Topographic Stress Parameterization in a Primitive Equation Ocean Model: Impact on Mid-latitude Jet Separation

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Abstract. In a recent paper, Griffa *et al.* (1995) showed that, despite the fact that it was developed for quasi-geostrophic motions, statistical mechanics theory is able to capture the main aspects of the inertial equilibrium states that are outside the range of validity of quasi-geostrophy. These results encourage the development of subgrid scale parameterizations for oceanic general circulation models based on statistical mechanics predictions. In this paper, the effect of this type of parameterizations on one particular aspect of the oceanic wind-driven circulation, the separation of a western boundary current from the coast and its dependence on bottom topography, is investigated. The maximum entropy state predicted by statistical mechanics is characterized by a southward flow in the western part of the North Atlantic basin, opposite to the wind-driven northward boundary current. It is then natural to expect that, when parameterized in a numerical model, this tendency should have a significant impact on the current separation latitude by moving it to the south. This may be of importance as most coarse resolution numerical simulations of the North Atlantic circulation exhibit an overshooting Gulf Stream.

1. Introduction

The inertial characteristics of the oceanic circulation in a closed basin have been extensively discussed in the literature. In particular, the purely inertial limit (i.e., the limit of no forcing and no dissipation) for quasi-geostrophic flows has been studied using the theory of statistical mechanics. This theory predicts the existence of inertial equilibrium states corresponding to the maximum entropy of the system, characterized by mean flows with a linear relationship between streamfunction and potential vorticity (Salmon *et al.*, 1976). These flows are often indicated as "Fofonoff flows" because in the case of a one layer, flat bottom, β-plane basin, they correspond to the well known two-gyre solutions of the steady quasi-geostrophic equation first studied by Fofonoff (1954). In the presence of topography, the Fofonoff flows are modified and are given by solutions locked to the topography (Carnevale and Frederiksen, 1987).

The predictions of the theory of statistical mechanics, and in particular the emergence of mean Fofonoff flows, have been tested in a number of numerical studies using the quasi-geostrophic equation. The results show good agreement with the theory (e.g., Wang and Vallis, 1994; Cummins and Holloway, 1994). The question as to whether or not the inertial tendency toward the Fofonoff flows persists outside the range of validity of quasi-geostrophy was addressed numerically by Griffa *et al.* (1995). This question is not a simple one to address theoretically, as generalizations of statistical mechanics theories are difficult to achieve. They have been attempted only for some specific cases (e.g., Salmon, 1982; Errico, 1984). As suggested by Holloway (1992), the validity of the statistical mechanics theory outside quasi-geostrophy can have important and practical consequences. If the tendency toward a maximum entropy Fofonoff flow survives within the range of validity of the primitive equations, and if it is characteristic of the nonlinearity, it can then be used as a basis for a new and more accurate parameterization of the actions of subgrid scale nonlinear effects in low resolution ocean general circulation models (OGCMs). The parameterization proposed by Holloway (1992) replaces the traditional eddy viscosity that tends to drive the flow toward a state of rest with a term that would drive the barotropic part of the solution toward a Fofonoff flow (Alvarez *et al.*, 1994; Eby and Holloway, 1994; Fyfe and Marinone, 1995; Holloway *et al.*, 1995).

In Griffa *et al.* (1995), inertial solutions obtained with a primitive equation numerical model were interpreted using the statistical mechanics results developed in the framework of quasi-geostrophic theory. The experiments were "initial release" experiments, where an initial random field of eddies is allowed to evolve freely and the emergence of equilibrium solutions is observed. The process of equilibration of the solutions was studied in detail, and the final states were compared with the Fofonoff solutions predicted by the statistical mechanics theory. The experiments suggest that, despite the fact that the theory was developed for quasi-geostrophic motions, statistical mechanics theory is able to capture the main aspects of the inertial equilibrium states that are outside the range of validity of quasi-geostrophy.

These results therefore support the hypothesis of Holloway (1992) and encourage the development of subgrid scale parameterizations for OGCMs based on the statistical mechanics predictions (Eby and Holloway, 1994). In this paper, we study the effect of this type of parameterizations on one particular aspect of the oceanic wind-driven circulation, the separation of a western boundary current from the coast and its dependence on bottom topography. As shown by Eby and Holloway (1994), the maximum entropy state predicted by statistical mechanics is characterized by a southward flow in the western part of the North Atlantic basin, opposite to the wind-driven northward boundary current. It is then natural to expect that, when parameterized in a numerical model, the maximum entropy tendency should have a significant impact on the current separation latitude by moving it to the south. This may be of importance as most coarse-resolution numerical simulations of the North Atlantic circulation exhibit an overshooting Gulf Stream.

The layout of the paper is the following. In section 2, the impact of topography on mid-latitude jet separation is briefly reviewed. The numerical model characteristics are introduced in section 3. In section 4, the basic numerical experiments are described and discussed in relation to Holloway (1992). Implementation of the subgrid scale parameterization and its impact on the solution is presented in section 5. Finally, the results are summarized and discussed in the concluding section.

2. Background

Bottom topography has for a long time been recognized as an important factor in the determination of the path of western boundary currents (Greenspan, 1963; Warren, 1963). One of the earliest numerical studies of the influence of bottom topography on the ocean circulation was that of Holland (1967), in a homogeneous, β-plane numerical ocean model with steady wind stress curl. He showed that topography plays a dominant role in the separation of the western boundary current from the coast and concluded that the presence of a western continental slope tends to induce an earlier separation of the jet as the jet follows lines of constant potential vorticity.

Holland (1973) then considered the joint effect of baroclinicity and relief (JEBAR) and showed numerically that the transport of the anticyclonic subtropical gyre was enhanced with respect to the Sverdrup transport when both effects were considered. Holland (1973) noted that a horizontal velocity as small as 0.1 cm s^{-1} perpendicular to a continental slope with gradient 10^{-3} is able to produce topographic torques comparable to those of the average wind stress curl, suggesting that in the real ocean the topographic terms may be more important than the wind itself in determining the magnitude of the western boundary transport.

The effect of continental rises on the wind-driven circulation in a quasi-geostrophic framework was recently further investigated by Thompson (1995), who developed a modification to the theory of Rhines and Young (1982) and carried out three-layer eddy-resolving quasi-geostrophic numerical simulations. The effect of large scale topography has been addressed in the findings of Treguier and McWilliams (1990) that topography of largest scale has the most important effect on the momentum balance of the flow, while small scale topography has an indirect influence and does not contribute as greatly to the stress. Overall, large scale bottom topography has a significant impact on the oceanic flow, acting upon it mainly by means of effects on the potential vorticity field. Together with baroclinicity, it can account for much of the observed intensity and flow pattern of western boundary currents. The effects of topography are felt throughout the water column, but are most notorious in the deep ocean, where closed potential vorticity contours can "trap" the flow and drive it more efficiently.

3. The Numerical Model

The numerical model used in this study is the adiabatic version of MICOM (Miami Isopycnic Coordinate Ocean Model) (see Bleck and Chassignet, 1994, for details). It may be viewed as a stack of shallow water models, each consisting of a momentum and a continuity equation:

$$\frac{d\mathbf{v}}{dt} + f\mathbf{k}\times\mathbf{v} = -g\nabla\eta + \mathbf{F}$$
$$\frac{\partial h}{\partial t} + \nabla(h\mathbf{v}) = 0 \tag{1}$$

where $\mathbf{v}$ is the horizontal velocity field and $\mathbf{F}$ is an eddy viscosity operator that simulates the action of small scale processes. Other variables retain their conventional meanings. Horizontal velocities and vorticity are defined as layer properties.

The operator $\mathbf{F}$ is expressed as

$$\mathbf{F} = A\frac{1}{h}\nabla(h\nabla\mathbf{v}) \tag{2}$$

where A is the eddy viscosity coefficient. As shown by Gent (1992), the operator (2) has the important physical property of being energetically consistent, in the sense that it induces energy dissipation during the flow evolution. The operator $\mathbf{F}^*=A\nabla^2\mathbf{v}$, on the other hand, can actually generate energy in the context of the shallow water equations (1) as illustrated by Gent (1992).

The model is configured for this study in a square ocean basin 2580 km on a side, with constant mesh size in the horizontal and three layers in the vertical. The model is driven by a zonally symmetric wind stress

$$\vec{\tau} = \left[-\tau_m \cos\left(\frac{2\pi y}{L_o}\right), 0\right] \tag{3}$$

where

$$\tau_m = 1\times10^{-4}\ \mathrm{m^2 s^{-2}}.$$

Such forcing results in a Sverdrup circulation which consists of two gyres, subtropical and subpolar. The wind stress is specified as a body force acting only on the layer directly beneath the surface (Chassignet and Gent, 1991; Chassignet and Bleck, 1993). The eddy viscosity A is proportional to the grid spacing and is characterized by a constant diffusive velocity $u_d = A/\nabla x$ equal to 2 cm s^{-1}. The lateral boundary conditions employed on the four side-walls are free slip, i.e., zero vorticity. The bottom topography consists of four shelves (100 km wide) and four slopes (200 km wide of gradient α).

4. The Wind-Driven Experiments

Three weak slope ($\alpha = 2.5\times10^{-3}$) experiments (W1, W2, and W3) were performed with a mesh size of 20, 40, and 80 kilometers, respectively. A second set (S1, S2, and S3) was performed for a stronger slope ($\alpha = 1.25\times10^{-2}$). All the numerical experiments were integrated for 25 model years (1 model year is equal to 360 days) and the presented fields were averaged over the last 5 years. The 80-km experiments are considered the coarse mesh experiments and do not resolve the mesoscale eddies that are present in the fine mesh experiments (20-km grid).

The 5-year time-averaged layer streamfunctions for the weak slope experiments (W1, W2, and W3) are displayed in Figures 1, 2, and 3, respectively. In W1, the mid-latitude jet is highly nonlinear, with large meanders. Mesoscale eddies are formed through baroclinic instabilities and the bottom layer is set in motion. The resulting circulation in the bottom layer is cyclonic and locked to the f/H contours (Figure 4a). It is quite intense (about 31 Sverdrups) with a marked signature in the barotropic streamfunction. As the resolution is decreased from W1 to W3, the eddy activity diminishes and the eddy-driven flow in the bottom layer becomes weaker (Figures 2d and 3d). The jet separation latitude is south of the zero wind stress curl line (ZWCL) in both W1 and W2, but exactly at the ZWCL in W3. The two possible factors responsible for a southward separation of the western boundary current are (1) topography and (2) the fact that the wind is prescribed as a body force over the

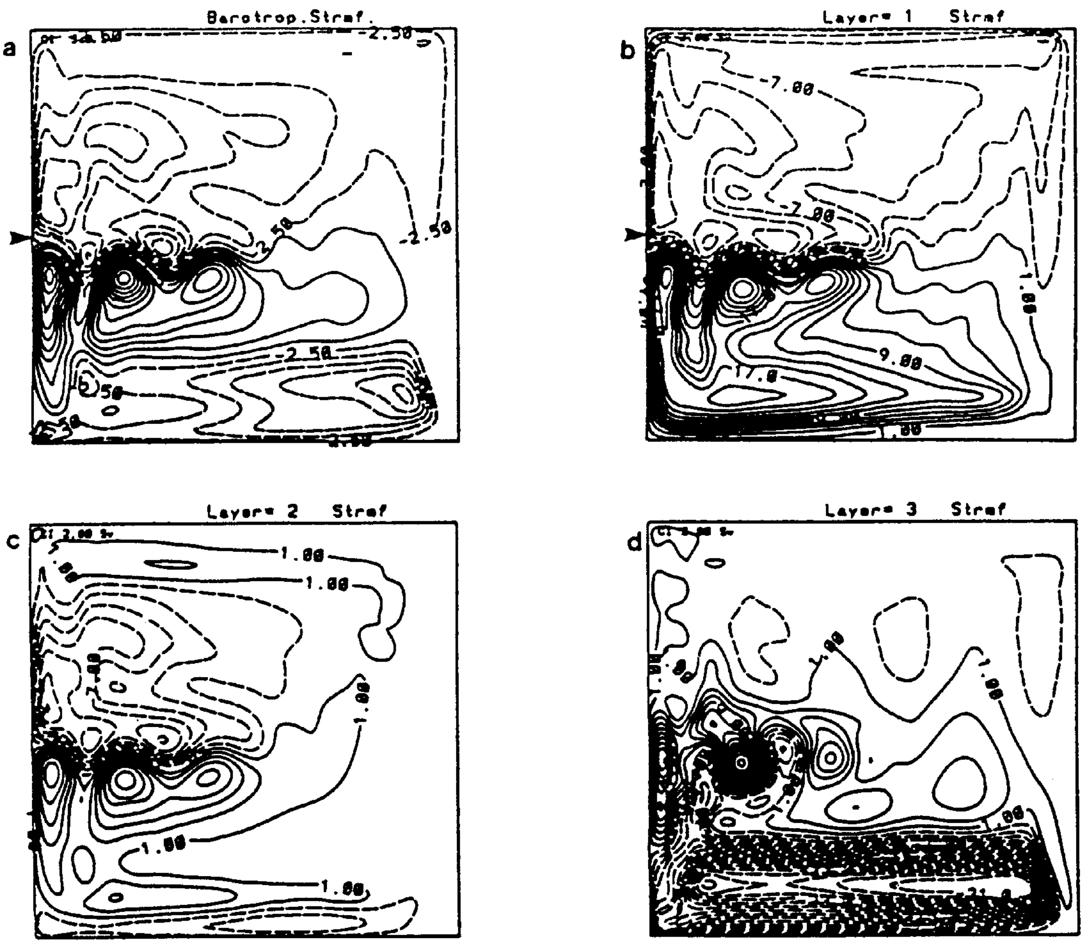

Figure 1. 5-year time average layer streamfunctions (in Sverdrups) for the weak slope experiment W1 (grid spacing 20 km). The arrow represents the ZWCL.

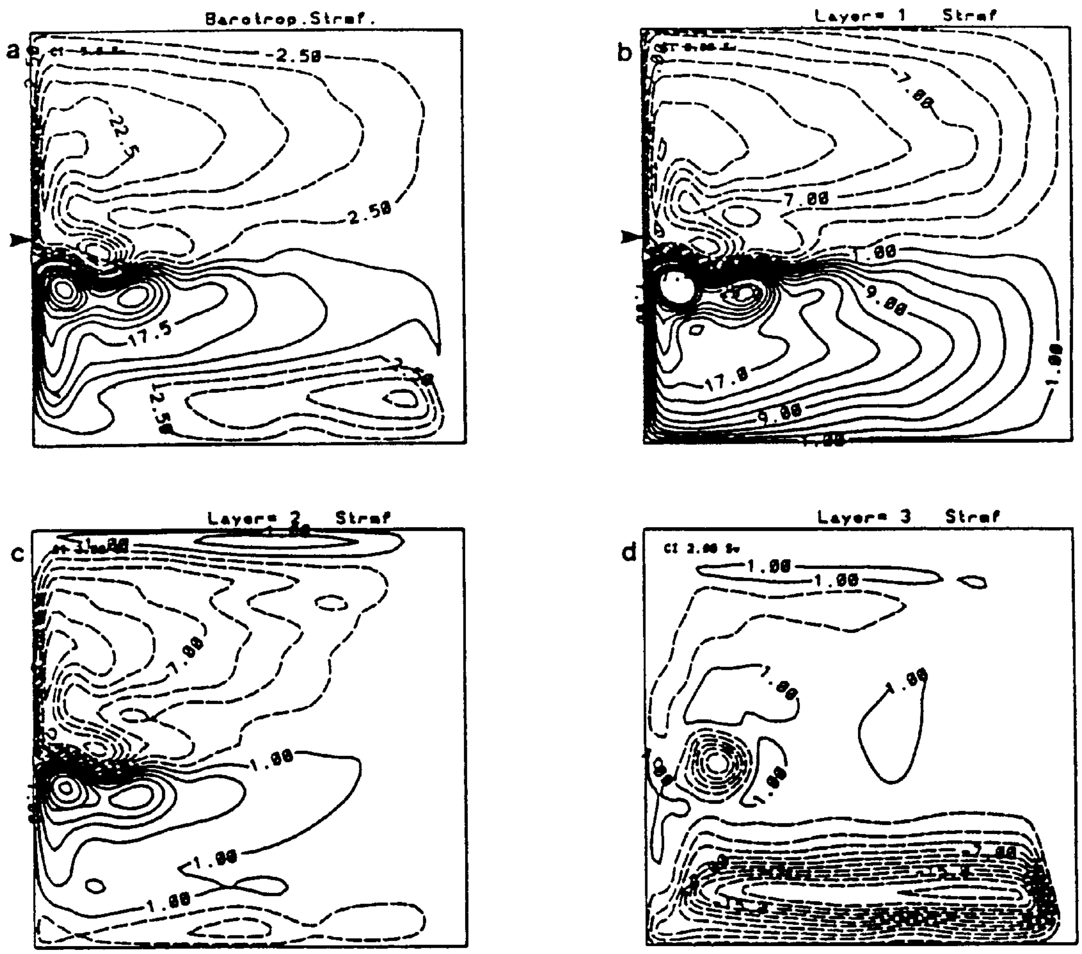

Figure 2. As in Figure 1, for experiment W2 (grid spacing 40 km).

uppermost layer (Chassignet and Gent, 1991; Chassignet and Bleck, 1993). To assess the effect of topography, a control experiment was performed with a flat bottom and high resolution (20 km). For this configuration, the separation is located at the ZWCL (Figure 5) implying that the southern separation in W1 and W2 can be attributed solely to the topography.

A reduction in the bottom layer flow intensity is also observed in the strong slope experiments (S1, S2 and S3) (Figures 6, 7, and 8) with a decrease in resolution, except that the bottom layer cyclonic circulation now encompasses most of the basin, following the *f/H* contours (Figure 4b).

Topography is seen to play a strong role in determination of the separation latitude, as all of the strong slope experiments show a separation point located farther south than that seen in their weak slope counterparts.

5. Implementation of the Neptune Effect and its Impact on Mid-Latitude Jet Separation

5.1 The Neptune Effect and its Implementation

The so-called "Neptune" effect (Holloway, 1992) is a subgrid scale parameterization that seeks to represent the effect of eddies interacting with topography, an interaction that is capable of exerting large stress upon the mean circulation. This parameterization is achieved by relaxing the velocities toward a maximum entropy solution that depends upon the shape of the topography. The theory (Salmon *et al.*, 1976) was developed using statistical mechanics in the context of quasi-geostrophy. It does not take into account the effects of external forcing or of dissipation.

As suggested by Eby and Holloway (1994), motions on scales larger than the first Rossby radius of deformation

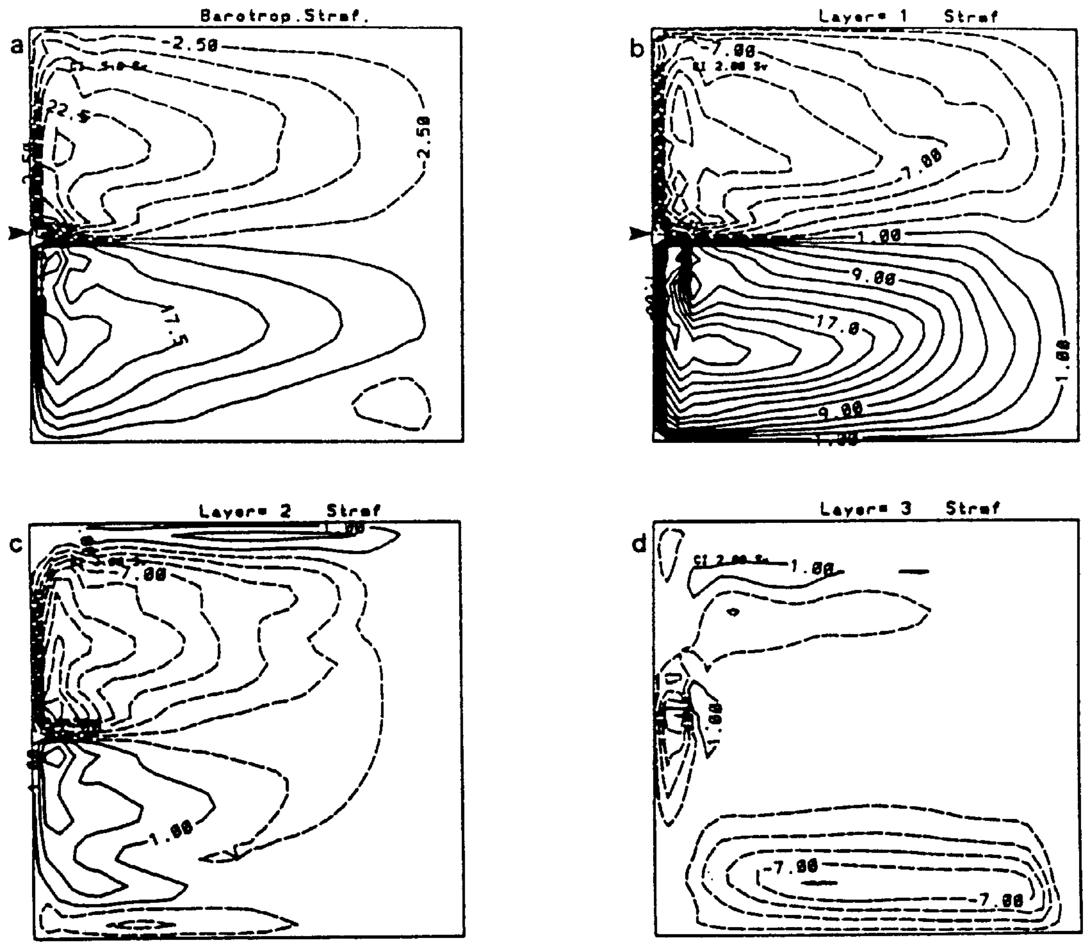

Figure 3. As in Figure 1, for experiment W3 (grid spacing 80 km).

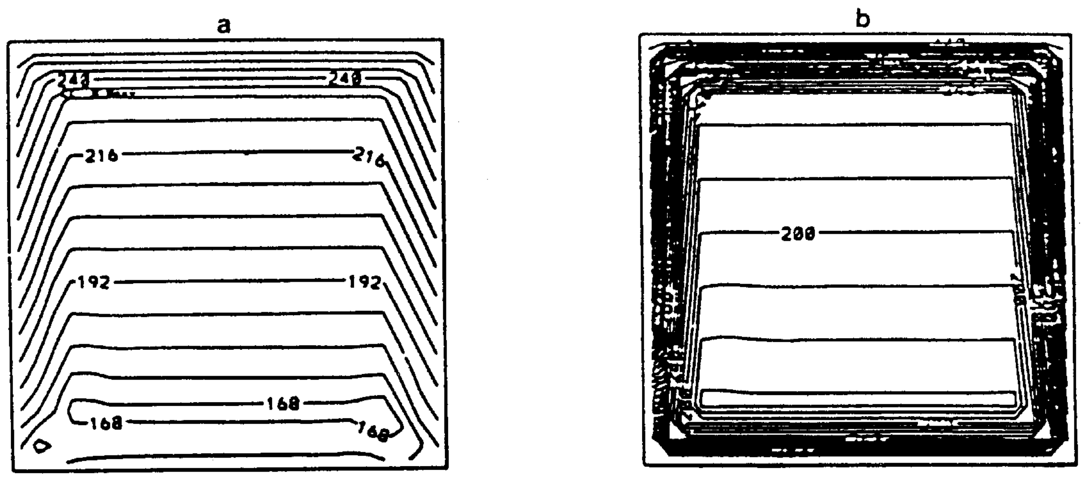

Figure 4. *f/H* contours for (a) the weak slope experiments ($\alpha=2.5 \times 10^{-3}$) and (b) the strong slope experiments ($\alpha = 1.25 \times 10^{-2}$)

are expected to be barotropic, and, according to the maximum entropy principle of statistical mechanics, their equilibrium states should satisfy

$$\left(\alpha_1/\alpha_2 - \nabla^2\right)\langle\psi\rangle = \langle q\rangle \tag{4}$$

where $\langle\psi\rangle$ is the time-averaged streamfunction, α_1/α_2 is a ratio of Lagrange multipliers, and $\langle q\rangle$ is the time-averaged depth integrated potential vorticity. For a coarse resolution model, Holloway (1992) simplified (3) by assuming that variations in topography are larger than variations of f and that the model grid is larger than $L = \left(\alpha_1/\alpha_2\right)^{1/2}$. He then expressed the maximum entropy equilibrium solution as

$$\psi^* = -f L^2 H \tag{5}$$

where H is the total depth. For more details, the reader is referred to Holloway (1992).

One may question the applicability of such a theory to forced solutions. A number of experiments have been performed with forcing and dissipation to study the relevance of the inertial equilibrium states to forced solutions. In these experiments, Fofonoff flows, despite the presence of forcing, appear to be representative of the

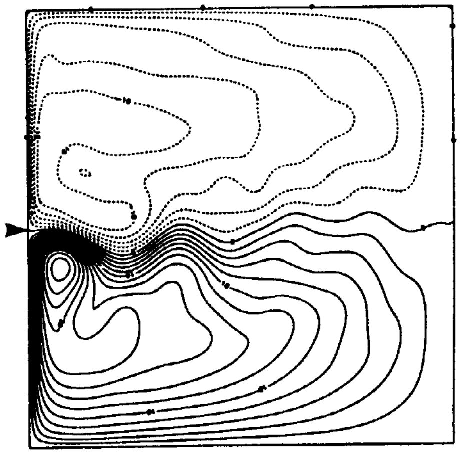

Figure 5. 5-year time average upper-layer streamfunction (in Sverdrups) for the flat-bottom experiment.

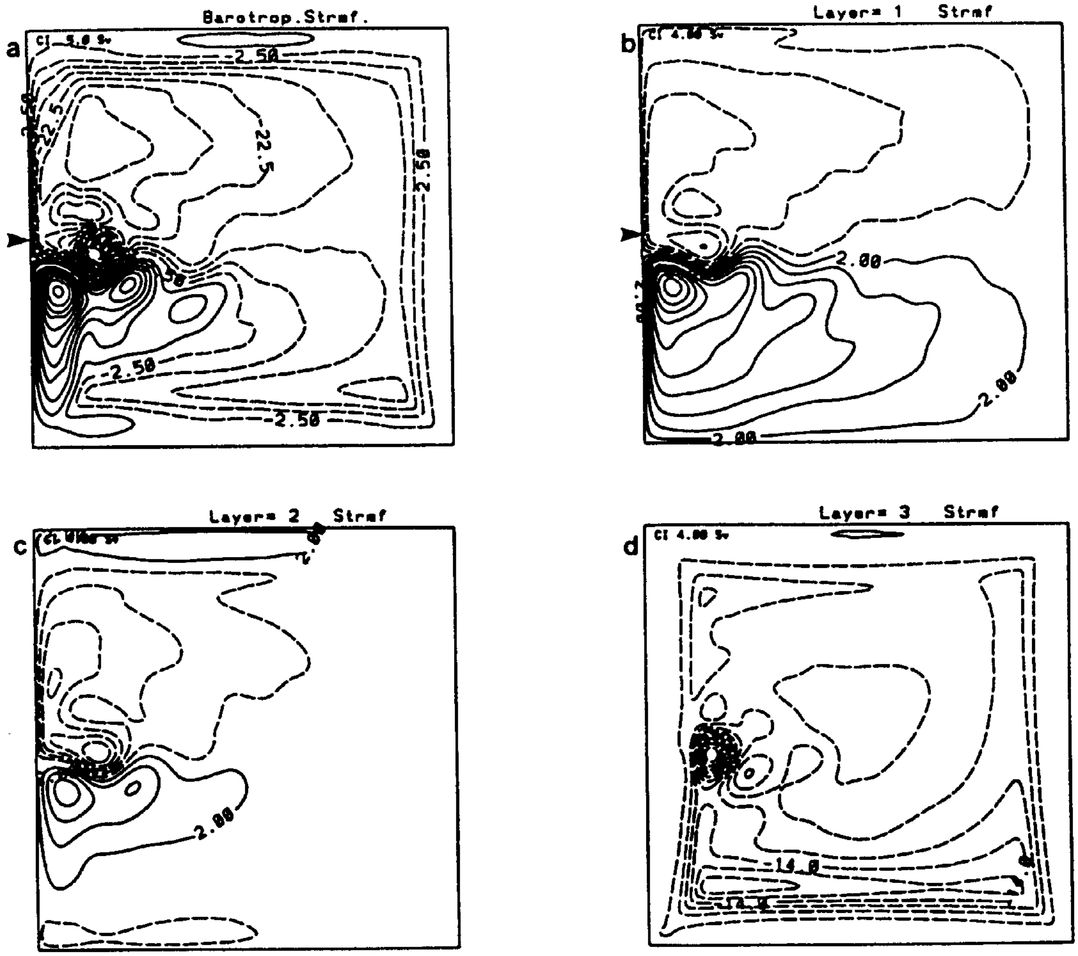

Figure 6. 5-year time average layer streamfunctions (in Sverdrups) for the strong slope experiment S1 (grid spacing 20 km).

tendency of the nonlinearity, and the actual shape of the forced solutions depends upon the competition between this tendency and the effects of the forcing (e.g., Griffa and Salmon, 1989; Cummins, 1992, Griffa and Castellari, 1991). These experiments were performed with a quasi-geostrophic model. Recently, Griffa et al. (1995) also showed that, despite the fact that the theory was developed for quasi-geostrophic motions, statistical mechanics theory is able to capture the main aspects of the inertial equilibrium states which are outside the range of validity of quasi-geostrophy.

Introduction of dissipation in a series of one-layer "initial release" experiments similar to the ones discussed in Griffa *et al.* (1995) does modify the $\langle\psi\rangle$-$\langle q\rangle$ scatter plot from a linear relationship to one with a small curvature and a smaller ratio of the Lagrange multipliers α_1/α_2 (Roubicek, 1995). In the high resolution wind-driven experiments (W1 and S1) introduced in the previous section, only the bottom layer can be considered as a random collection of eddies generated by fluctutions in the uppermost layer. While the forcing is continuous, these eddies tend to organize themselves as Fofonoff flows as illustrated by Figures 2d and 7d. The corresponding $\langle\psi\rangle$-$\langle q\rangle$ scatter plot (not shown) is in qualitative agreement with the dissipative "initial release" experiments, especially for the strong slope experiment S1 (Roubicek, 1995).

These results illustrate the possible relevance of statistical mechanics theory to wind-driven dissipative solutions. For practical applications, L is difficult to determine (Eby and Holloway, 1994) and can be obtained from the $\langle\psi\rangle$-$\langle q\rangle$ scatter plot only for idealized cases. In the remainder of this paper, L was chosen as a constant 15 km based on "initial release" experiments of Rossby number equivalent to the wind-driven experiments (Roubicek, 1995). The simplified maximum entropy solutions ψ^* (Equation 5) corresponding to the sloping topography is displayed in Figure 9. The subgrid scale parameterization proposed by Holloway (1992) relaxes the barotropic velocity field in the absence of forcing toward $\mathbf{v}^*$:

$$u^* = -\frac{1}{H}\frac{\partial\psi}{\partial y};\; v^* = \frac{1}{H}\frac{\partial\psi}{\partial x} \tag{6}$$

by modifying the operator $\mathbf{F}$ as $\mathbf{F} = A\frac{1}{h}\nabla\left(h\nabla(\mathbf{v}-\mathbf{v}^*)\right)$.

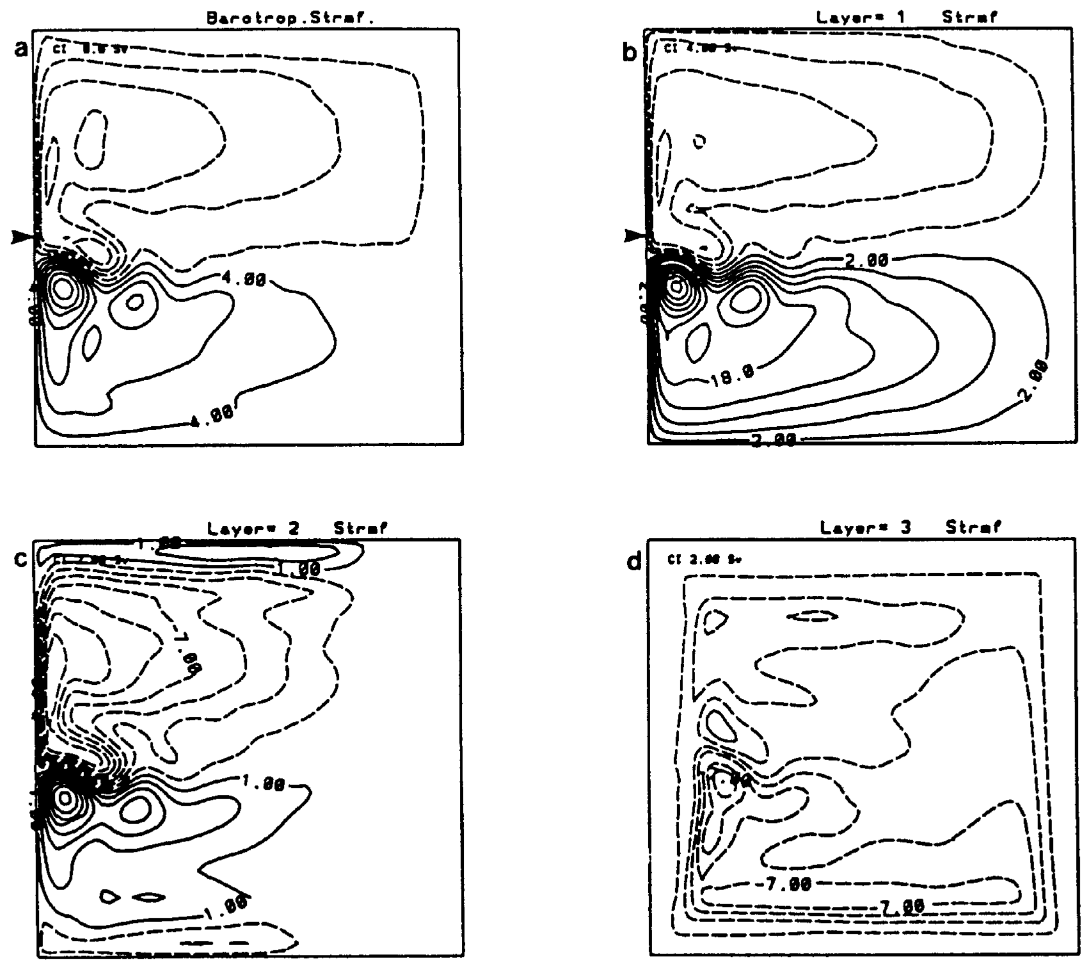

Figure 7. As in Figure 6, for experiment S2 (grid spacing 40 km).

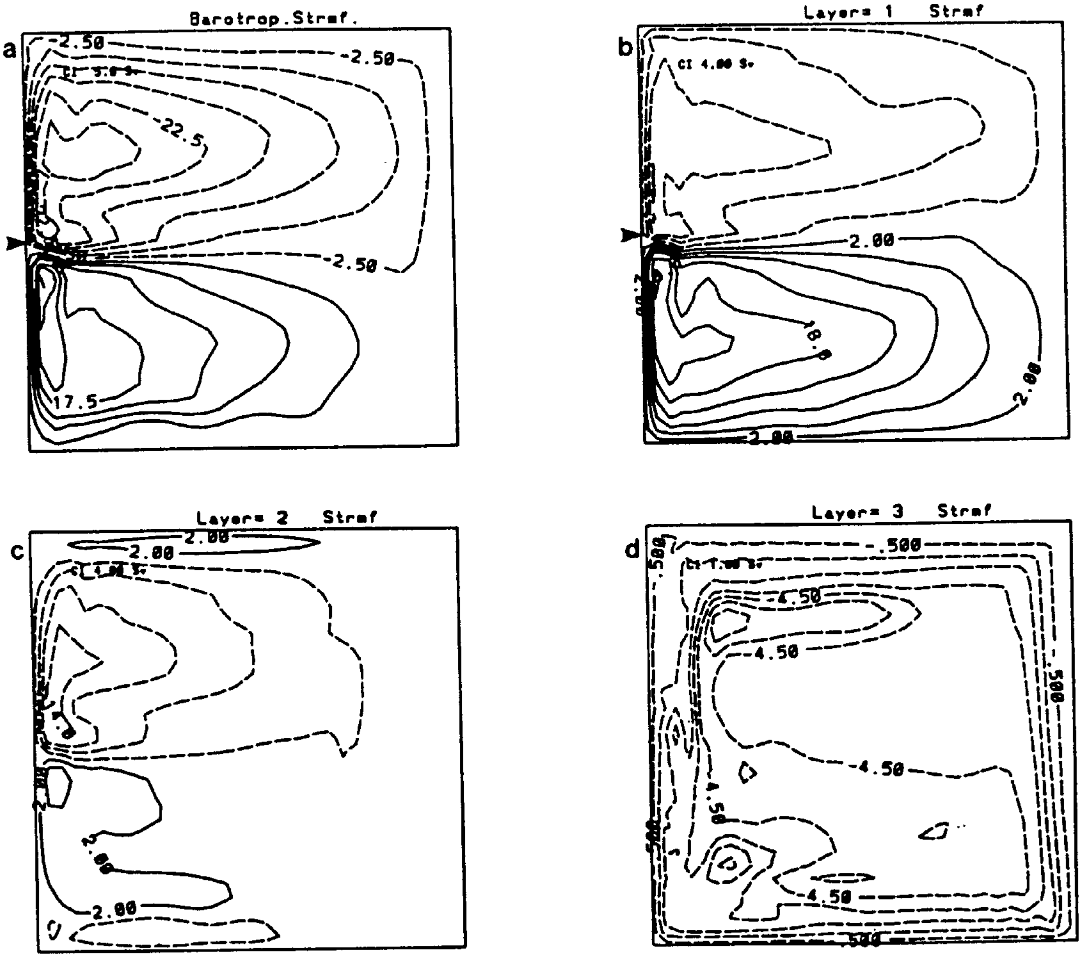

Figure 8. As in Figure 6, for experiment S3 (grid spacing 80 km).

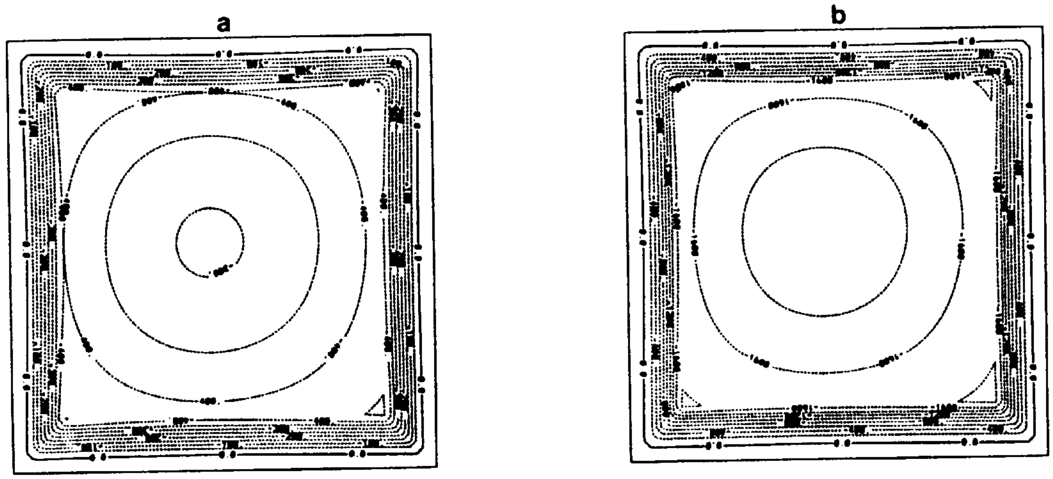

Figure 9. Transport streamfunction ψ^* (in Sverdrups) (a) for the weak slope experiment and (b) for the strong slope experiment.

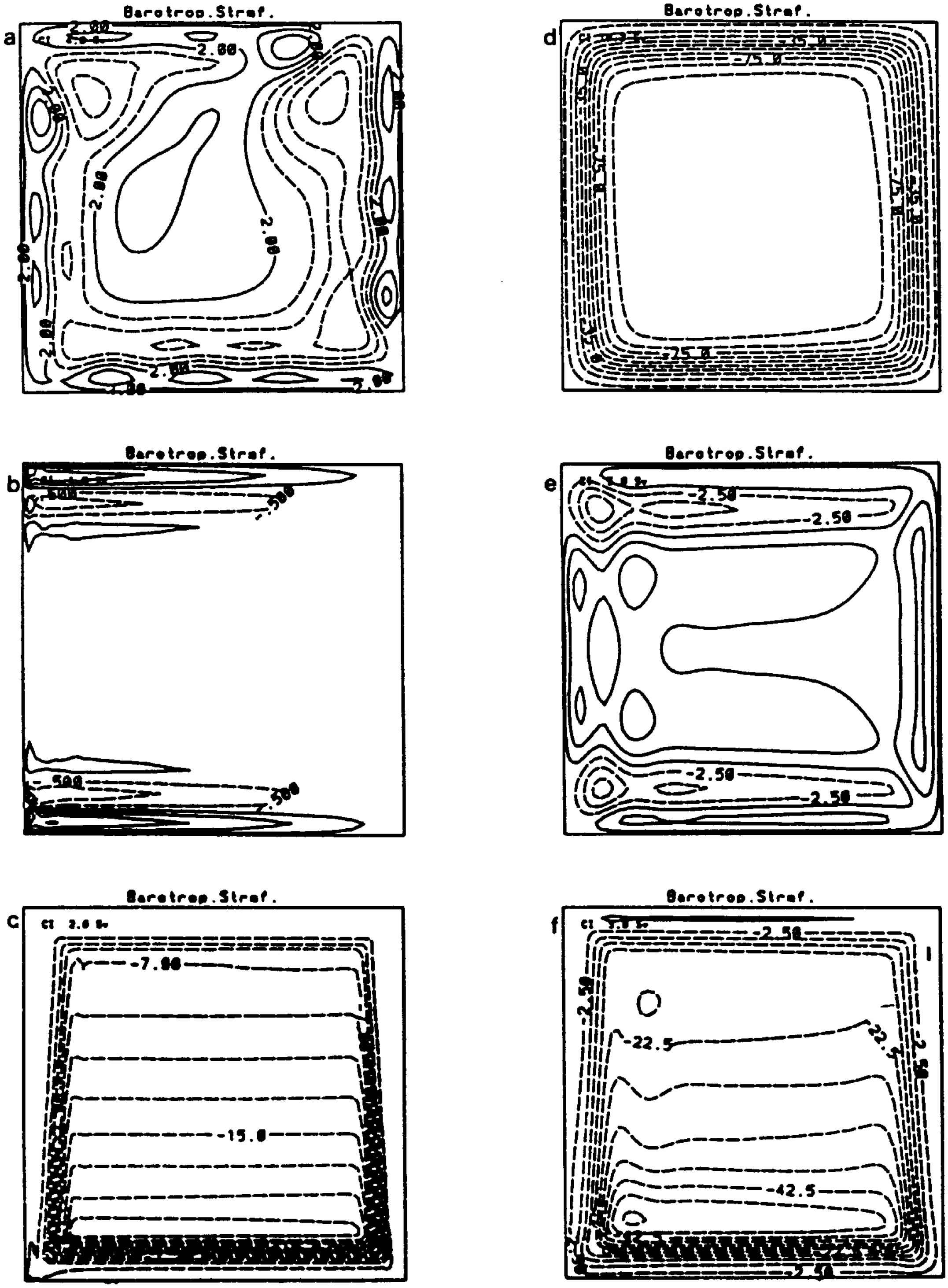

Figure 10. End-state barotropic streamfunctions (in Sverdrups) with the subgrid scale parameterization alone for the weak slope experiments, as described in the text.

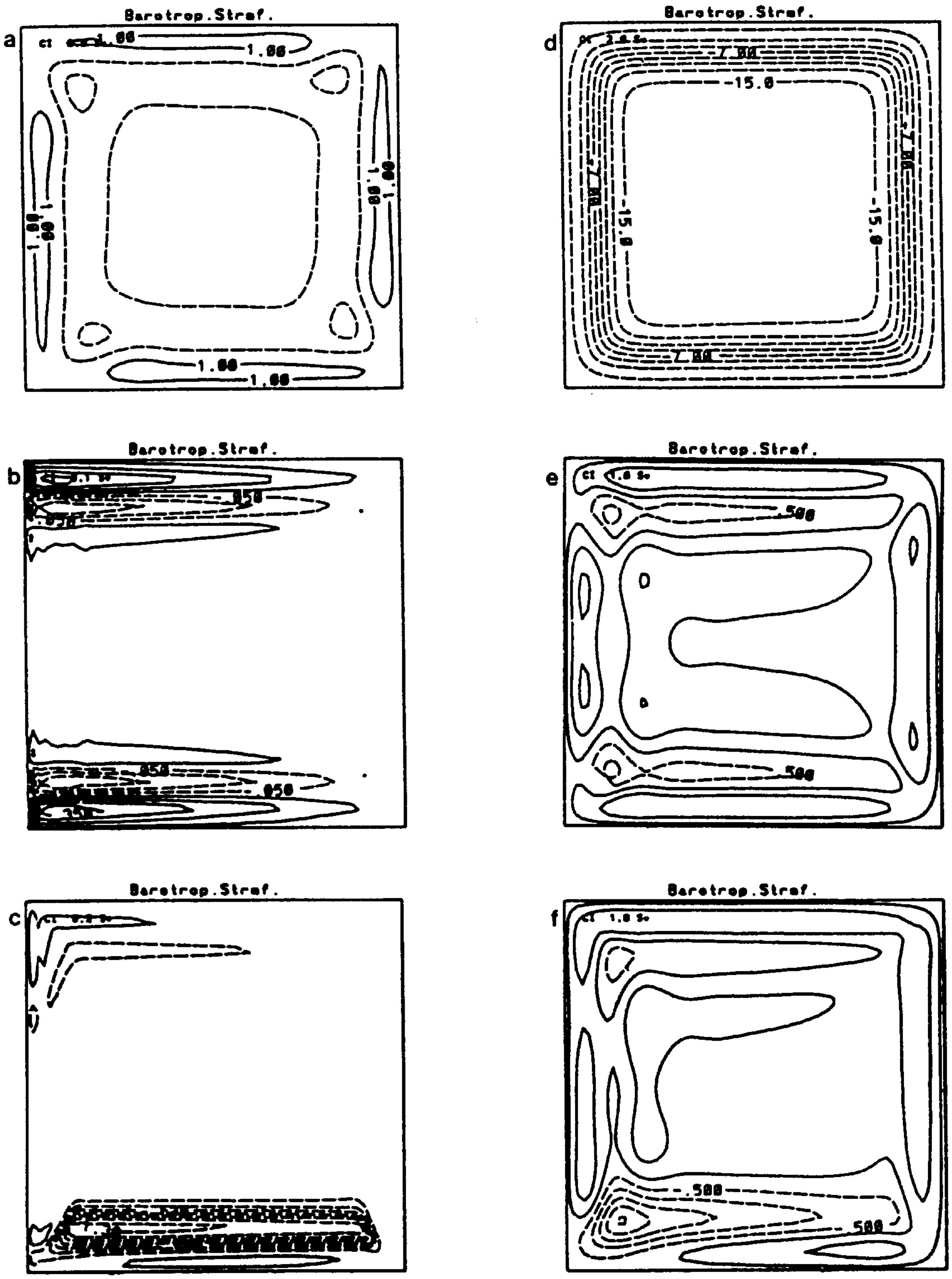

Figure 11. As in Figure 10, for the strong slope experiments.

The effectiveness of this relaxation is dependent upon the magnitude of the eddy viscosity coefficient A .

It is of interest to first investigate this relaxation mechanism in the absence of wind forcing, since both the β-effect and topography play a significant role in the adjustment, whereas only the topography effects are captured by the parameterization. Figures 10 and 11 show the end state barotropic streamfunctions resulting from the integration of (1) with zero forcing and with the sub-grid scale parameterization, for the experiments with weak and strong topography respectively. The adjustment is relatively fast, but the final kinetic energy level varies greatly as a function of the eddy viscosity coefficient (Roubicek, 1995). The left panels in Figures 10 and 11 are for experiments with A = 80 m^2s^{-1}, and the right panels for experiments with A = 8000 m^2s^{-1}. From top to bottom, the figures correspond to experiments that were run on an f-plane with no topography, on a β-plane without topography, and on a β-plane with topography.

On the f-plane, the flow for the low viscosity experiments (Figures 10a, 11a) does not have a strong organized cyclonic circulation when compared to the high viscosity cases (Figures 10d, 11d) and to the maximum entropy fields (Figure 9). On the β-plane, this flow is modified into zonal bands of cyclonic and anticyclonic cells (Figures 10b,e and 11b,e). Topography, when present, strongly traps the flows to a cyclonic circulation dictated by the f/H contours (Figures 10c,f and 11c,f). While the subgrid scale parameterization appears to be relatively effective in these experiments, especially for strong topography, the combination of the β-effect and topography can lead to a resulting field different from the maximum entropy solution.

5.2 Impact on Mid-Latitude Jet Separation

The subgrid scale parameterization was applied to the coarse resolution wind-driven experiments of section 4. The 5-year time-averaged streamfunctions for both the weak and the strong slope experiments (W4 and S4, respectively) are displayed in Figures 12 and 13.

When compared to the experiments without the parameterization, the differences are small for the weak slope case (W4). The parameterization has little impact on the circulation of the uppermost layer and the jet separation latitude remains at the ZWCL. The only visible signature is in the bottom layer where the topographically

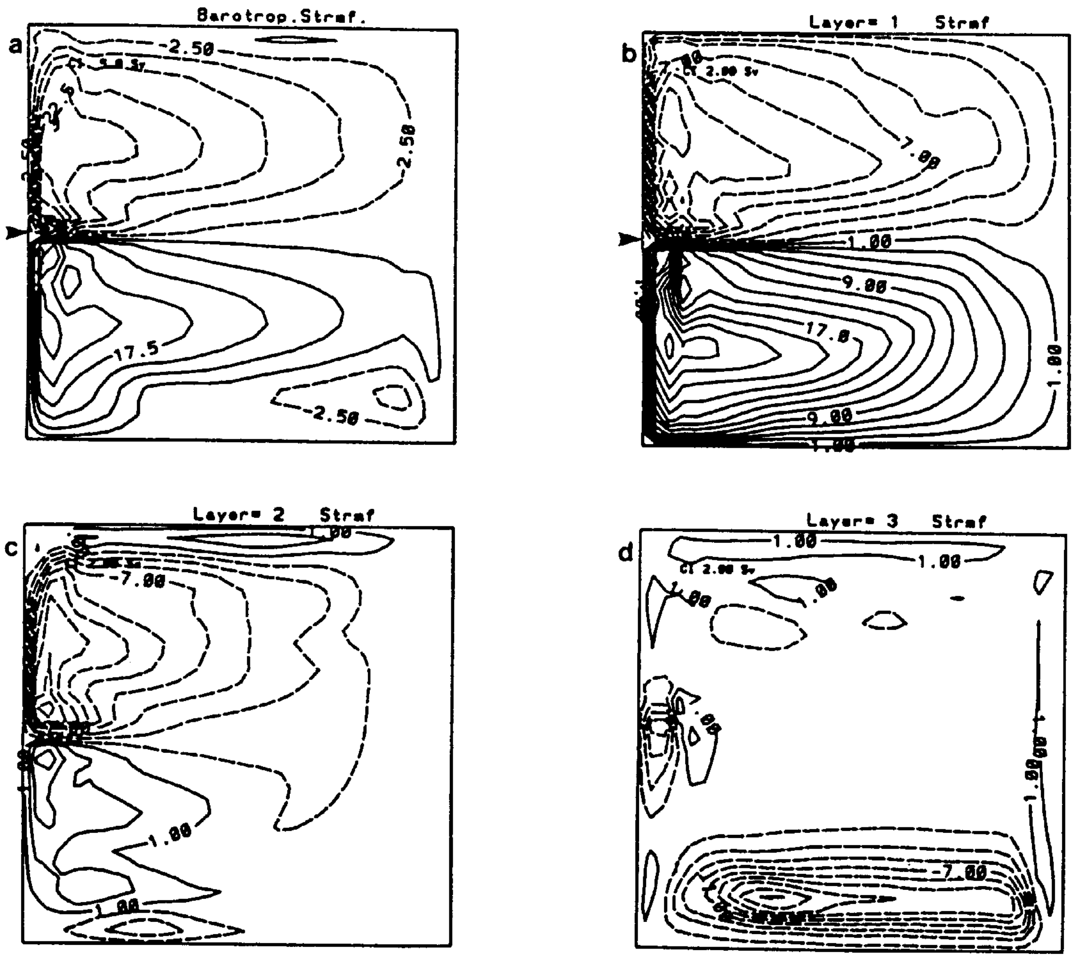

Figure 12. 5-year time average streamfunctions (in Sverdrups) for the weak slope experiment W4.

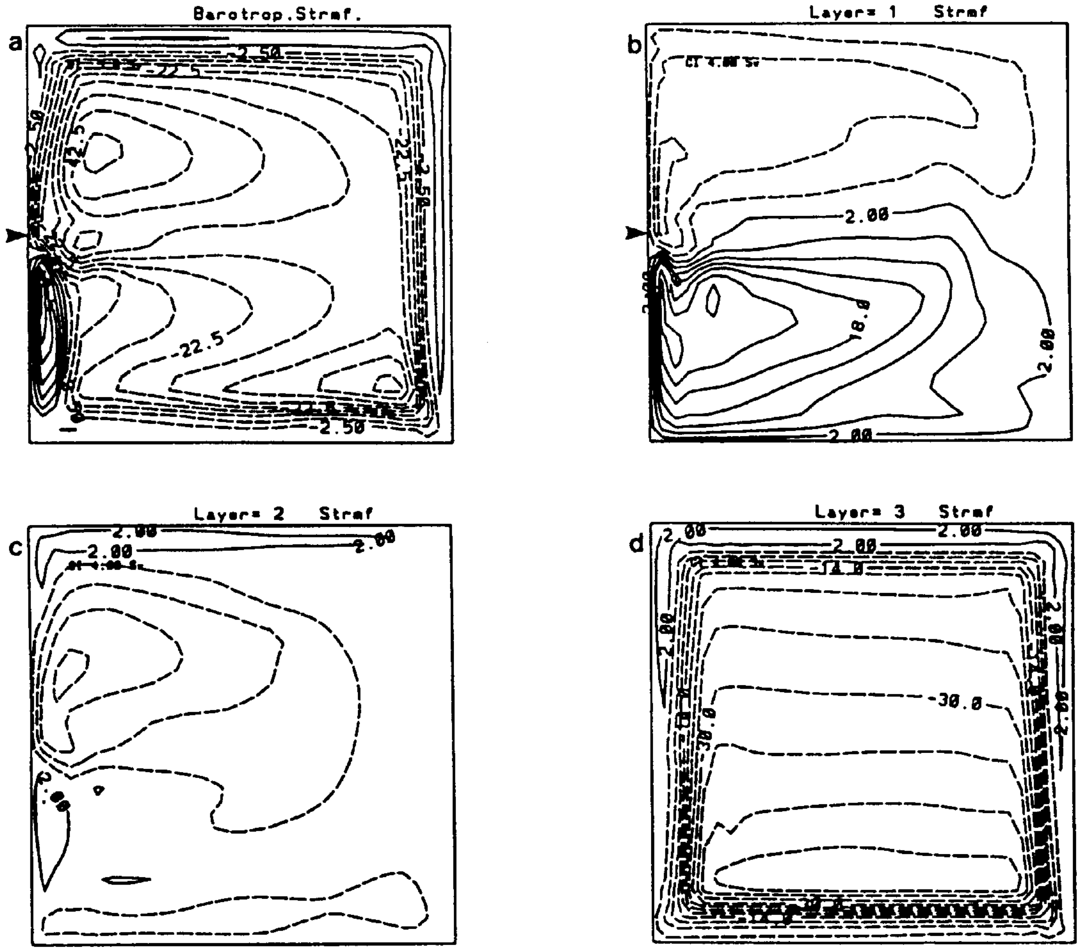

Figure 13. 5-year time average streamfunctions (in Sverdrups) for the strong slope experiment S4.

trapped cyclonic circulation is increased by about 10 Sverdrups (Figure 12d). The effect is more vigorous in the strong slope case (S4) where the signature of the parameterization is present in all layers (Figure 13).

In S4, several features characteristic of the high resolution experiment S1, not observed in the coarser resolution experiment S3, are now present. The mid-latitude jet separates from the coast at a point further to the south and penetrates the interior in a less zonal fashion than in S3. In the bottom layer, the circulation is intense, considerably stronger than in S1, and dominates the barotropic flow.

6. Summary and Concluding Remarks

Implementation of the "Neptune" parameterization in idealized wind-driven experiments with topography led to mixed results. On one hand, in cases with weak topography, the signature of the parameterization is very small and has very little impact on the upper layer circulation and the jet separation latitude. On the other hand, strong topography leads to a stronger parameterized maximum entropy flow and its signature is visible in all layers. The mid-latitude jet indeed separates at a more southern latitude, but the strong cyclonic circulation induced by the parameterization is predominant in the barotropic circulation and much more intense than in the fine resolution case. While it is apparent that such a parameterization is desirable in coarse-resolution experiments, its implementation is not straight forward. The experiments presented in this paper indicate that the value chosen for L may be a function of the chosen topography as one may wish for stronger (weaker) parameterization for weak (strong) topography. As stated by Eby and Holloway (1994), oustanding issues still include the physical basis for the estimation of L and the appropriateness of the operator **F**.

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