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LAG IN MARINE BAROMETERS ON LAND AND SEA.

BY

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LAG IN MARINE BAROMETERS ON LAND AND SEA.

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SUPERINTENDENT OF KEW OBSERVATORY.

§ 1. The "Marine," or, as it is often termed, the "Kew pattern" barometer* is, as the former title implies, intended primarily for use at sea. When an ordinary barometer is made use of at sea, in vessels of moderate dimensions liable to considerable amplitude of motion, the oscillation of the mercury is a serious obstacle to the taking of readings, and even if they could be taken their value would be doubtful. The late Mr John Welsh, F.R.S., when Superintendent of Kew Observatory, took up the question of devising a barometer suitable for conditions at sea, and the present "Marine" barometer is the result. The Report of the Kew Committee for 1853 mentions that the Committee had been consulted by Lieut. Maury of the U.S. Navy upon the best form of marine barometer, and that the subject was under consideration. The first instrument of the type seems to have been constructed by Adie; the specification is given in the Kew Report for 1853–54. Reports for 1854–55 and 1855–56 mention that a specimen "Marine barometer by Adie, London, supplied to ships by the British and American Governments, on the recommendation of the Kew Observatory Committee," was included in a number of exhibits shown at the Paris Exhibition of 1855, and that arrangements had been made with several London makers for the supply of the instrument at a fixed price.

The tube has a specially constricted portion which introduces great resistance to rapid oscillations of the mercury. It cannot, of course, wholly prevent oscillations when the sea is very rough—even with the barometer carried, as is always the case, on gimbals,—and at times the "pumping" of the mercury introduces an element of uncertainty.

In the ordinary marine barometer there is no pointer to be set to the surface of the mercury in the cistern. To take a reading, all that is necessary is to set the vernier to the top of the column in the tube. The apparent inches in the scale are not true inches, but are such that (with due allowance for temperature) when the

* The barometer here referred to has two peculiarities: (1) the variation of level in the cistern is compensated by the graduation so that only one setting is necessary; (2) the tube has a special constriction to diminish "pumping." We are now accustomed to use at the stations of the Meteorological Office barometers which are compensated for the cistern, but have no special constriction of the tube. These we call "Kew Station barometers," as distinguished from the barometers with both compensation and constriction, which we call "Kew Marine barometers." Inquiry has failed to elicit whether the "Kew Station barometer" is really entitled to be called a Kew barometer at all. The distinction, which seems somewhat trivial, is not without importance, because instrument makers, when a Kew barometer is asked for by an observer, are apt to supply what we should call one of the marine type, which is unsuitable for a land station.—W. N. S.

Wt. 38583/369—600—5/14.—N. & Co. Ltd. Gp. XV,

scale shows a fall of one "inch" in the mercury in the tube, the difference between the levels in the tube and the cistern has really diminished by one true inch. The ratio of the apparent inch to the true inch depends, of course, on the ratio between the cross sections of the mercury surfaces in the tube and in the cistern. Ordinarily the inch on the scale is about 0·96 of a true inch.

The constriction in the tube is an obstacle to *all* motion of the mercury, even when due to natural changes in the barometric pressure, and obviously some limit to it is necessary. It would be possible to specify that the constriction must not extend over more than a certain length of the tube, and that the diameter of the constricted portion must not fall below a certain value, but any test on these lines would have obvious difficulties in practice. Thus the condition actually laid down at Kew Observatory was that the barometer having been inclined, so as to bring the mercury in the tube above the equilibrium position when the tube is vertical, and then brought into the vertical, the time required for the mercury surface to fall from 1·5 to 0·5 inches above the true barometric height at the time should lie between three and six minutes.

§ 2. The theory of the Marine barometer was discussed over thirty years ago by Sir George Stokes * in a paper entitled "On the effect of sluggishness on the Readings of Marine Barometers on Shore." Assuming that the "sluggishness" arising from the contraction of the tube is the sole cause of possible lag in the indications of the instrument, Stokes deduced that if h is the true height of the barometer at the time t, the height x given by the marine barometer is connected with h by the equation

$$dx/dt + q(x-h) = 0 \quad . \quad . \quad . \quad . \quad . \quad (1),$$

where q is a constant for the particular instrument. From this he deduced that if "the rate of change is tolerably constant for a good many minutes" the equation

$$x = h - (1/q)dh/dt \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

can be accepted as satisfactory to determine "the error of lagging for a known rate of barometric change."

The solution of (1) obviously is

$$x = h + Ce^{-qt},$$

where C is a constant and e the base of Napierian logarithms. If, then, x_1 and x_2 be values of x answering to times t_1 and t_2, we have

$$(x_1 - h)/(x_2 - h) = e^{-q(t_1 - t_2)};$$

or if

$$t_2 - t_1 = T;$$

$$qT = \log_e (x_1 - h)/(x_2 - h).$$

Stokes made some experiments on the lines of those made at Kew when the time of falling from 1·5 to 0·5 inches is measured, from which he inferred that the above equations were applicable both to the conditions of the Kew experiments and to those presented by natural barometric changes.

In the Kew test

$$(x_1 - h)/(x_2 - h) = 1{\cdot}5/0{\cdot}5 = 3,$$

and thus we find

$$1/q = T \times (\log_{10} e) \div (\log_{10} 3),$$
$$= 0{\cdot}910\ T \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (3),$$

where T is the time to fall an inch as observed at Kew.

* Report of the Meteorological Council to the Royal Society, for the year ending 31st of March, 1880, pp. 28–32.

Now go back to equation (2), and in it suppose dt to represent 1 minute, and dh the corresponding rise Δh in the true barometric height; then substituting from (3) we have

$$x = h - 0{\cdot}910\, T \,.\, \Delta h,$$
$$= h - L \,.\, \Delta h \qquad (4),$$

where

$$L = 0{\cdot}910\, T \qquad (5).$$

At the time of observation the barometer has been supposed to be rising at the rate of Δh a minute, and thus in L minutes immediately prior to the time of observation—assuming the rate of rise constant for so long—it will have risen

$L \,.\, \Delta h$ inches.

Thus the height x shown by the marine barometer represents what the true height actually was L minutes previously.

Consequently the instrument on Stokes' theory behaves as if it had a constant "lagging time" L, or $0{\cdot}910\, T$. As Stokes remarked, "the permitted limits of T being 3 minutes to 6 minutes, those of L will be 2 minutes 44 seconds to 5 minutes 28 seconds, average say 4 minutes." It is rare for the barometric pressure to alter much in 4 minutes, so that if the above were the complete theory, this defect in the marine barometer would be of a very trifling character.

Stokes, however, goes on to say: "The effect of sluggishness properly so called is, however, mixed up with another which, if sensible, is not so easily allowed for, namely, that of an irregularity in the capillary depression depending on variability in the angle of contact of the mercury and the glass. This effect would certainly be sensible if the tube or mercury were at all dirty, and may perhaps be not insensible even when they are in the best condition." He says further that wholly to obviate this second cause on land, would require constant tapping; it is "not quite prevented by tapping only now and then." At sea he says "the motion of the vessel supplies what is equivalent to a constant tapping" As regards sluggishness proper, his final statement is "the sluggishness arising from viscosity . . . affects a barometer on shipboard equally with one on land, and *that* can easily be allowed for if the "lagging time (L) be known," *loc. cit.* p. 32.

§ 3. At the time of Stokes' investigations, marine barometers seem to have been in use in various land stations, and some criticisms were made on these by Dr Buchan when inspecting.

Reading Stokes' paper, one would be apt to regard it as a refutation of Dr Buchan's criticisms, and it is with some surprise that one reads his statement, "the (Meteorological) Council contemplate gradually replacing the marine barometers at the secondary stations by others in which the tubes are not contracted." This policy has been maintained at the Meteorological Office. Under these circumstances it might appear that the behaviour of the marine barometer on land is of purely academic interest. This, however, is not the case. In the first place, the attitude of the Meteorological Office towards marine barometers has not, I think, been universally known; at all events, it does not seem to have been universally acted on. In the second place, marine barometers have hitherto been tested on land, under normal land conditions, and the zero corrections issued to them have been based exclusively on land observations.

§ 4. The practice observed in testing marine and, in fact, all types of barometers at Kew Observatory, was to take a number of simultaneous, or practically simultaneous, observations of them and of the working standard barometer at atmospheric pressure, and to take an equal number of readings, with pressure falling and rising. Barometers were always tapped before reading. The object of taking an equal number of rising and falling readings was to eliminate lag and varying capillary action, and the tapping was intended to remove or, at all events, reduce the uncertainty in the behaviour of the meniscus referred to by Stokes. If the resultant of the errors had numerically equal and algebraically opposite values when the rates of rising and falling pressures were equal, and if the rates of change of pressure were the same during all the observations, then the zero correction obtained at Kew would represent something independent of the conditions prevailing during the test, which might be fairly regarded as a constant of the instrument, representing the proper correction to be applied at times when the barometer is steady.

It occurred to me some years ago that it was desirable to look a little more closely into the matter. With that object, particulars were extracted from the observation books of all the individual readings taken with a number of marine barometers. The algebraic excess of such a reading over the corresponding reading from the Kew standard, after application of the ordinary temperature corrections, is the "error" given by that one observation. The barometers, which took more than 5 minutes to fall the inch from 1·5 to 0·5 inch above the true barometric height, were few in number, and were left out of account. The others were distributed under two groups, according as the "time of fall" lay between 3 and 4 minutes, or between 4 and 5 minutes. Each of these principal groups was further subdivided into three sub-groups A, B, C. Of these sub-groups, A contained all the barometers sent by one maker, B all those sent by a second maker, while C represented the remainder. As it so happened, during the time selected, the large majority of the barometers had been sent by two makers only.

Tables I. and II. give the mean results obtained from the several sub-groups and groups, and Table III. extreme results obtained from barometers of the several sub-groups.

TABLE I.—INSTRUMENTS WHOSE "TIME OF FALL" LAY BETWEEN 3 AND 4 MINUTES. MEAN RESULTS. (Unit of Pressure 0·0001 inch.)

Sub-Group.	Number.	"Time of fall."	Mean Errors.			Extreme Errors.		
			Falling Pressure.	Rising Pressure.	Difference.	Falling Pressure.	Rising Pressure.	Difference.
		m s						
A	23	3 37	+ 43	− 88	131	+ 76	− 157	233
B	15	3 33	+ 61	− 65	126	+ 116	− 126	242
C	16	3 38	+ 118	− 60	178	+ 164	− 102	266
All	54	3 36	+ 70	− 73	143	+ 113	− 132	245

The standard barometer was always read to 0·001 inch, while some of the marine barometers were read by estimation to 0·001 inch, but others only to 0·005 inch. Individual differences were put down in all cases to 0·001 inch. Naturally, these individual differences are affected by a very appreciable uncertainty, even in the case of these instruments which were read to 0·001 inch, because the uncertainty of reading even in the standard barometer can hardly be put at less than 0·001 inch. This must be borne in mind when considering the figures in the tables.

§ 5. A short discussion of Table I. may make the significance of the figures clearer. The 23 barometers of maker A took, on the average, 3 minutes 37 seconds to fall

TABLE II.—INSTRUMENTS WHOSE "TIME OF FALL" LAY BETWEEN 4 AND 5 MINUTES. MEAN RESULTS. (Unit of Pressure 0·0001 inch.)

Sub-Group.	Number.	"Time of fall."	Mean Errors.			Extreme Errors.		
			Falling Pressure.	Rising Pressure.	Difference.	Falling Pressure.	Rising Pressure.	Difference.
		m s						
A	25	4 27	+ 55	− 92	147	+ 101	− 146	247
B	12	4 26	+ 62	− 87	149	+ 115	− 157	272
C	6	4 30	+ 83	− 98	181	+ 132	− 152	284
All	43	4 27	+ 61	− 91	152	+ 109	− 150	259

the inch. They read, on the average, ·0043 inch too high with falling pressure, and ·0088 inch too low with rising pressure—*i.e.* they showed a distinct lag in each case; the difference of these figures is ·0131 inch. Again, if one takes an average of the extreme errors in all these 23 barometers, one gets + ·0076 inches with falling and − ·0157 inches with rising pressure; the difference is ·0233 inches. The test usually included 6 rising and 6 falling readings, but the time it lasted, and the conditions

TABLE III.—EXTREME VALUES FROM INDIVIDUAL INSTRUMENTS. (Unit of Pressure 0·001 inch.)

"Time of fall."	Largest Values of						Least Values of					
	Mean Difference.			Greatest Difference.			Mean Difference.			Greatest Difference.		
	A.	B.	C.	A.	B.	C.	A.	B.	C.	A.	B.	C.
minutes. 3 to 4	22	23	31	36	41	43	5	3	6	13	11	15
4 to 5	24	25	25	36	39	39	9	6	12	16	21	22

prevailing during it, varied largely. Again, the zero errors of the instruments enter into all the results except the differences between the rising and falling readings. Thus no conclusion can safely be drawn as to a difference between the lags with pressure rising and falling, and the safest course is to regard the effect of lag as measured by half the "differences" given. On this view the average error due to lag in the 54 barometers, whose time to fall the inch lay between 3 and 4 minutes, just exceeded 0·007 inch ; but out of half a dozen readings with pressure rising or falling, one would ordinarily be in error by at least 0·010 inch, due to lag.

Comparing Table II. with Table I., we see a decided tendency towards an increase in the errors due to lag. The percentage increase in the error is somewhat over half that in the time required to fall an inch. Combining Tables I. and II., we infer that the average error due to lag in a marine barometer with pressure distinctly rising or falling is about ·0075 inch. This includes, it should be noticed, any difference between the effects of capillarity in the two cases.

From Table III. we see that in one case the *average* lag was as large as 0·015 inch, and that individual errors due to this cause exceeding 0·020 inches were observed.

Stokes' "lagging time" L for the average barometer of Table I. is 3 minutes 17 seconds. Thus, if his explanation were complete, the barometric pressure during the average rise or fall at Kew would have to alter at the rate of 0·007 inch in 3·3 minutes, *i.e.* 0·13 inch an hour. This is much in excess of the true average rate of change.

§ 6. To investigate the matter further, two marine barometers were obtained for experiment from the Meteorological Office. One, A 214, took only 3 minutes 20 seconds to fall an inch, while the other, A 658, took 7 minutes 43 seconds, so that the Stokes "lagging times" were respectively 3 minutes 2 seconds and 7 minutes 1 second, or, very approximately, 3 and 7 minutes. No. 658, of course, lies outside the limits allowed for the Kew certificate.

The two barometers were hung up side by side, and readings were taken regularly by Mr J. Foster, the assistant who had tested practically all the marine barometers dealt with in the previous tables. In the first set of experiments the barometers were tapped in the usual way.

The readings were arranged in three groups. The first group consisted of 104 readings in which pressure was rising at a rate between 0 and 0·010 inch per hour, or falling at a rate between 0 and 0·010 inch per hour. The limits for the second group, which comprised 52 readings, were 0·010 and 0·020 inch per hour; while the third group, comprising 17 readings, had for limits 0·020 and 0·030 inch per hour. There were in addition some 50 readings at times when the pressure was either steady or fluctuating; these were left out of account. Taking, say, the first group, mean errors were deduced from the rising pressures and the falling pressures separately, the algebraical excess (·0070 inch in No. 214) was taken of the mean error with falling pressure over the mean error with rising pressure, and half this excess (·0035 in No. 214) was accepted as representing the error due to lag in this group.

Then the average rate of change of pressure, irrespective of sign, was calculated for the 104 occasions included in the first group and was found to be 0·0058 inch her hour. The information in this case was derived from the hourly tabulations of the barometric curves. It is inferred that when barometric pressure is altering steadily at the time of reading at the rate of 0·0058 inch per hour, the error due to lag is 0·0035 inch in No. 214—which has less lag than the average marine barometer—and is ·0068 in No. 658, which has more lag than any barometer to which a Kew certificate has been awarded. The treatment of the other two groups of readings was exactly similar. The results appear in Table IV.

Table V. contrasts the "lagging times" actually observed with those given by Stokes' formula. For instance, the first group of readings in Table IV. gives ·0068 inch as the observed error in No. 658. The corresponding rate of pressure change was really ·00575,—taken in the table as ·0058,—thus the "lagging time" was (680/575) × 60, *i.e.* 71, minutes.

It is clear from Table V. that the "lagging time" decreases rapidly as the rate of change of barometric pressure increases, but throughout the range that ordinarily presents itself in nature the "lagging times" and the lagging errors are much in excess of these given by Stokes' formula.

TABLE IV.—"LAGGING ERRORS," BAROMETERS TAPPED.

Average Rate of Change per Hour.	Mean Error in No. 214.	Mean Error in No. 658.
ins.	ins.	ins.
0·0058	·0035	·0068
·0140	·00645	·0128
·0242	·00775	·0131

The increased lag in No. 658 as compared with No. 214, is a little less than according to Stoke's formula. The fact that the lagging error has not increased exactly in the proportion of the time to fall an inch may, however, be due to some difference in type between the two instruments.

TABLE V.—"LAGGING TIMES."

Average Rate of Change per Hour.	Time of Lag by Stokes' Formula.		Time of Lag Observed.		Ratio, $\frac{\text{Observed Time.}}{\text{Calculated Time.}}$	
	No. 214.	No. 658.	No. 214.	No. 658.	No. 214.	No. 658.
ins.	mins.	mins.	mins.	mins.		
·0058	3	7	37	71	12	10
·0140	3	7	28	55	9	8
·0242	3	7	19	33	6	5

§ 7. Observations were next taken of the two barometers, neither being tapped prior to reading. The results of 51 readings arranged in two groups, corresponding to the first two groups in Table IV., are given in Table VI.

The number of pressure rising readings was only 7 in the first and 6 in the second group, so that no great accuracy can be claimed. But it would appear that the presence or absence of tapping exerts no considerable influence on this particular phenomenon.

TABLE VI.—"LAGGING ERRORS," BAROMETERS NOT TAPPED.

Average Rate of Change per Hour.	Mean Error in No. 214.	Mean Error in No. 658.
ins.	ins.	ins.
0·0064	·0022	·0056
·0142	·0084	·0155

§ 8. At this stage of the inquiry the Director of the Office expressed a desire that observations should be made at sea. The making of the necessary arrangements was undertaken by the Marine Superintendent, and he secured the co-operation of Captain Main of the S.S. "Hesperian," a vessel of 9599 tons gross.

The barometers Nos. 214 and 658 used in the land investigations were mounted in the usual way in the "Hesperian," and readings were taken every four hours during a number of passages across the Atlantic by Captain Main and his officers. Data were kindly supplied by Captain Main not merely as to the readings of the barometers and the barometric conditions at the time, but also as to the weather, the state of the sea, and the motion of the ship. The observations extended from December 1911 to June 1912, but some change took place in one or both of the barometers early in April, rendering it difficult to combine the later observations satisfactorily with the earlier. The earlier series of observations extending from December 8, 1911 to April 12, 1912, are dealt with in Table VII.

The barometric conditions at the time of each observation were noted by the observer, who stated whether pressure was rising, steady, or falling. The so-called steady pressure readings included all those in which the change in progress at the time was so slow that its sign was uncertain.

No. 214 being the instrument with least lag, it would naturally read the higher when pressure was rising and the lower when pressure was falling, supposing, of course, both instruments free of "zero error." The "zero error," however, did not vanish in either barometer, and was not the same for the two, so that No. 214 read the higher—apart of course, from individual uncertainties of reading—under all conditions. Thus, what we have to look to is the difference in the excess of the reading from No. 214, according as the pressure was rising, steady, or falling. Table VII. shows that the excess in question was greater by 0·0026 inch on the average when pressure was rising than when it was falling. The difference is thus in the direction anticipated.

TABLE VII.—OBSERVATIONS AT SEA IN THE "HESPERIAN."

	Pressure Rising.	Pressure Steady.	Pressure Falling.
Number of observations	217	50	147
Mean excess of reading in No. 214 in inches . .	·0073	·0048	·0047

One would, however, have expected the excess to be markedly less with pressure falling than with pressure steady, which was not the case.

The observations were then divided into groups, according to the rate of change of pressure at the time. These rates were determined from the successive readings at 4-hour intervals of the barometers themselves, only those occasions being utilised when the direction of change was clearly the same at three successive readings. The estimates thus made of the rate of change of pressure are necessarily exposed to considerable uncertainty in individual cases. The results appear in Table VIII. The first group of 69 observations, it will be understood, includes all the cases in which the rate of rise, or of fall, of pressure was distinct, but was less than 0·01 inch per hour. The quantity tabulated is the algebraic value of

(excess of reading in No. 214 over 658 with pressure rising) – (same quantity with pressure falling).

It may be regarded as equal to twice the excess of the "lagging error" in No. 658 over the "lagging error" in No. 214.

The uncertainty in individual readings at sea is larger than on land, especially when there is much movement in the ship. Thus it is difficult to say whether any significance attaches to the fact that the entries for the first two groups of data in

TABLE VIII.—OBSERVATIONS AT SEA IN THE "HESPERIAN."

Rate of Pressure Change, Inches per Hour.	0·00 to 0·01.	0·01 to 0·02.	0·02 to 0·03.	0·03 to 0·04.	0·04 to 0·05.	Over 0·05.
Number of observations	69	71	41	21	15	30
Excess of lag difference in No. 658 (inches)	–0·0004	–0·0010	+0·0010	+0·0031	+0·0051	+0·0068

Table VIII. have the opposite sign to what they should have theoretically. It probably only means that under the conditions existent at sea the lagging error when pressure changes were not rapid was too small to make its presence felt. The last three groups in Table VIII. contain pressures in excess of those included in the land observations at Kew, but none of them shows as much lag as the second and third groups of observations in Table IV. Take, for instance, the last group in Table IV. The "lagging error" in No. 658 exceeds that in No. 214 by ·00535 inches. Thus the excess in the difference between rising and falling readings in No. 658 over No. 214 would be ·0107 inches. In the third group of Table VIII. this excess is only ·0010

TABLE IX.—OBSERVATIONS WITH BAROMETERS, "PUMPING," AND "NOT PUMPING."

Barometer.	Average Rate of Pressure Change per Hour.	Excess of Lag Difference in No. 658.
	ins.	ins.
Pumping	·027	·0046
Not pumping	·024	·0001

inch, or less than a tenth of that observed on land, the changes of barometric pressure having practically the same rate in the two cases.

§ 9. Of the 247 observations included in Table VIII., no less than 107 were taken at times when the barometers are reported to have been "pumping," *i.e.* the mercury was oscillating in the tubes. When this occurred the practice on board the "Hesperian" was to take the reading when the mercury was stationary at the *highest* point during the oscillation. There was here a misunderstanding of the instructions issued by the Meteorological Office, which were that the lowest point of the oscillation should be taken. In any case, more than usual uncertainty would naturally attach to readings taken with the barometers "pumping," and it thus appeared desirable to divide the observations into two groups according as "pumping" was or was not observed. The mean excess of lag difference in No. 658—the same quantity dealt with in Table VIII.—is given for the two groups of observations in Table IX.

It would thus appear that the apparent differences in lag between Nos. 214 and 658 in Tables VII. and VIII., trifling as they are, arise practically entirely from observations made while the barometers were "pumping."

§ 10. As already mentioned, some change took place in one or both of the barometers subsequent to the observations just discussed, and thereafter No. 658 read nearly 0·05 inch higher than No. 214.

The following were the mean excesses in inches observed in the readings of No. 658 after the change in April :—

TABLE X.—EXCESS OF READING OF NO. 658 (later experiments.)

	Pressure Rising.	Pressure Steady.	Pressure Falling.	
Number of observations .	35	26	40	31
Excess of reading in No. 658 . . .	·0475	·0426	·0569	·0466

On land the excess of reading of No. 658—as the more sluggish barometer—would be greatest with pressure falling and least with pressure rising. Two results are given in Table X. for pressure falling. The second excludes nine observations taken between April 30 and May 2, 1912. During this time there was no reading with rising pressure, and the observed differences between the two barometers appeared abnormally high compared with both earlier and later observations with falling pressure. Thus the second of the two results for pressure falling is probably the more comparable with the results for rising and steady pressure. Whichever alternative is preferred, the fact that the results obtained for pressure rising and falling in Table X. lie on the same side of that for steady pressure points to the same conclusion as the previous tables, viz., that under the conditions existing on board the "Hesperian," the effect of difference in lag between the two barometers was very small.

§ 11. One explanation of the extraordinary difference between the land and sea results which naturally suggests itself, is that the uncertainties in the readings at sea are so large as to mask the effects of lag. It has, however, to be remembered that to mask a persistent steady influence, such as the effect of lag was seen to be on land observations, would require the uncertainties in individual readings to be very large indeed. Further, on examining the differences between corresponding individual readings of the two barometers, one does not find them vary in a way which suggests any very large uncertainty. The fluctuations of the differences, even at first when the observers were strange to the barometers, were not large. Thus during the first voyage across the Atlantic there were 46 readings. The algebraic excess of the reading from No. 214 varied from + ·045 to − ·018 inch, but the average departure from the mean excess over No. 658 was only ·010 inch. After a month or two's practice, the variability in the excess of the reading from No. 214 was much less. Thus on a voyage extending from January 19 to January 27, 1912, during which 51 readings were taken, the fluctuation in the excess was between + ·020 and − ·006, and the average departure from the mean excess was only ·005 inch. During the next voyage, extending from February 8 to February 19—with a very rough sea most of the time,—during which 64 readings were taken, the fluctuation in the excess of the reading from No. 214 lay again between + ·020 and − ·006, and the average departure from the mean excess was slightly under ·005 inch. On this last voyage the barometers are described as "pumping" on exactly half the occasions. In this connection it should also be mentioned that while No. 214 had a vernier showing 0·002 inch directly, the vernier of No. 658—like that of most marine barometers now issued by the Meteorological Office—gave only 0·005 inch directly. In both cases the observer interpolated at times when the vernier did not seem to cut exactly at any one division on the scale; still, in the great majority of instances the last figure was a multiple of 2 in the one case and 5 or 0 in the other. This would naturally tend, of course, to increase the apparent variability in the difference of the readings.

§ 12. As the difference in "lagging times" between Nos. 214 and 658 on land is closely similar to the "lagging time" in the ordinary marine barometer, the natural conclusion to draw from the observations on the "Hesperian" is that at sea the effect of lag on the average marine barometer is exceedingly small. It would seem to be even smaller than it should be according to Stokes' formula. On land, on the other hand, the effect of lag is enormously greater than according to Stokes' formula, and to obtain the best possible value for the zero correction, care should be taken that the average rate of pressure changes should be the same during the observations with pressure rising and falling. If no attention is paid to this latter point, every now and then cases must occur where the changes in the rising pressure are either much more rapid or else much less rapid than the changes in the falling pressure. In the former case the tendency will be to give a correction algebraically too large, in the latter case a correction algebraically too small. This risk increases, of course, with the "lagging time" of the instrument. It is thus desirable that the "lagging time" should not be greater than is absolutely necessary, *i.e.* the constriction of the tube should not be in excess of what is required to enable readings to be satisfactorily taken at sea. In the absence of a third instrument, free from the drawbacks which attend the use of ordinary barometers on board ship, and similar in accuracy to the ordinary barometer on land, one cannot say which of the two barometers Nos. 214 and 658 gave the most accurate readings on board the "Hesperian." The officers who read them did not find the one more difficult to read or more liable to "pump" than the other. It would thus seem worth while to investigate whether barometers taking a shorter time than 3 minutes to fall the inch could not be satisfactorily used at sea.

In the event of any further investigation, involving comparisons on both land and sea, it would be advantageous, if possible, to have the readings taken by the same observer throughout, so as to eliminate any possibility of a personal influence coming in.

APPENDIX I.

Specification of the Kew Pattern Marine Barometer.

The following account of the construction of the Kew pattern marine barometer is extracted from Welsh's paper, "Kew Report, 1853–54."

The barometer as now constructed is thus described by Mr P. Adie, the maker :—

"The tube has a diameter of from 0·22 inches to 0·25 inches. About 4 inches of the tube, near the middle, has a capillary bore in order to produce the contraction necessary to prevent inconvenient oscillation at sea from the motion of the vessel. The degree of contraction is such that, when the barometer is first suspended, the mercury requires about twenty minutes to fall from the top of the tube to its proper level. A pipette, or Gay-Lussac's air-trap, about 2 inches long, is inserted a little below the contraction, which serves to prevent the entrance of air into the upper part of the tube, or into the capillary portion of it. The lower end of the tube, which is within the mercury in the cistern, is also contracted. With these precautions it is believed that, when the tube has been well filled at first, it is very unlikely to become deteriorated. The mercury is necessarily boiled in the tube in the process of filling.

"The cistern of the barometer is a cylinder of cast-iron, the tube being fitted into it mercury-tight by cement; a portion of the upper part of the cistern being covered with strong sheep-skin leather firmly fixed by abutting flanges. This leather has been found to be sufficiently porous to permit the free action of the air through it, but not to allow the mercury to pass without considerable pressure, to which it can never from the construction of the instrument be subjected. The cistern is filled with mercury to such a height that it can never, under any circumstances of temperature or pressure, be full, but always sufficiently so to prevent the lower end of the tube being ever exposed either during carriage or when in use. This renders any adjustment of the instrument when being mounted for observation unnecessary. The diameter of the cistern is about 1·3 inch. The barometer tube is protected by a cylindrical case of brass, which is screwed firmly to the upper portion of the iron cistern. The graduation is made on this brass tube, and the vernier moved by a rack and pinion, the index being adjusted to the top of the mercurial column by shutting off the light, as is commonly done in standard and other good barometers: the vernier reads to 0·002 inch. The correction for the relative capacities of the tube and cistern (which is usually applied as a numerical correction varying with the height) is in these instruments included in the graduation of the scale; the scale being shortened by the amount of the correction, but divided so as to *represent* the true measurements. The correction for capacity is obtained by computation from carefully measured diameters of the tube and cistern. The zero-point of the scale is determined by comparison with a standard barometer. A thermometer whose scale is divided in its stem, and having its bulb within the encasing brass tube, gives the temperature of the mercury. In making an observation it is only necessary to set and read off the vernier, and to note the height of the thermometer. The instrument presents much the appearance of a mountain barometer: it is suspended in gimbals from a point a little above the middle of the tube, the rack motion being close to the point of suspension so that the hand may rest on the supporting arm. The supporting arm is flat, of hammered brass, thin enough to give the elasticity necessary to counteract sudden jars, and is equivalent to the spring gimbals usually employed, while much simpler in its construction."

APPENDIX II.

ON THE CONSTRICTIONS IN BAROMETERS.

In Adie's specification (see Appendix I.) it is stated that "about 4 inches of the tube, near the middle, has a capillary bore in order to produce the contraction necessary to prevent inconvenient oscillation at sea." Actually the contracted portion in a marine barometer is generally longer than this: according to a specification drawn up by Mr R. H. Curtis in 1910, the length of the contracted portion is to be 15 inches, and the bore is to be "extremely fine."

In many of the old tubes which have been examined at the office, the capillary tube has been heated and the bore made much finer for a short distance.

The modern practice varies amongst different instrument-makers. One maker uses a tube with about 1 mm. bore and depends entirely on the constriction for producing the lag; the general method is to have about 30 cm. of tube with bore about 0·4 mm. and adjust the falling time by making a constriction. Apparently it is possible to take a tube with bore about 0·3 mm. and adjust its length to get the right falling time. This seems to have been the original practice, and one firm with a high reputation regards it as the best.

F. J. W. W.