The A. & M. College of Texas

DEPARTMENT OF OCEANOGRAPHY

PROGRESS REPORT FOR PERIOD
1 April 1952 to 31 May 1953

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Research Conducted through the

Texas A. & M. Research Foundation

COLLEGE STATION, TEXAS

The Agricultural and Mechanical College of Texas
Department of Oceanography
College Station, Texas

Texas A & M Research Foundation
Project 29

REPORT FOR CONTRACT PERIOD

1 APRIL 1952 TO 31 MAY 1953

Project 29 is a study of the atmospheric influence on the thermal structure of the oceans, sponsored by the Office of Naval Research (Project NR 083-061, Contract N7onr-487, Task Order 3). This report is a brief history of the progress since 31 March 1952.

Report Prepared July 1953

by

Archie M. Kahan

Dale F. Leipper - Project Supervisor

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ANNUAL REPORT

Project 29

INTRODUCTION

The purpose of this report is to present a brief history of the progress made during the period 1 April 1952 through 31 May 1953 on the study of the effect of the atmosphere on the thermal structure of the oceans. Some of this work has been previously reported in Quarterly Reports.

Since this is not a technical report many details of the technical studies have not been included. Instead, it is hoped that the reader will receive a clear picture of the general nature of the work undertaken, the tools used and the results obtained.

The preparation of this report has been a group effort under the general supervision of Mr. Archie M. Kahan. Mr. Robert A. Gilcrest contributed most of the sections on the Wind Stability and Mixed Layer Change forecasting. Mr. Glenn H. Jung contributed the discussions of Evaporation and Heat Budget studies. Mr. C. R. Sparger prepared the section on Horizontal Temperature Variation. Mr. U. Grant Whitehouse contributed the discussion of the relationship between Evaporation, Stability, Temperature Change and Wind Force subsequent to his reviewing the report in manuscript form.

STAFF AND STAFF CHANGES

At the close of the period covered by this report the staff of Project 29 was as follows:

1. Dr. Dale F. Leipper, Project Supervisor (Part time)
2. Mr. Archie M. Kahan, Chief Scientist, joined the project 4 January 1953
3. Dr. John C. Freeman, Meteorologist and former Chief Scientist (Part time)
4. Mr. Robert A. Gilcrest, Assistant in Oceanography
5. Mr. Carter R. Sperger, Assistant in Oceanography
6. Mr. Glenn H. Jung, Research Assistant (Half time)
7. Mrs. Jeanneane L. Cline, Secretary-Computer
8. Mrs. Bertha Darrow, Secretary-Computer (Part time)
9. Mrs. Marilyn C. Johnson, Computer (Half time)

Mr. Richard M. Adams, Assistant in Oceanography, left the project 30 June 1952 to join the staff of Project 24, Oceanographic Survey of the Gulf of Mexico. Mr. Talmage Y. Hicks, Research Assistant left the project 30 August 1952 to join Project 38, Wave Forces on a Hinged Pile. Mrs. Ella Frances Spears, Secretary-Computer, resigned 1 March 1953. Mrs. Jeanneane L. Cline is her replacement. Mrs. Jeanne Burja, Draftsman, resigned 1 September 1952, and was replaced by Mrs. Merle Cobb. Mrs. Cobb resigned 23 May 1953.

In addition to the above changes in permanent staff the following listed temporary employees worked during the year but are no longer employed:

1.	Frank C. Whitmore, Physicist	1 July 1952 - 30 Sept. 195
2.	Roger D. Longley, Graduate Assistant	8 Aug. 1952 - 6 Sept. 1952
3.	Melvin Pierce, Student Assistant	10 Nov. 1952 - 31 Jan. 1953

4. Ernest Prochaska, Student Assistant 10 Mar. 1952 - 30 Nov. 195
5. Edward V. Ruhnke, Student Assistant 2 June 1952 - 30 Aug. 195
6. John A. Rosequest, Student Assistant 10 Nov. 1952 - 30 Apr. 195
7. Van Rudolph Cammack, Student Assistant 9 Feb. 1953 - 1 May 1953

Biographies of the present technical staff are given at the end of this report.

EQUIPMENT AND FACILITIES

There was no change during the past contract period in the equipment and facilities available to Project 29. Texas A. & M. College Department of Oceanography provides the project with 900 square feet of office space and all necessary office furniture.

Capital equipment purchased with project funds is limited to a three-way combination, fire resistant, file for storage of classified material, a calculator and a microfilm reader. In addition a microfilm camera has been rented for the purpose of photographing bathythermograph cards loaned to the project by Woods Hole Oceanographic Institution and the Scripps Institution of Oceanography.

PROCESSING OF BATHYTHERMOGRAPH DATA

The basic information for studying the influence of the atmosphere in the thermal structure of the oceans consists of both meteorological and oceanographic data. While the required meteorological data are readily available in the form of published and microfilmed weather charts and records, the oceanographic temperature data are more difficult to obtain.

The bathythermograph data collected at fixed positions by weather patrol ships offer the best available continuous series of observations for this study. Files of the photographic prints made from the BT slides taken by Atlantic and Pacific weather ships have been loaned to this project on a short term basis by Woods Hole Oceanographic Institution and Scripps Institution of Oceanography respectively. The processing of these records by this project has been described in Technical Report No. 1, <u>Some Methods Used in Representing Bathythermograph Data</u>. Briefly, the steps taken are:

1. Selection of a typical BT trace for each day.
2. Reading of temperatures at ten selected depths as well as the depths at which selected differences from surface temperature occur. Each reading is checked by an independent reading which must agree within 0.1°F, in the case of temperatures, or three feet, in the case of depths.
3. Smoothing of daily data by five day moving averages. The value for any date becomes the average of the five day period for which the date is the midpoint.
4. Plotting and final drafting of smoothed data.
5. Microfilming of each BT card deck before returning to Woods

Hole Oceanographic Institution or Scripps Institution of Oceanography During the period 1 April 1952 to 31 May 1953 29,000 cards from 24 Weather Ship cruises were processed. As of 31 May 1953 only one shipment of Pacific BT data, approximately 3,500, cards remain to be processed.

STUDIES AND REPORTS

The early part of the past contract year was devoted to the preparation of the previous annual report and the final production in finished form of the following technical reports:

Technical Report No. 1 - Some Methods Used in Representing Bathythermograph Data, May 1952

Technical Report No. 2 - Deviations of a Mixed Layer Depth and Sea Surface Temperature in Different Years in the North Atlantic, July 1952, CONFIDENTIAL

Technical Report No. 3 - Summary of North Atlantic Weather Station BT Data - 1946-1950, September 1952

Correlation of Changes in Mixed Layer Depth with Meteorological Parameters

Following completion of the above listed reports, a study of the relationships between wind and changes in mixed layer depth was initiated. Earlier preliminary work with wind data from Atlantic Weather Ship Stations D, E, H, 8 and 7A for periods of varying length had given encouraging indications when plotted on a polar diagram with points labeled as to increasing or decreasing change in mixed layer depth (ΔH). It was decided to conduct a more detailed pilot study using data from one station only. Station "C", 52°45'N, 35°30'W was the station chosen. Selection of this station made more continuous simultaneous BT and weather data available for study. Resultant surface winds, the vector sum of individual daily wind vectors, were calculated for each period of seven days in the fall of 1946, 1947, 1948 and 1949. These wind data together with the following parameters for each period were tabulated on index cards:

H_1 = Initial Mixed Layer Depth in feet

H_2 = Final Mixed Layer Depth in feet

ΔH = Change in Mixed Layer Depth in feet

S_{t1} = Initial Slope of Thermocline in ft/deg. F

S_{t2} = Final Slope of Thermocline in ft/deg. F

$\overline{T_a - T_s}$ = Average Air-sea Temperature difference in degrees F

$\overline{ff}$ = Average Wind Speed in knots

The resultant wind vector for each period was plotted on polar coordinate paper together with a number identifying the period. This number was used to identify values of the above variables to be related to a particular vector. The earlier work with data collected by weather ships D, E and H had shown a distinct relation between the quadrant of the resultant wind and direction (increase and decrease) of ΔH. No such orientation was found on the Station "C" diagram. Therefore, it seemed desireable to look for the effect of relationships between H and variables which do not involve wind vectors. Initial thermocline slope and initial mixed layer depth were used to classify periods in various quadrants of the wind vector diagram into groups in which a given ΔH (increase, decrease or no change) occurred. This might have proven fruitful had more than the 28 seven-day periods been available. Since the data had to be divided into eight categories as few as one or two periods per category were available for study in some cases.

Relationship Between Wind, Stability and Changes in Mixed Layer Depth (WISTAI

The wind vector diagram based on the Stations D, E and H data and perusal of the surface weather maps together with coincidental time curves for mixed layer depth indicated that in general, cold outbreaks over the North Atlantic with their accompanying NW winds were associated with a positive ΔH and a southerly or southeasterly flow indicated a negative ΔH. The problem of establishing what processes take place can be studied by analysing measurements of meteorological parameters which apparently bring about these changes. First thoughts were that wind stirring and evaporation (or lack of same) might be the main controlling factors. Parameters included in the regular weather observations which might best be used as indicators of these processes were thought to be air-sea temperature difference and wind force. Stirring in the mixed layer depends on how effectively momentum from the air can be transferred across the air-sea boundary surface and carried into the ocean mixed layer as turbulence. This momentum transfer depends first on the wind force of the air (or available momentum and second on the vertical stability of the boundary region which can act either to aid or to retard the momentum flow acorss the boundary. The vertical stability of the boundary region depends on the air-sea temperature difference directly and on the windspeed range (less or greater than 13 knots) indirectly. Evaporation amount depends on the product of windspeed and air-sea vapor pressure difference parameters, according to Sverdrup, at al. (The Oceans, p. 120) and Sverdrup (Compendium of Meteorology, p. 1078). The air-sea vapor pressure difference is associated with the air-sea temperature difference.* Accordingly,

* The vapor pressure difference depends on the dewpoint temperature of the air (which in turn is a function of the air temperature and relative humidity of the air) and on the sea surface temperature.

averages of these parameters were computed for seven-day periods at one ship station. Station "C", 52°45'N, 35°30'W was chosen for study, because the observations here were most continuous and covered the longest period. The seven-day period was chosen as a reasonable length of time over which mean thermocline conditions might be predicted.

Data Used: The observations of wind force and air-sea temperature difference were taken from microfilm copies of the weather ship observer's logs. There are eight such observations per day, seven days per week. Arithmetic averages were computed for the 56 observations of T_a-T_s and ff, and these were plotted against each other. This plot (Figure 1) of average wind force against average air-sea temperature difference has been called a WISTAB diagram. The points were labeled with ΔH for the corresponding period, and a field of ΔH drawn.

The data included on the WISTAB were for the fall periods (September, October and November) of 1948 and 1949. The 1947 data were reserved for testing of the relationship. In these tests a correlation of 0.50 was found to exist between observed and forecast ΔH values. This correlation was not significant at the 5% level.

Note: The degree to which weekly averages of T_s and mixed layer depth in particular years follow the all-data-average curve of T_s and mixed layer depth is of interest (especially in the fall). If weekly points of T_s and mixed layer depth are plotted on a graph on which is drawn the all-data-average curve at the same ship, displaced by transposition to the position of "best-fit" to the data of the individual year, a decided tendency of the individual weekly values to follow the average trend is evident. Furthermore, a departure from the "normal" is usually followed by an immediate return to "normal" (i.e., in the next week).

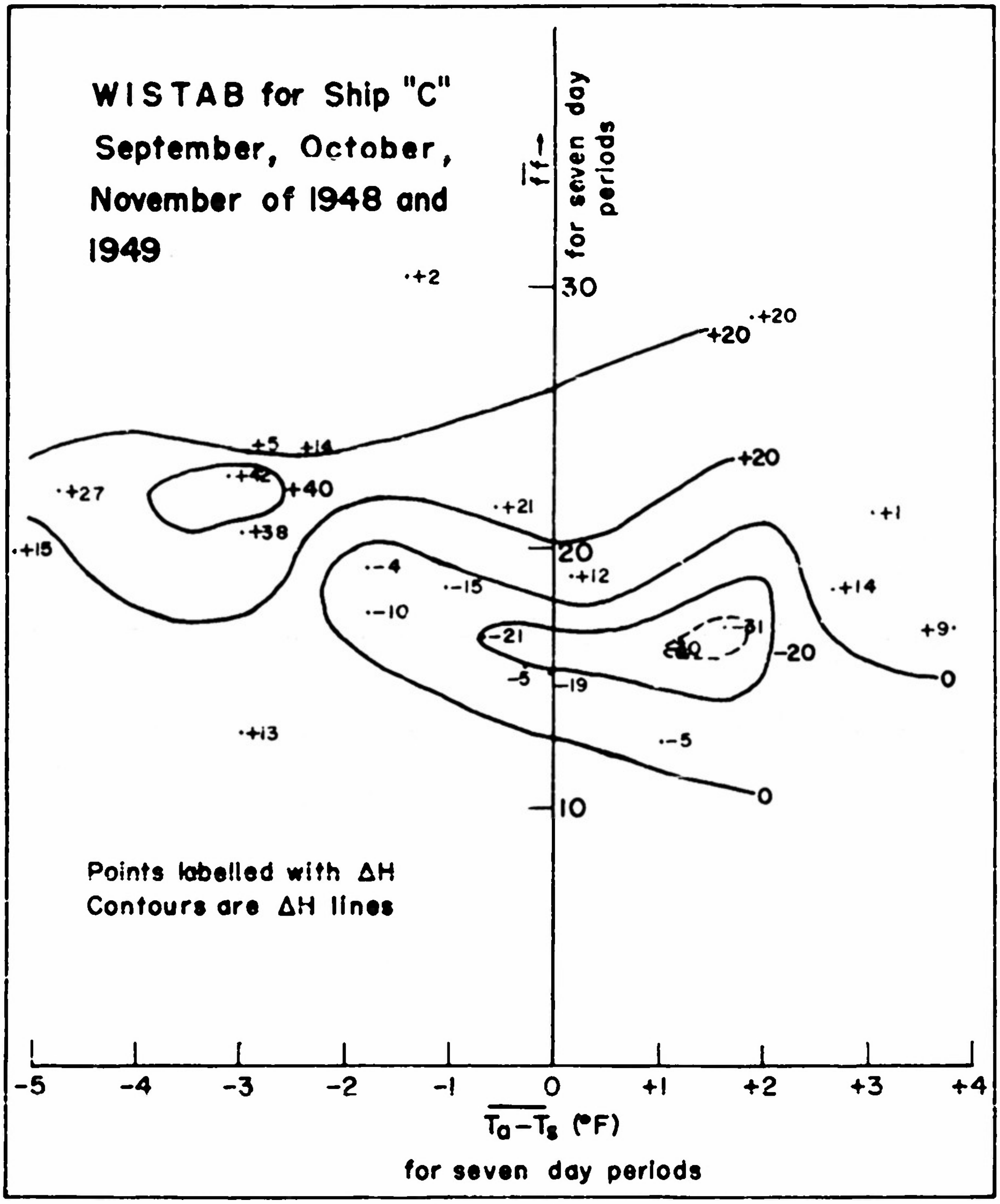
WISTAB for Ship "C"
September, October, November of 1948 and 1949
$\overline{ff}$ → for seven day periods
30
20
10
-5
-4
-3
-2
-1
0
+1
+2
+3
+4
$\overline{T_a - T_s}$ (°F)
for seven day periods
+2
+20
+20
+5
+14
+42
+40
+27
+38
+15
+21
+20
+1
20
+12
-4
-15
+14
-10
-21
-31
-20
+9
-5
-19
0
+13
-5
0
Points labelled with ΔH
Contours are ΔH lines

Figure 1

Evaporation

It next appeared desireable to see if evaporation (depending on windspeed and the sea-air temperature difference) could be used along with windspeed as the basis for an improved forecasting chart for mixed layer depth change (ΔH).

A literature search on evaporation research was made. The NEL Report on Evaporation Theory, the AMS Compendium of Meteorology and papers by McEwen, Jacobs and others were reviewed. The object of this search was to find a method which employed readily available meteorological data to compute weekly evaporation amounts. It was decided to make use of Jacobs' climatological formula, since other techniques involved assumptions which were not justified in the proposed usage, and were not in a form suitable for use of available meteorological data.

Jacobs' formula, employing the three-hourly observations of air- and sea-surface temperature, of windspeed and direction, was used to compute evaporation amounts per week:

$$E = 2.8 \times 10^{-6} \left[\sum \overline{(e_s - e_a) W_s} + 3.5 \sum \overline{(e_s - e_a) W_u} \right]$$

where the bars denote time averages, and e_s is the water vapor pressure at the temperature of the sea surface, T_s; e_a is the water vapor pressure at the air immediately above the sea surface, T_a; W_s equals the speed of the wind, for a hydrodynamically smooth surface (<13 knots). W_u equals the speed of the wind for hydrodynamically rough surface (>13 knots). The resulting seven-day evaporation amounts were plotted against seven-day average windspeeds, with the appropriate ΔH for each interval, during the fall season, 1947-1949, for the North Atlantic Weather Ship "C". Isolines of ΔH were drawn. The results were not as favorable as those obtained by using the air-sea temperature difference versus windspeed diagram (WISTAB). Figure 2 shows the evaporation-windspeed diagram. The pattern is more complex than is that of the WISTAB (see Figure 1) and there are some striking contrasts. For example, the regions of maximum ΔH are oriented differently in relation to each other on the two diagrams. This seems strange considering correlations which have been computed, giving a high relationship between evaporation and (T_s-T_a) (see Table I for correlations). On the evaporation-windspeed diagram, increasing windspeed and evaporation are related to a positive change in ΔH, then a negative change and finally to large positive values. One would expect that increased windspeed should cause turbulent motion to a greater depth in the top layers of ocean, and increased evaporation should act to increase instability and convection. Each of these effects should act to deepen the mixed layer of the ocean, or give a positive ΔH. However, if one considers $\bar{E}$ to be a function of (T_s-T_a), (ΔT), as well as a function of windspeed, $(\overline{ff})$, some of the observed variation in ΔH pattern may be explained. Then variations in ΔT may cause variations in the relative significance of the $\bar{E}$ induced convective instability and the $\overline{ff}$ turbulence effect on the mixed layer. $\bar{E}$ could remain constant as ΔT dropped and windspeed increased, while at the same time convective instability would decrease and lateral turbulence predominate in the mixed layer at high windspeeds.

If

$$\Delta H = f(\bar{E}, \overline{ff}) \text{ and}$$

$$\bar{E} = f(\Delta T, \overline{ff})$$

then

$$d(\Delta H) = \left(\frac{\partial \Delta H}{\partial E}\right)_{\overline{ff}} dE + \left(\frac{\partial \Delta H}{\partial \overline{ff}}\right)_E d\,\overline{ff}$$

$$d\,(E) = \left(\frac{\partial E}{\partial \Delta T}\right)_{\overline{ff}} d\Delta T + \left(\frac{\partial E}{\partial \overline{ff}}\right)_{\Delta t} d\,\overline{ff}$$

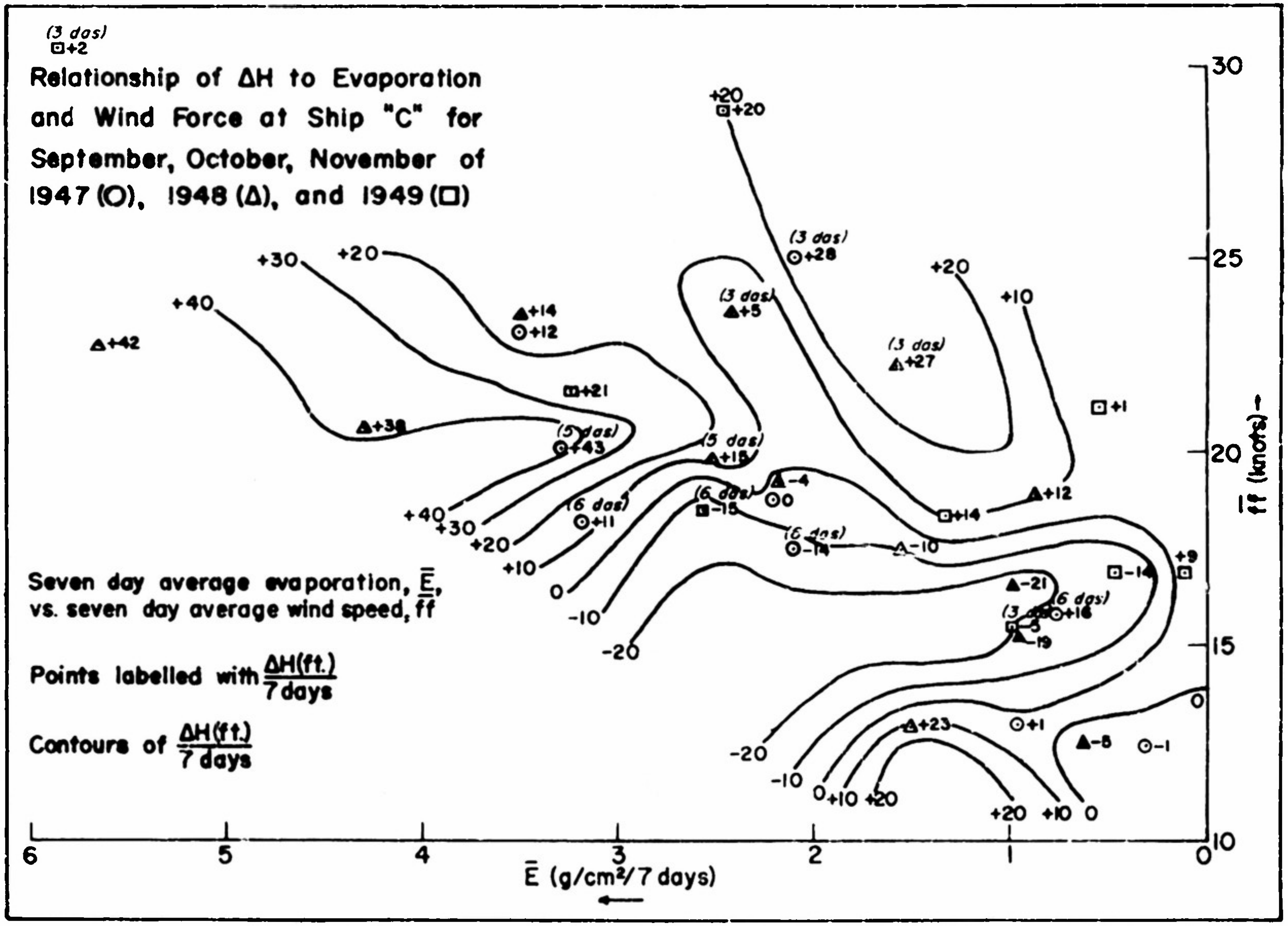
(3 das) ⊡+2
Relationship of ΔH to Evaporation and Wind Force at Ship "C" for September, October, November of 1947 (O), 1948 (Δ), and 1949 (□)
Seven day average evaporation, Ē, vs. seven day average wind speed, ff
Points labelled with ΔH(ft.)/7 days
Contours of ΔH(ft.)/7 days
+40
+30
+20
+10
0
-10
-20
Δ+42
▲+14
⊙+12
⊡+21
Δ+38
(5 das) ⊙+43
(6 das) ⊙+11
(5 das) Δ+15
(6 das) ⊡-15
(3 das) ▲+5
▲-4
⊙0
(6 das) ⊙-14
Δ-10
(3 das) ⊙+28
⊡+20
(3 das) Δ+27
⊡+14
▲+12
⊡+1
+9 ⊡
⊡-14
▲-21
(6 das) ⊙+16
(3 das) ⊡-5
▲-19
Δ+23
⊙+1
▲-8
⊙-1
Ē (g/cm²/7 days) ←
ff (knots) →
6
5
4
3
2
1
0
10
15
20
25
30

Figure 2

$$d\,(\Delta H) = \left(\frac{\partial \Delta H}{\partial E}\right)_{\overline{ff}} \left(\frac{\partial E}{\partial \Delta t}\right)_{\overline{ff}} d\Delta t + \left(\frac{\partial \Delta H}{\partial E}\right)_{\overline{ff}} \left(\frac{\partial E}{\partial \overline{ff}}\right)_{\Delta T} d\,\overline{ff} + \left(\frac{\partial \Delta H}{\partial \overline{ff}}\right)_{E} d\,\overline{ff}\,.$$

Then $d\Delta H$ would increase or decrease depending upon the magnitude and relative direction of $d\Delta T$ and $d\,\overline{ff}$. Thus ΔH would increase if both ΔT and $\overline{ff}$ increased. However ΔH would not necessarily increase if $\overline{E}$ increased without ΔT increasing, or ΔH would not necessarily increase if $\overline{ff}$ decreased without ΔT increasing at the same rate.

From these considerations, a plot of ΔT versus $\overline{ff}$ (WISTAB) would probably be expected to give a more realistic ΔH field than a plot of $\overline{E}$ versus $\overline{ff}$. This was actually observed to be the case, considering preliminary forecasting results using the WISTAB diagram as a forecast tool.

Smoothing attempts were made by projecting the data from the evaporation-windspeed diagram on to a plane passed perpendicular to the diagram through the "best-fit" regression line, and plotting the resulting points versus a new coordinate of initial H. Once more, the pattern of initial H versus Evaporation (and windspeed) seemed irregular and unreasonable from a physical basis.

At this time a re-examination of the WISTAB diagram was made, and trial forecasting was done for a number of intervals, based on the WISTAB. The correlation of forecasted versus observed ΔH values for seven-day intervals was 0.50 for nine pairs, which is not significant statistically.

Processes other than evaporation (i.e., stirring and convection of the mixed layer, etc.) are also dependent on the "stability" of the air-sea interface (air-sea temperature difference parameter) and on windspeed. This fact may be responsible for the more consistent pattern of ΔH on the WISTAB as compared with the evaporation-windspeed diagram pattern. Some effect of these auxiliary processes may be reflected only in the WISTAB pattern of ΔH.

It appeared (as is illustrated by the trial forecast) that only about 25% of the variance of ΔH was explained by variation in air-sea temperature difference and windspeed. The need for a study of the heat budget of the water column was indicated to gain insight into other important physical processes which may affect the change in H.

TABLE I

Correlations Between Evaporation Amounts
(Over Seven-Day Intervals) and Various Related Parameters

Correlated Variables	r	No. of Pairs	"t" Test
ΔH vs $\bar{E}$	0.73	20	Highly significant
Δe vs $\bar{E}$	0.60	20	Highly significant
ΔT vs $\bar{E}$	0.66	20	Highly significant
$\overline{ff}$ vs $\bar{E}$	0.65	20	Highly significant

ΔH is change in the mixed layer depth
$\bar{E}$ is evaporation

Δe is average sea-air water vapor pressure difference

ΔT is average sea-air temperature difference

$\overline{ff}$ is average windspeed in knots

Heat Budget Study

As a guidepost for emphasis in study of the various possible physical factors affecting the ocean thermal distribution, it next seemed desirable to undertake a limited study of the heat budget of a column of ocean water.

Data from the North Atlantic Weather Ship "C" were selected for study since they consisted of a continuous record of simultaneous observations of meteorological parameters and ocean temperature distribution with depth for a period of several years. Since changes in the ocean thermal structure appear more systematic in the autumn season than at other times of the year, the study was limited to the autumn.

Estimates of the amounts of solar radiation, back radiation, evaporation, vertical advection and the amount of total thermal energy change were made over seven-day periods, within a column of ocean water having a unit cross-section and extending to a depth of no temperature change with time.

It appears that much of the unexplained net amount of thermal energy change is attributed to effects of horizontal advection primarily, and to lateral heat conduction. Effects of precipitation on the column were assumed negligible.

For 1948 the data were almost continuous and a comparison of seasonal sums of energy amounts per week was made with the total thermal change indicated as occurring between the first and last temperature depth observations of the season.

For the 1948 autumn season, radiation and evaporation amounts were of the same magnitude and of opposite sign; this indicates once more that advection (horizontal and vertical) plays an important role in determining observed total heat changes in a water column for this region on a seasonal basis.

Data from 1947 and 1949 gave added cases of weekly change which were similar to the cases of 1948. The seasonal total energy change for each of these years varied from year to year. These ranged from about 435 ft-deg. for 1947 to 0 ft-deg. for 1948 to -1500 ft-deg. for 1949. The unit foot-degree as used above is the amount of heat required to warm a column of water one foot in depth and one centimeter squared in cross section one degree Fahrenheit.

A study of horizontal temperature variation seems indicated to explain total observed thermal energy changes in autumn within an ocean water column in the North Atlantic Ocean.

A technical report on this heat budget study is now in manuscript form and will soon be ready for publication.

Attempted MLD Forecasting Technique

In the course of computing the heat budget of a deep water column, some way of evaluating heat advected into or out of the column was sought. Due to lack of data from which a field of motion could be drawn, the effect of horizontal advection had to be neglected. Three approaches to vertical advection were tried:

1. Considering a deep ocean with its surface level fixed, consisting of two layers, and upper mixed layer of density ρ' and a lower layer of greater density ρ at first thought it would seem possible to regard the boundary between the upper and lower layers (the top of the thermocline) to be in hydrostatic equilibrium in the fluid column, providing that the pressure at the bottom does not change. This would require immediate adjustment of thermocline depth by advection of mass

to compensate for changes in atmospheric pressure:

$$P_2-P_1 = (H_2-H_1)\, g\, (\rho - \rho')$$

$$\text{or } H_2-H_1 = \frac{P_2-P_1}{g\,(\rho-\rho')}$$

H = mixed layer depth or depth of the top of the thermocline

where H_2-H_1 = change in thermocline depth at the station

P_2-P_1 = corresponding change in the atmospheric pressure at the station

g = acceleration of gravity

Since ρ and ρ' are not observed in BT observations, approximations must be made from the temperatures. Assuming that ρ and ρ' are functions of T only, $(\rho-\rho') = e\,\bar{\rho}\,(T_1-T_2)$ where T_1 is the mixed layer temperature and T_2 is the temperature of the lower water, e* is the coefficient of thermal expansion of sea water, and $\bar{\rho}$ the average density of sea water.

$$\text{Then } H_2-H_1 = \frac{P_2 - P_1}{g\, e\bar{\rho}\, (T_1-T_2)}$$

As an example:

let $P_2-P_1 = 5 \text{ mb} = 5 \times 10^3 \text{ dynes/cm}^2$ in seven days

$g = 980 \text{ cm/sec}^2$

$e = 167 \times 10^{-6} \text{ cm}^2/°C$

$T_1-T_2 = 6.11°C$

Five millibars is a small pressure change for seven days. The value of "e" chosen is that for $\bar{T}$ of a water column of 7.5 to 12.5°C, a typical average temperature at Station "C" in September. The value chosen for T_1-T_2, 6.11°C, is a typical temperature difference between upper and lower layers at Station "C" in September. Substituting these values in the above equation:

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* "The Oceans", p. 60.

$$H_2 - H_1 = \frac{5 \times 10^3}{980 \times 167 \times 10^{-6} \times 1.025 \times 6.11}$$

$$= 4.878 \times 10^3 \text{ cm/7 days or} \sim 49 \text{ m/7 days}$$

The values of $\partial H/\partial t$ computed under the above assumptions are much larger than any known to occur. The pressure change assumed in the example was a small one. It can be seen that a larger pressure change would give even larger $\frac{\partial H}{\partial t}$. Therefore it must be concluded that such a direct relationship between atmospheric pressure and H does not exist. Instead, the effects of air pressure on the surface water layer must be manifested through wind driven water movements.

2. If it be assumed that all water transport by wind takes place above the thermocline in a two layer ocean, a convergence of surface water brought about by a horizontal differential of wind speed ($\frac{dW}{dx} \neq 0$) may:

1) pile up water at the surface with no change in thermocline depth,
2) let the surface remain level and deepen the thermocline,
3) result in a combination of 1 and 2 above.

Of these possibilities, number 3 is the most probable result, but with the knowledge that observed surface water level changes are small, even along coasts where they are presumably much greater than those in the open ocean, we may take 2 as an approximation to 3.

Sverdrup and Ekman* have discussed mass transport of water by wind. It was decided to try evaluating mass transport in a two dimensional system (x, z) using Sverdrup's transport equations with the above assumptions:

Letting H = depth of thermocline

Q_x = volume transport of water in x-direction above the thermocline

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* "The Oceans", pp. 489-500.

Then $\frac{dQ_x}{dx} = -\frac{dH}{dt}$ = time change in MLD

$$Q_x = \frac{1}{\rho f} \tau_{ay} *$$

where ρ is the density, f the Coriolis parameter and τ_{ay} is the wind stress at the surface for a wind measure at anemometer height A and $\tau_{ay} = AW^2$, where A is the wind stress coefficient, W is windspeed in y-direction; hence $Q_x = \frac{AW^2}{\rho f}$. Replacing $\frac{A}{\rho f}$ by K, and differentiating with respect to x

$$\frac{dQ_x}{dx} = 2KW\frac{dW}{dx} = -\frac{dH}{dt} \quad \text{or} \quad \frac{\Delta H}{\Delta t} = -2K\bar{W}\frac{\Delta W}{\Delta x}$$ for purposes of calculation.

As an example:

Given: $\rho = 1$ g/cm^3

$f = 1.111 \times 10^{-4}$ per sec at $\phi = 52.8^\circ$N

$\bar{W} = 15$ m/sec

$\Delta x = 10$ mi $\sim 16 \times 10^4$ m

$\frac{\Delta W}{\Delta x} = 18$ m/sec/m ($W_1 = 6$ m/sec, $W_2 = 24$ m/sec)

$A = 3.2 \times 10^{-6}$ g/cm, 6.05×10^5 = sec/7 days

Let this wind blow over the 100 mile x-section for seven days, then

$$\frac{\Delta H}{7 \text{ days}} = 2 \times \frac{3.2 \times 10^{-6}}{1 \times 1.111 \times 10^{-4}} \times 15 \times 10^2 \times \frac{18 \times 10^2}{16 \times 10^6} \times 6.05 \times 10^5 \text{ cm}$$

$$= 58.8 \times 10 \text{ cm} = 58.8 \text{ meters}$$

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* "The Oceans", p. 498.

Substituting reasonable values for windspeed and change in windspeed in the x-direction, and evaluating $\frac{dH}{dt}$ for seven days gives changes in mixed layer depth several times as large as any known to have been observed. Evidently this model is not reasonable, but if the same problem is considered in three dimensions as in item 3 below, reasonable results are obtained.

3. Assuming

   1) no change in surface level
   2) no significant motion below MLD
   3) $u \frac{du}{dx} \ll fu$
   4) complete volume compensation (deep water movements are slow)
   5) complete pressure compensation by thermocline adjustment
   6) geostrophic currents in the mixed layer

$$\frac{dQ_x}{dt} \ll f \;\; T_y, \text{ etc.}$$

then $$\frac{\partial H}{dt} = -\frac{1}{\rho' f} \left(\frac{\partial \tau_y}{\partial x} - \frac{\partial \tau_x}{\partial dy} \right)$$

The development of this equation for $\frac{\partial H}{\partial t}$ as a result of three dimensional surface water divergence is being reported in the heat budget study, Technical Report No. 4, and in a separate paper, Technical Report No. 5 Whereas the purpose of the development was to evaluate the vertical advection term in the heat budget, it could obviously be tried as a forecasting tool for forecasting $\frac{\partial H}{\partial t}$.

Measurements of average wind stress were made from the five day mean surface pressure maps of the Extended Forecast Section of the U.S.W.B. for the fall of 1948 and part of the fall of 1949. $\frac{\partial H}{\partial t}$ was computed from curl of the wind stress according to the method discussed in Technical Report No. 4 of this project. Values of $\frac{\partial H}{\partial t}$ were computed from individual surface maps also. In most cases these $\frac{\partial H}{\partial t}$s were of the same order of magnitude as the corresponding observed $\frac{\partial H}{\partial t}$s.

Comparisons were made between computed and observed values on both the five-day and one-day bases. The five-day computed H's were compared to the all-data average values of H taken from Monthly Sonar Conditions Charts, H.O. Publication #761 and to values of H regarding persistance as a forecast. The computed values of H were better than the all data average values but not as good as persistance. A comparison of a value of $\frac{dH}{dt}$ computed from a five-day mean map and $\frac{dH}{dt}$ as the sum of values computed from five individual maps was made. No visible evidence resulted as to which curl computation was best. Finally computations of $\frac{dH}{dt}$ from individual maps were compared with daily observed values of $\frac{dH}{dt}$. More detail will be reported on this work in conjunction with Dr. Freeman's Technical Report on "Note on A Prediction Equation for A Deep Two Layer Ocean". None of these approaches alone appear to be useful as forecasting techniques. At the time they were tried the heat budget study was incomplete. The heat budget study now gives the magnitude of the vertical advective process in relation to the magnitudes of other processes. Examination of the heat budget summary shows that estimates of vertical advection must become part of any forecasting procedure. The main practical difficulty seems to be how to obtain an accurate average of the curl of wind stress over a short period (say one day to one week). A recent climatological study, "Variation in Atlantic Wind Stress Vorticity", by Ilmo Hela reported in the Bulletin of Marine Science of the Gulf and Carribean, Vol. 2, No. 1, pp. 313-323, November 1952, is of interest in this connection. This article presents the climatology of the quantity $\left(\frac{\partial \tau_y}{\partial x} - \frac{\partial \tau_x}{\partial y}\right)$ for the North Atlantic.

Horizontal Temperature Variation

While the weather ships which provide the basic data for the studies of ocean thermal structure are usually thought of as fixed, in actuality they sometimes cruise at considerable distance from established positions. If data collected at such times are to be compared with "on station" reports the need arises for a way to obtain on-station changes in temperature from data gathered by a wandering, "fixed" weather ship.

Such a ship was stationed in the vicinity of 42°N, 173°W in September 1944. Data taken by it between 1 September and 24 September were chosen for a detailed space-time study of temperature variation. Only one observation a day was at first considered; it being the one taken nearest 2300 GCT. All observations were made within a circle, centered at 42°N, 173°W, having a radius of 1.5° latitude. Twenty-four hour ship movements were essentially random.

Plots of sea-surface temperature versus time upon which lines of equal latitude were drawn indicated a very clean-cut north-south temperature gradient throughout the period. An analysis of temperatures at other depths (50 ft., 100 ft., 250 ft. and 350 ft.) showed similar gradients, but these were less definite and less stable.

The stability of the gradient at the surface was checked by vector analysis. A gradient (decrease with distance) was established on the basis of each pair of BT's taken successively. Of these, only one gradient vector had no north-component. Further, this one resulted from two observations between which the ship had an almost east-to-west movement. The ship movements having been random, the direction of the sum of these gradients is a good estimate of the average gradient-direction over the 24-day period. The result of summing was a direction 2° west of north.

If the isotherms at the surface were essentially straight lines and if their orientation was constant during a 48-hour period in which three observations were made, the magnitude and direction of the maximum gradient could be obtained. The marked stability of the gradient noted in the above studies led to an analysis on this basis. In three of 22 cases examined, the gradient magnitudes obtained were unreasonable, indicating that marked changes in water mass occurred during these intervals. The other gradients were reasonable in magnitude for changes within a water mass; their directions varied in a somewhat regular way about north to northwest and northeast.

A similar analysis of lateral and time variation of the temperature difference between 250 feet and 350 feet showed much less stability.

The set of data used was inadequate in many respects. It was used to develop a set of analysis techniques whereby no account is taken of causal factors. Data having greater continuity and length in time is now available and will be examined from these points of view.

As a result of the above analysis a quantitative definition of thermocline has been proposed. In brief, this definition gives physical boundaries to the thermocline based on points of tangency on the BT trace of two lines parallel to a characteristic line. A separate technical report discussing this definition and some of its properties is in manuscript form.

PLANS FOR THE COMING YEAR

No basic change in plan of attack is contemplated for the coming year. Studies proposed for the coming year continue, in a general way, along the lines previously followed.

A broadening of our interest in the oceanographic forecast problem is planned with incorporation of graphical correlation techniques as an aid to analysis of the effects of several variables on ocean thermal structures.

A continuation and intensification of the effort to specify a space-time picture, especially the horizontal aspects, of the oceans is planned. An important phase of this work will be deep water cruises designed to provide sequences of BT's not presently available. More information on the critical wind for rough flow will also be obtained. It is hoped that funds for these cruises will be made available

A study is planned wherein the transport of energy across a series of latitude sections in the North Atlantic Ocean will be estimated, based on all available data. The fluctuations of this transport within the top layers of the ocean will be estimated on a seasonal or monthly basis, insofar as possible, and the resulting interaction between the atmosphere and the ocean studied.

A study of the relation of computed sound range to variations in mixed layer depth and slope of the thermocline is planned to investigate the extent to which the effect of a deepening mixed layer is off set by the resulting change in thermocline slope.

Climatological studies of the relation between temperature and the curl of wind stress and the relation between weather variables and annual variation in sound range have been proposed for early consideration.

In the realm of theory, work is planned on the mechanism of wind mixing and the effect of wind mixing in bringing about organized horizontal motion. The effect of non-linear internal waves on the diurnal thermocline is also to be investigated.

If supplementary funds become available, the performance of data processing tests on the machine developed by Cook Research Laboratory will be undertaken.

In general, we are looking ahead eagerly to a year of productive effort balanced between theory and practice wherein we may move closer to solving the problem of oceanographic forecasting.

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Born	Houston, Texas, 1920
Training	The Rice Institute, Houston, Texas, 1937-41, B.A. Major - mathematics; minor - physics The California Institute of Technology, 1941-42, M.S. Major - meteorology Brown University, Rhode Island, 1946-48 Major - applied mathematics University of Chicago, Illinois, 1950-52, Ph.D. Major - meteorology
Experience	U. S. Army Air Force 1941-46, weather officer, forecasting and research in the Caribbean, Southern United States, New Guinea, and the Master Analysis Center in Washington. Brown University, Providence, Rhode Island, 1946-48, research in fluid dynamics The United States Weather Bureau, Washington, D. C., 1948, research in meteorology The Institute for Advanced Study, Princeton, New Jersey, 1949-50, research in theoretical meteorology The University of Chicago, Chicago, Illinois, 1950-52, research in meteorology Texas A. & M. College, Department of Oceanography, 1952- Assistant Oceanography (Meteorological), research in meteorology and oceanography
Organizations	Sigma Xi American Meteorological Society American Mathematical Society
Awards	Received the Meisinger Award for 1951 from the American Meteorological Society jointly with Morris Tepper for work in hydraulic analogies to meteorological phenomena
Publications	"Stability of Boundary Layers and Flow at the Entrance Section of a Channel," Hahneman, Freeman, Finston, Journal Aeronautical Sciences, Vol. 15, No. 8, 1948 <u>Stability of the Boundary Layer</u>, P. Chiarulli & J. C. Freeman, Graduate Division of Applied Mathematics, 1948 "An Analogy Between the Equatorial Easterlies and Supersonic Gas Flows", J. Meteor., 5:138-146 (1948) "Reply: The Usefulness of Incompressible Models", J. Meteor., 6:287 (1949) "Map Analysis in the Vicinity of a Pressure Jump", Bul. Amer. Meteor. Soc. 31, 324-325 (1950)

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- "The Wind Field of the Equatorial East Pacific as a Prandtl-Meyer Expansion", Bul. Amer. Meteor. Soc. 31: 303-304 (1950)
- "Analogy Between Equatorial & Supersonic Flows", Tepper & Freeman, J. Meteor. 6: 226 (1949)
- "Note on the Minimum Critical Reynolds Number and the Form Parameter", Journal of the Aeronautical Sciences Vol. 18, 16.5 (1951)
- "The Method of Characteristics in Meteorology", Compendium of Meteorology, 1951
- "The Squall Line as an Internal Wave", Mimeographed Report, University of Chicago, 1951

To be published

- "The Stability of the Boundary Layer Profile $u = 1 - e^{-y/\Delta}$"
- "A Meteorologically Significant Marching Problem"
- "Blocking as a Finite Disturbance of the Jet Stream"
- "Dynamics of a Jet Stream Model"
- "Flow Under an Inversion in Middle Latitudes" (Thesis, University of Chicago)

Full Name	GILCREST, ROBERT ALLEN
Born	Hartville, Ohio, 16 July 1916
Training	Mount Union College, Alliance, Ohio, 1938, B.S. Major - biology and chemistry Chanute Field Forecaster's School, Rantoul, Illinois, 1942 (left to become cadet) Massachusetts Institute of Technology, 1943, Certificate in Meteorology 1951, two semesters of graduate work in meteorology Texas A. & M. College, Department of Oceanography, 1952-date, graduate student in physical and meteorological oceanography
Experience	Actor in state of Ohio historical pageant and trek, 1938 Hartville, Ohio, 1939-41, farmer and vegetable grower U. S. Medical Corps, 1941, surgical technician MacDill Field, Tampa, Florida, 1942, in-station observer training and five months observer duty; discharged from U. S. Army Air Corps following commission December 1943 Eastern Air Lines, La Guardia, New York, 1943-46, domestic air line forecasting and traffic forecasting U. S. Weather Bureau, Keflavik, Iceland, 1946-47, ocean weather forecasting and observation supervision for Air Transport Command and commericial operations American Overseas Air Lines, Stockholm, Sweden and Shannon Airport, Ireland, 1947-51, worked with Swedish and Irish Meteorologists forecasting ocean weather and winds (cross-sections along routes across North Atlantic), terminal forecasting; helped maintain historical surface map series Texas A & M Research Foundation Project 29 (Atmospheric Influence on the Thermal Structure of the Oceans), 1951-date, research work
Organizations	College: Alembroic - honorary chemistry society Phi Sigma - honorary biology society Professional: American Meteorological Society American Geophysical Union
Publications	Research reports to be published

Full Name	JUNG, GLENN HAROLD
Born	Lyons, Kansas, 11 October 1924
Training	Colorado State College of Education, Greeley, Colorado, 1941-43, Major - mathematics Massachusetts Institute of Technology, 1943-44, completed Army Cadet Course in meteorology; 1947-49, S.B. Major - meteorology 1949-52, S.M. Major - meteorology Texas A. & M. College, Department of Oceanography, 1952-date, Major - oceanography
Experience	U. S. Air Force Weather Officer, 1944-47 Florence, South Carolina, prepared a stratus-fog study for surrounding region (published); Goldsboro, North Carolina, set up and helped operate mobile weather station; Louisville, Kentucky, weather forecaster Camp Detrick, Frederick, Maryland, helped organize long term micrometeorological research program; also supervised a class "A" weather station; trained in-station observers and instructed some in micrometeorological observing techniques Massachusetts Institute of Technology, 1950-51, research assistant in department of meteorology 1952, Division of Industrial Cooperation staff member Texas A. & M. College, Department of Oceanography, 1952-date, research assistant
Organizations	American Meteorological Society Sigma Xi
Publications	"Large-scale Atmospheric Exchange Processes as Diffusion Phenomena", co-author, Journal of Meteorology, Vol. 8, No. 5, 1951. "A Note on the Energy Transported by Ocean Currents", Journal of Marine Research, Vol. 11, No. 2, 1952.

Full Name	KAHAN, ARCHIE MARION
Born	Denver, Colorado, 18 January 1917
Training	University of Denver, 1936, B.A. Major - mathematics and chemistry University of Denver, 1940, M.A. Major - mathematics; minor - chemistry California Institute of Technology, 1942, M.S. Major - meteorology
Experience	Hamilton Trust Shares, Denver, Colorado, 1937-38, research statistician U. S. Corps of Engineers, Denison, Texas, 1938-41, engineering mathematician U. S. Air Force, 1942-45, Base weather officer, Elmendorf Field, Anchorage Alaska; staff weather officer, Eleventh Air Force Adak, Alaska; Chief of Forecast Section, Forecast Branch, Weather Division, Pentagon, Washington U. S. Weather Bureau, 1946-51, Official-in-Charge, Missouri River Forecast Center American Institute of Aerological Research, Denver, Colorado, 1951-52, Director of Technical Operations Texas A. & M. College, Department of Oceanography, 1953-date, assistant oceanographer, research in meteorology and oceanography
Organizations	Sigma Xi Phi Lambda Upsilon American Geophysical Union American Meteorological Society
Awards	Legion of Merit awarded for outstanding contribution to the success of the Aleutian Campaign as weather forecaster on the staff of the Commanding General, Eleventh Air Force

Full Name	SPARGER,CARTER REESE
Born	Wichita Falls, Texas, 23 November 1923
Training	Oklahoma Agricultural and Mechanical College, 1950, B.A., Major - meteorology and geography
Experience	U. S. Air Force, 1942-45, pilot, captain U. S. Civil Service, Tinker Air Force Base, Oklahoma City, Oklahoma, 1946, billing clerk, typist, etc. Ford Motor Co., Oklahoma City, 1948, billing clerk, typist, etc. Oklahoma City Public Libraries, 1950-51, reference and out-service departments Texas A. & M. College, Department of Oceanography, 1951-52, research assistant Texas A. & M. College, Department of Oceanography, 1952-date, Assistant in Oceanography
Organizations	Air Force Reserve