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May 1, 1995

A283038

Scientific Officer Code: 1122
Dr. Alan I. Weinstein
Office of Naval Research
800 North Quincy Street
Arlington, Virginia 22217-5000

Re: Grant Number N00014-93-1-0486
Professor Edward Hindman

Dear Dr. Weinstein,

Enclosed herewith please find three (3) copies of the Performance Report for the above referenced contract.

Sincerely,

Regina Masterson
Regina Masterson, Acting Director
Office of Research Administration

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Date: 4/25/95

To: Nellie Cerpa, RF/CUNY

From: Prof. Ward Hindman, PI Ward Hindman

Subject: Performance Technical Report, 1 March 1994 to 28 February 1995, RF/CUNY Project 447312, **Modern Methods in Meteorological and Oceanographic Data Acquisition and Analyses** (ONR Contract N00014-93-1-0486)

Technical objectives:

The first objective is to educate and train students to collect and analyze meteorological and oceanographic data using the developing CCNY weather station computer system.

The second objective is to purchase the necessary software and hardware to keep the system up-to-date.

The third objective is to teach students scientific programming.

Technical accomplishments:

First objective:

The system was used by undergraduate student-meteorologists Edward Kannar and Kwan-Yin Kong to collect and analyze high-resolution, hourly, satellite images of the eastern Pacific to identify ship-produced clouds during the ONR-sponsored Monterey Area Ship-Track (MAST) experiment, June 1994. Mr. Kong collected and analyzed the satellite images used by Hindman, et al. (1994, attached); the reported cloud line appears to be due to ship-produced particles and updrafts.

Second objective:

The systems engineer (David Ahn, Ph. D. candidate in Electrical Engineering) installed a Sun Sparc-20 and TeraScan software to display and analyze the NOAA satellite images graduate research assistant Theresa Najita collected during the MAST experiment. He also connected the Sun to Internet. As a result, our weather station computer system is used with Internet for teaching, research and data reception and transmission activities.

Third objective:

Undergraduate research assistant Robert Bodowski, a meteorology major, performed the computations reported by Hindman and Bodowski (1994, abstract attached). He investigated the role of ship-produced particles and updrafts on the modification of a marine stratus cloud; the particles were computed to play the dominant role. He also began to adapt the cloud and precipitation formation model of Silverman and Glass (1973) to study the effects of ship effluents on the formation of drizzle within marine stratus.

Graduate research assistant Xiaoping Zhang (M.A., CCNY, 1995) collaborated with the PI's colleague Prof. Stan Gedzelman to develop a numerical model that attempts to explain the isotopic composition of precipitation in a hurricane (Zhang, 1995, abstract attached).

References:

Hindman, E. E., W. M. Porch, J. G. Hudson and P. A. Durkee, 1994: Ship-produced cloud lines of 13 July 1991. *Atmos. Environ.*, **28**, 3393-3403.

Hindman, E. E. and R. Bodowski, 1994: A marine stratus layer modified by ship-produced CCN and updrafts. *J. Appl. Meteor.*, submitted.

Silverman, B. and M. Glass, 1973: A numerical simulation of warm cumulus clouds, Part I - Parameterized vs. non-parameterized microphysics. *J. Atmos. Sci.*, **30**, 1620-1637.

Zhang, X., 1995: Stable isotope ratios in hurricanes. M. A. Thesis, Earth and Atmospheric Sciences Dept., CCNY, NYC, NY.

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SHORT COMMUNICATION

SHIP-PRODUCED CLOUD LINES OF 13 JULY 1991

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(*First received* 16 *June* 1993 *and in final form* 11 *April* 1994)

Abstract–On 13 July 1991, a well-defined cloud line produced by an unidentified steaming ship was detected in satellite imagery and was simultaneously photographed from the *R/V EGABRAG III*. The *EGABRAG* produced a much less well-defined cloud line. Measurements made from the *EGABRAG* revealed that the cloud lines formed in a shallow boundary layer which was nearly saturated, unstable, drizzling and nearly free of cloud condensation nuclei (CCN). The *EGABRAG* passed through the plume of the ship as indicated by elevated CCN concentrations coincident with the cloud line. Thereafter, both ships passed under a shallow stratus layer where background CCN concentrations increased significantly. Only the cloud line produced by the ship extended into the stratus layer; the *EGABRAG* did not affect the layer. The CCN and updraft from the ship were involved in the formation of the cloud line. In contrast, the CCN and updraft from the *EGABRAG* were insufficient to produce a well-defined cloud line. Production of the cloud lines appeared dependent on a combination of environmental conditions and ship-produced CCN and updrafts.

Key word index: Ship trails, ship-produced clouds, ship effluents.

INTRODUCTION

Steaming ships can produce long, linear cloud lines in regions of marine fog and broken stratus as detected in 0.63 μm satellite images by Conover (1966) and Bowley (1967). Also, Scorer (1987) and Coakley *et al.* (1987) report that steaming ships can produce lines in marine stratus layers that are not always detected in 0.63 μm satellite images, but are often detected in the corresponding 3.7 μm images. The lines are detected in the 3.7 μm images because they contain smaller and more numerous droplets than the stratus in which they are embedded as deduced by Coakley *et al.* (1987) and measured by Radke *et al.* (1989). They postulated that cloud condensation nuclei (CCN) from steaming ships produced the more numerous and, hence, smaller cloud droplets. The ship-produced lines in marine stratus layers are not always detected in 0.63 μm images because this wavelength is not as sensitive to changes in droplet size as is 3.7 μm (Coakley *et al.*, 1987).

The relationship between ship-produced CCN and ship-produced clouds has not been established. In fact, Porch *et al.* (1990) indicate waste heat from steaming ships may, in part, trigger the clouds. We present here the first surface observations and measurements of ship-produced clouds to help understand their formation.

On 13 July 1991 a well-defined, ship-produced cloud line formed offshore of Baja California as preliminarily reported by Hindman *et al.* (1992) and Porch *et al.* (1992). The satellite images of the line and corresponding photographs from the *R/V EGABRAG III* which passed under the line are the first known simultaneous photographs of a ship-produced cloud. The satellite images and photos are used to define the structure of the cloud. CCN measurements, associated with high concentrations in the plume of an unidentified ship, correspond to the location of the satellite-detected cloud line indicating ship-produced CCN were involved in the formation of the cloud. However, the *EGABRAG* also was a source of CCN but did not produce a well-defined cloud line; its CCN output and updraft apparently were insufficient.

OBSERVATIONS AND MEASUREMENTS

A sequence of Geosynchronous Orbiting Environmental Satellite (GOES) high-resolution, visible images (Figs 1a–c) shows the ship-produced cloud line forming in a region of broken stratus with a solid stratus layer drifting from north to south. The unidentified ship producing the line was estimated from the image sequence to be steaming at about 310 degrees at 17 knots. It also can be seen in Fig. 1 that the *EGABRAG*, which was steaming at 360° at 10 knots, passed under the cloud line between 1701 Z and 1801 Z. The *EGABRAG* produced a poorly defined cloud line that was oriented almost N–S as can be seen

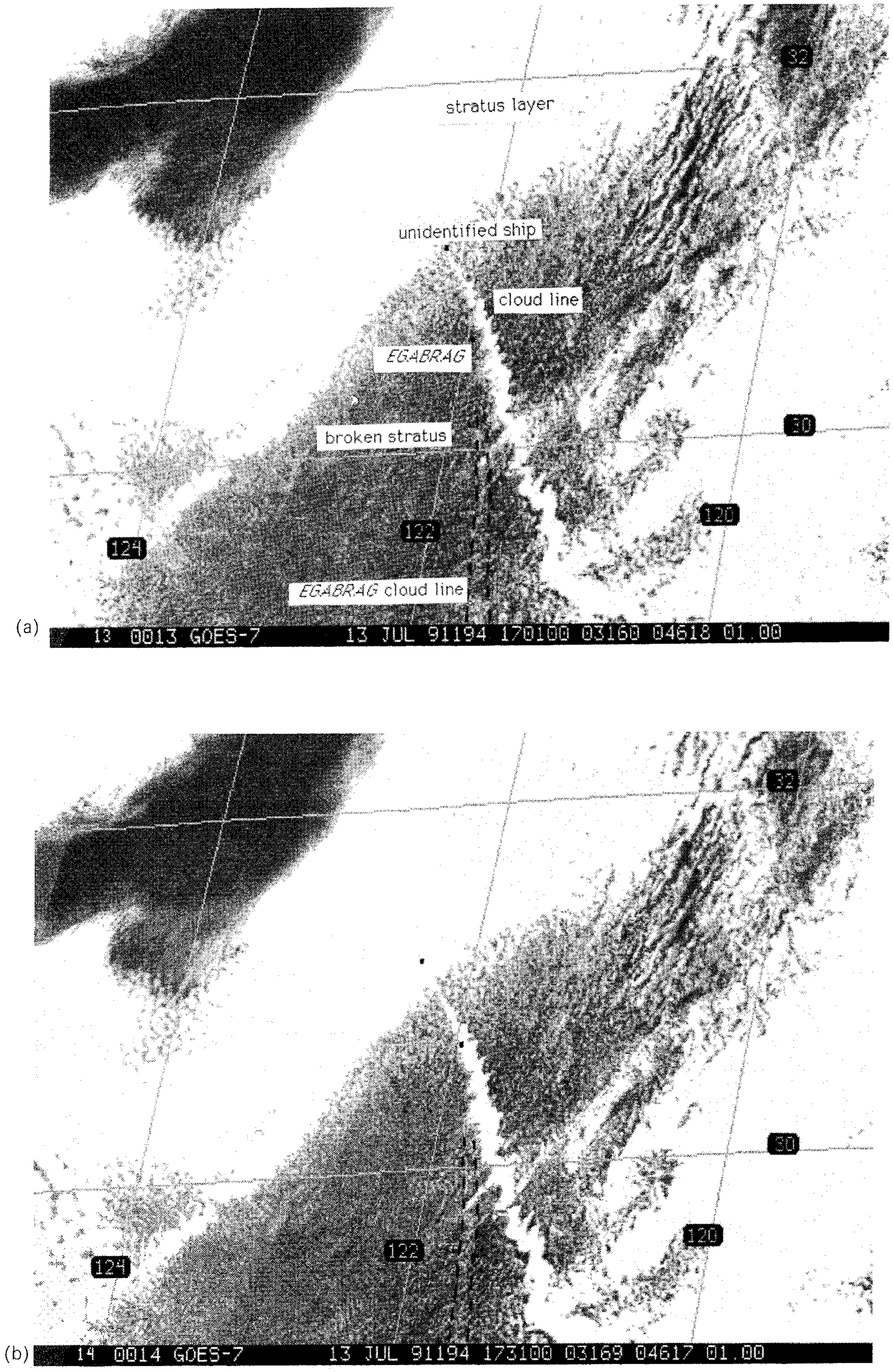
(a)
stratus layer
unidentified ship
cloud line
EGABRAG
broken stratus
EGABRAG cloud line
32
30
120
122
124
13 0013 GOES-7 13 JUL 91194 170100 03160 04618 01.00
(b)
32
30
120
122
124
14 0014 GOES-7 13 JUL 91194 173100 03169 04617 01.00

Fig. 1a, b.

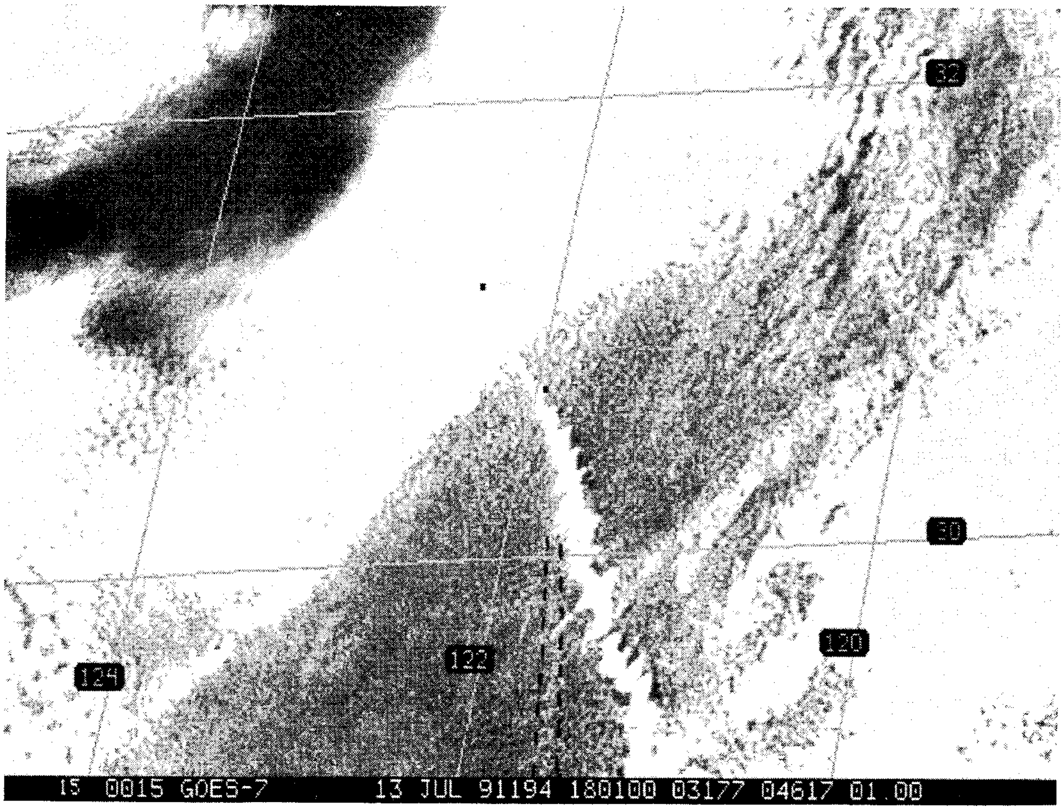

Fig. 1. Sequence of high-resolution (1 km) "stretched" GOES visible images of the ship-produced cloud line, the broken stratus region and the upwind stratus layer off shore Baja California, 13 July 1991: (a) 1701 Z (1001 PDT), (b) 1731 Z (1031 PDT) and (c) 1801 Z (1101 PDT). The estimated position of the unidentified ship producing the cloud line and the *R/V EGABRAG III* are indicated by the black squares. The position of the possible *EGABRAG*-produced cloud is given by the dashed lines.

in the GOES images. This line is a relatively bright, linear feature in the wake of the *EGABRAG*; the orientation of the wake (345 to 165°) was determined by subtracting the ship's heading and speed (360° true, 10 knots) from the surface wind direction and speed 340°, 20 knots).

Hand-held photographs from the *EGABRAG* that correspond to the GOES images in Fig. 1 are shown in Fig. 2. The approaching cloud line produced by the unidentified ship is pictured in Fig. 2a as the dark, linear feature low to the water; the surrounding broken stratus and fog in which the line was embedded did not have such a distinct cloud base. The fuzzy regions at cloud base appear to be regions of drizzle. In contrast, the stratus layer shown just north of the *EGABRAG* in Fig. 1 had a distinct cloud base and no drizzle was detected at the surface under this layer. The layer moved over the ship at about 1830 Z and the cloud base was estimated to be 350 m above mean-sea-level (m.s.l.) from the 2020 Z ship-board rawindsonde (Fig. 3; the rawindsonde was a Loran-based Vaisala with accuracies of ± 0.5°C in temperature, ± 1.0°C in dew point, $\pm 0.5\ \mathrm{m\,s^{-1}}$ in wind speed and ± 10° in direction).

The *EGABRAG* passed through the plume of the unidentified ship between 1028 and 1048 PDT (1728 and 1748 Z) as indicated by the sharp perturbation in the CCN and condensation nucleus (CN) concentrations shown in Fig. 4a [the CN were measured with a TSI 3020 CN counter (Agarwal and Sem, 1980) and the CCN with the DRI instantaneous CCN spectrometer (Hudson, 1989), accuracies of both instruments are better than ±10%]. The relative wind abroad the *EGABRAG* was 24 knots as it passed through the plume. Thus, the width of the ship-plume was approximately 8 nautical miles (24 knots × 0.33 h) which is consistent with the width of the cloud line in Fig. 1b. As can be seen from Fig. 1, the ship passed under the line between 1701 and 1801 Z. This period encompasses the period of elevated CCN. Thus, the high concentrations of CCN were at the same location as the cloud line.

The CCN concentrations in the ship-plume are expanded in Fig. 5a where three CCN peaks are evident. It can be seen from the figure, each peak is associated with a region of reduced solar energy [a non-gymballed pyranometer was used with a spectral response between 0.35 and 1.15 μm (0.85 μm peak) with an accuracy of ±5% (Matrix, Inc., Mesa, AZ)]. This result indicates the thickest regions of the ship-produced cloud coincided with the highest concentrations of CCN and CN. King *et al.* (1993) also measured ship-produced clouds to be optically thicker than nearby ambient stratus.

The photo in Fig. 2b shows the cloud line just off the port side of the *EGABRAG*. The top of the line appears taller than the surrounding broken stratus; the top is visible because of the narrow clear zone adjacent to the line. Clear zones on either side of the line are visible in the original GOES images but were lost in the reproduction here. Examples of clear zones adjacent to ship-produced cloud lines are illustrated by the original Hasselblad photograph from the Apollo-Soyuz mission reported by Porch *et al.* (1990).

The *EGABRAG* was just north of the cloud-line at 1801 Z as shown in Fig. 1c. The line appears to be a series of long, cylindrical clouds in the near-simultaneous photograph (Fig. 2c). These clouds are visible in the GOES image as the sinuous appearance of the cloud line. The long, cylindrical clouds could explain the three regions of reduced solar energy in the ship-plume region in Fig. 5b. The cloud line could have been affected by rolls (horizontal vortex tubes) in the marine boundary layer. The rolls have been numerically simulated by Kuo and Schubert (1988) and Moeng and Schumann (1991). Further, the banded structure of the cloud line is similar to the banded structure seen in the original Apollo-Soyuz photograph (Porch *et al.*, 1990).

The 1200 Z sounding (Fig. 3) and CCN measurements (Fig. 4) made from the *EGABRAG* showed the cloud lines formed in a shallow, nearly CCN-free, nearly saturated (fog patches) and unstable marine boundary layer (MBL). Drizzle also occurred at daybreak; the *EGABRAG* 3rd level decks were wet. These conditions are similar to those in which ship-produced clouds were reported by Bowley (1967) and Twomey *et al.* (1968). Fog-bows were observed from the *EGABRAG* at daybreak and during the early morning in the broken stratus region indicating the cloud drop sizes were quite large; the minimum droplet diameters to produce a fog-bow are 20–30 μm according to E. Shettle (personal communication, 1993). The cloud droplets also were so sparse in this region they were sometimes invisible except near the fog-bow angle. The effect of the broken stratus was evident in the highly variable solar radiation trace from the *EGABRAG* during the morning hours (Fig. 4b).

When the *EGABRAG* passed under the stratus layer at about 1200 PDT, the background CCN concentrations increased from 5 to about 60 cm^{-3} (CN increased from 10 to 100 cm^{-3}) as seen in Fig. 4a. The drizzle at the surface appeared to have ceased. In the 1507 PDT (2207 Z) 3.7 μm image from the NOAA polar orbiting satellite, the cloud line produced by the unidentified ship extended into the stratus layer (Fig. 6a); the line was not detected in the corresponding visible image (Fig. 6b). It can be seen in both images that the *EGABRAG* did not affect the stratus layer. The detection of the line in the 3.7 μm image and not in the visible image indicates the cloud droplets are smaller and more numerous in the line than the nearby ambient stratus following the reasoning of Coakley *et al.* (1987); the airborne measurements of Radke *et al.* (1989) support Coakley *et al.*

The 1731 Z 11 μm GOES image (Fig. 7) reveals a regular transition from the warmer broken-stratus region (15°C) to the cooler cloud line (13°C) to the slightly cooler stratus layer (12°C). Combining this result with the sounding data in Fig. 3, indicates that the top of the cloud line was higher than the broken stratus and about as high as the top of the stratus layer. This result is consistent with the higher appearance of the cloud line surrounded by lower broken stratus in Fig. 2b. The higher cloud line plus the adjacent clear zones indicate a possible ship-produced vertical circulation as postulated by Porch *et al.* (1990) and Hindman (1990).

DISCUSSION

The broken stratus region contained low droplet concentrations and large droplet sizes. These conditions resulted from the low CCN concentrations. CCN may have entered the region by entrainment from the higher concentrations which often exist immediately above the cloud-topped MBL (Hudson and Frisbee, 1991; Hudson, 1993). Also, CCN may have been produced in the MBL as postulated by Hegg *et al.* (1992). CCN were removed from the layer by coalescence-scavenging and drizzle (Hudson and Frisbee, 1991). Albrecht (1989) postulated that low CCN concentrations enhance drizzle production in the MBL leading to the breakup of layers of marine stratus and, conversely, high CCN concentrations lead to a suppression of drizzle and an increase of cloud liquid water content which was apparently measured by Radke *et al.* (1989). The numerical simulations of Ackerman *et al.* (1993) support the Albrecht hypothesis. Our observation of possible drizzle settling from the ship-produced cloud line in Fig. 2a does not support the Albrecht hypothesis.

The unidentified ship emitted an estimated 2×10^{16} CCN s^{-1} as it passed through the broken stratus region. This value was determined using the Gaussian plume model (Slade, 1968) assuming a well-mixed MBL. The relevant formula for the centerline concentration (X) is

$$X = Q/((2\pi)^{1/2}\,\sigma_y\, h\, U)$$

where $X = 200$ CCN cm^{-3}, $\sigma_y = 7.5$ km, $h = 450$ m and $U = 24$ knots and Q is the source strength (CCN s^{-1}). On a different day than the ship-produced cloud event (20 July 1991) in a stratus-topped MBL, the plume of the *USS SEA–LAND PRODUCER* (32,000 hp steam-turbine, bunker oil-fueled) was traversed by the *EGABRAG* at about 32N and 122W at a distance of approximately 5 nmi as detected in the CCN measurements. The CCN emission rate from this ship was estimated to be 8×10^{15} s^{-1}. The CCN emission rates from the unidentified ship and the *SEA–LAND PRODUCER* are of the same order as the CN emission

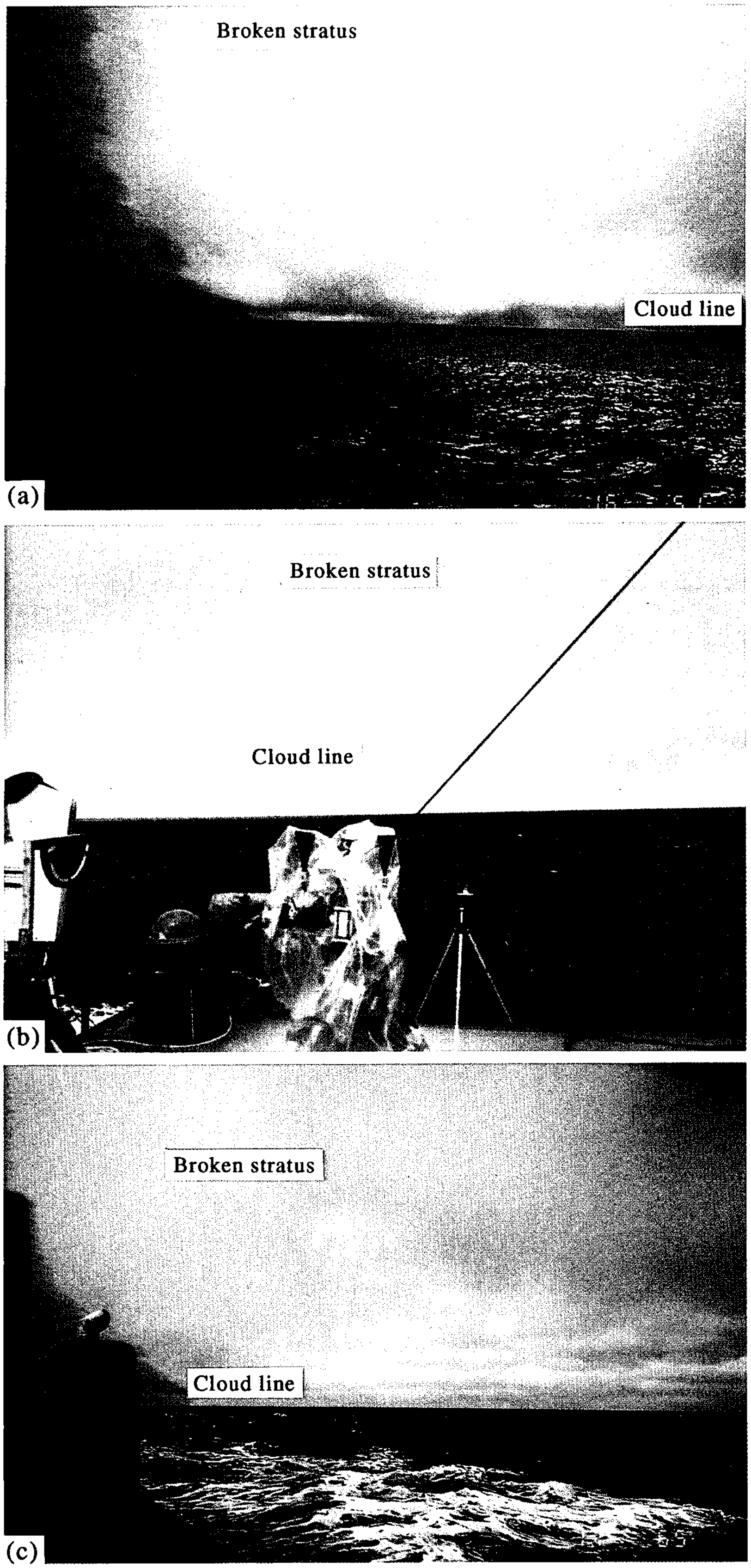

Fig. 2. Sequence of photographs from the *R/V EGABRAG III* of the ship-produced cloud line and the broken stratus clouds; the photos coincide with the satellite images in Fig. 1: (a) Photo by J. G. H. at 1651 Z (0951 PDT) looking about 3 points on starboard bow (Henderson, 1979), (b) Photo by J. Kocian at about 1730 Z (1031 PDT) looking about 2 points abaft the port beam and (c) Photo by J. G. H at 1755 Z (1055 PDT) looking about 2 points on the port quarter.

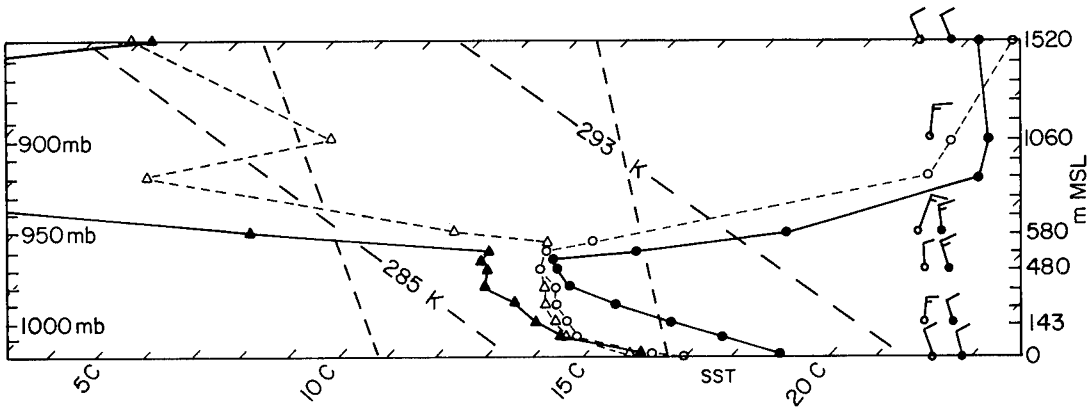

Fig. 3. The sounding from the *EGABRAG* on 13 July 1991 at 1200 Z (open symbols) at 30.0N, 122.07W in the broken stratus region and 2020 Z (solid symbols) at 30.89N, 121.89W under the stratus layer. A full barb on a wind flag is 10 m s^{-1}; the bucket-measured sea-surface-temperature (SST) is plotted.

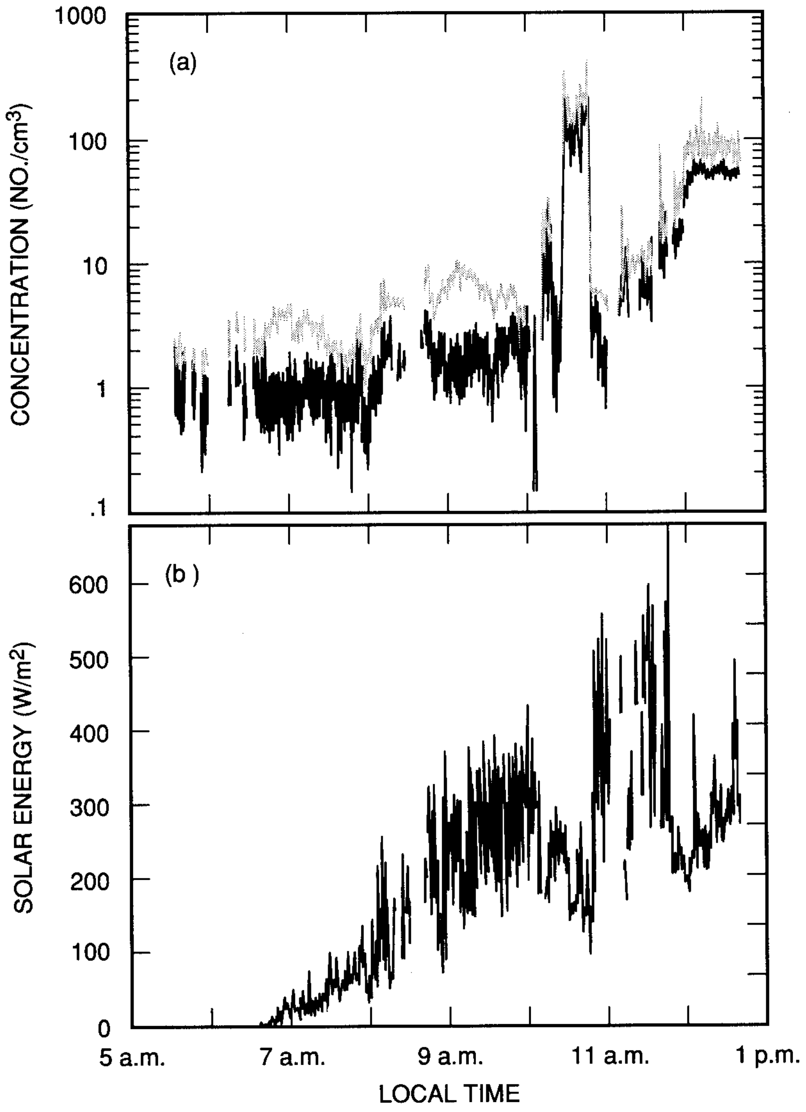

Fig. 4. Measurements from the *EGABRAG* on the morning of 13 July 1991 of (a) condensation nuclei (CN) concentrations (upper line) cloud condensation nuclei (CCN) concentrations (lower line), and (b) solar energy as a function of local time (PDT).

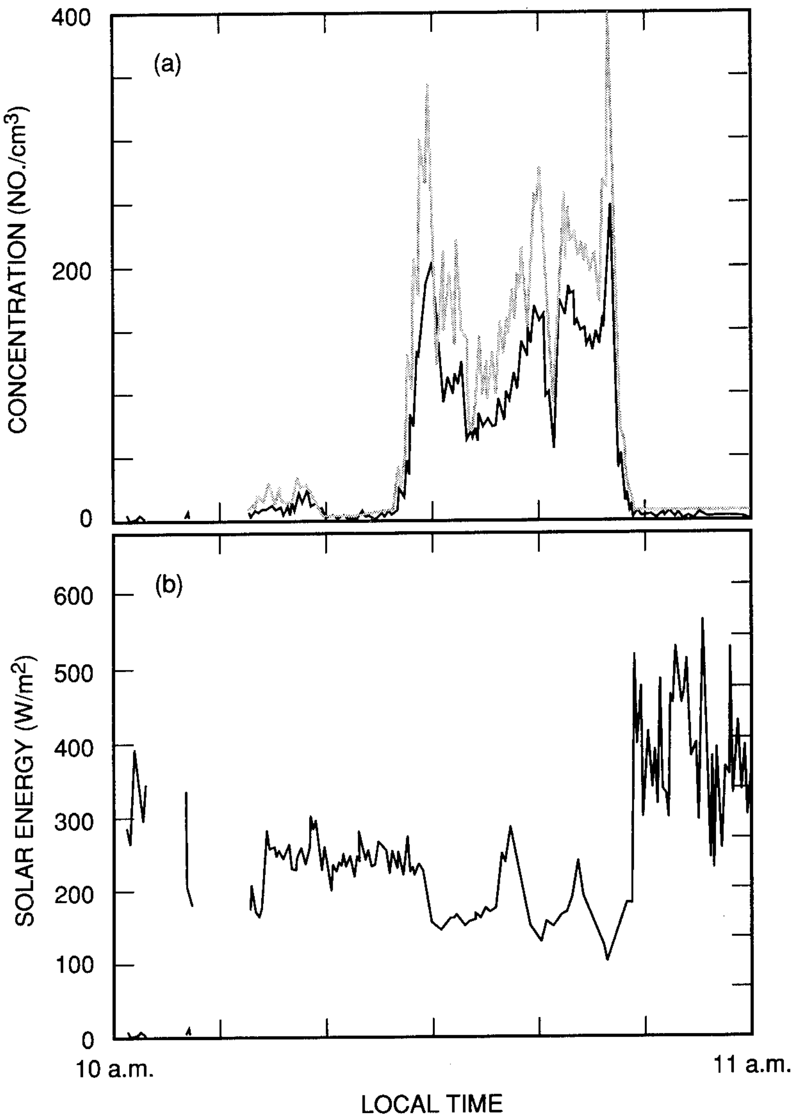

Fig. 5. Enlargement of the ship-plume portion of Fig. 4: (a) CN (top line) and CCN (bottom line) concentrations, and (b) solar energy.

rates measured by Radke *et al.* (1989) from a large ocean-going vessel.

The 1600 hp, diesel-fueled, 41 m *EGABRAG* also was a source of CCN. A crude estimate of its CCN emission rate is made based on the following approximations. When steaming downwind, the maximum CCN concentration measured at 0.8% supersaturation was as large as 10^5 cm^{-3}. Assuming a 2 m s^{-1} drift from the stacks to the CCN inlet (35 m) and dispersion into a cone 10 m in diameter at the inlet, the emission rate was 3×10^{12} s^{-1} or 3×10^{10} gal^{-1} [the *EGABRAG* consumed about 90 gallons of fuel per hour at 10 knots, Jonuz (1992, personal communication)]. Thus, the *EGABRAG* was a smaller CCN source than the unidentified ship by four orders of magnitude.

Twomey *et al.* (1968) measured 3×10^{10} CCN gal^{-1} (7% supersaturation) from combustion of fuel oil (surprisingly, no CCN were measured at 0.5%). Using this value and ship performance data for the *SEA-LAND PRODUCER* (Oneda, 1992, personal communication) the following CCN emission rate was calculated: 3×10^{10} CCN (7%) gal^{-1} oil $\times$ 1000 gal oil/0.264 gal oil $\times 0.333 \pm 0.1$ gal oil s^{-1} $= 3.8 \pm 1 \times 10^{13}$ CCN s^{-1}. This value is 131 times smaller that the CCN measured from the *SEA-LAND PRODUCER*; this result is assumed to be valid for the unidentified ship. Therefore, either the ships were not sources of all the measured CCN or the Twomey *et al.* CCN value is too small and not valid for steaming ships. The value may not be valid for steaming ships because the plume of the unidentified ship and the *SEA-LAND PRODUCER* contained CCN with $S_{\text{crit}} \leqslant 0.5\%$ in concentrations an order of magnitude above background values.

Radke *et al.* (1989) report that direct emission of CCN by a ship could not account for measured

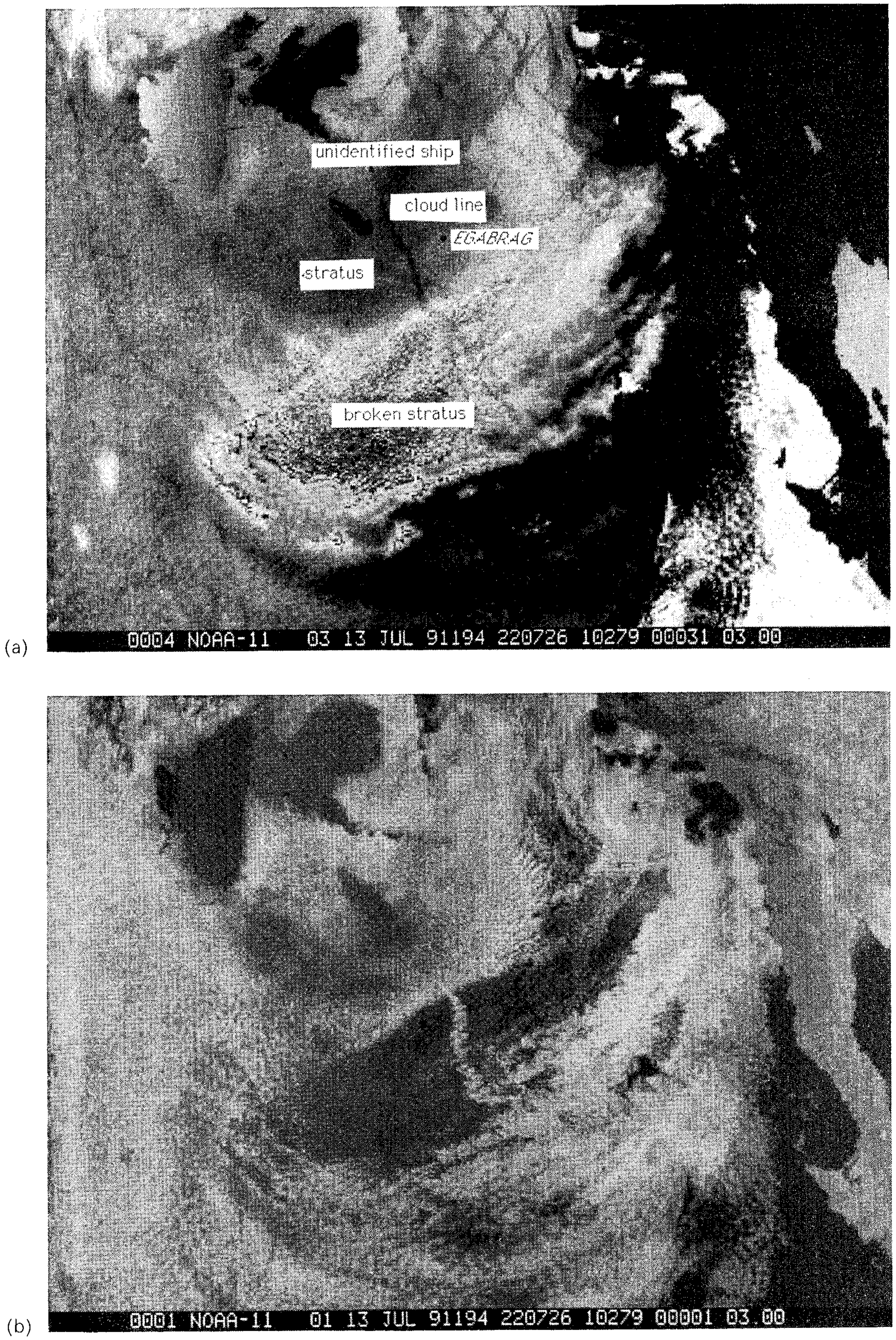

Fig. 6. NOAA advanced very high-resolution radiometer (AVHRR) images at 2207 Z (1507 PDT), 13 July 1991: (a) 3.7 μm image (dark regions mean large reflectance and light regions mean small reflectance); the estimated position of the unidentified ship and the position of the *EGABRAG* are indicated, (b) 0.63 μm image.

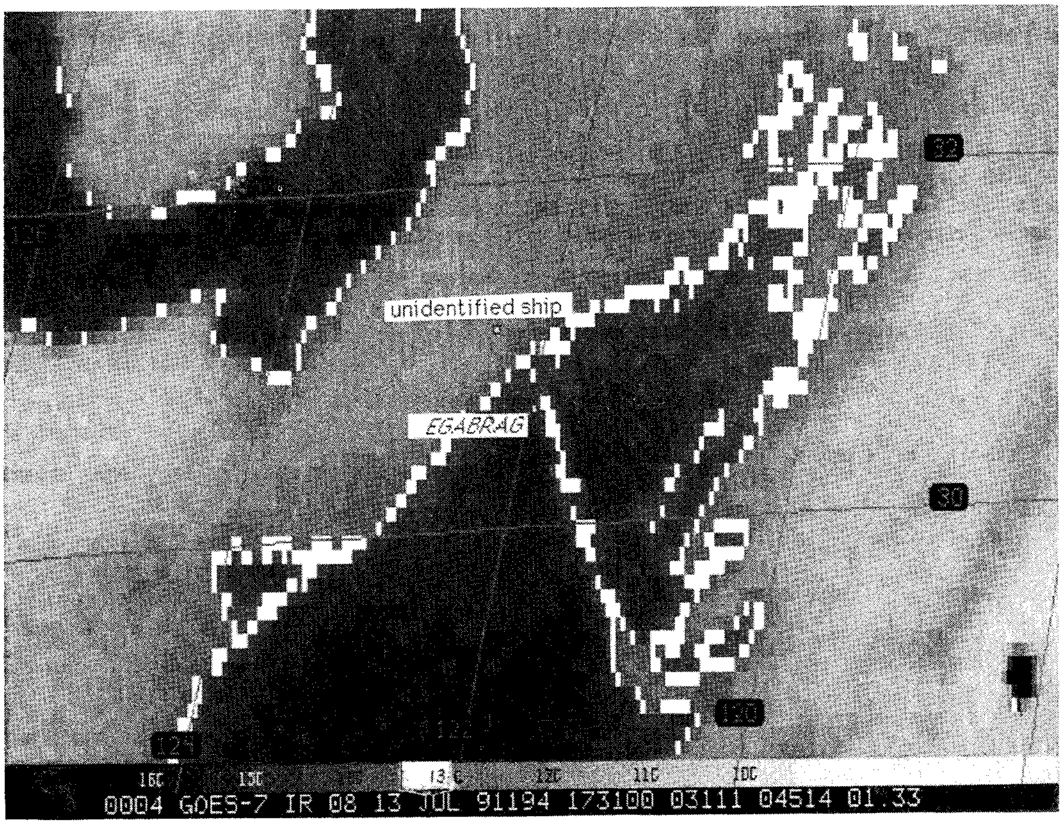

Fig. 7. Highly "stretched" 1031 PDT (1731 Z) infrared image from the GOES of the ship-produced cloud line. A grey-scale calibrated for temperature is at the bottom of the figure. The estimated position of the unidentified ship and the position of the *EGABRAG* are indicated.

droplet concentrations in a ship-produced cloud. They explain that the remaining CCN may be produced by gas-to-particle reactions within the ship plume.

Another mechanism may have been acting to augment the CCN from the unidentified ship. The ship's passage through the broken stratus region may have initiated or enhanced a vertical circulation which mixed CCN from above the boundary layer into the layer as suggested by Hindman (1990). Hudson and Frisbee (1991) and Hudson (1993) regularly measured larger concentrations of CCN and CN above the cloudy MBL. It may be more than mere coincidence that they measured rather consistent concentrations between 100 and 200 cm^{-3} just above the MBL. Additionally, the cloud line was shown to be taller than the broken stratus (Fig. 2b and 7) suggesting enhanced vertical motion in the line.

The *EGABRAG* did not produce a well-defined cloud line in the broken stratus (Fig. 1) and did not produce any cloud line in the solid stratus layer (Fig. 6a). Its CCN output may have been too small; the output was estimated to be four orders of magnitude smaller than the unidentified ship's estimated output. Also, the vertical circulation produced by the *EGABRAG* may have been too weak and, hence, diffuse to transport the few CCN produced by the *EGABRAG* to the stratus layer. In contrast, the unidentified ship's plume appeared to rise coherently to the stratus layer as indicated by the well defined plume in Fig. 6a; the coherent plume was likely a result of waste heat and air wake from the ship.

CONCLUSIONS

The ship-produced cloud lines formed in a nearly CCN-free, shallow, nearly saturated, unstable marine boundary layer confirming the findings of Bowley (1967). Elevated CCN concentrations measured in the plume from an unidentified ship coincided with the cloud line indicating the CCN were involved in the formation of the cloud line. All the CCN in the ship-plume may not have originated from the ship. The heat release and air wake from the unidentified ship may have caused a vertical circulation which mixed CCN from the warm inversion layer above the boundary layer into the boundary layer, assisting the formation of the line. The *R/V EGABRAG III*, from which the measurements were made, did not produce a well-defined cloud line. Its CCN output may have been too small and vertical circulation too weak. These results indicate production of the cloud lines appeared dependent on a combination of environmental conditions and ship-produced CCN and updrafts.

Acknowledgements — This work was supported, in part, by ONR contracts N00014-89-1955, N00014-91-J-1777 and N00014-92-J-1783 (E.E.H.), DOE Office of Health and Environmental Sciences (W.M.P.), DOE DE-FG08-90ER61012 and ONR contract N00014-91-J-1090 (J.G.H.). The following CCNY undergraduate students contributed to this research: K. Y. Kong analyzed and interpreted images from the GOES and NOAA satellites and R. Hogen was an observer aboard the *EGABRAG*.

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A marine stratus layer modified by nuclei and updrafts from a ship plume*

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Abstract

On 13 July 1991, a steaming ship produced a long, linear feature in a marine stratus layer offshore Baja California as detected in the 2207Z NOAA-11 3.7 µm satellite image. Cloud condensation nucleus (CCN) measurements from the ship's plume and from nearby ambient air and assumed ship-enhanced and ambient updrafts are used with a one-dimensional cloud formation model to investigate the contribution of the CCN and updrafts to the formation of the ambient and modified stratus. The droplet sizes calculated using the CCN and ambient updraft reproduced the droplet sizes inferred from the satellite images: small droplets existed in the linear feature and larger droplets existed in the adjacent ambient region. These results indicate (1) the ambient CCN and updraft could explain the large droplets detected in the ambient stratus, (2) the elevated CCN concentrations in the ship plume could explain small droplets detected in the anomalous feature and (3) the assumed ship-enhanced updraft did not activate additional CCN and, thus, further reduce the size of the small droplets. The updraft, though, may have been important in transporting the nuclei in the plume to the stratus layer. The nuclei in the plume may not all have been produced by the ship; some nuclei may have been entrained from above the well-mixed boundary layer.

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STABLE ISOTOPE RATIOS IN HURRICANES

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ABSTRACT

Two models that include the physics of the stable isotopes of water are developed and applied to explain the anomalously low values and inward decrease of the stable isotope ratios of rain observed in hurricanes. The first model represents the hurricane as a series of fractionation chambers in the form of showers or rainbands and an outward sloping eye wall cloud. The second model is a 2-dimensional, kinematic, bulk cloud microphysical model with isotope physics developed by Gedzelman and Arnold (1993) that is modified to simulate the isotope ratios in the eye wall cloud of hurricanes. The mean isotope ratio decreases with increasing cloud depth as a result of more efficient fractionation. It decreases with decreasing radius and with time (gradually approaching a limit) largely as the result of diffusive isotope exchange between the incoming low level vapor and the rain. The low mean isotope ratio of hurricanes is thus largely a result of their great cloud thickness and relative longevity.

We next present a theory to determine the isotope ratios of vapor evaporating from sea during high winds, when substantial quantities of spray and spume droplets are generated. The diffusion equations for normal and heavy isotopes are solved and integrated over the composite spray and spume generation functions and droplet residence times proposed by Andreas (1992). The theory suggests that when the wind speed increases above 15 m s^{-1}, isotope ratios during evaporation begin to increase significantly because the fraction of spray and spume droplets becomes substantial. The limit of this process under extreme wind conditions is not known because no information on the spume drop size distribution exists for winds above 20 m s^{-1}. The value of using stable isotopes to help determine the water balance of hurricanes is then discussed.