WHOI-77-66

Woods Hole Oceanographic Institution

FINAL REPORT

BOUNDARY LAYER AND FRONTAL STRUCTURE
OVER THE EAST CHINA SEA

by

Andrew F. Bunker, Principal Investigator

November 1977

TECHNICAL REPORT

Prepared for the National Science Foundation under Grant ATM 73-0421.

WOODS HOLE, MASSACHUSETTS 02543

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Approved for Distribution ______________________
Valentine Worthington, Chairman
Department of Physical Oceanography

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I. Introduction

Weather systems influencing the Japanese Islands during the winter are generated or intensified by air mass modification over the warm water south and west of the Islands. In order to understand developments resulting from modification and to improve forecasting techniques, the Japanese National Committee for GARP proposed a program for the Air Mass Transformation Experiment (AMTEX) over the Kuroshio, the region around Okinawa, and the East China Sea. The committee emphasized that the main goal of AMTEX was to improve understanding of physical processes which provide heat and momentum from the sea and make it available for the large-scale circulation. To achieve this end it was planned to study the magnitude and distribution of surface fluxes of energy, the convergence and divergence of fluxes in the boundary layer, convective clouds, meso- and medium-scaled disturbances. Meteorologists from other GARP nations were invited to cooperate. Many accepted and worked on various aspects of the problem. In response to the invitation to join AMTEX the Principal Investigator submitted a proposal to NSF to participate in AMTEX by cooperating with NCAR personnel who would be using the NCAR Electra aircraft for observing over the East China Sea. The abstract of the proposal is repeated here.

> It is proposed to participate in the Air Mass Transformation Experiment (AMTEX) to be carried out over the East China Sea during February of 1974 and 1975. Participation would include cooperating with other AMTEX investigators in the planning and flying of observational missions with the National Center for Atmospheric Research (NCAR) Electra aircraft and analyzing the data obtained. The following problems associated with air masses moving over the warm waters of the East China Sea and the Kuroshio Current would be studied: (1) establishment of heat and water-vapor fluxes, accumulations, and gradients throughout the boundary layer; (2) determination of the turbulent, convective, and secondary instability circulative processes operating in the planetary boundary layer through analysis of mean values of the wind components, temperature, and humidity, and along-wind and cross-wind spectra and cospectra of turbulence, temperature, and humidity fluctuations; (3) the distribution of stress throughout the layer and its relation to the wind shear, stability, and the three types of processes studied under (2); (4) the kinetic and thermodynamic structure and energy transports of cold and warm fronts moving over the

water, mixing along the frontal zone, the changes that occur as the cold front becomes stationary, and the characteristics of the cold and warm fronts associated with a developing wave. Discussion and planning with other AMTEX investigators may show the need to modify this set of problems to avoid duplication of effort and to insure that other important problems are not ignored.

After the proposal was granted, planning started in earnest. The Principal Investigator attended a planning session, in September 1973 at NCAR, with several representatives from Japan, other countries, and the United States. Here the goals were reconsidered and plans were laid to achieve them. As the various participants described their interests in the AMTEX project it became clear that most of the problems stated in the above abstract except the study of frontal structure and modification would be studied by one or more groups. Hence it seemed wise for the Principal Investigator to concentrate on the problem of frontal characteristics and properties of the boundary layer in fronts. He has, however, also made a study of fluxes in the AMTEX region under different wind directions using ship weather reports.

The AMTEX staff at Woods Hole Oceanographic Institution was small since all preparations and calibrations of instruments used on the NCAR aircraft were made by NCAR personnel. Both the flying personnel and the technical staff of NCAR did a superb job of preparing for the project, carrying out the observational flights, and processing data afterwards. Besides the Principal Investigator, Margaret Chaffee and Mary Hunt aided in the work. Margaret Chaffee handled data and cloud-photograph processing and drafting of charts and diagrams. Mary Hunt wrote programs necessary to decode and transcribe the aircraft data and compute spectra and co-spectra.

II. AMTEX Observation Program

1. General AMTEX Meteorological Observations

The Japanese National Committee for GARP established a very effective network of surface and upper air observations in the AMTEX area which the present project has used extensively in the study of the February 26-28, 1975 frontal system. The network has been described in the Collected Scientific Papers of the AMTEX No. 1 published by the Japan National Committee. The core experiment is described on pages 52 through 58 of that issue. It is sufficient to report here that there was excellent coverage throughout the area by surface observations, radiosonde and radiowind observations, radar and satellite observations of clouds, oceanographic observations, and radiation observations. Synoptic analysis charts prepared by the Japanese Meteorological Agency have been published and distributed. Eight volumes of various types of data have been published for each of the observation periods.

2. Observational Program of the NCAR Lockheed Electra Aircraft

The 1974 flight to AMTEX had to be given up due to mechanical difficulties with the aircraft. All went well on the flight to Okinawa until a few hundred miles off the coast of California, the cabin pressure system failed. Shortly afterward the propeller control on one engine failed and we returned to San Francisco. The propeller could not be fixed in time to arrive in Okinawa before the end of AMTEX '74 and the flight was cancelled.

In March a shake-down flight was made to the east coast to test equipment over the Gulf Stream and to calibrate the Inertial Navigation System within range of the Wallops Island precision radar station. Four flights were made over the Gulf Stream in addition to flights around the radar station and a cooperative flight to Penn State University. Some instrumental difficulties were found and overcome. Faulty recording of data on the mag tapes was traced to the camera-shutter timing device and was corrected. Two flights over the Stream were made in cold air outbreaks with great turbulent exchange of heat and water vapor. Little of these data has been processed.

The flight of the NCAR Lockheed Electra aircraft to Okinawa and participation in the 1975 AMTEX were very successful. The aircraft with instruments, observers, and some scientists, including the

Principal Investigator, took off from Jeffco Airport south of Boulder, Colorado on the 3rd of February, landing at Travis Air Force Base, California. Plans to leave for Honolulu on the 4th had to be canceled because of high head winds produced by a deep, semi-stationary low pressure center located south and east of its normal position. By the 7th the low showed no signs of moving, so the aircraft took off for Kodiak Island thereby taking advantage of tail winds to fly around the low. On the 8th tail winds helped us into Midway Island on the westward side of the low. On the 9th the aircraft flew to Guam and on to Okinawa the next day (11 February by the Japanese calendar). Planning and coordination meetings were held with other meteorologists. A flight could not be made on the 14th because of a low pressure system passing over the island with extreme turbulence and thunderstorms reported. The first observational flight was made on the 15th in post-cold-frontal conditions. Turbulence runs were flown at nine heights over the East China Sea northwest of Okinawa. AMTEX '75 Flight 2 was flown on February 16 also in the cold air mass. Eight turbulence runs, with right angle legs, were made at levels between 1009 and 854 mb. A climb to 6 km was made to look for convection cells observed on satellite photographs. Even at this altitude the cloud distribution appeared to be random. Flight 3 was made on February 18 to Miyako Island to study the boundary layer in conjunction with tower installations. Flight 4, February 19, was planned and flown to study the modification of the air mass as it moved southwestward over the sea north of Okinawa. Soundings were made from 1013 to about 575 mb. A strong inversion was observed near 2000 m which acted as a lid on the cumulus convection. Flight 5, flown on February 21, was another flight to Miyako. Four large boxes were flown at low levels near the towers. Later a box was flown at 2 km. On February 22 another flight was made to Miyako with more low and intermediate level boxes flown. Flight 7 was made on February 24 in southeast winds produced by a high pressure cell northeast of Okinawa. Eight right angle turbulence runs were made at levels between 1019 and 555 mb. The eighth flight was made on February 26 to study a front which extended across Korea and the East China Sea. The front dissipated before it could be studied and the plan was changed to study the fluxes over the Kuroshio. Nine boxes or right angle turbulence runs were made between 1009 and 674 mb. The flight that was the primary concern of this project was made on February 28, the last day of AMTEX '75. A cold front passed Okinawa during the night and was observed about 600 km southeast of Okinawa at 8:30 JST by satellite. A flight was planned to observe the structure of the front at as many levels as could be accomplished within the capabilities of the aircraft. Upon take-off the aircraft climbed to 3300 m and headed southeast toward the retreating front. We passed over the sharp leading edge of the front at 0323 GMT about 700 km from Okinawa. The flight was continued at the same altitude for another 50 km into the completely clear air ahead of the front. A descent to 100 m was made and a flight was made under the front on a 315° heading. After about 250 km a climb to 300 m and course reversal was executed. Other climbs and reversals were made so that the front was penetrated at 900 m, 1600 m, and 2400 m. The flight home was made at 100 m to study the surface layer turbulence. All of the instruments were working properly on this flight except the infrared hygrometer. The back-up refractometer system was used for the study of rapid water vapor fluctuations and water vapor transport.

III. Processing of Aircraft and other Meteorological Data

1. Processing by NCAR Personnel and Facilities

The method of processing data obtained by instruments mounted aboard the Electra aircraft and recorded on magnetic tapes has been the subject of several articles by NCAR in Numbers 1 and 2 of Atmospheric Technology, the NCAR house publication. These techniques and electronic facilities will not be described here. Rather, the various forms of output produced and the steps required to continue the processing at Woods Hole will be discussed.

Several 'quick-first-look' diagrams and charts are output by the computer and photographed onto microfilm. Charts of the flight paths of the aircraft are plotted with times written in at turn-points. Tabulated values of pressure, latitude, longitude, and heading made the charts very valuable to scientists wanting to use the data. Charts with wind vectors plotted at the proper positions were produced and distributed. Time versus temperature, water vapor, pressure, or any other variation also are produced. Tabulations of 30-second means and standard deviations are available for every minute of flight.

Copies of magnetic tape containing 1 second averages of 66 variables and 1/20 second averages of 34 variables were made available to all participates and users of AMTEX material. To produce these tapes, analog signals were filtered electrically with a 10 cycle low pass filter, sampled at a rate of 50 times per second and finally 1/20 second and 1 second averages were formed and recorded. Each variable average was biased and scaled so that the data could be packed efficiently on magnetic tape. With this method data acquired during about 70 minutes of flight time could be contained on 1 reel of 7-track tape.

Spectral analysis of 17 3-minute segments of the data were carried out by the NCAR computing center for the present project. These calculations were made both for analysis and as a basis for comparison with spectral analysis carried out at Woods Hole with the Xerox Sigma-7 computer. It was found that the two systems gave spectral curves that differed only in minor respects.

2. Processing of Data at Woods Hole

The first step in processing the data at Woods Hole was to write a program to unpack and decode the data from their format and separate the high frequency (1/20-second data) from the low frequency data (1-second data) and rewrite the 2 sets onto separate tapes. This procedure was decided upon because the two sets were to be analyzed separately by different techniques.

The spectral analysis program used to process the high frequency data is a fast Fourier method called TIMSAN used primarily by oceanographers for buoy data analysis. The computer package has a large number of options such as filters, number of variables to be processed, cospectra, plotting formats, averaging of raw data, and smoothing of estimates. With this program many spectral and cospectral analyses were made at the six levels within the front. Generally, 8,000 points for five variables, temperatures, humidity, and the three wind components were analyzed. This corresponds to a duration of 400 seconds of flight time or a distance of about 40 km. To extend the spectra range to the lower frequencies, the option of averaging the raw data was used and runs up to 1,600 seconds or 160 km were analyzed.

The one-second data were used to compute auxiliary variables such as virtual and potential temperatures and quantities such as divergence and convergence within the front, vertical velocities, gradients and frontogenesis. Some of the work was carried out by desk computer. Magnetic tapes containing ship weather reports in the Okinawa region were obtained from the National Climatic Center to compute fluxes of energy from the sea surface. A program developed under another project was used for this work.

Time lapse cameras were mounted on either side of the Electra aircraft pointing out perpendicular to the fuselage. A timing mechanism tripped the shutters every four seconds and recorded the event on the magnetic tape of the aircraft's data recording system. Kodachrome film was used to give the best contrast between sky and clouds. Following the method of Ronne (see Bunker and Chaffee, 1969)[1] the photographs were read and processed to determine the heights and distances of the clouds. From these observations, cloud charts and cross-sections were constructed which aided in the analysis of the cold front.

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[1]Bunker, A. F. and M. Chaffee, 1969: Tropical Indian Ocean Clouds. Internat. Indian Ocean Exped. Meteor. Monograph. No. 4. East-West Center Press, Honolulu, 193 p.

IV. Energy Exchange over the East China Sea Determined from Ship Weather Reports

1. Variation of Fluxes with Wind Direction

Using bulk aerodynamic and empirical radiation formula, the energy fluxes and climatological averages of Marsden Square 96, the square surrounding Okinawa, were found for the years 1961 to 1968. The data for this study were contained in one reel of 9-track magnetic tape obtained from NCC. The method and program for this study has been described by Bunker and Worthington (1976)[1] and Bunker (1976).[2] Much of this work was presented at the Tokyo AMTEX meeting in September 1975 and published in AMTEX Report No. 8. The paper is reproduced here since no reprints have been made available.

VARIATION OF ENERGY EXCHANGE WITH WIND DIRECTION AND ITS RELATION TO COLD FRONT MODIFICATION

Andrew F. Bunker

INTRODUCTION

A preliminary study of cold fronts in the AMTEX region indicates that the frontal zones are wider than the corresponding zones over continents, temperature gradients are smaller than continental zonal gradients and become smaller with distance from shore. To study these modifications it is necessary to know the magnitudes and variations of the air-sea interactions. The sensible heat flux is particularly important because non-adiabatic heating of the air may cause the front to weaken even though the heating may intensify the associated cyclone. The latent heat flux plays an important role by supplying additional moisture for the condensation process. Whether or not the heat of condensation is made available to the system in significant amounts depends largely on the convergence pattern in the area.

To study the effect of the oceans on fronts, the flux patterns associated with four wind directions have been computed. This was carried out by applying the bulk aerodynamic equations to 60,000 ship observations in the AMTEX region for the years 1961 to 1968. A variable exchange coefficient similar, but not identical, to that

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[1] Bunker, A. F. and L. V. Worthington, 1976: Energy Exchange Charts of the North Atlantic Ocean. Bull. Amer. Meteor. Soc. 57, 670-678.

[2] Bunker, A. F., 1976: Computations of surface energy flux and annual air-sea interaction cycles of the North Atlantic Ocean. Mon. Wea. Rev. 104, 1122-1140.

developed by Kondo (1973) was used. A study over the entire North Atlantic Ocean using the same coefficients gave an annual heat loss by the ocean which agreed very well with the oceanographically determined heat loss. Averages of the fluxes and meteorological parameters were formed for winds blowing from the northeast, southeast, southwest, and the northwest.

SENSIBLE AND LATENT HEAT FLUX AVERAGES

The sensible and latent heat fluxes from each of the four wind directions have been averaged over all Januaries and Februaries during the study period for 30 areas of Marsden Square 096 (20 to 30 N, 120 to 130 E). These averages are based on 7082 ship observations: 4021 observations with NE winds, 840 with SE winds, 346 with SW winds, and 1875 with NW winds. These figures indicate the relative frequency of occurrence of winds from each direction and account for the random variation of the averages between adjacent areas with southerly winds.

Four charts presented as Figure 1 give the values and isopleths of the sensible heat flux in W m^{-2}, and show the great variation of flux with wind direction. Cold air from the NW is warmed by the waters off the China coast while air from the SE is cooled. All air is warmed by the Kuroshio Current but air from the NW is warmed 8 times faster than air from the SE and SW. Figure 2 presents the latent heat fluxes for the same directions. Here again the flux is larger for north winds and the influence of the Kuroshio Current is a predominating feature. After NW winds have passed over the Kuroshio they encounter the cooler water around the Ryukyu Islands and the evaporation is decreased. Later as they pass over the warmer Pacific water the evaporation increases again for a short distance and slowly decreases as the humidity of the air mass increases.

The annual cycles of the sensible and latent heat fluxes into the air blowing over the Kuroshio northwest of Okinawa from the four directions have been determined. The monthly averages of each flux are presented in Figure 3. It is seen that for northwest winds the fluxes rise sharply in September and reach their maxima in January. They then fall rapidly until they reach their minima in July. The NE winds have similar cycles but their maxima are lower and their minima are higher. Southerly winds have cycles with much smaller amplitudes with maxima and minima which come earlier in the year. The October to March average sensible heat flux is 131 W m^{-2} for NW winds, 74 for NE winds. and 24 and 29 W m^{-2} for SE and SW winds.

SENSIBLE HEAT ACCUMULATION AND COLD FRONT MODIFICATION

A first step in understanding how cold fronts are modified over the East China Sea is to evaluate the magnitude of nonadiabatic heating of the air masses. Over continents the

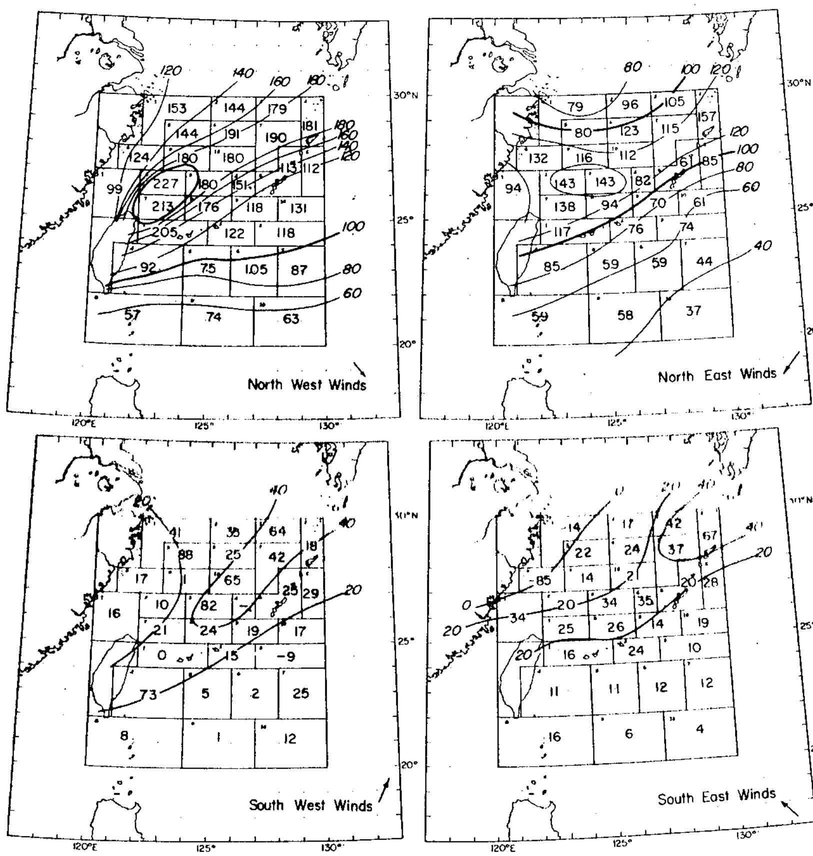

Figure 1. Sensible Heat Flux, $\rho c_p C_E (\Delta T)(W)$, W m^{-2}.

January and February Average.

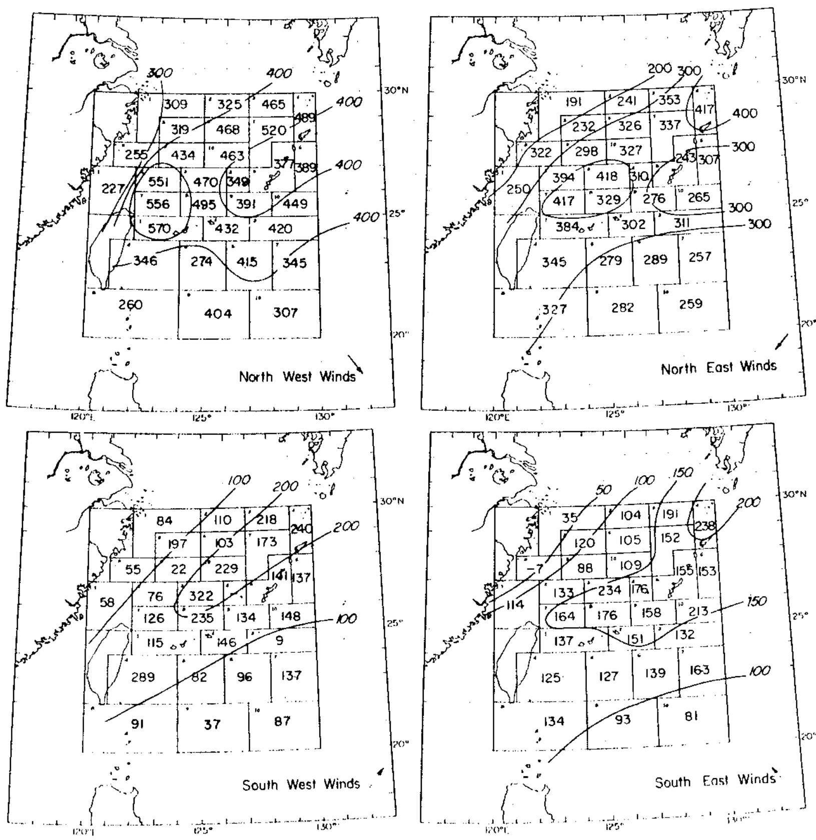

Figure 2. Latent Heat Flux, $L\rho C_E(\Delta Q)(W)$, W m^{-2}.

January and February Average.

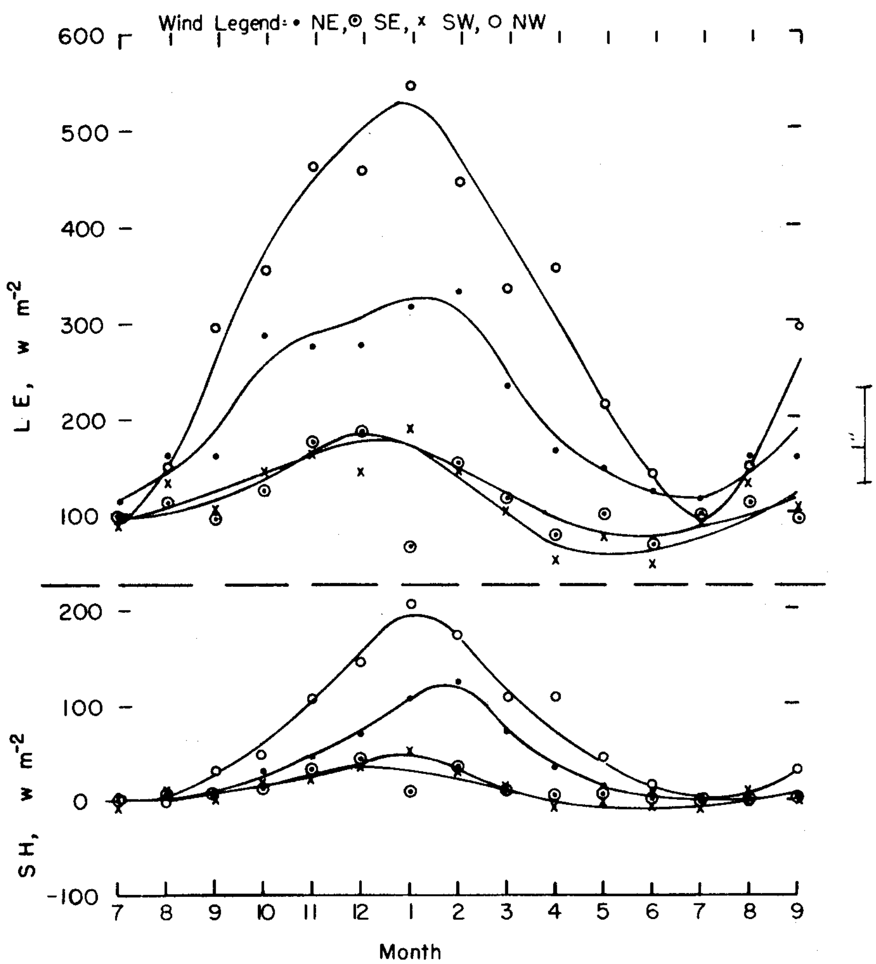

Figure 3 Annual heat flux cycles for different wind directions

the non-adiabatic heating term of the frontogenesis equation can usually be ignored with safety. Over the oceans, however, this term may become significantly large. The heating of a cold air mass crossing the AMTEX area from the north northwest is shown in Figure 4. On the left the sum of sensible and radiational heat exchange experienced by the air is plotted. The radiational exchange is the net of solar radiation absorbed by the lower atmosphere and the net infrared radiation as given by London (1957). On the right the heating of a 1 km depth of air is plotted assuming the air is moving 10 m s^{-1}. Under these conditions the lowest kilometer of air will warm rapidly 8K until it passes the Kuroshio and then slowly warm 4K more by the time it arrives at 20 N. At this latitude the air is only slightly cooler than air arriving from other directions. AMTEX '74 ship and island reports show temperature drops after frontal passages of 10K at 33 N, 8K at 28 N, 6K at Naha, and 4K at 23 N.

A weak cold front which developed over the East China Sea was penetrated at 6 levels by the NCAR Electra aircraft on 28 February 1975 between 23 and 22 N. The front exhibited the very small temperature gradient of only 0.5K/100 km within the frontal zone. Such a gradient contrasts greatly with the 45K/100 km gradient observed by Sanders (1955) in a strong continental cold front. The accumulation of heat from the warm water accounts for some weakening of the gradient, but release of latent heat over a broad area also contributed to the weakening of the front. Cyclonic shear in the lowest kilometer intensified cumulus convection which released heat over the broad frontal zone and in the cold air mass behind the front. The convection was suppressed above 1500 m by an anticyclonic circulation and subsidence, thus preventing the release of latent heat throughout the troposphere and the maintenance of the pressure trough along the front.

Further analysis when more data is available will be necessary to study the structure of the front and the strength of the various processes operating to dissipate the front.

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Kondo, J., 1973: Air-sea transfer coefficients in diabatic conditions. Ms 47 pp. Geophys. Inst. Tohoku Univ., Sendai, Japan.

London, J., 1957: A study of the atmospheric heat balance. New York Univ. Report AFCRC-TR-287, AD 117227. 99 pp.

Sanders, F., 1955: An investigation of the structure and dynamics of an intense surface frontal zone. Journ. Meteor. 12, 542-552.

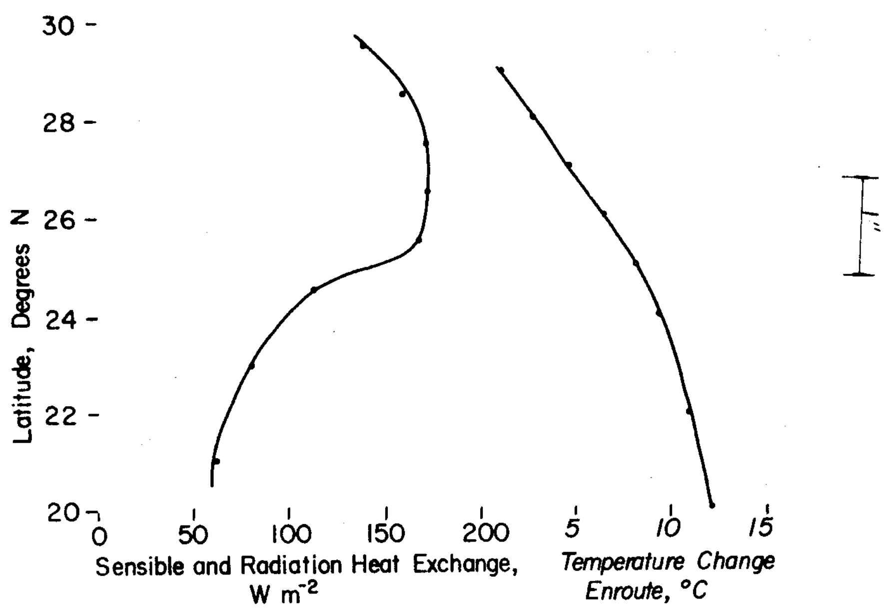

Figure 4 Heating of a cold air mass crossing the East China Sea

In addition to the study presented in the paper at Tokyo, other analyses of the data have been made which could not be presented at the meeting. Figure 5 is reproduced here to show the net heat gain by the ocean during January and February when the wind is blowing in different directions. This heat gain is found by summing algebraically the solar radiation absorbed, the net infrared radiation, the latent heat flux and the sensible heat flux. It is seen that with northwest winds all parts of Marsden Square 96 lose heat. The maximum loss is noted northeast of Taiwan where the Kuroshio flows northward into the East China Sea. Near 27° N, 124° W the current turns to the east and another maximum is noted between 28 and 29° N where the warm water leaves the sea. During its brief journey through the East China Sea the temperature of the water drops, in February, from 22.2 to 20.9° C. Northeast winds also produce a heat loss over all parts of the square, with the maximum still in the region northeast of Tiawan. With southeast winds the central section of the square is cooled moderately while the southeast and northwest sections gain a small amount to heat. With southwest winds most of the southern section gains heat. Large heat losses occur only over the warm current.

2. Variations of Monthly Averages of Fluxes and Variables

The flux program forms averages of the variables and fluxes for each month of the series of data, punches them on cards, and plots them by means of a Versatec electronic plotter. The data for the northern section, between 27 and 30°, of Marsden Square 96 are reproduced as Figures 6 and 7 to show annual cycles and year-to-year variations. Annual cycles of energy exchange are very clearly depicted on the graphs and show great regularity. Annual cycles of temperatures and mixing ratios also are very regular. On the other hand the wind speed and direction and wind stress components are much less regular although annual cycles are discernable through the 'noise'.

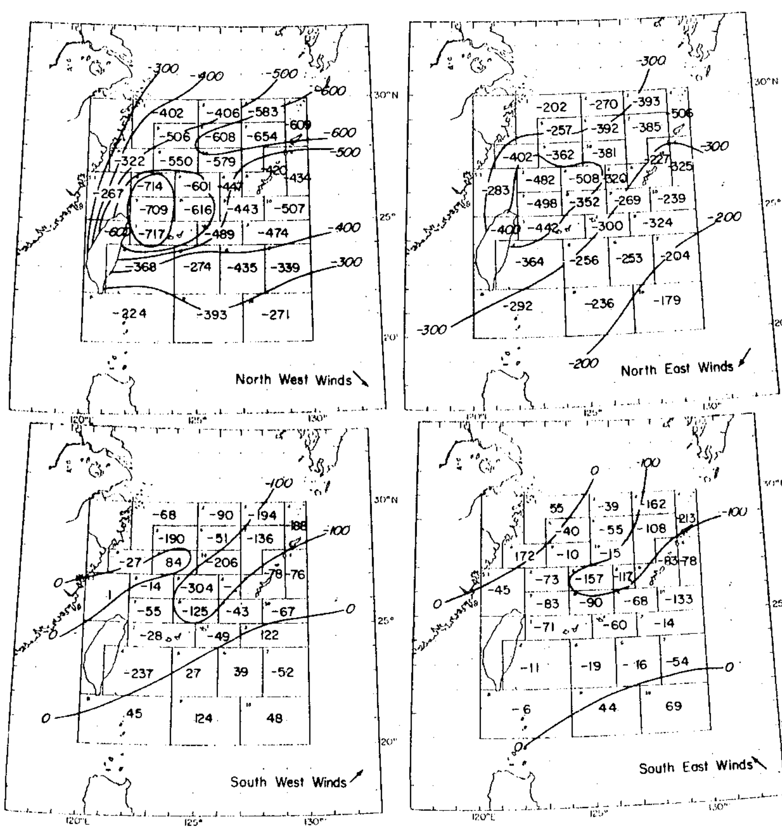

Figure 5. Net Heat Gain by the Ocean, January and February Average, W m^{-2}.

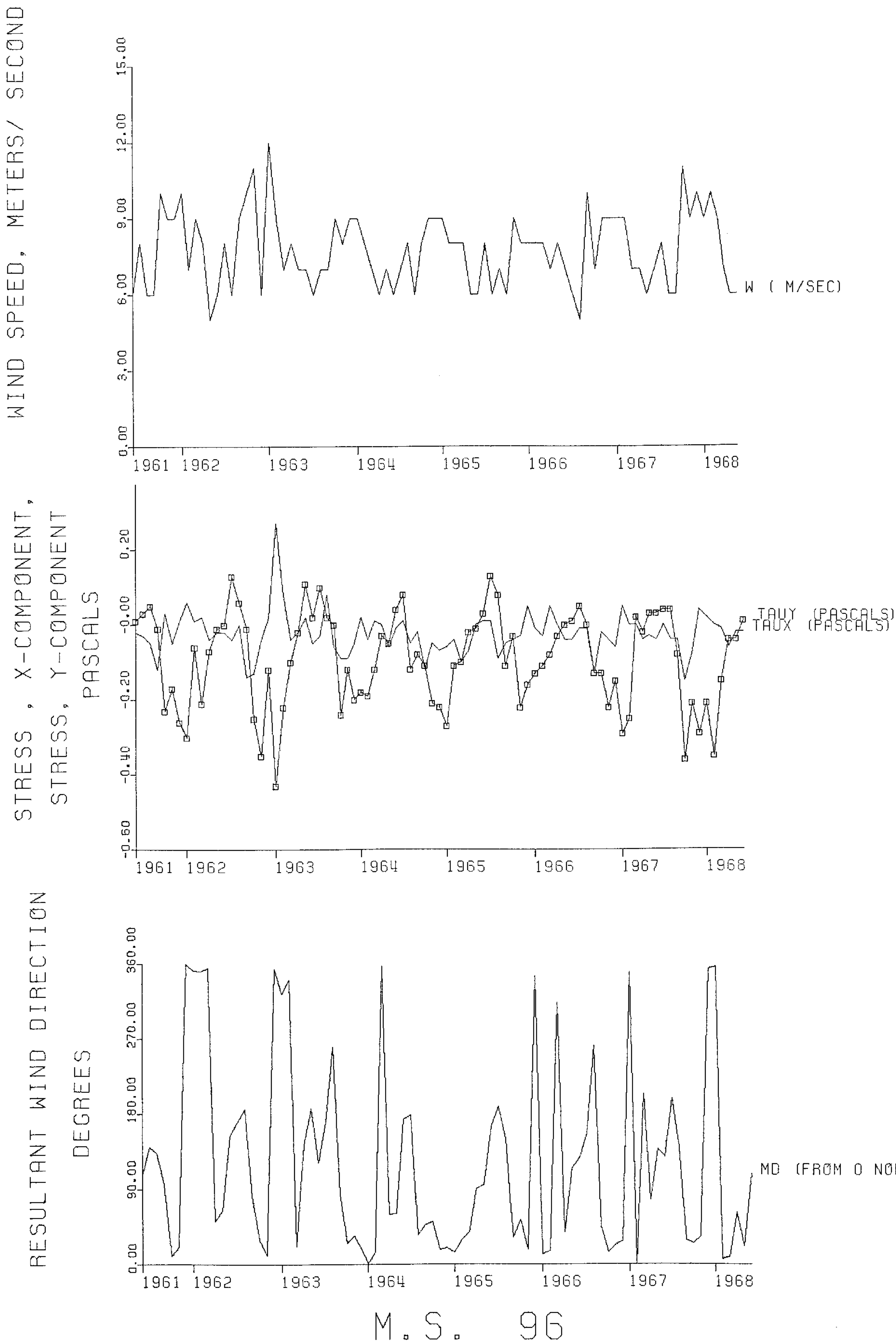

Figure 6 Monthly averages of wind and stress over the northern section of Marsden Square 96

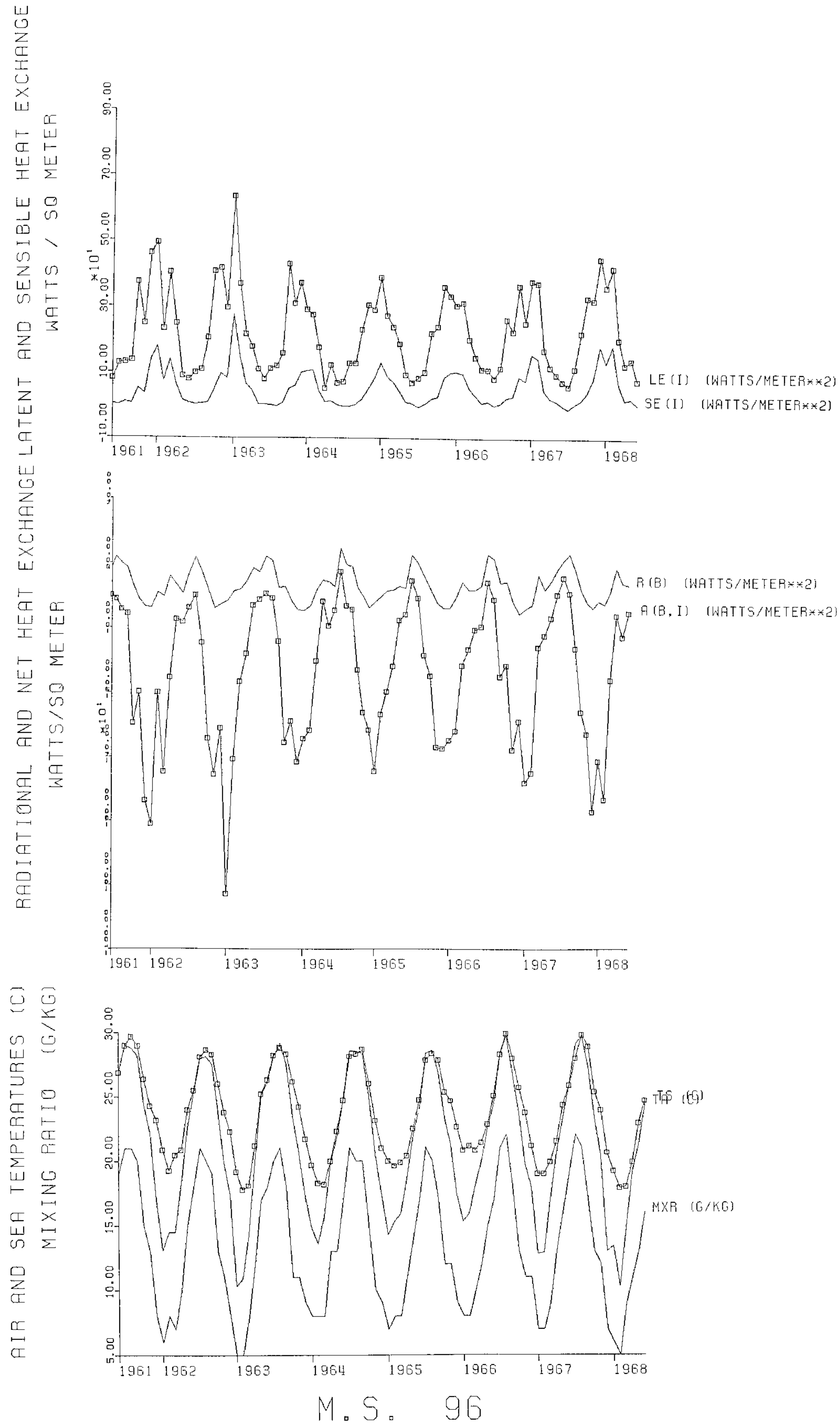

Figure 7 Monthly averages of fluxes, temperatures and mixing ratios over the northern section of Marsden Square 96.

Large year to year variation in winds, temperatures, and fluxes are apparent from inspection of the graphs. Both the summer and winter time fluxes show these variations but in general the winter values show greater variability. Relations between wind speed and direction to temperatures and fluxes can be seen by studying the events occurring in particular months. For example, during January 1963 the wind was strong from the north northwest instead of the more usual north northeast direction. The air from this direction was more continental and hence colder and drier than normal as shown in the graph. The sea temperature was about normal in January but in February was below normal probably because of a greater heat loss during January. Both the latent and sensible heat fluxes were much greater than normal as a result of the cold dry air and the stronger winds. The radiation absorbed by the sea was greater than normal because cloudiness (not shown in the plot) was less than normal. The greater loss of heat by evaporation and conduction overwhelmed the small increase in absorbed radiation and the heat loss was a record 828 $W\ m^{-2}$. Three winters later the winds were weak from the NNE and the heat loss was only 350 $W\ m^{-2}$.

V. Analysis of the Cold Front of February 26-28 during AMTEX 1975

During the last 48 hours of the AMTEX '75 observing period cold fronts developed over the East China Sea and the Sea of Japan. In 24 hours they had merged in the eastern parts and were a few hundred kilometers east of Okinawa. On the morning of February 28 the NCAR Electra aircraft flew out to the front and made observations within it as has been described earlier. Figure 8 shows the motions of the fronts and the flight path. A very complete analysis of the structure and turbulence of the fronts has been made. A paper has been written entitled 'Structure, turbulence, fluxes, and transformations of a maritime cold front during AMTEX.' This paper has been submitted to the Journal of the Meteorological Society of Japan. The paper was presented at the IAMAP Air-Sea Interactions Session at Seattle, Washington, August 22 to September 3, 1977. Since the paper will probably be published in the near future, only the abstract will be presented here.

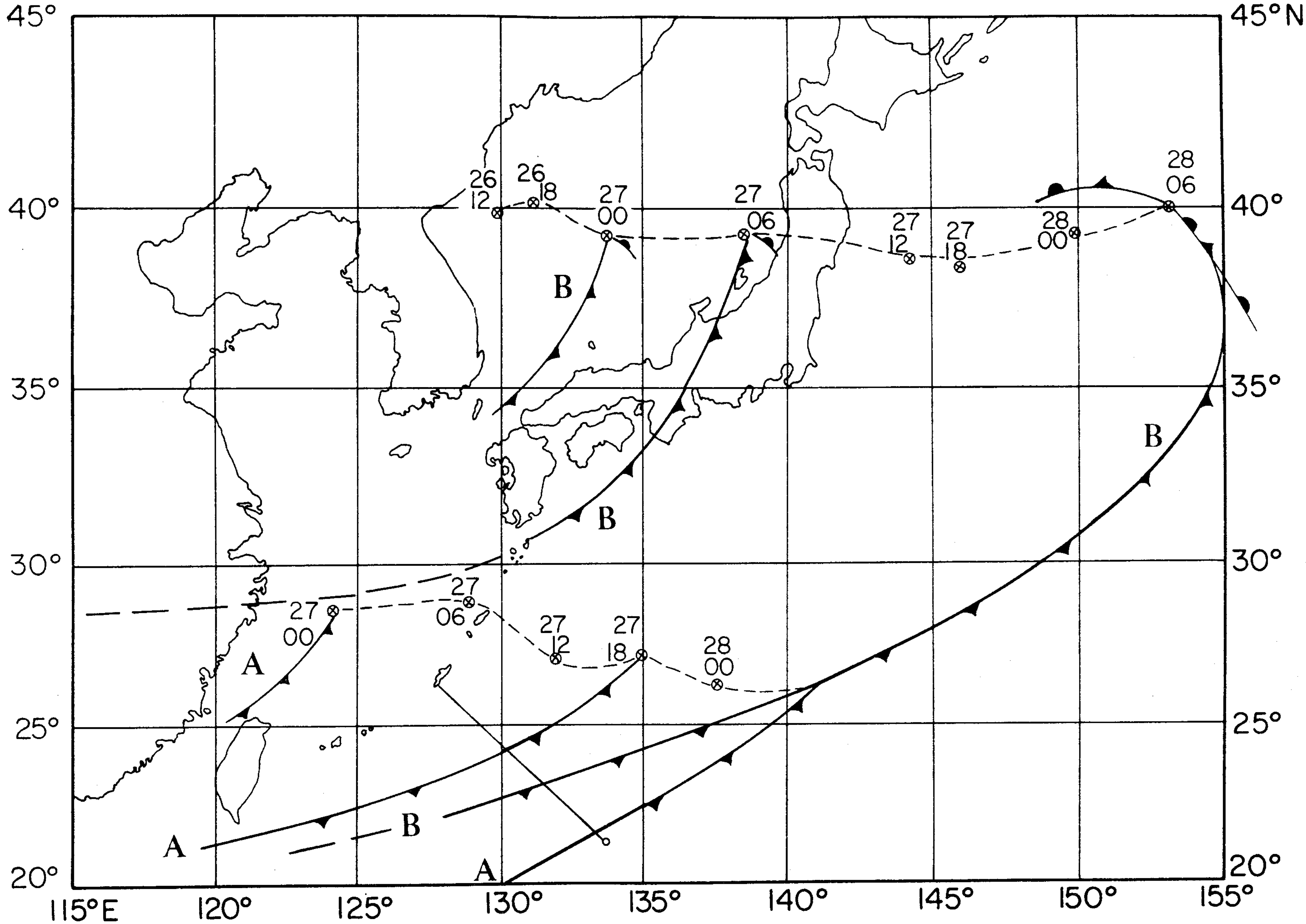

Figure 8. FRONTAL DEVELOPMENTS AND MOTIONS FEBRUARY 26-28,1975. LINE INDICATES AIRCRAFT TRACK FROM OKINAWA.

Abstract

To analyze features of maritime cold fronts measurements of many meteorological variables were made at six levels from the NCAR Electra aircraft flying through a cold front moving southeast from Okinawa during AMTEX. The front was relatively weak and atypical in that it was double and no middle or high clouds existed above a stratocumulus shield at 2 km. The history of the fronts is given and the structure described. Characteristics of several frontal air masses are determined from flight and radiosonde data. Mixing, primarily vertical by cumulus convection, between the various air masses is demonstrated. Regions of upward motion ahead of the fronts located by aircraft inertial navigation system measurements and from divergence of winds agreed well and confirmed the double structure of the front. Local areas of frontogenesis are found ahead of each front. Averaged over the entire system, weak frontolysis was occurring primarily as a consequence of the warming of air behind the fronts. Both positive and negative fluxes of heat and water vapor occurred within the frontal zone as a result of turbulent transport, direct cumulus convection, overshotting of equilibrium levels, and subsidence of cloud remanents. Normalization of velocity spectra in the frontal zone by height times energy dissipation and frequencies by height over aircraft speed gives a universal spectral pattern indicating the dominance of generation of turbulent energy by shearing processes. Spectra observed within cold air behind the front fits the shapes and nondimensional values characteristic of well-mixed air heated from below and capped by an inversion, indicating the dominance of heating as a source of turbulent energy.

VI. Bibliography of Papers Published under Grant ATM 73-0421

1. A paper entitled, 'Variations of energy exchange with wind direction and its relation to cold front modification' was presented at the Fourth AMTEX Study Conference in Tokyo, September 26-29, 1975. It was later published in AMTEX Report No. 8 by the Management Committee for AMTEX, pages 130-133.

2. A paper entitled, 'Structure, turbulence, fluxes, and transformations of a maritime cold front during AMTEX' was written and has been submitted to the Journal of the Meteorological Society of Japan. The paper also was presented at the IAMAP meetings held in Seattle, Washington in August 1977.

BIBLIOGRAPHIC DATA SHEET	1. Report No. WHOI-77-66	2.	3. Recipient's Accession No.

4. Title and Subtitle FINAL REPORT - BOUNDARY LAYER AND FRONTAL STRUCTURE OVER THE EAST CHINA SEA	5. Report Date November 1977
	6.
7. Author(s) Andrew F. Bunker, Principal Investigator	8. Performing Organization Rept. No.
9. Performing Organization Name and Address Woods Hole Oceanographic Institution Woods Hole, MA 02543	10. Project/Task/Work Unit No.
	11. Contract/Grant No. ATM 73-0421
12. Sponsoring Organization Name and Address National Science Foundation	13. Type of Report & Period Covered Technical
	14.

15. Supplementary Notes

16. Abstracts

To analyze features of maritime cold fronts, measurements of many meteorological variables were made at six levels from the NCAR Electra aircraft flying through a cold front moving southeast from Okinawa during AMTEX. The front was relatively weak and atypical in that it was double and no middle or high clouds existed above a stratocumulus shield at 2 km. The history of the fronts is given and the structure described. Characteristics of several frontal air masses are determined from flight and radiosonde data. Mixing, primarily vertical by cumulus convection, between the various air masses is demonstrated. Regions of upward motion ahead of the fronts located by aircraft inertial navigation system measurements and from divergence of winds agreed well and confirmed the double structure of the front. Local areas of frontogenesis are found ahead of each front. Averaged over the entire system, weak frontolysis was occurring primarily as a consequence of the warming of air behind the fronts. Both positive and negative fluxes of heat and water vapor occurred **

17. Key Words and Document Analysis. 17a. Descriptors

1. Air-mass modification
2. Cold front structure
3. AMTEX

within the frontal zone as a result of turbulent transport, direct cumulus convection, overshooting of equilibrium levels, and subsidence of cloud remanents. Normalization of velocity spectra in the frontal zone by height times energy dissipation and frequencies by height over aircraft speed gives a universal spectral pattern indicating the dominance of generation of turbulent energy by shearing processes. Spectra observed within cold air behind the front fits the shapes *

17b. Identifiers/Open-Ended Terms

***and nondimensional values characteristic of well-mixed air heated from below and capped by an inversion, indicating the dominance of heating as a source of turbulent energy.

17c. COSATI Field/Group

18. Availability Statement	19. Security Class (This Report) UNCLASSIFIED	21. No. of Pages 22
	20. Security Class (This Page UNCLASSIFIED	22. Price

FORM NTIS-35 (REV. 3-72) USCOMM-DC 14952-P72

Woods Hole Oceanographic Institution
WHOI-77-66

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To analyze features of maritime cold fronts, measurements of many meteorological variables were made at six levels from the NCAR Electra aircraft flying through a cold front moving southeast from Okinawa during AMTEX. The front was relatively weak and atypical in that it was double and no middle or high clouds existed above a stratocumulus shield at 2 km. The history of the fronts is given and the structure described. Characteristics of several frontal air masses are determined from flight and radiosonde data. Mixing, primarily vertical by cumulus convection, between the various air masses is demonstrated. Regions of upward motion ahead of the fronts located by aircraft inertial navigation system measurements and from divergence of winds agreed well and confirmed the double structure of the front. Local areas of frontogenesis are found ahead of each front. Averaged over the entire system, weak frontolysis was occurring primarily as a consequence of the warming of air behind the fronts. Both positive and negative fluxes of heat and water vapor occurred within the frontal zone as a result of turbulent transport, direct cumulus convection, overshooting of equilibrium levels, and subsidence of cloud remanents. Normalization of velocity spectra in the frontal zone by height times energy dissipation and frequencies by height over aircraft speed gives a universal spectral pattern indicating the dominance of generation of turbulent energy by shearing processes. Spectra observed within cold air behind the front fits the shapes and nondimensional values characteristic of well-mixed air heated from below and capped by an inversion, indicating the dominance of heating as a source of turbulent energy.

1. Air-mass modification
2. Cold front structure
3. AMTEX

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