III. "On the Refraction of Sound by the Atmosphere." By Prof. Osborne Reynolds, Owens College, Manchester. Communicated by Prof. Stokes, Sec.R.S. Received March 18, 1874.

(Abstract.)

The principal object of this paper is to show that sound is refracted upwards by the atmosphere in direct proportion to the upward diminution of the temperature, and hence to explain several phenomena of sound, and particularly the results of Prof. Tyndall's recent observations off the South Foreland.

The paper commences by describing the explanation of the effect of wind upon sound, viz. that this effect is due to the lifting of the sound from the ground, and not to its destruction, as is generally supposed.

The lifting of the sound is shown to be due to the different velocities with which the air moves at the ground and at an elevation above it. During a wind the air moves faster above than below, therefore sound moving against the wind moves faster below than above, the effect of which is to refract or turn the sound upwards; so that the "*rays*" of sound, which would otherwise move horizontally along the ground, actually move upwards in circular or more nearly hyperbolic paths, and thus, if there is sufficient distance, pass over the observer's head. This explanation was propounded by Prof. Stokes in 1857, but was discovered independently by the author.

The paper then contains the description of experiments made with a view to establish this explanation, and from which it appears that:—

1. The velocity of wind over grass differs by one half at elevations of 1 and 8 feet, and by somewhat less over snow.

2. When there is no wind, sound proceeding over a rough surface is destroyed at the surface, and is thus less intense below than above.

3. That sounds proceeding against the wind are lifted up off the ground, and hence the range is diminished at low elevations; but that the sound is not destroyed, and may be heard from positions sufficiently elevated with even greater distinctness than at the same distances with the wind.

4. That sounds proceeding with the wind are brought down to the ground in such a manner as to counterbalance the effect of the rough surface (2); and hence, contrary to the experiments of Delaroche, the range at the ground is greater with the wind than at right angles to its direction, or where there is no wind.

On one occasion it was found that the sound could be heard 360 yards with the wind at all elevations, whereas it could be heard only 200 yards at right angles to the wind, standing up; and, against the wind, it was lost at 30 yards at the ground, 70 yards standing up, and at 160 yards at an

elevation of 30 feet, although it could be heard distinctly at this latter point a few feet higher.

As might be expected, the effect of raising the bell was to extend its range to windward, to even a greater extent than was obtained by an equal elevation of the observer.

These results agree so well with what might be expected from the theory as to place its truth and completeness beyond question.

It is thus argued that, since the wind raises the sound so that it cannot be heard at the ground, by causing it to move faster below than above, any other cause which produces such a difference in velocity will lift the sound in the same way; and therefore that an upward diminution in the temperature of the air must produce this effect; for every degree of temperature between 32° and 70° adds nearly one foot per second to the velocity of sound. Mr. Glaisher's balloon observations * show that when the sun is shining with a clear sky, the variation from the surface is 1° for every hundred feet, and that with a cloudy sky 0°·5, or half what it is with a clear sky. Hence it is shown that "rays" of sound, otherwise horizontal, will be refracted upwards in the form of circles, the radii of which are 110,000 feet with a clear sky, and 220,000 with a cloudy sky —that is to say, the refraction on bright hot days will be double what it is on dull days, and still more under exceptional circumstances, and comparing day with night.

It is then shown by calculation that the greatest refraction (110,000 radius) is sufficient to render sound, from a cliff 235 feet high, inaudible on the deck of a ship at $1\frac{3}{4}$ mile, except such sound as might reach the observer by divergence from the waves passing over his head; whereas, when the refraction is least (220,000 radius), that is, when the sky is cloudy, the range would be extended to $2\frac{1}{2}$ miles, with a similar extension for the diverging waves, and under exceptional circumstances the extension would be much greater. It is hence inferred that the phenomenon which Prof. Tyndall observed on the 3rd of July and other days (namely, that when the air was still and the sun was hot he could not hear guns and other sounds from the cliffs 235 feet high more than 2 miles, whereas when the sky clouded the range of the sounds was extended to 3 miles, and, as evening approached, much further) was due, not to the stoppage or reflection of the sound by clouds of invisible vapour, as Prof. Tyndall has supposed, but to the sounds being lifted over his head by refraction in the manner described; and that, had he been able to ascend 30 feet up the mast, he might at any time have extended the range of the sounds by a quarter of a mile at least.

* Brit. Assoc. Report, 1862, p. 462.