TECHNICAL MEMORANDUM

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A survey of the performance of GCM's in the tropics. Part 1: Other models

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1. INTRODUCTION

This is part I of a review of the performance of general circulation models in the tropics. The ECMWF model will be discussed in Part II. Part I attempts to describe the systematic errors in the tropics, of other general circulation models, in climate simulations and weather forecasting. For brevity the results of earlier reviews are wherever possible not duplicated, for this reason it may be useful to refer to the following for more information.

1. GARP Report No.20 (ICSU/WMO, 1978)
   This gives a brief review of the performance of GCM's in simulating the global climatology.

2. Gilchrist (1977)
   This discusses the ability of GCM's to simulate the Asian summer-monsoon.

3. Gilchrist et al (1980).
   This discusses the impact of GATE on large-scale numerical modelling.

4. Rowntree (1978)
   This gives a useful discussion of sensitivity studies performed using GCM's.

General circulation models are large and complex, and are usually a product of a group effort rather than individual work. For this reason I have concentrated on reviewing the work of certain groups, rather than individuals, who are, or have been, actively engaged in research or forecasting using GCM's. Section 2 contains a survey of the work carried out at the selected Centres, Section 3 compares the models used by these Centres and Section 4 summarizes the main features of the errors.

Much of the material discussed here may be found in the literature, however some of the material is as yet unpublished. I have written to most of the active groups in the field in order to obtain material for this review. I have not received replies from some groups as yet therefore this review is not perhaps as complete as it might be.

2. SURVEY OF WORK CARRIED OUT AT VARIOUS CENTRES

In discussing the work at various Centres relevant to the subject of this paper I have restricted the discussion to a small number of Centres. These are listed below. Clearly, any global, hemispheric or limited area tropical model of the atmosphere is related, to some extent, to the problem in hand and there are a large number of these models, many more than I have discussed here. However, most if not all of these models, are run by Centres whose principal concern is in the extratropics. The models may produce global fields, but the tropical fields are rarely looked at and even more rarely documented. Much of what is known of the performance of the models, in the tropics, described in this Section is a by-product of studies into the 'global' performance of the models; the emphasis is usually on the extratropics. Recently, however, the importance of the tropical circulations on the global weather is being realized; much more attention is being focussed on forecasting in the tropics and many Centres intend to concentrate more attention in this area. The Centres described here are the ones that have looked, to some extent, into the performance of their models in the tropics.

Florida State University Department of Meteorology Tallahassee, Florida, USA	(FSU)
Geophysical Fluid Dynamics Laboratory NOAA Princeton University Princeton, New Jersey, USA	(GFDL)
Institute for Space Studies Goddard Space Flight Center NASA, New York, USA	(GISS)
Laboratory for Atmospheric Sciences Goddard Space Flight Center NASA, Greenbelt, Maryland, USA	(GLAS)
National Center for Atmospheric Research Boulder, Colorado, USA	(NCAR)
UK Meteorological Office Bracknell, Berks, UK	(UKMO)

The Japan Meteorological Agency is engaged in operational numerical weather prediction using a six-level, fine-mesh, limited area model (Nitta et al 1979). The model only extends as far south as about 15^{o}N and essentially only covers the area around Japan. There is no evidence to suggest that the Japanese are engaged in tropical prediction as such.

I understand that a dynamic hurricane model aimed at improved prediction of position one or two days in advance has been developed at the NMC which was due for operational testing during the 1975 season (Hovermale et al 1975). I have been unable to ascertain, as yet, what their current interests in tropical prediction/simulation are.

There is a plan to evaluate the performance of the US Navy's forecasting model in the tropics, but it will not be started until next year. They suggest that many general circulation models cannot model the location of the ITCZ consistently, which implies grave problems with the simulated Hadley circulation and that the root of the problem probably lies in cumulus parameterization schemes. They are interested in our tropical evaluations and intend to keep us informed when their tropical evaluations get started. (C.P. Chang, personal communication).

2.1 FSU

2.1.1 Past work

In low latitudes the work at FSU has been mainly concerned with limited area single and multiple level baroclinic models. In the single level barotropic and the single level primitive equation experiments a detailed data base from GATE during phase III was examined in a series of 34 short range NWP experiments. The main conclusion of the work (Krishnamurti et al 1980) was that the intensity and position of westward propagating African waves were handled very well at 700 mb for up to 48 hours by the simple models that utilize the principles of conservation of absolute or potential vorticity.

The heights of the mountains of West Africa are of the order of 1 km. Short range prediction experiments with and without the mountains show that the intensity of a disturbance that arrives near the GATE A/B scale ship array is influenced by the inclusion of the mountains. An adiabatic multi-level primitive equation model is shown to have less skill than a one level primitive equation model, with bottom topography, at 700 mb due to the misrepresentation of vertical coupling by the former model. The vertical coupling in disturbances that are embedded in the lower tropospheric monsoonal westerlies and high level tropical easterlies is improved by the inclusion of several physical effects in the multi-level primitive equation model. They note that the model with full physics produces a very realistic vertical structure of the African wave. "Full Physics" here includes the diurnally varying radiative processes as well as a cloud feedback mechanism for both shortwave and longwave radiation. Suppression of these physical processes leads to a gradual decay of the broad-scale West Africal monsoon and an unrealistic prediction of the embedded African wave. Their experiments on resolution for NWP suggest that a 1° lat/lon resolution is desirable for studies of tropical waves. (Krishnamurti et al 1979).

2.1.2 Current work

A global spectral model has recently been constructed (Krishnamurti et al, 1982). The model is constructed with the aim of looking especially at the behaviour of the atmosphere in the tropical latitudes. The model utilizes real data over the entire globe and is designed for medium range prediction experiments. Their eventual interests are towards contributing to the improvement of low latitude as well as global numerical weather prediction studies, focussing in the areas of analysis, initialization and parameterization of physical processes. A few experimental ten day forecasts have been performed, in one of which they note a deterioration of the velocity potential field at 850 mb within a few days of the start of the forecast. The streamfunction field is well forecast out to six days. The divergence field does not seem to be as unrealistic as the isopleths of the velocity potential field. The rainfall rates appear to be quite reasonable for the first 7 days of the prediction over the northeast coast of India. They suggest that the deterioration of the velocity potential field is related to the deterioration of the planetary scale forcing.

2.2 GFDL

2.2.1 Past work

Manabe et al (1974) described the seasonal variation of the tropical circulation as simulated by a global model of the atmosphere[1]. The model was integrated for 3½ (model) years using a model produced January mean state as initial conditions. The first 1½ model years were integrated on a low resolution (~500 km) grid and the final two model years on a high resolution (~250 km) grid. The results of the final 1½ model years were analyzed. Examinations of the annual march of various quantities indicated that they do not repeat themselves

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[1] Model described as GFDL(1) in Section 3.

exactly in the same manner from one year to another. It is not clear whether this interannual variation is due to the transient behaviour of the model originating from the imbalance of initial conditions, or whether it is due to a natural variability in the model. They investigated the zonal mean state of the model atmosphere and showed qualitative agreement with the actual atmosphere, an exception being the stratospheric easterlies which were much too strong. In the upper troposphere of the model tropics weak westerlies and weak easterlies appear in January and July respectively, whereas easterly winds are observed in the atmosphere in both months. The seasonal evolutions of the general features and intensities of the two Hadley cells in the model tropics compare reasonably well with those of the actual tropics obtained by Oort and Rasmusson (1971). There are, however, some systematic differences. The heights of the centres of the Hadley cells of the model were systematically lower than those in the actual tropics. They suggested that this was probably due to their assumption of no subgrid scale vertical mixing in the free atmosphere of the model. In the annual mean the intensities of the two Hadley cells of the model were approximately 15% weaker than those of the actual atmosphere. They showed a good qualitative agreement between the model forecast precipitation in the annual and seasonal means with observed precipitation (Budyko, 1956) but quantitatively the model tended to overestimate the zonal mean precipitation in the tropics by ~20%. The vertical distribution of static stability in the troposphere of the model tropics was significantly different from the observed distribution; in particular, the model was too stable in the upper troposphere. The relative humidity in the lower troposphere of the model was systematically higher than the observed humidity. It was suggested by the authors that these last two errors were primarily due to the poor representation in the model of moist convection.

Miyakoda et al (1974) described a two week experimental prediction of the tropical atmosphere using a 9 level global primitive equation model.[1] The model demonstrated some ability in predicting the day to day tropical tropospheric flow field. The best simulated region appeared to be the upper troposphere with less skill for higher and lower levels. In the forecasts for 700 mb, the March monsoon westerlies of the south Indian Ocean, between the equator and 15°S, were maintained as a recognizable current up to three days; however, the eastern end of the monsoon system, north and east of Australia, decayed very rapidly and vanished after day two. The stratospheric prediction was recognized by the authors to be a complete failure. Even at the first day the predicted pattern of the 50 mb flow was entirely different from the analysis.

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[1] Model described as GFDL(2) in Section 3

The forecast at the surface was not good. There were a number of well observed vortices, the horizontal scale of which was about 1000 km, that were rarely found in the forecast. Two tropical storms (hurricanes) were included in this case over the Indian Ocean. Their behaviour was simulated to some extent, but the storms tended to weaken rapidly and were very shallow. The precipitation forecast for the first day was surprisingly good, but it deteriorated rapidly. The predicted rain pattern appeared to be erroneously spotty after about two days, and had undue concentration along the equator. In the zonal mean averaged for 10 days the forecast zonal component of the wind showed a systematic bias in which the stratospheric easterlies were too strong, as were the low level easterlies.

2.2.2 Current work

As far as I have been able to ascertain, little work is currently being performed on the tropical forecasting problem. Some work is being performed on hurricane modelling using moveable nested-mesh primitive equation models (Kasahara et al, 1980). Other work is concerned with experiments on four-dimensional analysis using the GATE data (Miyakoda et al, 1981).

2.3 GISS

2.3.1 Past work

Somerville et al (1974) describe a January climate as simulated by the GISS global general circulation model. In the January simulation the model was producing too little precipitation and evaporation over most of the globe. In the zonal mean the tropical easterlies have the right magnitude. The model's westerly jet in the northern hemisphere is too broad and the meridional circulations are too weak. The energy cycle is in good agreement with observational estimates, together with generally realistic zonal mean fields of most parameters.

A similar study for the July climate has been performed by Stone et al (1977). Sea surface temperatures, ice cover, snow line and soil moisture were assigned values based on climatological values for July and the integration was started from real data for 18 June, 1973. The model rapidly approached a quasi-steady state from the realistic initial condition. Mean statistics were computed for the simulated calendar month of July and compared with climatological data, mainly for the northern hemisphere troposphere. Qualitatively, the model-generated energy cycle, distribution of winds, temperature, humidity and pressure, dynamical transports, diabatic heating, evaporation, precipitation and cloud cover were all realistic. Quantitatively, the July simulation, like the January simulation, tended to underestimate the strength of the mean meridional circulations, the eddy activity and some of the associated transports. The simulation of the climatological fields in the vicinity of the Himalayas and southeast Asia was noticeably poorer than in other areas; for example, in southeast Asia in the July simulation the rainfall was half the observed amount. The zonal mean fields of the zonal wind in the lower troposphere for the July simulation exhibit weak westerlies at 10^{o}N where observations show weak easterlies.

In the January simulation the low level winds in the Bay of Bengal and southeast Asia were much too weak and in the wrong direction. This defect, the authors suggest, was probably caused by the fact that the simulated Siberian high in January was weaker and further east than in reality. Also, there was a tendency for the simulated ITCZ in the Indian Ocean in January and in the central Pacific in both seasons to be too near the equator, and to be too far north over Africa in July. The displacement over Africa in July the authors claim to be caused by the ground albedo in the model always being taken to be 0.14. Other studies have shown that a more realistic value over the Sahara of 0.35 leads to a correct positioning of the ITCZ over Africa in July (Charney et al, 1975). The rainbelt across Africa in the July simulation, like the ITCZ is actually about 6^{o} latitude too far north; this, the authors claim, is partly a result of the unrealistic ground albedo in the Sahara.

Druyan et al (1975) describe six cases of two-week numerical weather prediction experiments, using the GISS global GCM, begun from and verified against actual data. The forecasts were all for the northern hemisphere winter. The climatology of the model is different from that of the atmosphere and this contributes to the decay of the forecast skill. The northern hemisphere subtropical jet maximum in the model was realistic in magnitude and location, but less clearly separated from the polar night jet than it should be. The model tropical easterlies were much weaker than observed near the surface but too strong and broad in the upper troposphere. The model tended to be colder than the observed atmosphere in the middle and lower troposphere particularly in the north polar region and the middle latitudes of the southern hemisphere. The model also tended to be too warm near the tropopause, particularly in the vicinity of the subtropical jet maxima of both hemispheres. The mean static stability of the model was, therefore, greater than that of the observed atmosphere.

2.4 GLAS

2.4.1 Past work

The GLAS 4th order global GCM started off its life as the GISS 4th order global GCM described by Kalnay-Rivas et al (1977). The basic equations and the parameterizations of physical processes are the same as those of the standard 2nd order GISS global model (Somerville et al, 1974). It is based on 4th order quadratically conserving differences with the periodic application of a 16th order filter on the sea level pressure and potential temperature equations, a combination which is approximately enstrophy conserving. Several short range forecasts indicated a significant improvement over 2nd order forecasts with the same resolution (400 km). However the 4th order forecasts are somewhat inferior to 2nd order forecasts with double resolution. The authors suggest that this is probably due to the presence of short waves in the range between 1000 km and 2000 km, which are computed more accurately by the 2nd order high resolution model.

Kalnay-Rivas et al (1981a) describe some data assimilation experiments, using the FGGE II-b data, with the GLAS analysis scheme and 4th order global model. They noted that the FGGE special observing systems had a very significant impact in the southern hemisphere, but little or no impact in Europe or North America.

2.4.2 Current work

Current work involves the examination of the mean error characteristics of forecasts of the tropical flow using the GLAS 4th order atmospheric model described by Kalnay-Rivas et al (1977) and Kalnay-Rivas and Hoitsma (1979). Some preliminary results of the study are presented in Kalnay-Rivas et al (1981b) which are results obtained from the global assimilation and forecast experiments performed by Halem et al (1981).

The GLAS analysis/forecast system for producing a global gridded analysis consists of an objective analysis scheme which makes use of the continuity provided by a first guess which is a six hour forecast from the previous analysis. The first guess is then corrected by all the data collected within a ± three hour window about each analysis time. The analysis scheme (Baker et al, 1981) is a modified successive correction method (Cressman, 1959) which takes into account the density and quality of the observations.

In Kalnay Rivas et al (1981b) two analysis cycles were performed for the first FGGE Special Observing Period (SOP-1), from January 5 to March 5, 1979. In one of them all available FGGE II-b data were assimilated. In the second experiment only conventional data were utilized. Fourteen five day numerical forecasts were then generated every four days from the initial conditions of both these assimilation experiments. They present preliminary comparisons of the mean and standard deviation of the forecast error. The mean errors represent the systematic forecast errors and the standard deviation of the forecast error is a measure of the skill in predicting the evolution in time of atmospheric systems. The error was computed by subtracting the GLAS FGGE analysis from the forecast.

Their results indicate that the systematic error in the meridional velocity at 850 mb, after 1,3 and 5 days, is dominated by the large scales, both in the tropics and the extratropics. This, combined with the fact that their phase is rather constant, indicates that they are associated with forcing, both thermal and orographic. For example, the fact that the forecasts overpredicted the equatorward flow over the Andes even after one day indicates that the mountains are generating more drag in the model than in the real atmosphere. At 300 mb the average error in the tropics was still of planetary scale, but in the extratropics the error was of cyclonic scale. This, and the change in phase in the error after 1,3 and 5 days indicates that the error in the extratropics is dominated by the systematic component in the forecast of moving cyclones. The systematic error grew in amplitude from day one to day three. The growth was most rapid in the tropics. By day three the systematic error in the tropics had ceased to grow, perhaps indicating a limit to the predictability of about three days. In the extratropics, however, the systematic error continued to grow through to day five suggesting further forecast skill. In the extratropics errors in the transient component of the flow were dominant, whereas in the tropics the systematic error was very important, especially at low levels. Investigation of the heating rate at 500 mb confirmed that the large systematic errors were associated with regions of strong heating, as well as with orographic forcing.

The systematic errors in the zonal velocity at 300 mb were only slightly larger with the conventional data as initial conditions than with the FGGE data as initial conditions. This indicates that the systematic errors were due more to model parameterization deficiencies than to initial data. It is interesting to note that both forecasts showed characteristics similar to those of a "warm episode" of the Walker circulation, with enhanced easterlies and stronger subtropical jets in the Pacific (Howe and Wallace, 1981); Julian and Chervin, 1978). At low levels the error was reversed, completing an east-west circulation.

They claim the model forecast error became comparable to the persistence forecast error in three to five days. On the other hand, the model retained some skill in the prediction of transient features in the tropics after three days. They suggest that a major obstacle in accurate low latitude forecasting is the prediction of the large-scale quasi-stationary flow.

2.5 National Center for Atmospheric Research, Boulder, Colorado, USA (NCAR)

2.5.1 Past work

Previous work has been related to climate and sensitivity studies. Kasahara and Washington (1971) produced January simulations of climate with and without orography, using the NCAR six layer global GCM. Their main conclusion was that the Earth's orography plays a minor role over the thermal effect of continentality in determining the major features in the transport mechanism of momentum, water vapour, heat and energy in terms of the zonal mean state. However, for the regional aspects of the general circulation of the atmosphere the effects of orography are significant.

In a series of short range (five day) forecasts, starting from the NMC analysis of 0000 GMT 11/1/73, Williamson (1978) used the NCAR GCM to determine the relative importance of resolution, accuracy and diffusion. He used the six-layer model without mountains, hemispherically and using height as the vertical coordinate. Forecasts were made with 5°, $2\frac{1}{2}^{\circ}$ and $1\ 1/4^{\circ}$ horizontal resolution and second and fourth order horizontal, centred finite difference approximations, integrations were also carried out with two types of horizontal diffusion. His main conclusion was that improvements in the simulation of eddy activity obtained with increased resolution are mainly due to a reduction in the effective dissipation.

2.5.2 Current work

I am given to understand that NCAR is not involved in making tropical forecasts at the moment (W.M. Washington, personal communication).

2.6 UKMO

2.6.1 Past work

Gilchrist (1974) described the performance of the UKMO 5-level global GCM (Corby et al, 1972) when the boundary layer formulation was changed to incorporate an explicit boundary layer top. The parameterization of surface exchanges and convection were altered to incorporate it. A slight overall improvement was evident particularly as regards the realism of the rainfall distributions and the depth of low pressure systems in the southern hemisphere. The author notes that the surface flux formulations were capable of producing excessive heating and evaporation in very unstable conditions and that this may have led to the very deep Atlantic depressions produced by the model in winter. January and July simulations are discussed. The January rainfall is generally well reproduced by the model. The July rainfall is less well simulated: the ITCZ is too far north over Africa, and further east, rain centres, caused by a lack of proper ground hydrology, are produced in what ought to be desert regions. There is a good maximum over India, associated with the Indian monsoon.

Gilchrist (1976) presents some tropical results from a July integration of the model described by Gilchrist (1974). The paper consists of mean wind vectors at grid points for days 71-100 of the integration for each of the model's five (sigma) levels, these means are compared with climatology. At the lowest model level the Atlantic easterlies extended too far north by about 9° of latitude. Over west Africa the northerlies extended too far south, and the easterlies which should exist over southern Africa were not reproduced by the model; the latter may be due to the ground elevation since the model winds were probably more like the 700 mb climatological values in this area. The flow associated with the south west Asian monsoon was on the whole well captured by the model. The very extensive low level easterly flow across the Pacific was simulated by the model, but it occurred too far north. At the second sigma level (.7) the model had weak westerlies over Africa where climatology shows easterlies. The model had easterlies in the Atlantic but they extended too far north. In the southern hemisphere the model again failed to obtain the broad equatorial easterly flow. The errors at the third sigma level (.5) were essentially similar to those at the second sigma level. The model produced two anticyclonic circulations centred at about 45W, 39N and 15W, 18N separated by a well marked trough off west Africa. The climatology shows a simpler situation with a single anticyclone orientated E-W with easterlies south of 25N. At the fourth sigma level (.3) errors were still evident in the troughs off west Africa and over the easter Mediterranean but the overall flow pattern is better than at lower levels. At the top sigma level (.1) the winds gave a reasonable representation of the overall flow pattern but disagreed in detail.

The UKMO 11 layer high resolution model is described by Saker (1975). The basic framework of the model is similar to that of the UKMO 5 layer model described by Corby et al (1972), but the boundary layer formulation and radiation scheme are changed. A limited area version of this model centred on the GATE B-scale area has been used to make short range forecasts (Lyne et al, 1976). Forecasts for up to three days could be made without serious contamination of the forecast by boundary effects. A series of twenty four hour forecasts were produced. The model exhibited a tendency to underpredict the westward movement of troughs at the 850 mb level and to slightly overpredict the westward movement at 500 mb. The errors at 500 mb were much smaller and independent of longitude; the authors suggest that the better prediction at 500 mb arose because of the relatively small effects of convergence and divergence at this level. On the large scale the rainfall forecasts were reasonably good both as regards position and intensity; on the small scale they noted large spurious amounts of rain forecast at a few grid points, particularly over central Africa. They suggested that this may be due to the occurrence of spurious thickness maxima produced by faulty analysis in data-sparse regions; these spurious thickness maxima tend to generate intense vortical disturbances. They noted that the parameterization of convection was also a contributing factor as improved results were obtained with an improved scheme. In the mean the forecasts tended to increase the surface temperatures too much over desert regions. A cooling in the mid troposphere of the model appeared to be due to insufficient compensation of radiative cooling by convective heating. The model also has a tendency to make the air too moist. Shaw and Rowntree (1976) using the same model showed skill in forecasting the movements and intensities of easterly waves up to 72 hours. Areas of rainfall associated with the African waves were located with reasonable accuracy but intensities were underestimated; the error increased between day one and day two then remained fairly steady to day three.

Another series of short range prediction experiments with the UKMO limited area model has been described by Shaw (1977) this time in the monsoon region. The model showed a tendency to become unstable after about three days, the author suggested that this was related to the very steep topography to the south of the Himalayas and the influence of the lateral model boundaries. The model demonstrated some success in predicting the movement of tropical depressions out to 48 hours and their intensities to 24 hours, tending to over-intensify them by 48 hours.

Two integrations were made with the UKMO limited area model one using a 1° mesh and the other the normal 2° mesh; there was insufficient improvement evident in the forecasts to justify the 8-fold increase in computer time required (Rowntree, 1978).

An assessment of the rainfall distributions forecast by the UKMO 11-layer global general circulation model has been carried out by Cunnington (1979). January and July simulations were investigated by taking a mean of the last 30 days (days 21 to 50) of general circulation integrations started from January 3 and July 3. The simulations were compared with climatic values taken from Schutz and Gates (1971, 1972) which are based on data from Möller (1951). The January simulated precipitation is in broad agreement with climatology in the zonal mean, though at 40° - 60°N and 5° - 20°S the model precipitation is too intense, the excessive rainfall at 40° - 60°N being associated with the model's deep Icelandic and Aleutian depressions and weak Siberian anticyclone. Looking at the geographical distribution in more detail, the model simulates the positions of the main wet and dry areas. However, the model has excessive rainfall in the tropical regions (especially the western Pacific, Brazil and Africa): this results in a global mean value about 20% higher than most climatological estimates. The July simulation also exhibited excessive rainfall in the tropics particularly in the Asian monsoon region. The Sahara and continental regions north of 50°N are also regions of excessive rainfall in the July simulation. The incorporation of the interactive, fixed cloud amounts, radiation scheme (Walker, 1977) in July improves the rainfall totals by reducing them by around 10%. The rainfall distribution shows a slight improvement in that there is less rainfall over the continents north of 50°N. The convective adjustment scheme produces, in the tropics, intense grid point sized areas of rainfall with no definite daily cycle, whereas using the penetrative scheme suggests a more realistic result, giving larger smoother areas, often in the form of bands wlich do show a dirunal variation. There is, however, no clear improvement in the geographical distribution of the rainfall and there is a slight increase in the global mean value when the penetrative scheme is used.

2.6.2 Current work

Current work at the UKMO related to the tropics is largely concerned with the predictability of the onset of the south-west summer monsoon. Newman (1981) discussed simulations of the onset of the 1979 summer monsoon by the UKMO 11 and 5 layer models.

3. A BRIEF SURVEY OF THE MODEL FORMULATIONS

This section contains a brief comparison between the main models used by the groups whose work has been discussed in the previous section. The work discussed in the last section has in general been performed over many years; the model formulations during this period have not remained static in all details. What I shall present here is the basic formulation of the models. I have tried to indicate in the previous section when results are derived from a modified form of a model.

3.1 References to model formulations

FSU, global spectral model	Krishnamurti et al, 1982
GFDL(1), global gridpoint model	Manabe et al, 1974.
GFDL(2), hemispheric grid point model	Miyakoda et al, 1969.
GISS, global gridpoint model	Somerville et al, 1974.
GLAS, global gridpoint model	Kalnay-Rivas et al, 1977.
NCAR, global gridpoint model (5^{o} model)	Kasahara and Washington, 1971.
UKMO(1) 5 layer model	Corby et al, 1972.
UKMO(2) 11 layer model	Saker, 1975.

3.2 Model formulations

3.2.1 Vertical grid, upper boundary conditions, variables etc.

Seven of the models use σ-coordinates where $\sigma = (p-p_T)/(p_*-p_T)$ where p, p_* are pressure and surface pressure, and p_T is specified below. The model levels are given in bars for $p_* = 1000$ mb.

FSU: σ-coordinates; $p_T = 0$ mb?; 11 levels (.95, .9, .85, .8, .7, .6, .5, .4, .3, .2, .1).

GFDL(1): σ-coordinates; $p_T = 0$ mb; 11 levels (.99, .94, .835, .685. .5, .315, .19, .11, .065, .038, .01).

GFDL(2): σ-coordinates; $\sigma_T = 0$ mb, 9 levels (.991084, .925926, .811385, .663923, .5, .336077, .188615, .074074, .008916).

GISS: σ-coordinates; $p_T = 10$ mb; 9 levels (.945, .835, .725, .615, .505, .395, .285, .175, .065)

GLAS: σ-coordinates; $p_T = 10$ mb; 9 levels (.945, .835, .725, .615, .505, .395, .285, .175, .065).

NCAR: z-coordinates; 6 levels (1.5, 4.5, 7.5, 10.5, 13.5, 16.5 km)

UKMO(1): σ-coordinates; $p_T = 0$ mb; 5 levels (.9, .7, .5, .3, .1).

UKMO(2): σ-coordinates; $p_T = 0$ mb; 11 levels (.98744, .93701, .84320, .71772, .57717, .43626, .31738, .23047, .15741, .08856, .02207)

For the σ-coordinate models, the upper boundary condition is $\dot{\sigma} = 0$ at $\sigma = 0$, for the NCAR model it is $\dot{z} = 0$ at 18 km.

3.2.2 Horizontal grid (All models use spherical coordinates)

FSU: Spectral model, 29 wave rhomboidal truncation (roughly equivalent to a 2 degree mesh model or triangular T40 truncation). Global.

GFDL(1): 265 km irregular grid. Global.

GFDL(2): N=40, the grid size is approximately 320 km at the Pole, 270 km at midlatitude and 160 km at the equator. Hemispheric.

GISS: 4^{o} latitude x 5^{o} longitude. Global.

GLAS: As GISS

NCAR: 5^{o} latitude x 5^{o} longitude except longitude mesh increases poleward of 60^{o} latitude. Global.

UKMO(1): 333 km irregular grid

UKMO(2): 220 km irregular grid

3.2.3 Finite differences

FSU: Only used for vertical derivatives. Semi implicit time differencing and time filtered.

GFDL(1): Energy-conserving flux formulation

GFDL(2): Arakawa-Lilly kinetic energy conserving formulation

GISS: Staggered grid; Arakawa (1972) space differencing; Matsuno predictor-corrector time integration.

GLAS: 4th order quadratically conservative horizontal differences, 2nd order vertical differences. In the absence of diabatic and dissipative processes the differences conserve mass and energy except for marginal terms at the poles. The combination of the 4th order quadratically conservative scheme with the periodic application of a high order filter successfully replaces the use of an enstrophy conserving scheme.

NCAR: Time staggered grid; second order scheme.

UKMO(1): Energy conserving flux formulation.

UKMO(2): Energy conserving flux formulation.

3.2.4 Sub grid scale mixing

FSU:

GFDL(1): Deformation-dependent non-linear viscosity for u,v,T,q.

GFDL(2): Internal non-linear viscosity with an effective Karman constant $k = .4$.

GISS: Longitudinal smoothing of zonal mass flux and zonal pressure force to avoid timestep reduction near poles. Vertical diffusion of u,v,T,q.

GLAS: No horizontal diffusion except for the use of a dissipative time scheme and the periodic application of a high order filter.

NCAR: Deformation-dependent non-linear viscosity for u,v,T,q. Stability dependent vertical diffusion of u,v,T,q.

UKMO(1): Non-linear lateral viscosity with coefficients proportional to modules of Laplacian of the variable for variable u,v,q,θ and the boundary layer depth.

UKMO(2): Non-linear lateral viscosity.

3.2.5 Surface exchanges and boundary layer

FSU: Air sea interactions include transfers of momentum, moisture and sensible heat, they follow the bulk aerodynamic principles. Over the land areas surface fluxes are evaluated following the relations given by Businger et al (1971). The vertical distribution of fluxes of momentum, heat and moisture between $\sigma = 1$ and .7 follows the mixing length concepts as in Manabe et al (1965). Above $\sigma = .7$ the fluxes vanish.

GFDL(1): Bulk aerodynamic formulae used to calculate surface fluxes. Vertical diffusion of u,v,T,q within boundary layer (lowest 3 layers).

GFDL(2): Turbulent transfer of momentum heat and moisture in the boundary layer are taken into account.

GISS: Bulk aerodynamic formulae used to calculate surface fluxes. The transfer coefficient is a function of wind speed, stability, surface type and mountain height.

GLASS: As GISS

NCAR: Bulk aerodynamic formulae to calculate surface fluxes. The transfer coefficient is 3×10^{-3} except 2.1×10^{-3} for latent heat flux. Latent and sensible heat fluxes are assumed equal over land.

UKMO(1): Bulk aerodyanic formulae used to calculate surface fluxes. The boundary layer depth is carried as an extra variable. The transfer coefficient is dependent on stability and surface type.

UKMO(2): Approach adopted similar to that suggested by Clarke (1970). Two parts to formulation (a) surface fluxes, (b) the turbulent diffusion of properties through the boundary layer, assumed to occupy the three lowest levels. In addition there is an ice phase. Snow lying on the ground is melted when the surface temperature rises above $0^{o}C$, the amount determined by the temperature and the latent heat of fusion of water.

3.2.6 Convection

FSU: The treatment of deep cumulus convection is based on Kuo (1974) where the partitioning of the available moisture supply into two parts (namely large scale moistening and heating) is carried out following Krishnamurti et al (1976). Also, dry convective adjustment.

GFDL(1): Convective adjustment when superadiabatic to dry adiabatic lapse rate or, if saturated, to saturated adiabatic lapse rate.

GFDL(2): As GFDL(1)

GISS: Dry convective adjustment; penetrative moist convection based on Arakawa (1969) applied when the static energy at a lower level exceeds the saturation static energy at an upper level.

GLAS: As GISS

NCAR: Convective adjustment when superadiabatic to dry adiabatic lapse rate with descent, to saturated adiabatic lapse rate with ascent.

UKMO(1): Shallow and penetrative convection with environment modified by subsidence and by detrainment which depends on buoyancy at next level; evaporation of falling rain if relative humidity is less than 80%.

UKMO(2): Generalization of UKMO(1).

3.2.7 Large-scale precipitation

Except as stated below all models use a large scale precipitation condition of relative humidity >100% and include no evaporation of falling rain.

GISS: Rainfalls to ground only if all the lower layers are saturated.

GLAS: As GISS

NCAR: Condition on precipitation relative humidity >95%

3.2.8 Radiation

All except the UKMO(1) model calculate the long-wave cooling and solar heating rates from flux divergence computations with explicit dependence on model temperature and humidity and on fixed or modelled clouds.

FSU: Detailed calculations of radiative transfers of short and long wave irradiances include the effects of cloud feedback processes, diurnal changes and a determination of the heat balances of the earth's surface. The long wave calculations are based on the emissivity method, while the calculations of the short wave radiative processes invoke an absorptivity function. Three types of clouds (low, middle or high) are defined via threshold values of relative humidity. The predicted distributions of the humidity variable defines these clouds. This also permits the simultaneous occurrence of more than one cloud type. A cloud albedo of 60% is assigned in the short wave radiative fluxes. The low and middle clouds act as black body radiates while the high level clouds are treated as partially black (40%) to avoid excessive cooling on the top of high level clouds. A variable zenith angle of the sun provides the mechanism of the diurnal change via its definition of the incoming solar radiation.

GFDL(1): O_3 and CO_2 included; 3 layers of clouds with fixed radiative properties are a function of latitude and height only; no diurnal variation.

GFDL(2): Shortwave and longwave radiation is calculated by Manabe and Strickler's (1964) scheme. Cloud coverage is climatological and a function of latitude and height only.

GISS: O_3 included in solar, CO_2 in long-wave scheme. Model clouds depend on occurrence of large-scale precipitation and shallow or penetrative moist convection with albedo and optical thickness dependent on cloud type and level. Cyclic variation of vertical location of deep clouds. All clouds treated as black bodies for longwave radiation. Diurnal variation.

GLAS: As GISS

NCAR: CO_2 in long-wave scheme. Model clouds at 3 and 9 km depend on relative humidity with cloud amount restricted to 80% at 3 km, 8% at 9 km to allow for partial transmission of radiation through clouds. Diurnal variation.

UKMO(1): Solar heating and long-wave cooling rates based on Rodgers' (1967) calculations for zonally averaged climatology with implicit climatological q and clouds and a T^4 dependence for long wave cooling. Simple zonally symmetric diurnal variation.

UKMO(2) Radiation flux determined by vertical distribution and type of absorbing gases (H_2O, CO_2 and O_3); vertical temperature and pressure profiles; clouds (which are currently inserted at level 10 only). H_2O mixing ratios are obtained from the model's values, O_3 mixing ratios are climatological (seasonal) and the CO_2 mixing ratio is a global constant. Diurnal cycle.

3.2.9 Treatment of land surfaces

FSU: Specification of seasonal surface albedo, based on Kondratchev (1972) and Posey and Clapp (1964). The model includes climatological ice cover and ice albedo in its radiative calculations. The surface humidity fluxes include a specification of soil moisture from an empirical formula based on the prevailing surface humidity distribution.

GFDL(1): Albedo from Posey and Clapp (1964), modified by modelled snow; soil moisture from hydrologic cycle; T_* from heat balance.

GFDL(2): The land surface temperature is determined through heat balance at the surface, where the soil is assumed to have no heat capacity. The albedo of the sea is taken from Budyko (1956). The albedo of the land is assumed to be a function of latitude only, taken from Kung, Bryson and Lenschow (1964) and Posey and Clapp (1964). The snowline is fixed with time, and, when computing the heat budget at the ground, the surface temperature north of this snowline is not allowed to exceed $0^{o}C$.

GISS: Albedo of 0.14 except over snow; snow cover dependent on latitude and season; soil moisture geographically fixed; T_* from heat balance.

GLAS: As GISS

NCAR: Albedo geographically fixed; no soil moisture available; T_* from heat balance including flux to sub-surface layer proportional to upward heat flux.

UKMO(1): Albedo a function of T_* (implying snow cover) and latitude only (varies in tropics from 0.225 at $20^{o}N$ to 0.146 at equator and 0.224 at $30^{o}S$). No soil moisture variable; T_* found prognostically.

UKMO(2): Albedo set to .2 for land, .8 for permanent snow cover, .8 for sea ice and .5 for seasonal snow cover. Soil moisture and snowdepth are parameters held by the model, held at each gridpoint that is not sea, sea-ice or permanent snow.

2.3.10 Sea surface temperatures

The sea surface temperatures are fixed, apart from seasonal variation in all these models.

4. DISCUSSION

It is remarkable that perhaps the most noticeable feature of the model errors is their similarity between models. This suggests that the errors are due either to a deficiency in data or a deficiency in representation by the models of important processes. In Section 2 we saw a considerable variety of initial data being used for all the various experiments and in most cases the models produced similar systematic errors. In Section 3 we saw the variety of parameterizations used in the models. It is most likely that the dominant errors are due to a common deficiency in the parameterization of certain key physical processes.

The systematic errors in the tropics we have seen to be dominated by the large scales and are largely stationary, associated with the thermal and orographic forcing. The studies have demonstrated the importance of vertical coupling and the 'correct' representation of physics, particularly convection, interactive radiation and a diurnal cycle. A strong sensitivity to surface parameters has been noted especially albedo and soil moisture.

All models experience difficulties in correctly simulating the low level tropical easterlies and the stratospheric easterlies, usually making the low level easterlies too weak and the stratospheric easterlies too strong. Hadley cells are usually simulated too shallow and too weak, the meridional circulations are usually too weak and the troposphere is often too stable caused by a cooling in the lower troposphere and a warming in the upper troposphere.

Most models from the simplest to the most complex find the 700 mb level in the tropics easiest to simulate or forecast. This is apparently because the level of non-divergence is closest to this level in the tropics.

To summarize, it appears the the principal problem in the tropics is the maintenance/simulation of the quasi-stationary large scale circulation and that the cause of the problem is generally believed to be related to parameterization difficulties, especially cumulus convection.

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