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Ship-Track Clouds, Aerosol, and Ship Dynamic Effects; A Climate Perspective from Ship-Based Measurements

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ABSTRACT

Ship-track clouds are marine boundary layer clouds that form behind ocean ships and are observed from satellites in the visible and near infrared. Ship-track clouds provide a rare opportunity to connect aerosol cloud condensation nuclei (CCN) emissions and observable changes in marine stratiform clouds. A very small change in the reflectivity of these eastern Pacific and Atlantic clouds (about 4 %) provides a climate feedback of similar magnitude to doubling CO_2 (increasing cloud reflectivity corresponds to global cooling). The Department of Energy sponsored research from 1991 to 1995 to study ship-track clouds including two ocean-based experiments in the summers of 1991 and 1994. These experiments showed that ship-track cloud properties were often more complex than those related to a reduction of droplet size with an increase in number associated with increasing CCN from the ship's plume. The clouds showed evidence of morphological changes more likely to be associated with cloud dynamic effects either initiated by the increased CCN or directly by the ship's heat output or turbulent air wake. The fact that marine stratiform clouds, that are susceptible to ship track formation, are starved for both CCN and convective turbulence complicates the separation of the two effects.

INTRODUCTION

Ship-based measurements in June 1991 and June 1994 sponsored by the Department of Energy provided information about ship-track clouds and associated atmospheric environment. These observations from below cloud levels provide a perspective different from satellite and aircraft measurements. Ship-track clouds observed by satellites occur usually in the summer months over the cold and windy eastern ocean margins. They can be over 400 km long and persist for several days. They are much more rare than aircraft contrails (perhaps a peak frequency of one or two occurrences a week off the Coast of California). Though a small direct climate effect is possible, the ship-track phenomenon is studied mainly to improve our understanding of how aerosol and cloud dynamics affect low level stratocumulus clouds (the main cloud cooling mechanism for the planet). Separation of aerosol Cloud Condensation Nuclei (CCN) effects and ship-dynamic effects is difficult in this region of the ocean as potential cloud forming regions can be starved for both CCN and turbulence mechanisms usually prevalent in other ocean regions.

Marine stratiform clouds are a major cooling mechanism for regulating the earth's climate[1]. A 4% increase in such low stratus clouds can offset a warming associated with a doubling of CO_2. These clouds occur more frequently over cool water and an increase in CO_2 may increase sea surface temperature. It has been suggested that this process may reduce marine cloud cooling. This would lead to a strongly positive climate feedback[2]. However, the CO_2 effect could be just the opposite. The eastern Pacific Ocean margins experience the coldest ocean temperatures in July and August. This is caused by increased summer winds and the up-welling of colder ocean waters. If the hemispheric climate due to increasing CO_2 amplifies normal summer conditions, this implies that marine stratiform clouds would increase. This means a negative feedback for global warming. The treatment of marine stratus clouds in Global Circulation Models (GCMs) is highly parameterized and uses coarse vertical resolution. GCMs at present support neither a positive nor a negative marine stratus cloud feedback hypothesis. Model calculations of a cloud feedback range from strongly positive to slightly negative feedback[3]. Therefore, in order to estimate the sign of marine stratiform cloud/climate feedback a combined study of marine cloud fraction, albedo, SSTs, and meteorological context is required. This is not a simple task, however. Even after intensive stratocumulus cloud studies[4,5] the effect of perturbations on these clouds is not well understood.

Ship-trail clouds offer a method of isolating the marine stratiform clouds most sensitive to external forcing. Our limited experience with ship trails and simultaneous meteorological profiles imply that the presence of both a relatively shallow marine boundary layer and stratiform clouds are required for ship-trail formation[6]. The background stratiform clouds are often difficult to observe from low resolution satellite images. We have also found that in many cases the background cloud modification generated by ships involves a change in the cloud dynamics as well as the albedo[6]. These modifications may be caused by buoyancy effects from the heat release of the ship's engines, the latent heat of condensation released by ship CCN introduction into the cloud[7], forcing by modification of radiative cooling with resulting circulations, and/or by vertical updrafts from the air wake of the ship up to the top of the boundary layer[8,9].

Additional information can be gained from the fact that ship-trail clouds appear differently depending on the wavelength of the satellite detector. Ship trails observed by the Geostationary Orbiting Environmental Satellite (GOES) at visible wavelengths appear as anomalous cloud lines in regions of broken marine stratocumulus and/or fog that are too small to be resolved by the sensor. These regions with broken clouds appear in visible GOES images as gray. Marine stratus clouds in other regions are white, and cloud free regions are black. This form of ship trail (called anomalous lines by Conover[10]) is relatively rare compared to a form (usually described as ship track clouds) that is invisible in the GOES image but obvious in the National Oceanic and Atmospheric Administration-Advanced Very High Resolution Radiometer (NOAA/AVHRR) Channel 3 near-infrared wavelength. Possible explanations for why the contrast of ship tracks in stratiform clouds is enhanced in channel 3 are described in Coakley[11], and Platnick and Twomey[12].

Only a few studies of the *in situ* characteristics of ship-tracks have been carried out. In studies to date, emphasis has been on the aerosol microphysical characteristics of ship tracks[7,13,14,15], while cloud dynamic aspects have been largely ignored. This is due to the subtle boundary layer cloud perturbations that may trigger ship tracks and the difficulty in measuring these perturbations. The marine environment associated with ship tracks represent extremes in respect to low concentrations of cloud condensation nuclei (CCN) and the lack of surface temperature and roughness differences associated with convective turbulence effects in clouds. Numerical models that go beyond most plume rise and dispersion models can be useful in understanding the sensitivity of marine stratiform clouds to CCN and turbulence effects. Innis[16] calculate that temperature differences as small as 0.1 ^{o}C can increase cloud-level aerosol concentrations by over a factor of two in decoupled boundary layer conditions. Systematic vertical velocities as low as a few centimeters per second and/or associated air temperature increases of less than 1 K have produced modifications of marine boundary layer clouds in a statistical-dynamic numerical model that mimic many of the morphological and cloud liquid water characteristics associated with ship tracks[6].

SEAHUNT 1991

Research vessel-based measurements of atmospheric parameters associated with ship tracks have several advantages over aircraft measurements, such as the research vessel being stationed for long periods at sea. Consequently, data were obtained on the evolution of conditions leading to ship-track formation during the day and at night. A ship-based experiment on the research vessel *Egabrag* to study ship tracks and other external forcing on marine boundary-layer clouds called SEAHUNT (Ship-Track Evolution Above High Updraft Naval Targets) was performed in June 1991 off the coast of southern

California and northern Mexico[9]. This experiment documented the first surface observation of a ship-track cloud that was known to be a ship-track cloud simultaneously observed by satellite.

Separate aspects of this experiment are described in Hindman[9] and Hudson[17]. The major ship trail observed persisted for only one day (Figure 1). The background cloud form within which we encountered this ship-trail cloud on 13 July was low-level patchy surface fog. This cloud form was associated with extremely low surface concentrations of CCN. We encountered four well formed ship trails at night (three on the night of 12-13 July and one on the night of 24-25 July). A very prominent and well defined ship trail was observed about 11:00 PDT on 13 July. Heavy drizzle was observed the preceding day and night. Although it may not be clear in the reproduction of Figure 1, a small ship trail was associated with our research vessel (Figure 2). This is surprising given the small size and CCN release rate from our ship. Also surprising is the wavelength dependence of this feature in the satellite imagery. As Coakley[11] points out, AVHRR channel 3 permits observation of ship trails that cannot be seen at visible wavelengths.

The ship trail produced by our research vessel can be observed in the visible wavelength channels of GOES and AVHRR satellite images, but is not readily detectable on the channel 3 AVHRR image. Since channel 3 is very sensitive to droplet size, this seems to imply that though the ship appears to have increased the cloud liquid water in clouds in its wake, the clouds in the trail do not appear to have significantly different cloud droplet sizes. This is expected in low CCN environments since the channel 3 reflectance/droplet size relationship is flat at large droplet sizes (12-15 mm radius). The fact that the trail observed was our own and no droplet spectral measurements were made during this experiment means that we could not independently verify the lack of size differences suggested by the satellite. Visual observations of fogbows during this time showed a lack of color separation consistent with larger droplets[18].

The CCN levels increased beneath the ship trail (Figure 3) to levels about a factor of two higher than mean levels observed below fully developed marine stratus encountered about an hour later. The low CCN levels observed on this day were necessary for unique discrimination of the ship trail from shipboard observations. Visual observations from the ship indicated that the ship-trail cloud top was higher than the background cloud tops. This was done by observing photographs of the trail as background clouds passed between our ship and the ship trail. Cloud free regions were also observed on both sides of the ship trail from our ship and from GOES satellite imagery. The cloud free region was much more extensive on the upwind (about 1.5 km) than downwind side of the ship trail. The cloud-free region on the upwind side of the ship trail is seen as an increase in the solar radiation in Figure 3. The clear region on the downwind side was shadowed by the ship-trail cloud and is not distinct in the solar radiation record. The existence of these cloud free regions implies that there was a strong cloud dynamic effect. The possible importance of cloud dynamic effects on ship-trail formation was proposed by Porch[6]. Recent support for this hypothesis has come from analysis of features generated by islands in the California current that appear identical to ship trails in satellite images[19].

Figure 4 shows the evolution of the marine boundary layer through the ship-trail period of July 12 and 13 as reflected in daytime rawinsonde soundings. This figure shows the background boundary layer structure within which the ship-track cloud formed. These profiles show that this period was associated with increasing wind speeds, drying above the boundary layer, and descent of the top of the boundary layer to about 400 m. The nighttime sounding on 13 July (the day of the ship trail observed in Figure 1) showed a small, secondary temperature inversion at about 200 m.

The meteorological conditions before the ship-trail encounter on 13 July included heavy drizzle and surface fog. Albrecht[20] have shown from FIRE 1987 analysis that the adiabatic liquid water content is often a good estimate of liquid water content estimated from microwave radiometry of marine stratocumulus clouds. We can determine the adiabatic liquid water content from the profiles shown in Figure 4. These calculations yield adiabatic liquid water contents for the nighttime clouds of 0.40, 0.35, and 0.52 g/m^3 for July 11, 12, and 13, respectively. The analogous daytime values were 0.38, 0.19 and 0.46 g/m^3. These values are more than a factor of two lower than the adiabatic liquid water contents observed by Albrecht[20]. These lower values may indicate the effect of the drizzle and the warmer sea surface temperature. The lower liquid water contents after drizzle may be associated with a greater sensitivity to small changes due to ship modification. All that we know for certain is that these clouds were thinner or cooler than those observed during FIRE 1987 when less drizzle was experienced. The drizzle period between 11 July and the morning of 13 July may have precipitated some of the cloud liquid water.

Both GOES and NOAA/AVHRR satellite images for the month of SEAHUNT have been obtained and we are continuing to relate the ship-board measurements to the satellite data. The focus of the satellite analysis is the period from 11 to 13 July. During this period we passed beneath five discrete ship trails in various stages of evolution (a few hours to 2 days old). Each appears in the AVHRR Channel 3 image and in two cases in the AVHRR and GOES visible data. Each ship-trail crossing was associated with increased CCN levels as observed by the CCN spectrometer.

MAST 1994

Multiple observations were made from a small research vessel (*R/V Glorita*) during the Monterey Area Ship Tracks (MAST) experiment in June 1994 were combined to describe the physical and dynamic characteristics of ship-track clouds. A wide variety of aerosol and meteorological parameters were measured from the *R/V Glorita* simultaneous with aircraft flights. The focus of the surface, airborne and satellite studies during MAST was to improve the characterization of aerosol microphysical properties and cloud dynamic processes in ship tracks[21]. Important measurements were made during the MAST experiment from the *R/V Glorita*. Vertical profiles of background meteorological parameters (needed as input to numerical models simulating ship tracks) were obtained from both rawinsonde and tethered balloons launched from the *R/V Glorita*[22]. Also, surface properties such as sea surface temperatures, heat and moisture fluxes, were obtained from measurements on the ship. Surface aerosol properties and lidar measurements of the interaction of ship plumes and marine boundary layer clouds were made from the ship[23]. Measurements of cloud bottom heights related to ship-track clouds were measured from the ship with commercial ceilometers.

The properties of clouds affected by ships were remotely sensed with the ceilometers, microwave radiometers, and Doppler radars. Figure 5 shows the raw return signal for the tilted ceilometer during periods that ship tracks passed overhead of the *R/V Glorita* on 12, 27, and 28 June. The ceilometer laser could not penetrate most of the clouds observed so only the cloud bottoms (shown in white) are quantitative. The top of the white regions are more a measure of the optical depth in the cloud rather than the cloud top heights. Relatively strong effects on cloud morphology were detected on 12 June, with weaker changes associated with ship-affected clouds the other two days. Most of the changes are associated with the base of the clouds. The bottoms were lower by about 50 m than the background clouds. This condition has characteristics similar to the interaction of cooling tower plumes with overlaying clouds over land. Two cases on 27 June, on the other hand, seem to show a slightly raised cloud bottom (about 20 m) associated with older tracks (the *Tai He* at about 11:00 PDT and an older track at 15:40). Supporting pyranometer data are also shown in Fig. 4. The pyranometer data generally show a relative decrease in solar radiation associated with the ship track and often regions of relatively stronger solar radiation at the sides of the ship track (especially on 12 June).

Figure 6 shows an example of the LANL CW Doppler radar data for the second ship-affected cloud feature (*USS Safeguard*) on 12 June 14:44 through 15:04 PDT. Data storage capacity limited the observation periods for this instrument to about 1 hour. This figure compares the radar return strength (arbitrary units), the integrated Doppler vertical velocity (compensated for ship and cloud motion), the liquid water path from the microwave radiometer, the pyranometer signal (compensated for sun angle), and the ceilometer estimated cloud height. The CN measurements showed a very strong plume associated with this feature with CN concentrations rising to a maximum of about 10,000 cm^{-3}. Concentrations outside the plume were in the range of 1,000 cm^{-3} (this was a very clean day, as observed by aircraft measurements and may indicate some sample contamination in this case). The remote sensing comparison in Figure 6 shows that there is an apparent correspondence between the radar return strength and the cloud liquid water. Also, where the cloud liquid water is reduced at the sides of the feature, the Doppler vertical velocities show small peaks in subsidence. The transparency of the cloud, as shown by the pyranometer, peaks when the cloud liquid water decreases at the sides of the feature; the subsidence is maximized and the cloud bottom height reaches relative maximum.

The changes in cloud base features may be due to either cloud dynamic or cloud droplet microphysics. Adiabatic cooling, either from the initial convective plume from the ship or from evolved dynamic convection in the ship track, could explain the lowering of cloud base height associated with the ship track. Dynamic effects are consistent with the thinner cloud regions at the sides of ship tracks if general lofting in the ship track is compensated for by subsidence at the edges. It is also possible that the lower parts of the cloud are related to drizzle. However, this would require drizzle production rather than suppression associated with the ship tracks that showed a cloud-base lowering.

NUMERICAL MODEL RESULTS

The small rises in cloud base heights in the ship tracks on 27 June is a more subtle effect than the lowered cloud base observed near the origin of the ship track. Analysis from a three-dimensional statistical dynamic stratiform cloud model (Figure 7)[24] indicates that once ship tracks are formed the combination of cloud radiative effects and the latent heat released as the cloud develops causes the cloud bottom height to gradually rise with time. Figure 7 shows the effect of a 20 MW heat source moving diagonally through the computer domain. The dashed contours represent regions of subsidence (about 1 cm/s) on the sides of a central uplift region (again about 1 cm/s) generated by the heat source. The liquid water contours at different heights (maximum contour about 0.1 g/kg) are also shown. The fact that the ship track seems to rise slowly with time may partially explain the ceilometer observations shown in Figure 5. These observations show that the ship affected clouds had a lower base than background clouds on 6/12 and 6/28, but were higher than the background clouds on two occasions on 6/27/94.

CONCLUSIONS

Ship-based measurements provided unique information related to ship-track clouds from surface measurements and meteorological profiles from tethered- and free-balloons. The data are critical as inputs to, and constraints on, numerical models designed to simulate the effects of ship-plume aerosols, heat and moisture, and ship air wakes on marine stratiform clouds. Aerosol measurements of CN at ship-mast-level identified ship plumes. Lidar backscattering images show ship plumes couple with convective elements in overlaying cloud layers.

The SEAHUNT experiment was the first to combine marine boundary layer profile measurements with ship-trail observations. In order to quantitatively assess the relative impact of CCN, buoyancy, and turbulence contributions to ship-trail formation. Results from the SEAHUNT experiment in 1991 showed that the effect of external forcing mechanisms on marine stratus clouds varied from dramatic variation in cloud height and sensitivity associated with the tropical storm. The sensitivity of marine stratiform clouds to perturbations associated with ship effects was observed during SEAHUNT when five ship trails were intercepted by our research vessel. These days had the lowest marine boundary layer depths observed during the month. This is consistent with model calculations showing that ship trail clouds formed by buoyant heat release from a ship or lofting caused by the air wake of a ship would be restricted to relatively low boundary layer conditions. The ability of CCN from the ship to modify clouds to form ship trails may also require relatively low boundary layer heights. Conditions were so ideal on 13 July 1991, that our small research vessel formed a barely detectable ship trail feature while passing through patchy surface fog. This feature was somewhat unique in that it was observable by satellite in the visible and not the near infrared. Much more detailed information is needed on how a ship's effluent plume impacts marine stratiform clouds than provided by the SEAHUNT experiment.

The Office of Naval Research sponsored Monterey Area Ship Track (MAST) experiment conducted June, 1994 was designed to provide more information related to the ship's effluent plume. Information was obtained on cloud morphological changes associated with ship tracks. Comparison of data from remote sensors aboard the ship show that ships often affected the base and top heights of clouds. Comparison of data from remote sensors aboard the ship show that ships often affected the base and top heights of clouds by as much as 50-100 m. Relatively strong effects on cloud morphology were detected on 12 June showing a drop in cloud base of 100 m in a freshly produced ship track. Pyranometer measurements showed increased solar irradiance values of about 400 W/m2 on both sides of the ship track. Also, ship-affected clouds often have thin cloud or cloud-free regions on their sides. These physical features indicate that cloud dynamics may often be an important component of ship-track features. These features, combined with the fact that ship tracks seem to occur only within a relatively narrow range of boundary layer depths[25] (about 0 to 600 m) are difficult to explain based on aerosol CCN cloud droplet interactions alone. The possibility that cloud-droplet distributions may differ with height in ship-track clouds compared to background clouds due to internal dynamics, presents a challenge to the interpretation of aircraft measurements of aerosol and droplet spectra.

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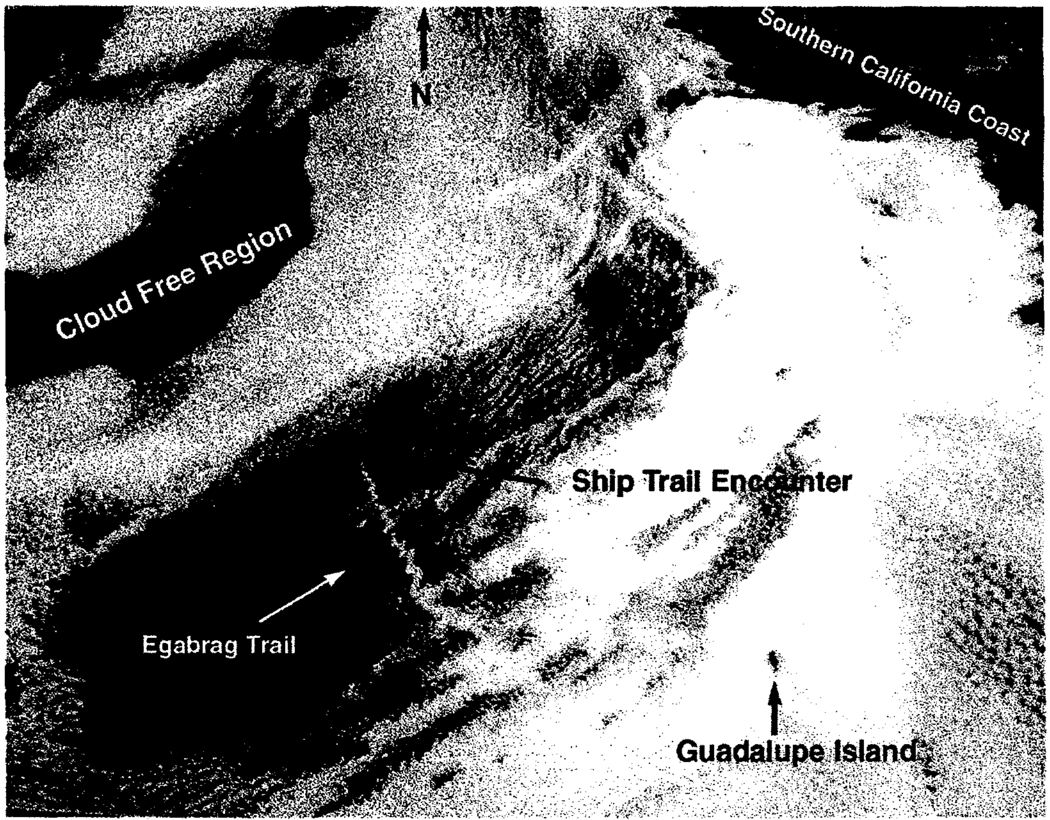
Figure 1. Ship-track cloud satellite image from GOES showing both a large isolated ship trail encountered on 13 July.



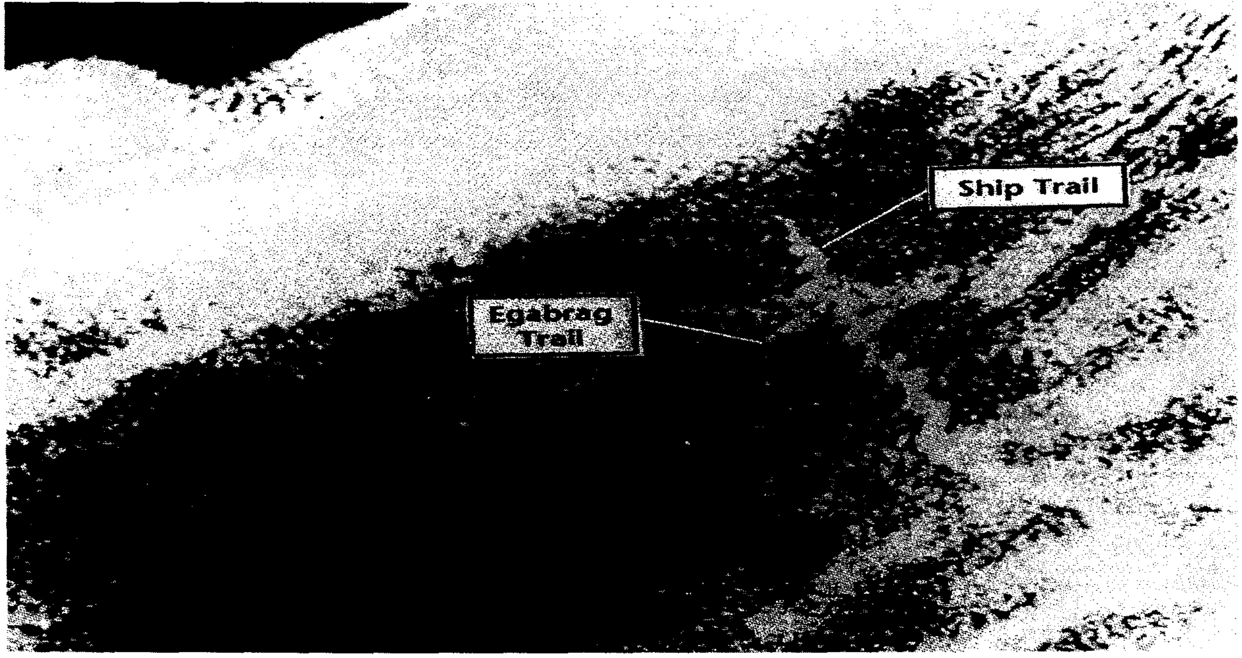


Figure 2. An enlargement of ship-track cloud in Figure 1 showing a small ship-track feature associated with our research vessel.

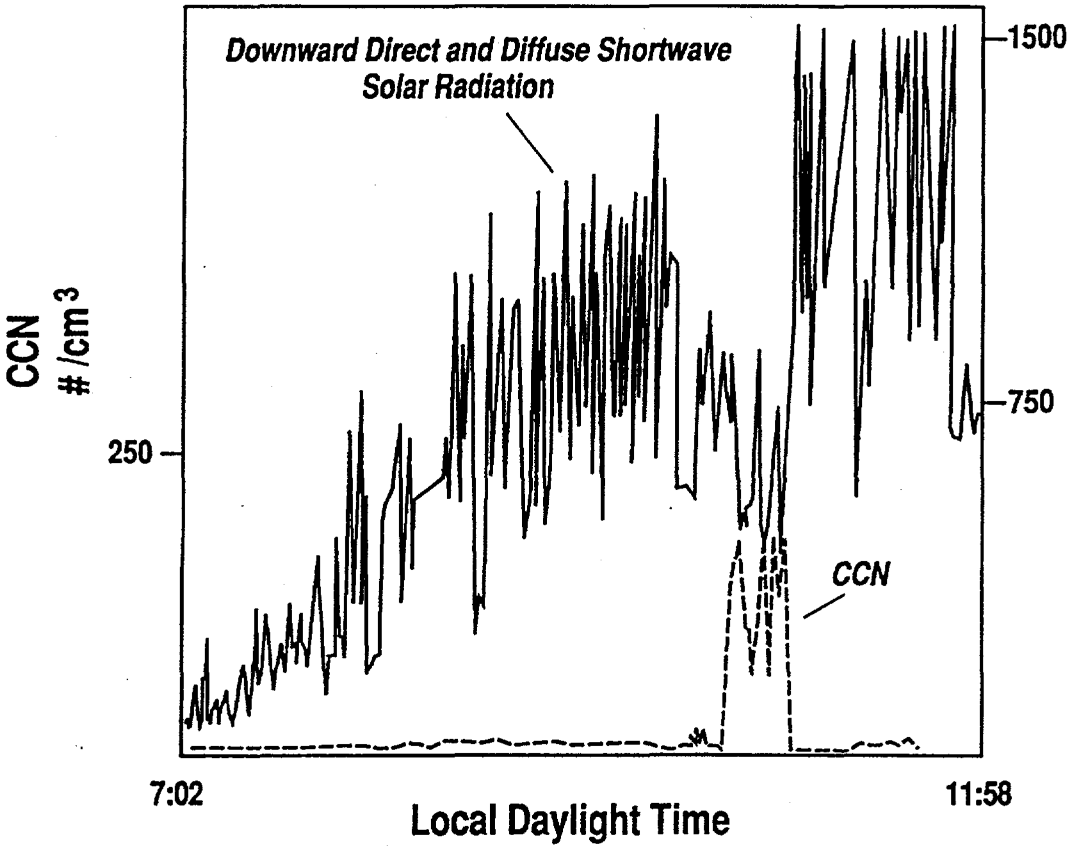


Figure 3. Surface measurements of (a) condensation nuclei (CN) concentrations (upper line) and cloud condensation nuclei (CCN) concentrations (lower line), and (b) solar energy as a function of local time (PDT) on the morning of 13 July 1991 (from Hudson[7]). The peak in CCN corresponds to the ship track encounter in Figure 1.

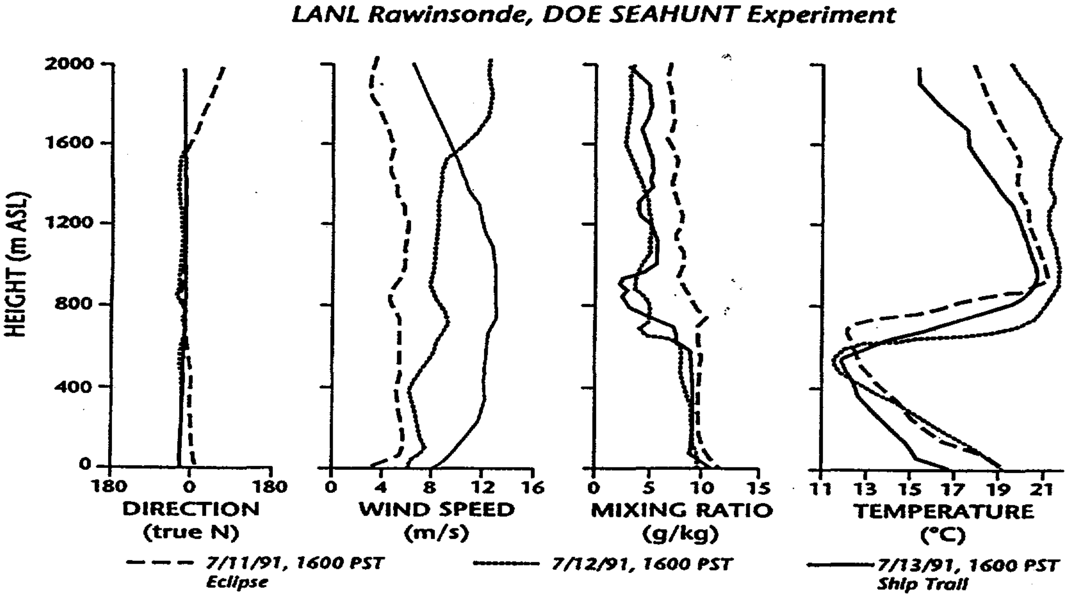


Figure 4. Evolution of boundary layer depths over ship-trail period during afternoon soundings.

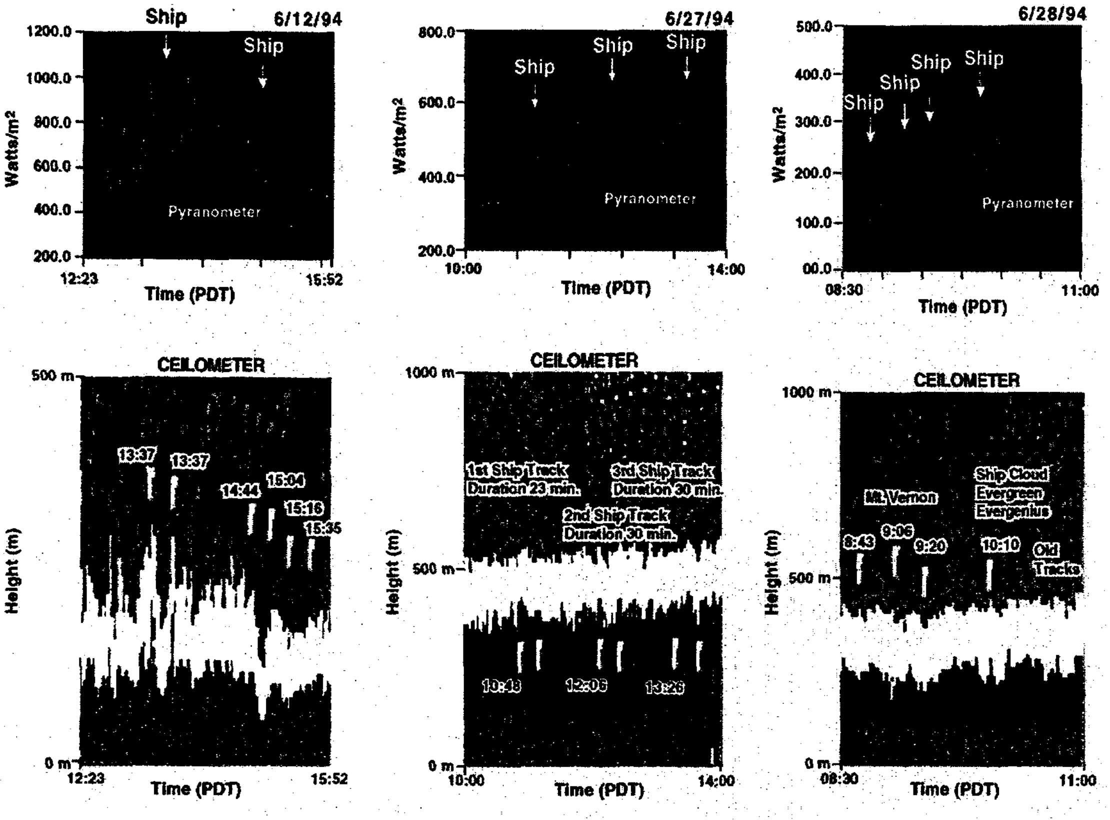


Figure 5. Ceilometer raw backscatter data arbitrarily scaled backscatter units in $[10000 \cdot \mathrm{srad} \cdot \mathrm{km}]^{-1}$ for 12, 27, 28 June 1994 and pyranometer comparison. White corresponds to the highest backscattering values (cloud), followed increasingly darker hues (increased aerosol and virga, boundary layer aerosol and black background aerosol concentrations). When the ship tracks are fresher and the cloud bottoms are lower (12 and 28 June), the ship track cloud is lower than background clouds. When the clouds are higher and older the track features are higher than the background clouds (27 June).

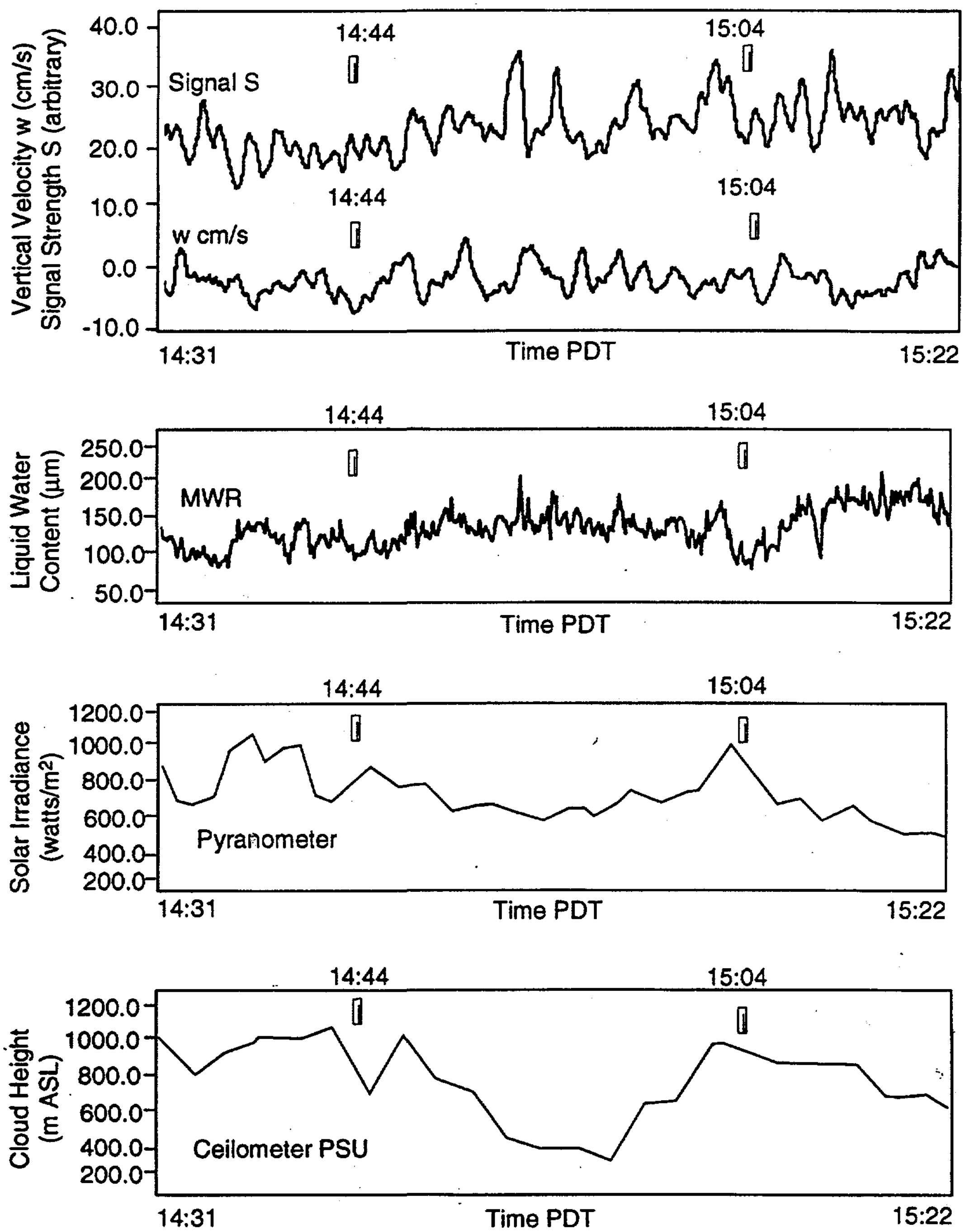


Figure 6. LANL Doppler radar, MWR, and pyranometer comparison for 12 June 1994. The vertical bars bound the ship plumes as detected in the CN data. These comparisons show the higher radar signal level and slightly increased vertical velocities from the Doppler radar and associated higher liquid water content (LWC) from the microwave radiometer, decreased solar irradiance and cloud bottom height associated with the smaller ship track feature shown in Fig. 5 for 12 June.

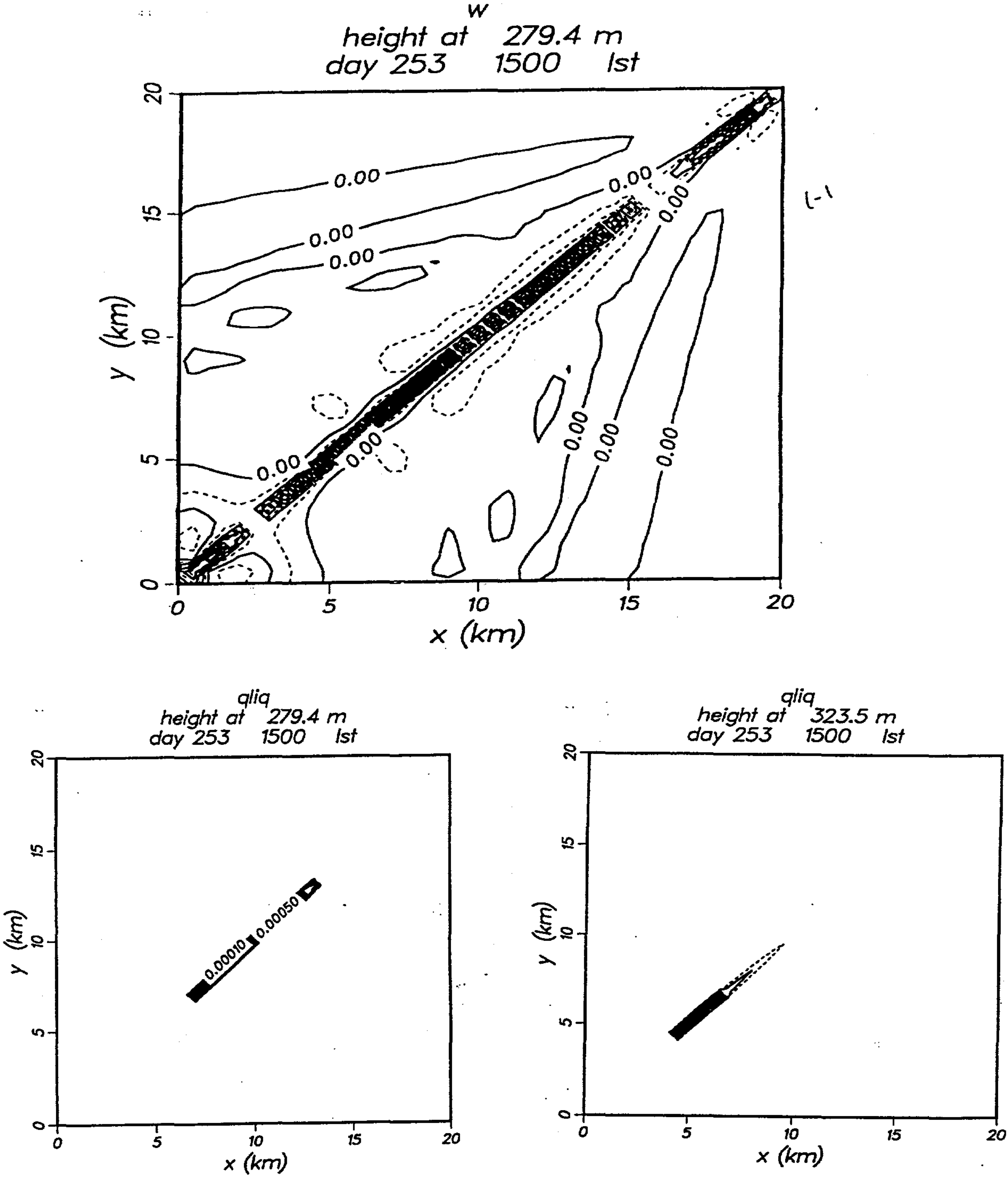


Figure 7. Numerical model of the effect of a moving heat source (20 MW) from lower left to upper right for a 300 m deep marine boundary layer on vertical velocity a) [highest contour 1 cm/s], b) cloud liquid water [highest contour 0.1 g/kg] at a height of 279.4 m, and c) 323.5 m.