GLOBAL CLIMATE MODELLING AND ITS VALIDATION WITH EMPHASIS ON THE HYDROLOGICAL CYCLE

Klaus Arpe
Max-Planck Institut für Meteorologie, D-20146 Hamburg
Tel (+49 40) 41173354, Fax (+49 40) 41173366, email arpe@dkrz.d400.de

ABSTRACT

The availability of observations for global data assimilation and problems with analysing them is discussed. Short-range forecasts from ECMWF can be used to estimate daily precipitation distributions. As an example of GCM's the MPI model will be described. The ability of the ECHAM3 model to simulated the hydrological cycle of the atmosphere is investigated. Results from decadal simulations of the atmosphere will be shown and compared with observations. Problems with model validation will be demonstrated, which partly are due to uncertainties in observed data and partly due to uncertainties in boundary values in model runs. Also uncertainties in the model formulations will be shown. Mostly the model simulations lie within the range of realizations of climatological estimates though some model deficiencies become obvious.

Keywords: Atmospheric modelling, analysis, validation, precipitation

1. INTRODUCTION

Scientists have a long-standing interest to simulate the atmosphere with numerical models. Smagorinsky et al. (1965) reported the first comprehensive model that was able to simulate successfully all principal processes of the atmosphere.

The driving force for the atmospheric circulation is the hydrological cycle in which water is evaporated mainly from the subtropical oceans, much of the water vapour is then condensed in the inner tropics which heats the tropical atmosphere. Radiative processes cool the atmosphere, particularly in polar regions. The atmospheric circulation is the result of the temperature differences mainly due to the two diabatic processes mentioned above. An atmospheric circulation model must be able to simulate these diabatic processes reasonably well if there is any chance of success. Earlier numerical (simpler and mostly dry) models had been used for short-range forecasts. Their forecast skill declined quickly after a day or two of forecasts, partly because major baroclinic developments can only be simulated successfully when diabatic processes are incorporated in the model. It was a natural development to marry the short-range forecast systems with climate simulation models to gain even better forecasts, extending them into the medium-range. A pioneer in this respect was Miyakoda et al. (1972) who showed very encouraging results. The use of a model which contains all the features of a climate simulation model for operational weather forecasts seemed to be impossible in those days for a single meteorological office because of the immense computer costs required. Therefore several European countries decided to pool their resources and founded the European Centre for Medium-Range Weather Forecasts (ECMWF). Medium-range forecasts can reasonably be done only with a global model which require global initial data. Because of the lack of conventional observational data over large oceanic areas, the creation of global analyses depends heavily on satellite data. The need for creating a global analysis scheme to support medium-range forecasting coincided with the need for global analyses for diagnostic purposes requested for FGGE (First GARP Global Experiment). Both tasks were carried out at ECMWF and complemented each other very successfully. Similar developments happened in the USA at the National Meteorological Center (NMC) in Washington D.C. Operational analyses from these meteorological centres are the most commonly used source for validating climate models.

Because of a strong demand for global daily and monthly analyses of precipitation and the lack of an adequate global network of precipitation observing stations, scientists have used precipitation distributions from short-range forecast as estimates of the truth. Arpe (1991) investigated the justification for using these forecasts as truth and pointed out the many problems involved. One problem results from inconsistencies between observational data and formulations in the analysis/forecasting scheme which can lead to a spin-up during the first few hours or days of forecast. When the Global Precipitation Climatology Centre (GPCC) in Offenbach had to decide how to complement global monthly mean analyses of precipitation in areas where there are no observational precipitation data at all, they decided to use ECMWF means of 12 to 36 hour forecasts as a compromise to avoid the period of spin-up in the early forecasts and the loss of predictability in the medium-range. For the validation of climate models the timing of meteorological events is of no interest. Important are the statistical properties of such events, e.g. time mean, extremes, frequency distribution.

When running models beyond the range of predictability one can study their ability to represent the climatology of the atmosphere. As an example we use the ECHAM3 model. The ECHAM3 model originates from the ECMWF model and still resembles in the formulation of the dynamical part the version of their cycle 36 while the parameterization of sub-grid scale processes have mainly been developed in Hamburg. For a more detailed description of the model and improvements in respect to earlier versions of the ECHAM models see Roeckner et al. (1992). In this study we analyse the ability of the model to simulate the hydrological cycle.

2. GENERATING INITIAL FIELDS FOR FORECAST MODELS - ANALYSIS

The ECMWF data assimilation scheme is run in cycles 4 times a day, each cycle consisting of a first-guess which is a result of a 6 hour forecast from the previous initial state, a statistical interpolation procedure of the differences between observations from a time window of +/- 3 hours around the analysis time and the first-guess (analysis increments), and finally a diabatic non-linear normal mode initialization. The data cut-off time for the main analysis of 12 GMT data is around 20.30 GMT, which gives time enough to collect most of the observed data, i.e. around 95% of available radiosonde soundings of the southern hemisphere and a considerably higher percentage of the northern hemisphere data. This scheme will be further discussed below and detailed descriptions can be found in Bengtsson et al. (1982) and Shaw et al. (1987).

Data checking is a major part in the scheme. A datum is checked against climatological means, the first guess, neighbouring data and against a preliminary analysis which uses all data except the datum being checked. Some time consistency checks are also carried out, e.g. the positions of ships are traced. These checks may result in a rejection of a datum because of it being judged to be incorrect. There is also a blacklist of observational platforms which have given erroneous observations over a period of time. Error statistics are continuously produced and investigated. An interesting aspect of this is that in data rich areas for the resolved scales the first guess data are of similar accuracy to observational data. Such statistics have also resulted in corrections of observational procedures. One can recognize a clear trend in the use of satellite sounding data from an initially faithful acceptance to a more cautious approach in more recent years. In May 1991 ECMWF stopped the use of the retrievals by NOAA/NESDIS (National Environmental Satellite and Data Information System) for the northern hemisphere completely. From June 1992 onwards satellite soundings are being used again, however, with a 1-dimensional variational method (Eyre, 1993).

Data checking has turned out to be an important part of the system especially in data sparse areas. If there is a single wrong datum, perhaps a ship observation giving wrong coordinates of its position, it can have a large adverse impact. Investigating cases in which the UK Meteorological Office forecasts differed considerably from the ECMWF ones, it was mostly possible to trace the forecast differences back to a different use of observational data, often one scheme rejected a datum as likely incorrect while the other scheme accepted it.

The mass and wind field analysis is based on a 3-dimensional optimum interpolation concept that allows a consistent interpolation of observational data with different characteristics within their error bars (Lorenc, 1981). The analysis of differences between observations and the first guess (analysis increments) is carried out in "analysis boxes" of about 600 km size, which can be smaller in regions of good data coverage. The resolution of the analysis is determined by the size of the analysis boxes as well as by the resolution of the structure functions, though finer scales may enter the final analysis through the first guess. Within a box the geostrophic balance is to a degree imposed on the analysis increments and therefore the divergent winds in the analysis on a fine scale result mainly from the first guess. Since January 1988 some divergent wind increments are explicitly allowed within analysis boxes (Undén, 1989).

Despite the imposed balance between wind and mass field within an "analysis box", inconsistencies between both fields can occur, which would result in the generation of gravity waves during a forecast. These gravity waves hardly interact with the large-scale flow and eventually disappear due to frictional forces in the model. Therefore they are of minor importance for medium-range weather forecasting. However, within the analysis cycle a 6 hour forecast is too short for damping these gravity waves and spurious noise can cause problems with quality control of observations. Also noise may accumulate during the course of many analysis cycles. Precipitation forecasts in the short-range would most likely be severely affected by such gravity waves. Therefore an initialization is needed to prevent the growth of gravity waves (Wergen, 1989). The forecasts are carried out with the operational ECMWF medium-range model which is described below.

Since September 1982 the ECMWF initialization scheme takes account of diabatic forcing. This is important for the divergent flow, especially in the tropics, with subsequent effects on the initial precipitation in the forecasts. To estimate diabatic forcing in the analysis, a 2 hour forecast from the un-initialized analysis is carried out from which the diabatic forcing is stored and averaged and then used as input for the initialization. The introduction of this scheme improved many quantities derived from or connected with the analysed divergent wind but it also enhanced the reliance of the analysis on the model formulation. Using other observations or estimates of diabatic forcings would ease this reliance. Because of operational requirements only estimates of precipitation from satellite as input can be envisaged. Heckley et al. (1990) have addressed this possibility and found a potential for improving the analyses of the divergent component of the wind, though it is not ready for operational use.

While the mass and wind fields are assimilated together by the 3-dimensional multivariate optimum interpolation scheme, the analysis of the humidity fields is based on a 2-dimensional correction scheme of the Cressman-type. Humidity increments are interpolated horizontally to the analysis grid-points using a simple 'weighted average' method and then added to the first-guess field. This method has recently been replaced for the northern hemisphere by a 1-dimensional variational method. Humidity analyses are strongly influenced by the formulations in the model which is producing the first guess.

The use of a variety of variables with a wide range of characteristics in accuracy, distribution and representativeness concerning scales in time and space is an important feature of the system, especially over data sparse areas. Wind distributions can be inferred from temperature observations and vice versus and provide the possibility of checking data and of filling of gaps in the data coverage of one or the other parameter. The use of a forecast model for creating the first guess provides the best available extrapolation into data void areas.

3. THE ECMWF FORECAST MODEL

The first ECMWF operational model was a grid-point model with grid a size of 1.875°, in 1983 it became a spectral model, first with a T63, in 1985 with a T106 and in 1991 with a T213 resolution (Simmons et al., 1989). The use of a spectral or grid-point model is probably less important for the simulation of precipitation as both methods perform the essential calculations in the grid-point domain, than for calculating the horizontal advection in which both methods are quite different. However as the orography has been fitted spectrally in the spectral model, there are often some spurious ripples in the precipitation over the oceans parallel to steep mountain ranges e.g. the Andes.

Much more important is the horizontal resolution, especially if one is interested in smaller scale features, e.g. in connection with orography. A T106 resolution (any feature with wavelengths shorter than 360°/106 on a great circle cannot be resolved) is not sufficient to e.g. represent the mountains of Wales and therefore one cannot expect the model to reproduce the excessive precipitation on the western coast of Wales and the relative minimum over the Thames Valley of England. Missing orographic effects can also affect precipitation means on a coarser grid. For example, high steep mountains of only small horizontal extent such as over the Canary Islands can make a big difference for an area mean because it would hardly rain in such an area without those mountains and these islands are not at all represented by a T106 model resolution.

Important subgrid-scale processes have been accounted for by the parameterization schemes. The model distinguishes between large-scale or frontal precipitation and convective precipitation though there is a gradual transition and in the absence of the parameterization of one process the other would take over eventually. Large-scale precipitation occurs when there is super-saturation but only if the total precipitable water in a column exceeds 2mm. Rain drops can evaporate again, if they fall through an unsaturated layer of air. The formation of convective precipitation is much more complicated but the main necessary condition for convection is a convergence of moisture flux in the lower troposphere into a conditionally unstable layer. The earlier operational convection parameterization scheme was that originally designed by Kuo (1974) and improved by Tiedtke et al. (1988), however replaced in 1989 by a mass-flux scheme (Tiedtke, 1989).

Another important process for the simulation of precipitation in the model is the parameterization of radiation because it controls to a degree the static stability of the atmosphere, a further condition for convective precipitation. The radiation scheme was in the beginning the one described by Geleyn and Hollingsworth (1979) and improved by Ritter (1985). The importance of radiative processes for the model performance has been demonstrated by Morcrette (1990), who suggested and implemented an improved radiation scheme at ECMWF in May 1989.

Changes in the forcing of the atmosphere due to radiative processes, even stronger than those due to changes in the radiation schemes, can occur through the interaction with the clouds in the model. The clouds are presently determined diagnostically after a method by Slingo (1987). Several types of clouds connected with convection, frontal activities and inversions can be diagnosed, which can interact with the radiation scheme. However, the advection of liquid water, which would provide a real prognostic scheme of cloudiness is still missing in the ECMWF scheme but has been implemented in the ECHAM3 model for climate simulations (Section 5).

4. QUALITY OF SHORT-RANGE FORECASTS

Here we are mainly interested in the ability of the ECMWF system to forecast the precipitation. Although an initialization step is applied in the analysis cycle some inconsistencies between the analysis data and the model formulation remain which can lead to a spin-up during the initial period of the forecasts. There are different effects for the large-scale and the convective precipitation. In averages for the globe during the course of 10-day forecasts one finds a strong variability which has different characteristics when using a Kuo-convection scheme or a mass-flux convection scheme. With the Kuo convection scheme the precipitation increases from the first to the second day of forecast, with a strong underestimation during the first few hours, and then decreases towards a lower equilibrium value around 10 days of forecasts. With the mass-flux scheme the convective precipitation decreases rapidly from the first to the second day of forecast and stays then fairly constant to the end of the 10 day forecasts on a higher level than with the Kuo convection.

The large-scale precipitation is underestimated in the first hours or days. If one investigates this in more detail one finds that this underestimation is mainly confined to oceanic areas, especially the southern oceans, i.e. in areas where the main observational data come from satellites. Further investigations have shown that the TOVS (TIROS Operational Vertical Sounder) data, i.e. vertical soundings of temperature (derived from radiation measurements on several narrow bands), are unable to describe vertical tilts of troughs and ridges as well as sharp horizontal gradients, even destroying them when present in the first-guess fields. Both these structures are decisive for the development of baroclinic waves and these produce most of the large-scale precipitation. A new variational method was introduced in the ECMWF analysis scheme in 1992 which reduces this problem (Eyre, 1993).

The humidity analysis strongly influences the precipitation in the short-range forecasts. Observational humidity data have a wide margin of uncertainty, to a great deal due to unrepresentativeness. The correlation of 850 hPa relative humidity between neighbouring radiosonde stations 500 km appart in winter is only 30% while the corresponding correlation of 500 hPa geopotetial height is near 90%. Over the oceans the analyses are strongly biased by the model formulation and therefore one can find in time series of ECMWF humidity analysis abrupt decreases or increases with changes in the model formulation (Arpe, 1990). When comparing analyses data of humidity for 12GMT with those at 00GMT one finds at radiosonde stations which report only once a day, lower analysis humidity values at times when observations are available. Assuming that radiosonde data are the most accurate ones from all available observational platforms, it has to be concluded that for some reason the analysed humidity is too high over subtropical oceanic areas where this feature occurred, at least during 1989. However, it is not clear if this results from a model bias or from other observational data. The use of satellite data (TOVS) for the analysis is at least a main contributor, as this problem did not show up in experiments in which all observational data from satellites were neglected. It was mentioned earlier that some of the baroclinic structures are not supported, even partly destroyed by the use of satellite data from which a suppression of frontal precipitation in the short-range forecasts can be expected. This would be consistent with too high humidity in the first guess fields which would bias the analysis towards too high humidity.

Arpe and Cattle (1993) have investigated the ECMWF precipitation data for Antarctica and found the data to be reasonable as far as can be judged, at least as far as the variability in time and space is concerned. They also pointed out that different analysis/forecasting schemes can provide quite different precipitation amounts over inner Antarctica.

The strong impacts of the formulation of the analysis/forecasting scheme on the precipitation forecasts is quite unsatisfactory. Using forecast precipitation as estimates for the truth is therefore severely limited. Especially long time series will suffer from model changes which might result in larger signals than precipitation anomalies due to atmospheric events. The forthcoming re-analysis by ECMWF over the period from 1979 onward with a frozen system will provide a valuable data set also for precipitation as it overcomes at least the problem of inhomogeneities connected with system changes.

The use of operational analysis-forecasting systems for estimating the precipitation has the potential of providing better estimates than any system based exclusively on precipitation observations. The analysis-forecasting systems can combine a wide range of observational data, which gives the possibility of data checking and filling gaps in the data coverage of one or the other parameter. It can provide the best possible extrapolation into data void areas. This method will provide true daily averages, not a few snap shots like estimates from SSM/I data. It also provides true area averages and not spot values like conventional observations. It has also the advantage of being constantly supervised by large teams of scientists which most likely can hardly be afforded for other schemes. Inclusion of precipitation related observations into the scheme would most likely be of advantage. Its main disadvantage is that the precipitation estimates are strongly model dependent, at least as long as there are so many unresolved problems with modelling.

5. USING FORECAST MODELS FOR CLIMATE SIMULATIONS

The ECMWF model has been further developed for the use of simulating the climate by MPI, Hamburg, this model is called ECHAM3. We start by investigating long term means of precipitation. Fig. 1 displays for the seasons DJF (December, January, February) zonal means of precipitation, separately for land and sea. In the lower panels 3 different climatological estimates (anaJ=Jaeger, 1976, anaL=Legates, 1987, and Legates and Willmott, 1990, anaN=NASA, which is a blend of estimates from MSU observations over oceans by Spencer, 1993, and from conventional observations over land by Schemm et al., 1992) are compared with 30 year means from the ECHAM3 T42 model, in the upper panel the Legates climatology is compared with 3 different resolution runs with the ECHAM3 model. The T106 results consist of 6 years while T21 and T42 results consist out of 30 years, all using climatological SST. Over the oceans, especially during JJA (not shown) there is a marked relative minimum at the equator in the T42 and T106 experiments which is not present in the T21 model nor in the climatological estimates. However, it is difficult to judge if this minimum is unrealistic because of the large uncertainty in the observations. We can be more sure that the northern ITCZ over the oceans is simulated too far north because all climatological estimates agree in this respect. In the belt 20° to 30°S over land during DJF the models simulate consistently more precipitation than the climatological estimates, a problem over Australia and South Africa which will be discussed below. Over the southern extra-tropical oceans the climatological estimates suggest clearly larger precipitation amounts than the model simulations. Though the climatological estimates agree with each other, many doubts about the accuracy in this respect have been raised.

Global averages the models show a steady increase of precipitation with resolution but still stay within the range of the climatological estimates. The annual global mean values are as follows: Legates: 95, Jaeger: 79, NASA: 102, T21: 81, T42: 85, T106: 89 mm/month. The Legates data have been corrected for observational errors. If one would apply the same cor-

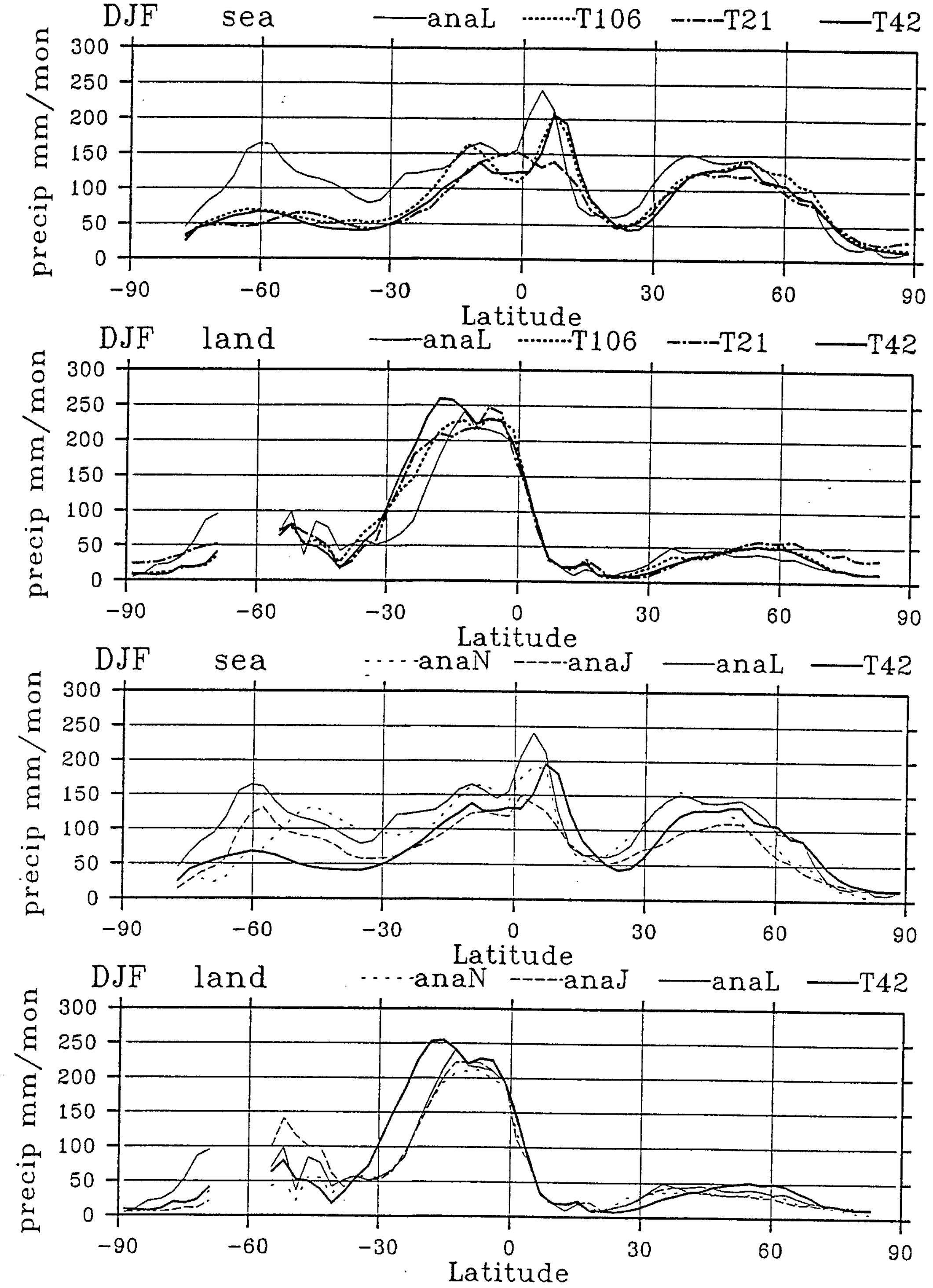

Figure 1: *Zonal mean precipitation separately for sea and land points for the season DJF. In the upper panels simulations with the ECHAM3 T21, T42 and T106 models are compared with climatological estimates by Legates and Willmott (1990). In the lower panels the T42 model results are compared with 3 climatological estimates: anaJ=Jaeger (1976), anaL=Legates and Willmott (1990), anaN=NASA, which is a blend of estimates from MSU observations over oceans by Spencer (1993) and from conventional observations over land by Schemm et al (1992).*

rection to Jaeger's data the spread between them would decrease as the correction always leads to an increase of precipitation estimates, strongest at high elevations and in snow conditions.

In the following we describe some features concerning the geographical distribution of precipitation in the climate model. Because of the large uncertainty in the observations, the simulations are mostly within the range of climatological estimates and there are only few points where the model deviates from the climatologies significantly. Over subtropical oceanic upwelling areas the models show much larger areas with very low precipitation amounts than the estimates by Legates or Jaeger but the estimates from MSU observations are quite near to the model results. A relative minimum at the equator, shown in the zonal means over oceans for the model simulations results mainly from the Pacific where the models look unrealistic. There is excessive precipitation over Australia and South Africa, a problem which was introduced into the simulations when changing the parameterization of convection from a Kuo (1974) to a mass-flux scheme (Tiedtke, 1989) though this may not necessarily be the cause of the problem. The latter problem improves with increasing resolution.

During winter all climatological estimates agree that there should be a precipitation maximum over the eastern Mediterranean though with quite different amplitudes. The higher resolution models agree reasonably well concerning the pattern but are on the low side even when compared with the lowest climatological estimate by NASA. The T21 model gives an unrealistic distribution of precipitation. The relatively low simulated precipitation values over the Mediterranean is connected with an eastward shift and strengthening of the Azores anticyclone, as discussed by Roeckner et al. (1992).

The orographically influenced precipitation over the Alpine area is simulated quite different in the T21 compared to the higher resolution models. The higher resolution models provide clearly better positions of maxima but with too low values, i.e. 2 mm/month or less compared to 3 mm/month and more in the climatological estimates. The annual cycles of precipitation at stations in mid-latitudes show a maximum in the observations probably due to convective activities which are simulated too weakly in the model. The precipitation over the Indian area during JJA has a clearly better simulated distribution of precipitation with the higher resolution, however the amounts are too low in all simulations especially by the higher resolution models.

6. THE INTERANNUAL VARIABILITY OF PRECIPITATION

We investigated further the impact of Sea Surface Temperature (SST) anomalies on the variability of precipitation by running several experiments with different initial states but with the same observed SST. For the inner tropics the impact of the SST turned out to be extremely strong, especially over the eastern Pacific. Experiments starting with different initial data but using the same observed SST repeat very similar interannual variabilities of precipitation in the tropical areas. Comparing the model simulations with estimates of precipitation of the real atmosphere using MSU observations (Spencer, 1993) and of infra-red observations from satellite (GPI, Meisner and Arkin, 1987) one finds that the interannual variability is simulated very realistically. Also in the extra tropics, e.g. the eastern US, realistic impacts from SST anomalies can be found.

7. THE WATER BALANCE CALCULATIONS

River run-off data are available for the main catchment areas and is probably the best source of data if we want to validate long term series of large-scale means. It is said that in addition to the flow in the rivers there is a further flow of water below ground in the order of one third of the flow above ground with a much slower speed which is not covered by the run-off data set. This may be much less of a problem if only large catchment areas as the Amazon river basin are considered. This basin we will discuss further in the following as an example.

The precipitation for the Amazon basin is simulated reasonably well for the annual mean but with a larger amplitude of the annual cycle. The climatological estimates shown are those by Jaeger which are close to the ones by Nasa but lower than the ones by Legates for this area. The annual mean values for the T21 model are clearly lower than the lowest climatological estimates (145mm/month vs. 153mm/month by NASA) while the T106 model gives higher amounts than the highest estimate (190mm/month vs. 171mm/

month by Legates). For the evaporation one sees a clear trend towards higher values in summer with the higher resolution model, approaching the "climatological estimates" by Mintz and Serafini (1992). During summer in the simulations the evaporation exceeds the precipitation, but the model has only a maximum storage of water in the soil of 0.2 m and none in rivers and lakes and we believe that this is too little for this area. In the models all excess water is leading to immediate run-off into the ocean. The observed run-off shows an annual cycle which is about 4 month out of phase with the precipitation. This is caused by the slowness of flow in the rivers and in the ground. Some but too little delay is also indicated in the simulations due the drying and wetting of the soil. Because of the lack of supply of water to the ground by the rivers in the simulations, the ground can run dry in summer and this leads to excessively high temperatures for the Amazon basin.

The river run off is an important factor for the climate which has to be taken into account in the models and work on this is in progress.

8. CONCLUSIONS

Although there is a clear deficit of observational data for analysing meteorological fields globally, the combination with a forecasts scheme as done at ECMWF provides a most consistent product. The disadvantage of it is a strong influence of the parameterization scheme on some sensitive quantities like the hydrological cycle. Interannual variabilities of such quantities are often dominated by changes in the analysis-forecasting scheme which conceals the natural variability.

When comparing maps of long term mean precipitation in the model simulations with estimates of the true precipitation one finds generally that model results lie mostly well within the range of realisations. Simulations of the atmosphere with general circulation models have now reached a high level of quality so that a detailed validation is severely hampered by the lack of observational data, their uncertainty and/or their unrepresentativeness. At least we do not know these characteristics in all cases.

Though the range of realisations of the "truth" is quite large, there is clearly too much precipitation simulated over Australia and South Africa during DJF, connected with too hot surfaces. An improvement with increased resolution has been noticed. There is also too much precipitation over central America during JJA. Both these problems were introduced or enhanced with the introduction of the mass-flux scheme for parameterizing convective precipitation and are common to other models as well. Over oceanic upwelling areas, e.g. over the Pacific off Peru, the model simulates a much dryer climate than the estimates by Legates and Willmott (1990). The model produces a strong relative minimum of precipitation at the equator with main contributions from the central Pacific. Different estimates of climatological means differ considerably in this respect leaving the model simulation within their range of realisation. Any monthly mean of model simulation can hardly be judged to be unrealistic, the long term mean errors mentioned above are a result of many extreme though possible situations of the same kind.

We found river discharge to be valuable independent observations for model validation and intend to make more use of these data. For a better use of these data but also for improving the model performance, the storage of water and its transport has to be parameterized in the model. On the whole the T106 and T42 version of the ECHAM3 model give results which are much more similar to each other than to the T21 version.

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