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Concerning The Origin of Enhanced Sodium Layers

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ABSTRACT: A mechanism is proposed for the formation of the thin layers of enhanced sodium concentration observed in the atmospheric sodium layer. The proposed mechanism involves the windshear distortion of initially thick sodium clouds of limited horizontal extent, originally produced by meteoric deposition. It is pointed out that this mechanism is capable of explaining all the observed characteristics of the enhanced layers, including their height of ocurrence, small vertical extent, vertical motion and highly variable duration.

Introduction

Over the past twenty years, laser radar measurements of the atmospheric sodium layer have greatly improved our knowledge of its structure and morphology, although it is doubtful if this has led to a better understanding of the mechanisms which lead to its formation. A curious feature, which a number of workers have observed, is the occasional formation of very narrow layers with densities as much as an order of magnitude greater than normal and thicknesses about an order of magnitude less. The observation of such layers has been reported at São José dos Campos (23° S) by Clemesha et al (1978, 1980), at Mauna Kea (20° N) by Kwon et al (1988), at Svalbard (78° N) by Gardner et al (1987) and at Andoya (69° N) by von Zahn et al (1987) and von Zahn and Hansen (1988).

A number of possible explanations for the formation of these layers have been discussed in the literature. Clemesha et al (1978), who first reported the phenomenon, suggested that it was produced by the ablation of a single meteor of the loose conglomerate type, and calculated that a minimum meteor mass of about 10 Kg would explain the event which they observed. A difficulty with this explanation is the enormous difference between the vertical and horizontal dimensions of the sodium cloud. Three-point measurements of one event (Clemesha et al 1980) showed a horizontal extent for the enhancement of the order of 100 km, against a vertical extent of only 1 km. Other observations, where the enhancement has lasted for several hours, suggest even larger horizontal extents, and commensurately greater meteor masses. To produce such a layer directly, the incoming meteor would have to ablate in a very narrow height range, and it is difficult to see how this could happen.

Von Zahn et al (1987) have suggested a quite different mechanism for the generation of the thin layers which they see at 79° N. They believe that the sodium might be liberated by the bombardment of thin dust layers by energetic particles during auroral events. There seem to be several problems with this mechanism: firstly it does not explain how the dust gets concentrated in a narrow layer, and, secondly, it does not seem to be applicable to the dust layers seen at low latitudes, where energetic particle precipitation would be orders of magnitude less than in the auroral regions. In view of the great similarity between the layers seen at high and low latitudes, it seems extremely improbable that they are produced by different mechanisms. Furthermore, if energetic particle bombardment releases sodium from dust particles, one should expect the appearance of thin layers to be accompanied by an increase in the background layer density, since there is no reason to believe that all the dust should be concentrated into a thin layer, but such a general increase is not observed.

A third possible mechanism, discussed by Clemesha et al (1980), is the concentration of sodium ions into a thin layer by the windshear mechanism (Whitehead, 1961) and their subsequent neutralization by charge exchange reactions. Whitehead (1961) proposed the windshear mechanism to explain the formation of sporadic E layers, and it may be significant that both Clemesha et al (1980) and von Zahn and Hansen (1988) have found the appearance of enhanced sodium layers to be accompanied by the observation of sporadic E on ionograms. Von Zahn et al (1987) reject this possibility because of the very rapid build-up of the layers which they observed, but they do not appear to have considered the possibility that the observed rapid increase could have resulted from the horizontal motion of a sodium cloud of limited horizontal extent. Clemesha et al (1980) reported the observation of such an event using a steerable lidar, which made it possible to show that the rapid increase did, indeed, result from the passage of a sodium cloud over the observing site. There appears to be no reason to believe that the rapid increases seen by Von Zahn and his co-workers were not caused in the same way, so it is unnecessary to postulate a very rapid liberation of sodium atoms. A major difficulty with this mechanism, however, is the lack of sodium ions. Rocket experiments (see, for example, Zbinden et al ,1975) have generally measured very low Na^+ concentrations, such that the total abundance of ions would be several orders of magnitude less than the total abundance of sodium observed in the thin layers. It is also difficult to see how this mechanism could produce a patch with a well defined horizontal extent of only about 100 km. The wind-shears which give rise to sporadic E layers are tidal in origin, and such winds must be relatively uniform for thousands of kilometres.

It is clear that none of the proposed mechanisms is very satisfactory as it stands. It is the purpose of this letter to show that the effects of windshear on an initially thick sodium cloud, probably originating in meteor deposition, can explain all of the observed characteristics of the enhanced sodium layers.

Effect of windshear on a sodium cloud

Windshears can be produced by tides, gravity waves, or even by the vertical gradient in the prevailing wind velocity. For the purposes of illustrating how windshear can lead to the formation of a thin layer we will use a simplified semi-diurnal tidal mode. An empirical model for such a tide could have a vertical wavelength of 30 km, an amplitude of about 10 $m.s^{-1}$ at a height of 80 km, and a growth rate corresponding to an e-folding distance of about 20 km. For such an oscillation we can write:

$$V(z,t) = V_o \exp(z/H) \sin\{2\pi(t/T + z/L_z) - p\} \ldots\ldots (1)$$

Where $V(z,t)$ = horizontal velocity at height z and time t

V_o = $V(z,t)$ at $z = t = 0$

H = e-folding distance for amplitude growth

T = tidal period

L = vertical wavelength

p = phase angle of tide = $2\pi T_o/T$, where T_o is the time of occurrence of zero phase

Integrating equation 1 to give the horizontal displacement, $X(z,t)$, and taking $X(z,t) = 0$ as an initial condition gives

$$X(z,t) = (V_oT/\pi)\sin(2\pi z/L_z+\pi t/T-p)\sin(\pi t/T)\exp z/H \quad \ldots (2)$$

Equation 2 gives us the horizontal displacement produced by the tidal wind as a function of height and time. Figure 1 shows this displacement for our empirical semidiurnal tide at t = 0, 2, 4, 6, 8, and 10 hours. Note that the x scale in this figure is compressed by a factor of 30 in comparison with the z scale. If we now imagine what would happen to an initially thick (tens of km) layer of limited horizontal extent, subject to this displacement, it is easy to see that it would be distorted into a thin layer whose height would vary with X and t according to equation 2. This is illustrated in Fig. 2, where the insert, (b), shows a section of the resulting layer with equal x and z scales. In this case, after 6 hours and starting from a 10 km wide initial cloud, the resulting layer is only 240 m thick.

The height, $Z(t)$, at which the layer will be observed from the position of the original cloud will descend with the phase of the tidal oscillation and is given by

$$Z(t) = pL_z - L_zt/T \quad \ldots (3)$$

Except immediately after its formation, the thickness, $Q(z,t)$, of the windshear distorted layer is proportional to the horizontal, rather than vertical, extent of the original sodium cloud, and is simply equal to its initial horizontal extent, D_o, divided by $dX(z,t)/dz$:

$$Q(z,t) = \frac{(D_o/V_oT)\ \exp{-z/H}\ \mathrm{cosec}(\pi t/T)}{(1/\pi H)\sin(2\pi z/L_z+\pi t/T)+(2/L_z)\cos(2\pi z/L_z+\pi t/T)} \quad ....(4)$$

The inclination of the layer, $S(z,t)$ is given by

$$\tan(S(z,t)) = \frac{(1/V_oT)\ \exp{-z/H}\ \mathrm{cosec}(\pi t/T)}{(1/\pi H)\sin(2\pi z/L_z+\pi t/T)+(2/L_z)\cos(2\pi z/L_z+\pi t/T)} \quad ..(5)$$

The horizontal displacement of the sodium cloud, illustrated in Fig. 1, means, of course, that it will be visible in locations other than that of its initial formation, and its height and thickness will depend on this position.

A layer produced by this mechanism would be highly elongated in the direction of the windshear, and the time for which it would be observed at a given point would depend on the direction of the wind relative to this orientation. In our simplified analysis we have considered only one horizontal dimension, in practice the meridional and zonal components of the oscillatory winds could have different phases leading to a more complicated horizontal structure. This explains why some observations have lasted for only a few minutes while others have lasted for many hours. It should be noted that this mechanism does not require any particular angle for the radiant of the meteor or meteors causing the initial cloud, but merely requires that the initial deposition should be concentrated in an area of limited horizontal extent.

Discussion

The mechanism outlined above appears to be capable of explaining all of the observed characteristics of the enhanced sodium layers. Firstly we have the small vertical extent of these layers, from a few hundred meters to a few km. The production of such thin layers is a natural result of the proposed mechanism. Secondly we have the temporal change in height. All the reports of enhanced sodium layers indicate a predominantly downward motion, although occasional upward velocities have been observed for short time periods. This is exactly the behavior to be expected. An upward motion could be observed if the prevailing wind carries the wind-sheared layer in an appropriate direction with respect to the observer, but the descending phase of the tidal (or gravity wave) oscillation would result in the most frequently observed motion being downward. Thirdly we have the widely differing durations of the observed layers.

As we have already pointed out, the wind-sheared layer would be highly elongated, so that the duration of its observation would depend on its motion relative the the observer. A layer produced by an initial cloud 10 km across, moving perpendicular to its direction of elongation with a typical mesospheric velocity of 30 m, s^{-1}, would be seen for about 3 minutes; moving parallel to the direction of its elongation it could be seen for many hours. This is just the behavior observed in practice. Obviously, short durations would be more commonly observed, again in agreement with the observations.

One might inquire as to why the original, thick undistorted cloud has never been observed, but this again is in accordance with expectation. The probability of observing an enhanced layer would be proportional to the area swept out by its motion perpendicular to its elongation. Given the small number of sodium lidars in operation, and the comparatively short periods for which they have been operated (a total of perhaps 10000 hrs for all the systems which have ever been in operation) the chances of observing an initial cloud which covers an area of, perhaps, 100 km^2, are very slim. This is even more obvious when one considers that the cloud would have to be observed within a few tens of minutes of its formation; after this time it would already have been stretched into a thin layer. The probability of observing the windshear distorted layer, sweeping out an area as much as 50 times greater, and having a lifetime at least as long as 10 hours, would be several thousand times greater.

It is interesting to discuss the lifetime of the layer. Sodium may be lost in several ways: chemical oxidation, ionization and attachment to aerosols have all been suggested in the literature. The thin layers should also suffer the effects of diffusion (Kirchhoff and Clemesha, 1983). Above 90 km the concentration of atomic oxygen is such that chemical loss is negligible, and in any case, local chemical equilibrium would maintain the high concentration of free sodium. From our knowledge of the general shape of the sodium layer we know that loss processes must be more rapid below this height. This again is in agreement with the observations. The majority of observed enhanced layers have occurred at heights above 90 km. Von Zahn and Hansen (1988), for example, state that most of the layers they observed occurred in the region of 95 km. Ionization processes are also thought to be slow, and direct photo-ionization would be absent at night, when most of the layers have been observed. The effects of diffusion are difficult to assess because of our poor knowledge of the effective eddy diffusion coefficient (molecular diffusion is negligible below 100 km). Clemesha et al (1978) estimated an effective diffusion coefficient of 50 m s^{-1} from their observation of an enhanced layer over a period of 6 hrs. This value is a little lower than the generally "accepted" coefficients for the region, but it should be remembered that these coefficients probably correspond to the effects of comparatively large scale motions in the upper mesosphere, and that the appropriate value for distances of a few km might be much lower.

Conclusions

A mechanism has been proposed for the formation of thin layers of enhanced sodium concentration. It is proposed that these layers are produced by the windshear distortion of initially thick clouds of free sodium deposited by incoming meteors. This mechanism explains all of the observed characteristics of the enhanced layers, including their extremely limited vertical extent, height of occurrence, vertical motion, and highly variable duration.

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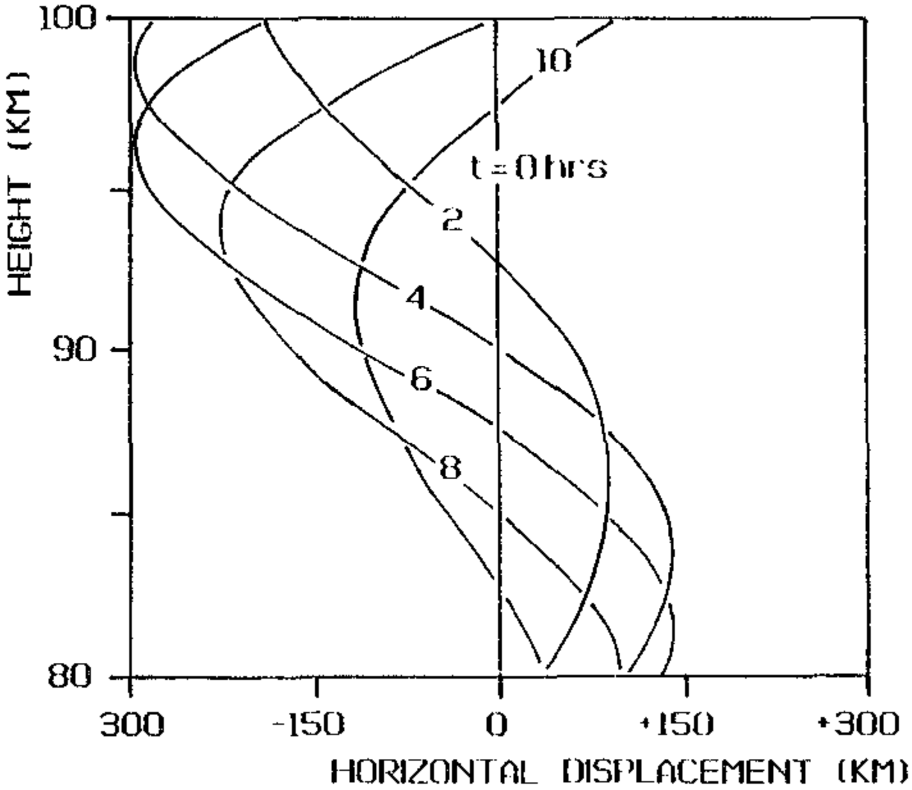

Fig. 1 Horizontal displacement as a function of height and time for an empirical semi-diurnal tide.

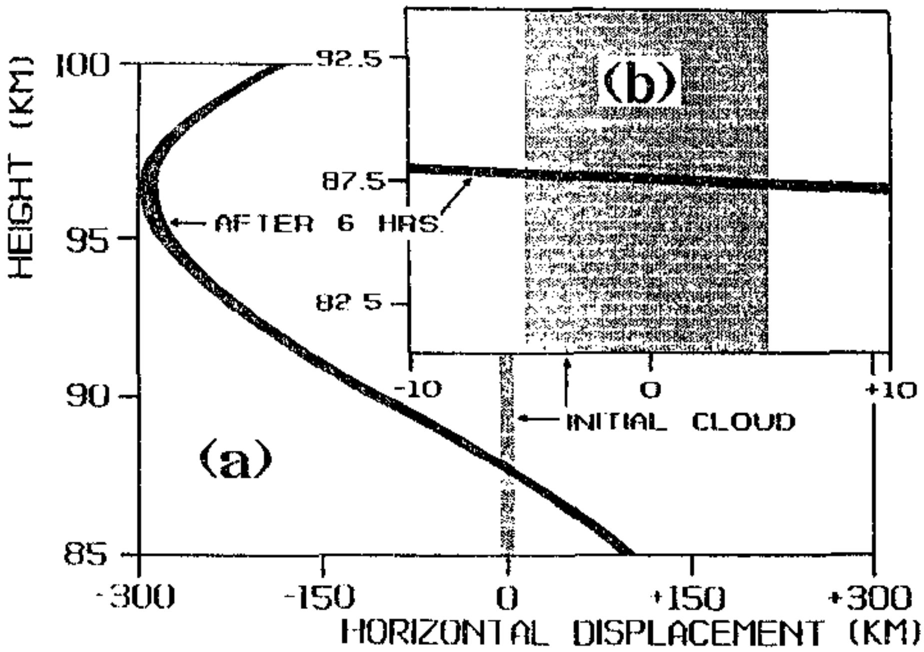

Fig. 2 Effect of wind shear on a sodium cloud. Note that in (a) the horizontal scale has been compressed by a factor of 30.