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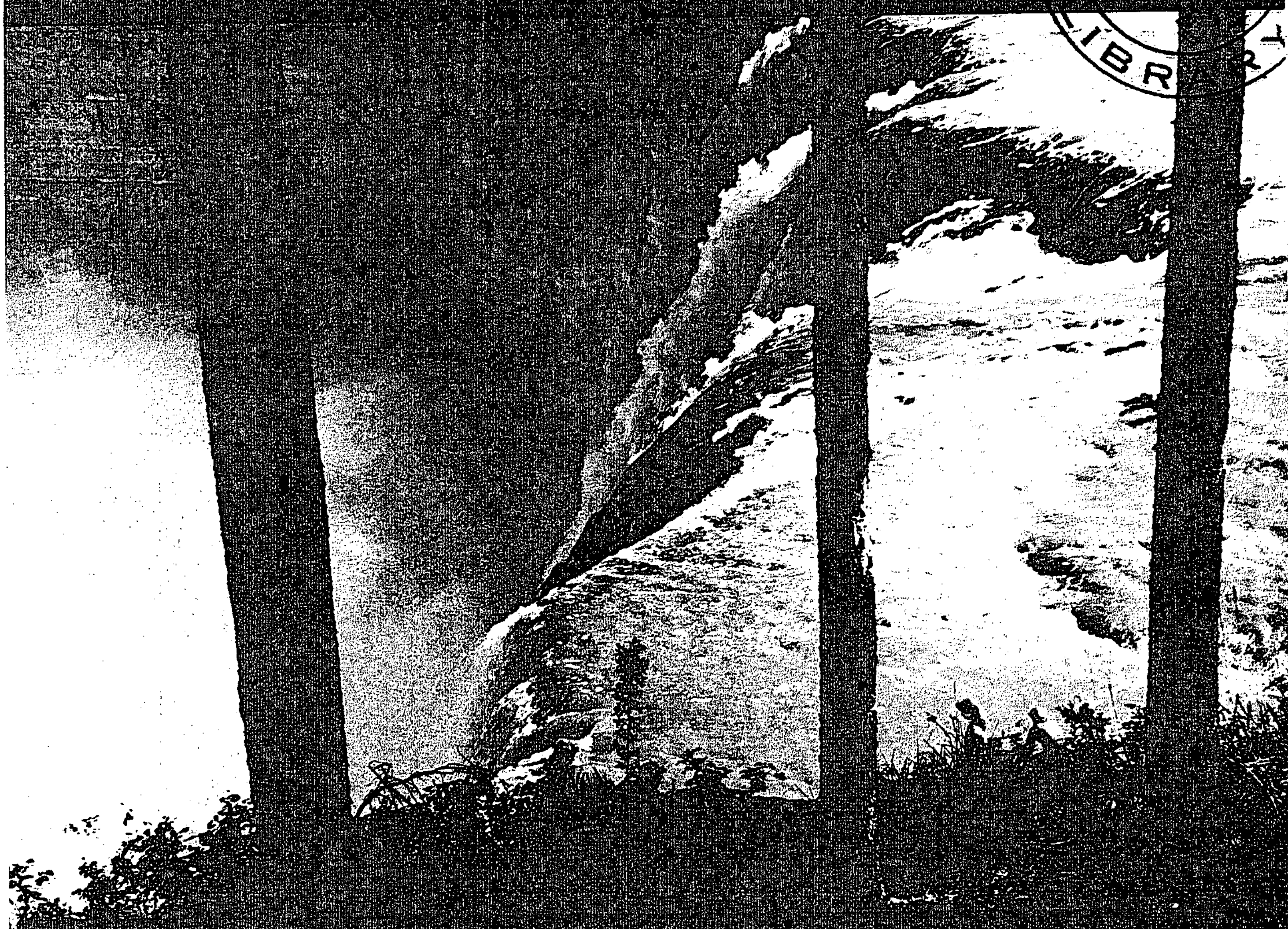
A Meteorological Buoy System for Great Lakes Studies

Floyd C. Elder and Bryan Brady



TECHNICAL BULLETIN NO. 71

CANADA CENTRE FOR INLAND WATERS
BURLINGTON, ONTARIO, 1972

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Contents

Illustrations

Tables

Abstract

A buoy-mounted instrument system for making meteorological measurements over large lakes has been developed. The system consists of a toroidal buoy of expanded styrafoam; sensors for measurement of air temperature, wind speed and direction, relative humidity, atmospheric pressure, solar radiation, and near-surface water temperature. The recording system is self-contained and capable of recording up to 40 days of data at 10-minute observation intervals on magnetic tape in digital format. Laboratory and over-lake evaluations indicate that data of accuracies comparable to standard network meteorological observations are obtainable.

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INTRODUCTION

Knowledge of the meteorological variables over the water surfaces of lakes is required in many studies of lake processes. Evaluation of the energy budgets of the water bodies must include estimates of the latent and sensible heat terms while the primary driving force for circulation and mixing processes is the surface wind stress. Present model techniques for determination of these estimates are based largely on the aerodynamic method and require input of the wind, temperature and water vapor fields over the lake surfaces.

Such measurements are not available in general except for measurements from ships operating on the lake and these records constitute only a "quasi-Eulerian" measurement in that the sensor is on a slowly moving platform. This lack of direct measurement has led to efforts to describe the lake meteorological fields in terms of the land station measurements. Hunt (1958), Bruce and Rogers (1962), Lemire (1961) and Richards, Dragert and McIntyre (1966) have all used adjustments of the land measured variables to obtain estimates of the over-lake conditions. The need for extended measurements of the meteorological variables over the water surfaces clearly exists both to verify the lake-land ratios which have been derived and to permit the estimation of the energy fluxes over a large lake from actual measurements.

A meteorological buoy system was produced for the Great Lakes – Illinois River Basin Project and employed in studies over Lake Michigan as reported by Holleyman (1966). However, serious instrumentation problems were encountered and extensive analysis of collected data has not been reported. In the early planning of the International Field Year for the Great Lakes (IFYGL), it was recognized that a vital element of the program would be the accumulation of meteorological measurements over the lake surface (see Richards, 1967). To meet this requirement, development of a system was undertaken at the Canada Centre for Inland Waters.

METEOROLOGICAL BUOY SYSTEM DESCRIPTION

Buoy and Mooring System

Choice of a buoy platform for meteorological sensors must be subjected to compromises of the basic objectives. One, in general, wishes to obtain information about the meteorological fields which is comparable either directly to similar land based measurements or which can be corrected so as to permit comparison. Buoys are, however, floating bodies and as such are subject to motion from wave forces which are not encountered in observations ashore. Such motions can mask real information in certain frequency bands. The choice involves consideration of the buoy motions, convenience of mooring and servicing, survival potential, and cost.

The spar buoy design has the least platform motion but subjects the sensors to exposure at a variable distance from the water surface. As wave heights reach the height of the sensors, they are submerged and are likely to be damaged for further use. Surface-following buoys expose the sensors at a constant height above the surface but subject them to the roll, pitch, and heave induced by the wave slope which occurs. Various degrees of damping can be achieved in both cases but in no case can conditions of a fixed-tower mounting be realized.

The buoy platform selected for this system is the Geodyne, Model A-92, toroidal instrument buoy of expanded styrafoam encased in fiberglass. The buoy with sensor system attached is shown in Figure 1. This buoy has been employed in several measurement programs including that reported by Holleyman (1966) but its dynamic characteristics have not been quantitatively evaluated.

Experimental tests were conducted to determine the ballast arrangement which would minimize the pitch and roll motions and yet permit the buoy to follow the longer components of the wave field. Ballast weights up to 680 kg

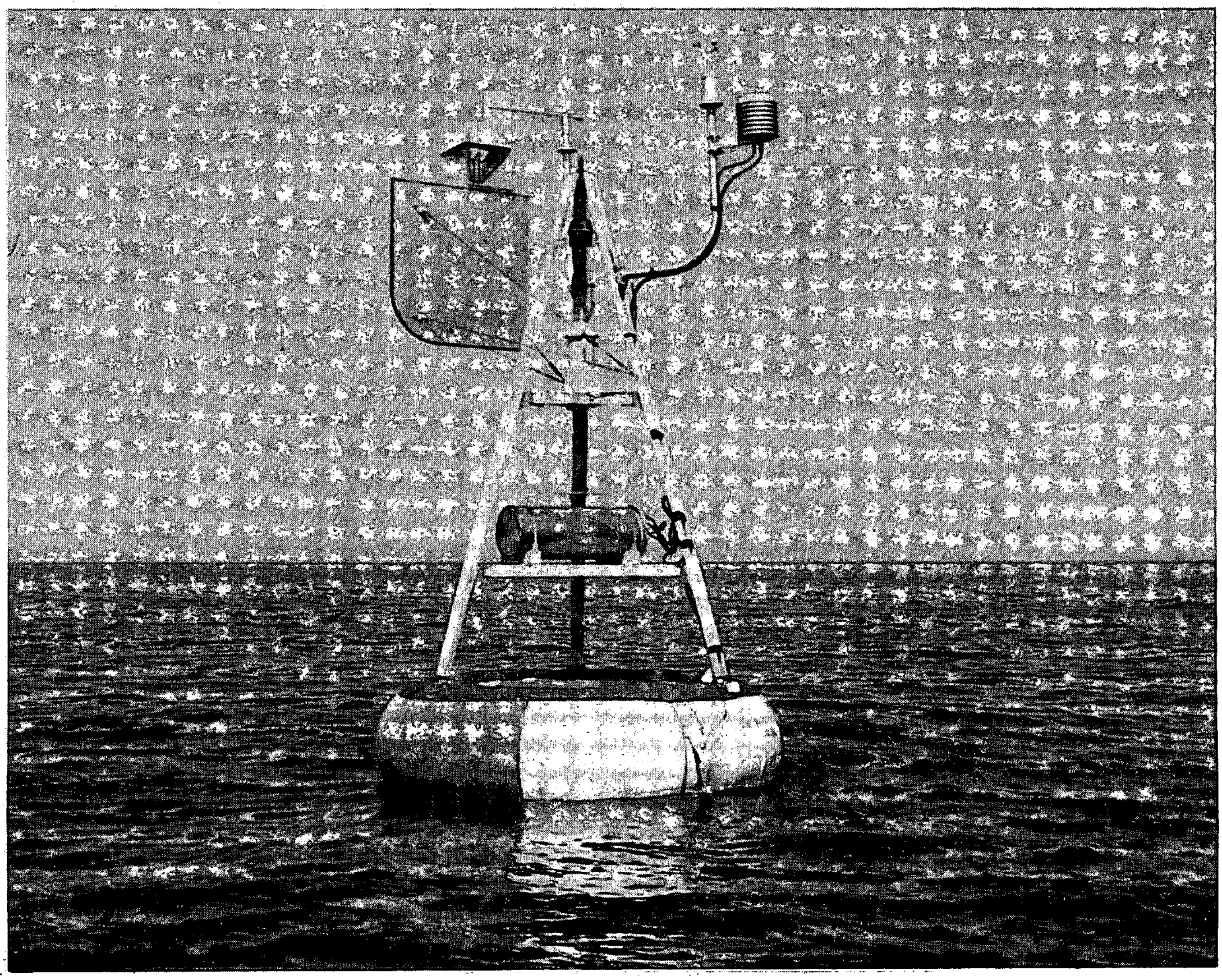

Figure 1. Meteorological buoy system in Lake Ontario.

were employed and buoy motions observed from a nearby fixed tower with the aid of motion pictures. The ballast and mooring arrangement shown in Figure 2 was accepted as perhaps the optimum for conditions most often encountered in Lake Ontario.

The buoy has survived, and given realistic measurements under wind speeds up to 15 mps and wave heights up to 3 m. Under such conditions, buoy motion is great with pitch of up to 30° but sensors have survived undamaged. Errors of some magnitude certainly occur under such conditions but are considered acceptable so that more accurate data can be obtained under more frequently encountered conditions. The exact magnitude of the errors induced by the high sea conditions has not been evaluated but comparisons with fixed tower instrumentation under moderate sea state, presented below, indicate that only small errors should be expected.

Buoy Instrumentation

The instrumentation system has been adapted from that designed by Weiler and Birch (1968) for meteorological measurements on a fixed tower. The system consists of a basic 8-channel, digital magnetic tape recorder which accepts either voltage or resistance type of sensor input signals. A record giving resolution of one part per thousand for an unattended operation period of 55,000 measurements is obtained. Battery power is supplied for self-contained operation. Most system components are available commercially so are identified and only specifications are presented. Test evaluations are presented in Table 1.

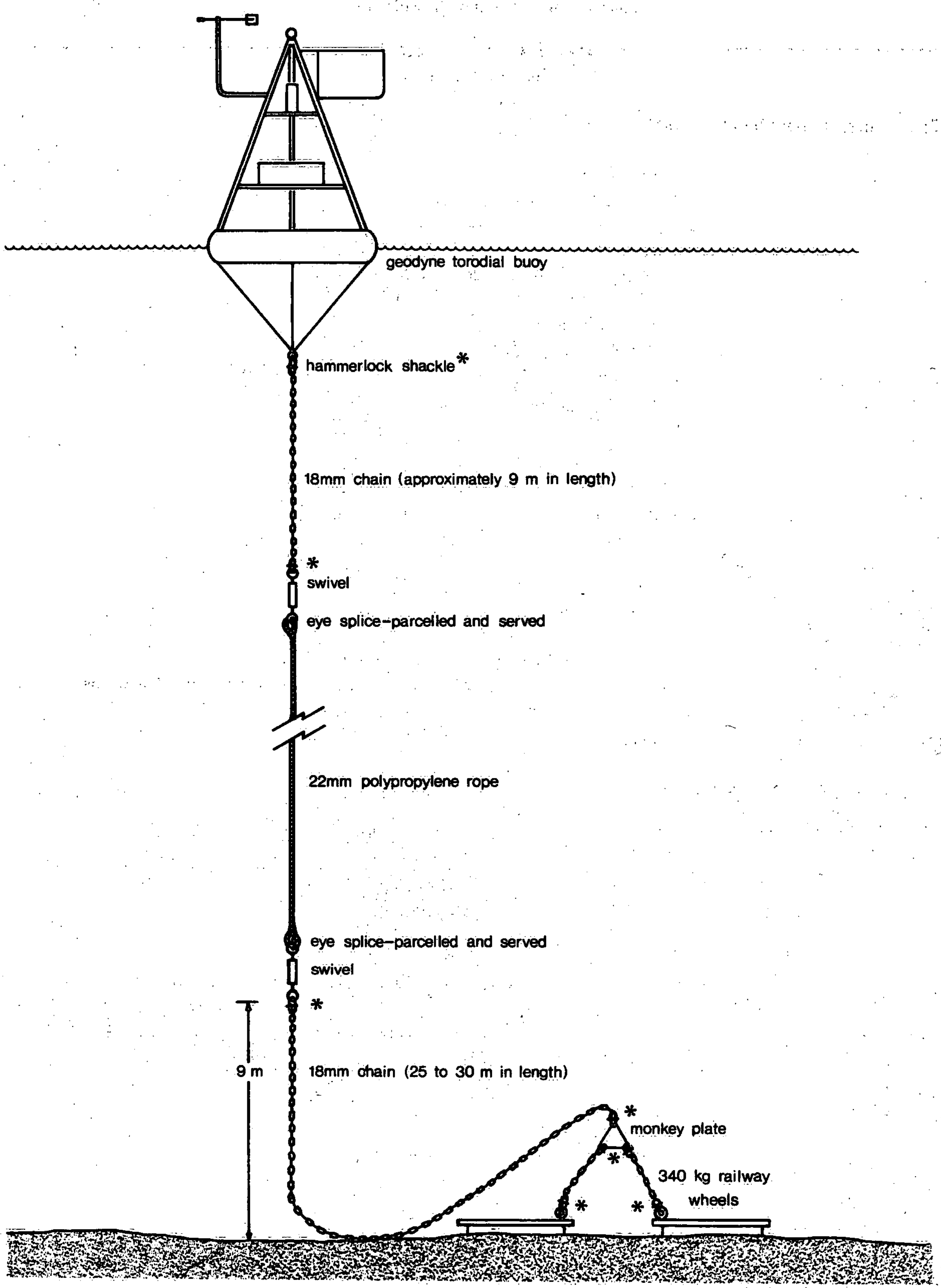

Figure 2. Mooring system for meteorological buoy.

Table 1. Instrumentation Specifications

	Recording System
Plessey Electronics, Hymet Model	MM-1.
Recording speed	4.3 mm/sec
Medium	183 m, 6.4 mm magnetic tape
Format	Digital serial form 10 digit binary number
Storage capacity	55,000 measurements (each of ten bits)
Recording modes	1. Automatic (battery driven clock) 2. External trigger 3. Continuous operation 4. Single sample
Automatic sampling rate	Adjustable, but set at 10-minute intervals for this application
Temperature range	$-10^{\circ}C$ to $+40^{\circ}C$
Electrical	
Power requirements	18 volts battery operated
Input voltage	0 to 5.120 volts
Input impedance	2 M ohms per volt – minimum at balance
Recorder accuracy	± 1 part in 1024
Resolution	5 mV
Recording time	8 seconds/channel
Reference voltage for resistive input signal	5.120 Volts ± 3 mV at 20 mA maximum
Signal	Negative going rectangular pulses of 4 volts amplitude from 11 K ohms source impedence
Duration	Binary 1 pulse 50 mS, Binary 0 pulse 170 mS
Dimensions and Weights (Approximate)	
Overall recorder dimensions	36 cm X 20 cm X 19 cm (14" X 8" X 7 1/2")
Recorder weight	5.9 Kg. (13 lb)
	Sensor System
Wind Speed	
Anemometer	3-cup (Beckman and Whitley, Model 170-41) cups geared to a single continuous turn potentiometer through a 11,106.46: 1 speed reducer
Sampling period	10 minutes, summation of air passage during sample period
Ambiguity speed	2680 cm sec^{-1} (60 mph)
Starting/stopping speed	45 – 89 cm sec^{-1} (1-2 mph)
Distance constant	130 cm (4.3 ft)
Accuracy	± 2% above 200 cm sec^{-1}
Static torque at cups	0.36 gram-cm maximum (0.005 oz-in)
Wind Direction	
Sensor	Single, flat plate vane coupled to an oil-damped magnetic compass. Instantaneous position read on command every 10 minutes by solenoid clamping of the compass
Accuracy	$\pm 5^{\circ}$
Dynamic response of vane	Damping constant of vane 0.4 to 0.5 (estimated)
Hysteresis	Within limits of accuracy

Table 1. Instrumentation Specifications (Cont'd)

Relative Humidity	
Sensor	Modified Hugrodynamics, Model 15-7012 W humidity transducer Mfrg. Specifications
Humidity range (modified)	40 to 99%
Accuracy	± 3% R. H. between 4.5 and 49 °C
Time constant	5.5 minutes
Modifications	Lithium chloride cells utilized below 40% R. H. are removed. The sensor is enclosed in a water vapor pervious cellulose acetate film to reduce liquid water contact and to prevent contamination by atmospheric borne salts
Mounting	Installed within a Thaller type radiation shield
Air Temperature	
Sensor	Yellow Springs Instrument No. 44005 precision thermistor in a copper heat sink
Range	− 10 to + 40°C.
Accuracy	± 0.1°C (calibration individually checked)
Time constant	Approximately 30 sec without radiation shielding
Exposure	Mounted in a naturally aspirated Thaller type radiation shield
Water Temperature	
Sensor	Yellow Springs Instrument No. 44030 precision thermistor installed in a 2.5 cm dia. X 15 cm plexiglass housing
Range	− 2 to + 35°C
Accuracy	± 0.1°C (Individual Calibration)
Time constant	Approximately 5 minutes
Atmospheric Pressure	
Sensor	Sostman Model 2014 pressure transducer
Accuracy	+ 0.5 mb (estimated but does not include dynamic influences of wind and buoy motion)
Exposure	Enclosed in a manufacturer supplied, weatherproof housing
Solar Radiation	
Sensor	Kipp Solarimeter, CM-2
Integrator	Plessey Electronics Radiation Integrator
Resolution	0.1 g. cal. cm^{-2}/10 min

The sensors are mounted on the buoy platform as shown in Figure 3. Wind speed and direction sensors are mounted on arms extending upwards from the tripod supports to provide exposure at 4 m above the mean water surface. A large vane attached to the buoy provides for orientation such that the sensors do not cause mutual interference. Air temperature and humidity sensors are exposed below the wind sensors in a modified Thaller (1970) radiation shield. Water temperature is measured under a protective bracket mounted near the pitch axis of the buoy and which serves as a radiation shield for the sensor which is maintained in water near the mean surface. The Kipp Solarimeter is mounted on an unshadowed platform but is subjected to the mean motions of the buoy.

The recording system interrogates the sensor array at 10-minute intervals as determined by an internal crystal controlled timer. Six data points are recorded from each variable each hour. Battery and tape duration provides for record lengths of about 40 days when operated in this mode.

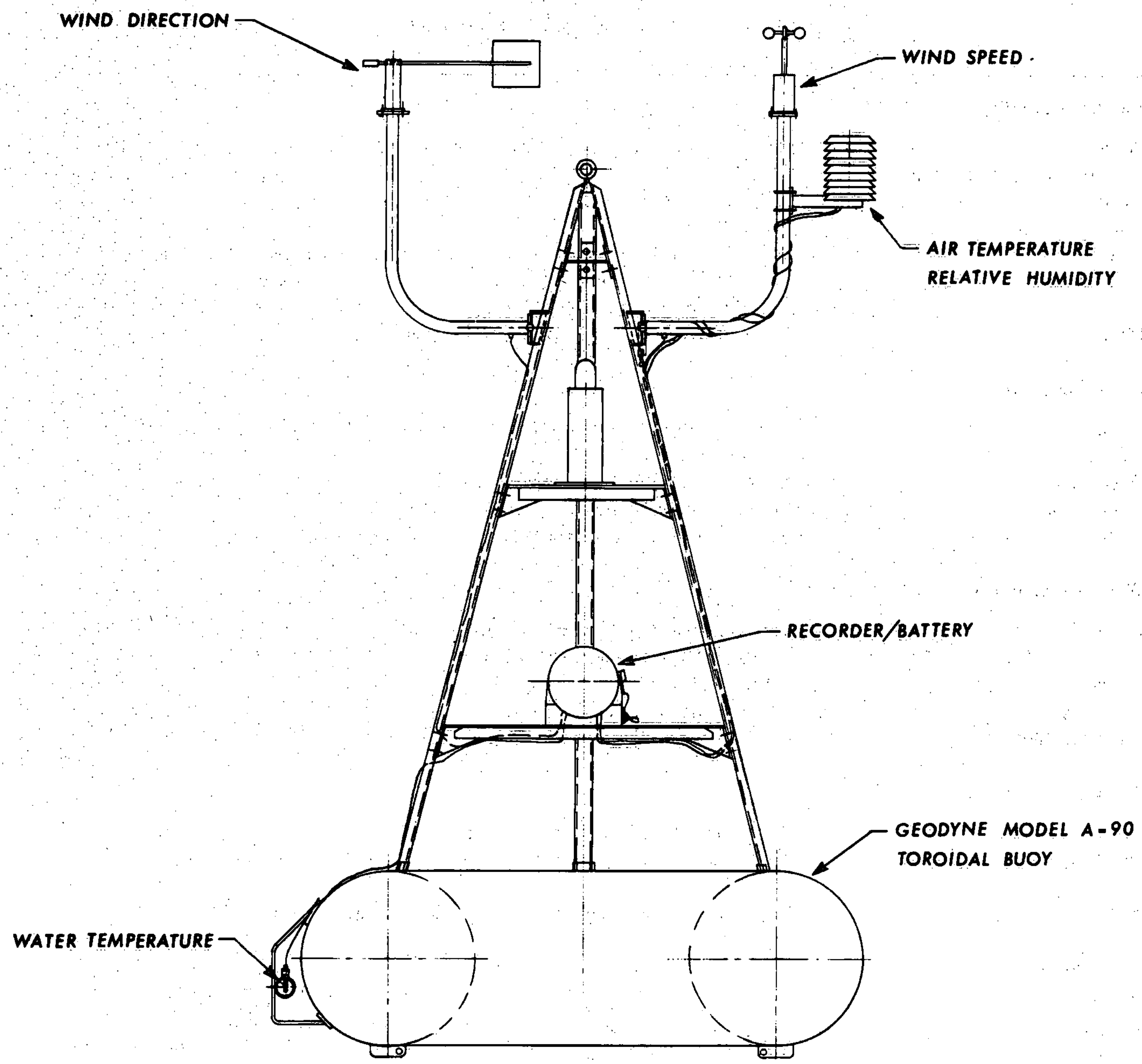

Figure 3. Sensor configuration on meteorological buoy system.

System Evaluation

Three sources of error exist in the data system. These are, (a) sampling error due to the discrete 10-minute sampling period, (b) errors inherent in the sensor recording system, (c) errors induced into the sensor output by the buoy motions. An attempt to assess the relative importance of these errors has been conducted.

Sampling Errors

The sampling error is difficult to evaluate in quantitative terms. It becomes most serious when the observed data are analyzed in terms of the spectral distribution of variance but can also cause errors in the mean values under some conditions. The first case has been considered in detail by Millard (1971). Energy contained in the variance at frequencies greater than the Nyquist frequency is redistributed into the sampled frequency range.

The data recording system does not permit a high sample rate. Since the basic purpose of the meteorological buoy system is to determine mean values of the variables, averaging to remove the high frequency variance is employed where possible to reduce the sampling error.

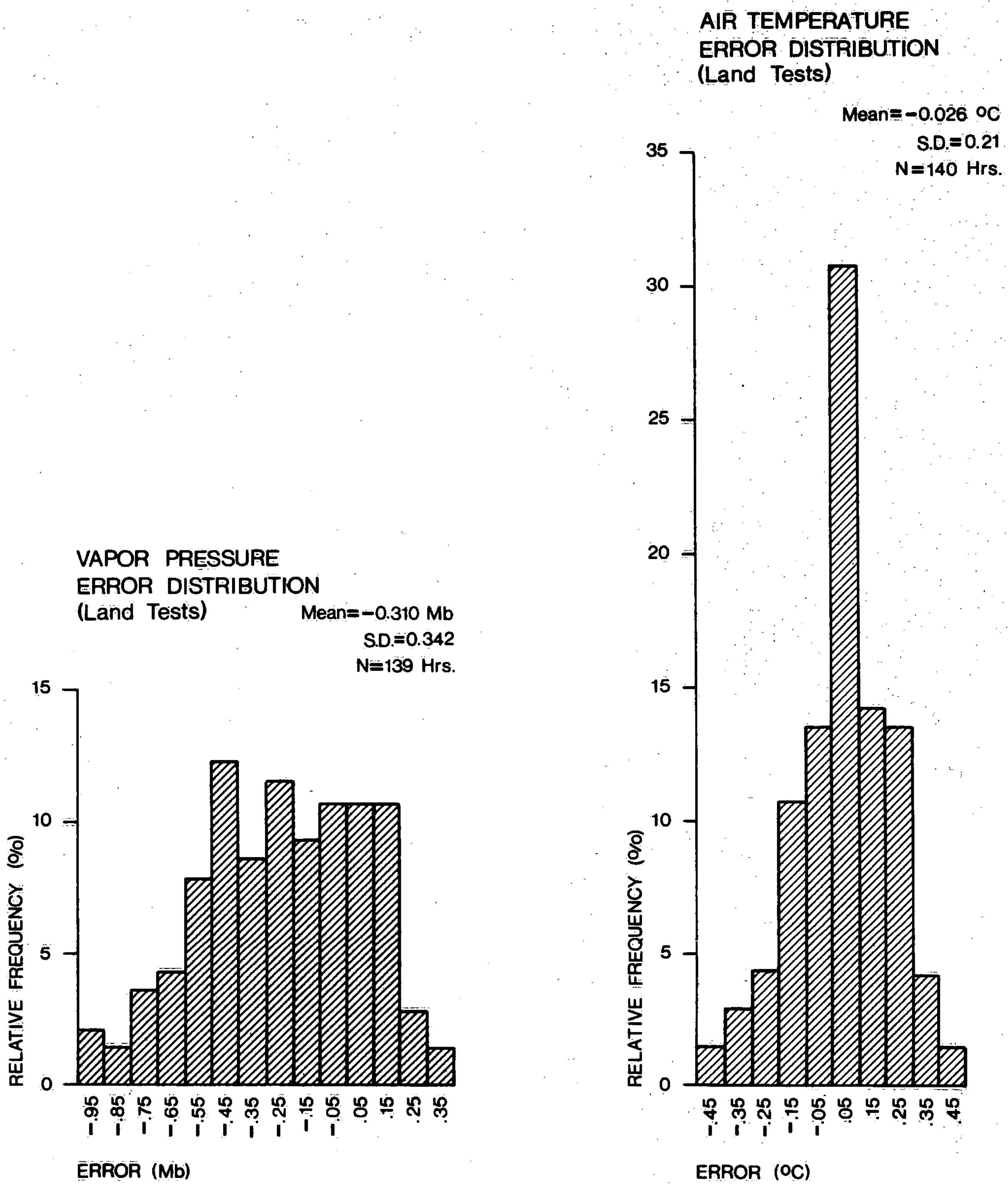

Figure 4. Evaluation of buoy system temperature and water vapor sensors on land.

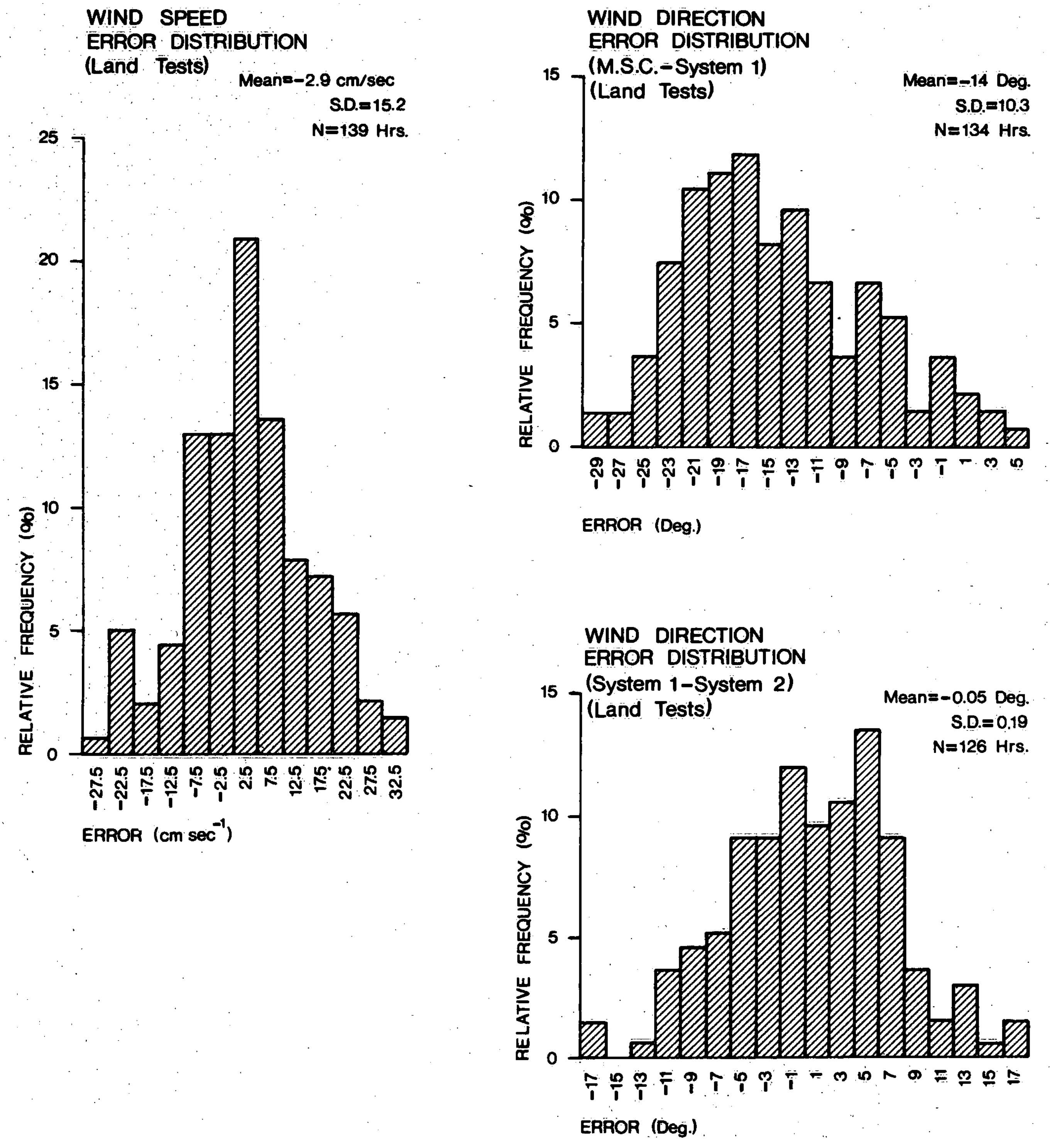

Figure 5. Evaluation of buoy system wind sensors on land.

Wind speed and solar radiation are recorded as true summation over the recording interval. The water temperature and relative-humidity sensors have long-time constants. Only the air temperature and wind-direction sensors have response rates such that periods, small compared to the sample period, are sensed. Thus, the sampling error in recorded data should be small with the exception of possible significant but unevaluated errors in the wind direction and air temperature.

Recorder and Sensor Errors

Sensor and recording systems are subjected to a basic calibration where comparison to an accepted standard is achieved. These methods are described by Mollon (1971). The calibrations are under controlled steady-state conditions and give accuracy estimates as in the above stated sensor specifications. These may not, however, be valid indications of the errors which may arise in field use under realistic conditions.

A field experiment was carried out to evaluate the total system by comparison of measurements with an "accepted" high quality, standard meteorological sensor system under a range of conditions over homogeneous terrain at the Meteorological Research Station, Woodbridge, Ontario. Two of the meteorological buoy systems were mounted on towers; one to either side of a third tower on which a wind, temperature, and humidity-sensor system, specified and operated by the Instrument Division Section, Canadian Meteorological Service (now Atmospheric Environment Service), was mounted. Intercomparison of measurements of these sytems under a range of conditions provided an evaluation of the instrumentation system in the absence of wave-motion induced influences.

The "reference" instrumentation system consisted of a Cardian-West Wind system which produced a paper chart analog record. Air temperature and wet-bulb temperature were obtained from Rosemount Platinum resistance thermometers housed in an aspirated psychrometer system designed by CMS. Both the wind and psychrometer systems had been calibrated recently in the Instrumentation Laboratories of CMS.

The three systems were operated continuously for a period of about six days during May 1970. All data were evaluated in terms of the ten-minute sample period of the buoy system recorder. These values were then averaged over an hour to give an unweighted hourly average of each variable from each system. An "error" value was then formed by obtaining a difference between the "reference" measurement and that of the system to be evaluated. The resulting error values were then summarized statistically to obtain the system evaluation.

Figures 4 and 5 present the results obtained. The mean, standard deviation, and frequency distribution of errors are shown. The air and wet-bulb temperatures of the reference system and the relative humidity of the buoy system were both reduced to vapor pressure for comparison. The mean error of -0.3 mb is within the specified accuracy of the sensor over the ranges encountered. The air temperature error of -0.026C and the wind speed error of -2.9 cm sec^{-1} are also within the calibration accuracies. The mean error of -14 degrees in wind direction is, however, much greater than the expected accuracy and not acceptable.

Recheck of the calibrations of the wind direction sensors did not indicate the source of error. However, comparison of the wind direction measurements of the two buoy systems, shown in Figure 5-c indicates good agreement with a mean difference of only 0.05 degrees. While the error in relation to the reference system remains unexplained, it is accepted that the two-systems tested do provide measurements of the meteorological variables within the specified accuracy under real conditions when not subjected to buoy motions.

Errors Induced by Buoy Motion

A buoy system was operated within about 0.5 km of a second system with sensors mounted at the same height above mean water level on a Bedford Stable Tower, (Doe, 1965), 10 km from shore in Lake Ontario near Oshawa. Thus, measurements from the buoy system when subjected to real wave motions were obtained for comparison with measurements from an identical system mounted on a stable support. Continuous measurements for about twenty days were obtained which included wind speeds up to 1120 cm sec^{-1}.

Error values were obtained as above for unweighted hourly averages and results are shown in Figures 6 and 7. Vapor pressure and air temperature errors are again within calibration accuracies and show no influence of buoy motion. Wind speed errors could be evaluated only when wind direction was such that the sensor was up-wind of the tower support. Of the 205 hours, when this direction prevailed, a mean error of -6.5 cm sec^{-1} was observed with the higher wind speed indicated by the buoy-mounted system.

If buoy motion were the cause of error, it would be expected that the error would be greater for greater wave heights. Since wave height is related in general to wind speed, the correlation between error and wind speed was examined. The results are shown in Figure 7. The linear regression indicates a slight increase in error with wind speed but the correlation coefficient of -0.39 indicates little significance. The error of about 25 cm sec^{-1} at wind speed of 1100 cm sec^{-1} is within the calibration accuracy. It appears that buoy motion does not cause significant errors at the wind speeds encountered.

The wind direction sensor on the stable tower failed to give valid measurements so error evaluation of wind direction was not obtained. Data obtained from this experiment and from subsequent exposure, do, however, indicate that reasonable wind-direction measurements are obtained but quantitative evaluations are not available.

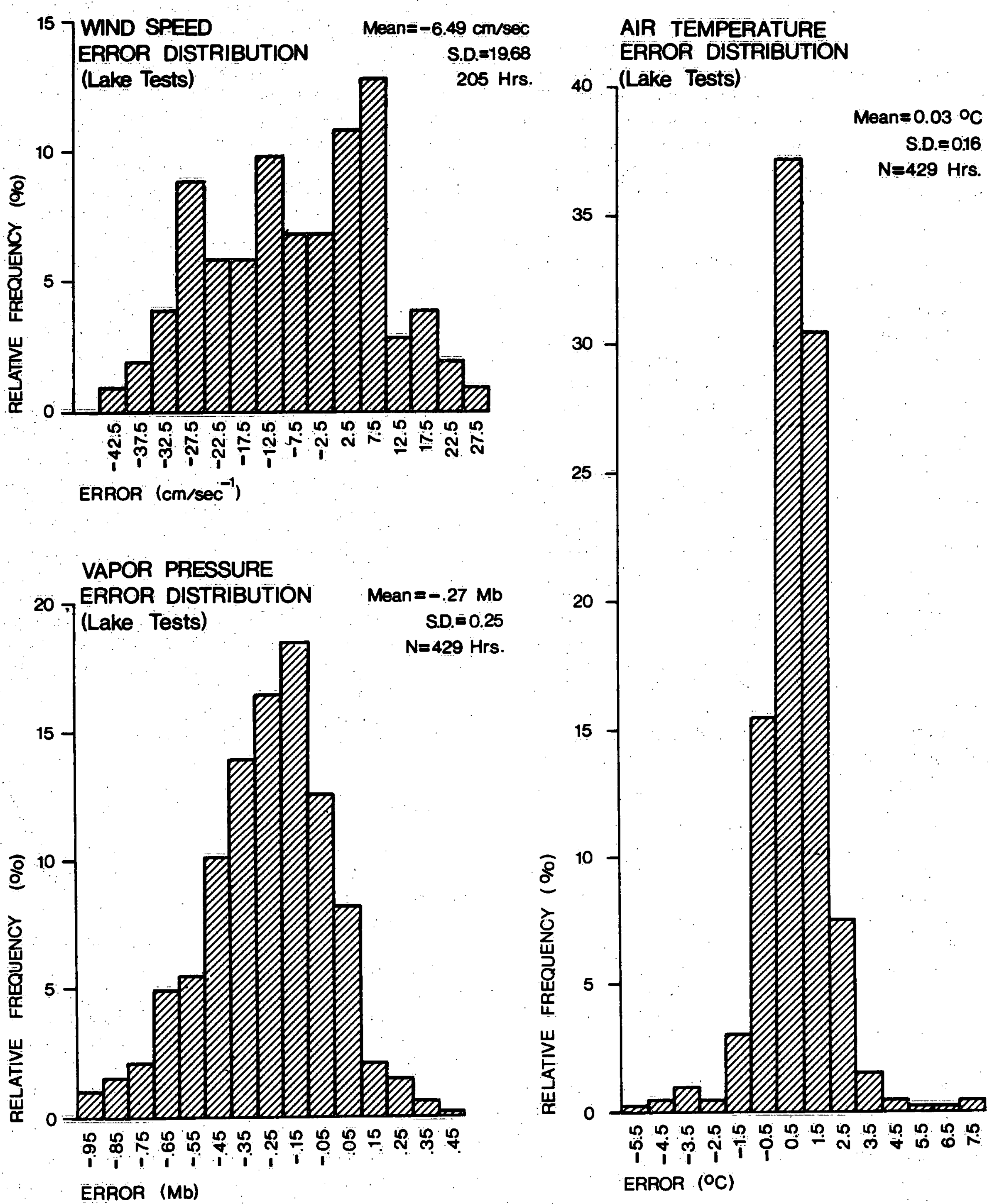

Figure 6. Buoy system error evaluation from over-water tests.

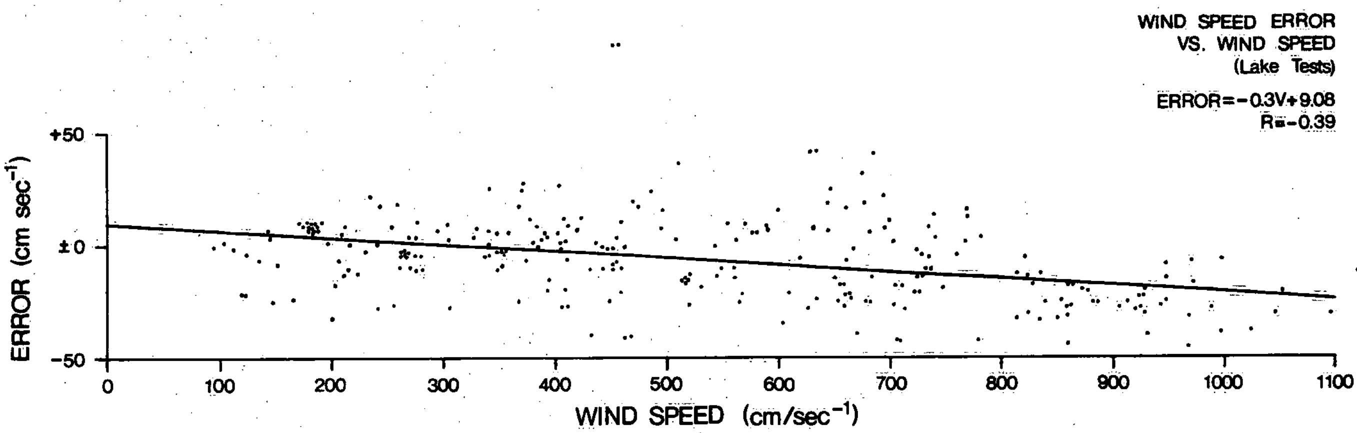

Figure 7. Wind speed error as related to wind speed (wave influence).

Actual measurements have been obtained through use of the buoy systems on Lake Ontario during 1970 and 1971. Seven systems have been operated for a total of twenty-nine buoy months with a return of greater than 90% of useful data. Only two losses have been experienced, one through ship collision and one through a mooring failure.

ACKNOWLEDGEMENTS

Dr. H. S. Weiler and Mr. K. N. Birch designed and built the first prototype models from which the present design has evolved. Personnel of the Canadian Meteorological Service provided essential assistance in the field evaluations and provided the Bedford Stable Tower for the lake evaluations. These contributions and assistance of the technical support staff are gratefully acknowledged.

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