~~Bob Fox~~ library

NATIONAL SCIENCE FOUNDATION
Washington, D.C. 20550

FINAL PROJECT REPORT

NSF FORM 98A

PLEASE READ INSTRUCTIONS ON REVERSE BEFORE COMPLETING

PART I–PROJECT IDENTIFICATION INFORMATION

1. Institution and Address
The University of Wisconsin-Madison
Space Science & Engineering Center
1225 W. Dayton
Madison, WI 53706

2. NSF Program: Meteorology

3. NSF Award Number: ATM 78-22384

4. Award Period: From 10/1/79 To 3/31/83

5. Cumulative Award Amount: $322,800

6. Project Title: Diagnostics of the Heat Sources and Sinks of the Asiatic Monsoon and the Thermally Forced Planetary Scale Response

PART II–SUMMARY OF COMPLETED PROJECT *(FOR PUBLIC USE)*

Diagnostics of planetary scale heat sources and sinks and its thermally forced response have been conducted using the operational analyses prepared by the National Meteorological Center during the First GARP Global Experiment (December 1978 -November 1979). Emphasis has been placed on the determination of three-dimensional diabatic heating and mass and energy transport, and the investigation of the forcing and maintenance of the zonally-averaged global circulation in both isobaric and isentropic coordinates.

Three-dimensional distributions of diabatic heating estimated from the isentropic mass continuity equation reveal realistic seasonal variations in both intensity and location of the heat sources and sinks. Vertical mass transport is upward through isentropic surfaces in the heat source region and downward in the heat sink region; horizontal mass transport is from heat sources to heat sinks in upper isentropic layers and vice versa in lower isentropic layers. Net energy transport from heat source to heat sink regions is accomplished through the condition that more energy exists in the upper isentropic layers. A common horizontal scale exists for the mass and energy transport.

Due to differing degrees of freedom for transport in isentropic coordinates which do not exist within the zonally averaged isobaric structure, the mean mass transport yields an isentropic Hadley-type mass circulation spanning individual hemispheres. The forcing of lateral branches of the mass circulation are associated with pressure torques in mid-latitudes and a frictional torque in low latitudes while diabatic heating explicitly forces the vertical mass transport. The isentropic Hadley-mass circulation determines the hemispheric scale and intensify of meridional energy transport.

PART III–TECHNICAL INFORMATION *(FOR PROGRAM MANAGEMENT USES)*

1. ITEM *(Check appropriate blocks)*	NONE	ATTACHED	PREVIOUSLY FURNISHED	TO BE FURNISHED SEPARATELY TO PROGRAM: Check (√)	TO BE FURNISHED SEPARATELY TO PROGRAM: Approx. Date
a. Abstracts of Theses		X			
b. Publication Citations		X			
c. Data on Scientific Collaborators		X			
d. Information on Inventions		X			
e. Technical Description of Project and Results	▨	X			
f. Other *(specify)*	▨				

2. Principal Investigator/Project Director Name *(Typed)*: Donald R. Johnson

3. Principal Investigator/Project Director Signature: Donald R. Johnson

4. Date: 7/6/83

NSF Form 98A (5-78) Supersedes All Previous Editions

Form Approved OMB No. 99R0013

FINAL PROJECT REPORT

TO

THE NATIONAL SCIENCE FOUNDATION

FOR A RESEARCH GRANT IN SUPPORT OF

Diagnostics of Heat Sources and Sinks of the Asiatic Monsoon and the Thermally Forced Planetary Scale Response

October 1, 1979 - March 31, 1983

NSF GRANT ATM 78-22384

FROM

Donald R. Johnson
Principal Investigator

The Space Science and Engineering Center
The University of Wisconsin-Madison

1225 W. Dayton Street
Madison, Wisconsin 53706

Donald R Johnson
Donald R. Johnson
Principal Investigator

July 6, 1983
Date

Part III: Technical Information

A. Abstracts of Theses

Theses completed:

Townsend, R. D., 1980: A diagnostic study of the zonally-averaged global circulation in isentropic coordinates. Ph.D. thesis, University of Wisconsin, Madison, 221 pp.

Schaack, T., 1982: The global angular momentum balance for January 1979. M.S. thesis, University of Wisconsin, Madison, 104 pp.

Snook, J., 1982: Mass and angular momentum balance of a developing Bay of Bengal monsoon depression observed during MONEX. M.S. thesis, University of Wisconsin, Madison, 82 pp.

A DIAGNOSTIC STUDY
OF THE ZONALLY-AVERAGED GLOBAL CIRCULATION
IN ISENTROPIC COORDINATES

BY

RONALD DEAN TOWNSEND

A thesis submitted in partial fulfillment of the
requirements for the degree of

DOCTOR OF PHILOSOPHY
(Meteorology)

at the
UNIVERSITY OF WISCONSIN-MADISON

1980

ABSTRACT

The forcing and maintenance of the zonally-averaged global circulation is investigated in both isobaric and isentropic coordinates through transport diagnostics of mass, angular momentum, and energy. A FGGE Level IIIa data set generated by NMC's global data assimilation system provided a common data base for both the isobaric and isentropic diagnostic computations.

The diagnostic results in isobaric coordinates are consistent with the results of previous investigations conducted within an isobaric framework. The mass circulations consist primarily of direct Hadley cells in low latitudes and indirect Ferrel cells in mid-latitudes of both hemispheres. Transport by the ageostrophic mean mode in tropical latitudes and by the transient and standing eddy modes in extratropical latitudes maintains the angular momentum and energy balance requirements of the general circulation.

Within the isentropic framework a mean meridional circulation is isolated that explicitly links the planetary scale heat sources and sinks. The asymmetric structure of active mid-latitude baroclinic waves provides the degree of freedom for a geostrophic mean mode of transport in isentropic coordinates which does not exist within the zonally-averaged isobaric structure. The combination of an ageostrophic mean mode of mass transport in tropical latitudes and a geostrophic mean mode of mass transport in extratropical latitudes yields an isentropic Hadley-type mass circulation spanning the hemisphere. The lateral branches of the mass circulation are associated with pressure torques in mid-latitudes and a friction torque in low latitudes while diabatic heating explicitly forces the vertical mass transport. In addition, diabatic heating estimated from the mean meridional mass transport through the isentropic continuity equation reveals realistic seasonal variations in the intensity and location of the heat sources and sinks of the zonally-averaged atmosphere. The physical processes inferred from the heating distribution emphasize the importance of latent heat release in tropical latitudes and radiational cooling in higher latitudes of both the Northern and Southern Hemispheres during all seasons. Another principal heat source in northern mid-latitudes that attains maximum intensity during the winter season is due to sensible and latent heating over oceanic regions off the east coasts of Asia and North America.

In isentropic coordinates the mean meridional circulation is the dominant means of relative angular momentum transport in low latitudes and provides some net poleward transport in mid-latitudes. In extratropical latitudes the transient and standing eddy circulations accomplish most of the relative angular momentum transport in the Northern Hemisphere while the transient mode dominates in the Southern Hemisphere. Within the zonally-averaged isentropic structure the Hadley-type mass circulation not only determines the sense and scale of meridional energy exchange but also provides virtually all the energy transport. The isentropic standing eddy and transient modes of energy transport are not important.

The isobaric and isentropic diagnostic results confirm that the perspective of the forcing and maintenance of the circumpolar vortex is coordinate dependent. Within both coordinate systems the baroclinic waves and embedded extratropical cyclones are the fundamental transport mechanism of mid-latitudes. In isobaric coordinates the baroclinic waves contribute primarily to an eddy mode of angular momentum and energy transport. On the other hand, the baroclinic wave structure provides both a mean and an eddy mode of angular momentum transport and yields a dominant geostrophic mean mode of energy transport in isentropic coordinates.

THE GLOBAL ANGULAR MOMENTUM BALANCE FOR JANUARY 1979

BY

TODD K. SCHAACK

A thesis submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE
(Meteorology)

at the

UNIVERSITY OF WISCONSIN-MADISON

1982

THE GLOBAL ANGULAR MOMENTUM
BALANCE FOR JANUARY 1979

Todd K. Schaack

Under the supervision of Professor Donald R. Johnson

ABSTRACT

The global angular momentum balance for January 1979 is investigated through application of the generalized transport equation. The FGGE Level IIIa data set is utilized to perform diagnostic computations in isentropic coordinates. The balance within individual isentropic layers, in the vertically integrated and the vertically and zonally integrated atmosphere is discussed. Numerical adjustments are employed to ensure consistent results between absolute and relative angular momentum perspectives.

Within individual isentropic layers the large scale distributions of the divergences of absolute angular momentum transport and earth angular momentum transport are similar. The low latitude balance of absolute angular momentum is primarily maintained by horizontal and vertical divergent mass transports. In mid and high latitudes advections by the westerly flow become significant resulting in horizontal convergence of absolute angular momentum transport in the front half and divergence in the rear half of the planetary troughs. Pressure torques within the mid-latitude baroclinic flow nearly counter the effect by extracting angular momentum from regions of horizontal convergence and imparting angular momentum to regions of horizontal divergence.

Vertically and zonally integrated results are in general agreement with previous investigations of the northern winter season. Angular momentum created through frictional stress at the surface in polar, subtropical and tropical latitudes is transported to mid-latitudes where it is destroyed by surface friction within the westerlies. Maximum poleward transports occur at latitudes of the subtropical highs in both hemispheres. Within the isentropic structure the mean mode of meridional transport is significant over most latitudes.

MASS AND ANGULAR MOMENTUM BALANCE OF A DEVELOPING BAY OF BENGAL MONSOON DEPRESSION OBSERVED DURING MONEX

By

JOHN SNOOK

A thesis submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE
(Meteorology)

at the

UNIVERSITY OF WISCONSIN-MADISON

1982

MASS AND ANGULAR MOMENTUM BALANCE OF A DEVELOPING BAY OF BENGAL MONSOON DEPRESSION OBSERVED DURING MONEX

John Snook

Under the supervision of Professor Donald R. Johnson

ABSTRACT

Isobaric and isentropic mass and angular momentum budgets of the developing Bay of Bengal monsoon depression of 3 through 8 July 1979 are studied to investigate cyclone development. Subjective analyses based on FGGE Level IIb data acquired during the summer Monsoon Experiment and some surface information from the NMC FGGE Level IIIa data are used for the computations.

The monsoon depression progresses through a well defined life cycle. The pre-formation stage exhibits mid-tropospheric cyclonic circulation which descends with time until a surface circulation develops on 6 July over the Bay of Bengal. The depression enters the mature stage on 7 July as it moves northwestward over the east coast of India.

The depression's mass circulation is inward in the lower troposphere and outward in the upper troposphere. The magnitude of the diabatic heating within the circulation is two to three times larger than the heating within a typical extratropical cyclone. The angular momentum budgets show a net increase of absolute angular momentum resulting from the dominance of inward angular momentum transport in the lower troposphere over outward angular momentum transport in the upper troposphere. This structure indicates the existence of upward vertical transport of angular momentum in which cumulus momentum transport is likely an important component. In accordance with Eliassen's theory for a symmetric vortex, negative torques in the lower troposphere force the inward branch of the mass circulation. However, the relation between mass circulation and forcing is inconsistent in the upper troposphere where computations indicate an outward mass transport and negative torques in some layers.

The mass and angular momentum transport within the monsoom depression is similar to the transport within a moist baroclinic extratropical cyclone. Even though special efforts were made during MONEX to obtain better data over the Bay of Bengal, more upper air data is needed to accurately resolve baroclinic processes of the upper troposphere.

B. Publication Citations

Gallimore, R. G., and D. R. Johnson, 1981: The forcing of the meridional circulation of the isentropic zonally averaged circumpolar vortex. *J. of Atmos. Sci.*, 38, pp. 584-599.

Gallimore, R. G., and D. R. Johnson, 1981: A numerical diagnostic model of the zonally averaged circulation in isentropic coordinates. *J. of Atmos. Sci.*, 38, pp. 1870-1890.

Johnson, D. R., and R. D. Townsend, 1981: Diagnostics of the heat sources and sinks of the Asiatic monsoon and the thermally-forced planetary scale. ICSU/WMO GARP Proc. of Int. Conf. on Preliminary FGGE Data Analysis and Results, (23-27 June 1980, Bergen, Norway), Geneva, 1981, 523-533.

Johnson, D. R., R. D. Townsend, M. Y. Wei, and R. D. Selin, 1981: The global structure of energy transport within thermally-forced planetary scale mass circulations. ICSU/WMO GARP Proc. of Int. Conf. on Early Results of FGGE and Large-Scale Aspects of its Monsoon Experiments (12-17 January 1981, Tallahassee, Florida). Geneva, 1981, pp. 3.27-3.34.

Johnson, D. R., R. D. Townsend, and M. Y. Wei, 1983: The thermally forced response of the planetary scale circulation to the global distribution of heat sources and sinks. Submitted to *Tellus*.

Johnson, D. R., M. Y. Wei, and T. Schaack, 1981: Planetary-scale mass, momentum and energy exchange. ICSU/WMO GARP Proc. of Int. Conf. on Scientific Results of the Monsoon Experiment. Bali, Indonesia, 26-30 October 1981, pp. 2.40-2.43.

Otto-Bliesner, B. L., and D. R. Johnson, 1981: Thermally-forced mean mass circulations in the Northern Hemisphere. *Mon. Wea. Rev.*, 110, 916-932.

Townsend, R. D., and D. R. Johnson, 1981: The mass and angular momentum balance of the zonally-averaged global circulation. ICSU/WMO GARP Proc. of Int. Conf. on Preliminary FGGE Data Analysis and Results (23-27 June 1980, Bergen, Norway), Geneva, 1981, pp. 542-552.

Wei, M. Y., and D. R. Johnson, 1981: The spatial and temporal variation of diabatic heating during the summer monseen. ICSU/WMO GARP Proc. of Int. Conf. on Scientific Results of the Monsoon Experiment. Bali, Indonesia, 26-30 October 1981, pp. 1.3-1.6.

Wei, M. Y., D. R. Johnson, and R. D. Townsend, 1981: The structure of the planetary scale diabatic processes for the atmosphere during FGGE. ICSU/WMO GARP Proc. of Int. Conf. on Early Results of FGGE and Large-Scale Aspects of its Monsoon Experiments (12-17 January 1981, Tallahassee, Florida). Geneva, 1981, pp. 3.35 - 3.42.

Wei, M. Y., D. R. Johnson, and R. D. Townsend, 1982: Seasonal distribution of diabatic heating during the first GARP global experiment. To appear in Tellus.

Zillman, J. W., and D. R. Johnson, 1983: Thermally forced mean mass circulations in the Southern Hemisphere. Submitted to Tellus.

C. Data on Scientific Collaborators

Donald R. Johnson, Principal Investigator

Ming-Ying Wei, Assistant Scientist

Richard Selin, Scientific Programmer

Mitiko Masutani, Research Assistant

Todd Schaack, Research Assistant

Gong-Wang Si, Research Assistant

John Snook, Research Assistant

D. Information on Inventions

None

E. Technical description of project and results.

TABLE OF CONTENTS[1]

---

[1] The first three sections of this summary were extracted in part from the proposal submitted to NSF for further support on planetary scale circulation studies. The last section was extracted from the Ph.D. thesis by R. D. Townsend. The proposal has been favorably reviewed and funded.

I. INTRODUCTION

With the completion of an unprecedented international effort to observe the atmosphere during the First GARP Global Experiment (FGGE), the scientific challenge is now to utilize the information from FGGE to study atmospheric circulation and address fundamental problems in atmospheric science. For the first time the atmosphere's circulation was observed globally. This provides the opportunity to investigate planetary, secondary and regional scales of atmospheric circulation along with the means to study interaction of these scales with each other and teleconnections linking different geographical regions. Such studies involve analysis, diagnosis and prediction along with verification to gain insight on the physical processes that force circulation and the transport of properties required for the balance of mass, momentum and energy.

In addition to the global structure of the atmosphere, the FGGE data set provides the opportunity to study the evolution of the planetary scale circulation throughout the course of an entire year. Insight is already being gained directly from observations on the seasonal variation of planetary and regional circulation through changes of the global distribution of differential heating. If the forcing of climatic changes or the evolution of the circulation over longer time scales are to be understood, it is absolutely essential that the variations within the annual course of events be resolved.

Through NSF support for a proposal entitled, "Diagnostics of the Heat Sources and Sinks of the Asiatic Monsoon and the Thermally Forced Planetary Scale Response", planetary scale mass circulation, energy transport and differential heating have been studied (Johnson and Townsend, 1981; Townsend and Johnson, 1981; Johnson, Townsend, Wei and Selin, 1981; Wei and Johnson, 1981; Wei, Johnson and Townsend, 1981). The capability to diagnose planetary scale differential heating directly from atmospheric circulation has been established. Key results are now summarized. Sections II and III focus on the relationship between three dimensional mass circulation and energy transport and justify why analysis within the isentropic framework elucidates the thermally forced planetary scale of circulation with clarity. The forcing and maintenance of the zonally averaged circumpolar vortex within an isentropic framework and its contrast with an isobaric viewpoint are discussed in section IV.

II. DETERMINATION OF THE PLANETARY SCALE STRUCTURE OF MASS, ENERGY AND ANGULAR MOMENTUM TRANSPORT WITHIN THE CONCEPT OF THERMALLY FORCED CIRCULATION

Theories of general circulation have evolved under a basic premise that atmospheric response is ultimately the result of differential heating. However, in latitudes where the earth's rotation becomes important and geostrophic balance prevails, patterns of mean circulation associated with planetary scale heat sources and sinks are not readily apparent. As a result, the current view of the general circulation largely emphasizes the important role played by the eddies in the global balance of energy and momentum. The failure to determine a direct link between the planetary scale circulation and heat sources and sinks stems jointly from methods of analyses and the use of certain coordinate systems which preclude isolation of thermally forced transport processes within regimes dominated by hydrostatic and geostrophic balance. However, the use of isentropic coordinates in conjunction with analyses of mean and eddy modes of transport to divide the flow into components directly links the mean mass circulation and its associated transport of properties with differential heating within the atmosphere (Johnson and Downey, 1975a and b).

Diagnostics of the transport processes in the isentropic framework accomplished so far have established the role of heat sources and sinks in the planetary scale mass and energy transport and provided insight on the thermal forcing of atmospheric circulation. A review of these results for the planetary scale mass transport and heating distribution, as well as energy and angular momentum transport determined from FGGE Level IIIa (NMC) data set is presented below. Particular emphasis is placed upon the Asiatic monsoon. Although work has been done for different months and seasons during the FGGE year as well as the temporal evolution of the summer Asiatic monsoon, only results from January and July 1979 are included here to summarize the approach that provides a point of departure for the proposed research.

<u>Planetary scale mass transport</u>

The quasi-horizontal transport of mass within the isentropic framework is represented by the stream function (ψ_ρ) and transport potential (χ_ρ) through the use of Helmholtz's theorem given by

$$\overline{\rho J_\theta \underset{\sim}{U}} = \nabla_\theta \chi_\rho + \underset{\sim}{k} \times \nabla_\theta \psi_\rho \tag{1}$$

The transport potential and stream function are solutions to Poisson equations,

$$\nabla_\theta^2 \chi_\rho = \nabla_\theta \cdot \overline{\rho J_\theta \underset{\sim}{U}} \tag{2}$$

and

$$\nabla_\theta^2 \psi_\rho = \underset{\sim}{k} \cdot \nabla_\theta \times \overline{\rho J_\theta \underset{\sim}{U}} \tag{3}$$

which are numerically evaluated by the method of overrelaxation (Johnson and Townsend, 1981).

The global nature of the mass transport illustrated by rotational and irrotational components for the 300-310 K and 340-350 K isentropic layers during January and July (Johnson, Townsend and Wei, 1982) is presented in

Figs. 1 and 2. The latitudinal and layered separation of polar and subtropical jet streams is clearly portrayed in the winter hemisphere. The larger amplitude of the wave structure in the Northern Hemisphere, in contrast with the more zonal flow in the Southern Hemisphere, reflects the influence of continents and oceans in the Northern Hemisphere. Subtropical anticyclones in the 300-310 K isentropic layer are evident over oceanic regions. Note particularly the easterly flow over tropical latitudes in the 340-350 K isentropic layer during July and the Somali jet near 900 mb in the 300-310 K layer in the Indian Ocean that is a feature of the Indian summer monsoon.

The mass transport potential for the 300-310 K and 340-350 K layers portray coupled mass circulations which link regions of heat sources and sinks. The area of maximum (minimum) potential values are regions of quasi-horizontal mass convergence (divergence). By and large, the patterns of the potential functions for the two layers are inverse to each other, thus indicating the two layered structure of the planetary scale horizontal mass transport joined by vertical mass flux in regions of maximum heating and cooling. The strong gradients in both meridional and zonal directions are evidence of Hadley and Walker type circulations which span the entire globe.

During the month of January the dominant feature is the upward mass transport in the Asiatic monsoon centered just east of New Guinea, which is directly linked to the downward mass transport in the northern and southern polar regions, the eastern Pacific, the Sahara and adjacent eastern Atlantic. Strong coupling between high and low latitudes and planetary scale east-west overturning are suggested. Smaller scale features such as upward mass flux over South America and eastern Africa are also evident. Although not shown, the mass circulations in the Northern Hemisphere below 300 K, which occupy mostly the lower troposphere in higher latitudes, clearly indicate the exchange of polar air between continental and oceanic sectors (Johnson and Townsend, 1981). The mass transport between 260 K and 280 K is divergent over the Arctic area and convergent over the oceanic regions just east of Asia and North America. This pattern is reversed between 280 K and 300 K.

For the month of July the Asiatic monsoon has moved northwestward and is centered near the Philippines. Examination of the mass potential functions for April and October reveals that the Asiatic monsoon is a persistent planetary scale phenomenon, moving northwestward in the first half of the year and southeastward in the latter half, thus completing a yearly cycle. The area over the Gulf of Mexico and Mexican highlands is another center of maximum upward mass transport. Downward mass transport prevails over the Pacific and Atlantic Oceans, particularly in the eastern portions of the subtropical anticyclonic circulations.

While the relation between planetary scale circulation and diabatic heating will be clarified in the discussion on diabatic heating, it is evident from mass continuity that for the time averaged circulation, centers of mass convergence (divergence) in lower isentropic layers and divergence (convergence) in higher layers are associated with regions of net upward (downward) mass flux due to heating (cooling). Consequently, the distribution of heat sources and sinks determines the horizontal scale of the isentropic mass transport as well as a systematic scale for the mean mode transport of other properties.

The results for the mass transport discussed here were determined from the FGGE Level IIIa data set. It should be pointed out that the major features of the FGGE IIIA analyses verify with the results of Zillman and Johnson (1982) for the Southern Hemisphere and Otto-Bliesner and Johnson (1982) for the Northern Hemisphere, which were inferred indirectly from climatic heating distributions.

The link to the thermal forcing of the atmosphere is further demonstrated by examining the zonally averaged mass circulation (Townsend and Johnson, 1981) shown in Fig. 3. In contrast to the three-celled structure observed in isobaric coordinates, a direct cell with upward mass flux in association with net heating in the tropics and downward mass flux in association with net cooling in polar regions spans each hemisphere. The intensity is stronger in the winter hemisphere. The secondary direct cell in the extratropical regions in northern winter is related to the latent and sensible heating in lower isentropic layers over the oceanic regions off the east coasts of Asia and North America. The isentropic mass transport which includes geostrophic and ageostrophic modes (Townsend, 1980; Townsend and Johnson, 1981) is mostly accomplished by the ageostrophic mode in the tropics and by the geostrophic mode in higher latitudes.

Diabatic heating distribution

With the steady-state assumption and the boundary condition that the vertical mass flux vanishes at the top of the atmosphere, the diabatic mass transport within the atmosphere determined by vertically integrating the isentropic mass continuity equation is given by

$$\overline{\rho J_\theta \dot{\theta}} = \int_{\theta}^{\theta_T} \overline{\nabla_\theta \cdot \rho J_\theta \underset{\sim}{U}} \, d\theta \ . \tag{4}$$

The diabatic heating rate obtained from the definition of mass weighted average is related to the diabatic mass transport by

$$\hat{\dot{\theta}} = \overline{\rho J_\theta \dot{\theta}}/\overline{\rho J_\theta} \ . \tag{5}$$

The vertically averaged diabatic heating for January and July 1979 are shown in Fig. 4. During January the heating in the Asiatic monsoon centered just east of New Guinea exceeds 1.5 K day^{-1}. Cooling in the eastern equatorial Pacific is over 1 K day^{-1}. The heating and cooling correspond respectively with the upward and downward branches of a Walker circulation. Heating due to convection is clearly identifiable over South America and eastern Africa. Except for the heating due to air-sea interaction and latent heat release along the storm tracks just off the Asian and North American continents, the polar regions in the Northern Hemisphere, the interior of the two continents and the desert area in Africa are all dominated by cooling. During July, the fully developed Indian summer monsoon is now part of the Asiatic monsoon system. Maximum heating over 1.5 K day^{-1} extends from Tibet and the

Philippines into the western Pacific. The heating rate associated with intense convection over Central America is more than 1 K day^{-1}. The Intertropical Convergence Zone is located mostly north of the equator and meanders around the globe. The contrast between net heating over land and net cooling over the oceans is particularly evident in the Northern Hemisphere. Most of the southern oceans experience cooling with heating in some regions being related to cyclone activity. A cross-comparison between the heating distribution and the isentropic mass transport verifies that the horizontal scales of mass circulation correspond to that of the heating distribution, a result fundamental to the concept of thermal forcing.

Global three dimensional estimates of the diabatic heating distribution have been limited in the past. One such attempt was by Budyko (1963). His annually averaged diabatic heating determined by summing up the radiational, sensible and latent heating is compared with the annually averaged heating determined from the FGGE IIIA data set (Fig. 5). In view of the difference in methodology and data sources, the similarity between the two analyses in both a qualitative and quantitative sense is striking. Listing some of the key similarities, heating occurs over central Africa, the equatorial Indian Ocean, the East Indies, the western equatorial Pacific with two branches stretching eastward into the North and South Pacific, and then connecting with heating over South America and the equatorial Atlantic. Net heating is also shown in the eastern portion and coastal regions of Asia and North America. Cooling prevails over the polar latitudes, the interior of continents and the eastern portion of the North and South Pacific and the Atlantic. Perhaps the most notable difference occurs over Australia and adjacent south Pacific. Whether this is characteristic of the FGGE year or is due to spurious information has not been resolved at this point.

Planetary scale energy transport

With a similar approach to the analyses of the mass circulation, the energy transport can be studied by examining the stream and potential functions shown in Figs. 6 and 7 (Johnson, Townsend and Wei, 1981). A two-layered structure that is characteristic of the isentropic horizontal mass transport (Fig. 8) is also evident in the energy transport. Except for scaling, the rotational and irrotational components of the energy transport are nearly identical with the corresponding components of the mass transport. This suggests that the sense and intensity of the energy transport is primarily determined by the mass circulation which in turn is directly linked to the planetary scale distribution of heat sources and sinks.

Under the steady assumption, the vertically integrated mass divergence vanishes everywhere while the vertically integrated energy transport must be divergent in heat source regions and convergent in heat sink regions. This requires that the upper branch of the isentropic mass circulation exports more energy from the heat source to the heat sink region than the reverse lower branch imports from the heat sink to the heat source region. The results verify this requirement. The potential function for the vertically integrated energy transport during January (Fig. 9) shows divergence over the Asiatic monsoon area, South America, eastern Africa and east coasts of Asia and North America as well as convergence over polar and oceanic regions. A decomposition of the total isentropic energy transport into mean and eddy modes also establishes that the mean mode isentropic transport dominates the eddy mode, thus implying that it is the thermally forced isentropic mass circulation which primarily determines the energy transport (Johnson and Townsend, 1981). Note that such vertically integrated results and conclusions regarding energy transport are not dependent upon the coordinate framework utilized. The net energy transport across each latitude during January and July 1979 for the zonally averaged circulation is also accomplished primarily by the mean mass circulation in the isentropic framework (Townsend, 1980; Townsend and Johnson, 1981).

Planetary angular momentum transport

Potential functions for the planetary-scale transport of angular momentum during January 1979 are presented in Figures 10A through D from Johnson, Wei and Schaack (1981). See attached paper for the angular transport equations and preliminary analysis. The interpretation of the patterns of the divergence of quasi-horizontal angular momentum transport and the vertical diabatic flux is best accomplished through a comparison with the mass circulation in Fig. 1. Note in Fig. 10A that in the tropical region of the Asiatic monsoon, the angular momentum transport is convergent where the mass circulation is convergent. This region is located beneath a region of strong divergence of both the horizontal mass and angular momentum transport at the 340-350 K isentropic layer. Inspection of the two levels indicates that the vertically-integrated angular momentum transport from this region would be divergent due to the dominance of the divergence in the upper levels. This result shows the means by which angular momentum created within the easterly trade wind regimes of the Pacific tropical latitudes is carried upward through diabatic convective transport (Figs. 10C and D) and then transported meridionally and zonally to sink regions by planetary-scale transport. This region must be considered to be a primary source of angular momentum for the upper tropospheric westerlies in both hemispheres. It is extremely interesting, however, to note that the strong degree of the zonal variation of the fields of the horizontal and vertical divergence of angular momentum transport in Fig. 10 suggests that the impact of differential heating in the redistribution of angular momentum is substantial. The transient vertical diabatic flux of angular momentum has not been estimated at this time. This component is, in all probability, important in the vertical redistribution of angular momentum particularly in regions where moist convection is important.

Two particularly interesting features in the distribution of the 290-300 K potential function for angular momentum transport are the divergent angular momentum transport over Asia and convergent transport over the north central Pacific. During the winter, the Siberian high and Aleutian low are quasi-stationary features of the high latitude circulation. By virtue of the pressure and viscous stresses at the lower boundary and the relative circulation, angular momentum will be transferred from the earth to the atmosphere within the Siberian anticyclonic circulation and from the atmosphere to the earth in the Aleutian cyclonic circulation (Johnson and Downey, 1976; Lenzen, 1980). The patterns clearly suggest that angular momentum created in the Siberian region is transported quasi-horizontally to the Aleutian region; thus, the maintenance of these two circulations, one anticyclonic and the other cyclonic, are closely coupled. These circulations are also closely coupled with the isentropic mass circulation (Fig. 2) through which eastward moving cold Siberian air is heated over the warm western Pacific during periods of strong cyclogenesis (Johnson and Townsend, 1981).

The distribution of the potential function for pressure torques (Johnson and Downey, 1975) is presented in Figs. 10E and F. Within the time-averaged angular momentum transport, the results show that a portion of the angular momentum transported from the Asian to the Aleutian sector is transferred in the reverse sense from the Aleutian to the Asiatic sector by waves within the westerlies. However, the net gradient of potential between the two regions is less in Fig. 10E than in Fig. 10A suggesting that the net of the angular momentum transport and pressure torque transfers angular momentum from the Siberian high to the Aleutian low. In any event, some poleward and meridional transport of angular momentum results from the fact that the large relative extrema of the potential function for pressure torques near 45°N for the 290-300 K layer appear at the same latitude while the corresponding extrema in the angular momentum transport potential function are displaced meridionally. With Eliassen's (1951) perspective of the forcing of the mass circulation, the positive torque over Asia forces polar air equatorward while the negative torque over the north central Pacific forces subtropical air poleward. Such forcing is basic to the maintenance of the Asiatic winter monsoonal mass circulation. The zonal average of such torques are a primary degree of freedom by which the isentropic mass circulation is forced within extratropical latitudes (Gallimore and Johnson, 1981).

III. THE LINK BETWEEN MASS AND ENERGY TRANSPORT

At the recent International Conference on the Scientific Results of the Monsoon Experiment at Bali, a question was asked which dealt with why the diabatic heating distribution can be determined with relative ease from analysis within isentropic coordinates and why is the matter so difficult in isobaric coordinates. An answer to this question and an understanding of the nature of the problem is important to appreciate fully the research outlined in this document; either currently in progress or proposed for the future. In a discussion of this question, an analysis of the mass circulation attending convection in a simple system is first developed, after which the more general problem of mass and energy transport is pursued. The results in this section and the following section are part of a manuscript being prepared for publication.

Isobaric and isentropic mass circulations for a simple system

Based on methodology used in convective parameterization (e.g., Arakawa and Schubert, 1974) the simple system will consist of a cumulus cloud with upward vertical motion $\omega_1<0$ within its areal extent (A_1) and downward vertical motion $\omega_2>0$ over the areal extent (A_2) of the immediate environment. See schematic in Fig. 11. The areally averaged large scale vertical motion ω^A for the total area A equal to A_1 plus A_2 is given by

$$\overline{\omega}^A = (A_1\omega_1 + A_2\omega_2)/A \ . \qquad (6)$$

With the isobaric vertical motion divided into adiabatic and diabatic components

$$\omega = \omega_a + \omega_d \,, \tag{7}$$

substitution in (6) with the diabatic component of the environment equal to zero and a rearrangement yields

$$A_1\omega_{d1} = \overline{A\omega}^{A} - [A_1\omega_{a1} + A_2\omega_{a2}] \,. \tag{8}$$

Given the nature of atmospheric compensation as manifested in isobaric coordinates, the latent heat released within clouds does not directly warm the environment. Instead, the environment is warmed by subsidence while the latent heat release offsets the adiabatic cooling due to the upward motion within the cumulus. As a first approximation the upward mass flux $A_1\omega_1$ within the cloud tends to balance the downward mass flux $A_2\omega_2$ in the environment. In such a case, the area averaged vertical mass flux vanishes and (8) reduces to

$$\omega_{d1} = -\, [\omega_{a1} + (A_2/A_1)\omega_{a2}] \,. \tag{9}$$

The result points out the fine state of balance that exists between diabatic and adiabatic components of vertical motion in regions of cumulus convection, the intensities of which are modulated by the ratio of the area of ascent to descent. Such compensation is characteristic of an atmosphere within which the large scale motion tends to be non-divergent. Note under these conditions that an integration of the isobaric equation of continuity over the area A and use of the divergence theorem yields

$$\int_A \frac{\partial \omega}{\partial p}\, dA = \frac{\partial}{\partial p}\int_A \omega \, dA = 0 \tag{10}$$

$$= -\int \underset{\sim}{n}\cdot\underset{\sim}{U}\, dl = 0 \tag{11}$$

provided that exact compensation occurs at all levels. The results point out that the areally averaged horizontal divergence in isobaric coordinates is not uniquely linked to diabatic processes, thus allowing the larger scale flow away from the convective region to be non-divergent even in the presence of deep convection. Consequently, the isobarically analyzed mass circulation attending this scale of convection may be of local or regional nature, with no requirement for the mass circulation forced by convection in a heat source region to be systematically linked with a branch of a large scale circulation that transports energy to a heat sink. The isobaric energy transport for the large scale, in latitudes where atmospheric motion tends to geostrophic balance, is through eddy transport processes (Lorenz, 1967). Consequently, an isobaric analysis of the divergent component of the mass circulation does not yield insight directly on the planetary scale distribution of differential heating and energy transport within the atmosphere.

Now the consequences of the diabatic heating are explored within isentropic coordinates. For the time scale during which convection is occurring in this example, quasi-steady conditions are assumed for the hydrostatic mass ($g^{-1}\partial p/\partial\theta$), an inverse measure of the thermal stratification. For this example the areally averaged vertical mass flux in isentropic coordinates defined by

$$\overline{\rho J_\theta \dot{\theta}}^{A} = \frac{1}{A} \int \rho J_\theta \dot{\theta} \, dA \tag{12}$$

is given by

$$\overline{\rho J_\theta \dot{\theta}}^{A} = (A_1/A) \, \rho J_\theta \dot{\theta} > 0 \, . \tag{13}$$

Thus upward vertical mass flux exists with respect to the stratification. An integration of the isentropic equation of continuity from the level of maximum heating θ_m to the top of the atmosphere θ_T over the area A, along with the condition that the vertical mass flux through the top of the atmosphere vanishes and use of (13), yields

$$\begin{aligned} \int_A \int_{\theta_m}^{\theta_T} \frac{\partial}{\partial\theta} \rho J \dot{\theta} \, d\theta dA &= - \int_A \rho J_\theta \dot{\theta} \Big|^{\theta_m} dA \\ &= - \int_{\theta_m}^{\theta_T} \int \underset{\sim}{n} \cdot \rho J \underset{\sim}{U} \, dl d\theta < 0 \, . \end{aligned} \tag{14}$$

Within the stratification of the atmosphere, this establishes that the mass circulation above the level of maximum heating must be divergent while below this level the mass circulation must be convergent. Since these conditions result in systematic horizontal mass transport through the lateral boundary, the mass circulation in the region of convection is linked with the mass circulation of the environment regardless of the characteristic state of dynamic balance of the motion field.

In view of the condition that the global scale of differential heating determines systematic vertical mass flux within isentropic coordinates, the length scale of the horizontal branches of the isentropic mass circulation is determined by the distance between heat source and sink. See schematic in Fig. 12. Thus analysis of the isentropic mass circulation yields insight directly on the planetary scale of differential heating while analysis of the isobaric mass circulation does not. It should be recognized that the discussion of this simple system up to this point has not involved explicitly any requirements for energy transport. However, the requirement of a systematic mass circulation with low level inflow and upper level outflow provides for systematic export of energy from the domain. In a hydrostatic atmosphere the

$$\int_{\theta_{S_0}}^{\theta_T} \frac{\partial}{\partial t_\theta}\overline{(\rho J_\theta e)}\, d\theta + \int_{\theta_{S_0}}^{\theta_T} \nabla_\theta \cdot \overline{(\rho J_\theta \underset{\sim}{U} \nu)}\, d\theta = - \int_{\theta_{S_0}}^{\theta_T} \overline{\psi \frac{\partial}{\partial \theta}(\rho J_\theta \dot{\theta})}\, d\theta + \overline{p_S \frac{\partial z_S}{\partial t_\theta}} - \overline{E^2} \qquad (18)$$

where E^2 is the vertically integrated time-averaged viscous dissipation function. With the of averaging over an appropriate time interval for which the steady assumption becomes valid and fixing the earth-atmosphere interface, (18) reduces to

$$\int_{\theta_{S_0}}^{\theta_T} \nabla_\theta \cdot \overline{(\rho J_\theta \underset{\sim}{U} \nu)}\, d\theta + \overline{E^2} = - \int_{\theta_{S_0}}^{\theta_T} \overline{\psi \frac{\partial}{\partial \theta}(\rho J_\theta \dot{\theta})}\, d\theta = \int_{\theta_{S_0}}^{\theta_T} \overline{\rho J_\theta \dot{\theta} \frac{\partial \psi}{\partial \theta}}\, d\theta \qquad (19)$$

where boundary conditions that energy flux vanishes at θ_T and θ_S ($\rho J_\theta = 0$ for $\theta < \theta_S$) have been utilized. With ψ always positive and monotonically increasing upward, energy advection is upward in regions of heating and the vertically integrated horizontal energy transport is divergent, while in regions of cooling, the energy advection is downward and the horizontal energy transport is convergent.

The sense of the energy transport

The balance of the energy transport in (19) is between the divergence of the energy transport vector and viscous decay of kinetic energy on the left hand side and the source of energy by diabatic processes on the right hand side. Although this relation is expressed in isentropic coordinates, the result is general in the sense that the vertical integration demands that the scale and intensity of the integrated horizontal transport of total energy be invariant with respect to coordinate systems. Thus the balance as well as the sense of the energy transport determined by the following analysis is of a general nature.

For illustrative purposes in this analysis for the planetary scale, geographic regimes of diabatic heating are assumed to be distinct from regimes of diabatic cooling. Within each regime, profiles of vertical diabatic mass flux are assumed to increase or decrease monotonically from zero to an extremum at some intermediate isentropic surface, θ_m, within the atmosphere, above which the magnitude of the mass flux decreases back to zero. The maximum magnitude for the vertical mass flux occurs through the surface θ_m within each geographic domain of cooling or heating. See Fig. 8 for characteristic profiles of heating and cooling determined from a diagnostic study of the time-averaged isentropic mass transport.

A vertical integration of the derivative of the vertical mass flux from the earth's surface to the top of the atmosphere yields

$$\overline{\int_{\theta_{S_0}}^{\theta_T} \frac{\partial}{\partial \theta}(\rho J_\theta \dot{\theta})\, d\theta} = 0 \ . \qquad (20)$$

With a division into a lower and an upper layer separated by a level of maximum absolute value of the vertical mass flux, $\theta_m(t)$, (20) becomes

$$0 = \overline{\int_{\theta_{s_o}}^{\theta_T} \frac{\partial}{\partial\theta}(\rho J_\theta \dot{\theta})\,d\theta} = \overline{\int_{\theta_{s_o}}^{\theta_m(t)} \frac{\partial}{\partial\theta}(\rho J_\theta \dot{\theta})_\ell\,d\theta} + \overline{\int_{\theta_m(t)}^{\theta_T} \frac{\partial}{\partial\theta}(\rho J_\theta \dot{\theta})_u\,d\theta} \,. \qquad (21)$$

Under the assumed conditions for the profiles of heating, the right hand integrals are equal in magnitude and opposite in sign. The level of maximum upward (downward) diabatic mass transport, $\theta_m(t)$, separates the lower layer (ℓ) where the upward (downward) mass transport is increasing (decreasing) with respect to potential temperature from the upper layer (u) where the upward (downward) mass transport is decreasing (increasing). Thus, in regimes of heating, $\partial(\rho J_\theta \dot{\theta})_\ell/\partial\theta$ is positive and $\partial(\rho J_\theta \dot{\theta})_u/\partial\theta$ is negative, while in regions of cooling, $\partial(\rho J_\theta \dot{\theta})_\ell/\partial\theta$ is negative and $\partial(\rho J_\theta \dot{\theta})_u/\partial\theta$ is positive. Now the right hand integral of the energy transport equation (19), similarly split into two parts, is given by

$$\int_{\theta_{s_o}}^{\theta_T} \overline{\nabla_\theta \cdot (\rho J_\theta U \underset{\sim}{v})}\,d\theta + \overline{E^2} = -\left[\overline{\int_{\theta_{s_o}}^{\theta_m(t)} \psi \frac{\partial}{\partial\theta}(\rho J_\theta \dot{\theta})_\ell\,d\theta} + \overline{\int_{\theta_m(t)}^{\theta_T} \psi \frac{\partial}{\partial\theta}(\rho J_\theta \dot{\theta})_u\,d\theta}\right] . \qquad (22)$$

Since $\partial(\rho J_\theta \dot{\theta})/\partial\theta$ of each integral is either positive or negative, by the mean value theorem (22) becomes

$$\int_{\theta_{s_o}}^{\theta_T} \overline{\nabla_\theta \cdot (\rho J_\theta U \underset{\sim}{v})}\,d\theta + \overline{E^2} = \overline{-\psi_\ell \int_{\theta_{s_o}}^{\theta_m(t)} \frac{\partial}{\partial\theta}(\rho J_\theta \dot{\theta})_\ell\,d\theta} \; \overline{-\psi_u \int_{\theta_m(t)}^{\theta_T} \frac{\partial}{\partial\theta}(\rho J_\theta \dot{\theta})_u\,d\theta} \,, \qquad (23)$$

where the inequality $\psi(\theta_{s_o}) < \psi_\ell < \psi(\theta_m) < \psi_u < \psi(\theta_T)$ is always satisfied within the vertical column of a hydrostatic atmosphere. Again, with the uniqueness of the sign of each right hand integral, the mean value theorem is used with respect to the averaging integral over time to determine the result from (23) that

$$\int_{\theta_{s_o}}^{\theta_T} \overline{\nabla_\theta \cdot (\rho J_\theta U \underset{\sim}{v})}\,d\theta + \overline{E^2} = -\tilde{\psi}_\ell \overline{\int_{\theta_{s_o}}^{\theta_m(t)} \frac{\partial}{\partial\theta}(\rho J_\theta \dot{\theta})_\ell\,d\theta} - \tilde{\psi}_u \overline{\int_{\theta_m(t)}^{\theta_T} \frac{\partial}{\partial\theta}(\rho J_\theta \dot{\theta})_u\,d\theta} \qquad (24)$$

where the tilde over ψ_u and ψ_ℓ represents an appropriate mean value over the time interval of averaging. With a combination of (21) and (24), the final result is

$$\int_{\theta_{s_o}}^{\theta_T} \overline{\nabla_\theta \cdot (\rho J_\theta U \underset{\sim}{v})}\,d\theta + \overline{E^2} = -(\tilde{\psi}_u - \tilde{\psi}_\ell) \overline{\int_{\theta_m(t)}^{\theta_T} \frac{\partial}{\partial\theta}(\rho J_\theta \dot{\theta})_u\,d\theta} \,. \qquad (25)$$

Since ψ_u is always greater than ψ_ℓ in a hydrostatic atmosphere at each point in time, the value of energy of the time-averaged state expressed by ψ_u is always greater than ψ_ℓ and the difference $(\psi_u - \psi_\ell)$ is always positive. With this result and the condition that E^2 is always positive, the energy transport equation (25) states that for quasi-steady conditions the energy transport is directly coupled with the vertical mass transport that is determined by the distribution of diabatic heating.

With $\partial(\rho J_\theta \theta)_u/\partial\theta$ being negative in regions of heating, the vertically integrated energy transport for a region of heating must be divergent with the result that the layers above θ_m export more energy than the lower levels import. Likewise with $\partial(\rho J_\theta \theta)_u/\partial\theta$ being positive in regions of cooling, the vertically integrated energy transport must be convergent with the result that the layers above θ_m import more energy than the lower layers export.

With the steady assumption and constraint on the mass circulation, one can now conclude that the net energy transport from source to sink region represented by (25) occurs through the condition that the upper branch of the mass circulation transports more energy from source to sink region than is returned by the lower return branch.

While these results may be self-evident from physical considerations, it is important to recognize that the sense of the isentropic mass transport uniquely determines both the sense of the energy transport and the scale of the energy transport, all of which are determined by the planetary distribution of heat sources and sinks. The actual amount of energy transported depends explicitly on the combination of the heating and mass distribution (the latter also determines ψ through integration of the hydrostatic equation) while the modes of energy transport are free to be transient or steady, divergent or nondivergent, geostrophic or ageostrophic, etc. The modes of energy transport are determined through the mutual adjustment of mass and momentum, the boundary conditions and the time scales of the thermodynamic and inertial forcing.

IV. ISOBARIC AND ISENTROPIC DIAGNOSTICS OF THE ZONALLY AVERAGED ATMOSPHERE

The comparison of the isobaric and isentropic diagnostic results demonstrates that the mean and eddy statistical structures of transport processes within the circumpolar vortex are coordinate dependent. The differing results for these statistics computed in isobaric and isentropic coordinates are not contradictory but emerge from a non-uniqueness of statistics computed within a particular coordinate system. In this case the differences stem largely from the representation of the mass distribution, being horizontally uniform in isobaric coordinates, in contrast with a horizontally variable distribution within the isentropic coordinate system. As a result the isobaric and the isentropic transport processes within the circumpolar vortex correspond to the modes of transport permitted within a vortex with a symmetric mass distribution and a vortex with an asymmetric mass distribution, respectively.

The zonally-averaged isobaric mean and eddy structures computed from FGGE Level IIIa analyses are basically consistent with the results of past investigations conducted in isobaric coordinates. Thus, based on Level IIIa data, the general circulation during the FGGE year does not appear to be anomalous with one possible exception. The Hadley circulation of the winter Northern Hemisphere is weaker than previous results suggest. This discrepancy has not been completely resolved.

The diagnostic analyses in isobaric coordinates of the mass, angular momentum, and energy balance of the zonally-averaged circulation support the current theory of the forcing and maintenance of the general circulation from an isobaric perspective. The mass circulations consist primarily of direct Hadley cells in low latitudes and indirect Ferrel cells in mid-latitudes of both hemispheres with the Hadley circulations, in particular, demonstrating remarkable seasonal variation in strength and location. Transport by the ageostrophic mean meridional circulations in tropical latitudes and by the large scale eddies in extratropical latitudes maintains the angular momentum and energy balance of the circumpolar vortex in each hemisphere. In the Northern Hemisphere both the transient and standing eddy modes of angular momentum and energy transport are important while the transient mode clearly dominates in the Southern Hemisphere.

In contrast with the isobaric perspective, the isentropic perspective of the forcing and maintenance of the circumpolar vortex is fundamentally different. Within the isentropic framework a mean meridional circulation is isolated from the observed mass and wind fields that displays a scale of response which is directly determined by the scale of the thermodynamic forcing. The asymmetric structure of active mid-latitude baroclinic waves provides the degree of freedom for a geostrophic mean mode of transport associated with net positive and negative torques within the zonally-averaged isentropic structure. The combination of an ageostrophic mean mode of mass transport in tropical latitudes and a geostrophic mean mode of mass transport in extratropical latitudes yields a Hadley-type mass circulation which spans the hemisphere and explicitly links the planetary scale heat sources and sinks. The geostrophic mean mode of mass transport occurring within the wave regime and the ageostrophic mean mode in low latitudes are components of the isentropic response to large scale differential heating.

The diabatic heating distributions calculated indirectly from the isentropic mean meridional mass transport reveal realistic seasonal variations in the intensity and location of the heat sources and sinks of the zonally-averaged atmosphere. A primary heat source in tropical latitudes associated with latent heat release within the ITCZ is well-defined during all seasons and is a maximum in the summer Northern Hemisphere due to intense convection within the Asiatic monsoon. Another principal heat source in the

Besides the modes of transport, the forcing of the mass circulations is different in the isobaric and isentropic coordinate systems. The isobaric Hadley and Ferrel circulations can be explained only by considering the forcing due to the divergence of eddy heat transport and the divergence of the eddy transport of relative angular momentum. Within the isentropic framework the lateral branches of the Hadley-type mass circulation spanning the hemisphere are forced by a combination of pressure torques in mid-latitudes and a friction torque in low-latitudes; whereas, the vertical branches are forced explicitly by diabatic heating.

Basic to all the diagnostic results is the fundamental condition that large scale differential heating in association with rotation forces atmospheric motion. A mean circulation linking planetary scale heat sources and sinks has not been isolated in an isobaric coordinate system. In latitudes where the earth's rotation is important, the scale of response within the isobaric framework corresponds to the scale of the quasi-horizontal waves. However, within the zonally-averaged isentropic structure a mean circulation is isolated from the observed mass and wind fields that directly couples the planetary scale heat sources and sinks. The scale and intensity of the atmospheric response is explicitly determined by the scale and intensity of the differential heating.

Northern Hemisphere mid-latitudes associated with sensible and latent heating over oceanic areas off the east coasts of the Asian and North American continents attains maximum intensity during the winter season. Regions of energy deficit or heat sinks include the middle and upper troposphere in the subtropical latitudes of the winter hemisphere, the higher latitudes of the Southern Hemisphere, and the polar region of the Northern Hemisphere.

Both mean and eddy modes of transport exist to satisfy the relative angular momentum balance requirement of the general circulation in isentropic coordinates. The isentropic mean meridional circulation is the dominant means of relative angular momentum transport in low latitudes and provides some net poleward transport in middle latitudes. However, the transient and standing eddy circulations accomplish most of the required relative angular momentum transport in extratropical latitudes of the Northern Hemisphere while the transient mode dominates in the southern extratropical region. Within the isentropic structure a physical means exists for the vertical transfer of angular momentum that is not present in an isobaric framework. Through the action of net pressure stresses or torques within isentropic layers of the zonally-averaged atmosphere, absolute angular momentum is transferred downward from the upper to lower isentropic layers.

Diagnostic analysis of the energy balance confirms the interesting concept that mean mass circulations within the zonally-averaged isentropic structure determine the scale and sense of energy exchange. The Hadley-type mean meridional circulation provides virtually all the energy transport; whereas, the isentropic standing eddy and transient modes of energy transport are not important. The energy flux is upward in regions of heating (energy source) and downward in regions of cooling (energy sink). To maintain large scale balance the thermally-forced isentropic mass circulations transport energy from heat source to heat sink in higher isentropic layers and from heat sink to heat source in lower isentropic layers.

From the isobaric and isentropic perspectives of the general circulation the baroclinic waves in the westerlies and embedded extratropical cyclones play fundamental but different roles in the large scale transport processes. In the isobaric framework the baroclinic waves contribute primarily to an eddy mode of angular momentum and energy transport. Within the isentropic structure the active baroclinic waves provide the degree of freedom for a geostrophic mean mode of transport which accounts for nearly all of the energy transport in mid-latitudes and some of the angular momentum transport. Interestingly, the baroclinic wave structure in isentropic coordinates yields the dominant eddy mode of relative angular momentum transport and at the same time provides virtually no energy transport by the eddy mode.

INSTRUCTIONS FOR FINAL PROJECT REPORT
(NSF FORM 98A)

This report is due within 90 days after the expiration of the award. It should be submitted in two copies to:

National Science Foundation
Division of Grants and Contracts
Post-Award Projects Branch
1800 G Street, N.W.
Washington, D.C. 20550

INSTRUCTIONS FOR PART I

These identifying data items should be the same as on the award documents.

INSTRUCTIONS FOR PART II

The summary (about 200 words) must be self-contained and intelligible to a scientifically literate reader. Without restating the project title, it should begin with a topic sentence stating the project's major thesis. The summary should include, if pertinent to the project being described, the following items:

- The primary objectives and scope of the project.
- The techniques or approaches used only to the degree necessary for comprehension.
- The findings and implications stated as concisely and informatively as possible.

This summary will be published in an annual NSF report. Authors should also be aware that the summary may be used to answer inquiries by nonscientists as to the nature and significance of the research. Scientific jargon and abbreviations should be avoided.

INSTRUCTIONS FOR PART III

Items in Part III may, but need not, be submitted with this Final Project Report. Place a check mark in the appropriate block next to each item to indicate the status of your submission.

a. Self-explanatory.
b. For publications (published and planned) include title, journal or other reference, date, and authors. Provide two copies of any reprints as they become available.
c. Scientific Collaborators: provide a list of co-investigators, research assistants and others associated with the project. Include title or status, e.g. associate professor, graduate student, etc.
d. Briefly describe any inventions which resulted from the project and the status of pending patent applications, if any.
e. Provide a technical summary of the activities and results. The information supplied in proposals for further support, updated as necessary, may be used to fulfill this requirement.
f. Include any additional material, either specifically required in the award instrument (e.g. special technical reports or products such as films, books, studies) or which you consider would be useful to the Foundation.