sitivity. Manabe and Wetherald (1967) have discussed this problem extensively in connection with a very large value of sensitivity published by Möller (1963).

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# Reply

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We agree completely with Dr. Watts' comments. He has correctly pointed out the need for a nonconstant, net-sensible and net-latent heat term ($L$) in our model (Bryson and Dittberner, 1976). In calculating the sensitivity of hemispheric mean surface temperature to changing atmospheric carbon dioxide concentration, it is thought that by accounting for feedback between surface temperature and net-sensible and latent heat fluxes, more meaningful results would occur. We agree with this goal, but there still appears to be some uncertainty regarding the form of parameterization. In lieu of attacking the problem of $L$ variation we turned instead to the question of $CO_2$ parameterization in the original model. In later work the original formulation of $CO_2$ emissivity ($e_c$) was replaced by one in which model temperature sensitivity to $CO_2$ concentration was forced to be equal to that derived from Table 5 of Manabe and Wetherald (1967), that is, ±0.03 K for a 1% change in the $CO_2$. This equation is

$$e_c = 0.01 \ln(CO_2) + 0.13,$$

where "$CO_2$" is the concentration of atmospheric $CO_2$ in parts per million by volume (ppmv). This expression, plus other modifications (such as allowing tropospheric aerosols to absorb and re-radiate in the longwave part of the spectrum; and including ice and snow in addition to land and sea in the thermal heat capacity) are described in Dittberner (1978). Using this model, a reconstruction of Northern Hemisphere mean surface temperature shows what appears to be only slight changes compared to the original model.

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The second item identified by Dr. Watts is parameterization of the emissivity of water vapor. As he correctly points out, feedback between the effect of water vapor emissivity and surface temperature may be important. This point was the subject of a thorough study by Redmond (1977). He related the emissivity of water vapor, as used in the model, to climatological, latitude-dependent soundings of temperature and moisture. His results merit careful consideration in future model work. They are used in our current models.

Dr. Watts' comments are directed toward things that should be done rather than what has been done. Indeed there are improvements possible in addition to those he suggests. Cloud amount and cloud altitude feedbacks represent an area of great uncertainty in climate models, including radiative-convective models (see Ramanathan and Coakley, 1978). Schneider *et al.* (1978) were among the first to address this problem quantitatively. Cloud amount is particularly important. For example, if the cloud amount is allowed to vary proportionally with the latent and sensible heat then the sensitivity to $CO_2$ may be negative, depending on the proportionality. Another item related to clouds is treatment by the model of cloud base temperature ($T_c$). Instead of setting $T_c$ a fixed amount cooler than surface temperature, it would be more realistic to represent $T_c$ in terms of lapse rate and cloud base height.

Potential reduction of uncertainty in use of the model could be attained by using a more accurate estimate of beam radiation in deriving some model parameters. Goodman (1977), using virtually all original measurements, reconstructed the historical series of beam radiation received at the surface in the Northern Hemisphere from 1883 to 1976. Goodman presents evidence supporting the hypothesis that these new values are perhaps more meaningful than previously published results.

There are many areas of uncertainty remaining in the Bryson-Dittberner model. These include means to improve the parameterization of the effects of external factors such as solar variation, anthropogenic factors and volcanic influences, inclusion of more feedback mechanisms such as between albedo and temperature, latent heat and cloudiness, and cross-equatorial heat transport, other anthropogenic heat input, etc. It is our hope that further thoughtful consideration of these problems will lead to improvements in realistic, physically-based climate models. We cannot have much confidence in modeled future climates unless the model realistically simulates the past.

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# Global-Scale Disturbances and Dynamic Similarity

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ABSTRACT

Terms in the linearized primitive equations for a generally baroclinic atmosphere are evaluated for their significance in maintaining balance for global-scale disturbances. For gravity waves, the linearized advection term $\mathbf{v}'\cdot\nabla$ reduces to the vertical component, but for Rossby waves, apparently both components are of primary order. Both wind shear terms are shown to be small for the Rossby case. As a by-product of the scaling developed, the traditional viscous and thermal diffusion terms are reduced to simple forms.

The disturbance energy equation is developed for the general basic state, and the influence that the approximations have on its balance is evaluated.

## 1. Introduction

A number of earlier papers have examined the relative importance of terms in the primitive equations for large-scale atmospheric flow. Charney (1948) addressed flows of moderately large dimension, where the ratio of the horizontal scale $L$ to the planetary radius $a$ was small [termed type I motions by Phillips (1963)]. Burger (1958) considered motions of planetary scale where $L/a$ is O(1) (type II motions). Dickinson (1968) discussed yet a third scaling appropriate to motions whose zonal dimension was of the same order as the planetary radius, but whose meridional scale was smaller than $a$. These studies focused on the nonlinear equations, and hence, the influence of basic state gradients on linear disturbances was not explicitly evaluated.

Because of the reduced meridional scales, Charney and Dickinson were able to consider the equations in $\beta$-plane geometry. In general, when this is not the case, spherical geometry plays an important role. Lindzen (1967) showed that much of this effect can be approximated by both an equatorial and a midlatitude $\beta$-plane, but that, in general, neither will suffice alone. Longuet-Higgins (1964) demonstrated that the simple two-dimensional Rossby solutions on a sphere tend to those on a $\beta$-plane in the limit of large total horizontal wavenumber. For global-scale modes, however, the error in going to the $\beta$-plane remains significant.

When the primitive equations are linearized about

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