PRELIMINARY NOTE ON THE DIURNAL VARIATION OF
LEVEL AT KIMBERLEY.

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This paper gives the preliminary results of observations made during the course of three years upon the diurnal variation of the level of a concrete pier supporting a seismograph. The pier itself is a solid block of concrete 1·3 m. square, standing 0·58 m. high above ground and extending 1·35 m. below ground, so that the total height of the pier is 1·93 m. Round this pier, at a distance of 15 cm. or so, is built a brick wall, which serves the double purpose of supporting the floor of the seismograph-room and keeping the earth away from the sides of the pier. Therefore the indications of the seismograph may be taken as applying to the stratum 1·35 m. below the surface of the ground. The seismograph is of the horizontal pendulum form, the boom carrying a weight of nearly 6 kilograms. There is an adjusting screw for sensibility, and a graduated micrometer screw for the purpose of measuring the tilt. The indications of the pendulum are received upon a sheet of smoked paper travelling at the rate of 15 cm. an hour. The pendulum part of the apparatus (which was made to my design, with some modification, by the Cambridge Instrument Company) has served the purpose I had in view very well. There is room for a good deal of improvement, however, in the clockwork and drum. The apparatus is housed in a wooden hut of weather-boards, the walls being double and lined with cinders. There is not a window to the hut, a space being left under the eaves for ventilation.

The pendulum is adjusted in the meridian to a mean period of 18 seconds, which, however, varies somewhat during the course of the year. A tilt of 1 second of arc corresponds to an average deviation of the extremity of the boom of almost exactly 2 mm.

In Table 1, at the end, will be found the results in monthly averages.

This table gives the mean monthly deviations from the mean position of the pendulum for each hour of the day. It appears from this that the movements in the ground which set up corresponding movements on the seismograph at Kimberley are very great. Assuming that the mean position of the pendulum indicates the undisturbed level of the ground, then the maximum westerly elongation of the pendulum occurs at $5\frac{1}{2}$ h., a.m.; the maximum easterly about $4\frac{1}{4}$ h., p.m.; the median positions a little before 11 h., a.m., and $9\frac{1}{2}$ h., p.m. Geometrically these movements may be represented on the hypothesis that the hemisphere facing the sun bulges out, the bulge forming a sort of meniscus to the geo-sphere. The enormous rises and falls of the surface of the land that such a supposition would postulate are, however, mechanically difficult. Moreover, it is impossible that they should be due to the alternate expansion and contraction of the earth's crust, by day and night, in the heat of the sun's rays and the nocturnal cooling. For the direct heat of the sun during the course of the day does not penetrate below a depth of 3 feet, and even then it penetrates so slowly downwards that the maximum earth temperature at a depth of 1 foot is not felt until some two hours after sunset, while it takes more than as long again before the wave of temperature reaches the 2-foot depth. Thus it is out of the question that the direct heat of the sun can affect the levels at the depth of the base of the pier on which the pendulum is fixed.

Professor Milne, who has made and discussed many elaborate experiments and observations for the purpose of ascertaining the cause of the diurnal variation of level as it has been observed in Japan and other countries, has found that it may be met with in cases 12 feet below the ground-level; but that in a space sheltered by trees from the sun's rays it is scarcely appreciable. He found further that when the character of the country to the east of a pendulum differed from that to the west—say when there were many trees or buildings on one side, but bare ground on the other—the diurnal variation of level was large. The general conclusions to which the observations at his disposal point is that the movements which take place during the day are due to the removal of a load from the side of the station most exposed to the effects of radiation. This load may be represented by aqueous vapour carried upwards and dissipated. And a very important observation in this connection is that, at many stations, on wet or cloudy days diurnal waves are absent.* It is known that in a damp country the diurnal variation of temperature may easily set up an alternate loading and unloading of the upper strata of the earth's crust. During the night, when radiation has cooled the surface, dew will be deposited from the air; and, besides, the flow of moisture in

* J. Milne, "Movements of the Earth's Crust," *Geographical Journal*, March, 1896.

consequence of the surface tension of water, will be from the warmer lower levels to the colder upper levels.* In the heat of the day, on the other hand, the same surface tension will tend to direct the flow of moisture downwards, that is to say, so much moisture as is not evaporated. It will readily be allowed therefore that the movements of moisture in a damp earth are probably in some measure competent to set up some such diurnal oscillation of the pendulum as is actually observed. At the same time it is not so obvious that the same explanation will apply to Kimberley. The soil of Kimberley is not often very wet: mostly it is very dry, and it is a curious fact that when it is driest, namely, at the end of the winter, the range of the pendulum's excursion from west to east is twice as great as it is in summer.

Not so much connection as might have been expected can be traced between the variations of weather and the movements of the pendulum at Kimberley. Cloud and variations of barometric pressure are perhaps the most potent disturbers in a small way of the regular diurnal march of the pendulum. Whether the cloud disturbance arises because under a cloudy sky there is usually more moisture in the air, and so less evaporation from the soil, or whether it arises because the clouds mitigate the direct heat of the sun is a question. As to the barometric pressure, one would expect the elastic crust of the earth to fall under a high pressure and to rise under a low pressure. Hence we should expect the crust to sink under the increased load of air at the time of the morning maximum of pressure at, say, 10 a.m., and to rise under the lightened load at the time of the afternoon minimum of pressure, say, at 4 p.m. That is, we should expect the pendulum to swing away from the place at which the local time is 4 p.m., and to swing towards the place where it is 10 a.m. There are no very obvious indications that such is the case. Nor does the pendulum respond always in a very marked fashion to the passage of a barometric depression. This is probably due to the fact that the usual type of South African storm passes across the country in a direction S.W.-N.E., and as often as not exaggerates rather than obstructs the normal diurnal sequence of meteorological phenomena. Did our storms travel from W. to E., as certain amateur meteorologists assert, or from E. to W. as others believe, the effect upon the pendulum would of course be much more marked.

* Dr. W. J. Humphreys in pointing this out ("Note on the Movement of Water in Soils," *Bulletin of the Mount Weather Observatory*, vol. i., part 2) remarks that the temperature effect upon evaporation, condensation, and surface tension tends to conserve whatever moisture is in the earth. Surely Nature is not quite so beneficent! Would it not be more correct to argue that the temperature effect promotes loss? For surface tension brings the underground water to the surface at night just where it may be the more readily evaporated by day.

TABLE 1.

HOURLY VARIATION IN MILLIMETRES OF THE HORIZONTAL

	Midn't.	I.	II.	III.	IV.	V.	VI.	VII.	VIII.	IX.	X.	XI.
1903												
May	1.0 W	1.0 W	1.3 W	1.5 W	1.8 W	1.9 W	2.1 W	2.5 W	2.5 W	2.4 W	1.6 W	0.3 W
June	1.2	1.3	1.6	1.9	2.1	2.3	2.6	2.6	2.5	2.3	1.6 W	0.3 W
July	1.5	1.8	2.1	2.3	2.5	2.5	2.6	2.7	2.7	2.5	1.7 W	0.4 W
Aug.	1.9	2.2	2.4	2.5	2.7	2.8	2.8	2.6	2.2	2.0	1.3 W	0.0
Sept.	1.9	2.2	2.4	2.5	2.6	2.7	2.7	2.4	2.1	1.6	0.7 W	0.7 E
Oct.	1.9	2.0	2.1	2.1	2.2	2.2	2.1	1.9	1.5	1.1	0.3 W	0.7 E
Nov.	2.5	2.6	2.6	2.6	2.5	2.4	2.1	1.8	1.4	0.7	0.1 E	1.2 E
Dec.	1.0	1.3	1.4	1.3	1.4	1.5	1.3	1.2	0.9	0.5	0.3 E	0.9 E
1904												
Jan.	0.8	0.9	1.1	1.2	1.2	1.4	1.5	1.3	1.1	0.8	0.2 W	0.4 E
Feb.	0.0	0.2	0.4	0.5	0.7	0.9	1.1	1.2	1.1	0.7	0.1 W	0.5 E
Mar.	0.9	1.0	1.2	1.3	1.5	1.7	1.8	1.9	1.8	1.5	0.8 W	0.2 E
April	0.8	1.0	1.3	1.4	1.7	2.1	2.1	2.2	2.0	1.7	1.0 W	0.2 E
May	0.8	1.1	1.4	1.7	1.7	1.8	2.0	2.1	2.1	2.0	1.3 W	0.2 W
June	0.7	1.1	1.4	1.6	1.8	2.0	2.2	2.4	2.2	1.9	1.5 W	0.5 W
July	1.0	1.3	1.6	2.0	2.2	2.3	2.4	2.7	2.6	2.3	1.7 W	0.6 W
Aug.	1.5	1.8	2.1	2.3	2.5	2.6	2.6	2.5	2.4	2.1	1.2 W	0.2 E
Sept.	1.4	1.7	2.1	2.4	2.5	2.5	2.5	2.4	2.1	1.9	0.8 W	0.3 E
Oct.	1.5	1.9	2.2	2.4	2.5	2.5	2.3	2.0	1.5	1.0	0.4 W	0.6 E
Nov.	2.0	2.3	2.5	2.7	2.8	2.7	2.3	1.9	1.5	0.7	0.1 E	1.1 E
Dec.	1.5	1.9	2.1	2.3	2.3	2.1	1.9	1.7	1.6	1.0	0.3 W	0.5 E
1905												
Jan.	0.9	1.3	1.6	1.6	1.6	1.5	1.4	1.5	1.5	1.2	0.5 W	0.3 E
Feb.	1.6	1.8	2.1	2.1	2.0	2.0	2.0	1.8	1.6	1.0	0.3 W	0.3 E
Mar.	1.4	1.6	1.9	1.9	2.2	2.3	2.4	2.3	1.8	1.7	0.8 W	0.1 E
April	1.2	1.5	1.8	2.1	2.3	2.5	2.8	2.6	2.0	1.7	1.0 W	0.0
May	1.4	1.6	1.8	1.9	2.1	2.3	2.5	2.5	2.3	1.9	1.1 W	0.1 W
June	1.3	1.7	1.9	2.3	2.6	2.8	2.8	2.9	2.8	2.5	1.9 W	0.5 W
July	1.7	2.1	2.3	2.4	2.5	2.8	3.1	3.2	3.1	2.8	1.9 W	0.2 W
Aug.	2.0	2.3	2.6	2.8	3.0	3.1	3.3	3.4	3.1	2.3	1.5 W	0.0
Nov.	1.4	1.7	1.9	2.1	2.1	2.1	1.7	1.6	1.2	0.5	0.2 E	0.7 E
Dec.	1.3	1.5	1.7	1.7	1.7	1.7	1.7	1.6	1.4	1.0	0.4 W	0.1 E
1906												
Jan.	1.3	1.3	1.4	1.4	1.5	1.4	1.5	1.5	1.2	1.0	0.6 W	0.1 W
Feb.	1.0	1.2	1.6	1.8	2.0	2.1	2.2	2.2	1.9	1.3	0.6 W	0.1 E
Mean	1.3 W	1.6 W	1.8 W	2.0 W	2.1 W	2.2 W	2.2 W	2.1 W	1.9 W	1.5 W	0.8 W	0.2 E

TABLE 1.

PENDULUM FROM ITS MEAN POSITION IN MONTHLY MEANS.

Noon.	XIII.	XIV.	XV.	XVI.	XVII.	XVIII.	XIX.	XX.	XXI.	XXII.	XXIII.	Range.
0.9 E	1.7 E	2.4 E	3.1 E	3.6 E	3.7 E	2.7 E	2.1 E	1.0 E	0.4 E	0.0	0.5 W	6.2 mm.
1.1	2.3	3.1	3.6	4.1	4.1	3.0	2.0	0.7 E	0.2 W	0.8 W	1.1	6.7
0.9	2.2	3.3	4.1	4.7	4.9	4.0	2.3	1.1 E	0.3 E	0.5 W	1.1	7.6
1.5	2.6	3.5	4.1	4.4	4.4	3.3	2.2	1.3 E	0.7 E	0.0	0.7	7.2
1.8	2.7	3.3	3.8	4.2	4.2	3.3	1.9	0.8 E	0.1 W	0.7 W	1.3	6.9
1.5	2.1	2.5	3.0	3.4	3.3	2.4	1.1	0.0	0.7 W	1.4 W	1.9	5.6
1.9	2.4	2.8	3.2	3.5	3.5	2.8	1.4	0.4 E	0.4 W	1.0 W	1.6	6.1
1.5	1.9	2.2	2.3	2.1	2.0	1.4	1.0	0.1 W	0.9 W	1.5 W	2.1	3.8
0.8	1.2	1.6	1.9	2.1	1.9	1.6	1.0	0.4 E	0.1 W	0.6 W	1.0	3.6
1.1	1.5	1.8	1.9	1.9	1.6	1.2	0.5	0.2 E	0.9 W	1.4 W	1.7	3.1
1.0	1.5	2.0	2.2	2.3	2.3	2.0	1.5	0.7 E	0.2 E	0.1 W	0.4	4.1
1.0	1.7	2.2	2.7	3.0	2.9	2.4	1.7	0.8 E	0.1 E	0.6 W	0.9	5.2
0.8	1.5	2.3	2.8	3.1	3.3	2.8	1.9	1.1 E	0.2 E	0.3 W	0.8	5.4
0.3	1.4	2.3	2.9	3.2	3.5	2.9	1.9	1.1 E	0.3 E	0.2 W	0.7	5.9
0.6	1.9	2.6	3.4	4.1	4.4	3.6	2.4	1.4 E	0.5 E	0.2 W	0.9	7.1
1.2	2.2	2.9	3.5	3.9	4.4	3.8	2.3	1.2 E	0.3 E	0.6 W	1.2	7.0
1.6	2.3	2.9	3.1	3.4	3.6	3.1	2.1	1.1 E	0.1 E	0.6 W	1.3	6.1
1.4	2.1	2.6	2.7	3.0	3.1	2.8	1.8	1.0 E	0.3 E	0.3 W	0.8	5.6
1.9	2.4	2.7	3.0	3.2	3.2	3.0	2.2	1.2 E	0.2 E	0.5 W	1.0	6.0
1.4	2.0	2.4	2.8	3.0	3.3	2.9	2.2	0.9 E	0.1 W	0.8 W	1.4	5.6
1.0	1.6	1.9	2.3	2.5	2.5	2.1	1.4	0.6 E	0.0	0.3 W	0.7	4.1
1.0	1.5	2.0	2.4	2.8	2.9	2.6	2.0	1.2 E	0.4 E	0.2 W	0.6	5.0
1.2	1.9	2.4	2.7	2.8	2.8	2.5	1.9	1.0 E	0.5 E	0.2 E	0.3	5.2
1.1	2.0	2.8	3.1	3.2	3.1	2.7	2.0	1.2 E	0.7 E	0.1 E	0.3	6.0
1.3	2.1	2.9	3.3	3.5	3.4	2.9	1.9	1.0 E	0.1 E	0.3 W	0.9	6.0
1.1	2.4	3.2	3.7	3.9	4.0	3.5	2.6	1.7 E	0.8 E	0.2 E	0.5	6.9
1.4	2.9	3.7	4.5	5.0	4.8	3.8	2.5	1.4 E	0.3 E	0.8 W	1.7	8.2
1.5	2.9	3.7	4.3	4.8	4.5	3.8	2.8	1.6 E	0.6 E	0.4 W	1.0	8.2
1.2	1.6	2.1	2.4	2.5	2.3	2.0	1.5	0.8 E	0.4 E	0.2 W	0.7	4.6
0.6	1.1	1.5	1.9	2.3	2.4	2.2	1.5	1.0 E	0.5 E	0.1 E	0.4	4.1
0.5	1.2	1.5	1.8	2.0	2.3	2.2	1.8	1.1 E	0.3 E	0.2 W	0.7	3.8
0.8	1.5	1.9	2.4	2.7	2.7	2.5	2.0	1.2 E	0.6 E	0.0	0.6	4.9
1.2 E	1.9 E	2.5 E	3.0 E	3.3 E	3.3 E	2.7 E	1.9 E	0.9 E	0.2 E	0.3 W	1.0 W	5.5 mm.

One very remarkable fact is that in the years under discussion there was a strong tendency for the pendulum to deviate more and more to the west of its mean position during the winter, and to the east during the summer. This may be provisionally explained—pending further investigation—as a tilting of the whole sub-continent in response to the loading of the east coast by rain in summer and the west coast in winter, supplemented, of course, by the unloading of the west coast in summer by evaporation and of the east coast in winter. Be the cause of this what it may, the effect is too great to be measured satisfactorily by any means at my command.*

It is interesting to compare the harmonic elements of temperature and barometric pressure (Table 2) with those of the variation of level. In each case the time is counted from local mean midnight. In the case of the latter element the results are expressed in terms of the deviation in millimetres to the west. The near agreement in point of time of the second harmonic terms of barometric pressure, temperature variability, and variation of level is certainly remarkable. If this is to be regarded as having a physical explanation it would seem to be that the original gradients set up by the principal agencies—whatever they may be, whether temperature or the movement of underground moisture—in the ground are modified by the semi-diurnal wave of pressure so that the final gradients are actually steeper at the places where the local time is $9\frac{1}{2}$ h. a.m. and p.m.

Perhaps a word in conclusion may not be out of place as to the advantages of such a place as Kimberley for seismological research. Griqualand West is exactly the uniform and equally exposed prairie-like plain that Professor Milne asks for. Moreover, it is almost exactly in the centre of the South African Tableland. The great majority of stations in the world are not well balanced, so to speak, in their position with reference to land and water; and as a consequence most of them are relatively too near the sea to get the diurnal oscillation of level clear of such disturbances as are set up by the tides and waves of the ocean.†

* Observations of the variation of level made at the Royal Observatory, Cape Town, at a depth of 30 feet, show a tilt to the east in winter, and to the west in summer—just the opposite to what is found at Kimberley. The line of greatest winter rain is, as it happens, somewhat to the east of Cape Town. This result would seem to confirm the suggestion that the annual oscillation of level is due to incidence of rainfall.

† For an interesting discussion of the general question see a paper by Prof. E. Lagrange, on "Périodicité Sismique," in *Bulletin de la Société belge d'Astronomie*, July, 1904. It appears from this that the diurnal variation of level at Uccle is extremely feeble. At Strassburg, four times as far from the sea, it is much greater. Mr. T. F. Claxton, in *Results of Mag. and Met. Observations* made at Mauritius in 1906, mentions the curious fact that when the Milne seismograph of the Port Alfred Observatory was removed from the electrometer hut to the magnet basement the phase was changed by approximately 12 hours and the amplitude reduced to about one-fourth.

TABLE 2.

SOME HARMONIC CONSTANTS IN THE DIURNAL CURVES OF BAROMETRIC PRESSURE, TEMPERATURE VARIATION, TEMPERATURE VARIABILITY, AND VARIATION OF LEVEL, AT KIMBERLEY.

	Barometric Pressure.	Temperature Variation.	Temperature Variability.	Variation of Level.
V_1	355°	229°	320°	24°
V_2	154	58	150	159
V_3	358	16	114	194
V_4	351	215	—	288
u_1	·0276	12·009	3·269	2·690
u_2	·0243	3·074	1·568	·607
u_3	·0017	·697	·654	·040
u_4	·0001	·764	—	·094