SATELLITE VALIDATION OF UNIFIED MODEL SIMULATIONS OF CLOUDS AND RELATED VARIABLES

A. Slingo, A. Jones and M.J. Webb
Hadley Centre for Climate Prediction and Research
Meteorological Office, Bracknell, UK

Summary: Recent research carried out in the Clouds and Climate group at the Hadley Centre is described, with the emphasis on climate simulations with the Meteorological Office Unified Model. Applications of the SAMSON system are shown, in which the seasonal variations in the clear-sky greenhouse effect have been studied and systematic errors in the Unified Model simulations identified. Satellite retrievals of the Earth's radiation budget (from ERBE) and of cloud liquid water paths (from SSM/I) have also been extremely useful in validating the model. However, at present there is no satellite validation for the model's simulated ice water paths, which dominate the cloud water paths at low temperatures.

1. THE UNIFIED MODEL

The Meteorological Office has developed a Unified Model (UM) for operational weather forecasting and climate research (Cullen, 1993). The model has variable horizontal and vertical resolution and may be configured in a number of different ways. Operational versions include a mesoscale model covering the UK, a limited area model covering the North Atlantic and Europe and several global models. The climate version currently uses 19 levels and a 2.5° x 3.75° grid. Unification has resulted in many savings and benefits. For example, new parametrisations developed and tested in one version are immediately transportable for evaluation in other versions of the model.

The UM includes the cloud-prediction scheme described by Smith (1990), which includes prognostic cloud water equations for both the liquid and ice water contents. Cloud radiative properties are interactive with the water contents. The effective radii of ice and water clouds are presently fixed, but interactive schemes are being investigated.

The model has been run with prescribed sea surface temperatures and sea-ice limits for the period 1979-88, as part of the Atmospheric Model Intercomparison Project (AMIP; Gates 1992). Brief results from various aspects of the simulation of the radiation budget and clouds are presented here.

2. GLOBAL RADIATION BUDGET

The radiation budget from the AMIP integration has been examined in detail for the period 1985-88, the period of overlap with the Earth Radiation Budget Experiment (ERBE; Harrison et al. 1990). Table 1 shows that the UM simulations of the global means of the Earth's radiation budget compare favourably with ERBE. The largest disagreement comes from the clear-sky albedo, which is slightly too low. This may be due to problems with the surface albedos, but may also be due to the neglect of aerosol scattering in this version of the model. The cloud amounts in the model were tuned to compensate for this shortcoming, as can be seen by the (delib-

Table 1 *Global means of Earth radiation budget quantities from ERBE and from the 'AMIP' integration of the Unified Model, averaged over the period January 1986 to December 1988.*

Source	Incoming shortwave	Albedo	Clear-sky albedo	Absorbed shortwave	Net Radiation	OLR	Clear-sky OLR	SW cloud forcing	LW cloud forcing	Net cloud forcing
ERBE	341.63	0.2950	0.1570	240.72	5.07	235.65	266.27	-48.05	28.69	-19.11
AMIP	341.41	0.3010	0.1393	238.62	1.21	237.40	263.97	-55.22	26.57	-28.65

erate) overestimate of the shortwave cloud forcing. As a result, the net radiation averaged over the year is close to zero, as it should be.

3. CLEAR-SKY GREENHOUSE EFFECT

Slingo and Webb (1992) describe a system for the Simulation and Analysis of Measurements from Satellites using Operational aNalyses (SAMSON). They show that the system is capable of simulating the distribution of the clear-sky outgoing longwave radiation (OLR) at the top of the atmosphere with an accuracy comparable with that of the corresponding ERBE product. Webb et al. (1993) use SAMSON to study the factors which control the clear-sky greenhouse effect over the oceans. They define the normalized clear-sky greenhouse effect $\mathcal{G}$ as the ratio of the surface longwave emission to the clear-sky OLR. They show that there is a strong seasonal variation in $\mathcal{G}$ at high latitudes, with larger values in winter. This is a surprising result, because water vapour is known to be the primary greenhouse gas and so one might expect the greenhouse effect to be highest in summer, when the water vapour content of the atmosphere is highest. Webb et al. point out that $\mathcal{G}$ depends not only on the water vapour amounts but also on the atmospheric temperatures. In summer, water vapour amounts are indeed higher than in winter, but so are atmospheric temperatures. The higher temperatures reduce the temperature contrast between the atmosphere and surface and reduce the value of $\mathcal{G}$. This effect is strong enough to dominate over the forcing from the water vapour amounts. The drier, colder winter hemisphere thus has a higher clear-sky greenhouse effect than the moister, warmer summer hemisphere. Figure 1 shows this result from ERBE data, SAMSON and from the Unified Model AMIP integration. Despite the observational scatter, the ERBE data show the seasonal variation at high latitudes. This is much clearer in the SAMSON simulation, which does not suffer from the retrieval errors and incomplete sampling of ERBE.

The Unified Model shows the same general features as are apparent in the ERBE and SAMSON plots, although there are some disparities at low latitudes. Such comparisons can provide valuable information on the realism of the simulated atmospheric temperatures and humidities. Care must be taken, however, because the ECMWF analyses themselves contain systematic errors, particularly in the humidity fields, which influence the SAMSON simulations (Slingo and Webb 1992). One method for dealing with this problem is to select areas for comparison where the SAMSON simulations agree well with ERBE, suggesting that the analyses are reasonable

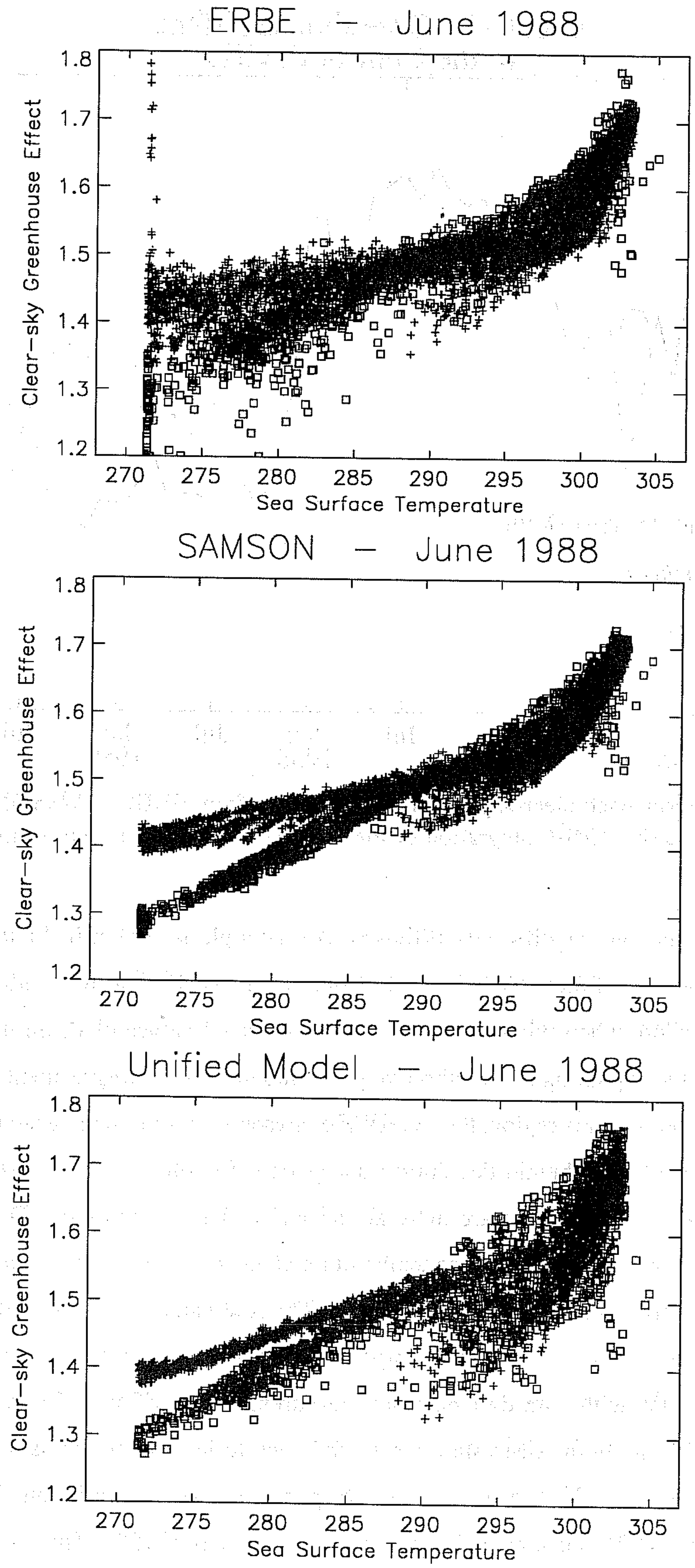

Fig. 1 Normalised clear-sky greenhouse effect versus sea surface temperature for June 1988 from ERBE (top), SAMSON (middle) and the AMIP integration of the Unified Model (bottom). Northern hemisphere (summer) points are shown as open squares and southern hemisphere (winter) points as plus signs.

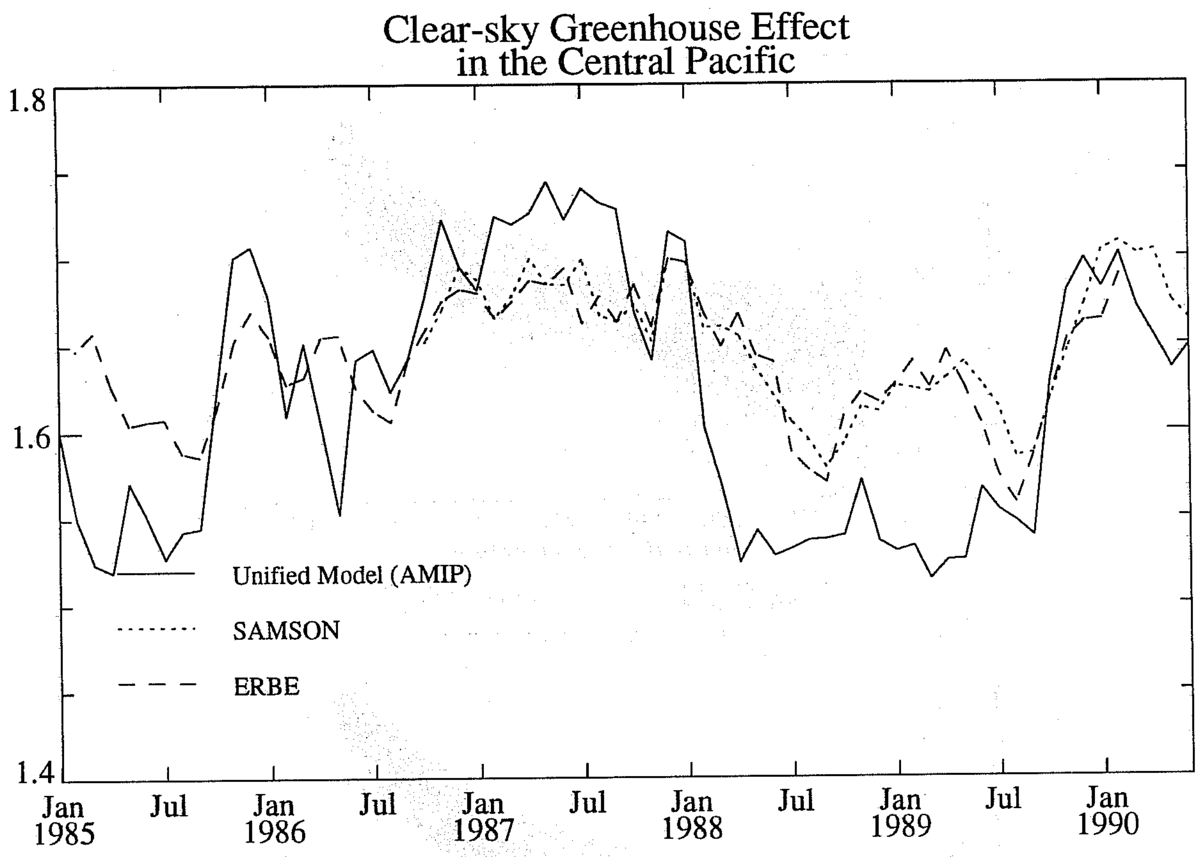

Fig. 2 Time-series of the normalised clear-sky greenhouse effect $\mathcal{G}$ from ERBE, SAMSON simulations using ECMWF analyses and the AMIP integration of the Unified Model, for a point in the central Pacific at 177.7° W, 2.6° S.

here, but where the UM results are significantly different. An example is shown in Figure 2. In the central Pacific, the SAMSON simulations follow ERBE closely from the end of 1986 to the beginning of 1990. This period covers the 1987 El Niño, when this region experienced elevated values of $\mathcal{G}$, through the 1988/89 La Niña, when $\mathcal{G}$ was lower, to the beginning of the subsequent El Niño in 1990. The agreement between SAMSON and ERBE indicates that, at least in this region, the ECMWF analyses are providing a reasonable representation of the atmospheric temperatures and humidities during this period. In contrast, the AMIP integration of the Unified Model shows variations in $\mathcal{G}$ which are more abrupt and of larger amplitude. This suggests that the model is responding too strongly to the sea surface temperature changes imposed during the integration. Some evidence in favour of this interpretation is shown in Figure 3. The first panel shows the same data as in Figure 1, but for a more limited period. The second panel compares the column integrated water vapour (w) from the ECMWF analyses and the UM with data derived from measurements by SSM/I. There is good agreement between the analyses and SSM/I, but the UM values are much lower during the initial phase of the La Niña. The close correspondence between the UM curves on these two panels shows that variations in w are mainly responsible for the variations in $\mathcal{G}$. This is most striking during the first half of 1988. The lower panel shows that the local sea surface temperature declines only slowly, so that the rapid drop in both $\mathcal{G}$ and w during 1988 may be forced as much by changes in the sea surface temperature outside this region as by the local value. A more detailed analysis of these simulations is in progress.

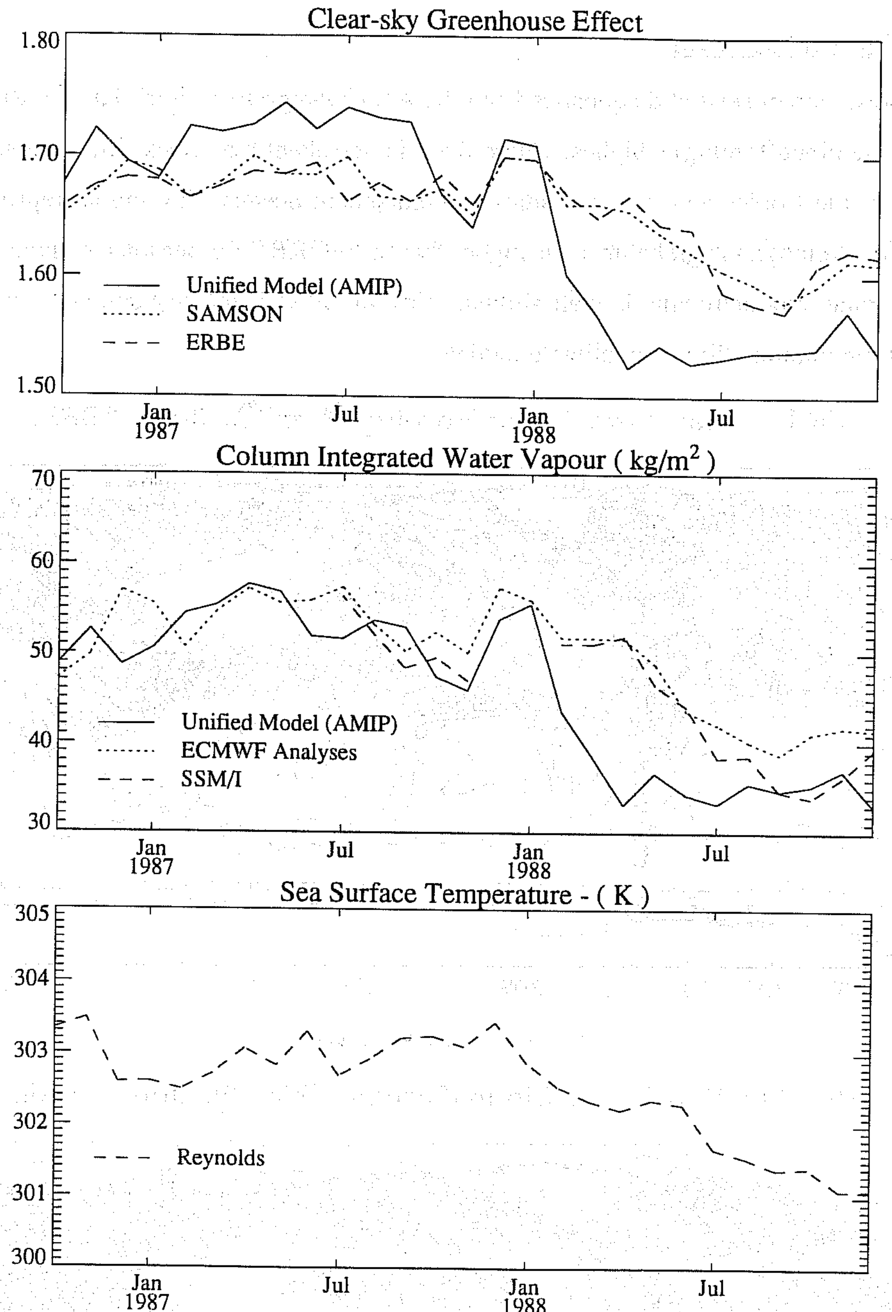

Fig. 3 Time-series of the normalised clear-sky greenhouse effect $\mathcal{G}$ from ERBE, SAMSON simulations using ECMWF analyses and the AMIP integration of the Unified Model (top), the column integrated water vapour w from the SSM/I retrievals of Greenwald et al. (1993), the ECMWF analyses and the AMIP integration (middle) and the local sea surface temperature (bottom), for the same point as in Fig. 2.

ECMWF will soon begin a complete re-analysis of atmospheric data for the period 1979-93, which will be invaluable for climate and other investigations. Our contribution is known as project CLERA (Clear-sky Longwave from the ECMWF Re-Analyses), in which SAMSON will generate clear-sky fluxes and heating rates for studies of the greenhouse effect over this period.

4. SIMULATION OF CLOUDS

Figure 4 shows one of several diagnostics from the AMIP integration which have been compared with ERBE. The shortwave cloud forcing is highest where there is persistent cloudiness illuminated by significant insolation, such as in the tropics and over the summer hemisphere oceans. The model reproduces the main features satisfactorily, although the global mean is higher than from ERBE, for reasons explained earlier. In this example, the Californian stratocumulus is well simulated by the model, but in general the amount of these clouds is deficient (in common with many climate models).

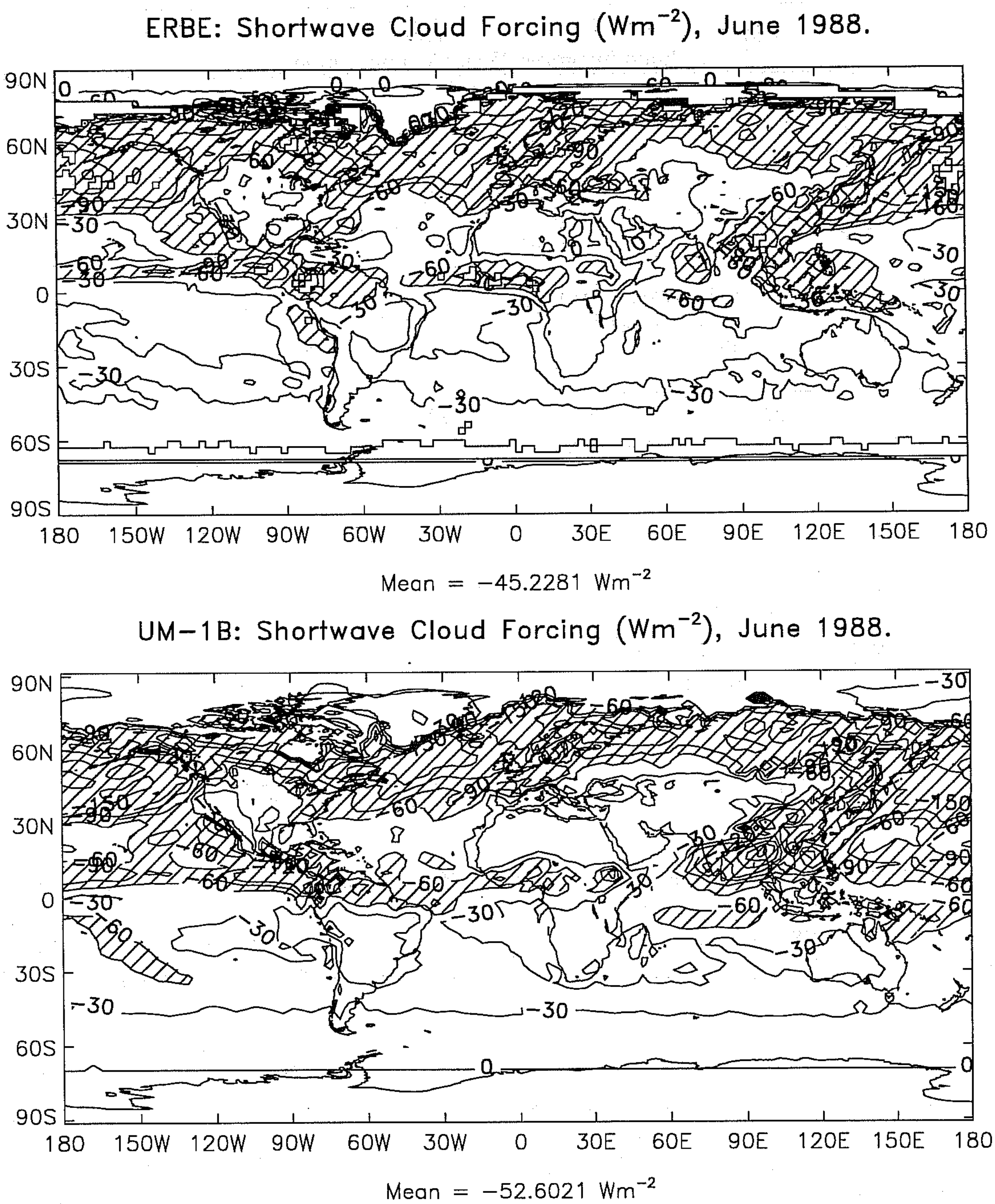

Fig. 4 Shortwave cloud radiative forcing for June 1988 from ERBE (top) and from the AMIP integration of the Unified Model (bottom). Values below -60 Wm^{-2} are shaded.

Clouds provide one of the largest sources of uncertainty in projections of future climate change. It is now believed that changes in cloud microphysical properties (e.g. particle size, water and ice contents) may be just as important as those in cloud amount and distribution. The dependence of the reflectivity of water clouds on the liquid water path and effective radius of the drops is shown in Figure 5. Increases in liquid water path lead to increases in cloud reflectivity, but increases in the effective radius of the cloud drops has the opposite effect. At high values of the liquid water path, the reflectivity asymptotes to a limiting value determined only by the size of the drops. Using this parametrisation, Slingo (1990) studied the sensitivity of the NCAR Community Climate Model (CCM) to changes in low-level clouds. He showed that the top of atmosphere radiative perturbation from doubling CO_2 could be balanced by 15-20% increases in cloud amount, 20-35% increases in liquid water path and 15-20% decreases in effective radius.

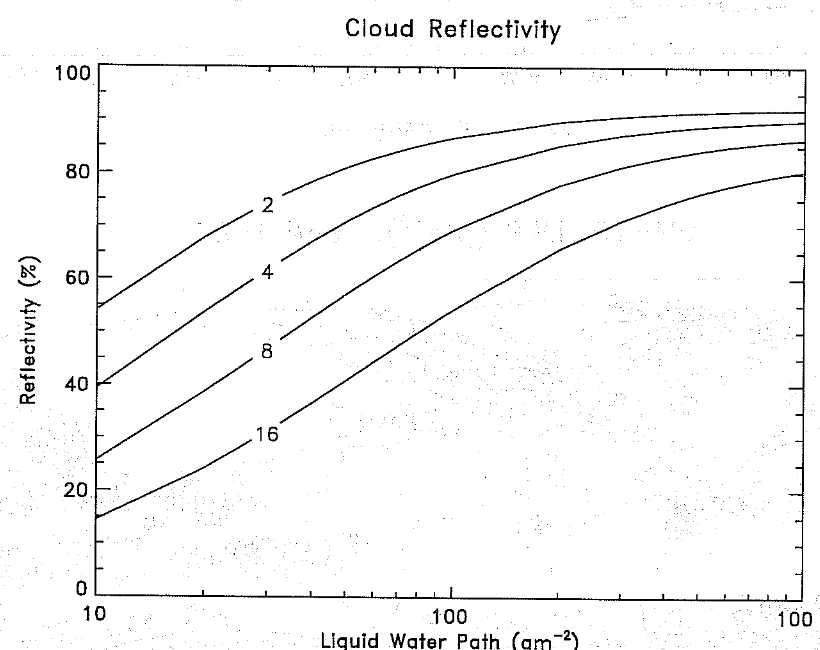

Fig. 5 Reflectivity of water clouds at a solar zenith angle of 60°, as a function of the cloud liquid water path, for various values of the effective radius, in μm. Adapted from Slingo (1989).

A programme of work has been initiated to study the sensitivity of the Unified Model to changes in cloud microphysics. Using the AMIP version of the model, the sensitivity of the model's radiation budget to changes in low-level clouds was studied. Many single-timestep runs were performed in which the low-level cloud droplet effective radius, liquid water path and cloud amount were varied independently within a physically reasonable range of plus or minus 20%. The effect of these changes was examined in the net radiation and planetary albedo at the top of the atmosphere.

Considering the change in planetary albedo, the parameter which had by far the greatest impact was low-level cloud *amount*. Changes in cloud liquid water path or droplet effective radius had a much smaller effect on the albedo. This is contrary to the results of Slingo (1990), where similar changes in the three parameters had

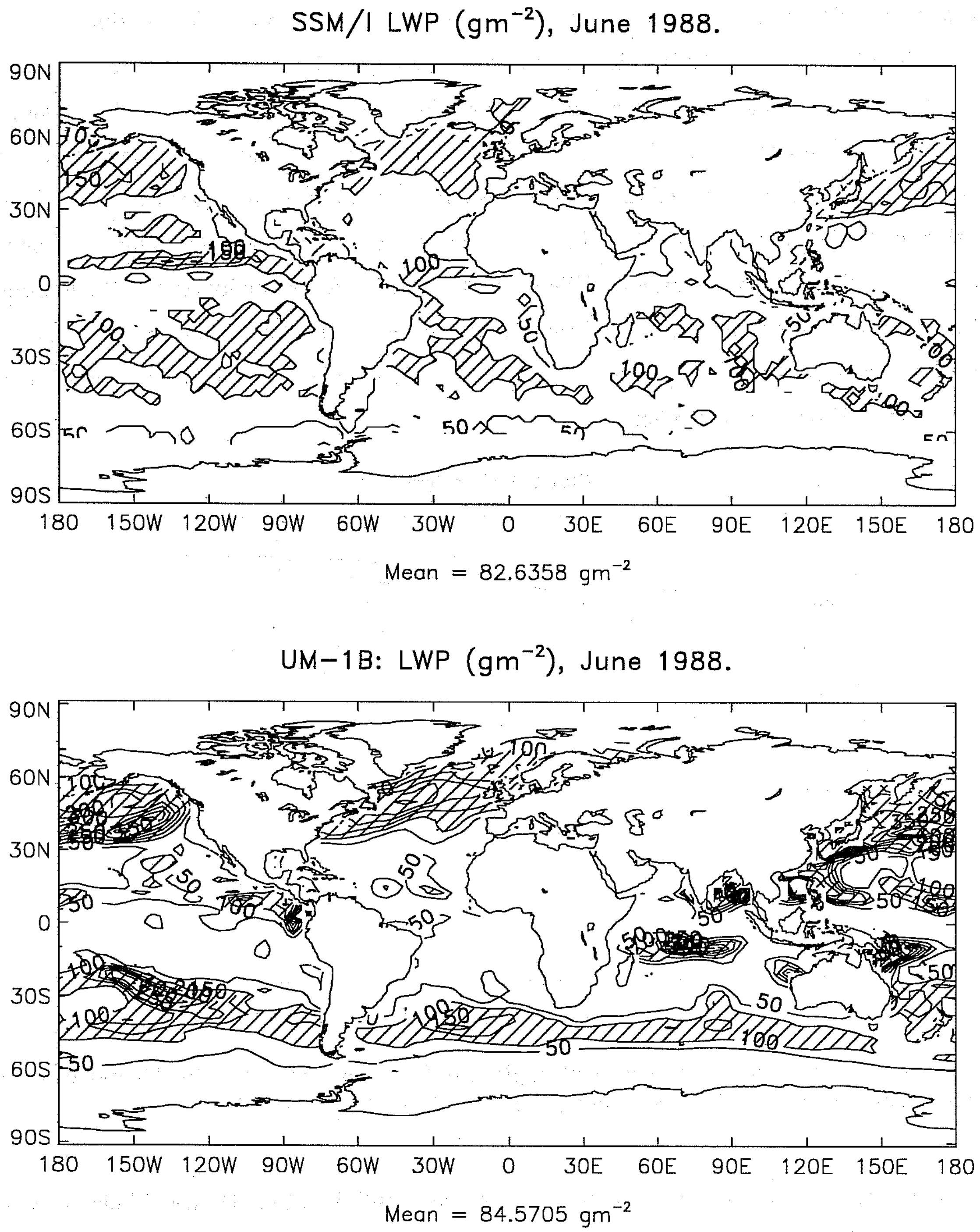

Fig. 6 Vertically integrated liquid water path averaged over the gridbox for June 1988, from the SSM/I retrievals of Greenwald et al. (1993) and from the AMIP integration of the Unified Model.

similar effects on the albedo.

Investigation revealed that the UM's lack of sensitivity to the microphysics of low-level clouds was due to unphysical distributions of cloud amount and liquid water path. This was due to details of the cloud prediction scheme, known as the 1B scheme, incorporated into the model because it produced the satisfactory representation of the radiation budget evident in Table 1 and Figure 4. Unfortunately, this was achieved through errors in

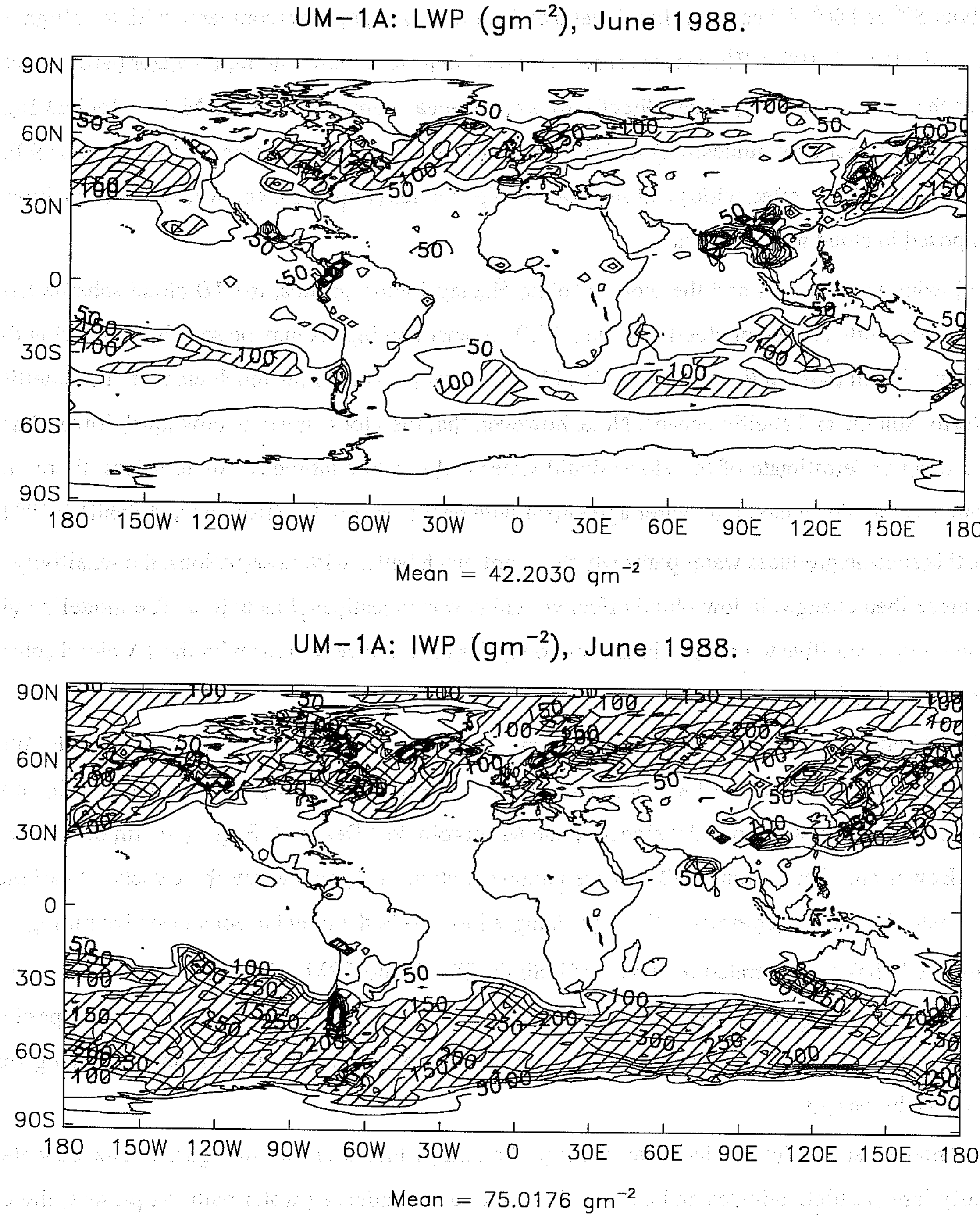

Fig. 7 Vertically integrated liquid water path averaged over the gridbox for June 1988, from the integration of the Unified Model with the 1A cloud scheme (top). The lower frame shows the ice water path.

the representation of these clouds. Firstly, liquid water paths were much higher than observed in important areas, for example over the summer hemisphere oceans. A comparison between the cloud liquid water path derived from SSM/I data and that from the model (shown as a *gridbox-mean* value so as to allow a meaningful comparison with the satellite data) is shown in Figure 6. Despite similarity in the global means, the model values exceed those from SSM/I by a considerable margin in many areas, particularly in the northern hemisphere between about 30° and 60° N. Secondly, low-level cloud amounts were too low compared with the climatologies of Warren *et al.* (1986 & 1988). These two errors combined to produce in-cloud liquid water paths which were much larger than those observed, either directly by aircraft measurements from the Meteorological Research Flight (Martin, personal communication) or inferred indirectly from satellite data (Curry et al. 1990). As a result, the low-level cloud reflectivities had saturated at high values (Figure 5), and were thus insensitive to the changes imposed in cloud microphysics.

Following these results and the work of other Hadley Centre groups, the 1B cloud scheme has been discarded. Results with a different cloud scheme ('1A') are encouraging, as may be seen by comparing the first frame in Figure 7 with those in Figure 6. The cloud liquid water paths are now much closer to the satellite data over the North Atlantic and Pacific oceans. Note, however, that the global mean is now much lower than from SSM/I, due to an underestimate of the cloud liquid water paths at low latitudes. Nevertheless, there are now larger amounts of low-level cloud, in better agreement with data from ISCCP (Rossow and Schiffer 1991).

As this scheme produces water paths which accord much better with observations, the sensitivity of this version to prescribed changes in low cloud effective radius was investigated as before. The model's radiation budget is now more sensitive to changes in the microphysics of low-level clouds with the 1A cloud scheme, in better agreement with Slingo (1990).

Work is currently under way to tune the model's radiation budget, using data from ERBE. With the improved cloud simulation from the 1A scheme, it should be possible to investigate the impact on the model of the effective radius parametrisations developed at the Meteorological Research Flight (Martin et al. 1993) and at UMIST (Bower and Choularton 1992). These parametrisations will also allow the effects of variations in aerosol concentrations to be determined, through changes induced in the cloud droplet effective radius.

This study has demonstrated the value of both the ERBE and SSM/I data and the importance of comparing models with as many different and complementary satellite datasets as are available. This is particularly important in a complex model such as the UM, to ensure that physical parametrisations are giving realistic results for the right reasons.

The model also predicts the ice water content of clouds, which is shown in Figure 7. The ice water path is particularly large at high latitudes and can dominate the total condensed water path. At present, there is no global climatology available for ice water paths, so the model results cannot be validated. This is a serious problem, although information may be retrievable from combinations of visible and microwave radiometry (Lin and Rossow 1993). Further work is needed in this important area, as models presently have too many degrees of freedom by which they are able to produce a reasonable radiation budget from cloud amounts and water contents which may not be realistic.

5. ACKNOWLEDGEMENTS

This work was funded by the U.K. Department of the Environment under contract PECD 7/12/37 and by the

International Petroleum Industries Environmental Conservation Association (IPIECA).

6. REFERENCES

Bower, K.N. and Choularton T.W., 1992: A parameterisation of the effective radius of ice free clouds for use in global climate models. *Atmos. Res.*, **27**, 305-339.

Curry J.A., Ardeel C.D. and Tian L., 1990: Liquid water content and precipitation characteristics of stratiform clouds as inferred from satellite microwave measurements. *J. Geophys. Res.*, **95**, 16659-16671.

Cullen, M.J.P., 1993: The unified forecast/climate model. *Meteorol. Mag.*, **122**, 81-94.

Gates W.L., 1992: AMIP: the atmospheric model intercomparison project. *Bull. Am. Meteorol. Soc.*, **73**, 1962-1970.

Greenwald T.J., Stephens G.L., Vonder Haar T.H. and Jackson D.L., 1993: A physical retrieval method of liquid water over the global oceans using SSM/I observations. *J. Geophys. Res.*, In press.

Harrison E.F., Minnis P., Barkstrom B.R., Ramanathan V., Cess R.D. and Gibson G.G., 1990: Seasonal variation of cloud radiative forcing derived from the Earth Radiation Budget Experiment. *J. Geophys. Res.*, **95**, 18687-18703.

Lin B. and Rossow W.B., 1993: Observations of cloud liquid water path over oceans: optical and microwave remote sensing methods. Submitted for publication.

Martin G.M., Johnson D.W. and Spice A., 1993: The measurement and parametrisation of effective radius of droplets in warm stratocumulus clouds. *J. Atmos. Sci.*, submitted for publication.

Rossow, W.B. and Schiffer R.A., 1991: ISCCP cloud data products. *Bull. Amer. Meteorol. Soc.*, **72**, 2-20.

Slingo A., 1989: A GCM parametrisation for the shortwave radiative properties of water clouds. *J. Atmos. Sci.*, **46**, 1419-1427.

Slingo A., 1990: Sensitivity of the Earth's radiation budget to changes in low clouds. *Nature*, **343**, 49-51.

Slingo A. and Webb M.J., 1992: Simulation of clear-sky outgoing longwave radiation over the oceans using operational analyses. *Q. J. R. Meteorol. Soc.*, **118**, 1117-1144.

Smith, R.N.B., 1990: A scheme for predicting layer clouds and their water content in a general circulation model. *Q. J. R. Meteorol. Soc.*, **116**, 435-460.

Warren S.G., Hahn C.J., London J., Chervin R.M. and Jenne R.L., 1986: Global distribution of total cover and cloud type amount over land. *NCAR Technical Note* NCAR/TN-273.

Warren S.G., Hahn C.J., London J., Chervin R.M. and Jenne R.L., 1988: Global distribution of total cover and cloud type amount over the ocean. *NCAR Technical Note* NCAR/TN-317.

Webb M.J., Slingo A. and Stephens G.L., 1993: Seasonal variations of the clear-sky greenhouse effect: the role of changes in atmospheric temperatures and humidities. *Climate Dynamics*, In press.