Dynamical Constraints for the Analysis of Sea Level Pressure and Surface Wind Over the World Ocean

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Introduction

In the study of climate and its variability the interaction between the atmosphere and ocean is of particular interest due to the time scales it entails. Fortunately, one of the most comprehensive sources of data for climate research is that of marine observations collected over more than a century by ocean-going vessels, mostly through a voluntary effort of mariners under the guidance of different national weather services. The archive of these reports, which is known as COADS (Woodruff et al., 1987), has been extremely useful to climate research. Of the variables observed routinely over the oceans, sea level pressure and surface wind are important for determining the forcing of the ocean by the atmosphere and for monitoring ocean-atmosphere interaction. Evidence to their importance in the study of climate variability can be found in numerous diagnostic studies early and more recent (e.g., Namias, 1965; Namias and Cayan, 1981; Wallace and Jiang, 1987; Cayan, 1992a, b; Deser, 1993; Kushnir, 1994). Many modeling studies have used these variables to determine the necessary forcing fields and evaluate the model performance.

The present study is part of our effort to construct a dynamically constrained statistical analysis of the monthly averaged sea level pressure (SLP) and surface wind fields of COADS. Such an analysis enables the minimization of the errors involved in the monthly averaged ship reports. It also provides a controlled way to interpolate and extrapolate data in regions of missing information. This paper outlines the methodology of the analysis and the construction of a simplified momentum balance for the oceanic boundary layer to be applied in the course of analysis.

Methodology

The goal of our analysis project has been to construct a monthly time history of the SLP and surface wind fields over the world ocean from the turn of the century to the present. Our analysis does not compete with the operational products coming from numerical weather prediction centers with their state-of-the-art assimilation techniques, but rather enables the handling of the early part of the data record before the advent of comprehensive upper level and satellite data. Thus we have planned to achieve our goal by using the 2° monthly summaries in COADS and linear statistical techniques. The proposed analysis procedure will enable filling up some gaps in the record and more importantly minimize the errors in the representation of monthly averages in COADS (for a comprehensive discussion of the sources of such errors, see Trenberth et al., 1992).

The statistical analysis procedure we wish to apply to the 2° monthly summaries in COADS is based on the variational approach first outlined by Sasaki (1970). The analysis involves the minimization of a "cost function" S that is a function of the analyzed field a(x,t) (x being the location in space and t is time). Thus the analysis is a solution to the condition:

$$\frac{\delta S(a)}{\delta a} = 0 \qquad (1)$$

In Sasaki's original work the cost function included the constraint that while the analysis stays close to observations (hereafter denoted as o), its variables also obey a dynamic relationship. The degree of constraining the analyzed variables can be varied from the requirement that they obey the dynamic relationship exactly (so-called a "strongly constrained" analysis), or just in a general sense (a "weakly constrained" analysis). Schematically the cost function for a weakly constrained analysis can be written as:

$$S = \frac{1}{2}\left\{ (o - Ta)' E_{o}^{-1} (o - TA) + (Ma)' E_{m}^{-1} (Ma) + Sc \right\} \qquad (2)$$

where ' denotes a transpose operation, T is a transformation matrix that interpolates the analyzed field to the observation point, and M is a matrix representing the dynamic constraints, i.e., a model written as:

$$Ma = 0 \qquad (3)$$

(Note that we have assumed that both the transformation T and the dynamic model are linear.) The matrices E_o, E_m are the error covariance matrices associated with the observations and dynamic model, respectively. In the strong constraint problem the error covariance matrix E_m is replaced by a Lagrangian multiplier that is determined in the minimization process. The quantity SC symbolizes a statistical constraint applied to the analysis (such as a requirement that the large scale structure of the variability is close to its long-term statistical properties). This constraint helps fill gaps in the record provided we have information on the behavior of the data covariance matrix there.

An initial attempt to assess the feasibility of such approach was presented by us in the previous COADS Workshop (Kushnir et al., 1992). That pilot study focused on a tropical Pacific data set that was spatially complete and temporally continuous. In that study we used the linear momentum balance of Zebiak (1990) to constrain the data. This constraints entail a linear balance between the pressure gradient force, the coriolis force, and friction. Symbolically this balance can be written as:

$$f k x V_s = -\rho^{-1} \nabla p + F \qquad (4)$$

where friction F is parameterized as proportional to the wind vector (“Rayleigh” friction):

$$F = -\varepsilon V_s \quad (5)$$

Here V_s is the surface wind vector, p is sea level pressure, ε is the Rayleigh friction coefficient, *f* is the coriolis factor, and ρ is the surface air density. When performing the analysis wind and pressure deviations from climatology were considered, and ρ was taken from climatology. Extending the pilot study outside of the tropical Pacific requires the reassessment of the simple, linear momentum balance (1). This discussion is concerned mainly with this issue.

To determine the feasibility of a linear momentum balance in constraining the wind and SLP fields two data sets were utilized:

- A monthly averaged, global 1000 mb ECMWF analysis (uninitialized) from 1980 to 1989. This data set includes the geopotential height, air temperature and winds (vector averaged and scalar averaged) on a 2.5° grid resolution.
- A 43-year integration of the NOAA/GFDL general circulation model with SST specified from observations 1946-1988. This data set included the 990 mb geopotential height, winds and temperature. In addition and as will be explained later, we included the 940 mb level wind (second model level from the surface). This data set has a resolution of 7.5° in longitude and ~4.25° in latitude.

In using these data the pressure gradient term in (4) was replaced by the geopotential gradient. Aside from that we have also made a comparable estimate with the more noisy and gappy COADS SLP and winds to assure that the results obtained for the above two data sets are in general agreement with COADS.

Determining the Parameters of Linear Dynamical Constraints

The issue of the agreement of observed pressure and wind data with the linear momentum balance has been addressed in several previous studies (Zebiak, 1990; Allen and Davey, 1993; Deser, 1993). In these studies attempts were made to asses the error in the balance when applied to tropical Pacific winds and/or to determine the free parameter in the balance, i.e., the Rayleigh friction coefficient ε. Results from these studies were quite satisfactory in statistical terms, i.e., in the statistical sense the monthly mean circulation in the tropics agrees with the balance. In the present study we extended the approach to the entire world ocean (excluding high latitude areas that are generally covered by sea ice) in an effort to determine the optimal value for ε.

The problem of finding the Rayleigh friction coefficient is of regressing the net geostrophic balance on the wind vector. Deser (1993) showed that if the regression is performed in the zonal and meridional directions separately, using the *climatological* values for surface winds and SLP, the coefficient of the zonal momentum balance differs significantly from that of the meridional momentum balance. Deser further argued that this difference is the result of the vertical structure of the wind vector in the planetary boundary layer (PBL) and the fact that the simple linear balance {(4), (5)1 fails to represent the friction vector correctly as the vertical derivative of the wind stress.

Applying the same approach to the *anomalous* winds and 1000 mb height values from the ECMWF analysis we find that the difference in the Rayleigh parameters of the zonal and meridional balances holds for all latitude belts (Fig. la). Moreover the friction parameter displays a distinct latitudinal structure. This behavior is emulated also by the GFDL model (Fig. 1b, where the model monthly mean frictional force is taken from its history files and regressed against the model 990 mb vector wind). Note that the GCM parametrizes the friction as the vertical derivative of wind stress, the latter assumed to be proportional to the vertical wind shear i.e.,

$$F = \frac{\partial}{\partial z}\left(K\frac{\delta V}{\delta z}\right) \qquad (6)$$

where *K* is a stability dependent eddy viscosity coefficient (see Gordon and Stem, 1982).

The availability of GCM data allows us to examine more carefully the directional dependence of ε., or more precisely, the effect of a more careful parameterization of friction in terms of wind. Using low level (~990 mb) model wind V_s and the wind at the next level above the ground (~940 mb) V_u we can write the following approximation to the friction vector F in (4):

$$F = -\varepsilon_1 V_s + \varepsilon_2 (V_u - V_s) \qquad (7)$$

This formulation assumes that the stress at the surface is proportional to the low I.evel wind and the stress at the top of the lowest model layer is proportional to the difference between the wind vectors at the two levels. Using this formulation and regressing the monthly mean model friction separately on the x and y components of the monthly average total wind vector we obtain similar values for the values of ε_1, and ε_2 (Fig. 2). These results confirm the explanation offered by Deser (1993). Their application to the problem of analyzing surface winds and SLP from COADS is however not straight forward since we do not have observations of the wind above the surface layer.

The latitudinal dependence of E could be attributed to at least two factors:

- Changes in the vertical structure of the PBL with latitude (e.g., PBL depth that is implicit in the coefficients both in (5) and (7)).
- The non linearity in the surface stress usually expressed in terms of a drag coefficient parameterization:

where w_s is the surface wind speed.

$$\vec{\tau}_s = \rho C_D w_s V_s \qquad (8)$$

It is possible to address the latter factor in the context of our linear approach, by substituting the instantaneous value of w_s by its climatological value $\overline{w}_s$. This approach was tested by regressing the geostrophic balance calculated from the ECMWF data against the value of $\overline{w}_s\mathbf{V}$ as a function of latitude (Fig. 3). Results show that the new regression coefficient stays much more constant with latitude than the one in the old formulation (Fig. la). The value of the new coefficient is still dependent on the direction, with the meridional balance coefficient about twice as large as the zonal balance coefficient. These new coefficient can also be used to parameterize the frictional force **F** by writing:

$$F = -\alpha \overline{w}_s V_s \quad (9)$$

remembering that different α's are used in the zonal and meridional directions, respectively.

Estimating the Errors in the Linear Constraints

Examination of the error in the linear balance can be done by substituting the ECMWF "observations" of wind and 1000 mb heights into the linear momentum balance, and calculating the residual. We have to remember however that the monthly means were calculated from uninitialized analyses and thus may still exhibit some data related errors. Figure 4 represents the rms error of the linear balance (4) with friction parameterized as in (5) using latitudinally and directionally dependent values for ε. The balance error increases with latitude and is largest north of ~50°N. A more revealing way of judging the quality of the balance is to examine the ratio between the rms residual of the frictional balance and that of the geostrophic balance. This is shown in Fig. 5 for two cases, one with a Rayleigh friction parameterization and the other with the so-called "drag coefficient" parameterization (9). In the latter case we used a globally fixed a with values of $1.9 \times l0^{-6}$ for the zonal balance and $3.l \times 10^{-6}$ for the meridional balance. Both methods for parameterizing friction offer an improved representation of the momentum balance in the extratropics. In the tropics the results are strongly sensitive to data errors (a 1 ms^{-1} error in wind speed could result from a small, ~0.4 m error in geopotential height). This can be verified by comparing with a similar figure calculated from a fit to the GFDL model data (Fig. 6). Here the tropics do not stand out as very different form the rest of the globe.

Summary and Additional Considerations

The feasibility of using a linear momentum balance to constrain sea level pressure and wind in a variational analysis procedure was assessed by fitting the balance equations to data. Adding linear drag to the geostrophic balance improves the constraints for SLP and winds by reducing the error. This is shown clearly with model data and only partly successfully with assimilated data. To better assess the applicability of these constraints one would have to compare the ECMWF data with the results of a full variational analysis according to (1). We are planning to take this approach in the near future.

The error fields calculated based on the data (Fig. 5) reveal a zonal asymmetry that could be attributed to other terms neglected in the linear model. In particular, effects of stability in the PBL, as well as the effect of transient motions, were not included. Including these effects in a linear model is another level of complication that should be addressed in future research.

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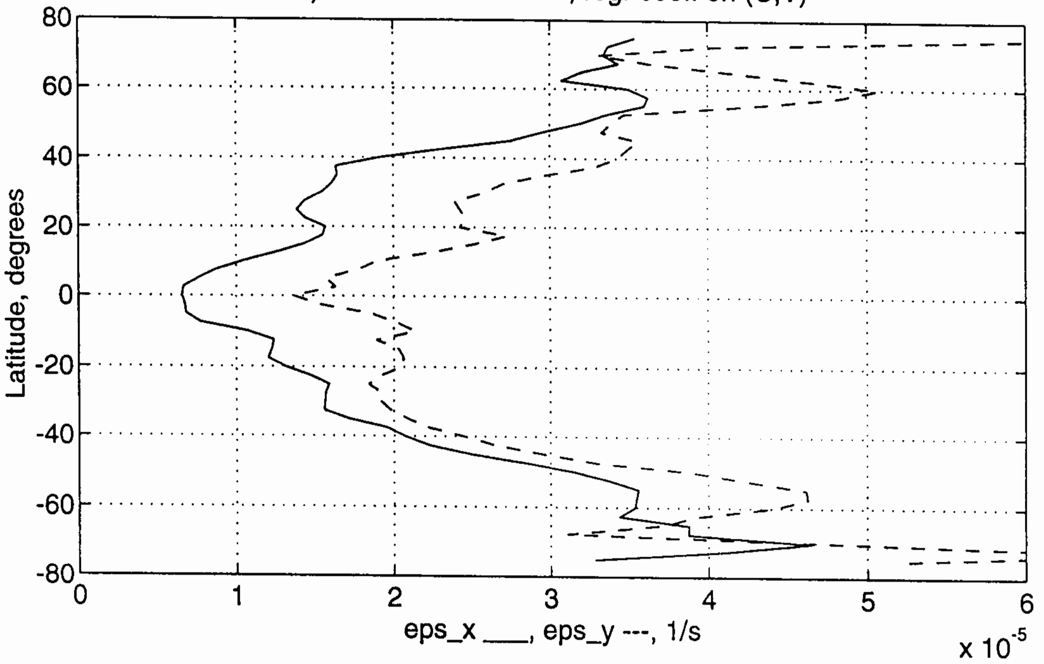
Figure 1: The regression coefficient between the geostrophic balance residual for anomalous 1000 mb height and wind values, and the anomalous wind vector over the world ocean, based on: a) ECMWF analysis using the months December, January, and February from 1980 to 1989. b) GFDL GCM using the same month but for a 33-year interval. Regression is performed separately for the zonal balance (solid curve) and the meridional balance (dashed curve). Units are in 10^{-5} sec^{-1}.

a). ECMWF DJF anom, regr coeff on (U,V)



b). GFDL GCM DJF anom, regr coeff on (U,V)

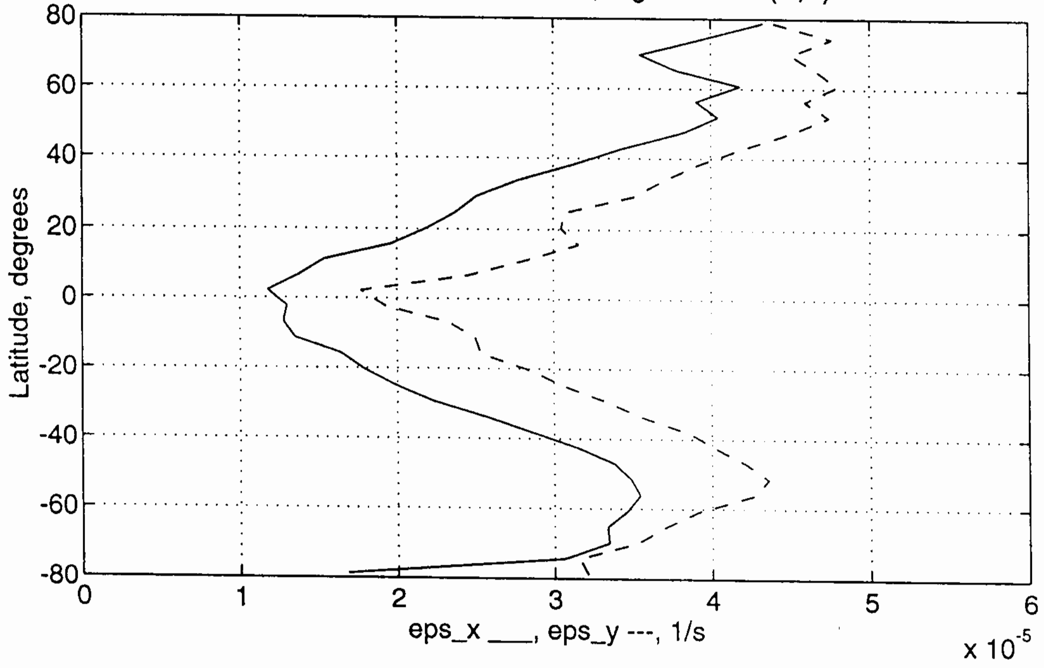


Figure 2: The result of a regression calculation meant to determine the x- and y-direction coefficients ε_1 and ε_2 (see equation (7) in text) using GFDL GCM data. Solid and dashed lines are for ε_1 in the x- and y-direction respectively. Dash-dotted line and dotted line are ε_2 in the x- and y-direction respectively. Units are in 10^{-5} $\sec^{-1}$.

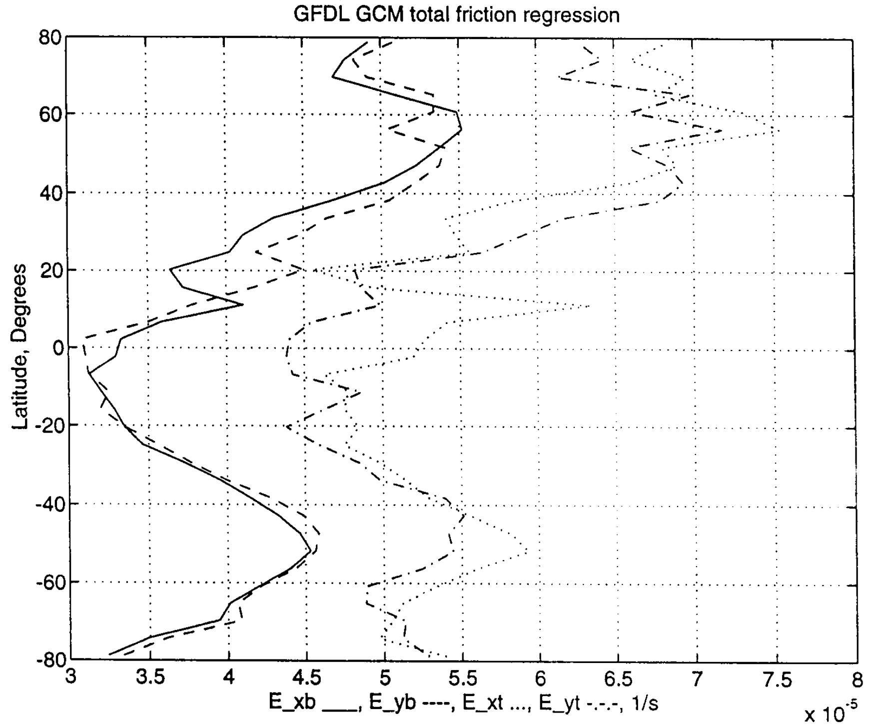


Figure 3: Results of a regression analysis to determine the coefficient α in equation (9) using ECMWF wind and 1000 mb height anomalies as well as the corresponding climatological wind speed for December-February. Solid line is for the x-direction coefficient and dashed line for the y-direction coefficient. Units are in 10^{-6} $\sec^{-1}$.

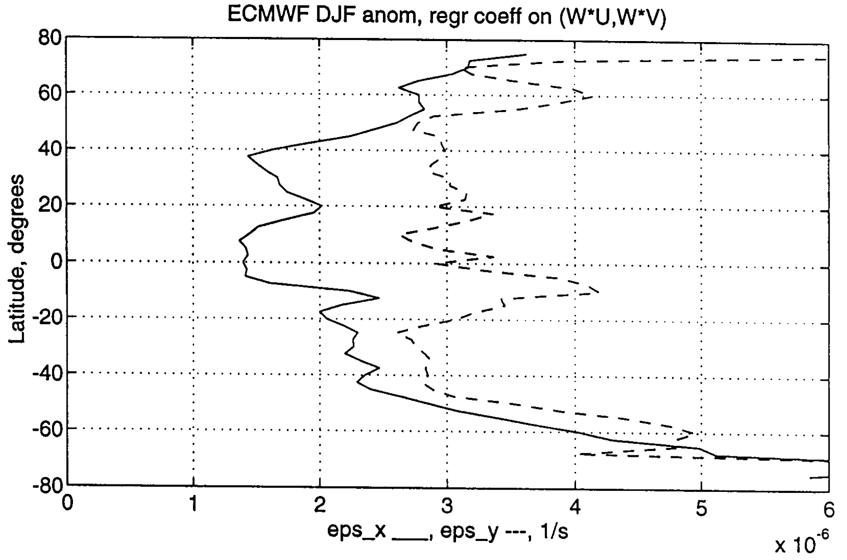


Figure 4: Absolute rms error in the linear frictional balance for anomalous ECMWF wind and 1000 mb height values, and directionally and latitudinally-dependent Rayleigh coefficients. Units are in 10^{-5} sec^{-2}.

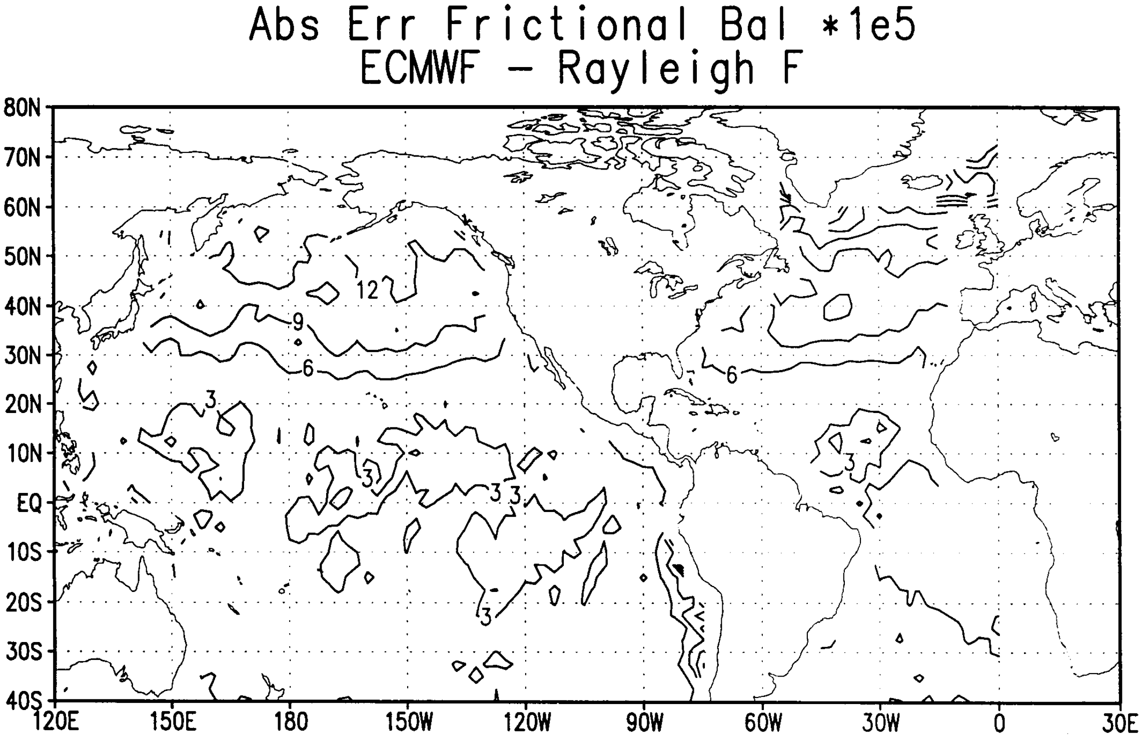


Figure 5: Ratio between error in the linear frictional balance and the geostrophic balance for anomalous ECMWF wind and 1000 mb height values using a) directionally and latitudinally dependent Rayleigh coefficients. b) globally constant but directionally dependent "drag" coefficients. Regions where values are larger than 0.8 are shaded.

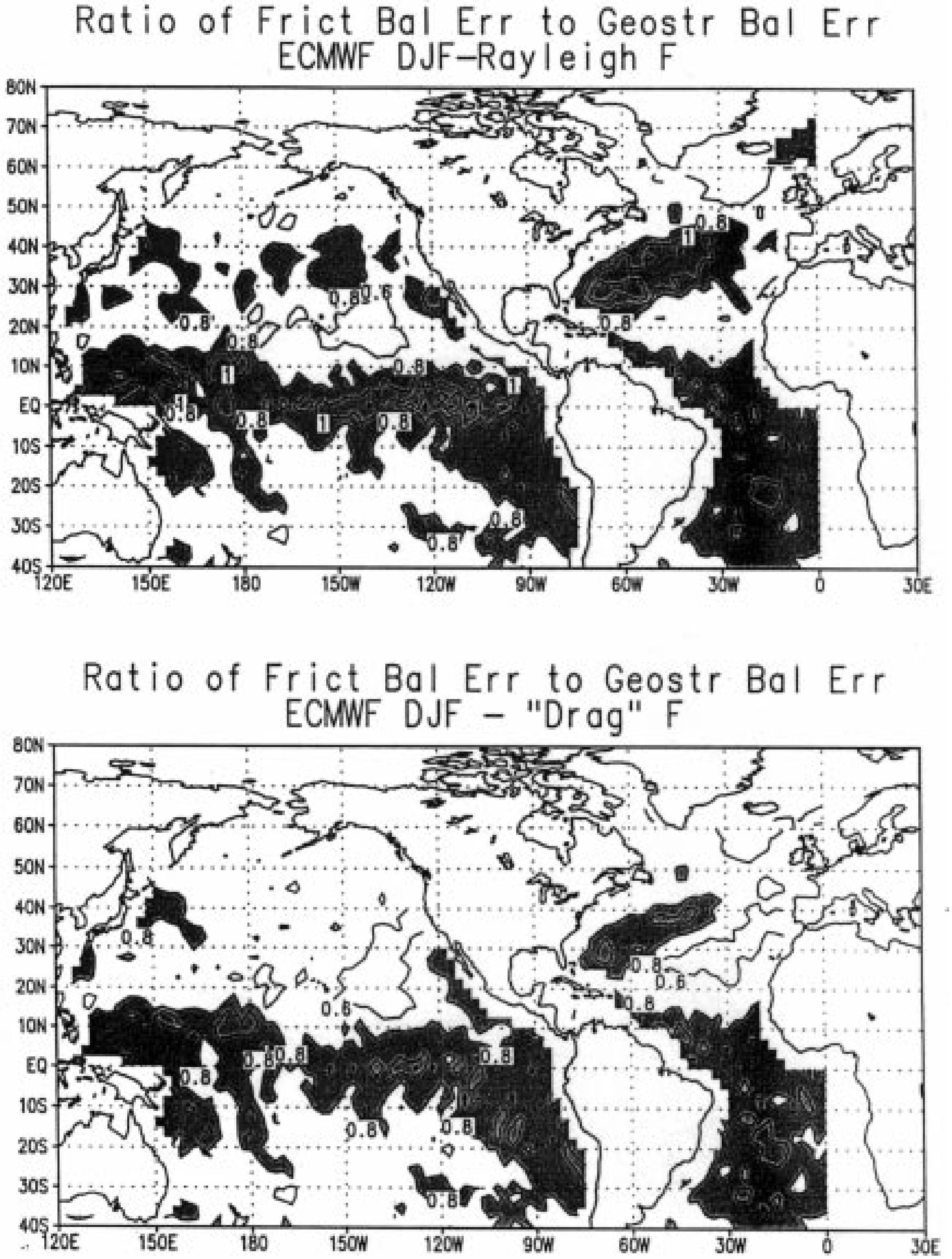


Figure 6: As in 5a but for the GFDL GCM data at the 990 mb level.