Geophysics. — *"The propagation of sound in the atmosphere".* By Dr. E. VAN EVERDINGEN. (Communicated by Dr. J. P. VAN DER STOK).

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§ 1. In various investigations on the propagation of heavy sounds over great distances, especially in the case of volcanic eruptions and explosions, deviations have been found, partly regular, partly irregular. The source of sound is always surrounded by an area of regular or irregular shape, where the sound is heard everywhere; but the source is far from being always situated symmetrically within this area, and the dimensions of the latter are not even in the first place determined by the intensity of the sound. In many cases a second area of audibility occurs, separated from the first by a region where no sound at all is heard. Sometimes this second area partly surrounds the first, sometimes it only consists of isolated spots — only this can be said generally, that the smallest distance from the source of sound for this second area as a rule is much more than 100 KM. and that the intensity of sound at this smallest distance is by no means smaller than at the outer border of the first area of audibility, which is much nearer to the source of sound.

To illustrate this we have collected on plate I. some of the cases that have been investigated most carefully.

1. (Fig. 1). Dynamite explosion (15000 KG.) at Förde in Westfalen, December 14th 1903. Investigated by Dr. G. VON DEM BORNE [1]).

The small crosses indicate, in this and all following figures, the places where sound was heard, the circles those where nothing was heard.

With one single exception the places where the explosion was heard are enclosed by two border-lines: the first line small, 20 to 50 KM. round Förde, but displaced towards NW., the second one large, with an inner border at about 110 KM., and reaching outwards to about 180 KM., within a sector of 90° opening E. of Forde.

2. (Fig. 2). Dynamite explosion (25000) KG.) near the Jungfrau railway on November 15th, 1908. Investigated by Dr. A. DE QUERVAIN [2]). Again with one exception the region of audibility may be divided into two parts: The first, which extends from the "Eigerwand", where the explosion occurred, some 30 KM. towards NE. and NW., whereas at a distance of 60 tot 70 KM. sound was heard at isolated mountain summits; the second much larger, within a sector with

1) Die Erdbebenwarte 4, p. 1—4, 1904.

2) Annalen der Schweizerischen Meteorologischen Zentralanstalt; 1908.

an opening of 90° towards NE., the inner border being formed by a circle with a radius of about 140 KM., the outer border lying at about 180 KM. not counting isolated spots at 200 and 220 KM.

Hence in both cases the two areas of audibility are separated by an interspace, which VON DEM BORNE baptized "Zone des Schweigens" and which we shall call the "silent region".

3. Three eruptions of the volcano Asama in Japan, investigated by S. FUJIWHARA [1]).

a. December 7th 1900. (Fig. 3). Heavy eruption, in which the sound and air-wave broke woodwork and windowpanes at a distance of more than 10 K.M. With the exception of one report, all places where the sound was heard are enclosed within a single line, starting from a place at the coast South of the volcano, passing by the volcano at a small distance Westward, curving round towards a place on the coast NE. of the volcano and, of course, following the coast thence. Within this area there lies a smaller one on the south coast where nothing was heard.

Remarkable is the propagation of sound in almost exclusively easterly directions, coinciding with the direction in which the ashes fell. The extreme distance is about 300 KM.

b. (Fig. 4). December 25th 1910. Moderate eruption. The sound was heard eastward up to a distance of 100 KM., and moreover at two isolated spots at 130 and 210 KM. distance. To the west there is scarcely other than abnormal audibility, which starts at 90 KM. and goes on up to 150 KM.

c. (Fig. 5). April 4th 1911. Also a moderate eruption. First region of audibility small, nowhere surpassing the 50 KM. limit; second region larger and at 120—210 KM. mostly in westerly directions. The density of the reports is especially large at 140—150 KM. in W.

In all, silent regions occur in 9 of the 18 cases which were investigated by FUJIWHARA, at least if we decide to use that name for every region of silence which is bounded inside and outside by regions of audibility. The distances vary between 90 and 220 KM., usually between 120 and 200 KM.

4. A case of gunpowder and dynamite explosion at Kobe on April 3rd 1910, described by the same investigator (Fig. 6). The region of audibility is single and much more regularly shaped than is the case in most of the volcanic eruptions, but still far from symmetrical round the source of sound. The "silent region" indicated in the chart is somewhat dubious, being supported by only one observation.

[1]) Bulletin Central Meteorological Observatory Japan, II, 1. 1912.

5. (Fig. 7). The explosion of the gunpowder-magazine at Wiener-Neustadt on June 7th 1912 (200.000 KG.), investigated by J. N. DÖRR[1]). Here the inner region of audibility is developed almost exclusively eastward and extends there to 120—140 KM., neglecting isolated reports; the outer region lies exclusively on the westside, where it forms almost half a circle, beginning at 160 KM. and reaching so far as 300 KM.

For want of space in Figs. 2, 3 and 4, here and there a group of reports is indicated by a single cross and a number; the same occurs in Fig. 7, on account of the mode of representation chosen by DORR.

§ 2. Part of the irregularities in the propagation of sound in the above cases can be accounted for by the nature of the surface. The propagation mostly in one direction, so far as the inner region is concerned, may sometimes be easily explained by the presence of mountains, which prohibit propagation in a definite direction.

Besides, it is long since the theory in elementary form was proposed, which ascribes the abnormal propagation of sound to the influence of variations in temperature and wind-velocity in the superposed layers of air in the atmosphere. Usually the starting point has been the supposition, that the velocity of sound in moving air is equal to the vector-sum of the velocity of sound in air at rest and the velocity of the wind, whereas the influence of temperature was allowed for in the usual way.

FUJIWHARA[2]) has treated the problem by drawing up the hydrodynamic equations for sound motion in a moving medium. The solution, however, meets with such difficulties that he was obliged to content himself with an approximation for the case of the simplest suppositions: a windvelocity in the same direction at all heights, and increasing or decreasing uniformly with height, and an equally linear variation of the velocity of sound on account of the variation in temperature. It appears that in this case the solution practically agrees with the supposition mentioned above.

Even without going into particulars or calculations, it is easy to see how, by certain suppositions about the vertical distribution of wind-velocity, peculiarities of the propagation of sound, especially the silent region, may be explained.

The influence of temperature, which in the mean decreases upwards, is a decrease of the velocity of sound, which causes the sound-rays

[1]) Wien. Sitzungs Berichte IIa. 122, p. 1683, 1913. Meteorologische Zeitschrift' 32 p. 207, 1915.

[2]) l. c. p. 24.

to curve upwards from the earth. Hence each ray, which deviates ever so little from the horizontal direction, will depart faster and faster from the earth, and that is the reason for the relatively low audibility of sounds in the free air under normal conditions. A wind e. g. from the SW., increasing upwards, may counteract this temperature-effect, and lead to an increase upwards of the velocity of sound for propagation in north-easterly direction — the sound-rays are curved towards the earth: with a linear variation of the velocity of sound the radius of curvature in each point of the orbit is $\frac{V_a}{c}$, if V_a means the velocity of sound in the summit of the orbit and c the variation in velocity per unit of length. The sound may then return to the earth up to great distances in north-easterly direction, after a path through the atmosphere with small friction and relatively small loss of intensity.

If we then suppose, that at a certain height the increase of wind-velocity ends or changes in a decrease, (resp. that the SW.-wind changes into a NW.-wind or into a wind of still more northerly direction), then the ray, the summit of which just lies at that height, will be the last to return to the earth. A slightly steeper ray is curved upwards above this level and cannot return to the earth for the next future. If we assume at a greater height another increase of the wind from the SW., then once more a curvature towards the earth may be found and at great distances the ray may reach the earth.

Towards the SW. the curvature of the ray from the earth is increased by a SW.-wind. Hence very little sound will reach the earth there. But if at a higher level a strong wind from NE. occurs, then a second region of audibility may be found at a greater distance.

For a direction perpendicular to that of the wind as a first approximation no change in the normal propagation is found.

From a theoretical standpoint little can be opposed to this mode of explanation; the suppositions as to the increase of wind with height, which have been made, are sometimes to be regarded as not improbable But we know of no case, where, on the basis of *measurements* or even estimates of windvelocity at great height above the place of observation the *proof* was obtained, that the peculiarities of the propagation of sound may be explained entirely by the variations of wind.

§ 3. An entirely different aspect was opened by VON DEM BORNE's [1]) supposition, that the appearance of silent regions ought to be ascribed,

[1]) Physikalische Zeitschrift, **11** p. 483, 1910.

in some cases at least, to the change in composition of the atmosphere, which is caused by the unequal decrease of the partial pressures of the constituents of the atmosphere.

If no mixing by convective currents occurred, each of the gaseous constituents of the atmosphere would form, entirely according to its own laws, an atmosphere, the pressure p of which at the height h would be given approximately by a formula such as

$$log\, p = log\, p_0 - \frac{hT_0}{HT}.$$

In consequence hereof at great height the denser gases can only occur to a very small percentage, and the lighter constituents, of which hydrogen is the most generally known, must gradually begin to domineer. The convection-currents alter this state of affairs only so far as the lower atmosphere (the troposphere) is concerned. Above 10 or 11 KM. (at least in the temperate zone) little convection occurs, and above this level the change in composition begins nevertheless. Above that same level the fall of temperature with height ceases.

As the velocity of sound in hydrogen is much greater than that in nitrogen or oxygen, it follows from this, that at very great heights the velocity of sound increases so much that the sound rays are curved towards the earth. This is illustrated by fig. 8, which has been deduced from suppositions to be mentioned afterwards.

Von dem Borne's hypotheses differ only quantitatively from these — the entirely smooth character of the sound rays is quite in harmony with his reasoning. Therefore it is really a pity that the words "total reflection" have not been avoided, and that he and his supporters, especially Wegener, have repeatedly spoken of "reflection against the hydrogen atmosphere". Many writers, therefore, thought themselves entitled to dispose of this theory simply by drawing attention to the gradual character of the change in density. Our figure 8 shows that, notwithstanding that gradualness, a sharp limit is produced, within which no sound can be observed, unless particular circumstances cause an entirely unusual course of the rays of little elevation.

Without for the moment going into the details of the numerical results, which are obtained according to different hypotheses about the constitution of the atmosphere, we indicate here the principal features which the silent region ought to show according to this explanation.

1. At the outer limit of the silent region a comparatively large intensity of sound must be expected. The intensity of the sound within the surface between A and B ought to be much greater than that between C and D.

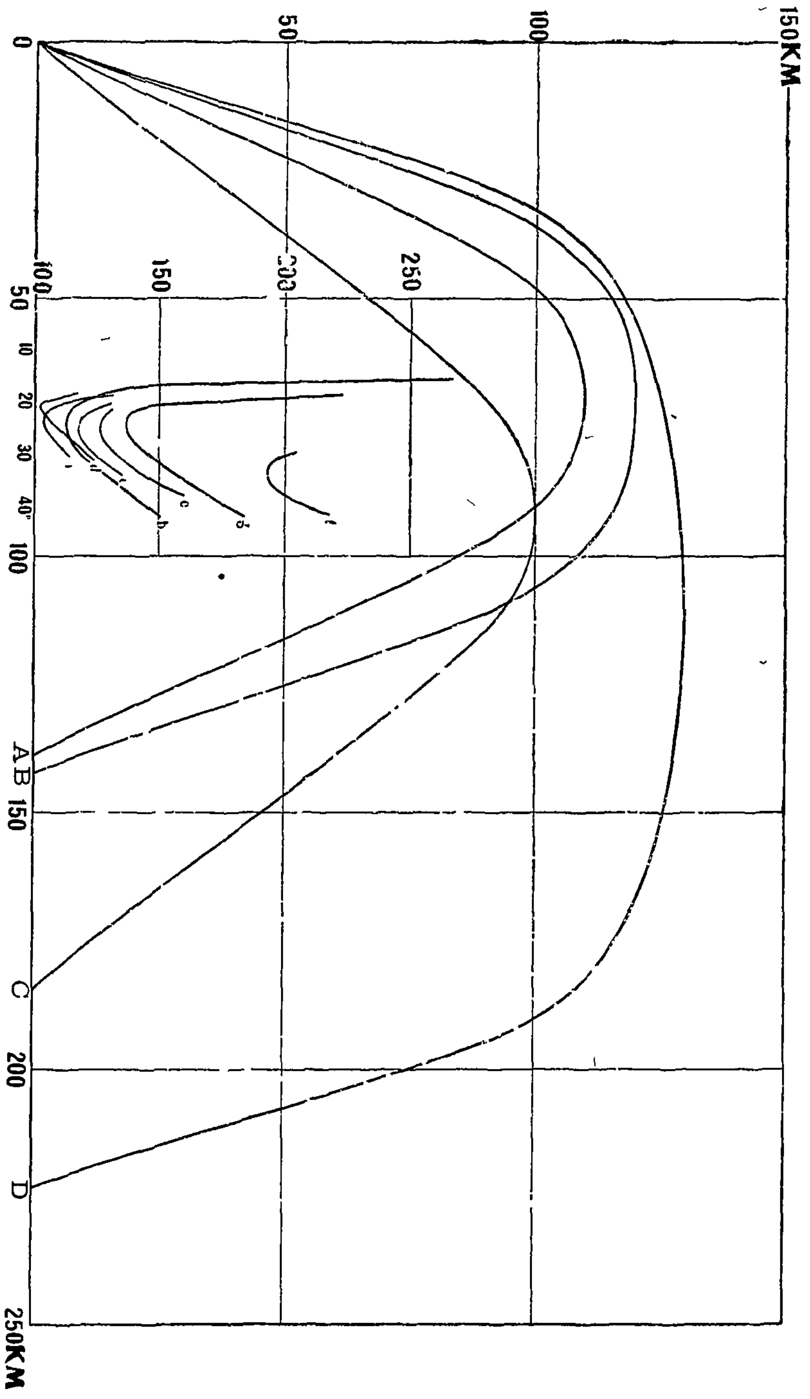

Fig. 8.

2. Apart from disturbances by influence of wind and temperature, the silent region ought to be situated symmetrically with respect to the source of sound, and the abnormal audibility should be found on every side, at least in diametrically opposed points.

§ 4. Before proceeding we will communicate the results of an investigation about the observations of the roar of cannons made by a number of observers of the Royal Dutch Meteorological Institute, temporarily reinforced by other correspondents. These observations have been continued until now by some observers, but have been rather numerous during the months October—February. A preliminary report about the results for October 8th appeared in the periodical "Hemel en Dampkring" for October 1914, p. 81, and was partly reprinted by Prof. MEINARDUS in "Meteorologische Zeitschrift" for May 1915, p. 199. The latter paper gave us the opportunity of extending the observational area for October 8th east and southeastward, so that almost half a circle round the source of sound near Antwerp was formed.

On account of the extraordinarily large number of separate sounds there was no possibility of attributing the observations of definite sounds to well-defined causes. The only thing possible was to classify the reports according to the degree of clearness with which the sound was heard, the duration of the observations and the degree of certainty with which a direction was indicated. In figures 9—16 this is shown by indicating a report without particularities by —, a report of moderate intensity and number of the sounds by + and the reports of very heavy sounds, accompanied by vibrations of window-panes, etc. by $\mp$. A circle, which sometimes occurs, means that there is a definite statement that *no* roar of cannons was observed.

In all figures circles have been drawn indicating the distance from the source of sound.

For the bombardment of Antwerp, especially heavy on October 7th—9th, the place from where the heaviest gunfire was directed was known exactly enough, a little north of Malines. For the other cases of more numerous reports we had first to find out from what part of the battlefield the sounds might have come. Very useful in this inquiry has been a complete number of the mail-edition of the "Nieuwe Rotterdamsche Courant" and a collection of the copies of that paper for periods of 10 days from the date chosen, which we obtained through Mr. VAN MANEN, one of the editors of the paper, from Miss Dr. CH. VAN MANEN. We readily grasp this opportunity to repeat here our cordial thanks for this co-operation. In the second place we used the monthly war-reviews, published by the "Times".

By combining the information from different sources we succeeded in every case in obtaining a high degree of certainty about the cause of particularly intense noises of the war. For the naval battles the determinations of place often were vague enough, nevertheless the place indicated will not be far from the real one. We shall enumerate here the dates;

October 7th—9th.	Bombardment of Antwerp.
„ 17th.	Naval battle on the North Sea, ending in the destruction of 4 German torpedo-destroyers.
„ 18th.	First bombarding of German positions at the Yser by *English naval guns*.
„ 22nd.	Heavy fighting on the line Ostend—Nieuport—Ypres.
„ 24th.	Heavy fighting at the *Ysercanal* (*Y*): the Germans force their way over the Yser. Severe fighting E. of *Ypres* (Y_p) and S. of *Lille*.
„ 28th.	Heavy English naval guns (12-inch) bombard heavy German artillery in Flanders.
November 1st.	Severe attack of Germans on Ypres. English naval guns in action. Heavy fighting at Dixmuiden, on the Lys, and at *Messines*.
January 24th.	Naval battle in the North Sea, ending in the sinking of the "Blücher".

In one of the figures (fig. 11) the supposed position of the English naval guns and the places mentioned in the above list are indicated by their initial letters; at the circles these same letters indicate their centre.

§ 5. *The silent region.*

The little chart for October 8th (October 7th and 9th with fewer reports show exactly the same features) forms a very clear example of a silent region. Though there are a few reports in our country between the circles with 100 and 158 K.M. radius, these do not count against the numerous reports within the circle of 100 and without that with 158 K.M. radius. Especially remarkable is that at the very large distance of over 158 K.M. reports appear again, which talk of vibrating window-panes etc. — a thing which never occurs in the silent region.

Some observers reported that the sound arrived at a rather large angle with the horizon.

The reports, collected quite independently by Meinardus, fall exactly into line with the Dutch ones. In the neighbourhood of Cleve a few reports fall within the circle of 158 K.M. radius, but we must take into account that these reports were not asked for until several days after the siege of Antwerp, and that, with a view to a preliminary account in the press, suggestion or mistakes in dates appear not quite impossible, whereas in our country there can be no question of such a thing.

If we consider that on later occasions also the lightships "Schouwenbank" and "Maas" sent in reports, we are entitled to say that the inner circle has been verified over 180°, the outer one over more than 90°.

It is this symmetry with regard to the source of sound which speaks immediately against every effort to explain this silent region by influence of wind. Any wind, which keeps the same direction over a certain distance, must form a limit of the area of audibility, which is less curved than the circle round the source of sound through the point, where the ray that has the same direction as the wind reaches the surface once more.[1]) No trace of such a thing is shown here. We shall see afterwards, that also meteorological observations do not give any reason to ascribe the reappearance of the sound at 160 K.M. and farther to the influence of the wind.

Whereas this seemed to be in support of VON DEM BORNE's view, the distance was somewhat at variance with that view. Indeed, VON DEM BORNE calculated that the shortest distance at which the rays curved back by the high atmosphere should reach the surface, was 114 K.M.

One might be inclined to think that meteorological circumstances might be the reason why another value for the minimum distance was found. In calculating the influences to be expected, it soon appears that these influences will be hardly perceptible. We return to this question in § 8 and will see first, whether the silent region was shown also on other days, and whether other distances were observed on these occasions. The various dates will be treated in succession.

§ 6. *October* 17th. The initial position of the battle has been assumed according to a report of the "Drathning Sophia", who reported to have been at 3°45′ E. Long. and 53°3′ N. Lat. when

[1]) Indeed, for a direction making an angle φ with the wind, the velocity of sound V at the level of the maximum windvelocity v becomes $V_\varphi = V_1 + V\cos\varphi$; hence the initial angle of the ray, which becomes horizontal at this level, is determined by $\sin\alpha_\varphi = \frac{V_0}{V_1 + V\cos\varphi}$. When φ grows, $\sin\alpha_\varphi$ increases and every element of the orbit is longer the more φ increases. For a definite value of φ, α_φ may become imaginary: in that case the area of abnormal audibility, belonging to this wind-distribution, is enclosed within a definite sector.

she saw the battle developing to the West, and continuing in a northerly direction.

The reports from the south originate from the battlefield in Belgium or northern France, and indeed generally indicate a southerly direction as origin. The three reports in Groningen and Friesland are distinguished in the first place by the time of observation, which falls between 2 and 4 p.m., hence exactly the time of the battle in the North Sea, and indicate northwesterly or southwesterly directions. The distance from the most westerly places of observation to the line of battle is about 160 KM. Evidently the first area of audibility did not extend to the North Sea Isles.

October 18th. The English naval guns were reported to have fired from war-ships lying 4 KM. off the coast at Nieuport.

With the relatively scarce reports from Zealand, the numerous reports from the province South-Holland form a striking contrast; these reports begin at the circle of 160 KM. round Ypres, on which circle a report of vibrating window-panes occurs. The reports of heavy sounds on the 196 KM. line have been connected with the naval guns. We shall see that a distance of about 200 KM. is met with every time when these guns have been in action.

October 22nd. Very heavy was on this day the roar of cannons in Zealand — according to one observer more intense than during the siege of Antwerp. The observations at Zierikzee and Stavenisse, where one noted very heavy sound, the other nothing at all, might be taken to indicate that some cause put a sharp limit to the first region of audibility. But the circumstance that the observation at Zierikzee was made on a light-house may have had a certain influence.

The sudden ceasing of reports past the limit of 100 KM. makes the reappearance at about 160 KM., where also heavy sounds are reported (Noordwijk) the more striking. It is open to doubt whether the second region of audibility had really as sharp an outer limit as would seem. In Limburg the line of 218 KM. runs along our frontier, and on the whole the reports are scanty.

October 24th. As compared with the simple picture offered by the 22nd of October, this day at first seems very perplexing. However, the reports along the New Waterway, now met with for the first time, find their natural explanation in the fighting at Lille (R.) — there are two silent regions here, and both have as outer limit a circle with a radius not far from 160 KM. It is open to doubt whether the line of 200 KM. has any meaning here.

October 28th. According to the reports, no less than 16 English men-of-war joined in the bombardment of the Flemish Coast, and 12-inch guns were said to have been in action.

And yet, in Zealand this time little was heard. So much the stronger were the battle-noises at great distance. The line of 160 KM. plays a certain part again, but that of 200 KM. likewise is clearly indicated. The reports from the province of Groningen give a northerly origin, but evidently as far as Kampen and Dalmsholte (280 KM.) the sound of the naval guns penetrated.

November 1st. The location of the battle is based upon corresponding reports from English and German sides, which place the end of the fighting, at which moment probably the bombardment was most severe, at 40 sea-miles W. of Helgoland. Also in this case there is no real silent region; however, if we look at the heavy sounds, which were frequent enough here, one sees that these are wanting between the circles of 118 and 175 KM. round the terminal spot of the battle, whereas they are rather numerous in the province of North-Holland at the line of 198 KM. Hence there is sufficient evidence of an increased audibility beyond 160 KM.

Concluding, we think we are allowed to say that in many of these cases an increased audibility has been established near the line of 160 *KM., and that beyond this line more roar of cannons was heard than in the belt of* 40 *or* 60 *KM. bordered outwards by this circle.*

In none of these cases is there a clear indication of a unilateral, asymmetrical propagation of the sound — but only rarely the reports were numerous enough to allow definite conclusions in this respect.

7. The foregoing shows clearly, in our opinion, that under the widely varying meteorological circumstances occurring in our country on the days mentioned, there was never an indication of a silent region that would end as early as 114 KM. For the rest, however, the state of things resembles in many respects that state which VON DEM BORNE's theory would lead one to expect. The question therefore arises: how is it to be explained that this theory is not verified quantitatively?

We have already observed that the meteorological circumstances can alter little in the minimum distance. Hence nothing remains but a criticism of the hypotheses about the composition of the atmosphere, on which VON DEM BORNE's theory is founded.

VON DEM BORNE takes 280° abs. for the temperature at the surface, 220° abs. at 12 KM. and a constant temperature from there. In explaining his formulae he starts from the assumption that the molecular weight of the air remains constant up to 12 KM. in consequence of the convection currents; above that height every partial pressure diminishes according to its proper molecular weight. The partial pressures at 10 KM. height are taken from HANN[1]); here, however, the influence of mixture, though this influence is discussed, seems not to have been taken into account; this makes a difference in the first place for the percentage of hydrogen, which without mixing has increased $3^1/_2$ times already at 10 KM. The influence of this omission on the molecular weight in the first 20 KM. is very small, but at great heights the differences are large enough. Moreover, the calculation has been largely simplified by considering the atmosphere as built up of two gases: hydrogen and an imaginary gas with a molecular weight 28.6. For the percentage of hydrogen at the surface, HANN takes 0.01 $^0/_0$; from one of VON DEM BORNE's illustrations we take:

0	20	40	60	80	100 KM.
0.01	0.1	3.0	37.2	94.4	98.6 $^0/_0$

The smallest distance at which sound rays may return to the earth is with these assumptions 114 KM.; the sound ray becomes horizontal at a height of 75 KM.

Of his method of calculation of the sound rays, VON DEM BORNE only says that it was tedious and was performed only in a cursory way. When it appeared from a preliminary control-calculation, that near the summit of the orbit the calculation ought to be made rather exactly in order to avoid great errors, we sought a mode of calculation, which, without taking too much time, would give results exact to about 1 KM. for the horizontal projection of the sound rays.

The following general course was taken:

Starting from different assumptions, to be mentioned afterwards, the composition of the atmosphere was calculated from 10 to 10 KM. by considering the partial pressure of each gas to decrease above the level of 10 KM. according to the law:

$$log\, p = log\, p_0 - \frac{hT_0}{HT},$$

the meaning of which is sufficiently known. Above 20 KM. T was taken = 215, from 10—20 KM. 223, from 0 to 10 KM. 255^5.[2])

From the composition thus obtained, the molecular weight was calculated and thence the velocity of sound by the formula:

$$V = V_0 \sqrt{\frac{T}{T_0}\frac{\mu_0}{\mu}}$$

[1]) Lehrbuch der Meteorologie. 2te Auflage. p. 7. 1905. In the third edition (1914) the calculations of HUMPHREYS, to be mentioned hereafter, are also quoted.

[2]) The latter value as assumed by HANN, l.c. p 8.

From a graphical representation of these velocities, the velocities of sound at 5, 15, 25 KM. etc. were read, and in order to simplify the calculation we assumed that for the less curved part of the orbit a sufficient approximation was obtained by considering these velocities as constant every time over 10 KM.

Starting from some initial zenith-distance of the ray α_0 we find α_h from $\sin\ \alpha_0 : \sin \alpha_h = V_0 : V_h$; the horizontal projection of the sound rays is then given by $\Sigma\ 10\ tg\ \alpha_h$.

For the more curved part of the orbit and especially when it becomes horizontal, this method, however, would cause too great errors. It appeared, that up to the last 5 KM. height a sufficient accuracy was obtained by making the calculation by steps of 1 instead of 10 KM.; hence reading the velocity at each full KM. and using the mean value, which practically means calculating 11 steps, the first and last of which only count for one half.

Also this method would cause errors for the last kilometers as the tg. approaches ∞ for $\alpha = 90°$.

To get a simple approximation here, we used the simplified differential-equation of the orbit for the case where the velocity of sound at this height varies in a linear way, hence may be represented by $v = v_n - ch$.

If we call x and h the co-ordinates of a point of the orbit, starting from the summit of the orbit as origin, then :

$$cotg = \frac{dh}{dx} \qquad \sin \alpha = \frac{v}{v_n} = 1 - \frac{c}{v_n} h = 1 - c'h$$

$$\cos \alpha = \sqrt{2c'h - c'^2 h^2}$$

$$dx = dh\ tg\ \alpha = \frac{(1 - c'h)\ dh}{\sqrt{2c'h - c'^2h^2}}$$

$$x = \frac{1}{c'} \left|\sqrt{2c'h - c'\cdot h^2}\right|_0^h = h \sqrt{\frac{2v_n}{v_n \quad v_h} - 1}.$$

On further inquiry it appears that in this case the orbit is a circle with a radius $\frac{1}{c'} = \frac{v_n}{c}$.

The approximation obtained in this way happens to be closest in the vicinity of the ray which reaches the earth at the minimum distance from the source of sound, because this ray is inverted in the region where the velocity of sound varies most rapidly, and therefore the curve of sound-velocities shows an inflexion.

This method of calculation was also applied to the results communicated graphically by VON DEM BORNE for the velocity of sound

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with his suppositions. Though the order of magnitude for the distances at which the ray returns to the earth remains the same, all distances, and with them the radius of the silent region, become sensibly smaller.

We give here only the results near this point:

	α.	Height H, where the ray becomes horizontal.	Return to the earth at distance D.
a.	30°56′	75 KM.	114 KM.
	24°27′	80	103
	20°53′	85	109
	19°12′	90	131

Hence at all events we find a value for the limit of the silent region, far from those encountered in reality.

In the first place, we had to consider further the suppositions on the composition of the atmosphere made by other writers.

b. WEGENER's [1]) hypothesis about the occurrence of geocoronium in the atmosphere.

WEGENER takes at the surface the lower percentage of hydrogen 0.0033 °/₀ according to RAYLEIGH, but does not allow for the mixing by convection currents. As VON DEM BORNE practically did not do that either, or at least only very partially, WEGENER's percentage of hydrogen remains much lower.

	0	20	40	60	80	100 KM.
Hydrogen	0.0033	0.0	1	12	55	67
Geocoronium	—	—	–	5	19	29

Partially the low percentage of hydrogen is balanced by the hypothetical geocoronium, as this would be 5 times lighter than hydrogen. On the whole, therefore, the course of the rays is only slightly changed, as the course depends on the rapid decrease of the molecular weight between 60 and 80 KM.

The limit of the silent region is indicated by the following sets of values:

α	H.	D.
16°43′	105	148
20°26′	95	118
31°44′	82.7	121
42°32′	77.2	151

If these data are combined in a graphic (fig. 8), we find as limit of the silent region 114 KM. for an initial angle of 25° of the sound ray.

[1]) A. WEGENER, Beiträge zur Geophysik, **11**, p. 104, 1912.

Hence also this figure is far below 160 KM. We may remark here by the way, that the addition of geocoronium accelerates the decrease of density between the heights of 80 and 90 KM., where the inversion of the ray takes place, and hence adds to the shortening of the distance. Therefore, if indeed the silent region in the case of no disturbance ends at 160 KM., this is not in favour of WEGENER's hypothesis, and we should be forced at all events to the conclusion, that the quantity of geocoronium ought to be much smaller than was assumed by WEGENER.

c. HUMPHREYS' [1]) calculation, whereby the mixing in the lowest 11 KM. is taken into account, but the percentage of hydrogen at the surface is again put equal to 0.01 $^0/_0$. The temperature was taken equal to 284 abs. at the surface, thence decreasing by 6° per KM. up to 11 KM., and thence equal to 218° abs.

HUMPHREYS' calculation has not been executed with the same accuracy in all details, so that his figures show a somewhat irregular course. Starting from his fundamental hypothesis, we find the following percentages of hydrogen:

0	20	40	60	80	100 KM.
0.01	0.04	0.7	10.7	67.7	97.3

This again does not produce much alteration and we find in the same way as before:

α	H.	D
34°27′	85	135
27°18′	90	118
22°47′	95	120
20°25′	100	131.

The limit of the silent region then comes at 117 K.M. for an angle of 25°.

As the suppositions of WEGENER and HUMPHREYS, apart from geocoronium, differ principally in two respects: the percentage of hydrogen at the surface and the influence of mixing in the lower 10 or 11 KM., two further calculations were made in order to elucidate the influence of each of these factors:

d. According to WEGENER's hypotheses, but with 0.01$^0/_0$ hydrogen as assumed by HANN and HUMPHREYS (which means that the quantity of geocoronium, which at 200 KM. is put equal to that of hydrogen, becomes much larger).

[1]) W. J. HUMPHREYS. Bulletin Mount Weather 2, p. 66, 1909.

e. Without geocoronium, but with a hydrogen percentage as assumed by WEGENER, and moreover mixing up to 10 KM.

At greater heights the percentage of hydrogen then becomes:

	0	20	40	60	80	100	120 KM.
d.	0.01	0.14	2.6	30.4	68.7	70.5	67.0
e.	0.0033	0.014	0.25	5.2	42.3	91.0	98.2

These assumptions are the most diverging as to the quantity of hydrogen, a thing which becomes especially important at 60 KM. The course of the rays is then characterised by the following figures:

	σ	H.	D.
d.	31°5′	75	124
	23°29′	81.7	106
	20°38′	85	102
	18°27′	90	119
e.	38°48′	90	160
	30°32′	95	133
	25° 4′	100	126
	21°49′	105	131

Minimum distance for *d* ± 102 *e* ± 126.

We see how the decrease of the quantity of hydrogen leads to shifting the limit of the silent region farther off. Therefore the question arises: Is there a reason to assume a still smaller quantity of hydrogen?

This really appears to be the case. The determination by CLAUDE [1]), in which very large quantities of air were liquefied, led to the result, that the volume percentage of hydrogen in the atmosphere at the surface would be only 0.0001, against 0.0005 Helium. For the three rare gases Neon, Helium and Hydrogen together 0.0021 was found.

The most recent determination of these constituents was made by ERDMANN [2]) in samples of air, collected at various heights in the atmosphere at the time of the nearest approach to the earth of the tail of HALLEY's comet on 18/19 May 1910. The quantity of air in these determinations was never more than 650 cm^3. Per liter of air 26 to 37 mm^3. of the gases mentioned was found; only for the height of 4500 to 8000 M. it was possible to ascertain the presence of hydrogen by means of the spectroscope, most clearly in the latter case. Hence at the surface the percentage of hydrogen is far below 0.0026.

From the increasing proportion of rare gases with greater height

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1) G. CLAUDE, C.R. 148 p. 1454, 1909.

2) ERDMANN, Ergebn. d. Arb. d. K P. Aeron. Obs. Lindenberg, 6. p. 227, 1911.

we may conclude, that the mixing by convection currents is imperfect; this increase however is rather irregular and smaller than ought to be expected without mixing. On account of the uncertainty of the determinations and the unknown percentage of hydrogen it is not possible to calculate the degree of mixing.

Still another consideration leads us to reckon for the higher strata with the possibility of a much smaller percentage of hydrogen. For a long time it has been doubted, on account of the kinetic theory of gases, that it would be possible for hydrogen to remain in the earth's atmosphere; since its presence in the lower strata has been put beyond doubt, the possibility has been urged that hydrogen is being produced continually at the surface, e.g. from mineral waters, etc. If this be right, it might be that in higher strata in consequence of the powerful ultra-violet radiation a combination with oxygen took place, and hence the percentage of hydrogen happened to be much lower than we should have to assume according to the gas-laws.

In order to determine further the influence of the decrease in the percentage of hydrogen, we first calculated how the course of the rays would be if there were no hydrogen at all. The gaseous constituent, which then comes under consideration first, on account of its low molecular weight, is Helium. Starting from the figure 0.00015 °/₀ Helium at the surface, as assumed HANN, we arrive at the following composition of the atmosphere:

	0	20	40	60	80	100	120	140 KM.
N	78.03	81.8	87.5	91.5	92.9	78.5	23.8	2.2
O	20.99	17.7	12.3	8.4	5.5	3.0	0.6	—
Ar	0.94	0.5	0.2	—	—	—	—	—
He	0.00015	—	—	0.1	1.6	18.5	75.6	97.8

As the change from the "nitrogen-atmosphere" to the "helium-atmosphere" occurs at much greater height than that to the "hydrogen-atmosphere", and moreover the velocity of sound varies more gradually, the sound rays now become higher and less curved. The results are:

f.	α	H.	D.
	42°18′	120	218
	35° 8′	125	193
	31°30′	130	196

The limit lies at about 190 KM. for rays with an initial angle of 34°.

Hence, in order to arrive at a limit of 160 KM. we have to assume a small percentage of hydrogen in the higher strata. That this percentage ought to be very small appears from the calculation which, by way of test, was made with a percentage, 6 times smaller than the smallest percentage assumed thus far in our calculations i.e. 0.00055 %.

This gives as composition:

	0	20	40	60	80	100	120	140 KM.
N	78.03	81.8	87.5	90.8	82.6	28.9	2.5	0.2
O	20.99	17.7	12.3	8.3	4.9	1.1	0.1	—
Ar	0.94	0.5	0.2	—	—	—	—	—
H	0.00055	—	—	0.7	10.9	63.1	89.6	93.1
He	0.00015	—	—	0.1	1.4	6.8	7.9	6.7

and for the sound rays:

g.	α	H.	D.
	42°33′	100	184
	27°41′	110	139
	21° 8′	120	142
	19°20′	130	223

The limit is found here at 136 KM. for an initial angle of 25°. It is this calculation which served as a basis for fig. 8.

By a rough interpolation we find that the limit of 160 KM. would be obtained at a percentage of hydrogen, amounting to 0.0001 at the surface. It would be useless to make this estimate more accurate, as in all preceding calculations certain influences, e.g. the curvature of the earth's surface, have been left out of consideration, and the results therefore have no absolute value. Moreover it appears that at present a larger percentage of Helium is assumed than we derived from HANN and others. When Prof. E. COHEN was so kind as to draw my attention to the research of CLAUDE, time failed to make another calculation with a percentage of Helium about three times larger. The order of magnitude of our result, however, will not be altered by this circumstance, and the percentage of hydrogen calculated will remain very near that determined by CLAUDE.

§ 8. We have treated the calculations about the sound orbits in air at rest somewhat at length, in order to make clear that the data about the constitution of the atmosphere are by no means so accurately known, that one would be in a position to reject VON DEM BORNE's explanation only because the limit of the silent region does not occur at 114 KM., as VON DEM BORNE's calculation would have it. It appears to us, that given the uncertainty existing in this respect, more weight ought to be attached to the *shape* of the silent region and the distribution of sound intensity at its limit than to the absolute dimensions, and we have pointed out already that in this respect the results for October 8^{th} are very much in favour of that explanation. When DE QUERVAIN[1]) maintains, that even in this case the proof has not been given that the silent region shows a circular form, this can only refer to the absence of reports from the southern battlefields. But he forgets to remark that already the semi-circular form following from the reports obtained, nay, even a circular form over 90°, comes into conflict with what ought to be expected in the case of a wind influence, sufficient to make the sounds return to the earth at 160 KM. distance from the source.

As may appear from what precedes, we are of opinion, that the two explanations of the silent region, which we shall call for the sake of brevity the physical and the meteorological explanation, are both true and ought to be applied in combination. The question then arises: how is the path of the rays changed speaking generally, e.g. in case g, when the air is not at rest or large irregularities of the temperature gradient occur?

We leave on one side at this moment the rays, starting with a small elevation, which will contribute most to the audibility in the first region, and shall concentrate our attention on the rays in the neighbourhood of 25° zenithdistance, which reach the surface again at the border of the silent region. Secondly we have in mind, that disturbances by wind and temperature will be confined almost wholly to the first 10 KM., at least in the temperate zone; in the stratosphere no *great* variations of wind or temperature occur. Then we may also perceive, without going into details, that even very heavy disturbances in the lower strata can exert only little influence on the position of the silent region. E.g. if we take an increase of wind of 0.5 M. per 100 M., as DE QUERVAIN assumes in his case, then the velocity of sound at 10 KM. height is increased by 50 M. for horizontal propagation in the direction of the wind, but only by $50 \sin 25°$ or 21 M. for a ray of about 25° zenithsdistance. The velocities of sound in case g at the height of 10 KM. are thus changed in the proportion 1 : 1.07, which changes the elevation there only from 22°37′ into 24°13′. Nevertheless this might have a rather great influence on the limit of the silent region, were it not that for the further propagation the rôle of the ray with initial angle of 25° is taken up by the ray, which starts with 23° 30′ and enters the stratosphere at an angle of 22° 37′. The entire change in the total horizontal path of the rays with minimum distance will hence

[1]) Die Umschau, **19**, No. 27, 1915. Here a case of a very widespread audibility of roar of cannons in the Sundgau on December 25^{th} 1914 is described, in which the propagation is rather unsymmetrical and the silent region of little importance.

be confined to at most the difference 2×10 (*tg.* 23° 49′—*tg.* 23°3′), that is about 0.32 KM.

Variations in the fall of temperature, even considerable inversions, have neither a great influence on these steep rays, the more so, because the *mean* fall of temperature over 10 KM. seldom undergoes great variations. E.g. a sudden rise of temperature of 10°, which was not balanced afterwards, would at 5 KM. increase the velocity of sound in the proportion 1 : $\sqrt{\frac{265}{255}}$, which would alter the elevation by 0°30′. In other words: for these steep sound rays even the most heavily disturbed air behaves as a bad window-pane for a perpendicularly incident ray: it goes through almost undisturbed. Hence the sound, refracted by the high strata of the atmosphere, always returns to the earth at practically the same distance; regular modifications of the sound-limit, which are connected with the regular and pretty great velocities, which may occur in the higher atmosphere, will always show the same features, since we may assume at these considerable heights a practically constant state of motion.

§ 9. From this we may immediately infer, that the singularly shaped silent regions, observed in many of the cases quoted in the introduction, cannot be ascribed to a co-operation of the refraction in the high atmosphere and the disturbances of the lower atmosphere, but ought to be explained by the latter alone. That in these and other cases the regular second region of audibility does not appear, will often be explained sufficiently by the fact, that this sound is rather weak, absolutely speaking, and may easily be covered by sounds transferred in another way. Moreover we have already indicated the possibility, that originally little sound is emitted in certain definite directions. In the case of volcanic eruptions the emitted hot gases and vapours, mixed with ashes, may cause tremendous disturbances in the distribution of windvelocity and temperature. Yet it seems to us, that among these cases some indications are found of an increased audibility at distances of the order of 140—160 KM.

a. In the case of the dynamite-explosion at the Eigerwand (2) near the Bodensee, distance exactly 160 KM.

b.	December 7th	1909	Asama	170	K.M.	(Fig. 3)
	April 4th	1911	,,	140	,,	(Fig. 5)
	,, 3rd	1911	,,	150	,,	
	December 25th	1910	,,	145	,,	(Fig. 4)
	,, 2nd	1912	,,	140	,,	

c. At the gunpowder explosion at Wiener-Neustadt, where the second area, not counting spurious observations, begins only at 160 KM. Whether the greatest intensity of sound, which was found here at 210 KM., might be ascribed to a special distribution of the energy of sound at the source, cannot be decided by the present writer.

It would be possible in these cases to decide immediately whether the sound had made its way through the very high strata of the atmosphere, or had been held back in the lower 10 or 20 KM., if the time of propagation were known accurately. Some data about this point are indeed available, but often the accuracy leaves much to be desired. In the case of the explosion at the Eigerwand (2) the two statements for the immediate neighbourhood about the time of explosion differ by 2 minutes, and the times of propagation for distances of 160 to 170 KM. vary from 3 to 13 minutes. Along the orbit assumed by DE QUERVAIN for this distance, 8 to 9 minutes would be required, for an orbit in case *g*, ascending to a height of 115 KM., 12.5 minute. Hence the mean time of observation is in favour of an orbit more like that of DE QUERVAIN, but the observation cannot be called decisive.

In the case of the volcanic eruptions, investigated by FUJIWHARA, thanks to the observations of a number of meteorological stations, the uncertainty of the time determinations is not so great, though an uncertainty of 2 minutes forms no exception. Among these there are at least two, that of December 7th 1909 and May 25th 1910, where at distances above 140 km. beside normal, also abnormal large times of propagation occur, whereas in the former case times of 15 and 16 minutes are stated, which would agree very well with a propagation through the layers above 100 km.

Also in the Wiener-Neustadt case at great distances times of propagation above the normal value are mentioned.

Hence, though the times of propagation support to a certain degree the applicability of the physical explanation, it cannot be denied, that the first impression generally pleads for a meteorological explanation; a decision however is not yet arrived at.

So we are forced to the conclusion that in the case of Antwerp, where the silent region appeared so extremely regular, extraordinary weather-conditions have co-operated to procure an image so little disturbed.

FUJIWHARA, as well as DE QUERVAIN and DÖRR, has tried to ascribe the abnormal propagation of the sounds to the meteorological influences mentioned. Unhappily these writers did not as a rule dispose of anything like sufficient data about the conditions in the higher strata, so that they had usually to resort to suppositions or theoretical speculations. E.g. DE QUERVAIN in his case assumes, that from 4000 to 11000 m. height a SW.-wind occurred, increasing to a velocity of 35 m. per second, whereas the observation of Cirrus-clouds in our country on the 15th gave Ci. in NW. (probably rising from NW.), and on the 16th and 17th really a rather fast motion from WNW. (17 m. at 10000 m.) was stated. Inspection of the weather-chart, in connection with the motion of the isallobars, would lead one in the first place to suppose a motion from SE. in the intermediate layers. If the sound rays have really taken their way exclusively through the lower atmosphere, we should be more inclined to admit the influence of a strong inversion in the A-Cu-level in the same manner as was observed on that day at a much lower level at Lindenberg. Be this as it may, observations of the air-motion in the levels above 4000 m. over Switzerland fail on this occasion.

Fortunately, for some of the cases of roar of cannons in the Netherlands treated above, a greater certainty exists. We have collected in a table the observations obtained from clouds, and by means of pilot-balloons, kites and cable-balloons for the days mentioned, and shall consider how far the particularities of the sound phenomena may be explained by these observations.

The table gives in the first column the dates, in the second a short review of the weatherconditions, principally the distribution of pressure. Under the heading "Wind- and cloudmotion" then follow the observations of wind and clouds at the stations Helder (He), Flushing (Vl) and Winterswijk (Wi), where the observations of clouds have been made since 1897 and have been made daily since 1905, whereas at De Bilt (De B) they are made on special occasions. The direction and relative velocity are determined accurately by BESSON's nephoscope, the height of the clouds has to be estimated according to the type of cloud and has been put for simplicity equal to 1000 m. for the lower clouds, 2000 m. for the Strato-Cumulus (St. Cu), 3000 m. for the Alto-Cumulus (A-Cu) and 10000 m. for the Cirrus (Ci). By these assumptions we are enabled to calculate the velocity in meters per second. In consequence of variations in height for the lower clouds, the real velocities may differ from the calculated ones by the factor 0.4 to 1.5; for the higher clouds the deviations will probably remain below 20 %.

Evidently it was desirable to supplement these estimates by more exact measurements, which might consist in observations with pilot balloons, cable balloons, or kites. Unhappily enough the first mentioned observations have suffered much by the difficulty of obtaining pilot balloons during the war, a difficulty which was solved only later. The observations with kites and cable balloons at Soesterberg (S) continue to suffer strongly under the absence of a private ground, the negotiations for which only recently met with success. By way of supplement, therefore, under the heading "Distribution of wind and temperature", we have resorted to observations at Hamburg, Lindenberg and Friedrichshafen, so far as these were at hand at the time. The latter have already been published in their definitive form [1]), the former are quoted only partially in the German daily weather reports and therefore may afterwards be largely supplemented or amended. Afternoon observations are indicated by adding the index p to the name of the station.

On *October 8th* there was almost no increase of wind from the St.-Cu level up to the height where the Ci floated, and certainly no increasing SW.-wind such as would be required to bend back to the earth rays which left the source of sound with some elevation. Up to 2000 M. no S.-components are met with, and no nearer than Helder a W.-ly wind of some importance. The direction of the Ci, observed at Flushing, is nearly perpendicular to the principal direction of propagation. Given the position of the anticyclone. in general, nothing else was to be expected. Hence the abnormal audibility as far as 220 KM. cannot be ascribed to an increase of wind in the troposphere. One might suppose, that in the stratosphere an increasing SW.-current or a decreasing NE.-current reigned, and that these currents caused the rays, practically straight in the troposphere, to curve in the stratosphere. The smallest distance, at which the rays may return to the earth, is then determined by the height up to which one makes the wind increase and by the amount of that increase. But in that way we can never get anything else but a curvature of the rays, which propagate the sound in the direction of the wind. For a ray perpendicular to the wind the effect is practically equal to zero, and the limit of the silent region cannot be a circle, but must show a smaller, perhaps even an inverted curvature so that half a circle, as our figure 9 shows, cannot at all be explained in this way (see the footnote on page 941).

At this moment we indicate once more a remarkable deduction, which must be made from the theory of the bending of sound rays in consequence of the decrease of temperature with height. In the normal case of fall of temperature with increasing height, the sound rays are curved from the surface upwards. Rays starting with a

[1]) Ergebnisse der Arbeiten der Drachenstation am Bodensee im Jahre 1914. Stuttgart 1915.

very small elevation, therefore, depart faster and faster from the surface. It follows from this, that audibility at greater distances is only possible, if the source of sound lies at some height above the surface and rays occur which start with a negative elevation. The necessity of placing speakers in open air meetings on a platform with a soundboard above their heads, depends on the same phenomena of course.

If then the audibility at great distances on October 8th is not to be attributed to the wind, how is the wide-spread first area of audibility to be explained?

The answer to this question is given by the ascensions of cable-balloons at Soesterberg on October 7th and 8th. On the 7th a very strong inversion was met with at 1600—2200 M. height, a rise indeed from 0°.4 to 9°.9 C; on the 8th the inversion lay a little higher, 2500—3000 M. and had decreased to 3.8 → 10.8 or a little lower.

The masses of air, which were above Soesterberg on the 7th, moved southward with a small velocity, some 2 M. per second or 7 KM. per hour. From a comparison with the observations at Friedrichshafen and Hamburg and with the distribution of temperature, it appears certain enough, that the southerly motion extended to Belgium and lasted for a considerable time. Thus in 24 hours a distance of 168 KM. would have been traversed, so that those masses of air found themselves then above Belgium.

There is every reason to assume, that especially in the early hours of the morning, when the surface temperature fell very low, the temperature at 2000 M. was much higher than that at the surface, and at noon only a little lower. Under these circumstances in the morning sound rays with an elevation even of 9° might be bent back to the earth at the limit of the inversion layer; if we assume reflection for simplicity's sake, they would reach the earth again at 12 KM. distance. Rays with a smaller elevation would return at a greater distance, and this might be repeated several times, so that the rays undulated between the earth and the inversionlayer until either the energy was exhausted or the inversion layer ceased or decreased and the rays ascended into space. It is reasonable to assume, that with the very large angles of incidence, occurring at the layer of discontinuity a great proportion of the energy of sound fell on the "reflected" rays, the more so because the sky was everywhere heavily clouded or overcast on October 7th and 8th in our country.

Summing up, we may say that the meteorological circumstances on October 8th were extraordinarily favourable for a wide propagation of sound in the area which surrounded the source of sound, but that rays, starting with large elevation were not disturbed at all in the lower strata, so that a return to the earth was made possible only in connection with the change in composition of the higher strata of the atmosphere.

October 17th. This time, too, almost no curvature is to be expected for steep rays in the lower 10 KM.; the increase of wind from NE. ± 5 M. to S. 10 M. per second in the Ci does not neutralize the curvature from the surface, caused by the normal decrease of temperature. Also the inversions are of little importance, at least in our country and at Lindenberg. The temperature does not at all rise to the surface temperature.

In consequence, little is heard in this country of the war-noises in Flanders, in Zealand-Flanders nothing at all. The naval battle on the North Sea is likewise not heard at Helder and further in the province of North-Holland; the motion of the Ci. from the South, indeed, was not apt to cause a downward curvature of rays from a Westerly direction. For the undoubtedly heard sounds in Friesland and Groningen, therefore, no other explanation remains than the refraction by the higher strata of the atmosphere.

October 18th. Cirrus-observations have not come to our knowledge; the weather conditions of the previous day and the fact, that the high pressure was increasing, allow us however to assume, that no very great velocities occurred in higher strata. Hence there was only an increase of the NE. wind up to the A.Cu level at ± 3000 M., an increase decidedly unfavourable for the refraction of the sound towards the earth in the troposphere, but of little influence on the curvature of the sound rays in the higher atmosphere. The ESE-wind, observed with probably very high A.Cu, has no influence on the propagation of the sound in a NE.-ly direction, as was observed on this day. Inversions will have been of little importance in our neighbourhood.

That the NE-wind, increasing upwards, was unfavourable for the propagation near the surface appears clearly enough from the scarcity of observations in Zealand, which contrast remarkably with the numerous reports, even of heavy sounds, beyond 160 KM.

For the first time here an indication appears of the limit of increased audibility at about 200 KM. from the place, where the English naval guns were in action. If these guns were indeed the most audible at this distance, we should have to assume, that the very steep sound rays, wanted for the minimum distance with these guns, were endowed with less energy than the less steep rays, required for a distance of 200 KM. We cannot tell, whether this assumption be right, but a priori it does not look improbable, that the distribution of sound over the various initial angles is not equal. For the noises of the battles on shore, where also very steep guns are used, the distribution certainly will be more regular.

October 22*nd*. The SE. wind at the surface changes into a stronger S.-ly current, which increases up to the A-Cu-level.

The consequences in Zealand are evident; numerous reports of heavy roar of cannons, according to some observers stronger than during the siege of Antwerp. But this propagation does not extend beyond ± 100 KM.; then a distinct silent region is shown. It would again be extremely arbitrary to ascribe the sounds beyond 160 KM. to the influence of wind; up to the Ci.-level little variation has been observed in the wind-velocity, and we know that an important increase of the wind-velocity up to this level would be required in order to allow the sound to be bent back. Inversions of some importance failed further Eastward, and those in the low pressure area will probably have been even of less importance. The explanation by refraction in the higher strata, on the contrary, does not meet with difficulties.

October 24*th*. Neither the distribution of temperature nor the distribution of wind above our country were especially favourable for a propagation of sound along the surface or in the lower strata. The number of reports, but especially the intensity of the sound in Zealand, are indeed smaller than on October 22nd. Probably the rather strong Southerly current, which moved above the Eastwind in Zealand, caused the rather numerous reports in that quarter. Considering the smaller number of reports from Zealand, it is evident that the sounds, suddenly heard on that day on the South-Holland-Isles and along the New Waterway, must certainly have belonged to a second area of audibility around Lille, for which the distance again is in the neighbourhood of 160 km.

October 28*th*. Probably inversions were of little importance in our neighbourhood. Also the increase of wind near the A-Cu-level is smaller than on October 22nd, when the surface wind was SE. and hence the whole SW. wind might be taken as increase of wind, whereas in this case already at a pretty small height above the surface a SW. wind blows, which then increases only a little to 2 and 3 km. Thus may be explained that in Zealand so little was heard, while at the same time the naval guns were heard from about 160 to 300 km. In this case the possibility that an increase of wind towards the Ci-level played a certain part cannot be denied, but it is probable, that this influence made the rays return to the surface at a distance greater than 160 km. Especially numerous are the reports near the circle of 200 km., as was observed every time in the case of the naval guns.

November 1st. There is a rapid increase of wind upwards, but always in a SE.-ly direction, hence perpendicular to the direction from the battlefields towards our country, so that for this direction no influence was to be expected on the bending back of the sound towards the surface. For a propagation from the S. and still more from the SE. certainly some influence was to be expected, and it is possible that the rather confused picture, which the reports furnish on this day, ought to be ascribed to war noises from much more southerly quarters, which were carried to our country this time by the strong upper wind, e. g. from the Argonne. The inversions, extraordinarily large at Lindenberg, must have been smaller over our country on account of the higher surface-temperature.

January 24th. The inversion at Lindenberg is important enough; on account of the Sunday (October 18th and November 1st were Sundays likewise) no observation from our country is available. Considering the position of the high pressure, the supposition that the inversion was present likewise above the North Sea and perhaps more intense, is not risky. De Bilt, Helder and Flushing had an overcast sky all day and the temperature only rose to 2°, resp. 3°5 and 3°. Above the layer of fog probably the same or a slightly higher temperature will have reigned. Hence it is possible, that rays but slightly inclined reached the inversion layer above the northern part of Groningen, and were bent back there, aided by an increasing North-component of the wind. We therefore leave undecided, whether the weak sounds, at the place where otherwise the silent region would have been, must be ascribed to altogether horizontal propagation or to rays of little elevation bent back. The heavy sounds however at 170—200 KM., which emerge there suddenly enough, can be explained hardly otherwise than by propagation through the higher atmosphere.

Conclusions.

1. In the literature of these last few years a number of cases have been described, in which according to careful investigations in the propagation of heavy sounds through the atmosphere a "silent region" occurs. With the roar of cannons during the siege of Antwerp (October 7th—9th 1914) such a silent region is displayed in an extraordinarily regular form, whereas on a number of other days of heavy

fighting on shore or at sea, likewise more or less distinct silent regions may be indicated.

2. The two theories proposed for the explanation of silent regions: explanation by influence of variations of wind and temperature with height (e. g. MOHN, RAYLEIGH, FUJIWHARA), and explanation by the change in composition of the atmosphere in very high strata (VON DEM BORNE) give silent regions of a very different character. The meteorological theory leads one to expect i. a. asymmetry with respect to the source of sound and difference between two mutually perpendicular directions, and permits all kinds of distances; the physical explanation requires complete symmetry with respect to the source of sound. It is shown that the latter particularity is also preserved for the greater part, if considerable irregularities occur in the distribution of wind or temperature and that the outer limit of the silent region is thereby only slightly changed.

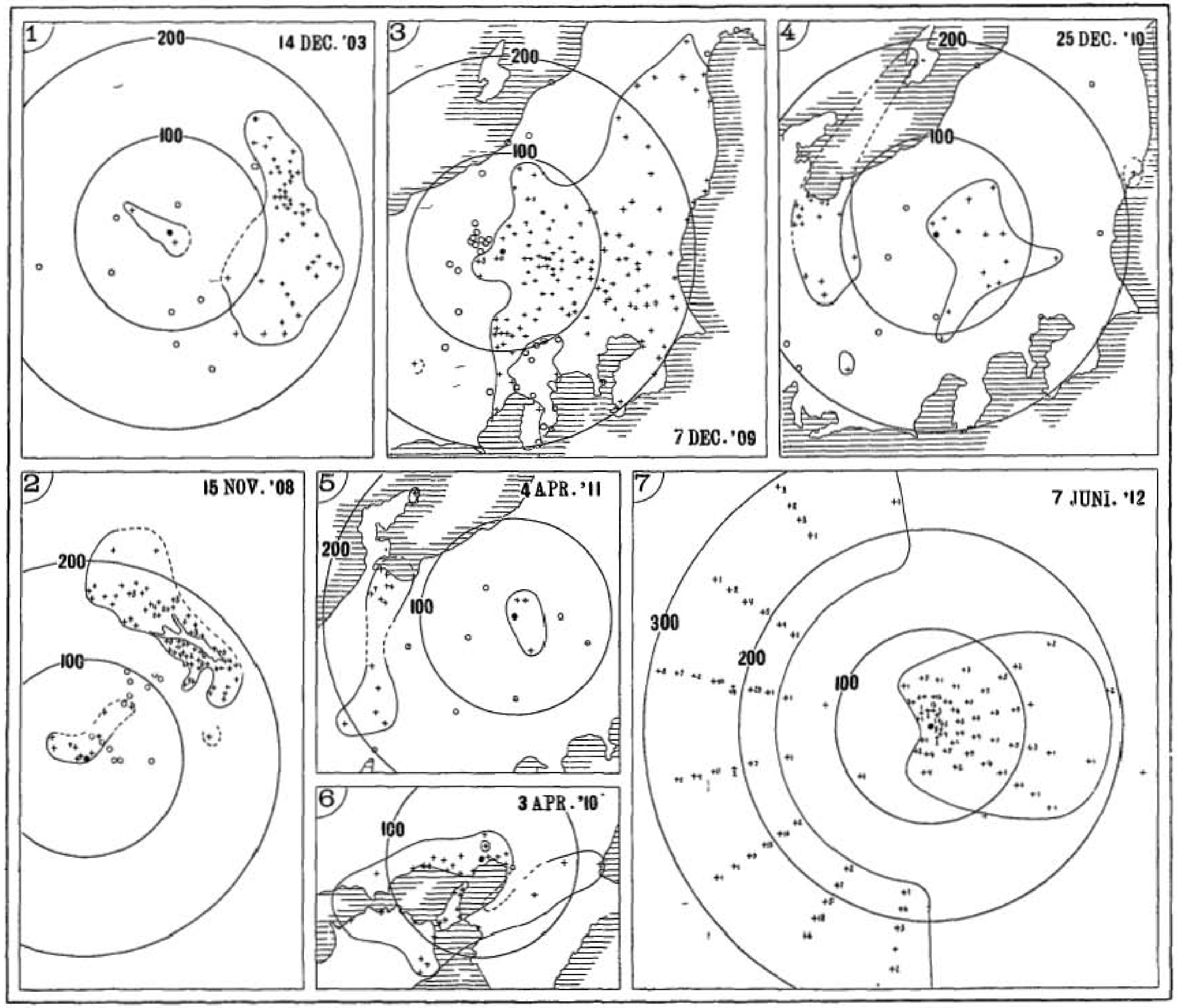
3. Though for want of observations in most cases the proof cannot be given, we must assume that the majority of the well described cases of silent regions have been caused by meteorological circumstances.

4. The meteorological observations in the upper air, made in or near our country on the dates treated in this investigation, fail to give an explanation of the silent regions observed, though they are sufficient to explain the great differences in the first, normal area of audibility.

5. For the physical explanation of these silent regions pleads the fact, that the distance from its border to the probable source of sound has been always near 160 KM., and that no appreciable deviations from the circular form have been found.

6. The figure, 160 KM., does not agree with the suppositions on which VON DEM BORNE has founded his calculations, nor yet with other suppositions published hitherto by meteorologists, but agrees fairly well with the much smaller percentage of hydrogen in the atmosphere according to CLAUDE, if we assume that up to 10 KM. height the composition of the atmosphere does not undergo a perceptible change.

7. A percentage of geocoronium as assumed by WEGENER is at variance with the results of this investigation. If geocoronium is present in the atmosphere, we think that the amount must be much smaller than was assumed by WEGENER.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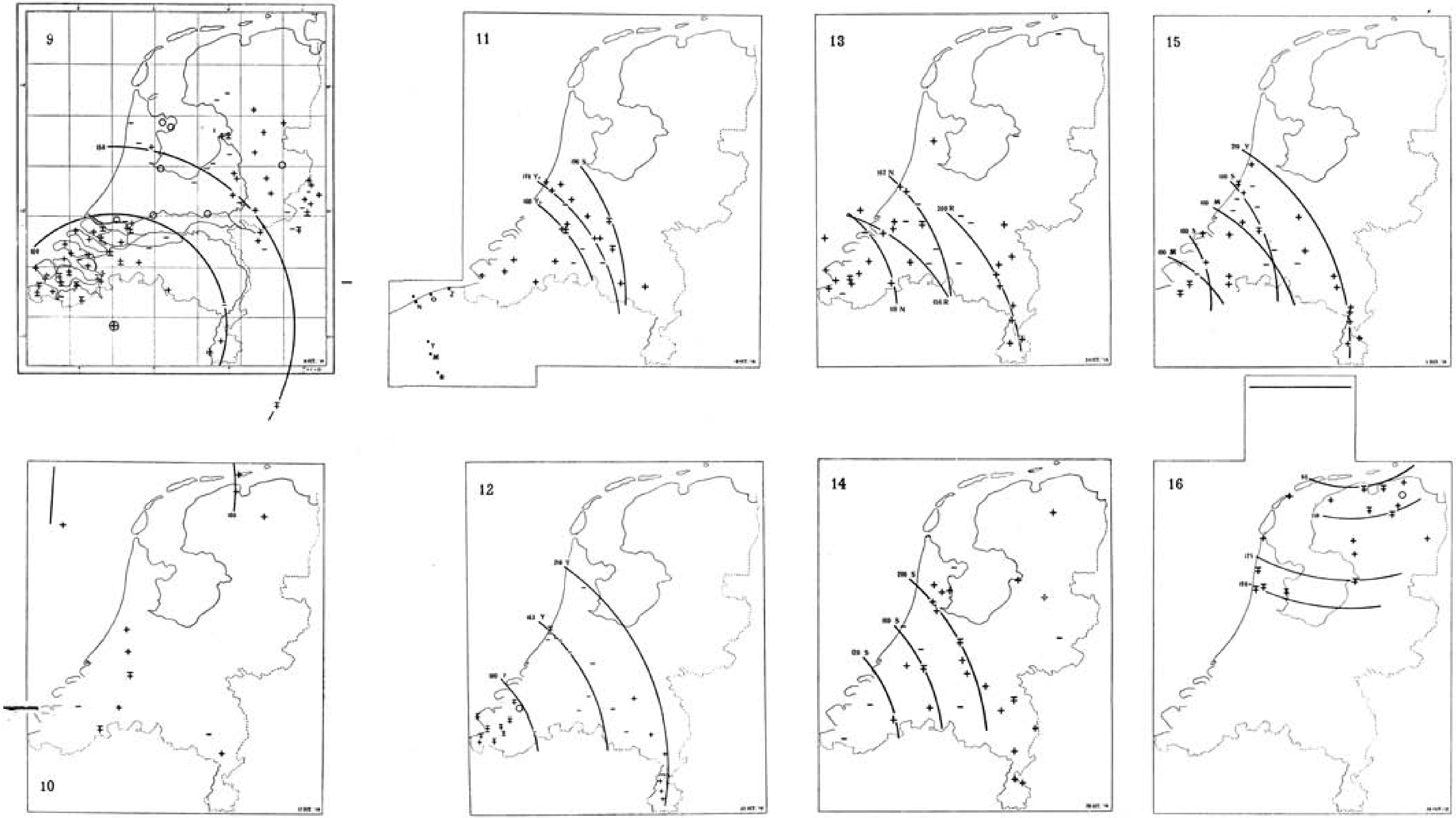
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DATE	WEATHERCONDITIONS	WIND- AND CLOUDMOTION					DISTRIBUTION OF WIND AND TEMPERATURE						
		Station	Surface	Clouds			Station	Surface	1000	2000	3000	4000	Inversions
				Low ± 1000 M.	Intermediate 2000—3000 M.	High ± 10.000 M.							
1914 October 7th	High pressure above 770 mm. over Western Europe, centre over the southern part of the North Sea. Shallow depressions in the extreme North.	He.	N-NW. 1-2	Cu. W. 4	St. Cu. N. 60 W. 5 A. Cu. N. 5 W. 14	Ci. N. 6 E. 28	S.p.	11.9° SW. 2.5	3.7° NNW. 2	3.2° NNW. 2			1510—2220 0.4→9.9
		Vi.	NE. 2—4 ([illegible] variable)		St. Cu. NE. 10 A. Cu. N. 30 E. 11—17		H. (I) H.p. (I) L.p.	NW. 2 WNW. 1 8.6 NNW. 6	NNW. 4 WNW. 4	N. 6 NNW. 8 − 8.9 NNW. 5			−0.1 NNW. 9
		Wi.	S.-SW. 1-3		St. Cu. N. 10 E. 8		Fr.	5.4 NNE. 6	2.9 ENE. 4	−2.3 NE. 7	−6.4 NNE. 10	−8.6 N. 12	1820—1930 −3.2→−2.0 3190—3240 −7.0→−6.2
							De B. (I)	0—500 W. 10 N. 4	500—1000 N. 7 E. 3				
October 8th	As above, maximum near Antwerp.	He.	NW.-W 1-2		St. Cu. W. 11		S.p.	14.0 W. 2	6.4 WNW. 7	5.6 C.			1100—1300 7.0→8.3 2450—2950 3.8→10.8 ?
		Vi.	SSW.-W. 3-5		St. Cu. N. 30 E. 7 A. Cu. N. 20 E. 7—8	Ci. E. 18 S. 11	L. L.p.	4.8 SE. 2 10.4 SW. 3	−0.9 N. 1 −0.2 NW. 2	−7.4 N. 3 −4.0 N. 3			
		Wi.	W.-SW. 1-2		St. Cu. NW.-NE. 12-2		Fr.	2.3 NNE. 4	1.0 E. 2	−0.1 NNE. 2—3	−3.0 NNE. 9	−9.6 NNE. 8	510—630 1.6→2.2 1400—1520 −1.3→1.1 2660—2780 −2.3→−1.4
October 17th	High pressure above 770 mm. over Scandinavia with a ridge above 765 mm. over the North Sea as far as Portugal, and a rapidly deepening depression West of Scotland,	He.	NNE. 5 - 7	Cu. N. 40 E. 6	St. Cu. N. 25 E. 18		S.p	12.2 NNE. 6	4.8 NE. 11	5.2 NNE. 6			1530—1600 1.4→6.5
		De B.	NE.-NNE. 3-5	Fr. Cu. N. 45 E. 10	A. Cu. N. 30 E. 21	Ci S. 10	L. L.p.	6.6 NNW. 2 9.8 N. 3	2.8 SW. 3 2.6 C.	3.0 SW 2 3.2 C.	−2.5 SW. 2 −2.8 C.		122—300 6.6→7.6 1000—1800 2.8→4.8 1220—1550 1.8→5.2
		Vi.	NE. 5—9	Fr. St. N. 60 E. 11	St. Cu. N. 30 E. 17 A. Cu. N. 50 E. 15		r.	8.3 NNE. 4	7.2 S. 3	7.3 SSW. 3	0.8 SSW. 3	−2.7 SSW. 5	930—1310 5.2→11.3 3750—3920 −3.2→−2.2
		Wi.	N-NNE. 3-7	Nb. N. 30 E. 7									
October 18th	which on October 18th already decreases again without having altered much in the high pressure. In our country NE.-ly winds prevail with a sky heavily clouded or overcast.	He.	NE. 3—7		St. Cu. NNE.-NE. 10-3		L.p.	11.5 NE. 2	5.1 SW. 1	6.1 C.	−0.9 C.		1500—2000 3.1→6.1
		Vi.	N.-NE. 4-7	Fr. S. N. 15 E. 14	A. Cu. S. 64 E. 10 (?) A. Cu. N. 15 E. 20		Fr. (I)	N. 5 E. 5	E. 2[5]				
		Wi.	NE. 1—5		Cu. Nb. N. 15 E. 15								
October 22nd	High pressure above 775 mm, over the Bothnian Gulf and a depression below 750 mm. over Ireland, which spreads its influence just to our country and causes an overcast sky.	He.	SE. 3—5		St. Cu. S. 20 E. 11		L.	7.6 E. 3	5.2 E. 3	−1.4 SE. 1	−5.1 SE. 1		770—1000 4.8→5.2
		Vi.	S.—SE. 6 9	Fr. S. S 11	St. Cu. S. 10 E. 10 A. Cu. S. 14		Fr.	8.4 SSE. 2	3.8 S. 1—2	0.3 WSW. 3	−6.4 W. 4	−10.2 W. 4	1030—1230 3.6→5.4 3340—3420 −9.2→−8.6
		Wi.	SE.-ESE. 1-5		St. Cu. S.—SW. 2[5] —6	Ci. S. W. 14							
October 24th	High pressure above 765 mm. over Scandinavia, depressions over Ireland below 755 mm. Sky hazy, heavily clouded or overcast, little rain.	He.	S. 2—4	Nb. S. 30 W. 10	St. Cu. S. 50 W. 10		De B. (I)	0 500 1000 1500 2000 2500 3000 3500 4000 4500 5000 5500 6000 S. 4 SW. 5 WSW. 6 W. 4 WNW. 9 WNW. 7 W. 5 WSW. 7 WSW 7 SW. 6 SW. 5 SW. 4					
		Vi.	S.—E. 3—4	Fr. Nb., St. S. 6	A. Cu. S. 27 W. 14		L. L.p. Fr.	5.6 ESE. 3 12.8 SE. 3 9.2 C.	5.9 S. 3 6.2 SSW. 4 8.0 W. 1	0.5 S. 1 2.0 C. 3.2 WSW. 2	−3.9 WSW. 2 −3.2 C. −3.5 WSW. 4	−10.3 SW. 5 5000 M. −13.0 WSW. 3—4	190—390 4.9→7.9 700—760 8.2→8.8 4220—4400 −11.4→−9.4
		Wi.			St. Cu. S. 20 W. 2[5] A. Cu. W. 10 N. 5								
October 28th	High pressure above 765 mm, over North Scandinavia and Spain. Rather deep depression below 745 mm. north of Scotland, which extends to the Mediterranean and the centre of which moves very rapidly towards France.	He.	SSE. 1—2 ([illegible] variable)	Cu. S. 30 W. 2[5]	A. Cu. S. 6 Cu. Nb. S. 20 W. 8		H. (I) L. L.p.	C. 6.6 SSW. 2 10.2 ESE. 3	WSW. 1 2.6 SW. 4 4.7 S. 4	SW. 6 −1.8 SW. 4 ? −3.9 S. 3			122—200 6.6→8.0
		Vi.	S—W. 1—5		St. Cu. W. 40 S. 8 A. Cu. W. 35 S. 10	Ci. Cu. W. 18 S. 20	Fr	7.3 W. 2—3	5.9 SE. 2—3	−1.7 WSW. 3	−6.6 SW. 7	10.8 WSW. 6	560—800 6.4→6.8 2640—3000 −6.6
		Wi.	E. 1, C.		St. Cu. S. 25 W. 7 A. Cu. S. 30 W. 11								
November 1st	High pressure above 770 mM. above the Bothnian Gulf, depression below 740 mm in the Bay of Biscay. Pressure gradient in our neighbourhood rather small, sky heavily clouded or overcast.	He.	ESE. 3 5	St. E. 15 S. 8 ?			L. L.p.	3.9 ESE. 14 4.6 ESE. 16	8.8 E. 18 11.0 SE. 15	5.6 SE. 14 9.2 SE. 17			410—500 1.5→11.0 940—980 8.5→9.0 1050—1250 8.6→10.2
		Vi.	SE.—E. 5—10	Fr. St. E. 53 S. 6	A. Cu. E. 30 S. 11	Ci. E. 28 S. 25	Fr. (I)	S. 70 E. 2[5]	S. 40 E. 3[5]	S. 12 W. 13	S. 15 W. 20		
		Wi.	E. and W. 1—3	Fr. Nb. E. 10 N. 2									
1915 January 24th	High pressure above 755 mm. over the British Isles, the North Sea and Scandinavia, depression below 740 mm. over Ireland and the Mediterranean. Sky overcast or hazy, moderate ENE.-wind on the North Sea, temperature on shore slightly above the freezing point.	He.	NE. 3—7	Nb. N. 45 E. 16 ?			L. L.p.	−1.0 E. 5 −0.5 N. 4	0.0 ENE. 3 −0.9 E. 3	−5.2 NE. 2			730—850 −4.8→+1.2 730—1000 −4.4→−0.9
		Wi.	NE. 3—5										