ON THE SCIENCE OF A SPACE-BORNE CLOUD RADAR

Graeme L Stephens[*]
Department of Atmospheric Science
Colorado State Universit

1. INTRODUCTION

One of the most conspicuous features of the Earth when viewed from space is the ever-changing distribution of clouds. Clouds tend to be organized into large-scale systems controlled by the large-scale characteristics of the atmospheric circulation. The movement of the large coherent cloud features in turn trace out the patterns of these circulation features.

These cloud systems also exert an enormous influence on our weather and climate. In addition to their key role in the atmospheric hydrological cycle, they dominate the energy budget of the planet through their effect on the Earth's solar and thermal radiation budgets. Clouds provide a tendency to cool the Earth by reflecting sunlight back to space and simultaneously warm the Earth by trapping thermal radiation emitted by the surface and lower atmosphere. By modulating the pole-to-equator variations of both solar insolation, and radiation emitted to space, clouds provide a fundamental drive for the global circulations of the atmosphere and oceans.

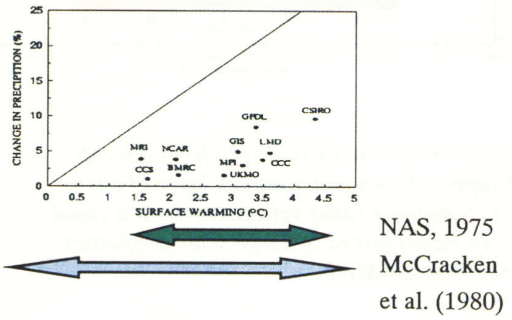

Fig. 1 The spread in the prediction of global warming by current climate models compared to the range of uncertainty derived from earlier studies

Because of the profound influence of clouds on the Earth's radiation budget, even small changes in their abundance or distribution could alter the climate response associated with changes in greenhouse gases, anthropogenic aerosols, or other factors associated with global change. Predictions of global warming using climate models forced with a prescribed increase of atmospheric CO2 are uncertain (Fig. 1) and the range of uncertainty has not substantially changed over the past two decades. One of the main reasons for this uncertainty arises from the difficulties in adequately representing clouds and their radiative properties in climate models and the subsequent effects of cloud feedbacks (e.g. Cess et al., 1989; Senior and Mitchell, 1993).

2. CLOUD-CLIMATE FEEDBACK

The atmospheric circulation imposes is a large-scale control on clouds in the sense that it governs where and when clouds form. The heating of the atmosphere and surface induced by clouds also affect the atmospheric circulation. The cloud feedbacks that are a source of the noted uncertainty of climate model predictions is represented by the connection between cloudiness, heating and circulation in the form of a complex feedback loop (Fig. 2) that requires a deeper understanding than presently exists.

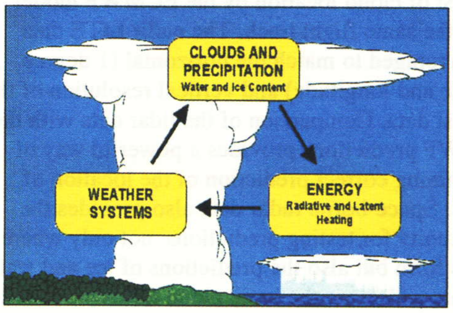

Fig.2 The main elements of cloud feedback emphasizing the connection between atmospheric circulation, cloud formation and radiative heating

Global cloud radar data to become available with the launch of the CloudSat mission (Stephens et al., 2000) as well as to be provided by the proposed ATMOS-B and ERM missions will furnish data needed to evaluate and improve the way clouds are parameterized in global models, thereby contributing to better predictions of clouds and thus ultimately to the poorly understood cloud-climate feedback problem. The key missing data not obtainable from current satellite measurement systems, include:

- vertical profiles of cloud occurrence
- vertical profiles of cloud liquid water
- vertical profiles of cloud ice water content
- precipitation (solid and liquid) occurrence in relation to the above

- cloud optical properties (when radar data are combined with other sensor data).

This information is required to evaluate the connection between the dynamics resolved by global models and cloudiness predicted by them, the association between clouds and the radiative heating of the atmosphere and the link back to the circulation. The information that can also be extracted from space-borne radar data, especially when combined with other sensor information, is a valuable source of information both for testing and promoting new methods of observing clouds.

3. EVALUATING MODELS

An important step toward developing the necessary understanding of cloud feedback is the quantitative evaluation of the cloud products derived from NWP models. Such an evaluation of the ECMWF forecast model is an ongoing activity (e.g. Jakob, 1999; Miller et al., 1999). Figure 3 provides an example of the use of simple cloud masking profile information in the evaluation of cloud prediction by a weather forecast model. In this example, the lower panel shows Orbit 124 of the LIdar in space Technology Experiment (LITE, Winker et al., 1996) flown on the Space Shuttle, matched to within 30 minutes of the ECMWF prediction. The upper shows a 24-hour forecast of cloud location by the ECMWF model along the same flight track. The nadir LITE data were averaged to match the horizontal (1 degree latitude and longitude) and vertical resolution of the forecast data. Comparison of the lidar data with the ECMWF predictions provides a powerful way of determining correct prediction of the location of clouds. Space-borne radar data also provides the opportunity for testing predictions not only where clouds form but also the predictions of ice and water contents which are the basic cloud fields predicted by models.

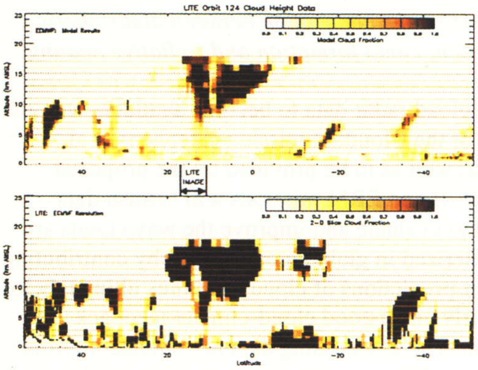

Fig. 3 Comparison of cloud location (by layer) predicted by ECMWF (upper) and observed by LITE (lower) along portion of orbit 124 (Miller et al., 1999)

Another important application of the space-borne cloud radar is as a tool to evaluate predictions of cloud properties derived from cloud resolving models. In this way, such data are a valuable resource in the evaluation of parameterizations of cloud processes.

An example of this particular application using the data obtained from an airborne cloud radar is provided in Fig. 4 in the form of a vertical cross-section of radar reflectivity obtained along the flight track of the aircraft . The particular example corresponds to the case of a single layer of cirrus cloud observed on the 30th of April 1999 west of Kuaui, Hawaii (Stephens et al., 2000). These observations are compared to simulated observations derived from cloud data obtained from both a cloud resolving model and the forecast model of the European Centre for Medium range Forecasting (ECMWF).

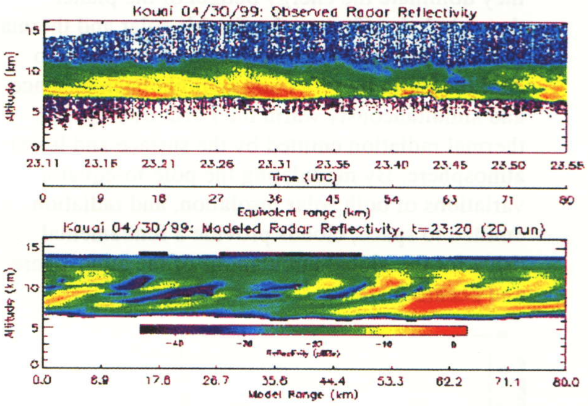

Fig. 4 Radar reflectivity observed from aircraft radar (upper) flown under a thick layer of cirrus. (Lower) Simulated radar reflectivity from a cloud resolving model forced by large scale properties obtained from ECMWF

The radar measurements indicate a relatively deep layer of cirrus between approximately 10-14 km especially after 2300 hrs UTC. The optical depths retrieved from both GOES image data suggests that the cloud varied in its optical thickness up to a maximum of about 4 over the thickest portions of the cloud during the period from 2300-2400 UTC. Radar reflectivity cross-sections simulated from the ice-water content obtained from time integrations of a two dimensional cloud resolving model are also shown. The radar reflectivity-ice water content relation of Sassen and Liao (1994) were employed to convert the model ice water contents to equivalent radar measured quantities. The cloud resolving model used to simulate the cirrus ice water content has full dynamics, radiation and bulk microphysics and its heritage is the Regional Atmospheric Modelling System (RAMS, Walko et al., 1996). The model was forced with the environmental profiles of temperature, moisture and horizontal winds obtained from the 24 hr forecast provided by the ECMWF.

It is not expected that the model simulations of the cloud variability should match the observations in any real quantitative detail. There are a number of reasons why the mesoscale structure the predicted by the cloud model differs from the observed cloud. The forcing applied in the model is homogeneous and lacks any meso-scale structure, the model cloud is two dimensional and the model cross-section shown is not directly comparable to the measured cross-section obtained from the aircraft data. More appropriate is the comparison of the statistics of the model fields as shown in Fig. 5. Sown are reflectivity profiles averaged along portion of the flight track and compared to the equivalent domain averaged reflectivity derived from the cloud ice water contents as well as the simulated observations derived from the ECMWF 24 hour forecast ice water content field. The comparisons reveal a remarkable degree of similarity between model and observation.

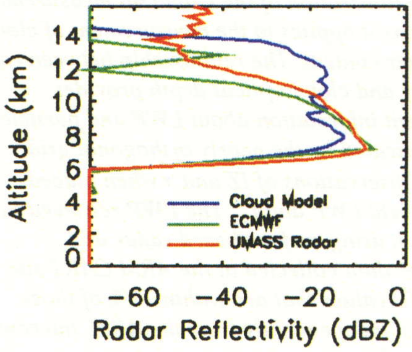

Fig. 5 Simulated radar reflectivity profiles averaged over the domain of a cloud resolving model, and averaged over a portion of an aircraft flight leg compared to the areal mean profile deduced from ECMWF forecast clouds

4. CONNECTING CLOUDS AND RADIATION

Cloud information derived from cloud profiling radars provides unique insight on the effect of clouds on the radiation budget of the atmosphere and surface. It is convenient to view the connection between clouds and radiation in two different ways - one view explores the relation between cloud properties and the fluxes at the atmospheric boundaries. The second view requires an understanding of the absorption within the atmosphere and its relation to cloud properties.

Figures 6a and b offer some sense of the key issues that define the relationships suggested under these views. In Fig 6a, the albedo of clouds derived from ERBE data in the manner discussed by Stephens and Greenwald (1991) is plotted as a function of the cloud liquid water path (LWP) deduced from coincident satellite microwave radiometer data. The relationship shown is compared to that predicted by simple theory given some assumption about the cloud particle sizes. Testing these relationships in this way is important since these tests involve parameters directly predicted by models (i.e. LWP) with radiative properties that derive from parameterizations of cloud optical properties and radiative transfer. Current measurement systems cannot unambiguously test model parameterizations because the observations generally do not exist that provide simultaneous cloud optical properties, cloud water contents and cloud radiative properties. The ability of a cloud radar to derive cloud water content, and when combined with other sensors, cloud optical properties provides an important step forward in reducing current ambiguities.

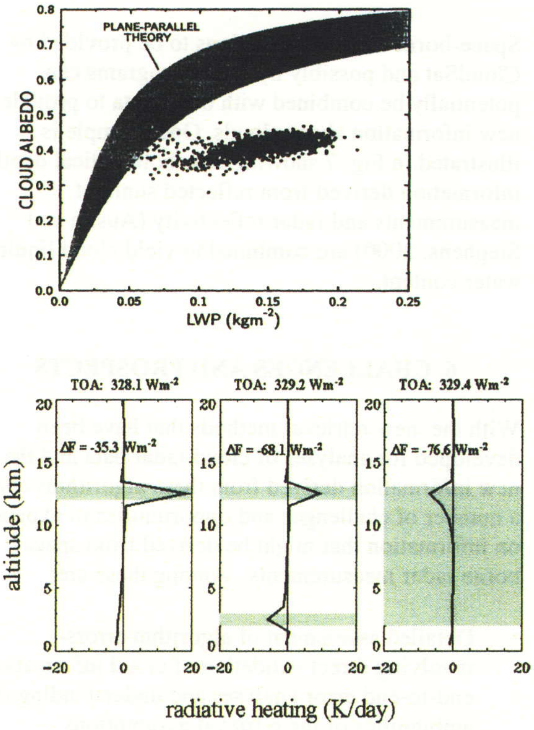

Fig 6 a (upper) showing the relationship between cloud liquid water path and cloud albedo as deduced from satellite observations compared to model relationships.Fig. 6 b(lower) the column cooling of the atmosphere ΔF and the related profiles of radiative heating for three different cloud configurations.

Fig. 6b provides a slightly different perspective showing the radiative heating profile and the net radiative column divergence (in W.m^{-2}) for three different cloud configurations. The total column absorption is altered by a factor of two depending on the vertical configuration of clouds despite the fact that the total radiation leaving the atmosphere (sum of OLR and solar reflection) is essentially the same. The in-atmosphere heating thus depends substantially on how clouds are structures in the vertical.

These two examples underscore the key to improving our understanding of how clouds affect radiation. On the one hand the optical properties of clouds and the association of these properties to cloud microphysics is important. On the other hand, the geometric organization of clouds is a governing factor. The unique attribute of a cloud radar is that it provides both an unambiguous geometric view of cloud systems and also contains relevant bulk microphysical information.

5. PROMOTING NEW METHODS FOR OBSERVING CLOUDS

Space-borne radar observations to be provided by CloudSat and possibly by future programs can potentially be combined with other data to provide new information about clouds. One example is illustrated in Fig. 7 showing how both optical depth information derived from reflected sunlight measurements and radar reflectivity (Austin and Stephens, 2000) are combined to yield cloud liquid water content.

6. CHALLENGES AND PROSPECTS

With the new retrieval methods that have been developed for analyses of cloud radar data and the new information derived from these algorithms come a number of challenges and opportunities to expand on information that might be derived from space-borne radar measurements. Among these are:

- Detailed assessment of algorithm errors- involving direct validation of cloud information, end-to-end error analyses and understanding the ambiguities of the retrieval assumptions.
- Understanding the detection characteristics of the space-borne radar and the relation of these detection limits to cloud optical properties.

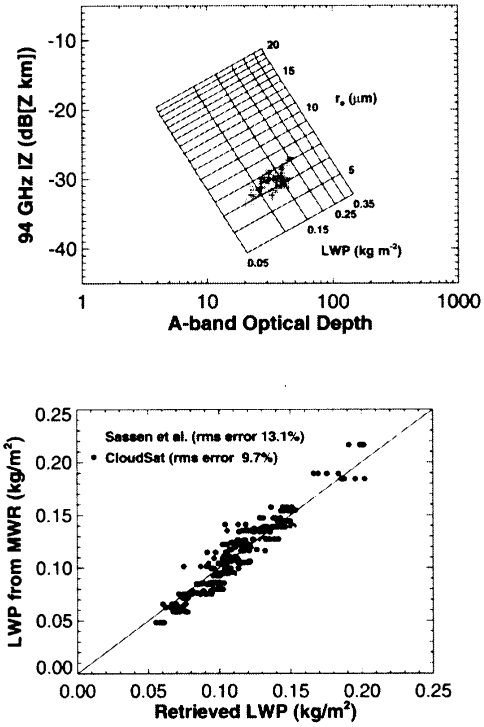

Fig. 7. An illustration of the CloudSat measurement approach as it applies to the measurement of cloud liquid water content. The relationship between radar reflectivity and cloud optical depth provides independent information about LWP and particle size as indicated by the nearly orthogonal grid (upper). Observations of IZ and τ when placed together yield LWP and r_e. The LWP retrieved in this fashion using surface based radar and radiometer data collected at the ARM CART site yields LWP values that are within 10% of those determined independently from the ARM microwave radiometer(lower).

- Expanding on cloud information contained in the radar measurements (such as precipitation, surface reflectivity properties among others)
- Develop necessary techniques that integrate cloud radar data with other sensor information so as to optimize the

Figure 8 illustrates a few of the issues noted. The upper panel of Fig 8 presents the same information as that shown in Fig 7 but for a cloud in which drizzle is detected. The presence of drizzle alters the basic relation between reflectivity and optical depth suggesting that it might be possible to identify the presence of drizzle. Retrieving liquid water contents under these circumstances remains a challenge. The second panel of Fig. 8 presents the airborne radar data discussed previously in relation to Figs. 4 and 5 contrasted against the cloud visible optical depth obtained from sensors flown coincidentally with the radar. These kind of observations provide a better understanding of the detection characteristics of the radar.

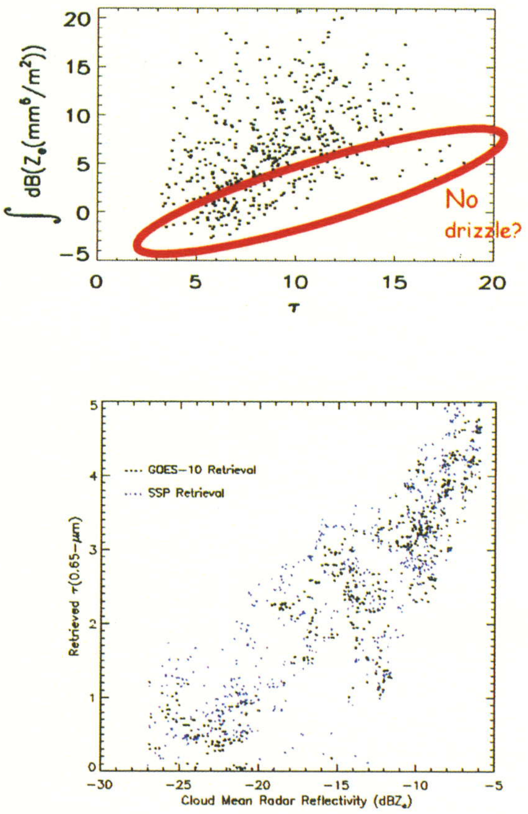

Fig. 8 The radar optical depth relationship derived from coincident measurements in low-level water clouds containing drizzle (Austin and Stephens, 2000). The lower panel is the visible optical depth-radar reflectivity as derived from coincident data obtained for the cirrus cloud layer discussed previously.

7. REFERENCES

Austin, R.T and G.L. Stephens, 2000;Retrieval of stratus cloud microphysical parameters from millimetric radar and visible optical depth, submitted to *J.Appl. Met.*

Cess, R. D., et al.,1989; Interpretation of cloud-climate feedback as produced by 14 atmospheric general circulation models. *Science*, 245, 513-515.

Jakob, C. 1999;

Miller, S. D., G.L. Stephens, and A.C.M. Beljaars 1999; A validation survey of the ECMWF cloud prognostic scheme using LITE. *Geophys. Res. Lett.* ,

Sassen K. and L. Liao, 1994; Investigation of relationships between Ka-band radar reflectivity and ice and liquid water contents, Atmospheric Research, 34(1-4): 231-248.

Senior, C. A. and J. F. B. Mitchell, 1993; Carbon dioxide and climate; The impact of cloud parameterization. *J. Clim.*, 6, 393-418.

Stephens, G.L. and T. Greenwald, 1991: part II

Stephens, G.L., et al., 2000; The Department of Energy's Atmospheric Radiation Measurement (ARM) Unmanned Aerospace Vehicle (UAV) Program, submitted to *Bull.Amer.Met.Soc.*

G. L. Stephens, D. G.Vane, and S. J. Walter, 2000; The CloudSat mission: A new dimension to space based observations of clouds.

Walko, R. L. Cotton, W. R. Meyers, M. P. Harrington, J. Y. 1996; New RAMS cloud microphysics parameterization. Part I: The single-moment scheme. *Atmospheric Research*, 38(1-4): 29-62.

Winker, D. M., R. H. Couch and M. P. McCormick, 1996; An overview of LITE: NASA's Lidar In-space Technology Experiment. Proc. IEEE, 84,164-180.