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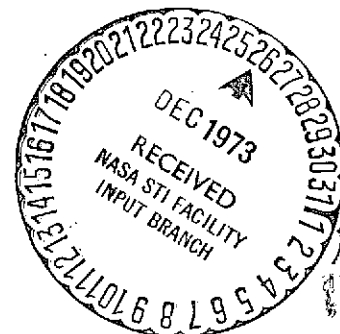
FINAL REPORT

on

INVESTIGATION OF MODELS FOR LARGE-SCALE  
METEOROLOGICAL PREDICTION EXPERIMENTS

by

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## Introduction

Grant NGR 33-016-174 was initiated at New York University (NYU) on 1 November 1971 for a nominal period of one year, and extended for a second year with an expected anniversary date of 31 October 1973. Because of the closing of the NYU School of Engineering and Science on 31 August 1973, the grant has been prematurely terminated as of the latter date. By accelerating our efforts in anticipation of the NYU closing, we have been able to accomplish most of our research objectives. However, as noted below, two of our principal research results will not be ready for publication before the new termination date, although all the computations and most of the figures have been completed. This report does, nevertheless, present a brief account of all the research completed since the inception of the grant.

The major purpose of the research project has been to carry out two main tasks in cooperation with the Goddard Institute for Space Studies (GISS). The first task was to provide assistance to GISS in its work on the development and application of numerical-dynamical models of the atmospheric global circulation. The second task has been to answer certain basic questions regarding the feasibility of long-range weather prediction by dynamical methods. The principal effort under the second task was devoted to studies of long term responses of the model atmosphere to anomalies in snow cover and sea surface temperature (SST).

Technical support to GISS, as part of the first task, was carried out primarily through conferences and visits to GISS by the principal investigator. Experimental outputs from several dynamical prediction models developed at GISS were analyzed in concert with the GISS staff to determine if the models faithfully simulated properties of the real atmosphere. Most of this work was associated with the efforts at GISS to develop a global nine-level atmospheric model on the foundation of the original two-level model developed at UCLA by Mintz and Arakawa. No reports or publications by the NYU project staff resulted from this phase of the project, as our contributions were mainly consultative and advisory.

Most of the project work has been devoted to the second task, with primary emphasis on the response of the two-level Mintz-Arakawa general circulation model to pools of anomalously warm SST in the North and South Pacific Oceans. Three reports and two publications, plus a third probable publication, have resulted thus far from these efforts. Two additional reports, by research assistants, S.H. Chow and L. Lewis, are now being completed as a Ph.D. thesis and M.S. thesis respectively, and will be submitted for publication at a later date. In this final report, the results already reported and/or published are presented only in the form of abstracts. However, a more extensive account of the work by Chow and Lewis is given here, as that work has not been previously reported.

Most of the computations for this research project were carried

out on the IBM 360/95 computer at GISS through the courtesy of Dr. Robert Jastrow, director, and Dr. Milton Halem, and with the aid of Mr. John Liu. Some preliminary computations were performed on the UNIVAC 1108 computer at NYU.

### Reports and Publications

The following technical reports have already been distributed.

Jerome Spar, "Effects of Surface Anomalies on Certain Model  
Model Generated Meteorological Histories". NYU Geophysical Sciences Laboratory Report No. GSL-TR-72-2, April 1972. 54 pages.

Jerome Spar, "Transequatorial Effects of Sea Surface Temperature Anomalies in a Global General Circulation Model". NYU Geophysical Sciences Laboratory Report No. GSL-TR-72-7, September 1972. 28 pages.

Jerome Spar, "Supplementary Notes on Sea Surface Temperature Anomalies and Model-Generated Meteorological Histories". NYU Geophysical Sciences Laboratory Report No. GSL-TR-72-9, December 1972. 24 pages.

The following paper has been published.

Jerome Spar, "Some Effects of Surface Anomalies in a Global General Circulation Model", Monthly Weather Review, Vol. 101, No. 2, February 1973, pp. 91-100.

The following paper has been accepted for publication in the July (or August) 1973 issue of the Monthly Weather Review.

Jerome Spar, "Transequatorial Effects of Sea Surface Temperature Anomalies in a Global General Circulation Model".

The following paper has been submitted for publication to the Monthly Weather Review, and is now in the editorial review process.

Jerome Spar, "Supplementary Notes on Sea Surface Temperature Anomalies and Model-Generated Meteorological Histories".

A report on the project research was presented by Jerome Spar in the form of an invited paper at a conference on "Climatic Changes on Time Scales from a Month to Millenia" at the Scripps Institution of Oceanography in La Jolla, Calif. on 15-17 November 1972. This paper, titled "Response of a Model Atmosphere to Monthly and Seasonal Sea Surface Temperature Anomalies", is described briefly in the review of the conference published in the Bulletin of the American Meteorological Society, Vol. 54, No. 5, May 1973, pp. 425-432.

## Computed Responses to Surface Anomalies in a Global Atmospheric Model

(Abstracts of previously issued reports and publications)

The Mintz-Arakawa 2-level general circulation model was used in a series of experiments to compute the response of the model atmosphere to (1) a positive sea surface temperature (SST) anomaly in the North Pacific Ocean in summer and in winter, (2) an identical anomaly in the South Pacific Ocean in the southern hemisphere winter season, and (3) anomalous northward and southward displacements of the northern hemisphere snow line over the continents. In each case computations were carried out for 90 "forecast" days. Results were studied in terms of the differences between anomaly and control histories. Time series of certain regional response indices, including area-average sea level pressure and 600 mb circulation indices, as well as 30-day mean sea level pressure maps, were used in the analysis.

The experiments showed significant interhemispheric effects after about one month, phase shifts of 1-2 weeks in major cyclonic developments, stronger reactions to sea temperature anomalies in winter than in summer, and marked influence of the snow line on the winter monsoonal pressure difference between the continents and the North Atlantic Ocean.

The global response of the atmosphere, as simulated by the Mintz-Arakawa model, to a persistent, anomalous pool of warm sea surface temperatures in the extratropical Pacific Ocean was also examined in terms of the meridional pole-to-pole profile of the zonally-

averaged 600 mb surface for periods up to 90 days. Following an initial hydrostatic inflation of the isobaric surface in the latitude of the warm pool, effects spread poleward within the hemisphere, then began to appear after about two to three weeks in high latitudes of the opposite hemisphere, but with little or no response in the tropics. The same sea temperature anomaly field generated a stronger response in winter than in summer, and a very different reaction when located in the Southern Hemisphere than when in the Northern Hemisphere. After a month of thermal forcing, the response to the SST anomaly was at least as large in the opposite hemisphere as in the hemisphere of the anomaly. The winter hemisphere responded more rapidly to the SST anomaly in the opposite hemisphere than did the summer hemisphere. Vacillation between low and high meridional wave number patterns was observed in the computed reactions to the warm pool.

In seasonal computations, the Mintz-Arakawa model was found to be sensitive to a minor alteration in the computational program. Effects of the program change on monthly mean sea level pressure fields were small in the first month, but large in the second and third months, although the meteorological histories generated by both the original and modified programs were equally credible.

The inherited effects of a "transient" SST anomaly (lasting only one month) on the computed monthly mean sea level pressure fields over the period of a season were about as large in absolute magnitude as those generated in the model by a "persistent" SST anomaly lasting three months.



The effects of the transient SST anomaly in the North Pacific Ocean on monthly mean temperature and precipitation in the eastern United States were large enough to produce changes corresponding to one or two of the class intervals used by the National Weather Service for these "predicted" weather elements. The model-generated precipitation in the equatorial region was also found to be sensitive to the SST anomaly in the North Pacific.

Effects of a Transient Sea Surface Temperature Anomaly on the  
Energetics of the Mintz-Arakawa Model Atmosphere

(Shu-Hsien Chow)

Some experiments concerning the effects of sea surface temperature (SST) anomalies have been carried out at the Goddard Institute for Space Studies with the two-level Mintz-Arakawa global general circulation model (Gates, et al., 1971). Certain hypothetical anomaly patterns were superimposed on the sea surface temperature field of the Pacific Ocean in those experiments with the anomaly pattern either persistent over a season or over one month. The response of the model atmosphere to the SST anomalies were discussed in terms of the monthly mean sea level pressure patterns and the regional indices. In order to gain more insight into the effects of the anomalies, we have also investigated them from the energetics point of view.

The energetics of the atmosphere have been investigated intensively during the past few years. It is generally confirmed that the major energy source for the atmosphere is the generation of zonal available potential energy by diabatic processes (e.g., Oort, 1964, Dutton and Johnson, 1967). Most of the zonal available potential energy, which is generated by low-latitude heating and high-latitude cooling, is converted into eddy available potential energy (Wiin-Nielsen, Brown and Drake, 1963, 1964), while only a small energy exchange takes place between the zonal available potential energy and the zonal kinetic energy (Wiin-Nielsen, 1959, Saltzman and Fleisher, 1960, 1961).

All the observational studies indicate that energy is transformed from eddy available potential energy to eddy kinetic energy through the rising of warm air and the sinking of cold air around a latitude circle (Wiin-Nielsen, 1959, Saltzman and Fleisher, 1960, 1961, Krueger, Winston and Haines, 1965). A large fraction of the eddy kinetic energy is dissipated by frictional processes, while the remaining small part is converted into zonal kinetic energy for maintaining the zonal wind system (Wiin-Nielsen, Brown and Drake, 1963, 1964).

The basic nature of the energetics of the atmosphere may be changed in unusual circumstances. For example, diagnostic studies of the kinetic energy exchange between zonal flow and large-scale eddies for the troposphere north of  $20^{\circ}\text{N}$  have indicated the existence of an unusual type of circulation in January 1963 (Wiin-Nielsen, Brown and Drake, 1964, Murakami and Tomatsu, 1965, Brown, 1967). Diagnostic calculations for that month indicate that kinetic energy was transformed from zonal flow to large-scale eddies during this winter period, whereas this exchange mechanism is usually in the opposite direction as mentioned before.

The abnormality of the circulation in January 1963 has been studied particularly by Namias (1963) and O'Connor (1963). According to Namias (1963), positive SST anomalies in the central and eastern north Pacific Ocean were quite persistent during the last half of 1962 and early 1963. The case of January 1963 seems to suggest that SST

anomalies may produce significant effects on the energetics of the atmosphere. Following the hints provided by these synoptic and diagnostic studies, we have undertaken to calculate the effects of an SST anomaly on the energetics of the model atmosphere over a period of a season. For these model diagnostic calculations we have used the case of the transient (one month) SST anomaly in the North Pacific Ocean.

The equations for studies of the energetics of the whole global atmosphere in the wave-number domain were first treated systematically by Saltzman (1957) using one-dimensional Fourier analyses around latitude circles. The method of zonal harmonic analysis is also adopted in this study. The energy equations for the  $n$ th component of eddies and for the zonal flow, per unit mass over a latitude belt, may be written as

$$\begin{aligned} (K(n))_t = & F(K(n)) + \langle K_z, K(n) \rangle + \langle K(m), K(n) \rangle \\ & + \langle P(n), K(n) \rangle + W(n) - D(n), \end{aligned} \quad (1)$$

$$\begin{aligned} (P(n))_t = & F(P(n)) + \langle P_z, P(n) \rangle + \langle P(m), P(n) \rangle \\ & - \langle P(n), K(n) \rangle + G(n), \end{aligned} \quad (2)$$

$$(K_z)_t = F(K_z) - \langle K_z, K_E \rangle + \langle P_z, K_z \rangle + W_z - D_z, \quad (3)$$

$$(P_z)_t = F(P_z) - \langle P_z, P_E \rangle - \langle P_z, K_z \rangle + G_z \quad (4)$$

where  $( )_t$  means the partial derivative with respect to time,  $K(n)$  is the eddy kinetic energy of the  $n$ th component,  $P(n)$  is the eddy available potential energy of the  $n$ th component,  $K_z$  is the zonal kinetic energy,  $P_z$  is the zonal available potential energy,  $F(K(n))$  is the flux convergence of eddy kinetic energy of the  $n$ th component,  $F(P(n))$  is the flux convergence of eddy available potential energy of the  $n$ th component,  $F(K_z)$  is the flux convergence of zonal kinetic energy,  $F(P_z)$  is the flux convergence of zonal available potential energy,  $\langle K_z, K(n) \rangle$  is the kinetic energy transfer from zonal flow to eddy of the  $n$ th component,  $\langle P_z, P(n) \rangle$  is the available potential energy transfer from zonal flow to eddy of the  $n$ th component,  $\langle K_z, K_E \rangle$  is the kinetic energy transfer from zonal flow to all the eddies,  $\langle P_z, P_E \rangle$  is the available potential energy transfer from zonal flow to all the eddies,  $\langle K(m), K(n) \rangle$  is the kinetic energy transfer from eddies of other components to the  $n$ th component through nonlinear wave interactions,  $\langle P(m), P(n) \rangle$  is the available potential energy transfer from eddies of other components to the  $n$ th component through nonlinear wave interactions,  $\langle P(n), K(n) \rangle$  is the conversion from available potential energy to kinetic energy for the eddy of the  $n$ th component,  $\langle P_z, K_z \rangle$  is the conversion from available potential energy to kinetic energy for the zonal flow,  $W(n)$  is the energy exchange with the surroundings through the eddy pressure interaction of the  $n$ th component,  $W_z$  is the energy exchange with the surroundings through the zonal pressure interaction,  $D(n)$  is the frictional dissipation of the eddy kinetic energy of the  $n$ th component,  $D_z$  is the frictional dissipation of zonal kinetic energy,  $G(n)$  is the generation of eddy avail-

able potential energy of the  $n$ th component by diabatic heating and  $G_z$  is the generation of zonal available potential energy by diabatic heating.

Note that by integrating Eqs. (1) - (4) over the whole global atmosphere, the resulting equations can be used to estimate the atmospheric energy cycle in the wave-number domain. Further, by summing up over all the waves, the atmospheric energy cycle in the space domain can also be estimated.

As mentioned above, the transient (one month) SST anomaly experiment carried out by Spar (1972) was the subject of this study. Because the two-level Mintz-Arakawa general circulation model is designed to simulate the troposphere, only the energetics of the troposphere are discussed. In the calculation of energetics, Lorenz's (1955) definition of available potential energy is adopted. Therefore  $p$ -coordinates are used instead of  $\sigma$ -coordinates. ( $\sigma = (p - p_T)/(p_S - p_T)$ , where  $p_T$  is the pressure of the tropopause and is taken to be 200 mb, and  $p_S$  is the pressure of the earth's surface). The troposphere is assumed to be bounded between 200 mb and 1000 mb, and equally divided into two layers with the 600 mb surface as the interface between them. All of the variables at the  $p$ -surface are interpolated from those at the  $\sigma$ -surfaces.

Velocities, frictional forces and diabatic heatings are interpolated linearly in  $\sigma$ -space. For the interpolations of temperatures and temperature lapse rates, it is assumed that potential temperature is linear in  $p^k$  space, which is also adopted in the two-level

Mintz-Arakawa general circulation model. ( $p$  is pressure and  $\kappa$  is the Poisson constant, 0.288.) For the vertical  $p$ -velocities, a parabolic profile in  $\sigma$ -space is assumed.

The energy transformation terms are calculated from the Fourier representations of variables defined at isobaric surfaces, and the harmonics are computed up to wave number 15, based on information at 72 points around a latitude circle.

Two aspects of the problem under investigation are (1) how well does the model atmosphere simulate the atmospheric transformation processes and energy contents, and (2) what are the effects of a transient SST anomaly on the energetics of the atmosphere. For the first problem, the energetics of the control run, which was designed to simulate the real atmosphere, are compared with observations. For the second problem, the energetics of the anomaly run are compared with the control run.

Table 1 shows the model energy budget in the spatial domain for the winter control run for the region north of  $20^\circ\text{N}$  averaged over 90 days, together with observational results for the same region from Krueger et al. (1965) and Saltzman (1970). The energy values of Krueger et al. (1965) are for an average of 5 winter (December - February) seasons, and are based on data from 850-500 mb, extrapolated to include the entire troposphere. Saltzman's estimates are for the six-month "cold season", October - March, and are based on a variety of sources.

The zonal available potential energy,  $P_z$ , of the model con-

Table 1. Energy budget for 90-day winter control run averaged over area north of latitude 20°N. Observational values from Krueger et al. (1965) and Saltzman (1970) are shown for comparison.

	Model	Krueger et al.	Saltzman
A. <u>Energy contents</u>		( $10^4$ joules $m^{-2}$ )	
$P_z$	670	350	355
$K_z$	130	152	100
$P_E$	104	119	113
$K_E$	79	134	143
B. <u>Energy Conversions</u>		( $10^{-2}$ watt $m^{-2}$ )	
$\langle P_z, K_z \rangle$	- 85	- 83	0
$\langle P_z, P_E \rangle$	348	513	525
$\langle P_E, K_E \rangle$	589	371	303
$\langle K_E, K_z \rangle$	51		48
C. <u>Generations, Dissipations, and Flux Convergences</u>		( $10^{-2}$ watt $m^{-2}$ )	
$G_z$	387	430	300
$G_E$	62	- 142	- 159
$W_z$	247		
$W_E$	1		
$D_z$	268		48
$D_E$	374		255
$F(P_z)$	154		
$F(P_E)$	13		
$F(K_z)$	4		
$F(K_E)$	11		



trol run appears to be too large compared with the "observed" values. One reason for this discrepancy is that, in one sense, the domain considered for the model computations is different from that of the observational diagnostics. Squares of the temperature deviations from the global mean temperature were used to compute  $P_z$  in the model computations, while deviations from the limited area mean temperature (north of  $20^\circ\text{N}$ ) were used for the observational energetics. Furthermore, the model produces excessively high temperatures in the upper troposphere in the tropics, which also exaggerates  $P_z$ .

The zonal kinetic energy,  $K_z$ , of the model is in good agreement with observations, and so is the eddy potential energy,  $P_E$ . On the other hand, the eddy kinetic energy,  $K_E$ , computed from the model is too low, probably as a result of the low horizontal resolution of the model.

The term  $\langle P_z, K_z \rangle$  indicates a conversion from zonal kinetic to zonal potential energy in the model, in good agreement with the data of Krueger et al. (1965). The negative value of this conversion reflects the dominance of the indirect Ferrel cell north of latitude  $20^\circ\text{N}$ . On the other hand, the conversion,  $\langle P_E, K_E \rangle$ , from eddy potential to eddy kinetic, appears to be too large in the model as compared with "observations". However, this conversion is calculated from a computed vertical velocity, which in turn is determined dry adiabatically in the "observational" diagnostics. Thus, the model, with its moist convection, may actually give more realistic values than the "observations".

The conversion  $\langle K_E, K_Z \rangle$ , from eddy to zonal kinetic energy, shows good agreement between the control case model and observations, but the term  $\langle P_Z, P_E \rangle$ , representing conversion from zonal to eddy potential energy, seems somewhat too low in the model.

The generation of zonal available potential energy,  $G_Z$ , by diabatic heating in the model agrees well with the values estimated in the diagnostic studies, but the same cannot be said of the generation of eddy potential energy,  $G_E$ , for which there is a disagreement in sign. In view of the fact that  $G_Z$  and  $G_E$  are computed as residuals, rather than directly, in the observational diagnostic studies, they cannot be viewed as reliable standards against which to judge the model.

The total kinetic energy dissipation,  $(D_Z + D_E)$ , in the model is  $6.42 \text{ watts m}^{-2}$  compared with Saltzman's residual estimate of  $3.03 \text{ watts m}^{-2}$ . However, Kung (1967) has estimated a value of  $4.94 \text{ watts m}^{-2}$  for the winter dissipation north of  $20^\circ\text{N}$ , which is in better agreement with the model. It does appear likely, however, that  $D_Z$  is somewhat too high in the model.

In general, the model control run exhibits a reasonable and realistic energy budget in the spatial domain that is well within the error limits of the diagnostic studies.

The effects of the transient North Pacific SST anomaly on the gross energetics of the model in the spatial domain can be examined in terms of the conversions and generations listed in Table 2.

Table 2. Model computations of energy generations and conversions for each winter month of control and anomaly runs in three zonal sections: 28°N - 60°N ("NH"), 20°N - 20°S ("Tropics"), and 28°S - 60°S ("SH").

Transient North Pacific SST anomaly. Units:  $10^{-2}$  watts  $m^{-2}$ .

	"NH"		"TROPICS"		"SH"	
	Control	Anomaly	Control	Anomaly	Control	Anomaly
Month No.	1	1	1	1	1	1
$G_z$	177	151	932	945	118	126
$G_E$	78	105	840	865	52	46
$\langle P_z, K_z \rangle$	- 335	- 307	1088	1095	- 101	- 91
$\langle P_z, P_E \rangle$	555	571	- 162	- 188	99	108
$\langle P_E, K_E \rangle$	1014	1058	813	863	665	644
$\langle K_E, K_z \rangle$	79	91	21	13	47	46
Month No.	2	2	2	2	2	2
$G_z$	291	323	727	713	210	197
$G_E$	88	0	1407	1327	31	13
$\langle P_z, K_z \rangle$	-100	64	1087	1134	- 95	-138
$\langle P_z, P_E \rangle$	512	425	- 356	- 410	78	- 38
$\langle P_E, K_E \rangle$	852	600	1203	1207	556	573
$\langle K_E, K_z \rangle$	11	-8	-14	-30	36	59

Table 2. (Cont'd.)

	"NH"		"TROPICS"		"SH"	
	Control	Anomaly	Control	Anomaly	Control	Anomaly
Month No.	3	3	3	3	3	3
$G_z$	231	176	861	533	185	172
$G_E$	84	38	1025	167	34	28
$\langle P_z, K_z \rangle$	-112	-191	1080	815	-149	-163
$\langle P_z, P_E \rangle$	460	363	- 248	- 30	129	87
$\langle P_E, K_E \rangle$	690	729	906	155	628	561
$\langle K_E, K_z \rangle$	19	65	- 15	10	51	82

For each month of the experiment, the two generation values,  $G_z$  and  $G_E$ , and the four conversion values are given for both the anomaly and control run for three regions of the globe:  $28^\circ\text{N} - 60^\circ\text{N}$  ("NH"),  $20^\circ\text{N} - 20^\circ\text{S}$  ("Tropics"), and  $28^\circ\text{S} - 60^\circ\text{S}$  ("SH"). The units are the same as in Table 1.

During the first month, the effects of the SST anomaly on the regional generations and conversions of energy are quite small, particularly in the tropics and Southern Hemisphere. In the Northern Hemisphere, the SST anomaly in the North Pacific appears to have caused a slight reduction in the diabatic generation of zonal potential energy and an increase in the generation of eddy potential energy, as might have been expected, together with slightly increased conversions from  $P_z$  to  $P_E$ ,  $P_E$  to  $K_E$ , and  $K_E$  to  $K_z$ . (The last result is contrary to the anomalous kinetic energy conversion of January 1963). The slight decrease in the magnitude of  $\langle P_z, K_z \rangle$  reflects a weaker indirect Ferrel cell as one result of the SST warming.

The effect of the transient North Pacific SST anomaly on the energetics is more apparent in the second month, and again mainly in the Northern Hemisphere. It must be recalled that the SST anomaly in this experiment was inserted as a step function, beginning as a discontinuous SST warming on the first day of the first month and ending as a discontinuous SST cooling of the same magnitude on the first day of the second month. Thus, in the second month there are delayed carry over effects of the first month's warm pool, as well as effects of the SST cooling that returned the sea temperature field to the cli-

matological mean annual value used in the control run. Hence, a simple interpretation of the resulting energetics is not possible. Nevertheless, there are some noteworthy energy effects, particularly in the Northern Hemisphere which are indicative of the disturbing effect of the transient warm pool. For example, in the anomaly run in the Northern Hemisphere the eddy generation term,  $G_E$ , has fallen to zero, the meridional generation term,  $\langle P_z, K_z \rangle$  has been reversed in sign, indicating a positive, or direct, energy conversion cell in place of the negative, or indirect, Ferrel cell, and the  $\langle K_E, K_z \rangle$  conversion has also changed sign, indicating an anomalous conversion from zonal to eddy kinetic energy. Outside the Northern Hemisphere, the most noteworthy effects of the anomaly in the second month are the reversal in sign of  $\langle P_z, P_E \rangle$  in the Southern Hemisphere and the intensification of the indirect energy conversion process in the Southern Hemisphere represented by the increased negative value of  $\langle P_z, K_z \rangle$ . These results for the second month seem to indicate that transient SST anomalies can indeed have a disturbing effect on the global energetics of the atmosphere after a period of about one month.

The third month, as indicated in Table 2, is characterized by a return of the global energetics to the "normal" state represented by the control run (but with an important exception in the "Tropics"). In the Northern and Southern Hemispheres poleward of latitudes  $28^\circ$  (approximately the latitudes of the subtropical high pressure belts), the generation and conversion values for the anomaly run are not notably

different from those for the control run, now that the sea temperature fields are the same. This does not mean that the extratropical synoptic meteorological patterns and structures are the same for the two runs. But it does indicate that the gross regional energetics in the spatial domain are once again similar.

On the other hand, the energetics in the "Tropics" are seriously distorted in the third month in the anomaly run compared with the control run. Especially noteworthy are the order of magnitude decreases of  $G_E$ ,  $\langle P_Z, P_E \rangle$ , and  $\langle P_E, K_E \rangle$ . There is good reason to believe that these latter results reflect a defect in the model, namely in the parameterization of convection. In the tropics, the precipitation and latent heat release are due primarily to convection, which is very sensitive to the model's thermal structure. For some reason which has not yet been completely diagnosed, the precipitation in the third month in the equatorial region was severely altered in the anomaly run compared with the control run. The convective precipitation has a dominating influence on the tropical energetics, with the results shown in Table 2. As of this writing we are of the opinion that this tropical effect is a computational artifact resulting from a model defect, and not a valid reflection of nature.

A preliminary analysis of the model energetics in the wave number domain leads to the certain tentative conclusions regarding both the model's simulation of the spectral energetics of the real atmosphere and the effects of the SST anomaly on the spectral energetics.

Except for the eddy generation terms,  $G(n)$ , the model energy flow diagram in the wave number domain shows good qualitative agreement with the observational results of Saltzman (1970). The available

potential energy generated by diabatic heating takes place mainly in the zonal form, and flows to all the eddies mainly through eddy sensible heat transfer, with the dominant transfer in the larger eddies (smaller wave numbers). Available potential energy is further transferred from longer waves to intermediate and short waves through the non-linear wave interactions. All waves convert their potential energy to kinetic energy through baroclinic processes, represented by  $\langle P(n), K(n) \rangle$ , and supply kinetic energy to the zonal flow through the barotropic process represented by  $\langle K_z, K(n) \rangle$ . Intermediate waves lose kinetic energy, and most longer waves and short waves gain kinetic energy through the wave interactions,  $\langle K(m), K(n) \rangle$ . However, the eddy energies,  $P(n)$  and  $K(n)$  are generally smaller in the model (except for  $n = 1$  and  $2$ ) than in nature, as are the conversions from zonal to eddy form and the transfers of kinetic energy by wave interactions. Some of these shortcomings of the model are undoubtedly due to the coarse horizontal resolution, as shown by Manabe, et al. (1970).

Maximum energy conversion,  $\langle P(n), K(n) \rangle$ , in the model is found in the very long waves (near  $n = 2$ ), whereas some theoretical and "observational" studies indicate a maximum in the cyclone scale, around  $n = 6$ . However, those studies are based on dry adiabatic models, or on diagnostic calculations for which the vertical velocities were computed dry adiabatically. In the work of Haltiner (1967), Murakami and Tomatsu (1965), and Manabe, et al. (1970) it is shown that, when sensible heat transfer and other diabatic effects are included, maximum conversion does take place in the very long waves, as in the model. The fact that the model conversions at all wave numbers are larger than those reported by Saltzman is probably also due to the use of adiabatic



vertical motions in the "observational" diagnostics.

The effects of the SST anomaly on the spectral energetics are even more complex than on the gross energetics in the spatial domain. In this brief summary, we will confine our attention to effects in the Northern Hemisphere.

In the first month, the SST anomaly is found to increase the eddy generation in the northern middle latitudes, mainly in waves 1 and 2, due to the increase of eddy generation by heating and condensation and the reduction of eddy destruction by sensible heat exchange. The energy conversions,  $\langle P(n), K(n) \rangle$ , in the intermediate-scale cyclone waves are found to increase in the anomaly run, probably because of increased baroclinic instability resulting from the increased sea surface temperature gradient. Both eddy kinetic energy and eddy available potential energy are also found to increase at intermediate wave numbers in the anomaly run, and the kinetic energy transferred from eddy to zonal is found to increase as well. The kinetic energies transferred from eddy to zonal at waves 2 and 3 are found to decrease in the anomaly run.

In the second month, removal of the SST anomaly from the anomaly run produces cooling effects. As expected, this decreases the heating and condensation, and reduces the eddy generation. The results show that the reduction occurs at all wave numbers with the major reduction in the longer waves. The energy conversion is also found to decrease over almost all waves, with the major decrease in the longer

waves. This is probably due to the decrease in vertical motion resulting from the decreased heating and condensation. Eddy kinetic and available potential energy are found to decrease at almost all the wave numbers in the anomaly run.

In the third month, the combined effect of heating of the first month and cooling of the second month in the northern middle latitudes is found to result in increased eddy activity in the long and intermediate waves from  $n = 2$  to  $n = 7$ . This can be seen in the increase of eddy kinetic energy, eddy available potential energy, eddy energy conversion, and the kinetic energy transferred from eddy to zonal at these wave numbers. In general, the spectral energetics in the Northern Hemisphere are as much disturbed in the third month as in the second month by the SST anomaly, unlike the gross energetics in the spatial domain.

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The Angular Momentum Budget of the Mintz-Arakawa  
Model, and Effects of a Transient SST Anomaly

(L. J. Lewis)

As a further diagnostic test of the two-level model, and to gain additional insight into the dynamical effects of a transient North Pacific SST anomaly, the zonal absolute angular momentum budget of the model atmosphere was computed for the 90-day winter simulations with and without the anomalous warm pool.

Due to surface friction (as well as pressure differences across mountains), there is a transfer of westerly (positive) angular momentum from the earth to the atmosphere in the belts of surface easterly winds (mainly the trade wind region), and from the atmosphere to the earth in the mid-latitude belts of surface westerlies. To balance these additions and subtractions, there must be meridional transports of zonal angular momentum, particularly from the trades to the westerlies. In this study we have computed, as a function of latitude, each of the various contributions to the local time-variation of zonal angular momentum in toroidal atmospheric rings, integrated over the total depth of the model troposphere.

The terms in the angular momentum equation include (a) convergences of meridional fluxes of relative angular momentum by mean meridional motions and by eddies, (b) convergences of meridional fluxes of earth momentum by mean motions and by eddies, (c) convergences of vertical fluxes of relative and earth momentum by mean motions and

by eddies, (d) momentum generation or dissipation by zonal pressure differences across mountains, and (e) momentum generation or dissipation by surface friction.

Preliminary results of the calculations, based on the analyses completed thus far, indicate the following tentative conclusions.

(1) The 90-day average meridional profile of the meridional momentum flux by mean motions in the Northern Hemisphere in the model control run is in good qualitative agreement with observational results. However, the maximum poleward flux in the model, at  $16^{\circ}$  -  $20^{\circ}$  N, is about 50% higher than in the mean winter atmosphere, apparently due to an excessively strong Hadley circulation in the model control run.

(2) Meridional fluxes by eddies in the model are of the same magnitude, generally, as in nature. However, the profiles indicate that the width of the westerlies is narrower in the model control run than in the mean winter atmosphere in the Northern Hemisphere. There are marked changes in the eddy fluxes from month to month in the model control run, indicating changes in regime from low to high zonal index.

(3) The mountain term in the model control run does not agree with that computed from the observed mean winter Northern Hemisphere. This discrepancy appears to be due to the presence of a very strong Himalayan anticyclone in the model.

(4) There is generally good qualitative agreement between the model and "observed" profiles of the surface stresses, and, hence, of the frictional torque terms. However, in the model, the strong Hadley

cell is associated with stronger than average trade winds, and, therefore, higher values for the surface stresses and frictional torques.

All the comparisons with "observation" mentioned above are for the Northern Hemisphere, as there is a paucity of data in the Southern Hemisphere. However, in the comparison of the model control and anomaly runs, we are able to examine world-wide effects. Although the analysis of the anomaly run is still not complete, the following effects of the SST anomaly are indicated.

(5) The meridional fluxes by eddies are slightly increased and the fluxes by mean motions slightly decreased in the anomaly case relative to the control run, when averaged over the whole 90-day period. This effect is greatest, however, in the third month when, in the Northern Hemisphere, the mean flux is reduced about 25% and the eddy flux about 50% below the control run, bringing the anomaly profile into closer agreement with "observations". The surface stress profile also shows better agreement with observations in the anomaly run than in the control run. These results appear to be due to a reduction in the strength of the Hadley cell in the case of the transient North Pacific warm pool compared with the control. The reasons for this behavior are not yet understood.

A complete report on the angular momentum study will be presented in the M.S. thesis by L.J. Lewis, and will be published or distributed at a later time.