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As part of the Monterey Area Ship Track (MAST) Study, the University of Washington's Cloud and Aerosol Research Group used its integrated airborne research facility to obtain *in situ* measurements of the particles and gases emitted by various types of ships, the dispersion and evolution of these effluents downwind, and their effects on the microstructure and optical properties of marine stratiform clouds, particularly as they affect the formation of so-called "ship tracks" in clouds. The results of these studies confirmed that it is the effluents from ships that produce "ship tracks" under appropriate cloud and meteorological conditions.

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FINAL REPORT ON ONR GRANT GN00014-92-J-1587, AND PROJECT NUMBERS PR 214J005 AND PR 43AB005 TO THE UNIVERSITY OF WASHINGTON ENTITLED "STUDIES OF MARINE AEROSOLS AND THEIR EVOLUTION IN THE EASTERN NORTH ATLANTIC AND ANALYSIS OF MAST DATA." PRINCIPAL INVESTIGATORS: PETER V. HOBBS AND RONALD J. FERREK

Background

It has long been known that under certain conditions ships can leave tracks in low-level marine stratiform clouds (so called "ship tracks") that are detectable from satellites.

The Monterey Area Ship Track (MAST) Study was designed to obtain further information on ship tracks for the purpose of elucidating the mechanism(s) responsible for their formation.

Objectives of the University of Washington Studies

The Cloud and Aerosol Research Group (CARG) of the Department of Atmospheric Sciences, University of Washington (UW), participated in MAST. The objectives of the CARG were to obtain airborne in situ measurements of the particle and gas emissions from various types of ships and their effects on the microstructures (drop sizes and liquid water contents) of marine stratiform clouds.

Approach

The field portion of MAST was carried out from June 1-June 30, 1994, off the California Coast. The approach was to use aircraft to measure the emissions from various ships and their effects on marine stratiform clouds and the production of ship tracks.

Data Obtained

During the course of the MAST field project, the UW/CARG used its research aircraft to sample the plumes from 17 ships (12 ships of opportunity and 5 U.S. Navy ships). In 14 cases

(11 ships of opportunity and 3 U.S. Navy ships), the plumes from ships were sampled in clouds; 8 of these plumes produced measurable in situ cloud microphysical perturbations that were readily measured from the aircraft.

A listing of the parameters measured the UW aircraft, summaries of each flight, and maps showing the flight tracks for each case are given in a report entitled: "*University of Washington C-131A Research Flights for the Monterey Area Ship Track (MAST) Experiment, June 1-30, 1994, Flight Summaries and Aircraft Position Plots*" by P. V. Hobbs and R. J. Ferek, Cloud and Aerosol Research Group, Atmospheric Sciences Department, University of Washington, December 1994.

Results

The full results of the MAST study will be described in a Special Issue of the *Journal of the Atmospheric Sciences*, which will probably appear in 1998. Many of the papers in this Special Issue contain data acquired by the UW/CARG and co-authored by CARG members (see Publications below). A brief summary of some of the main results that were obtained for the UW/CARG is given below.

Emissions of particles, gases, heat and water vapor from ships were measured. These measurements were used to derive emission factors of SO₂ and NO from diesel-powered and steam turbine-powered ships, burning low grade marine fuel oil (MFO); they were ~15–89 and ~2–25 grams per kilogram of fuel burned, respectively. By contrast a steam turbine-powered ship burning high grade navy distillate fuel had an SO₂ emission factor of ~6 g kg⁻¹.

Various types of ships, burning both MFO and navy distillate fuel, emitted from ~4 × 10¹⁵ to 3 × 10¹⁶ total particles per kilogram of fuel burned (~8 × 10¹⁵–2 × 10¹⁶ particles per second). However, diesel-powered ships burning MFO emitted particles with a larger mode radius (~0.03–0.05 μm) and larger maximum sizes than those powered by steam turbines burning navy distillate fuel (mode radius ~0.02 μm). Consequently, for similar chemical compositions, the particles emitted by diesel ships burning MFO serve as cloud condensation nuclei (CCN) at lower

supersaturations (and are therefore more likely to produce ship tracks) than particles emitted by steam turbine ships burning distillate fuel. Since steam turbine-powered ships fueled by MFO emit particles with a mode radius similar to that of diesel-powered ships fueled by MFO, it appears that, for given ambient conditions, the type of fuel burned by a ship is more important than the type of ship engine in determining whether or not a ship will produce a ship track. However, more measurements are needed to test this hypothesis.

The particles emitted from ships appear to be primarily organics, possibly combined with sulfuric acid produced by gas-to-particle conversion of SO_2 . Comparison of model results with measurements in ship tracks suggest that the particles from ships contain only about 10% water-soluble materials. Measurements of the total particles entering marine stratiform clouds from diesel-powered ships fueled by MFO, and increases in droplet concentrations produced by these particles, show that only about 12% of the particles serve as CCN.

Enhancements of droplet concentrations in ship tracks were usually fairly accurately predicted from ship emission factors and plume and background CCN spectra. Ship exhausts can thus account for the increased droplet concentrations (and decreases in droplet sizes) in clouds, which give rise to ship tracks.

The fluxes of heat and water vapor from ships are estimated to be $\sim 2\text{--}22$ MW and $\sim 0.5\text{--}1.5$ kg s^{-1} , respectively. In MAST, these emissions rarely produced measurable temperature perturbations, and never produced detectable perturbations in water vapor, in the plumes from ships. Nuclear-powered ships, which emit heat but negligible particles, do not produce ship tracks. Therefore, it is concluded that heat and water vapor emissions do not play a significant role in ship track formation and that particle emissions, particularly from those burning low-grade fuel oil, are responsible for ship tracks.

Measurements from several sources produced data signals consistent with a reduction in drizzle drops in stratus clouds affected by ship effluents. Concurrent increases in liquid water in the cloud droplet size range, due to redistribution from the drizzle mode, were not always observed, possibly because of the relatively small and often negligible amounts of water in the

drizzle mode. Significant changes in cloud droplet size distribution, as well as reductions in drizzle flux and concentrations of drops $>50 \mu\text{m}$ radius, were observed in ship tracks when drizzle was more uniformly present in the ambient cloud. Therefore, under appropriate conditions, increases in liquid water contents in clouds affected by ship effluents may enhance the formation of ship tracks.

Peer-Reviewed Publications

(University of Washington (UW) personnel are underlined.)

- 1) "Measurement of Ship-Induced Cloud Tracks Off the Washington Coast" by R. J. Ferek, D. A. Hegg, P. V. Hobbs, P. Durkee and K. Nielsen. *J. Geophys. Res.*, 1997 (in press).
- 2) "Emissions from Ships with Respect to their Effects on Clouds" by P. V. Hobbs, T. J. Garrett, R. F. Ferek, S. R. Strader, D. A. Hegg, G. M. Frick, W. A. Hoppel, R. F. Gasparovic, L. M. Russell, D. W. Johnson, C. O'Dowd, P. A. Durkee, K. E. Nielsen and G. Innis. *J. Atmos. Sci.*, MAST Special Issue (in press).
- 3) "Drizzle Suppression in Ship Tracks" by R. J. Ferek, T. Garrett, P. V. Hobbs, S. Strader, D. Johnson, J. P. Taylor, K. Nielsen, A. S. Ackerman, Y. Kogan, Q-F. Liu, B. A. Albrecht and D. Babb. *J. Atmos. Sci.*, MAST Special Issue (in press).
- 4) "Cloud Condensation Nuclei and Ship Track Clouds" by J. G. Hudson, T. J. Garrett, P. V. Hobbs, S. R. Strader, Y-H. Xie, and S. S. Yum. *J. Atmos. Sci.*, MAST Special Issue (in press).
- 5) "Effects of Aerosols on Cloud Albedo: Evaluation of Twomey's Parameterization of Cloud Susceptibility Using Measurements of Ship Tracks" by A. S. Ackerman, O. B. Toon, J. P.

Taylor, D. W. Johnson, P. V. Hobbs and R. J. Ferek. *J. Atmos. Sci.*, MAST Special Issue (in press).

- 6) "The Appearance and Disappearance of Ship Tracks on Large Spatial Scales" by J. A. Coakley Jr., P. A. Durkee, K. Nielsen, J. P. Taylor, S. Platnick, B. A. Albrecht, D. Babb, F.-L. Chang, W. R. Tahnk, C. S. Bretherton and P. V. Hobbs. *J. Atmos. Sci.*, MAST Special Issue (in press).
- 7) "The Role of Background Cloud Microphysics in Ship Track Formation" by S. Platnick, P. A. Durkee, K. Nielsen, J. P. Taylor, S-C. Tsay, M. D. King, R. J. Ferek and P. V. Hobbs. *J. Atmos. Sci.*, MAST Special Issue (in press).
- 8) "Effects of Aerosols on the Radiative Properties of Clouds" by J. T. Taylor, M. D. Glew, J. A. Coakley Jr., W. R. Tahnk, S. Platnick, P. V. Hobbs and R. J. Ferek. *J. Atmos. Sci.*, MAST Special Issue (in press).
- 9) "A Case Study of Ship Track Formation in a Polluted Marine Boundary Layer" by K. J. Noone et al. *J. Atmos. Sci.*, MAST Special Issue (in press). (Includes three UW authors.)
- 10) "Case Studies of Ships that Formed and Did Not Form Ship Tracks in Moderately Polluted Marine Air" by K. J. Noone et al. *J. Atmos. Sci.*, MAST Special Issue (in press). (Includes three UW authors.)

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