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Viúdez, Álvaro

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An Explanation for the Curvature of the Atlantic Jet past the Strait of Gibraltar

ÁLVARO VIÚDEZ*

Department of Meteorology, Naval Postgraduate School, Monterey, California

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ABSTRACT

A consistent explanation for the anticyclonic curvature of the Atlantic jet as it passes through the Strait of Gibraltar and flows into the Mediterranean Sea (eastern side of the strait) is provided. The anticyclonic curvature of the Atlantic jet, which is the key feature to understand the upper-layer circulation in the western Alboran Sea, is simply related to the positive net evaporation over the Mediterranean. The result of this positive net evaporation, that mainly occurs in areas of the Mediterranean far from the Strait of Gibraltar, is a net inflow transport through the strait. It is proposed that the positive net evaporation is able to produce such a net inflow in the strait because of an anomalous large-scale pressure gradient. This anomalous pressure gradient is found to be approximately collinear to the strait orientation. The time-averaged inflow of Atlantic water at the eastern side of the Strait of Gibraltar must therefore be supergeostrophic, and hence it must have anticyclonic curvature.

1. Introduction

An explanation of the surface circulation on the eastern side of the Strait of Gibraltar must successfully address the simple question: Why does the Atlantic jet (hereinafter AJ) gain negative curvature as it enters into the Mediterranean Sea through the Strait of Gibraltar? The anticyclonic curvature of the AJ and the presence of the western Alboran gyre (hereinafter WAG) in the surface circulation (0–200 m) of the western Alboran basin has been well known since the first experimental reports (Seco 1959; Donguy 1962). Since then a considerable number of field, analytical, modeling, and laboratory studies have measured and described, or tried to explain or to simulate, the AJ–WAG system [see, e.g., Parrilla and Kinder (1987) for a general description with abundant bibliography, or Speich et al. (1996) and Viúdez et al. (1996a) for more recent references]. Because this anticyclonic surface jet on the Mediterranean side of the Strait of Gibraltar is quasi-permanent, it appears to require a necessary and sufficient condition for its existence. Consequently, most of the theories have tried to explain the AJ and WAG from a single idea, conservation law, or parameter. Since some of these different theories have been already revised (e.g., see Werner et al. 1988; Speich et al. 1996), we comment only on those that, to date, appear more plausible. These are basically related to the finding of some source of negative relative vorticity for the AJ–WAG system based on the vorticity equation or on the conservation theorem for potential vorticity. It has been suggested that the cyclonic vorticity of the upward and westward flow of Mediterranean Deep Water could provide the source of anticyclonic vorticity necessary to maintain the WAG against frictional dissipation (Bryden and Stommel 1982). It has also been suggested that a gain of negative relative vorticity occurs due to the divergence of the flow produced by a sharp variation in the meridional pressure gradient when the AJ passes the strait (Speich et al. 1996). A difficulty in these explanations arises because they do not clearly distinguish between the AJ, which basically has open streamlines starting at the Strait of Gibraltar, and the WAG, which has closed streamlines (see La Violette 1986; Viúdez et al. 1996a). This makes the interpretation and validation of these ideas somewhat difficult because the relative vorticity of the AJ, even when it turns anticyclonically, is mainly positive, while that of the WAG is mainly negative. This is possible because in the AJ the negative vorticity due to curvature (curvature vorticity) is not large enough to reverse the sign of the relative vorticity, which continues being positive due to the large positive shear vorticity (Viúdez and Haney 1997). Vorticity changes are not necessarily related to curvature changes in the AJ, and therefore it appears that a valid explanation of the AJ curvature cannot be based on vorticity alone. On the other hand, the theorem of potential vorticity conservation alone is not useful to infer the cause of motion because it provides a noncausal relation be-

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* Current affiliation: Departament de Física, Universitat de les Illes Balears, Palma de Mallorca, Spain.

Corresponding author address: Álvaro Viúdez, Departament de Física, Universitat de les Illes Balears, 07071-Palma de Mallorca, Spain.
E-mail: DFSAVL4@ps.uib.es

tween different quantities. For example, in the simple quasigeostrophic case, it is not possible to infer, based on the conservation of potential vorticity, that a change in the vertical thickness between two isopycnal layers forces a change in the vertical component of the vorticity of the water particle because the opposite interpretation, which changes in the vertical component of vorticity forces a change in the thickness, could be equally valid. Although Speich et al. (1996) also observe in their model results a gain of negative vorticity by the solenoidal term in the vorticity equation [term 4d in their Eq. (4)], this appears to be in contradiction with the fact that their model uses the Boussinesq approximation.

This note, combining earlier results with a new analysis, presents a consistent and simple explanation for the anticyclonic curvature of the AJ. No use of vorticity or potential vorticity is made. It is found that the sign of the AJ curvature is, for a given sign of the Coriolis parameter, mainly related to just one feature, that is, the excess of evaporation over precipitation and runoff in the entire Mediterranean Sea.

2. Ageostrophy and curvature apparent to a rotating observer

Let us consider the horizontal momentum equation for viscid horizontal flow under the Boussinesq and f-plane approximations,

$$d\mathbf{v}/dt + f\mathbf{k} \times \mathbf{v} = -\nabla\phi + \mathcal{F}, \qquad (1)$$

where $\mathbf{v}$ is the horizontal velocity, $\phi \equiv p/\rho_o$, p is the pressure, ρ_o is the mean density, $\mathcal{F}$ is the frictional force, ∇ is the horizontal gradient operator, $\mathbf{k}$ is the unit vector directed upward, and d/dt is the material derivative.

It is well known that the net evaporation in the Mediterranean Sea presents an annual cycle with extreme values of $\sim 15 \times 10^4$ m^3 s^{-1} in summer to $\sim 3 \times 10^4$ m^3 s^{-1} in winter (Carter 1956; Bunker 1972; Bormans et al. 1986). On the other hand, the anticyclonic curvature of the AJ has been observed throughout most of the year, although it is believed to have sporadic disappearances (Heburn and La Violette 1990; Perkins et al. 1990). For our purpose of seeking only an expression for the averaged AJ curvature we restrict this study to the *quasi-steady* state in which the local acceleration, for those temporal scales shorter than the seasonal one, is balanced by the friction term. Let $\mathbf{s}$ be the unit tangent to the streamline, and $\mathbf{n} \equiv \mathbf{k} \times \mathbf{s}$ be the unit normal. The $\mathbf{s}$ and $\mathbf{n}$ projection of (1) are

$$dv/dt = -\delta\phi/\delta s, \qquad v^2\kappa + fv = -\delta\phi/\delta n, \qquad (2)$$

where κ is the trajectory curvature, and $\delta\phi/\delta n \equiv \mathbf{n} \cdot \nabla\phi$ and $\delta\phi/\delta s \equiv \mathbf{s} \cdot \nabla\phi$ stand for the *directional* derivative of ϕ in the direction of $\mathbf{s}$ and $\mathbf{n}$, respectively. Note that, for the AJ in quasi-steady state, κ is very similar to the streamline curvature $\kappa_s \equiv \mathbf{k} \cdot \nabla \times \mathbf{s}$. Both curvatures are related through the so-called Blaton's equation (e.g., Dutton 1976, p. 318)

$$v(\kappa - \kappa_s) = \theta_t, \qquad (3)$$

where $\theta_t \equiv \mathbf{n} \cdot \partial\mathbf{s}/\partial t$ is the magnitude of the local rate of rotation of current direction (positive for anticlockwise rotation). For a maximum $\theta_t = 2\pi$ yr^{-1} $= 2 \times 10^{-7}$ s^{-1}, and a typical AJ speed of 0.5 m s^{-1}, we obtain $\kappa - \kappa_s \sim 4 \times 10^{-7}$ m^{-1}, which is two orders of magnitude smaller than the expected curvature of the typical AJ. Geometrically this means that, for the AJ in quasi-steady state, streamlines and trajectories are very similar because the seasonal timescale is large compared with the temporal scale associated with a water particle traveling along the AJ, which for a typical speed of 0.5 m s^{-1} and a distance of 200 km is $\Delta t = 200 \times 10^3$ m/(0.5 m s^{-1}) ~ 5 days. Therefore, although we refer to κ as the trajectory curvature, it is *numerically* equivalent, for the purpose of this study, to the streamline curvature κ_s. In an analogous way $dv/dt \approx v\mathbf{s} \cdot \nabla v = v\delta v/\delta s$.

Defining the geostrophic velocity by $f\mathbf{k} \times \mathbf{v}^g \equiv -\nabla\phi$ and since $\mathbf{v}^g = v^g_{(s)}\mathbf{s} + v^g_{(n)}\mathbf{n}$, we have $fv^g_{(s)} = -\delta\phi/\delta n$. Substituting the above expressions into $(2)_2$, and defining the ageostrophic velocity by $\mathbf{v}^a = v^a_{(s)}\mathbf{s} + v^a_{(n)}\mathbf{n} \equiv \mathbf{v} - \mathbf{v}^g = (v - v^g_{(s)})\mathbf{s} - v^g_{(n)}\mathbf{n}$, that is $v^a_{(s)} = v - v^g_{(s)}$, Eq. $(2)_2$ is rewritten

$$v^2\kappa = -fv^a_{(s)}, \qquad (4)$$

which states the well-known feature (e.g., Dutton 1976, p. 314) that, in the Northern Hemisphere ($f > 0$), supergeostrophic flow ($v^a_{(s)} > 0$) has anticyclonic trajectory curvature ($\kappa < 0$). Although there are a large number of causes of ageostrophic motion, we are only interested in the one that can produce the observed quasi-permanent anticyclonic curvature of the AJ and not other more transient features. In the following, we explain how positive net evaporation can be responsible for such an ageostrophic motion at the eastern side of the Strait of Gibraltar.

3. The effect of the positive net evaporation

It is well known that, ignoring short timescale inertial and tidal effects, the flow regime in the Strait of Gibraltar is basically a two-layer flow, with relatively light Atlantic water flowing eastward in the surface layer (the AJ) and relatively dense Mediterranean Water flowing westward underneath (lagoonal circulation). It is also well-known (Waitz 1755; see Deacon 1985) that this two-layer regime is due to the positive net evaporation over the entire Mediterranean Sea. The net evaporation transport F_E is here defined as the sum of the evaporation transport ($F_e > 0$), the precipitation transport ($F_p < 0$) and the river inflow ($F_r < 0$), for the entire Mediterranean Sea area. Therefore $F_E \equiv F_e + F_p + F_r$. Since only freshwater is evaporated, the positive F_E produces a salt flux (by decreasing the amount of dissolvent), which produces density gradients, changing then the pressure field through the hydrostatic equilibrium, and hence producing the two-layer flow at the strait. How-

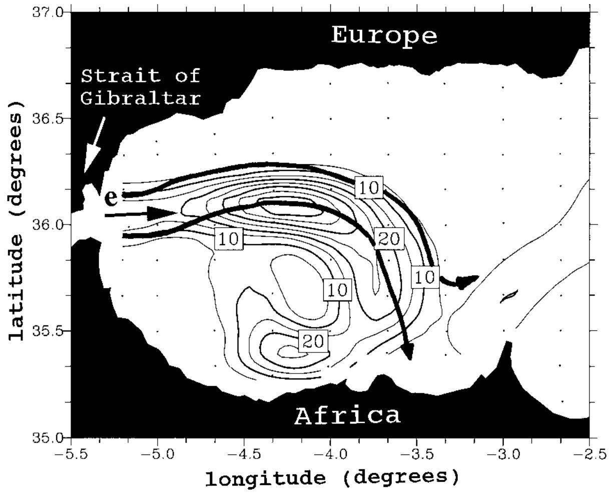

FIG. 1. Horizontal distribution of the (twice) kinetic energy (per unit mass) of the water column from $z_1 = -150$ m to $z_2 = -10$ m, i.e., $\int_{z_1}^{z_2} v^2\,dz$, from the dataset described in Viúdez et al. (1996a,b). The horizontal velocity has been referred to 150 m. The Atlantic jet, which has a maximum depth of ~150 m and an approximate width of 25 km, is represented by the two boundary streamlines. The arrows indicate the direction of the flow. The points indicate the CTD stations ($\Delta = 5$ m^3 s^{-2}).

ever, another important effect of the positive F_E is that it acts as a sink of water. The objective of this section is to show that, although the salt flux effect of the positive F_E is related to the *existence* of the AJ, the water-sink effect of the positive F_E is responsible for its anticyclonic *curvature*, or more precisely, for its "negative" centripetal acceleration relative to an observer fixed to the rotating earth.

In order to clarify the reasoning let us consider only the water-sink effect by assuming an ideal World Ocean system, including the Mediterranean, filled with freshwater on a nonrotating earth. Then the positive F_E will produce, in the steady state, an anomalous pressure gradient $\nabla p'$, observable by a depression of the sea surface, in the entire Mediterranean. This anomalous pressure gradient $\nabla p'$ is responsible, in the steady state, for the water transport from the Strait of Gibraltar (the only source of water) to the places of large net evaporation in the Mediterranean. This transport preserves the total water volume of the Mediterranean, while negative net evaporation does the same over the rest of the World Ocean. In the Strait of Gibraltar and western Alboran Sea, a small region far away from where the large evaporation takes place (e.g., Bunker 1972), it is reasonable to infer that at least the direction of the anomalous pressure gradient is spatially constant. Let **e** be the unit director vector antiparallel to the anomalous pressure gradient, that is, $\mathbf{e} \equiv -\nabla p'/|\nabla p'|$. Since the Strait of Gibraltar is located in the westernmost boundary of the Mediterranean, the vector **e** must basically point eastward, having the same orientation as the Strait of Gibraltar channel (see Fig. 1). For an observer in a rotating system of reference this motion will have a curvature opposite to that associated to the rotating system, that is, anticyclonic if the rotating system is associated to the Northern Hemisphere.

Consider now the realistic case of a salty World Ocean on a rotating earth. Now the positive F_E is also the cause of a salt flux effect that, together with the heat transfer processes, modifies the density field and hence the pressure field. Momentum is also transferred to the fluid by means of the solid boundary rotation. Therefore, there occurs, in comparison with the previous case, a generation of density gradients, thus a distortion of the pressure field and the free surface, which leads to the observed two-layer flow in the Strait of Gibraltar. But it is important to note that both rotation and thermohaline processes do not significantly modify the positive net evaporation F_E, which continues to be responsible for the observed net water inflow through the strait. Thus, having a very similar evaporation regime, the anomalous pressure gradient $\nabla p'$, with its temporal variability, is still there, though now, superimposed with other effects, contributing to the total pressure gradient ∇p. As a consequence, the flow in the upper layer in the eastern side of the Strait of Gibraltar (the AJ), which is *topographically* forced by the strait boundaries to have an **e** direction (i.e., $\mathbf{v} = v\mathbf{e}$), experiences the anomalous pressure gradient $|\nabla p'|\mathbf{e}$ (having its same direction). By virtue of $(2)_1$ there is an acceleration (strictly speaking speed acceleration) of the flow, and, when acceleration is referred to axes fixed to the rotating earth, such a flow becomes supergeostrophic and hence has anticyclonic vorticity.

How can we demonstrate that the above idea is feasible? Although we have no measurements of $\nabla p'$, we can exploit the fact that there are estimates of F_E. Thus, in order to obtain a relation between F_E and the AJ curvature, we may integrate $(2)_2$ for the cross area of the AJ at the eastern side of the Strait of Gibraltar. After dividing by f we obtain the transport balance equation

$$f^{-1}\iint_{\mathrm{AJ}} \kappa v^2\,dz\,dn = -\iint_{\mathrm{AJ}} v\,dz\,dn - f^{-1}\iint_{\mathrm{AJ}} \frac{\delta\phi}{\delta n}\,dz\,dn. \qquad (5)$$

The term on the lhs of (5) is the integral of the centripetal acceleration (divided by f). The first term on the rhs represents the (minus) total volume transport of the AJ. The second term, when the hydrostatic equation ($\partial p/\partial z = -g\rho$) is used, represents the (minus) geostrophic transport of the AJ. The rhs of (5) represents therefore the (minus) *ageostrophic volume transport*

$$f^{-1}\iint_{\mathrm{AJ}} \kappa v^2\,dz\,dn = -\iint_{\mathrm{AJ}} v^a_{(s)}\,dz\,dn. \qquad (6)$$

This result can also be obtained by direct integration of (4). At the eastern side of the Strait of Gibraltar $\mathbf{s} = \mathbf{e}$;

that is, $\mathbf{v}$ is parallel to $-\nabla p'$, and therefore the transport induced by $-\nabla p'$ is entirely ageostrophic. Now, based on the previous comments about the steadiness of the AJ curvature, the *main hypothesis* of this study is that, although there are a large number of causes of ageostrophic transport, the only quasi-steady one acting on the AJ is the anomalous pressure gradient $-\nabla p'$. The consequence of this hypothesis is that the ageostrophic transport of the AJ at the eastern side of the strait must equal the volume transport due to the net evaporation; that is,

$$\iint_{\mathrm{AJ}} v^{\mathrm{a}}_{(s)}\, dz\, dn = F_{\mathrm{E}}, \tag{7}$$

and therefore, using (6), we obtain

$$f^{-1} \iint_{\mathrm{AJ}} \kappa v^2\, dz\, dn = -F_{\mathrm{E}}. \tag{8}$$

This expression relates the integral of the centripetal acceleration apparent to a rotating observer to the net evaporation. It states that the flow has an integrated negative centripetal acceleration provided that $F_{\mathrm{E}} > 0$. We can still go a little further and make two reasonable *approximations.* The first is that, because streamlines of the AJ have little z-dependence before impinging on the African coast (e.g., Viúdez and Haney 1997) and because we are interested in the mean curvature of the AJ and not in the curvature of every fluid particle, approximately $\kappa_{\mathrm{AJ}} \neq \kappa_{\mathrm{AJ}}(z)$. The second is that, because $-\nabla p'$ is codirectional to the strait's axis, that is, isolines of the anomalous pressure are constant in the direction perpendicular to $\mathbf{e}$, and for the same purpose of seeking an averaged AJ curvature, the cross-stream dependence is irrelevant. Therefore, if L is the width of the AJ at the exit of the Strait of Gibraltar, we deduce

$$\kappa_{\mathrm{AJ}} f^{-1} L \int_{\mathrm{AJ}} v^2\, dz \approx -F_{\mathrm{E}}. \tag{9}$$

This result states that *the Atlantic jet curvature* κ_{AJ} *is negative provided that the net evaporation* F_{E} *is positive.* In the Southern Hemisphere ($f < 0$) the curvature induced by such net evaporation would be positive.

Although the sign of κ_{AJ} depends only on the sign of F_{E}, its value depends on the kinetic energy (per unit mass) integrated over the water column. Let $L = 25$ km be the width of the AJ (in the western Alboran Sea the AJ cross section is somewhat larger than the averaged width of the Strait of Gibraltar $L_o = 20$ km), and $f = 8.6 \times 10^{-5}\ \mathrm{s}^{-1}$ the Coriolis parameter at 36°N. A map of the vertically integrated kinetic energy is shown in Fig. 1. This distribution was computed through a data assimilation technique based on in situ density observations taken in the second half of September 1992 (Viúdez et al. 1996a,b). Since this distribution is the integral of the squared total speed (a positive definite quantity), a very similar result would be obtained if geostrophic currents were used instead of the assimilated ones. The estimate temporal mean of net evaporation over the Mediterranean Sea is $F_{\mathrm{E}} \approx 7.6 \times 10^4\ \mathrm{m}^3\ \mathrm{s}^{-1}$ [Béthoux (1979); see also similar estimates in Sverdrup et al. (1942, p 648); Defant (1961, p 517); Bryden and Kinder (1991)]. For the month of September the net evaporation is very similar to the temporal mean (Bunker 1972; Bormans et al. 1986). Taking twice the kinetic energy of the AJ water column equal to 15 $\mathrm{m}^3\ \mathrm{s}^{-2}$ (Fig. 1), we obtain

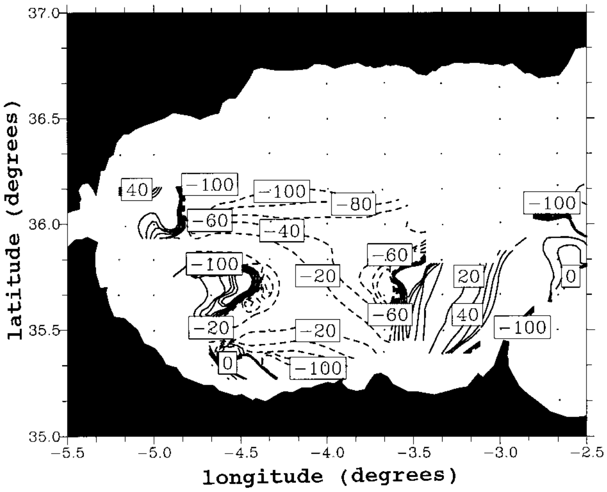

FIG. 2. Horizontal distribution of the curvature radius at 75 m. Note that the curvature radius is $\pm\infty$ when the streamlines change curvature and that is not defined when $v = 0$. Also, the left edge of the AJ (facing downstream) is a discontinuity surface where trajectories are unstable and can ''U-turn'' suddenly (Farmer and Armi 1988; Armi and Farmer 1988; Viúdez and Haney 1996). For this reason the areas where $v < 0.1\ \mathrm{m\ s}^{-1}$ have been blanked, and only contour levels from -100 to $+100$ km are plotted. The points indicate the CTD stations. ($\Delta = 20$ km).

$$\kappa_{\mathrm{AJ}} \approx (-60\ \mathrm{km})^{-1}, \tag{10}$$

and therefore a curvature radius $R_{\mathrm{AJ}} \equiv \kappa_{\mathrm{AJ}}^{-1} \approx -60$ km. The streamline curvature radius field (Fig. 2), computed from the assimilated currents in the second half of September 1992, shows that the radius of curvature of the AJ streamlines when they turn anticyclonically ranged between 50 km for the inner part of the curved jet (right side facing downstream) to 80 km (left side). Thus, $R_{\mathrm{AJ}} \approx -60$ km is a very reasonable average curvature radius for the observed AJ in the western Alboran basin. Note that the curvature radius of a jet of width L has an inherent uncertainty of $\pm L/2$. The above agreement in both sign and magnitude of the AJ curvature is the *main numerical result* that supports the hypothesis that the anomalous pressure gradient $\nabla p'$, due to the mass-sink effect of the positive net evaporation F_{E} is the main source of the quasi-steady ageostrophic motion at the eastern side of the strait. Note that, as has been already mentioned, the value of 15 $\mathrm{m}^3\ \mathrm{s}^{-2}$ taken for twice the kinetic energy of the AJ water column is not a quantity sensible to the ageostrophic motion. In fact, the mean velocity of the AJ can be determined, using a simple analytical model (Defant 1961, p. 519), from the density difference between the Mediterranean and Atlantic waters. Defant provides the mean value $\overline{u} \approx 33 \times 10^{-2}$ m

s^{-1}, and then, for the AJ average depth $H = 150$ m, we obtain also $\bar{u}^2 H \approx 15\ \mathrm{m}^3\ \mathrm{s}^{-2}$.

It must be also mentioned that, since the exit of the Strait of Gibraltar is an area that is very active with high-frequency motion, especially tidal flow and tidal induced pulses (Kinder 1984; La Violette 1986; Farmer and Armi 1988; La Violette and Lacombe 1988; Perkins et al. 1990), the AJ can have initially any direction between NE and SE. These high-frequency features appear to be, however, of little relevance to the theory introduced here, because we deal with curvature (changes in direction) rather than with direction itself, and because the temporal scales of these phenomena are very different. On the other hand, the present approach is to be applied to the AJ when its velocity is antiparallel to the anomalous pressure gradient, and this can happen 40 or 60 km eastward from the Strait of Gibraltar, where the above high-frequency features are less important. Furthermore, as we discuss in the next section, the anomalous pressure gradient due to the positive net evaporation, and therefore the tendency of the AJ to gain apparent anticyclonic curvature, can be counterbalanced by the presence of a local high pressure region in the western Alboran Sea (the WAG).

4. Discussion

There are several points that must be noted for the correct interpretation of the expressions (8)–(9). First, in deriving (8) a quasi-steady state has been assumed where $F_\mathrm{E} > 0$ (and therefore that *there is* an AJ). But, what would happen if the Mediterranean Sea reaches an analogous quasi-steady state in which $F_\mathrm{E} < 0$? A possible cause for such an inversion could be a climate change. It has been suggested that 8000 years ago the circulation in the Mediterranean was estuarine instead of lagoonal (Huang and Stanley 1972; Thunell and Williams 1989). In such a situation the Mediterranean Water would be less dense (fresher) than the Atlantic water. As a consequence of this reversed density difference there would be a light ‘‘Mediterranean jet’’ flowing into the Atlantic Ocean in the surface layer of the Strait of Gibraltar, and a relatively dense ‘‘Atlantic current’’ flowing into the Mediterranean underneath. The flow in the surface layer is therefore reversed, but the anomalous pressure gradient would be also reversed due to the negative net evaporation, in such a way that the ‘‘Mediterranean jet,’’ now on the Atlantic side of the strait, would be again supergeostrophic and then again would have anticyclonic curvature (if this is allowed by the coastline).

Second, it has to be noted that expressions (8)–(9) are only valid when $\mathbf{v}$ is parallel to $\mathbf{e}$ (recall that $\mathbf{e}$ is assumed to be independent of position in the western Alboran Sea). As the AJ curves anticyclonically, flowing southward toward the African coast, it changes its orientation and the effect of $\nabla p'$ on the integrated centripetal acceleration is less important.

Third, it is convenient to clarify why (8)–(9) represent an *explanation* for the sign and value of the AJ curvature. It does so because it relates a cause (F_E) with an effect (strictly speaking the integral of the centripetal acceleration of the AJ). Since every cause is previous to the effect and although the time dependence does not appear explicitly in (8)–(9), it must be interpreted that the value of F_E is previous to the value of the integrated centripetal acceleration. The temporal variable does not appear in (8)–(9) because we have implicitly assumed that, in the quasi-steady state, the total volume of Mediterranean water is constant, that is, that the evaporation transport in the ‘‘remote’’ Mediterranean is *instantaneously* compensated by the corresponding input of water through the Strait of Gibraltar. This is equivalent to assigning an infinite speed of propagation to the processes responsible for the anomalous pressure field in the western Alboran Sea. Obviously, this is not true. Water volume in the Mediterranean is not required to be conserved instantaneously, and there are transient features (waves) responsible for carrying the pressure disturbances from one side to the other. However, these transient processes occur on timescales much shorter than those of the quasi-steady AJ (seasonal variability). Therefore, it can be assumed that, for the *numerical computation* of (8)–(9) associated with the seasonal timescale, these transient processes have such a short timescale that they can be considered to have an infinite propagation speed, even though physically this is not true. This concept of quasi-steadiness resembles the quasi-static change of a thermodynamic process where it is assumed that the intermediate states form a continuous sequence of equilibrium states.

The anomalous pressure gradient introduced in this note tends to accelerate the water particles in the AJ. When these fluid particles leave the Strait of Gibraltar, they are free from being topographically constrained by the strait's geometry (i.e., the transfer of momentum by the solid boundary ceases), in such a way that, for an observer fixed to the rotating earth, the AJ particles describe an apparent trajectory with an average curvature radius of -60 km. As soon as the AJ approaches the coast, there is again a transfer of momentum by the solid boundary, and an interesting jet–coast interaction appears. As a result of this interaction the flow splits in two branches and generates a small anticyclonic eddy on its right side (facing downstream). The generation and growth of this eddy has been repeatedly observed in numerical and laboratory experiments, although the supergeostrophic character of the motion of the simulated AJ, and hence its negative curvature, was probably caused by the large and transient geostrophic imbalance (the Coriolis term differs from the pressure term in the horizontal momentum equation) due to the initial velocity and density fields instead of the quasi-permanent anomalous pressure gradient due to the positive net evaporation. That is, although the cause of the ageostrophic motion was not realistic, these experiments reproduced a growing anticyclonic gyre. However, since the positive net evaporation is not considered in these simulations, the source of ageostrophic motion eventually ceases, and the gyre circulation no longer can be maintained.

In actuality, the increasing high pressure anomaly associated with a growing anticyclonic eddy in the western Alboran Sea eventually counterbalances the pressure gradient due to the positive net evaporation and therefore is able to deflect the AJ and change its curvature. This change in curvature, along with small changes in total vorticity, was *described* as a curvature-shear-vorticity conversion by Viúdez and Haney (1997). However, once the AJ has been deflected by the anticyclonic gyre (WAG), it is still under the influence of the anomalous pressure gradient due to the positive net evaporation, and therefore it is again accelerated and has again an apparent negative curvature. This appears to be the configuration of the flow observed in September 1992 and shown in Figs. 1–2. Therefore, for a rotating observer, the interaction of the AJ with the African coast appears to be a consequence of the tendency of the AJ to have negative curvature. For a nonrotating observer this interaction would instead appear to be a consequence of the solid-body rotation of the African coast and the westward migration of the Atlantic water relative to the rotating Mediterranean. The anticyclonically curved AJ impinges on the African coast providing a mechanism for the trapping of surface Atlantic water (located at the right-hand side of the AJ, facing downstream) in between the AJ and the African coast. It appears, therefore, possible that this coast–jet interaction (tendency of the AJ to turn anticyclonically and the presence of the African coast) is responsible for forcing the convergence of surface water that is observed in the western Alboran gyre producing the downwelling in the core of the gyre and the upwelling of waters at the Iberian coast (Lanoix 1974; Viúdez et al. 1996b).

At this point it seems convenient to summarize the role played for every variable in the idea suggested here. The positive net evaporation can be considered a remote cause for both the two-layer flow at the Strait of Gibraltar and the apparent anticyclonic curvature of the AJ. The medium that transfers the effect of this positive net evaporation, which takes place far away from the Alboran Sea, is the same fluid (the water in the Mediterranean) and is expressed by means of an anomalous pressure gradient. Gravity causes the more dense MW to sink in the strait, and gravity and the transfer of momentum by the heavy MW and by the strait's boundaries causes the AW to move through the strait and into the Mediterranean. For this reason we can relate the mean velocity of the AJ with the density difference between Atlantic and Mediterranean waters. Thus, the Mediterranean Water circulation underneath the AJ locally influences the kinetic energy of the AJ water column, and therefore influences the value, not the sign, of the AJ curvature.

The theory presented in this note is simple and general enough to be applied to other straits of semienclosed seas. Note that it only considers the effect of the net evaporation over the Mediterranean Sea, the width of the Atlantic jet, the Coriolis parameter, and the integrated kinetic energy of the jet. Given the simplicity of this explanation (no numerical nor analytical solutions are required to infer the sign and approximate value of the AJ curvature), one might ask why it went unnoticed in previous studies. In my opinion, the main reason resides in the different consequences that the positive net evaporation has in observed variables. The salt-flux effect of the positive net evaporation can be clearly observed by means of conductivity measurements taken in conventional oceanographic cruises, and hence the pressure gradient due to density inhomogeneities can be computed. But, on the other hand, measurements of the anomalous sea level field due to the anomalous pressure gradient $\boldsymbol{\nabla} p'$ cannot be computed from the thermohaline properties of seawater. However, given the seasonal variability of the net evaporation in the Mediterranean, it appears to be possible to infer the seasonal variability of the anomalous pressure gradient in the Alboran Sea by means of satellite altimetry observations. In fact, it has been recently shown from altimetry observations (Larnicol et al. 1995) that the western and eastern Alboran gyres experience a clear seasonal cycle.

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