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OBSERVATIONS OF MULTI-LAYERED CLOUDS USING K-BAND RADAR

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Abstract

Rudimentary ground-based K-band radars were once used by the U.S. Air Force to monitor clouds over air bases. The NOAA Wave Propagation Laboratory has developed a significantly advanced dual-polarization Doppler K-band system that provides remarkably detailed visualizations of the structure and kinematics of non-precipitating and weakly precipitating clouds. Unlike lidar and infrared radiometer systems, K-band radar can penetrate liquid water cloud layers and obtain measurements through moderate rainfall and heavy snowfall to reveal intricate cloud features including multiple layers of cloud. This is accomplished at less cost than would be possible with traditional longer wavelength weather radars. The radar's capabilities have been demonstrated in several recent cloud research field projects. In combination with measurements by other remote sensors, the radar can help detect aircraft icing hazards and infer microphysical properties of clouds. An automated, unattended version of the radar could provide a continuous, detailed depiction of the cloud environment in the vicinity of airports.

1. Introduction

By virtue of its excellent sensitivity, spatial resolution, and velocity measurement precision, the Wave Propagation Laboratory (WPL) K_a-band (λ = 8 mm) Doppler radar is ideally suited for detailed observations of the structure and kinematics of non-precipitating clouds. Signals at this wavelength are not attenuated by liquid water as seriously as those of lidars, infrared radiometers, and shorter wavelength radars. Thus, the WPL K-band radar can penetrate liquid cloud layers and continue to obtain measurements through moderate rainfall and heavy snowfall. It provides very detailed visualizations of cloud locations and properties even in situations of multiple cloud layers. Furthermore, power in the radar antenna's side lobes is very weak, thus it is relatively immune to ground clutter contamination problems.

The WPL radar has been used in several recent research projects ranging from studies of aircraft icing hazards to the radiative effects of cirrus and marine stratus clouds. Scans of multi-layer clouds excerpted from these projects are reproduced in this article to illustrate a few of the radar's capabilities. The potential usefulness for cloud surveillance at airports is discussed for a proposed automated version of this radar system.

2. Background

For the last three decades, radar meteorology research has been dominated by studies of severe storms; less dramatic, but important, cloud systems have been largely ignored. This very focused emphasis is now broadening with the new widespread interest in how clouds affect radiative transfer in the atmosphere and, thereby, climate and climate change. The traditional longer wavelength radars (λ = 5-11 cm), used so effectively for severe storm monitoring and research, may not be the best tools for observing the details of non-precipitating clouds.

For particles much smaller than the observing wavelength (Rayleigh scattering conditions), the backscattering cross section of a sphere is inversely proportional to the fourth power of the wavelength. Thus, longer wavelength radars have an inherent disadvantage for detecting signals backscattered from very small hydrometeors, such as cloud droplets and new ice crystals. In practice, however, long wavelength weather radar systems can compensate for this disadvantage by using very powerful transmitters, large antennas, and very sensitive receivers, all at considerable expense. Thus, the primary advantages of a short wavelength radar, are its relatively small size and cost, in addition to its excellent sensitivity, resolution, and clutter minimization.

The main disadvantage of short wavelength radar is signal attenuation from rain and cloud liquid water that becomes more severe for decreasing wavelengths. For optical and infrared systems such as ceilometers, lidars, and IR radiometers, attenuation by liquid water is so extreme that it prohibits probing beyond the first 100-200 m of a liquid cloud boundary. Low stratus, fog, drizzle, or rain will block these instruments and prevent them from detecting all higher cloud features and layers.

K-band radar represents a reasonable compromise between the expense limitations of longer wavelength radars and the attenuation limitations of shorter wavelength systems, including shorter wavelength radars. Thus, although K-band is unsuitable for monitoring severe convective storms and weather systems with widespread moderate to heavy rain, its proper niche is for observing non-precipitating and weakly precipitating clouds. These clouds are common, often pervasive, and can be significant factors for aviation, weather modification, and climate.

3. K-band Radar Systems

In the 1960s, K-band radars were used by the U.S. Air Force as "radar ceilometers" to monitor clouds at numerous air bases[1]. These vertically pointing, non-Doppler, AN/TPQ-11 radars provided useful information on the heights and structure of overpassing clouds, but suffered from frequent hardware failures and poor displays, and were eventually abandoned. The University of Washington added Doppler capability to a surplus AN/TPQ-11 and has productively used it for cloud physics studies[2].

The WPL K-band radar is an original design with dual-polarization and full scanning and Doppler capabilities[3]. Recent extensive upgrades, including a new antenna, have significantly improved the system's capabilities[4]. The radar can transmit linear, circular, or elliptical polarizations and receive the co- and cross-polarized backscattered signals; the amount of depolarization is related to the hydrometeors' shapes, orientations, and thermodynamic phase. The beamwidth is 0.5° and the range resolution is 37.5 m. The system is capable of detecting signals as weak as -31 dBZ at a range of 10 km, and the radial velocity measurements are demonstrated to be accurate to within 0.05 m s^{-1} in typical situations. The antenna side lobes are very weak, thus ground clutter is seldom a serious problem. Table 1 summarizes the radar's characteristics; its offset Cassegrain antenna is shown in Figure 1.

4. Multi-layer Cloud Examples

The ability of the WPL K-band radar to detect weak clouds has been demonstrated in a number of recent experiments, including the Cloud Lidar and Radar Exploratory Test (CLARET-I & II) in Colorado, the Winter Icing and Storms Project (WISP) in Colorado, the First International Satellite Cloud Climatology Project Regional Experiment (FIRE-II) in Kansas, and the Atlantic Stratocumulus Transition

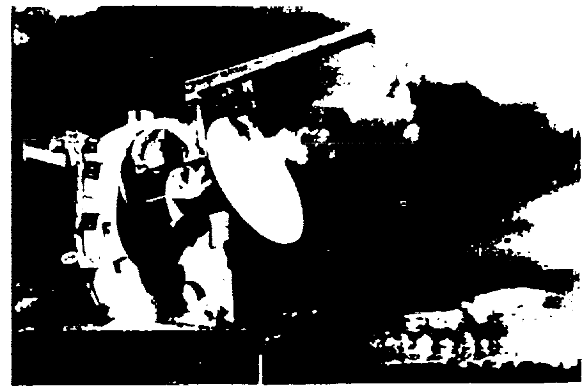

Figure 1. Offset Cassegrain antenna of the WPL K-band radar.

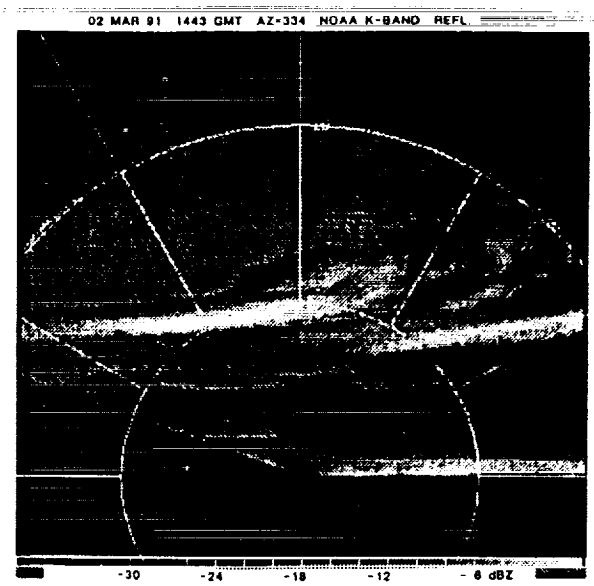

Figure 2. K-band radar reflectivity factor (dBZ) pattern for an RHI scan from the WISP project in Colorado. Cirrus (upper), altostratus (middle), and stratus (lower) cloud layers are shown. Range rings are shown at 5-km increments.

Table 1

CHARACTERISTICS OF THE NOAA/WPL K-BAND RADAR

Major capabilities:	reflectivity, velocity, and depolarization for atmospheric research, including observations of non-precipitating clouds
Frequency:	34.6 GHz = 8.7 mm wavelength (K_a-band)
Peak transmitted power:	85 kW
PRF:	625 to 2500 μs
Sensitivity:	approximately -30 dBZ at 10 km
Polarization:	circular typical, but elliptical and linear possible by rotating quarter-wave plate
Beam Width:	0.5° circular
Antenna:	Millitech offset Cassegrain with 1.2 m diameter parabolic dish; 49.5 dB gain; -30 dB sidelobes
Scan Types:	PPI (incl. sector scans), RHI (incl. over the top), zenith, fixed beam
Pulse width:	fixed, 0.25μs (37.5 m)
Range gate spacing:	(n)*(37.5 m) where n = 1, 2, 3 ...
Number of range gates:	up to 328 gates
Scan rates:	0-30 deg/s; fastest rate depends on sector size
Parameters measured:	reflectivity (main- & cross-polarized), mean Doppler velocity, variance of Doppler spectrum, circular depolarization ratio (CDR), correlation of successive pulses, full Doppler spectrum in a separate recording mode
Doppler processing:	pulse-pair or time-series techniques
Data system:	Data General S-120 computer controls antenna operation, recording and displays through NOAA's Radar Control Program. Hundreds of pre-programmed scans can be retrieved from disk for immediate use. SUN workstation for post-processing in field.
Recording:	Exabyte 8mm video cassette tape drives. VCR used for recording visual weather in direction of radar beam. PC electronic logbook for operator's comments.
Real-time displays:	color monitor of Doppler velocity, reflectivity, CDR and correlation patterns; Video monitor of weather along beam; digital displays of azimuth, elevation, and time; field tapes can be played back through color monitor.

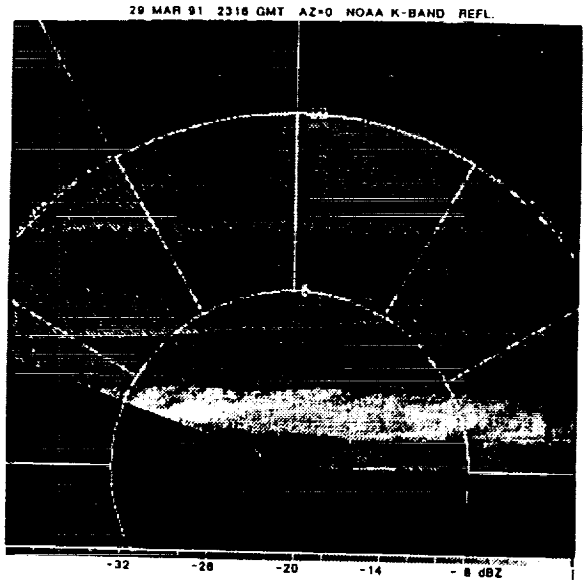

Figure 3. As in Fig. 2, except for another date.

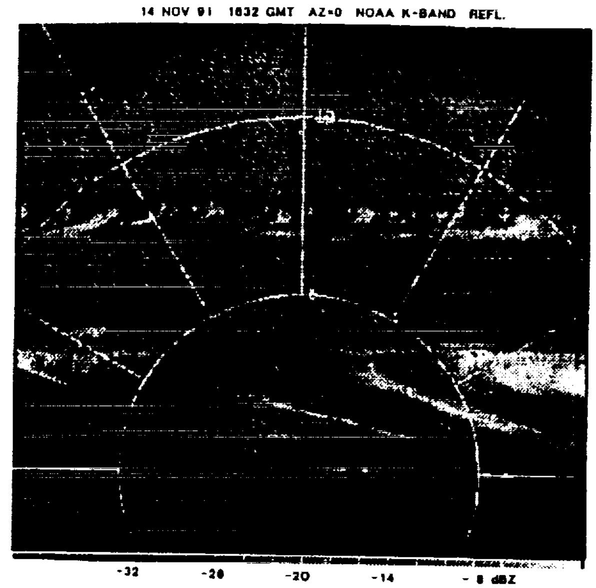

Figure 5. Reflectivity pattern for an RHI scan from the FIRE-II project in Kansas. Cirrus and precipitating altostratus layers are shown.

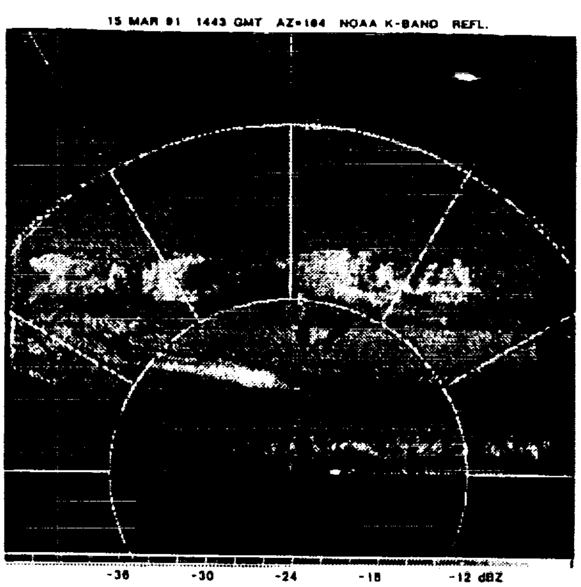

Figure 4. As in Fig. 2, except for cloud layers with more broken and cellular structure.

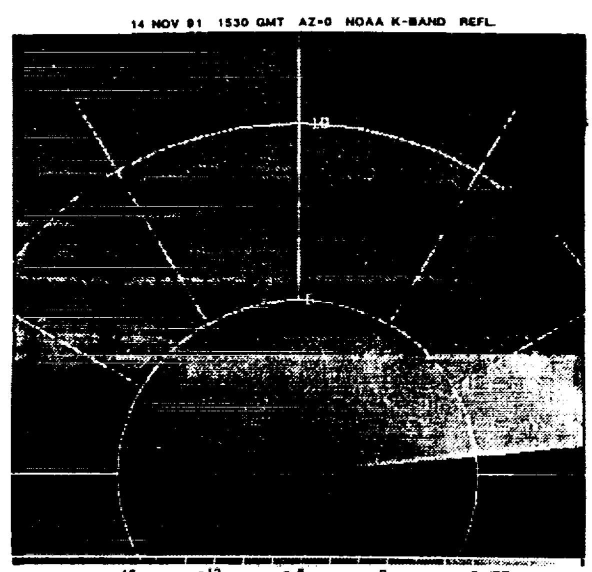

Figure 6. Reflectivity pattern of cirrus and nimbostratus from an RHI scan during the FIRE-II project. The thin horizontal line near 3.5 km AGL is the melting layer bright band.

Experiment (ASTEX) in the Madeira Islands of Portugal. A sampling of cloud reflectivity and velocity patterns from these projects are shown in Figures 2-12. These are black and white (gray scale) renditions of the color images used in data analysis, therefore some detail is lost in these reproductions. Darker shadings represent weaker reflectivities. Black speckles on some of the figures are random noise between cloud layers that has not been entirely edited from the data by thresholding schemes.

Figures 2, 3, and 4 from different days during WISP show combinations of stratus, altostratus, and cirrus layers. These are range-height indicator (RHI) displays of scans from one horizon over the top of the radar to near the opposite horizon. They are nearly instantaneous, vertical cross section "snapshots" of the cloud reflectivity structure. In Fig. 4, the stratus cloud from just above the ground to about 1.5 km AGL was penetrated by a research aircraft and found to contain only small supercooled liquid water droplets. This aircraft icing hazard cloud was not detected by other, longer wavelength radars used in WISP. Its cellular structure is apparent in the K-band data.

Figure 5 from FIRE-II shows two altostratus layers below 5 km and a cirrocumulus layer near 7.5 km. Precipitation streamers from the upper and lower layer are stretched in opposite directions by shear of the horizontal winds.

Figure 6 from FIRE-II shows an RHI scan of a cirrus layer above a deep nimbostratus cloud. The horizontal line of stronger reflectivity at 3.5 km is the radar bright band caused by melting. It marks the transition from snowfall (above) to rainfall (below) in the cloud. The radar's ability to penetrate precipitation and detect clouds beyond the precipitation is clearly illustrated.

Figure 7 from CLARET-II is a time-height reflectivity display of clouds passing over the radar while its antenna was pointed at the zenith. It shows an altostratus layer at 2-4 km and cirrus clouds above 5.5 km. A similar situation from FIRE-II is shown in Fig. 8, but the altostratus' reflectivity pattern has a more cellular appearance in this case.

Marine stratus and stratocumulus clouds from ASTEX are shown extending less than 2 km above the surface in the time-height display of Fig. 9. At such close ranges, reflectivities as weak as -50 dBZ are detectable from these liquid water clouds. Streamers of drizzle can be seen reaching the surface on the lower right side of the figure.

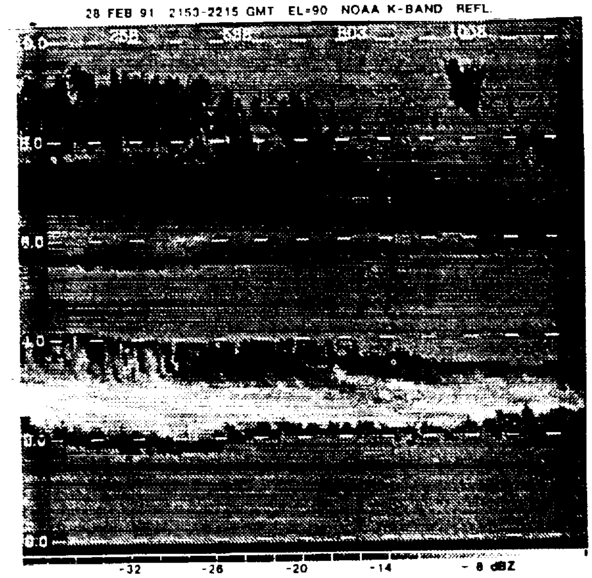

Figure 7. Reflectivity time-height display of cirrus and altostratus clouds passing over the vertically pointing radar during the CLARET-II project in Colorado. The horizontal scale spans 24 minutes (time increases toward the right), and the vertical scale spans 10 km above ground level with tick marks shown at 2-km increments.

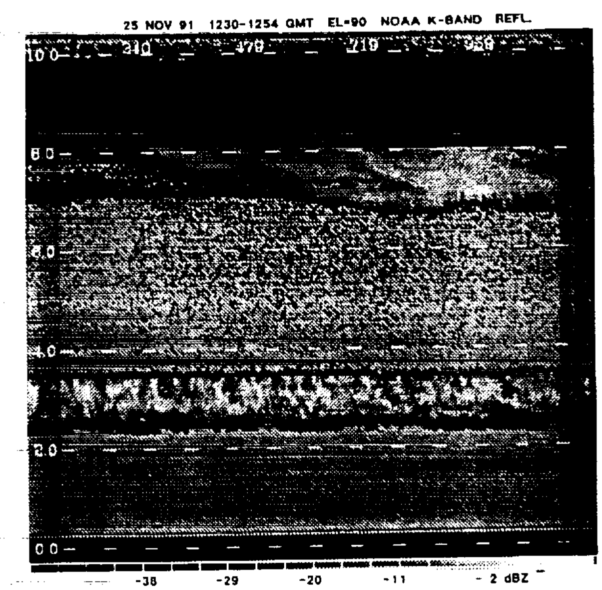

Figure 8. As in Fig. 7, but for clouds observed in the FIRE-II project.

Figure 10 is a time-height display of a deep stratiform cloud that produced drizzle during FIRE-II. Cloud base was near 2 km (+3°C) and cloud top was near 8 km (-36°C). The radar easily penetrated the drizzle streamers to reveal detailed structure in the cloud to its top. As time progressed, Kelvin-Helmholtz instability billows developed at cloud top and eventually took the shape of breaking waves in the upper right part of the figure.

Figures 11 and 12 are time-height displays of reflectivity and vertical Doppler velocity, respectively, for a pair of cirrus layers during FIRE-II. The Doppler velocity, which is the air's updraft speed minus the mean hydrometeor fallspeed, varies from about -1.25 to +0.75 m s^{-1} with a 2-min periodicity. These velocity undulations are offset in time in the two layers, as shown by the tilted pattern. This suggests the undulations were the result of either a vertically propagating wave or a slightly tilted wave front that propagated horizontally, reaching the lower layer first.

5. Cloud Detection and Boundaries

The radar's ability to detect various weak clouds has been demonstrated in these recent projects. Comparisons with measurements by a collocated WPL lidar have been made in the CLARET and FIRE-II experiments. From this experience we conclude that the radar can detect almost all clouds overhead, with the notable exception of some tenuous cirrus. This exception may be a serious shortcoming in some kinds of studies, but is probably insignificant for aviation applications, for which the radar's ability to penetrate liquid cloud layers is a much more important attribute.

How well the radar echo tops and bases agree with actual hydrometeor cloud tops and bases has not yet been established. In the WISP experiment the radar echo tops were compared with cloud top heights recorded by research aircraft flying in 21 nearby stratus and altostratus layers and the agreement was excellent. It is expected, however, that the radar echo tops will often underestimate the cloud top height of weak cirrus because the ice particles may be very small and present in low concentrations at relatively long range. The radar's usually precise measurement of cloud base height is sometimes obscured by precipitation and virga, as in Fig. 6, but it can be estimated if the streamers are intermittent, as in Fig. 10. Lidars have much narrower beamwidths that allow them to miss very sparse precipitating hydrometeors and therefore obtain a more precise measurement of cloud base. However, if the rain rate increases to light intensity, the optical beam becomes blocked near the surface and its measurements are not useful.

6. Combined Remote Sensors

Combining simultaneous data from different collocated remote sensors presents an opportunity to obtain new information on cloud microphysics and overcome the shortcomings of individual instruments. For example, the combined data from a vertically pointing microwave radiometer, Radio Acoustic Sounding System (RASS), ceilometer, and K-band radar have been used to estimate profiles of liquid water aloft and determine aircraft icing altitudes[5]. Several additional remote sensors may also be useful for detecting icing conditions[6]. In separate but related studies, the WPL K-band radar measurements have been combined with those of a lidar[7], an infrared radiometer[8], and an infrared spectrometer[9] to infer microphysical properties of clouds, such as characteristic particle sizes.

7. Aviation Applications

Knowledge of the heights and thicknesses of all cloud layers in the vicinity would be useful for vectoring aircraft near a terminal area. The sensitivity demonstrated by the WPL K-band radar is clearly sufficient to detect low reflectivity and low-level cloud layers that are not detectable by conventional longer wavelength radars available today at similar cost. In addition, the excellent ground clutter performance of this system allows detection of weakly reflecting clouds at rages within a few hundred meters.

The WPL K-band radar is designed for research. As such it generally cannot be operated unattended. However, a simplified, durable version could be designed today with the engineering sophistication necessary to allow long-term, continuous, unattended operation. Such an operational radar system could be used in a vertically pointing, fixed-beam mode or in a scanning mode to monitor the spatial distribution of clouds in the airport vicinity. By combining measurements from the radar to locate cloud boundaries, RASS to measure profiles of temperature, and a microwave radiometer to measure the total amount of liquid water along its beam, layers of supercooled liquid water that produce aircraft icing would be detected and isolated. With such a system, the airport of the future would have a much more complete depiction of the cloud environment than the rudimentary ceiling and visibility information available today. Such a system would also be very useful for climate-related field studies of how clouds modulate the atmosphere's radiation budget.

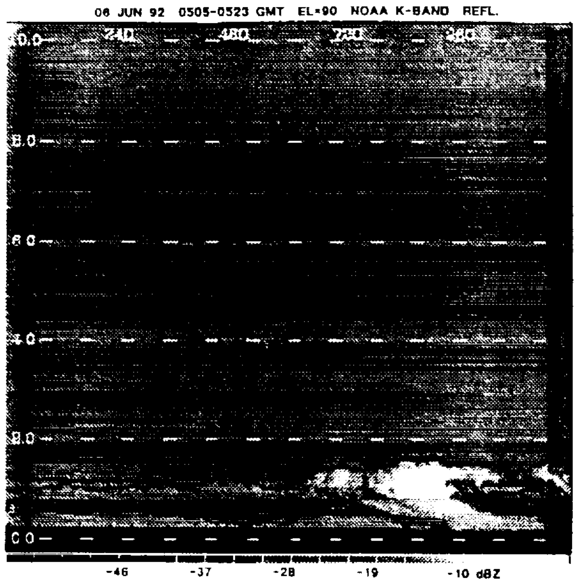

Figure 9. Time-height display of the reflectivity pattern of marine stratus and marine stratocumulus from the ASTEX project in the eastern Atlantic Ocean. The horizontal scale spans 18 minutes.

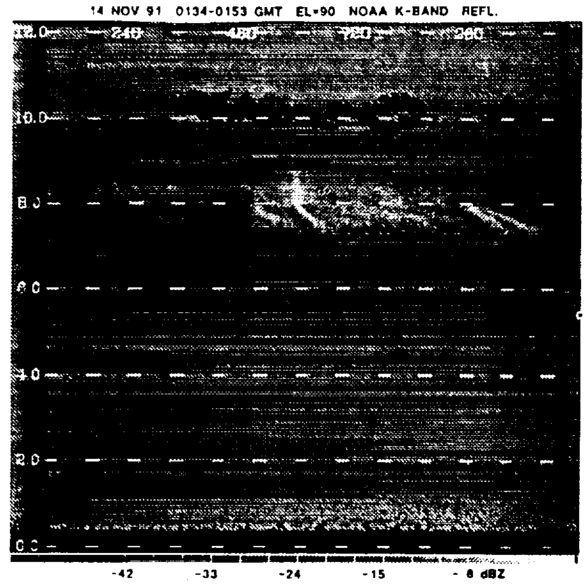

Figure 11. Time-height display of reflectivity of two cirrus layers during the FIRE-II project. The horizontal scale spans 19 minutes.

Figure 10. Time-height display of a deep stratiform cloud that produced drizzle during the FIRE-II experiment. The horizontal scale spans 14 minutes. Note the breaking waves at cloud top in the upper right corner.

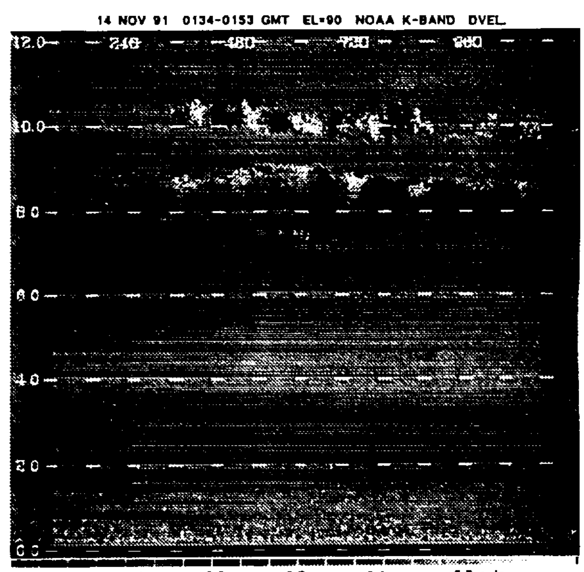

Figure 12. As in Fig. 11, except showing the vertical Doppler velocity pattern in the cirrus layers. Positive values indicate upward motion.

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