could change in principle. In this case it would be of great interest to assess the sensitivity of the value of such ratios to variations of the baroclinic transports through the strait. This subsection is devoted to such an analysis.

In the numerical experiments C1, C2, and C3 (Table 1) all the boundary fluxes of the basic experiment A are reduced by a factor 2, 4, and 8, respectively, and Figs. 9a,b show the ratios R_{maw} and R_{liw} obtained as a result. The asymptotic values for R_{maw} in experiments A, C1, C2, and C3 are ~0.43, ~03, ~0.25, and ~0.23 respectively, indicating that, for realistic baroclinic transport values O(1 Sv), the regime is definitely non-

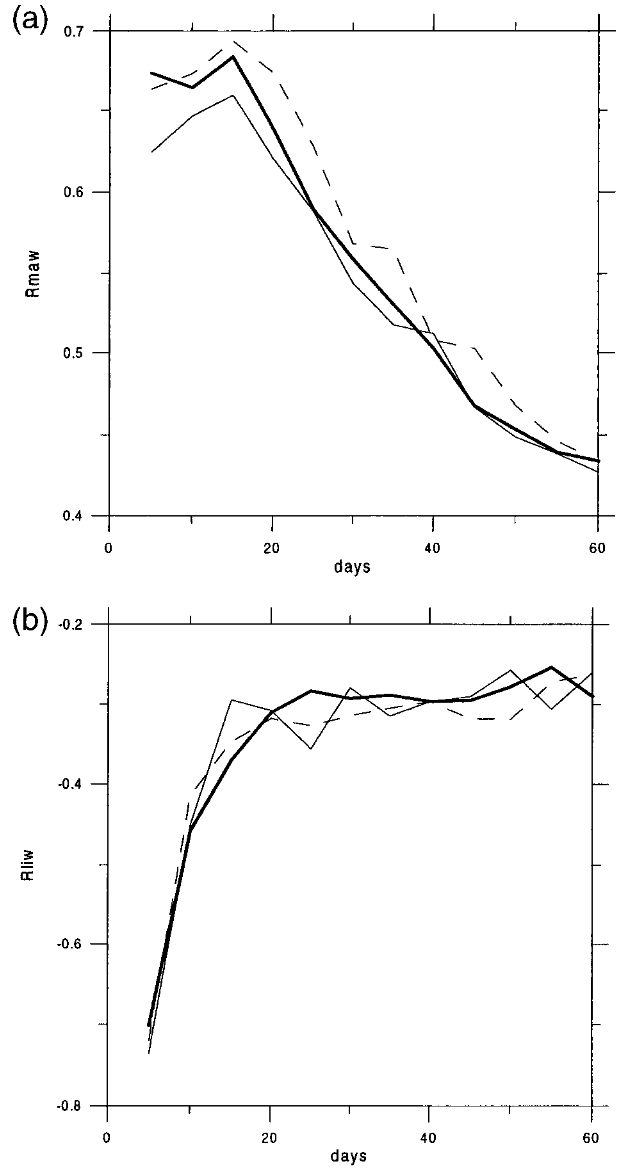

FIG. 8. (a) R_{maw}; (b) R_{liw} (see Section 4a). Thick solid line: expt A; solid line: expt B1; dashed line: expt B2.

linear, the structure of the MAW bifurcation depending strongly on the local transports, and that only for unrealistically small values O(0.1 Sv) the system responds almost linearly to the boundary forcing. In general, fluctuations that increase the strait transports are associated to a larger R_{maw}, while fluctuations that decrease the strait transports are associated to a smaller R_{maw}. For unrealistically small transports O(0.1 Sv) an almost linear regime is reached and R_{maw} becomes independent of the baroclinic transports, yielding the value $R_{maw} \approx 0.2$ (we emphasize that we are dealing with cases in which the barotropic transport through the strait is zero).

Finally we notice that, unlike R_{maw}, R_{liw} is very weakly sensitive to variations of the baroclinic transports. Fig-

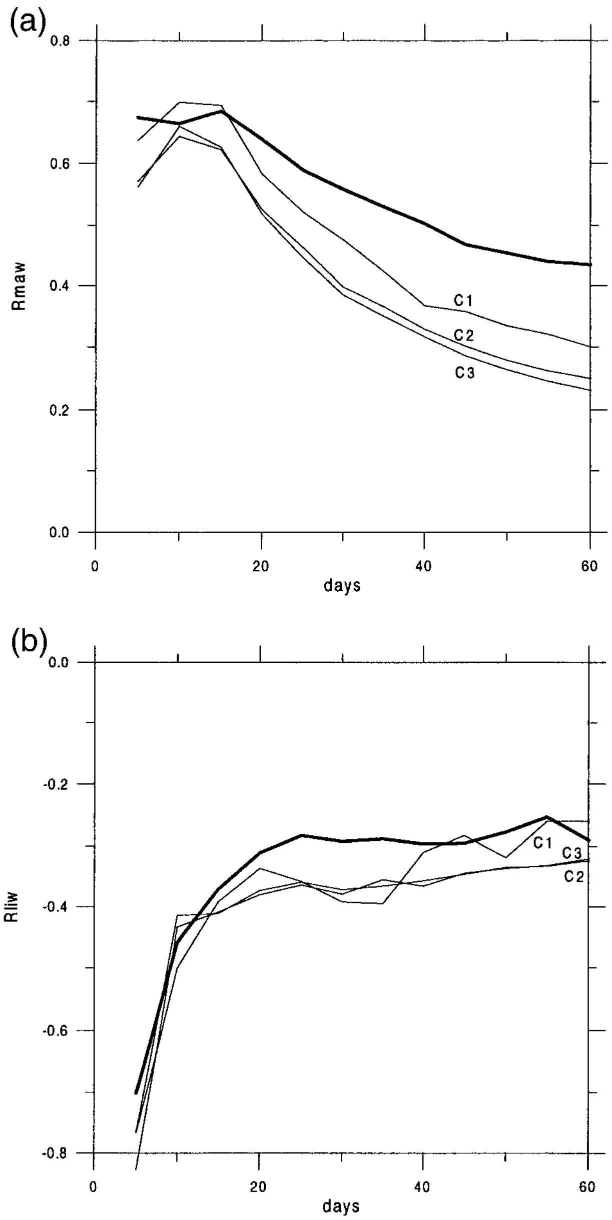

FIG. 9. (a) R_{maw}; (b) R_{liw} (see sec. 4b). Thick solid line: expt A. The experiments C1, C2, and C3 are indicated in the graph.

ure 9b shows that the ratios for C2 and C3 are virtually undistinguishable, but also the values for A and C1 are all very close to ~0.3. We will see in the next section that this lack of sensitivity of R_{liw} to variations of the baroclinic transports includes also the case of nonvanishing barotropic transports in the strait.

5. The main MAW and LIW bifurcations: Nonvanishing barotropic transport through the strait

We saw in section 4 that in the case in which the barotropic transport through the Strait of Sicily (denoted BT) is zero, the system selects well-defined ratios R_{maw} and R_{liw} (Figs. 8a,b) in so determining the character of the main MAW and LIW bifurcations. The choice BT $= 0$, that is, a perfect balance between the flux of MAW toward the eastern basin and the flux of LIW toward the western basin, is implied by the conservation of mass over a sufficiently long time, if one neglects a small unbalance in the baroclinic transports (which is however dynamically irrelevant in the strait) related to the concentration nature of the Mediterranean Sea: the excess of evaporation over precipitation and river runoff in the whole Mediterranean leads at Gibraltar to a surplus of Atlantic water transport with respect to that of LIW of a mere 0.04 Sv (Bryden et al. 1994) and an unbalance of the same order of magnitude is expected at the Strait of Sicily.

However, although on average (over a sufficiently long time) BT $= 0$, fluctuations of BT over timescales as large as the seasonal one can in principle be expected because the MAW and LIW fluxes yield important variabilities associated to different causes and, on the other hand, there is no mechanism that requires an exact instantaneous local balance between the two transports. The observed seasonality of the LIW formation in the Eastern Mediterranean has its counterpart in the observed seasonal variability of the LIW transport through the Strait of Sicily, which can amount to as much as $\sim\pm0.5$ Sv about its mean value of ~1 Sv, as shown by Astraldi et al. (1996, 1999), who also measured important interannual variations of the LIW transport associated to anomalies in the meteorological forcing. Direct measurements of the MAW strait transport analogous to those of the LIW are not yet available because of the nature of the surface flow (that presents an intense mesoscale dynamics and involves the whole strait, rather than being canalized in a restricted submarine area, as for the LIW), but similar transport variations can be expected.

In this section we therefore investigate the behavior of the MAW and LIW bifurcations when a nonvanishing barotropic transport in the strait is present. The numerical experiment D1 (Table 1) differs from the basic numerical experiment A in that the boundary forcing for the upper layer is scaled by the factor $r = 0.5$, resulting in a -0.5 Sv BT through the strait. Figure 10a (upper panel) shows the MAW flow pattern, which clearly yields a ratio R_{maw} sensibly larger than that of experiment A (central panel). On the other hand in the numerical experiment D2 (Table 1, Fig. 10a, lower panel), for which the boundary forcing for the intermediate layer is scaled by the factor $r = 0.5$, resulting in a $+0.5$ Sv BT through the strait, the ratio R_{maw} is sensibly smaller than that of experiment A. In other terms the MAW bifurcation appears to be extremely sensitive to variations in the barotropic transport through the strait. Figure 10b shows that $R_{maw} \approx 0.1$ for experiment D2 while this ratio is an order of magnitude larger ($R_{maw} \approx 1.1$) for experiment D1. Also in these two cases, as in experiments B1 and B2, the remotely imposed Algerian

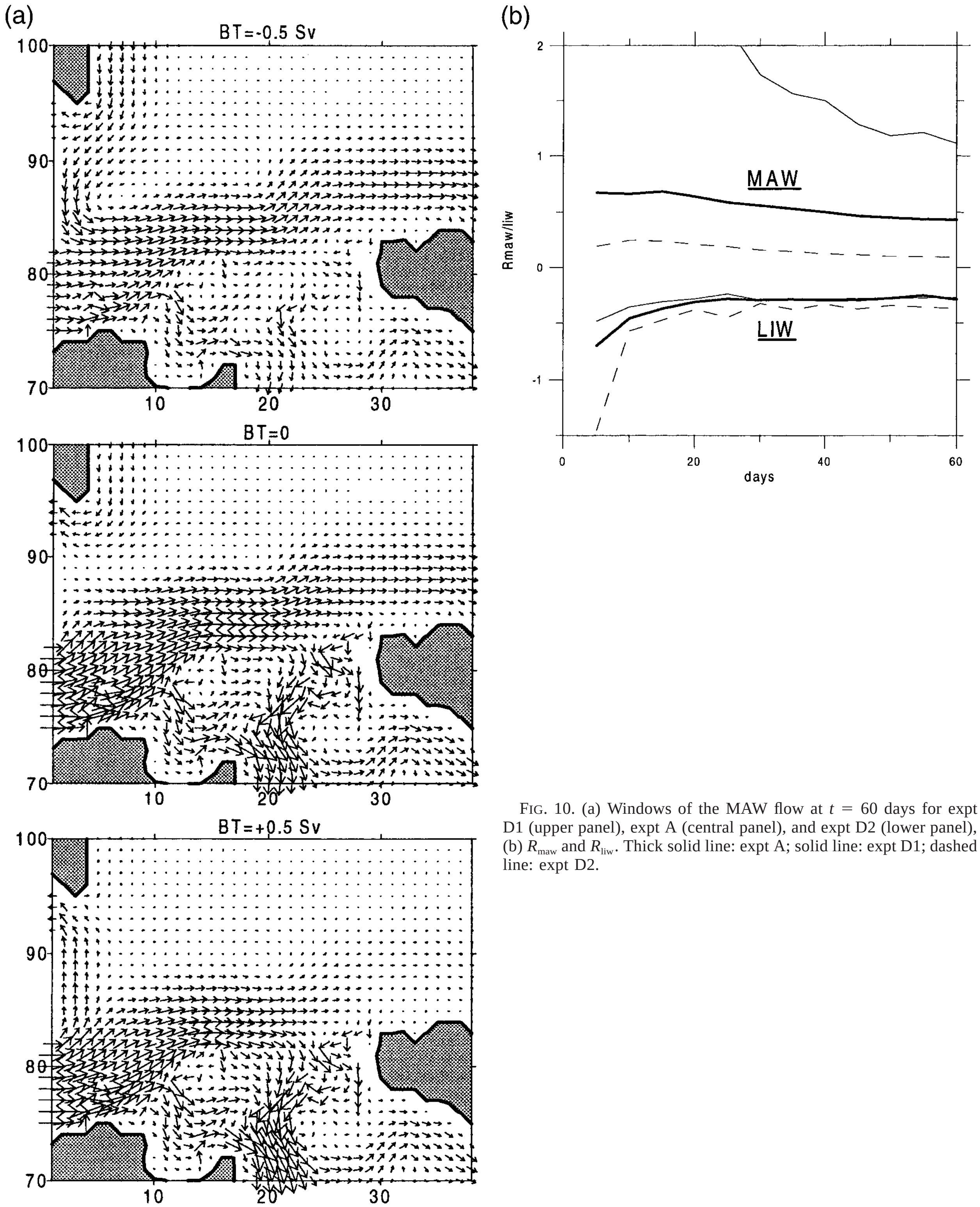

FIG. 10. (a) Windows of the MAW flow at $t = 60$ days for expt D1 (upper panel), expt A (central panel), and expt D2 (lower panel), (b) R_{maw} and R_{liw}. Thick solid line: expt A; solid line: expt D1; dashed line: expt D2.

Current transport is irrelevant in the bifurcation functioning (notice the induced cyclonic Tyrrhenian circulation in Fig. 10a, upper panel, and the MAW discharge of part of the Algerian Current directly through the northern section of the Strait of Sardinia in the lower panel, as in Fig. 7a, upper and lower panels respectively). In conclusion, the control that the Strait of Sicily exerts on the MAW bifurcation is strongly sensitive to unbalances of the MAW and LIW transports through the strait. If a 1 Sv LIW transport is twice that of MAW (expt D1), then the transport of MAW entering the Tyrrhenian Sea is almost equal to that crossing the strait, but if a 0.5 Sv LIW transport is half that of MAW (experiment D2), then the transport of MAW entering the Tyrrhenian Sea is only ~1/10 of that crossing the strait.

Finally, it is interesting to notice that, while R_{maw} is strongly dependent on BT, R_{liw} is virtually independent of BT. This is shown in Fig. 10b, where it is evident that for all the three experiments A, D1, and D2, the ratio R_{liw} tends to a value ~0.3. This lack of sensitivity of R_{liw} (which adds to its lack of sensitivity to variations of the baroclinic transports when BT = 0, as shown in sec. 4.2) can presumably be accounted for by the important role played by the bottom topography in the potential vorticity balance in the LIW layer in the area of the Strait of Sicily. In conclusion, the LIW vein forming a cyclonic circulation in the Tyrrhenian Sea has a transport that is ~1/3 of the total LIW transport crossing the strait, while the remaining 2/3 of the transport flows directly toward the Strait of Sardinia, and this partition is not sensitive to MAW–LIW transport imbalances in the Strait of Sicily.

6. Conclusions

In this paper dynamic scenarios of the seasonal variability in the area of the Strait of Sicily have been obtained by forcing a three-layer numerical model by means of boundary-imposed MAW and LIW transports, representing the large scale thermohaline circulation along the open boundaries of the domain of integration. A basic numerical experiment was first discussed, in which boundary conditions inspired by experimental observations produced an oceanic response in terms of circulation patterns and bifurcations in the surface and intermediate layers in good agreement with what is generally known on the basis of experimental results. In addition to that, information was provided about the shape of boundary and topographically controlled jets in regions not sufficiently studied experimentally. We then proceeded to study the sensitivity of the main MAW and LIW bifurcations to variations of the boundary conditions, in order to obtain information about the role played by the Strait of Sicily in shaping and, possibly, controlling the exchange flow between the western and the eastern Mediterranean subbasins.

As far as the MAW bifurcation is concerned, a dynamic control exerted by the region of the strait on the separation of the incoming Algerian Current (into a part crossing the strait and another flowing into the Tyrrhenian Sea) is implied by the independence of the parameter R_{maw} on the boundary imposed Algerian Current transport. For vanishing barotropic transports through the strait, R_{maw} yields a value ~0.4 for baroclinic transports O(1 Sv) (in excellent agreement with water budget estimates) and it reduces to ~0.2 in the linear regime, reached only for unrealistically small baroclinic transport values O(0.1 Sv). On the other hand, for barotropic transport variations of ±0.5 Sv about baroclinic transports of 1 Sv, R_{maw} undergoes great changes, yielding values ranging from 0.1 to 1. Thus, the MAW transport entering the Tyrrhenian Sea north of Sicily appears to be always strictly connected to the MAW transport crossing the Strait of Sicily, the ratio between the two transports depending dramatically on both the barotropic and the baroclinic transports through the strait.

As far as the LIW bifurcation is concerned, we have found that its behavior is quite different. Unlike the MAW bifurcation, the character of the LIW separation into two parts appears to be very weakly dependent on both the barotropic and the baroclinic transports through the strait of Sicily, the ratio R_{liw} always yielding a value ~0.3. This can be accounted for by the important role played by the bottom topography in the potential vorticity balance in the LIW layer in the area of the Strait of Sicily. In large parts of this region the LIW represents in fact the bottom layer.

In this paper we have therefore obtained information on the functioning of the bifurcations of surface and intermediate water transports in a crucial environment such as the Strait of Sicily, where the connection between the two large Mediterranean subbasins takes place. Understanding the dynamical mechanisms that determine such a behavior is a more ambitious task. A fundamental contribution in this direction is provided by a theoretical analysis of Herbaut et al. (1998), in which the separation of a coastal current approaching an idealized strait in a two-layer fluid was studied in a linearized framework in terms of Kelvin, double Kelvin, and Poincaré waves interacting with the coasts and the bottom topography. The outcomes of the present paper suggest that additional effects could be important in determining the bifurcations in the Strait of Sicily. First of all nonlinear effects should be taken into account. We saw in detail in section 4b that the system does not respond linearly to variations of the boundary transports for realistic values of the baroclinic transports in the case of a vanishing barotropic transport but, more in general, a strong dependence of the character of the local circulation on the amplitude of the transports was always found, so nonlinear effects are expected to play always an important role in the bifurcation process in the Strait of Sicily. Second, different baroclinic dynamics should be considered since we found that the bifurcations depend crucially on them.

The next step toward a realistic modeling of the dynamics in the Strait of Sicily, within the same framework proposed in the present paper, requires realistic time-dependent boundary conditions (that could be provided by a general circulation model of the whole Mediterranean Sea) and the inclusion of the wind forcing, which will introduce a high frequency variability. An interesting aspect to be assessed is the interaction of the wind-driven flow with the mean flows such as those considered here. For example, it is well known that in winter the prevailing positive vorticity input provided by the wind stress curl induces a mainly barotropic cyclonic circulation in the Tyrrhenian Sea (e.g., Pierini and Simioli 1998), so the barotropic transport across section E we found in the present study should be reinforced by the wind. However, the total barotropic transport may not be simply the sum of the two components since nonlinear interactions can add complexity to the dynamics. Understanding in general how the wind-driven circulation interacts with the mean baroclinic flows and modifies the bifurcation properties determined in this paper is of great importance. Furthermore, the role played by the mesoscale motions associated to baroclinic instabilities (Onken and Sellschopp 1998) and to topographically controlled rotational waves (Pierini 1996) in the overall dynamics is also worth considering.

Acknowledgments. We are grateful to G. P. Gasparini for valuable discussions on experimental aspects of the circulation in the region of the Strait of Sicily. We wish to thank also M. Astraldi, P. Brandt, G. Budillon, M. Crépon, L. Gervasio, C. Millot, M. Moretti, E. Sansone, D. Sein, G. Spezie, and E. Zambianchi for valuable discussions. This research was supported by the European Commission under Contract MAS3-CT96-0051 ''MTP-II-MATER'' and by the Sonderforschungsbereich-512 Programme of the University of Hamburg.

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