Cloud Plumes Observed at Nauru Using GMS Imagery

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Introduction

As part of the Atmospheric Radiation Measurement (ARM) Program, the Atmospheric Radiation and Cloud Station 2 (ARCS-2) was placed on the leeward side of the island of Nauru (0.521°S, 166.916°E) to monitor the equatorial Tropical Western Pacific (TWP). We hoped the measurements of radiation and cloud properties from Nauru would represent the surrounding ocean. Observations at the ARCS-2 started during the Nauru99 (mid June to mid July 1999) field campaign. During this campaign, island-induced clouds in the form of cloud plumes were observed overhead at the ARCS-2 site. These plumes had previously been cited in the Nauru99 Science and Operations Plan. Although the plumes are an insignificant part of the overall radiation budget in the TWP, they are being monitored in the ARCS-2 measurements and may not be indicative of the surrounding ocean.

Nauru (orographic extent of 61 m) produces a daytime heat dome, below the prevailing easterlies, which acts as a catalyst in plume generation. These plumes are advected downwind. Plume generation is not unique to Nauru; the island of Banaba (0.8°S, 169.5°E) also produces cloud plumes. Nauru is located in the subsidence zone between the Intertropical Convergence Zone (ITCZ) in the north and the South Pacific Convergence Zone (SPCZ) in the south.

Given the goals of ARM, how much error would these cloud plumes add to the measurements taken at ARCS-2? Would it be worth the effort to move the site to the windward side? In order to address these questions, cloud plume behavior needs to be evaluated for at least one annual cycle. The goal of this observational study is to determine the length, frequency, and direction of the cloud plumes and determine any diurnal or seasonal cycles. The period of study is from mid-June 1999 through the end of June 2000.

Cloud Plume Data and Methods

Hourly visible (VIS; 0.65 μm) Geostationary Meteorological Satellite (GMS-5) 1.25-km images from June 15, 1999, to June 30, 2000, were examined for cloud plumes between 7:30-16:30 local standard time (LST). The evolution of a cloud plume on October 28, 1999, is shown in Figure 1. At the

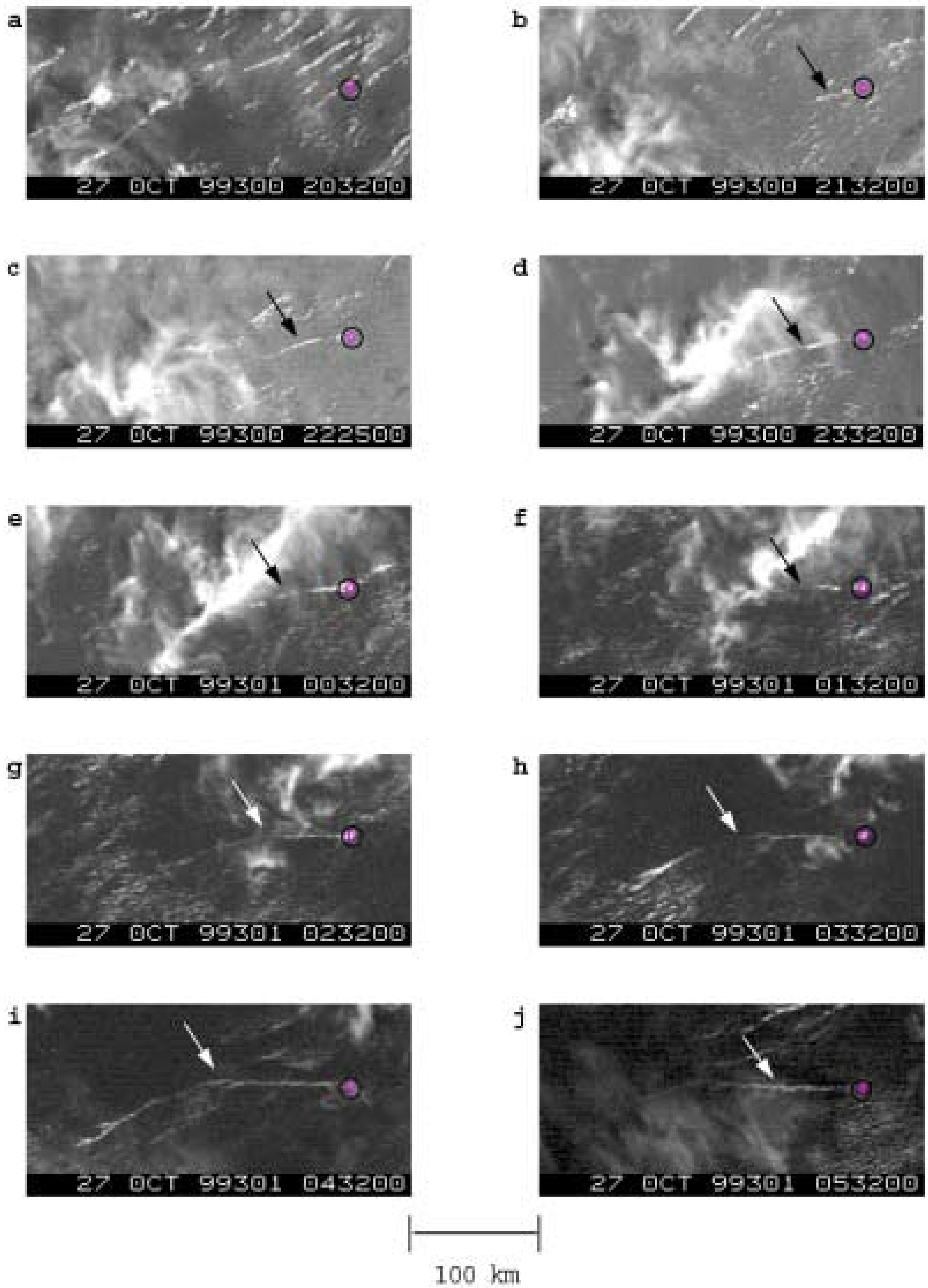

Figure 1. Time series of a cloud plume near Nauru on October 27-28, 1999, Universal Time Coordinates (UTC). Local times of each image are as follows: (a) 0732, (b) 0832, (c) 0925, (d) 1032, (e) 1132, (f) 1232, (g) 1332, (h) 1432, (i) 1525, and (j) 1632. Arrows are used to help pinpoint the location of the cloud plume.

beginning of the day (7:30 LST) no plume is present, but one hour later the plume has formed and increases until the last visible image (16:30 LST), when the cloud plume reaches an extent of 199 km. Cloud plumes cannot be identified in the GMS-5 infrared (IR; 10.8 μm) imagery, because of decreased resolution and the small temperature difference between plume and ocean. In Figure 1g, the plume changes direction to the southwest, where it has lifted to the level of the rest of the low-level cloud formations. During the period of study, the low-level clouds seem to be closer together and thinner in the morning than the afternoon, where they are more convective and spaced further apart.

The images were examined manually for three conditions: (1) if clouds obscure the island (usually optically thick convective clouds), (2) if a plume is detected, and (3) no plume. If a cloud plume is observed, its length and direction are calculated by measuring the straight-line distance between the island and the endpoint and noting its direction from Nauru. The estimation of length is somewhat subjective because the plume sometimes blends in with background low-cloud formations, which tend to have similar features. Sometimes, the plume appears to be broken into segments. A clear category was not possible because the overhead cloud amount at Nauru is difficult to determine with the GMS VIS imagery because the island is rather bright in the visible. Liquid water content (LWC) data collected by the research aircraft, C-404, were also examined. Observations from the aircraft revealed a clear region approximately 3-km wide on either side of the plume. The LWC measurements indicate increasing LWC with distance from the island (Stewart Matthews, personal communication).

Cloud Plume Length

Interest for this research resulted from the extraordinary lengths and growth rates of these cloud plumes. The plume formation is believed to be the result of the diurnal heating of the island. The surface air temperature amplitude was 3° K at ARCS-2 during Nauru99. The skin temperature may not be indicative of the island because the site was on crushed rock placed on the beach. For the period of study, the average cloud plume length increases rather linearly throughout the day (Figure 2). The average cloud plume length at 1630 LST is 125 ± 75 km. 95% of all plumes were less than 200 km in length. There were two peaks of plume length occurring in the fall and spring (Figure 3). The seasonal signal was greatest in the afternoon.

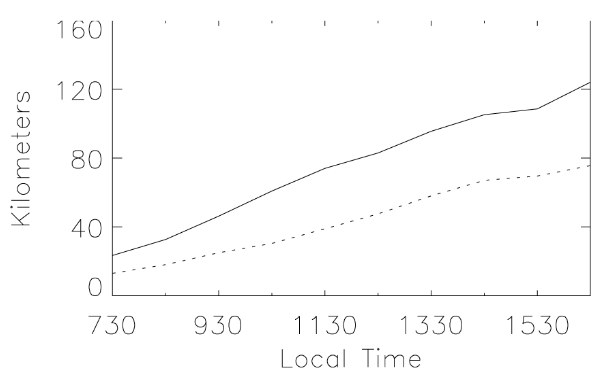

Figure 2. Mean length of cloud plumes from June 1999-June 2000 as a function of LST.

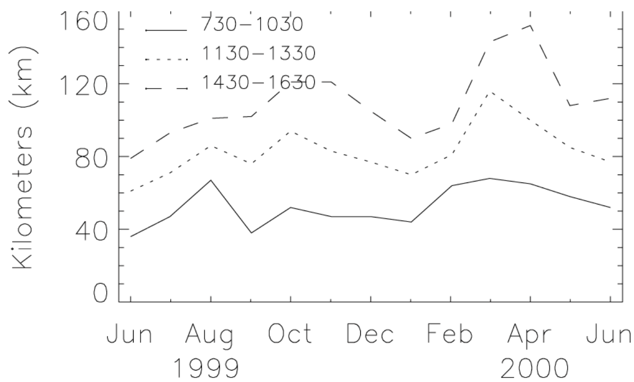

Figure 3. Same as Figure 2 except as a function of month.

The longest plume occurred on April 21, 2000, ultimately reaching a length of 425 km at 16:30 LST. This shows a growth rate greater than 40 km/hr. The radiosonde (1030 LST) for the day, however, indicated wind speeds at 900 mb of 15 ms^{-1} (54 km/hr). The growth rates of the plume are entirely within the range for advection. In fact, the mean growth rate is 20 ± 6 km/hr. Radiosondes launched at 1030 LST from the island of Nauru from June 1999 to May 2000 were matched with the times of plume occurrences within the half-hour. A histogram of mean and maximum wind speeds between 950 hPa and 850 hPa is shown in Figure 4. The average maximum wind speed was 11.3 ms^{-1} (42 km/hr) and mean wind speed 9.6 ms^{-1} (35 km/hr). Perhaps in some cases the plume forms before sunrise. On November 18, 1999, a plume of 46 km was seen at 0730 LST. This plume was even present in the sunrise image (0630 LST). This case had a 950 hPa wind speed of 6 ms^{-1} (20 km/hr).

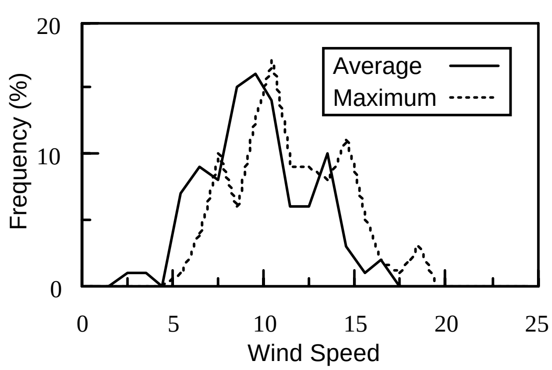

Figure 4. Histogram of wind speed between 950 hPa and 850 hPa taken from daily radiosonde (2330 UTC) when plume was present.

Cloud Plume Heading

The mean directional heading (from north) of the cloud plumes was 265° (plume forming to the west of the island) and there was no diurnal cycle. The heading gradually declined from 270° to 260° from June 1999 to June 2000. The exception was September 1999 when the heading was 280°. The range of headings was between 220° to 320° with a standard deviation of 20°. The plumes observed outside of 240° to 300° had shorter lengths. However, there was an anomaly on January 22, 2000, when the heading was 130° (SE).

From the coincident radiosonde data, the wind direction at plume top was assumed to correspond to the maximum wind speed between 850 hPa and 950 hPa. Figure 5 shows the scatterplot of plume versus wind directions. The root mean square (rms) difference is 13°, which is within a standard deviation of the plume direction. In the GMS IR images taken during the study period, the ITCZ was observed between 5° and 10°N and the SPCZ from 5° to 10°S confirming that no large-scale circulation changes and little seasonal variation in directional heading had occurred.

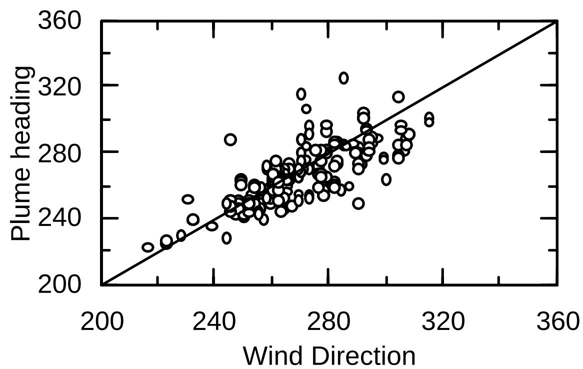

Figure 5. Same as Figure 4 except for wind heading +180° at maximum wind speed and cloud plume heading.

Generally, the cloud structure is the plume at the lowest atmospheric level heading west, followed by the low-level clouds heading southwest, and the high-level cirrus heading towards the northeast.

Cloud Plume Frequency

Figure 6 shows the frequency of plume, non-plume, and obscured conditions during the period of study. The three categories are constant after 1130 LST except near sunset. Afternoon plume frequency is 65%. The greatest variability is in the first three morning hours. Obscured conditions, which suggest convective clouds, are mostly observed in the morning when the non-plume probability is greatest. Breaking up the categories into morning (0730 LST to 0930 LST) and the rest of the day revealed that most of the seasonal variability occurred in the morning. In fact, there was no significant seasonal cycle between 1030 LST and 1630 LST. The mean frequency is around 60%. Figure 7 shows the morning category frequencies. Obscured or convective conditions peaked during September and March; whereas, plume frequency peaked in November and December. The morning frequency variations could be used to infer seasonal atmospheric stability.

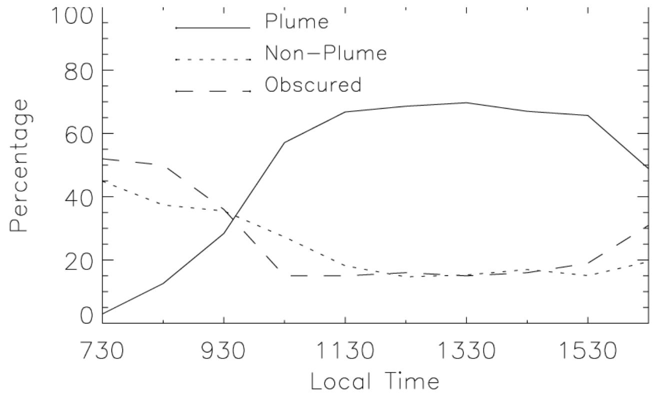

Figure 6. Cloud plume, non-plume, and obscured conditions as a function of LST.

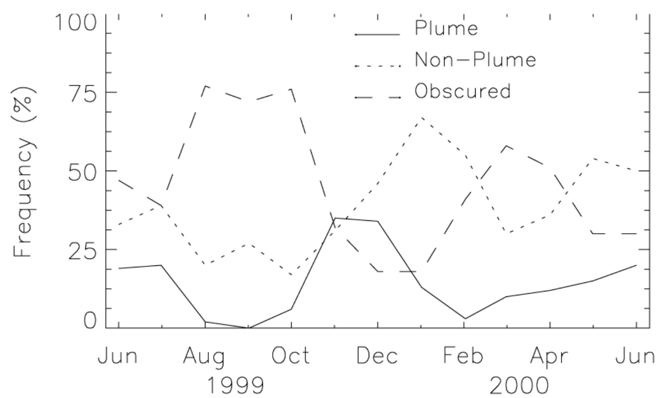

Figure 7. Same as Figure 6 except as function of month for times between 0730 LST and 0930 LST.

Conclusion and Future Work

The site is located in the middle of the leeward side of the island of Nauru. If the frequency of plume occurrence is indicative of plumes observed at ARCS-2, then the prevalence of afternoon plumes would increase the low cloud amount at ARCS-2 relative to the surrounding ocean. This would have the greatest effect on downward-looking radiation measurements. The plumes have rather similar characteristics as the low clouds that are already present. Cloud retrieval instruments, such as radar, should still able to monitor the high clouds through the plume. Perhaps plume frequency can be used as an indication of low-level atmospheric stability. It may be preferable to move ARCS-2 to a windward site to minimize the island effects; however, it is not clear that the windward side would yield more representative low-cloud statistics.

GMS-derived cloud amounts and radiation for a small region (0.3° latitude by longitude) centered on the ARCS-2 site will be compared with ARCS-2 data to determine whether the plumes have any significant radiative impact. Comparison between GMS-derived parameters and the instrument measurements obtained from the Mirai and Ron Brown during Nauru99 will determine the robustness of the GMS retrievals, while comparisons between the ARCS-2 and ship data will help confirm the inferences drawn here about the plume effects

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