USING SATELLITE OBSERVATIONS AND REANALYSES TO EVALUATE CLIMATE AND WEATHER FORECAST MODELS

Richard P. Allan
Environmental Systems Science Centre
University of Reading
Reading, Berkshire, RG6 6AL, UK
Email: rpa@mail.nerc-essc.ac.uk

ABSTRACT

Satellite observations of water vapour and radiative fluxes are used in combination with reanalyses data to evaluate the Met Office weather and climate prediction models. Using reanalysis vertical motion data, it is established that much of the climate model error in radiative fluxes relates to errors in dynamical fields. Radiative feedback processes are to a large extent independent of these positional errors in the large-scale circulation. It is therefore of great value to analyse the relationships between water vapour, clouds and radiation in terms of dynamic regime or by averaging over large-scale circulation systems. Using the latter approach, it is found that the monthly and interannual relationships between water vapour and clear-sky radiation are consistent between models and satellite data. However, the variation in cloud radiative effect appears much larger in the observations than the model. To further understanding of radiative feedback processes involving water vapour and cloud, in is necessary to examine sub-monthly time-scales. Comparisons between the Met Office weather forecast model and Geostationary Earth Radiation Budget (GERB) data are currently in progress and illustrate the potential of this strategy.

1. INTRODUCTION

Satellite radiance measurements provide valuable information on the distribution and variability of clouds, water vapour and the Earth's radiative energy budget. Using this information to initialise, evaluate and improve global climate and weather forecast models is vital in reducing the uncertainty in predictions. The following paper shows some examples in which data from satellite instruments and reanalyses are used to evaluate model simulations and understand radiative feedback processes.

2. SAMPLING DIFFERENCES

In evaluating models using satellite data, it is vital to first ensure that similar physical quantities are being compared. For example, outgoing longwave radiation (OLR) estimated from satellite instruments is readily comparable with the corresponding model diagnostic. It is also important that the spatial and temporal sampling is consistent. For example, the spatial and temporal sampling of clear-sky OLR (OLRc) in models and satellite data are often inconsistent (e.g., Allan et al. 2003). This is because satellite estimates of OLRc can only be made for cloud-free regions while models can compute OLRc diagnostically for all grid points at all times.

Further difficulties arise when using regional measurements of radiative fluxes or humidity to evaluate model processes. This is because locally, model errors are highly sensitive to small positional errors in the large-scale circulation. This is illustrated using model simulations from the Hadley Centre climate model, HadAM3 (see Allan et al. 2003 for details), with OLR data from the Clouds and the Earth's Radiant Energy System (CERES; e.g., Wielicki et al. 2002) and 500 hPa vertical motion (ω) products from the ECMWF 40-year reanalysis (ERA-40; Uppala et al. 2005). Figure 1 shows the positive spatial correlation between model OLR error and model ω error over the tropical Pacific for April 1998.

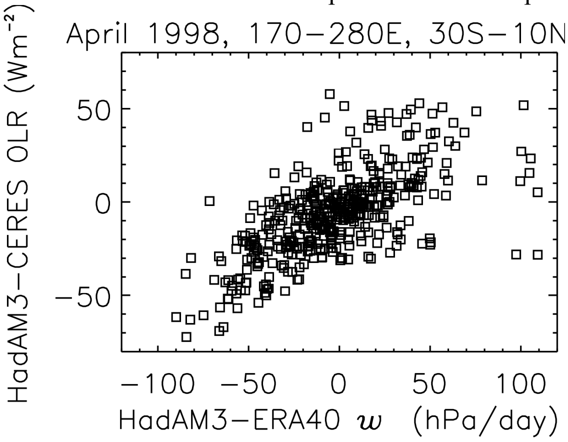

Figure 1: Errors in model OLR (HadAM3 minus CERES) as a function of model vertical motion error at 500 hPa (HadAM3 minus ERA40) over the tropical Pacific (170-280^{o}E, 30^{o}S-10^{o}N) for April 1998.

While errors in atmospheric circulation are important for local predictions of atmospheric conditions, these positional errors are not generally crucial to the radiative feedback processes operating in models. It is therefore of great value to remove this effect. To address this issue the adopted approach has generally been either to (i) analyse spatial averages over entire circulation systems (e.g., Soden et al. 2002; Allan and Slingo 2002) or (ii) to examine dynamical regimes using vertical motion fields from reanalyses (e.g., Bony et al. 2004; Ringer and Allan 2004). In the following two sections we adopt approach (i) to diagnose large-scale radiative feedback processes involving water vapour and cloud.

3. WATER VAPOUR FEEDBACK

The radiative properties of water vapour dictate that absorption of radiation increases with the logarithm of water vapour concentration over much of the longwave spectrum. Additionally, the Clausius-Clapeyron equations describe a quasi-exponential increase in the water vapour holding capacity of the atmosphere as temperatures rise. Combined, these theoretical constraints predict a strongly positive water vapour feedback providing that the water vapour concentration remains roughly at a constant fraction of the saturation specific humidity (unchanging relative humidity, RH).

The largest uncertainty in water vapour feedback is arguably related to how tightly the relationship between humidity and temperature is controlled by thermodynamics. Recent evidence from models and satellite data suggest that water vapour variations are strongly constrained by constant RH (e.g., Wentz and Schabel 2000; Soden et al. 2002; Allan et al. 2003). However, it remains vital to verify the invariant nature of global mean RH in models.

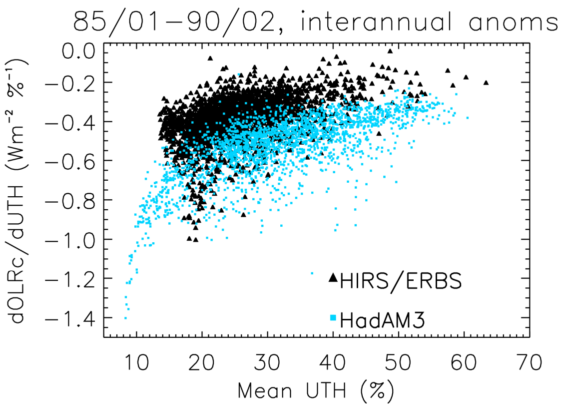

Figure 2: Sensitivity of clear-sky OLR to interannual changes in upper tropospheric humidity (UTH) as a function of mean UTH for a model (HadAM3) and combination of satellite data (ERBS and HIRS).

It is also important that models correctly simulate relationships between water vapour, cloud and radiation. For example, Figure 2 shows simulations and observations of the sensitivity of OLRc to upper tropospheric RH (UTH) as a function of mean UTH. The satellite measurements were made by the Earth Radiation Budget Satellite (ERBS) scanner (e.g., see Wielicki et al. 2002) and the High Resolution Infrared Sounder (HIRS) instrument (e.g., see Allan et al. 2003). The sensitivity was calculated at each grid-point for the region 30^{o}S-30^{o}N using interannual monthly anomalies relative to a seasonal climatology. Both model and satellite data show a more strongly negative sensitivity of OLRc to changes in UTH for low humidity regions. The HadAM3 model appears to produce larger magnitude sensitivity for most grid-points. Sampling inconsistency between the ERBS and HIRS measurements may explain the tendency for a larger spread in dOLRc/dUTH for a given UTH. It is unclear why the observed UTH does not display values below 13%. Measurement error relating to calibration and orbit drift are also likely to influence the comparisons, despite careful calibration of the HIRS record. Further work is required to extend these analyses to evaluate regional radiative feedbacks involving water vapour and other components of the hydrological cycle including cloud and precipitation.

4. CHANGES IN LOW-LATITUDE RADIATION BUDGET AND CLOUDINESS

Crucial to the evaluation of radiative feedback simulated by models is the monitoring of the Earth's radiation budget at the top of the atmosphere. Figure 3 displays monthly variations in components of the low latitude radiative energy balance for the HadAM3 model (black) and satellite data (grey lines and symbols). The observations comprise data from ERBS (1985-1990), ScaRaB (1994/5) and CERES (1998) which are described in Wielicki et al. (2002) and references therein. Consistent with the previous section dealing with water vapour feedback, OLRc simulated by the HadAM3 model appears broadly consistent with the variation observed using a variety of satellite instruments (Fig. 3a). However, CERES OLRc is up to 2 Wm^{-2} larger than model values during summer 1998; this primarily results from differences over land regions and may relate to errors in model land surface temperature.

Also shown in Fig. 3a is the model all-sky OLR (dashed line). This variability is almost identical to the clear-sky variability indicating that, for the low-latitude mean, changes in the longwave radiation budget relating to variations in cloudiness are small. Comparing the all-sky OLR (Fig. 3b) and the all-sky reflected shortwave radiation (RSW) however (Fig. 3c) indicates that the decadal changes observed by the satellite data are much larger than simulated by the models (Wielicki et al. 2002).

The satellite data suggests a reduction in cloud radiative effect from the 1980s to the 1990s, which is not reproduced by the model. Although it is possible the data is in error, the agreement between a number of independent satellite instruments (Wielicki et al. 2002) and the differing responses of clear-sky and cloudy-sky OLR on the same scanning instruments suggests that the changes are real. The ERBS non-scanner data employed is similar to the data presented in Wielicki et al. (2002) but has been corrected for errors relating to diurnal aliasing in the seasonal cycle and orbital degradation (T. Wong pers. comm.).

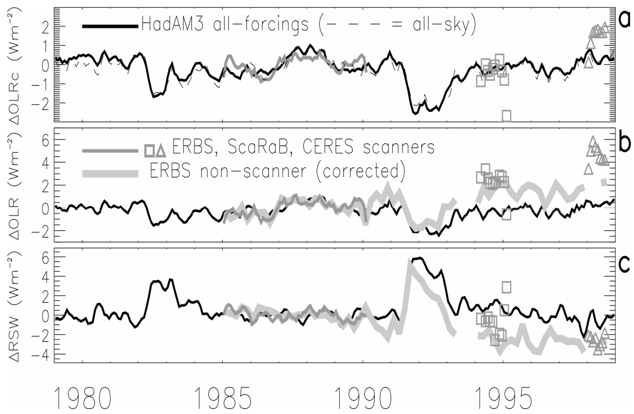

Figure 3: Time series of 40°S-40°N mean (a) clear-sky OLR, (b) OLR and (c) RSW anomalies with respect to the 1985-1989 mean seasonal climatology. Bold line denotes HadAM3 while grey lines and symbols represent satellite observations (see also Allan and Slingo 2002; Wielicki et al. 2002).

The reason for the differing changes in low-latitude cloudiness between models and data remain unclear. While monthly or longer averages are useful for monitoring large-scale changes in clouds, water vapour and the Earth's radiation budget, it is difficult to relate these variations to the physical processes generally operating on much shorter time-scales. It is therefore important to assess the performance of models on time-scales ranging from the model time-step up to hours and days. During these time-scales, model parametrizations are directly contributing to the evolving processes important for weather forecasts and climate prediction. The next section presents preliminary work comparing the Met Office forecast model with new geostationary satellite data on such time-scales.

5. EVALUATION OF AN NWP MODEL USING GEOSTATIONARY EARTH RADIATION BUDGET (GERB) DATA

New radiative flux data from the GERB instrument on the Meteosat-8 satellite is being exploited in comparisons with the Met Office forecast model. The GERB instrument measures broadband radiances, which are converted to fluxes using angular dependence models. These measurements contribute to data products every 15 minutes at a sub-satellite resolution of about 40 km, covering the African/Atlantic hemisphere. For further details of the instruments and preliminary validation results, see Harries et al. (2005).

GERB observations of OLR and RSW are being routinely accessed from the Royal Meteorological Institute of Belgium (RMIB) and compared with model simulations based on the forecast analysis at 00, 06, 12 and 18 hours UTC. These comparisons are displayed at http://www.nerc-essc.ac.uk/~rpa/GERB/gerb.html and the data stored for further analysis. The methodology, first results and validation of GERB clear-sky fluxes over the ocean are described in Allan et al. (2005).

Figure 4 shows an example comparison of GERB and model albedo (RSW normalised by the calculated incoming solar radiation) for 12 UTC, 27 October 2004. The bright regions indicate thick cloud or bright surfaces, such as the Sahara desert. Dark regions of low albedo correspond with clear-sky ocean regions. Pole-ward from the tropics, the distribution of cloud, relating to large-scale mid-latitude weather systems, appears well simulated by the model. Cloud data is not assimilated as part of the model initialisation (or analysis). However, the large-scale atmospheric dynamics are well constrained by the model assimilation system which utilises observed variables such as water vapour, temperature and wind-fields to produce a reasonable distribution of humidity. The model cloud parametrizations convert this information into realistic cloud fields.

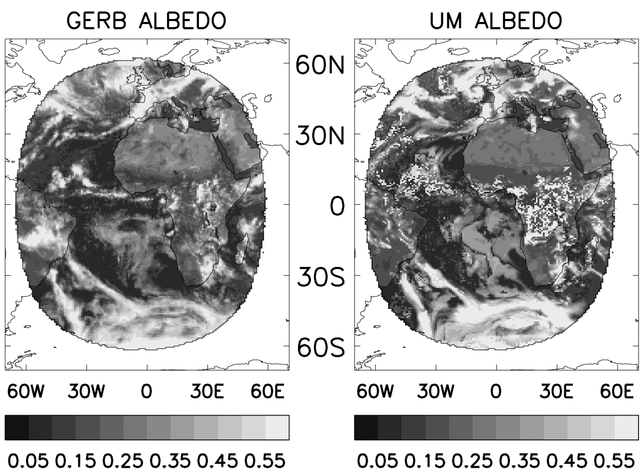

Figure 4: Shortwave albedo measured by GERB satellite data (left) and simulated by the Met Office forecast model (right) for 27 October 2004, 1200 UTC.

Over lower latitudes, errors in surface albedo are apparent over the Sahara, while errors in cloud-related albedo are present over Brazil (the model underestimates cloud cover) over tropical Africa (the amount and spatial variation in cloud cover is overestimated by the model) and over the southeast Atlantic marine stratocumulus region (the model albedo is too large). There is also a tendency for simulated convection to lack the organisation shown in the GERB observations. Further model evaluation using GERB data is currently underway. It is planned to use the high temporal resolution of the Meteosat-8 data in evaluation of the model by conducting numerical forecast experiments that explore the sensitivity of the model simulations to changes in surface properties and new physical parametrizations. It is also planned to use the GERB data, in combination with narrow-band radiance data from the SEVIRI instrument, also onboard Meteosat-8, in studies of water vapour and cloud radiative processes (e.g., Futyan et al. 2004) and aerosol (e.g., Haywood et al. 2005).

6. CONCLUSIONS

Satellite radiance measurements provide valuable information on clouds, water vapour, aerosol and surface properties that are vital in evaluating and improving weather and climate prediction models. It is important to ensure that the observed quantity and its spatial and temporal sampling are consistent with corresponding model diagnostics in such comparisons between models and data. It is also informative to separate model errors relating to positional errors in the large-scale atmospheric circulation from the errors relating to physical processes (e.g., Bony et al. 2004), although errors in physical processes (e.g. water vapor transport or convection) can also lead to positional errors.

The large-scale variation in water vapour and clear-sky radiation appears consistent between models and satellite data, suggesting that water vapour feedback processes are well represented by such models. However, this is not the case for the radiative effect of cloud, which exhibits greater variability in the satellite data compared to model simulations. The reasons for this discrepancy are not yet clear (Wielicki et al. 2002).

A strategy to more closely relate radiative feedbacks involving water vapour and other variables such as cloud, precipitation and aerosols is described. Analyses from the Met Office forecast model are compared with instantaneous geostationary broadband radiative flux data from the GERB instrument. These data are preliminary and currently under validation. However, initial comparisons suggest this approach may elucidate radiative forcing and feedback processes on the time-scales at which the model parametrizations are directly contributing to the evolving forecasts, thereby enabling model improvement.

ACKNOWLEDGMENTS

This work was funded through the NERC/Met Office Connect-B grant NER/D/S/2002/00412. The input and support of Tony Slingo is gratefully acknowledged. Thanks also to the SINERGEE project collaborators at the Met Office and the GERB International Science Team, in particular colleagues at Imperial College and also the Royal Meteorological Institute of Belgium, who process the GERB data. The ERBS and CERES data were retrieved from the NASA Langley DAAC, the ERA-40 data was obtained from the ECMWF, the ScaRaB data was taken from the Centre National d'Etudes Spatiales, Toulouse and the HIRS data was provided by Darren Jackson.

REFERENCES

Allan, R.P. and A. Slingo, 2002: Can current climate forcings explain the spatial and temporal signatures of decadal OLR variations?, Geophys. Res. Lett., 29(7), 1141, doi:10.1029/2001GL014620

Allan, R.P., M.A. Ringer, and A. Slingo, 2003: Evaluation of moisture in the Hadley Centre Climate Model using simulations of HIRS water vapour channel radiances, Quarterly Journal of Royal Met. Soc., 129, 3371-3389.

Allan, R.P., A. Slingo, S.F. Milton and I. Culverwell, 2005: Exploitation of geostationary Earth radiation budget data using simulations from a numerical weather prediction model: Methodology and data validation, *J. Geophys. Res., in press.*

Bony, S., J.-L. Dufresne, H. Le Treut, J.J. Morcrette and C.A. Senior, 2004: On dynamical and thermodynamical components of cloud changes, Clim. Dyn., 22, 71-86

Futyan, J.M., J.E. Russell and J.E. Harries, 2004: Cloud Radiative Forcing in Pacific, African, and Atlantic Tropical Convective Regions. *J. Climate,* 17, 3192–3202.

Harries, J.E. and co-authors, 2005: The Geostationary Earth Radiation Budget (GERB) Experiment, *Bull. Amer. Meteorol. Soc, in press.*

Haywood, J.M., R.P. Allan, I. Culverwell, A. Slingo, S.F. Milton, J.M. Edwards and N. Clerbaux, 2005: Can desert dust explain the outgoing longwave radiation anomaly over the Sahara during July 2003? *J. Geophys. Res.,* 110, D05105, doi:10.1029/ 2004JD005232.

Ringer, M.A. and R.P. Allan, 2004: Evaluating climate model simulations of tropical cloud *Tellus,* 56A, 308-327.

Soden, B.J., R.T. Wetherald, G.L. Stenchikov and A. Robock, 2002: Global cooling after the eruption of Mount Pinatubo: a test of climate feedback by water vapor, *Science,* 296, 727-730

Uppala, S. M. and co-authors, 2005: The ERA-40 Re-analysis, submitted to *Q. J. Roy. Meteorol. Soc.*

Wentz, F.J. and M. Schabel, 2000: Precise climate monitoring using complementary satellite data sets, *Nature,* 403, 414-416

Wielicki, B.A., T. M. Wong, R. P. Allan, A. Slingo, J. T. Kiehl, B. J. Soden, C. T. Gordon, A. J. Miller, S.-K. Yang, D. A. Randall, F. Robertson, J. Susskind and H. Jacobowitz, 2002: Evidence for large decadal variability in the tropical mean radiative energy budget, *Science,* 295, 841-844.