NOAA Climate Studies of Stratocumulus Clouds and Air-Sea Interaction in Subtropical Cloud Belts.

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Nov. 16, 2003

Greetings from the South Pacific. I am writing from the Research Vessel Roger Revelle, (Fig. 1) presently located at 20 S latitude 85 W longitude hundreds of miles off the coast of Northern Chile. My name is Chris Fairall and I am a scientist at NOAA's Environmental Technology Laboratory in Boulder, Colorado. A group of 4 ETL scientists is participating in a study of oceanography and meteorology in a region of the ocean that is known for its persistent stratus clouds. We share the ship with more than 20 other scientists from around the world who are involved in different aspects of the study.

The Woods Hole Oceanographic Institution (WHOI) has maintained a climate monitoring buoy at this location for the last 3 years. Each year they come out to take out the old buoy and replace it with a brand new one with fresh batteries and new sensors. A year in the marine environment takes a toll on the toughest instruments. This is a special buoy which is festooned with atmospheric sensors to measure air-sea fluxes and with a long chain of subsurface instruments to measure ocean currents, temperature, and salinity (Fig. 2). If you go to the WHOI website http://uop.whoi.edu/stratus you can read about this project and see data from the buoy. The data are transmitted by via satellite every day. WHOI will be removing the old buoy on Monday (Nov. 17) and putting in the new one right after that.

Why are these clouds so important? Because the earth's climate is driven by energy from the sun and clouds dominate how much solar energy reaches the surface. On average, almost 40% of the sun's energy is reflected back to space and half of that is reflected by clouds. In cloudy regions more than 60% of the sun's energy can be reflected by clouds. The surface temperature of the ocean is the result of a near balance between solar heating and cooling by evaporation and cooling by infrared (IR) radiation from the water surface into the sky. The global circulations of the atmosphere and ocean are driven by region differences in this net heat input, so clouds have a large direct effect on the winds and currents.

Cloud effects on the ocean surface energy balance are very tricky because clouds affect both the solar flux (i.e., by reflecting energy back to space) and the IR flux. It might surprise you, but the sky is 'warmer' when there are low clouds present than when the sky is clear. Think about those cold, clear nights in the winter and note that 'cold' often appears with 'clear'. More specifically, the IR radiation coming down from the sky is higher when clouds are present than when it is clear. In the tropics and subtropics, the solar refection cooling effect of the clouds is much stronger than their compensating IR warming effect. Thus, these stratus clouds play an important role in keeping the subtropical oceans cool. The region we are studying is one of 5 stratus regions around the globe (west coast of the US, west coast of S. America, west coast of S. Africa, west coast of N. Africa/Europe, and the west coast of Australia) that occupy vast expanses of ocean. Figure 3 shows some examples of stratocumulus clouds in this region. Each of these cloud types has about the same area-average liquid water content but, because of their horizontal distribution, vastly different radiative properties. The physical processes that lead to these different forms are one of the objectives of our study.

In climate small energy imbalances can be important. For example, a change of just 5 Watt/m^2 in the surface heat balance would eventually cause the ocean surface temperature to change about 1 degree C, or, by about the total global warming observed in the last century. How big is 5 W/m^2? Well, for completely clear skies the annual average solar flux at the ocean surface is here is about 260 W/m^2, so 5 W/m^2 is less than 2%. In fact, it strains the state-of-the-art to measure the heat balance with an accuracy of 10 W/m^2.

Clouds are formed through various related mechanisms; most involve cooling air to below its dew point temperature so droplets condense (i.e., clouds are suspensions of liquid water drops with typical sizes of about 10 micrometers radius). Convective clouds are associated with cooling in strong updrafts; fog and many mid-atmospheric clouds form when an atmospheric layer cools by IR radiation. The stratus clouds we are studying are quite different. The key elements are a strong atmospheric cap that traps ocean moisture in a fairly thin (about 1 km high) boundary layer over the surface. The stratus clouds occupy the top of the trapped layer from just below the cap down to the altitude (cloud base height) where temperature and dew point just meet. Below that, the relative humidity is less than 100%. The 'cap' on the atmospheric boundary layer is warm/dry air descending in subtropical regions, particularly on the western boundaries of continents. This descending air is actually driven by deep convection in the tropics. To meteo-nerds this is an amusing paradox – cool, stratus clouds off Chile and California are essentially caused by thunderstorms near the Equator.

Clouds are a pain to study because they are so inaccessible. To get into the cloud with sensors you need a really tall tower, a tall building, or an aircraft. Most of these are hard to come by 500 miles from land. Thus, most climate studies of clouds rely on remote sensing methods using satellites or surface based sensors. ETL has deployed a suite of remote sensors on the Revelle to study clouds from the bottom. The showcase sensors are a special high frequency cloud radar and a two-frequency microwave radiometer system (Fig. 4). This is the 6th time such sensors have ever been deployed from ships and only the second time to a stratocumulus region. The first time was to this same spot in 2001; see the web site http://www.etl.noaa.gov/programs/2001/epic/ for information on this cruise. The radar has a wavelength of 8 mm, which is so small that it is sensitive enough to receive detectable signals from scattering by cloud droplets. With this device we can determine profiles of cloud properties (such as the size of the droplets) through the entire cloud. The microwave radiometer uses the emissions from the atmosphere at two frequencies (21 and 31 GHz, or wavelengths of 14 and 9 mm) to determine the total amount of liquid in the cloud. We use a laser ceilometer to determine cloud base height and, most importantly, we also measure the IR and solar radiative energy reaching the surface.

Sample data from the ceilometer (Fig. 5) and the cloud radar (Fig. 6) give an interesting view of clouds. Instead of just looking at the cloud, we collect megabytes of data every minute. The beauty of this setup is we simultaneously measure the effect the clouds have on the surface energy budget of the ocean and the cloud properties (liquid water content, thickness, soiled versus broken, number of cloud droplets per unit volume) that go with the radiative effects. We are only out here a few weeks each year, but our detailed measurements provide vital information to interpret long-term continuous time series measured by the buoy or inferred from satellite overpasses.

To illustrate the cap on the boundary layer (also referred to as an inversion), I have attached a radiosonde profile of temperature and relative humidity as a function of altitude that was launched about 1800 on Nov. 14. This corresponds to the latter part of the 24-hr period shown in the ceilometer picture and to the beginning of the period shown for the cloud radar. You can use a spreadsheet program (excel or quatropro) to view and plot this file. Notice that as you go up from the surface the temperature decreases and the relative humidity increases. RH peaks at about 97% whereas RH should be 100% in the cloud. This is because the simple RH sensor on a radiosonde is not super accurate (dare we say cheap?). Questions for the reader: what heights are cloud base, cloud top, and the inversion? Notice that it is warmer at 2 km altitude than it is at the surface. Exercise for more advanced students: look up the term *potential temperature* and ponder its implications for this sounding and how strong the boundary layer is capped.

Figure 1. The Scripps Oceanographic Institution Research Vessel Roger Revelle at 20 S Latitude 85 W Longitude supporting NOAA's Ocean Obsevations and Climate Variability programs. ETL's seagoing flux system is on the mast on the bow; the cloud radar and microwave radiometer container is forward on the second white level (you can see the antenna on top). The replacement WHOI climate buoy is the round white object sitting low on the stern. The buoy is lying on its side are you are looking at the bottom.

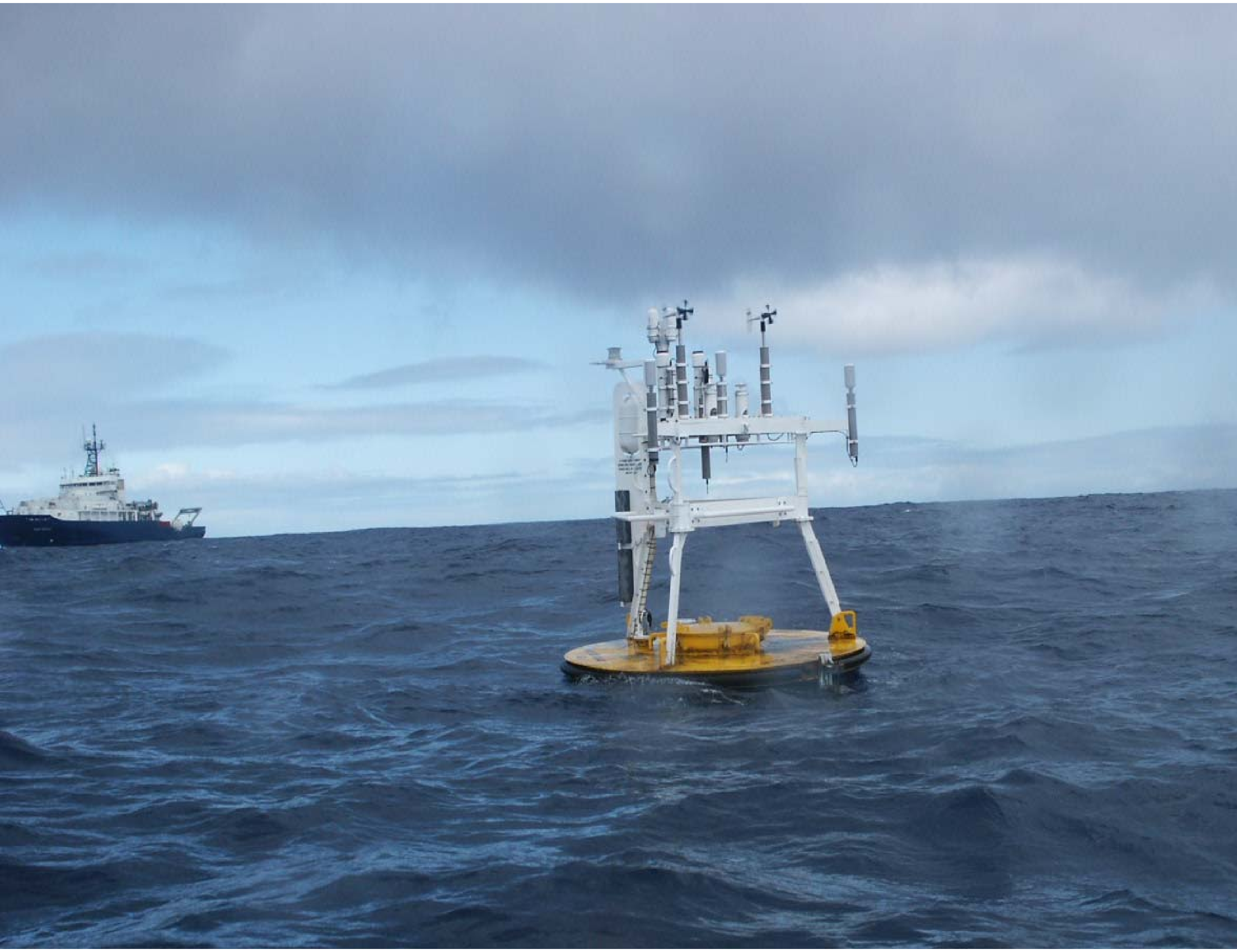

Figure 2. The old WHOI buoy awaiting replacement after a year on the job.

Figure 3. Three pictures showing the stages in the transition from solid, homogeneous stratus cloud (upper) to broken clouds (lower) with multiple layers in the boundary layer.

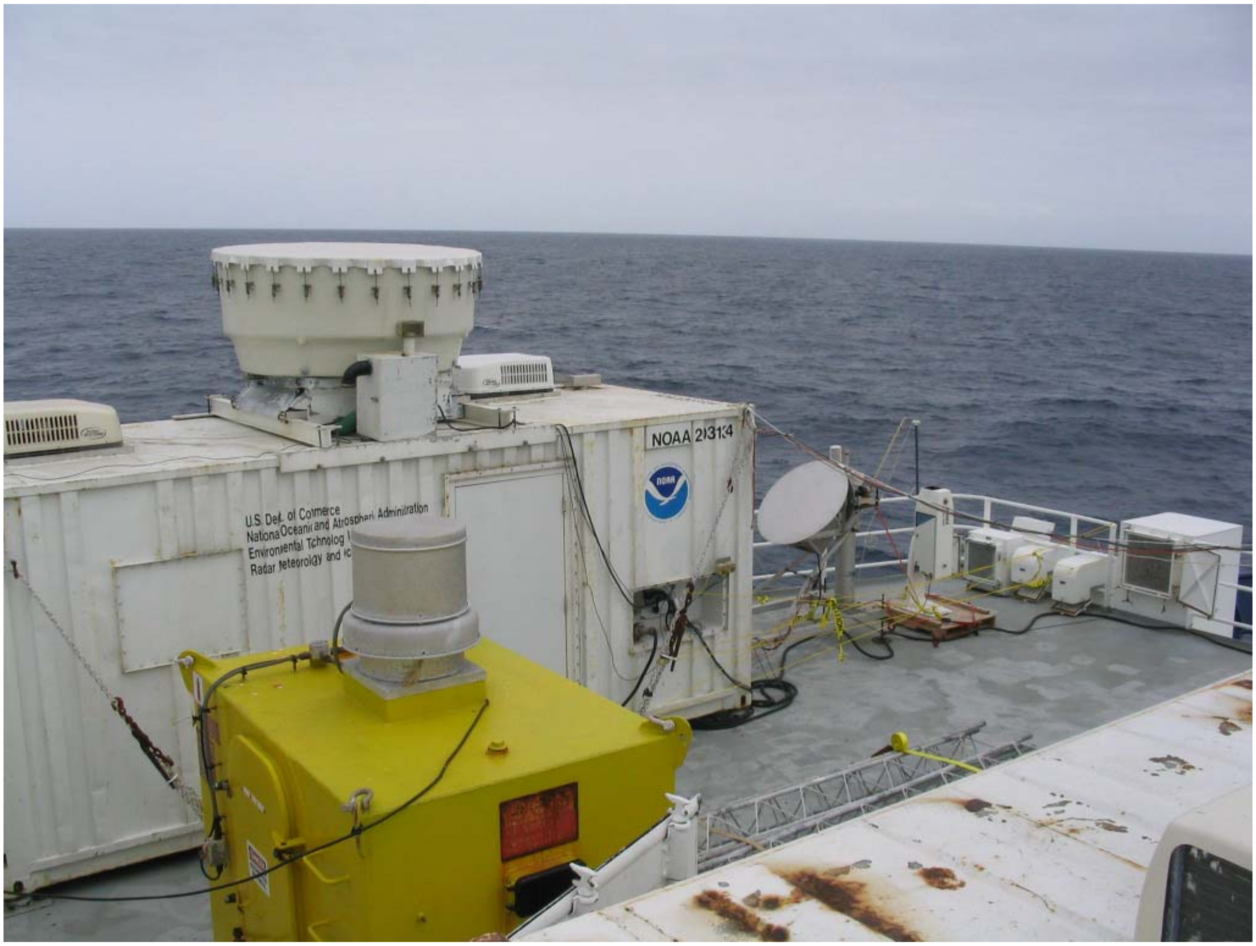

Figure 4. The ETL cloud radar antenna on top of the container on the forward deck of the R/V Roger Revellle. The large flat disc just to the right of the container is the reflector for the microwave radiometers inside the container. The laser ceilometer is the small white R2D2-like device on the pedestal just to the right of the reflector. The yellow box is a hazardous materials locker. The trailer in the foreground houses aerosol sampling instruments from Texas A&M University. The dark blue stuff in the background is the ocean.

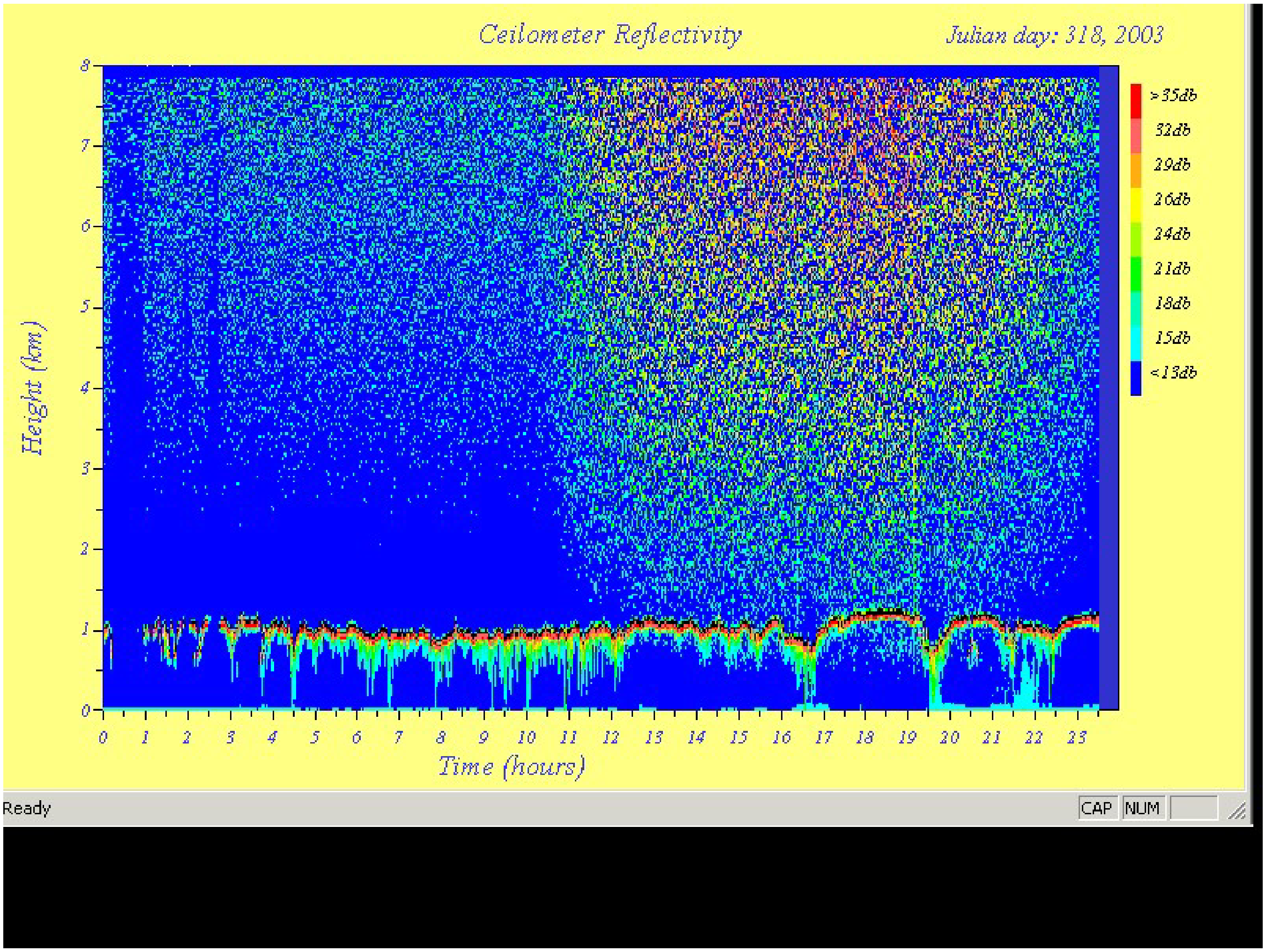

Figure 5. Image from laser ceilometer showing a time-height cross section of the atmosphere over the ship for Nov. 14, 2003. Cloud base is evident as the black dots running at about 1 km altitude. Since this indicates the bottom of the cloud, the body of the stratus cloud is above this level, but is not displayed by the ceilometer because the laser beam only penetrates a few meters into the cloud. Light bluish regions below the cloud indicates light scattering from aerosols that have grown to haze particles in the high relative humidity just below the cloud.

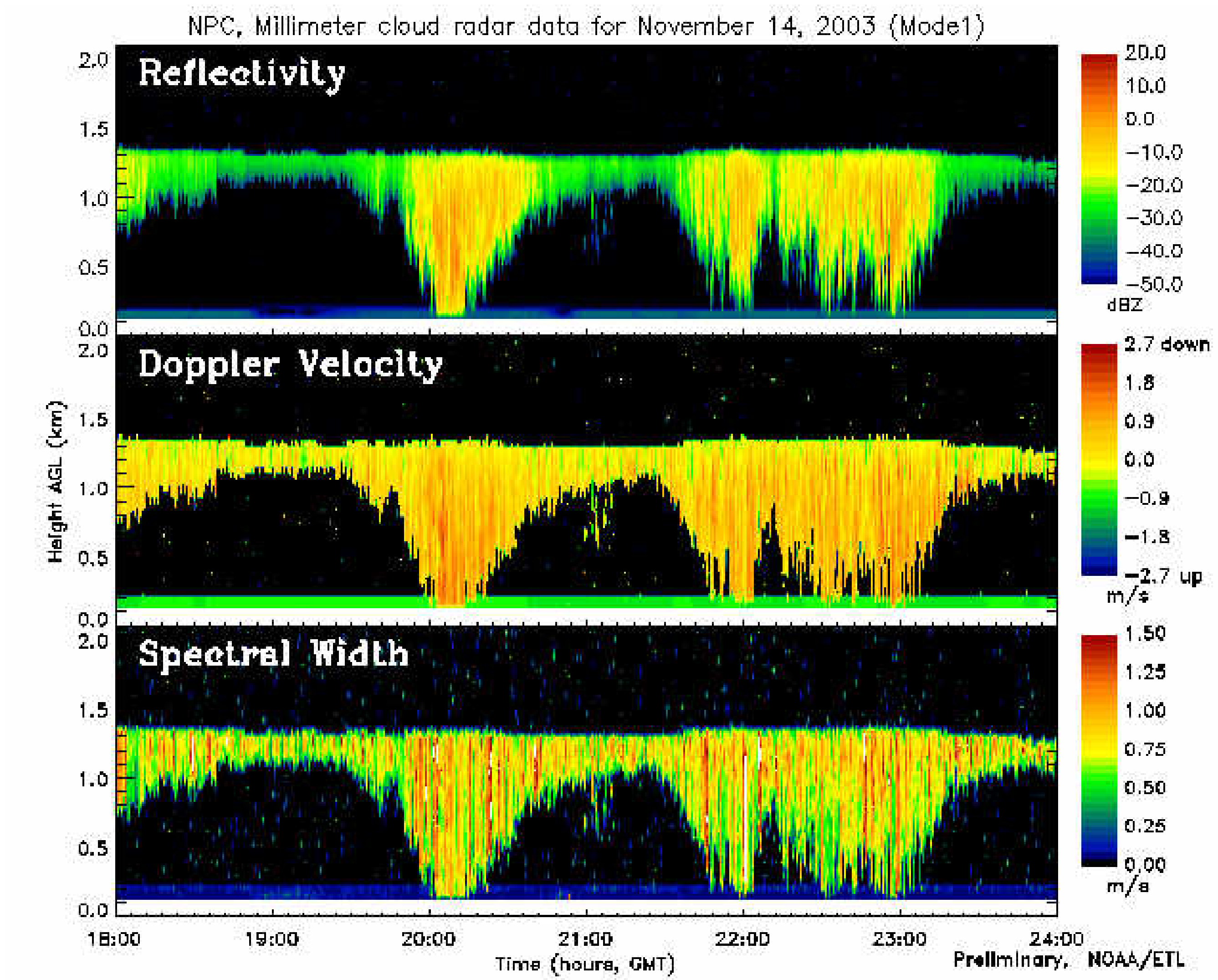

Figure 6. Time-height cross-section from the ETL cloud radar showing stratus clouds for 6 hours on Nov. 14. The upper panel is the backscatter intensity from the cloud and drizzle droplets; the middle panel is the mean vertical fall velocity of the particles (positive means downward motion). The deep regions of return that reach the surface indicate light rain (drizzle). This case has highly varying cloud characteristics.