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DYNAMIC RESPONSES OF WARM MONSOON CLOUDS TO SALT SEEDING

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Abstract. High resolution temperature measurements during single-level aircraft penetrations through warm monsoon clouds before and after salt seeding had a significant wave-length of about 2 km. The slope of the spectra relating to not-seeded traverses followed a -5/3 power law. The slope of the spectra relating to seeded traverses increased when liquid water content increased and rain formed. The temperature spectra of the seeded traverses showed a net energy gain in the larger wave-lengths (>540 m) and a net energy loss in the shorter wave-lengths. The net-energy gain could be due to condensation of water vapor on the salt particles, the net energy loss to the decrease in the small scale turbulence resulting from the invigoration of the updraft. These features could be manifestations of the alteration of the dynamics of the cloud through salt seeding.

1. INTRODUCTION

During aircraft penetrations at a single level in warm cumulus clouds before and after they were subjected to massive salt seeding, the electrical, microphysical and dynamical responses to the seeding were documented (Ramachandra Murty et al., 1975 a, b; 1976). The observations suggested increases in (i) temperatures of cloud air by 1 to 2^{o}C, (ii) liquid water content of up to 200 percent and (iii) vertical thickness of the cloud up to 60 percent before the onset of the rain from the seeded clouds whose initial thickness was more than 5000 ft. at time of seeding (Ramachandra Murty et al., 1975 a, b). Also, the electric field in maritime cumulus clouds which developed rain following seeding showed sign reversal, from the initial negative to positive occasionally preceded by intensification (Ramachandra Murty et al., 1976).

The one-dimensional spectra of clear air temperatures obey the -5/3 power law in the inertial subrange (Corrsin, 1951), and the average spectra of motions inside the cloud also tend to follow the -5/3 power law (Almeida, 1979). When the slope of the temperature spectra follows the -5/3 power law, the turbulence in the cloud is indicated to be isotropic with balance between energy input and dissipitation. An increase in slope beyond -5/3 indicates higher energy dissipation rates. The longer wave lengths of the temperature spectra are generated as a result of the latent heat of condensation and the shorter wave lengths primarily represent the small scale turbulence (Warner, 1970). Therefore, the variations noticed in the in-cloud temperature spectra before and after their seeding deserve study to contribute to the physical understanding of the dynamical responses of warm cumulus clouds to salt seeding. Such studies are rare (Cunningham and Glass, 1972).

High resolution observations of temperature and cloud liquid water content (LWC) were obtained during aircraft penetrations at a single level in warm cumulus clouds before and after massive salt seeding. The variations in five cloud cases following seeding are presented here.

2. MEASUREMENTS

Continuous recordings of the temperature of the cloud and cloud-free air were obtained from an aircraft vortex thermometer (Vernekar and Mohnan, 1975) as a part of the cloud seeding experiments in the Poona and Bombay regions during the summer monsoon of 1973. These observations were obtained about 600 m above the base of the cloud. Temperatures were extracted at 3 second intervals (150 m resolution) from the continuous recordings and subjected to spectral analysis after removal of linear trend.

The temperature data were not corrected for compressive heating of the air due to aircraft speed (Ruskin and Scott, 1974) since the DC-3 aircraft was slow, about 55 m sec^{-1}; the maximum error due to compressive heating is about ± 0.15^{o}C (Mary Selvam et al., 1980). Also, as the lower atmosphere in the regions of the observations is nearly saturated during the summer monsoon (relative humidities exceed 80 percent), the error from wetting the thermometer and subsequent evaporative cooling will be negligible.

Data relating to three cloud cases near Poona, (18^{o} 32'N, 73^{o}51'E,559 m ASL) and two near Bombay (18^{o}51'N, 72- 49'E, 11 m ASL) were utilized. In addition to temperature measurements, cloud liquid water contents were measured with a Johnson-Williams hot wire meter; details of the cloud seeding experiment have been described elsewhere (Ramachandran Murty et al., 1975 a). The seeding mixture consisted of salt and soapstone in the ratio 10:1 with particle model diameter of 10 μm. The entire flight paths were seeded.

3. RESULTS

Horizontal temperature spectra are shown in Fig. 1 for successive penetrations in five isolated cumulus clouds, three at Poona, two at Bombay, and one clear-air case near Poona. In all the cloud cases, the first traverse was not seeded, the second and subsequent traverses were seeded.

Horizontal temperature spectra are shown in Fig. 2 for observations at Poona in clear air at the same aircraft flight level.

In both cloud and cloud-free air, the temperature spectra showed a significant wavelength of 2 km. The clear air temperature spectra between 0.03 and 0.16 Hz (wavelengths between 2 km and 350 m) obeyed the -5/3 power law (Fig. 2) but temperature spectra in the cloud air deviated from this law.

The vertical extent of Cloud A was 5000 ft. with a base diameter of about 6 km. After one traverse in the cloud, 1500 kg of salt mixture were released during traverses 2 to 5. The LWC increased from 0.3 to 1.6 g/m^3 following seeding and then decreased after the onset of rain. In-cloud temperature was between 15 and 16^{o}C; heavy rain was observed visually in traverses 3 and 5. The slope of the temperature spectra for traverse 1 (not-seeded) followed a -5/3 power law, but increased steeply on subsequent traverses.

The vertical thickness of Cloud B was 5000 ft. with base diameter of about 6 km. After the first cloud traverse, 800 kg of salt mixture was released during traverses 2 to 6. The LWC increased between 0.5 and 1/0 g/m^3 following seeding in traverse 4; in-cloud temperature varied between 13 and 14^{o}C. Wetting of aircraft windows by impacting drizzle drops was observed during traverses 2 and 3. The slopes of the temperature spectra nearly followed a -5/3 power law in traverses 1, 2, 3, and 6, increased in traverse 4 and decreased slightly on traverse 5.

The vertical thickness of Cloud C was about 5000 ft. with base diameter of about 4 km. Seven traverses were made in the cloud, and 1500 kg of salt mixture were released during the last six. The LWC showed a progressive increase from 0.20 to 0.95 g/m^3 following seeding, with maximum value in traverse 4. The in-cloud temperature varied between 14 and 15^{o}C. Aircraft windows were wetted by impact of drizzle drops during the first two traverses and by heavy condensation on the subsequent traverses. Light rain was noticed during traverse 7. The slopes of the temperature spectra followed -5/3 power law on traverse 1, but on traverses 2, 3, 4 and 5 the slope increased steeply and on subsequent traverses the slopes showed tendency towards -5/3 power law. The LWC also progressively increased during traverses 1 to 5 and steeply decreased in traverses 6 and 7.

The vertical thickness of Cloud D was about 5000 ft. base diameter of about 4 km. Seven traverses were made in the cloud and 775 kg of salt mixture was released during traverses 2 to 7. The LWC showed sharp increases in traverses 4 and 6 when the temperature spectra also showed steep increase in the slope; LWC varied from 0.75 to 3.0 g/m^3. Rain was observed visually in all seeded traverses. The in-cloud temperature varied between 13.7 and 15.7^{o}C. The slopes of the temperature followed -5/3 power law in traverses 1 and 2, but spectra exhibited steeper slopes in all seeded traverses except traverse 7, when the cloud was dissipating.

The vertical thickness of Cloud E was only 4000 ft. with a base diameter of about 4 km. Nine traverses were made in the cloud and 725 kg of salt mixture released during traverses 2 to 9. The LWC showed no marked variations in traverses 1 to 6, but a sharp increase in traverse B, when the slope of the temperature spectra also showed a steep increase. The values of LWC varied between 0.90 and 2.0 g/m^3; heavy rain was observed in traverse 8 when the maximum value of LWC was recorded. The slope of the temperature spectra followed -5/3 power law in traverses 2, 3, 4 and 6 and showed a steep increase in traverses 8 and 9. The cloud was still developing actively when observations terminated.

4. DYNAMIC RESPONSES

The slope of the in-cloud temperature spectra followed the -5/3 power law in not-seeded traverses and increased in seeded traverses when cloud liquid water content increased and rain was observed. A net energy gain in the longer wavelength (>540 m) of the temperature spectra of the seeded traverses could be due to condensation of water vapor on salt particles. The net energy loss in the shorter wavelengths of the in-cloud temperature spectra could be due to the decrease in the small scale turbulence resulting from invigoration of the updraft. These features may manifest the alteration of the dynamics of the cloud through salt seeding.

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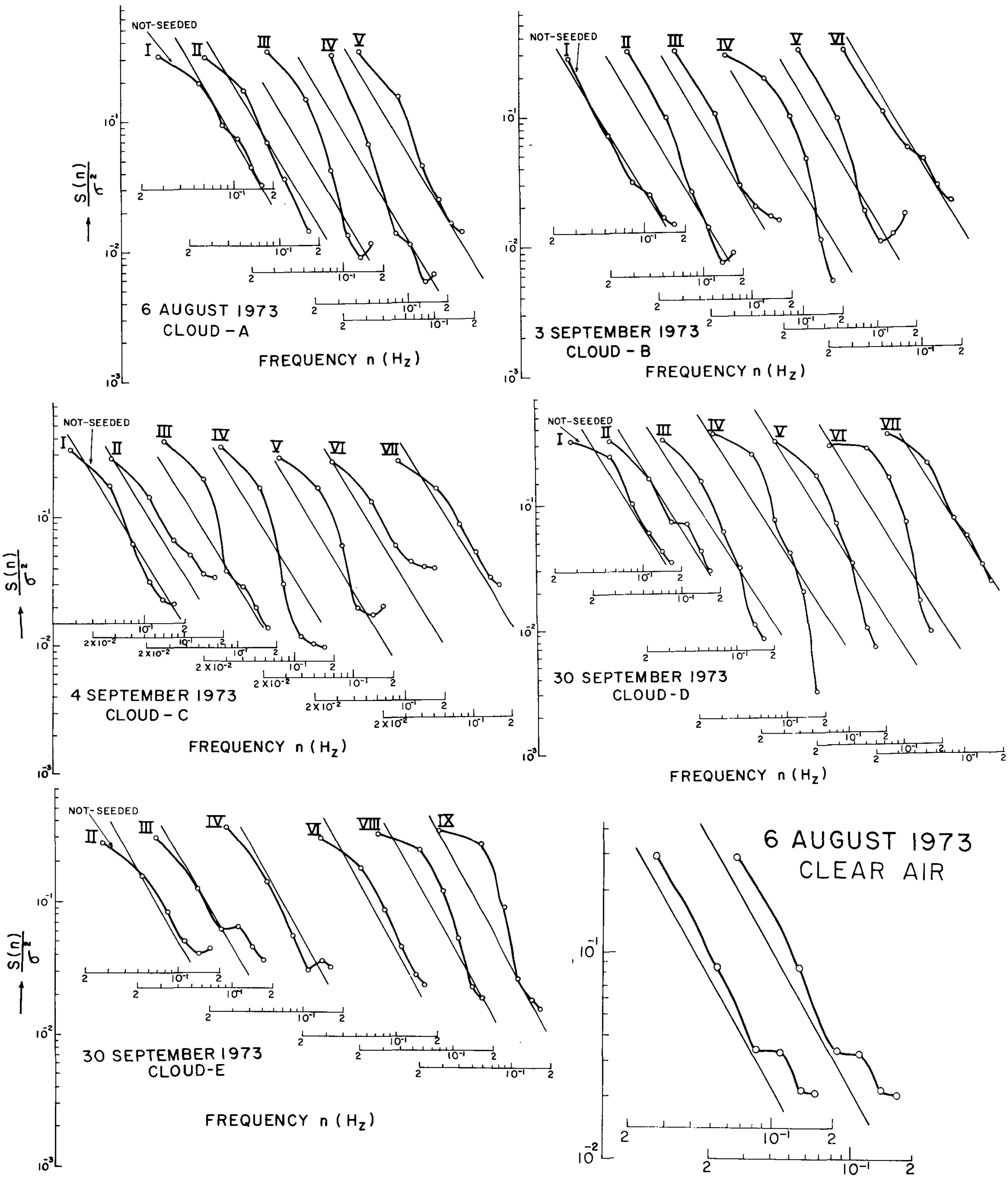

Figure 1. In-cloud temperature spectra for five clouds, and one clear-air case. Traverse 1 in each cloud was not seeded, subsequent traverses were seeded with 10:1 salt-soapstone mixture.