1. INTRODUCTION

The organisation of symposia and workshops is a part of the Centre's research activity. The following publication contains the proceedings of a workshop on "Tropical meteorology and its effects on medium range weather prediction at middle latitudes" which was held at ECMWF, Shinfield Park, Reading, from 11 to 13 March, 1981. The workshop came at an opportune time in the Centre's development. Having been operational for rather more than a year there is an increased recognition of the need to produce better tropical analyses and forecasts as an aid to improving the quality of the mid-latitude forecasts. There is good evidence of tropical influences being important when considering mid-latitude forecasts in the range 4-10 days. Additionally there is considerable interest being shown in our analyses and predictions for the tropical belt itself. Currently ECMWF is one of only a very few centres producing tropical analyses and predictions on a routine, operational basis.

The purpose of the workshop was to exchange information on those aspects of tropical meteorology which are thought likely to have an impact on the Centre's main function of medium range weather prediction, and to recommend further research activities towards improving the quality of such a product. The workshop was organised in the usual way: in the first section invited scientists and scientists from the Centre presented papers on special subjects (their contributions are included in this report as appendices). In the second part, the following subjects were discussed in working groups:

1. Impact of the tropics on medium range weather prediction in middle and high latitudes. (Kållberg, Miller, Ruprecht, Simmons).

2. Predictability of the tropical atmosphere. (Cubasch, Moncrieff, Pearce, Shukla, Tiedtke).

3. Data assimilation in the tropics. (Gustavsson, Julian, Lönnberg, Lyne, Pailleux, Shaw, Wergen).

4. Simulation and maintenance of large scale regional circulations in the tropics. (Hollingsworth, Kanamitsu, Krishnamurti, Young, Heckley).

The results of these discussions are summarized in the following chapters.

2. IMPACT OF THE TROPICS ON MEDIUM RANGE WEATHER PREDICTION IN MIDDLE AND HIGH LATITUDES

2.1 Review

It has long been known that the tropical region exerts a profound influence on the zonal-mean circulation of the extratropical atmosphere through its role as the main region of atmospheric heating and as the source of substantial westerly momentum. In addition, it has become evident through observational and theoretical studies, together with idealized and general circulation model experiments, that the tropics may influence significantly both standing and transient wave perturbations of the middle-latitude circulation. Examples, several of which are discussed or refereneced in the written versions of the workshop lectures, include:

i) the teleconnection patterns which have been associated with the theory of latitudinal Rossby-wave propagation;

ii) tropical influences on the equatorward limits of deep middle latitude troughs, which may significantly affect the momentum transfer into middle latitudes; and

iii) the movement of tropical cyclones into middle latitudes. The importance of the latter for medium range prediction may be seen in the relatively poor September 1980 ECMWF forecasts of a series of baroclinic waves which originated from tropical disturbances.

Studies of the impact of tropical observing systems on medium range forecasts, plus other specialized forecast experiments, indicate that the influence of the tropics may, in general, be felt in middle latitudes after some four days, although there can be variability from case to case. We do not, however, yet possess a quantitative estimate of the extent to which deficiencies in the model's treatment of the tropics influence the predictability of middle latitudes. This too, presumably, will vary with the synoptic situation.

2.2 Discussion

The evidence for significant influences of the tropics on middle and high latitudes appears sufficient that for a fixed availability of effort, priority should be given to improving the performance of the model and data assimilation system in the tropics, rather than to a major programme to demonstrate further the nature of these influences. This is reflected in the recommendations given in the following section. Nevertheless, it is felt that there is still a need for further impact studies. The reasons are given below.

i) Quantitative estimates of the importance of the tropics for extra-tropical prediction are required in order to assign priorities within the Centre's research programme, and in order to assess the relative amounts of computer time to be allocated to different processes when the next generation of forecast model is constructed.

ii) Impact studies may lead to a better understanding of the temporal variability of middle-latitude predictability, since the lower short-term predictability of the tropics may, in strongly interactive cases, be reflected in lower mid-latitude predictability. Objective measures of tropical/extratropical interaction during the course of a forecast may yield an indicator of confidence in that forecast.

iii) More may be learnt indirectly about deficiencies of the model in the tropics.

iv) The importance of analysing the sea surface temperature (SST), the soil water content (SWC) and other surface properties should be determined.

v) Although not one of the Centre's immediate objectives, an improved understanding of some factors influencing seasonal mean predictability should also result from such studies.

2.3 Recommendations

2.3.1 General comments on the verification and diagnosis of tropical forecasts

i) Basic verification of wind and humidity analysis structures is evidently required. The model's performance in the tropics should be systematically evaluated both subjectively and objectively. A comprehensive synoptic review of the performance of the forecast model in the tropics should be prepared, preferably by an experienced tropical synoptician. The dissemination of the Centre's products over the GTS may help in this respect. It is important to determine the extent to which any unrealistic output from parameterization schemes is due to unrealistic input fields.

ii) Verification of structures (against observations as well as analyses) should be made for characteristic tropical circulation systems.

iii) Estimates of the vertical and horizontal distribution of diabatic heating from mean analyzed fields should be made for comparison with forecast model calculations and for use in simple model studies. Efforts should be made to implement those recommendations of the workshop on diagnostics of diabatic processes relating to this aspect.

iv) Many tools already exist for tropical verification within the Centre. These should be made generally and easily available, and documented in a form which should be updated as required.

2.3.2 General comments on improvement of the Centre's forecasting system

i) Despite the many deficiencies in the Centre's forecast model in the tropics highlighted during the workshop, Observing System Experiments indicate extra-tropical sensitivity to the availability of tropical data. Work on improvement of the various aspects of the data assimilation in the tropics (e.g. data selection, quality control) should thus continue.

ii) The existing work on various parameterizations of convection should continue with high priority.

iii) Deficiencies in the boundary layer structure must also be investigated as these may have a direct bearing on the convective activity in the model.

iv) Planned work on the incorporation of the diurnal cycle should proceed and results should be carefully diagnosed to determine the extent to which the currently inadequate activity over land is improved.

v) The horizontal resolution required to simulate accurately the development (possibly by barotropic and/or inertial instability) of monsoon vortices should be determined.

vi) Particular attention should be paid to cases from the FGGE year. This is firstly because of the enhanced tropical data, and secondly because of the future availability of results from other models. The latter should be subjected to particularly close scrutiny in any areas where they show improvements over the Centre's models.

2.3.3 Diagnostic studies of tropical/extratropical interaction

Specific objective diagnosis and verification should be made of tropical/extratropical interaction and its relationship with temporal variations in predictability. Three possible studies are:

i) Study of the correlation between short-range predictive skill in the tropics and medium-range predictive skill in middle and high latitudes. (For example, do cases with good day 0-4 scores in the tropics correlate positively with cases with good day 4-8 scores in the extratropics?).

ii) Study of the correlation between forecast quality for the Northern Hemisphere and that for the Southern Hemisphere. Positive correlation would indicate an interhemispheric connection.

iii) Study of the correlation between objective measures of the level of tropical/extratropical interaction, such as the magnitude of the meridional energy flux, and extratropical forecast quality.

In addition to these objective studies, special attention should be paid to features which strongly affect the interaction between the tropics and middle latitudes. Particular examples include the structure of the mid-latitude jet, the characteristics of monsoon circulations, and possibly the large scale structures of the divergent wind flow.

2.3.4. The limited area model

The limited area model is potentially a very useful tool for examining some of the above questions. Standard representative cases from the FGGE year should be chosen, and the appropriate boundary files set up in order that the general user might have as ready an access to the model as is currently possible for the Global model using the RUNEXP procedure.

If this approach is adopted, it will be important that the tropical verification package can run from limited-area grid-point data sets as well as the Centre's standard global archive.

2.3.5 Impact studies of forecast experiments

Experiments in which tropical (or extratropical) regions are relaxed towards analyses should continue in order to quantify tropical influences on middle-latitude predictability (and, conversely middle-latitude influences on tropical behaviour). Cases should be carefully selected, both from synoptic considerations and from the objective diagnoses proposed above.

2.3.6 Idealized experiments

Simple model studies should continue to be performed. Future work could include:

i) Calculations for monthly, or 5-day (say) mean, situations, again seeking relationships between strong latitudinal propagation and predictability.

ii) Calculations using mean model diabatic heating rates and heating rates deducted from analyses, when these become available.

iii) Extension of the calculations to include examination of the response of an initially-undisturbed flow in a non-linear, three-dimensional model to the initiation of localized tropical heating. The objective would be to test the propagation rates and sensitivity to zonal flow variations found in barotropic calculations.

iv) Use of Webster's iterative approach as a test vehicle for parameterization schemes.

3. PREDICTABILITY OF THE TROPICAL ATMOSPHERE

3.1 The problem

Current experience, although limited, suggests that the forecast errors in the tropics are comparable to the persistence error within 2-3 days (Shaw, workshop paper). This is not different from the results of classical predictability studies (Shukla, workshop paper) in which random errors in the initial conditions take only 3-5 days to grow to their maximum value. Possible reasons for the limited short range predictability can be viewed as due to the following intrinsic nature of the tropical disturbances.

i) Small amplitude equilibration of synoptic waves.

ii) Latent heat of condensation as the primary energy source and large growth rate of condensation driven instabilities.

iii) Small horizontal scale (2000-3000 km) of synoptic waves and even smaller scale of embedded mesoscales.

These fundamental characteristics of the tropical disturbances create special practical problems in numerical weather prediction. Since the errors of observations are initially large, and since the maximum tolerable error is small, it takes only a few days for the errors to reach their saturation value. Latent heat of condensation being the main energy source and most of the condensation heating being released in small scale moist convective elements, one is faced with the very difficult problem of parameterization of latent heating as a function of model predicted large scale meteorological variables. Since the latent heating effects feed back to the large scale flow, which determine the magnitude and organisation of latent heating in the first place, the model evolutions are very sensitive to the parameterization schemes. Finally, smaller spatial scales of the tropical waves require very high resolution models to describe their three dimensional structure.

The potential for predictability of time averages in the tropics seems to be better than that for the short range prediction. Charney and Shukla (1981) have suggested that the slowly varying boundary conditions may play an important role in determining the inter-annual variability of the space-time averages of the tropical atmosphere. For somewhat the same reasons in which the deterministic predictability is limited in the tropics, the time averages of large spatial scales are meaningfully definable. Since the variability of the large-scale overturning of Hadley and Walker type circulations are influenced by slowly varying boundary conditions of SST, SWC, etc. there is hope for prediction of space-time averages.

From synoptic and qualitative analysis of observations it appears that it is only the quasi-steady components of tropical heat and moisture sources which affect the mid-latitude variability and therefore it may be possible to account for these effects by prescribing either the tropical tendencies for the large scales or the diabatic forcing on the large scale.

3.2. Recommendations

These fall into two main groups - diagnostic studies and numerical experiments.

3.2.1. Diagnostic studies

The following are necessary to provide the basis for the assessment of model predictability.

i) Diagnostic studies of tropical variability (for different space and time scales of the observed flow, including model derived quantities (e.g. diabatic heating and velocity potential). These are necessary to increase understanding of atmospheric predictability as well as to assess model performance.

ii) Diagnoses of specific synoptic situations, e.g. those with persistent ageostrophic outflows, especially the transtropical jets emanating from tropical heat sources. These should be carried out for both the observed flow and the model predictions. This will enable an assessment to be made of the model's ability to preserve such features for different forecast periods.

iii) A comprehensive statistical verification of predicted rainfall together with vertical profiles of wind, moist static energy, divergence and vorticity against observations (in data-rich regions only). The verification should be carried out for different space scales (e.g. using spectral decomposition).

3.2.2 Predictability and sensitivity experiments

a) Predictability experiments for transient waves (easterly waves, tropical cyclones). The time evolution of transient waves such as easterly waves and tropical cyclones should be studied in simulation experiments. Predictability studies should be carried out for:

i) perturbed initial conditions of moist and divergent wind

ii) various parameterization schemes for convection (moist adiabatic adjustment, Kuo, Arakawa-Schubert, Miller-Moncrieff). These should additionally examine the significance of momentum and vorticity transfer by the parameterization.

These experiments should be performed with the Centre's limited area model using differing horizontal resolutions.

b) Predictability experiments for the evolution of the large-scale flow (10 day period)

One of the most striking features of the Centre's operational forecasts is the rather rapid transition from the initial tropical circulation to a typical model circulation (Hollingsworth, workshop paper). Studies should therefore be undertaken to see how sensitive the simulated flow is to

i) Surface conditions (SWC, SST, surface roughness, albedo) and

ii) The parameterization of convection and boundary layer flow and of radiation/cloud interaction.

The forecast model should be global, but could probably be a low order spectral model (T21). Parameters for verification should be: divergent flow, precipitation, boundary layer flow and boundary layer depth, diabatic heating, location and intensity of ITCZ and Walker circulations.

c) Effects of tropical forcing on mid-latitude circulation

Experiments have been started at GLAS and at the ECMWF to investigate the effect of the tropics on the mid-latitude flow by prescribing the tropical circulation. This work should be continued. We recommend the following hierarchy of experiments:

i) To prescribe the tropical flow of the model to the initial large-scale state.

ii) Assume the large-scale tropical flow is largely forced by quasi-stationary diabatic heating and therefore prescribe the large-scale forcing (diabatic heating, surface drag, etc., given by space-averaging the model diabatic heating).

d) Predictability of space-time averaged flow

Numerical experiments should be carried out to determine the role of the global boundary conditions, i.e. SST, SWC, sea ice and snow cover, for the predictability of monthly (and longer) time-averages over different parts of the globe.

For a given year a number of 60-90 day integrations should be carried out using observed, but random perturbed, initial and boundary conditions. For several sets of these integrations an analysis of the variance should be carried out to determine the level of significance for differences in the flow pattern arising due to differences in the boundary conditions.

These studies could use a low resolution version of the ECMWF model.

4. DATA ASSIMILATION IN THE TROPICS

4.1 Aspects of data assimilation raised in the workshop lectures

4.1.1 Sensitivity of predictions to the initial specifications of SWC and SST

Using GLAS model, much of the observed atmospheric variability in the tropics can be accounted for through the forcing imposed at the lower boundary - specifically the SWC and SST. The SST experiment was conducted with observed temperature anomalies, the SWC experiment being an extreme test with SWC being set to zero everywhere. In a SW monsoon case study the sensitivity of the ECMWF forecast to the SWC has been demonstrated. Such impacts of the initial specification of surface conditions support the recommendations made in the earlier sections for their full evaluation in the ECMWF scheme.

4.1.2 Exploitation of additional data sources

It has been shown that a high positive correlation exists between divergent flow and cloud IR pictures. It may be possible to quantify this cloud information and hence incorporate the implied convergence/divergence information in the tropical wind analysis (in those regions where such information is not being provided by the cloud wind data). The availability of such data may be a problem in practice. Another possibility is the use of rainfall data to provide a measure of vertically integrated heating. There appeared to be several practical problems in ascribing appropriate time and space scales to point measures of rainfall that are typically quantified over 12 or 24 hours, or to rainfalls inferred from other data sources.

4.1.3 Initialisation

The main purpose of the initialisation in the ECMWF scheme is to maintain stability in the data assimilation cycles which, in the absence of initialisation, quickly diverge from reality. Until now the initialisation scheme has also served as a tool to suppress unrealistic grid point storms during the assimilation phase. A better understanding of the development of the grid point storms within the model is required. The ultimate goal of the scheme should be to achieve both a dynamical and a physical balance.

4.1.1 Possible errors in satellite wind data

The sensitivity experiments relating to the usefulness of satellite winds raised doubts about the quality of such data over high terrain and also possibly on the periphery of the satellite's field of view. The former possibility merits investigation. Regarding the latter there is no a priori reason why the height assignment should be degraded, unless the heights are being specified subjectively.

4.1.5. Importance of initial divergence and humidity to the ensuing forecast

There may be a conflict between the results of Krishnamurti and Hollingsworth. The former demonstrated that the initial specification of divergence and humidity is very important and greatly affects the forecasts in the SW monsoon region. The latter showed that initialised fields with notably different velocity potentials produced very similar forecasts. We should try to resolve these apparently conflicting results.

4.2. Tropical aspects of the current ECMWF assimilation scheme

4.2.1. Forecast error statistics

The statistical interpolation method assumes the knowledge of the 3-dimensional structure of the error of the first-guess. Several empirical investigations exist on the covariance fields for extratropical regions, but very few calculations have been made for the tropics. The specified error levels not only determine the relative importance of observations but influence the rejection criteria as well.

4.2.2. The analysis of the windfield

The breakdown of the geostrophic relation in the tropics implies that the wind covariances must be deduced from wind data. The good quality of the forecast divergent wind field outside the tropical region justifies the use of non-divergent structure functions. However, the structure of the stream function and velocity potential fields for the tropics should be determined. The sparse data density renders a geographical and seasonal distinction of the covariances difficult. The FGGE data base should be used for the calculations.

The present assimilation scheme produces the wind field by an interpolation of the streamfunction which is coupled to the mass field by a latitudinally varying height/stream function correlation. This modelling produces analysis increments which are perforce non-divergent within each analysis box. The assimilation scheme thus leaves the model the task of generating synoptically reasonable divergence fields on scales less than that of an analysis box (600K'm^2). In extratropical latitudes such confidence is well-placed: however, in the tropics evidence to date suggests that the model has difficulty generating realistic divergence patterns on such scales.

With a tropical observing system as existed during the Global Experiment the assimilation scheme was able to produce a reasonable, vertically coherent divergent wind field when compared with what would be expected in the vicinity of major organised cloud clusters. The resolution of that divergent field, however, was on scales larger than 6 degrees (as expected) and depended in its more successful depictions on wind data densities not likely to be matched by the Global Observing System in the immediate future. To compensate for the inadequate observational network in the tropics and to ensure that the model maintains a realistic tropical circulation, it seems prudent to consider directly analysing a divergent wind component.

There are perhaps a number of ways of accomplishing this, but without information independent of the wind observations themselves the analysis can hardly succeed. There is no theoretical or empirical relationship between the streamfunction and velocity potential strong enough to suggest how the former might be modelled. The most obvious candidate for the additional information would seem to be the relationship between the velocity potential and the occurrence of cloud convective systems. The addition of a quantitative measure of convection such as satellite IR data provides an attractive candidate for modelling the velocity potential in the statistical interpolation scheme.

4.2.3. Vertical interpolation $\sigma \to p \to \partial$

At present there are two entirely different interpolation schemes being used at the Centre. On the one hand, there is a sophisticated 3-dimensional multivariate analysis scheme to interpolate the observations to the model gridpoints and, on the other hand a purely mathematical approach to interpolate between σ- and p-surfaces. The question could be raised, whether the vertical interpolation would not benefit from an interpolation which incorporates some physical principles (such as thermal wind relation, geostrophic wind, hydrostatic equation), thus leading to more consistent meteorological fields. Considerable efforts have been made already to reduce the problems arising from the need for vertical interpolation, but it may well be that further work may prove necessary.

4.2.4. Data network experiments and tropical wind observing systems

The value of the data network experiments carried out to date is recognised. Further experiments, particularly relating to TWOS and ASDAR/AIDS are welcome, in support of the work of WGNE and the ECMWF working group.

4.3. Recommendations

4.3.1. Climatologies of SST and SWC

Currently the ECMWF model makes use of monthly climatological specifications of both SST and SWC; these will shortly be replaced by analysed fields. Comparison of our SST analyses with Deutsche Wetterdienst is already planned; we know of no other independent source for comparison of our SWC analysis. Since both analyses will continue to use climatology as a base, comparisons of our climatologies with other sources (e.g. SWC, GLAS, SST, Met. Office) should be made.

4.3.2 Initialisation and the role of convection

Further initialisation experiments are required, particularly to examine the degree of initialisation required. Efforts to include physical forcing in the present non-linear normal mode scheme should be made in order to overcome the problems with physically driven processes, thus perhaps achieving a reduced spin-up time. The details of how a grid point storm develops in the model needs to be studied.

4.3.3 Humidity analyses

Some small impact arising from the incorporation of a humidity assimilation (rather than using a first guess field) has recently been demonstrated in a single case study. It is not clear if further effort should be devoted to the humidity analysis until an improved convection parameterisation has been formulated. Case studies for other tropical circulations than those of the recent experiment (Jan '81) should be made. The possibility of using satellite data should be investigated.

4.3.4. Observational error statistics

A horizontal error correlation should be introduced for satellite winds. Ideally this should only apply to winds within the same fleet. It will be possible to reduce the error level of radiosonde geopotentials by elimination of their systematic biases (tables are now available).

4.3.5. Forecast error statistics

In the statistical interpolation analysis there is a pressing need for a revision of the 3-dimensional structure functions of the first guess errors, and for the variances of those errors. Currently these are based on values suggested from various independent studies. Values appropriate to our particular model should be produced, using the FGGE period as a working data base. Particular attention should be given to the elimination of the negative lobes currently being used in the u-u and v-v forecast error correlations, since these have been seen to yield unrealistic analyses in the tropics and to the specification of forecast error variance which is currently derived from an estimated analysis error (from the previous 6 hr analysis cycle) relaxed towards a climatological error. As was shown by Shukla (workshop paper), there are large latitudinal variations in the predictability of the flow. A revision of the error forecasting scheme is therefore necessary with, perhaps, provision for the advection of forecast errors.

4.3.6. Quality control

A crucial part of the assimilation process is the recognition of incorrect data. The ECMWF data assimilation scheme has a number of checks of varying degrees of sophistication which together provide a generally effective means of quality control. There appears to be two areas which may usefully be improved:

i) The check against a model forecast value could be made more stringent in the tropics. At present an observation is labelled incorrect only if it differs by more than 8 standard deviations of error from the model value. It is labelled as probably incorrect if the difference lies between 6 and 8 standard deviations.

ii) Attempts should be made to identify systematic errors in data from a single source. An example of this is a "fleet" of satellite winds all assigned to the same but erroneous level. These may not be identified as incorrect in the present system since the data will support one another. Three possibilities which could be considered to overcome this are:

a) Look for bias in such data when comparing with a model forecast.

b) When checking against an analysed value, exclude all other data from the same source from making a contribution to that value. This could be inserted as an extra step immediately before the present check against an analysed value, but with a less stringent acceptance criterion.

c) Having identified an incorrect satellite wind we should consider excluding all other satellite winds within the analysis box. (In practice at the moment only a few satellite winds are rejected because of the relatively large error level ascribed to them).

4.3.7. Satellite winds

Such winds are a major source of data in tropical analyses. In the ECMWF scheme particular attention should be given to the validity of such data over high terrain. The Centre should recommend that satellite wind producers should have available current analyses for assignation of heights and quality control of data.

As a further aid to analysis it would be helpful to have an identification of the fleet (i.e. cloud cluster group used in the derivation of the winds). The availability of such information within the coded GTS message is advocated.

4.3.8. The importance of the divergent wind in the tropics, and the use of IR data in its analysis.

It is necessary to establish the importance, or otherwise, of the correct specification of the initial divergent flow to the ensuing forecast. If its importance can be clearly demonstrated then the usefulness of IR satellite data in its analysis should be actively considered.

5. SIMULATION AND MAINTENANCE OF LARGE SCALE REGIONAL CIRCULATIONS IN THE TROPICS

5.1. Introduction

In this analysis we review some of the problem areas in medium range numerical weather prediction in the low latitude regional areas. In terms of time scales these are divided into longer time scale problems and transients. It appears that many of the problems with regional circulations stem from inadequacies in the parameterisation of cumulus convection. Some of these are identified here.

5.2. The steady persistent components

The most important large scale steady circulations are the Trades, the summer and winter monsoons and the desert heat lows. As outlined in some of the contributions, there are substantial errors in the forecasts in the treatment of the steady component of each of these major wind systems. The first thing to be done is to define more clearly the symptoms of the problems. So far only the monthly mean χ, ψ fields have been studied for the analyses and the forecasts. There is a need for a much more thorough documentation of the systematic errors of the forecasts in the tropical regions.

5.2.1. Trade winds

In the forecasts there is a steady weakening of the trade winds in the East Pacific and East Atlantic in the first few days of the forecasts. In the later stages of the forecasts the trades regain strength but there appear to be changes in the positions of regions of strongest wind. There seems to be a baroclinic component to these changes in that the weakening is more marked at 850mb than at 1000mb.

The zonally extensive trade wind errors suggest the possibility that the Hadley circulations of the model might be a contributing factor. The apparent tendency for the relaxation of the trades to be strongest in the Southern Hemisphere suggests an anti-symmetric mode. On the other hand, there are two pieces of evidence which point to other sources: the development of trade weaknesses seemed to be initiated in the eastern oceans and spread westward, and the weak trades were found whether the Hadley circulation was initially present (analysis data was used to initialise) or not (normal mode initialisation was used).

The vertical resolution of the model in the planetary boundary layer (PBL) seems adequate to capture the gross profiles of basic variables, but the resolution and parameterizations might not be adequate for representing the turbulent physical processes of the tropics. No cloud transports by trade cumulus are currently parameterised, and no entrainment processes at the capping inversion are included. A potentially serious source of error is the vertical truncation error in friction: many of the variables which contribute to friction are strongly height dependent, such as the pressure gradient force (decreasing with height in the trades), the Richardson number (involving wind shear and lapse rates of temperature and humidity), and especially the eddy viscosity coefficient K as a function of the Richardson number. The friction force depends upon the first derivative of K and the second derivative of V, and so may suffer major error in this finite difference estimation.

5.2.2. The Monsoons

In the summer monsoon circulation over the Indian Ocean several errors have been demonstrated - the weakness of the trades south of the equator, the weakness of the cross-equatorial flow, the northward shift of the Somali Jet, the flow from Central Africa into the Somali Jet, and the excessively strong winds over South East Asia. The dynamical checks suggested for the Trades should also be carried our here.

In addition, it is important to recognise that upstream influences as well as local conditions may well be required to successfully simulate the low-level southwesterly monsoon flow: its links to the cross-equatorial flow and the southeastern trades of the Southern Hemisphere might be crucial. Theoretical evidence for this includes (1) simple models conserving absolute vorticity along streamlines extending between the hemispheres seem to capture some of the basic properties, and (2) consideration of the wind response to fixed pressure gradient fields which are monsoon-like (monotonic pressure variations with latitude) allow for curved streamlines in the inertial regime near the equator, and downstream acceleration, finally coming into confluence with an essentially geostrophic flow further to the north. Young's IIb diagnosis of satellite winds seems consistent with this description. His mean fields indicated possible local pressure gradient support for the Somali jet over the Horn of Africa, and the presence of the strongest cross-equatorial flow near the coast, with a clear negative shear (negative vorticity). These features must all be consistent with a steady-state flow. In addition, theory indicates that trapped disturbances propagating up the African coast in the Southern Hemisphere will not be able to continue up the coast in the Northern Hemisphere.

5.2.3. Heat Lows

The heat lows over Africa in summer are consistently forecast to be too intense. This could be caused by anomalously low pressures at all levels or to anomalously warm temperatures in the troposphere. The thermal mixing over the deserts is very intense by day and non-existent at night, and its effects are easily seen in profiles of temperature and humidity, which are well mixed up to about 500mb, where there is often a moderate capping inversion. Subsidence is expected, at least in the upper troposphere.

5.2.4. Divergent circulations

The maintenance of slowly varying divergent circulations is an important requirement for a medium range NWP model. As an example, the trade winds blowing steadily in the same general region for many days is maintained by a steady supply of energy from the slowly varying divergent circulation.

Monitoring of fields such as $\overline{\psi}, \nabla^2\overline{\psi}, \overline{\chi}$. $\nabla^2\overline{\chi}^3$, $\overline{f\nabla\psi\cdot\nabla\chi}$ may have some important elements for the assessment of the model. Sensitivity of the above to such features as sea surface temperatures, heating by cumulus convection and vertical distribution of radiative cooling are worthwhile areas of investigation. Warm climatogological sea surface temperature may produce its own bias in organising convection over certain areas; the intensity of downward motion in the divergent circulation tends to match its adiabatic warming with the radiation cooling. This problem may be worthy of examination over land areas as well. The cold winter time air mass over Siberia, under excessive radiative cooling could encounter strong downward motion and enhance the divergent circulations. The intensity and vertical distribution of heating for Kuo's scheme is important for the strength of the divergent circulation. A systematic lack of orientation of the $\nabla\chi$ field with respect to $\nabla\psi$ could produce an excessive loss of the divergent kinetic energy thus weakening the divergent circulations. Monitoring of the $\langle\psi - \chi\rangle$ interaction may be important in this regard.

5.3. Transients

Although the systematic errors in the middle latitudes are more closely related to the errors in maintaining the large scale features in the tropics, the role of transient phenomena cannot be neglected. In particular, the onset of the monsoon is a global phenomena of transition from one quasi-stationary state to the other and its correct prediction is vital. The prediction of this event requires accurate description of the large scale diabatic heating and its proper interaction with the large scale dynamics to maintain them. The observed heating presented by Krishnamurti provides a very useful guide for the examination of heatings provided by the forecast model. Experiments of the onset prediction will thus provide performances of the diabatic heating and its dynamical interaction in the model.

Another important transient phenomena in the tropics is the easterly waves. The role of such waves for maintaining large scale circulation in the tropics may not be critical but the ability of the model to predict such phenomena is closely related to the validity of the physics treated in the model. The synoptic as well as the dynamical and thermodynamical structure of the predicted disturbances can be compared with typical structures obtained during GATE. The convection scheme, effect of the SST, etc., may be well tested by such comparisons.

In this relation, the grid point storms which frequently appear in the operational forecast must be examined in detail. The condition of their initiation, development and decay may provide some idea of problems existing in the convection scheme. It is also desirable to examine the physical parameters that determine the space and time scales of the convective heating in the model.

5.4. Parameterisation of cumulus convection

At the present time a version of Kuo's 1974 cumulus parameterisation scheme (with a closure based on Anthes' work for the moisture storage parameter b) is being used at ECMWF. This scheme is quite sensitive to the choice of the parameter b, i.e. the closure. Runs made by Kållberg and Kanamitsu show that the character of the trade (i.e. its strength) and of the south-west monsoon (i.e. its positions) are altered by setting b=0, which implies that all of the available moisture supply is being rained out. However, it appears that this extreme setting of 'b' may not be appropriate for all of the tropics. The undesirable feature being that it produces several local convective centres, i.e. grid point storms. The monsoons and the trade winds over the Indian Ocean are, however, handled much better with this prescription of 'b'.

Since observations do not exhibit such small scale storms, it seems that some modification of the scheme for the parameterisation of cumulus convection may be necessary for it to handle organised convection rather than a grid point storm. To some extent single grid point convection would be unavoidable since the model should anticipate the formation of a new convective region where convection could start out from a very small area and spread out. This means that artificial remedies for the removal of single grid point convection are not desirable.

Another aspect of the model's response to convection is its tendency to form large centres of divergent inflows and outflows with a large planetary scale (around wave number 1) organisation. At this stage the organisation of convection and its response seems to exhibit another extreme scale. Evidently both features, i.e. the grid point storms and the eventual build-up of divergent kinetic energy in the planetary scale seem undesirable aspects. Careful diagnostic studies are needed to isolate the source of these problems (i.e.the grid point storms and planetary scale build-up of the divergent circulations).

Another area of cumulus convection presently not handled by the Kuo scheme is that of the vertical transports of momentum or vorticity. Its absence in the cumulus parameterisation might tend to over intensify low level cyclonic systems and upper level anticyclonic systems over convective regions. This must be examined, in the light of the aforementioned problem areas.

5.5. Recommendations

5.5.1. Deficiencies in the representation of the trade winds

One should examine closely the mean changes in all the dynamical fields (surface pressure, χ, ψ, ω, T) through the initialisation procedure and during the first few days of the forecast with a view to checking for any dynamical imbalances.

The possibility that the errors are related to diabatic processes in the model is suggested by the apparent geographical preferences documented above. The question arises whether the errors would then appear to be geographically forced and perhaps rather steady. To answer this, maps at different times should be examined to identify recognisable transient planetary modes, forced or free modes, etc..

A spot check of case studies indicated that the 850mb flow may have weakened faster than that at the surface, if the corresponding pressure fields similarly weakened, then a horizontal temperature gradient error between these levels is indicated, with warmer virtual temperatures near the equator. Attention should be given to the low-level thermal field and boundary layer heating to identify possible time variations of a systematic nature.

Regarding possible deficiencies in the representation of frictional effects in the PBL, samples of wind vector hodographs in the PBL should be examined for mid-latitudes and the equator, taking into account the pressure and temperature fields in order to assure a reasonable balance of forces. Sample fields of K(x,y) should be mapped at various levels to check for reasonable and smooth fields in the trade region. Long-term consideration should be given to alternative representations of friction which might better represent the physical processes implicitly in more detail while retaining the same resolution of basic variables (e.g.,"layer" models mentioned in the Exeter report).

5.5.2. Deficiencies in the representation of the monsoons

The pressure and ψ patterns in the Southeast trades extending to the equator should be studied to make certain that they have a configuration typical of a normal established monsoon (isobars which are too zonal will not support a strong cross-equatorial flow).

The cross-equatorial flow of the model should be examined to make certain that it is relatively steady and not longitudinally smoothed by the lateral friction ("del-fourth").

The structure of the Somali jet should be examined in detail. A particular feature to be looked for is the baroclinic process which must be present and which is probably related to a confluence of air masses.

5.5.3. The structure of heat lows in the model

There is a need to check the vertical temperature and moisture profiles for correct absolute values and the correct "mixed layed" shapes. The vertical motion and its role in satisfying the first law of thermo-dynamics, especially above the inversion, should also be checked.

5.5.4. Deficiencies in the divergent circulations of the model

Comparisons of 10 day averages of observed versus the predicted (10 day average of day 10) fields may identify systematic problem areas. From an inspection of some of the forecasts it appears that this statistic would be most relevant to the problem in the divergent circulations. For instance, after a few days of integration, the active centres of χ appear to shift from their original location and acquire a planetary scale (wave number 1) orientation. It is important to diagnose the reasons for this shift and scale growth.

5.5.5. Diabatic Heat Sources

Tropical disturbances are essentially convectionally driven through latent heat release which is highly correlated with the rainfall. Thus the most obvious feature to study (and the most easily verified) is the rainfall distribution. Any systematic trends or errors in the forecasts will be most easily seen in the mean statistics.

It is recommended that monthly mean rainfall statistics of 24 hour rainfall amounts be examined for 1, 2, 3 etc. day forecasts and compared against each other to reveal systematic trends. For verification over land areas the monthly climatic data available from Ashville may be used, but over oceans satellite derived precipitation amounts should be used. TIROS-N data describing cloud brightness may be averaged to obtain monthly means from which the rainfall may be obtained using correlation methods (Griffith et al 1978). Rainfall data obtained in this way may be examined for consistency over land areas by comparing with the monthly climatic data.

Monthly mean statistics of the total diabatic heating and latent heating should be obtained from the model and verified against rainfall, with particular reference to maintenance of heat lows.

Estimates of the latent diabatic heating should be obtained from satellite data and used to estimate the effect of the diurnal cycle on continental convection. It is by no means clear if the model can provide enough heating over the Amazon Basin without a diurnal cycle and we notice that the convection tends to die out there during the forecast.

5.5.6. Absence of vertical transport of momentum and vorticity in the convective parameterisation scheme.

Diagnosis of the intensity of the predicted tropical systems at the end of days 1, 2 ... 10 versus observed structures of vorticity for the same periods may reveal possible systematic differences IN THE VORTICITY STRUCTURES. This might give some clues for the need to incorporate the momentum/vorticity parameterisation.

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