INFORMATION TO USERS

This material was produced from a microfilm copy of the original document. While the most advanced technological means to photograph and reproduce this document have been used, the quality is heavily dependent upon the quality of the original submitted.

The following explanation of techniques is provided to help you understand markings or patterns which may appear on this reproduction.

- 1. The sign or "target" for pages apparently lacking from the document photographed is "Missing Page(s)". If it was possible to obtain the missing page(s) or section, they are spliced into the film along with adjacent pages. This may have necessitated cutting thru an image and duplicating adjacent pages to insure you complete continuity.**
- 2. When an image on the film is obliterated with a large round black mark, it is an indication that the photographer suspected that the copy may have moved during exposure and thus cause a blurred image. You will find a good image of the page in the adjacent frame.**
- 3. When a map, drawing or chart, etc., was part of the material being photographed the photographer followed a definite method in "sectioning" the material. It is customary to begin photoing at the upper left hand corner of a large sheet and to continue photoing from left to right in equal sections with a small overlap. If necessary, sectioning is continued again — beginning below the first row and continuing on until complete.**
- 4. The majority of users indicate that the textual content is of greatest value, however, a somewhat higher quality reproduction could be made from "photographs" if essential to the understanding of the dissertation. Silver prints of "photographs" may be ordered at additional charge by writing the Order Department, giving the catalog number, title, author and specific pages you wish reproduced.**
- 5. PLEASE NOTE: Some pages may have indistinct print. Filmed as received.**

University Microfilms International

300 North Zeeb Road
Ann Arbor, Michigan 48106 USA
St. John's Road, Tyler's Green
High Wycombe, Bucks, England HP10 8HR

7824593

GOERSS, JAMES SEYMOUR
DRIFT ANALYSIS OF GATE SHIP SURFACE
MEASUREMENT SYSTEMS.

THE UNIVERSITY OF OKLAHOMA, PH.D., 1978

University
Microfilms
International 300 N. ZEEB ROAD, ANN ARBOR, MI 48106

THE UNIVERSITY OF OKLAHOMA
GRADUATE COLLEGE

DRIFT ANALYSIS OF GATE SHIP SURFACE MEASUREMENT SYSTEMS

A DISSERTATION
SUBMITTED TO THE GRADUATE FACULTY
in partial fulfillment of the requirements for the
degree of
DOCTOR OF PHILOSOPHY

By
JAMES S. GOERSS
Norman, Oklahoma
1978

DRIFT ANALYSIS OF GATE SHIP SURFACE MEASUREMENT SYSTEMS

Approved By

Claude E. Duckert
James F. Kinnip
Ormy F. Kinnip
W. B. Schuyler
Fred V. Brock

DISSERTATION COMMITTEE

ACKNOWLEDGMENTS

I would first like to thank Dr. Claude E. Duchon who provided the inspiration for this research and the support needed to carry it out. Thanks are given to Drs. Amos Eddy, Jeff Kimpel, Al Schwarzkopf, and Fred Brock not only for their critical review of this manuscript but also for the many and various lessons each has taught me during the course of my graduate study. Special thanks are given to Dr. Ward Seguin of the Center for Experimental Design and Data Analysis for his valuable assistance in acquiring the data used in this research and to the many participants in two seminars conducted at CEDDA for putting some of the ideas contained in this study in sharper focus. I would also like to thank Ms. Jo Ann Oberst for her help in preparing this manuscript.

This research was jointly supported by the Global Atmospheric Research Program, Division of Atmospheric Science, National Science Foundation, and the GATE Project Office, National Oceanic and Atmospheric Administration under Grant ATM77-08001.

TABLE OF CONTENTS

	<u>Page</u>
LIST OF TABLES	v
LIST OF FIGURES.	vii
Chapter	
I. INTRODUCTION	1
II. FORMULATION OF THE PROBLEM	7
III. DRIFT ANALYSIS PROCEDURE	12
IV. APPLICATION AND RESULTS.	20
V. SUMMARY AND CONCLUSIONS.	70
BIBLIOGRAPHY	74
APPENDIX A	102
APPENDIX B	112
APPENDIX C	119
APPENDIX D	124

LIST OF TABLES

<u>Table</u>	<u>Page</u>
1. Dates of GATE observation and intercomparison periods.	7
2. A comparison of the actual differences (mb) between 7-day averages of Type 1 and Type 2 pressure measurements made during Phase III with those differences implied by the drift analysis	31
3. A comparison of the actual differences ($^{\circ}$ C) between 7-day averages of Type 1 and Type 2 wet-bulb measurements made during Phase I with those differences implied by the drift analysis. . . .	38
4. A comparison of the actual differences ($^{\circ}$ C) between 5-day averages of Type 1 and Type 2 sea-surface temperature measurements made during Phase II with those differences implied by the drift analysis.	46
5. Phase III day (08Z-19Z) and night (20Z-07Z) average dry-bulb temperature ($^{\circ}$ C) for both Type 1 (*) and Type 2 systems.	49
6. The distribution of Phase III dry-bulb observations (20Z-07Z).	51
7. A comparison of Phase III dry-bulb system drift estimates ($^{\circ}$ C) using 13-day and 13-night averaging periods with those obtained by Seguin, <u>et al.</u> (1978).	56
8. A comparison of actual differences ($^{\circ}$ C) between 11-night averages of undisturbed Type 1 and Type 2 dry-bulb measurements made during Phase I with those differences implied by the drift analysis	57
A.1. Differences between the parabolic surface and modeled atmospheric waves ($^{\circ}$ C)	106

<u>Table</u>	<u>Page</u>
B.1. A comparison of AR and linear interpolations for twelve missing hourly observations between 17 GMT, 8 September 1974, and 06 GMT, 9 September 1974, for the <u>Researcher</u> Type 2 wet-bulb temperatures	117
B.2. A comparison of AR and linear interpolations for eight missing hourly observations between 11 GMT and 20 GMT, 11 September 1974, for the <u>Researcher</u> Type 2 pressures (mb). . . .	118
C.1. Hypothetical set of 100 wind direction observations.	121
C.2. Sample means and standard deviations in degrees for varying c	121

LIST OF FIGURES

<u>Figure</u>	<u>Page</u>
1. Ship array during Phase I	77
2. Ship array during Phase II.	78
3. Ship array during Phase III	79
4. Flow chart of analysis procedure.	80
5. Phase and intercomparison drift estimates for pressure measurement systems (<u>Researcher</u> Kollsman benchmark)	81
6. Same as Fig. 5.	82
7. Same as Fig. 5.	83
8. Results of artificial drift analysis for pres- sure measurement systems during Phase III (<u>Researcher</u> Kollsman benchmark)	84
9. Phase and intercomparison drift estimates for wet-bulb temperature measurement systems (<u>Meteor</u> Type 1 benchmark)	85
10. Same as Fig. 9.	86
11. Same as Fig. 9.	87
12. Phase and intercomparison drift estimates for sea-surface temperature measurement systems (aggregate benchmark)	88
13. Same as Fig. 12	89
14. Same as Fig. 12	90
15. A comparison of Type 1 and Type 2 temperature measurements made aboard the <u>Oceanographer</u> on 10 September 1974	91

<u>Figure</u>	<u>Page</u>
16. <u>Oceanographer</u> Type 1 temperature measurements, 10-12 September, 1974.	92
17. Phase and intercomparison drift estimates for dry-bulb temperature measurement systems (<u>Meteor</u> Type 1 benchmark)	93
18. Same as Fig. 17	94
19. Same as Fig. 17	95
20. Phase and intercomparison drift estimates for wind speed measurement systems (<u>Meteor</u> Type 1 benchmark).	96
21. Same as Fig. 20	97
22. Same as Fig. 20	98
23. Phase and intercomparison drift estimates for wind direction measurement systems (<u>Oceanographer</u> Type 1 benchmark)	99
24. Same as Fig. 23	100
25. Same as Fig. 23	101
A.1. Plot of Eq. (A.1) for $y_i = 8.50$, $\alpha = 0.575$, $\phi = 0$, $t = 0$, and $\lambda = 28^\circ$	104
A.2. Plot of waves characterized in Fig. A.1 using Eq. (A.2) in which $\beta = 0.5$, $\phi = 0$, $\lambda = 28^\circ$ and $c = 4^\circ/\text{day}$, where a two-day averaging time is used.	105
A.3. Plots of modeled and actual drifts where the only non-zero actual drifts are at positions 3, 5, and 7. Vertical axis is drift magnitude, horizontal axis is time step.	109
A.4. Same as Fig. A.3 except non-zero drifts are at positions 3, 5, and 9.	110
D.1. Parabolic surfaces (mb) fitted to seven-day averages of pressure centered on 5 September 1974.	126

<u>Figure</u>		<u>Page</u>
D.2.	Same as Fig. D.1 except for 12 September 1974.	128
D.3.	Estimated drifts (mb) for pressure measurement systems relative to the <u>Researcher</u> Kollsman.	130
D.4.	Hand analysis of 7-day averages of Type 2 pressure (mb) centered on 12 September 1974 and corrected using the intercomparison drift estimates contained in EDS 17	133

DRIFT ANALYSIS OF GATE SHIP SURFACE MEASUREMENT SYSTEMS

CHAPTER I

INTRODUCTION

The need for determining the relative accuracy of atmospheric measurement systems has been made more apparent in recent years by large-scale meteorological experiments [e.g., BOMEX (Barbados Oceanographic and Meteorological Experiment), NHRE (National Hail Research Experiment), and GATE (GARP Atlantic Tropical Experiment)] in which many measurement platforms have been used. In such projects physical phenomena are sampled simultaneously by many diverse as well as spatially separated measurement systems. If the input to two such measurement systems is unknown but identical and the resulting output of both systems is the same, then the relative accuracy of these two systems is perfect. If this input is known and the resulting output of both systems is exactly the known input, then the absolute accuracy of the two systems is perfect. The evaluation of data collected from these systems without proper identification of error content could lead to incorrect physical interpretations. For example, in a comparison of various measurement systems aboard the same

ship during the 1968 Barbados Experiment, Seguin and Garstang (1971) found that considerable variation occurred from system to system measuring the same variable. Specifically, differences as large as 0.5°C , 1.0°C , and 2.0°C were found between systems simultaneously measuring sea-surface, dry-bulb, and wet-bulb temperatures, respectively. Furthermore, they demonstrated that such differences could result in 100% to 1000% errors in estimates of sensible and latent heat flux computed using bulk aerodynamic techniques. Thus, the need for determining the relative accuracy of such systems is quite apparent. In order to accomplish this a technique such as field intercomparison of measurement systems must be employed during the experiment itself.

A field intercomparison may be thought of as any period of time during an experiment when two or more measurement systems sample data in the same physical location. It might consist of three instrumented aircraft flying in tight formation for five minutes or eight instrumented ships anchored in the same location for three days. In either case the object of the field intercomparison is to try to subject each system to the same unknown input and then compare the output of the various systems in order to estimate their relative accuracies.

In order to determine the quality of data collected by airborne measurement systems, an intercomparison in which two NCAR aircraft flew in close formation across the upper Texas

coast was conducted in June 1967 (Duchon, 1968). Intercomparison flights were conducted in a similar fashion during 1969 by aircraft participating in BOMEX (Holland and Acheson, 1973). By 1971 intercomparison flights were an integral part of aircraft operations in NHRE (Duchon, 1972). As mentioned previously Seguin and Garstang (1971) found during the 1968 Barbados Experiment that considerable variation occurred from system to system measuring the same variable aboard the same ship. This result suggested that even more variation from system to system could be expected in an experiment like GATE in which many ships from several nations were to collect data off the African coast in 1974. Therefore, intercomparison schemes were planned for both the GATE Aircraft (Aanensen, 1974) and ship operations (Tarbeev and Petersen, 1974).

The purpose of field intercomparisons is to determine the error content of the various measurement systems involved in an experiment. An observation at a given time can be modeled simply as the sum of the actual value of the measured variable, a noise term, and a constant bias. The bias is the expected value of the differences between the observations and reality. In practice one never knows the actual value of the meteorological variable being measured and must be content with estimating relative biases among systems.

Detailed analyses of measurement system noise have been conducted for both aircraft (Duchon and Goerss, 1976a; Goerss, 1975; Goerss, 1977) and ship systems (Duchon and

Goerss, 1976b). Due to the fact that aircraft intercomparisons are normally conducted over short periods of time (on the order of minutes), these analyses primarily reveal information about the high frequency noise content of such systems. The fact that estimates of the relative biases among various aircraft systems have been found to change from flight to flight (Duchon, 1972) indicate that very low frequency noise or drift is also present. Henceforth, the term drift will be used to denote measurement system noise whose period is on the order of days. Shannon (1973) presented techniques to determine whether relative biases estimated among systems in an aircraft intercomparison are significant and whether they are functions of aircraft heading or altitude. However, the nature of aircraft intercomparisons makes the determination of very low frequency noise quite difficult.

On the other hand the ship intercomparisons in GATE were conducted over periods of two to three days so that the noise analysis techniques of Duchon and Goerss (1976b) were capable of detecting measurement system drifts. Noise spectra computed for Rosemount pressure measurement systems were found to possess much more low frequency power than those computed for Kollsman pressure measurement systems aboard the GATE ships during Intercomparison Period 2. In their analysis of the GATE ship intercomparison data Godshall, Seguin, and Sabol (1976) found that in general the Rosemount systems showed considerable drift from intercomparison to intercomparison

while the Kollsman systems did not. The data they analyzed consisted of differences between the outputs of each system and a pre-specified benchmark system. For certain Rosemount systems the mean of these differences changed more than 0.5 mb from one intercomparison to the next.

While the results of Godshall, et al. (1976) can indicate that a measurement system must have drifted from one intercomparison to the next, they do not permit one to model this drift. The GATE ship surface data which is of paramount importance for meteorological analysis was that collected during the observation phases. These observation phases were conducted between the intercomparisons. Thus, it is vital that the nature of such drifts between the intercomparisons be determined. The purpose of this research is to develop techniques for estimating the drift in GATE ship surface measurement systems during the observation phases themselves.

In the next chapter the format of the GATE ship operations is described in detail, intercomparison results are discussed which point out the need for this research, and the objectives of this research are spelled out. The drift analysis procedure is developed in Chapter III and evaluated in Appendix A using simulated input data. The analysis procedure is then applied to the output of ship systems measuring six different atmospheric variables (pressure, wet-bulb temperature, sea-surface temperature, dry-bulb temperature, wind speed, and wind direction) and the results are discussed in Chapter IV.

In Chapter V the results of this research are summarized and recommendations designed to optimize the relationship between intercomparisons and observation phases are made based on these results.

CHAPTER II

FORMULATION OF THE PROBLEM

Format of the GATE Ship Operations

Before the problem to be solved in this study can be properly defined the format of the GATE ship operations must be described. The Experiment was conducted from June 17 through September 23, 1974 and included three formal ship intercomparisons (IC's) and three observation phases. Table 1 summarizes the chronological order of events.

Table 1. Dates of GATE observation and intercomparison periods.

Periods	Date
Intercomparison Period 1	June 17-19
Phase I	June 26 - July 16
Phase II	July 28 - August 16
Intercomparison Period 2	August 16-18
Phase III	August 30 - September 19
Intercomparison Period 3	September 21-23

A total of nineteen ships and one meteorological buoy from various nations took part in the experiment at

one time or another. The positions of the various ships during the three observation phases are displayed in Figs. 1-3 (Seguin, et al., 1977). As one can see in these figures during all three phases the GATE ship array enclosed an area of approximately 175,000 square nautical miles (roughly the size of New Mexico and Colorado). Only during Phase III did all nineteen ships participate at the same time. However, fifteen of the ships took part in all three phases.

All of the ships measured the six meteorological variables to be investigated in this study (pressure, wet-bulb temperature, sea-surface temperature, dry-bulb temperature, wind speed, and wind direction). Measurements of each variable fall into two categories: the Type 1 measurements which consist of continuous and automatically recorded observations; and the Type 2 measurements which consist of observations hand-recorded at 15 or 30 minute intervals. All ships made Type 2 measurements while five ships and the meteorological buoy recorded Type 1 measurements as well.

The ship operations of GATE were conducted over a period of almost 100 days. During that period approximately 60 days were devoted to on-station observations and 9 days to intercomparisons. Only during the second intercomparison period (IC2) did all available ships (eleven) assemble in the same position. During the first intercomparison period eleven ships intercompared at one location (IC1) and three at another (IC1A) while during the third intercomparison

period eight ships intercompared at one location (IC3A) and eight at another (IC3B). Two of the ships did not participate in any intercomparison at all. From Table 1 it can be seen that two observation phases were conducted between the first and second intercomparison periods. Only the third observation phase was both preceded and followed by intercomparison periods. Thus, given the size of the area over which measurements were made, the many different ships and measurement systems which participated at various times, and the time and space scheduling of the intercomparison periods, it can be seen that assessing the relative accuracy of the ship surface data collected during the GATE observation phases is far from a trivial problem.

Need for Research

Prior to GATE, the Convection Subprogram specified that sea-level atmospheric pressure should be measured to the nearest 0.1 mb, dry-bulb temperature to the nearest 0.2°C, and wet bulb temperature to the nearest 0.2°C (Rodenhuis and Betts, 1974). In their analysis of the GATE ship intercomparison data Godshall, et al. (1976) averaged the differences between the output of each measurement system and a pre-specified benchmark system for each intercomparison. They found that the mean of these differences for the Dallas Kollsman pressure (a Type 1 measurement) ranged from -0.25 mb to -0.91 mb between IC1 and IC2. All of the Type 1 Rosemount pressures were found to possess significant drifts between intercomparisons. The mean of

these differences changed 0.22°C and 0.29°C between the first and third intercomparisons for the Quadra Type 1 dry-bulb system and the Gilliss Type 1 wet-bulb system, respectively. Due to the fact that Godshall, et al. (1976) will be frequently used in the rest of this paper, it will henceforth be simply denoted by EDS 17.

The means of the aforementioned differences for the Oceanographer Type 2 pressure were -0.44 mb, -0.60 mb, and -0.84 mb for IC1, IC2, and IC3A, respectively. Changes between intercomparisons greater than 0.2°C were found for the Gilliss, Dallas, Quadra, and Meteor Type 2 dry-bulb measurement systems as well as for the Researcher and Oceanographer Type 2 wet-bulb systems. The analysis of the intercomparison data clearly indicates that for some measurement systems the drift from intercomparison to intercomparison is greater than the aforementioned maximum allowable error of measurement specified by the Convection Subprogram.

It is clear from the intercomparison studies of Duchon and Goerss (1976b) and those in EDS 17 that some of the ship measurement systems drifted. What is not clear is the nature of these drifts during the observation phases themselves. Furthermore, there is no guarantee that systems which appear to be drift-free from the intercomparison studies actually possess that desirable property. Thus, before the output of the various ship measurement systems can be confidently used for meteorological or oceanographic

analysis it is necessary that the drift in each system during the GATE observation phases be estimated.

Objective of Research

As has been pointed out in the preceding section of this chapter some of the GATE ship measurement systems displayed drifts. The detection of the presence of drift in a measurement system is a relatively simple task during inter-comparisons when many ships are assembled in one location and are essentially sampling the same atmospheric signal. The estimation of these drifts, however, becomes a complicated problem during the observation phases when each ship takes its station in the vast ocean area covered by the ship array and begins sampling an atmosphere quite different from that sampled by its nearest neighbor. The objective of this research is to develop an analysis scheme capable of estimating the drift in each ship surface measurement system during the three observation phases of GATE. An integral part of this development will be an assessment of how well the scheme works for the six atmospheric variables whose measurements are investigated.

CHAPTER III

DRIFT ANALYSIS PROCEDURE

Data Model

The first step in the analysis is to model the output of a ship measurement system. The model chosen for measurement system i is given by

$$X_i(t) = Z_i(t) + N_i(t) + K_i \quad (1)$$

where: $X_i(t)$ output signal (observed data)

$Z_i(t)$ input signal (atmospheric data)

$N_i(t)$ noise in output signal

K_i bias in output signal

t time.

Henceforth, following the usual convention, the bias is defined to be a constant, K_i , while the drift will be regarded as very low frequency noise whose period is on the order of days and is embedded in the noise term, $N_i(t)$, whose expected value is zero. Given the observation $X_i(t)$ one would like to obtain the best possible estimate of the actual value of the atmospheric variable being measured, $Z_i(t)$. In order to do this the sum of the bias and noise at time t must be estimated. Since the actual value of the atmospheric

signal is never known, one must be content with estimating the relative bias between measurement systems rather than the absolute bias of a particular system itself. Thus, as has been done in the various intercomparison studies discussed previously, it is convenient to select a measurement system as a benchmark and then estimate the relative accuracy of the other systems with respect to it.

Using the data model described by (1), it will be shown mathematically how the analysis procedure employed in EDS 17 can detect drift in a measurement system from one intercomparison period to the next. The benchmark system is assumed to be unbiased and noise-free. If one assumes that during an intercomparison each system samples the same atmospheric data, then the output of the benchmark system is simply denoted by $Z_i(t)$. Using an overbar to denote an arithmetic time average over the intercomparison, then the mean of the differences between system i and the benchmark system would be:

$$\overline{X_i(t) - Z_i(t)} = \overline{X_i(t)} - \overline{Z_i(t)} = \overline{N_i(t)} + K_i. \quad (2)$$

The effect of the averaging process on the noise term is to act as a low-pass filter. Since each intercomparison is typically about three days long, this filter would only effectively pass waves with periods greater than three days (this is because the frequency response function is $[\sin(\pi f T)]/\pi f T$ where f is frequency and T is averaging time). Thus, the term $\overline{N_i(t)}$ would represent the value of the

very low frequency noise or drift at the center of the intercomparison period for the i -th measurement system. Suppose this process is repeated for system i for the next intercomparison period. If the average difference so obtained is not the same as that found for the previous intercomparison, then the system must have drifted (i.e., the value of $\overline{N_i(t)}$ has changed) since K_i is a constant. Of course, this type of analysis yields no information about the behavior of $\overline{N_i(t)}$ between the intercomparisons. It can point out systems which must have drifted but it cannot describe the nature of this drift or even guarantee that systems which showed no apparent drift actually possessed that property. Thus, a method must be developed to estimate the system drift during the observation phases.

Analysis Scheme

Suppose that each of the L ships participating in a particular observation phase have reached station in the GATE ship array (see Figs. 1-3). For each variable to be analyzed an M -day average is computed and the following L values are obtained:

$$\overline{x_i^1(t)} = \overline{z_i^1(t)} + \overline{N_i^1(t)} + K_i, \quad i = 1, \dots, L, \quad (3)$$

where the superscript denotes the first such M -day average for the observation phase. It is anticipated that the length of the averaging period will be a function of the

variable being analyzed. An important part of this research will be the determination of the appropriate value for M.

If, for the ships which participated in an intercomparison immediately before the observation phase, sample estimates of $\overline{N_i(t)} + K_i$ have been obtained, then $\overline{N_i(t)} + K_i$ can be subtracted from (3) and denoting $\overline{N_i^1(t)} - \overline{N_i(t)}$ by ΔD_i^1 , one obtains

$$x_i^{1*} = \overline{x_i^1(t)} - (\overline{N_i(t)} + K_i) = \overline{z_i^1(t)} + \Delta D_i^1, \quad i = 1, \dots, L. \quad (4)$$

The term x_i^{1*} represents the average of a meteorological variable for the first M-days of the phase, $\overline{z_i^1(t)}$, plus the change in the drift from the center of the intercomparison period to the center of the M-day period, ΔD_i^1 , for the i-th ship. On the other hand some of the ships may not have participated in the intercomparison or the observation phase may not have been immediately preceded by an intercomparison. For such cases the $\overline{N_i(t)} + K_i$ in (4) would be set to zero and ΔD_i^1 would simply become $\overline{N_i^1(t)} + K_i$, the sum of the drift and bias at the center of the M-day period for the i-th ship.

At this point the problem would be solved if the input to each measurement system including the benchmark were the same. Since ΔD^1 is assumed to be zero for the benchmark system, one would merely subtract x^{1*} for the benchmark from the remaining x_i^{1*} to obtain ΔD_i^1 for each i. Unfortunately, such a simplifying assumption is hardly realistic since each

system will not possess the same input, and another approach must be taken to account for the differences among the $\overline{Z_i^1(t)}$.

In order to model the $\overline{Z_i^1(t)}$ a parabolic surface will be fitted to the X_i^{1*} using linear regression techniques (Lindgren, 1976, p. 549; Draper and Smith, 1966, p. 59). A parabolic surface has the form

$$S(x_i, y_i) = A_1 x_i^2 + A_2 y_i^2 + A_3 x_i y_i + A_4 x_i + A_5 y_i + A_6, \quad (5)$$

where x_i and y_i represent the longitude and latitude of the i -th ship position, respectively. All of the ship positions lie between 5°N and 12°N where the length of a degree of latitude is never more than 1.5 percent greater than the length of a degree of longitude (List, 1971). Therefore, for the sake of simplicity but with little loss in accuracy, degrees of latitude and longitude will be treated as units of equal length.

From (4) it can be seen that the difference between $S^1(x_i, y_i)$ and X_i^{1*} will be the sum of ΔD_i^1 and an error term made up of two parts: one due to the inability of the surface to perfectly model the average meteorology, $\overline{Z_i^1(t)}$, and the other due to the influence of the change in drift or the sum of drift and bias, ΔD_i^1 , upon the surface. In order to accurately estimate the ΔD_i^1 , these error terms must be small with respect to ΔD_i^1 . The choice of the 6-parameter parabolic surface as the model was made in order to minimize the size of these error terms. A model with fewer parameters (e.g.,

3-parameter linear) would be less capable of fitting the $\overline{Z_i^1(t)}$ and would thus increase the size of the error terms. On the other hand a model with more parameters (e.g., 10-parameter cubic) would be greatly influenced by the ΔD_i^1 (especially in consideration that for Phases I and II there were only 13 different ship positions) and would again increase the size of the error terms.

In order to extend the analysis procedure for successive M-day averages within an observation phase, denote $\overline{N_i(t)} + K_i$ in (4) by ΔD_i^0 . Then (4) can be generalized to

$$x_i^{j*} = \overline{x_i^j(t)} - \Delta D_i^{j-1} = \overline{z_i^j(t)} + \Delta D_i^j, \quad i=1, \dots, L, \quad (6)$$

where ΔD_i^j represents the change in drift from the center of the (j-1)th averaging period to the center of the jth averaging period and j ranges from one to the maximum number of consecutive M-day averages possible within the observation phase. By modeling the $\overline{z_i^j(t)}$ using a different parabolic surface $S^j(x_i, y_i)$ for each averaging period estimates of the ΔD_i^j are obtained for each time step. Thus, beginning with ΔD_i^1 and plotting successive ΔD_i^j 's the drift in measurement system i can be estimated for the observation phase. A flow chart outlining this analysis procedure is displayed in Fig. 4.

If the observation phase is immediately preceded and followed by an intercomparison, the estimated drift at the end of the phase can be compared with its counterpart deter-

mined from the next intercomparison. This would serve as a useful check on the analysis procedure. Unfortunately, as the schedule of observation phases and intercomparisons listed in Chapter II points out, only Phase III was preceded and then immediately followed by intercomparisons. Furthermore, since the third intercomparison period consisted of two distinct intercomparisons (IC3A and IC3B) each with its own benchmark system, the relative drift between these two systems must be estimated before the results of IC2, IC3A, and IC3B can be fully utilized. Fortunately, the same benchmark system was used for IC2 and IC3A so that, if the drift analysis scheme is successful, it can be used to relate the two benchmarks to each other during Phase III and thus permit the results of IC3A and IC3B to be combined.

Before applying this analysis scheme to actual data, its capabilities were tested in a simulation study whose details are contained in Appendix A. The meteorological field to be sampled by the GATE ship array was a moving two-dimensional wave. Linear drifts were then added to certain ship positions and the analysis scheme was implemented. It was found that the analysis procedure was quite powerful at determining these drifts for interior ship positions (see Figs. 1-3). Drifts at the outer positions were less easily discerned and the results at those positions were suspect since they appeared to be prone to anomalous drifts. In any case it was concluded from this simulation study that the drift

analysis scheme is capable of providing information about the drifts in ship measurement systems that is otherwise unavailable.

CHAPTER IV

APPLICATION AND RESULTS

Preliminary Data Analysis

Before the drift analysis scheme described in Chapter III can be applied, a preliminary analysis of the data from each observation phase must be performed. One can see from Figs. 1-3 that certain ships occupied different positions in the ship array from one phase to the next. For each observation phase Seguin, et al. (1978) determined the average and standard deviation of the latitude and longitude positions held by the GATE ships as well as the time periods in which they were on station. These standard deviations for virtually all of the ships were less than 10 nm during the on-station times. Therefore, for all three phases these average positions were used to provide the x_i 's and y_i 's necessary for fitting (5) to the observed data. Since this reference will be frequently used in the rest of this paper, it will henceforth be simply called EDS 25.

During the course of the observation phases certain ships left station for various reasons. The off-station times were also given in EDS 25. Before the drift analysis

scheme could be implemented these off-station times had to be determined and the missing data interpolated using the autoregressive scheme described in Appendix B.

The data used in this study consisted of hourly observations of various Type 1 and Type 2 measurement systems. These data were processed by the Center for Experimental Design and Data Analysis (CEDDA) and recorded on magnetic tape (Sequin, et al., 1977) along with quality flags for each observation denoting missing or erroneous data. All data used were first scanned in order to locate consecutive strings of missing or erroneous data. If such a string occurred in the middle of a data set, interpolated values were determined using the methods described in Appendix B. However, if these strings occurred at the beginning or end of the data set for a phase, extrapolation was not performed. Thus, although each observation phase was about 20 days long, the number of consecutive days within each phase during which all ships were on station and collecting data that could be used in applying the drift analysis scheme was limited by the data quality itself.

Pressure

Hourly observations of both Type 1 and Type 2 pressure measurement systems were used in this analysis. While an hourly observation for a Type 2 system is just that, those for the Type 1 systems which recorded data continuously consist of ten-minute averages centered on the hour.

Although according to the GATE International Data Management Plan (WMO, 1974), all pressure data were to have been adjusted to sea level, the large biases in certain systems detected in this study as well as in EDS 25 indicate that this adjustment may not have been properly done.

The Type 1 observations aboard the U.S. ships Researcher, Gilliss, and Dallas were made by Kollsman barometers. Those made by the West German ships Meteor and Planet were acquired by Digibar barometers. The Canadian ship Quadra and the U.S. ship Oceanographer used a microbarograph and a Rosemount barometer, respectively, to obtain their Type 1 pressures. With the exception of the Meteor and the Planet, all Type 2 pressures were measured with standard precision aneroids. Both the Meteor and the Planet used Digibar sensors. Details about the various measurement systems are contained in EDS 17.

The Researcher Kollsman pressure measurement system served as the benchmark for IC1, IC2, and IC3B. The Musson Type 2 measurements were used as the benchmark for IC3A. The results of IC1 and IC2 where the Musson intercompared with the Researcher Kollsman indicate less than a 0.1 mb difference between these sensors. Therefore, in order to relate the results of the drift analysis to the intercomparisons, the Researcher Kollsman is used as the benchmark in this analysis. What this means in terms of the analysis scheme presented in the previous chapter is that at each time step

the estimated drift for the benchmark system is subtracted from the estimated drifts for the other systems. Thus, the relative drift between each of the other ships and the benchmark will be estimated. This subtraction is performed independent of the analysis itself and has no effect upon it. The choice of the benchmark system is totally arbitrary and, as mentioned before, is done only for convenience.

The first step in the application of the drift analysis procedure described in Chapter III is the determination of the appropriate averaging interval. The purpose of this averaging is to low-pass filter the observed data so that high frequency meteorology and system noise are removed. The filtered or averaged data contain only low frequency meteorology and system noise. Since the drifts that we are interested in estimating have periods as great if not greater than the lengths of the observation phases themselves, there is no chance that they will be filtered out by the averaging process. However, due to the nature of the analysis procedure, one would like to choose as short an averaging period as possible since the filter length places a limitation on the number of points at which drifts can be estimated within a phase. For example, suppose good data were collected from all ships for 16 consecutive days during a phase. If a 7-day averaging period is used and drift estimates are computed one day apart, only 10 estimates can be made since three days on each end of the period are lost by averaging.

Note also that only drift estimates separated by 7 days in this example will be independent. In practice, when actual data are used the choice of the averaging period length is quite subjective. For the pressure data it was found that the drift estimates were quite erratic from one day to the next when this length was less than 7 days. The simulation study described in Appendix A suggests that this can be attributed to the inability of the surface to fit the meteorology passed by the filter. Thus, for the pressure data a 7-day averaging period was chosen since it was the shortest one for which reasonably smooth drift estimates were produced.

The analysis procedure using a 7-day averaging period was applied to the pressure data collected during the three observation phases of GATE. The estimates of drift plus bias (relative to the Researcher Kollsman) so obtained are displayed for the interior ships in Figs. 5-7 along with estimates obtained from the intercomparisons (EDS 17). The reasons why estimates were not obtained for the outer ships will be explained later in this section. Henceforth in this study estimates of relative drift plus bias will simply be referred to as drift. It is important to note that the values plotted in these figures as well as those to follow are actually estimated drift corrections and are simply the additive inverses of the drift estimates themselves. This was done so that the results presented here would be consistent with those presented in EDS 17 and EDS 25.

The number of estimates obtained for a particular ship is contingent upon the quality and availability of data from that ship. For example, one can see from Fig. 5 that only two drift estimates were made for the Gilliss systems during Phase II. This was due to the fact that the ship was only on station for the last half of the phase. These figures display all of the drift estimates that it was possible to make.

In order to facilitate the evaluation of the drift analysis scheme, lines were drawn connecting intercomparison estimates wherever possible. In Fig. 5 it can be seen that the drift estimates for the observation phases seldom deviate more than 0.2 mb from these lines. The worst offender is the Researcher Type 2 during Phase I. However, this deviation cannot be blamed on the analysis procedure since the estimated drifts for that system were determined directly and are simply the actual differences between 7-day averages of the Type 2 and Type 1 measurements taken aboard the Researcher. This result points out that one must not place absolute faith in linear interpolation between the intercomparison results even though it does provide the only real check upon the estimates obtained during the phases from the drift analysis scheme. Essentially all of the results displayed in Fig. 5 seem to indicate that a hypothesis of linear drifts based on intercomparison results is a good one. For these ship systems the drift analysis verifies that no radical changes occur

between the intercomparisons.

On the other hand, in Fig. 6, we can see the potential power of the drift analysis scheme. The Dallas Type 1 system was known to have drifted during Phase II (EDS 17). This drift is depicted nicely by the analysis scheme. Furthermore, one can see from Fig. 6 that a linear drift correction based on IC1 and IC2 would have caused errors of almost 0.5 mb. Unfortunately, the Dallas did not participate in the third intercomparison but the drift estimates for Phase III are quite consistent with the estimate for IC2. For the Quadra Type 1 system only the results for Phase II and IC2 appear to agree. However, the quality of the drift estimates for this system from IC1 and IC3A is quite questionable. For those two intercomparisons the standard deviation of the differences between that system and the benchmark exceeded 0.50 mb. A typical value of this standard deviation for other Type 1 pressure systems was about 0.10 mb. In fact, for IC2 the standard deviation for the Quadra Type 1 was 0.14 mb. In EDS 25 Seguin estimated the bias plus drift at the center of each observation phase using a subjective analysis scheme. Averages for each system were computed over the entire phase, corrections were made based on the intercomparison results, and an average meteorology was hand analyzed from these corrected values. The difference between this hand analysis and the average of a ship's observations represented his estimate of bias plus drift at the center of the phase. Using this approach Seguin

obtained estimates of -1.2 mb, -1.9 mb, and -1.7 mb for Phases I, II, and III, respectively. It can be seen in Fig. 6 that these values agree quite well with the estimates made using the drift analysis scheme at the center of each phase. What cannot be depicted by Seguin's method is the linear drift displayed during Phase I. The fact that his estimate for Phase II is 0.7 mb lower than that for Phase I helps substantiate the presence of this drift.

The estimated drifts and intercomparison results for the Vize agree quite well for the first two phases and intercomparisons, but those for Phase III do not at all agree with the results of IC3A. Since the Vize and Meteor were positioned in virtually the same location during Phase III (See Fig. 3) and the drift estimates for both Meteor systems appear to be reliable, a comparison of the actual measurements made aboard the two ships should indicate whether the Phase III drift estimates for the Vize are believable. A check of the observed data shows that the Meteor Type 1 system consistently measured pressures about 1.0 mb less than the Vize system. This agrees almost exactly with the differences between their estimated drifts. Thus, it would appear in this case that a correction for the Vize Phase III pressures based on linear interpolation between IC2 and IC3A would have led to an error of almost 0.5 mb.

As shown in Fig. 7 the estimated drifts during Phases I and II for the Oceanographer Type 1 system agree very well

with the linear interpolation between IC1 and IC2. This was a Rosemount pressure sensor which the intercomparison studies indicated possessed drift. The estimated drifts for Phase III, however, do not correspond to a linear drift between IC2 and IC3A. In EDS 25 Seguin obtained drift estimates of -0.1 mb, 0.4 mb, and 0.5 mb for Phases I, II, and III, respectively. These are all within 0.1 mb of the drift estimates at the center of each phase displayed in Fig. 7.

Furthermore, the results shown for the Oceanographer Type 2 system compare quite favorably for all three phases with the intercomparison results, and the actual differences between the two systems aboard the Oceanographer are almost identical to the estimated differences deduced from the analysis scheme. Therefore, it would again appear that the results of the drift analysis scheme are valid and that the Oceanographer Type 1 system did not display a linear drift between IC2 and IC3A.

The estimated drifts for the Dallas Type 2 appear to be quite reasonable with respect to the intercomparison results as do those for the Quadra Type 2, except for IC1. As was seen for the Quadra Type 1 system the results of IC1 for that particular ship appear to be questionable. In EDS 25 a drift estimate of 0.1 mb was obtained for Phase I for the Quadra Type 2 system, a result which agrees with those shown in Fig. 7. The Vanguard did not participate in any intercomparisons, but the drift analysis results displayed in Fig. 7 are consistent with those obtained in EDS 25. This

with the linear interpolation between IC1 and IC2. This was a Rosemount pressure sensor which the intercomparison studies indicated possessed drift. The estimated drifts for Phase III, however, do not correspond to a linear drift between IC2 and IC3A. In EDS 25 Seguin obtained drift estimates of -0.1 mb, 0.4 mb, and 0.5 mb for Phases I, II, and III, respectively. These are all within 0.1 mb of the drift estimates at the center of each phase displayed in Fig. 7.

Furthermore, the results shown for the Oceanographer Type 2 system compare quite favorably for all three phases with the intercomparison results, and the actual differences between the two systems aboard the Oceanographer are almost identical to the estimated differences deduced from the analysis scheme. Therefore, it would again appear that the results of the drift analysis scheme are valid and that the Oceanographer Type 1 system did not display a linear drift between IC2 and IC3A.

The estimated drifts for the Dallas Type 2 appear to be quite reasonable with respect to the intercomparison results as do those for the Quadra Type 2, except for IC1. As was seen for the Quadra Type 1 system the results of IC1 for that particular ship appear to be questionable. In EDS 25 a drift estimate of 0.1 mb was obtained for Phase I for the Quadra Type 2 system, a result which agrees with those shown in Fig. 7. The Vanguard did not participate in any intercomparisons, but the drift analysis results displayed in Fig. 7 are consistent with those obtained in EDS 25. This

ship used a sensor during Phase III which was different from the one used during the first two phases. Since it did not take part in an intercomparison, one can especially see the need for this drift analysis procedure in estimating the drift for this ship.

The results displayed in Figs. 5-7 strongly support the hypothesis that the drift analysis scheme can successfully and accurately estimate the drift in the pressure systems during the observation phases. In most cases the drift estimates during the phases were consistent with the intercomparison estimates. In those cases where they disagreed, other evidence was presented which supported the results of the drift analysis. It was seen in several cases that corrections based solely on the intercomparison estimates could cause errors of up to 1.0 mb in the pressure data. Thus, one can conclude from this comparison of phase and intercomparison drift estimates that the drift analysis procedure is quite effective when applied to the output of pressure measurement systems.

In order to provide further proof that the analysis scheme is effective, the drift estimates for Type 1 and Type 2 systems aboard the same ship were compared with the actual differences between the measurements made by the two systems. For each observation phase two separate drift analyses were performed with the Researcher Kollsman serving as the benchmark. The first used the Type 1 systems for the ships that possessed them (about one third of the ships) and the Type 2

systems for the remaining ships while the second employed Type 2 systems for all ships except the Researcher. Since the drifts found for most of the Type 1 and Type 2 systems aboard the same ship were quite different, if the value of the parabolic surface fit to the data changes from one analysis to the next one can conclude that the surface is being influenced by the drift. This is one of the possible errors discussed in the previous chapter which would reduce the effectiveness of the analysis scheme in accurately estimating the drift. In Table 2 the actual differences between 7-day averages of Type 1 and Type 2 pressure measurements made aboard the same ship during Phase III are compared with the model differences implied by two separate applications of the drift analysis scheme. It can be seen that even though the actual average measurements made by some of these systems differed by as much as 1.73 mb (Quadra), the model differences were virtually identical to the actual differences. Similar results were found for both Phases I and II. Thus, one can conclude that for the pressure data, the relative shape of the parabolic surface fitted to the averaged data is not influenced by the drifts themselves. The effect that drifts might have on the mean level of the surface is explored in Appendix D. Whether the surface actually represents the average meteorology can only be subjectively determined by examining phase and intercomparison drift estimates as was done for Figs. 5-7.

A final check upon the performance of the analysis scheme was made in the following way. Three interior ships

and one outer ship were given artificial drifts for Phase III and then drift analysis was performed. If the analysis

Table 2. A comparison of the actual differences (mb) between 7-day averages of Type 1 and Type 2 pressure measurements made during Phase III with those differences implied by the drift analysis.

Ship	A-actual			M-model (from drift analysis)				
	September							
	5	6	7	8	9	10	11	12
Quadra	A-1.73	-1.72	-1.68	-1.67	-1.64	-1.62	-1.62	-1.60
	M-1.74	-1.73	-1.69	-1.67	-1.65	-1.63	-1.62	-1.61
Oceanographer	A 0.97	0.98	1.00	1.06	1.09	1.15	1.18	1.20
	M 0.97	0.98	1.00	1.06	1.09	1.14	1.17	1.19
Gilliss	A 0.30	0.28	0.26	0.25	0.27	0.29	0.31	0.34
	M 0.29	0.27	0.25	0.25	0.27	0.29	0.31	0.34
Planet	A-0.07	-0.07	-0.06	-0.06	-0.06	-0.05	-0.04	-0.04
	M-0.07	-0.07	-0.06	-0.06	-0.06	-0.05	-0.05	-0.05
Dallas	A-0.64	-0.64	-0.62	-0.63	-0.61	-0.61	-0.61	-0.60
	M-0.65	-0.64	-0.62	-0.63	-0.62	-0.62	-0.63	-0.62
Meteor	A 1.40	1.43	1.45	1.44	1.43	1.39	1.37	1.38
	M 1.39	1.42	1.44	1.43	1.42	1.38	1.36	1.37

scheme were perfect one would expect to obtain for these ships new drift estimates which are the sum of the old estimates and the artificial drift. Fig. 8 displays the results of this experiment. The solid lines represent the result expected from a perfect analysis while the symbols denote the drift estimates produced by the analysis scheme when applied to the artificial data. For the three inner ships (Oceanographer Type 1, Vize, and Gilliss Type 1) the estimated drifts

agree quite closely with the expected result. For the outer ship (Poryv) the artificial drift was not detected at all. The Dallas Type 1 system did not have an artificial drift given to it and is typical of the other systems which were left unchanged. The new drift analysis produced negligibly different drift estimates for the unchanged systems. Therefore, as was implied by the simulation study described in Appendix A and explained by the regression analysis discussion in Appendix D, one cannot hope to estimate drifts in the outer ships. For this reason the drift analyses in this study were conducted only for the inner ships.

Thus, we can conclude from the subjective analysis of results displayed in Figs. 5-7 and the two verification schemes (Table 2 and Fig. 8), that the drift analysis scheme is quite effective when applied to pressure data collected by the inner ships. For many systems the estimated drifts during the observation phases could reasonably be represented by linear interpolation between intercomparison estimates. However, several ships were found to display totally different behavior during the phases themselves. In any case the relative accuracy of the pressure data collected during the GATE observation phases can be greatly improved due to the results of this analysis.

Wet-bulb Temperature

Just as was done for the pressure measurement systems, hourly observations of both Type 1 and Type 2 wet-bulb

temperature measurement systems were used in this analysis. For the wet-bulb temperature and the remaining four variables to be investigated an hourly observation for a Type 1 system consists of a 10-minute average ending on the hour. On every ship except the Quadra wet-bulb temperatures were measured directly. The Type 1 sensors were either thermistors or platinum resistance wires covered with a muslin wick. On the Quadra the Type 1 data were acquired using a dew-point hygrometer which measured the dew point directly. These dew points were then converted to wet-bulb temperatures. The Type 2 sensors on every ship were mercury-in-glass thermometers covered by a muslin wick. The Meteor buoy Type 1 moisture data were in the form of specific humidity and also were converted to wet-bulb temperatures. Further details about the various measurement systems are contained in EDS 17 and Seguin, et al. (1977).

The Meteor buoy Type 1 measurement system was used as the benchmark for IC1, IC2, and IC3B. The Oceanographer Type 1 system served this purpose for IC3A. The results of IC1 and IC2, in which the Oceanographer intercompared with the Meteor buoy, indicate less than a 0.1°C difference between these sensors. Thus, as was done for the pressure data, a particular system, namely the Meteor Type 1, will be used as the benchmark in order to relate the results of the drift analysis to the intercomparisons.

The drift analysis procedure was applied to the wet-

bulb data using averaging periods of various lengths. After subjectively examining the resulting analyses, a 7-day averaging period was chosen. This length was the shortest one which produced reasonably smooth drift estimates from one day to the next. Wherever possible, subject to the limitations of data availability or data quality, drift estimates for the inner ship positions were determined for the three observation phases. The results of this analysis are compared with the intercomparison results in Figs. 9-11. Before discussing these figures in detail some general comments about the wet-bulb intercomparison results in EDS 17 are in order. First, none of the Type 1 or Type 2 measurement systems were found to drift significantly from intercomparison to intercomparison. All of the wet-bulb temperatures measured by the ships were found to be higher than those measured by the buoy with the Type 2 measurements being higher than the Type 1. However, during IC3B the Gilliss Type 1 observations were abnormally high due to a problem with the wick drying out. This must be considered when the drift and intercomparison estimates are compared.

In general one can see in Figs. 9-11 that the estimated drifts during the observation phases agree fairly well with linear interpolation between the intercomparisons. In fact as seen in Fig. 11 during Phase II the Meteor Type 2 drifts, which are simply the actual average differences between its measurements and those of the benchmark, deviate about as

much as any from the intercomparison results.

In Fig. 9 the problem mentioned previously about the Gilliss Type 1 measurements can be seen. During Phase III the drift estimates are approximately -0.2°C which agrees with IC1 but not IC3B where problems were encountered with the wick drying out. It is interesting to note that the difference between the drift estimates for the Gilliss Type 1 and Type 2 systems during IC1 is almost the same as those displayed in Phase III while during Phase I the difference is much smaller as it was for IC3B. This suggests that the Gilliss Type 1 may have also experienced wick problems during Phase I.

The drift estimates for some of the ship systems changed appreciably within a particular phase. For example, as shown in Fig. 9 the estimates for the Oceanographer Type 2 decreased about 0.4°C from the beginning of Phase I to the end while those for the Vize shown in Fig. 10 decreased nearly 0.5°C during the same period. Unfortunately, in situations like this it is hard to verify whether these changes are real or are due to the inability of the parabolic surface to fit the average meteorology. Since these ships were not located in the same position, it is not likely that these drifts were caused by the aforementioned model fitting problem. Furthermore, the difference between the drift estimates for the Oceanographer Type 1 and Type 2 systems changed from about 0.3°C to about 0.5°C during Phase

I, a change which was substantiated by an examination of the actual differences of the two measurements made aboard this ship. This problem points out the need for having intercomparisons immediately before and after an observation phase since the results of such intercomparisons would permit one to assess the reliability of the drift estimates.

In Fig. 10 the phase estimates for the Vanguard are displayed. This ship did not take part in an intercomparison but the results shown here compare quite well with those obtained by Seguin in EDS 25. In Fig. 11 it can be seen that the Bidassoa drifted nearly 1.0°C during Phase III but that the estimated drifts do not agree at all with IC3B. However, this intercomparison result is suspect since the standard deviation of the differences during IC3B between the Bidassoa and Meteor Type 1 measurements was 0.64°C . This was more than twice the value of typical standard deviations found during the intercomparisons. Furthermore, for Phase III Seguin estimated the drift for the Bidassoa to be -1.3°C , a value which roughly agrees with the drifts estimated at the center of the phase using the analysis scheme. The Type 1 dew-point sensor aboard the Quadra, from which the wet-bulb temperatures were derived, dried out between July 9 and July 13 (EDS 25). The result of this can be seen in Fig. 11 where the Phase I drift estimates show the marked decrease one would expect due to this problem.

On the whole a comparison of phase and intercomparison

estimates of the drift in wet-bulb measurement systems indicates that the drift analysis scheme is successful. A question was raised about estimated drifts during Phase I which really can't be answered given the intercomparison schedule of GATE. This points out the need in the future for intercomparisons to be held both immediately before and after the observation phases. In almost every case the results shown in Figs. 9-11 are in agreement with those contained in EDS 25. Apart from a few exceptions one can conclude that for the wet-bulb systems the drifts during the observation phases correspond fairly well with those found from the intercomparisons.

Just as was done for the pressure measurement systems, the drift estimates for Type 1 and Type 2 systems aboard the same ship were compared with the actual difference between the measurements made by the two systems. The analysis was conducted exactly as it was for the pressure data and the results for Phase I are displayed in Table 3. These results are typical of those found in the other two phases. The agreement between the actual and model differences shown in Table 3 is not as good as those shown in Table 2 for the pressure data but is still quite good. The reason for this is discussed in Appendix D. Typical disagreement in Table 3 is about 0.03°C while the largest is 0.07°C . Again, what this means is that the relative shape of the surface fitted to the averaged data is not greatly influenced by the themselves.

Table 3. A comparison of the actual differences ($^{\circ}\text{C}$) between 7-day averages of Type 1 and Type 2 wet-bulb measurements during Phase I with those differences implied by the drift analysis.

Ship	A - actual				M - model (from drift analysis)					
	July									
	3	4	5	6	7	8	9	10	11	12
Quadra	A 0.13	0.12	0.12	0.09	0.06	0.04	-0.01	0.00	-0.01	-0.01
	M 0.19	0.18	0.19	0.16	0.13	0.10	0.06	0.02	0.02	0.02
Oceanographer	A 0.32	0.31	0.32	0.36	0.41	0.43	0.48	0.51	0.54	0.57
	M 0.29	0.27	0.29	0.32	0.37	0.39	0.44	0.47	0.50	0.52
Researcher	A 0.36	0.37	0.39	0.41	0.44	0.47	0.45	0.44	0.46	0.45
	M 0.34	0.35	0.36	0.38	0.41	0.44	0.42	0.41	0.43	0.42
Gilliss	A 0.19	0.15	0.10	0.08	0.13	0.11	0.12	0.13	0.15	0.17
	M 0.18	0.15	0.10	0.08	0.12	0.11	0.11	0.12	0.14	0.16
Dallas	A 0.44	0.45	0.48	0.55	0.54	0.53	0.50	0.48	0.46	0.41
	M 0.41	0.42	0.45	0.51	0.50	0.49	0.45	0.44	0.41	0.37

Finally, three inner ship systems and one outer ship system were selected at random for each phase and artificial linear drifts were added to their output. The slopes of these drifts were also selected at random although they were limited in size so that the maximum change over a phase was about $\pm 0.5^{\circ}\text{C}$. Results similar to those displayed in Fig. 8 for the pressure data were obtained. In every case the drift analysis procedure was capable of detecting the drifts for the inner systems but was incapable of detecting the drift for the outer system. The drift estimates for the systems with no artificial drift were virtually unchanged.

Summarizing the results for the wet-bulb temperature measurement systems, we have seen that the analysis procedure is consistent when Type 1 and Type 2 measurement systems are analyzed separately. When artificial drifts are added to inner ship systems they can be accurately detected by the drift analysis scheme. A subjective comparison of the phase and intercomparison results shown in Figs. 9-11 indicate that although it does not appear as effective as it did for pressure systems, the drift analysis procedure is still quite capable of estimating wet-bulb measurement system drift during the observation phases.

Sea-surface Temperature

The hourly observations of Type 1 and Type 2 sea-surface temperature measurement systems used in this analysis were taken in the same manner as those for the wet-bulb

systems. All Type 1 data were acquired by thermistors except for the Quadra which used a radiometer. The Type 1 measurements by the Meteor buoy were made at a depth of 16 cm while all other Type 1 measurements were made at 10 cm. For the ships the thermistors were attached to a float secured to the bow. All Type 2 measurements were bucket temperatures taken off the fantails of the ships and measured with mercury-in-glass thermometers.

There were two problems encountered in making measurements that were peculiar to the sea-surface temperature systems. Normally, the superstructure of the ship acted as a sail moving the ship more rapidly than the current. However, in light wind conditions the ships were prone to become imbedded in pools of their own engine cooling water. This water was quite warm relative to the actual sea temperature and caused anomalously warm temperatures to be measured. The other source of error occurred whenever the sensor was pitched out of the water because of ship motion. This problem only affected the Type 1 systems and the resulting wet-bulb cooling effect caused erroneously cool temperatures to be recorded.

The Meteor buoy Type 1 system was used as the primary benchmark for the intercomparison analyses. However, the drift analysis indicated that it had significant drifts during Phases I and II because, when it was used as the benchmark, all other systems showed a mirrored image of those drifts. As a consequence, the use of the Meteor Type 1 as the bench-

mark was scrapped and an aggregate benchmark was used for both the phase and intercomparison estimates of the drift. The aggregate benchmark is a mythical system whose drift estimate at a given time is simply the average of the drift estimates for that time of all other systems. All of the sea-surface temperature drift estimates are relative to this "system".

As was done for the two variables discussed previously, a proper length averaging period was chosen. For the sea-surface temperature systems a 5-day averaging period was found to provide acceptable results. Using this averaging period the drift analysis procedure was employed and its results are shown in Figs. 12-14. One can see in Fig. 12 that the drift estimates for both Meteor systems during Phase III agree quite well with the lines connecting those for IC2 and IC3B. Those for the beginning of Phase I and the end of Phase II correspond closely to the results for IC1 and IC2, respectively. However, the fact that during the first two phases the drift pattern is the same for the Meteor buoy (Type 1) as well as the ship (Type 2) is suspicious and may indicate that this apparent drift is actually meteorology that could not be modeled by the parabolic surface. Again, this is a question which could only be answered if inter-comparisons had been held immediately after Phase I and before Phase II.

The phase and intercomparison results shown in Fig. 12

for both Oceanographer systems are in good agreement while those for the Quadra systems warrant special discussion. During Phase II the drift estimates for both Quadra systems show marked changes and yet by the end of the phase both correspond closely to the estimates for IC2. At the start of Phase II the drift for the Type 2 system was about 0.2°C greater than that for the Type 1 system. At the end of Phase II the opposite was true. The estimated differences between the output of these systems corresponds almost exactly to the actual differences. Thus, the drift analysis procedure provides the correct relative drift between these systems. Certainly, for these systems a linear correction based on interpolation of intercomparison results would not be appropriate for Phase II.

It can be seen in Fig. 13 that during Phase I the drift estimates for both Researcher systems display a marked decrease followed by an increase. The fact that both systems show such a pattern leads one to believe that the parabolic surface is not accurately modeling the meteorology. A check of the actual ship data itself confirms this. During the middle stages of Phase I both sensors aboard the Researcher recorded higher sea-surface temperatures than did any of the surrounding ships. Since this pattern was not present in any other ship, it was not reflected in the parabolic surface fit to the ship data. Thus, it was treated as drift rather than actual meteorology. It is not known whether these higher

sea-surface temperatures are an indication of a relatively small area of warm sea water or the result of the Researcher engine cooling water. In any case this type of occurrence, wherein one ship senses a peculiar signal, is identified by the drift analysis scheme so that one might take a closer look at the data for that time in order to ascertain the reason for the anomaly.

Other than the aforementioned period during Phase I and the last part of Phase III, the drift estimates for both Researcher systems are consistent from phase to intercomparison. One can also see in Fig. 13 that during Phases II and III the estimated drifts for the Vize closely follow the interpolated intercomparison results. Whether the Phase I drifts for that ship are real or the result of model inadequacy cannot be determined. In this case the results of drift analysis do not agree with those obtained in EDS 25. There Seguin's hand analysis of the average sea-surface temperature field for Phase I indicates a very strong gradient in the vicinity of the Vize. Such a gradient could not be modeled by a parabolic surface, thus accounting for the difference between the two analyses. In order to determine which drift estimate, if any, is accurate, an intercomparison immediately after Phase I would have been necessary.

The Vanguard did not participate in any intercomparison, but its drift estimates in Fig. 13 are consistent with those found in EDS 25. The drift estimates for both Dallas systems

at the end of Phase II and for all of Phase III agree quite well with those for IC2. The actual differences between the two systems aboard the Dallas during Phase II are almost exactly the same as those implied by the drift analysis. The results of IC1 for the Dallas Type 1 system are considered questionable since the temperatures measured showed no variability (EDS 17). For the Type 2 system the drift estimates for Phase I are in reasonable agreement with the line connecting the estimates for IC1 and IC2.

The estimated drifts shown in Fig. 14 for the Gilliss Type 1 system during Phases I and III agree almost exactly with the intercomparison estimates. Those for the Type 2 system do not agree nearly as well but the actual differences between these two systems are accurately depicted by the estimated drifts. The results for the Fay agree well with those for IC3A while the downward trend in drift for the Bidassoa tends toward the intercomparison result. The Phase III and IC3A drift estimates for the Planet Type 2 do not agree well at all. However, it was indicated in EDS 17 that during the third intercomparison period when the winds were quite calm, ships were more likely to remain in warm pools of water produced by engine cooling. This might account for the difference in this case.

A subjective comparison of the phase and intercomparison drift estimates for the sea-surface temperature measurement systems does not support the effectiveness of the drift

analysis procedure as strongly as those made for the pressure and wet-bulb systems. In some cases the phase and intercomparison results were consistent and in certain others, where they disagreed, evidence was presented to support the results of drift analysis. However, in too many cases it became painfully obvious that one could not truly determine whether the drift estimates were right or wrong given the intercomparison schedule of GATE.

The drift estimates for Type 1 and Type 2 systems aboard the same ship were compared with the actual differences between the measurements made by the two systems. The results for Phase II, which are typical of those found for Phases I and III, are shown in Table 4. For the sea-surface temperature systems the agreement between the actual and model differences is better than for the wet-bulb systems but not quite as good as the pressure systems. One can see in this table the relative change in the drift between the two Quadra systems that was described in the previous discussion of Fig. 12. From Table 4 one can also conclude for the sea-surface temperature data that the surface-fitting portion of the drift analysis procedure is not adversely influenced by the drifts themselves.

Using the random procedure described in the last section for the wet-bulb systems, an artificial drift analysis was conducted for the sea-surface temperature systems. The results so obtained were similar to those found for the pressure and wet-bulb systems. The random artificial drifts

Table 4. A comparison of the actual differences ($^{\circ}\text{C}$) between 5-day averages of Type 1 and Type 2 sea-surface temperature measurements made during Phase II with those differences implied by the drift analysis.

AUGUST 1964												
		A - actual				M - model (from drift analysis)						
		August										
Ship		2	3	4	5	6	7	8	9	10	11	12
Quadra	A	-0.24	-0.24	-0.17	-0.09	-0.05	-0.02	0.09	0.17	0.21	0.23	0.23
	M	-0.21	-0.21	-0.14	-0.07	-0.03	0.00	0.10	0.17	0.20	0.22	0.22
Oceanographer	A	-0.02	-0.06	-0.09	-0.04	-0.02	-0.01	0.03	0.08	0.05	0.07	0.06
	M	-0.01	-0.05	-0.08	-0.03	-0.02	-0.01	0.02	0.07	0.04	0.05	0.05
Dallas	A	0.25	0.24	0.27	0.30	0.30	0.29	0.26	0.22	0.18	0.14	0.09
	M	0.24	0.23	0.26	0.28	0.29	0.28	0.24	0.21	0.17	0.13	0.09
Meteor	A	-0.09	-0.09	-0.09	-0.07	-0.07	-0.05	-0.07	-0.06	-0.09	-0.10	-0.13
	M	-0.07	-0.07	-0.07	-0.06	-0.06	-0.04	-0.06	-0.06	-0.09	-0.11	-0.14

could be recovered when they were added to an inner ship but not when they were added to an outer one, and the drift analysis remained virtually the same for ships which had no artificial drift added to their output.

In conclusion, it was shown that the drift analysis procedure was subject only to errors caused by the inability of the parabolic surface to accurately model the meteorology. Artificial drifts could be detected and accurately determined when added to inner ship positions without degrading the drift estimates for other ships. A subjective comparison of phase and intercomparison drift estimates still supported in many cases the hypothesis that the drift analysis scheme was successful but pointed out more than ever the need for proper intercomparison scheduling in order to validate such results. Finally, the drift analysis scheme was found to be useful in pointing out anomalous situations where only one measurement system records a phenomenon. Such instances can then be more fully investigated to determine their probable cause.

Dry-bulb Temperatures

In spite of the ease with which dry-bulb temperature measurements can be made, good accuracy is difficult to achieve. Roll (1965) examined many of the difficulties of making precise measurements of meteorological variables at sea aboard large research vessels and found that an important problem is the effect of ship heating upon temperature

measurements. Seguin and Garstang (1971) showed that instrumentation mounted on bow booms suffers least from this effect. This finding is supported by examining Type 1 and Type 2 measurements of dry-bulb temperature made aboard the GATE ships. Table 5 summarizes the results of computing day and night averages for the various systems aboard the GATE ships during Phase III. It can be seen in this table that except for the Researcher, none of the Type 1 dry-bulb measurement systems showed the effects of daytime heating while all of the Type 2 systems did (some much more than others). Except for the Meteor buoy all Type 1 dry-bulb measurements were made from a boom on the ship's bow. Aboard the Quadra these measurements were made with a thermistor, which was part of a dew-point hygrometer. Aspirated and radiation shielded platinum resistance wires were used aboard the Planet and on the Meteor buoy. The other four Type 1 systems employed aspirated and shielded thermistors. On the other hand all Type 2 dry-bulb temperatures were measured with mercury-in-glass thermometers on the bridge of the ships. The Soviet ships employed 2.5 m booms designed to hold the sensors away from the windward side of the bridge in order to minimize the ship heating effect. As one can see in Table 5 this probably helped since the Soviet ships typically display less difference between day and night averages than the other Type 2 systems do. The effects of ship heating are graphically illustrated in Fig. 15 where observations for the Oceanographer

Table 5. Phase III day (08Z - 19Z) and night (20Z - 07Z) average dry-bulb temperatures (°C) for both Type 1 (*) and Type 2 systems.

Ship	No. of Obs.	Day	No. of Obs.	Night
Korolov	240	26.44	228	26.02
Poryv	240	26.17	228	26.03
Krenkel	240	25.87	228	25.50
Zubov	240	25.93	228	25.61
Musson	240	25.91	228	25.73
Okean	204	25.70	192	25.61
Priboy	204	26.40	192	25.92
Meteor	228	25.84	216	25.72
Meteor*	192	25.77	180	25.80
Vize	240	25.94	228	25.65
Vanguard	240	26.88	228	26.07
Quadra	216	26.11	204	25.83
Quadra*	192	25.67	180	25.77
Oceanographer	240	26.44	228	25.81
Oceanographer*	228	25.73	216	25.63
Researcher	240	26.25	228	25.43
Researcher*	240	25.87	228	25.52
Bidassoa	240	26.15	228	25.90
Gilliss	240	26.17	228	25.77
Gilliss*	228	25.97	216	25.95
Planet	240	26.10	228	25.98
Planet*	156	25.50	144	25.76
Dallas	240	26.40	228	25.89
Dallas*	228	25.61	216	25.53
Fay	216	25.70	204	25.59
Hecla	240	25.62	228	25.39

Type 1 and Type 2 systems can be seen to differ by more than 2°C. This phenomenon is most noticeable on sunny days but its intensity is a function of wind speed as well as cloud cover. Since cloud cover and wind speed vary from day to day, this phenomenon is non-stationary. Furthermore it will contaminate drift estimates produced by the analysis scheme since it will be falsely treated as instrument error. In order to combat this problem only night (20Z - 07Z)

averages will be employed in the drift analysis scheme.

To further complicate the analysis of the dry-bulb systems, the passage of tropical disturbances with their associated squall lines and thunderstorms had the most drastic effect upon the measurements made by those systems. The effect upon the measurement of dry-bulb temperature aboard the Oceanographer of the passing of two such disturbances is shown in Fig. 16. Between 18Z and 21Z on September 11 the temperature dropped almost 6°C then slowly recovered until 12Z September 12 when it began a second rapid drop of over 4°C . The changes recorded by the wet-bulb and sea-surface temperature systems were not nearly as pronounced. The large disturbances may be detected by a number of ships, but at different times and with different intensities. At other times a disturbance may only be observed by one or two of the ships. In the latter case the effect upon the drift analysis is similar to that illustrated in Fig. 13 for the Researcher sea-surface temperature systems where that particular ship was the only one to measure a warm pool of water. That is, the drift analysis procedure will regard the disturbance as drift due to the inability of the parabolic surface to fit such strong, local differences in the meteorology. Since the occurrence of disturbances was quite frequent during the observation phases of GATE, their effects must be removed before accurate drift estimates for the dry-bulb systems can be determined.

In order to make feasible the removal of the disturbance

effects from over twenty measurement systems, each of which obtained nearly 1500 hourly observations over the course of the GATE, an automatic screening procedure was developed. First, the distribution of the dry-bulb measurements for each system was investigated. For each system and observation phase the mean of the night (20Z - 07Z) measurements was computed. Only the night measurements were used so that the ship-heating effects present in the Type 2 systems would not distort the analysis. For each system the number of observations within 0.4°C intervals on both sides of the mean were determined. The distribution of the 5561 night observations made during Phase III is shown in Table 6. The interval 1R has the mean of each system as its lower bound and a value 0.4°C greater than the mean as its upper bound while the interval 1L has the mean as its upper bound and a value 0.4°C less than the mean as its lower bound. The interval 2R has a value 0.4°C greater than the mean as its lower bound and a value 0.8°C greater than the mean as its upper bound and so on. One can see in Table 6 that the peak in the distribution

Table 6. The distribution of Phase III dry-bulb observations (20Z - 07Z).

Interval	<4L	4L	3L	2L	1L	1R	2R	3R	4R	>4R
Number of Observations	302	232	393	530	855	1279	1096	713	164	7

function occurs at a point greater than the mean of the observations. The distribution function decreases in value quite

rapidly to the right of this peak but very slowly to the left. This is caused by the occurrence of disturbances which only cause unusually cool temperatures to be measured. The modifying effect of the ocean environment prevents abnormally warm temperatures from being recorded. The right tail of the distribution function suggests that the undisturbed dry-bulb measurements may be normally distributed. The problem then becomes that of extracting the disturbed values which produce the non-normal left tail described by Table 6.

After examining the distribution function, mean, and standard deviation for each ship system for each phase, an objective criterion was decided upon. All dry-bulb temperatures more than 1.5 standard deviations less than the mean are assumed to be disturbed. When this criterion was applied to several of the dry-bulb data sets, it was found to work quite well whether a ship experienced many or few disturbances. Of course, some disturbed values were treated as undisturbed but the number was not excessive. However, all observations that are treated as disturbed actually are. Thus, an easily programmable method has been established which can be used to satisfactorily separate the large amounts of dry-bulb data collected into disturbed and undisturbed portions.

The drift analysis procedure was then applied to the dry-bulb data using 11-night averages of undisturbed values. Since an 11-night averaging period was required to produce reasonably smooth drift estimates, fewer estimates were made for each phase.

To further compound the problem of comparing the resulting phase and intercomparison drift estimates in Figs. 17-19 is the fact that only the Type 1 system intercomparison results are uncontaminated by the ship-heating effect. These are the only intercomparison values plotted in the figures.

The Meteor buoy Type 1 system served as the benchmark for IC1, IC2, and IC3B and serves the same purpose in this study. In Fig. 18 it can be seen that the drift estimates for the first two phases and intercomparisons agree very well for the Oceanographer Type 1 system, the benchmark for IC3A. However, during Phase III the drift estimates for this system are a little over 0.2°C greater than those made previously. Both the Quadra and the Planet took part in IC3A. It can be seen in Figs. 17 and 19 that the agreement between the Phase III and IC3A drift estimates for both of these systems is improved if the IC3A drift estimates are adjusted upward by that amount.

For the Researcher Type 1 system the drift estimates for Phases I and II can be seen in Fig. 17 to agree very well with the estimates for IC1 and IC2 while those for Phase III do not agree with those for IC2 and IC3B. It should be pointed out, however, that the third intercomparison period was plagued by sunny skies and light winds, conditions which amplify the ship-heating effect. Since Table 5 shows that the Researcher Type 1 system appeared to be the only Type 1 system during Phase III which suffered from this effect, the IC3B drift estimates for this system are probably too low. On the other hand the results

for the Gilliss Type 1 show agreement between the Phase III and IC3B drift estimates and disagreement between those for Phase I and IC1. What is pointed out by these two comparisons is that for the dry-bulb systems it is not only necessary that intercomparisons be conducted both immediately before and after an observation phase, but that intercomparison results themselves be subdivided into night and day averages so that information can be gained for systems with ship-heating problems.

In Figs. 18 and 19 it can be seen that, like the Researcher, the phase and intercomparison drift estimates for the Dallas, Oceanographer, and Quadra Type 1 systems compare quite well for the first two phases and intercomparisons and not as well for Phase III. The fact that for all of these systems the Phase III drift estimates are too high leads one to believe that a problem might lie in the benchmark system. In Fig. 18 it can be seen that the actual differences between the 11-night averages for the Meteor ship Type 2 system and the Meteor buoy Type 1 system do not change appreciably from phase to phase. However, in Fig. 19 one can see that the drift estimates for the Vize, a ship which during Phase III was located in almost the same position as the Meteor, are also markedly higher for Phase III than the first two phases. Thus, it may be possible that a systematic error was made in the archiving of the output of the two Meteor systems during Phase III.

Unfortunately, little more can be said about the results shown in Figs. 17-19 due to the lack of intercomparison estimates and the fact that the drift analysis performed in EDS 25 was contaminated by the effects of ship heating. In order to accentuate the dangers inherent in drift estimation without regarding the ship-heating effect the analysis procedure used in this study was applied to 13-day (08Z - 19Z) and 13-night (20Z - 07Z) averages of undisturbed Phase III dry-bulb data. The 13-day period was the longest one for which all ships had good data and was used so that the results could be compared with those obtained in EDS 25. The results of this analysis are listed in Table 7. As before the Meteor Type 1 system was used as the benchmark. From Table 7 one can see that the drift estimates subjectively determined using a hand analysis of the dry-bulb data averaged over Phase III without regard to ship heating or the effects of disturbances are in every case within 0.2°C of the average of the day and night drift analyses. What is important is that for certain ships, misleading drift estimates are obtained due to the ship-heating effect. For example, Seguin estimated drifts of -0.3°C , -0.4°C , and -0.6°C for the Oceanographer, Dallas, and Vanguard Type 2 systems. These estimates are 0.3°C to 0.4°C different from those obtained using the night averages due to the strong ship-heating problem aboard those ships. Since this effect is not drift but a non-stationary phenomenon, these drift correction estimates are in error and, if used to correct

the data from these systems, would in turn result in erroneous data.

Table 7. A comparison of Phase III dry-bulb system drift estimates ($^{\circ}\text{C}$) using 13-day and 13-night averaging periods with those obtained by Seguin, et al. (1978).

Ship	Day	Night	Seguin, <u>et al.</u>
Researcher 1	-0.2	0.1	0.1
Researcher 2	-0.6	0.2	-0.1
Oceanographer 1	0.1	0.1	0.2
Oceanographer 2	-0.6	0.0	-0.3
Quadra 1	0.1	0.0	0.0
Quadra 2	-0.2	0.0	-0.2
Dallas 1	0.3	0.2	0.2
Dallas 2	-0.5	-0.1	-0.4
Planet 2	-0.3	-0.1	-0.1
Gilliss 1	0.0	-0.1	0.0
Gilliss 2	-0.3	0.0	-0.1
Vize	-0.1	0.1	0.2
Vanguard	-0.8	-0.2	-0.6
Bidassoa	-0.5	-0.2	-0.2
Fay	0.2	0.2	0.2

For the dry-bulb systems the actual differences between 11-night averages of undisturbed Type 1 and Type 2 measurements made aboard the same ship were compared with the differences implied by the drift analysis. The results for Phase I are typical of those for the other two phases and are listed in Table 8. The agreement between the actual and model differences in this table are comparable to that for the pressure

systems shown in Table 2. Thus, the surface-fitting portion of the drift analysis scheme is influenced very little by the measurement system drift at a particular ship position.

Table 8. A comparison of actual differences ($^{\circ}\text{C}$) between 11-night averages of undisturbed Type 1 and Type 2 dry-bulb measurements during Phase I with those differences implied by the drift analysis.

A -- actual		M - model (from drift analysis)				
		July				
Ship		6	7	8	9	10
Quadra	A	0.05	0.03	0.00	0.02	0.02
	M	0.05	0.03	0.01	0.02	0.02
Oceanographer	A	0.36	0.34	0.35	0.37	0.32
	M	0.34	0.32	0.34	0.36	0.30
Researcher	A	-0.17	-0.18	-0.16	-0.16	-0.16
	M	-0.18	-0.19	-0.17	-0.17	-0.17
Gilliss	A	-0.09	-0.12	-0.14	-0.15	-0.10
	M	-0.10	-0.13	-0.14	-0.16	-0.11
Dallas	A	0.46	0.45	0.45	0.47	0.45
	M	0.44	0.43	0.43	0.44	0.43

As was done for the previously discussed systems, an artificial drift analysis was conducted for the dry-bulb temperature measurement systems with similar results. The random artificial drifts were recovered when they were added to an inner ship while the drift analysis remained virtually unchanged for ships which had no artificial drift added. Drifts could not be detected when they were added to an outer ship.

In summary, the dry-bulb temperature systems presented

special problems which had to be solved in order to perform the drift analysis. The Type 2 measurement systems were found to be greatly influenced by the ship-heating effect. In order to counter this problem the drift analysis was performed using night averages. Unfortunately the intercomparison results presented in EDS 17 were not separated into day and night averages so that the estimates for the Type 2 systems were contaminated by this effect. Thus, only a subjective comparison of phase and intercomparison drift estimates for Type 1 systems could be made in Figs. 17-19. Of all the variables measured, the passage of weather disturbances had the most drastic effect upon the dry-bulb temperatures. In order to prevent these disturbances from producing anomalous drift estimates, only measurements undisturbed by weather were used in the averaging process. It was found necessary to use an 11-night averaging period, and, thus, fewer drift estimates were available for each phase. For most of the Type 1 systems the phase and intercomparison drift estimates agreed quite well until the final phase. During Phase III most of the drift estimates appeared too high, possibly pointing out a problem with the benchmark system. For future experiments it was discovered by this analysis that for the dry-bulb systems it is not only important that intercomparisons be scheduled immediately before and after each phase but also that day and night intercomparison averages be computed due to the ship-heating problem. Furthermore, it was seen in a comparison with drift estimates made by Seguin in EDS 25 that when no provision

is made for this effect, erroneous estimates of the drift are obtained.

Wind Speed and Direction

The problems involved in measuring wind speed and direction from a ship at sea are complex and interrelated. The measurements of these variables taken aboard ship are relative to the ship heading and speed. The absolute wind speed and direction can only be determined when the ship heading, speed, and direction of motion are known. For a drifting ship this direction of motion is not necessarily the direction of the ship heading. The heading data were derived from the main gyros of each ship and only the Dallas data presented any problems which required special treatment before the archived wind data could be computed (Seguin, et al., 1977). Ship velocities were derived from the navigation data since the ship speeds as measured by underwater sensors were of poor-to-useless quality. Although the quality of the relative wind speed and direction data measured aboard the ships was generally good, a study by Kidwell and Seguin (1978) upon the ship obstacle effect in which a comparison of boom and mast wind measurements aboard the U.S. ships was made points out still another problem area. The speed and direction differences between mast and boom wind measurements made aboard the same ship were found to show fluctuations which were dependent not only upon the relative wind speed and direction but also the atmospheric stability. Furthermore, these

fluctuations varied from one ship to the next. Thus, errors related to the relative wind direction and speed as well as the atmospheric-stability are imbedded in the archived wind data for each ship measurement system.

The Type 1 wind speed and directions were measured by cup anemometers and vanes mounted on the booms of the ships or on the Meteor buoy. All Type 2 wind measurements were taken from instruments mounted on ship masts. Cup anemometers and vanes were again used except for the Researcher, Gilliss, Dallas, Oceanographer, and Vanguard which used the Aerovane sensor. This sensor measures wind speeds by a propeller on the leading edge of the vane. Although these sensors were located at various heights, no height correction was made to the archived wind speed data. Further details about the sensors are available in Seguin, et al., (1977).

An 11-day averaging period was selected and the drift analysis procedure was applied to both the wind speed and wind direction data. Due to the 360° period of wind directions, a special averaging scheme was developed for that parameter. The details of this scheme are contained in Appendix C. The phase and intercomparison drift estimates for the wind speeds are compared in Figs. 20-22 while those for the wind directions are compared in Figs. 23-25. The Meteor Type 1 system was used as the benchmark for the wind speeds while the Oceanographer Type 1 system served the same purpose for wind directions.

One can see in Fig. 20 that for the first two phases the drift estimates for both Researcher wind speed measurement systems are in fairly close agreement with the lines connecting the estimates for IC1 and IC2. The same cannot be said for Phase III although the relative differences between the two systems implied by the drift analysis are almost exactly the same as the actual relative differences. The drift estimates for both Gilliss systems for Phase III are in good agreement with linear interpolation between the intercomparison results while those for Phase I are not.

The phase and intercomparison results do not correspond well at all for the Planet systems. However, this ship participated in IC3A in which the Oceanographer Type 1 system was used as the benchmark. One can see in Fig. 21 that during Phase III the drift estimate for that Oceanographer system is nearly 1.0 m/sec. If the results of IC3A for the Planet are adjusted upward by that amount, the Planet Type 1 system will show close agreement between Phase III and the intercomparison. The estimated differences between the two Planet systems shown here are substantiated by the actual differences, thus, pointing out the danger in automatically accepting intercomparison drift estimates as a good reflection of phase drift estimates.

In Fig. 21 only the Phase II drift estimates for the Dallas Type 1 system agree very well with linear interpolation between the intercomparison estimates. However, the actual

differences between the two types of measurements made aboard that ship are accurately depicted for all three phases by the drift estimates. This again questions the reliability of the intercomparison drift estimates. Furthermore, it is known that for the Dallas Type 1 system nearly half of the archived wind speed data collected between 06Z September 8 and 01Z September 18 were questionably low (Seguin, et al., 1977). As successive averaging periods incorporate more and more of these data, one would expect the drift estimates determined for that system to increase. As one can see in Fig. 21 for Phase III, this was indeed the case. The phase and intercomparison results for the Oceanographer do not agree well at all. The apparent agreement between the results of Phase III and IC3A for the Type 2 system is misleading. Since the Oceanographer Type 1 system served as the benchmark for IC3A, what is really shown in this figure is that the difference between the two systems changed from almost 1.0 m/sec to almost zero between the phase and intercomparison. This result can be substantiated by the actual differences themselves. Finally, in this figure it can be seen that for the Bidassoa the drift estimates at the end of Phase III correspond closely to the result for IC3B.

The Quadra, Fay, and Vize all intercompared with the Oceanographer during IC3A. One can see in Fig. 22 that if the results of IC3A are adjusted upward as mentioned previously, the agreement between the drift estimates at the end

of Phase III and those for IC3A will be greatly improved for each of the ships. For the Quadra Type 1 system the drift estimates for Phase II closely agree with the line between those for IC1 and IC2, but the differences between the two Quadra systems during the first two phases are much greater than those found for the first two intercomparisons. Again, these estimated differences are verified by the actual differences between the two systems. The reliability of the intercomparison results is further questioned by examination of the drift estimates for the Meteor Type 2 system. Since the Meteor buoy served as the benchmark in the drift analysis, the phase estimates displayed here are in reality the actual average differences between the two Meteor systems. One can see that the drift estimates for Phase I and IC1 are quite different. The phase drift estimates for the Vize during Phases I and II are consistently above the respective intercomparison estimates. Since the Vanguard did not take part in an intercomparison, little can be said about the results presented here.

The two verification schemes performed for the previously analyzed systems were also performed for the wind speed systems with similar results. For all three phases the estimated differences between 11-day averages of measurements made aboard the same ship are almost identical to the actual differences, and artificial drifts can be recovered only when they are added to inner ships with little change caused in the

estimated drifts of the unmodified systems.

In conclusion, it can be stated that of the systems examined so far in this study the intercomparison estimates of drift for the wind speed systems are the least reliable. Time and again in the discussion of Figs. 20-22 it was shown that the differences between Type 1 and Type 2 measurements made aboard the same ship implied by an intercomparison were quite different from those which were found during the observation phases. A possible explanation for this could be that the fluctuations in the differences between boom and mast wind speeds caused by changes in the relative wind speed, wind direction, and atmospheric stability (Kidwell and Seguin, 1978) are smoothed out by the 11-day averaging period used in the phase analysis. Since each intercomparison was only about three days long, the intercomparison averages may have included some of these fluctuations. In any case the unreliability of the intercomparison estimates makes it difficult to assess the ability of the analysis procedure in estimating the measurement system drifts. Certainly the relative drifts between Type 1 and Type 2 systems were preserved and a known drift during Phase III in the Dallas Type 1 system (see Fig. 21) was indicated. As the study by Kidwell and Seguin (1978) indicates, the errors in the wind speed measurement systems are quite complex suggesting that in the future more sophisticated intercomparisons with relative differences between systems categorized by both wind speed and direction along

with comparable phase observations are needed in order to obtain more satisfactory drift estimates than those found here.

Before discussing the drift estimates produced by the analysis procedure for the wind direction measurement systems, some comments must be made about the intercomparison estimates. First, the Meteor buoy Type 1 system which was used as the benchmark for IC1, IC2, and IC3B had possible changes in its calibration from one intercomparison to the next (EDS 17). Thus, the Oceanographer Type 1 system, which served as the benchmark for IC3A, was used for the same purpose in the drift analysis. Second, the intercomparison analysis also indicated that the quality of the estimated drifts steadily degraded from the first to the third intercomparison. For IC1 the standard deviation of the differences between each system and the benchmark was typically 20° . Typical values for the second and third intercomparisons were 40° and 60° , respectively. During IC2 a disturbance passed through the intercomparison array while the third intercomparison was conducted in light-wind conditions. Both factors contributed to the larger standard deviations found for those periods. Thus, the intercomparison results for the wind direction measurement systems are probably the least reliable of those utilized in this study.

In Fig. 23 the actual differences of 11-day averages between the Oceanographer Type 2 system and the benchmark system are plotted. One can see that at the beginning of

Phase I and for all of Phase III these differences agree with the lines connecting intercomparison estimates. From the results for Phase II and the end of Phase I it can be seen that large and rapid drift changes actually can occur for a system, and that large disagreements with the lines connecting intercomparisons results are possible. The rapid changes in the Quadra drift estimates during the first part of Phase I are due to a problem with the analysis procedure; similar changes for other systems can be seen in Figs. 24 and 25. During the first part of Phase I the 11-day averaged wind directions changed so much from one inner ship position to another that the parabolic surface was unable to provide an adequate model of the average meteorological field. By the end of the phase this problem was alleviated. For example, as shown in Fig. 1 the Quadra was positioned about 90 nm north of the Meteor. The first 11-day average wind direction used in this analysis for the Quadra Type 1 system was 346° while that for the Meteor Type 1 system was 246° . The last averages used for these systems were 271° and 242° , respectively. Thus, the difference in average wind direction between the two systems dropped from 100° to 29° over the analysis period. Due to this surface-fitting problem the drift estimates at the beginning of Phase I are considered to be anomalous.

For the Quadra Type 2 system the drift estimates at the end of Phase I and for Phases II and III loosely correspond to the lines connecting the intercomparison estimates. It

should be pointed out that Type 2 wind directions were only measured to the nearest 10° so that differences in these figures are blown up more than those shown in the previous figures. For example, pressure was measured at least to the nearest 0.1 mb and the labeling interval for the pressure figures was 0.5 mb. In these figures the labeling interval is only twice as large as the increment of measurement. The differences between the Quadra systems implied by the drift analysis during the phases (including the large difference for the first estimate of Phase I) are all substantiated by the actual average differences. The unreliability of the intercomparison estimates is pointed out by the large difference between the two systems during IC2, although, as was seen in Phase I large changes between the two systems can occur very rapidly. The results for the last two phases and intercomparisons are in remarkable agreement for the Vize. Unfortunately, the same cannot be said for IC1 and Phase I. The Fay occupied roughly the same position as the Dallas did during Phase III and its drift estimates are consistent with the actual differences between its measurements and those made by the Dallas.

In Fig. 24 it can be seen that the drift estimates for both Dallas systems for Phases II and III are in reasonable agreement with that for IC2 while those at the end of Phase I appear to be too low when compared with the lines connecting the intercomparison estimates. The estimated drifts for both Meteor systems at the end of Phase I and during Phase II

correspond fairly well with linear interpolation between IC1 and IC2 while those for the Type 2 system during Phase III are in good agreement with the intercomparison results. Little can be said about the Vanguard or Bidassoa since no intercomparison information was available and a drift analysis for the wind direction measurement systems was not performed in EDS 25.

The drift estimates for the Researcher Type 1 system during Phase II and for the Type 2 system during Phase III agree fairly well with the lines connecting intercomparison estimates shown in Fig. 25. For both Gilliss systems only the results of the third phase and intercomparison are in agreement. The Planet systems had no reliable intercomparison results upon which to base a comparison.

As was done for all other measurement systems, the two previously described verification schemes were applied to the wind direction systems with similar results. For all three phases the differences between Type 1 and Type 2 measurements made aboard the same ship estimated by drift analysis are virtually identical to the actual differences. Artificial drifts can be recovered when added to inner ships without degrading the drift estimates for unchanged ships. When added to an outer ship these artificial drifts cannot be recovered by the analysis procedure.

In summary it can be seen from these figures that there is little rhyme or reason to the intercomparison estimates. In

one intercomparison the drift in a Type 1 system aboard a ship may be much greater than that for the same ship's Type 2 system. The opposite may be true for the next intercomparison while the phase estimates in between may show a totally different relationship. Although in the discussion of these figures it was found in some cases that phase and intercomparison drift estimates were in good correspondence, the nature of the intercomparison estimates makes it difficult to place much confidence in such results. It was seen in the early part of Phase I that the wind direction data were the first in which serious problems were encountered in fitting a parabolic surface to the average meteorology. This combined with the previously mentioned unreliability of intercomparison results makes it virtually impossible to assess the capabilities of the drift analysis procedure. The same problems that Kidwell and Seguin (1978) found for the wind speeds also existed for the wind directions. Thus, it is likely that in order to make satisfactory drift estimates for the wind direction systems in the future both phase and intercomparison observations must be categorized according to wind speed and direction relative to the ships themselves. The drift analysis scheme presented in this study can not be shown to provide accurate estimates of wind direction measurement system drift although it does preserve the relative drifts between Type 1 and Type 2 systems aboard the same ship.

CHAPTER V

SUMMARY AND CONCLUSIONS

During the late 60's and early 70's the use of field intercomparisons as a technique to determine the error content of data collected by meteorological measurement systems had developed to the extent that such comparisons became an integral part of both the ship and aircraft operations in GATE. From an intercomparison one can gain information about the noise content and can estimate the relative biases among the various systems. During GATE the estimated relative biases for many of the ship measurement systems were found to show changes from intercomparison to intercomparison greater than the desired accuracy specified by the Convection Subprogram prior to the experiment. This indicated that certain systems possessed very low frequency noise or drift which must be determined before their output can be useful for later meteorological studies.

In order to determine the nature of the drift in ship measurement systems between the intercomparisons, an analysis scheme was developed and tested on simulated data. The output of each ship system is filtered to pass only very low frequency

noise and meteorological signal. A parabolic surface is then fitted to the filtered values for the various ships as they maintain their stations in the GATE array, and the differences between the surface and the filtered values are taken as estimates of the drift. The procedure was tested upon simulated data sets in which known drifts were assigned to certain ships and was found to be quite successful at estimating these drifts for systems aboard ships occupying interior positions in the GATE array.

Before the drift analysis scheme could be applied to the ship surface data collected during GATE, the problem of missing or erroneous data had to be dealt with. An interpolation scheme based on autoregressive modeling was developed in order to fill data gaps due either to poor data quality or the temporary absence of a ship from its station. This scheme was employed prior to the application of the drift analysis procedure in order to provide as extensive a data base as possible.

The analysis scheme was employed to estimate the drifts in ship systems measuring pressure, wet-bulb temperature, sea-surface temperature, dry-bulb temperature, wind speed and wind direction. There were two types of possible error inherent in the analysis scheme: the first due to the inability of a parabolic surface to accurately model the average meteorology; the second due to the influence of the drift in each measurement system upon the surface to be modelled. The presence of the first type of error could only be revealed by a subjective

comparison of phase and intercomparison drift estimates. Although such errors occasionally were noted for the first five variables, the only serious occurrence was found for the wind direction systems during the first part of Phase I. For all the variables measured the second type of error was found to be virtually nonexistent when actual and model differences of measurements made aboard the same ship were compared.

For the pressure measurement systems the drift estimates were found to be excellent. Furthermore, it was seen that if only intercomparison estimates of drift were available, pressure corrections in error by as much as 1.0 mb would have been determined during the observation phases. The analysis scheme was also found to be quite successful in estimating the drifts for the various temperature measurement systems. Again, numerous cases were found where significant errors would have been caused by making corrections based only on intercomparison results. Due to the nature of the data and the unreliability of the intercomparison estimates, it was impossible to accurately assess the ability of the analysis scheme to estimate drifts in the wind speed and direction measurement systems.

In the course of performing these analyses much insight was gained about how an experiment should be designed in order to best estimate measurement system drifts. Many times trends were indicated in the drift in a certain system within an observation phase that could not be verified because the phase did not begin

and end with an intercomparison. In order to determine the reliability of drift estimates obtained using this analysis scheme, it is important that each observation phase be immediately preceded and followed by an intercomparison period. Furthermore, due to the pronounced ship-heating effect found in many dry-bulb measurement systems, it is not only important that this effect be considered when drift analysis is performed but also that dry-bulb intercomparison results be subdivided into day and night categories. Finally, it is suggested that the intercomparison and phase wind observations be categorized by speeds and directions relative to the ship speed and heading so that the relationship between these categories and measurement system drift can be determined.

In conclusion, it was seen in this study that the drift analysis procedure provided much information about the error content of systems measuring pressure and the various temperature variables that is otherwise unavailable. Little success was found in the analysis of the wind data. It was seen that during GATE the intercomparison drift estimates provided the most effective way of determining the reliability of the phase drift estimates. Clearly, the intercomparison results could be used to much better advantage in the future if they are routinely conducted as an integral part of each observation phase.

BIBLIOGRAPHY

- Aanensen, C. J. M., 1974: The aircraft operations plan. Section I of the GATE Aircraft Plan. GATE Rept. No. 11, ISMG, WMO, Geneva.
- Akaike, H., 1969: Fitting autoregressive models for prediction. Ann. Inst. Statist. Math., 21, 243-247.
- Burg, J. P., 1967: Maximum entropy spectral analysis. Paper presented at the 37th Annual International Meeting, Soc. of Explor. Geophys., Oklahoma City, Oklahoma.
- _____, 1968: A new analysis technique for time series data. Paper presented at Advanced Study Institute on Signal Processing, NATO, Enschede, Netherlands.
- Draper, N. R. and H. Smith, 1966: Applied Regression Analysis. John Wiley and Sons, Inc., New York, 407 pp.
- Duchon, C. E., 1968: Techniques for evaluating meteorological aircraft data. Atmospheric Science Group Report No. 9, College of Engineering, The University of Texas at Austin.
- _____, 1972: Interaircraft calibration experiment. Final Report, Subcontract NCAR 183-71, Dept. of Meteor., University of Oklahoma.
- Duchon, C. E. and J. S. Goerss, 1976a: Variance spectrum analysis of aircraft dew-point measurement system noise. J. Appl. Meteor., 15, 77-93.
- _____, 1976b: Noise and bias analyses of dry bulb, wet bulb and pressure from selected GATE ships during Intercomparison Period II. Rept. No. DEC-1-76, Dept. of Meteor. University of Oklahoma.
- Durbin, J., 1960: The fitting of time series models. Rev. Int. Inst. Stat., 28, 233-244.

- Godshall, F. A., W. R. Seguin, and P. Sabol, 1976: Analysis of ship surface meteorological data obtained during GATE intercomparison periods. NOAA Technical Report EDS 17, Washington, D. C.
- Goerss, J. S., 1975: Evaluation of a simultaneous equations technique for the determination of aircraft measurement system noise. Masters Thesis, Dept. of Meteor., University of Oklahoma.
- _____, 1977: An improved method for the determination of measurement system noise. J. Appl. Meteor., 16, 989-991.
- Holland, J. Z. and D. T. Acheson, 1973: Observation system intercomparison-examples from BOMEX. IEEE Trans. Geosci. Electron., GE-11, 101-109.
- Kidwell, K. B. and W. R. Seguin, 1978: Comparison of mast and boom wind speed and direction measurements on U.S. GATE B-scale ships. NOAA Technical Report EDS 28, Washington, D. C.
- Jones, R. H., 1964: Prediction of multivariate time series. J. Appl. Meteor., 3, 285-289.
- Lindgren, B. W., 1976: Statistical Theory. Macmillan Publishing Co., Inc., New York, 614 pp.
- List, R. J., 1949: Smithsonian Meteorological Tables. Smithsonian Institution Press, Washington, D.C., 527 pp.
- Rodenhuis, D. and A. Betts, 1974: The convection subprogram for GATE. GATE Rept. No. 7, WMO, Geneva.
- Roll, H. U., 1965: Physics of the Marine Atmosphere. Academic Press, New York, 426 pp.
- Seguin, W. R. and M. Garstang, 1971: A comparison of meteorological sensors used on the USCGSS Discoverer during the 1968 Barbados Experiment. Bull. Amer. Meteor. Soc., 52, 1071-1076.
- Seguin, W. R., P. Sabol, R. Crayton, R. S. Cram, K. L. Echternacht, and M. Poindexter, 1977: B-scale surface meteorological and radiation system, including instrumentation, processing, and archived data. NOAA Technical Report EDS 22, Washington, D.C.
- Seguin, W. R., R. Crayton, P. Sabol, and J. W. Carlile, 1978: GATE Convection Subprogram Data Center: Final report on ship surface data validation. NOAA Technical Report EDS 25, Washington, D.C.

Shannon, J., 1973: Inter-instrument Calibration. Dept. of Meteor., University of Oklahoma.

Tarbeev, Y. V. and S. R. Petersen, 1974: Ship operations. Part II of the International Operations Plan. GATE Rept. No. 10, WMO, Geneva.

Ulrych, T. J. and T. N. Bishop, 1974: Maximum entropy spectral analysis and autoregressive decomposition. Rev. Geophys. Space Phys., 13, 183-200.

WMO, 1974: GATE international data management plan (Parts I, II, III). GATE Rept. No. 13, prepared by Terry de la Moriniere, WMO, Geneva.

Figure 1.--Ship array during Phase I.

Figure 2.--Ship array during Phase II.

Figure 3.--Ship array during Phase III.

Fig. 4. Flow chart of analysis procedure.

Fig. 5. Phase and intercomparison drift estimates for pressure measurement systems (Researcher Kollsman benchmark).

Fig. 6. Phase and intercomparison drift estimates for pressure measurement systems (Researcher Kollsman benchmark).

Fig. 7. Phase and intercomparison drift estimates for pressure measurement systems (Researcher Kollsman benchmark).

Fig. 8. Results of artificial drift analysis for pressure measurement systems during Phase III (Researcher Kollsman benchmark).

Fig. 9. Phase and intercomparison drift estimates for wet-bulb temperature measurement systems (Meteor Type 1 benchmark).

Fig. 10. Phase and intercomparison drift estimates for wet-bulb temperature measurement systems (Meteor Type 1 benchmark).

Fig. 11. Phase and intercomparison drift estimates for wet-bulb temperature measurement systems (Meteor Type 1 benchmark).

Fig. 12. Phase and intercomparison drift estimates for sea-surface temperature measurement systems (aggregate benchmark).

Fig. 13. Phase and intercomparison drift estimates for sea-surface temperature measurement systems (aggregate benchmark).

Fig. 14. Phase and intercomparison drift estimates for sea-surface temperature measurement systems (aggregate benchmark).

Fig. 15. A comparison of Type 1 and Type 2 temperature measurements made aboard the Oceanographer on 10 September, 1974.

Fig. 16. Oceanographer Type 1 temperature measurements, 10-12 September, 1974.

Fig. 17. Phase and intercomparison drift estimates for dry-bulb temperature measurement systems (Meteor Type 1 benchmark).

Fig. 18. Phase and intercomparison drift estimates for dry-bulb temperature measurement systems (Meteor Type 1 benchmark).

Fig. 19. Phase and intercomparison drift estimates for dry-bulb temperature measurement systems (Meteor Type 1 benchmark).

Fig. 20. Phase and intercomparison drift estimates for wind speed measurement systems (Meteor Type 1 benchmark).

Fig. 21. Phase and intercomparison drift estimates for wind speed measurement systems (Meteor Type 1 benchmark).

Fig. 22. Phase and intercomparison drift estimates for wind speed measurement systems (Meteor Type 1 benchmark).

Fig. 23. Phase and intercomparison drift estimates for wind direction measurement systems (Oceanographer Type 1 benchmark).

Fig. 24. Phase and intercomparison drift estimates for wind direction measurement systems (Oceanographer Type 1 benchmark).

Fig. 25. Phase and intercomparison drift estimates for wind direction measurement systems (Oceanographer Type 1 benchmark).

APPENDIX A

SIMULATED DRIFT ANALYSIS

In order to test the capabilities of the drift analysis procedure, a simulation experiment was developed to be applied to the GATE ship array in which a simple moving two-dimensional wave is used to represent a meteorological field. Using an M-day averaging period the errors in fitting a parabolic surface to the average field as a function of wavelength or period and phase angle for a given wave speed are examined. Then linear drifts are prescribed at selected ship positions and the estimated drift at each ship position is observed as a function of successive time steps.

Parabolic Surface Fitting Without Drift

Let $z_i^j(t)$ be the instantaneous value of a meteorological variable during the j-th M-day averaging time for the i-th ship with coordinates $[x_i(\text{deg}), y_i(\text{deg})]$. Then let

$$z_i^j(t) = (y_i - 8.5)/3.5 + \alpha \cos\left[\frac{2\pi}{\lambda}(x_i - 23.5) - \frac{2\pi c t}{\lambda} + \phi\right] + 25.0, \quad (\text{A.1})$$

where λ is the wavelength in degrees of the atmospheric wave,

c is the wave speed (deg/day) and φ is the phase angle. Eq. (A.1) is plotted in Fig. A.1 with $y_i = 8.5^\circ$, $\alpha = 0.575$, $\varphi = 0$, $t = 0$, and $\lambda = 28^\circ$. The form of Eq. (A.1) and the values used are intended to provide a measure of realism to the simulation.

If one lets $t = 0$ correspond to the mid-point of the M-day averaging time, then the formula for the M-day average is

$$\overline{z}_i^j = (y_i - 8.5)/3.5 + \beta \cos\left[\frac{2\pi}{\lambda}(x_i - 23.5) + \varphi\right] + 25.0. \quad (\text{A.2})$$

Furthermore, if $\lambda = 28^\circ$, $M = 2$ days, and $c = 4^\circ/\text{day}$, then β is about 87% of α (i.e., $\beta = 0.5$). With these conditions Eq. (A.2) is plotted in Fig. A.2, which represents a spatial plot of the two-day average of the wave shown in Fig. A.1 moving westward with a period $T = 7$ days ($cT = \lambda$). Calculations were made also for various values of φ .

Using $M = 2$ days additional simulations were carried out for $\lambda = 21^\circ$ (thus $\beta = 0.78 \alpha$ and $T = 3.5$ days). Values of $\overline{z}_i^j$ were determined for each ship position and, using linear regression techniques, a parabolic surface was fitted to each case. The differences between the surface and the $\overline{z}_i^j$ at each ship position were computed and were found to be greatest when $\varphi = 180^\circ n + 90^\circ$, $n = 0, \pm 1, \dots$. Table A.1 summarizes the results of the computations.

Now suppose Z represents ambient temperature. In order to discover a linear drift of 0.5°C over a span of 20 days,

Fig. A.1 Plot of Eq. A.1 for $y_1 = 8.5^\circ$, $\alpha = 0.575$, $\varphi = 0$, $t = 0$, and $\lambda = 28^\circ$.

Fig. A.2 Plot of waves characterized in Fig. A.1 using Eq. (A.2) in which $\beta = 0.5$, $\varphi = 0$, $\lambda = 28^\circ$ and $c = 4^\circ/\text{day}$, where a two-day averaging time is used.

then since there would be 10 independent two-day averaging times one would have to measure a drift change ΔD_1^j of 0.05°C with reasonable accuracy. It can be seen in Table A.1 that this would not be possible for a wavelength of 14° and a period of 3.5 days since at certain ship positions the part of the error term caused by the inability of the model to fit the atmospheric wave is greater than the difference in drift. The ability of the procedure to usefully measure ΔD_1^j for $\lambda = 21^\circ$ and $T = 5.25$ days is marginal while for $\lambda = 28^\circ$ and $T = 7$ days the error becomes sufficiently small so that one should be able to determine ΔD_1^j . If, in practice, the errors of fit are random across the time span of a phase then a low order polynomial may be fitted to the computed fluctuating drift and thereby an improved estimate of the drift with time can be obtained.

Table A.1. Differences between the parabolic surface and modeled atmospheric waves (C).

Ship Position	$\lambda = 14^\circ$	$T = 3.5$ days	$\lambda = 21^\circ$	$T = 5.25$ days	$\lambda = 28^\circ$	$T = 7$ days
	$\varphi = 0^\circ$	$\varphi = 90^\circ$	$\varphi = 0^\circ$	$\varphi = 90^\circ$	$\varphi = 0^\circ$	$\varphi = 90^\circ$
1	0.007	0.000	0.002	0.000	0.001	0.000
2	.006	.000	.002	.000	.001	.000
3	-.005	.051	-.002	.023	-.001	.012
4	-.005	.051	-.002	.024	-.001	.012
5	.006	.000	.002	.000	.001	.000
6	-.005	-.051	-.002	-.023	-.001	-.012
7	-.005	-.051	-.002	-.023	-.001	-.012
8	-.001	.000	.000	.000	.000	.000
9	.001	-.022	.000	-.010	.000	-.005
10	.001	-.022	.000	-.010	.000	-.005
11	-.001	.000	.000	.000	.000	.000
12	.001	.022	.000	.010	.000	.005
13	.001	.022	.000	.010	.000	.005

The purpose of the averaging process is to pass only meteorology which can be fitted with a parabolic surface. In this experiment it is implicitly assumed that the meteorological variance passed by the filter (two-day averaging) is contained in the modeled atmospheric waves. This type of ideal situation is not likely to be encountered in practice. What the results displayed in Table A.1 imply is that longer averaging periods (at least 5 days) will probably have to be used to filter out meteorological waves that cannot be adequately fitted by the surface.

Parabolic Surface Fitting With Drift

In this experiment the average meteorology is again modeled by Eq. (A.2). Values of $\lambda = 28^\circ$, $M = 2$ days, and $T = 7$ days were chosen, and ϕ was varied from time step to time step in order to simulate a wave propagating from east to west at a speed of $4^\circ/\text{day}$. Each time step was taken to be two days. In Fig. A.2 the first arrow indicates the part of the averaged atmospheric wave that will be located at 23.5°W for time step 1 while the second arrow indicates the same thing for time step 2. It was assumed that there are ten independent time steps between intercomparisons and that no ship system possessed a bias upon completion of the first intercomparison.

In the first example the ships in positions 3, 5, and 7 (See Fig. A.2) were given linear drifts so that after ten time steps they possessed accumulated drifts of -0.6 , 0.4 , and 0.3 ,

respectively. In Fig. A.3 the actual drift for each position can be compared with the model drift produced by the analysis procedure. In each case the model drift quite accurately depicts the actual drift. The model drifts for three other ship positions are also shown in Fig. A.3. The worst deviation from zero was seen at position 9 where an accumulated drift of 0.17 was produced. The model drift at position 4 was typical of the interior ship positions while that at position 12 was typical of the outer positions. As it is expected to be more difficult to accurately fit a surface at the outer positions, it is not surprising to see the largest deviations from the actual drift occur there.

In the second example the ship systems in positions 3, 5, and 9 were given linear drifts so that after ten time steps they possessed accumulated drifts of -0.6, 0.5, and 0.4, respectively. In Fig. A.4 one can see that the model drift almost perfectly depicts the actual drift for the interior positions 3 and 5. A drift of 0.24 instead of 0.40 is determined for the outer position 9. As in the first example the worst deviation from zero was seen at an outer position, a drift of -0.14 at position 12. The model drifts at positions 4 and 11 were typical of the rest of the inner and outer positions, respectively.

The results of these examples are quite encouraging. Although one can never perfectly simulate the actual atmosphere, these studies have provided insight into problems

Fig. A.3 Plots of modeled and actual drifts where the only non-zero actual drifts are at positions 3, 5, and 7. Vertical axis is drift magnitude, horizontal axis is time step.

Fig. A4. Plots of modeled and actual drift where the only non-zero actual drifts are at positions 3, 5, and 9. Vertical axis is drift magnitude, horizontal axis is time step.

that may be encountered in practice. The analysis procedure appears to be quite powerful at determining drifts for the interior positions. Drifts at the outer positions are less easily discerned and may even be suspect since those positions appear to be prone to anomalous drifts. In any case one can conclude that this analysis procedure is capable of providing useful information about the drifts in ship measurement systems that is otherwise unavailable.

APPENDIX B

DATA INTERPOLATION USING AUTOREGRESSIVE METHODS

The surface meteorological data from the GATE were processed by the Center for Experimental Design and Data Analysis (CEDDA) and recorded on magnetic tape (Seguin, et al., 1977). Among the data recorded were hourly observations of the Type 1 and Type 2 measurement systems investigated in this study along with quality flags which denote missing or erroneous data. Since the analysis scheme used in this study requires that averages of such hourly observations be computed over periods of many hours, interpolated values must be inserted for missing or erroneous data. Furthermore, as indicated in EDS 25, during Phases II and III several ships left station for periods as long as three days. For the purpose of this analysis such periods must be treated as missing data and interpolated values must be supplied. In order to fill such data gaps, an autoregressive (AR) interpolation scheme was developed and implemented. Its performance will be compared with that of two simpler methods.

Before describing the autoregressive interpolation scheme, a discussion of AR modeling of time series is in order. The time series to be modeled, x_t , is assumed to be a realiza-

tion of a stationary stochastic process. The model to be fitted to this time series is

$$(x_t - \mu) = \alpha_1(x_{t-1} - \mu) + \dots + \alpha_p(x_{t-p} - \mu) + z_t \quad (\text{B.1})$$

where p is the order of the discrete AR process and z_t is white noise with zero mean and variance σ_z^2 . This process can be completely described by the AR parameters $(\alpha_1, \alpha_2, \dots, \alpha_p)$ and σ_z^2 . Given that one wishes to fit a p -th order AR process to series x_t , there are two methods for estimating the process parameters. The first method is described in detail by Jones (1964). It requires that one determine estimates for the autocovariance function of the process using the time series itself. Using the estimated values of the autocovariance function the Yule-Walker equations are solved using a recursive procedure developed by Durbin (1960) to produce estimates $(a_1, a_2, \dots, a_p; s^2)$ of the AR parameters and the white noise variance. One drawback to this approach is that in the estimation of the autocovariance function an unrealistic assumption about the process being sampled must be made. All values of the process are assumed to be μ except for those in the observed series itself.

The second method for estimating the process parameters was proposed by Burg (1967, 1968) and is described in considerable detail by Ulrych and Bishop (1975). This method does not require that any unrealistic assumptions be made about the process outside the sampling interval as it uses only the

observed data to produce estimates of the process parameters. For this reason the Burg method is employed in this study.

The procedures for estimating the AR process parameters are well-documented and present no problem to the AR modeler. The major stumbling block has been the selection of the proper order model to be fit to the observed data. A reasonable choice for the proper order model would be the one whose one-step prediction error variance is smallest. In words the problem can be described in the following way. If the model order selected is too small, the residual terms, z_t , in (B.1) will not be white noise and the prediction error variance will not be minimized because there still exists predictability in the time series that has not been modeled. On the other hand, if the model order selected is too large, the residuals will be uncorrelated but the model itself will be so dependent upon the particular realization of the stochastic process observed that its prediction error variance will be large. In order to solve this problem Akaike (1969) developed the final prediction error (FPE) criterion whereby one can objectively determine the order process for which the one-step prediction error variance is a minimum. It was this development which removed the subjectivity from AR modeling and made it the practical procedure it is today.

Suppose now that one has a data gap which must be filled. The time series of data preceding the gap is modeled

by (B.1) where the process parameters are estimated using the Burg method and the order process is chosen using the Akaike FPE criterion. Employing the estimated AR coefficients (B.1) is used to predict the missing data values where successive predictions are made by incorporating previously predicted values. The entire process is then repeated for the time series of data following the gap with the predictions being made backward in time (the nature of the univariate backward autoregression is such that this is accomplished by simply reversing the order of the time series and treating the "back-cast" as a forecast). Suppose that n interpolated values are needed to fill the gap. Estimates of the i -step prediction error variances can be determined (Jones, 1964, p. 286) for both the forecast and back-cast values ($i = 1, 2, \dots, n$). Each forecast and back-cast is then inversely weighted by its prediction error variance and the weighted sum is taken to represent the interpolated value. Of course, the two weights are normalized so that they sum to one. For example, the first interpolated value would be determined by

$$\frac{f_1 \cdot \frac{1}{V_{f1}} + b_n \cdot \frac{1}{V_{bn}}}{\frac{1}{V_{f1}} + \frac{1}{V_{bn}}} \quad (\text{B.2})$$

where f_1 is the one-step forecast, b_n is the n -step back-cast and V_{f1} and V_{bn} are estimates of their respective prediction error variances.

In order to assess the performance of the AR interpolation scheme it is compared with two simpler methods. The first is simply the assignation of the last good value to the missing values. The second is linear interpolation between the last good datum and the next good one. The three interpolation schemes are compared for short (order of hours) and long (order of days) data gaps. Due to the fact that some ships were required to leave station for as long as three days, a scheme capable of filling such long gaps is necessary.

Table B.1 summarizes the results of an interpolation experiment in which twelve hourly Type 2 wet-bulb observations taken aboard the *Researcher* during Phase III were assumed to be missing. The root mean square error (RMSE) for the first interpolation scheme where the last good value is assigned to each of the twelve missing hours is 0.40°C . The RMSE's for the linear and AR schemes are 0.30°C and 0.19°C , respectively. As can be seen in Table B.1 the wet-bulb temperatures do not vary much over the period and their change is reasonably linear. However, the AR scheme still produces the smallest RMSE of the three methods.

A second interpolation experiment is summarized in Table B.2. One can see that for this case, where eight hourly Type 2 pressure observations from the *Researcher* were assumed to be missing, that the missing data are decidedly non-linear. Values for the RMSE of 1.89 mb, 0.82 mb, and 0.46 mb are found for the

Table B.1. A comparison of AR and linear interpolations for twelve missing hourly observations between 17 GMT, 8 September 1974, and 06 GMT, 9 September 1974, for the Researcher Type 2 wet-bulb temperatures ($^{\circ}\text{C}$).

Hour (GMT)	Actual	AR	Error	Linear	Error
17	24.0	-	-	-	-
18	23.5	23.9	0.4	24.0	0.5
19	23.8	23.9	0.1	24.0	0.2
20	23.8	23.8	0.0	23.9	0.1
21	23.5	23.7	0.2	23.9	0.4
22	23.5	23.7	0.2	23.9	0.4
23	23.5	23.7	0.2	23.9	0.4
00	23.9	23.7	-0.2	23.8	-0.1
01	23.3	23.6	0.3	23.8	0.5
02	23.7	23.6	-0.1	23.8	0.1
03	23.7	23.7	0.0	23.8	0.1
04	23.8	23.7	-0.1	23.7	-0.1
05	23.7	23.6	-0.1	23.7	0.0
06	23.7	-	-	-	-

first, linear, and AR interpolation schemes, respectively.

This is a case where the AR method is clearly superior to the other two.

The Dallas Type 2 pressure and wet-bulb measurement systems collected data during all of Phase II. In order to compare the various interpolation schemes a data gap will be assumed between 17Z August 7 and 11Z August 10 for both systems. This corresponds to the actual time period for which the Researcher was off-station during this phase. The three different interpolation schemes were employed to fill this gap and the RMSE for

Table B.2. A comparison of AR and linear interpolations for eight missing hourly observations between 11 GMT and 20 GMT, 11 September 1974, for the Researcher Type 2 pressures (mb).

Hour (GMT)	Actual	AR	Error	Linear	Error
11	1016.0	-	-	-	-
12	1015.9	1015.8	-0.1	1015.8	-0.1
13	1015.6	1015.1	-0.5	1015.6	0.0
14	1014.7	1014.4	-0.3	1015.3	0.6
15	1013.9	1013.5	-0.4	1015.1	1.2
16	1013.8	1013.0	-0.8	1014.9	1.1
17	1013.6	1012.9	-0.7	1014.7	0.9
18	1013.4	1013.3	-0.1	1014.4	1.0
19	1013.8	1013.7	-0.1	1014.2	0.4
20	1014.0	-	-	-	-

each was computed for both systems. For the wet-bulb measurement system RMSE's of 0.53°C , 0.53°C , and 0.41°C were determined for the first, linear, and AR schemes, respectively. For this particular data gap the linear method was identical to the "last good value" one. The RMSE's for the pressure measurement system were 1.44 mb, 0.87 mb, and 0.71 mb, respectively. Thus, for both long and short data gaps the AR interpolation scheme is found to be superior to the other two.

APPENDIX C

A WIND DIRECTION AVERAGING SCHEME

During GATE the various ships measured the wind direction directly. In order to implement the drift analysis procedure these wind directions must be averaged over a period of many days. Due to the nature of wind direction data, computing the mean by simply taking an arithmetic average can produce misleading results. For example, suppose two winds from 340° and 40° have been measured. The average of these two numbers is 190° . This would indicate that the average wind direction was just west of south when the actual winds were essentially northerly! However, the 340° wind direction can also be represented as -20° and a new mean of 10° would be computed. This is certainly a much better representation of the average wind direction.

When faced with the problem of determining the average wind direction for a large volume of data, the first temptation is to convert the wind observations into u- and v- components, compute the average of each component, and then let the average wind direction be determined by those average wind components. In fact this method was used to produce the 4-second to 1-hour average wind direction archived by CEDDA (Seguin, et al., 1977, p. 27). The following example points out a serious problem

with this approach. Suppose the following three wind directions and speeds have been measured: 170° at 20 kts, 260° at 5 kts, and 350° at 10 kts. It can be easily seen that the average wind direction is 260° . However, the average u- and v- components are 3.2 kts and 10.7 kts, respectively, indicating an average wind direction of 197° . One can see that this approach will tend to force the average wind direction towards the direction where the wind speeds are greatest. It should be pointed out that this method can be effective if normalized wind components are determined and the average of these normalized components is used to compute the average wind direction.

Since drifts in the wind direction measurement systems were sought in this study, it was decided that an averaging scheme based on the directly measured quantity, wind direction, rather than derived quantities, u- and v- components, would be desirable. Suppose N observations of wind direction have been taken. Each observation, x_i , can be expressed in three ways: $x_i - 360^\circ$, x_i , or $x_i + 360^\circ$. Given some c in the half-open interval $(0, 360^\circ]$ (the set of all c's such that 0° is less than c and c is less than or equal to 360°) each wind direction observation can be expressed in one of those three ways and denoted by x_{ci} , an element of the half-open interval $(c - 180^\circ, c + 180^\circ]$. The key to the averaging scheme is to find the c for which the sample variance

$$s_c^2 = \frac{1}{N} \sum_{i=1}^N (x_{ci} - \bar{x}_c)^2, \quad (C.1)$$

$$\text{where } \bar{x}_c = \frac{1}{N} \sum_i^N x_{ci}$$

is minimized. For such a c , $\bar{x}_c$ would represent the best available estimate of the mean wind direction since any other choice would result in an increase in the wind direction variance.

In order to gain a better understanding of this averaging scheme consider the set of 100 observations given in Table C.1. Using these values and (C.1), Table C.2 was constructed for

Table C.1. Hypothetical set of 100 wind direction observations.

Wind Direction	45°	90°	135°	180°	225°	270°	315°	360°
No. of Obs.	36	6	3	0	2	4	29	20

four different values of c . Note that for $c = 180^\circ$, the observed data remain unchanged. It can be seen that for $c = 360^\circ$

Table C.2. Sample means and standard deviations in degrees for varying c .

c	$\bar{x}_c$	s_c
90	27.9	74.2
180	204.3	136.6
270	355.5	63.2
360	6.3	54.8

the standard deviation is minimized (at least for the values of c in Table C.2) and the mean is estimated to be 6.3° (366.3°). When normalized wind components were determined and averaged for the data in Table C.1, the average wind direction was found

to be 7° . It is interesting to note that if one uses $c = 360^\circ$ and substitutes 7° (367°) for $\bar{x}_c$ in (C.1), the value of s_c so obtained is slightly larger than when 6.3° (366.3°) is used for $\bar{x}_c$. Thus, from the standpoint of minimizing s_c^2 the estimated mean derived from this analysis scheme is better than that obtained using normalized wind components.

In order to successfully implement this averaging scheme for large amounts of data, some method must be found for quickly determining the proper value of c . To do this for a given data set the number of observations in 180° half-open intervals, each separated by 5° , is computed. There are 72 such sectors beginning with $(360^\circ, 180^\circ]$ and ending with $(355^\circ, 175^\circ]$. Next, the sector with the maximum number of observations is found and c is set equal to the midpoint of that sector. For example, in Table C.1 the interval $(270^\circ, 90^\circ]$ contained 91 of the 100 observations and would indicate that the proper choice for c is 360° . It should be noted that all intervals from that one up to and including $(310^\circ, 130^\circ]$ contain the same number of points indicating c could range from 360° to 40° . However, for each such choice of c the value of $\bar{x}_c$ remains the same, namely 6.3° .

In conclusion, it can be seen that the averaging of wind directions is not a trivial problem due to the periodic nature of the parameter itself. Erroneous estimates of the average wind direction can be obtained if one simply averages wind components and then derives an average direction. The use of average normalized wind components provides much better estimates but

does not guarantee that the sample variance of the given observations is minimized. The scheme presented here and used in this study is designed to produce an estimated mean wind direction for which the sample variance of the observations is a minimum.

APPENDIX D

SOME ASPECTS OF PARABOLIC SURFACE FITTING

In the simulated drift analyses performed in Appendix A it was seen that accurate drift estimates could be made for the interior ship positions but not for the outer positions. A similar result was found in Chapter IV when, for each variable, artificial drifts were added to randomly selected ships. The reason for this becomes evident when 95% confidence surfaces are estimated for the parabolic surfaces used in the various drift analyses. These estimates were obtained for each variable using standard regression techniques described by Draper and Smith (1966, p. 61). In every case it was found that the distance between the upper and lower 95% confidence surfaces was about three times greater at the outer ship positions than it was at the interior positions. What this means in words is that given that the average meteorology can be modeled by a parabolic surface, better estimates of that surface can be made at the interior positions. Thus, when the drift analysis procedure is applied, better drift estimates will in turn be made at those positions.

Suppose two separate drift analyses are performed for

a particular variable using the same benchmark system. In the first analysis, Type 1 and Type 2 systems are used while in the second only Type 2 systems are employed (with the exception of the benchmark). If the relative shape of the parabolic surface fit in each analysis is preserved, the actual average differences between the output of two systems aboard the same ship will agree with those differences inferred from the drift analysis. This will be true even though the level of the surfaces could be quite different. The actual surfaces themselves must be examined in order to determine the difference in levels.

This type of analysis was performed for each variable investigated in Chapter IV and suggested in every case that the relative shape of the parabolic surface was preserved for the interior positions. In order to determine the effect of such an analysis on the level of the surfaces the parabolic surfaces fitted to seven-day averages of pressure centered on September 5 are plotted in Fig. D.1 for the two separate analyses. For the Type 2 analysis the values of the surface are uniformly about .05 mb greater than those for the Types 1 and 2 analysis at the interior ship positions. For the outer ship positions there is virtually no difference between the values of the two surfaces. The grand mean of the observations used in the Type 2 analysis was about .05 mb greater than that for the other analysis. Thus, for the interior positions the shape of the parabolic surface is preserved from one analysis to the next while the difference between

Fig. D.1. Parabolic surfaces (mb) fitted to seven-day averages of pressure centered on 5 September 1974.

their levels is roughly the same as the difference between the grand means.

The plots in Fig. D.2 show the same information for seven-day averages of pressure centered on September 12. In this case the values of the surface for the Type 2 analysis at the interior positions are from .01 mb to .04 mb greater than those for the other analysis. For the outer positions the values for the Type 2 analysis are from .03 mb to .08 mb less than those for the other analysis. The net result is a change in the overall shape of the surface from one analysis to the next but small change in the region of the interior positions. For this case the grand mean of the observations used in the Type 2 analysis was about .03 mb greater than that for the other. Thus, for the interior positions the differences between the two parabolic surfaces were all within about .01 mb of the difference between the two grand means.

In general the results shown in Figs. D.1 and D.2 are typical of those found for the other variables. When the two separate analyses are performed the resulting parabolic surfaces in the area of the interior positions agree quite closely in shape while the difference in their levels agrees with the difference in the grand means. Representative values for the grand mean differences are .05 mb, $.02^{\circ}\text{C}$, $.05^{\circ}\text{C}$, $.05 \text{ m sec}^{-1}$, and 2° for the pressure, sea-surface temperature, dry-bulb temperature, wind speed, and wind direction measurement systems, respectively. In Chapter IV it was found that the

Fig. D.2. Parabolic surfaces (mb) fitted to seven-day averages of pressure centered on 12 September 1974.

actual average differences between Type 1 and Type 2 measurements made aboard the same ship for each of these variables agreed very closely with those differences implied by the separate drift analyses. The worst agreement was found for the wet-bulb temperature measurement systems whose grand mean differences are typically about $.15^{\circ}\text{C}$. The reason for this relatively large difference becomes apparent when one examines Figs. 9-11 where it can be seen that Type 2 wet-bulb measurements made aboard a ship were typically about 0.5°C greater than their Type 1 counterparts. Thus, when Type 1 systems are substituted for Type 2 the grand mean is significantly reduced. Furthermore, since this difference is quite consistent in size from ship to ship and all ships with Type 1 systems occupied interior positions, the net result is that the shape of the parabolic surface substantially changes between the two separate analyses. Thus, the results shown in Table 3 were the poorest of those for the variables examined in Chapter IV.

The drift estimates relative to the Researcher Kollsman obtained using the parabolic surfaces shown in Figs. D.1 and D.2 are plotted in Fig. D.3. Only the interior positions are shown in these plots. Ships which possessed both types of measurement systems are denoted by a shaded circle. For both type systems one can see that the drift pattern is consistent with time even though the average meteorology showed an appreciable change (see Figs. D.1 and D.2). The distribution of

Fig. D.3. Estimated drifts (mb) for pressure measurement systems relative to the Researcher Kollsman.

the drifts in space shows little organization indicating that the drift estimates are not dependent upon the meteorology. One can see the disastrous effect upon physical interpretation that would result if no drift corrections were made. A fictitious pressure difference of almost 3 mb would be found between the Meteor and the Quadra if Type 1 pressures were used. In Figs. D.1 and D.2 the parabolic surfaces would indicate that the actual difference is about 0.1 mb.

At this point two questions can be asked about the parabolic surfaces displayed in Figs. D.1 and D.2. First, could a lower order surface be used to model the average meteorology? In order to answer this question the regression techniques described by Draper and Smith (1966) were used to determine 95% confidence intervals for the coefficients of the four surfaces shown in the figures. For September 5 (Fig. D.1) only the coefficients for the first-order terms were found to be significantly different from zero. This result is not surprising as the surfaces shown in that figure appear to be quite close to plane surfaces. However, for September 12 (Fig. D.2) the coefficients of second-order terms were found to be significantly different from zero. Thus, the parabolic shapes shown in this figure are statistically significant.

This brings up the second question. Are the surfaces, especially those shown in Fig. D.2, a good estimate of the average meteorology? In order to answer the second question,

let us examine Fig. D.2. Both surfaces shown here indicate that a ridge of high pressure extends from the south into the interior array of ships. Seven-day averages of the observed pressures centered on 12 September 1974 were corrected using the intercomparison estimates of bias and drift in EDS 17 and plotted in Fig. D.4. A hand analysis of these pressures, which have now been corrected independently of the drift analysis scheme, was performed and is also shown in this figure. One can see that even in this rough analysis a ridge of high pressure is seen extending from the south into the inner ship array. Thus, it appears that the parabolic surfaces of Fig. D.2 are reasonable models of the average meteorology. Similar results were obtained for variables other than pressure.

Finally, in order to facilitate the use of the drift corrections computed in this study, some type of confidence interval about these estimates must be determined. As mentioned previously 95% confidence surfaces can be found for the parabolic surfaces used in the drift analysis scheme. Since the drift estimates are found by subtracting the value of such a surface from the averaged observations at a particular location, the distance between the upper and lower confidence surface is simply the width of the 95% confidence interval about the drift (i.e., drift plus bias) estimate. Values for these confidence intervals of just under ± 0.1 mb

Fig. D.4. Hand analysis of 7-day averages of Type 2 pressure (mb) centered on 12 September 1974 and corrected using the intercomparison drift estimates contained in EDS 17.

and $\pm 0.1^{\circ}\text{C}$ were found for the pressure and various temperature measurement systems which occupied interior positions. Values of approximately $\pm 0.3 \text{ m sec}^{-1}$ and $\pm 4^{\circ}$ were found for the interior wind speed and wind direction measurement systems. These intervals can be used to determine whether a drift estimate is significantly different from zero or whether successive independent drift estimates differ from each other. Due to the averaging periods used in the drift analysis scheme, drift estimates must be separated by at least the length of the averaging period in order to be independent.

In conclusion, it was seen that the empirical results obtained in Appendix A and Chapter IV which suggested that reliable drift estimates can only be computed for interior ship positions can be substantiated by the theory of linear regression analysis. Comparisons were made between parabolic surfaces fitted using only Type 2 systems and those determined using Type 1 and Type 2 systems. It was found that for the interior ship positions these surfaces varied little in shape while the difference between their levels was roughly equal to the difference between the two grand means (Type 2 vs. Types 1 and 2). For all of the variables except the wet-bulb temperature these grand mean differences were found to be quite small. Space and time plots of the drift estimates for the pressure measurement systems show that these estimates are independent of changes in the average meteorology. Furthermore,

these plots illustrate that the use of uncorrected data would result in incorrect physical interpretations. It was seen that the use of parabolic surfaces to model the average meteorology made sense both from a statistical as well as meteorological viewpoint. Finally, confidence intervals were determined for the drift estimates contained in this study so that future users might be better able to apply drift corrections in solving their particular problem.