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RADIATIVE AND DYNAMICAL IMPLICATIONS OF CIRRUS PROPERTIES OBSERVED AT TWO ARM SITES IN THE EQUATORIAL REGION OF THE PACIFIC OCEAN

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1. Introduction

Convective activity in the tropical western Pacific strongly influences frequency of occurrence and microphysical properties of cirrus clouds. High clouds typical of convectively active regions tend to have larger depths and more structure than those observed in suppressed regions, where cirrus are often thin and laminar. In this study, we examine cirrus occurrence and radiative properties observed over two sites in the tropical western Pacific (TWP). Ground-based lidar measurements demonstrate the differences in cirrus properties and cloud occurrence at each location. The dynamical mechanisms typically responsible for cirrus formation greatly impacts local cirrus radiative properties and heating rates, which influences both the radiation budget and dynamical response of the upper troposphere to the presence of cirrus clouds. Tropical cirrus may also play a role in the exchange of water vapor between the stratosphere and troposphere, which can influence stratospheric ozone destruction (Sherwood 1999; Kirk-Davidoff et al. 1999).

2. Measurements and Location

Manus (1.058°S, 147.425°E) and Nauru (0.521°S, 166.916°E) islands are located in the equatorial region of the western Pacific Ocean and are fully equipped with a wide variety of active and passive remote sensors as part of the U. S. Department of Energy, Atmospheric Radiation Measurement (ARM) program (www.arm.gov). In this study, we use the Micropulse Lidar (MPL; Spinhirne 1993; Campbell et al. 2002) to determine cloud properties such as visible optical depth and cloud height.

Manus lies near the intersection of the Intertropical Convergence Zone (ITCZ) and the Southern Pacific Convergence Zone (SPCZ), which increases the frequency of convective activity in the region. Nauru lies farther east, and therefore, in a typical La Nina period, experiences only small amounts of local convection. However, during El Nino and active phases of the Madden-Julian Oscillation, the Nauru region will experience increased convective activity. Annual movement of the ITCZ and SPCZ will also affect convective activity and can provide sources of upper level moisture to the equatorial convective gap increasing the potential for *in situ* cirrus formation. Monthly mean outgoing longwave radiation (OLR) from NCEP data (Fig. 1) show that with rare exceptions (like the 1997 El Nino), the region around Manus is convectively active (indicated by low OLR values) while Nauru is much more variable. Since the 1997 El Nino, Nauru has experienced convectively suppressed conditions; however, measurements indicate that OLR is decreasing as low OLR values shift toward the East through January 2002 (Fig. 1).

3. Tropical cirrus formation mechanisms

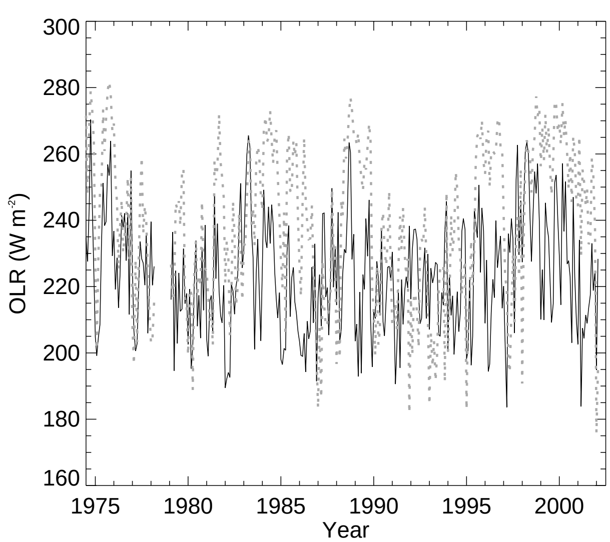

Fig. 1. Time series of OLR comparing Nauru (light dashed line) and Manus (dark solid line) between June 1974 and January 2002.

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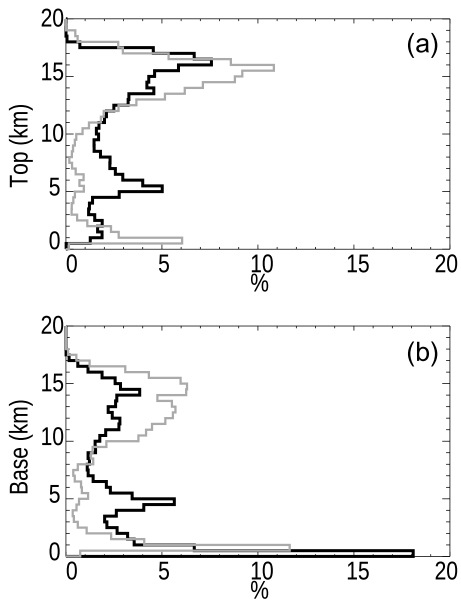

Fig. 2. Frequency of occurrence of cloud top (a) and base (b) height detected by the MPL at Nauru (light line) and Manus (dark line).

Two mechanisms are important in the formation of cirrus clouds in the tropics (Prabhakara et al. 1988; Jensen et al. 1996). First, cirrus form as outflow from cumulonimbus clouds (anvil cirrus). Anvil microphysical properties may vary depending on strength of convection, temperature, and distance of cirrus from the convective core (Heymsfield and McFarquhar 1996; McFarquhar and Heymsfield 1996).

Second, tropopause cirrus (TC) form *in situ* as a result of large-scale processes, producing thin, laminar clouds located near the tropical tropopause. Observations suggest that TC is not directly associated with local convection, but is a separate class from anvil cirrus (Winker and Trepte 1988; Comstock et al. 2002). The exact mechanism that forms tropopause cirrus is uncertain. One study has linked cirrus occurrence with cold temperature perturbations in the upper troposphere that occur as downward propagating Kelvin waves extend from the stratosphere (Boehm and Verlinde 2000; BV hereafter). Large-scale uplift is also suggested as a possible mechanism (Jensen et al. 1996). Little is known about the microphysical properties of tropopause cirrus because they exist above 15 km and are difficult to sample with aircraft probes. A few cases are examined in McFarquhar et al. (2000).

4. Cloud properties statistics

Cloud base z_b, top z_t, and visible optical depth τ are derived from MPL backscatter profiles (Clothiaux et al. 1998; Comstock and Sassen 2001). This method uses the above cloud molecular signal to normalize the backscatter profile, and therefore is subject to errors as the lidar signal becomes fully attenuated.

Due to instrument problems, we do not have a significant time period when data are concurrently available at each site. Therefore, we analyze MPL measurements from Nauru in 1999 and Manus in 2000. Upon examination of shortwave cloud forcing at the surface (not shown), we conclude that convective activity at Nauru is similar during both years. While this comparison is not ideal, it still provides a useful comparison between sites for typical La Nina periods. Frequency of occurrence of cloud base (z_b) and top (z_t) height (Fig. 2) reveals a higher frequency of clouds with z_b>10 km at Nauru than observed at Manus. However, Manus has a higher frequency of lower clouds with z_b<7 km, which corresponds with a higher frequency of local convection during this time period. The lidar is likely attenuated for lower, thicker clouds. Therefore, z_t is best trusted for clouds with z_t>10 km (Fig. 2a).

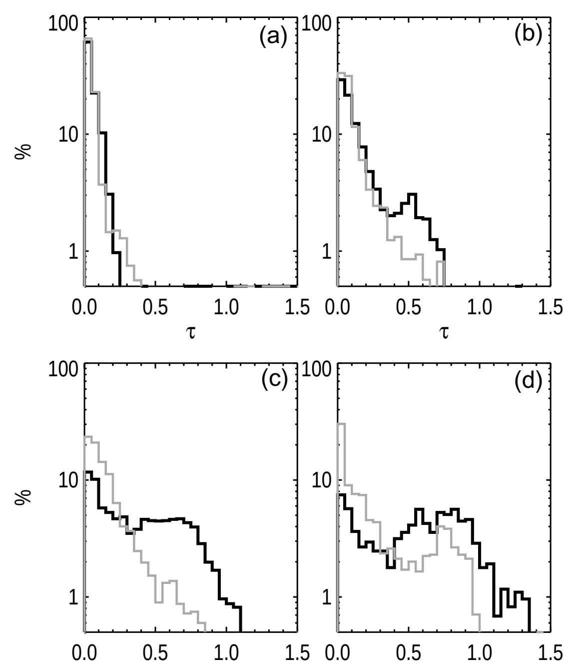

Fig. 3. Visible optical depth divided into 4 categories based on height comparing Nauru (light line) and Manus (dark line). (a) z_b>14 km, (b) 12<z_b<14 km, (c) 10<z_b<12 km and (d) 8<z_b<10 km.

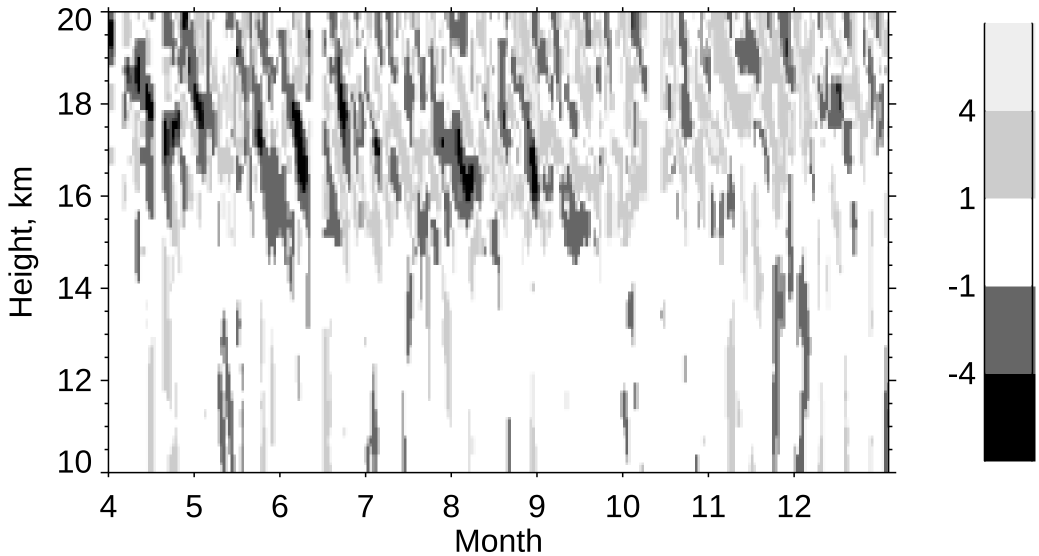

Fig. 4. Temperature anomalies (K) derived from radiosonde profiles at Nauru during 1999.

Frequency of occurrence of τ is divided into 4 groups according to cloud base height (Fig. 3). When z_b>14 km, distributions of τ at both sites are similar, with nearly 90% having τ<0.1. This implies that the frequency or strength of local convection does not influence the cloud properties of TC. This means that TC is not directly influenced by convective activity. However, it is commonly believed that tropical convection deposits the moisture needed to form TC.

As z_b lowers, differences in τ at each site become apparent. Due to the higher frequency of lower, thicker clouds, it is not surprising that τ is larger at Manus when z_b<14 km (Fig. 3c). Since convection generally detrains below 14 km, it is assumed that clouds with z_b<14 km are anvils. Since convection rarely occurs at Nauru during this time period, anvil cirrus observations at this site are likely farther away from the convective core, and thus have lower optical depths. Manus, on the other hand, experiences frequent local convection. Subsequently, measurements of anvils at Manus are often close to the convective core and have larger τ, lower z_b and are thicker.

5. Tropopause Cirrus Formation

As discussed in Sec. 4, tropical cirrus properties are influenced by their formation mechanisms. The specific mechanisms responsible for the formation of TC is uncertain; however, it appears that convection does not directly affect the basic cloud properties. One mechanism that may influence TC formation is stratospheric waves (BV). To explore how often TC is correlated with stratospheric waves, we calculate temperature anomalies using a 30-day running average at each height level (200m resolution) between 10-20 km (Fig. 4). Each profile represents a 12 hour time period during 1999 at Nauru. Negative temperature anomalies are identified as Kelvin waves propagating downward from the stratosphere (Holton et al. 2001). There are distinct periods between April and September when strong cold anomalies extend below 16 km where TC is often located. However, in October through December, the frequency of these anomalies decreases.

To further examine the BV mechanism, we correlate cirrus observations when at least one cloud layer has z_b>15 km with temperature anomalies at Nauru during 1999. Temperature anomalies are taken at the height of the highest cloud top in the column. TC correlates with cold anomalies ~75% of the time in May through July, but only 45% in August through October. Since BV studied cirrus during the Nauru99 intensive observing period (17 June-17 July, 1999), they found a good correlation between TC and cold anomalies. By adding several months of cirrus observations, it is clear that the correlation may have a seasonal dependence. As more data becomes available, we can examine this mechanism further.

6. Summary

Cloud properties measured at Nauru and Manus Islands in the TWP reveal distinct characteristics that are likely linked to the relative frequency of local convection. Tropopause cirrus have distinct radiative and macrophysical properties when compared with anvil cirrus, and appear to form detached from local convection. However, convection is the likely source of the water vapor needed to form TC.

Specific mechanisms that are important in the formation and persistence of TC are difficult to verify with ground-based measurements; however our results indicate that the correlation influence of stratospheric waves on TC formation is not always apparent. Future work on this subject will include analysis of satellite imagery and trajectory analysis to help determine the source of water vapor and determine specific mechanisms associated with tropical cirrus. We also plan to compare our ground-based retrievals with MODIS and MISR cloud algorithms.

7. Acknowledgements

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