REPORT DOCUMENTATION PAGE Sheet1	*Form Approved* *OMB No. 0704-0188*

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED **Final Report 6/1/97 - 5/31/00**

4. TITLE AND SUBTITLE **COUPLED OCEAN-ATMOSPHERE INTERACTION AND THE DEVELOPMENT OF THE MARINE ATMOSPHERIC BOUNDARY LAYER**	5. FUNDING NUMBERS AASERT GRANT **N00014-97-1-0762**
6. AUTHOR(S) **Dr. David P. Rogers**	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **University of California, San Diego** **Scripps Institution of Oceanography** **Physical Oceanography Research Division** **9500 Gilman Drive** **La Jolla, CA 92093-0230**	8. PERFORMING ORGANIZATION REPORT NUMBER **UCSD 97-1180**
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) **Office of Naval Research** **800 N. Quincy Street** **Arlington, VA 22217-5660**	10. SPONSORING/MONITORING AGENCY REPORT NUMBER
11. SUPPLEMENTARY NOTES	
12a. DISTRIBUTION/AVAILABILITY STATEMENT **Available to public**	12b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)

Please see attached report.

14. SUBJECT TERMS	15. NUMBER OF PAGES **7**
	16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	Unlimited

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANS Std. 239-18
298-102

COUPLED OCEAN-ATMOSPHERE INTERACTION AND THE DEVELOPMENT OF THE MARINE ATMOSPHERIC BOUNDARY LAYER

FINAL REPORT for ONR N00014-97-1-0762

PI: Dr. David P. Rogers
Physical Oceanography Research Division
Scripps Institution of Oceanography, La Jolla, CA 92093-0230
drogers@ucsd.edu
Phone: (858) 534-6412, FAX: (858) 534-7452

SUMMARY
The goal of this research was to provide an understanding of the processes that control the structure of the marine atmosphere and its interaction with the ocean. In particular, we focussed on understanding the processes that control the exchange of heat and moisture between the ocean and the atmosphere and understanding the physical processes that control the formation, development and decay of stratocumulus clouds in the marine boundary layer.

These results have led to new insight into the
We used a combination of observational studies and numerical models of the marine atmosphere to address these problems. We completed six related field programs and developed a new modeling technique to simulate the detailed physiscal structure of the marine atmosphere. The Internal Boundary Layer Experiment (IBLEX) conducted around the U.K. coast (Rogers et al. 1995a and b), the Atlantic Stratocumulus Transformation Experiment (ASTEX) in the Azores (Rogers et al. 1995c, Martin et al. 1995), the Coupled Ocean Atmosphere Response Experiment (COARE) in the western Pacific (Serra 1997, Serra et al 1997), SHAREM 115 in the Persian Gulf (Brooks et al. 1997) and the Coastal Waves Experiment 1996 (CW96) off the coast of California (Rogers et al. 1997). We have also incorporated the data collected during the Monterey Area Ship Tracks (MAST) Experiment originally supported under a separate ONR award (Brooks and Rogers 1997).

Each of these studies addressed a different aspect of the development of the marine boundary layer. IBLEX was concerned with the development of internal boundary layers that result from horizontal temperature and roughness gradients. For example, we investigated the evolution of the marine boundary layer as warm air flows from land to sea in a littoral environment. ASTEX is concerned mostly with the development and evolution of stratocumulus clouds. COARE is concerned primarily with the processes that control the structure of the surface layer in the tropics. SHAREM 115 extended the study of the marine boundary layer into a coastal region, characterized by a high aerosol content and high humdity, and tested our ability to collect environmental data in a warfare scenario. CW96 was developed to investigate the structure of the stable coastal boundary layer off the west coast of the US, building on our undersanding of coherent fields onbserved during MAST, the stable boundary layer studies of IBLEX and the cloud observations of ASTEX.

TASKS COMPLETED:

- Developed a smooth particle hydrodynamic model. Dr. Peter Norris was awarded the Ph.D. from UCSD for this work.

- Completed a study of the processes that couple the ocean and atmosphere in the tropics. Dr. Yolande Serra was awarded the Ph.D. for this work.

- Published one papers in the Journal of Atmospheric Sciences on ASTEX and submitted two others. Published one paper in the Journal of Geophysics.

- We have demonstrated the integration of a basic research program with an applied program supporting systems testing in SHAREM 115. Completed the processing of aircraft data collected during SHAREM 115. These data have been given to NRL Monterey to aid in the development of aerosol models and to test electromagnetic systems.

- Completed the processing of aircraft data collected during CW96. Preliminary results have been shared with NRL Monterey to help test the COAMPS model. We have demonstrated that COAMPS model performed well during the experiment providing forecasts of wind fields in agreement with the aircraft observations.

SCIENTIFIC RESULTS:

- Most existing numerical solutions in computational fluid dynamics use the widely studied Eulerian approach, that is, prognosis of field variables at fixed locations within the domain. By contrast, smoothed particle hydrodynamics (SPH) is a Lagrangian technique, that is, it makes prognosis at positions which follow fluid elements within the domain. The technique was designed to deal with the unbounded simulations required in astrophysics, but finds increasing application in a variety of problems, ranging from high speed metallic impact to wave generation. Lagrangian methods require that the equations of motion be evaluated at a set of disordered points representing small fluid elements. The advective terms, which are difficult to evaluate in an Eulerian framework due to inherent non-linearity, are simply evaluated in a Lagrangian framework, because the prognosis positions are, by definition, advected with the local fluid velocity. This makes the method very amenable to other parcel processes, such as cloud microphysics, for example. Non-local processes, however, such as those involving the calculation of field gradients, are not so trivial. These gradients are estimated by first interpolating from the disordered fluid element positions and then using the gradients of the interpolation. In SPH, the fluid is divided into a large but finite number of elements, which are localized as so-called "particles". Interpolation is then accomplished using a local weighting function, called the kernel, which distributes the properties of the fluid about the disordered positions of these particles. The kernel has some small finite range, which implies that the properties of a given particle are only affected by those other particles, called "neighbors", which fall within a certain range of the particle in question. We have applied the SPH method to the atmosphere, with a view to performing improved simulations of the cloud-topped marine boundary layer (CTMBL). The first part of our work has involved designing a code to model the SPH equations for a stratified geophysical fluid. This involves a basic time-stepping routine for the compressible Navier-Stokes equations, a special design to allow efficient collection of near-neighbor particles, and a system for correctly initializing particle positions. In addition, we devised a new type of boundary condition to handle particle-wall interactions within a stratified fluid. The code has been written for operation on parallel machines, and an initial series of test runs (sound propagation, viscous diffusion, and buoyancy oscillations) indicate the method to be robust and accurate.

- We have completed a study of the aircraft measured surface fluxes in the vicinity of deep cumulus convection over very warm water and in suppressed conditions over cooler sea surface temperatures in the tropics. Despite the light winds observed during COARE (<3 m/s), a wide range of convective conditions was observed. Within the surface layer, the convective conditions were divided into three categories; forced convection, free convection and a transition region, which is a mixture of free and forced convection. Free convection, where buoyancy dominates over mechanical production of turbulence in the boundary layer, results in enhanced surface heat and buoyancy fluxes for the given wind conditions, compared with those observed for forced conditions.

  While the temperature of the warm pool region in COARE is found to be largely independent of local conditions measured by the aircraft, we observe that the warmest temperatures (>30 C) coincide exclusively with the lightest winds, which highlights the importance of wind-driven mixing in determining the thermal structure of the upper ocean.

- The COARE bulk flux algorithm has been further tested with data from other experiments and a slightly revised version of the code has been released. Estimates of the surface fluxes within a convective region of COARE indicate that the bulk flux algorithm captures the overall spatial patterns of the sensible and latent heat fluxes. However, large discrepancies exist for the momentum flux. This occurs because the source of the velocity variance is associated with the convective activity, which is consistent with our observations from MAST. The latter results show that organized rolls can transport large amounts of momentum when compared with conditions observed outside of the roll regime.

- Preliminary results from CW96 lidar measurements reveal well-defined boundary layer coherent structures. Coincident, in situ turbulence measurements indicate that the stable boundary layer may be ventilated by discrete events that overturn the entire layer. These measurements are the first that we are aware of that combine lidar and turbulence measurements on a single airborne platform.

- Preliminary results from CW96 also address the problem of fog formation and boundary layer cloud development. Measurements of the surface fluxes, boundary layer depth and the air-sea temperature difference reveal that fog forms quite often at the boundary between stable and unstable air. A large latent heat flux enables a very shallow boundary layer to saturate quickly forming fog. Further offshore, with increased buoyancy the boundary layer depends and the fog lifts to form a stratus or stratocumulus cloud layer.

SIGNIFICANCE:

- We have demonstrated that the SPH model is useful tool that can be applied to a variety of atmospheric processes. While we have focused primarily on the development of clouds in the marine boundary layer, we anticipate that we will be able to apply the same technique to interactions of the atmosphere and ocean. This will include the effects of surface gravity waves on the exchange of momentum across the air-sea interface.

- The COARE results highlight the importance of considering free convection in the parameterization of surface fluxes and the likelihood of large errors, if the effects of buoyancy on the vertical velocity variance in light winds is not considered.

- We have provided the scientific community with a more accurate algorithm to calculate surface fluxes from ship and buoy data. This algorithm is available for testing in global models and could be provided to NRL to test in the COAMPS model. Uncertainties exist in connecting the surface layer, Monin-Obukhov similarity theory to large scale, coherent, convective and shear driven processes that may dominate the boundary layer structure. These need to be tested in a high resolution mesoscale model.

- The CW96 lidar and turbulence measurements afford us the opportunity to understand the structure of the stable coastal boundary layer in great detail. These observations will reveal the spatial scales and processes that control the exchange of heat, moisture and momentum between the surface layer and the free atmosphere. The results will lead to a better parameterization of the coastal region in regional models and a better understanding of the spatial variability of aerosols in the coastal regime. The latter will be applicable to electromagnetic propagation problems in the littoral zone.

- The CW96 cloud and boundary layer observations indicate that we should be able to improve the prediction of formation and distribution of fog on scales much smaller than the current operational model grid scale, which may aid in the development of an appropriate parameterization.

PUBLICATIONS:

P - Rogers, D. P., D. W. Johnson, C.A. Friehe, 1995: The Stable Internal Boundary Layer over a Coastal Sea. Part I. Airborne Measurements of the Mean and Turbulence Structure. *J. Atmos. Sci.*, 52 (6), 667-683.

P - Rogers, D. P., D. W. Johnson, C. A. Friehe, 1995: The Stable Internal Boundary Layer over a Coastal Sea. Part II. Gravity Waves and the Momentum Balance. *J. Atmos. Sci.*, 52 (6), 684-696.

P - Rogers, D. P., X. Yang, P. M. Norris, D. W. Johnson, G. M. Martin, C. A. Friehe, and B. W. Berger, 1995: Diurnal Evolution of the Cloud-Topped Marine Boundary Layer Part I. Nocturnal Stratocumulus Development *J. Atmos. Sci.*,.52 (16), 2953-2966.

P - Rogers, D.P., 1995: Air-Sea Interaction - Coupling the Ocean and Atmosphere. Reviews of Geophysics, Supplement, pp. 1377-1383, U.S. National Report to International Union of Geodesy and Geophysics 1991-1994.

P - Rogers, D.P., 1995: Coastal Meteorology. Reviews of Geophysics, Supplement, pp. 889-895, U.S. National Report to International Union of Geodesy and Geophysics 1991-1994.

P - Martin, G. M. D. W. Johnson, D. P. Rogers, P. R. Jonas, P. Minnis, and D. A. Hegg, 1995: Observations of the interaction between cumulus clouds and warm stratocumulus clouds in the marine boundary layer during ASTEX. *J. Atmos. Sci.*, 52 (16), 2901-2922.

P - Fairall, C., E.F. Bradley, D. P. Rogers, J. B. Edson and G. S. Young, 1996: Bulk parameterization of air-sea fluxes for Tropical Ocean Global Atmosphere Coupled Ocean Atmosphere Response Experiment. *J. Geophys. Res.*, 101, 3747-3764.

P - Tjernstrom, M. and D. P. Rogers, 1996: Turbulence structure in decoupled marine stratocumulus: A case study from ASTEX field experiment. *J. Atmos. Sci.*, 53, 598-619.

P - Serra, Y. L., D. P. Rogers, D. E. Hagan, Carl Friehe, R. Grossman, R. Weller and S. Anderson, 1996: Surface fluxes over the central equatorial and western warm pool of the Pacific Ocean. *J. Geophys. Res.*, Accepted for publication.

P - Yang, X. D. P. Rogers, and P. Norris, 1995: The diurnal evolution of the cloud-topped marine boundary layer II. Simulation of the night-time boundary layer. *J. Atmos. Sci.*, accepted for publication.

P - Brooks, I. M. And D. P. Rogers, 1996: Aircraft observations of boundary layer rolls of the coast of California. *J. Atmos. Sci.*, accepted for publication.

P - Norris, P.M. and D.P. Rogers, 1994: Radiatively-driven convection in marine stratocumulus clouds: numerical modeling. Preprints of the Second International Conference on Air-Sea Interaction and on Meteorology and Oceanography of the Coastal Zone. American Meteorological Society, 64-65.

P - Yang, X., D. P. Rogers, P. M. Norris, D. W. Johnson, and G. M. Martin, 1994: Stratocumulus cloud evolution. Preprints of the Second International Conference on Air-Sea Interaction and on Meteorology and Oceanography of the Coastal Zone. American Meteorological Society, 74-75.

PS - Hagan, D.E. and D.P. Rogers, 1995: On the effects of water vapor on thermal infrared retrievals of sea surface temperatures in the tropics. *J. Geophys. Res.*, Submitted for publication

PS - Johnson, D.W., G. M. Martin, I. M. Brooks, D. P. Rogers and C. A. Friehe, 1994: Aircraft observations of the evolution from stratocumulus to trade wind cumulus during ASTEX. *J. Atmos. Sci.,* submitted for publication.

C - Brooks, I. M. and D P Rogers, 1996: Turbulence in the Marine Atmospheric Boundary Layer: Aircraft Measurements and Lidar Visualization. *EOS*, 76, Supplement.

C - Rogers, D. P., L. V. M. Ström, and I. M. Brooks, 1996: Aerosol Variability and Cloud Development in the Stable Coastal Boundary Layer. *EOS*, 76, Supplement.

C - L. V. M. Ström, L. V. M, D. P. Rogers, and C. E. Dorman, 1996: Topographic Forcing of the Atmospheric Boundary Layer During CW96. *EOS*, 76, Supplement.

C - Burns, S, P., C. A. Friehe, A. Grant, D. P. Rogers, R. L. Grossman, 1995. Meteorological and turbulent flux results from the NOAA WP3D aircraft in TOGA COARE. Twenty-first General Assembly of the International Association for the Physical Sciences of the Oceans, Honolulu, Hawaii, 5-12 August.

C - Hagen, D. E., D. P. Rogers, 1995. Response of the tropical boundary layer to weak surface forcing. Twenty-first General Assembly of the International Association for the Physical Sciences of the Oceans, Honolulu, Hawaii, 5-12 August.

C - Rogers, D. P., Y. L. Serra et al., 1995. Mean structure and surface fluxes in TOGA COARE. Twenty-first General Assembly of the International Association for the Physical Sciences of the Oceans, Honolulu, Hawaii, 5-12 August.

C - Serra, Y. L. and D. P. Rogers, 1995. Comparison of enhanced surface fluxes and ocean mixing in determining sea surface temperatures. Twenty-first General Assembly of the International Association for the Physical Sciences of the Oceans, Honolulu, Hawaii, 5-12 August.

C - Walsh, E. J., D. C. Vandemark, R. N. Swift, J. F. Scott, D. E. Hagan, R. Pinkel, D. P. Rogers, R. A. Weller, 1995. Scanning radar altimeter measurements of sea surface mean square slope during TOGA COARE related to SST and internal waves. Twenty -first General Assembly of the International Association for the Physical Sciences of the Oceans, Honolulu, Hawaii, 5-12 August.

C - Norris, P.M. and D.P. Rogers, 1994: Radiatively-driven convection in marine stratocumulus clouds: numerical modeling. Second International Conference on Air-Sea Interaction and on Meteorology and Oceanography of the Coastal Zone. American Meteorological Society, Lisbon, Portugal. Poster presentation.

C - Yang, X., D. P. Rogers, P. M. Norris, D. W. Johnson, and G. M. Martin, 1994: Stratocumlus cloud evolution. Second International Conference on Air-Sea Interaction and on Meteorology and Oceanography of the Coastal Zone. American Meteorological Society, Lisbon, Portugal.