JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 94, NO. A11, PAGES 15,349–15,358, NOVEMBER 1, 1989

CHARACTERISTICS OF THE SPORADIC SODIUM LAYERS OBSERVED AT 23°S

P. P. Batista, B. R. Clemesha, I. S. Batista, and D. M. Simonich

Instituto de Pesquisas Espaciais, São José dos Campos, São Paulo, Brazil

Abstract. The mesospheric sodium data, obtained between 1975 and 1987 at São José dos Campos (23°S,46°W) with a laser radar, have been analyzed in order to identify the appearance of thin sporadic sodium layers. In this search, a total of 65 events were identified. The average height of the peaks is 95.0 km. The ratio of the maximum peak density to the average layer density is normally 2.5 to 3.0, but values as high as 7 have been observed in the most outstanding cases. The events last from a few minutes to several hours, although durations of 1-2 hours are more typical. The events occur more often during periods of large meteor showers, especially in August. The diurnal variation shows an increasing number of observed peaks from 1500 LT to midnight and remains almost constant from midnight to 0600 LT. In 52 out of 54 days for which sodium and ionosonde data are available there was an sporadic E layer nearly coincident with the sodium cloud. The coincidence is good for short-lived sporadic layers, but a substantial increase in sporadic E critical and blanketing frequencies normally precedes the long-lasting and broader ones. These results are compatible with the suggestion that the enhanced layers are produced by the wind shear distortion of sodium clouds originating in meteor deposition, but we cannot rule out the possibility of an ion conversion mechanism.

Introduction

Laser radar measurements of free sodium atoms in the upper mesosphere and lower thermosphere were first made in the late sixties [Bowman et al., 1969]. Since that time, measurements have been made in several parts of the world, making it possible to delineate the characteristics of the average layer. Such an average layer extends from 80 to 105 km altitude, with a maximum density of 3-5 x 10^9 atoms m^{-3} at around 92 km. These long-term average characteristics do not appear to vary significantly with latitude, although there are differences in the seasonal and diurnal variations in low and mid-latitudes, as described by Simonich et al. [1979] and Gardner et al. [1986], respectively. This average profile is perturbed by the propagation of atmospheric waves which distort and displace the layer with an amplified effect caused by the large layer density gradients [Gardner and Shelton, 1985]. Atmospheric tides, which reach large amplitudes at the height of the layer, affect its behavior mainly through the vertical wind field, so it is possible to estimate the latter on the basis of the lidar measurements [Batista et al., 1985; Kwon et al., 1987]. Internal gravity waves with periods of ~5 min to ~6 hours and vertical wavelengths ≤15 km can also be observed to propagate in the layer, and their characteristics can be studied [Gardner and Voelz, 1987]. Besides these regular characteristics, the sodium layer frequently displays irregular stratified structures. These structures can have horizontal scales as small as a few tens of kilometers and move with the prevailing winds, appearing in measurements taken at one position as short-lived phenomena. Observations of these structures were first made at three separated locations in the sodium layer by Thomas et al. [1977] and later by Clemesha et al. [1981]. The latter authors used the time lag between the measured density at each location to infer the velocity of the horizontal winds at the layer heights.

Among the structures which occasionally appear in the sodium layer, stand out the very narrow and sometimes very short-lived sporadic layers, which seem to be independent of the behavior of the regular layer. Clemesha et al. [1978a] reported the appearance of a layer 2.5 km thick (measured with a 0.5-km height resolution) with characteristics much different to any previously observed enhancement. They interpreted the event as evidence of the entrance of extraterrestrial material into the layer. Another event of singular intensity was observed in August 25-26, 1979, in São José dos Campos, Brazil (23°S, 46°W) and reported by Clemesha et al. [1980]. This event was observed by a steerable lidar at three different positions in the sky, and also by measurements of the sodium nightglow emission at two locations situated 107 km apart. On this occasion a sodium peak appeared at 95 km with an intensity seven times larger than the average density at that height. The duration of the event was extremely short, lasting no more than 15 min between the appearance and disappearance of the layer. Considerable differences were observed between the time variations of the sodium profile observed at the three positions, making it clear that the event had limited spatial dimensions and that the limited temporal duration was due to the advection of the structure over the measurement site. Clemesha et al. [1980] also observed a strong correlation between the sodium event and the sporadic E layer observed by a nearby ionosonde. The authors attributed the phenomenon to the ablation of a single meteoroid of the loose conglomerate type. It is important to note that from 1980 to 1987 no further events of this type were reported, although many sodium measurements were made, mainly at stations located in mid-latitudes (e.g., Illinois, (40°N, 88°W) [Gardner et al., 1986]; Haute Provence, France (44°N) [Granier and Megie, 1982]).

Renewed interest in the thin layers has arisen since von Zahn et al. [1987] observed a similar

Paper number 89JA01207.
0148-0227/89/89JA-01207$05.00

phenomenon at a high-latitude station, Andoya (69°N, 16°E), attributing its origin to the release of sodium, stored in an aerosol layer, by auroral particle bombardment. Subsequently, many events of this type were observed at high latitudes [von Zahn and Hansen, 1988; Gardner et al., 1988]. Besides the low-latitude observations by Clemesha et al. [1978a, 1980], many sporadic sodium enhancements were observed at another low-latitude station (Mauna Kea, Hawaii (19°50'N, 155°28'W), by Kwon et al. [1988]). It seems, therefore, that these events occur frequently at low and high latitudes but they are much less frequent at mid-latitudes [Clemesha et al., 1988]. It also seems, comparing the events reported in the literature, that the nature of the low and high latitude enhanced sodium peaks is the same. If this is really the case, then the hypothesis put forward by von Zahn et al. [1987] is untenable. Clemesha et al. [1988] have extended the explanation based on meteor deposition by pointing out that the initial meteor track would be stretched by wind shear, thus producing layers of different thickness and durations, depending on the creation time and the intensity of the shear. This suggestion removes one of the main obstacles to the meteor ablation hypothesis, namely the necessity of assuming meteor incidence at almost 90° zenith angle. Nevertheless, as pointed out by Clemesha [1989], none of the proposed mechanisms can unequivocally explain all the observations.

A knowledge of the principal parameters related to the sporadic sodium layers (hereafter referred to as SSL) such as the average peak height, average thickness, rise and fall times, diurnal and seasonal variation, as well as their correlation with other geophysical parameters, should at least enable us to reject mechanisms which do not agree with the experimental evidence, even if it does not allow us to arrive at a definitive explanation.

The sodium density has been measured at São José dos Campos, Brazil, since 1972. A large amount of data has been accumulated since that time, enabling us to make a statistical and correlative study of the SSL phenomenon. For this purpose, data from 1975 to 1987, corresponding to approximately 3500 hours of measurements or about 30,000 individual profiles were reviewed in order to identify the existence of sporadic layers and to determine their parameters. The purpose of this paper is to present the results of a statistical analysis of the main parameters of these peaks, the correlation of these with other geophysical parameters, and a few examples of other interesting events in order to better characterize the phenomenon.

Statistics of the Measurements

The identification of SSLs was carried out by visually examining plots of individual profiles integrating a minimum of 50 laser shots. Only peaks which appeared systematically in more than two individual profiles with a ratio between the sodium peak density and the density of the average layer at the same height ≥2 have been considered. The photon counting rate was such that a precision better than 10% was always achieved for the peak density of the average layer. Time resolution of the measurements was variable during this 13 years, ranging from 1.66 min during 1979 and 1980 to 5, 7.5, or 15 min on the remaining years. The height resolution normally used was 2 km until 1979 and 1 km from 1980 on. On some occasions when a strong SSL was observed, the height resolution was increased to 0.5 km. Some of the events were already developing when the measurements started; in other cases the measurements stopped before the event had terminated. For some statistical uses (e.g., rise and fall time and duration), only those events observed throughout their complete development have been considered.

The first parameter determined was the total frequency of occurrence of SSLs. The total number of days of observation was 578, so that the total of 65 events gives an 11.2% probability of finding a SSL. This estimate is not altogether meaningful, since the duration of the measurements is highly variable. A more useful estimate of this probability is the ratio between the total duration of the events (206 hours) and the total number of hours of measurement (3500 hours), which yields approximately 6% of the time; or equivalently, on the average it is possible to observe one event in 17 hours of measurement.

It is interesting to see if there is any seasonal variation in the occurrence of events. Since the number of measurements per month is not uniform throughout the year, the occurrence of events must be compared with the number of hours of data obtained in each month. Figure 1a shows

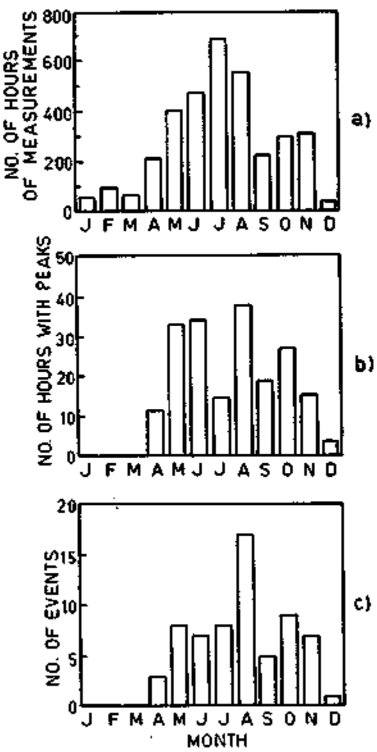

Fig. 1. Statistics of sodium measurements and SSL events: (a) Number of hours of measurements per month. (b) Number of hours per month when a SSL is present. (c) Number of SSL events per month.

a histogram of the total number of hours of measurements for each month, and Figure 1b shows the number of hours when a SSL was observed. It is seen that the number of occurrences is comparatively low in July when the number of measurements is a maximum, and higher in May/June and October. The distribution of events per month, shown in Figure 1c, is somewhat different, with a much greater occurrence in August than in other months. This point will be discussed later in connection with meteor phenomena.

The diurnal variation of the occurrence of events (number of days when a SSL was observed for each hourly interval) together with the diurnal variation of the total number of measurements (number of hours of sodium measurements for each interval) is shown at Figure 2a. It can be seen that the majority of the measurements are concentrated in the first half of the night and so are the events. We have not observed any SSL from 1000 LT to 1400 LT. This does not necessarily reflect a real tendency in the occurrence frequency of SSLs, but could be a result of the poor data obtained near noon, when the individual profiles are generally too noisy to observe any but the strongest events. Attention should be paid to the interval from 1500 LT to 0900 LT. Figure 2b shows the percentage ratio between the number of days with peaks and the number of hours with measurements. A clear trend is seen, with a continuous increase in the frequency of occurrence of SSLs from 1500 LT to midnight and an almost constant value for the remainder of the night. It is not clear if the occurrence tends to decrease at around 0600 LT, or if it continues to increase until 0700/0800 LT, because we have few data for this time interval owing to the occurrence of local ground fog. Kwon et al. [1988] found that for their 30 hours of measurements at Mauna Kea the SSLs had a tendency to occur between 2100 and 0100 LT. Our results, based on a much longer data base do not confirm that tendency.

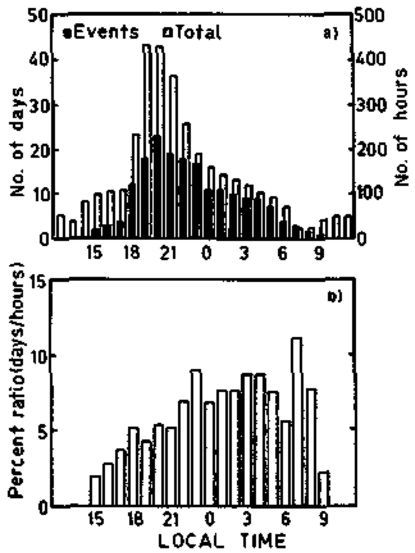

Fig. 2. (a) Diurnal variation of the number of hours of measurements (open bars, right scale) and number of days when a SSL appears at that time (solid bars, left scale). (b) Percentage ratio between the number of days with peaks and the number of hours with measurements.

The distribution of the peaks with height is shown in Figure 3. The height plotted is that of the SSL peak at its maximum amplitude. Peaks tend to appear more often between 92 and 98 km, with an average height of 95.0 km. A few events have been detected at lower altitudes (86 and 87 km), and one event was seen at 102 km. It is interesting to note that the height distribution of SSLs is quite different to the average vertical distribution of sodium, and that the average height of the sporadic peaks is about 2 km above the average height of the normal layer peak.

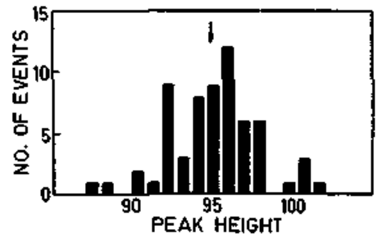

Fig. 3. Height distribution of sporadic peaks. The arrow indicates the average height.

The widths of the SSLs have been measured at their half maxima, and the results are presented in Figure 4. The bar chart shows separately the full width at half maximum (FWHM) for data obtained with 2 and 1 km height resolutions. The average value of the FWHM is 2.0 km, considering only data with 1 km height resolution, and 2.2 km, considering the whole set. The comparatively small number of events observed with the lidar operating with 2-km resolution is partly a result of the fact that fewer measurements were made in this configuration, and is partially caused by the fact that with 2-km height resolution the narrower layers might not be distinguished from the background sodium.

To define the intensity of the event we use the same definition as von Zahn and Hansen [1988]. The strength factor is defined as the ratio between the sodium peak density, at the maxi-

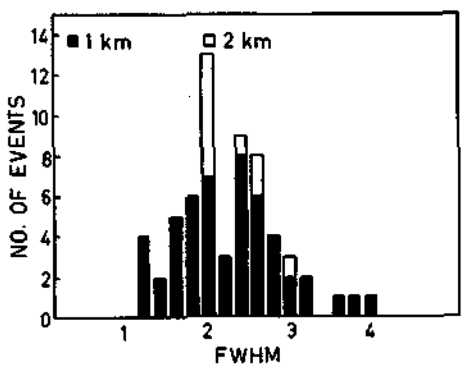

Fig. 4. Incremental frequency distribution of SSL width in 0.2-km interval. Solid bars refer to measurements with 1 km height resolution and open bars to measurements with 2 km height resolution.

mum SSL evolution, and the density of the average layer at the same height before the start of the enhancement. The distribution of this strength factor is shown in Figure 5. It is seen that most of the events have strengths between 2.5 and 3.

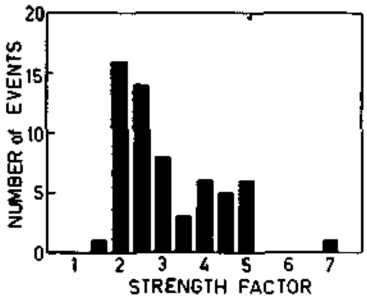

Fig. 5. Frequency distribution of the strength factor.

With regard to the duration of events, Figure 6 shows a histogram of the number of events observed in 30-min time bins. Only 32 events, in which the beginning and ending time could be precisely determined, were considered for this plot. It is observed that the SSLs can persist from less than 30 min to many hours. Although the number of events is not very large, there is some indication that they are divided into two groups, one with durations smaller than 2 hours and other with longer durations, including a few which persisted for more than 8 hours. Events with durations of 3-4 hours have been reported by Kwon et al. [1988], but almost all of the events discussed by von Zahn and Hansen [1988] have shorter durations (<2 hours).

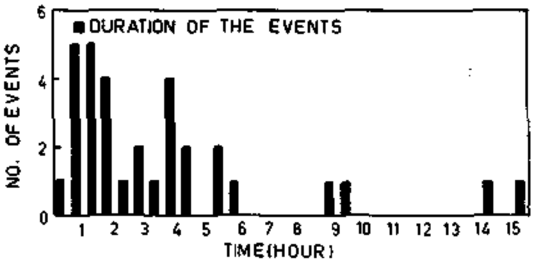

Fig. 6. Frequency distribution of the duration of the events in half hour intervals.

Two very important parameters related to the possible mechanisms for SSLs generation are the rise and fall times of the layer. These parameters are defined as the time elapsed between the first appearance of a peak and its reaching maximum amplitude and from this point to the last profile where the peak was still distinguishable. Figure 7 shows histograms of the number of events as a function of their duration with a 30-min increment. Open bars refer to the rise time and solid bars to the fall time. It is clearly seen that the rise time, with an average value of 50 min, is much smaller than the fall time, which averages 174 min.

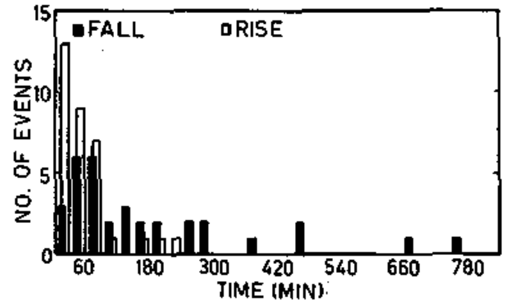

Fig. 7. Frequency distribution of the rise time (open bars) and fall time (solid bars) of the sporadic peaks.

After being first observed, a SSL generally does not remain at the same height. Kwon et al. [1988] reported that for long-duration SSLs they observed an apparent downward velocity of 30 cm s^{-1}. We have followed the evolution of the peak height for 52 events, and a plot showing all of the trajectories of these peaks is shown in Figure 8a. A downward motion of the peaks is observed in the majority of the events, although in a few cases an upward movement is apparent. The average downward velocity determined for events with more than 2 hours duration was 0.97 ± 0.13 km h^{-1} (27 ± 3.6 cm s^{-1}), very close to the value determined by Kwon et al. [1988]. Another feature which can be observed in the figure is the decrease of the average height of the peaks during the night. This average height, calculated for each hour on the hour and plotted as open circles in Figure 8b is about 96 km at 1800 LT and 94.5 km at 0600 LT. A least mean square linear fit from 1700 LT to 0600 LT gives a slope of −0.27 ± 0.05 km h^{-1}(−7.5 ± 1.3 cm s^{-1}). It is interesting to note that this behavior of the average sporadic peak height is opposite to that of the average normal peak sodium layer height, shown by triangles in Figure 8b.

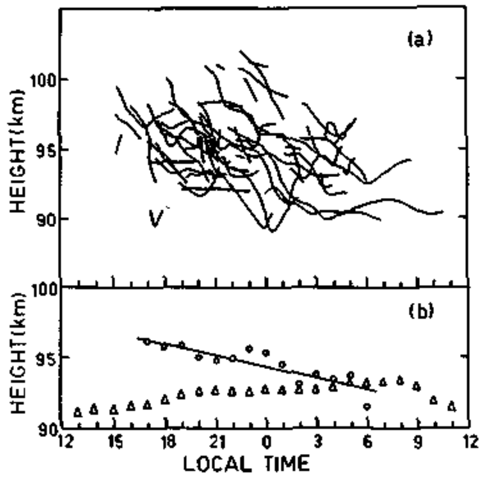

Fig. 8. (a) Trajectories of the height of the sporadic peaks. (b) Average height of the sporadic peaks (open circles) and the average height of the centroid of the normal layer (triangles).

Correlative Studies

The mechanisms responsible for SSL formation, whatever they might be, would be expected to affect other geophysical parameters. Clemesha et al. [1978a, 1980] have associated the events which they observed to the entrance of meteoroids into the atmosphere. Gibson and Sandford [1971] reported the detection of sporadic E layers (Es) about 2 hours before the appearance of small secondary maxima in the sodium layer at 103 km on two nights and pointed to the need for further work in order to determine the statistical significance of these occurrences. For the August 26, 1979, event, Clemesha et al. [1980] found a good correlation with the formation of a sporadic E layer. Von Zahn and Hansen [1988] and Kwon et al. [1988] have also reported a correlation with sporadic E. It is worthwhile, therefore, to extend this correlative study to all the SSLs observed at São José dos Campos, not only with respect to sporadic E, but also in relationship to meteor occurrence.

Local measurements of meteor rates are, unfortunately, not available, but we can compare the annual variation of the occurrence of SSLs with mean meteor rates observed at other locations. Figure 9 shows the occurrence frequency of SSLs for half month periods (solid bars) and the hourly visual meteor rate, also averaged for half month periods (open bars) based on Hawkins [1964]. The visual meteor rate is smaller between January and June than it is between July and December. More SSL events have also been observed during the second half of the year. The visual meteor rate includes sporadic and regular meteor streams, with the more outstanding peaks being caused by the stronger meteor showers such as the Perseids in August, Orionids in October, and Geminids in December. It is noteworthy that the highest number of SSL events is observed during the first two weeks of August, at the same time as the Perseids meteor shower. We have also detected an enhancement of the number of SSLs following the days of Eta-Aquarids (May) and Orionids (October).

With respect to the correlation with sporadic E, we have examined the ionospheric data obtained by an ionosonde operated at Cachoeira Paulista (22°42'S, 45°01'W), about 107 km northeast of São José dos Campos. In 52 out of 54 days, when simultaneous SSL data and ionograms were available, a sporadic E layer occurred at almost the same time as the SSL. Since sporadic E is a very common characteristic over Cachoeira Paulista [Abdu and Batista, 1977] we decided to compare the SSLs not just with Es occurrence but rather with quantitative parameters of the Es layer, namely, the blanketing frequency (fbEs) and the critical frequency (foEs). Note that fbEs is proportional to the Es layer maximum electron density and foEs is related to the structure of the layer irregularities [Reddy and Rao, 1968]. When we compare the temporal evolution of the sodium density at the peak with the sporadic E parameters for all the complete SSL events, we observe that, for most of the short-lived SSLs, sporadic E is not present before the sodium event but appears at almost the same time and disappears after the SSLs. When sporadic E is already present before the SSLs, there is an increase of the fbEs and foEs following the SSLs. An example of this temporal evolution is shown in Figure 10 for August 16, 1983. On this occasion a 96-km peak appeared at 1505 LT, attained its maximum density at 1530 LT, and almost disappeared by 1600 LT. The same peak subsequently increased again to attain a maximum density between 1615 LT and 1630 LT. The same pattern is displayed by fbEs and foEs in a sporadic E layer which appeared below 100 km.

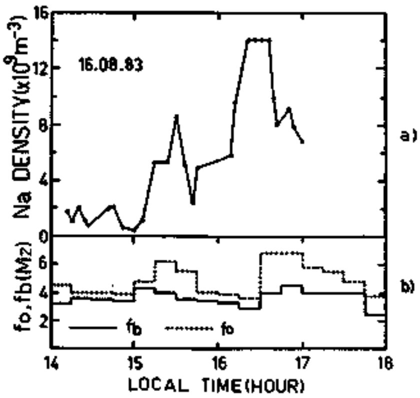

Fig. 10. (a) Sodium density variation at the maximum of the sporadic peak. (b) Blanketing and critical frequency, both for August 16, 1983.

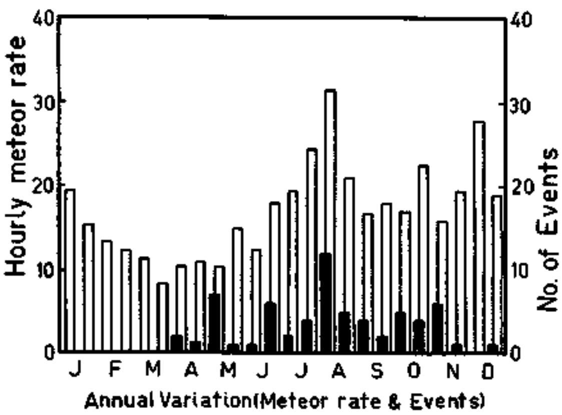

Fig. 9. Half month averages of the daily meteor rate (open bars) and SSL occurrence (solid bars).

Noteworthy are the high values of fbEs during both SSL events and a small delay in fbEs and foEs for the second increase. In order to summarize the results for several events in a single figure we have performed a superposed epoch analysis of the sporadic sodium peak intensity, foEs and fbEs, considering the time of maximum SSL peak as time zero. The parameters have also been normalized by dividing by their values at time zero. The result is shown in Figures 11a, b and c for the normalized peak density, foEs and fbEs, respectively. The circles represent the average values, the vertical bars represent the rms dispersion of the values around the average, and the horizontal tick marks indicate the standard deviation of the average. The dispersions are, of course, large because Figure 11 is the superposition of many different events, with different

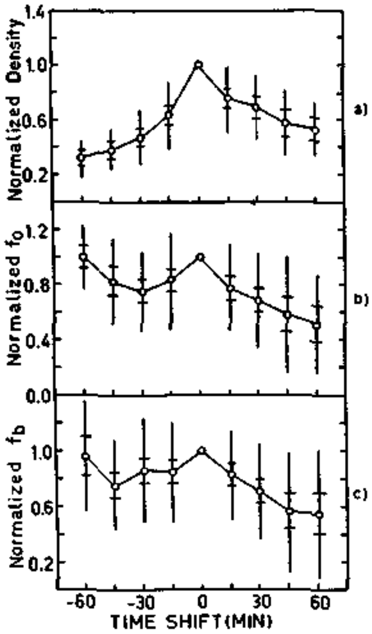

Fig. 11. Superposed epoch analysis of the: (a) normalized sodium density at the sporadic peak, (b) foEs, and (c) fbEs. The circles represent the average values, the vertical bars show the rms dispersion of the values around the average, and the horizontal tick marks indicate the standard deviation of the average. Time zero is taken as the point where the sporadic peak attains its maximum value.

time histories, but the figure very clearly shows that, on the average, foEs and fbEs show maximum values in coincidence with the SSL peak and decrease monotonicaly afterward. We can test the significance of the relationship indicated by the superposed epoch analysis by testing the null hypothesis for a binomial distribution. Figure 11b, for example, involves a total of 91 independent values of foEs, 70 of which were less than that for time zero. If the distribution of the values of foEs about their time zero values were random, then the probability of finding 70 out of 91 less than the time zero value would be 1.2×10^{-7}. For the fbEs values the probability would be 5.8×10^{-9}. It can also be seen from Figure 11 that SSL events are typically preceded by high values of foEs and fbEs, so that the presence of sporadic E might constitute a precursor condition for the formation of SSLs. Figure 11a also shows, in a different way, that the mean rise time of SSLs is shorter than the fall time.

When individual SSLs are analyzed it becomes apparent that the long-duration events have a common behavior which differs from that associated with the short-lived ones. Besides their long duration, they present relatively broad peaks which vary from 2.5 to 4 km FWHM, appear and disappear at similar altitudes, and are frequently associated with a high sodium columnar abundance. Another characteristic which we have observed in seven events of this type is that they are preceded by a substantial increase of fbEs (>4 MHz) and foEs (>6 MHz), and that the SSL peaks continue to exist even after the disappearance of the Es layer. The total abundance increases after the appearance of a peak and continues high even after the peak disappears. Three examples of this kind of variation are shown at Figure 12. Solid circles represent the peak density, and open circles the total abundance. The lower plot shows the foEs (dashed lines) and fbEs (solid lines). Zero values indicate the absence of an Es layer at that time, and the hatched areas in Figure 12a indicate a lack of data. Figure 12a shows an example where a peak with a factor of 2.5 density increase appears after midnight.

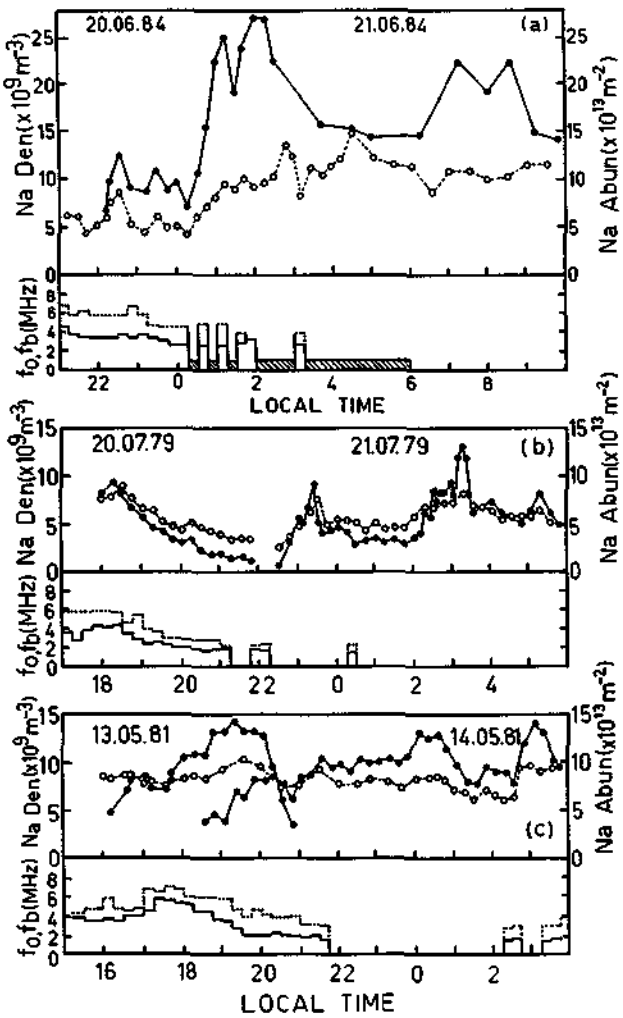

Fig. 12. Sodium density at the sporadic peak (solid circles) and sodium total abundance (open circles) for three selected days. Also shown are the Es layer parameters fbEs (solid line) and foEs (dotted lines) on (a) June 20, 1984, (b) July 20, 1979, and (c) May 3, 1981.

The abundance is about 5×10^{13} m^{-2}, and it is doubled after the complete development of the peak. This high value continues for many hours, while the peak almost disappears and appears again. The sporadic E parameters are very high before and during the first detected peak, but no sporadic E layer is present during the evolution of the second peak. Similar behavior can be seen in Figures 12b and 12c. In Figure 12b a peak, which was already present at 98 km when the measurements started, decreased in amplitude until it disappeared at 2200 LT. Before and during this time a strong Es layer was present near 100 km. The peak reappeared at 2300 LT, almost disappeared again between 0000 LT and 0200 LT, and subsequently appeared for the third time, attaining a maximum value at 0300 LT. The abundance follows the peaks, but Es was absent during the second two SSL events. Figure 12c shows the variations for a day on which a very strong Es layer with fbEs reaching 5.8 MHz at 1715 LT was present. Near 1600 LT a SSL peak appears at 97 km and descends to 94 km before disappearing at 2100 LT. A second peak appeared at 1830 LT at a height of 98 km, before the disappearance of the first. The Es layer was present before and during the occurrence of the first peak but was absent during the presence of the second peak. The total sodium abundance is consistently high during the whole event.

Since 1978, sodium nightglow observations have been carried out on a routine basis at Cachoeira Paulista (CP). On 23 nights when a SSL was observed at São José dos Campos (SJC), airglow data were available for CP, but on only two occasions was a sudden increase in airglow intensity observed. One of these enhancements was the strong event described by Clemesha et al. [1980], and in the other the lidar stopped working shortly after the development of the peak. On this second occasion the airglow showed a 2.3 times intensity increase and continued high for the rest of the night. Although the observation of enhancements in the sodium nightglow appears to be much less frequent than for the lidar (by a factor of 10), some very striking cases have been detected both in SJC and CP, as reported by Kirchhoff and Takahashi [1984]; unfortunately, no lidar data were available for these nights. That the observation of sudden enhancements in the sodium nightglow should be less frequent than that of SSLs seen by lidar is not surprising. The SSLs occur mainly above 92 km, but the airglow, which is believed to be produced by the Chapman mechanism [Chapman, 1939] comes mainly from below this height [Heppner and Meredith, 1958; Clemesha et al., 1978b]. In other words, SSLs rarely occur at the heights where there is sufficient ozone to produce Na nightglow. Another factor which limits the probability of seeing coincident enhancements is the 107-km separation of the observing sites, together with the limited horizontal extent of the sodium cloud. This limited extent was shown by Clemesha et al. [1980] for the August 25-26, 1979, event, and has been confirmed by other observations carried out by our group. During 1979 and 1980, most of the lidar measurements were carried out in three positions in the sky, including 19 nights with SSLs. All of these data show different behavior at the three positions. A good example of this was displayed by the July 30-31, 1979, event, where a SSL appeared at 101 km. Figure 13 shows the sodium number density at 101 km from 2200 LT to 0100 LT, measured at a zenith angle of 20.9° for three different azimuths. In position 1, located about 37 km west-northwest of the observing site, a very fast enhancement occurred at 2300 LT, but the density decreased to the normal level at 0000 LT. At position 2, about the same distance east, there was a delay in the enhancement, and the density remained high until 2343 LT, when it started to decrease. At position 0 located in the south-southeast direction the event was not observed at all. The results shown in Figure 13, together with other events observed at three positions, make it quite clear that many of the SSLs observed have horizontal dimensions, at least in one direction, of the order of 100 km or less. A better characterization of the horizontal structure of the SSLs could be obtained by observing events like those studied by Kirchhoff and Takahashi [1984] with all-sky imaging photometers.

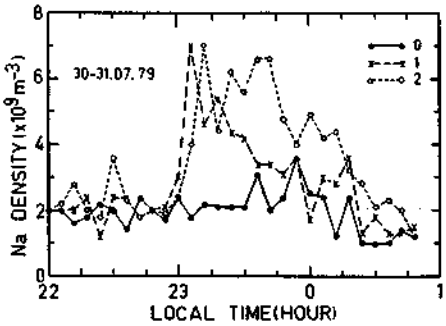

Fig. 13. Sodium density variation at 101 km obtained with a steerable lidar on July 30, 1979. Symbols refer to the three positions in the sky separated by an average distance of 65 km.

We have also investigated the geomagnetic Kp indices for the days when the events occurred and for 15 days before and after the events. A superposed epoch analysis of the normalized ΣKp has been carried out, taking as zero time the day when the peak appeared. The analysis was done separately for the 7 days which show long duration layers and the remaining days. In both cases we have not found any significant indication of correlation.

Discussion

Our purpose in carrying out the analysis of the sodium data presented above is to attempt to understand the mechanisms responsible for the production of sudden sodium layers. Three different mechanisms for SSLs production have been discussed in the literature: (1) meteor deposition [Clemesha et al., 1978a, 1980] and the subsequent wind shear distortion of the initially thick cloud of sodium atoms [Clemesha et al., 1988]; (2) wind shear concentration of sodium ions and their subsequent neutralization [Gibson and Sandford, 1971; Clemesha et al., 1980]; (3) release of sodium atoms from a thin aerosol layer [von Zahn et al., 1987; von Zahn and Hansen, 1988].

A number of characteristics of the observed enhancements support the meteor hypothesis. First, the annual variation, with a maximum in August, at the time of the Perseids meteor shower, is consistent with a meteoric origin for the SSLs. Second, the diurnal variation, with a maximum between midnight and 0600 LT, is similar to that of radio meteors [McKinley, 1961], which have their peak occurrence at 0600 LT, when the local vertical points in the direction of Earth's orbital velocity vector. Third, the correlation with sporadic E layers observed in ionograms, a phenomenon thought to be related to meteor deposition, at least in some of its manifestations, is consistent with a meteoric source for the SSLs. None of these relationships alone could be considered as conclusive evidence for a meteoric source for SSLs, but taken together, they make such a source extremely probable. The possibility that the SSLs are produced by the release of sodium atoms from thin aerosol layers by the effects of energetic particle bombardment appears to be negligible in the case of the events observed at low latitudes. Even for São José dos Campos, which is within the South Atlantic anomaly region and therefore subject to enhanced particle precipitation, the particle fluxes are many orders of magnitude less than those in the auroral region. In the case of Mauna Kea, a low-latitude location outside the anomaly region, particle fluxes would be even less. The analysis by von Zahn et al. [1987] suggests that auroral precipitation might be just sufficient to cause the layers seen at Andoya, so any precipitation at São José dos Campos or Mauna Kea would obviously be insufficient. The lack of any significant correlation with geomagnetic activity also rules out this mechanism for low-latitude stations.

The experimental evidence is conflicting with respect to the wind shear concentration of sodium ions. The close correlation with sporadic E, a phenomenon for which the wind shear mechanism is generally accepted as one of the principal causes, supports this hypothesis. It should be noted that the relationship between SSLs and sporadic E is not restricted to the temporal correlation between their occurrences. Both phenomena involve layers typically 1 km thick with horizontal dimensions of the order of 100 km, which tend to descend in height with time. On the other hand, one of the biggest difficulties with regard to the possibility of SSLs being produced by the neutralization of ion layers is the lack of evidence for adequate Na^+ concentrations. Swider [1984] has summarized the available rocket data up until 1982, and only one measurement appears to have been published since that date. Approximately 10 Na^+ profiles have appeared in the literature, and only two of these, published by Aikin and Goldberg [1973], are fully night time profiles. One other, presented by Kopp et al. [1985], is for a solar zenith angle of 97° and thus refers to twilight conditions. The first night time profile, obtained at Thumba, an equatorial station, at 1938 LT, showed maximum Na^+ of about 90 cm^{-3} in the region of 98 km, decreasing to less than 10 cm^{-3} at 110 km. The second profile, obtained 5.5 hours later on the same night, showed a peak of about 20 cm^{-3} around 90 km, decreasing to less than 1 cm^{-3} at 120 km.

Daytime Na^+ densities appear to be appreciably higher than the night time values, but even here the typical peak values are only about 200 cm^{-3}, although a value of 10^4 cm^{-3} was reported by Herrmann et al. [1978]. On the basis of these measurements, it is extremely difficult to see how sufficient ionized sodium can exist in the 100-120 km region for the wind shear mechanism to generate thin ion layers, especially at night, when most of the SSLs have been seen. It should be pointed out here that, as noted by Swider [1984], because of the highly reducing nature of the atmosphere at heights above 90 km, the possibility that most of the ionized sodium is in the form of molecular ions is slight. It is also significant that the frequency of occurrence of the SSLs observed by us increases between sunset and midnight, an interval when the sodium ion densities must be decreasing. It should also be remembered that the correlation with sporadic E is not invariable; on a number of occasions when a very strong SSL appeared no Es layer was present. The occurrence of Es is much more common than that of SSLs, so that most occurrences of sporadic E are not accompanied by SSLs. The number of SSL events not accompanied by a corresponding Es layer seems to be higher for Mauna Kea, Hawaii [Kwon et al., 1988]. The small horizontal extension of most SSLs may be responsible for the lack of correlation for short-lived events but does not explain the disappearance of the Es layer in cases like those shown in Figure 12. It would be better if the correlative studies had been carried out with the lidar and the ionosonde at the same site. Unfortunately, for the three studies carried out so far the ionosondes were located 107, 129, and 150 km away from the lidar for measurements in São José dos Campos, Andoya, and Mauna Kea, respectively.

It is, of course, possible that SSLs are caused by different mechanisms at different latitudes. This does not seem very likely, in that we are dealing with a phenomenon having a very similar basic appearance at high and low latitudes. On the other hand, there are some major differences between the characteristics of the SSLs seen at Andoya and those observed at São José dos Campos. Although the rise time of our sporadic layers is considerably smaller than the fall time, we have found that on the average it is much greater than the value found by von Zahn and Hansen [1988]. As was shown in Figure 7, in several events the rise time was less than 30 min, but in many cases it was between 30 and 90 min, giving an average of 50 min, 10 times greater than the value for Andoya. The values found by Kwon et al. [1988] are intermediate; they found an average rise time of 15 min and a fall time of 28 min. The time of most frequent occurrence is also different at different locations: at both Andoya and Mauna Kea most of the observed SSLs occurred between 2100 and midnight local time. Although this tendency is derived on the basis of smaller data bases than ours, the difference seems to be sufficiently marked to be significant. The restricted time interval during which the SSL events are seen at Andoya and Mauna Kea might be a result of the fact that the observations at these locations span periods of only a few months, while our data cover a period of 13 years. If the SSLs are produced by meteor showers, then a specific shower would produce maximum effect at a given time, according to its radiant. The concentration of SSLs into a narrow time interval could be the result of the Andoya and Mauna Kea events belonging to a restricted number of meteor showers. Another difference between the Andoya and Mauna Kea results and ours is the frequency of occurrence, which is considerably higher at the former two stations.

It is interesting that the same downward vertical velocity for the height of peak enhancement has been found both by Kwon et al. [1988] and by us, and that this velocity is similar to that expected for the phase propagation of the diurnal tide. A 0.97 km h^{-1} phase velocity would be associated with a 23.3-km vertical wavelength for the diurnal tide. This wavelength is consistent with the propagation of the $S_{1,1}$ diurnal tidal mode with some contribution of higher modes. The analysis of the diurnal variation of the sodium layer [Batista et al., 1985] has shown that for individual days the diurnal tide associated with small vertical wavelengths is very variable and almost disappears when several days' data are averaged. This variability can explain the appearance of peaks at different heights and times. This behavior makes it virtually certain that the velocity does not represent a sedimentation velocity of aerosols, but that it represents the phase velocity of atmospheric waves.

Conclusions

The analysis of a large data base showing more than 60 SSL events makes it clear that we are dealing with a complicated and puzzling phenomenon. The analysis has shown that sudden sodium layers are observed during 6% of the time. These SSLs have durations which vary from a few minutes to many hours. The height and intensity of the peaks are very scattered, with an average height of 95.0 km and average FWHM of 2 km. The time of increase of the peak density is normally smaller than the time of decrease. The diurnal variation of the frequency of occurrence shows a steady increase from 1500 LT to midnight and an almost constant value for the rest of the night. A correlation with meteor events is found, revealed mainly by the larger occurrence of peaks following the Perseids meteor shower. The correlation of the SSL events with sporadic E layers was confirmed, but SSLs are not always accompanied by the presence of Es layers on ionograms taken at a station 107 km from the lidar installation.

An important result which emerged in this analysis is that the long-lived SSLs appear to have a nature different to that of the short-lived events. The difference is manifested not only in the larger duration and broader thickness, but also in the way the events are correlated with sporadic E layers. Among the mechanisms which have been suggested, the best candidate to explain the observations appears to be that of meteor deposition followed by wind shear to produce a thin layer. As pointed out by Clemesha et al. [1988], this mechanism is consistent with nearly all the observed characteristics of SSLs. It does not, however, explain why there should be such a pronounced difference between the frequency of occurrence of the phenomenon at different locations. Simultaneous observations of ionospheric parameters and mesospheric winds at the same site, together with measurements of the spatial variation of sodium airglow by imaging photometers, would provide important clues to the nature of this puzzling phenomenon.

Acknowledgments. We are indebted to our colleagues H. Takahashi and V. W. J. H. Kirchhoff for many discussions and help in data acquisition. This work was partially supported by the Fundo Nacional de Desenvolvimento Científico e Tecnológico (FNDCT) under contract FINEP-537/CT.

The Editor thanks S.K. Avery and another referee for their assistance in evaluating this paper.

References

Abdu, M. A., and I. S. Batista, Sporadic E-layer phenomena in the Brazilian geomagnetic anomaly: Evidence for a regular particle ionization source, J. Atmos. Terr. Phys., 39, 723-731, 1977.

Aikin, A. C., and R. A. Goldberg, Metallic ions in the equatorial ionosphere, J. Geophys. Res., 78, 734-745, 1973.

Batista, P. P., B. R. Clemesha, D. M. Simonich, and V. W. J. H. Kirchhoff, Tidal oscillations in the atmospheric sodium layer, J. Geophys. Res., 90, 3881-3888, 1985.

Bowman, M. R., A. J. Gibson, and M. C. W. Sandford, Atmospheric sodium measurements by a tuned Laser Radar, Nature, 221, 456-457, 1969.

Chapman, S., Notes on atmospheric sodium, Astrophys. J., 90, 309-316, 1939.

Clemesha, B. R., Stratification processes in the atmospheric sodium layer: Observations and theory, Adv. Space Res., in press, 1989.

Clemesha, B. R., V. W. J. H. Kirchhoff, D. M. Simonich, and H. Takahashi, Evidence of an extraterrestrial source for the mesospheric sodium layer, Geophys. Res. Lett., 5, 873-876, 1978a.

Clemesha, B. R., V. W. J. H. Kirchhoff, and D. M. Simonich, Simultaneous observations of the Na 5893 Å nightglow and the distribution of sodium atoms in the mesosphere, J. Geophys. Res., 83, 2499-2503, 1978b.

Clemesha, B. R., V. W. J. H. Kirchhoff, D. M. Simonich, H. Takahashi, and P. P. Batista, Spaced lidar and nightglow observations of an atmospheric sodium enhancement, J. Geophys. Res., 85, 3480-3484, 1980.

Clemesha, B. R., V. W. J. H. Kirchhoff, D. M. Simonich, and P. P. Batista, Mesospheric winds from lidar observations of atmospheric sodium, J. Geophys. Res., 86, 868-870, 1981.

Clemesha, B. R., P. P. Batista, and D. M. Simonich, Concerning the origin of enhanced sodium layers, Geophys. Res. Lett., 15, 1267, 1988.

Gardner, C. S., and J. D. Shelton, Density response of neutral atmospheric layers to gravity wave perturbations, J. Geophys. Res., 90, 1745-1754, 1985.

Gardner, C. S., and D. G. Voelz, Lidar studies of the nighttime sodium layer over Urbana, Illinois, 2, Gravity waves, J. Geophys. Res., 92, 4673-4694, 1987.

Gardner, C. S., D. G. Voelz, C. F. Sechrist, Jr., and A. C. Segal, Lidar studies of the nighttime sodium layer over Urbana, Illinois, 1, Seasonal and nocturnal variations, J. Geophys. Res., 91, 13,659-13,673, 1986.

Gardner, C. S., D. C. Senft, and K. H. Kwon, Lidar observations of a substantial sodium depletion in the summertime Arctic mesosphere, Nature, 332, 142-144, 1988.

Gibson, A. J., and M. C. W. Sandford, The seasonal variation of the night time sodium layer, J. Atmos. Terr. Phys., 33, 1675-1684, 1971.

Granier, C., and G. Megie, Daytime lidar measurements of the mesospheric sodium layer, Planet. Space Sci., 30, 169-177, 1982.

Hawkins, G. S., The Physics and Astronomy of Meteors, Comets and Meteorites, McGraw-Hill, New York, 1964.

Heppner, J. P., and L. H. Meredith, Nightglow emission altitudes from rocket measurements. J. Geophys. Res., 63, 51, 1958.

Herrmann, U., P. Eberhardt, M. A. Hidalgo, E. Kopp and L. G. Smith, Metal ions and isotopes in sporadic E layers during the Perseid meteor shower, Space Res., 18, 249-252, 1978.

Kirchhoff, V. W. J. H., and H. Takahashi, Sodium clouds in the lower thermosphere, Planet. Space Sci., 32, 831-836, 1984.

Kopp, E., P. Eberhardt, and U. Herrmann, Positive ion composition of the high-latitude summer D region with noctilucent clouds, J. Geophys. Res., 90, 13,041-13,053, 1985.

Kwon, K. H., C. S. Gardner, D. C. Senft, F. L. Roesler, and J. Harlander, Daytime lidar measurements of tidal winds in the mesospheric sodium layer at Urbana, Illinois, J. Geophys. Res., 92, 8781-8786, 1987.

Kwon, K. H., D. C. Senft, and C. S. Gardner, Lidar observations of sporadic sodium layers at Mauna Kea observatory, Hawaii, J. Geophys. Res., 93, 14,199-14,208, 1988.

McKinley, D. W. R., Meteor Science and Engineering, McGraw-Hill, New York, 1961.

Reddy, C. A., and M. M. Rao, On the physical significance of the Es parameters fbEs, fEs, and foEs, J. Geophys. Res., 73, 215-224, 1968.

Simonich, D. M., B. R. Clemesha, and V. W. J. H. Kirchhoff, The Mesospheric sodium layer at 23°S: Nocturnal and seasonal variations, J. Geophys. Res., 84, 1543-1550, 1979.

Swider, W., Ionic and neutral concentration of Mg and Fe near 92 km, Planet. Space Sci., 32, 307-312, 1984.

Thomas, L., A. J. Gibson, and S. K. Bhattacharyya, Lidar observations of a horizontal variation in the atmospheric sodium layer, J. Atmos. Terr. Phys., 39, 1405-1409, 1977.

von Zahn, U., and T. L. Hansen, Sudden neutral sodium layers: A strong link to sporadic E layers, J. Atmos. Terr. Phys., 50, 93-104, 1988.

von Zahn, U., P. von der Gathen, and G. Hansen, Forced release of sodium from upper atmospheric dust particles, Geophys. Res. Lett., 14, 76-79, 1987.

I. S. Batista, P. P. Batista, B. R. Clemesha, and D. M. Simonich, Instituto de Pesquisas Espaciais (INPE), CP 515, 12201 São José dos Campos, São Paulo, Brazil.

(Received December 20, 1988;
revised May 30, 1989;
accepted June 12, 1989.)