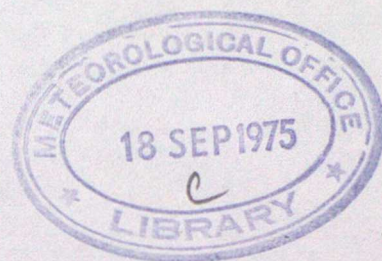


# MET.O.14

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Measurement of surface pressure by HMS "Hecla"<sup>1</sup> during GATE<sup>2</sup>  
phase 111 (GATE Report No. 5)

by

N. Thompson

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Measurement of surface pressure by HMS "Hecla"<sup>1</sup> during  
GATE<sup>2</sup> phase III (GATE Report No 5)

by N Thompson

Summary

Observations of wind velocity made by instruments close to Hecla's static pressure head have been compared with wind speeds measured by Meteor's<sup>3</sup> profile buoy during intercomparisons on 16 and 17 September. The airflow was found to accelerate slightly over the ship with a measured maximum increase of about 15% for relative wind direction near 320 degrees. Speeds fell sharply within the approximate range 260 to 305 degrees due to sheltering by the mainmast. Comparison of nearly simultaneous measurements of pressure on board Hecla and by Hecla's buoy showed a significant reduction in ship pressure for direction between about 270 and 295 degrees, of magnitude about 0.15 mb in winds of  $9 \text{ ms}^{-1}$  but the scatter in the data was large enough to mask any systematic variations for other relative directions. Surface pressure data obtained during the intercomparisons in which the relative wind was in the sector 260 to 305 degrees have been tabulated and it is recommended that these are not used in comparing Hecla's and Meteor's barometers. Less than 3% of Hecla's routine hourly observations were made with relative winds between 270 and 295 degrees and most of these in winds less than  $9 \text{ ms}^{-1}$  and it is

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1. Hecla: a hydrographic survey ship which took part in the third (final) phase of GATE (see note 2 below) near the centre of the C-scale array of ships (scale 100km) at 9N 23W. The C-scale ships were concerned particularly with observations of boundary-layer structure: Hecla's main contributions included high-accuracy low-level windfinding and tethered balloon observations of low-level turbulence structure.

2. GATE: GARP Atlantic Tropical Experiment, a three-month study in 1974 of the evolution and structure of tropical cloud clusters.

3. Meteor: West German research ship on the western side of the C-scale array during GATE phase III. It also had an accurate wind-finding system and a tethered balloon, and a tethered buoy measuring profiles and eddy fluxes.

suggested therefore that apart from the intercomparison period no attempt is made to select and correct pressure data for the (small) perturbation caused by the distortion of airflow over the ship.

Measurement of surface pressure by HMS "Hecla" during  
GATE phase III (GATE Report No 5)

by N Thompson

1. Introduction

Pressure measurements of high (relative) accuracy were required to define the horizontal pressure gradient in the GATE area because the average gradients were small: a geostrophic wind of  $10 \text{ ms}^{-1}$  at 10 degrees North is produced by a horizontal variation of less than 0.2 mb per 100 Km. General attempts were made in GATE to achieve good relative accuracy by intercomparison of observations when ships were adjacent. However it is well known that, aside from errors caused by inadequate transducers and static pressure heads, the ship on which the pressure measuring system is installed disturbs the airflow over it and thus produces local pressure changes: good instrumentation can do no more than faithfully record the perturbed pressures. Measurements made during JASIN<sup>1</sup> 1972 (Thompson 1975) demonstrated that even with mast-mounted static pressure heads significant changes of indicated pressure occurred when ship's heading relative to wind altered. For one ship an alteration from wind ahead to wind abeam produced a pressure change of -0.3 mb in a wind of  $10 \text{ ms}^{-1}$  (Figure 1).

The pressure perturbation may be expressed in terms of a velocity perturbation, if it can be assumed that Bernoulli's equation applies to this situation: thus

$$(\rho v^2/2 + P)_{\text{free stream}} = (\rho v^2/2 + P)_{\text{ship}}$$

: here  $\rho$  is air density, P is static pressure and V wind speed. The static pressure error on the ship is then

$$P_{\text{ship}} - P_{\text{free stream}} = \rho (v_{\text{free stream}}^2 - v_{\text{ship}}^2)/2 \quad (1)$$

For a wind of  $10 \text{ ms}^{-1}$  and a speed change of  $\pm 1 \text{ ms}^{-1}$  over the ship the pressure error is then  $\pm 0.12 \text{ mb}$  and for a change of  $\pm 5 \text{ ms}^{-1}$  the error is  $(\pm 0.75 \text{ mb})$ .

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1. JASIN: Joint Air-Sea Interaction Experiment. A series of experiments in the North-East Atlantic studying the atmospheric and oceanographic boundary layers on horizontal scales up to 100 km or so. Experiments took place in 1970 and 1972 and more are planned for 1977 and 1978.

If an acceptable error after correction is around 0.05 mb then the differences between free-stream speed and wind speed at static head must be known to better than  $0.5 \text{ ms}^{-1}$  at  $10 \text{ ms}^{-1}$  and  $0.8 \text{ ms}^{-1}$  at  $5 \text{ ms}^{-1}$  (Figure 2).

GATE intercomparisons determined the differences between pressure readings for the various ships for the speeds and headings prevailing during those periods but it is unlikely that a sufficiently wide range of these parameters occurred during those periods to allow subsequent correction of observations for all conditions experienced during GATE. Because of this extra wind speed measurements were made aboard Hecla so that further corrections might be applied where necessary along the lines described above. The remainder of this report describes the relevant instrumentation and procedures, and results.

## 2. Instrumentation and procedures

The pressure transducer used was the Meteorological Office Precision Aneroid Barometer (PAB). Two were mounted nearly amidships about 1.5m above sea level and were connected to a Meteorological Office-pattern static head attached to a starboard side-arm near the top of the main-mast, about 2m to starboard and 22m above sea level. A small anemometer and wind vane were mounted on the same arm and their outputs (electrically averaged over running 10-second periods) were sampled at 1-minute intervals by a potentiometric recorder.

The PABs use a manually-operated micrometer (calibrated in tenths of millibars) and an electrical make-and-break to sense the capsule deflection: there was some hysteresis in the system and because of this a reading accuracy to higher than 0.05 mb was not thought justified. The PABs were calibrated before and after GATE against a precision Bourdon gauge in the Meteorological Office Test Room: the gauge itself was checked at three-monthly intervals against a National Physical Laboratory standard. The measured calibration corrections are given in Table 1.

Table 1 PAB corrections

Instrument	Calibration date	Pressure (mb)	Correction to be added (mb)
Standard	4/7/74	1000	+0.10
		1020	+0.05
	15/10/74	1000	+0.15
		1020	+0.10
Spare	4/7/74	1000	+0.05
		1020	0.00
	15/10/74	1000	-0.05
		1020	-0.05

Observers were instructed to average out as far as possible the effects of ship accelerations and height changes on the pressure readings. Both standard and spare were read hourly (quarter-hourly during intercomparisons with "Meteor" on 16 and 17 Sept). Calibration corrections and corrections for height above sea level were applied to the readings. The archived readings are those for the standard PAB but values from the spare were also recorded on the observation sheets. Because of the small calibration changes between July and October only the July calibrations were used for data correction.

Results from JASIN 72 showed that systematic differences occurred between pressure readings made by different observers, due it was thought to different ways in which they averaged out the effects of ship motion. Hecla's five observers carried out an intercomparison at the end of GATE with the results shown in Table 2. Standard and spare PABs were read by all observers in turn and the series of observations were repeated a further four times. A linear trend was subtracted from the readings to eliminate the observed synoptic change of pressure of 0.25 mb between start and finish. Combining readings from both standard and spare it appears that observer 4 reads significantly low. Corrections

of +0.05 mb were made to all his observations with the standard PAB. The Table also shows large differences between standard and spare. The differences appeared to change fairly progressively through phase III, though perhaps with the most rapid change at the start of the experiment (Table 3). The increasing difference is in the sense shown by the calibration changes (Table 1) but is substantially larger than those. The reason for the discrepancy may be connected with the fact that the spare had a substantially larger reading hysteresis than the standard. At the start of the observations the sea was nearly smooth and ship motion was small, and then hysteresis effects were unimportant (readings were taken on the electrical "break"). There was a fairly steady increase of ship motion as the experiment went on, due to increasing swell, and the effects of ship motion became harder to average out especially in the case of the spare where some bias may have been introduced into the observations by hysteresis. For lack of any other evidence it is assumed that the standard's readings showed insignificant drift with time during phase III.

Table 2 Intercomparison of Hecla's observers, 20 Sept 1974

Observer	Measured pressures (mb)			
	Standard		Spare	
	Mean	S.D.	Mean	S.D.
1	1012.50	.013	1012.84	.013
2	.49	.019	.89	.034
3	.52	.007	.89	.053
4	.46	.040	.77	.046
5	.51	.041	.88	.018

Table 3 Daily means of PAB observations

Date	Standard	Spare	Differences
28/8	1011.77	1011.93	-0.16
29	1012.14	1012.26	-0.12
30	1012.38	1012.59	-0.21
31	1011.82	1012.04	-0.22
1/9	1011.46	1011.70	-0.24
5	1012.54	1012.80	-0.26
12	1012.11	1012.45	-0.34
19	1012.85	1013.22	-0.37

### 3. Results and discussion

On 16 and 17 September Hecla intercompared her systems with "Meteor". Data obtained from Meteor's profile buoy during the period included 10-minute averages of the wind at 10m height ( $\bar{U}_{10}$ ) and sea-air differences of potential temperature ( $\theta_s - \theta_{10}$ ) and specific humidity ( $q_s - q_{10}$ ). Approximate values for L were deduced from these using the expression

$$L = -1.6 \bar{U}_{10}^2 / [(\theta_s - \theta_{10}) + 114(q_s - q_{10})] \quad (2)$$

which follows from that given by Thompson (1971) after increasing the exchange coefficient for the vertical flux of sensible heat from  $1.3 \times 10^{-3}$  to  $2.0 \times 10^{-3}$  (Muller-Glewe and Hinzpeter 1975). The wind gradient near the surface in diabatic conditions may be represented by  $\partial U / \partial z = (u_* / \kappa z) \phi_m(z/L)$

with  $\phi_m = (1 - 16z/L)^{-1/4} \quad (\text{Businger } 1966)$

and from this it may be shown that the variation of wind with height is given by

$$U = (u_* / \kappa) (\ln(z/z_0) - \psi_m) \quad (3)$$

where  $\psi_m = 2 \ln((1+y)/2) + \ln((1+y^2)/2) - 2 \tan^{-1} y + \pi/2 \quad (4)$

and  $y = 1/\phi_m \quad (\text{Paulson } 1970).$

The wind at 22m was estimated from the ten-minute average winds from the buoy using eqn 2 and 3 with  $Z_0 = 1.5 \times 10^{-4}$  ( $C_D = 1.3 \times 10^{-3}$ ). Corrections (typically around  $0.05 \text{ ms}^{-1}$ ) were applied for the drift velocity of the buoy, estimated from 4 satellite navigator fixes over a period of 10 hours to be  $0.1 \text{ ms}^{-1}$  towards 315 degrees. Hecla's course was plotted over the same period using 1-minute values of speed and heading from the ship's log (ie by dead-reckoning) and compared with the satellite navigator fixes. The observed differences in position were due to the combined effects of current and wind-induced drift of the ship, and indicated a movement towards 070 degrees at about  $0.3 \text{ ms}^{-1}$  superimposed on the indicated ship velocity. Ten-minute periods coincident with those of the buoy data were selected when ship's course and speed, and relative wind direction, showed only small changes. Relative wind speeds were also extracted for these periods from the anemograph records and were corrected for ship movement using the indicated ship velocity (from log) and allowing for the drift of  $0.3 \text{ ms}^{-1}$ . Typical corrections were around  $0.2 \text{ ms}^{-1}$ .

The ratio of these corrected speeds to those estimated for the same height from Meteor's buoy data were then plotted against relative wind direction (Figure 3). The data span little more than a quadrant and in general are rather scattered but they reveal some useful features of the airflow in the vicinity of the static head. Winds from more or less dead ahead appear to be a few percent higher than their free-stream values but as the flow backs the difference increases to at least ten percent. With further backing the difference decreases sharply, presumably because the anemometer is now in the wake of the mast and partially in the wake of a lower platform on its forward side supporting a small radar scanner, and of a higher platform carrying the satellite navigator aerial. Speeds rise again once the flow comes from behind the mast. A feature not revealed by the Figure is the high level of turbulence for wind directions between about 260 and

310 degrees, caused by vortex-shedding from the upwind obstructions. For other directions the flow is smoother and because of the generally low levels of turbulence might be considered quasi-irrotational so that Bernoulli's equation is applicable. In this case for a typical wind speed of about  $7 \text{ ms}^{-1}$  the pressure perturbation is less than about 0.05 for directions between 340 and 020 degrees but increases to around 0.08 mb at 320 degrees where the speed perturbation is around 15 percent.

The pressure distribution in the turbulent wake can only be roughly surmised. Some indication is given by empirical data on the distribution of pressure over the surface of a cylinder in high Reynolds-number flow. Figure 4 (Batchelor 1967) and results presented by Goldstein (1938) show that in rotational flow the pressure at the rear of the cylinder is significantly less than for the irrotational case, by an amount dependant on the Reynolds number and approximately equal to  $(e V^2)_{\text{free stream}}$  for  $R$  between  $10^4$  and  $10^5$ , and by  $e V^2/2$  at a critical number near  $5 \times 10^5$ . At higher  $R$  values the pressure difference increases again to near  $e V^2$ , corresponding to a pressure perturbation from the free-stream value of  $e V^2/2$  or 0.3 mb at  $7 \text{ ms}^{-1}$ . However application of the results to the present case ( $R \sim 10^5 - 10^6$ ) is not straightforward, partly because the ship's mast with its impedimenta bears little resemblance to a circular cylinder but especially because the static head, though located in the wake region, was not close to the surface of the upwind obstruction. The pressure deficit extends presumably some way downstream of the cylinder and hence in spite of the low mean speeds in the wake the pressure there may well be somewhat lower than would be measured at the same position and with the same relative wind direction but in the absence of the mast and its obstructions. This latter pressure may itself be different from the free-stream pressure, probably lower because of the likely acceleration of the airflow over the ship when nearly abeam of the wind.

Pressure was measured at 15-minute intervals on Hecla's buoy during the inter-comparison and this provided a series of observations which could be compared directly with Hecla's pressures which were also observed at quarter-hourly intervals during this period. The buoy pressure transducer was an aneroid capsule with electronic position-sensing producing a voltage output directly proportional to pressure. During the early stages of Phase III ship and buoy pressures were in close agreement but by the time of the intercomparison there was a systematic error of about 0.5 mb between the two. However during the relatively short period of the intercomparison it is probably safe to assume that there was insignificant relative drift of the two barometers. Hecla's pressures were measured exactly on each quarter-hour whereas those from the buoy were electrically averaged values ( $CR \approx 100s$ ) sampled about 4 minutes after the quarter-hour. The separation of the ship and buoy was typically around 1 Km and because of this, and also the displacement in time of the observations, one would expect significant differences occasionally between "free-stream" pressures at the buoy and ship positions. The difference between ship and buoy pressures is plotted against relative wind direction in Figure 5. There is a considerable scatter in the data, typically around 0.3 mb at particular wind directions, though there are a few points well outside this range. The scatter is generally large enough to conceal any systematic variation with relative direction except in the range 270 to 295 degrees where the difference was on average about 0.15 mb lower than for the other directions. These are of course cases where the static head was in the wake of the mast. The average wind here was  $9 \text{ ms}^{-1}$ . Rough corrections could be applied to measured pressures on other occasions when the static head was in the mast's wake, assuming the correction was 0.15 mb at  $9 \text{ ms}^{-1}$  and proportional to the square of the wind speed (cf Figure 4) but would be very tentative: in any case Figure 3 implies that the correction is very sensitive to wind direction and not constant over an angular range as broad as 25 degrees and it therefore cannot be applied

accurately. It is suggested therefore that Hecla's pressure data obtained during the intercomparisons are selected so that only those observations obtained with relative wind direction outside the range 260 to 305 degrees are compared in order to check the barometers: the rather broad angular range follows from Figure 3 which demonstrates a wake effect over roughly this range. The observations not to be used (about 40 percent of those made in the intercomparisons) are listed in Table 4.

Table 4 Hecla pressure data not to be used in  
intercomparing her barometer with Meteor's

Time	Relative wind direction	Time	Relative wind direction
16/1630	302	0145	275
1700	269	0200	285
1715	283	0215	304
1915	294	0245	285
2030	266	0300	283
2045	266	0315	285
2315	269	0330	269
2345	269	0400	296
17/0000	304	0545	299
0015	288	0615	272
0045	299	0630	270
0115	294	0645	260
0130	280		

The results plotted in Figure 3 also implied a slight underestimation of pressure for relative wind directions between 305 and 020 degrees. The average increase in wind speed caused by the ship over this range was about 8 percent which for typical speeds of  $7 \text{ ms}^{-1}$  produced a pressure reduction of less than 0.05 mb which may be neglected.

Table 5 shows the distribution of relative wind direction at the time of the hourly observations of pressure for the period 021200Z to 192300Z. Over 75% of all observations were made with the relative wind between 320 and 040 degrees and

less than 7% with the wind between 260 and 305 degrees (less than 6% if inter-comparison data are excluded). There were about 50 observations with wind between 021 and 050 degrees for which no information exists on probable pressure perturbation due to the ship's influence, but it seems unlikely that the perturbation would have been large on the evidence of Figure 3 (for winds on the port forward quarter) and from Figure 1 (which, containing data from another ship, must be accepted with caution).

Table 5 Relative wind direction at time of hourly observations

(02/1200 - 19/2300Z)

Relative direction (deg)	Number of obs	Relative direction (deg)	Number of obs
001 - 010	84	181 - 190	1
010 - 020	44	191 - 200	0
021 - 030	20	201 - 210	0
031 - 040	20	211 - 220	1
041 - 050	11	221 - 230	1
051 - 060	3	231 - 240	1
061 - 070	3	241 - 250	3
071 - 080	5	251 - 260	1
081 - 090	0	261 - 270	4
091 - 100	2	271 - 280	4
101 - 110	4	281 - 290	5
111 - 120	2	291 - 300	12
121 - 130	3	301 - 310	18
131 - 140	0	311 - 320	16
141 - 150	1	321 - 330	13
151 - 160	0	331 - 340	28
161 - 170	0	341 - 350	51
171 - 180	0	351 - 360	51
TOTAL	202	TOTAL	210

#### 4. Concluding remarks

It appears that Hecla's static pressure head was sited in a position which assured that at least 90% of the observations were in error by less than about 0.05 mb as a result of the disturbance to the airflow caused by the ship. Excluding intercomparisons about 5% of the observations were made with the relative wind in the sector between 260 and 305 degrees in which some significant reduction in pressure occurred perhaps due to sheltering effects of the mast. The most severe effect appeared to occur in the range 270 to 295 degrees where the average reduction was about 0.15 mb in winds of  $9 \text{ ms}^{-1}$ . However these latter directions comprised less than 3% of the data and most of these were for occasions with relative wind less than  $9 \text{ ms}^{-1}$  and thus with smaller error than 0.15 mb. It is suggested then that apart from the intercomparison period no attempt is made to select and correct pressure data for the (small) perturbations caused by the distortion of the airflow over the ship.

References

- |                                     |      |  |
|-------------------------------------|------|--|
| Batchelor, G K                      | 1967 | An introduction to Fluid Dynamics, p 340<br>(Cambridge Univ Press)   |
| Businger, J A                       | 1966 | Transfer of momentum and heat in the<br>planetary boundary layer, Proc Symp on<br>Arctic Heat Budget and Atmos Circul, 305-332,<br>The Rand Corporation          |
| Goldstein, S                        | 1938 | Modern Developments in Fluid Dynamics, Vol. II,<br>p 421-424 (Oxford, Clarendon Press)   |
| Muller-Glewe, J and<br>Hinzpeter, H | 1975 | Turbulent fluxes in the ITCZ during GATE<br>phase III at Station 27, GATE Report No 14,<br>Vol. I, 224-232   |
| Paulson, C A                        | 1970 | The mathematical representation of wind speed<br>and temperature profiles in the unstable<br>atmospheric boundary layer, J Appl Met, <u>9</u> ,<br>857-861       |
| Thompson, N                         | 1971 | Relations between turbulent fluxes over the sea<br>and near-surface mean parameters, Unpublished<br>Met Office (Met O 14) Turbulence and Diffusion<br>Note No 14 |
| Thompson, N                         | 1975 | Shipboard pressure measurements during JASIN<br>1972, Met Mag, <u>104</u> , 157-179  |

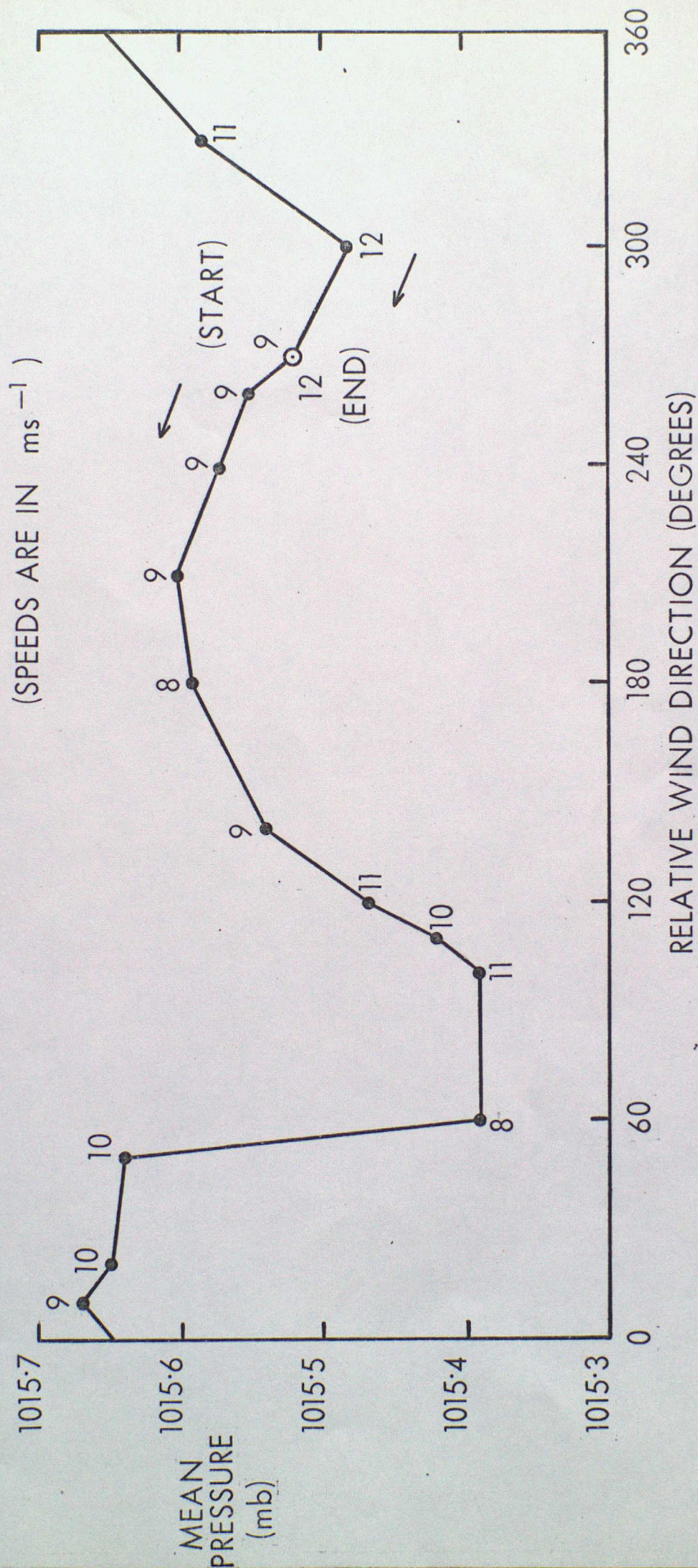


FIGURE 1. VARIATION OF PRESSURE WITH RELATIVE WIND DIRECTION, RESEARCHER 6/9/72 1022 — 1110Z

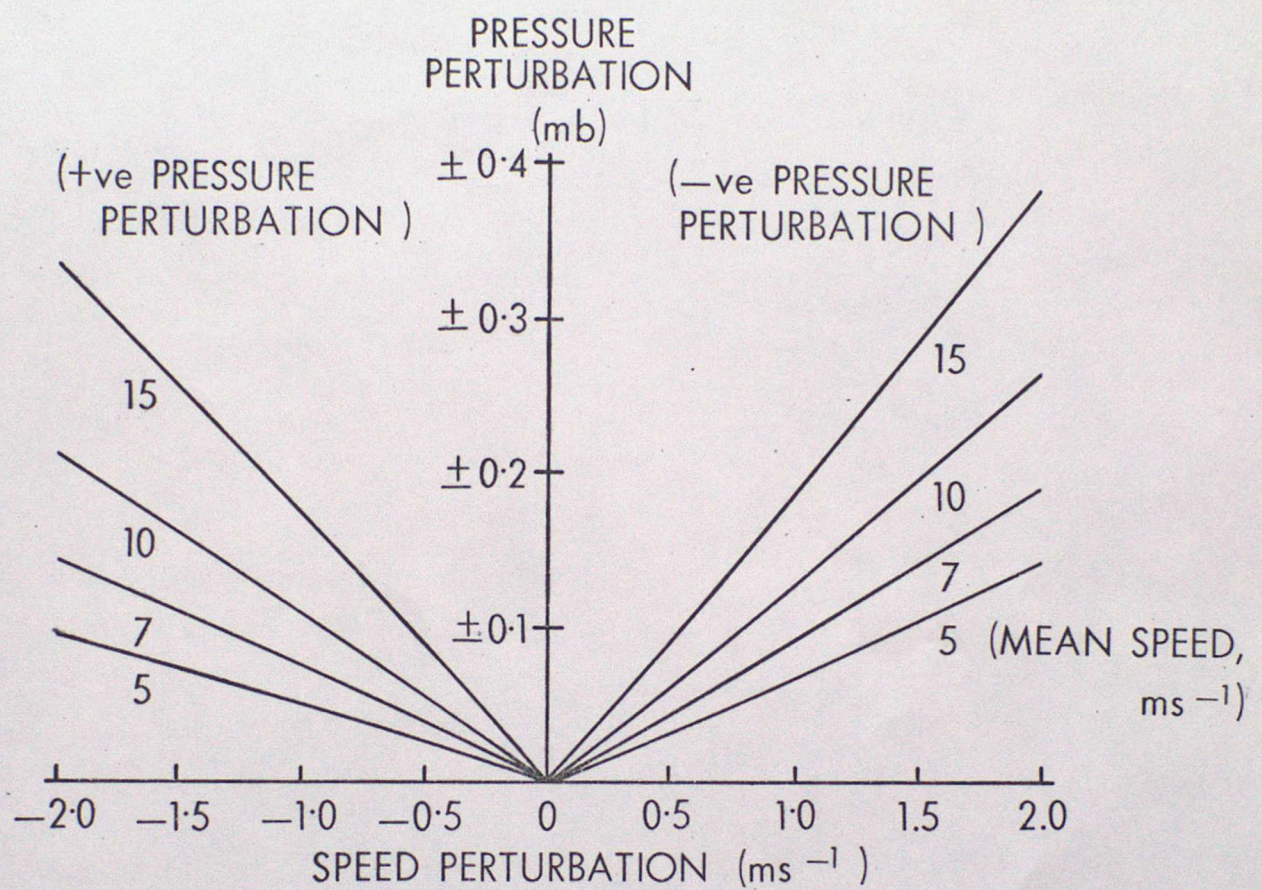


FIGURE 2. RELATION BETWEEN SPEED PERTURBATION AND PRESSURE PERTURBATION AT DIFFERENT MEAN SPEEDS (FOLLOWING BERNOULLI)

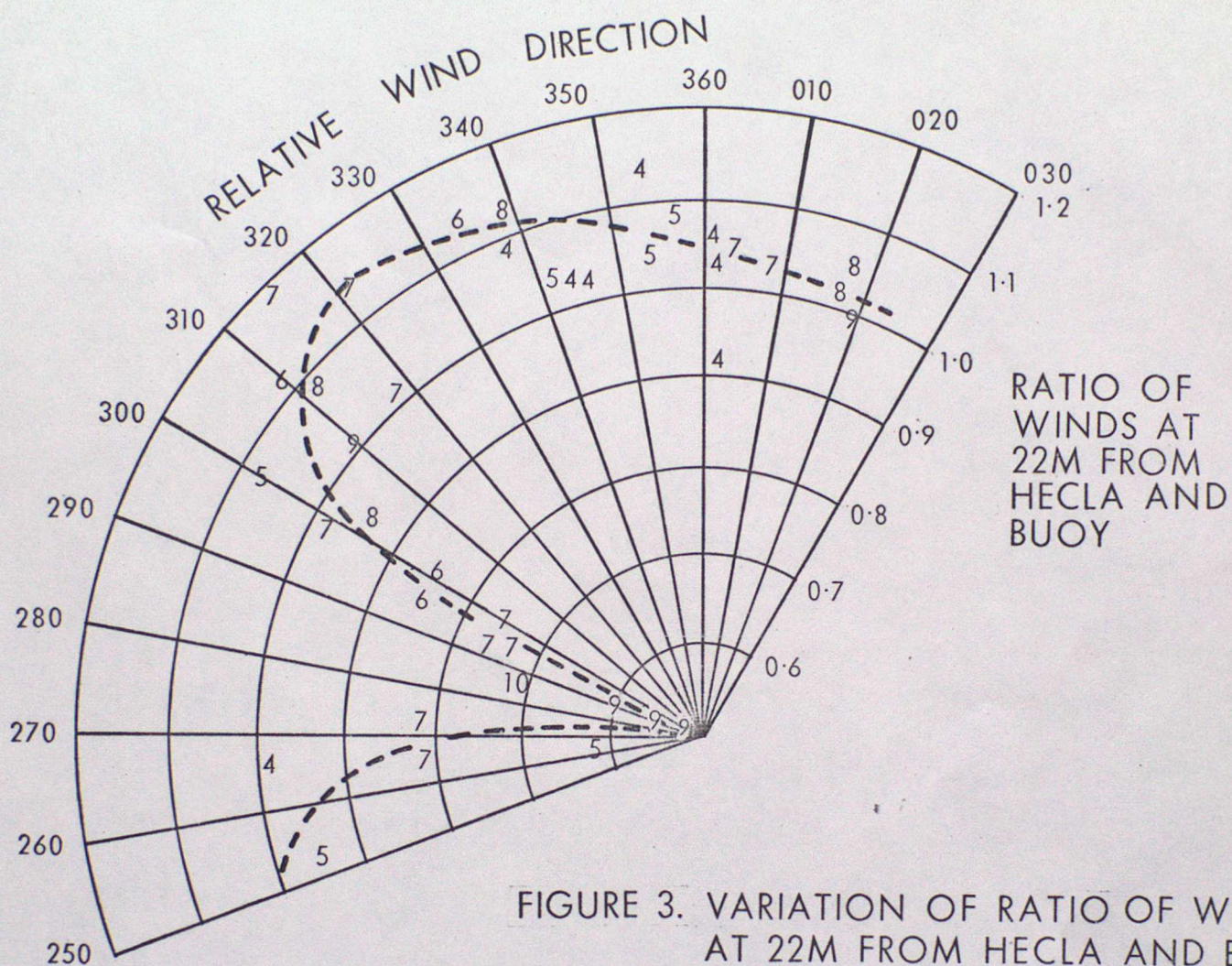


FIGURE 3. VARIATION OF RATIO OF WINDS AT 22M FROM HECLA AND BUOY TO RELATIVE WIND DIRECTION (PLOTTED NUMBERS ARE SPEEDS IN  $\text{ms}^{-1}$ )

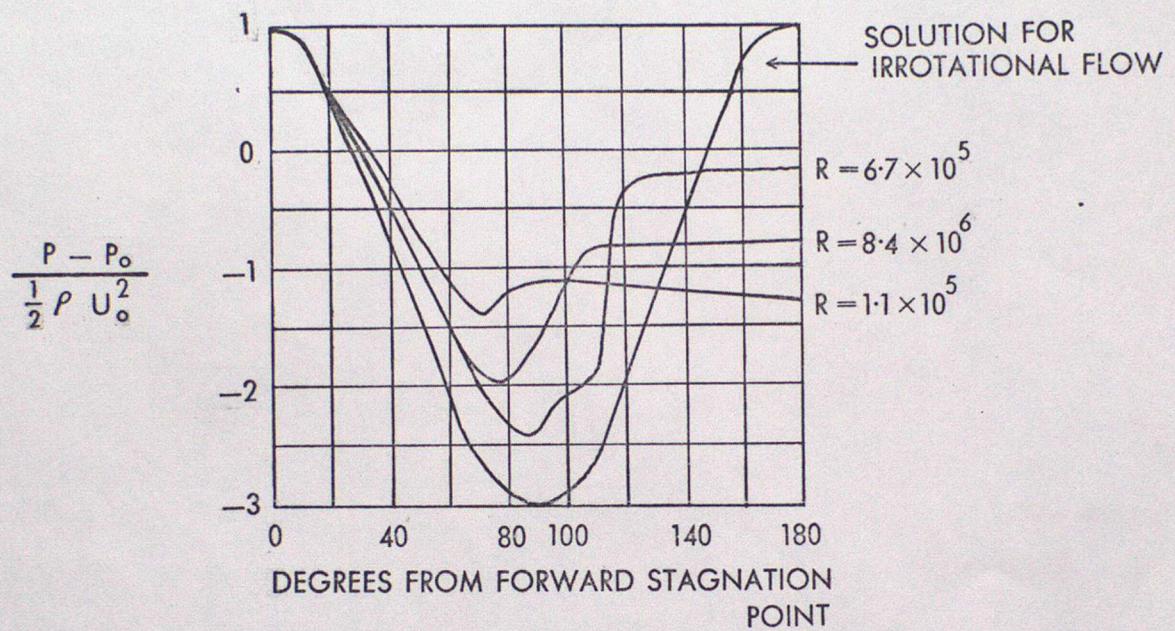


FIGURE 4 . THE MEASURED PRESSURE AT THE SURFACE OF A CIRCULAR CYLINDER IN A STREAM OF SPEED  $U_o$  AT DIFFERENT REYNOLDS NUMBERS ;  $P_o$  = PRESSURE AT INFINITY

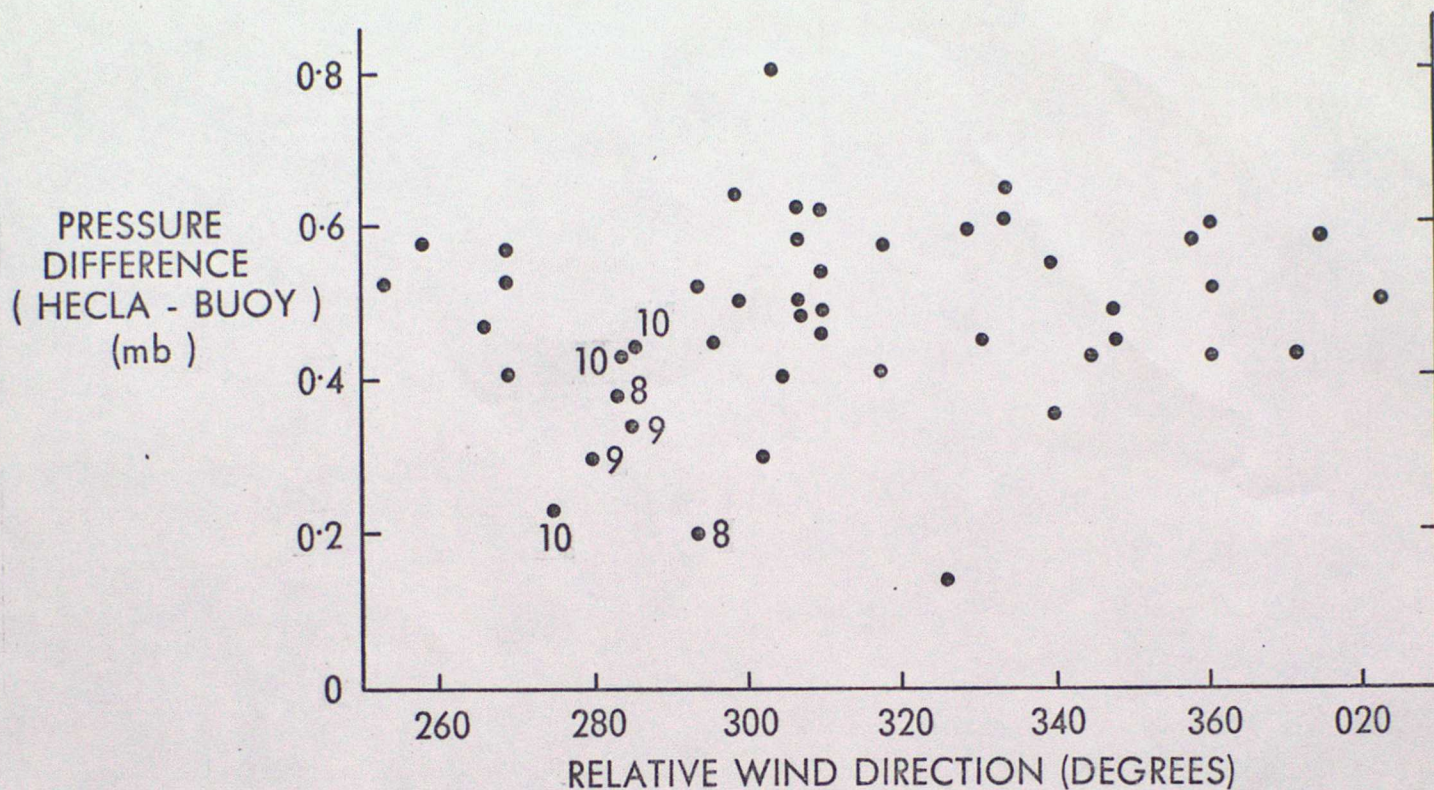


FIGURE 5. VARIATION OF DIFFERENCE BETWEEN SHIP AND BUOY PRESSURES WITH RELATIVE WIND DIRECTION. ( NUMBERS ON GRAPH ARE ESTIMATED WIND SPEEDS AT 22m )