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Evaluation of tropical cirrus cloud properties derived from ECMWF model output and ground based measurements over Nauru Island

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[1] Cirrus clouds play an important role both radiatively and dynamically in the tropics. Understanding the mechanisms responsible for the formation and persistence of tropical cirrus is an important step in accurately predicting cirrus in forecast and climate models. In this study, we compare ground-based measurements of cloud properties with those predicted by the ECMWF model at a location in the tropical western Pacific. Our comparisons of cloud height and optical depth over an 8 month time period indicate that the model and measurements agree well. The ECMWF model predicts cirrus anvils associated with deep convection during convectively active periods, and also isolated cirrus events that are influenced by large-scale vertical ascent. We also show through examination of an upper tropospheric cirrus case that the model produces tropospheric waves that appear to influence the morphology and maintenance of the cirrus layer. *INDEX TERMS:* 3374 Meteorology and Atmospheric Dynamics: Tropical meteorology; 3360 Meteorology and Atmospheric Dynamics: Remote sensing; 3337 Meteorology and Atmospheric Dynamics: Numerical modeling and data assimilation. **Citation:** Comstock, J. M., and C. Jakob (2004), Evaluation of tropical cirrus cloud properties derived from ECMWF model output and ground based measurements over Nauru Island, *Geophys. Res. Lett.*, *31*, L10106, doi:10.1029/2004GL019539.

1. Introduction

[2] Identifying the mechanisms responsible for the formation of cirrus clouds is important in understanding the role of cirrus in the tropical atmosphere. Thin cirrus clouds near the tropical tropopause transition layer (TTL) can have significant impacts on the radiative heating in the upper troposphere [*McFarquhar et al.*, 2000]. These clouds may also affect the transport of water vapor through the TTL into the stratosphere [*Rosenfield et al.*, 1998; *Sherwood*, 1999]. The ability of large-scale models to correctly simulate tropical cirrus occurrence is important in predicting the role of these clouds on climate. Climate models failure to properly simulate cloudiness in the tropics has been identified as a critical improvement needed for the accurate prediction of future climates [*Wielicki et al.*, 2002]. In this preliminary study, we explore the skill at which a large-scale forecast model predicts the presence of tropical cirrus. The motivation for this is twofold. First, assessing the model's ability to simulate the observed characteristics of tropical cirrus may identify important weaknesses in the model. Second, if the model exhibits sufficient skill in simulating these characteristics we might be able to use it as a tool for identifying and understanding cirrus formation mechanisms and large-scale features that are important in maintaining extensive cirrus sheets that persist in the tropics over long time periods. It is this understanding that is the ultimate aim of our work. In this study we compare ground based lidar and radar measurements of cirrus occurrence and optical properties obtained at the Department of Energy's Atmospheric Radiation Measurement [ARM; *Ackerman and Stokes*, 2003] site located on Nauru Island with those generated by the European Centre for Medium Range Weather Forecasts (ECMWF) model as a first step to assess the accuracy of a forecast model in predicting tropical cirrus.

[3] We first compare cloud height and visible optical depth τ derived from measurements and model simulations over an 8-month period. Second, we discuss the different cirrus types observed in the tropics and the dynamic processes that are responsible for their formation. Finally, we present a case study that illustrates the ability of the model to predict thin tropical cirrus.

2. Clouds in the ECMWF Model

[4] For comparison with ground based measurements, we use ECMWF model output, which has a 60 km horizontal resolution. A time series of hourly model variables are created using concatenated operational 12–35 hr forecasts for the grid point that includes the location of Nauru. The cloud parameterization is a fully prognostic cloud scheme [*Tiedtke*, 1993; *Jakob*, 2001] and includes a strong coupling between the convection and cloud scheme. Both cloud fraction and ice water content (IWC) have an explicit convective source.

[5] Over the period of study, several changes were made to the ECMWF model. First, the vertical resolution changed from 50 levels to 60 levels on 13 October 1999, with extra levels added primarily to the boundary layer. The ice cloud parameterization was also changed in October 1999. The initial cloud scheme had a single parameterization relating ice crystal fall velocity (V) to IWC. The new cloud scheme assumes the same V-IWC relationship for large particles (>100 μm), but for small particles (<100 μm) a zero fallspeed is assumed. These changes improved agreement

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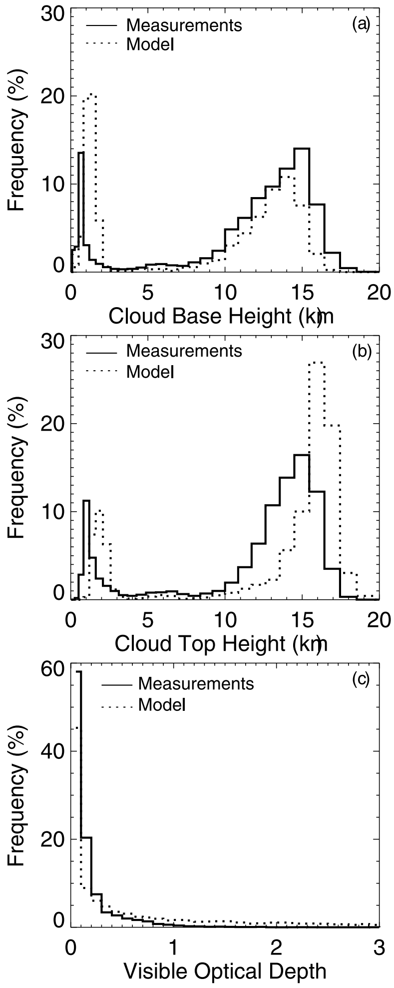

Figure 1. Composite statistics comparing measured and model cloud properties. (a) base height, (b) Cloud top height, and (c) high cloud visible optical depth.

between the modeled and measured surface radiative fluxes (not shown).

[6] The model produces a vertically varying profile of cloud fraction, thereby generating a number of different cloud situations within each model grid box. In order to sample this sub-grid scale variability, each grid box is subdivided into 100 sub-boxes to give 100 cloud configurations following an algorithm devised by *Jakob and Klein* [1999]. Each of the 100 sub-boxes is treated as an independent sample of both the cloud geometry (cloud base and top location) and optical thickness. Note that the IWC (or liquid water content LWC) is assumed the same in each cloudy sub-box for a given level so that differences in these parameters arise solely from the cloud cover variations with height by applying cloud overlap rules to each sub-box. The threshold value of condensate for the existence of a cloud in the model is 10^{-8} kg kg^{-1}. The model calculates τ using a relationship between ice water path (IWP) and effective radius [*Ebert and Curry*, 1992]. The latter is prescribed as a function of temperature. Cloud boundaries are identified by the presence of condensate (ice or water) in each atmospheric layer. The direct accounting for sub-grid scale variability alleviates some of the problems of comparing model output for a 60 km grid box with single point measurements, although some uncertainty remains.

3. Cloud Statistics

[7] In this study, we use the Active Remotely-Sensed Cloud Locations (ARSCL) algorithm [*Clothiaux et al.*, 2000] to obtain cloud boundaries. This algorithm has the benefit of combining both micropulse lidar [MPL; *Campbell et al.*, 2002] and millimeter cloud radar [MMCR; *Moran et al.*, 1998] observations to obtain complete cloud boundaries. This is particularly important in the tropics where high cirrus clouds near the tropical tropopause are below the detection limit of the MMCR because they are optically thin and likely consist of small ice crystals [*Comstock et al.*, 2002]. For cloud conditions when low level boundary layer clouds lie below cirrus layers, or optically thick anvil and middle level clouds, the MMCR provides better estimates of cirrus cloud top height because lidar is unable to penetrate through optically thick layers. During 1999 at Nauru, low clouds block high clouds approximately 11% of the time [*Comstock et al.*, 2002].

[8] ARSCL cloud boundary statistics between April and November 1999 are compared with cloud boundaries output from the ECMWF model. The cloud parameterization modifications mentioned above improve the representation of ice clouds in the ECMWF model; however, most of the time period of this study lies before the change was made. Therefore, we compensate for a model overestimation of high cirrus cloud amount by removing cloud occurrences when $\tau < 0.005$. This threshold was chosen by determining that 95% of clouds with $\tau < 0.01$ produced by the ECMWF model have $\tau < 0.005$. This removes residual small ice contents that exist in small quantities in the model upper troposphere.

[9] Comparisons between model and measured cloud base frequency (Figure 1a) reveal very good agreement for high and middle level clouds. Cloud base (z_b) height frequency for boundary layer clouds with $z_b < 2$ km do not agree as well. The majority of model cloud bases in the boundary layer lie above 1 km, whereas measured bases are typically below 1 km. Previous ECMWF model and radar comparisons also found that the model tended to have fewer clouds below 1 km and more clouds above 1 km as compared with measurements [*Mace et al.*, 1998]. Cloud top height frequency of occurrence (Figure 1b) in the upper troposphere does not agree as well as cloud base frequency. Despite the removal of residual ice layers in the upper troposphere from the results, the model has significantly higher cloud tops than in the measured tops. This implies that model clouds tend to be vertically deeper.

[10] We use MPL measurements to obtain cloud visible optical depth [*Comstock and Sassen*, 2001] for optically thin cirrus clouds in the upper troposphere. Lidar measurements typically become attenuation limited when τ approaches 3.0. Previous studies have shown that radar and lidar retrievals of optical depths compare well for this time period at Nauru [*Comstock et al.*, 2002]. The frequency of occurrence of τ for model and measurements (Figure 1c) is also in good agreement. The ECMWF

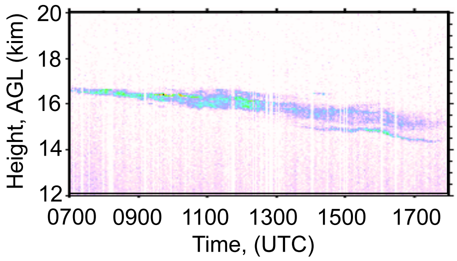

Figure 2. Height vs. time display of MPL normalized backscattered energy observed on 21 September 1999.

model has a lower frequency of $\tau < 0.2$, and a higher frequency of τ larger than 0.3.

4. Cirrus Cloud Formation Mechanisms

[11] Both model and observations show that tropical cirrus fall into two distinct categories: those observed near convection (anvils) and those observed detached from convection. Cirrus detached from convection are often thin, laminar in appearance, and located near the tropical tropopause. Anvil cirrus are usually physically and optically thicker than upper tropospheric (UT) cirrus located near the TTL, have a lower cloud base height and have more visible structure within the cloud. To assess the frequency that the ECMWF model predicts each cirrus type, we examine whether convective rain is present within a 1 hour window of the cirrus event. Approximately 54% of cirrus forms when no precipitation is present in the grid box over the previous 1 hour.

[12] One possible mechanism for the formation and maintenance of UT cirrus is the presence of large-scale ascent. The model predicts vertical ascent in ~77% of UT cirrus cases when cloud base $z_b > 15$ km (ascent is defined as any value of $\omega < 0$ Pa/s at the same time that cirrus is present in the grid-box). For cirrus clouds with $z_b > 7$ km, there is still a 75% frequency that cirrus occurs under conditions of large-scale ascent.

[13] Tropical tropopause cirrus are also linked to cold temperature perturbations in the upper troposphere. We estimate that 76% of cases where all cloud layers in the model column are located above 15 km are associated with cold temperature anomalies, which is consistent with previous studies [*Boehm and Verlinde*, 2000; *Comstock et al.*, 2002]. To determine this, we use the 30 day temperature anomaly located at the level of the model cloud top height. Cold temperature perturbations in the tropical upper troposphere are sometimes linked with the occurrence of stratospheric waves [*Boehm and Verlinde*, 2000]. These results indicate that the primary generation/maintenance mechanism for cirrus away from convection in the model is large-scale ascent and cirrus are typically associated with cold temperature anomalies.

5. Analysis of a Thin Cirrus Case Study

[14] To analyze the ability of the ECMWF model to predict specific cirrus cases observed over Nauru, we examined numerous cases that exhibited characteristics typical to anvil and UT cirrus clouds as judged by lidar and satellite measurements. As an example, we show measurements and model output for a thin cirrus case observed on 21 September 1999. For this typical UT cirrus case, a thin cirrus cloud was observed by the MPL at Nauru for nearly 12 hours (Figure 2). The depth of this cirrus ranges from ~200 m to 2 km and has an optical depth ranging from 0.001 to 0.05. Small scale waves are apparent in the lidar backscatter image, particularly between 1300 and 1800 UTC. Inspection of Geostationary Meteorological Satellite (GMS) imagery (not shown) indicates convection is not present in the region surrounding Nauru during the cirrus event. The closest convection occurred to the south of Nauru 4–5 days before the thin cirrus observation. This implies that the source of the moisture for cirrus formation could be convection but the formation mechanism is likely another source, such as large-scale ascent.

[15] On this day, the ECMWF model predicts thin cirrus above 15 km with a cloud cover varying between 50 and 100% (Figure 3a) and maximum ice water contents of less than 1 mg kg^{-1} (Figure 3b). The cloud persists in a region of large-scale ascent (Figure 3c). The model predicts no precipitation in the grid box during the 24-hour period around the cirrus event. The sloping layer observed by the lidar may indicate sedimentation of ice crystals (Figure 2). We estimate from Figure 2 that ice is falling at roughly 4 cm s^{-1}. Therefore, the model assumption of zero fall

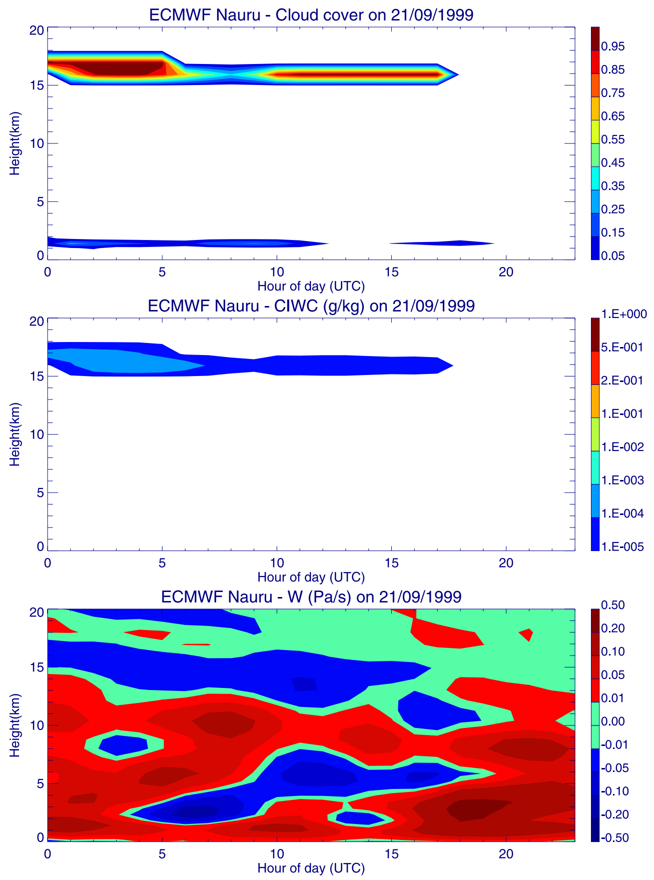

Figure 3. ECMWF model output for 21 September 1999. Each 100 sub-boxes are averaged at 1 hour time intervals. (a) Cloud cover, (b) IWC (g kg^{-1}), and (c) vertical pressure velocity (Pa s^{-1}).

velocity for small ice crystals maybe incorrect. Although the model did not simulate the sloping nature of the cloud, the model does correctly predict the dissipation time to be ~1800 UTC. The difference in cloud thickness is not surprising given that the model vertical resolution at 15 km is ~1 km, whereas the lidar is ~0.03 km. Also apparent in the model vertical velocity are tropospheric waves just below cloud base that appear to modulate the cirrus cloud cover and IWC. During periods of peak downward motion (red contours ~0800 UTC) the cirrus cloud cover and IWC decrease in magnitude. Thicker sections and higher IWC occur when the downward motion decreases (~0300 UTC). This phenomena does not necessarily hold true at ~1400 UTC; however, the magnitude of the downward vertical velocity is not as strong.

[16] We found similar results after examination of several cirrus cases observed over Nauru. Of the 32 cases examined, 56% were associated with convection, and 66% were influenced by tropospheric waves (61% of anvils and 71% of UT cirrus) as determined in the model vertical velocity field. On occasion, the model failed to predict cirrus when it was detected by the lidar (21% of UT cirrus cases). During these times, the model predicted insufficient water vapor and there was an absence of vertical upwelling in the upper troposphere.

6. Summary and Future Work

[17] In this study, we have compared cloud properties derived from the ECMWF model and measurements at the ARM site located on Nauru Island. In addition to composite statistics, as an example, we also examined a thin tropopause cirrus case to evaluate the ECMWF model's ability to forecast UT cirrus and under what conditions. Although there is some difficulty comparing a model grid box with single point measurements, our preliminary results show that the model predicts both convective anvils and isolated tropopause cirrus reasonably well. Cirrus persisting near the tropopause under convectively suppressed conditions occur when the model predicts overall ascent. Model vertical velocity indicates that cirrus morphology is often modulated by tropospheric waves.

[18] Although it seems obvious that tropopause cirrus clouds form during periods of large-scale ascent, the mechanism that produces these conditions is not straightforward, and there are few measurements to verify the large-scale environment in the TTL. Several studies have attempted to explain the formation and persistence of tropical UT cirrus clouds using models and measurements. Some of the current theories for UT cirrus formation are ice nucleating by slow large-scale ascent or in shear turbulent mixing [*Jensen et al.*, 1996], or by cold temperature perturbations in the UT caused by stratospheric waves [*Boehm and Verlinde*, 2000]. One theory explains the presence of large-scale ascent in the TTL as the result of momentum transport by convectively driven Rossby waves in the ITCZ region [*Boehm and Lee*, 2003]. Given the demonstrated skill of the model to predict cirrus, studying the frequency of these phenomena as well as identifying tropical cirrus formation mechanisms and large-scale features using the ECMWF model simulations combined with ARM measurements appears to be a promising avenue for future work.

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