PROGRESS REPORT

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Research Project on CO₂-Induced Climate Change

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SUMMARY OF CURRENT PROGRESS

This summary of current progress in the research project at SUNY Stony Brook on CO₂-induced climate change is classified into three tasks corresponding to the task categories in the US DOE/PRC CAS cooperative project on climate change. Task 1, led by Dr. Robert Cess, is concerned with intercomparison of CO₂ related climatic warming in contemporary general circulation models. A summary of work accomplished in Task 1 in the current funding period begins on page 1. Task 2, directed by Dr. Sultan Hameed, aims at understanding the natural variability in climatic data and comparing its significant features between observations and model simulations. A summary of current progress in Task 2 begins on page 9. Task 3, also directed by Dr. Hameed focuses on analysis of historical climate data developed at the Institute of Geography of the Chinese Academy of Sciences. A summary of current research in Task 3 begins on page 14.

TASK 1: ANALYSIS AND INTERCOMPARISON OF GENERAL

Work that has been completed under the present grant has resulted in the following 13 publications:

1. R. D. Cess, M.-H. Zhang, G. L. Potter, H. W. Barker, R. A. Colman, D. A. Dazlich, A. D. Del Genio, M. Esch, J. R. Fraser, V. Galin, W. L. Gates, J. J. Hack, J. T. Kiehl, A. A. Lacis, X.-Z. Liang, J.-F. Mahfouf, B. J. McAvaney, V. P. Meleshko, J.-J. Morcrette, D. A. Randall, E. Roeckner, J.-F. Royer, D. A. Sheinin, A. P. Sokolov, K. E. Taylor, W.-C. Wang and R. T. Wetherald, Intercomparison of CO₂ Radiative Forcing in Atmospheric General Circulation Models, *Science* (in press).

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2. R. D. Cess, G. L. Potter, M.-H. Zhang, J.-P. Blanchet, S. Chalita, R. Colman, D. A. Dazlich, A. D. Del Genio, V. Dymnikov, V. Galin, D. Jerret, E. Keup, A. A. Lacis, H. Le Treut, X.-Z. Liang, J.-F. Mahfouf, B. J. McAvaney, V. P. Meleshko, J. F. B. Mitchell, J.-J. Morcrette, P. M. Norris, D. A. Randall, L. Rikus, E. Roeckner, J.-F. Royer, U. Schlese, D. A. Sheinin, J. M. Slingo, A. P. Sokolov, K. E. Taylor, W. M. Washington, R. T. Wetherald and I. Yagai, Interpretation of Snow-Climate Feedbacks Produced by 17 General Circulation Models, *Science* **253**, pp. 888-892, 1991.
3. D. A. Randall, R. D. Cess, J. P. Blanchet, S. Chalita, R. Coleman, D. A. Dazlich, A. D. Del Genio, V. Dymnikov, V. Galin, D. Jerrett, E. Keup, A. A. Lacis, H. Le Treut, X.-Z. Liang, B. J. McAvaney, J. F. Mahfouf, V. P. Meleshko, J. F. B. Mitchell, J.-J. Morcrette, P. M. Norris, G. L. Potter, L. Rikus, E. Roeckner, J. F. Royer, U. Schlese, D. A. Sheinin, J. Slingo, A. P. Sokolov, K. E. Taylor, R. T. Wetherald, I. Yagi and M.-H. Zhang, Analysis of Snow Feedback in Fourteen General Circulation Models, Submitted to *J. Geophys. Res.*
4. Zhang, M. H., J. J. Hack, J. T. Kiehl and R. D. Cess, A Diagnostic Approach for Understanding Climate Feedback Processes in General Circulation Models, Submitted to the *J. Geophys. Res.*
5. Zhang, M. H., R. D. Cess, T. Y. Kwon and M. H. Chen, Approaches to Compare Clear-Sky Radiative Fluxes Between General Circulation Models and the Earth Radiation Budget Experiment (ERBE) Data, Submitted to the *J. Geophys. Res.*
6. P. G. Falkowski, Y. K. Kim, Z. Kolber, C. Wilson, C. Wirick and R. Cess, Natural Versus Anthropogenic Factors Affecting Low-Level Cloud Albedo over the North Atlantic, *Science* **256**, pp. 1311-1313, 1992.
7. D. A. Randall, R. D. Cess, J. P. Blanchet, G. J. Boer, D. A. Dazlich, A. D. Del Genio, M. Deque, V. Dymnikov, V. Galin, S. J. Ghan, A. A. Lacis, H. LeTreut, Z.-X. Li, X.-Z. Liang, B. J. McAvaney, V. P. Meleshko, J. F. B. Mitchell, J.-J. Morcrette, G. L. Potter, L. Rikus, E. Roeckner, J. F. Royer, U. Schlese, D. A. Sheinin, J. Slingo, A. P. Sokolov, K. E. Taylor, W. M. Washington, R. T. Wetherald, I. Yagai and M.-H. Zhang, Intercomparison and Interpretation of Surface Energy Fluxes in Atmospheric General Circulation Models, *J. Geophys. Res.* **97**, pp. 3711-3724, 1992.
8. R. D. Cess, E. F. Harrison, P. Minnis, B. R. Barkstrom, V. Ramanathan and T. Y. Kwon, Interpretation of Seasonal Cloud-Climate Interactions Using Earth Radiation Budget Experiment Data, *J. Geophys. Res.* **97**, pp. 7613-7617, 1992.
9. R. D. Cess, G. L. Potter, W. L. Gates, J.-J. Morcrette and L. Corsetti, Comparison of General Circulation Models to Earth Radiation Budget Experiment Data: Computation of Clear-Sky Fluxes, *J. Geophys. Res.* **97**, pp. 20,421-20,426, 1992.

10. R. D. Cess, S. Nemesure, E. G. Dutton, J. J. DeLuisi, G. L. Potter, and J.-J. Morcrette, The Impact of Clouds on the Shortwave Radiation Budget of the Surface-Atmosphere System: Interfacing Measurements and Models, *J. Climate* **6**, pp. 308-316, 1993.
11. Z. Li, H. G. Leighton and R. D. Cess, Surface Net Solar Radiation Estimated from Satellite Measurements: Comparisons with Tower Observations, *J. Climate* (in press).
12. S. Nemesure, R. D. Cess, E. G. Dutton, J. J. DeLuisi, Z. Li and H. G. Leighton, Impact of Clouds on the Shortwave Radiation Budget of the Surface-Atmosphere System for Snow-Covered Surfaces, *J. Climate* **6**, pp. 308-316, 1993.
13. Y. Kim and R. D. Cess, Effect of Anthropogenic Sulfate Aerosols on Low-Level Cloud Albedo over Oceans, *J. Geophys. Res.* **98**, pp. 14,883-14,885, 1993.

A major effort of the current research has focused on the GCM intercomparison, or FANGIO (Feedback Analysis of GCMs and in Observations), project. Even for the most straightforward climate-change simulation, a change in equilibrium climate on doubling atmospheric CO₂, there is a roughly threefold variation in the predicted increase in global-mean surface temperature (1,2). Global climate change caused by a CO₂ doubling may be conceptually interpreted as a two-stage process: forcing and response. The forcing is the direct radiative perturbation of the surface-troposphere system caused by the CO₂ increase, whereas the response is the climate change associated with restoring the global-mean radiation balance. Climate feedback mechanisms that govern the response differ substantially among GCMs (3-7), but it has not been previously known if there are significant differences in their forcings.

To address this question, the radiative forcing for a CO₂ doubling has been evaluated for 15 GCMs, as illustrated in Fig. 1, and the differences are substantial. For example, on average GCMs produce, for a CO₂ doubling, a global warming of about 4° C (1, 2), whereas the models in our study produced an average CO₂ forcing of 4.0 W m⁻², so this amounts to an average climate sensitivity of 1° C warming for each 1 W m⁻² of forcing. Now imagine 15 GCMs, all with the same climate sensitivity, a 1° C warming per 1 W m⁻² forcing, but CO₂ forcing varying like the 15 GCMs in this study (Fig. 1). They

would give global warming projections ranging from 3.4 to 4.7° C just because of their forcing differences. This range is substantial, and is nearly half the often-quoted range of uncertainty of 1.5 to 4.5° C (1, 8), which has been based on feedback uncertainties assuming no differences in the forcing. In the following the reasons for these differences are examined.

While near-infrared bands of CO₂ absorb shortwave (SW) radiation and thus heat the atmospheric column, this heating occurs mostly in the stratosphere; thus less SW reaches the troposphere, and the SW forcing is negative. On average, this reduced the forcing by 4.7%, whereas if the models that do not include SW forcing are deleted (CCM/LLNL, CSU and DNM) the reduction is 6.0%. Because of this small magnitude, SW forcing is a minor contributor to model-to-model differences in net forcing (Table 1).

Table 1. Summary of standard deviation (SD) and range for individual processes contributing to differences in CO₂ radiative forcing.

Process	SD(W m ⁻²)	Range (W m ⁻²)
CO ₂ SW radiation [†]	0.08	0.32
Water-vapor overlap*	0.12	0.41
Temperature and humidity profile differences*	0.11	0.37
Clouds (LW)*	0.16	0.58
CO ₂ LW radiation	0.62	2.12

[†]Refers only to those models that include SW forcing.

*Computed as the residual (see Fig. 2).

Radiative overlap of CO₂ absorption bands by water vapor absorption is often regarded as a major source of uncertainty (9). To isolate differences caused by this, we modified the radiation codes for all GCMs except CNRM so as to remove overlap. The longwave (LW) clear (with clouds removed) forcings with and without overlap are correlated (Fig. 2A) and show that variations about the linear fit are the actual contributions by water-vapor overlap to forcing differences; the standard deviation (SD) of this residual is only 0.12 W m⁻² (Fig. 2A and Table 1). This small SD includes the effects of model-to-model differences in humidity profiles and the way overlap is parameterized in the radiation codes.

To further isolate differences caused by model-to-model variations in humidity profiles and lapse rates, we inserted humidity profiles and lapse rates for a standard mid-latitude summer atmosphere (9) into column (one-dimensional) versions of the GCM radiation codes. As shown in Fig. 2B, these are not significant sources of differences, because the column-model calculations adopt a single humidity profile and lapse rate. This result was confirmed by inserting global-mean humidity profiles and lapse rates for the GCMs into the CCM2 column radiation code. The LW clear forcings computed in this manner were in remarkable agreement; SD = 0.03 W m⁻² without overlap and 0.06 W m⁻² with overlap. The implied invariance to vertical resolution is consistent with a related sensitivity study in which vertical resolution was varied in the CCM2 column radiation code while keeping the humidity profile and lapse rate fixed.

Although inclusion of clouds reduces the LW forcing by an average 14% and there are substantial differences among the GCM's cloud fields (6), clouds were not a major cause of LW forcing differences, as demonstrated in Fig. 2C.

The largest single cause of forcing differences was model-to-model differences in the LW radiation codes for CO₂ (Table 1). Earlier GCM comparisons (5, 6, 7) considered climate-change feedback mechanisms for which there are no standards for comparison. For CO₂ forcing, however, line-by-line (LBL) calculations of LW clear forcing are avail-

able as standards of comparison (9). Deviations of the GCM column-model forcings from the LBL results, both with and without water-vapor overlap, are large for many models (Fig. 3A), particularly those that predict low forcings. Although results for CNRM (which was not included in Fig. 2A because "without water-vapor overlap" GCM forcing was not available) agreed well with the LBL results when water-vapor overlap was included, there was substantial disagreement in the forcing without water-vapor overlap. Here, overly strong overlap compensated for a positive forcing bias produced by this model's CO₂ radiation code.

The tendency for models to underestimate LW clear forcing (Fig. 3A) is due partly to the neglect of certain CO₂ absorption bands. CO₂ has a dominant 15 μm band complex, but also absorption bands at 10.4, 9.4 and 4.3 μm . None of the models incorporated the 4.3 μm band; the 10.4 and 9.4 μm bands are included in some models but not in other models. A fairer test (although not a test of reality) of the radiation codes is to delete those bands in the LBL calculation that are not included in the respective GCM radiation codes. This did reduce the tendency of the models to underestimate the forcing (Fig. 3B).

Paper No. 2 and 3 address a response process, namely snow feedback. Conventional wisdom dictates that as the globe warms the ensuing reduction in the area coverage of snow and ice results in a darker planet which absorbs more SW radiation, thus resulting in further warming; i.e., a positive feedback mechanism. Simulations with a number of GCMs, however, suggest that reality is far more complex. To demonstrate this, attention was directed solely to the change in snow cover by holding sea ice fixed. Two simulations, in which sea-surface temperature was increased uniformly by 4° C, were considered. In one the snow cover was held fixed, while in the other the snow was allowed to retreat. Differencing the output from the two simulations delineated the impact of snow retreat.

The corresponding change in the components of the global-mean surface energy budget are summarized in Fig. 4 for 14 GCMs. Only CCM/LLNL approximates the conventional expectation. The retreat of snow produces a darker surface and consequently an

increase in the SW flux absorbed by the surface, with the other components of the surface energy budget remaining almost constant. Other models, however, provide quite different behavior. For example, CSU produces negative SW feedback due largely to enhanced cloudiness associated with snow retreat. Thus, although snow retreat darkens the surface, the snow-induced cloudiness increase means that less insolation reaches the surface, so the net effect is that surface SW absorption is actually reduced. But the increased cloudiness significantly increases the downward LW flux to the surface, and this acts as the dominate, and positive, feedback.

The real point of Fig. 4, of course, is that the GCMs have taught us that snow feedback is a much more complex phenomenon than we had previously envisioned.

In order to obtain a more comprehensive understanding of climate feedback mechanisms in GCMs, a diagnostic method has been developed (Paper No. 4) to study climate feedbacks due to water-vapor, lapse rate and clouds. Figure 5 demonstrates this approach with respect to water-vapor and lapse-rate feedbacks for clear skies with the NCAR CCM2. The climate-change simulation consisted of uniformly increasing the SST by 4° C for a perpetual July simulation.

The curve labeled "surface temperature" represents the increase in the TOA clear-sky LW zonal-mean flux as caused solely by $\Delta\text{SST} = 4^\circ \text{C}$; i.e., with atmospheric water vapor and lapse rate held fixed. For "plus water vapor" the atmospheric water vapor abundance is allowed to adjust, and this positive feedback thus reduces ΔF , reducing the planet's efficiency to emit energy. Lapse-rate feedback, on the other hand, is found to be a moderately strong negative feedback, at least for CCM2.

The method was further employed (Paper No. 4) to study differences in climate feedbacks between CCM2 and two hybrid versions of CCM2, one with the mass-flux cumulus convection scheme (Mass) replaced by the moist-adiabatic scheme (Moist), and the second with a further decoupling of the planetary boundary layer in the convection scheme (No PBL). Water-vapor and temperature feedbacks differ among the models due to dif-

ferent efficiencies of heat and moisture transport. Figure 6 shows that CCM2 (Mass) has the strongest positive feedback as caused by climate-change induced variations of upper-tropospheric water vapor. But it also has the strongest negative feedback from variations of upper tropospheric temperature. The model with the moist-adiabatic scheme, and without the PBL, has the weakest positive water-vapor feedback and weakest negative temperature feedback. Large compensations, however, occur between the two feedbacks (Fig. 6c).

The three models also exhibit differences in cloud feedback. To demonstrate this we employ the cloud feedback parameter $\Delta\text{CRF}/G$ (5, 6), where CRF is cloud-radiative forcing and denotes the radiative impact of clouds of the Earth's TOA radiation budget. ΔCRF in turn represents the climate-induced change in CRF, while G is the radiative forcing that causes the change in climate, such as the CO_2 forcing of Fig. 2. If $\Delta\text{CRF}/G = 1$, then cloud feedback is positive and acts to amplify the climate change by a factor of two, whereas zero cloud feedback corresponds to $\Delta\text{CRF}/G = 0$.

For CCM2 the LW and SW components are of opposite sign (Fig. 7), with the negative LW component being dominate so that net feedback is negative. The No PBL model, on the other hand, has weaker negative LW feedback, and the net feedback is essentially zero. These model differences in LW cloud feedback are primarily caused by high clouds. CCM2 has the strongest convection and a broader warming in the upper troposphere for the $\Delta\text{SST} = 4^\circ \text{C}$ simulation (Fig. 8), that produces a large reduction in relative humidity and cloudiness. It is the cloudiness reduction that produces the negative LW feedback, since this increased the TOA LW flux. That the No PBL model has weaker negative LW feedback is because of its weaker convection and thus weaker upper tropospheric warming (Fig. 8).

In another study (Paper No. 5), we obtained a statistical relationship between grid cloud cover and the availability of ERBE clear-sky measurements. Fig. 9 shows the number of clear pixels in an ERBE 2.5° by 2.5° grid, in terms of the fraction of clear-sky data,

against the total cloud cover for two different regions in the summer of 1986. A fifty per-cent grid cloud threshold was then derived to sample GCM clear-sky data. Figure 10 shows good agreement of clear-sky sampling from this method with ERBE sampling. The point here is that this provides a means of evaluating GCM clear-sky TOA fluxes in a manner that is consistent with the ERBE data reduction procedure. Large spatial vari-abilities of the difference of clear-sky fluxes over the ocean between the CCM2 simulation and ERBE data are also greatly reduced by using this sampling method.

Papers No. 6 though 13 have dealt with several issues related to the radiative im-pacts of clouds.

TASK 2: COMPARISONS OF GCM SIMULATIONS OF CLIMATE VARIABILITY WITH DATA

Summary of Work Completed in the Current Funding Period

The focus of our research on climate variations is to test the simulation of observed modes of variations in General Circulation Models and to investigate the suitability of these models in representing regional climates. In particular, we have studied the North Atlantic Oscillation, the North Pacific Oscillation and the Southern Oscillation in multi-year integrations of the coupled ocean-atmosphere OSU GCMs. In addition, the simulation of precipitation in Northeastern Brazil, Sahel and China were compared with observations. The results were presented in the following publications:

1. I. Pittalwala and S. Hameed, "Simulation of the North Atlantic Oscillation in a General Circulation Model", *Geophys. Res. Letters* **18**, 841-844, 1991.
2. K. R. Sperber and S. Hameed, "Southern Oscillation in the OSU Coupled Upper-Ocean-Atmosphere GCM", *Climate Dynamics* **6**, 83-97, 1991.
3. S. Hameed and I. I. Pittalwala, "The North Pacific Oscillation: Observations Compared with Simulations in a General Circulation Model", *Climate Dynamics* **6**, 113-122, 1992.

4. K. R. Sperber, S. Hameed, W. L. Gates and G. L. Potter, "Interseasonal Air-Sea Interactions in the OSU Coupled Upper-Atmosphere GCM", *Proceedings of the 15th Annual Climate Diagnostics Workshop*, National Climatic Data Center, Asheville, NC, 331-336, 1991.
5. K. R. Sperber, S. Hameed, and W. L. Gates, "Surface Currents and Equatorial Thermocline in a Coupled Upper Ocean-Atmosphere GCM", *Climate Dynamics* 7, 121-131, 1992.
6. K. R. Sperber and S. Hameed, "Resonant Modulation of Nordeste Precipitation by Tropical Atlantic and Pacific Sea-Surface Temperatures", *Proceedings of the 16th Annual Climate Diagnostics Workshop*, University of California, Los Angeles, CA, 35-40, 1992.
7. S. Hameed, K. R. Sperber and A. Meinster, "Teleconnections of the Southern Oscillation in the Tropical Atlantic Sector in the OSU Coupled Upper-Ocean-Atmosphere GCM", *J. of Climate*, 6, 487-498, 1993.
8. K. R. Sperber and S. Hameed, "Phase Locking of Nordeste Precipitation with Sea Surface Temperatures", *Geophys. Res. Lettrs.* 20, 113-116, 1993.
9. S. Hameed and R. G. Currie, "Deterministic Signals in Interannual Variability", *Proceedings of the 17th Annual Climate Diagnostic Workshop*, Norman, Oklahoma, October 18-23, 1992.
10. G. L. Potter, J. S. Boyle, K. R. Sperber and S. Hameed, "Effect of Spatial Resolution on the Simulation of Regional Precipitation in China in a Global Climate Model", *Proceedings of the AMS Fourth Symposium on Global Change Studies*, UCRL-JO-111835,34-37, Anaheim, CA, January 17-22, 1993.

In papers 1-3 and yet to be published results we verified the simulation of the North Atlantic Oscillation (NAO), the North Pacific Oscillation (NPO) and the Southern Oscillation (SO) in the OSU GCM. We have analyzed three versions of the OSU GCM: (1) the Slab Model in which the ocean is treated as a static heat reservoir of fixed depth, (2) the coupled upper ocean-atmosphere model in which the ocean dynamics are calculated in two layers of variable depths representing the mixed layer and the thermocline; this model is referred to as OSU2 in the following discussion, and (3) the coupled full ocean-atmosphere model in which the ocean is represented by six layers of variable depth; this model is referred to as OSU6 in the discussion. Multi-year integrations of these

models were carried out at Lawrence Livermore National Laboratory (LLNL) by Drs. G. L. Potter and W. L. Gates.

The observed teleconnections associated with the oscillations were also shown to be qualitatively simulated by the GCM. These include the anomalies of precipitation in the Pacific and Indian Oceans associated with the SO (given in paper 2), the modulation of precipitation in Northwest Africa by the NAO and the Greenland-North Europe winter air temperature see-saw (given in paper 1), the Alaska-Western Canada winter air temperature see-saw associated with the NPO and the distribution of anomalies of Pacific sea surface temperatures associated with the NPO (paper no. 3).

While the detection of the SO, the NAO and the NPO in GCM calculated SLP fields is interesting, it is important to verify the simulation of teleconnection patterns for two reasons. First, the simulation of teleconnections shows that the physical processes associated with oscillation is reproduced by the model, otherwise the SLP anomaly that characterizes the oscillation may be interpreted as a statistical fluctuation. Secondly, the observed teleconnections usually refer to climate variations in particular regions; their verification in a GCM lends credibility to its application to the study of regional climates.

The simulated SO, NAO and NPO anomalies in the SLP fields of the OSU GCM have magnitudes smaller than observations. While Sperber and Hameed (paper 2) suggested that the weak signal of the SO may be due to the underestimation of the east-west SST gradient in the tropical Pacific, no generally satisfactory explanation of the underestimation of the amplitudes of the oscillations has been obtained.

The detection of the SO, the NAO and the NPO illustrates that a model may give a qualitatively plausible simulation of aspects of interannual variability even though the mean climatology of the model may not compare well with observations. For example, Sperber (10) has shown that the OSU2 GCM calculates sea surface temperatures and air temperatures that are too cold by several degrees. This may be related to the distortions in the simulated SLP climatology. One example is that the calculated Icelandic Low is displaced

several degrees south and west of its mean observed position. Nonetheless, the GCM gives a credible simulation of the NAO. The superior simulation of aspects of interannual variations in regions where the simulated mean fields do not compare well with observations occurs in several of the investigations reported in the papers listed above. This unexpected result is yet to be understood and suggests an orthogonality between the mean fields and the modes of interannual variations that were examined.

An application to regional climates is illustrated in paper no. 7 where it was shown that the OSU2 GCM reproduces important aspects of the circulation mechanisms associated with Nordeste drought. The large interannual variation of precipitation in this section of Brazil has a long history of investigation beginning with Walker (11). Our study showed that the observed condition of anomalous warm waters in the Pacific and North Atlantic during droughts in Nordeste is simulated by the GCM. Moreover, the establishment of the north-south temperature gradient in the Atlantic and its impact on Brazil's precipitation is a consequence of the Southern Oscillation simulated in the GCM. Fourier analysis of the observed Nordeste precipitation showed that its interannual variations are dominated by a few band-limited signals, shared with signals in the tropical Atlantic and Pacific oceans in particular combinations. This idea was pursued further in paper no. 6 where it was found that frequencies that are common to the precipitation and the SST's are phase locked. This idea can be reversed and used to develop a method to identify regions in the oceans that vary in unison with changes in precipitation in a given area. This procedure was illustrated further in paper no. 8.

The ability of the ECMWF model (Cycle 33) to simulate the East Asia summer monsoon was evaluated at four different horizontal resolutions: T21, T42, T63 and T106 in paper no. 10. Generally, the large scale features of atmospheric circulation were found to compare well with observations at T42 and higher resolutions. However, when the details of the regional distribution of precipitation are considered, the higher resolution models, particularly T106, captured several features of both the spatial and temporal char-

acteristics observed in the summer monsoon. One aspect of improved simulation with higher resolution is illustrated in Fig. 11 which shows 500 hpa winds and geopotential heights for June and July simulated by ECMWF and also in the ECMWF analyses. The analyses (Figs. 21i-j) show eastward deflection of the monsoon wind east of the Tibetan Plateau. The T106 simulation (Figs. 21a-b) produces a more intense trough in this region, clearly portraying the confluence between the southerly and northerly winds. The T63 model (Figs. 21c-d) simulates this confluence in June, but in July winds in this region are southerly resulting in deficient precipitation in the Yangtze Valley. The June simulation by T42 (Fig. 11e) gives a reasonable depiction of the confluence zone but in July (Fig. 11f) the flow near 110° has a negligible eastward component south of 30°N , resulting in dry conditions in the Yangtze Valley and rains to the north. Thus T106 seems to have a systematic advantage in resolving the quasi-stationary front formed east of the Tibetan Plateau. The question as to whether the improvement can be attributed to the better resolution of topography in higher resolutions remains to be investigated.

The investigations described above analyze GCM output data by 'time-domain methods' of analysis. Useful insights into model characteristics are obtained also by applications of 'frequency-domain methods'. This has been illustrated earlier in the identification in the OSU GCM of modes of variability that are found in the observations such as the quasi-biennial oscillation (QBO) (12), and the Chandler Wobble or the Atmospheric Pole Tide (APT) (13). Later an approach emerged that explains the physical origins of a large number of peaks seen in the Fourier spectra of SLP simulated by the OSU2 GCM. In addition to the QBO and the Atmospheric Pole Tide, the atmosphere-ocean system also generates a quasi-triennial oscillation (QTO) which is found in observations as well as in the OSU GCM. These low frequency modes may be understood as the subharmonic responses of the nonlinearity of the ocean-atmosphere system to its forcing by the annual cycle in the solar radiation. The QBO, the QTO and the APT combine with the 12 month period and its harmonics at 6 months, 4 months, 3 months, 2.4 months and 2 months to

generate 33 additional frequencies. These frequencies are predicted by a simple combination formula and most of them are found to be generated by the GCM. This was illustrated for high latitudes in the northern and southern hemispheres in paper no. 9. Figure 12 presents the spectra of SLP in the Arctic and the Antarctic regions in the OSU2 GCM simulation. T_1 , T_2 , T_3 identify the QTO, the QBO and the APT in the two regions. These frequencies combine with the annual cycle and its harmonics to generate the other frequencies shown in Figs. 22(a), (b). The discrepancy between the predicted frequencies and those generated by the GCM averaged to 0.0002 ± 0.0045 cycles/month.

TASK 3: STUDIES OF CLIMATE VARIATIONS IN CHINA

Summary of Work Completed in the Current Funding Period

China's rich heritage of historical documents contain records of climate and weather conditions. The task of collecting information on particular variables of climate interest from a vast and dispersed literature is a major focus of work at the Institute of Geography (IG) of the Chinese Academy of Sciences. Professor Gaofa Gong of the IG visited Stony Brook during 1988-92. Several analyses of the historical climatic records were carried out in this collaboration between IG and Stony Brook. Three papers summarizing our results were published in the volume Climate Variation and Its Impact, edited by Zhang Yi et. al., issued by the Meteorology Press in Beijing in 1993:

1. Hameed, S. and G. Gong, Temperature variation in China during historical times, pp. 57-69.
2. Gong, G. and S. Hameed, Relationship between temperature and moisture in China during the last two thousand years, pp. 71-77.
3. Gong, G. and S. Hameed, Identification of climatically sensitive agricultural areas of China, pp. 78-90.

In paper no. 1 a reconstruction of winter air temperature in China from approximately 5000 BC to the present is given and is compared with the temperature curve of Zhu Kochen (15). Our curve was developed from a much larger data base of recent pollen and archaeological results as well as agricultural and phenological information from historical documents of the Ming and Qing periods. In Fig. 13, our result is given by the dashed line and Zhu's curve is shown by the solid line. A more detailed reconstruction is obtained in our curve for the Holocene Climatic Optimum. Also, we present documentary evidence to support the result that the Little Optimum of the 13th Century was warmer than estimated by Zhu.

In paper no. 2, the time series of moisture index of the past two thousand years presented earlier by Gong and Hameed (16) were compared with the temperature variation of Fig. 13. Of the three regions for which we developed the moisture index, the semi-arid area in Northwest China shows a systematic relationship with temperature; this region tends to be wetter in warm epochs and vice versa as shown in the correlation given in Fig. 14. This conclusion is verified by several independent data sources in agricultural and archaeological records. The suggested relationship between precipitation and temperature is of interest in possible predictions of the regional impact of a future climatic warming. This relationship can be investigated in a GCM to understand the mechanism for enhanced precipitation in Northwest China during a warm climate.

Based on historical data on climate and agriculture we have identified in paper no. 3 five areas in China where agriculture is particularly sensitive to climate change. Three of these areas are narrow geographical belts within which agriculture shifts according to the prevalent climatic condition. One sensitive belt separates the non-agricultural cool highlands of the west from the neighboring agricultural regions (I1 in Fig. 15). Agricultural productivity here is related to the ambient temperature in the growing season. The narrow belt extending northeastward from the Yellow River Valley and bordering Ordos Desert and Inner Mongolia (I2) separates the regions of animal husbandry and agriculture; crop

growth in this belt is sensitive to summer rainfall. A belt where agriculture is sensitive to low temperatures in winter and to accumulated temperatures extends westward from the lower Yangtze River Valley (I3) and divides the subtropical and the temperate regimes. Agriculture in the generally cool region of Northeastern China (I4) is particularly sensitive to the temperature in the growing season. Agriculture in the region bordering the Pacific Ocean and the Yellow and Huai Rivers (I5) is vulnerable to frequent droughts and floods as well as to locust epidemics. Historical data illustrating the relationships between agricultural production and climatic factors were presented.

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Fig. 1. Summary of global-mean carbon-dioxide radiative forcing for 15 GCMs.

Fig. 2. Scatter plots of LW radiative forcing.

Fig. 3. (A) Percent deviation of the GCM LW column-model forcings from the LBL results. (B) The same as Fig. 3A but with carbon dioxide bands removed in the LBL calculations so as to represent those included in the GCMs.

Fig. 4. Change in the components of the surface energy budget caused by the retreat of snow. In all models the surface darkened.

Fig. 5. Change in the TOA clear-sky LW flux, ΔF , as induced by a global warming, for CCM2.

Fig. 6. Change in the global-mean TOA clear-sky LW flux, ΔF , for CCM2 and the two hybrid versions. These refer to water-vapor and temperature feedbacks above 500 mb.

Fig. 7. Summary of cloud radiative feedback for CCM2 and the two hybrid versions.

TEMPERATURE VARIATION FROM Δ SST (K)

Fig. 8. Temperature variation and model difference.

Fig. 9. Fraction of clear-sky pixels versus cloud amount in a 2.5° by 2.5° grid.

Fig. 10. Clear-sky days sampled in CCM2 and in ERBE.

Fig. 11. 500 hPa winds and geopotential heights (m) in East Asia in June and July in a seasonal ECMWF simulation: (a,b) T106; (c,d) T63; (e,f) T42; (g,h) T21; (i,j) ECMWF Analyses.

Fig. 12 (a) Frequency spectrum of SLP for 58°N-90°N simulated in the OSU2 GCM

Fig. 12 (b) Frequency spectrum of SLP for 58°S-90°S simulated in the OSU2 GCM

Fig. 13. The dashed line (a) gives the new winter temperature reconstruction for China. The solid line (b) is the temperature variation presented by Zhu Kochen (18).

Fig. 14. The correlation between winter temperature in China and the moisture index for the semi-arid area given in (19) since 200 A.D. Each point represents a 50-year average.

Fig. 15. I₁, I₂, I₃, I₄ and I₅ represent regions of China where historical data indicate significant sensitivity of agricultural output to climate change.

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