NOTES AND CORRESPONDENCE

Cooling Spirals and Recirculation in the Subtropical Gyre*

MICHAEL A. SPALL

Woods Hole Oceanographic Institution, Woods Hole, Massachusetts

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ABSTRACT

The influence of cooling in a western boundary current on the recirculation of parcels in the subtropical gyre and their eventual transfer into the subpolar gyre is investigated. It is shown that heat loss to the atmosphere and the resulting vertical convection of dense water in the Gulf Stream of a general circulation primitive equation model forces a counterclockwise spiral of the velocity vector with depth (a cooling spiral). Parcels that pass through this region of cooling are forced to cross under the upper-level trajectories from south to north, in opposite sense to the beta spiral experienced in the interior of the subtropical gyre. This crossing of trajectories is an important consequence of the cooling in the western boundary current as it influences both scale and structure of the subtropical gyre recirculation. A simple expression is derived that relates the spatial scale of the recirculation to the cooling rate in the western boundary current and the wind forcing in the subtropical gyre.

1. Introduction

The role of the western boundary current in the recirculation of parcels through the subtropical gyre is an important and not well-understood piece of the general circulation puzzle. Analytical models of the thermocline, such as those of Luyten et al. (1983, hereafter LPS) and Rhines and Young (1982), have greatly advanced our understanding of the circulation within an idealized interior of the wind-driven subtropical gyre. There is an inherent assumption in these models, however, that the western boundary current somehow closes the circulation. The manner in which this is accomplished in the real ocean and the extent to which it does not conflict with the basic thermocline theory is not well understood. Cushman-Roisin (1987) investigated the influence of cooling of the recirculation gyre on the potential vorticity budget of a two-layer analytic model. The Gulf Stream in that model is represented through the boundary conditions, which require conservation of potential vorticity along parcel trajectories, thus not allowing any heating or cooling in the western boundary current. Further progress with analytic methods has been inhibited due to the complexities of the nonlinear, wind- and buoyancy-forced system. A better understanding of the relationship between cooling processes in the western boundary current and the resulting subtropical gyre recirculation is needed.

The present analysis uses a general circulation primitive equation model to investigate the influence of cooling in the western boundary current on the recirculation in the subtropical gyre. The numerical model is described in section 2. The presence of a cooling spiral in the western boundary current is demonstrated in section 3 and its influence on parcel recirculation is discussed in section 4. Final conclusions are given in section 5.

2. The numerical model

The model used in the present study is the GFDL primitive equation model documented by Cox (1984). The model integrates the three-dimensional equations of motion, tracer equations for temperature and salinity, and a nonlinear equation of state. The subgrid-scale processes are parameterized with a second-order operator in the vertical and a Laplacian operator in the horizontal. The vertical mixing of the density field is uniform for stable density profiles and infinite for unstable density profiles. The equations and numerical properties of the model are well documented in the reference above and are not reproduced here.

The heat flux at the surface is parameterized by a relaxation of the temperature at the uppermost level in the model to the apparent atmospheric temperature of Han (1984). This apparent temperature is similar to the surface temperature of the ocean but takes into account radiative and evaporative effects. The freshwater flux (evaporation minus precipitation) at the

* Woods Hole Oceanographic Institution Contribution Number 7604.

Corresponding author address: Dr. Michael A. Spall, Woods Hole Oceanographic Institution, Clarke Laboratory, #331A, Woods Hole, MA 02543.

surface is parameterized by a relaxation of the salinity at the uppermost level of the model to the climatological mean surface salinity of Levitus (1982). Because the present focus is on the effects of cooling in the western boundary current, the climatological mean buoyancy forcing in the central experiment reported here has been chosen to represent winter conditions. The relaxation time constants for both temperature and salinity are chosen to be 100 days. The surface wind forcing is taken from the annual mean winds derived by Hellerman and Rosenstein (1983).

The model is non-eddy-resolving with 2° horizontal resolution and 10 levels in the vertical. The model domain extends from the equator to 64°N and from 80° to 10°W. The horizontal resolution is chosen to represent major current features such as the Gulf Stream, North Atlantic Current, deep western boundary current, and the gyre recirculations while remaining computationally affordable for long time integrations. The model levels are placed at 25, 75, 150, 300, 500, 800, 1250, 1750, 2500, and 3500 m, resulting in a maximum bottom depth of 4000 m. The coefficients of horizontal dissipation are 4×10^8 cm^2 s^{-1} (viscosity), 1×10^7 cm^2 s^{-1} (diffusion), and the coefficients of vertical viscosity and diffusion are 1 cm^2 s^{-1}.

Water mass exchange, which takes place outside the model domain, is parameterized by adding a term that relaxes the model temperature and salinity back toward the climatological mean over a band 6° wide near the northern and southern boundaries. While this technique does not allow any mass exchange between the basins, it does simulate some of the water mass conversion that actually takes place outside of the model domain (see Sarmiento 1986).

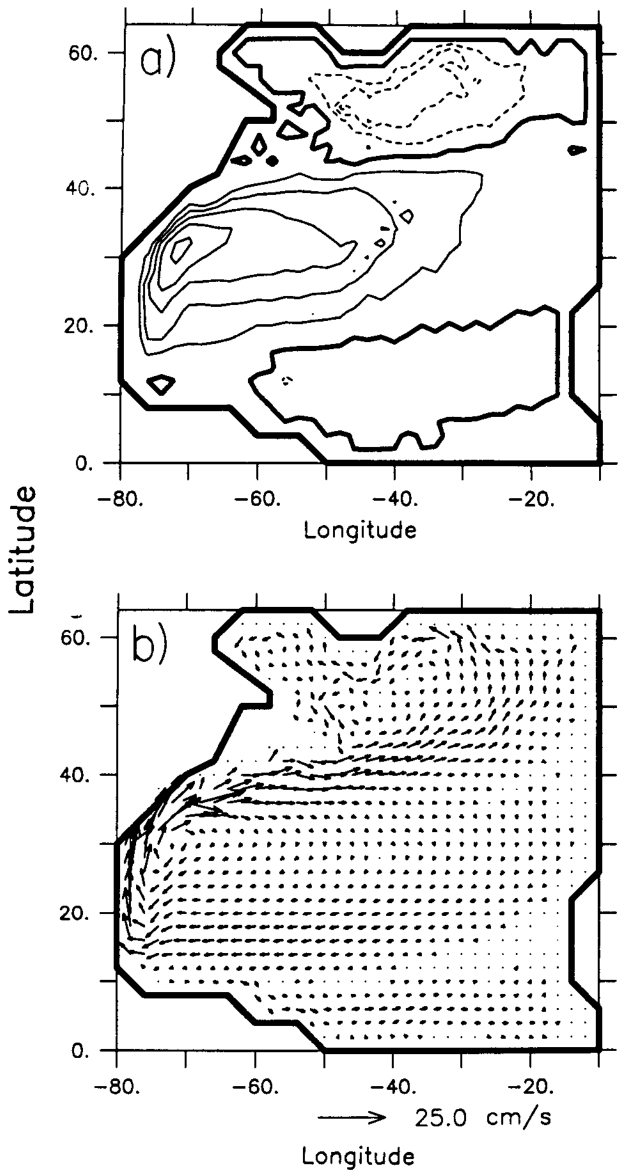
Non-eddy-resolving resolution is chosen both for interpretive and computational reasons. Although the Gulf Stream is a region of strong mesoscale variability, we believe it is prudent to begin the investigation of such a complex problem by first understanding the dynamics of the simpler (although less realistic) models before moving on to the more complex models. The non-eddy-resolving results presented in this note provide a large-scale dynamical framework from which to progress into the more realistic eddy-resolving regime. With the non-eddy-resolving results in hand, the role of the eddies will be more easily understood once they are added to the problem.

The model was initialized with the annual mean density field of Levitus interpolated to the model grid and forced with the steady wind, surface heat flux, and evaporation minus precipitation data described previously. After a period of 400 years the model fields had essentially arrived at their equilibrium state. The analysis in this paper were carried out at after both 300 and 400 years of integration and found to be virtually the same.

The transport streamfunction is shown in Fig. 1a. The presence of the anticyclonic and cyclonic gyres is clear. The depth-integrated transport in the subtropical gyre is over 50 Sv (1 Sv ≡ 10^6 m^3 s^{-1}), while that of the subpolar gyre is approximately 30 Sv. The intensification of the western boundary current and its penetration into the interior are evident. The subtropical and subpolar gyres and Gulf Stream are also evident in the velocity field at 300 m (Fig. 1b). The maximum velocity in the stream is approximately 40 cm s^{-1}, occurring at the western boundary. From here, the stream flows along the coast of the United States toward the northeast before completely separating from the coast downstream of the Grand Banks. In the following analysis, the section of the stream between Cape Hatteras and the Grand Banks is referred to as the Gulf Stream extension region. It is this portion of the stream that is believed to play an important role in the subtropical recirculation and transfer of parcels into the subpolar gyre. Downstream of the Grand Banks the flow is generally referred to as the North Atlantic Current. While the depth-integrated transport (Fig. 1a) leads one to believe that there is a clear separation between the anticyclonic subtropical gyre and the cyclonic subpolar gyre, the upper thermocline velocity indicates that such a distinction is not so easily made. The North Atlantic Current transports the warm, saline waters of the subtropical gyre to high latitudes, across the line of zero depth-integrated meridional transport. Once at high latitudes, some of this water is converted to the cooler, fresher intermediate and deep waters through heat loss and precipitation and some recirculates back into the subtropical gyre. The more dense intermediate and deep waters return to low latitudes primarily through the deep western boundary current. The meridional overturning in the model is approximately 17 Sv.

The rotation of the velocity vector with depth, θ_z, is shown in Fig. 1c at 225 m in the model fields. The velocity rotation is somewhat noisy near the coasts as the flow follows the model topography; however, the interior balances are smooth and relevant for the large-scale flow. The most noticeable feature is the positive rotation throughout most of the subtropical gyre, indicating a clockwise rotation with depth. This is the beta-spiral driven by Ekman pumping as discussed by Schott and Stommel (1978). The rotation is nearly uniform in the zonal direction and is a maximum at the midlatitude of the subtropical gyre. The symmetry in the meridional direction is broken down by the change in sign at about 30°N, near the eastward extension of the western boundary current. There is a counterclockwise rotation along the eastward extension of the Gulf Stream and along the northern portion of the recirculation region. Much of this counterclockwise spiral is in a region of Ekman pumping.

Another interesting feature of the rotation is the sharp, nearly zonal front along 10°–20°N. This is coincident with the shadow zone in the model. Wind and buoyancy-driven ventilated thermocline theory



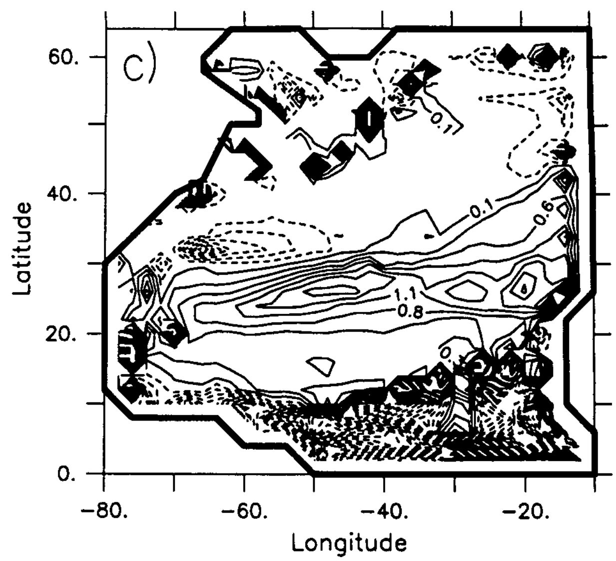


FIG. 1. Model fields: (a) depth-integrated transport streamfunction (CI = 10 Sv), (b) velocity field at 300 m, and (c) velocity rotation with depth (1.0 = 180° 1000 m^{-1}).

(Pedlosky 1986; Luyten and Stommel 1986) predicts that the thermocline flow is to the southwest in the interior and that a weak flow returns to the northeast in the shadow zone. As a consequence of the northward shift of the shadow zone deeper in the water column, there is an abrupt change in the rotation with depth at the shadow zone boundary. A similar result is found in the diagnostic study of the potential vorticity balance in the subtropical gyre by Spall (1991). It is both surprising and encouraging that this feature shows up so clearly in the present large-scale, diffusive numerical calculation.

3. The cooling spiral

The mechanisms that force these opposite spirals can be illustrated by first considering the idealized equation for the rotation of the velocity vector with depth. We start with the steady density equation, including horizontal and vertical subgrid-scale dissipation,

$$u\rho_x + v\rho_y + w\rho_z = A_H\nabla^2\rho + A_V\rho_{zz} + Q, \quad (1)$$

where Q represents local heating/cooling of the water as a result of vertical convection. The vertical shear of the velocity field may be related to the horizontal density gradient, assuming the velocity field is geostrophic and hydrostatic, as

$$u_z = \gamma\rho_y, \quad v_z = -\gamma\rho_x, \quad \gamma = g/f\rho_0.$$

The expression for the rotation of the velocity vector with depth is now obtained, using $u = V\cos\theta$ and $v = V\sin\theta$, as

$$\theta_z = \frac{\gamma}{V^2}\left(w\rho_z - Q + \frac{1}{\gamma}A_H\zeta_z - A_V\rho_{zz}\right). \quad (2)$$

This equation is similar to the nondiffusive version derived by Schott and Stommel (1978). The rotation of the velocity vector with depth is driven by the vertical advection of density, heating/cooling, and diffusion. In the upper thermocline of the subtropical gyre interior, we expect the large-scale vertical velocity to be negative (as a consequence of Ekman pumping) and ρ_z to be negative (for stability) so that, in the absence of heating/cooling and diffusion, the rotation of the velocity vector with increasing depth will be clockwise. The horizontal diffusion term is proportional to the vertical gradient of relative vorticity and leads to a counterclockwise (clockwise) spiral on the anticyclonic (cyclonic) side of the Gulf Stream. In the interior of the subtropical gyre, the rotation due to the horizontal diffusion is expected to be negligible because the relative vorticity is very small there. The vertical diffusion will result in a clockwise spiral for vertical density profiles representative of the interior subtropical gyre. Local cooling will result in a counterclockwise velocity spiral with depth, as in the subpolar gyre analysis of Stommel (1979). Note that the rate of rotation is inversely proportional to the square of the velocity so that in the Gulf Stream, where V is large, a smaller rotation rate is expected than in the interior for the same amount of heating or cooling.

The counterclockwise spiral found in the model must be a result of either cooling or horizontal diffusion because it is in a region of Ekman pumping. An order of magnitude for the cooling required to reverse the spiral forced by Ekman pumping, in the absence of diffusion, is estimated as follows. The cooling over some depth Δz may be related to the surface heat flux, Q_S, as

$$\Delta\rho = \frac{Q_S\alpha}{C_p\Delta z},$$

where α is the coefficient of thermal expansion (10^{-4} K^{-1}) and C_p is the specific heat of seawater (4×10^3 J kg^{-1} K^{-1}). Typical values of the Ekman pumping in the subtropical gyre are $w = 3 \times 10^{-5}$ cm s^{-1} and $\rho_z = 3 \times 10^{-8}$ g cm^{-4}, and Δz is taken to be 500 m. The cooling required to offset the clockwise spiral driven by Ekman pumping is then calculated as $Q_S = w\rho_z C_p \Delta z/\alpha = -18$ W m^{-2}. Cooling in excess of this number will result in a counterclockwise spiral. The actual cooling along the Gulf Stream and northern recirculation region is on the order of 50–100 W m^{-2}, so expect to see such a rotation with depth along the region of strong heat loss, even in the absence of diffusive effects.

The terms in the brackets on the right-hand side of Eq. (2) are now calculated directly from the steady temperature and salinity balances in the model. Note that the actual rotation rate is equal to the sum of these terms, scaled by γ/V^2. Figures 2a–d are the contributions to the velocity spiral due to the vertical advection of density ($w\rho_z$), vertical convection ($-Q$), horizontal diffusion ($\gamma^{-1}A_H\zeta_z$), and vertical diffusion ($-A_V\rho_{zz}$). The vertical advection, primarily due to Ekman pumping in the interior of the subtropical gyre, is driving the clockwise rotation with depth throughout the interior, with a small contribution from the vertical diffusion term. There is a slight counterrotation as a result of horizontal diffusion of the front along the southern edge of the subtropical gyre. In the shadow zone, the vertical advection term is partially balanced by vertical diffusion, resulting in the net counterclockwise spiral seen in Fig. 1c. The cooling due to vertical convection is strongly active along the eastward penetration of the Gulf Stream and northern recirculation region, coincident with the region of counterclockwise spiraling. Horizontal diffusion acts in the same sense, although it is smaller in magnitude and located primarily to the west of the region of strong convection. Vertical diffusion contributes throughout the eastward-flowing Gulf Stream, but is an order of magnitude less than the cooling term.

These balances demonstrate that the cooling of parcels and change in rotation of the spiral in the eastward extension of the western boundary current and northern portion of the recirculation are due primarily to heat loss to the atmosphere and the resulting vertical mixing of the dense water. Evidence for such a cooling spiral in this region is found in the diagnostic study based on climatology by Spall (1991). The vertical convection of density is actually driven by the net buoyancy flux at the surface, with contributions due to both heating/cooling and net evaporation minus precipitation. In the Gulf Stream region, the net density flux at the surface is dominated by the heat flux term (Schmitt et al. 1989); hence, the resulting spiral is referred to as a "cooling spiral."

4. Parcel recirculation

A Lagrangian analysis is now applied to the steady, three-dimensional fields to illustrate the influence of the cooling spiral on the recirculation of parcels in the subtropical gyre. The time history of an individual water parcel is recovered from the Eulerian model fields by integrating the Lagrangian trajectory equation

$$d\mathbf{x}(t;\mathbf{x}_0)/dt = \mathbf{u}(\mathbf{x}(t;\mathbf{x}_0), t). \quad (3)$$

The vector $\mathbf{x}$ is the three-dimensional particle position, $\mathbf{x}_0$ is the position at time zero, and $\mathbf{u}$ is the local velocity. Equation (3) is integrated using a fourth-order Runga–Kutta scheme. To carry out the integration, the velocity at the location of the water parcel is determined from the surrounding model grid points using a linear interpolation between the eight adjacent grid points. We have a considerable advantage here in that our three-dimensional velocity fields are steady, thus removing

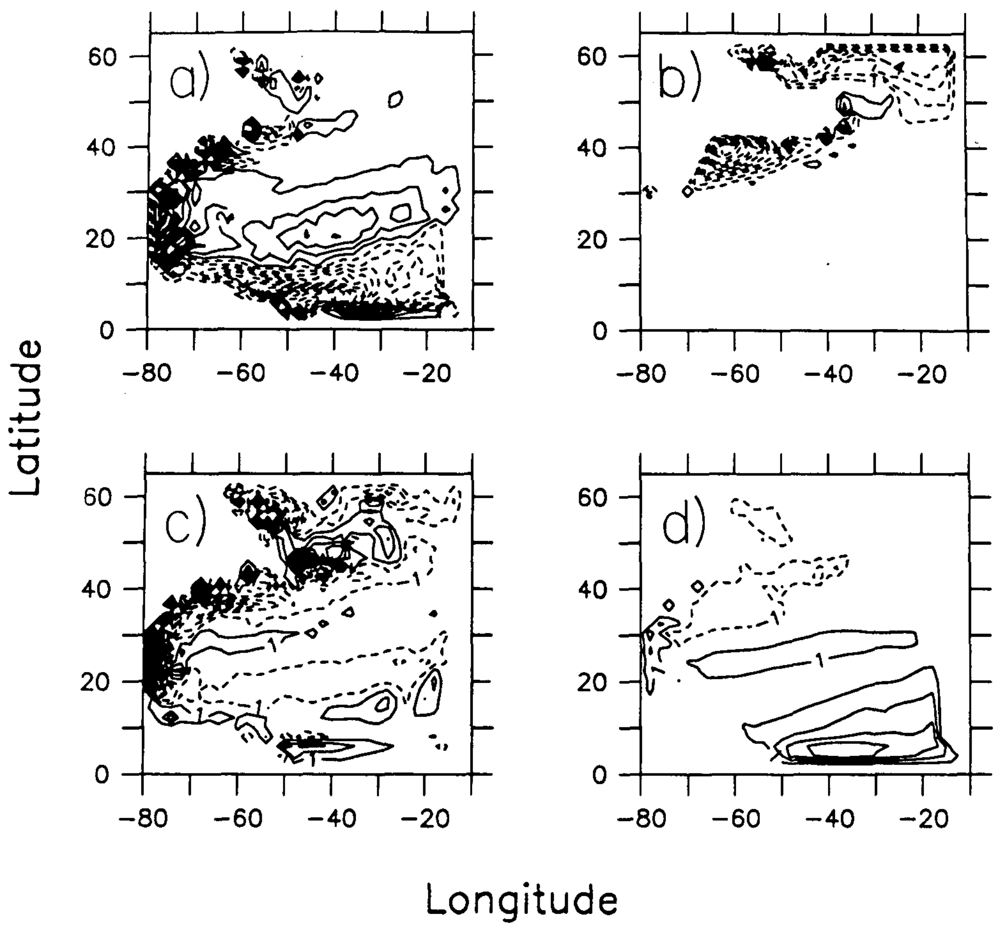


FIG. 2. Contributions to the rotation of the velocity vector with depth due to (a) vertical advection, (b) vertical convection, (c) horizontal diffusion, and (d) vertical diffusion.

the need for interpolation in time and reducing the inherent errors. The reliability of the Lagrangian trajectories, which were recovered from the Eulerian fields, was tested by comparing the value of temperature interpolated from the surrounding grid points with that obtained from integrating the terms in the temperature equation along the same trajectory. Conservation of temperature (or salinity) is the appropriate measure because it is conserved by the numerical model. The heating and cooling of the parcels are recovered well by the Lagrangian integration, so it is believed that the method is adequate for the present purposes. We are further encouraged by the fact that small variations in the initial position of a parcel result in only small changes in the subsequent trajectory of that parcel.

Parcels were placed near the base of the Ekman layer (35 m) in the western portion of the subtropical gyre and tracked for a period of 50 years. Figure 3a shows a plan view of two typical trajectories, labeled as A (solid line) and B (dashed line). Parcel A is initially carried to the northeast while it is still within the upper layer before it is forced downward into the subtropical gyre circulation by Ekman pumping. Once it leaves the uppermost layer it travels to the south and west. The parcel is entrained into the western boundary current near 16°N, 76°W and carried rapidly to the north and east until, at about 50°W, it leaves the eastward-flowing Gulf Stream and returns to the subtropical gyre recirculation. This process is repeated a second time, where the parcel is carried further to the east before exiting the Gulf Stream. On its final trip through the western boundary current, the parcel does not get recirculated but flows to the north with the North Atlantic Current. This trajectory is quite similar to that hypothesized by Stommel (1987) for a parcel introduced at the surface of the subtropical gyre. Parcel B, however, seems to be trapped in a tight recirculation region adjacent to the western boundary current. Whereas A recirculates each cycle farther to the north and east as it passes through the western boundary current, B only extends slightly more to the east and, after 50 years, has made very little progress, at least in the horizontal plane. This trajectory is typical of parcels initialized between 25° and 30°N, 71° and 76°W. Those parcels

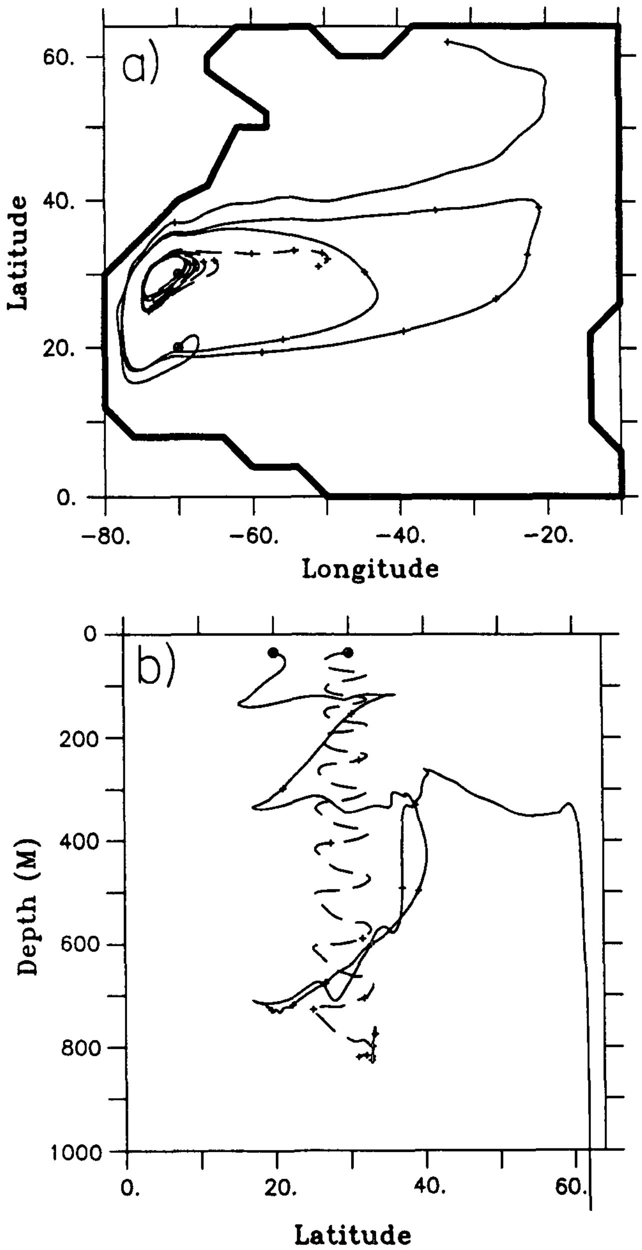


FIG. 3. Lagrangian trajectories for parcels A (solid line) and B (dashed line): (a) plan view and (b) depth versus latitude. Initial position marked by small circle, "+" marks are placed at five-year increments along trajectories.

initialized outside this area follow trajectories similar to A.

Additional differences between parcels A and B are revealed by examining their depths as a function of latitude, Fig. 3b. As A is carried to the south in the subtropical gyre recirculation, it also moves deeper in the water column, consistent with the structure of the density surfaces predicted by the wind-driven thermocline theory of LPS. The parcel enters the western boundary current and is carried rapidly to the north at nearly constant depth. The parcel leaves the Gulf Stream and begins to move to the south, once again increasing in depth as it follows the bowl shape of the subtropical gyre. The parcel is now on a deeper density surface as a result of being cooled as it passed through the western boundary current extension (by vertical convection, Fig. 2b). This process is repeated again and, on the third passage through the boundary current, the parcel upwells and escapes to high latitudes. Once north of 60°N, the parcel is strongly cooled in the damping region and sinks below 1000 m, eventually to return to low latitudes in the deep western boundary current. Trajectory B spirals down very rapidly through the water column, moving downward about 60 m in each recirculation. In the upper ocean the density of parcel B is increased in the western boundary current as a result of vertical convection, while in the deep ocean it is increased as a result of horizontal diffusion. After 30 years, parcel B is at a depth of about 800 m, where it remains nearly stationary for the final 20 years of integration. A similar trajectory was found in the study by Cox and Bryan (1984).

Now let us consider the general consequences of the cooling spiral on parcel recirculation. In order for the velocity vector to spiral clockwise with depth in the subtropical gyre (as required by the beta spiral), the southward-moving parcels on deeper trajectories must pass under the upper-level trajectories from the eastern side to the western side, indicated by the crossing paths at location 1 in the schematic shown in Fig. 4. (Cooling in the western boundary current requires that the parcels are deeper in the water column when they recirculate.) The deep trajectory is directed to the southwest with the thermocline circulation and enters the Gulf Stream at location 2. Once in the western boundary current, there are two possible paths this parcel may take (if the unlikely possibility of heating in the western boundary current is excluded). At location 3, the deeper trajectory must either follow the solid line, which crosses under the upper-level trajectory, or follow the dashed line, which remains to the south of the upper-level trajectory. The parcel will follow the dashed line if there is insufficient cooling to drive the counterclockwise spiral and will reenter the subtropical gyre somewhere to the west of the shallower trajectory. It is clear that a series of such recirculations would result in an ever-tightening recirculation driven by the beta

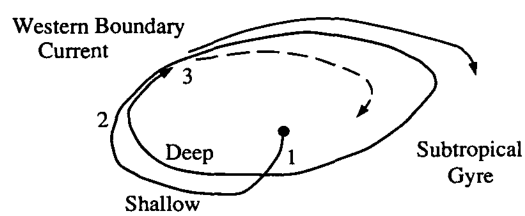


FIG. 4. Schematic of parcel recirculation.

spiral in the subtropical gyre. This is the mechanism that trapped parcel B in the model circulation. A series of parcel recirculations that follow the solid line, however, will lead to transfer into the subpolar gyre, as was found for parcel A. The boundary between those parcels that remain trapped and those that escape is defined by the trajectory whose clockwise spiral with depth induced by the beta spiral in the subtropical gyre is balanced by the counterclockwise spiral with depth due to cooling in the western boundary current extension.

The ability of the cooling spiral to reverse the local clockwise spiral driven by Ekman pumping is an important component of the present thermocline circulation. If the parcel follows the solid line in Fig. 4 and crosses under the upper-level trajectory, it will reenter the subtropical gyre to the east of its previous trajectory. This implies that there is a compatibility condition between the beta spiral in the subtropical gyre and the distance parcels travel in the Gulf Stream before they enter the subtropical gyre recirculation. In order for successive recirculations of a parcel to enter the western boundary current at the same horizontal location, the extra distance traveled to the east by the deeper trajectory (relative to the upper-level trajectory) must be accounted for by the clockwise spiral with depth in the recirculation. The distance a deeper trajectory will travel perpendicular to a shallower trajectory (η) can be approximated as

$$\eta = ut\sin(\theta) = ut\sin(\theta_z\delta z), \qquad (4)$$

where u is the velocity of the parcel on the deeper trajectory, t is the time the parcel takes to pass through the subtropical gyre, θ_z is the rotation of the velocity vector, and δz is the change in depth between the shallower trajectory and the deeper trajectory. Typical values for the subtropical gyre are $u = 1$ cm s^{-1}, $t = 25$ yr, and $\theta_z = \gamma w\rho_z/V^2 = 6°/100$ m. The total rotation between successive trajectories (θ) is obtained by taking the change in depth as 450 m (from Fig. 3b) times the rotation rate of 6°/100 m, giving $\theta = 27°$. This results in a distance traveled normal to the upper-level-trajectory of $n = 3.5 \times 10^8$ cm, or approximately 28° of longitude. This compares very well with the scale of the recirculation between the first time parcel A left the Gulf Stream (at approximately 50°W) and the second time parcel A left the Gulf Stream (at 20°W).

Many other simulations have been carried out that support the assertion that the cooling spiral is a robust characteristic of the model thermohaline circulation. Increases or reductions of the horizontal and vertical diffusion (within numerical stability constraints) do not significantly alter the results presented here for the central case. A simulation with buoyancy forcing representative of summer conditions does, however, give a much different result. The heat loss to the atmosphere in the western boundary current is significantly reduced and, as a result, the counterclockwise cooling spiral is also weakened. Lagrangian trajectories indicate that those parcels, which eventually transfer into the subpolar gyre, must recirculate through the subtropical gyre many more times before doing so, even with the same relatively large diffusion coefficients. In addition, the region over which parcels remain trapped in the subtropical gyre becomes much larger in spatial extent.

5. Conclusions

It has been shown that cooling in the western boundary current and northern recirculation of a general circulation primitive equation model forces a counterclockwise rotation of the velocity vector with depth. This cooling spiral influences both the scale and structure of parcel recirculation in the subtropical gyre. Through this reversal of the beta spiral, parcels on deeper trajectories are forced to cross under the upper-level trajectories and thus extend farther to the east in the Gulf Stream before recirculating in the subtropical gyre. A series of such trajectories eventually leads to a transfer of the parcel from the subtropical gyre into the subpolar gyre. Those parcels that do not pass through the cooling spiral remain in a recirculation that is trapped in the subtropical gyre. A simple relationship was derived between the recirculation scale of the water parcels and the rate of spiral (or Ekman pumping) in the subtropical gyre for a given cooling in the western boundary region. This result emphasizes the complex way in which the buoyancy-forced and wind-forced aspects of the gyre-scale circulation interact.

The present study is based on a steady, large-scale, somewhat diffusive, system. We have chosen to exclude mesoscale eddies and variable forcing in order to isolate the processes investigated here. In the presence of these transients, the cooling spiral may no longer be the only mechanism with which to unwind the beta spiral and force a cross-gyre exchange. For example, eddy mixing and Gulf Stream meandering may also allow parcels to cross under the upper-level flow and subsequently escape into the subpolar gyre. In addition, the cross-gyre transfer via ring formation events is not included in the present study and is another, fundamentally different, way in which parcels may cross from one gyre into the other. Note, however, that the quasigeostrophic study of Lozier and Riser (1990), which included internal instability processes and ring formation events but did not include buoyancy forcing, found very little exchange of parcels in the upper ocean between the subtropical and subpolar gyre.

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