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SPACED LIDAR AND NIGHTGLOW OBSERVATIONS OF AN ATMOSPHERIC SODIUM ENHANCEMENT

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Abstract. On the night of August 25-26, 1979, a large enhancement was observed in the density of atmospheric sodium at a height of 95 km. The enhancement, lasting about 15 min and extending over a height range of about 2 km, was observed at three positions about 50 km apart. Increases in sodium airglow occurring almost simultaneously were observed at two points separated by 107 km. From the time lags between the occurrence of the enhancement at the various measuring points it is concluded that it was caused by the horizontal motion of a cloud of sodium with a density about 10 times the normal density at the peak of the sodium layer. The cloud appears to have been moving in an approximately SW direction with a velocity of the order of 200 m s^{-1}. On the assumption that the sodium was of meteoric origin, it is concluded that a minimum of 10 kg of meteoric material was necessary for its formation. From the magnitude of the observed increases in sodium abundance and sodium airglow a value of 3 x 10^{13} m^{-3} is derived for the ozone density at 95 km.

Introduction

Observations of the vertical profile of atmospheric sodium, by means of a laser radar tuned to the D_2 resonance line, have been made by a number of different groups working at various locations [Sandford and Gibson, 1970; Megie and Blamont, 1977; Simonich et al., 1979; Rowlett et al., 1978]. These observations generally show the presence of considerable time-varying structure in the layer, and this structure has generally been interpreted in terms of gravity waves [Blamont et al., 1972] or tides [Kirchhoff and Clemesha, 1973]. Very occasionally, structures which involve a very large increase in the sodium density are observed, and these do not appear to be caused be atmospheric waves [Clemesha et al., 1978 a]. The purpose of this paper is to report observations of a very large short-lived enhancement which was studied in considerably greater detail than anything previously reported.

Observations

On the night in question, 25-26 August, 1979, observations were made by a steerable laser radar and a sodium D line airglow photometer at São José dos Campos (SJ: 23°S, 46°W) and photometers measuring the Na D line, several OH bands, and the OI 5577-Å emission at Cachoeira Paulista (CP: 23°S, 45°W). At the latter site a Magnetic AB ionosonde was also operating. The lidar was operated at a zenith angle of 20.9° and was pointed at three azimuths in sequence. Each sodium profile, involving 20 shots of the laser, took 1.33 min, so that each of the three measuring points was sampled every 5 min. The SJ photometer sampled every 3.7 min, the Na D and OH photometer at CP every 7.5 min, and the green line photometer every 15 min. The ionosonde also operated at 15-min intervals. The lidar is the same as that described by Simonich et al. [1979] and uses a 48-in. plane mirror mounted on a searchlight drive to reflect the beam from its initially horizontal direction to the required elevation and azimuth. Details of the Na D, OH and OI 5577-Å observational and data reduction techniques are given by Clemesha et al. [1978 b], Takahashi et al. [1974], and Sahai et al. [1974], respectively. Figure 1 shows the relative locations of the various measuring points. The lidar positions shown in Figure 1 refer to a height of 95 km, where the enhancement to be discussed was a maximum. All the airglow observations were made at zenith.

Until 0100 LT on August 26 the various parameters monitored showed no unusual behavior, with sodium abundance about 6 x 10^{13} m^{-2}, peak sodium density around 4 x 10^{9} m^{-3}, sodium airglow about 50 R for the sum of the D_1 and D_2 lines, and no sporadic E visible on the ionograms. Between 0100 and approximately 0115 LT, the sodium density at 95 km increased by a factor of 10, the sodium abundance and airglow intensities doubled, and sporadic E appeared on the ionograms. No effects were observed on the atomic oxygen or hydroxyl emissions. By 0130 the various parameters measured had returned almost to their preenhancement values. Not only was the increase in sodium density restricted to a narrow time interval, but it was also contained within a height interval of little more than 2 km. The height/time variation of sodium density for the whole night is shown in Figure 2, and the sodium abundance, the SJ and CP sodium airglow variations, and the E_s occurrence are shown in Figure 3. The last of these parame-

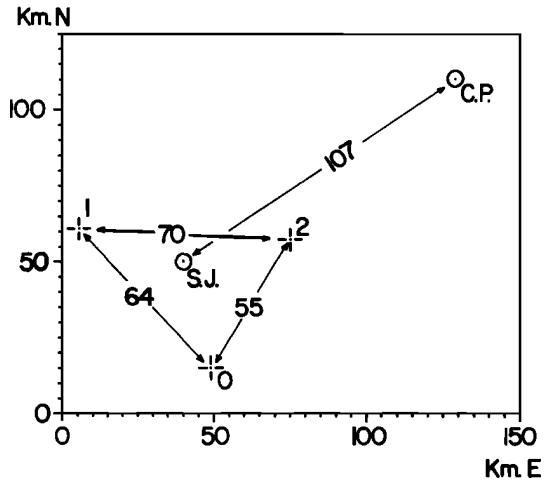

Fig. 1. Locations of measuring positions.

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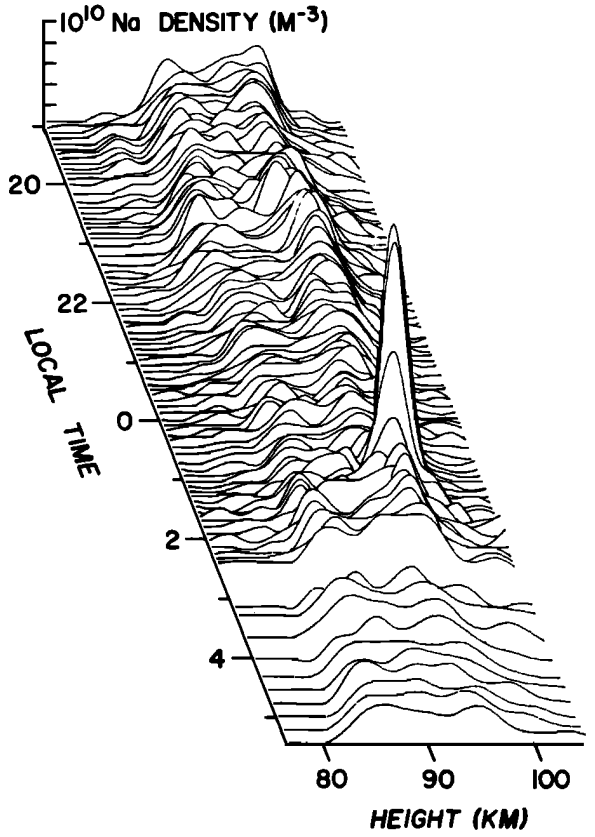

Fig. 2. Nocturnal variations of the vertical distribution of sodium density, 25-26 August, 1979.

ters was determined by measuring the film density on each ionogram in the interval 1.95-2.05 MHz between the heights of 92 and 98 km. The E_s trace was centered on approximately 95 km. The film density is, of course, only very approximately proportional to the echo strength but is at least an objective measure of the latter's variation with time. As may be seen from Figure 3, the sodium increases occur almost simultaneously with the appearance of sporadic E. It should be noted that no E_s was visible on the ionograms between 2030 and 0045 LT and between 0145 and 0345 LT, with the exception of a very faint echo at 0215 LT, the nonzero film densities during these intervals being caused by noise. The sodium density profiles shown in Figure 2 are equivalent vertical profiles obtained by averaging the three-point data.

A careful examination of the sodium density and the airglow variations shows the presence of time lags. In Figure 4 we have plotted the sodium density variations at 95 km for each of the three measuring points and the SJ and CP airglow variations between 0030 and 0200 LT. It can be seen that the SJ airglow lags the CP airglow and that the position 0 density lags the position 1 and 2 densities. Note that there is a gap in the SJ airglow measurements between 0100 and 0110 LT and the increase probably started some time after 0100 LT. The time lags strongly suggest that the variations were caused by the horizontal translation of a patch of high-density sodium, and as will be discussed later, there appears to be no other explanation of the observed variations. Although the observation of a single feature of this nature does not enable us to determine the velocity and direction of motion unambiguously, we may use the observed time lags to make reasonable estimates of these parameters. Unique values for velocity and direction can only be determined if we know the shape of the patch; lacking this knowledge, we must assume that it is symmetrical about a vertical plane perpendicular to the direction of motion. It should be noted that the techniques developed by Briggs et al. [1950] and Phillips and Spencer [1955], to deal with anisotropic ionospheric irregularities which suffer random changes, are not applicable to the present case.

The height/time variations of sodium density at the three positions are not identical, and in Figure 5 we show contour maps for each position from 0050 to 0140 LT and 85 to 100 km. These differences in the structure of the patch could result in serious errors in the velocity vector calculated from the time lags at a given height. A more reasonable approach is to use the total abundance variation, where differences in the height distribution between the three positions will not have a major effect. A correlation analysis of the abundance variations between 0130 and 0200 LT shows that the variations at position 2 lead those at positions 1 and 0 by 112 and 264 s, respectively. These time lags give a velocity of 205 m s^{-1} at 201° azimuth. This direction of motion is almost exactly in the direction from position 2 to position 0. Consistent with this result is the fact, observable in Figure 5, that the density contours at position 0 and 2 are very similar to each other and rather dissimilar to those at position 1. We can also use the airglow enhancements observed at CP and SJ to provide one of the two base lines required to determine the velocity vector. The delay between these enhancements was 320 s, with CP leading SJ. Taken together with the abundance time lag between positios 1 and 0, this delay gives a velocity of 268 m s^{-1} at 199° azimuth. The agreement between these two velocities is remarkably good, particularly with respect to the direction of motion. The

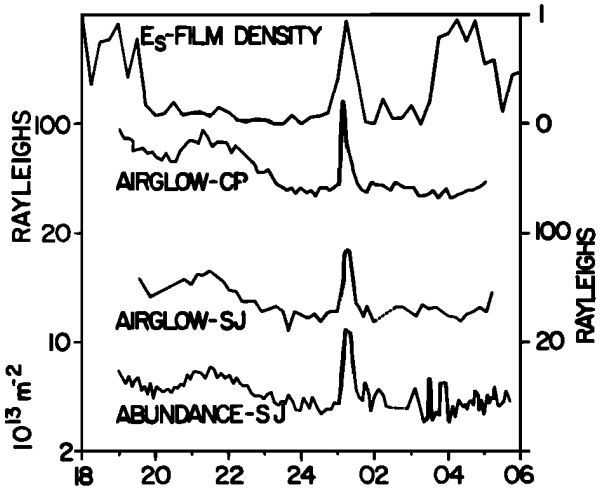

Fig. 3. Nocturnal variation of E_s occurrence, Na airglow intensity, and Na abundance, 25-26 August, 1979.

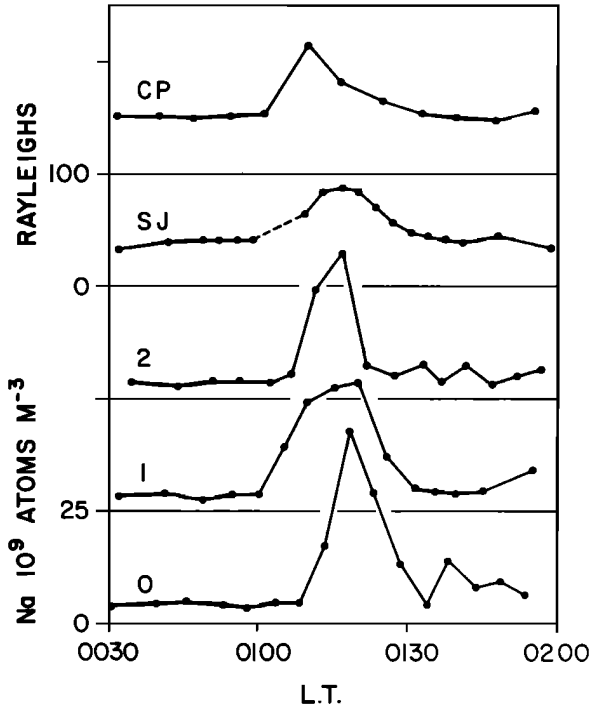

Fig. 4. Variations in airglow observed at Cachoeira Paulista (CP) and São José dos Campos (SJ) and 95-km sodium density measured at three positions.

fact that the velocity calculated from the airglow measurements is slightly higher probably results from the data gap at the beginning of the enhancement observed at SJ. The correlation program used to determine the time lag simply interpolated over the gap, consequently assuming that the SJ enhancement started at 0100 LT, when, in fact, it probably started somewhat later.

Using the average of the two velocities calculated above, we can convert the time scale in Figure 5 to a distance scale, so that Figure 5 represents a vertical cross section through the sodium layer in the direction of motion. Of course, in doing this we assume no vertical velocity gradients. Although this assumption is almost certainly not valid for the entire layer, it should be a reasonable approximation for the few kilometers of vertical extent of the sodium cloud. On this basis we find that the extent of the patch, in its direction of motion, was of the order of 100 km. Our observations do not allow us to determine the extent of the patch in a direction perpendicular to the direction of motion, but from the geometry of the experiment we put an absolute lower limit of 80 km to this quantity. This is simply the greatest distance between measuring points, orthogonal to the velocity vector. Since the amplitude of the increase was roughly the same at all the measuring points, it is extremely probable that the horizontal extent perpendicular to the direction of motion was considerably greater than 80 km, and it is reasonable to use a value of 100 km to calculate a minimum value for the total sodium in the patch. Using this value and a time-shifted average of the abundance increases at the three measuring points gives the total content of the patch as 1.5×10^{24} atoms, or 55 g of sodium. This, of course, is a lower limit, and it is possible that the cloud contained considerably more material than this.

Discussion

The main question raised by the observations reported above concerns, of course, the origin of the sodium. The possibility that the very high sodium concentration resulted from unusual conditions relating to the chemical equilibrium between sodium and its compounds appears to be highly unlikely. Recent models for sodium in the mesosphere [Megie and Blamont, 1977; Liu and Reid, 1979; Richter and Sechrist, 1979] show either negligible sodium compounds at the height in question or, in the case of the Liu and Reid model, a concentration of NaOH of the same order of magnitude as the free sodium but with a very slow rate of conversion to free sodium. This, together with the fact that no correlated effects were seen in the OI 5577 Å or OH emissions, virtually excludes the possibility of photochemical effects being responsible for the increase. Two

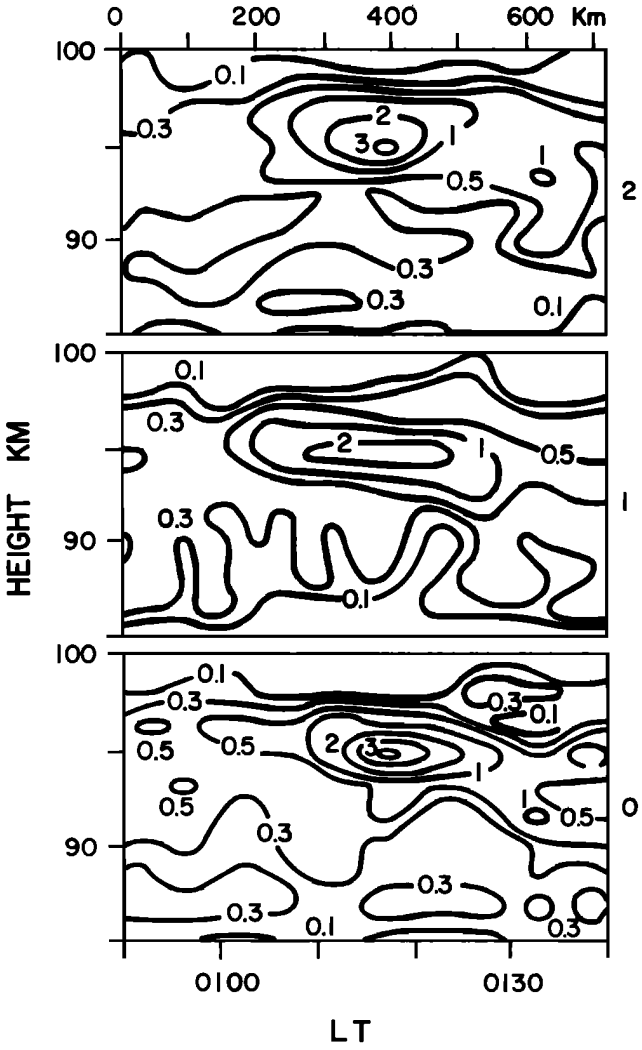

Fig. 5. Na density isopleths for three measuring positions. Contours are marked in units of 10^{10} m^{-3}.

other mechanisms, which appear to be worthy of more serious discussion, are the redistribution of existing sodium and an influx of sodium from outside the earth's atmosphere.

Megie [1976] has investigated the possibility of wind shear concentration of sodium ions and their subsequent recombination to produce a layered structure in the neutral sodium and found that the mechanism should have negligible effect. On the other hand, the formation of sporadic E layers by the wind shear process is well established, and the simultaneous appearance of E_s is suggestive. It may also be significant that the horizontal velocity of the patch was in excess of 200 m s^{-1}. Such high velocities would be expected to be associated with unusually high wind shears, and the dumping mechanism of Chimonas and Axford [1968] might lead to the buildup of an ion layer at 95 km. Against this is the very limited horizontal extent of the observed sodium patch; the winds responsible for the formation of wind shear sporadic E appear to be tidal in origin and thus would extend over large distances. It would seem, then, that although our lack of adequate knowledge of ion concentrations and recombination rates prevents us from definitely ruling out wind shear, it is unlikely that this mechanism was responsible for the formation of the observed layer.

The most likely source of the increase would appear to be an influx of meteoric material. On the basis of our calculation of 55 g as the minimum mass of sodium involved, this would need about 10 kg of meteoric material, assuming 0.6% sodium. A single fireball type meteor entering the earth's atmosphere at a very shallow angle might deposit most of its mass in the relevant height region, although fireballs are normally observed at much lower heights. The evaporation of such a large amount of material at 95 km might be explained if the meteor were of the loose conglomerate type.

Regardless of the source of the sodium we can use the observations to estimate the ozone density at the height of the enhancement. It is generally accepted that the excited sodium atoms which give rise to the Na D emission are produced by the oxidation of Na to NaO by ozone followed by the reduction of NaO by atomic oxygen, leaving the Na atom in the ^2P state:

$$Na + O_3 \xrightarrow{K_1} NaO + O_2 \qquad (1)$$

$$NaO + O \xrightarrow{K_2} Na + O_2 \qquad (2)$$

Since reaction (2) is the main loss process for NaO [Megie and Blamont, 1977], the excitation rate is simply $K_1[Na][O_3]$, and we may equate this rate with the volume emission rate. Using Shimazaki and Laird's [1972] model atmosphere for the ozone density, and measured sodium distributions, Kirchhoff et al. [1979] have shown that Kolb and Elgin's [1976] value of 3.3×10^{-16} m^3 s^{-1} for K_1 gives the right value for the measured airglow intensity, and we shall therefore adopt this value for the reaction coefficient. We observed increases of 70 R in the airglow and 6.5×10^{13} m^{-2} in the Na abundance, leading to a value of 3.3×10^{13} m^{-3} for the ozone density at 95 km. In making this calculation we assume that the ozone density does not change significantly over the height range of the sodium enhancement. Since most of the additional sodium was contained in an interval of about 2 km, this is a reasonable assumption.

Our derived ozone density at 95 km is in good agreement with the mass spectrometer measurement of Trinks [1975] and the stellar occultation measurements of Hays and Roble [1973] but disagrees with the stellar occultation measurements of Riegler et al. [1977]. At first sight it might appear that our determination of the ozone density at 95 km is based on a circular argument, since our validation of Kolb and Elgin's value for K_1 is based on a calculation of the Na emission intensity which uses a model ozone profile. However, the significance of this result lies in the fact that we are able to obtain a value for the ozone density at 95 km, whereas our acceptance of Kolb and Elgin's rate coefficient is based on the integrated emission, which, according to Clemesha et al. [1978b], comes mainly from the 83- to 93- km region.

In calculating the velocity and direction of motion of the sodium cloud we have assumed that the observed time variations resulted from a horizontal motion with respect to the point of measurement and not from an actual time variation in the density of sodium. If we assume that the enhancement resulted from an influx of meteoric material, then the time of onset might represent the actual moment at which the influx occurred, although in this case it is difficult to see why the onset should not have occurred simultaneously at all measuring positions. The subsequent decay in sodium density, if it was caused other than by the horizontal motion of a patch, would require a chemical sink for the sodium at 95 km. As has already been pointed out, however, recent models show that sodium is predominantly in the free state at this height. Liu and Reid [1979] have included reactions involving NaOH in their model and find that approximately 50% of the sodium would be in this form at 95 km. According to Liu and Reid's reaction scheme, NaOH at this height would mainly be produced by the reaction between NaO_2 and H, the former being mainly produced by the oxidation of NaO by O_3. If we accept Liu and Reid's estimated rate coefficients for these reactions, the loss rate of sodium would still be much too low to explain the observed rate of decay. We conclude that the decay in sodium density could only have resulted from the horizontal motion of a patch of sodium, and that we are justified in using the time lags between the variations observed at the various measuring positions to calculate the horizontal velocity of the sodium cloud.

The appearance of E_s on the ionograms at the time of the sodium enhancement strongly suggests that the sporadic E was also caused by a meteoric influx. This suggestion is strengthened by the fact that the E_s was centered on the same height as the sodium enhancement. Although the possibility that meteors contribute to sporadic E has been debated for many years, experimental evidence in its favor is scarce. It would appear that the present results add to this evidence. The fact that the E_s occurred over a slightly longer period than the sodium increase could be

due to the influence of the earth's magnetic field on the motion of the ionized material. The possibility of oblique reflections is ruled out by the lack of any significant variation in the range of the E_s echo.

Conclusions

A short-lived factor of 10 increase in the density of atmospheric sodium at a height of 95 km appears to have been caused by the passage of a cloud of high-density sodium over the observing positions. From the time lags between the increases observed at different measuring positions we estimate that the sodium cloud was moving with a velocity between 200 and 270 m s^{-1} at an azimuth of 200°. It appears that the sodium was meteoric in origin and must have involved the deposition of at least 10 kg of meteoric material. This meteoric deposition appears to have caused sporadic E ionization simultaneously with, and at the same height as, the sodium enhancement. From the magnitude of the observed increase in sodium abundance, together with the increase in Na D airglow intensity, observed simultaneously, we obtain a value of 3.3×10^{13} m^{-3} for the ozone density at 95 km.

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