NUMERICAL SIMULATION OF ATMOSPHERIC RESPONSE TO OBSERVED SST ANOMALIES AND OCEANIC RESPONSE TO OBSERVED WIND STRESS: INTERCOMPARISON OF RESULTS FROM VARIOUS GCMS.*

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1. INTRODUCTION

It has been generally recognized that the slowly varying boundary conditions at the earth's surface, and particularly the sea surface temperature (SST) anomalies, can produce significant changes in atmospheric circulation and rainfall. During the last 10 years this problem has received considerable attention because of several new results showing significant correlations between observed SST anomalies and observed atmospheric circulation, and the development of several general circulation models (GCMs) which have shown a remarkable degree of success in simulating the stationary and transient properties of the mean climate. Starting with the premise that deficiencies of GCMs are not too serious to invalidate the results of sensitivity experiments (model integrations with and without boundary anomalies), a large number of such numerical experiments have been carried out by the various modeling groups of the world. This is particularly the case for the SST anomalies in the tropics.

Recognizing the particular importance of tropical SST anomalies, as expounded by the plans and aspirations of TOGA (Tropical Oceans Global Atmosphere), it was decided by WGNE (Working Group on Numerical Experimentation) to coordinate the GCM numerical experiments on the sensitivity of tropical SST anomalies.

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* Summary of a workshop organized by WGNE, Boulder, Colorado, U.S.A., December 9-12, 1985.

At its first meeting, at GFDL (Geophysical Fluid Dynamics Laboratory), Princeton, during December, 1982, WGNE had organized one half day session to review some of the ongoing SST sensitivity experiments. Subsequently at the 16th Hydrodynamics Colloquium at Liege, Belgium (JSC/CCCO Symposium on Coupled Ocean/Atmosphere Models, May, 1984), at the request of WGNE, the author organized a one day session of presentations describing the results of sensitivity experiments carried out by about ten atmospheric modeling groups for the observed 1982-83 SST anomalies. After reviewing the papers of this session and recognizing the tremendous interest of the atmospheric GCM community in intercomparing their model results, WGNE asked M. Blackmon and the author to organize a workshop to address this question in detail. The purpose of the workshop was twofold: 1) to bring atmospheric and tropical ocean modelers together to intercompare the sensitivity of various atmospheric GCMs for the same SST anomaly forcing, and the sensitivity of various tropical ocean models for the same atmospheric (stress and heat flux) forcing; 2) to intercompare and evaluate the structure and variability of surface stress and heat fluxes produced by atmospheric GCMs (which would be a possible forcing for the tropical ocean models), and to evaluate the ability of tropical ocean models in simulating the SST anomaly. Brief abstracts and summaries of all the papers presented at this workshop will be published as a report of the World Climate Research Program.

2. DESCRIPTION OF THE WORKSHOP

The presentations and discussions at the workshop were divided into three main parts.

2.1 Atmospheric Climate Simulations

Several modeling groups presented results of extended integrations and described the 'equilibrium response' of the respective GCMs for the 1982-83 El Nino SST anomaly. The tropical response was generally similar to the observed anomalies during 1982-83; in particular, the eastward shift of the rainfall maximum and the associated velocity potential centers were well simulated. The mid-latitude response showed considerable variability among different GCMs, as well as for the same GCM with different formulations for the treatment of gravity wave drag and orography. In general, it appeared that the equilibrium mid-latitude response was largely determined by the mean climate of the model, whereas the 'transient response' (first 30-90 days) was largely determined by the initial conditions.

These experiments confirmed the earlier results that the anomalous moisture flux convergence accounts for a major fraction (> 70%) of the rainfall anomaly in the tropics and the anomalous evaporation accounts for the rest. There is not yet a clear explanation for the exact location of the rainfall anomaly centers, although it appears to be related to the locations of the maximum SST (not SST anomaly) and its gradient. The eastward shift of the rainfall maximum was common to all the GCMs, but the magnitude of the rainfall anomaly was different for different GCMs, perhaps due to different parameterizations of the boundary layer and moist convection. The dipole pattern of the upper tropospheric anticyclonic circulation anomalies associated with the rainfall anomalies was also a common feature for various GCMs, but the intensity and exact locations with respect to the rainfall anomaly were variable.

2.2 Ocean Modeling Experiments

There were only a few ocean modeling presentations at the workshop and the complexity of models ranged from a simple tropical ocean model to complex coupled ocean-atmosphere GCMs. It was very encouraging to see that complex tropical ocean GCMs are able to produce realistic simulations of interannual warm and cold episodes of SST fluctuations in the Pacific Ocean if the models are forced by observed wind stress and simple parameterizations of heat fluxes at the ocean-atmosphere interface. This has been done for about 2 years for one model and for about 26 years for another model.

The modeling of the coupled ocean-atmosphere system has not yet reached a stage where realistic El Nino-like episodes have been simulated by complex coupled GCMs, although simple coupled models have produced realistic simulations of the development and decay of El Nino episodes. In fact, the confidence of some investigators in the results of their simple coupled models has reached a stage where they are willing and ready to make predictions for future Los Ninos.

2.3 Forecasting Experiments

Several atmospheric modeling groups also presented results of forecast experiments (30-90 days) with and without El Nino SST anomaly observed during 1982-83. A list of these investigators is given in Table 1.

TABLE 1

Investigator	Institution	Initial Conditions	Forecast Period
Boer	Canadian Climate Center (CCC), Canada	25-31 Dec. 1982	30 days
Cubasch	ECMWF	15-17 Dec. 1982	90 days
Fennessy	Center for Ocean-Land-Atmosphere Interactions (COLA), U.S.A	15-17 Dec. 1982	60 days
Michaud	LMD	15-16 Dec. 1982	45 days
Miyakoda	GFDL	1 Jan. 1983 1 Dec. 1982	30 days 60 days
Palmer	UKMO	15-17 Dec. 1982	90 days
Sirutis	GFDL	1 Jan. 1983	30 days
Tibaldi	ECMWF	19 Jan. 1983	50 days
Tokioka	Meteorological Research Institute (MRI), Japan	1-3 May 1983	60 days

3. RESULTS OF ATMOSPHERIC GCM FORECAST EXPERIMENTS

This paper summarizes the results of only those atmospheric GCM experiments which used the observed initial conditions of 15, 16, 17 December 1982, and observed El Nino SST anomalies during the winter season of 1982-83, and compares their model results with the actual observations. Presentations by Michaud, Palmer, Cubasch and Fennessy fall into this category. The presentations by Michaud, Palmer and Cubasch are summarized only briefly.

3.1 Michaud

Michaud and Sadourny have used a standard version of the LMD General Circulation Model to carry out two 45 day integrations starting from the initial conditions of 15 and 16 December 1982, and boundary conditions of

SST for winter of 1982-83 as given by the Climate Analysis Center. The LMD GCM has 64 points equally spaced in longitude and 50 points equally spaced in sine of latitude,and therefore the grid is most anisotropic near the poles and the equator. At the equator the grid lengths along the latitude and longitudes are 625 km and 255 km respectively, and at 50°N the grid is a 400 km square. This is a sigma coordinate model but the lateral diffusion of velocity and potential temperature is carried out on pressure surfaces. Michaud and Sadourny also used the initial conditions of 15 December for the years 1979, 1980 and 1981, and climatological SST,and integrated the model for 45 days to obtain the 'control' climate of the model. The predicted January mean circulation and rainfall using the observed SST anomalies were clearly closer to the observations than those with the climatological SST. The eastward shift of the rainfall maximum and the structure of the Hadley-Walker cells were more realistic in the integrations with the observed SST anomalies.

3.2 Palmer

Palmer and Owen used the UK Meteorological Office 11-layer GCM to carry out a pair of 90 day integrations starting from the observed ECMWF analyses for 12Z of 15, 16 and 17 December 1982, with seasonally varying climatological SST and with superimposed observed SST anomalies in the tropical Pacific. The difference between the 200 mb stream function with and without SST anomaly for the first 30 days for each of the forecasts from 15, 16 and 17 December showed somewhat similar features of anticyclonic pairs over the tropical East Pacific and the cyclonic centers over the Southern United States. However, there were also large differences among the three difference fields indicating a significant role of internal dynamics in the evolution of small initial differences. A lagged-average ensemble of three forecasts verified against the observed data for days

1-30, 31-60 and 61-90 showed a spectacular improvement in forecast skill in the tropics with observed SST anomalies. There was a slight improvement in the forecast skill even in the extratropics but only for days 31-60 and 61-90.

3.3 Cubasch

Cubasch integrated the ECMWF spectral model (T42) for 90 days using climatological SST and the observed 1982-82 SST anomalies in the equatorial Pacific for initial conditions of 12Z for 15, 16, 17 December 1982. The 90 day mean rainfall difference between the integrations with the observed SST anomaly and the climatological SST showed little resemblance to the observed anomaly of the outgoing longwave radiation during 1982-83. This deficiency of the model reduces the possibility of a positive impact on forecast skill for tropical or extratropical circulation because the rainfall anomaly is a measure of one of the important diabatic forcing functions. No quantitative comparison was made between the ensemble mean forecast and observed flows either for the tropics or mid-latitudes. It was noticed, however, that there were large differences in the difference fields for 500 mb geopotential height using observed SST anomalies and climatological SST. Difference fields for rainfall as well as the 500 mb geopotential height starting from 15 and 17 December had more in common with each other than either one had with integrations from 16 December.

It was quite difficult to understand why the simulated rainfall anomaly near the equator between the dateline and 135°W had maxima both for the initial conditions of 15 and 17 December, whereas it was nearly zero for the 16 December case. It is, of course, even more difficult to understand why the model simulated rainfall anomaly patterns were so different from the observed outgoing longwave radiation anomalies.

3.4 Fennessy

Results of the forecast experiments carried out by Fennessy and the present author are presented in a little more detail. These results should be considered representative of the results for several other models.

GLAS model (global, 4° latitude x 5° longitude) was integrated for 60 days starting from the observed initial conditions of 15, 16, 17 December 1982 and climatological SST boundary conditions. An ensemble average of these 3 integrations will be referred to as the control run.

The above three integrations were repeated with modified SST in the equatorial Pacific. The modification of SST consisted of adding the observed SST anomaly for January 1983 to the climatological SST over the equatorial Pacific. The ensemble average of these 3 integrations will be referred to as the anomaly run. Fig. 1 shows the observed SST anomaly for January 1983. In the anomaly run the SST is modified only over the region shown in Fig. 1.

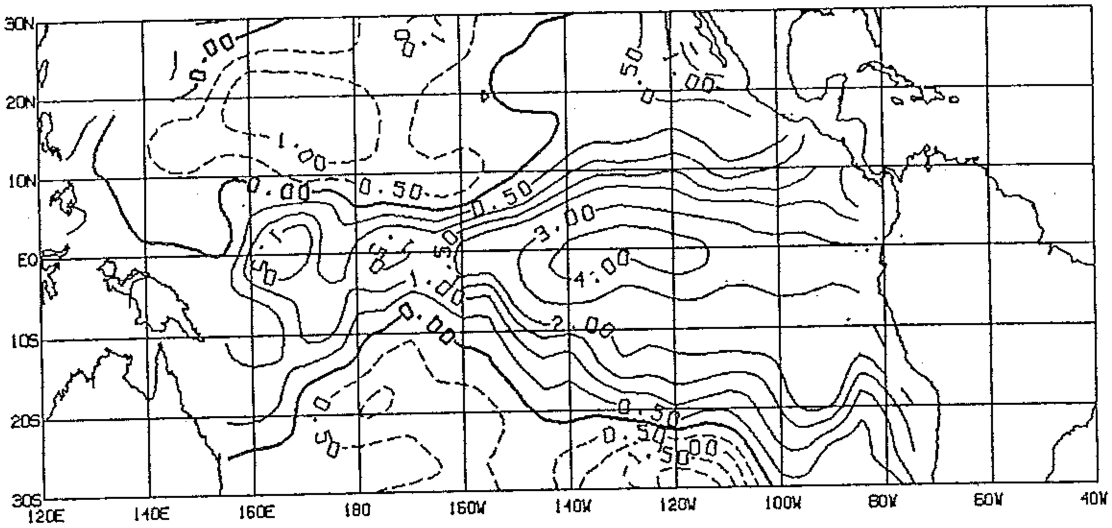

Fig. 1. SST anomalies (°C) during winter 1982-83.

Figure 2 shows the mean observed rainfall anomaly for winter (DJF) 1983. This is actually the observed anomaly of outgoing longwave radiation which has been converted into a rainfall anomaly using an empirical relation developed by Dr. P. Arkin of the Climate Analysis Center. This is considered to be appropriate for model comparisons. Fig. 3 shows the model simulated rainfall anomaly. This is the difference of the ensemble mean rainfall for the <u>anomaly runs</u> and the ensemble mean rainfall for the <u>control runs</u> for days 11-60. The first 10 days are not included in the averaging.

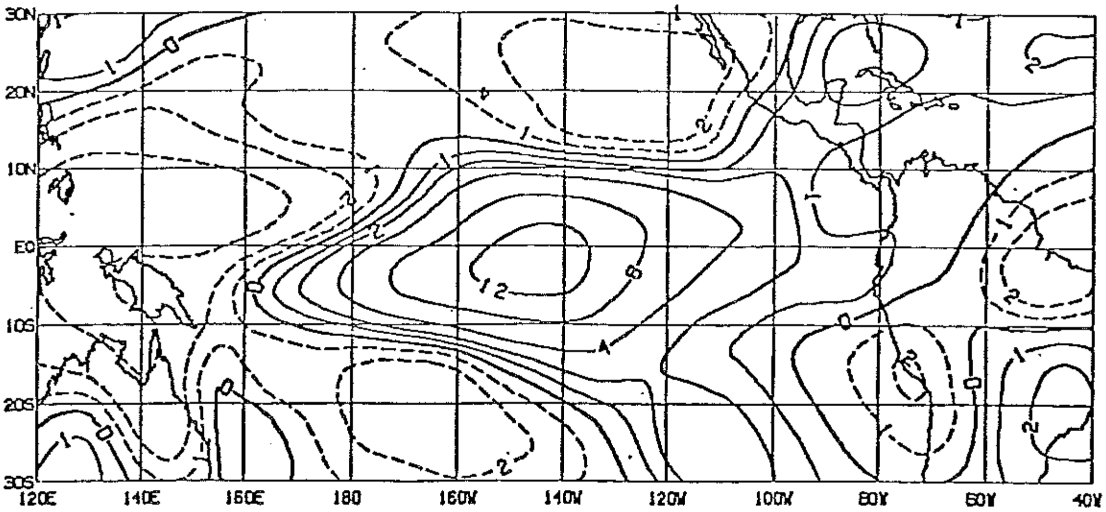

Figure 2. Observed rainfall anomalies (mm/day).

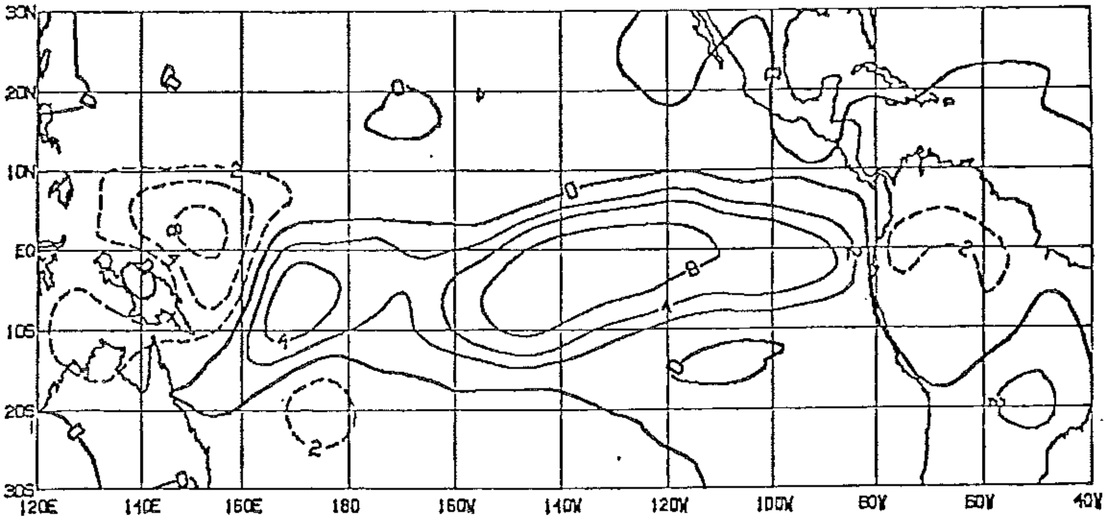

Figure 3. Forecast rainfall anomalies (mm/day).

These figures suggest that it is possible to simulate the observed patterns of rainfall anomaly rather well. The locations of maxima and minima are correctly simulated. The tropical circulation anomalies (shifts in Walker cells and large scale anticyclones, etc.) are also correctly simulated (not shown).

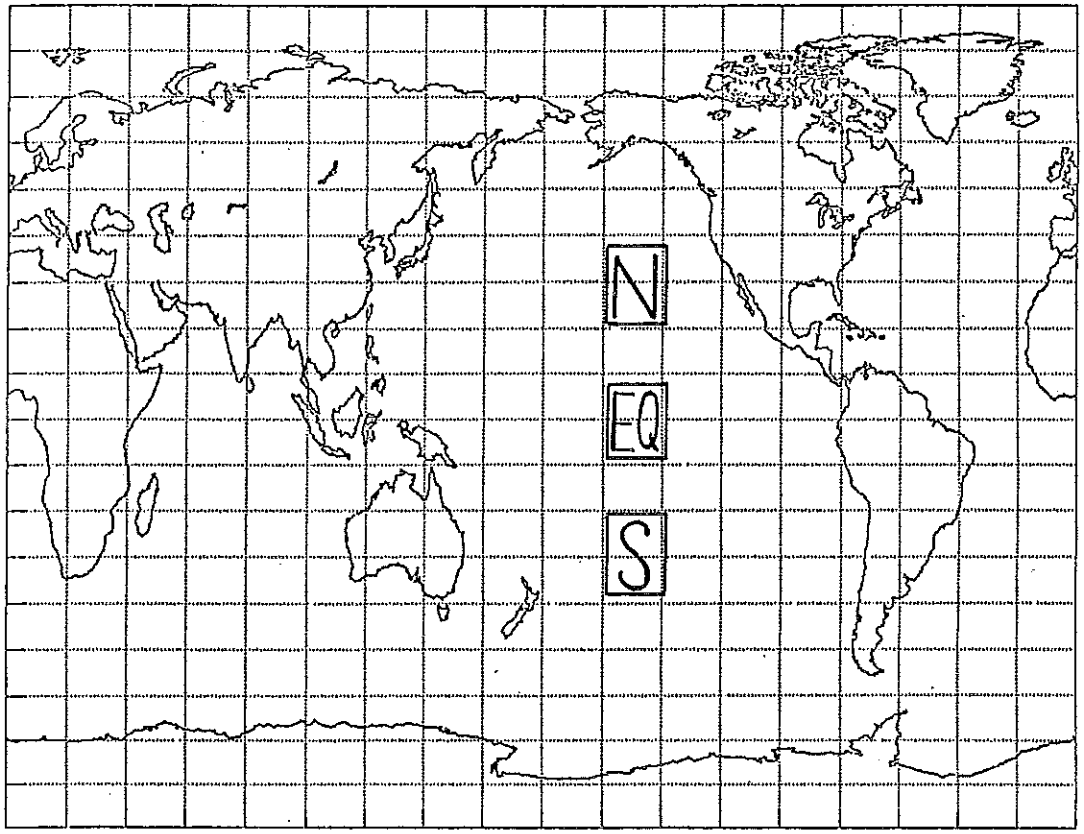

Figure 4

Figure 4 shows the areas over which observed and predicted zonal wind is averaged to show a time series for 60 days.

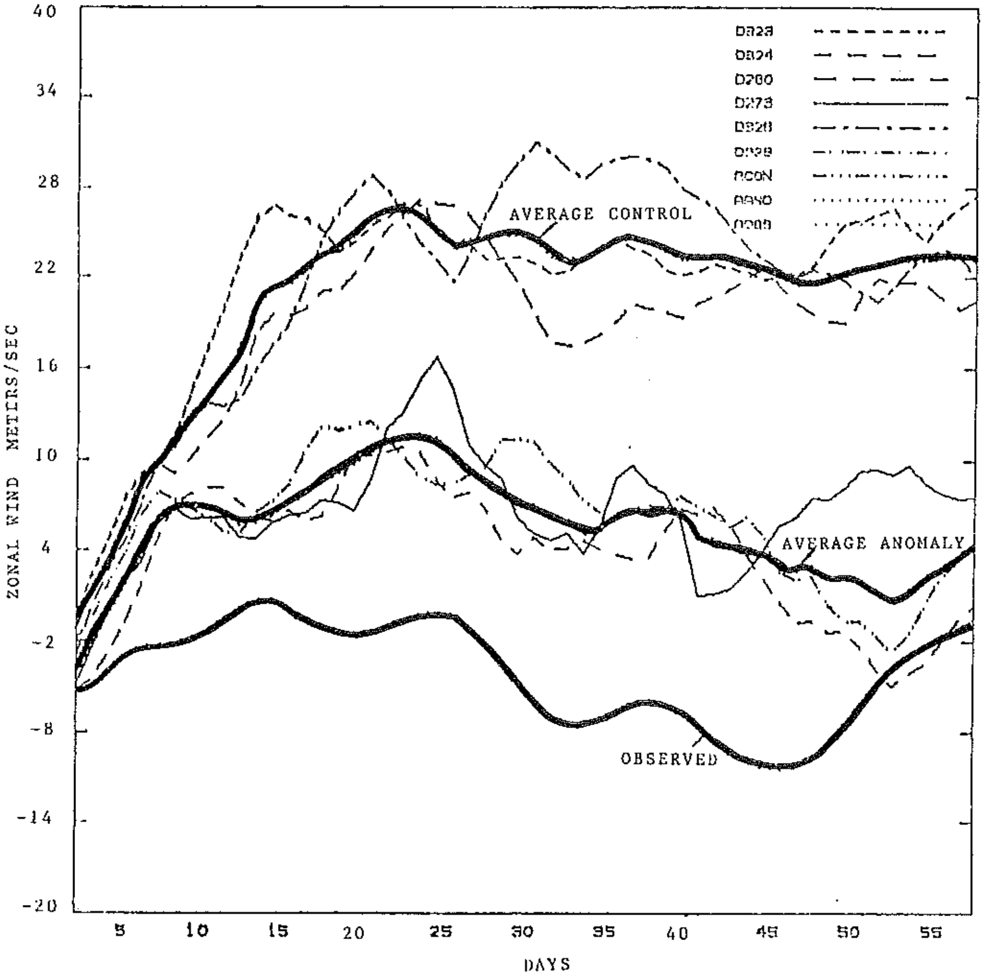

Figure 5. Five day running mean of control, anomaly and observed zonal wind.

Fig. 5 shows the time series of zonal wind averaged over the equatorial box (EQ) for control runs and anomaly runs. The x axis represents days of integration, the y axis represents zonal wind (m/s) at 200 mb averaged over the box (EQ) in Fig. 4.

The upper three thin curves correspond to the three control runs starting from the initial conditions of 15, 16, 17 December 1982. The thick curve is the ensemble average of the three control runs. Similarly, the middle three thin curves correspond to the anomaly runs using the same initial conditions (15, 16, 17 December 1982) and including the SST anomaly in the equatorial Pacific. The middle thick curve is the ensemble average of the three anomaly runs. The bottom thick curve is the observed zonal wind during the 1982–83 winter season averaged for the same box. All curves represent 5 day running means of daily values.

It can be seen that the ensemble mean anomaly run values of zonal wind in the tropics are much closer to the observations than the control runs. Of course the anomaly runs also have errors but not as large as the control runs. Correct SST boundary conditions corrected the tropical zonal wind forecasts quickly (within 10 days) and significantly (~ 15 m/s).

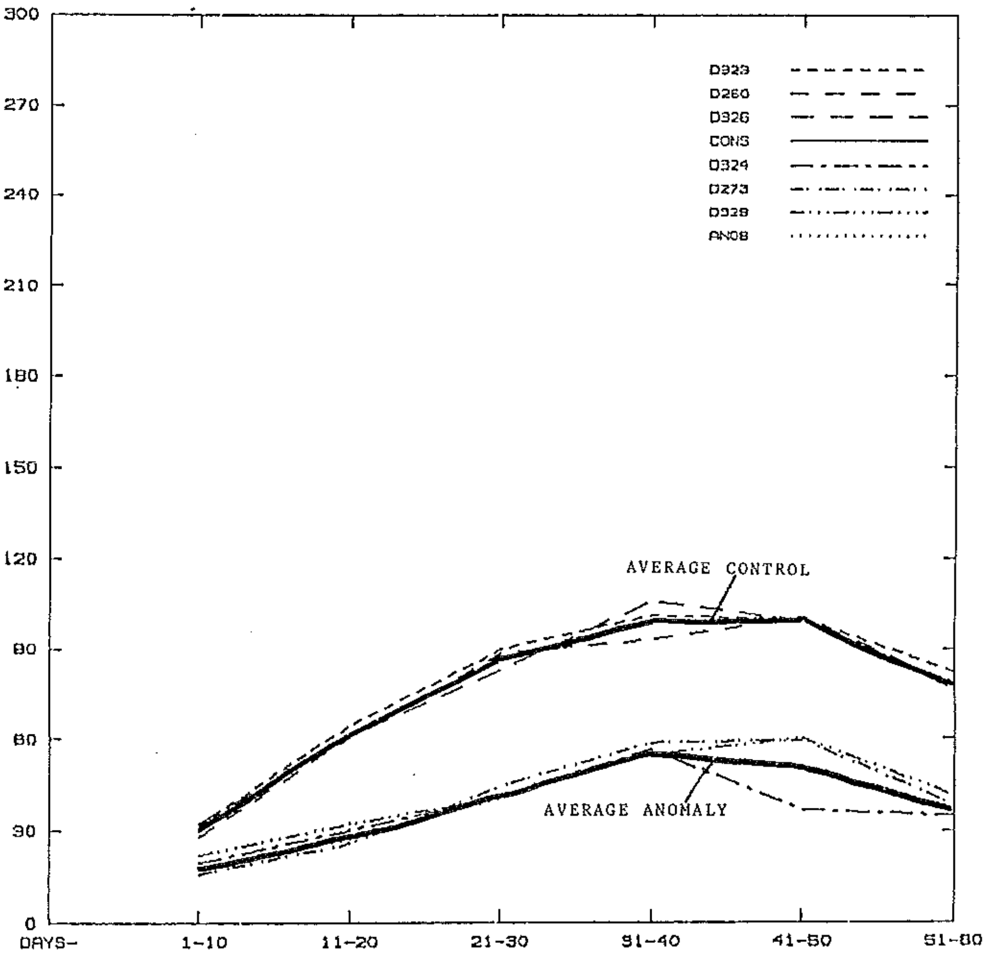

Figure 6. RMS error for 300 mb geopotential for 10 day averages for the tropics.

Fig. 6 gives the RMS (root mean squared) error between the observed and forecast geopotential height at 300 mb for the tropics (20S-20N) for 10 day averages. (Please note Fig. 5 was not the RMS error, but the zonal wind itself.) As in Fig. 5, the upper three curves correspond to the three control runs and the lower three curves correspond to the anomaly runs. Thick lines represent ensemble mean forecasts for control (upper line) and anomaly (lower line) runs. The RMS error of the 10 day mean forecast up to 60 days is reduced by about 50% due to the influence of observed SST anomalies in the equatorial Pacific. The curves for three

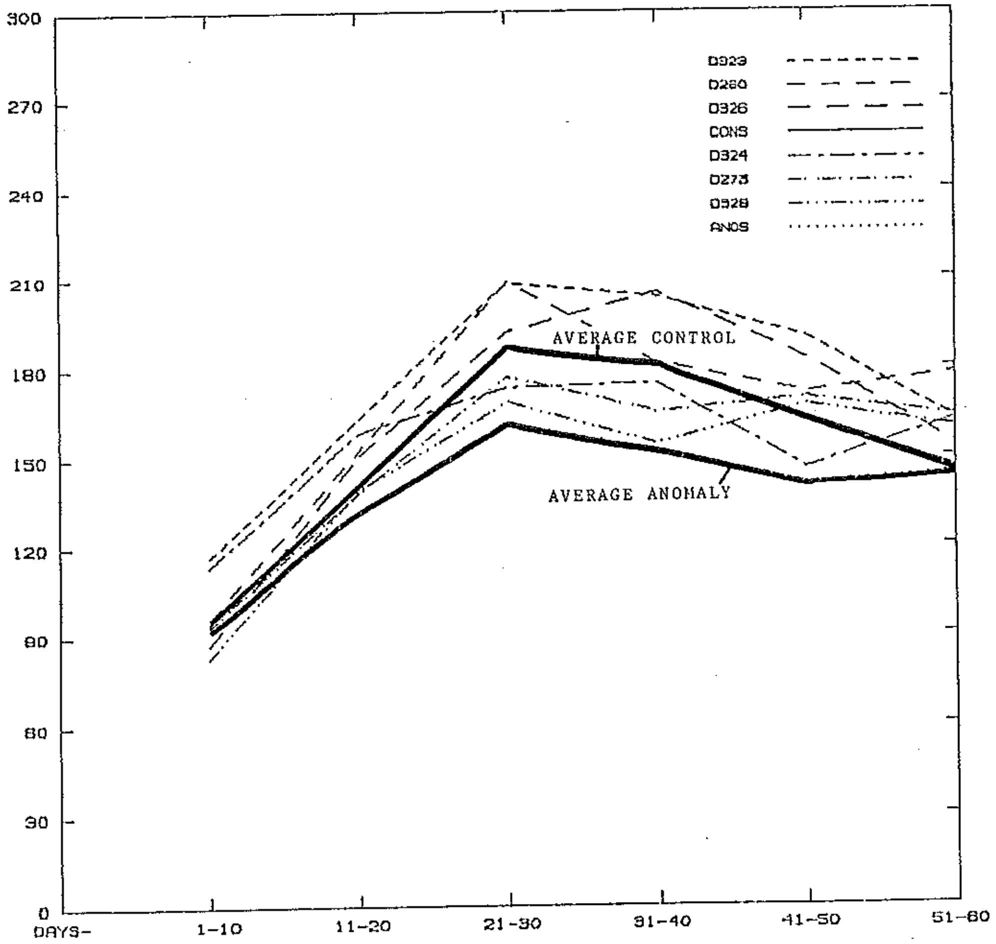

Figure 7. RMS error for 300 mb geopotential for 10 day averages for the northern hemisphere extratropics.

control cases are very close to each other and the three anomaly cases are also very close to each other but the ensemble means are well separated. This means that changes in the initial conditions do not produce large changes in the tropical circulation but changes in the boundary conditions do. This gives hope for the predictability of the tropical atmosphere using correct boundary conditions of tropical SST.

Figure 7 which follows is the same as Fig. 6 but for the mid-latitudes (20N-70N). The impact of tropical SST on predictability of the mid-latitudes is not as large as for the tropics. However, the encouraging result is that the inclusion of correct tropical SST does reduce the RMS error even in the mid-latitudes.

4. SUMMARY OF FORECAST EXPERIMENTS

Based on the oral presentations by the various authors and subsequent discussions, the following conclusions were drawn by the author:

1) Use of the observed tropical SST anomalies produced a clear and significant improvement in the prediction of the 30 day mean circulation and rainfall over the tropics. For some models the improvement was spectacular; for some models the improvement in prediction was clearly seen even in the first 10 days. Improvement for the second 30 days (days 31-60) was also clear and unambiguous.

2) Use of the observed tropical SST anomalies did not produce a significant improvement in the prediction of the 30 day mean (days 1-30) circulation over the mid-latitudes. There was large variability among runs with different initial conditions and among different models for the same initial conditions. However, there was a clear but small improvement in the prediction of circulation for the next 30 days (days 31-60) over the mid-latitudes. Forecasts for the first 30 days appear to be strongly

dominated by the initial conditions, and the tropical SST anomaly does not seem to have a notable effect.

3) The patterns of forecast error over the mid-latitudes with tropical SST anomaly were remarkably similar to those without the tropical SST anomaly. This suggests that the lack of correct boundary conditions over tropical oceans is not the primary cause of errors in extended range forecasts for mid-latitudes.

5. CONCLUDING REMARKS

The workshop concluded with a certain amount of optimism about the future success of TOGA. It was rather remarkable that most of the atmospheric GCMs could capture the large scale signature of tropical rainfall and circulation anomalies associated with the observed SST anomalies during 1982-83. Likewise, oceanic GCMs forced with observed stress could simulate the patterns of large scale SST anomalies. Success of these one-way forced simulations provides encouragement to proceed with the ultimate goal of coupling atmospheric and oceanic models; however, much more work needs to be done with the one-way forced simulations to enable us to interpret the results of coupled simulations.

It should be noted, however, that the success of one-way forced models does not guarantee a similar success of the coupled models for the predictability of El-Nino/Southern Oscillation episodes, and in order to understand the limits of predictability of the coupled system, it is necessary to investigate the nature of the instabilities of the coupled system.

6. ACKNOWLEDGEMENTS

The author would like to express his gratitude to all the speakers listed in Table 1 for the benefit of their useful and stimulating discussions during and after the workshop. This workshop represented, to this author, a new spirit in the GCM modeling community where scientists are willing and enthusiastically agreeing to participate in model intercomparison exercises.

Special thanks are due to M. Blackmon for planning, organizing and conducting the meeting at NCAR and for excellent local arrangements, in spite of the severe weather conditions. Also a special thanks to R. Newson for providing support and liason with WGNE and WMO.

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