NOAA Technical Report EDS 17

GATE Convection Subprogram Data Center: Analysis of Ship Surface Meteorological Data Obtained During GATE Intercomparison Periods

Washington, D.C.
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U.S. DEPARTMENT OF COMMERCE
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GATE Convection Subprogram Data Center: Analysis of Ship Surface Meteorological Data Obtained During GATE Intercomparison Periods

Center for Experiment Design
and Data Analysis

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GATE CONVECTION SUBPROGRAM DATA CENTER: ANALYSIS OF SHIP SURFACE METEOROLOGICAL DATA OBTAINED DURING GATE INTERCOMPARISON PERIODS

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ABSTRACT. The 1974 GARP Atlantic Tropical Experiment (GATE) ship surface meteorological data that was acquired during formal Intercomparisons have been analyzed. Two types of data were collected by GATE ships: Type 1, consisting of continuous and automatically recorded observations, and Type 2, the manually recorded observations. Differences and the standard deviations of these differences between selected reference data sets and all other individual data sets have been computed. These results clearly depict the nature and magnitude of biases in pressure, dry-bulb temperature, wet-bulb temperature, sea surface temperature, and wind speed and direction. In addition, the report summarizes the instruments that were used on each ship and the location and height of each sensor.

1. INTRODUCTION

This report documents the analysis of the 1974 GARP Atlantic Tropical Experiment (GATE) surface meteorological Intercomparison data. The analysis has been performed by the Convection Subprogram Data Center (CSDC) and is a part of the International validation of GATE observation data. The GATE consisted of three observation Phases and three formal ship Intercomparison periods. The Intercomparisons (IC) were held in order to establish biases and differences between measurements of similar variables by ships of several nations.

Table 1 gives the locations and dates of the Intercomparisons. Figures 1, 2 and 3 show the GATE ship arrays for the three observation Phases as well as the locations of the three Intercomparisons with the exception of IC-A1A. Appendix A contains a complete list of the ships and the Intercomparisons in which they participated.

1.1 Data Sets Used

This analysis is based on two types of data: Type 1, consisting of continuous and automatically recorded observations; and Type 2, manually recorded observations. The time resolution of the first data set varies from 3- to 60-min averages. Type 2 data were typically recorded on standard WMO marine observing forms. The time resolution for these data are typically 30-min, dropping to 15 min for disturbed weather periods or for the 3-hr Intensive Intercomparisons (IIC) when each ship pulled alongside the Meteor buoy. The National Processing Center (NPC) in the Federal Republic of Germany (FRG) provided two complete Type 2 data sets for the FRG ships Meteor and Planet, one referred to as the "bulk" data and the second being the standard WMO observations. These two sets are identical for temperatures, pressures, and winds. However, wind directions in the WMO data set are given to the nearest 10^{o} and wind speeds to the nearest knot, while in the bulk data they are given to the nearest degree and meter per second, respectively. For these reasons, the bulk data were selected for use in this analysis for those variables which are common to both data sets.

Appendix B contains an inventory of the data sets used in this analysis. In cases where individual NPC's provided revised data sets, these were used in the analysis and the dates on which they were received are given in Appendix B. Also, some National Processing Centers have contacted us concerning errors in their data sets and these have been incorporated in our analysis. The results strictly correspond to the data in the archive.

Six different variables were considered in the analysis: dry-bulb temperature, wet-bulb temperature, sea surface temperature, wind speed and direction, and pressure. All the variables except pressure were sampled by the Meteor buoy.

The brief information in the following sections concerns instruments, sensor heights above mean sea level, and data acquisition procedures based on the documentation accompanying the data supplied by the National Processing Centers. This information has been supplemented by correspondence with individual Centers.

1.2 Validation and Analysis

Validation and analysis of the Intercomparison data consisted of editing the NPC data, calculating basic statistics, and then interpreting the results of the statistics and graphical plots. Histograms, scattergrams, and time-series plots were constructed and compared. Basic statistics of single variates and paired variates were calculated, including means, standard deviations, skewness, and kurtosis.

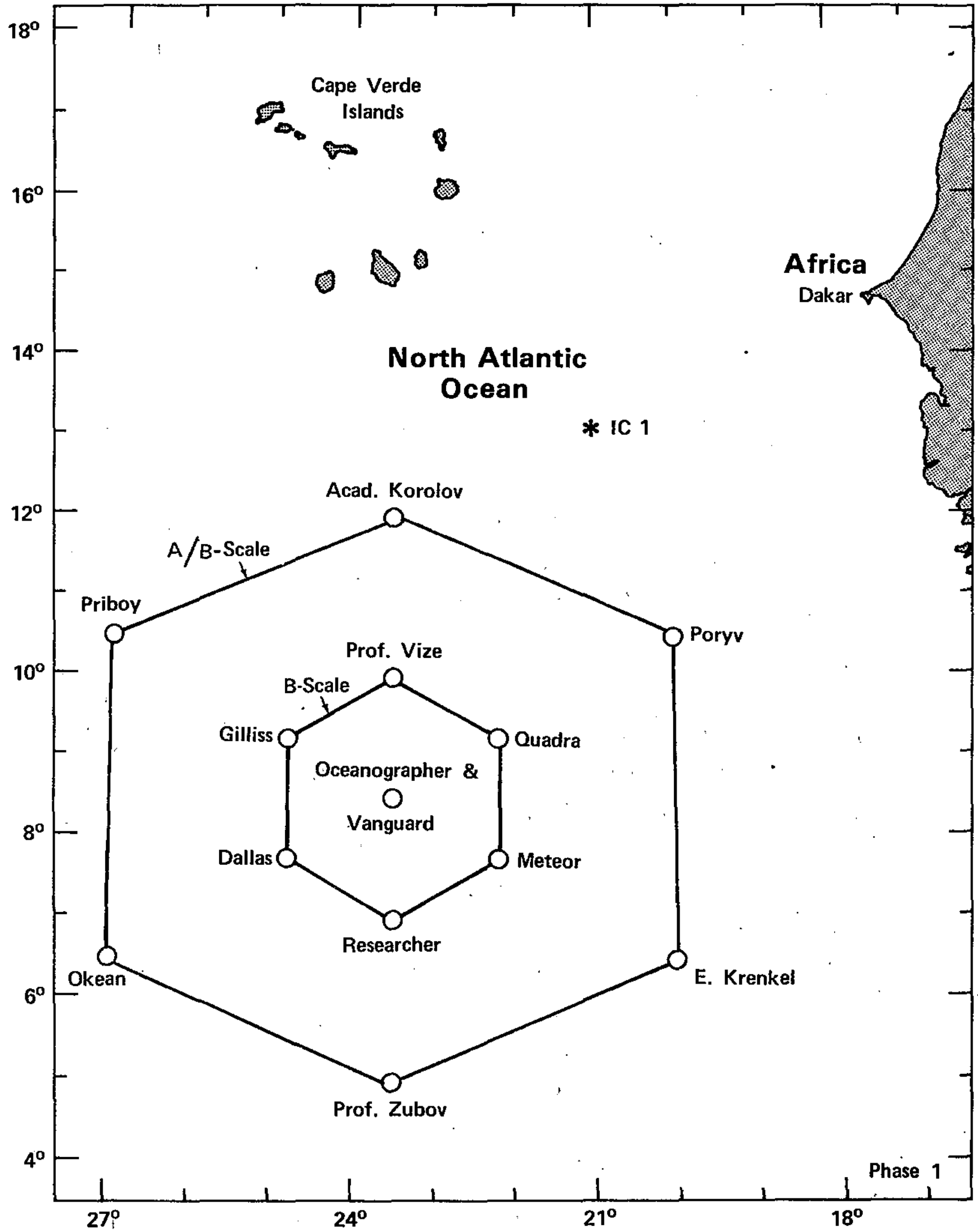

Figure 1.--Phase 1 ship array and the location of Intercomparison 1 (IC-1).

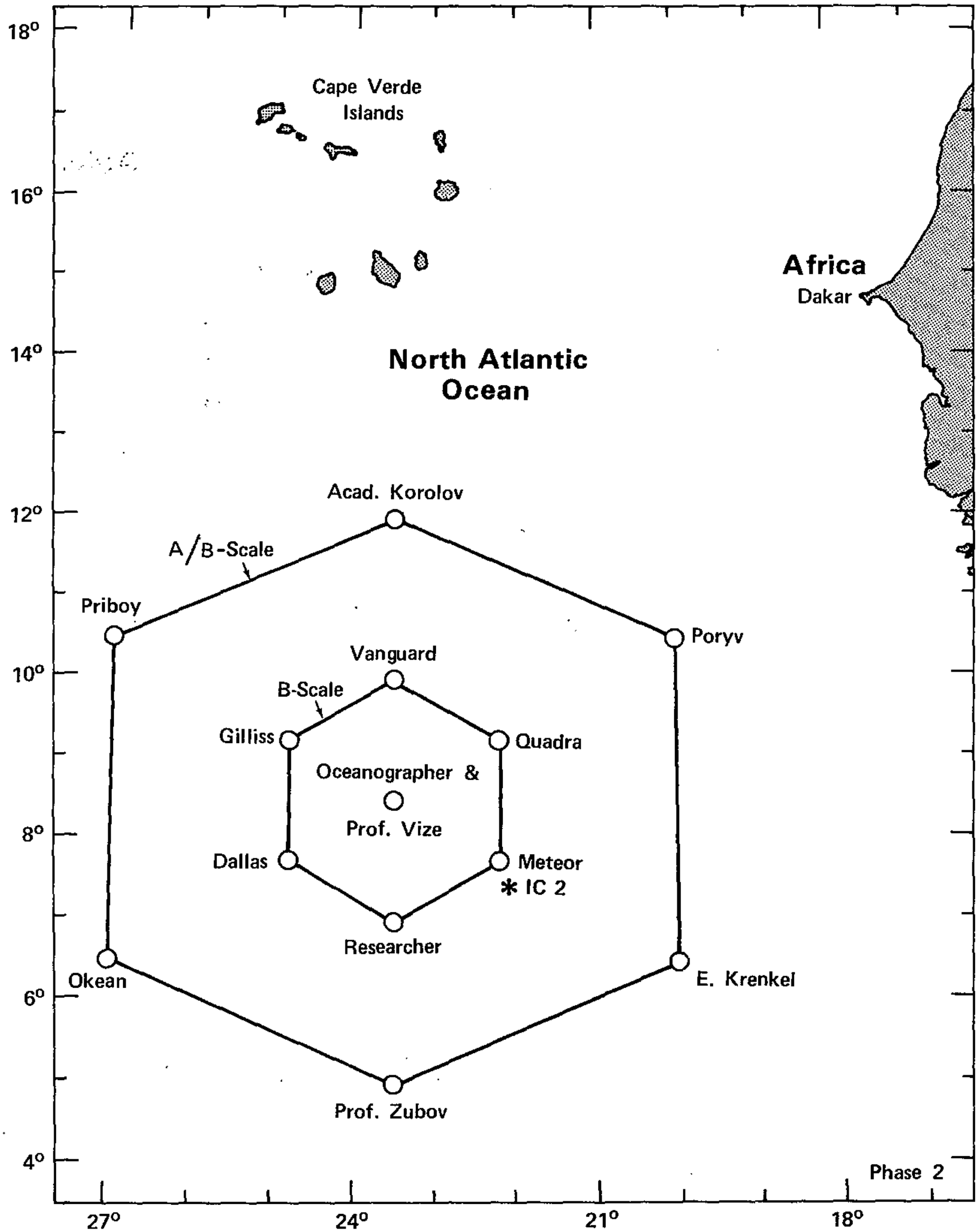

Figure 2.--Phase 2 ship array and the location of Intercomparison 2 (IC-2).

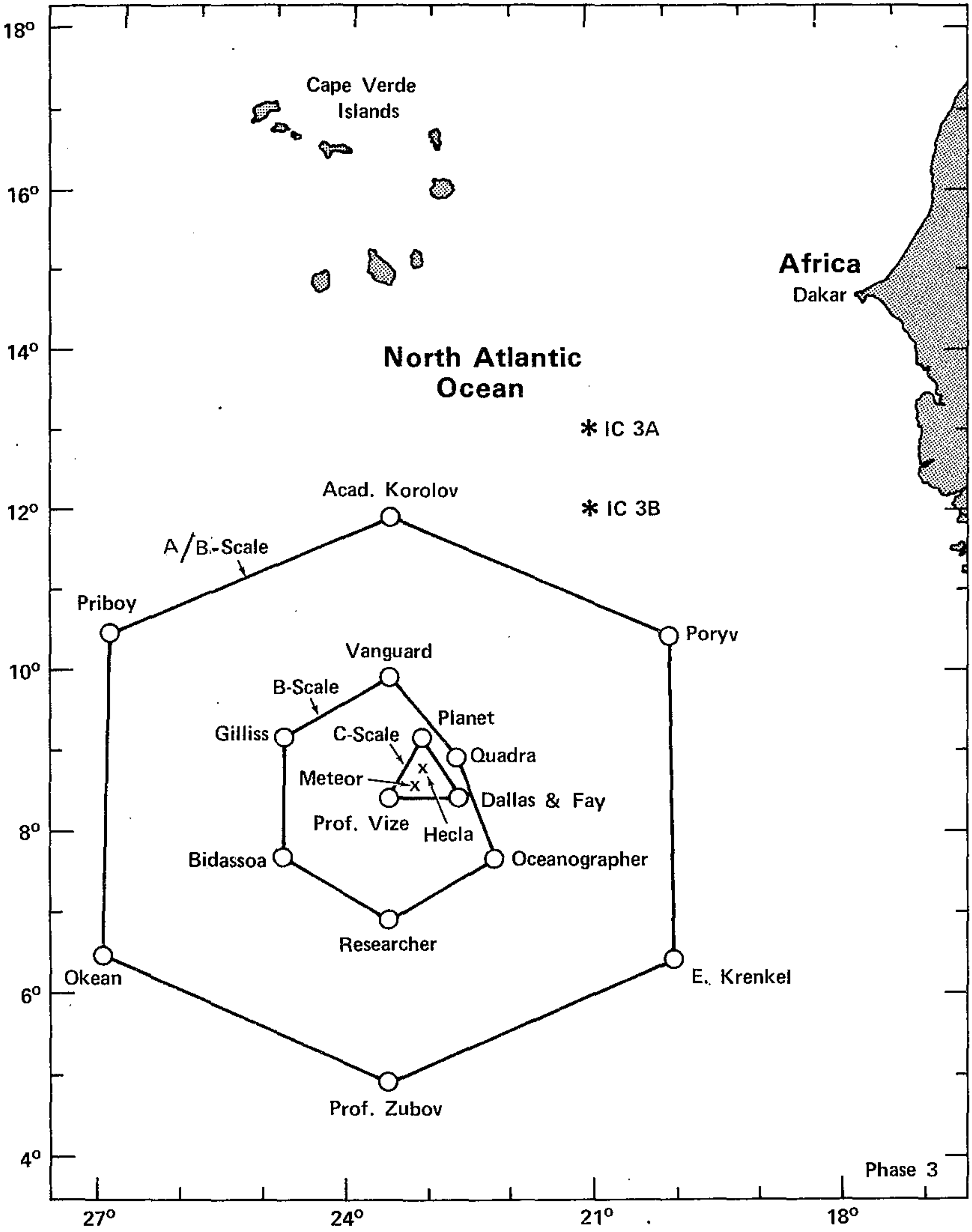

Figure 3.--Phase 3 ship array and the location of Intercomparison 3A and 3B (IC-3A and IC-3B).

Difference statistics were calculated for each data set by comparison with a reference data set (reference data set minus individual ship data). In general, these differences were calculated over the entire intercomparison period. Differences for those data acquired during Intensive Intercomparisons (i.e., when the ships pulled up to the Meteor's buoy for 3 hr of close proximity intercomparisons) were also computed. However, the results generally did not differ significantly from those statistics computed over the entire Intercomparison period.

In comparing data sets which had different time resolutions such as 3-min and 10-min averages, the 3-min average values were compared with the 10-min average values at the corresponding times. No attempt was made to construct 10-and 20-min averages from 3-min averages. Similarly, 3-min averages were compared with standard observations at the time of the observation.

Dry-bulb temperatures, wet-bulb temperatures, sea surface temperatures, and wind speeds and directions measured by the Meteor buoy were used as the reference for comparison during IC-1, 2, and 3B. Since the Meteor buoy was not used in IC-A1A or 3A and because pressures were not measured by the buoy, other ships and sensing systems were also used as reference for comparisons.

Table 2 shows the average and the standard deviations of the principal surface meteorological variables for each IC. The dry-bulb, wet-bulb, and sea surface temperatures increased notably from IC-1 through IC-2. Winds were strong, steady, and from the north during IC-1. During IC-2, they were slightly weaker, more variable, and from the west. IC-3 was characterized by very light and variable westerly winds. During both IC-2 and 3, weak tropical weather disturbances passed over the ships during the Intercomparisons and influenced the surface atmospheric and oceanic layer for time periods of up to 18 hr.

Table 1.--Intercomparison periods and locations

Intercomparison	Location Latitude (deg.)	Location Longitude (deg.)	Dates (1974)
1	13.0	-21.0	June 17 to 19
A1A	5.0	-44.0	June 17 to 19
2	7.7	-22.0	August 16 to 18
3A	13.0	-21.0	Sept. 21 to 23
3B	12.0	-21.0	Sept. 21 to 23

Table 2.--Averages and Standard Deviations for the *Meteor* buoy meteorological variables and the *Researcher* Kollsman pressures for each of the Intercomparisons.

Variable	Units	Intercomparison 1		Intercomparison 2		Intercomparison 3	
		Average	Standard Deviation	Average	Standard Deviation	Average	Standard Deviation
Temperature (buoy)	(°C)	23.6	0.4	26.0	1.3	26.1	0.6
Wet-bulb temperature (buoy)	(°C)	21.2	0.6	23.1	0.7	23.7	0.3
Sea surface temperature (buoy)	(°C)	24.5	0.2	27.0	0.1	27.9	0.2
Wind direction (buoy)	(deg)	1	17	260	36	234	61
Wind speed (buoy)	(m/s)	6	1.3	6.3	1.3	2.6	1.0
Pressure	(mb)	1013.9	1.1	1013.5	1.4	1012.1	1.4

2. INTERCOMPARISON OF ATMOSPHERIC PRESSURES

The Convection Subprogram, prior to the GATE, specified that sea-level atmospheric pressure should be measured to 0.1 mb. To accomplish this, several nations equipped their ships with up to three different kinds of pressure sensors and produced both Type 1 and Type 2 data sets. On the Researcher, Gilliss, Dallas, and Oceanographer, pressures were measured with the Kollsman and Rosemount barometers.

The Kollsman is a temperature-stabilized aneroid capsule which is forced to vibrate at a frequency dependent upon its shape, which, in turn, is determined by the atmospheric pressure. The Rosemount sensor is a drum-like transducer with a membrane that moves inward or outward as a function of external pressure. As the membrane moves, the capacitance of the sensor changes, a quantity which is then measured and converted to standard measuring units for pressures.

The FRG ships Meteor and Planet were equipped with the Digibar barometer, a temperature-stabilized precision pressure capsule, which is monitored by an electromechanical circuit. The Canadian ship Quadra used a microbarograph to obtain its Type 1 pressures. All Type 1 sensors acquired pressure information continually, and individual NPC's produced data sets with the time resolution shown in appendix B.

With the exception of the Planet, Type 2 pressures were measured with standard precision aneroids. The Planet used its Digibar sensor. Although the height of the barometers (table 3) varied from ship to ship, most NPC's corrected their pressure to sea level.

To eliminate the effects of the ship environment on the measurement pressure, static pressure heads were mounted on the bow booms or on the foremast. The Kollsman sensors were vented by static lines leading to the bow boom. The Rosemount and the precision aneroids used on the U.S. ships were vented on the foremast, as were the Quadra's sensors and Digibars aboard the Planet and Meteor.

The Researcher Kollsman Type 1 pressure data for IC-1, 2, and 3B were chosen as the standard for comparison. The Korolov and Musson Type 2 pressure data served as the reference for IC-A1A and 3A respectively. These data sets were selected after careful preliminary study of the basic statistics, which included scattergrams and time-series plots.

The GATE pressure data were subject to at least four sources of error: water collection in static lines leading to the barometers; inadequate venting of the sensors, which induces ship effects; sensor malfunctions, which included drift of the sensor calibration and irregular responses to pressure changes; and variation in pressure recordings due to the electronics. In general, there is no way to completely isolate the effect of each of these sources of error.

The following two subsections present the averages and standard deviations of the differences between each of the individual data sets compared with the reference data set. The computations were performed at the time resolution

Table 3.--Barometer heights above sea level

Ship	Sensor	Height (m)
	Type 1 pressures	
Researcher	Kollsman	7.2
"	Rosemount	12.6
Gilliss	Kollsman	5.9
"	Rosemount	8.2
Dallas	Kollsman	6.4
"	Rosemount	12.5
Oceanographer	Kollsman	8.9
"	Rosemount	12.3
Quadra	Microbarograph	21.0
Meteor	Digibar	10.5
Planet	"	5.5
	Type 2 pressures	
Researcher	Aneroid	12.2
Gilliss	"	8.2
Dallas	"	12.5
Oceanographer	"	12.6
Quadra	"	9.5
Meteor		
Planet	Digibar	5.5
Fay	Aneroid	10.0
Korolov	"	11.0
Okean	"	9.0
Priboy	"	9.0
Vize	"	12.0
Krenkel	"	10.0
Zubov	"	12.0
Musson	"	12.0
Poryv	"	10.0
Bidassoa		0.0

permitted by the paired data sets (see app. B).

The pressure data, as is the case for some of the other meteorological variables, appear to have one of three types of bias. The first is the constant difference or offset relative to the reference data set. The standard deviation of the differences is typically less than 0.15 mb. The second type of bias is the irregular bias, one which varies with time. The standard deviations of the differences were generally in excess of 0.23 mb for this type. Finally, some of the pressure data sets contain long-term drifts relative to the reference data set.

2.1 Results of Type 1 Pressure Intercomparison Analysis

Table 4 shows the averages and the standard deviations of the differences (the reference data minus the individual pressures) for Type 1 observations when compared with the reference. The standard deviations of the differences between individual Kollsman and Digibar pressure data and the Researcher Kollsman pressure data are generally smaller than between the Rosemount and microbarograph sensors and the Researcher data. At the same time, the analysis has shown that the Kollsman and Digibar pressure records were separated by the average differences given in table 4.

The Kollsman pressure sensor on the Dallas drifted late in Phase 2, accounting for the change in the average differences shown in table 4. The Oceanographer's Kollsman barometer functioned erratically throughout the experiment, and the data should be used with caution.

The Rosemount pressure sensors drifted throughout the GATE toward lower pressures. This is best illustrated by the change in the average differences for the Researcher Rosemount data. Short-term drifts were also found in the Rosemount data. Figure 4 shows a scattergram of the surface atmospheric pressure for the Researcher Kollsman and Rosemount barometers during IC-3B, which illustrates the short-term drift problem.

The Quadra barograph data for IC-1 and 3A contain irregular biases or time varying biases when compared with the reference data sets. However, the IC-2 pressure records are almost the same as the Researcher Kollsman records.

2.2 Results of Type 2 Pressure Intercomparison Analysis

Table 5 shows the average differences and the standard deviations of the differences for Type 2 observations when compared with the reference data sets. Data that appeared to have significant irregular biases are indicated. All Type 2 pressures were obtained with precision aneroid barometers, with the exception of the Planet data, which were derived from the Digibar pressure sensor.

As seen in table 5, only five intercomparison data sets have significant irregular biases. However, the standard deviations of the differences associated with the Type 2 data sets are generally larger than for the Type 1 data, probably because of small observing and recording errors.

Table 4.--Intercomparison of Type 1 pressures, showing average differences and standard deviations of the differences between the Type 1 ship pressures and the *Researcher* Kollsman Type 1 pressures, except where noted

Ship	IC period	Average difference (mb)	Standard deviation of the differences (mb)	No. of samples
		Kollsman pressure sensor		
Gilliss	1	-0.29	0.06	859
	3B	-0.24	0.06	1,015
Dallas	1	-0.25	0.10	876
	2	-0.91	0.11	1,090
Oceanographer	2	-0.04	0.09	1,020
	3A	-0.20*†	0.43	86
		Rosemount pressure sensor		
Researcher	1	0.23	0.21	1,182
	2	0.53	0.15	1,100
	3B	0.71	0.19	1,018
Gilliss	1	-1.19†	0.32	859
	3B	-0.10†	0.24	1,015
Dallas	2	0.75†	0.28	1,090
Oceanographer	1	-0.21	0.17	1,128
	2	0.48	0.18	937
	3A	0.74*†	0.26	86

Table 4.--(continued)

Ship	IC period	Average difference (mb)	Standard deviation of the differences (mb)	No. of samples
		Digibar pressure sensor		
Meteor	1	1.32	0.40	58
	2	1.01	0.12	54
	3B	1.11	0.14	25
Planet	3A	-2.69	0.16	88
		Microbarograph pressure sensor		
Quadra	1	-1.96	0.53	60
	2	-1.83	0.14	55
	3A	-1.88	0.52	46

* The Musson Type 2 pressures served as the reference for comparison during IC-3A.

† Irregular bias.

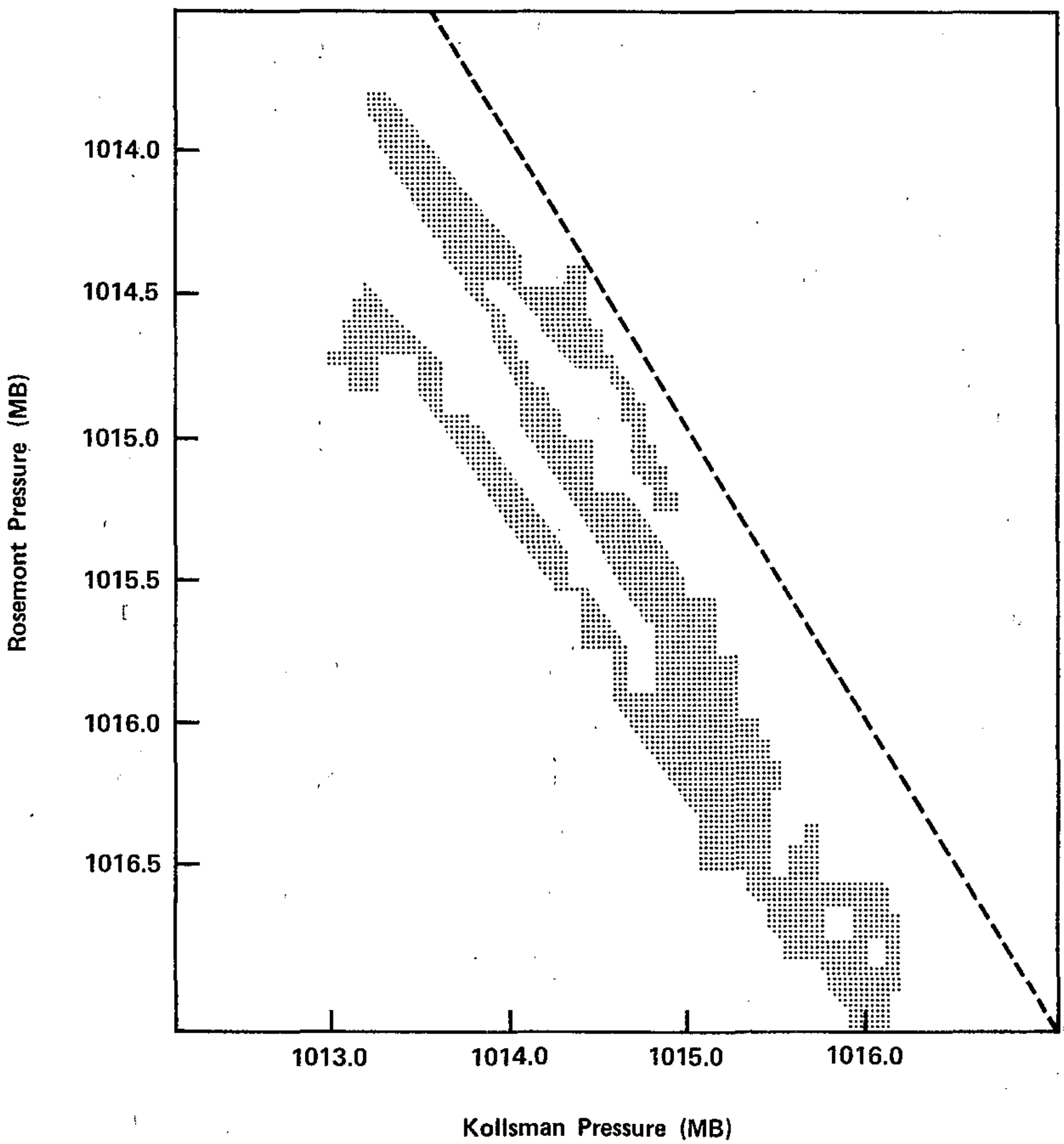

Figure 4.--Scatter diagram of surface atmospheric pressure observations from the Researcher Kollsman and Rosemount barometers during Intercomparison 1.

Table 5.--Intercomparison of Type 2 pressures, showing average differences and standard deviations of the differences between the Type 2 ship pressures and the Researcher Kollsman Type 1 pressure, except where noted.

Ship	IC period	Average difference (mb)	Standard deviation of the differences (mb)	No. of samples
Researcher	1	-0.59*	0.22	206
	2	-0.60	0.17	122
	3	-0.62	0.16	113
Gilliss	1	-0.59*	0.70	103
	3	-0.61	0.12	131
Dallas	1	-0.48*	0.24	131
	2	-0.31*	0.23	122
Oceanographer	1	-0.44	0.16	131
	2	-0.28	0.18	119
	3A	-0.84	0.26	86
Quadra	1	0.51	0.21	119
	2	0.02†	0.14	110
	3A	-0.14†	0.20	88
Meteor	1	-0.49	0.12	59
	2	-0.39	0.23	110
	3B	-0.32	0.10	102
Planet	3A	-1.55†	0.15	43
Fay	3A	-0.21†	0.30	25
Korolov	A1A	(reference data set)		
	2	-0.94	0.21	109
	3B	-1.06	0.17	101
Okean	A1A	0.31**	0.23	33
	2	-0.55	0.20	109
	3B	-0.60	0.26	102
Priboy	A1A	0.32**	0.21	111
	2	-0.65	0.33	96
	3B	-0.57	0.18	95

Table 5.--(continued)

Ship	IC period	Average difference (mb)	Standard deviation of the differences (mb)	No. of samples
Vize	1	-0.22	0.24	119
	2	-0.28	0.22	110
	3A	-0.16†	0.25	88
Krenkel	1	-0.19	0.30	119
	3A	-0.06†	0.19	88
Zubov	1	-0.30	0.26	118
	2	-0.05	0.20	110
	3A	-0.22*†	0.45	88
Musson	1	-0.05	0.18	119
	2	0.05	0.17	110
	3A	(reference data set)		
Poryv	1	-0.23	0.17	117
	3B	-0.04	0.19	101
Bidassoa	3B	0.36	0.17	97

* Irregular biases.

** The Korolov Type 2 pressures served as the reference for IC-A1A.

† The Musson Type 2 pressures served as the reference for IC-3A.

2.3 Summary of The Pressure Data

The preceding sections show that almost all the pressure data sets contain either fixed biases relative to the reference data sets or a bias that varies with time. For those data sets which contain fixed biases, the average difference represents a reasonable adjustment to the data in order to correct for this bias. This is true provided the average difference between the reference data set and the ship pressure in question did not change from the first to the last IC. A good example of this is the Researcher-Gilliss average differences, which varied little from the first to the last IC.

For those data sets which showed sizeable (> 0.2 mb) changes in the average pressure differences from IC to IC, for which there is only one IC period in which to judge them by, or for which the analysis has indicated that there are large irregular changes in the biases during the IC, the use of the average difference to adjust pressure records relative to the reference data set may be misleading and meaningless. The average difference and the standard deviation of the differences serve only as error estimators.

3. INTERCOMPARISON OF DRY-BULB TEMPERATURES

Shipboard dry-bulb temperature measurements tend to be biased by the heat island effect caused by the ship. This is a particularly acute problem when insolation is at a maximum and wind speeds are light, such as was the case during IC-3. The objectives of the GATE Convection Subprogram were to have temperatures measured to within 0.2°C. To accomplish this, Type 1 and Type 2 observations were made in a variety of ways.

On the Researcher, Gilliss, Dallas, and Oceanographer, Type 1 observations were made with aspirated and radiation-shielded thermistors mounted on a boom extending from the ship's bow. Those made on the Meteor buoy and the Planet's boom were made with aspirated and shielded platinum resistance wires. On the Quadra, temperatures were measured with a thermistor, which was part of a dew point hygrometer.

The Meteor buoy measured temperatures at multiple levels below 10 m. From these temperatures log-linear profiles were constructed, and 10 m temperatures were extrapolated for use in the analysis.

Type 2 temperatures were measured with mercury-in-glass thermometers on the bridge of the U.S. and U.S.S.R ships. The latter were equipped with 2.5-m booms designed to hold the sensors away from the windward side of the bridge and to remove them from the region of maximum ship heating. The Canadians used aspirated thermistors mounted inside Stevenson screens. There were two such screens, one mounted on each side of the bridge.

Table 6 lists the heights of the temperature sensors. Except for the Meteor buoy data, no attempt was made to extrapolate the temperatures to a standard level.

There were two types of biases in the temperature data: the constant or fixed, offset bias and the irregular bias or time dependent bias. The constant biases are most probably the result of small calibration differences. The irregular biases are principally the result of the strong ship heat island effect, which produces a maximum temperature departure during periods of maximum insolation and which differs from one ship to another.

Rain showers and associated cool downdrafts, which were part of weak disturbances, produced horizontal temperature gradients during the intercomparison periods and presented some problems and uncertainties in the analysis. To investigate the magnitude of the effect of these disturbances, paired statistics were calculated for those time periods which did not include the disturbed weather, and for observations taken while the ships were alongside the Meteor buoy.

The Meteor buoy Type 1 data served as the reference for temperature comparisons during IC-1, 2, and 3B. The Oceanographer Type 1 temperatures (sensor 1) served as the reference for comparisons during IC-3A and the Korolov Type 2 data served as the reference during IC-A1A.

Table 6.--Temperature sensor heights

Ship	Height (m)
Type 1 sensors	
Researcher	9.5
Gilliss	7.6
Dallas	8.2
Oceanographer	10.2
Quadra	7.5
Planet	8.0
Type 2 sensors	
Researcher	12.3
Gilliss	9.2
Dallas	12.2
Oceanographer	18.2
Quadra	15.0
Meteor	
Planet	
Fay	10.0
Korolov	11.5
Okean	10.0
Priboy	10.0
Vize	12.0
Krenkel	10.0
Zubov	13.0
Musson	9.5
Poryv	10.0
Bidassoa	6.0

3.1 Results of Type 1 Temperature Intercomparison Analysis

Table 7 presents the averages and the standard deviations of the differences for the Type 1 temperature data computed for each Intercomparison period. All temperatures were measured by sensors mounted on the booms of the ships. The results indicate little or no irregular or time-dependent biases in the observations.

Table 8 presents the averages and the standard deviations of the differences for the Intensive Intercomparisons (IIC) that is, when the ships were along side the Meteor buoy for 3 hr. The table illustrates that the results obtained for the IIC were substantially the same as for those obtained for the entire Intercomparison period.

3.2 Results of Type 2 Temperature Intercomparison Analysis

Table 9 shows the averages and standard deviations of the differences for the Type 2 temperature data sets. In general, the Type 2 temperature values were higher than those obtained from the Meteor buoy, and the standard deviations of the differences were larger than those associated with the Type 1 observations. Observations containing significant irregular or time-dependent biases are also indicated in table 9.

Figure 5 shows temperature time-series plots for the Meteor buoy, the Vize, and the Dallas. The sharp increase in the Dallas temperatures during the day is the characteristic feature of the data sets containing an irregular bias. Ship heating of up to about 1.5°C was found in the temperature data.

The meteorological disturbance during IC-2 also influenced the results presented in table 9. Therefore, statistics were calculated for August 28, 1700 GMT, through August 30, 0000 GMT, a period that did not include the disturbance. For the Meteor, the average difference for this time interval was -0.01°C, and the standard deviation of the differences was 0.13°C. These values are considered more representative of the differences in the Meteor Type 2 ship data than those shown in table 9. The discrepancies were caused by the fact that the Meteor temperatures warmed up very rapidly following the passage of the squall, much more so than those measured by the buoy or by the other ships.

3.3 Summary for the Temperature Data

The most serious problem in the temperature data is the effect of the heating of the ship's environment during periods of maximum insolation. The Type 1 temperatures measured on the Meteor buoy and the booms of several ships do not appear to be contaminated by this error. Neither are the Type 2 temperatures for many of the ships. However, there are a few Type 2 data sets (see table 9) that do contain large biases due to ship heating. Fortunately, Type 1 data are also available for most of these ships. The average differences given in tables 7 and 9 can be used in a meaningful way to adjust individual data sets to the reference data set, provided the changes in the average difference from IC to IC are less than 0.15 to 0.20°C and provided the individual data sets do not contain irregular biases.

Table 7.--Intercomparison of Type 1 temperatures showing average differences and standard deviations of the differences between the Type 1 ship temperatures and the Meteor buoy temperatures except where noted

Ship	IC period	Average difference (°C)	Standard deviation of the differences (°C)	No. of samples
Researcher	1	-0.02	0.09	834
	2	-0.02	0.14	940
	3B	-0.06	0.14	840
Gilliss	1	-0.05	0.12	603
	3B	-0.16	0.14	925
Dallas	1	-0.05	0.12	705
	2	0.05	0.16	839
Oceanographer	1	0.11	0.11	680
	2	0.10*	0.18	968
	2	0.08†	0.17	968
	3A	0.04††	0.04	941
Quadra	1	-0.09	0.15	102
	2	-0.21	0.30	98
	3A	-0.31††	0.18	95
Planet	3A	-0.05††	0.25	95

* Oceanographer dry-bulb sensor 1

† Oceanographer dry-bulb sensor 2 converted from a wet bulb during Phase 2

†† The Oceanographer boom Type 1 temperature sensor was used as reference during IC-3A.

Table 8.--Intensive Intercomparisons of Type 1 temperatures, showing average differences and standard deviations of the differences between the Type 1 ship temperatures and the *Meteor* buoy temperatures

IC period	Intensive IC period Month/Day/Hour (GMT)	Average difference (buoy minus ship)	Standard deviation of the differences	No. of samples
		Researcher		
1	6/18/0123-6/18-0400	-0.06	0.03	50
1	6/19/1228-6/19/1500	-0.01	0.03	42
2	8/17/0900-8/17/1135	-0.07	0.03	48
2	8/18/0110-8/18/0409	+0.08	0.07	59
3	9/22/0100-9/22/0400	-0.01	0.10	59
3	9/23/0915-9/23/1200	0.03	0.12	53
		Gilliss		
1	6/18/0422-6/18/0555	-0.10	0.04	31
1	6/18/0900-6/18/1200	-0.21	0.06	59
3	8/21/1932-8/21/2200	-0.13	0.04	47
3	8/22/1500-8/22/1800	-0.26	0.08	60
		Dallas		
1	6/17/1900-6/17/2200	-0.07	0.03	60
1	6/18/1500-6/18/1800	-0.15	0.04	57
2	8/17/2215-8/18/0110	0.06	0.04	57
2	8/18/1215-8/18/1500	0.10	0.16	19
		Oceanographer		
1	6/17/2205-6/18/0050	0.10	0.03	54
1	6/18/1201-6/18/1450	- .07	0.06	51
2	8/17/1202-8/17/1440	0.05	0.03	52
2	8/17/2216-8/18/0040	0.09	0.06	48
2	8/17/1202-8/17/1440	0.01*	0.03*	52*
2	8/17/2216-8/18/0040	0.07*	0.06*	48*

* Data derived from the *Oceanographer's* wet-bulb sensor 2.

Table 9.--Intercomparison of Type 2 temperatures showing average differences and standard deviations of the differences between the Type 2 ship temperatures and the <u>Meteor</u> buoy temperatures, except where noted.

Ship	IC period	Average difference (buoy minus ship, ^{o}C)	Standard deviation of the differences (^{o}C)	No. of samples
<u>Researcher</u>	1	-0.25*	0.41	180
"	2	-0.17*	0.25	113
"	3B	-0.36*	0.85	105
<u>Gillis</u>	1	-0.31*	0.69	82
"	2	-----	----	---
"	3B	-0.52*	0.38	115
<u>Dallas</u>	1	-0.51*	0.58	106
"	2	-0.18*	0.48	109
"	3B	-----	----	---
<u>Oceanographer</u>	1	-0.72*	0.48	111
"	2	-0.60*	0.64	111
"	3A	-0.76*†	0.62	93
<u>Quadra</u>	1	-0.18*	0.34	105
"	2	-0.23*	0.26	100
"	3A	-0.60*†	0.58	95
<u>Meteor</u>	1	0.06	0.16	54
"	2	-0.40	0.98	102
"	3B	-0.03	0.17	95
<u>Planet</u>	3A	-0.53*†	0.32	45
<u>Fay</u>	3A	-0.16*†	0.32	25
<u>Korolov</u>	2	-0.01	0.24	102
"	3B	-0.04	0.21	93
<u>Okean</u>	A1A	-0.12††	0.48	33
"	2	-0.11	0.44	102
"	3B	-0.10	0.22	95
<u>Priboy</u>	A1A	-0.10††	0.56	111
"	2	-0.17	0.63	98
"	3B	0.00	0.39	95

Table 9.--(continued)

Ship	IC period	Average difference (buoy minus ship, °C)	Standard deviation of the differences (°C)	No. of samples
Vize	1	0.07	0.21	103
"	2	-0.02	0.29	102
"	3A	-0.12†	0.19	95
Krenkel	1	0.03	0.13	102
"	3A	0.03†	0.24	95
Zubov	1	-0.06*	0.32	102
"	2	-0.02	0.22	102
"	3A	-0.06	0.36	95
Musson	1	-0.03	0.17	104
"	2	-0.06	0.32	102
"	3A	-0.15*†	0.38	89
Poryv	1	-0.07*	0.14	103
"	3B	-0.08	0.19	94
Bidassoa	3B	-0.28	0.24	89

* Data contained irregular biases.

† Oceanographer boom data used as reference.

†† Korolov Type 2 data used as reference in IC-A1A.

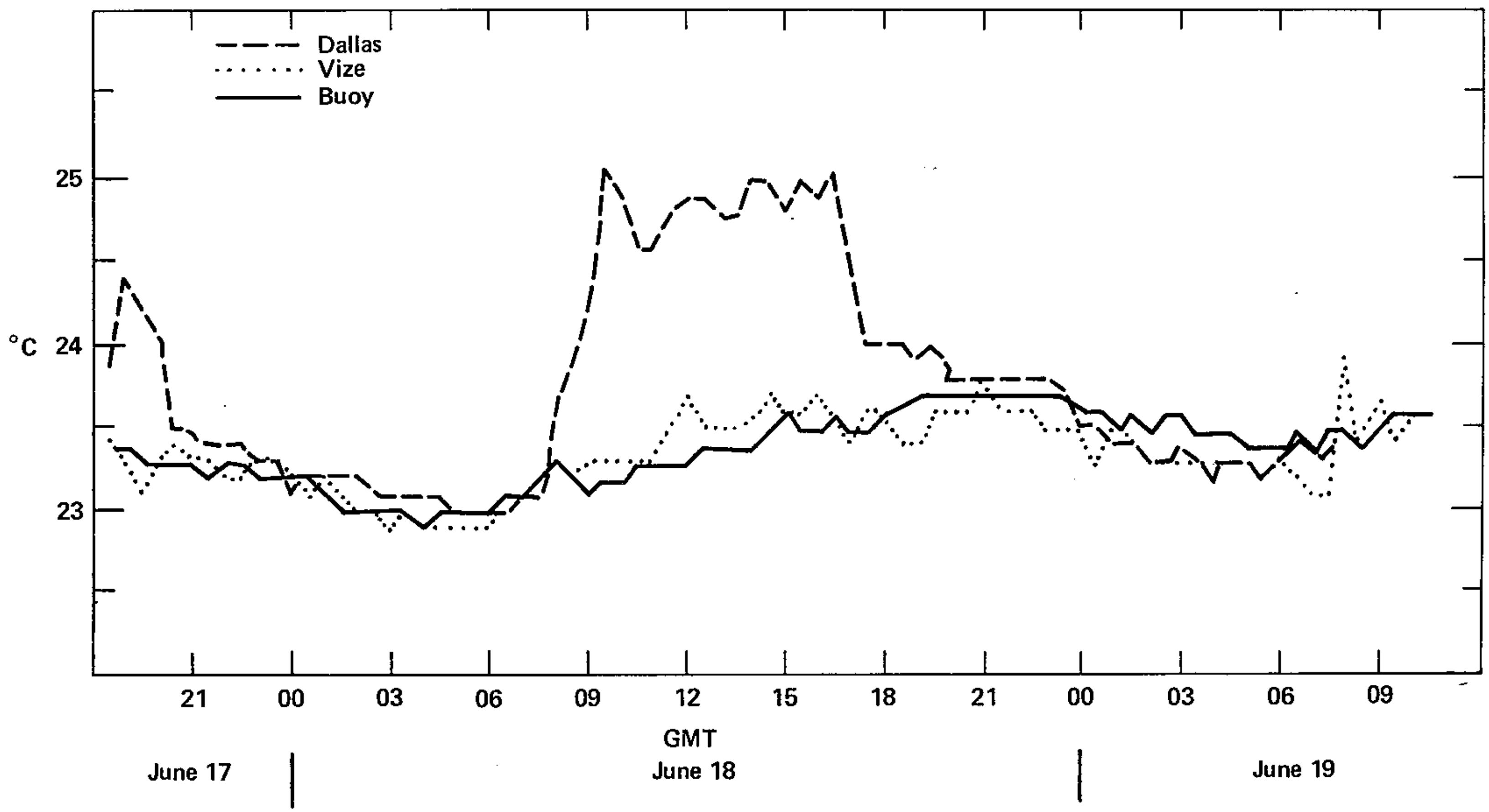

Figure 5.--Intercomparison 1 time - series plots of temperatures for the Meteor buoy Type 1 and the Dallas and Vize Type Z data.

Intercomparison 3 was a severe test of each ship's ability to measure air temperatures because of the pronounced warming of the ship's environment caused by the weak wind speeds. Those ships whose data sets are indicated as having irregular biases caused by such warming during IC-3 but not during IC-1 or 2 probably were capable of acquiring temperatures free of the warming influence for all atmospheric conditions when associated wind speeds exceeded 3 to 4 m s^{-1}.

4. INTERCOMPARISON OF WET-BULB TEMPERATURES

Much of what was said about dry-bulb temperatures in the preceding section holds true for the wet-bulb temperatures. These temperatures are difficult to measure because of the total ship environment (including heating during the day), the contamination of sensors by salt, the drying out of wet-bulb wicks, and the difficulty in providing sufficient ventilation. Yet, it was the objective of the GATE Convection Subprogram to have wet-bulb temperatures measured to the nearest 0.2°C.

On every ship, wet-bulb temperatures were measured directly and by both Type 1 and Type 2 instrumentation, with the exception of the Quadra, which acquired Type 1 moisture data with a dew-point hygrometer that measures the dew point directly. Type 1 sensors on the other ships were either thermistors or platinum resistance wires covered with a muslin wick. Type 2 sensors on all ships were mercury-in-glass thermometers, also covered by a muslin wick.

Wet-bulb temperatures were measured adjacent to the dry-bulb temperatures for both Type 1 and Type 2 data sets. The heights are given in table 6. The Meteor buoy measured wet-bulb temperatures at two levels below 10 m. Log-linear profiles were constructed from these wet-bulb temperatures, from which the 10-m temperatures were extrapolated for use in the analysis.

The Meteor buoy moisture data were in the form of specific humidity. These data were converted to wet-bulb temperatures and used as reference for comparison of wet-bulb temperatures during IC-1, 2, and 3B. The Oceanographer Type 1 wet-bulb temperature data (derived from sensor 1) served as the reference for comparison duirng IC-3A and the Korolov Type 2 wet-bulb temperatures served as the reference for IC-A1A.

The Canadian dew-point temperatures were converted to wet-bulb temperatures by first computing the actual and saturation vapor pressures, the relative humidity and finally by solving Ferrel's equation using a method described by Sullivan and Sanders (1974).

actual vapor pressure: $$e_V = 6.11 \times 10^{\frac{7.5 \times T_{DP}}{237.3 + T_{DP}}} \quad (1)$$

saturation vapor pressure: $$e_S = 6.11 \times 10^{\frac{7.5 \times T_D}{237.3 + T_D}} \quad (2)$$

relative humidity: $$RH = \frac{e_V \times 100}{e_S} \quad (3)$$

and Ferrel's equation

$$e_S\ (T_W) - e\ (T_D) = 0.00066 \times P \times (1+0.00115 \times T_W) \times (T_D - T_W) \quad (4)$$

where

T_{DP} = dew-point temperature, in ^{o}C

T_D = dry-bulb temperature, in ^{o}C

e (T) = vapor pressure of water at temperature T; and the subscripts denotes the saturation value, in mb.

T_w = wet-bulb temperature, in ^{o}C

P = ambient pressure, in mb.

The FRG specific humidities were converted to wet-bulb temperatures by computing the mixing ratio, the actual vapor pressure from the mixing ratio, the saturation vapor pressure (eq. 2), the relative humidity (eq. 3), and by solving Ferrel's equation (eq. 4) using Sullivan and Sander's method. The mixing ratio and actual vapor pressure are computed as follows:

$$\text{mixing ratio} = w = \frac{q}{1-q}$$

$$\text{actual vapor pressure} = e_v = \frac{W \times P}{(0.62197 + w)} \qquad P = 1013.25$$

where q = specific humidity and the remaining variables are defined above.

Both constant biases or fixed offsets, and irregular biases were found in the wet-bulb temperature data. Also present was the natural variability caused by squalls, which produced horizontal wet-bulb temperature gradients between the ships. For this reason, statistics were calculated for the 3-hr Intensive Intercomparisons (IIC) when the ships were alongside the Meteor buoy and for a time period during IC-2 that did not include the disturbance.

4.1 Results of Type 1 Wet-Bulb Temperature Intercomparison Analysis

Table 10 presents the averages and the standard deviations of the differences for the Type 1 temperature data for the Intercomparison periods. Differences were calculated by subtracting individual ship values from the reference values. All Type 1 wet-bulb temperatures were acquired by sensors mounted on the ships' booms.

The results show that all wet-bulb temperatures measured by the ships were slightly higher than those measured by the buoy.[1] The Gilliss wet-bulb

[1] In reviewing preliminary drafts of this report, the FRG has indicated that the wet-bulb temperatures that the CSDC calculated from the Meteor buoy specific humidities are 0.05°C cooler than the wet-bulb temperatures originally measured by the buoy instrumentation. This small difference is the result of differing conversion formula used by the FRG NPC and the CSDC in converting from wet-bulb temperatures to specific humidities and back. Warmer buoy wet-bulb temperatures generally improve the agreement between the buoy data and other data sets.

Table 10.--Intercomparison of Type 1 wet-bulb temperatures showing average differences and standard deviations of the the differences between the Type 1 ship wet-bulb temperatures and the Meteor buoy wet-bulb temperatures, except where noted

Ship	IC period	Average difference (buoy minus ship, °C)		Standard deviation of the difference (°C)		No. of samples	
		Sensor 1	Sensor 2	Sensor 1	Sensor 2	Sensor 1	Sensor 2
Researcher	1	-0.16	-0.16	0.14	0.14	818	806
	2	0.04	-0.08	0.25	0.25	970	970
	3B	-0.08	-0.13	0.14	0.15	834	834
Gilliss	1	-0.16	-0.12	0.15	0.16	596	595
	3B	-0.45	-0.41	0.18	0.16	918	916
Dallas	1	-0.12	-0.14	0.13	0.15	130	390
	2	-0.08	-0.06	0.22	0.22	868	868
Oceanographer	1	-0.08	-0.13	0.14	0.14	675	353
	2	-0.07	-----	0.26	----	993	---
Quadra	1	-0.24	-----	0.19	----	101	---
	2	-0.31	-----	0.40	----	100	---
	3A	-0.19*	-----	0.15	----	85	---
Planet	3A	-0.14*	-----	0.32	----	95	---

* Oceanographer Type 1 boom wet-bulb temperatures served as the reference for IC-3A.

temperatures are noticeably high, possibly because of a problem with the wick drying out, which was reported during IC-3B. The standard deviation of the differences are only slightly greater than the Type 1 temperatures (compare with table 7). Time-series plots indicate that there was little irregular or time-dependent bias in the boom wet-bulb temperatures.

Table 11 shows the averages and the standard deviations of the differences for the Intensive Intercomparison periods, when the ships were alongside the Meteor buoy for 3 hr. The table illustrates that the results are essentially the same as those obtained for the entire Intercomparison periods.

4.2 Results of Type 2 Wet-Bulb Temperature Intercomparison Analysis

Table 12 shows the average differences and standard deviations of the differences for the Type 2 wet-bulb temperatures. The differences were calculated by subtracting the individual ship values from the reference values. Table 12 also indicates those data which contain significant irregular or time-dependent biases.

As was done for the temperatures (sec. 3.2), the wet-bulb temperature difference statistics for August 28, 1700 GMT, through August 30, 0000 GMT, were calculated in order to exclude the influence of the disturbance.

With the exception of the Meteor data, no significant improvement resulted from removing the disturbance. The average differences and standard deviation of the differences for the Meteor are -0.29 and 0.20, respectively. These values are significantly smaller than those shown in table 12 and these values are considered more representative for the Meteor.

4.3 Summary for the Wet-Bulb Temperatures

Nearly all the Type 1 and 2 wet-bulb temperatures reported by individual ships were higher than the wet-bulb temperatures recorded on the Meteor buoy or contained in the other two reference data sets. However, most of the wet-bulb temperature biases are well defined in that they are nearly constant with time. A few Type 2 wet-bulb temperature data sets do contain irregular or time-dependent biases (see table 12) caused in part by the diurnal heating of the ships.

The average differences of the Type 1 and Type 2 data sets can be used to adjust individual wet-bulb records to the reference data sets, provided the average differences of the wet-bulb temperatures do not differ from IC to IC by more than 0.15 to 0.2°C and provided the individual IC data sets do not contain irregular or time-varying biases.

Table 11.--Intensive intercomparison of Type 1 wet-bulb temperatures showing average differences and the standard deviations of the differences between the Type 1 ship wet-bulb and the Meteor buoy wet-bulb temperatures

IC period	Intensive IC period Month/Day/Hour	Average difference (buoy minus ship, °C) Sensor 1	Average difference (buoy minus ship, °C) Sensor 2	Standard deviation of the difference (°C) Sensor 1	Standard deviation of the difference (°C) Sensor 2	No. of samples Sensor 1	No. of samples Sensor 2
			Researcher				
1	6/18/0123-6/18/0400	-0.15	-0.15	0.12	0.12	50	50
1	6/19/1228-6/19/1500	-0.14	-0.11	0.11	0.11	42	42
2	8/17/0900-8/17/1135	-0.02	-0.01	0.18	0.18	48	48
2	8/18/0110-8/18/0409	-0.08	-0.11	0.15	0.14	59	59
3	9/22/0100-9/22/0400	-0.11	-0.16	0.16	0.16	59	59
3	9/23/0915-9/23/1200	-0.01	-0.06	0.10	0.10	53	53
			Gilliss				
1	6/18/0422-6/18/0555	-0.21	-0.20	0.11	0.12	31	31
1	6/18/0900-6/18/1200	-0.24	-0.26	0.14	0.13	59	59
3	8/21/1932-8/21/2200	-0.51	-0.41	0.14	0.08	47	47
3	8/22/1500-8/22/1800	-0.57	-0.54	0.11	0.11	60	60
			Dallas				
1	6/17/1900-6/17/2200	-----	-0.13	----	0.13	0	60
1	6/18/1500-6/18/1800	-0.21	-0.21	0.12	0.13	21	57
2	8/17/2215-8/18/0110	-0.02	-0.02	0.15	0.15	57	57
2	8/18/1215-8/18/1500	-0.06	-0.03	0.17	0.17	19	19

Table 11.--(continued)

IC period	Intensive IC period Month/Day/Hour	Average difference (buoy minus ship, °C)		Standard deviation of the difference (°C)		No. of samples	
		Sensor 1	Sensor 2	Sensor 1	Sensor 2	Sensor 1	Sensor 2
			Oceanographer				
1	6/17/2205-6/18/0050	-0.05	-0.08	0.13	0.14	54	54
1	6/18/1201-6/18/1450	-0.15	-0.13	0.12	0.11	51	51
2	8/17/1202-8/17/1440	-0.15	-----	0.20	----	52	--
2	8/17/2216-8/18/0040	-0.08	-----	0.13	----	48	--

Table 12.--Intercomparison of Type 2 wet-bulb temperatures showing average differences and standard deviations of the differences between the Type 2 ship temperatures and the _Meteor_ buoy temperatures, except where noted.

Ship	IC period	Average difference (°C)	Standard deviation of the differences (°C)	No. of samples
Researcher	1	-0.42	0.25	178
"	2	-0.51	0.35	117
"	3B	-0.71*	0.43	104
Gilliss	1	-0.41	0.28	80
"	2	-----	----	---
"	3B	-0.43	0.22	114
Dallas	1	-0.61*	0.28	105
"	2	-0.68*	0.38	112
"	3B	-----	----	---
Oceanographer	1	-0.59*	0.30	110
"	2	-0.81*	0.44	115
"	3A	-0.60†	.23	94
Quadra	1	-0.41	0.19	105
"	2	-0.44	0.34	104
"	3A	-0.40*	0.33	95
Meteor	1	-0.31*	0.18	53
"	2	-0.44	0.58	106
"	3B	-0.25	0.20	94
Planet	3A	-0.28†	0.23	47
Fay	3A	-0.11†	0.16	25
Korolov	2	-0.38	0.37	106
"	3B	-0.35	0.30	92
Okean	A1A	0.01††	0.27	33
"	2	-0.47	0.39	106
"	3B	-0.37	0.23	94
Priboy	A1A	0.18††	0.30	110
"	2	-0.50	0.44	98
"	3B	-0.31	0.32	94

Table 12.--(continued)

Ship	IC period	Average difference (°C)	Standard deviation of the differences (°C)	No. of samples
Vize	1	-0.29	0.20	103
"	2	-0.44	0.34	106
"	3A	-0.25†	0.21	95
Krenkel	1	-0.39	0.19	102
"	3A	-0.18†	0.24	93
Zubov	1	-0.35	0.23	102
"	2	-0.41	0.36	106
"	3A	-0.19†	0.20	95
Musson	1	-0.33	0.18	103
"	2	-0.33	0.36	106
"	3A	-0.17*†	0.33	89
Poryv	1	-0.30	0.20	102
"	3B	-0.27	0.26	93
Bidassoa	3B	-0.69	0.64	88

* Data contain irregular biases.

† Oceanographer boom data used as reference during IC-3A.

†† Korolov Type 2 data used as reference during IC-A1A.

5. INTERCOMPARISON OF SEA SURFACE TEMPERATURES

Sea surface temperatures measured by stationary ships are subject to at least two problems: engine cooling water modifying the water environment, and the observations being made at varying depths. It was the objective of the GATE Convection Subprogram to acquire sea surface temperatures with an accuracy of 0.2°C. Observations were made with thermistors, mercury-in-glass bucket thermometers, and with a radiometer.

The Meteor buoy measured Type 1 water temperatures at depths of 16 cm and 21 cm. The former was used in this analysis. The Researcher, Gilliss, Dallas, and Oceanographer measured Type 1 sea surface temperatures with thermistors attached to floats from the bow of the ship. The float was designed to hold the sensor at a depth of 10 cm. The Quadra used a radiometer during IC-2 only. All Type 2 sea surface temperatures were acquired by mercury-in-glass bucket thermometers off the fantails of the ships when the ships were drifting. The Soviet ships used resistance thermometers mounted at the sea chest to measure sea surface temperatures when the ships were underway.

There were both constant and irregular biases in the data, but generally, the average differences and the standard deviations of the differences between the ships and the buoy were so small that the existence of irregular biases is almost of no consequence.

There were times during IC-3 when the Gilliss and Oceanographer Type 1 sea temperature probes were in warm pools of ship engine cooling water, and the scientific crews on the Gilliss used colored dye to trace the ship's cooling water on at least one occasion. The U.S. National Processing Center was able to delete those portions of the Gilliss IC data that were obviously biased by the cooling water. A similar problem exists in the case of the Oceanographer, but it was much more difficult to distinguish between the engine cooling water and the natural environment.

The existence of warm pools of water around the ships was more of a problem during IC-3 because of the weak winds. Normally, the ship's superstructure acts like a sail moving the ship through the water more rapidly than the water current. Hence, the ship is continually passing through fresh sea water. The calm winds during IC-3, however, allowed the ships to remain in warm pools of water.

The Meteor buoy Type 1 data served as the reference for the sea-surface temperature comparisons during IC-1, 2, and 3B; the Oceanographer Type 1 temperatures, for IC-3A; and the Korolov Type 2 temperatures, for IC-A1A.

5.1 Results of Type 1 Sea Surface Temperature Intercomparison Analysis

Table 13 presents the average differences and the standard deviations of the differences for the Type 1 sea surface temperatures. All data were acquired by thermistors, with the exception of the Quadra, which used a radiometer. The Dallas IC-1 data are questionable because they show no variability.

Table 14 shows the average differences and standard deviations of the

Table 13.--Intercomparison of Type 1 sea surface temperatures showing average differences and standard deviations of the differences between Type 1 *Meteor* buoy sea surface temperatures and the ship sea surface temperatures.

Ship	IC period	Average difference (buoy minus ship, °C)	Standard deviation of the differences (°C)	No. of samples
Researcher	1	0.09	0.06	753
"	2	0.21	0.06	765
"	3B	0.23	0.12	504
Gilliss	1	-0.01	0.05	504
"	3B	-0.13	0.12	694
Dallas	1	0.50	0.17	648
"	2	0.11	0.05	742
Oceanographer	1	0.03	0.03	513
"	2	0.05	0.04	828
Quadra	2	0.23	0.16	102

differences for the Intensive Intercomparison periods, when the ships were alongside the Meteor buoy for 3 hr. The table illustrates that the results obtained for these periods were substantially the same as those obtained for the entire Intercomparison periods.

5.2 Results of Type 2 Sea Surface Temperature Intercomparison Analysis

Table 15 lists the average differences and standard deviations of the differences for Type 2 sea surface temperature data. Intercomparisons 1 and 2 yield very good agreement with the Meteor buoy and the Korolov, while IC-3 shows significantly larger average differences for several ships. The standard deviations of the differences are relatively consistent.

5.3 Summary for the Sea Surface Temperature Data

The average and standard deviations of the differences for both Type 1 and Type 2 sea surface temperatrues were generally smaller than they were for dry- and wet-bulb temperatures. A few Type 1 and Type 2 data sets do contain irregular biases caused by ship engine cooling water. This was more noticeable during IC-3 because of the meteorological conditions and the manner in which the ships were forced to operate in order to maintain their stations relative to the reference buoy or the other ships. In general, however, the average differences and the standard deviations of the differences shown in tables 13 and 15 were generally less than 0.15°C, a value which is close to the expected accuracy of such instrumentation.

Table 14.--Type 1 sea surface temperatures showing average differences and standard deviations of the differences between the Type 1 ship sea surface temperatures and the *Meteor* buoy sea surface temperatures.

IC period	Intensive IC period Month/Day/Hour	Average difference (buoy minus ship, °C)	Standard deviation of the differences (°C)	No. of samples
		Researcher		
1	6/18/0123-6/18/0400	-0.07	0.01	48
1	6/19/0128-6/19/1500	-0.07	0.01	34
2	8/17/0900-8/17/1135	0.20	0.01	45
2	8/18/0110-8/18/0409	0.19	0.02	59
3	9/22/0100-9/22/0400	0.17	0.20	43
3	9/23/0915-9/23/1200	0.26	0.04	43
		Gilliss		
1	6/18/0422-6/18/0555	-0.04	0.01	31
1	6/18/0900-6/18/1200	-0.03	0.02	52
3	8/21/1932-8/21/2200	-0.10	0.03	25
3	8/22/1500-8/22/1800	-0.30	0.08	46
		Dallas		
1	6/17/1900-6/17/2200	0.32	0.02	59
1	6/18/1500-6/18/1800	0.73	0.03	57
2	8/17/2215-8/18/0110	0.07	0.03	44
2	8/18/1215-8/18/1500	0.13	0.02	21
		Oceanographer		
1	6/17/2205-6/18/0050	0.02	0.01	42
1	6/18/1201-6/18/1450	0.01	0.05	16
2	8/17/1202-8/17/1440	0.07	0.01	52
2	8/17/2216-8/18/0040	0.06	0.03	34

Table 15.--Intercomparison of Type 2 sea surface temperatures showing average differences and standard deviations of the differences between the Type 2 ship sea surface temperatures and the Meteor buoy sea-surface temperatures, except where noted

Ship	IC period	Average difference (°C)	Standard deviation of the difference (°C)	No. of samples
Researcher	1	-0.12	0.09	181
	2	-0.18	0.16	51
	3B	-0.12	-.12	45
Gilliss	1	-0.13*	0.36	77
	3B	-0.09	0.19	103
Dallas	1	-0.03	0.11	106
	2	-0.01	0.14	102
Oceanographer	1	0.02	0.09	112
	2	0.03	0.13	112
	3A	0.09†	0.20	91
Quadra	1	0.03	0.05	107
	2	0.01	0.07	102
	3A	-0.08	0.23	91
Meteor	1	0.05	0.07	54
	2	0.06	0.08	51
	3B	0.17*	0.17	94
Planet	3A	-0.17	0.21	44
Fay	3A	-0.06	0.25	25
Korolov	A1A	-----	----	---
	2	-0.06	0.09	103
	3B	-0.03	0.18	92
Okean	A1A	0.00††	0.16	33
	2	0.03	0.11	103
	3B	-0.09	0.17	94
Priboy	A1A	0.01††	0.20	111
	2	-0.01	0.08	99
	3B	0.01	0.12	94

Table 15.--(continued)

Ship	IC period	Average difference (°C)	Standard deviation of the difference (°C)	No. of samples
Vize	1	-0.04	0.07	105
	2	0.02	0.07	103
	3A	-0.08	0.19	91
Krenkel	1	-0.08	0.09	103
	3A	-0.18	0.22	91
Zubov	1	0.06	0.12	104
	2	0.20	0.15	103
	3A	-0.07	0.24	91
Musson	1	-0.03	0.10	105
	2	0.11	0.12	103
	3A	-0.06	0.23	87
Poryv	1	-0.04	0.08	104
	3B	0.01	0.14	93
Bidassoa	3B	-1.15	0.20	87

† Oceanographer Type 1 data used as reference during IC-3A.

†† Korolov Type 2 data used as reference during IC-A1A.

* The data contain irregular biases.

6. INTERCOMPARISONS OF WIND SPEEDS AND DIRECTIONS

Wind velocity measurements aboard ships are difficult to make because of the obstacle effect of the ships themselves. Such measurements have to be corrected for ship velocity, which is difficult to do particularly at low speeds. Some of the GATE ships attempted to operate in such a way that their bows were always into the wind in order to provide the boom and mast instrumentation with the best possible exposure. To determine ship velocities accurately, radar marker buoys or references were established by some ships at their respective stations. Frequent radar fixes relative to the buoys enabled more accurate determination of the ships' velocities, which were then used to correct the shipboard wind-velocity measurements.

Type 1 wind speeds and directions were measured by cup anemometers and vanes, respectively, which were mounted on the booms and the foremasts of ships. Type 2 wind velocities were also measured by cup anemometers and vanes on all but the Researcher, Gilliss, Dallas, Oceanographer, and Fay. These ships used the Aerovane sensor, which measures wind speeds by a propeller on the leading edge of the vane. Table 16 shows the heights of the Type 1 and Type 2 sensors.

The Meteor buoy measured wind speeds and directions at multiple levels on its 8-m mast. Log-linear profiles were then constructed from which 10-m wind speeds and directions were derived for use in the analysis.

The analysis of the wind-velocity data was carried out in two parts. First, the wind speeds were analyzed in the same fashion as the other scalar variables: pressures and temperatures. Average differences and the standard deviations of the differences were calculated over both the entire Intercomparison and the Intensive Intercomparison periods. Second, the winds were analyzed as vector quantities by the following scheme.

An entire wind record set with n observations for a given ship and Intercomparison period can be written $\left\{\rho_n e^{i\theta_n}\right\}$, where ρ_n are the wind speeds and θ_n are the wind directions. For two independent wind velocity records, such as ship versus buoy, one can seek an average wind direction factor and speed factor such that the sum of squares of the differences between the sets is a minimum:

$$\sum^{N} \left\{\rho_{1n} e^{i\theta_{1n}} - \eta\rho_{2n} e^{i(\theta_{2n} + \emptyset)}\right\}^2 = \mathrm{Min}(n.\emptyset)$$

The details of this technique are given in more detail in appendix C by Godshall and Jalickee.

The above procedure was applied to all Type 1 and Type 2 wind versus reference data, and the average and standard deviations of the reported wind directions were then computed for both the Type 1 and 2 data sets.

The Meteor buoy Type 1 data served as the reference for comparison during

IC-1, 2, and 3B. The Oceanographer Type 1 boom wind velocities served as reference for comparison during IC-3A, and the Korolov Type 2 data served as the reference during IC-A1A.

6.1 Results of Type 1 Wind Speed Intercomparison Analysis

Table 17 presents the average difference and the standard deviations of the differences for the Type 1 wind speeds averaged over the entire Intercomparison periods. The original objective of the Gate Convection Subprogram was to measure wind speeds with an accuracy of 0.5 m s^{-1}.

Wind speeds were generally higher on the masts than they were on the booms as one would predict from the boundary layer log wind law. For neutral conditions, the difference in wind speed for sensor heights between 10 and 30 m for a 10-m s^{-1} wind speed would be approximately 1 m s^{-1}. No adjustments were made for heights in the results presented in table 16.

The wind speeds measured on the Gilliss appear to decrease with height for unexplained reasons. Based on pre- and post-GATE calibration results, it is known only that the ship's sensors degraded more noticeably from the beginning to the end of the experiment than did the other U.S. ship sensors.

Table 18 presents the average difference and the standard deviations of the differences for the Intensive Intercomparisons. There are no significant discrepancies between the values given in tables 17 and 18, although the standard deviations of the differences are smaller for the Intensive Intercomparisons.

The Researcher, Gilliss, Dallas, and Oceanographer used the ship Meteor and its buoy for position determination during Intercomparisons 1, 2, and 3B. The Zubov was used during Intercomparison 3A. These two ships served as substitutes for radar-marked buoys which were used as substitutes during the Phases. Their positions were continually monitored and tracked by satellite and radar navigation systems. From the Meteor and Zubov positions, the drift velocities of the Intercomparison arrays were determined.

One of the reasons for the discrepancies between the wind velocity data of the individual ships when compared with the reference data sets is the inaccurate specification of ship motion. Figure 6 shows a scattergram, and figure 7 histograms, of the Meteor buoy versus Researcher boom wind speeds for IC-1. In addition to the variability in the wind records, both figures show a wider distribution of wind speeds for the Researcher than for the buoy. This is a result, in part, of the inaccurate specification of the ship speeds and the subsequent corrections of the wind velocities for those periods when the ships were maneuvering.

In addition, the FRG automatic data sets for the meteor buoy and Planet boom have not been corrected for the drift velocity of the Intercomparison arrays, which amounted to approximately 0.5 m s^{-1}.

Table 16.--Wind sensor heights

Ship	Boom sensors (m)	Mast sensors (m)
	Type 1 sensors	
Researcher	10.0	24.1
Gilliss	8.2	18.3
Dallas	8.7	23.8
Oceanographer	10.5	29.6
Quadra	7.5	
Planet	8.0	
	Type 2 sensors	
Researcher		22.8
Gilliss		18.3
Dallas		24.7
Oceanographer		36.0
Quadra		24.0
Meteor		
Planet		
Fay		14.0
Korolov		26.0
Okean		24.5
Priboy		29.0
Vize		29.0
Krenkel		27.0
Zubov		25.0
Musson		26.5
Poryv		27.0
Bidassoa		11.0

Table 17.--Intercomparison of Type 1 wind speeds showing average differences and standard deviations of the differences between Type 1 ship wind speeds (boom and mast sensors) and the Meteor buoy wind speeds, except where noted.

Ship	IC period	Average difference $m\ s^{-1}$		Standard deviation of the differences $m\ s^{-1}$		No. of samples	
		Boom	Mast	Boom	Mast	Boom	Mast
Researcher	1	-0.13	-0.71	0.89	1.02	833	865
"	2	0.01	-0.38	0.78	0.81	968	968
"	3B	0.13	0.01	0.46	0.48	929	930
Gilliss	1	0.09	0.47	0.82	0.88	604	605
"	3B	0.21	0.20	0.54	0.51	878	878
Dallas	1	0.02	-0.49	0.81	0.72	580	533
"	2	0.72	-0.23	0.89	0.77	988	988
Oceanographer	1	-0.28	-0.53	0.89	0.64	809	826
"	2	0.16	-0.26	0.93	0.91	1,005	1,013
"	3A	-----	-0.08*	----	0.20*	-----	893
Quadra	1	-0.23	-----	0.48	----	86	-----
"	2	-0.10	-----	0.18	----	95	-----
Planet	3A	-0.03*	-----	0.70*	----	91	-----

* Oceanographer boom wind speeds were used as reference during IC-3A.

Table 18.--Intensive intercomparisons for Type 1 wind speeds showing average differences and the standard deviations of the differences between the Type 1 ship wind speeds (boom and mast sensors) and the Meteor buoy wind speeds

IC period	Intensive IC period Month/Day/Hour (GMT)	Average difference ($m\ s^{-1}$) Boom	Mast	Standard deviation of the differences ($m\ s^{-1}$) Boom	Mast	No. of samples Boom	Mast
			Researcher				
1	6/18/0123-6/18/0400	-0.04	-0.19	0.45	0.47	50	50
1	6/19/1228-6/19/1500	-0.97	1.71	1.67	1.38	51	51
2	8/17/0900-8/17/1135	-0.06	0.49	0.43	0.44	50	50
2	8/18/0110-8/18/0409	-0.05	0.34	0.44	0.43	59	59
3	9/22/0100-9/22/0400	0.11	0.03	0.47	0.52	59	60
3	9/23/0915-9/23/1200	0.17	-0.04	0.37	0.39	54	54
			Gilliss				
1	6/18/0422-6/18/0555	0.58	0.86	0.53	0.52	30	31
1	6/18/0900-6/18/1200	-0.21	0.64	0.53	0.97	59	59
3	8/21/1932-8/21-2200	-0.08	0.04	0.26	0.29	47	47
3	8/22/1500-8/22/1800	0.13	0.19	0.36	0.35	33	33
			Dallas				
1	6/17/1900-6/17/2200	0.06	----	0.74	----	56	0
1	6/18/1500-6/18/1800	0.39	-0.43	0.68	0.46	60	60
2	8/17/2215-8/18/0110	0.22	-0.32	0.57	0.57	56	56
2	8/18/1215-8/18/1500	0.20	-0.01	0.58	0.62	21	21
			Oceanographer				
1	6/17/2205-6/18/0050	0.02	-0.23	0.63	0.62	58	58
1	6/18/1201-6/18/1450	-0.35	-0.78	0.61	0.57	55	55
2	8/17/1202-8/17/1440	0.26	-0.13	0.57	0.54	52	52
2	8/17/2216-8/18/0040	0.08	0.16	0.63	0.91	41	42

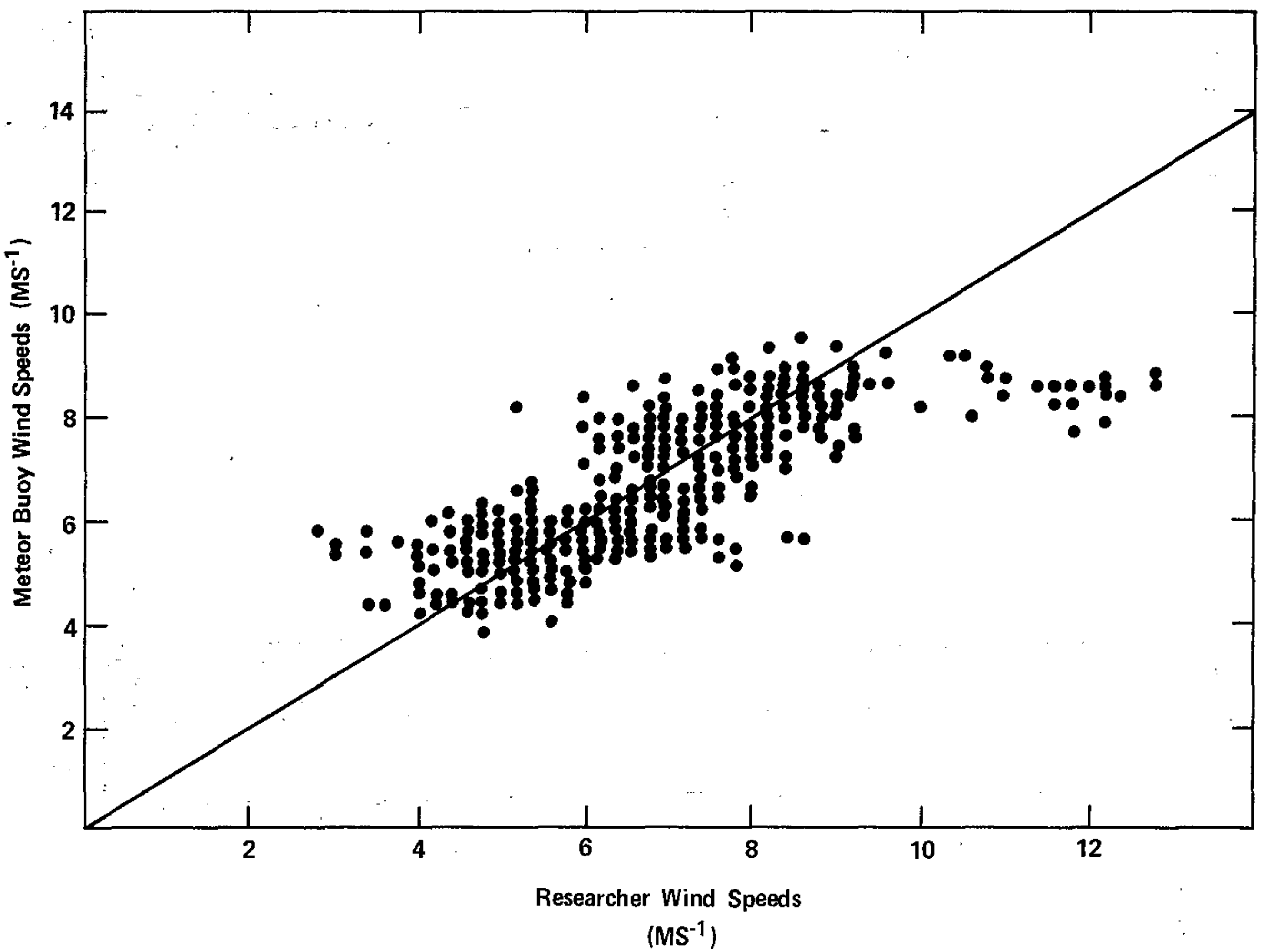

Figure 6.--Scatter diagram of the surface atmospheric wind speed observations from the Meteor buoy and the Researcher boom instruments for Intercomparison 1.

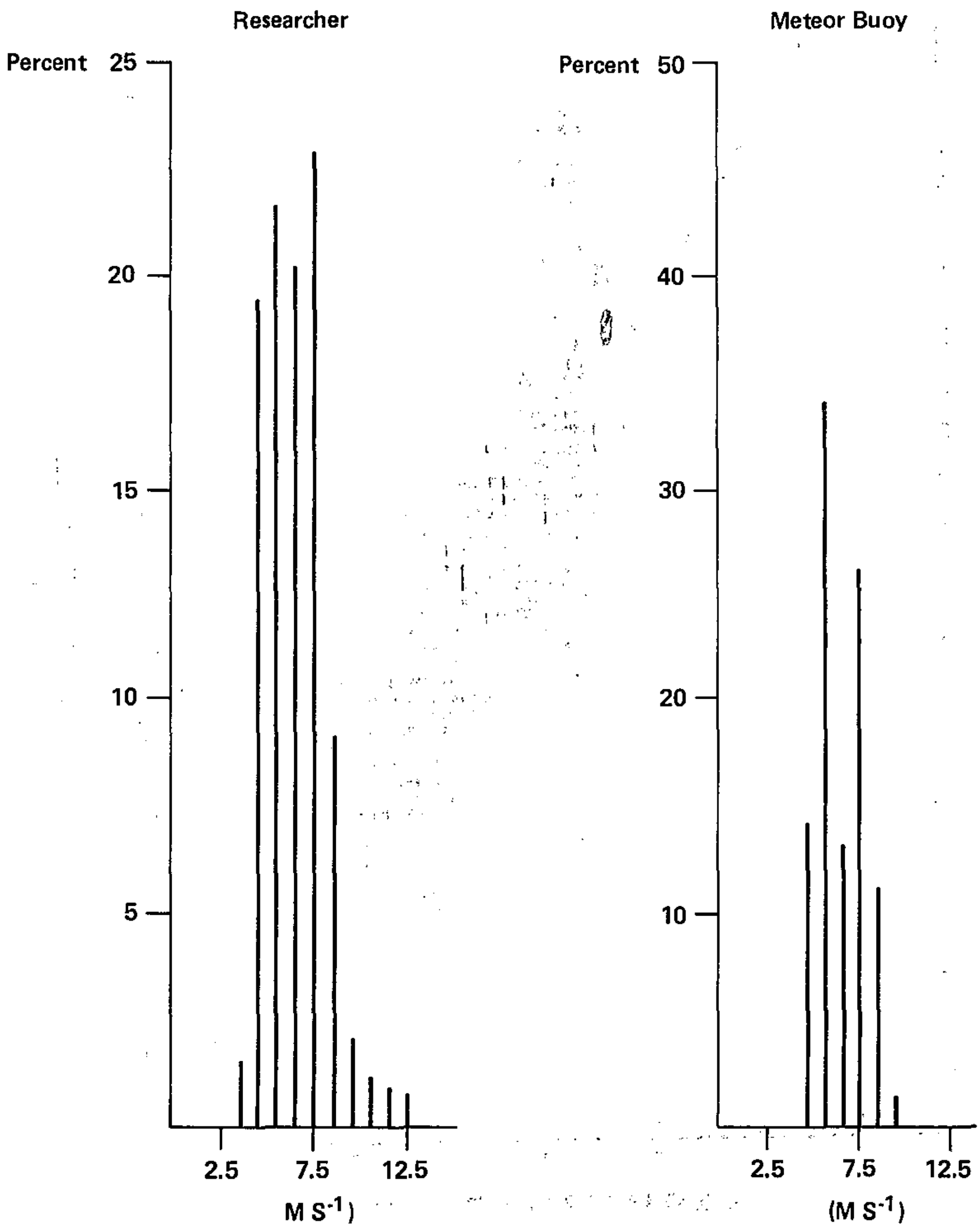

Figure 7.--Frequency distribution of wind speeds from the Meteor buoy and the Researcher boom instruments for Intercomparison 1.

6.2 Results of Type 2 Wind Speed Intercomparison Analysis

Table 19 lists the Type 2 wind speed average differences and the standard deviations of the differences. All these data were derived from sensors mounted 10 to 20 m higher than the sensors on the buoy, and no height corrections have been made for the Type 2 data. The standard deviations of the differences are somewhat larger than for the Type 1 data sets.

As mentioned earlier, the Type 1 observations represent continuous information recorded automatically, while the Type 2 observations were made once every 15 or 30 min and were manually recorded.

6.3 Results of Type 1 and Type 2 Wind Velocity Intercomparison Analysis

Table 20 shows the wind direction and speed corrections, which in the mean adjust the Type 1 wind velocity data of the various ships to the reference data sets. The *Meteor* buoy wind velocity measurements served as reference during IC-1, 2, and 3B, and the *Oceanographer* boom sensor during IC-3A. The wind direction factors shown are the angles in degrees that must be added to the ship record to adjust to the buoy wind directions. The speed correction factor is the number the ship winds must be multiplied by in order to adjust to the buoy.

An examination of all the wind direction correction factors (derived from Type 1 and Type 2 data sets) suggested that there was a shift in the calibration of the *Meteor* buoy wind direction sensors or of the compass aboard the buoy between the three Intercomparison periods. The FRG National Processing Center has indicated that, in fact, the buoy was placed in the water before each GATE Phase and Intercomparison except IC-2. For IC-2, the *Meteor* buoy's Phase 2 position was chosen as the Intercomparison site, making it unnecessary to remove the buoy from the water.

Because of possible changes in the calibration of the buoy wind direction data from one IC to another, these data should be used only in a relative, rather than an absolute, sense. It should be mentioned that the *Researcher* Type 1 mast wind direction sensor was adjusted after IC-1 and the results presented here therefore bear no relationship to the data obtained from this sensor during the subsequent observation phases. The *Planet* boom wind directions are questionable because of a lack of good ship heading data.

Table 21 shows the wind direction and speed correction factors for the Type 2 wind observations.

6.4 Averages and Standard Deviations of the Wind Directions for the Type 1 and Type 2 Data Sets

In order to provide some measure of the variability of the wind direction data, separately and independently, the averages and standard deviations of the Type 1 and Type 2 data sets were calculated. Table 22 shows the statistics for the Type 1 data. Although the average winds as measured by the different ships show considerable variation, the standard deviations of these directions are remarkably similar. This is true despite the fact that the ships moved around the IC arrays and were occasionally in unfavorable

Table 19.--Intercomparison of Type 2 wind speeds showing average differences and the standard deviations of the differences between the Type 2 ship wind speeds and the Meteor buoy, except where noted

Ship	IC period	Average difference ($m\ s^{-1}$)	Standard deviation of the differences ($m\ s^{-1}$)	No. of samples
Reseacher	1	0.41	0.86	167
"	2	0.73	0.95	118
"	3B	0.97	0.78	105
Gilliss	1	-0.20	0.70	82
"	2	-----	----	---
"	3B	-0.10	0.90	115
Dallas	1	1.27	1.68	106
"	2	1.69	1.74	115
"	3B	-----	----	---
Oceanographer	1	-0.65	0.89	103
"	2	-0.19	1.12	116
"	3A	0.04*	0.83	90
Quadra	1	-0.38	0.66	91
"	2	-0.12	0.83	105
"	3A	0.18	0.72	91
Meteor	1	0.45	0.52	46
"	2	-0.27	1.29	107
"	3B	0.28	0.51	95
Planet	3A	-0.10*	0.59	45
Fay	3A	0.25*	0.59	25
Korolov	A1A	-----	----	---
"	2	-0.39	1.06	107
"	3B	0.06	0.67	93
Okean	A1A	0.30†	1.02	33
"	2	-0.32	1.32	107
"	3B	0.00	0.69	95
Priboy	A1A	0.41†	1.08	111
"	2	0.01	1.75	99
"	3B	0.27	0.62	95

Table 19.--(continued)

Ship	IC period	Average difference (m s^{-1})	Standard deviation of the differences (m s^{-1})	No. of samples
Vize	1	-0.56	0.70	91
"	2	-0.55	0.80	107
"	3A	-0.48*	0.76	91
Krenkel	1	-0.88	0.92	91
"	3A	-0.42*	0.65	91
Zubov	1	-0.69	1.68	91
"	2	-0.62	1.71	107
"	3A	0.13*	1.33	91
Musson	1	-0.24	1.87	91
"	2	0.74	2.76	107
"	3A	0.65*	0.91	85
Poryv	1	-0.45	0.74	91
"	3B	-0.05	0.50	94
Bidassoa	3B	-0.55	0.69	89

* Oceanographer boom wind speed data used as reference during IC-3A.

† Korolov Type 2 data used as reference during IC-A1A.

Table 20.--Wind speed and direction factors for the Type 1 data sets (direction factors are in degrees and speed factors are dimensionless)

Ship	IC period	Direction factors		Speed factors		No. of samples	
		Boom	Mast	Boom	Mast	Boom	Mast
Researcher	1	-12.2	-12.2	0.99	0.92	832	863
"	2	- 8.2	- 6.9	1.02	0.96	968	968
"	3B	2.9	- 4.4	1.08	1.03	929	930
Gilliss	1	-12.7	-10.2	1.03	1.09	604	605
"	3B	- 8.2	2.8	1.10	1.12	878	878
Dallas	1	1.0	- 0.4	1.01	0.95	578	531
"	2	- 2.1	- 2.1	1.16	0.98	987	987
Oceanographer	1	-12.5	-12.1	0.96	0.93	782	800
"	2	-10.3	-13.5	1.05	0.98	1,005	1,012
"	3A	-----	1.7*	----	0.98*	---	893
Quadra	1	- 3.1	-----	0.99	----	77	--
"	2	-26.8	-----	1.24	----	88	--
Planet	3A	23.1*	-----	1.95*	----	90	--

* Oceanographer Type 1 boom wind velocities used as reference during IC-3A.

Table 21.--Wind speed and direction factors for the Type 2 data sets (direction factors are in degrees and speed factors are dimensionless)

Ship	IC period	Direction factors	Speed factors	No. of samples
Researcher	1	- 3.8	1.09	168
"	2	- 7.4	1.14	118
"	3B	+ 4.8	1.53	105
Gilliss	1	-21.4	0.99	83
"	3B	+ 6.0	1.03	115
Dallas	1	- 1.0	1.33	103
"	2	+ 1.3	1.47	115
Oceanographer	1	- 4.8	0.92	100
"	2	-12.9	0.99	116
"	3A	- 3.4*	1.00*	90
Quadra	1	+ 0.9	0.95	91
"	2	- 0.5	1.01	105
"	3A	+16.1*	1.31*	91
Meteor	1	- 6.5	1.11	45
"	2	- 6.8	1.07	107
"	3B	+ 2.2	1.11	94
Planet	3A	+20.9*	1.07*	25
Fay	3A	+34.4*	1.47*	26
Korolov	2	- 6.6	0.97	107
"	3B	- 1.4	1.29	92
Okean	A1A	-13.0†	1.09†	33
"	2	- 1.5	0.99	107
"	3B	+ 9.1	1.07	95
Priboy	A1A	-13.5†	1.15†	110
"	2	-12.9	1.05	99
"	3B	- 0.4	1.24	94
Vize	1	- 5.2	0.94	90
"	2	-20.3	0.95	107
"	3A	+ 3.0*	1.06*	91

Table 21.--(continued)

Ship	IC period	Direction factors	Speed factors	No. of samples
Krenkel	1	+ 2.8	0.90	91
"	3A	+24.7*	1.17*	91
Zubov	1	+ 2.1	0.92	90
"	2	+ .8	0.96	107
"	3A	- 4.0*	1.14*	91
Musson	1	+ 1.6	0.97	91
"	2	- 5.9	1.18	107
"	3A	+15.7*	1.78*	85
Poryv	1	- 9.6	0.94	91
"	3B	- 1.7	1.08	94
Bidassoa	3B	-27.2	1.05	89

* Oceanographer Type 1 boom wind velocities used as reference during IC-3A.

† Korolov Type 2 mast wind velocities used as reference during IC-A1A.

Table 22.--Averages and standard deviations of Type 1 wind directions for boom and mast sensors

Ship	Average direction (deg.)		Standard deviation (deg.)		No. of samples	
	Boom	Mast	Boom	Mast	Boom	Mast
			Intercomparison 1			
Researcher	11	11	17	18	1101	1149
Gilliss	14	15	15	19	807	780
Dallas	357	354	19	14	640	568
Oceanographer	10	9	14	14	1007	1025
Meteor buoy	---	1	--	17	----	1086
Quadra	3	---	22	--	334	----
			Intercomparison 2			
Researcher	272	270	40	41	1069	1069
Dallas	265	265	40	40	1077	1077
Oceanographer	269	272	36	37	1171	1177
Meteor buoy	---	260	--	36	----	1059
Quadra	292	---	53	--	313	----
			Intercomparison 3			
Researcher	232	238	54	55	1004	1005
Gilliss	245	234	51	51	953	953
Oceanographer*	168	165	89	89	894	943
Meteor buoy	---	235	--	61	----	941
Planet	94	---	83	--	293	----

* These ships participated in IC-3A, the others in IC-3B.

attitudes relative to the wind to properly measure the wind direciton. The larger wind direction standard deviations of IC-2 and IC-3 reflect the atmospheric disturbances and squalls that passed through during the Intercomparison periods.

The Type 2 averages and standard deviations of the wind directions are shown in table 23. Again the standard deviations are remarkably similar within each IC, and also compare favorably with the Type 1 wind direction results.

6.5 Summary of the Wind Velocity Data

Three sets of statistics have been presented for the wind velocity data. Most of the data sets contain biases relative to the reference data sets, resulting primarily from the following causes:

(1) Sensors being located at different heights above sea level.
(2) Sensors degrading with time.
(3) Inaccurate specification of the ship velocities that are used to correct the wind velocities.
(4) Modification of the wind flow over and around the ship.
(5) Sensor orientation and calibration changes.

The large amount of variance associated with naturally varying wind velocities has made it difficult or impossible to identify biases that varied with time. In addition, some of the above causes are themselves functions of wind speed and the orientation of the ship to the approaching winds. All of these statistics have been calculated without regard to these variables, and, therefore, have served to illustrate the total or combined effect of all of the potential sources of biases.

Table 23.-- Average and standard deviation of Type 2 wind directions for boom and mast sensors

Ship	Average direction (deg.)	Standard deviation (deg.)	No. of samples
	Intercomparison 1		
Researcher	4	20	159
Gilliss	31	12	86
Dallas	6	21	95
Oceanographer	9	21	114
Quadra	360	19	114
Meteor	8	15	66
Korolov*	82	28	113
Okean*	68	17	39
Priboy*	96	23	108
Vize	12	20	96
Krenkel	359	18	113
Zubov	1	19	95
Musson	1	20	100
Poryv	15	20	107
	Intercomparison 2		
Researcher	266	36	125
Dallas	265	37	126
Oceanographer	272	40	130
Quadra	259	38	118
Meteor	266	29	156
Korolov	266	37	118
Okean	262	40	119
Priboy	274	37	103
Vize	275	33	126
Zubov	258	39	121
Musson	262	29	104
	Intercomparison 3		
Researcher	226	58	67
Gilliss	230	48	123
Oceanographer†	174	71	56
Quadra†	145	36	74
Meteor	234	56	104
Planet†	81	94	45
Fay†	293	72	26
Korolov	194	61	100
Okean	219	57	97

Table 23.--(continued)

Ship	Average direction (deg.)	Standard deviation (deg.)	No. of samples
Priboy	231	53	89
Vize†	169	84	84
Krenkel†	178	92	91
Zubov†	172	71	44
Musson†	155	58	35
Poryv	226	59	101
Bidassoa	193	48	101

* These ships participated in IC-A1A.

† These ships participated in IC-3A.

7. CONCLUDING REMARKS

The GATE Convection Subprogram Data Center (CSDC) has calculated and analyzed basic statistics for surface meteorological data sets collected on the GATE A/B, B, and C scale ships. The CSDC has also assembled a limited amount of information concerning meteorological sensors and data acquisition procedures used during the experiment. This report represents a summary of the results.

The intercomparisons of the GATE ship surface meteorological observations have produced a description of the data that can be used to establish general limits of accuracy achieved in the observations. Because of the nature of the intercomparisons, only relative difference statistics could be calculated and these differences are functions of the general varying meteorological conditions from Intercomparison 1 through 3.

Three types of biases have been defined in this report: The constant, or fixed offset, bias; the time-varying bias; and the drift. Where possible, specific biases in the data sets have been described in these terms and probable causes discussed. The average differences between the reference data sets and the individual data sets represent reasonable adjustment factors for the normalization of the data to the reference data, provided the bias is constant with time and does not change significantly from one Intercomparison to another. A significant change can only be defined in terms of the intended use of the data. For those data sets which are indicated in the tables as having relatively large time varying biases, or for which the standard deviations of the differences are large, or if the data contain drifts, the average difference may be a misleading statistic.

The GATE formal ship comparisons have provided a wealth of information on the characteristics of the GATE ship surface meteorological observations and the relationships between differing observation systems. The data collected during these periods will provide valuable insight for dealing with specific questions that will arise with the continued use of the GATE data.

ACKNOWLEDGMENT

The Convection Subprogram Data Center would like to acknowledge each of the National Processing Centers for the documentation they provided with their data and for information they made available in response to direct communication.

APPENDIX A

Table A-1.--Ships and Intercomparison periods

Ship		Intercomparison period A1A	1	2	3A	3B
	Canada					
Quadra			X	X	X	
	FRG					
Meteor			X	X		X
Planet					X	
	US					
Researcher			X	X		X
Gilliss			X			X
Dallas			X	X		
Oceanographer			X	X	X	
Fay*					X	
	USSR					
A. Korolov		X		X		X
Okean		X		X		X
Priboy		X		X		X
Prof. Vize			X	X	X	
E. Krenkel			X		X	
Prof. Zubov			X	X	X	
Musson			X	X	X	
Poryv			X			X

* The surface meteorological data processed by the Federal Republic of Germany.

APPENDIX B

Table B-1.--Inventory of the Intercomparison data

National Processing Center	Ship	Date data received	IC	Type of data	Frequency of data
Type 1 data-automatically observed and recorded					
Canada	Quadra	9/2/75	1,2,3A	Microbarograph pressures	hourly
"	"	9/2/75	1,2,3A	Dry-and wet bulb temperatures (boom)	20-min averages
"	"	1/2/76	1,2,3A	Wind speeds and directions	10-min averages
		1/2/76	2	Sea temperature	30-min averages
FRG	Meteor buoy	6/7/75	1,2,3B	Dry-bulb, wet-bulb, and sea surface temperatures; wind speeds and directions	3-min averages
"	Meteor	3/1/76	1,2,3B	Digibar pressures	
"	Planet	6/18/75	3A	Boom dry-bulb, wet-bulb and	10-min averages
				boom wind speeds and directions;	
"	"			digibar pressures	10-min averages
US	Researcher	2/30/76	1,2,3B	Boom dry-bulb,	3-min averages
	Gilliss	"	1,3B	wet-bulb, and	
	Dallas	"	1,2	sea surface	
	Oceanographer	"	1,2,3A	temperatures; wind speeds	

Table B-1.--(continued)

National processing Center	Ship	Date data received	IC	Type of data	Frequency of data
Type 2 data-Manually observed and recorded					
Canada	Quadra	3/26/75	1,2,3A	Standard WMO marine observations	hourly
FRG	Meteor	4/19/75	1,2,3B	Bulk surface observations	30-and 60-min observations
	Planet	"	3A		
	Fay	"	3A		
US	Researcher	9/11/75	1,2,3B	Standard WMO marine observations	15-and 30-min observations
	Gilliss	"	1,3B		
	Dallas	"	1,2		
	Oceanographer	"	1,2,3A		
USSR	Musson	6/2/75	1,2,3A	WMO marine observations	15-and 30-min observations
	Korolov	"	A1A,2,3B		
	Vize	"	1,2,3A		
	Krenkel	"	1,3A		
	Zubov	"	1,2,3A		
	Okean	"	A1A,2,3B		
	Priboy	"	A1A,2,3B		
	Poryv	"	1,3B		

APPENDIX C
A STATISTICAL TECHNIQUE FOR THE ANALYSIS AND COMPARISON OF WIND OBSERVATION RECORDS

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John B. Jalickee

ABSTRACT. Wind observations from shipboard anemometry systems are compared. The records of wind speed and direction from one independent measuring system are treated as a population of vector quantities which are adjusted by speed and direction factors. These factors are determined by requiring the sum of the squared magnitudes of the vector differences between the paired observations of the first and of a second system to be minimum. An estimate of the vector standard deviation of these factors is computed and a technique for evaluation of the significance of deviation of factors in data subgroups is demonstrated.

1.0 INTRODUCTION

During the Global Atmospheric Research Program, Atlantic Tropical Experiment (GATE), wind direction and speed were measured on U.S. GATE ships by two independent shipboard observation systems. The sensors for one system were mounted on the ship's mast and the second system sensors were mounted on the ship bow-boom. Although these wind records were obtained under unique circumstances, the techniques used in analysis and comparison of these wind records are applicable to the analysis of wind records from any source.

By common experience, wind observation systems are expected to measure speed and direction with error which, one hopes, does not compromise the intended data usage. Our technique for wind analysis concerns a comparison of one wind observation record with a second. Such an analysis will permit deductions concerning data quality to be couched in terms of the relative variances between compared records. This analytical method indicates the probable existence of error, an estimate of intrasystem variance, and an estimate of confidence to be placed on a deduction concerning the magnitude of the variance.

Errors in measured wind direction and speed may be correlated; therefore observation analysis may not treat wind speed or direction separately, and variances between compared records will be considered here as vector quantities.

In our comparison of sets of wind observations, we seek direction and speed adjusting factors which may be used to change the wind observations in one set such that the sum of squared vector differences between the sets is a minimum. It will be assumed that the differences in wind measurements consist of a uniformerly occurring bias and a random error. In Section 4 of this paper it will be shown that the assumption of a uniform bias in all portions of the data set is not exclusive, and bias-caused data inhomogenety is detected by our analysis method. Our adjustment factors will be our estimate of the effect of the relative uniform bias from one system to the other. In practice, knowledge of this bias could permit application of corrections to be made to a data set. In the least, however, the simple recognition of the existence of bias is itself of frequent interest.

2.0 Wind Vector Differences

a. Nomenclature

Subscript numbers will be used to designate different data groups and subscript letters will identify specific data within a group. Superscript * identifies a complex conjugate. Superimposed ^ will indicate an estimated quantity and $\rightarrow$ a vector quantity.

ρ = the magnitude of a wind.

η = the magnitude of wind adjustment factor.

θ = the observed wind direction.

ϕ = a direction difference factor

i = $\sqrt{-1}$

δ = Kronecker's delta

ε = random differences

$|\vec{R}_{kj}|$ = magnitude of jth vector in group k.

$\langle R_K \rangle$ = average of vectors in group k.

$\{\vec{R}_{kj}\}$ = a set of N vectors, group k.

b. Analysis of Wind Vectors

The elements of a set of N wind vectors, $\{\vec{R}_j\}$, are expressed in complex notation by

$$R_j = \rho_j \exp \, i\,\theta_j$$

where ρ_j, θ_j are the speed and direction of the jth vector. The set $\{\vec{R}_{1j}\}$ will be compared to a second set $\{R_{2j}\}$ to which constant correctio to speed and direction are applied. These corrections are assumed to reflec consistant differences between the two sets. In particular we assume

$$\rho_{1j} \exp\left[i\theta_{1j}\right] = \eta\rho_{2j} \exp\left[i(\theta_{2j} + \phi)\right] + \varepsilon_j \tag{1}$$

where η and ϕ are the speed and direction correction factors, and the complex quantity ε_j denotes the random error of observation. The best esti mate of η and ϕ will be defined to be those values $\hat{\eta}$ and $\hat{\phi}$ whi make the sum of squared absolute differences between $\vec{R}_{1j}$ and $\vec{R}_{2j}$ a minimu Therefore:

$$\sum_{j=1}^{N} \left| \rho_{ij} \exp\, i\theta_{1j} - \eta\rho_{2j} \exp\, i(\theta_{2j} + \phi) \right|^2 = \mathrm{MIN}(\eta, \phi) = A. \tag{2}$$

After expanding the square in eq (2) and employing the identity eq (2) is as follows:

$$\sum_{j=1}^{N} \left[\rho_{1j}^2 + \eta^2 \rho_{2j}^2 - \eta\rho_{1j}\, \rho_{2j} 2 \cos(\theta_{1j} - \theta_{2j} - \phi)\right] = A. \tag{3}$$

Minimizing eq (3) first with respect to η gives

$$\frac{\partial A}{\partial \eta} = 2\sum_{j=1}^{N} \left[\eta\rho_{2j}^2 - \rho_{1j}\, \rho_{2j} \cos(\theta_{1j} - \theta_{2j} - \phi)\right] \tag{4}$$

$$\hat{\eta} = \frac{\sum^{N} \rho_{1j}\, \rho_{2j} \cos(\theta_{1j} - \theta_{2j} - \hat{\phi}).}{\sum \rho_{2j}^2} \tag{5}$$

Equation (3) is next minimized with respect to ϕ,

$$\frac{\partial A}{\partial \phi} = \sum_{j=1}^{N} - 2\, \eta\rho_{1j}\, \rho_{2j} \sin(\theta_{ij} - \theta_{2j} - \hat{\phi}). \tag{6}$$

By designating the angular difference $\theta_{1j} - \theta_{2j} =$ eq (6) may be transformed by use of the trigonometric identity $\sin(\alpha \pm \phi) = \sin\alpha \cos\phi - \cos\alpha \sin\phi$:

$$\sum_{j=1}^{N} \rho_{1j}\ \rho_{2j}\ 2\hat{\eta} \left[\mathrm{SIN}\ \alpha_j\ \mathrm{COS}\ \hat{\phi} - \mathrm{COS}\ \alpha\ \mathrm{SIN}\ \hat{\phi}\right] = 0. \qquad (7)$$

This equation may be rearranged and solved for ϕ

$$\hat{\phi} = \mathrm{ARCTAN}\left[\sum_{j=1}^{N} \rho_{1j}\ \rho_{2j}\ \mathrm{SIN}\alpha_j \Big/ \sum_{j=1}^{N} \rho_{1j}\ \rho_{2j}\ \mathrm{COS}\alpha_j\right]. \qquad (8)$$

3.0 STATISTICAL CHARACTERISTICS OF DIFFERENCE MINIMIZING FACTORS

We have assumed that the difference between $\{\vec{R}_{1j}\}$ and $\{\vec{R}_{2j}\}$ are produced by some regular bias in the wind measuring systems producing the wind data sets and some random error.

It is, of course, not possible to completely isolate these two sources of differences between our wind data sets, and repeated estimates of η and ϕ using different data sets from the two wind measuring systems will vary because of random error. We seek an estimate of this variance of $\hat{\eta}$ and $\hat{\phi}$ associated with our estimates of η and ϕ. The difference minimizing factors η and ϕ may be expressed in vector notation in complex coordinates. From eq (1),

$$\eta\rho e^{i(\theta + \phi)} = \eta e^{i\phi} \cdot \rho e^{i\theta} = Z\rho e^{i\theta}. \qquad (9)$$

If $\rho e^{i\theta}$ is assumed to be a constant, we may refer to statistics of the vector $\vec{Z} = \eta_e{}^{i\phi}$. The standard deviation expected in our estimates $\hat{\eta}$ and $\hat{\phi}$ will be expressed as a vector standard deviation of $\vec{Z}$.

Assuming that the frequency of any particular wind vector within a data set is described by a discrete probability function, the means of larger and larger subsets of the data (drawn by random selection with replacement from the full data set) are expected to approach the mean of the full set (Parzen 1963). Analogically, we have found that the magnitude of difference minimizing vectors, $\vec{Z}$, computed from progressively larger and larger data subsets, approach the magnitude of the difference minimizing vector computed from the full set. This does not imply that the vector standard deviation between difference minimizing vectors, computed from repeated subsets of a size N, approaches zero. However, using methods of statistical inference (Jenkins and Watts 1968) at 95% probability confidence interval for our statistical tests, we find that from subsets of our data of size one-half the full set there is no statistically significant difference between the magnitudes of the computed difference minimizing vectors for either half set. Therefore, a practical size limit for subsets, formed for computation of vector standard directions, is equal to one-half the full set. Graphical plots of difference minimizing vectors in polar coordinates indicate that the difference minimizing vectors from multiple subsets of size N = 50 are circularly distributed. Although this would imply no correlation between the minimizing factors $\hat{\eta}$ and $\hat{\phi}$, we find that there is indeed a probable correlation between these factors when data subsets are formed not by random selection processes but formed from criteria based on wind direction relative to ship heading. The analysis of difference minimizing vectors from data sets of sorted data (such as wind direction sorted according to ship head) will be presented in Section 4.0, "Computation of Statistical Parameters and Significance of Difference Minimizing Factors from Small Data Subsets."

The vector standard deviation S of difference minimizing vectors computed from multiple data subsets of size N can be shown to be related to the vector standard deviation S of difference minimizing vectors computed from data subsets of size N. That is,

$$S' / \sqrt{N'} = S \sqrt{N} \tag{10}$$

closely describes the relationship between these vector standard deviations when the subsets of data are randomly selected from the same large data source. In practical application, the utility of eq 10 is where N and N′ are within the small subset size range of about 5 to 50. In Figure 1, we have graphed the vector standard deviation of difference minimizing vectors for each group of 50 subsets of size N = 50, 45, 40, 35, etc., with the number of observations pairs (N) in each subset. It is evident from this graph that with subsets of size 50, the vector standard deviation of the computed differenc minimizing vectors is changing little with increased subset size. Therefore, for practicality, we will use the vector standard deviation at subset size 50 as the vector standard deviation of the full, large data set from which the subsets were drawn.

4.0 COMPUTATION OF STATISTICAL PARAMETERS AND SIGNIFICANCE OF DIFFERENCE MINIMIZING FACTORS FROM SMALL DATA SUBSETS

Sorting wind data into catagories according to wind direction and wind speed can be helpful in determination of causes of bias. Formulation of data subgroups through sorting may, however, produce some data sets which contain small amounts of data. The analyst must decide if the characteristics of data within a special data subgroup are unique because they exhibit the effect of a bias or, if the set size be small, could the observed data characteristics to be expected from a small data set? The following example of such an analysis problem will illustrate the usefulness of the difference minimizing factors and interpretation of the variation of factors from among subsets.

Wind observations from bow-boom and mast-mounted wind sensors aboard the U.S. ship Researcher were compared and the difference minimizing factors η and ϕ were computed for an observation period (GATE Intercomparison Period 3) during which 1004 observations were obtained with a time resolution of 3 minutes. The factor η was found to be 0.952 and $\hat{\phi}$ equal to -7.371 degrees. (Mast wind direction plus -7.371 degrees ≃ boom measured wind direction). From 50 subsets of 50 paired boom and mast wind observations, the vector standard deviation was estimated to be 0.0113.

These same 1004 paired observations of wind from the Researcher's boom and mast sensors were sorted into direction sections in which the wind struck the ship and according to high (>2.5 meters/sec) and low speed (< 2.5 meters/sec). The direction sectors are illustrated in Figure 2. Difference minimizing factors $\hat{\eta}$ and $\hat{\phi}$ for each of the sorted catagories of data are shown in Table 1. We note, from Table 1, that the speed adjustment factor in the third sector of wind direction for both high and low speed groups is lower than the factors for other sectors.

Since the third sectors of relative direction include cases where the wind is on the stern of the ship, we may hypothesize that the bow-boom sensors would measure such wind speeds with a bias; i.e., consistently measure wind of too low a speed. Therefore, the value of η, the vector speed ratio between mast-and boom-measured wind, would indicate the greatest speed differences for these cases. The frequency of cases in the third sector are low and we would like to know if the 0.858 factor for low speed or the 0.906 factor for high speed is significantly different from the 0.952 factor for unsorted wind data to support the hypothesis of bias. To make the test of significance we may employ the Students "t" test wherein, for example, we show calculation in the test of significance of the low speed factor 0.858.

$$t = (0.952-0.858)/S_{19} = 5.134 \qquad (11)$$

where S_{19} is the standard vector deviation found for 50 values of $\vec{Z}$ from 50 subsets of randomly selected data (of size equal to 19 paired observations) out of our field data set 1004 paired observations $S_{19} \simeq 0.018$. The value of S_{19} based on eq (10) may be expressed as

$$S_{19} = S_{50} \sqrt{50/19} \; . \qquad (12)$$

From a table of "t" values we find that such a difference (0.952-0.858) would be expected by chance to occur less than 5% of the time, therefore the hypothesis of bias in wind observations for this subgroup is supported. Although the hypothesis is not supported for data from the 150° - 210° sector at high speed at a confidence level of 95%, it is supported at a confidence level of 90%.

5.0 Tests of Statistical Significance

In the development of analysis procedures presented in Section 2.0 of this paper, it was assumed that differences in the compared wind observation data sets were due to a constant bias of all data and random error. Subsequently, in Section 4.0, we discovered that a non-uniform bias in the wind observations probably existed. Therefore, it would seem that there is a probable violation of the premise upon which the difference analysis is based. We shall show, through significance tests based on statistical inference, that our deductions concerning the uniqueness of some special data subsets are valid despite an apparent non-uniform data bias.

With a confidence level at 95% for our tests, we seek the expected ranges of magnitude of the individual difference minimizing factors estimated from each of the special data subsets. Overlapped ranges of these parameters will constitute a conclusion of no statistically significant difference between the parameters and, a conclusion that data from which these parameters were computed are statistically similar.

If η is the magnitude of the difference minimizing factor, then its range in magnitude may be estimated as $\eta \pm t\ \hat{S}(\eta)$ where t is the students t at a confidence level of 95% for data set of N paired observations and $\hat{S}(\eta)$ is the estimated standard deviation of η. We assume that all random differences, ε, which remain between compared sets $\{\vec{R}_{1j}\}$ and $\{\vec{R}_{2j}\}$ after application of the difference minimizing vector as a correction factor, are associated with $\{R_{1j}\}$.

To facilitate the derivation $\hat{S}(\eta)$, reformulate the statistical calculations in terms of complex quantities. The winds are assumed to be expressed as before.

$$R_{1j} = Z\ R_{2j} + \varepsilon_j$$

and random differences ε_k, $k = 1$ to j, is uncorrelated and normally distributed. Therefore,

$$\langle \varepsilon_j \rangle = 0$$

$$\langle \varepsilon_j\ \varepsilon_k \rangle = S^2\ \delta_{jk}$$

the least square estimate of $\vec{Z}$ follows from $\underset{(\hat{Z}^*)}{\mathrm{MIN}} \sum_{j=1}^{N} \left| R_{1j} - \hat{Z}\ R_{2j} \right|^2.$

Therefore, $\hat{Z} = \sum_{j=1}^{N} R^*_{2j}\ R_{1j} \Big/ \sum_{j=1}^{N} \left| R_{2j} \right|^2$ and, by

similar procedures, $\hat{Z}^* = \sum_{j=1}^{N} R^*_{1j}\ R_{2j} \Big/ \sum_{j=1}^{N} \left| R_{2j} \right|^2$

$$\mathrm{VAR}\ (Z) = \Big\langle (Z - \langle Z \rangle)\ (Z^* - \langle Z^* \rangle) \Big\rangle$$

Substituting from above: $$\mathrm{VAR}(Z) = \left\langle \left(\frac{\sum R_{2j}^* R_{1j}}{\sum |R_{2j}|^2} - \frac{\sum R_{2j}^* R_{1j}}{\sum |R_{2j}|^2} \right) \left(\frac{\sum R_{2k} R_{1k}^*}{\sum |R_{2k}|^2} - \frac{\sum R_{2k} R_{1k}^*}{\sum |R_{2k}|^2} \right) \right\rangle$$

$$\mathrm{VAR}(Z) = \left\langle \left(\frac{\sum R_{2j}^* (\varepsilon_j)}{\sum R_{2j}^{\;2}} \right) \left(\frac{\sum R_{2k} (\varepsilon_k^*)}{\sum |R_{2j}|^2} \right) \right\rangle$$

where sums are taken from j and k = 1 to N and

$$R_{1j} - \langle R_1 \rangle = R_{1j} - \langle Z \rangle R_{2j} = \varepsilon_j$$

$$\mathrm{VAR}(Z) = \left\langle \frac{\sum R_{2j} \sum R_{2k}\, \hat{S}^2\, \delta_{jk}}{\left(\sum |R_{2j}|^2\right)^2} \right\rangle$$

$$\mathrm{VAR}(Z) = \hat{S}^2 \Big/ |R_{2j}|^2$$

$$\hat{S}^2 = |R_{1j} - \hat{Z} R_{2j}|^2 \Big/ (N - 1)$$

$$S(\eta)^2 = \hat{S}^2 \Big/ |R_{2j}|^2$$

$$\hat{S}^2 = \sum (R_{1j} - \hat{Z} R_{2j})(R_{1j}^* - Z^* R_{2j}) \Big/ (N - 1).$$

Therefore: $$\hat{S}(\eta)^2 = \sum |R_{1j}|^2 - |Z|^2 |R_{2j}|^2 \Big/ (N - 1) \sum |R_{1j}|^2.$$

The estimated range of the magnitude of the difference minimizing vector is

$$\eta \pm t \sqrt{\hat{S}(\eta)^2 \sum |R_{2j}|^2}.$$

In Table 2 the estimated ranges of η at a confidence level of 95% are listed. From these ranges, it may be shown that the expected ranges of η for the direction sectors 150° - 210° and 210° - 270°, for low speed cases, do not overlap the ranges expected for the large data set from which these subsets were drawn nor do the ranges over lap the range of η for the 270° - 90° sectors. Therefore it must be concluded that data within these low speed data subsets are probably different from the data in the large data set. This conclusion is the same as derived from the statistical tests presented in Section 4.0 of this paper and therefore nonhomogeneous bias in our data is not consequential to our data analysis and conclusions.

6.0 CONCLUSIONS

The difference minimizing factors for speed given in Table 1 indicate that the mast-mounted wind sensors consistently measured wind speed greater than the speed measured by the bow-boom sensors because the factors for are all less than 1.0. The speed factors in the subgroup of data for wind of low speed following the ship were found to be significantly different from the factor relating speeds from boom and mast for unsorted wind data. Therefore, in addition to a bias in wind speed measurement of the order of 5%, an additional bias probably exists in the speed measurements for the case of "ship following" wind.

The difference minimizing factors for direction, ϕ, are all negative in Table 1, which indicates that there is a consistent bias in wind direction measurements from the ship sensors. The negative factors indicate that the mast-measured directions were consistently measured greater (clockwise) than the boom-measured directions.

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