

Vertical alignment of the Gulf Stream

By A. W. RATSIMANDRESY^{1*} and J. L. PELEGRÍ², ¹*Departamento de Clima Marítimo, Ente Público Puertos del Estado, Madrid, Spain;* ²*Departament de Geologia Marina i Oceanografia Física, Institut de Ciències del Mar, CMIMA-CSIC, Barcelona, Spain*

(Manuscript received 23 June 2004; in final form 8 November 2004)

ABSTRACT

A historical set of expendable bathythermograph (XBT) and Pegasus sections across the Gulf Stream in natural coordinates is examined to investigate the isopycnic structure of the current off Cape Hatteras. In isopycnic-natural coordinates, the axis of the Stream remains vertically aligned, in contrast to its well-known offshore tilting when plotted as a function of depth. These results are confirmed using the geostrophic velocities obtained from a synthetic temperature field for the Gulf Stream. We prove that a baroclinic current aligned with density cannot be aligned with depth, and vice versa, and we show that the density alignment of the Gulf Stream results from the distortion of the density field and has negligible dependence on the choice of reference level. The invariable character of intense geophysical jets is supported through analogous representations for the upper level atmospheric jet stream in isentropic coordinates. These show that the atmospheric jet, when plotted on to a section normal to the direction of its maximum velocity core, is vertically aligned with potential temperature.

1. Introduction

Ever since Rossby (1937, 1938), Cahn (1945), Charney (1955) and Veronis and Stommel (1956), there has been considerable interest in how a jet adjusts itself under the presence of rapid rotation and stratification. The conclusion of these and subsequent theoretical works is that the final state of the jet is of geostrophic adjustment, typically with a small fraction of the jet energy (which depends on the initial conditions) being lost into inertia-gravitational waves that radiate away. Probably the most important corollary of these investigations has been the extensive use of the geostrophic approximation to determine the intensity and structure of major quasi-permanent ocean currents. The geostrophic adjustment of the Gulf Stream, in particular, has been confirmed through direct measurements of density and velocity across the Gulf Stream (Johns et al., 1989).

Despite the above conclusive results, one puzzling aspect of the structure of the Gulf Stream, and other western boundary currents, is the way its velocity axis tilts with depth. This ubiquitous tilting may perhaps not fit with one's intuition of the behaviour of a jet. Thinking about the stratified ocean as a superposition of layers of increasing density, we expect that, within the jet, each layer will slope such to maintain a near-geostrophic balance, but there is no trivial reasoning that justifies the observed

cross-movement of the axis of maximum velocity with depth. To analyse this issue, we will examine a set of sections perpendicular to the jet ('natural cross-sections') in near-isopycnic coordinates and show that such cross-movement does not take place; in this coordinate system, the jet remains perfectly aligned in the vertical. Further, we will show that a similar alignment with potential temperature occurs for the upper-level atmospheric jet stream, the only requirement being that the jet structure has to be examined in a section perpendicular to the direction of the maximum velocity jet core.

2. Gulf Stream data

In this work we use a set of 20 repeated sections with expendable bathythermograph (XBT) and Pegasus velocity data, in both geographic and natural coordinates (Halkin and Rossby, 1985, hereafter HR). The geographic coordinates are those provided by the line along which all sections were taken (over the continental slope east of Cape Hatteras in a direction rotated clockwise by 141° from the true north, i.e. 141°T), which is perpendicular to the historical mean direction of the Gulf Stream (51°T) at this site. Bottom mounted transducers, used to track the falling Pegasus and infer the horizontal velocities, made this a fixed line along which the Pegasus and XBTs were launched. HR modified the original geographic Pegasus velocity sections, by taking into account their inclination with respect to the instantaneous Gulf Stream axis, to obtain what they called natural coordinate sections. This natural system reorients itself in the local (instantaneous) along-stream direction, regardless of whether this

*Corresponding author.
e-mail: andry@ratsimandresy.org
Current address: Biological and Physical Oceanography Section, Fisheries and Oceans Canada, St. John's, NL, Canada.

responds to meanders or to changes in the direction of the stream itself.

A detailed description of the Pegasus instruments was provided by Spain et al. (1981) and a thorough discussion of the structure of the Gulf Stream from the XBT temperature and Pegasus velocity sections was given by HR, Rossby (1987), Johns et al. (1989), Manning and Watts (1989) and Leaman et al. (1989). Here we employ this data set to examine again the structure of the Gulf Stream, but now with temperature rather than depth as the independent variable. Having temperature instead of density introduces some errors in the estimation of epipycnal quantities, but these are relatively small because of the monotonic dependence of density on temperature for this region (an analysis of the errors involved in obtaining dynamical quantities from XBT data has been carried out by Rodríguez-Santana et al., 1999). For this reason, in the conceptual discussions to follow we may talk about (near) isopycnal distributions, even though the dependent variable data are plotted as a function of temperature.

The temperature (T) and cross-stream/along-stream velocity (u , v) data for each individual section have been provided to us (courtesy of Tom Rossby, University of Rhode Island) in natural coordinates as a function of cross-stream coordinate (x) on a regular grid in depth (z , every 25 m). The origin is located at the position of the Gulf Stream front, this front defined as halfway between where the 12°C isotherm crosses 400 m and where it crosses 600 m (HR). Notice that with such an origin definition the surface along-stream velocity maximum will always lie at negative x values, typically about 5 km from the origin.

The instantaneous temperature and velocity sections may be easily recalculated in geographic coordinates, with the same

origin definition as the natural system, through an appropriate rotation of the coordinate system for each individual section. Through this rotation, the temperature field typically becomes slightly stretched in the cross-stream direction but the two horizontal velocity components may be substantially modified.

To obtain the mean fields as a function of depth (for either coordinate system) we use the following simple procedure. The temperature and velocity data in each section are interpolated to equally spaced intervals (25 km) in the cross-stream direction, and their mean distributions are obtained from the ensemble of the individual sections interpolated in depth and cross-stream distance (at 25-m and 25-km intervals, respectively).

In order to obtain the instantaneous and mean velocity fields as a function of temperature, we first perform the change of vertical axis (depth into temperature) for each interpolated individual section. For each section we next calculate, through linear interpolation, the velocity field at equally spaced isotherms (0.5°C interval). The mean velocity distribution is finally calculated from the ensemble of all individual sections as a function of temperature. The whole procedure is repeated for the data in both the natural and geographic coordinate systems.

3. Isothermal velocity structure

Figure 1a shows the distribution, in natural coordinates, of both the mean temperature and the mean along-stream velocity as a function of depth. A comparison of this plot with those in HR's fig. 10 indeed shows close resemblance. The velocity distribution does look like many along-stream velocity sections of the Gulf Stream beyond Cape Hatteras, which emphasizes the

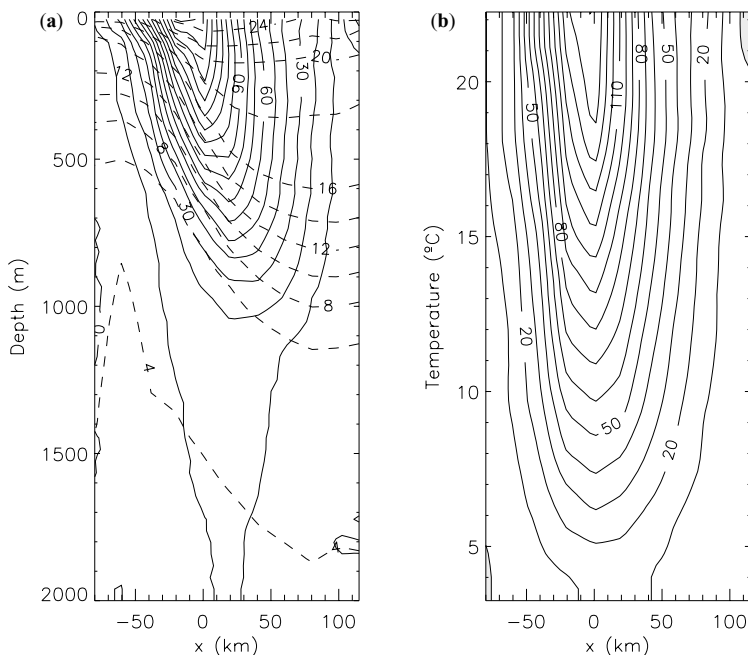


Fig 1. Mean distributions in natural coordinates. (a) Temperature (dashed line), in $^\circ\text{C}$, and along-stream velocity (solid line), in cm s^{-1} , as a function of depth. (b) Along-stream velocity, in cm s^{-1} , as a function of temperature. Adapted from Ratsimandresy (2002).

stable character of the current structure in this region despite its meandering and the downstream changes in transport (Rossby, 1987, 1999; Bower and Hogg, 1996; Rossby and Gottlieb, 1998). In particular, this figure clearly illustrates the tilting with depth of the axis of maximum along-stream velocity (to the right when looking downstream).

Figure 1b plots the mean along-stream velocity field with temperature replacing depth as the vertical coordinate (note from Fig. 1a that the 5°C isothermal is located at depths between 600 m in the near-shore end and 1200 m in the offshore end). A novel and remarkable characteristic in this figure is that the axis of the stream is not tilted. This corresponds to the velocity field being tangent to the isothermals at a near-constant cross-stream coordinate very close to the origin of coordinates, actually between -5 and 0 km (Fig. 1a). This feature was also apparent in the geostrophic velocity field obtained by Pelegrí and Csanady (1991, Fig. 3a) and Pelegrí and Csanady (1994, Fig. 6b), there plotted as a function of density. Its observation from an ensemble average of 20 sections with actual velocity measurements confirms its validity.

Although the tilting of the Gulf Stream core with depth is a well-known feature, the vertical alignment of the Gulf Stream with temperature has not yet received specific consideration in the available literature. The only related analyses we have found are those works by Bower et al. (1985), Leaman et al. (1989) and Huang and Stommel (1990). Bower et al. (1985) presented several figures of the distribution of the acceleration potential across the Gulf Stream as a function of temperature. A careful examination of these figures indeed shows that the acceleration potential is approximately aligned with temperature, but this aspect was not mentioned in their discussion. Leaman et al. (1989) calculated the transport within isopycnal layers and discussed how this transport changes with depth and along the Gulf Stream path, but gave no description at all of the structure of the velocity field as a function of temperature. This is surprising because transport is the result of multiplying velocity time layer thickness, so velocity is a much more direct quantity than transport. However, the transport field may be quite different from the velocity field; for example, in the Gulf Stream the transport field has a subsurface maximum while the maximum value of the velocity field is usually at the sea surface. Huang and Stommel (1990) formulated an idealized layered model for the Gulf Stream, which produces an axis of maximum velocity that is tilted in both depth and density, and they noted that the actual Gulf Stream does not show a clear tilt in density coordinates.

In order to assess whether the vertical alignment of the current with temperature is related to the transformation to the natural system, we have also examined the temperature structure of the mean along-stream velocity in geographic coordinates (not shown). It displays a pattern very similar to the true along-stream component (Fig. 1b), although with slightly less intense values, and remains aligned with temperature. This could perhaps suggest that the velocity field is always vertically aligned with tem-

perature, regardless of whether we use natural or geographic coordinates. However, a close examination of all individual sections warns us that some realizations show significant changes in the shape of the along-stream velocity field when represented in the geographic coordinate system, which approximately cancel out in the averaging process.

Figures 2 and 3 illustrate, as an example, the distribution of the velocity field during the May 1982 realization, in both natural and geographic coordinates. This realization corresponds to the largest departure of the instantaneous Gulf Stream from its mean direction, in the whole set of XBT/Pegasus realizations. At this time, the Gulf Stream was flowing 96°T, i.e. rotated clockwise by 45° with respect to the direction normal to the actual

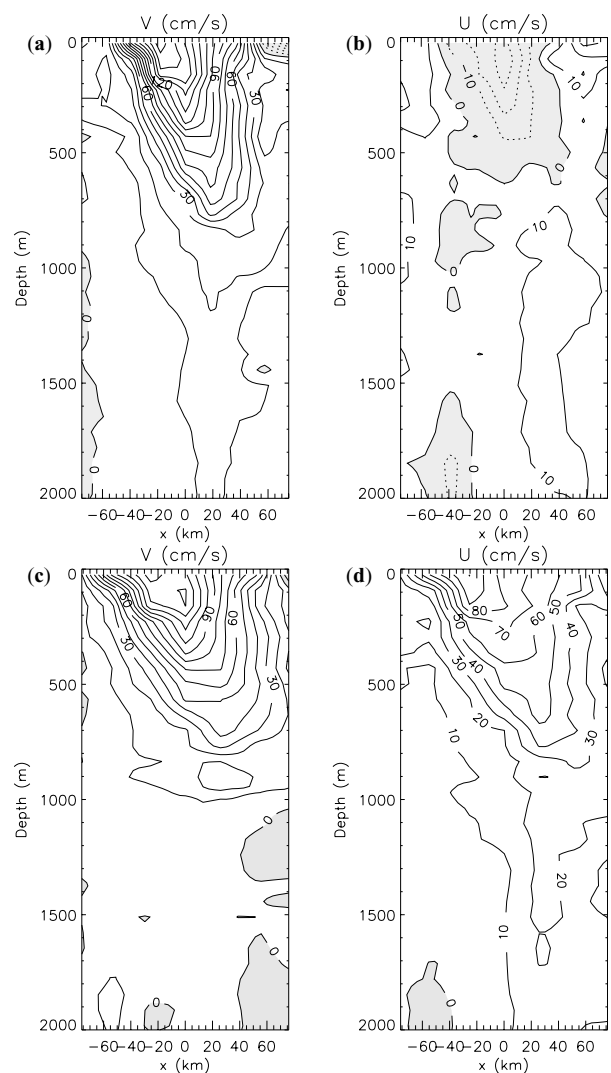


Fig 2. Distribution of velocity components for May 1982 as a function of depth, in (a), (b) natural and (c), (d) geographic coordinates. v and u denote the velocity components perpendicular and parallel to the section (along-stream and cross-stream in natural coordinates). The shaded area corresponds to negative values.

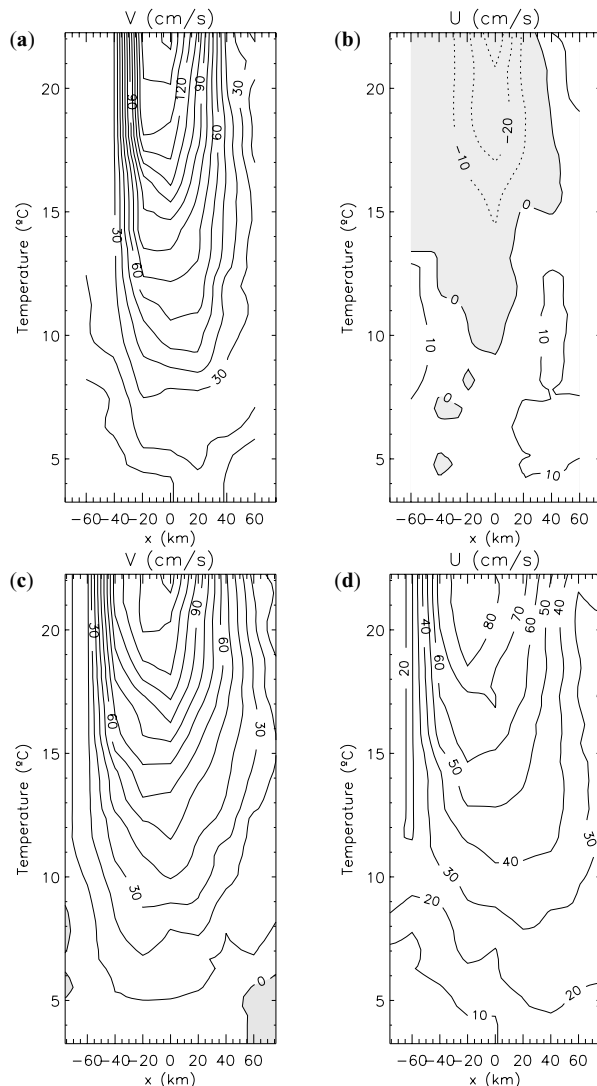


Fig 3. As in Fig. 2, but plotted as a function of temperature.

geographic section (51°T). Figure 2 illustrates the standard (x, z) view of both velocity components (perpendicular to and along the section) in geographic and natural coordinates. In geographic coordinates, we may appreciate the ubiquitous tilting of the axis of maximum velocity as a function of depth for both components, which have similar maximum values because of the temporary offshore heading of the Gulf Stream (Figs. 2c and d). In natural coordinates, the tilting is also evident for the perpendicular (along-stream) component (Fig. 2a), while the component of the velocity along the line (cross-stream) shows the expected very small values (Fig. 2b). The along-stream velocity field in natural coordinates closely resembles that found for the mean along-stream velocity (Fig. 1a).

Figure 3 presents these same observations but now as a function of temperature. In natural coordinates, the axis of the maximum along-stream velocity is well aligned with temperature

(Fig. 3a) and the cross-stream velocity is rather small (Fig. 3b). In the geographic representation, however, both components of the velocity tilt in opposite directions (Figs. 3c and d). The simple reason for this is that HR's definition of the Gulf Stream natural coordinate system is such that the absolute velocity is approximately equal to the actual along-stream velocity component all over the section. The natural system allows us to examine the distribution of the real along-stream velocity (by choosing the direction of the along-stream flow as the direction perpendicular to the section), which will usually differ from the distribution of the velocity components in an arbitrary coordinate system (like the geographic one).

Figure 4a illustrates how the central region is characterized by a vertically straight axis of zero mean (non-dimensional) relative vorticity, $\zeta/f \cong (\partial v/\partial x)/f$, where f is the Coriolis parameter and the along-stream velocity v is measured in the natural coordinate system. This relative vorticity is always smaller than the planetary vorticity so the Rossby number is everywhere less than 1. Figure 4b illustrates a similar situation for the May 1982 realization, although in this instance we may actually appreciate the existence of small lateral displacements in the line of zero relative vorticity. Maximum absolute (non-dimensional) relative vorticity values are everywhere less than 0.4 for the mean velocity field, although they reach values almost as large as 0.8 in the cyclonic side of the current during May 1982. Recall that the $x = 0$ position was chosen as the Gulf Stream front (HR), which causes the surface zero relative vorticity (along-stream velocity maximum) to take place a few kilometres west from the origin in both Figs. 4a and b.

4. Atmospheric jet stream analogy

The existence of many similarities between western boundary currents and the upper-level tropospheric jet streams has been long recognized. Several characteristics of the atmospheric jet stream, such as vertical structure, dynamics of meanders (waves in the jet stream) and vertical mixing processes, have been recognized to occur also in oceanic jets (Rossby, 1951; Newton, 1978; Bower, 1989; Bower and Rossby, 1989; Pelegrí and Csanady, 1994). It thus seems useful to dedicate some effort to investigate whether the velocity structure of the jet stream retains its vertical alignment when plotted in isentropic coordinates, i.e. as a function of potential temperature.

In an instantaneous section of the upper-level jet stream, the axis of maximum velocity approximately follows the frontal discontinuity, such that it appears tilted with height (see, for example, the review by Keyser and Shapiro, 1986, and references therein). Figure 7.10 of Dutton (1986) exhibits such a tilting in vertical coordinates, but it also presents the much less common perspective of a jet stream that becomes vertically aligned when plotted as a function of potential temperature. In order to examine this different perspective, we have used the National Center for Environmental Prediction (NCEP)

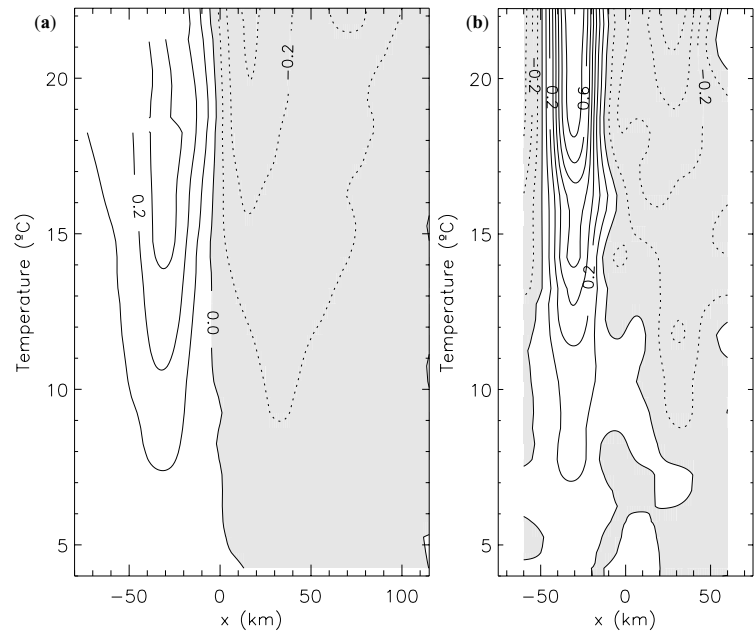


Fig 4. Non-dimensional relative vorticity, as a function of temperature in natural coordinates, obtained from (a) the mean Pegasus data and (b) the May 1982 Pegasus realization. The shaded region corresponds to negative vorticity values.

reanalysis data, provided by the National Oceanic and Atmospheric Administration—Cooperative Institute for Research in Environmental Sciences (NOAA—CIRES) Climate Diagnostics Center, Boulder, Colorado, USA (<http://www.cdc.noaa.gov/>). A word of caution seems appropriate here about the automatic procedure in this data resource, which allows taking averages over specified sections. This procedure differs markedly from our ensemble averages because it does not shift the origin to take into account the position of the jet maximum. This causes the mean ensembles obtained with NCEP's automatic procedure usually to display the opposite tilting to individual realizations, apparently because of the latitudinal shift in the level of maximum winds. This feature may also be observed on mean sections obtained from the European Centre for Medium-Range Weather Forecasts (ECMWF) operational analyses (e.g. Davies and Rossa, 1998) or in synthetic velocity fields for the jet stream (Trenberth, 1992).

Figures 5 and 6 present the zonal velocity field across the 57.5°E meridional section, for 7 and 13 February 1992, respectively. This section has been chosen as corresponding to a region where the stream has a rather stable zonal orientation (Tenenbaum, 1996). In each figure we present the velocity structure in isobaric (logarithmic scale, approximately indicative of height) and isentropic coordinates. The representation in isobaric coordinates illustrates how the upper-level jet stream axis of maximum (eastward) wind velocity is tilted approximately following the frontal zone. However, the orientation of this axis changes dramatically when plotted in the isentropic coordinate system, being aligned in the vertical on 7 February (Fig. 5) and tilted in the opposite direction on 13 February (Fig. 6).

In order to investigate the reason for this different behaviour, we have examined the orientation of the jet stream (at the level of

maximum winds) with respect to the meridional section. Figure 7 presents the velocity field at 250 hPa (approximately the level of maximum winds) every 2 d from 3 February to 13 February 1992. This figure illustrates the core of the jet stream stably aligned in a zonal direction from 3 February until 7 February. After 7 February, the orientation of the jet stream starts drifting noticeably towards the north, and by 13 February it has an important meridional component. In the above terminology, the section for 7 February (when the jet is vertically aligned with potential temperature) corresponds to a natural representation of the along-stream velocity field, while 13 February (jet tilted with potential temperature) is a geographic one.

5. Discussion

The representation of the velocity data in isopycnic (isentropic) coordinates provides a new view to the structure of oceanic (atmospheric) jets. One main feature is that the jet axis is untilted with (potential) temperature whenever the jet is viewed in a natural coordinate plane (where the jet is perpendicular to the section). In order to scrutinize the vertical alignment of the Gulf Stream in isopycnic coordinates, we may use the Hall (1994) synthetic temperature field, developed for the Gulf Stream from XBT data collected at about 68°W, some 300 km downstream of the Pegasus section. The Hall (1994) analytical expression for temperature, as a function of pressure and cross-stream coordinate, was obtained fitting the data to a cross-stream reference $x = 0$ defined as where the 15°C isotherm crosses the 200-m depth. In the plotted synthetic field, however, the origin appears to be very close to the origin used for the Pegasus data set, i.e. halfway between where the 12° isotherm crosses 400 and 600 m (HR).

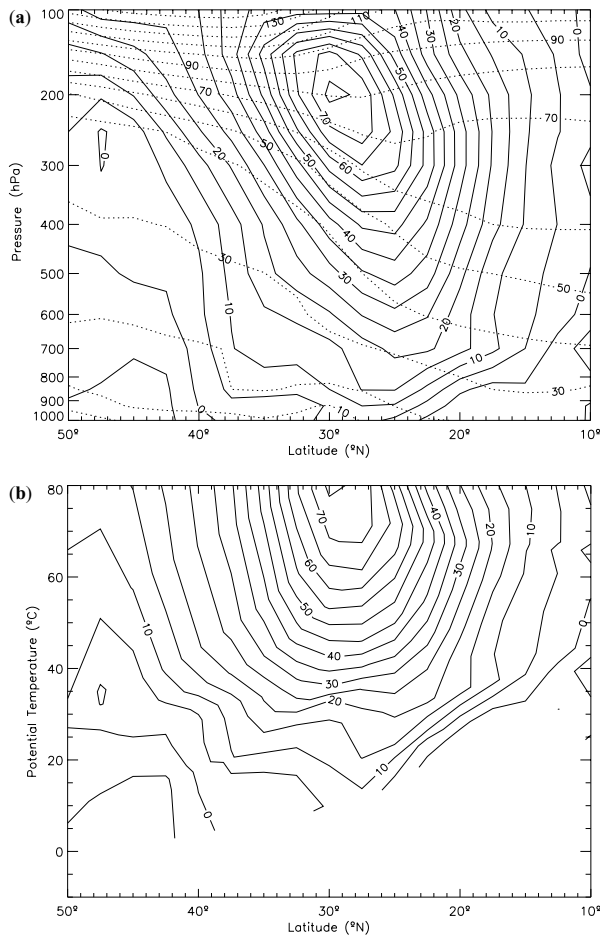


Fig 5. Isotachs of zonal wind, in m s^{-1} , across the 57.5°E meridional section on 7 February 1992 as a function of (a) logarithm of pressure and (b) potential temperature. In (a) the potential temperature field, in $^\circ\text{C}$, is also shown (dashed lines).

Figure 8a shows the synthetic temperature field and the corresponding along-stream geostrophic velocity distribution, v_g , under the assumption of a no-motion level at 1200 m. The velocity field clearly illustrates the tilting of the stream with depth. If we had used the 5°C isotherm as the level of no motion (a natural choice when making geostrophic calculations in the isopycnic system), the result would essentially be unchanged, although the slope of the axis of maximum velocity would slightly increase (not shown). Figure 8b shows the geostrophic velocity field now plotted as a function of cross-stream coordinate and temperature, and illustrates that the stream appears approximately aligned in the vertical. Figure 8c presents the (normalized) relative vorticity distribution calculated as $\zeta_g/f = (\partial v_g/\partial x)/f$. This figure emphasizes that the along-stream velocity field is vertically aligned with temperature by showing the existence of a zero ζ_g axis at $x \cong 0$, where the velocity field is tangent to the isopycnals (Fig. 8a), a situation similar to that observed in Fig. 4.

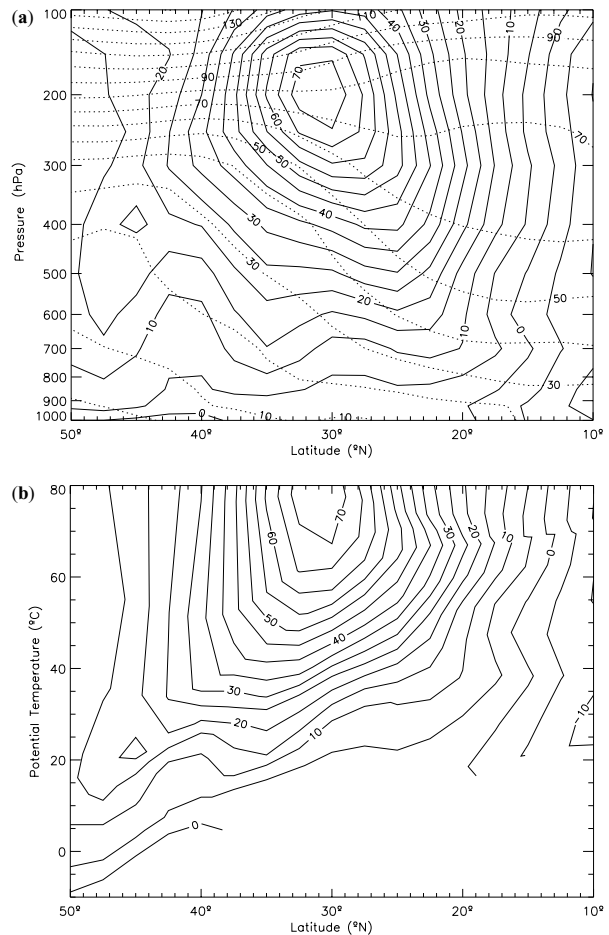


Fig 6. As in Fig. 5, but for 13 February 1992.

It may perhaps be argued that an appropriate choice of reference velocity would lead to any desired alignment. Such a choice could however approximately align the velocity field only within some limited depth range. To examine the actual importance of the selection of the reference level, we consider the following three cases in which the density surfaces retain an inverted symmetry around the z -axis (Fig. 9). In all cases, we assume that the deepest isopycnal is a reference level with zero velocity, that density changes by a constant increment between adjacent isopycnals, and that the slope of the isopycnals in the centre vertical line is twice the slope in the lateral vertical lines.

In the first case, we consider a flat isopycnal to be the zero velocity reference level and we let the overlying isopycnals become steeper towards the sea surface. In this case, the jet axis remains vertically straight when viewed in both density and depth coordinates (Fig. 9a). In the second case, we consider that all isopycnals have the same shape and are uniformly distributed with depth, and we let the lowest density surface have zero velocity. In this case, the axis of maximum velocity does appear as tilted (Fig. 9b) but the isotachs remain tangent to the isopycnals at $x = 0$,

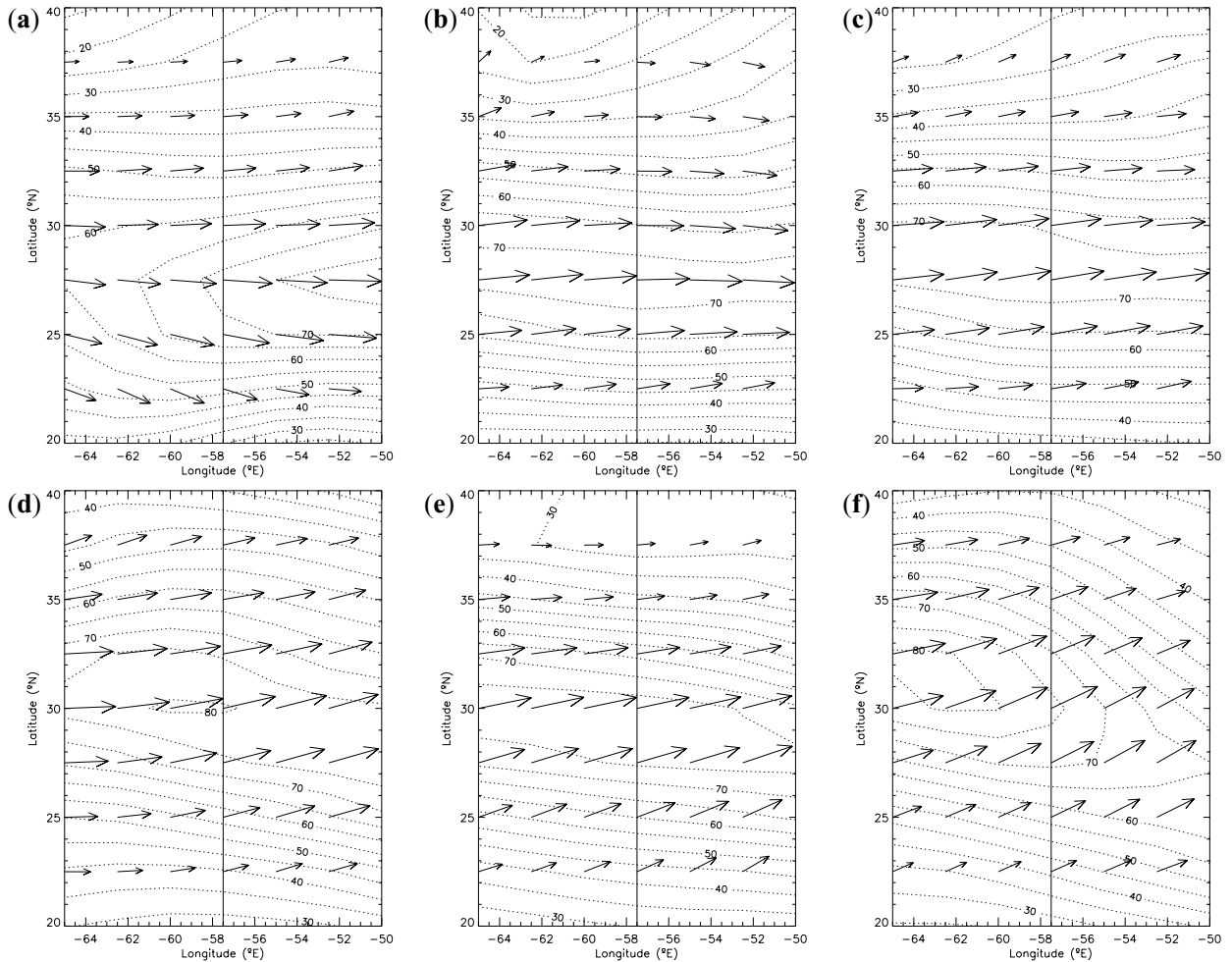


Fig 7. Horizontal velocity field at 250 hPa every 2 d, from 3 February to 13 February 1992. The vectors indicate the magnitude and direction of the velocity field at 2.5° latitude–longitude grid points, while the dotted lines represent the absolute isotachs in m s^{-1} . The solid line indicates the position of the meridional section in Figs. 5 and 6.

indicating that the velocity field would be straight when plotted as a function of density. In the last case, we consider again all isopycnals to have constant shape but we let the stratification decrease with depth. As in the previous case, the axis of maximum velocity tilts with depth but now this deviation is more noticeable in the less-stratified deep layers (Fig. 9c). The potential contribution arising from the selection of a reference level is however rather small. This is confirmed by the calculations performed using the Hall (1994) temperature field both with a 1200-m reference level (Fig. 8a) and with the 5°C isotherm as the reference level. The velocity field changes no more than a few cm s^{-1} so the choice of reference level cannot be held responsible for the observed vertical alignment. This result is consistent with an analogous behaviour for the jet stream, where no simple velocity distribution at the bottom boundary (or another reference level) may usually be specified.

The responsibility of the observed vertical alignment can thus only rest on the actual distribution of the density field. To check

this hypothesis, we have constructed a density distribution that has nearly perfect inverted symmetry around $x = 0$ (this has been done by choosing one single isothermal and successively changing its value while shifting it in depth; not shown). This idealized density distribution causes the geostrophic velocity field to become aligned with depth but tilted with respect to density, with isotachs crossing isopycnals within the stream core. The conclusion is that the observed density alignment of the jet axis has to be associated to the real density–depth structure, a somewhat distorted density field that lacks symmetry with respect to $x = 0$ (Figs. 1a and 8a).

Let us finally examine whether it is possible for the geostrophic velocity field to be vertically aligned with both (potential) temperature and depth. We focus on the oceanic case, the extension to the atmosphere being straightforward; writing $v = v(x, T) = v[x, T(x, z)]$ the following relation holds

$$\left. \frac{\partial v}{\partial x} \right|_z = \left. \frac{\partial v}{\partial x} \right|_T + \frac{\partial v}{\partial T} \left. \frac{\partial T}{\partial x} \right|_z. \quad (1)$$

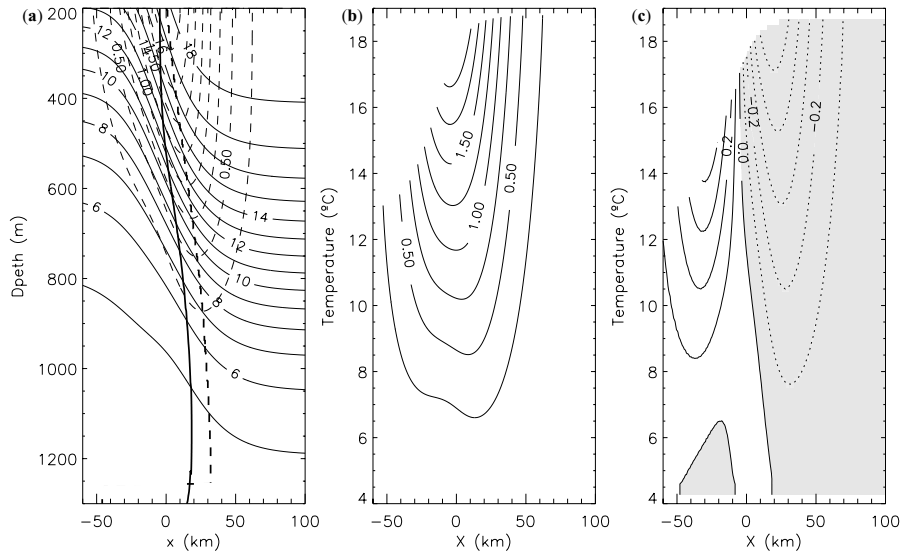


Fig 8. Distributions obtained using the Hall (1994) synthetic temperature field. (a) Temperature (solid line), in $^{\circ}\text{C}$, and along-stream geostrophic velocity (dashed line), in m s^{-1} , as a function of depth. (b) Along-stream geostrophic velocity, in m s^{-1} , as a function of temperature. (c) Non-dimensional relative vorticity as a function of temperature. The thick solid and dashed lines in (a) illustrate the orientation of the axis of maximum velocities as a function of temperature and depth, respectively. Adapted from Ratsimandresy (2002).

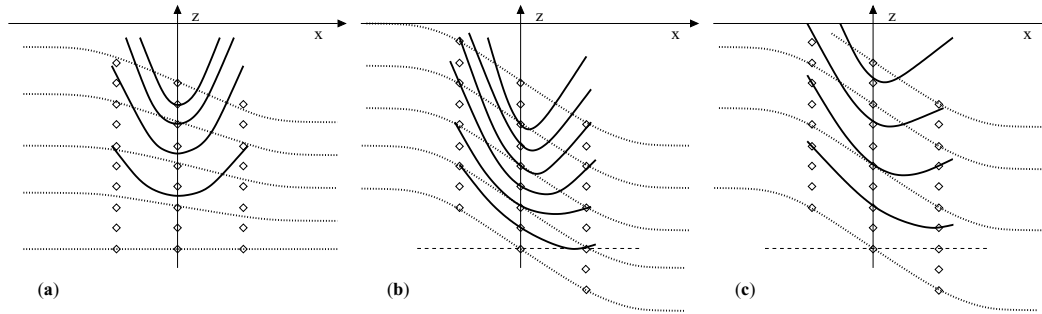


Fig 9. Schematic representation of three idealized density sections and the corresponding geostrophic velocities. The solid and dotted lines represent equally spaced isotachs and isopycnals, respectively (arbitrary units). The grid formed by small squares, and the thin dashed horizontal line in (b) and (c), are included for visualization purposes.

Hence, the location of the maximum current in (x, z) coordinates, $\partial v / \partial x|_z = 0$, must satisfy

$$\left. \frac{\partial v}{\partial x} \right|_T = - \left. \frac{\partial v}{\partial T} \right|_x = \frac{g\alpha}{\rho f} \left. \frac{\partial z}{\partial x} \right|_T \left. \frac{\partial T}{\partial x} \right|_z, \quad (2)$$

where α is the thermal expansion coefficient, $d\rho = -\alpha dT$, and the last equality is found after using the thermal wind equation in isopycnic coordinates $\partial v / \partial \rho = (g/\rho f) \partial z / \partial x$ (e.g. Pelegrí and Csanady, 1994).

Alternatively, by considering $v = v(x, z) = v[x, z(x, T)]$, we have the following relation

$$\left. \frac{\partial v}{\partial x} \right|_T = \left. \frac{\partial v}{\partial x} \right|_z + \left. \frac{\partial v}{\partial z} \right|_x \left. \frac{\partial z}{\partial x} \right|_T. \quad (3)$$

The requirement of a zero cross-stream v derivative at constant temperature, $\partial v / \partial x|_T = 0$, implies

$$\left. \frac{\partial v}{\partial x} \right|_z = - \left. \frac{\partial v}{\partial z} \right|_x \left. \frac{\partial z}{\partial x} \right|_T = - \frac{g\alpha}{\rho f} \left. \frac{\partial T}{\partial x} \right|_z \left. \frac{\partial z}{\partial x} \right|_T, \quad (4)$$

with the last equality again found after using the thermal wind equation, but now in isolevel coordinates, $\partial v / \partial z = -(g/\rho f) \partial \rho / \partial x$.

We wonder whether $\partial v / \partial x|_z = 0$ (eq. 2) or $\partial v / \partial x|_T = 0$ (eq. 4) at $x = 0$. The right-hand sides of eqs. (2) and (4) have the same size, always different from zero within a baroclinic jet. Relation (2) implies that if $\partial v / \partial x|_z$ is zero at $x = 0$, then $\partial v / \partial x|_T$ cannot be zero at this same location, the opposite arising from relation (4). The conclusion is that the jet may not be vertically aligned with both depth and (potential) temperature. For this to occur, the right-hand side terms in relations (2) or (4) have to be zero, which will not happen unless the isothermals

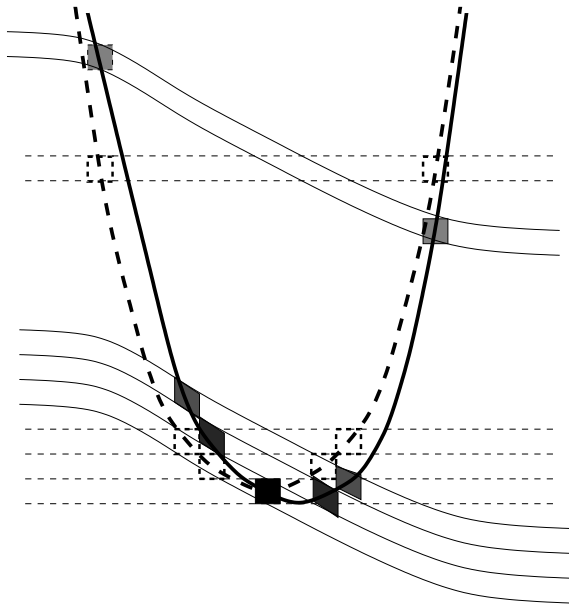


Fig 10. Illustration showing why the shape of an isotach differs whether plotted in isopycnic or vertical coordinates (see text for a detailed explanation). To facilitate the representation, we consider an upper-thermocline region where $\partial z / \partial \rho$ is constant.

become horizontal (i.e. the baroclinic current itself disappears). This analysis, of course, does not exclude the possibility that the stream may be aligned neither with depth nor with density, but the observational fact is that oceanic (and atmospheric) streams are vertically aligned with density (potential temperature).

Figure 10 illustrates the above ideas for the special case when $\partial z / \partial \rho$ is constant. In this case, the depth–density transformation is easily visualized by a vertical displacement of the water parcel between its corresponding depth and density values. The illustration clearly shows that a density-symmetric isotach becomes twisted when plotted against depth. Thin dashed lines represent both depth and flat density levels and thin solid lines represent the tilted (jet-like in geostrophic balance) density field. The squares represent water parcels; empty squares show their location in the isopycnic system (or in a non-rotating vertical reference system) while filled squares show their location in a rotating vertical reference system. The thick dashed line connects the empty squares and represents an isotach of a vertically straight jet (viewed in isopycnic coordinates) while the thick solid line connects the filled squares and illustrates how this isotach would be viewed in a rotating vertical reference system.

6. Conclusions

A remarkable result that arises from HR's unique XBT and Pegasus data set is that the Gulf Stream remains vertically aligned when plotted, in natural coordinates, as a function of temperature. This conclusion is true regardless of whether we consider individual or mean realizations. It is also true for both actual

and geostrophic velocities, the latter obtained from a synthetic temperature field for the Gulf Stream (Hall, 1994). These ideas are confirmed and strengthened by the analysis of the upper-level jet stream velocity structure, the atmospheric counterpart of the Gulf Stream. The axis of this jet, when viewed in a natural coordinate system, remains straight in isentropic coordinates.

We have shown that an oceanic (atmospheric) baroclinic current (jet) may be aligned either with depth or with density, but not simultaneously with both. The actual Gulf Stream density–depth field lacks symmetry with respect to the cross-stream origin but leads to a stream that is vertically aligned in density. This axis of maximum velocity, a vertically straight column, has its total vorticity value given by the local planetary vorticity. Although a locus of maximum velocity will always have zero relative vorticity, the fact that this happens simultaneously to a whole straight water column is remarkable. Because the upper-thermocline layers ($8^{\circ}\text{C} < \sigma_{\theta} < 18^{\circ}\text{C}$) have near-constant stratification (e.g. Pelegrí and Csanady, 1994), it turns out that this vertical column has near-constant potential vorticity.

The generalization of the observed alignment to different regions of the Gulf Stream and to other intense currents seems plausible given the number of realizations in the HR data set, and the atmospheric jet analogy. It is also consistent with the observations of Johns et al. (1995) that the Gulf Stream baroclinic transport is nearly invariant beyond Cape Hatteras, and agrees with the argument of Rossby (1999) on the immense supply of energy by the rapidly flowing Gulf Stream, such that it maintains a stiff structure along its path. Further verification of the above ideas requires simultaneous density and velocity measurements in other portions of the Gulf Stream and in other intense currents. These ideas could also serve for verification purposes, using high-resolution numerical models.

7. Acknowledgments

We are grateful to Tom Rossby, University of Rhode Island, for kindly providing the Pegasus data set as well as for encouraging comments. We thank John Young, University of Wisconsin-Madison, for a number of useful comments. We also wish to thank our reviewers for their helpful suggestions. Part of this work was written while JLP was at the University of Wisconsin-Madison with funding from the Secretaría de Estado de Educación y Universidades of the Spanish Government. This work has also been partly funded by the European Union through project OASIS (EVK3-CT-2002-00073-OASIS). The atmospheric data have been provided by the NOAA-CIRES Climate Diagnostics Center, Boulder, Colorado, USA.

References

- Bower, A. S. 1989. Potential vorticity balances and horizontal divergence along particle trajectories in Gulf Stream meanders east of Cape Hatteras. *J. Phys. Oceanogr.* **19**, 1669–1681.

- Bower, A. S. and Hogg, N. C. 1996. Structure of the Gulf Stream and its recirculations at 55°W. *J. Phys. Oceanogr.* **26**, 1002–1022.
- Bower, A. S. and Rossby, T. 1989. Evidence of cross-frontal exchange processes in the Gulf Stream based on isopycnal RAFOS float data. *J. Phys. Oceanogr.* **19**, 1177–1190.
- Bower, A. S., Rossby, H. T. and Lillibridge, J. L. 1985. The Gulf Stream – barrier or blender? *J. Phys. Oceanogr.* **15**, 24–32.
- Cahn, A. 1945. An investigation of the free oscillations of a simple current system. *J. Meteorol.* **2**, 113–119.
- Charney, J. G. 1955. The generation of ocean currents by wind. *J. Mar. Res.* **14**, 477–498.
- Davies, H. C. and Rossa, A. M. 1998. PV frontogenesis and upper-tropospheric fronts. *Mon. Wea. Rev.* **126**, 1528–1539.
- Dutton, J. A. 1986. *The Ceaseless Wind*. McGraw-Hill, New York, 617 pp.
- Halkin, D. and Rossby, T. 1985. The structure and transport of the Gulf Stream at 73°W. *J. Phys. Oceanogr.* **15**, 1439–1452 (HR).
- Hall, M. M. 1994. Synthesizing the Gulf Stream thermal structure from XBT data. *J. Phys. Oceanogr.* **24**, 2278–2287.
- Huang, R. X. and Stommel, H. 1990. Cross-sections of a two-layer inertial Gulf Stream. *J. Phys. Oceanogr.* **20**, 907–911.
- Johns, E., Watts, D. R. and Rossby, H. T. 1989. A test of geostrophy in the Gulf Stream. *J. Geophys. Res.* **94**, 3211–3222.
- Johns, W. E., Shay, T. J., Bane, J. M. and Watts, D. R. 1995. Gulf Stream structure, transport, and recirculation near 68°W. *J. Geophys. Res.* **100**, 817–838.
- Keyser, D. and Shapiro, M. A. 1986. A review of the structure and dynamics of upper-level frontal zones. *Mon. Wea. Rev.* **114**, 152–199.
- Leaman, K. D., Johns, E. and Rossby, T. 1989. The average distribution of volume transport and potential vorticity with temperature at three sections across the Gulf Stream. *J. Phys. Oceanogr.* **19**, 36–51.
- Manning, J. P. and Watts, D. R. 1989. Temperature and velocity structure of the Gulf Stream north-east of Cape Hatteras: modes of variability. *J. Geophys. Res.* **94**, 4879–4890.
- Newton, C. W. 1978. Fronts and wave disturbances in Gulf Stream and Atmospheric Jet Stream. *J. Geophys. Res.* **83**, 4697–4706.
- Pelegrí, J. L. and Csanady, G. T. 1991. Nutrient transport and mixing in the Gulf Stream. *J. Geophys. Res.* **96**, 2577–2583.
- Pelegrí, J. L. and Csanady, G. T. 1994. Diapycnal mixing in western boundary currents. *J. Geophys. Res.* **99**, 18 275–18 304.
- Ratsimandresy, A.W. 2002. *Transfer of water from the Subtropical Gyre into the Subpolar Gyre of the North Atlantic: the Gulf Stream and its extension*. PhD Dissertation, Universidad de Las Palmas de Gran Canaria, 126 pp.
- Rodríguez-Santana, A., Pelegrí, J. L., Sangrà, P. and Marrero-Díaz, A. 1999. Diapycnal mixing in Gulf Stream meanders. *J. Geophys. Res.* **104**, 25 891–25 912.
- Rossby, C.-G. 1937. On the mutual adjustment of pressure and velocity distributions in certain simple current systems, I. *J. Mar. Res.* **1**, 15–28.
- Rossby, C.-G. 1938. On the mutual adjustment of pressure and velocity distributions in certain simple current systems, II. *J. Mar. Res.* **2**, 239–263.
- Rossby, C.-G. 1951. On the vertical and horizontal concentration of momentum in air and ocean currents. *Tellus* **3**, 15–27.
- Rossby, T. 1987. On the energetics of the Gulf Stream at 73°W. *J. Mar. Res.* **45**, 59–82.
- Rossby, T. 1999. On gyre interactions, *Deep-Sea Res.* **46**, 139–164.
- Rossby, T. and Gottlieb, E. 1998. The Oleander project: monitoring the variability of the Gulf Stream and adjacent waters between New Jersey and Bermuda. *Bull. Am. Meteorol. Soc.* **79**, 5–18.
- Spain, P. F., Dorson, D. L. and Rossby, H. T. 1981. PEGASUS, a simple, acoustically tracked, velocity profiler. *Deep-Sea Res.* **28**, 1553–1567.
- Tenenbaum, J. 1996. Jet stream winds: comparisons of aircraft observations with analysis. *Wea. Forecasting* **11**, 188–197.
- Trenberth, K. E. 1992. Global analysis from ECMWF and atlas of 1000 to 10 mb circulation statistics. NCAR/TN-373, 191 pp.
- Veronis, G. and Stommel, H. 1956. The action of variable wind stresses on a stratified ocean. *J. Mar. Res.* **15**, 43–75.