.NOTES AND CORRESPONDENCE

Global Distribution of Vertically-Averaged Meridional Momentum Transport Statistics for January: A Comparison between Observations and General Circulation Model Simulations

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ABSTRACT

Vertically-averaged meridional transports of westerly momentum are analyzed in sampled ensembles of January simulations of an NCAR GCM and an equivalent ensemble of five years of observational January data according to a simple time-domain decomposition. Ensemble averages and standard deviations are compared in terms of both zonally-averaged and grid-point presentations for the steady and transient flux components highlighting the relative characteristics of the fundamental time-domain elements. Results from 5 and 2.5° horizontal resolution versions of the model demonstrate the impact of truncation error on model simulations of these flux statistics.

Comparing grid point measures constitutes a more stringent model performance evaluation since regional differences between observed and simulated transports often are found to be considerably larger than zonally-averaged differences. Such regional considerations also reveal substantial differences between model and observations in the location and orientation of transport maxima and minima. Typically the transient flux component is smaller in the model simulations than in the observations although there are some regional exceptions. The steady flux component, however, is generally larger in the model simulations (particularly the 2.5° version) than in the observations and is affected more than the transient component by resolution changes. Analysis of the estimated standard deviations of the flux components shows that the model's inherent variability is typically at least a factor of two lower than the observed interannual variability with substantial regional differences.

1. Introduction

The characteristics of large-scale momentum, heat and moisture transports (or fluxes) are fundamental descriptors of the atmospheric general circulation for understanding its mean state on a variety of time scales. The statistical analysis of such quantities has become a routine procedure for describing the observed climate and for verifying and analyzing simulations produced by a general circulation model (GCM).

In this paper an analysis of January mean momentum transports based on decomposition in the "time domain" is presented wherein the total flux is separated into steady and transient components. This approach offers important advantages for studying regional climate and for analyzing numerical model performance according to key physical processes. The presentation of the meridional flux of u-component momentum results serves to illustrate the implications of this type of analysis. Blackmon and Lau (1980) demonstrated the application of time-domain statistics to regional circulation studies for the Northern Hemisphere north of 20°N and included consideration of the transient eddy component for horizontal fluxes at specific pressure levels for a single seasonal model simulation.

The purpose of this study is to present a model verification analysis for flux statistics that extends previous work by 1) including both components for the time-domain viewpoint (steady and transient), 2) considering full global distributions and 3) examining second moments (i.e., standard deviations) of the statistics. Estimates of ensemble averages and standard deviations are obtained from multiple realizations (simulations) from a version of the GCM developed at the National Center for Atmospheric

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Research (NCAR) and a comparable verification data set is derived from five years of actual atmospheric observations. This approach provides a more complete description of the climate than that available from the analysis of only a single January realization (see Chervin, 1980). Vertically-averaged fluxes are presented which give a measure of atmospheric transports relevant to budget relationships for a vertical column, provide data compaction and reduce vertical sampling uncertainties. Speth (1976) used such vertical averaging in analysis for 1967–72 Northern Hemispheric observations. Results from two different horizontal resolution versions of the model demonstrate the impact of truncation error on model simulation of these flux statistics.

This study demonstrates the utility and implications of considering higher-order climate measures such as fluxes in model simulation evaluation for regional climate studies. The *u*-component meridional momentum flux selected for analysis relates directly to the maintenance and changes of the local values of the zonal momentum and is a critical indicator of a model's dynamical formulation and constraints. The time-domain components of the vertically-averaged form of this flux have not been previously subjected to regional analysis for this particular model. A complete performance evaluation of a GCM in terms of such climate measures would require examining entire budget equation relationships for momentum, heat and moisture including the vertical structure of the fluxes. However, such a level of detail is beyond the scope and purpose of the present study.

Section 2 describes the time-domain flux statistics. Section 3 details the data and the method of analysis used. Results of the analysis are given in Section 4. The summary and conclusions follow in Section 5.

2. Time domain and flux statistics

In this study, statistics based only on time-domain partitioning are used for analysis of both model and observational data. This approach has been used in several climatological and model studies (e.g., Lahey *et al.*, 1960; Manabe and Terpstra, 1974; Blackmon *et al.*, 1977; Lau, 1979a; Blackmon and Lau, 1980). The basic decomposition is

$$A = \bar{A} + A', \tag{1}$$

where A is any scalar, the overbar refers to a monthly time average and the prime to a deviation from the time average.

There are two advantages to time-domain statistics. First, only local data are required. The accuracy of the statistical estimates depends only on the characteristics of the local data. The great spatial variability in the global observational system density and quality (and, to some extent, in model performance) will be reflected locally but regions of poor data will not degrade the areas of high quality data, as can occur in the space-domain partitioning based on zonal averages.

The second important advantage is the correspondence of the statistical components to physical features and processes of the general circulation. The time-averaged quantities reflect not only the general latitudinal variations in the general circulation, but most importantly the global-scale wave modes forced by the longitudinal variations in topography and surface heating. The properties of these global-scale standing features are fundamental to the *regional climate* including monthly, seasonal or even annual anomalies. The transient component is an important indicator of cyclonic and larger scale activity which contributes to maintenance of the mean state. In contrast, the eddy component in the space-domain combines the standing forced modes and the transient free modes making it more difficult to distinguish the physical processes associated with each.

All meridional flux statistics were considered only in vertically averaged form which minimized interpolation problems associated with comparing real observations in pressure coordinates and GCM results in height coordinates. The average was taken from the earth's surface to 75 mb in the observations and to 18 km in the GCM data and thereby represents primarily the average tropospheric conditions. This averaging reduces the sensitivity of the results to irregularity in vertical structure noted even in zonally-averaged flux statistics by Lau (1979b). Variabilities in vertical structure are enhanced in the GCM due to poor vertical resolution and the upper-boundary constraint.

Vertically-averaged fluxes are explicit terms in the budget relationships for the mean states of vertically-averaged atmospheric variables and are important descriptors for regional climate. Studying the mean state for an entire atmospheric column does not require evaluating vertical fluxes within the atmosphere. This is an advantage because vertical motion is difficult to determine from conventional observations.

For an individual January the vertically- and time-averaged momentum flux for each grid point was partitioned as follows

$$\widehat{\overline{VU}} = \widehat{\bar{V}\bar{U}} + \widehat{\overline{V'U'}}, \tag{2}$$

where the first and second terms on the right-hand side are the steady and transient components respectively, and V is the meridional component of velocity, U is the zonal component of velocity and the caret denotes a vertical, mass-weighted average.

The formulation of the vertical, mass-weighted average required special attention to insure that the three-term representation of Eq. (2) is preserved for both pressure and height coordinate data. For the pressure coordinate data, the caret operator was formulated as

$$\hat{B} = \frac{1}{(\bar{P}_s - 75\text{ mb})} \int_{75\text{ mb}}^{\bar{P}_s} B dp, \tag{3}$$

where B is any of the three terms in Eq. (2) under the caret symbol and $\bar{P}_s$ is the January mean surface pressure at the given grid point. For height coordinate data in a hydrostatic system the equivalent form for the total flux term is

$$\widehat{\overline{VU}} = \left\{\int_{Z_s}^{18\text{ km}} \overline{\rho VU} dz\right\} \Big/ \left\{\int_{Z_s}^{18\text{ km}} \bar{\rho} dz\right\}, \tag{4}$$

where g is the acceleration of gravity, ρ is the density, and Z_s is the topographic height at the given grid point.

With some algebraic manipulation, an exact equivalence to the steady component for the height coordinate system can be shown to be

$$\widehat{\bar{V}\bar{U}} = \left\{\int_{Z_s}^{18\text{ km}} (\bar{U}\overline{\rho V} + \bar{V}\overline{\rho U} - \bar{\rho}\bar{V}\bar{U}) dz\right\} \Big/ \left\{\int_{Z_s}^{18\text{ km}} \bar{\rho} dz\right\}. \tag{5}$$

The transient component can be determined as a residual, i.e.,

$$\widehat{\overline{V'U'}} = \widehat{\overline{VU}} - \widehat{\bar{V}\bar{U}}. \tag{6}$$

All vertical integrals were evaluated by Simpson's method using the value of the integrand at the midpoint of the layer and multiplying by layer thickness.

Because the model and observational data consisted of more than one January realization, estimates of ensemble averages and standard deviations could be obtained even though the sample size was small (4 or 5 cases). The ensemble standard deviations were computed based upon the deviation of each 30-day January mean from the multi-year January mean. Comparable information in terms of interannual variability had been considered in zonally-averaged analyses of the observational data (Oort, 1977), but in this study it was possible to compute standard deviations for both the model and observational data on a grid-point-by-grid-point basis and thus compare model variability characteristics to observed interannual variability on a regional basis.

3. Basic Data

a. NCAR GCM

Perpetual January simulations from a version of the NCAR GCM were used in the analysis. This version of the model is global with six vertical layers (each 3 km in thickness) and is described by Washington and Williamson (1977).

Ensembles, consisting of several January simulations, were evaluated for both 5 and 2.5° versions of this model. Five independent realizations with the 5° grid model were available from previous studies (Chervin, 1979; Washington and Chervin, 1979). In addition, four independent realizations with the 2.5° grid model were available from Chervin (1980). Individual realizations differed from each other because of the addition of small random perturbations to the initial conditions (within one day of Day 30 of the parent control for the 5° ensemble and Day 60 for the 2.5° ensemble). Boundary and external conditions were not changed among the different realizations. For these sets of simulations to be considered as independent realizations, the time-spans for analysis of ensemble statistics were from Day 61 to 90 for the 5° ensemble and from Day 91 to 120 for the 2.5° ensemble (see Chervin and Schneider, 1976). The sampling rate for the data analysis was once every 12 h.

b. Atmospheric observations

The five-year data set for May 1968–April 1973 compiled by Oort (1977) was used. The set consists of rawinsonde station data (nearly 600 stations) and has major gaps in coverage in the region south of 30°S which represents the current status of long-term Southern Hemisphere data [see Fig. 1 in Oort's (1978) paper]. Time-domain statistics were determined at every station point for each January of the five-year data set separately with twice daily data using Eqs. (2) and (3). These statistical quantities are different from those reported in Oort (1971, 1977) where time- and space-domain statistics and departures from five-year means were considered.

The station data were then used to define grid-point values on a 5° longitude/2.5° latitude grid covering the entire globe with a conditional relaxation objective analysis method (Harris *et al.*, 1966) using the zonal average of all data in a latitudinal belt as a first guess (Oort, 1971).

4. Results of analysis

Fig. 1 shows the estimated ensemble averages of the zonal averages for the vertically-averaged momentum fluxes. These statistics show large differences among the three data sets. There is agreement in the magnitude of total flux at 30°N between the observational and 2.5° model data; however, the relative importance of the transient and steady components are reversed between the two. Manabe and Terpstra (1974) noted a similar reversal. Both model data sets fail to capture completely the major area of negative total, steady and transient fluxes observed between 50 and 80°N and the positive steady fluxes observed between 20 and 45°S. A. H. Oort (private communication, 1981) considers the steady flux values likely to be wrong in the observations particularly from 30 to 60°S due to inadequacies in the observing network. Both model data sets show a transient component far smaller in magnitude than and displaced northward from the observations; however, the more major difference between the 2.5 and 5° model results is not in the transient component but rather in the steady component.

Figs. 2 and 3 show the horizontal distributions for the steady and transient components, respectively, of the vertically-averaged meridional flux of zonal momentum for the observational ensemble and the 2.5 and 5° GCM ensembles. Analyses for the entire earth are shown although the verification data in the Southern Hemisphere is of limited value due to lack of observing stations. Subsequent discussion will focus primarily on the Northern Hemisphere.

The standing wave patterns in the middle latitudes result in dipole-like features in the steady flux component which are produced by the northward transport of westerly momentum (positive values) east of the steady long-wave troughs and the corresponding southward transport (negative values) west of the troughs. Both the observations and the model data depict dipole-like features in the total and steady flux fields over and east of the Asian and North American continents, with positive values tending to be off the east coast over the ocean and negative values over land or at the coast. However, the specific orientation and positioning of the dipoles are quite different between the observations and model data. The total momentum flux data of Lahey *et al.* (1960) for the 300 mb level also shows strong dipoles over the eastern sector of these continents. The patterns for steady flux agree between the 2.5 and 5° model ensembles although magnitudes from the 5° ensemble are generally less than half of those in the 2.5° model ensemble in both the Northern and Southern Hemispheres.

Substantial differences in horizontal structure for the steady fluxes exist between the observational and model data. The main negative and positive centers in the Northern Hemisphere are located more poleward and eastward in the model data compared to the observations. This shift of up to 20° in latitude and longitude and the specific differences in magnitude of individual centers are important features not revealed by the zonal averaged data in Fig. 1. Differences between observational and model data in details such as the position and orientation of zero lines, for example in the North American and European sectors, implies important deficiencies in the regional simulations of the model.

The transient component comparison (Fig. 3) shows even more striking differences between the three data sets. Centers in the Northern Hemisphere are again poleward in the model compared to observational data. Magnitudes in the 5° ensemble tend to be less than one-half of those in the 2.5° ensemble although patterns are similar. Unlike the case with the steady fluxes, magnitudes of transient fluxes in the 2.5° ensemble are considerably smaller than in the observational ensemble. The zonal averages for the transient component (Fig. 1) show the important

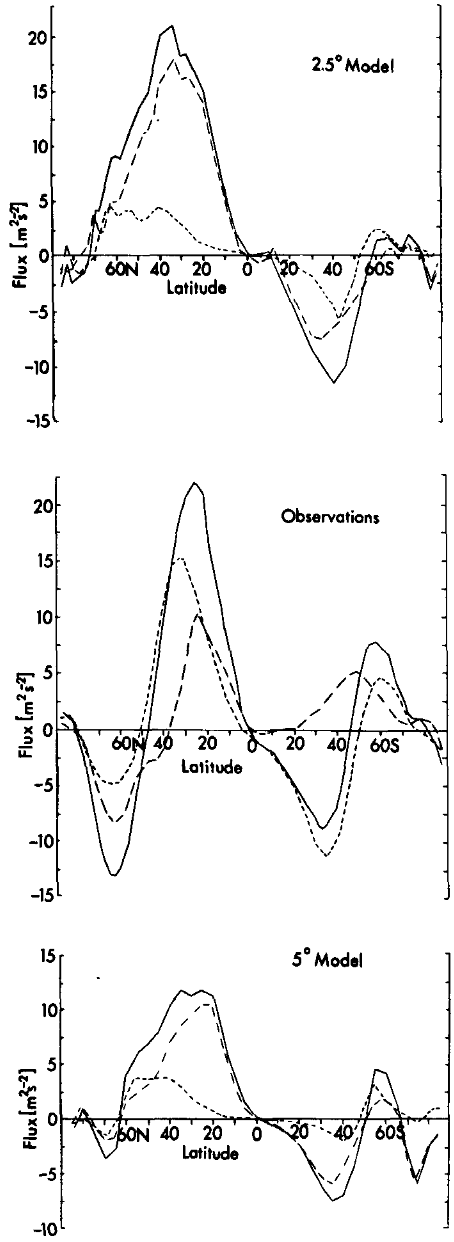
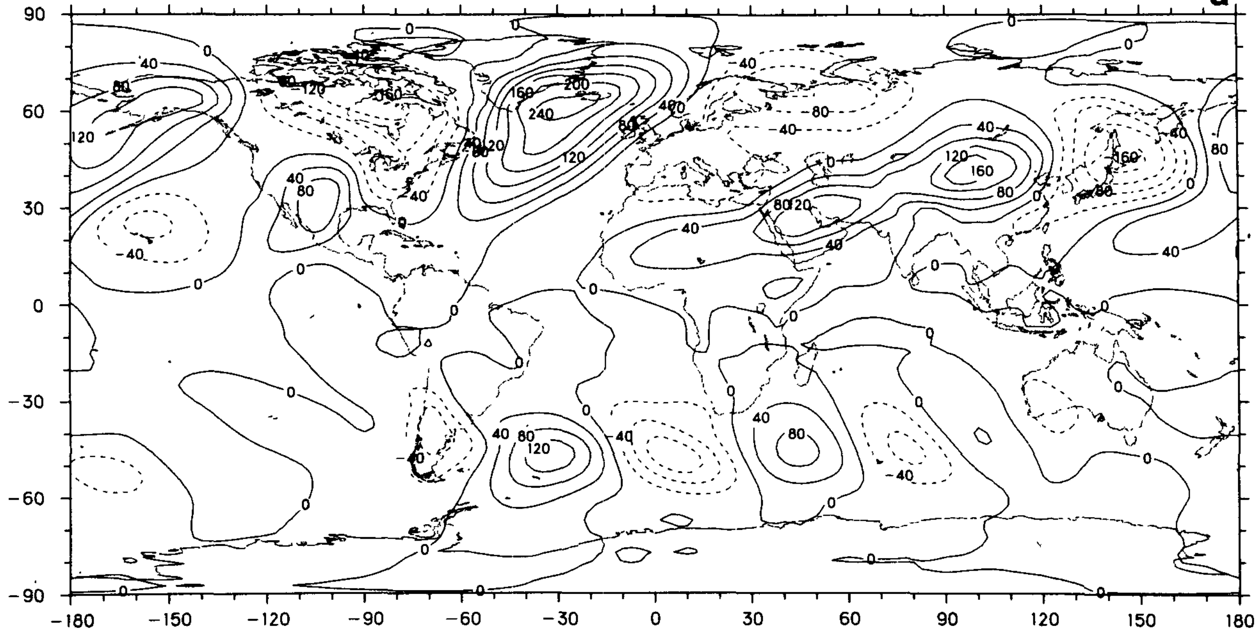


Fig. 1. Zonally averaged values of the vertically averaged meridional flux statistics of the U-component of momentum (m^2 s^{-2}) for the 2.5° model, observational and 5° model January ensembles. The total, steady and transient fluxes are shown by the solid, long-dashed and short-dashed lines, respectively.

Ensemble Average of Vertical-Mean Fields : Four 2.5° Januaries (Days 91-120)

Steady Momentum Flux (m^2 s^{-2})



Ensemble Average of Vertical-Mean Fields : Five Observed Januaries (1969-1973)

Steady Momentum Flux (m^2 s^{-2})

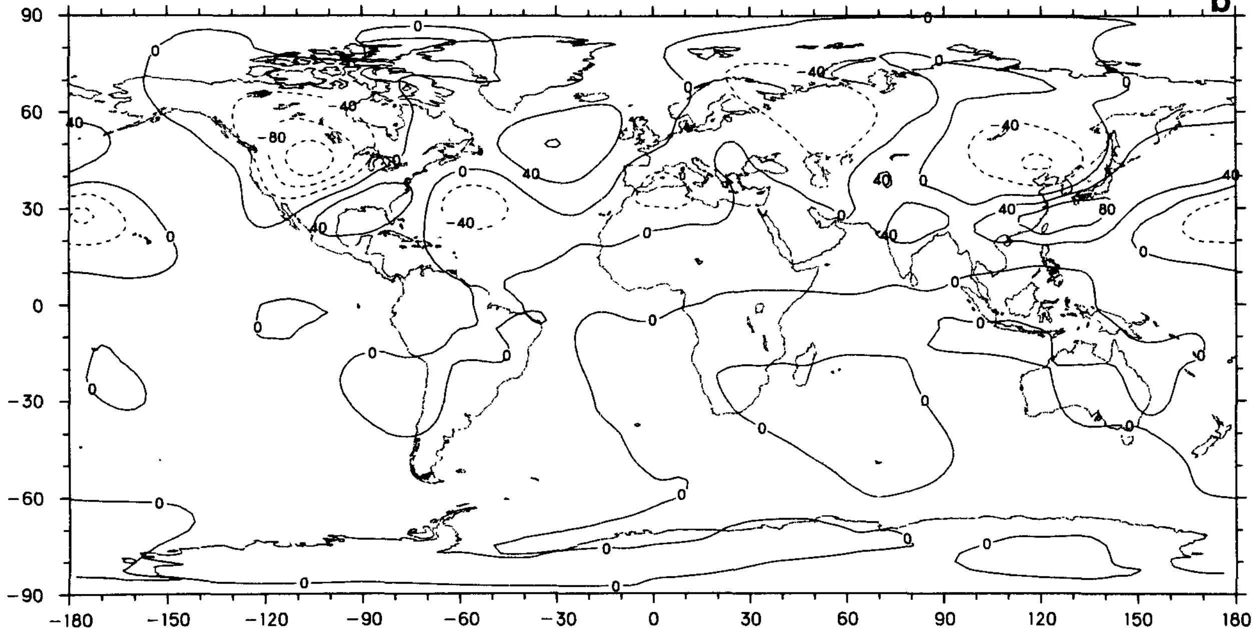
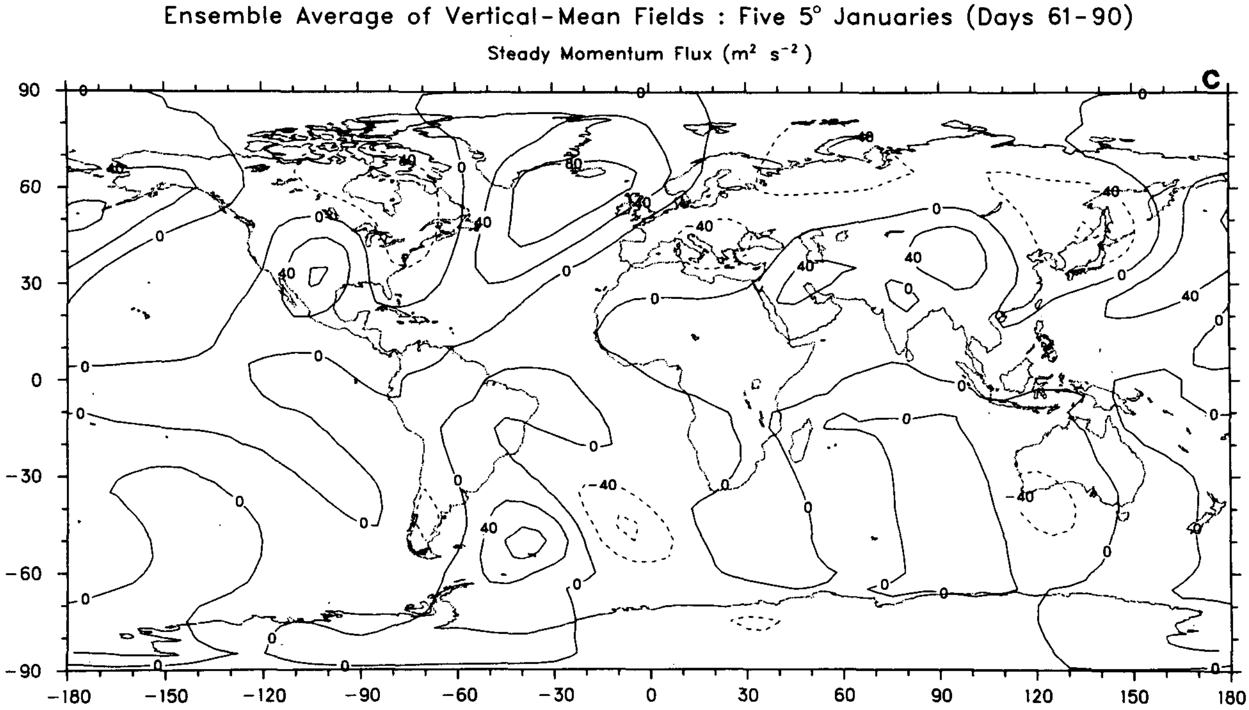


FIG. 2. Global distribution of the vertically-averaged steady component of the meridional flux of the *U*-component of momentum (m^2 s^{-2}) for (a) the 2.5° model, (b) observational and (c) 5° model January ensembles.

latitudinal and amplitude differences between the model and observations; however, they provide little measure of the major local differences such as over North America between the 2.5 and 5° model ensembles. Amplitudes of the observational values are similar to band-pass filtered data presented by Blackmon and Lau (1980) for the 300 mb level observations; however, the orientation and position of the


Ensemble Average of Vertical-Mean Fields : Five 5° Januaries (Days 61-90)

Steady Momentum Flux ($m^2\ s^{-2}$)

FIG. 2. (*Continued*)

flux patterns differ and, for example, over and east of North America do not correspond as well to the main storm track axis as their single-level data at 300 mb.

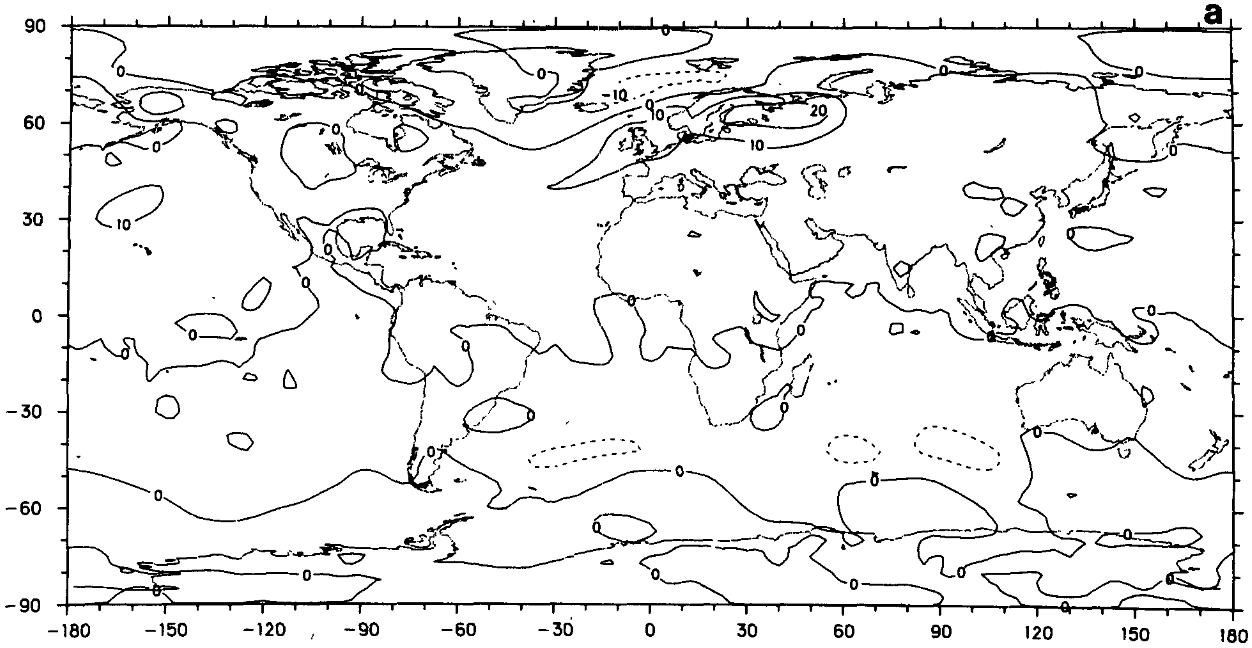
Outside of the European sector, the transient momentum fluxes are an order of magnitude smaller for the NCAR model than for the observations. In the European sector, where the magnitude of the momentum flux is comparable for both model and observations, the pattern is shifted considerably so that the band of positive values that is located near 40–50°N in the observations is found near 50–60°N in the model results. The differences between observations and the NCAR model for the transient momentum flux patterns are more extreme than differences for conventional storm track analyses (see Washington *et al.*, 1977).

Some of the differences noted above are consistent with the basic characteristics in the horizontal distribution of vertically- and time-averaged zonal ($\bar{U}$) velocity component. Fig. 4 shows the distributions for the estimated ensemble averages of this velocity component for the observational and model data sets. The observed zonal velocity maxima in the Northern Hemisphere are between 30 and 40°N and near the eastern coasts of North America and Asia, whereas in the 2.5 and 5° models the maxima are broader and extend farther north and eastward over the oceans. Magnitudes of the velocity fields in the model results tend to be smaller than in the observations except over and west of the Himalayan Mountains, a region where topography distorts the vertically-averaged results by shortening the atmospheric column through which the averaging takes place, thus increasing the emphasis on the upper tropospheric condition.

Although the model ensemble statistics show shifts of pattern when compared to the observational data, they retain an internal consistency which is similar to that in the observational data. As Figs. 3 and 4 show, the observed zonal velocity jet maxima over the eastern region of North America has well-defined centers of positive and negative transient momentum flux at its southern and northern flanks, respectively. The large positive flux values to the south extend farther to the west than the large negative values to the north. A similar relationship was found by Blackmon *et al.* (1977) for features in the 500 mb observations. In the model ensembles, the centers of transient flux magnitudes over the North Atlantic are shifted east and north into Europe consistent with the shift of the exit region, but the lack of transient centers over the central Atlantic and eastern part of North America is not simulated in a manner consistent with observations. However, in this exit region and opposite to the observations, the negative center to the north is farther to the west than the positive center to the south. The presence of the Himalayan and Rocky Mountains complicates the analysis of the vertically-averaged fields and makes it more dif-

Ensemble Average of Vertical-Mean Fields : Four 2.5° Januaries (Days 91-120)

Transient Momentum Flux ($m^2\ s^{-2}$)



Ensemble Average of Vertical-Mean Fields : Five Observed Januaries (1969-1973)

Transient Momentum Flux ($m^2\ s^{-2}$)

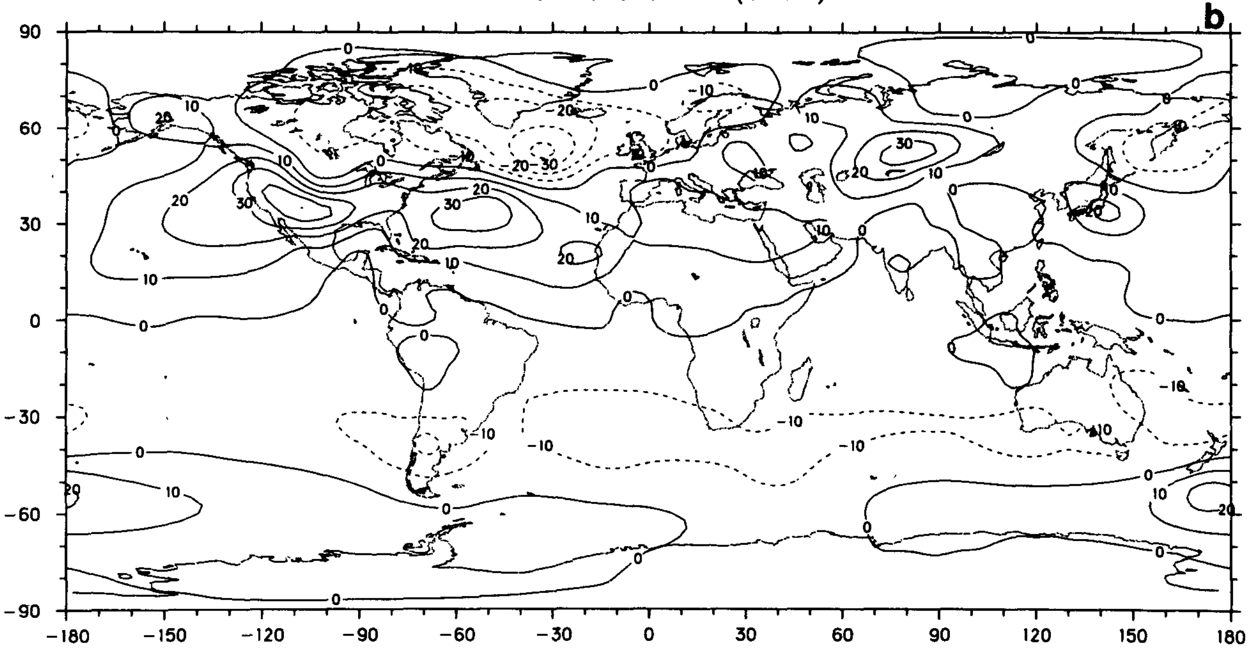


FIG. 3. Global distribution of the vertically-averaged transient component of the meridional flux of the *U*-component of momentum ($m^2\ s^{-2}$) for (a) the 2.5° model, (b) observational and (c) 5° model January ensembles.

ficult to discuss the dynamical consistency between model and observations in the entrance regions to the main Northern Hemisphere jet maxima. In general, the model simulation for the jet maximum and associated transient fluxes is better in the North American than in the East Asian sector.

Model results in the Southern Hemisphere for the variables examined here show more longitudinal

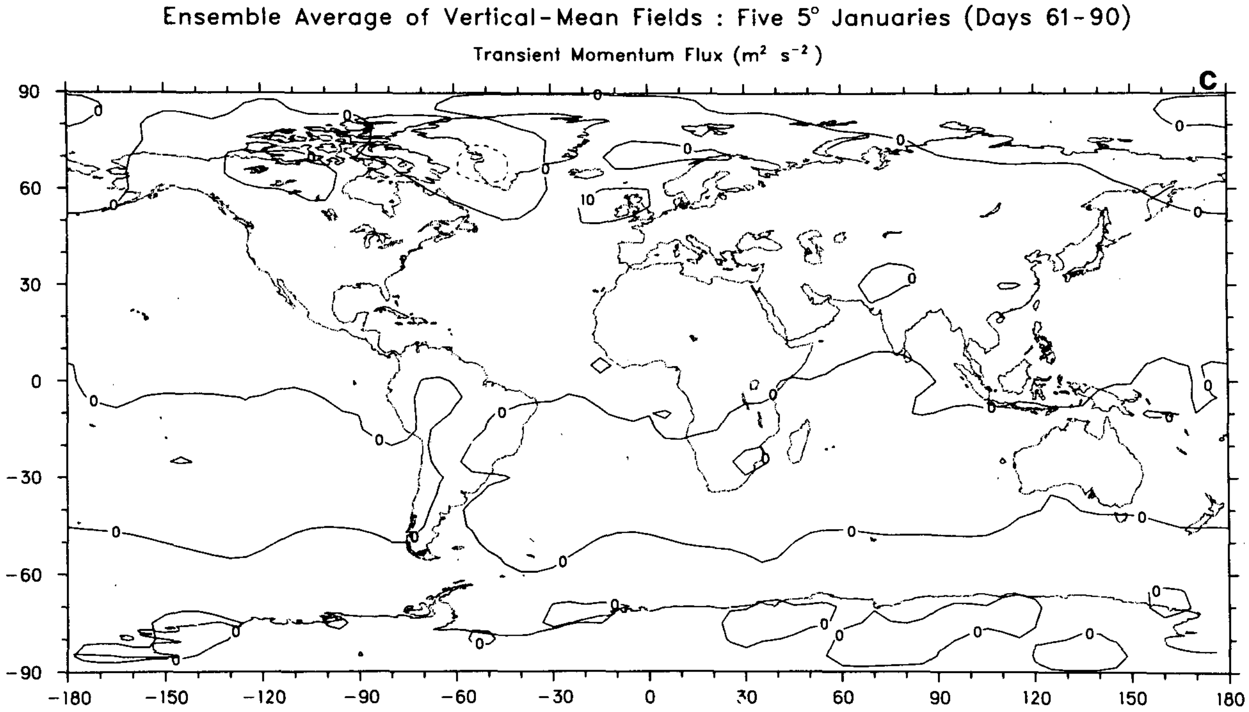


FIG. 3. (*Continued*)

variability than the observational data. This is not surprising since the long-term observational network is very sparse over the ocean areas south of 30°S so that the observation analyses are strongly weighted by zonally-averaged values used in the first step of the analysis procedure (Oort, 1978).

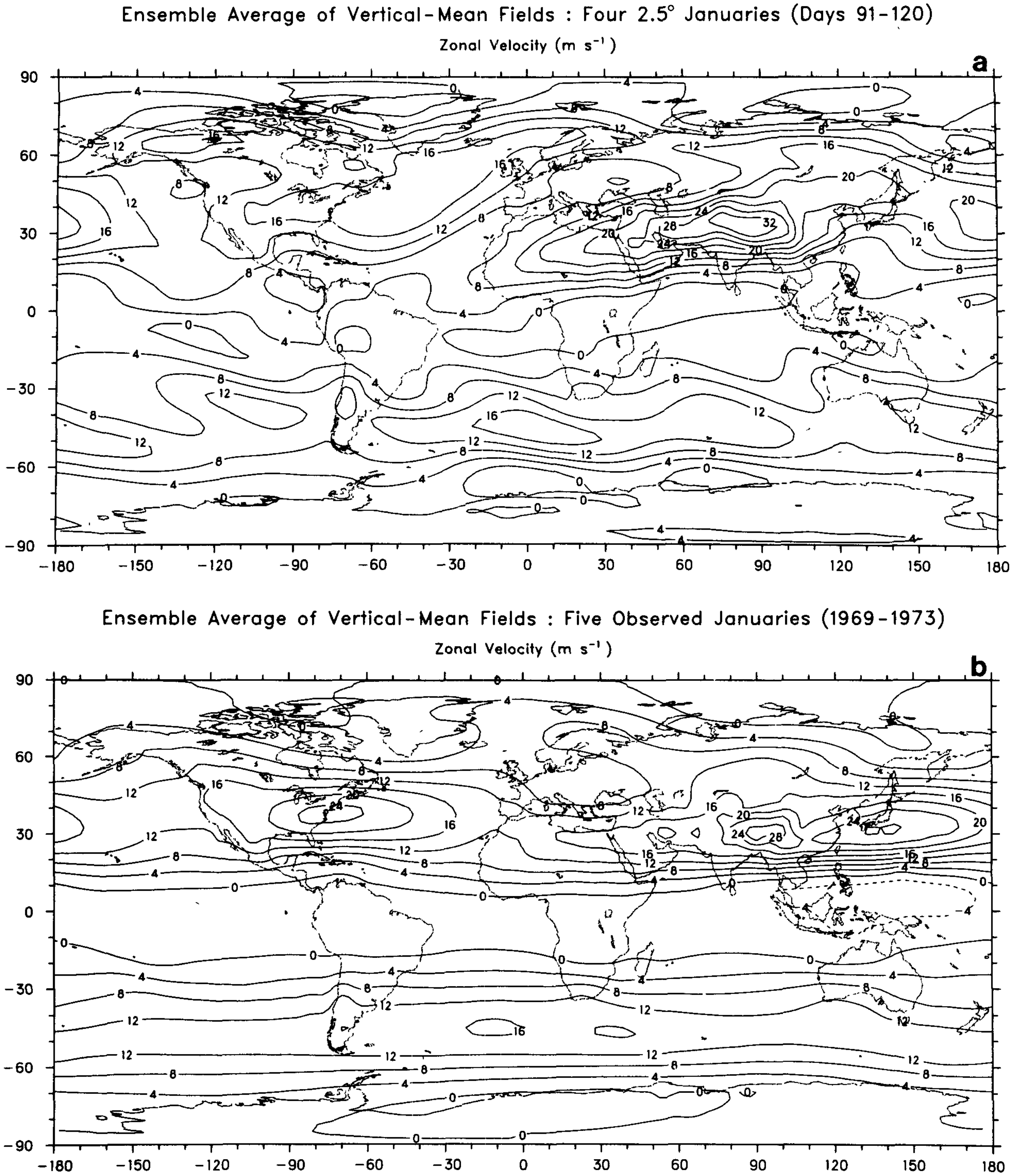
Oort (1977) describes interannual variability of certain general circulation parameters in terms of both scatter diagrams and standard deviation statistics for zonally-averaged quantities. Here, information for both the inherent model variability and observed interannual variability is presented in terms of horizontal distributions. The presentation of the estimated ensemble standard deviations (second moments) of various fluxes is restricted to the Northern Hemisphere.

The horizontal distributions of ensemble standard deviation of the steady flux component shown in Fig. 5 have deviation values for the observations which are comparable in magnitude to typical average values for the observations (compare with Fig. 2); whereas for the model ensembles, standard deviation values are less than half of typical average values. In local areas such as the Rocky Mountain region enormous differences exist between inherent model variability and observed interannual variability (up to one order of magnitude). A possible factor contributing to the small ensemble standard deviations in the model is, no doubt, the lack of any variation in the prescribed ocean surface temperature distributions among the individual model experiments. The relative importance of lower boundary condition variability on the "interannual variability" of various atmospheric statistics must await further experimentation.

5. Conclusions

Analysis of selected time-domain flux statistics for the meridional fluxes of the *U*-component of momentum for ensembles of GCM January simulations and an ensemble of five observed January data sets has demonstrated some important sensitivities and deficiencies in the model's representation of first and second moment regional climate characteristics with respect to the time-domain components and model resolution. The depiction of these statistics in horizontal charts reveals characteristics not at all evident in zonally-averaged fields and provide a basis for further study of model performance. These climate measures are not as susceptible to compensating errors as are the primary model variables like winds and temperature which allows for a more demanding model performance evaluation.

Large differences in the apportionment of the total flux into steady and transient components were noted between the model and observational data, with the transient component being too small and the steady component too large in the model. Truncation in the model was shown to affect the steady fluxes more



Ensemble Average of Vertical-Mean Fields : Four 2.5° Januaries (Days 91-120)

Zonal Velocity (m s⁻¹)

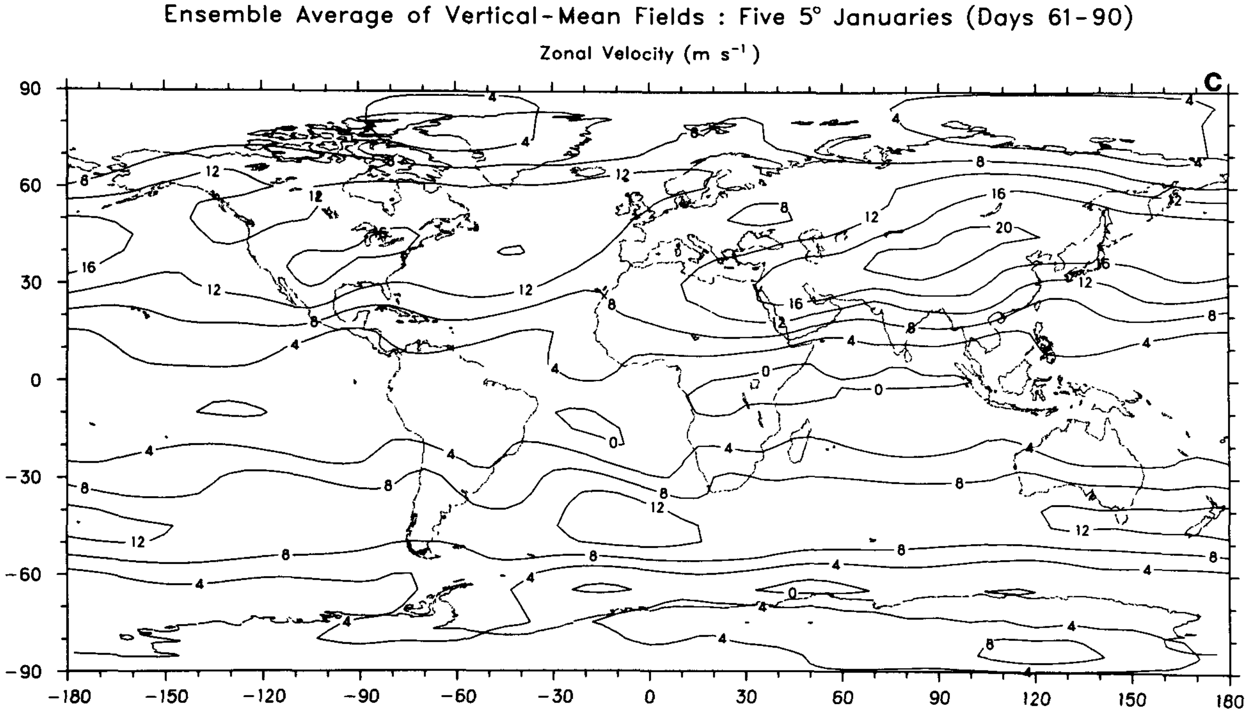
Ensemble Average of Vertical-Mean Fields : Five Observed Januaries (1969-1973)

Zonal Velocity (m s⁻¹)

FIG. 4. Global distribution of the vertically-averaged U-component of wind (m s^{-1}) in (a) the 2.5° model, (b) observational and (c) 5° model January ensembles.

than the transient component although both had large differences between the 5 and 2.5° model ensembles.

The flux statistics revealed large differences in patterns and magnitudes between model and observations, especially in the intense baroclinic zones off the east coasts of North America and Asia. These differences, in turn, reflected differences in the am-


Ensemble Average of Vertical-Mean Fields : Five 5° Januaries (Days 61-90)

Zonal Velocity (m s^{-1})

FIG. 4. (*Continued*)

plitude, position and structure of the steady long waves for the model and observations. For the model results, there was some correspondence between the pattern of transient fluxes of zonal momentum and the position of the jet stream.

The use of time-domain analysis with future models must be explored much further than done here. For example, vertical variations of fluxes could be examined to clarify the correspondence of single-level to vertically-integrated viewpoints. The flux data analysis should be extended to include complete sets of components for the total transport on a seasonal basis for all seasons leading to regional budget analyses. This future work will be an important test for general circulation numerical models and a valuable diagnostic for observational data, particularly for the study of the standing wave patterns (and their variability) that are so important for describing the climate.

The progression from a regional climate analysis, such as the one reported here, to a diagnosis of the basic causes of model simulation deficiencies and ultimately to a prescription for model re-formulation to produce improved climate simulations is not a clearly marked path. The specification of a detailed roadmap to this goal of developing a model capable of reproducing the many aspects of the observed climate and suitable for climate change or sensitivity experiments is a complex matter. It is clear, however, that the validity of using any model to simulate the climatic response to a prescribed change in forcing is enhanced by the extent to which the model is able to reproduce a wide variety of observed climate statistics (including the first and second moments of the momentum transport components discussed in this study).

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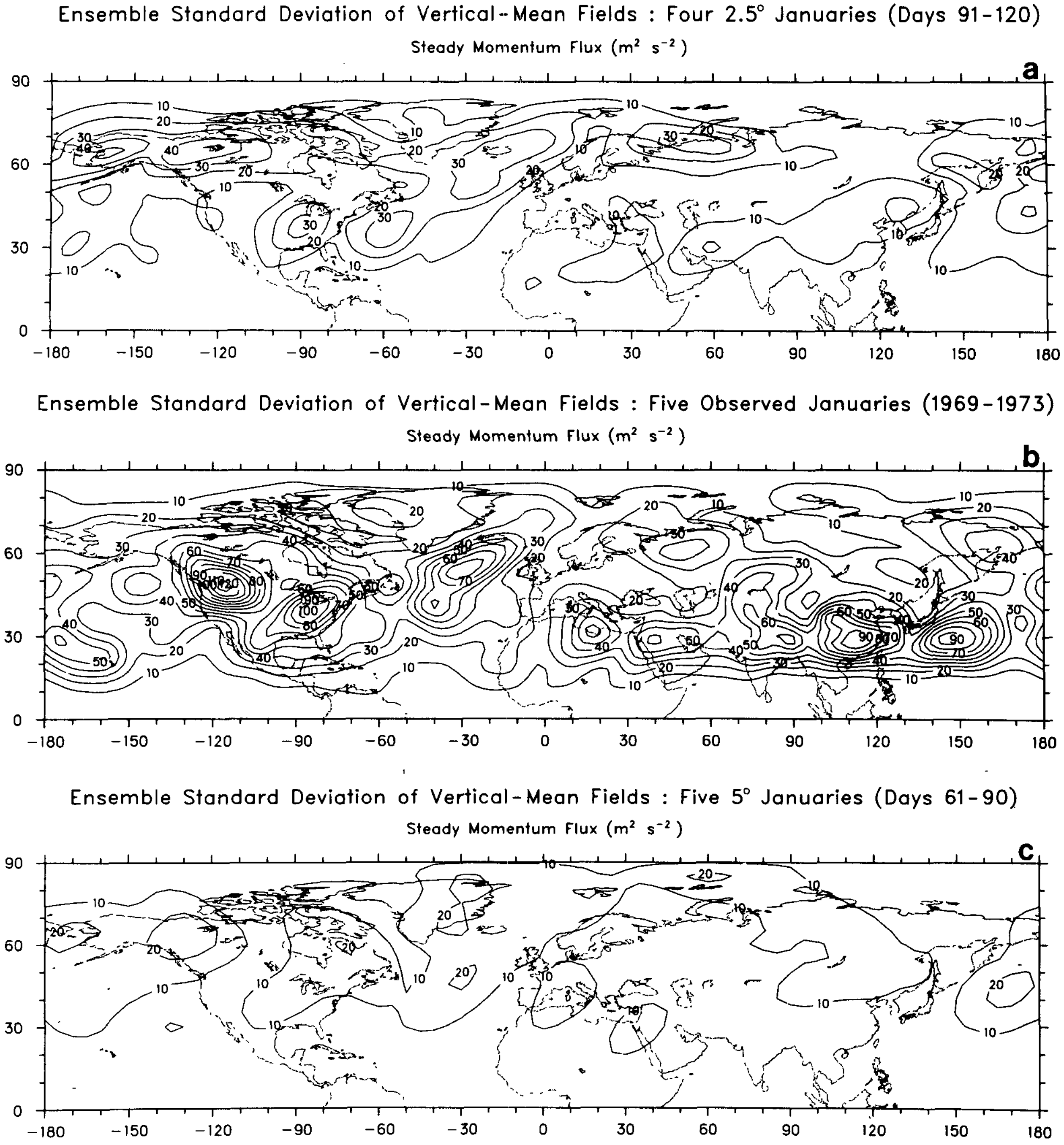

Ensemble Standard Deviation of Vertical-Mean Fields : Four 2.5° Januaries (Days 91-120)

Steady Momentum Flux ($m^2\ s^{-2}$)

Ensemble Standard Deviation of Vertical-Mean Fields : Five Observed Januaries (1969-1973)

Steady Momentum Flux ($m^2\ s^{-2}$)

Ensemble Standard Deviation of Vertical-Mean Fields : Five 5° Januaries (Days 61-90)

Steady Momentum Flux ($m^2\ s^{-2}$)

FIG. 5. Northern Hemisphere distribution of the ensemble standard deviation of the vertically-averaged steady component of the meridional flux of the *U*-component of momentum ($m^2\ s^{-2}$) for (a) the 2.5° model, (b) observational and (c) 5° model January ensembles.

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