AD-771 471

AN INVESTIGATION OF THE STRUCTURE OF TURBULENCE OVER WATER SURFACE WAVES

Donald J. Portman, et al

Michigan University

Prepared for:

Office of Naval Research

November 1973

THE UNIVERSITY OF MICHIGAN

COLLEGE OF ENGINEERING

Department of Atmospheric and Oceanic Science

Final Report

AN INVESTIGATION OF THE STRUCTURE OF TURBULENCE OVER WATER SURFACE WAVES

Donald J. Portman
Kenneth I. Davidson

ORA Project 08849

under contract with:

OFFICE OF NAVAL RESEARCH
DEPARTMENT OF THE NAVY
CONTRACT No. N00014-67-A-0181-0005
(Including Task Nos. 083-224 and 083-265)

administered through:

OFFICE OF RESEARCH ADMINISTRATION ANN ARBOR

November 1973

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER	2. GOVT ACCESSION NO. / 3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) An Investigation of the Structure of Turbulence over Water Surface Waves	5. TYPE OF REPORT & PERIOD COVERED Final (Summary) 1967-1973
	6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) Donald J. Portman and Kenneth L. Davidson	8. CONTRACT OR GRANT NUMBER(s) N00014-67-A-0181-0005
9. PERFORMING ORGANIZATION NAME AND ADDRESS University of Michigan, Ann Arbor, Michigan 48104	10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS Task Nos. 083-224 and 083-265
11. CONTROLLING OFFICE NAME AND ADDRESS ONRRR, The University of Michigan, 1215 IST Building, Ann Arbor, Michigan 48105	12. REPORT DATE November 1973
	13. NUMBER OF PAGES
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office) Head, Physical Oceanography Programs, Ocean Science and Technology Group, Office of Naval Research, Washington, D. C. 20360	15. SECURITY CLASS. (of this report) Unclassified
	15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Turbulence measurements over water surface waves, air-sea interaction, BOMEX

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Wind velocity components and air temperature fluctuations were measured within a few meters above lake and ocean waves to study the influence of waves on the three-dimensional structure of turbulence and the vertical fluxes of momentum and sensible heat. Analyses were made primarily interms of variances, co-variances, spectrum and cross-spectrum functions and joint probability distribution functions of the measured variables. The report summarizes the methods of measurement and data pro-

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE
S/N 0102-014-6601 |

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered) cessing used and gives fourteen abstracts of reports, theses and papers resulting from the investigation. It lists, also, twenty periods of measurement, made during BOMEX, data from which are to be placed in the BOMEX Permanent Archive.

This work was supported by Office of Naval Research
Contract N00014-67-A-0181-0055. (NR 083-224)

-1005?

ABSTRACT

Wind velocity components and air temperature fluctuations were measured within a few meters above lake and ocean waves to study the influence of waves on the three-dimensional structure of turbulence and the vertical fluxes of momentum and sensible heat. Analyses were made primarily in terms of variances, covariances, spectrum and cross-spectrum functions and joint probability distribution functions of the measured variables. The report summarizes the methods of measurement and data processing used and gives fourteen abstracts of reports, theses and papers resulting from the investigation. It lists, also, twenty periods of measurement, made during BOMEX, data from which are to be placed in the BOMEX Permanent Archive.

PREFACE

This is the final report of an investigation of turbulence over water surface waves conducted under Contract No. N00014-67-A-0181-0005, including Task Numbers 083-224 and 083-265. The contract was with the University of Michigan but the latter Task Number refers to work conducted at the Naval Postgraduate School under the direction of Davidson. The work began in 1967 with an over-water experiment and continued into 1973 with the preparation of technical papers.

A great amount of the voluminous data processing was conducted without financial cost to the project at NASA Mississippi Test Facility and at NASA Michoud Computer Operations at Slidell, Louisiana. Other computer operations had priority over our tasks and there was more than a year's delay in obtaining the results for further analysis and interpretation.

We are grateful, nonetheless, for the valuable service and assistance provided by NASA personnel. We are happy to acknowledge, furthermore, the important contributions over a four year period of Michael A. Walter who took part in the BOMEX experiment and carefully and expertly managed most of the data processing procedures at both the University of Michigan and the NASA facilities. Allen Davis was responsible for building, calibrating and operating the sensitive electronic circuits used for recording. Finally, we wish to acknowledge the assistance of Edward Ryznar in many different aspects of the work throughout the lifetime of the project.

TABLE OF CONTENTS

PURPOSE

The purpose of the investigation was to determine the nature of air flow adjacent to lake and ocean waves in order to clarify and to refine ideas relating wave motion to heat and momentum transfer at the air-sea interface. Specific characteristics to be examined were the degree of direct influence of waves on the three-dimensional structure of turbulence, the variation with height of such influence and how it depends on wind speed and wave characteristics, the variation of momentum flux with height above waves, and the extent of the high wave number range of isotropic turbulence.

A major phase of the investigation was participation in BOMEX (Barbados Oceanographic and Meteorological Experiment) and part of the purpose for this phase was to obtain direct measurements of vertical fluxes of sensible heat and momentum. The data contributed to the so-called "core experiment" which consisted of analyses of the energy budget of an atmospheric volume 500 km on a side and 5 km high and the heat budget of the upper part of the ocean underneath it.

MEASUREMENT PROCEDURES

The investigation was based primarily on simultaneous measurements of:

(1) Three orthogonal wind velocity components at one or two heights above lake and ocean waves;

(2) Air temperature at the same heights; and

(3) Wave heights.

Hot-wire anemometer techniques were used for the velocity and temperature measurements. Multi-channel magnetic tape recorders were used and the taped electronic signals were processed by automatic computer to obtain various distribution and spectrum function statistics which formed the basis of the subsequent analysis and interpretations.

Three "field" experiments were conducted. The first, in August 1967, took place in Buzzards Bay, about 4.5 miles southwest of the island of Cutty Hunk, Massachusetts. It was conducted with a buoy and a tending vessel supplied by the Massachusetts Institute of Technology. Serious difficulty was encountered because of a low signal-to-noise-ratio caused primarily by the sensitivity of the recording system to variations in the electrical power supplied by the tending vessel. The short period devoted to this experiment had its value primarily in experiencing and overcoming a number of difficulties in operating sensitive laboratory equipment in a difficult physical setting.

In the following summer the equipment, having been improved and more completely tested, was installed on a tower fixed to the bottom of Lake Michigan about one mile from its eastern shore near Muskegon, Michigan. During the period from 7 August to 11 October, on ten different days with westerly winds, recordings were made in 14 separate periods, varying in length from 35 to 94 minutes each. In all but three of the periods, recordings of wind vector components were made simultaneously at two levels, usually 1.5 or 1 meters and 2 or 4 meters above the average water surface.

In May 1969 the equipment was taken to sea aboard FLIP for participation in BOMEX. Measurements took place during the last two weeks in May, about 200 miles east northeast of Barbados. A total of 54 hours of recordings were made and of these, 23 had simultaneous recordings of wind velocity components and temperature fluctuations at two heights. Measurement heights were 2, 3, 6 and 8 meters above mean water level. As in the Lake Michigan experiments, wave heights measured simultaneously with the other recordings.

EQUIPMENT

For both the Cutty Hunk and the Lake Michigan experiments, velocity component measurements were made with Flow Corporation Model HWP-X-W12X-L24 (X-type) hot-wire probes. Each probe consisted of two tungsten filaments mounted at right angles, crossed at their centers where they were 0.03 inches apart. Each filament was 0.1 inches long and 0.00015 inches in diameter and had a time constant of about 0.0004 sec. The "u" and "v" components were obtained from two filaments mounted in the horizontal plane and the "w" component was obtained from two filaments mounted in the vertical plane.

Each filament of the probes formed one arm of a Wheatstone Bridge in a hot-wire solid-state amplifier circuit. It was a closed-loop feedback system consisting of a bridge circuit, a power amplifier and a high-gain differential amplifier. The filaments were operated in a constant resistance (therefore constant temperature) mode by means of a separate feedback for each.

For the BOMEX experiment, wind components were measured with Thermo-Systems Inc. hot film constant temperature anemometer systems, Model 1054B, with linearizers. Each probe (Model 1294-60) had three quartz-coated, mutually perpendicular sensors 0.15 mm in diameter and 2.0 mm long. Each sensor was a glass rod covered with a platinum film onto which a quartz coating had been sputtered. The frequency response of these sensors appeared to be well over 50 Hz in the conditions under which they were used.

For all experiments air temperature fluctuations were measured with a Flow Corporation, Model 900-A (two-channel), anemometer system operated in constant current mode. The sensors (Flow Corporation, Model HWP-BO) were 30-ohm tungsten filaments, 0.0038 mm in diameter and 5 mm long. They were operated as parts of bridge circuits with filament currents of about 2 milliamperes. The complete system included a Flow Corporation Model 990-1 constant temperature anemometer, a Model 900-2 Monitor and Power Supply Unit and a Model 900-3 Suppressor/Filter Unit. Manufacturer's specifications for this system were: Frequency response from d-c to 1 kHz, resolution 0.03 C and noise level 0.33 millivolts.

Wave measurements during the Lake Michigan experiment were made with a capacitance water depth gauge which consisted of a sensor and a bridge. The sensor was a teflon coated stainless steel rod 0.25 inches in diameter and 60 inches long. The rod was positioned vertically in the water with a similar but non-insulated rod parallel to and one inch away from the insulated one. The two rods served as capacitance arms of the bridge which was in essence a capacitance to current transducer.

During the BOMEX experiments wave measurements were made with a resistance gauge obtained on loan from Dr. R. E. Davis, Scripps Institution of Oceanography. The probe consisted of a nonconducting tube, approximately 2.5 cm in diameter, with a conducting wire wrapped spirally around it. It was positioned about 5 meters from the vertical mast that held the velocity and temperature sensors.

Sensor system outputs were recorded by frequency modulation on Ampex, Model SP-300, seven channel, magnetic tape recorders with one-quarter inch magnetic tape. Before they were recorded, however, they were amplified and suppressed with a known and constant opposing voltage . All recordings were made at a tape transport speed of 3-3/4 inches per second, making it possible, according to the recording specifications, to resolve frequencies between d-c and 625 Hz.

DATA PROCESSING

Recorded data selected for analysis were digitized at a rate of 300 points per second for Lake Michigan data and at 50 points per second for BOMEX data. A low-pass filter was applied to remove fluctuations with frequencies greater than about 10 Hz for the former and about 12.5 Hz for the latter. The resulting data were then edited to remove spurious points and to supply interpolated values for drop-outs. Conversion to engineering units was made on a point by point basis from sensor calibration data and wind vector components were computed. The vector components were based on a frame of reference oriented according to the average wind direction. In the BOMEX experiment it was not possible to position the sensors according to the average wind direction so that it was necessary to transform the arbitrary coordinate system, defined by the sensors, into one defined by the measurements obtained. During the process the velocity component means, trends and deviations from the means were determined.

The foregoing processing produced three velocity components and simultaneous temperatures for each height of measurement and, along with wave heights, all were stored on magnetic tape. Subsequent processing included the computation of values of variance, skewness, and kurtosis for each variable and covariances for different combinations of variable pairs. Joint probability densities of two variables were computed for conditional mean values of a third variable and the results were plotted in arrays to show relationships among the three.

Finally, Fourier coefficients were computed with a "Fast Fourier Transform" algorithm and variance and covariance spectral estimates were calculated. Smoothed spectra and cospectra were obtained by a logarithmic averaging technique and phase lag and coherence estimates were obtained from the smoothed cospectrum and quadrature spectrum estimates.

Data processing was conducted with several different computing facilities. The Lake Michigan data were processed at the University of Michigan computer center and with special analog-to-digital conversion facilities in the Department Meteorology and Oceanography. The BOMEX data were processed at the University of Michigan and also at NASA Mississippi Test Facility, at NASA Michoud Computer Operations and at the U.S. Naval Postgraduate School.

RESULTS

The results of the investigation have been presented and are described in the following forms:

(1) Eight (8) papers were presented at scientific meetings. One of these was given at the 15th General Assembly of International Union of Geodesy and Geophysics held in Moscow, USSR, in August, 1971.

(2) Three (3) reports prepared at the University of Michigan describe the three over-water experiments and methods of data processing and analysis. One of the reports is the doctoral dissertation of Kenneth L. Davidson. In addition to a description of the Lake Michigan experiment, including data processing and analysis procedures, it gives interpretation of the results.

(3) Eight (8) master's theses prepared by students at the Naval Postgraduate School under the direction of Dr. Davidson were submitted as reports under Task No. 083265. These deal with data analysis and interpretations for both the Lake Michigan and BOMEX results.

(4) Four (4) papers--two published, one in press and one in preparation--complete present plans for reporting the results of the investigation.

Data obtained during the BOMEX experiment have been stored on magnetic tape and punched cards to be placed in the BOMEX Permanent Archive.

Abstracts of the reports, theses and papers and a brief description of the archive data follow.

UNIVERSITY OF MICHIGAN REPORTS

1. Portman, Donald J. and Kenneth L. Davidson (1968): An Investigation of the Structure of Turbulence over Water Surface Waves, University of Michigan Report 08849-1-P, 32 pages.

ABSTRACT

A hot-wire anemometer system, a fast response resistance wire thermometer and a thermocouple circuit were used in an attempt to measure the structure of turbulence, the tubulent fluxes of heat and momentum and the mean vertical temperature difference over ocean waves. The sensors were mounted on a research buoy near the Buzzards Bay Entrance Light Station, about 4.5 miles southwest of Cutty Hunk, Massachusetts. The amplified outputs of sensor circuits were recorded via frequency modulation with a seven channel magnetic tape recorder. During a three-week period a total of about 7 hours of measurements were obtained. Concurrent measurements of wave heights and wind profiles with instruments attached to the same buoy were made by personnel from the Massachusetts Institute of Technology.

To study data reliability (1) the recorded information was converted to voltage analogs and recorded on a paper chart and (2) spectral analyses were made for all channels of information for a representative six minute interval. It was found that a high noise level was present in all recordings and that it could be accounted for by voltage and frequency fluctuations in the power supplied for the magnetic tape recorder. The noise level masked the temperature measurement outputs which, apparently, were very small because of the nearly neutral thermal stratification during the experiments. On the basis of the preliminary analyses it appears that meaningful velocity spectra and cross spectra for frequencies less than 1.5 Hz may be computed from the recordings; higher frequency information is probably obscured by the high noise level.

2. Davidson, Kenneth Laverne (1970): An Investigation of the Influence of Water Waves on the Adjacent Airflow, University of Michigan Report 08849-2-T, 259 pages.

ABSTRACT

An observational study was made during August, September and October 1968 to investigate the influence of water waves on the adjacent airflow. Simultaneous measurements of wind and temperature fluctuations and waves were made from a tower on Lake Michigan. 11 periods were analyzed, and 8 included

simultaneous measurements of velocity and temperature fluctuations at two levels above the mean water level. Pairs of levels (in meters) were; 1.5 and 4.0 or 1.5 and 15. or 1.0 and 2.0.

Hot-wire anemometers with X-probe sensors were used to obtain both the along-wind and vertical components of the fluctuating wind. High response resistance wires were used to measure temperature fluctuations and a capacitance gauge was used to measure the waves. Data were analyzed to obtain variance and covariance spectra over a frequency range from .01 to 15 Hz and are presented over a range from .03 to 10 Hz.

Velocity spectra show significant fluctuations in the airflow due to the waves. When the wind speed was much less than the phase speed of the dominant wave component, there is evidence of momentum transfer from the waves to the air. Cospectral results from one period clearly show upward transport of momentum at the frequency of the wave spectrum peak. However, at the same frequency but at an upper level, enhanced downward transport of momentum occurs. Enhanced downward transport of momentum at frequencies near wave spectra peaks occurs in most cospectral results. When the wind speed was comparable to the wave speed, phase relationships between the wave-induced fluctuations and the wave are in agreement with those inherent in Miles' wave generation theory.

The universal nature of velocity spectra at high frequencies (10 Hz) does not appear to be influenced by the waves. At high frequencies, velocity spectra have slopes which are in agreement with Kolmorogov's power law relation. Smoothed spectra have maxima occurring at non-dimensional frequencies comparable to those reported by other investigators.

Stress estimates obtained from hot-wires exceed those obtained from wind profiles and are not constant with height. Relative intensities and the sign of skewness of velocity components appear to be related to the waves' influence. The non-dimensional divergence term in the turbulent kinetic energy balance equation is positive when the ratio of the measurement height to the wave length is less than .1 and when the wave speed is much greater than the wind speed.

The results lead to a conclusion that the waves influence the airflow to such an extent that the ocean surface cannot be considered a rigid boundary for purposes of analysis of the adjacent boundary layer.

3. Portman, Donald J., Kenneth L. Davidson and Michael A. Walter (1970): Turbulent Measurements Made From FLIP in BOMEX, University of Michigan Report 08849-3-P, 40 pages.

ABSTRACT

Simultaneous measurements of wind velocity components with hot-film anemometers, air temperature fluctuations, and wave heights were made about 200 miles east northeast of Barbados during BOMEX. A total of 54 hours of measurements were made during the last two weeks in May, 1969. Of these, 23 had simultaneous recordings of wind velocity components and temperature fluctuations at two heights. Measurement heights were 2, 3, 6, and 8 meters above mean water level.

Three different computer facilities have been employed in processing the data to obtain probability distribution functions, joint probability distribution functions, spectrum functions and cross-spectrum functions for velocity components, temperature fluctuations and wave heights. Examples of the calculation results are given and briefly described. They show specific effects of waves on the velocity components.

NAVAL POSTGRADUATE SCHOOL MASTERS THESES

1. Frank, Allen Jesten (September 1971): An Investigation of the Properties and Influence of Wave-Induced Organized Motion in the Adjacent Airflow, 84 pages.

ABSTRACT

Turbulence data obtained over natural water waves were analyzed using joint probability distribution and conditional means methods. These data represented conditions when the waves were decaying and when the waves were building. In both cases, significant wave-induced fluctuations were identified in the airflow. All features of the velocity fluctuations were examined for two levels above mean water level. In the case of a decaying wave field, decelerations in the airflow can be associated with an assumed propagating pressure maximum over the crest of the wave. Other than this deceleration, the airflow appears to reflect simple streamline bending over the mobile irregular wave surface. In the case of a building wave field, velocity fluctuations appear to agree with those predicted by linear wave generating theories.

2. Safley, Gordon W. (March 1972): Investigations on the Fluctuations and Incidence of Micro-thermals in the Air Adjacent to Natural Water Waves, 91 pages.

ABSTRACT

Temperature, wind (u and w), and wave data observed over Lake Michigan were analyzed to yield results on properties of sensible heat transfer in the near-surface layer. Significant features in the overwater data are associated with positive temperature fluctuations which appear as ramps (micro-thermals) in continuous traces. Objective methods based on the distinctive shape of the ramps were used to identify the occurrences of the micro-thermals. Although micro-thermals accounted for only ten percent of the total record, they accounted for 32 percent of the total sensible heat flux. Results indicate that the occurrence and maintenance of the micro-thermals, and therefore, enhanced sensible heat flux are related to the presence of the waves. These results were obtained by considering Richardson numbers, significant wave height, and comparisons of wave and temperature traces. The Richardson number criteria for free convection do not appear to be the only determining parameters for the frequency of occurrence nor the development of the observed micro-thermals.

3. Bingham, Glenn Stevenson (September 1972): Spectra of Turbulent Fluctuations over Ocean Waves, 64 pages.

ABSTRACT

Spectral analyses are performed on turbulence data obtained over natural ocean waves during BOMEX. Results are obtained for variance and co-variance spectra, phase and coherence relationships, and amplitude ratios. Peaks in the horizontal and vertical velocity spectra are observed to correspond to the frequency of the wave spectra peaks. Phase relationships tend to obey predictions of potential flow theory in regions of the wave spectra peaks. However, the wave related motion contributes to the momentum transfer which is not predicted by potential flow theory. The ratio of the wave induced disturbance to the sea surface displacement is used to locate the wave spectra frequency for which the level of measurement is a critical level. Results of the study are readily compared to existing wind-wave coupling theories, both linear and non-linear.

4. Ihle, David M. (September 1972): An Investigation on Temperature Fluctuations over Ocean Waves, 89 pages.

ABSTRACT

Joint probability distributions and conditional means functions are used to analyze turbulent wind and temperature data obtained over natural ocean waves. The data were collected aboard R/V FLIP during BOMEX 1969.

Stable conditions prevailed during all time periods considered. The emphasis is to use the statistical procedures to describe the wave's influence on the temperature fluctuations at the 8 meter level.

Results are compared with predictions given by potential flow theory. The results consistently demonstrate that waves exert an influence on the temperature fluctuations. In addition, it is observed that under near neutral thermal stratification or prolonged periods of stable thermal stratification the temperature fluctuations approached those expected from potential flow.

5. Smith, Craig H. (September 1972): Application of Parametric Time Series Analysis Methods to Descriptions of Wave-Induced Fluctuations in the Adjacent Airflow, 62 pages.

ABSTRACT

Certain methods of analysis for testing the hypothesis that organized motion exists in the airflow above naturally occurring water waves are examined. In particular, two cur-

rent methods, spectral analysis and joint probability density function analysis, are briefly discussed; two new methods, matched filters and parametric time series analysis, are suggested.

An analysis is done with parametric time series analysis on wind-wave data. The results show the tractability of this data to parametric methods, and the results are in agreement with previous spectral analyses of the data in the regions of overlap.

6. Thompson, Stanley P. (September 1972): Wave-Related Disturbance in the Velocity Field over Ocean Waves, 77 pages.

ABSTRACT

Velocity fluctuations over ocean waves and wave heights are examined using joint probability density function-conditional mean function (JPDF-CMF) analyses. Results are compared with theoretical predictions from wind-wave coupling models which provide for interaction between the wave-induced motion and turbulence in the airflow, and also with predictions from potential flow theory.

Phase and amplitude results for wave-related fluctuations are examined in detail and consistent departures from potential flow are noted. These departures are phase differences in between u and w which are not in quadrature, amplitudes of u and w which vary throughout the periods, and phase shifts of u and w which differ from those predicted by potential flow theory.

Conclusions for the role of turbulence in the interactions are based on JPDF-CMF and phase amplitude analyses.

7. Aurand, David Robert (March 1973): Wave-Related Velocity Fluctuations over Ocean Waves as Measured from FLIP during BOMEX, 71 pages.

ABSTRACT

Wave-related velocity fluctuations over ocean waves and wave heights as measured from FLIP during BOMEX are examined using phase-amplitude results which are based on joint probability density function-conditional mean function (JPDF-CMF) analyses. Results are compared with predictions from various wind-wave coupling models.

Results are examined in detail and consistent departures from theory are noted. An attempt is made to qualitatively determine the effect on specific results of the moving, but relatively stable, sensor platform, FLIP.

It is concluded that the interaction between the wave-induced motion and airflow turbulence had a significant effect on the observed wave-related fluctuations. The effects of FLIP on the results appeared to be minimal on these results.

8. Stricker, Robert John (March 1973): Normalized Spectra of Turbulent Fluctuations over Ocean Waves, 43 pages.

ABSTRACT

Spectral and cospectral analyses are performed on turbulence data obtained over natural ocean waves during BOMEX. Results are obtained for normalized spectra and cospectra. Significant scatter is observed throughout the spectra and cospectra with a larger degree of scatter in the low frequency range. Kolmogorov's -5/3 power law is found to describe the longitudinal and vertical velocity spectra in the high frequency range. However, it is not applicable to the lateral velocity spectra while results for the temperature spectra are inconclusive. Monin-Obukhov similarity theory well describes the vertical velocity spectra yet its application to horizontal velocity spectra is doubtful. Similarity theory does not seem to adequately describe the uw cospectra. Results from comparing similarity theory to temperature spectra and wT cospectra indicate the presence of an influence not accounted for by similarity theory. When compared, uw and wT cospectra are found to be significantly different. All computed spectra and cospectra are found to have a relatively larger amount of energy in the low frequency range than their respective over land spectra and cospectra.

PAPERS FOR TECHNICAL JOURNALS

1. Davidson, K. L. and A. J. Frank (1973): Wave-related Fluctuations in the Airflow Above Natural Waves, <u>Jour. Phys. Oceanog</u>. 3 (1), pp. 102-119.

ABSTRACT

Simultaneous observations of wave heights and velocity fluctuations at two levels above the waves are analyzed to examine properties of the wave-related fluctuations in the airflow. Results are obtained from spectral and joint probability density function, conditional mean function (JPDF-CMF) analyses. Results are examined with respect to predictions from potential flow theory and recent theoretical formulations for wind-wave coupling. Of interest are recent formulations which allow interaction between the wave-induced motion and turbulence in the airflow, the so-called "turbulence" models.

Cospectral results exhibit features which are predicted by theoretical formulations with regard to height variations of the wave-related momentum transfer. These features include the oscillatory variations predicted by recent turbulence models and also enhanced transfer at both levels as predicted by the quasi-laminar model.

JPDF-CMF analyses are used to obtain phase-amplitude information for those variables examined in the spectral analyses. For a period in which the presence of the "critical level" could have been a factor, the phase relation between the wave-related vertical velocity and the wave height agrees with the quasi-laminar prediction. For periods in which only the turbulence in the airflow would be expected to influence the wave-induced motion, phase and amplitudes of the wave-related fluctuations differ from the potential flow predictions.

It is concluded that the interaction between the wave-induced motion and airflow turbulence had a significant effect on the observed wave-related fluctuations. Another conclusion is the assertion of the value in using JPDF-CMF analyses for examining wave-related fluctuations.

2. Davidson, K. L. and G. W. Safley (1973): Temperature Fluctuations and Heat Flux above Waves. <u>Proc. 15th Conf. Great Lakes Res</u>., pp. 464-476.

ABSTRACT

Occurrences of microthermals observed in data obtained over Lake Michigan were examined with respect to sensible heat transfer and the influence of the waves. Recent proposals for

microthermal formation and maintenance and for wind-wave coupling are considered which support the possibility of wave influence. Heat flux results indicate that the microthermals, which represented about 10% of the record, were responsible for about 30% of the total sensible heat transfer during the periods examined. An influence by the waves is inferred from similar statistical results in periods with different stabilities but similar underlying wave fields. (Key words: Microthermals; turbulence; wind-wave coupling; heat transfer; Lake Michigan).

3. Davidson, K. L. (1974): Observational Results on the Influence of Stability and Wind-Wave Coupling on Momentum Transfer and Turbulent Fluctuations over Ocean Waves, accepted for Boundary Layer Meteorology, Brocks Memorial Special Issue.

ABSTRACT

Turbulence data obtained over ocean waves during the BOMEX experiment of 1969 are presented. Procedures in measurement and analyses are described which include adjustments for possible platform, R/V FLIP, motion. Momentum and sensible heat flux results for levels below 10 meters are related to the large scale momentum variations and radiation induced stratifications. Momentum transfer is also shown to have been influenced by wind-wave coupling. The influence is separated from the stability influence and is described in terms of a linear dependence for C/u_* on the deviation to the logarithmic profile, where C is the phase speed corresponding to the wave spectrum peak. As observed by others, a value of C/u_* near 25 is associated with minimal wind-wave coupling influence. For C/u_* greater than 25, momentum transfer is decreased relative to the neutral profile prediction. Expressions are also presented for the wind-wave coupling influence on relative intensities, $\sigma u/u_*$, $\sigma v/u_*$, and $\sigma w/u_*$. Values of the relative intensities approximate neutral overland values when the expressions are written such that the wave influence is zero near a C/u_* value of 25.

4. Davidson, K. L. and R. J. Stricker (1974): Normalized Velocity Spectra over Ocean Waves, in preparation for submission to <u>Jour. of Phys. Oceanog</u>.

BOMEX DATA STORED ON TAPES AND CARDS

Digital copies of the original recordings obtained during the BOMEX experiment have been combined onto six 9-track, 800 bpi computer tapes. The data are in a format suitable for an IBM 360 computer. Digital records of variance and covariance spectra are similarly stored on three computer tapes. Mean, variance, covariance and skewness statistics for all variables, furthermore, are stored on punched cards. The dates and times of measurement periods, along with the variables and their heights of measurement, for the stored BOMEX data are as follows:

Period Number	Date May 1969	Inclusive Times (GMT)	Heights (meters)	Variables[1.] Measured	Number of[2.] Subperiods
1	17	2110-2230	6	1	7
"	"	"	3	1	7
2	19	0310-0430	6	2	7
"	"	"	2	2	7
3	19	0545-0700	6	2	7
4	"	1615-1730	8	2	6
5	"	1840-2000	6	2	7
"	"	"	3	2	2
6	"	2110-2150	8	2	3
7	24	2020-2130	8	1	4
8	26	1140-1200	8	2	2
9	"	1430-1455	8	2	2
10	"	1510-1545	8	2	3
11	"	1710-1730	8	2	2
12	"	2155-2240	8	2	4

Period Number	Date May 1969	Inclusive Times (GMT)	Heights (meters)	Variables[1] Measured	Number of[2] Subperiods
13	27	0500-0545	8	2	4
14	"	0900-1020	8	2	6
15	"	1100-1215	8	2	6
16	"	1615-1735	8	2	6
"	"	"	3	2	4
17	28	0600-0612	8	2	1
18	"	0930-1050	8	2	4
19	"	1755-1915	3	2	6
20	"	2030-2145	8	2	6

Total 115
Total with all variables 96

1
1 = u, v, w.
2 = u, v, w, T.

2
10.9 minutes each