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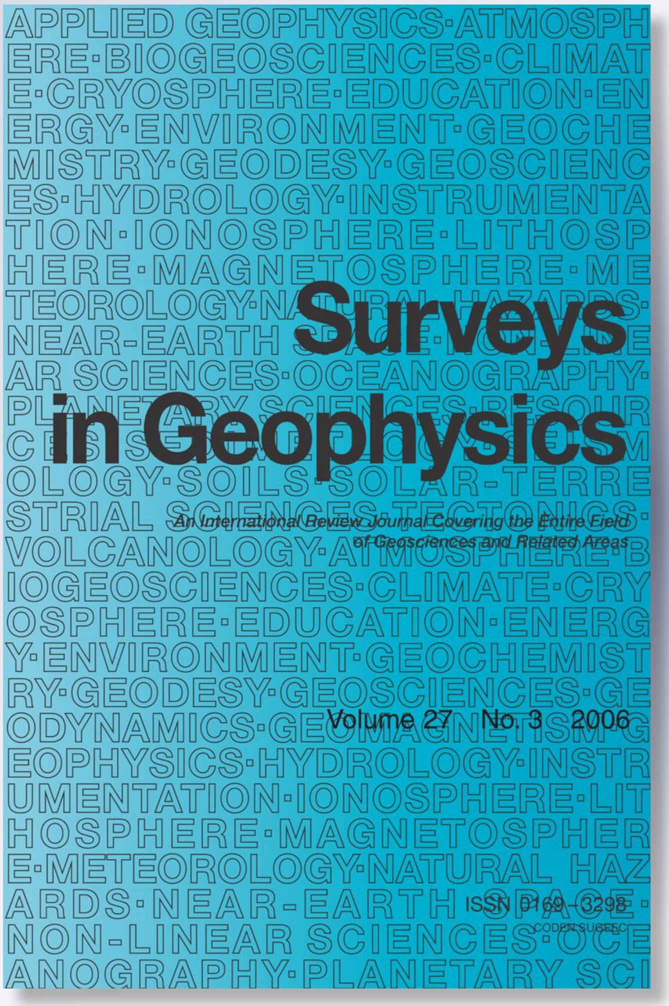

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Abstract This paper presents an overview of discussions during the *Cloud's Role* session at the *Observing and Modelling Earth's Energy Flows Workshop*. N. Loeb and B. Soden convened this session including 10 presentations by B. Stevens, B. Wielicki, G. Stephens, A. Clement, K. Sassen, D. Hartmann, T. Andrews, A. Del Genio, H. Barker, and M. Sugi addressing critical aspects of the role of clouds in modulating Earth energy flows. Presentation topics covered a diverse range of areas from cloud microphysics and dynamics, cloud radiative transfer, and the role of clouds in large-scale atmospheric circulations patterns in both observations and atmospheric models. The presentations and discussions, summarized below, are organized around several key questions raised during the session. (1) What is the best way to evaluate clouds in climate models? (2) How well do models need to represent clouds to be acceptable for making climate predictions? (3) What are the largest uncertainties in clouds? (4) How can these uncertainties be reduced? (5) What new observations are needed to address these problems? Answers to these critical questions are the topics of ongoing research and will guide the future direction of this area of research.

Keywords Clouds · Cloud feedback · Cloud radiative forcing · Cloud uncertainties · Model cloud evaluation

1 Introduction

Radiation emanating from the Sun provides energy for all Earth processes. Earth system energy is found in the fast moving winds of the jet streams, in the enormous latent heat release in hurricanes, and in the vibrations of molecules located in the deep ocean. The manner in which energy is distributed throughout the Earth system affects global temperature, precipitation, and wind patterns. Tracking and modeling Earth's energy flows are thus necessary for understanding climate.

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Clouds are a critical component of the climate system because they are a major modulator of energy flows through the Earth system. Clouds interact with solar and terrestrial radiative energy flows through reflection, absorption, and emission processes. The influence of clouds on solar and terrestrial radiative fluxes is traditionally defined as the difference between total- and clear-sky broadband fluxes, called the shortwave (SW) and longwave (LW) cloud radiative forcing (CRF), respectively (e.g., Ramanathan et al. 1989; Chen et al. 2000; Stephens 2005). The SW CRF quantifies the enhanced reflection of solar radiation, and removal of energy from the system, due to clouds with respect to clear sky. The LW CRF quantifies the reduction of energy leaving the system through LW emission to space by clouds with respect to clear sky. The Net top-of-atmosphere (TOA) cloud influence (Net CRF) is measured to be -20 W m^{-2} (Loeb et al. 2009) from Clouds and Earth's Radiant Energy System (CERES) observations, indicating an integrated cooling influence by clouds. Additionally, clouds influence Earth energy flows by acting as sources of latent heat and precipitation. Under equilibrium conditions, latent heating of the atmosphere by condensation within clouds and the sensible heating by surface fluxes must balance the net radiative cooling of the atmosphere by solar energy absorption and infrared energy emission and absorption. This condition provides an energetic constraint on the hydrologic cycle response to climate change, which couples the latent heating and atmospheric radiative cooling responses (Stephens and Ellis 2008). Further, vertical motion within clouds, especially deep convection, transports heat and momentum upward contributing to planetary-scale circulations, e.g., Hadley Circulation and the Madden Julian Oscillation (Hendon and Woodberry 1993). Clouds influence many facets of Earth energy flows and must be accurately represented in climate models to obtain reliable climate change projections.

General Circulation Model (GCM) projections of the Earth system response to an external climate forcing are fraught with uncertainty due to differences in the predicted cloud response. Forced with a doubling of CO_2, state-of-the-art GCMs exhibit a wide range of equilibrium climate sensitivities: ranging from +2.0 to larger than +4.5 K (Solomon et al. 2007). Most of this spread in climate sensitivity is due to climate feedback differences: temperature, water vapor, clouds, and surface albedo. Cloud feedbacks are considered the largest contributor to inter-model spread in climate sensitivity (Cess et al. 1990; Stephens 2005, Soden and Held 2006; Bony et al. 2006; Randall et al. 2007; Dufrense and Bony 2008). While all cloud types contribute to cloud feedback and significant uncertainties exist in all cloud processes (Stephens 2005), subtropical, marine boundary layer clouds contribute most significantly to the inter-model spread in cloud feedback (Bony and Dufresne 2005; Stephens 2005). As a result, all cloud-related processes, and specifically those important in subtropical marine boundary layer cloud regimes, must be better understood to reduce uncertainty in climate sensitivity.

Recent work suggests an additional cause of cloud-related climate sensitivity uncertainty, namely cloud forcing, cloud adjustment, or "fast feedback." Gregory et al. (2004) suggest that the significant inter-model climate sensitivity differences may result from differences in the radiative forcing. These differences are postulated to stem from a direct system response to the CO_2 forcing that occurs on short timescales, less than 1 year, before any significant surface temperature response. The cloud forcing can therefore be separated from feedback based on timescale. Clouds are suggested to represent a significant portion of the direct response to the CO_2 forcing (Andrews and Forster 2008; Gregory and Webb 2008). Therefore, the majority of the cloud impact on climate change may be a forcing rather than a feedback (Gregory et al. 2004; Andrews and Forster 2008; Gregory and Webb 2008). Whether this interpretation is realistic or strictly a model artifact is yet to be determined.

Clouds pose a unique challenge due to the large range of time and space scales at which cloud processes occur, and the complexities associated with observing cloud processes. Clouds occur in a multitude of different forms with each type influencing Earth energy flows differently. Low clouds, stratocumulus, and cumulus contribute strongly to the negative Net CRF because SW CRF $\gg$ LW CRF (Hartmann and Doelling 1991; Stephens 2005). High clouds, cirrus, and cirrostratus possess a positive Net CRF because LW CRF $\gg$ SW CRF (Hartmann and Doelling 1991; Stephens 2005). The Net CRF of deep convective clouds, however, is near zero due to a cancelation between large SW reflection and reduction in LW emission to space, SW CRF $=$ LW CRF (Kiehl and Ramanathan 1990; Kiehl 1994). These different cloud forms also contribute differently to non-radiative energy flows: global latent heating and momentum transports. The vast range of time and space scales encompassed by cloud-related processes also contributes to the unique challenges of understanding clouds. Cloud processes occur on time scales from seconds to days and spatial scales from microns to thousands of kilometers. To account for sub-grid scale processes in GCMs, simplifying parameterizations are required, which adds considerable uncertainty in climate model simulations. An implicit assumption in parameterization is that a scale separation exists between resolved and unresolved processes such that the behavior of unresolved processes can be represented by resolved variables. In many cases, this assumption does not hold and the need to parameterize contributes to the unique challenge.

Lastly, complexities associated with cloud process observations are another component contributing to the challenge of understanding clouds. In situ microphysical cloud observations require expensive airborne instrumentation generally only operated in short duration field campaigns. This limits the ability to obtain statistical distributions of cloud process observations under a range of atmospheric conditions. However, one attempt has been made to organize an airborne instrumentation campaign focused on obtaining a representative statistical sample over an extended period of time (Vogelmann et al. 2008). Due to the limited nature of in situ cloud observations, most research studies use satellite cloud observations. Satellite platforms allow global sampling of clouds; however, the interpretation of measured radiances is required to analyze physical cloud properties (e.g., cloud cover, emission temperature, particle phase/size, and water path). To transform observed radiances into physical cloud properties requires assumptions about the atmospheric state and cloud microphysics that can lead to retrieval biases and influence scientific conclusions. As a result, the nature and complexity of cloud processes lead to difficulties in the quantitative characterization and observation of clouds making clouds a unique scientific challenge.

The purpose of the chapter is to assess the current state of cloud process understanding, identify modeling uncertainties in Earth energy flows associated with clouds, and to identify future observations that are necessary to reduce cloud-related uncertainties. Workshop presentations encompassed a variety of cloud observational and modeling challenges that will be discussed in the papers that follow. The remainder of this paper will summarize the various topics discussed at the workshop.

2 Discussion Summary

Participants raised several critical questions around which this discussion is organized. The topics discussed below address five questions that received the most discussion: (1) What is the best way to evaluate clouds in climate models? (2) How well do models need to represent clouds to be acceptable for making climate predictions? (3) What are the largest uncertainties in clouds? (4) How can these uncertainties be reduced? (5) What new observations are needed to address these problems?

2.1 What is the Best Way to Evaluate Clouds in Climate Models?

The question, how should GCMs be evaluated, received significant discussion. D. Hartmann and A. Clement presented model evaluation tools asserting that models must be tested against understood physics. The issue was raised, however, that climate models are routinely evaluated against observed mean state variables, which does not directly represent a test of model physics. The use of CRF for model evaluation provides insight into the model representation of cloud radiative characteristics and individual cloud regimes biases (e.g., Kiehl and Ramanathan 1990; Bony et al. 2004; Zhang et al. 2005). However, LW, SW, and Net CRFs are integrated quantities determined by convolving cloud optical properties and frequency of occurrence, which enables models to correctly simulate CRF due to compensating errors between cloud optical properties and frequency (e.g., Zhang et al. 2005). Such compensations are frequently found within GCMs, namely negative cloud frequency and positive cloud optical depth biases (e.g., Zhang et al. 2005). Therefore, direct evaluation of model cloud frequency and optical properties was recommended in discussion.

Satellite observations have proven useful for the identification of model cloud frequency of occurrence and optical property biases; however, due to different sampling and cloud definitions, this comparison is not straightforward. To address these inconsistencies, satellite instrument simulators have been employed in GCM simulations (e.g., Klein and Jakob 1999; Haynes et al. 2007). The International Satellite Cloud Climatology Project (ISCCP) satellite simulator (Klein and Jakob 1999) has been successfully used to evaluate climate models (Zhang et al. 2005; Williams and Webb 2009). Recent research has also extended the satellite simulator methodology to A-Train active lidar and radar remote sensors (e.g., Chepfer et al. 2010; Bodas-Salcedo et al. 2011). Discussion outlined the utility of the satellite simulator methodology for model cloud evaluation; however, further refinement is required (Mace et al. 2011).

Categorizing cloud properties by atmospheric dynamic and thermodynamic conditions is an effective manner to evaluate model cloud properties. This strategy is useful because cloud formation under different atmospheric conditions results in different cloud characteristics. Bony et al. (2004) and Bony and Dufresne (2005) illustrate this evaluation technique in the tropics using annual mean 500-hPa vertical velocity. Eitzen et al. (2008) and Eitzen et al. (2011) extended this approach to evaluate model cloud optical properties and radiative characteristics by applying a joint probability distribution methodology and dynamic and thermodynamic state diagnostics. Meeting participants acknowledged the usefulness of such evaluation techniques. A. Del Genio and H. Barker stressed the need to go beyond monthly or annual mean evaluation techniques and rigorously test model parameterizations on the timescale they operate.

A critical component of parameterization development and evaluation is accurate atmospheric state knowledge. R. Wood stated that large-scale weather reanalysis is inadequate for climate purposes. One identified example is the poor treatment for boundary layer clouds in weather reanalysis. Marine stratocumulus clouds are largely neglected in meteorological reanalysis because no “significant” weather occurs in these regions. These cloud regimes, however, are critical to climate. Participants agreed that improved atmospheric state information is required to improve cloud parameterizations, and that further work in this area is necessary.

To address question (1), the best evaluation tool is likely to depend on the goal of the model simulation. A metric that indicates skill at the global scale may not have the same significance at regional scales. Murphy et al. (2004) illustrated that cloud and radiation variables are the best discriminators between high and low sensitivity models. For climate change prediction purposes, the answer to question (1) must be tied to evaluation techniques that possess skill in discriminating between high and low climate sensitivity. The current generation Cloud Feedback Model Intercomparison Project 2 (CFMIP2) GCMs have implemented a full suite of satellite simulators, enabling the comprehensive GCM-observational comparisons of model cloud and radiative characteristics. This new wealth of information on GCM cloud and radiation quantities will undoubtedly shed light on relationships between clouds, radiation, and climate sensitivity. The search for GCM performance metrics relevant to climate sensitivity is an active and critical area of research.

2.2 How Well Do Models Need to Represent Clouds to Be Acceptable for Making Climate Predictions?

Directly related to methods of GCM cloud evaluation, B. Wielicki raised another question regarding cloud representation in climate models: when is a model's cloud representation good enough for climate change prediction? To answer this question, one could consider the use of root mean square error metrics for CRF, cloud occurrence, or cloud optical properties applied spatially. However, it is unknown whether these metrics are tied to climate sensitivity. B. Wielicki stated that a model's ability to reproduce the current mean climate state is not necessarily a good indicator of climate change prediction skill, but that decadal change is a skillful metric (Soden et al. 2008). A potential metric discussed in a presentation by A. Clement tests the ability of a model to reproduce the covariance of physically related variables, for example sea surface temperature and low cloud amount (Clement et al. 2009). An argument linking a variable covariance metric to climate sensitivity can be made considering that fundamental covariances between critical climate variables at monthly, seasonal, or annual time scales will likely shape longer time scale covariances the describe climate feedbacks. A seasonal covariance analysis has proved useful for the surface albedo feedback (Hall and Qu 2006); however, an observational link between cloud covariance and cloud feedback strength has not been shown. In pursuit of an observational quantity linked to cloud feedback strength, Dessler (2010) found that cloud feedbacks inferred from short-term TOA radiative flux variability, a single decade or El Nino, have almost no bearing on the long-term, climate scale cloud feedbacks. The fidelity with which GCMs must represent cloud processes to provide accurate climate change prediction is unknown, and more research is needed to address uncertainty in climate models.

2.3 What Uncertainties Exist in the Role of Clouds in Modulating Earth Energy Flows? How Can These Uncertainties Be Reduced?

Recent modeling studies have highlighted the need to better understand "fast feedback" in the climate system. "Fast feedback," also referred to as cloud adjustment or cloud forcing, is the direct response of clouds to a radiative forcing at time scales of less than a year. T. Andrews reviewed cloud adjustment in a presentation where he discussed a possible link with the carbon cycle through a physiological response by plants. Gregory et al. (2004) and Gregory and Webb (2008) illustrated this effect in a GCM using an instantaneous 4xCO_2

step forcing. Andrews and Forster (2008) have suggested that the inter-model cloud feedback spread may be misinterpreted as a spread in cloud adjustment. Expressed in workshop discussion by S. Schwartz, uncertainty exists in this concept stemming from the unrealistic step-function forcing applied to analyze the model cloud adjustment. However, Gregory and Webb (2008) show for one model that the cloud response is approximately linear in the forcing magnitude within methodological uncertainties. The result suggests that this model phenomenon behaves similarly under different forcing magnitudes and is likely to operate in smaller, more realistic CO_2 forcing scenarios. However, the question moving forward, discussed in the chapter by T. Andrews, is does this phenomenon occur in the Earth system or is this only a GCM phenomenon?

Low cloud feedback under anthropogenic climate change remains a significant source of inter-model spread in climate sensitivity stemming from uncertainties in model parameterizations that influence marine boundary layer clouds (Bony et al. 2004; Bony and Dufrense 2005; Stephens 2005; Bony et al. 2006; Randall et al. 2007). Additional uncertainty in these cloud regimes is due to the relationship between cloud albedo and mean cloud liquid water path (LWP). Stephens (2010) in a GEWEX newsletter summarized a model inconsistency with observations where subtropical boundary layer clouds are simulated too thick, which suggests a misrepresented cloud albedo feedback. The relationship between cloud albedo and LWP is nonlinear. Stephens (2010) illustrated that current generation climate models underestimate the sensitivity of cloud albedo to a small perturbation in LWP. This illustrates the need for cloud evaluation metrics that link directly to climate sensitivity.

Another significant uncertainty discussed in this session is how cloud–aerosol interactions change the influence of clouds on Earth energy flows. Cloud–aerosol interactions can significantly influence Earth energy flows by modulating the radiative energy budget through changes in cloud albedo and the hydrologic cycle by influencing precipitation and drizzle frequency (e.g., Rosenfeld 2006; Stevens and Feingold 2009). The major cloud–aerosol interactions are termed the first and second aerosol indirect effects, namely cloud albedo and cloud lifetime. Both of these effects can influence the CRF by altering the column albedo (more information is available in the chapter on *Aerosol Forcing*). The main point in the discussion, expressed by B. Stevens, G. Stephens, and R. Wood specifically, was that the aerosol–cloud indirect effects are a first-order cloud formation and cloud precipitation problem. One motivation for this statement is that aerosol indirect effects in models cannot be correct if cloud frequency is poorly simulated. G. Stephens noted in his presentation that recent A-train observations indicate a smaller global impact of aerosol indirect effects than in GCMs that include cloud–aerosol interactions, due to misrepresentations of large but compensating effects; this point is also made by Stevens and Feingold (2009). Further, G. Stephens demonstrated compelling evidence indicating that open cellular marine stratocumulus clouds produce a column brightening in the presence of shiptracks; however, closed cells do not. Future work in cloud–aerosol interactions from space will likely require satellite sampling that resolves cloud lifetime scale processes.

2.4 What New Observations are Needed to Address These Problems?

Meeting discussion expressed that current satellite observations are difficult to use for process studies due to temporal sampling limitations. R. Kahn identified aircraft campaigns as the best way to perform cloud process studies. However, A. Del Genio noted that a weakness of field campaigns is the short duration and limited domain. Meeting participants discussed that a potential way forward could be to design satellite or high altitude balloon missions capable of observing cloud processes. One possible future satellite observation strategy could be to launch a constellation of small satellites with the same measurement capabilities and observe the same location a small time interval apart. This observational strategy would enable the measurement of time tendency terms for cloud process studies from space and greatly enhance cloud statistics toward improving model parameterization.

The general consensus was that current satellite cloud observation technology is generally sufficient, while acknowledging that adding the capability of scanning active sensors would greatly enhance the ability to observe clouds from space. Because scanning active sensor technology is expensive, there must be a continued emphasis on the fusion of passive and active remote sensors (e.g., Kato et al. 2010). The current generation of active sensors provides accurate retrievals of cloud location, including top and base height, and optical properties but is unable to scan. Passive sensors scan and retrieve cloud properties over a larger volume; however, passive retrievals can suffer from biases in cloud location and cloud properties. All meeting participants agreed that given the current state of technology, the synergy between passive and active sensors is the best future path (e.g., A-Train, EarthCARE, and ACE).

Participants expressed a need for improved cloud data products accurate enough for use in long-term climate trend analysis. Current methodologies can result in time-dependent biases in cloud properties because of limitations in instrument accuracy and ancillary input sources needed to characterize atmospheric state and surface properties. Secondly, current satellite cloud data products are limited by the accuracy of the instruments. To better understand Earth's energy flows and the role of clouds in modulating these flows, the group discussion expressed the need for a climate observing and monitoring system to detect decadal time scale climate trends, particularly clouds. G. Stephens stated in his presentation that a climate observing strategy is likely required for future progress on cloud feedback. The capabilities of the current global observing system are limited by accuracy. Meeting participants generally agreed that a step forward would be to fly a high-accuracy, well-calibrated instrumentation package that provides a stable calibration standard for all satellite sensors, similar to the CLimate Absolute Radiance and REfractivity Observatory (CLARREO) concept proposed in the United States National Research Council Decadal Survey (NRC 2007). Research and planning are required to obtain cloud information capable of detecting trends in cloud properties that are critical to unraveling cloud feedback.

3 Summary

Understanding the role of clouds in modulating Earth's energy flows is a complicated and an extremely important endeavor. Outlined above are key discussion topics motivated by the central role clouds play in future climate change. The *Cloud's Role* session at the *Observing and Modelling Earth's Energy Flows Workshop* served to identify the key cloud-related uncertainties and to stimulate discussion on how to address these issues. Many aspects of the questions discussed above are unanswered and require further research. Resolving these problems will lead to improvements in our understanding of climate change, Earth energy flows, and the role of clouds. The subsections of this chapter will elucidate the critical role of clouds in modulating Earth energy flows from observational (K. Sassen and H. Barker) and modeling (T. Andrews, A. Del Genio, and M. Sugi) perspectives, assessing the current state of knowledge and providing perspectives on future directions.

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