Vertical structure in the topside sodium layer

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Abstract. It is shown that the assumption that sodium can be used as a passive tracer for studying atmospheric waves in the region above 90 km is not always valid. An analysis of wave structures observed in the sodium layer by lidar shows that the associated oscillations in the mixing ratio of sodium are frequently too large to be produced by vertical displacements in the presence of mixing ratio gradients. On some occasions these large amplitude oscillations appear to be associated with the formation of sporadic sodium layers, and it is suggested that both phenomena are most probably related to the windshear concentration of sodium ions.

Introduction

Layers of meteoric metals, such as sodium, iron, potassium and calcium, occur at heights around 90 km. Lidar observations of these metal layers show that they are strongly influenced by tides [Batista et al., 1985] and gravity waves [Gardner and Voelz, 1987]. Layers of minor atmospheric constituents can be modulated by atmospheric waves partly because relative variations in the minor constituent concentrations accompany the waveinduced variations in the major constituents, and partly because of wave-induced vertical motions in the presence of vertical gradients in the concentration of the minor constituent [Chiu and Ching, 1978]. In most cases the effect of vertical displacements is much more important than the direct density modulation. Whereas the oscillations in major constituent densities in the 90 km region are typically only a few percent, strong gradients in minor constituent concentration can easily lead to oscillations as large as 50% at a given height. When an air parcel undergoes a vertical displacement in the atmosphere, on a time scale short compared with diffusion times, it will expand or contract quasiadiabatically. In such a process the mixing ratio of a chemically inert minor constituent is conserved. When such vertical displacements occur in the presence of a vertical gradient in mixing ratio, in an Eulerian coordinate system there occurs a change in local mixing ratio equal to the product of the vertical displacement and the mixing ratio gradient. It is obvious that this process will generate the largest variations in the concentration of the minor constituent on the bottomside of an atmospheric layer, where the vertical gradient in the concentration of the minor constituent is in the opposite direction to that of the main atmospheric components. For lack of a better term, we shall refer to this wellknown process as the "mixing -ratio gradient mechanism".

Starting from an analysis of the sort presented by *Chiu and Ching* [1978], several workers have used observations of the atmospheric sodium layer to study tides and gravity waves. In all such studies it has been assumed that sodium acts as a passive tracer, and in most cases a first-order linearized analysis has been used. In this way, *Batista et al.*, [1985], for example, were able to determine the principal tidal modes active at their location, and

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Gardner and Voelz [1987], for example, obtained gravity wave spectra and studied their seasonal variations. Most of the studies of this sort have been concerned with gravity waves, and at least a dozen papers have been published on this subject. In none of these studies has any serious attempt been made to check the validity of the assumption that sodium can be treated as a passive tracer. It is, in general, not immediately obvious whether or not wave-modulation of the sodium layer is simply the result of the mixing-ratio gradient mechanism, or whether it involves chemical or other processes. There is, however, one wave-related feature of the sodium layer which is clearly not explicable on such a basis; this is the appearance of sporadic (Nas) layers. There is a great deal of evidence for a connection between Nas layers and atmospheric waves. The measurements of Hansen and von Zahn [1990]. Hecht et al. [1993], and Gardner et al., [1993], [1995] all show the existence of a relationship between the vertical motion of Na, layers and atmospheric wave propagation in terms of temperature or winds. Although it has been suggested that sporadic layers might be produced by unusually strong vertical winds associated with gravity waves [Kirkwood and Collis, 1989], it is clear that this mechanism is untenable in the vast majority of cases [Clemesha et al., 1990]. In view of the fact that there is clear evidence linking Nas layers with waves, and that Nas layers cannot be explained as a simple wave modulation of the main meteoric metals layers, there can be no doubt about the sporadic existence of structures in these layers which cannot be explained by the mixing-ratio gradient mechanism. In this paper it will be shown that not only Na, layers, but also less extreme structures. seen on the topside of the sodium and other metals layers, and normally assumed to be produced by simple wave modulation of the background layer, cannot, in fact, be explained in this way.

Wave structure in the sodium layer

In Figure 1a we show the nocturnal variation in sodium concentration measured at São José dos Campos (23°S, 46°W) for the night of June 13/14, 1996, and in Figure 1b we compare the profile measured at 1830 LT with the nocturnal average. Figure la shows the typical downward phase propagation associated with a tide or gravity wave. The apparent vertical wavelength is just over 5 km, and the apparent wave period is 12 hours. Two wave peaks are visible throughout the night, and a third peak starts to appear above 100 km towards the end of the night. The sequence of profiles shown in Figure 1a is typical of those analyzed by various workers in terms of tides or gravity waves and. at first sight, it would appear quite reasonable that the deviations of the individual profiles from the average, as exemplified in Figure 1b, could be mainly due to vertical displacements. However, if we want to evaluate the possibility that a given sequence of profiles could result from the distortion of an "average" background layer by the mixing ratio gradient mechanism, then we should plot the data in the form of mixing ratio, since it is this quantity that is conserved in the wave-induced vertical oscillations of the layer. We have done this in Figure 2. The mixing ratios were calculated by dividing the sodium densities by the CIRA annual average atmospheric density profile for our latitude.



Figure 1. (a) Time history of sodium concentration observed at São José dos Campos on June 13-14, 1996; (b) profile for 1830 LT (continuous line) compared with the mean profile (broken line). Note that the concentration scales are in arbitrary units.

From Figure 2 it is immediately obvious that much of the wavelike structure cannot be explained by the mixing ratio gradient mechanism. For the first hourly profile, for 1830 LT, the mixing ratio at 102.5 km is similar to the average mixing ratio at 110 km, requiring a vertical displacement of 7.5 km if it is to be explained by vertical winds. Since the vertical wavelength of the observed wave is of this order, such a displacement is clearly impossible. Worse still, the peak mixing ratio for the 1830 LT profile is 45%



Figure 2. As for Fig. 1, but for mixing ratio.



Figure 3. As for Fig. 1, but for May 30-31, 1996. The continuous line shows the profile for 2330 LT.

greater than that for the average profile, so there is no way that the former could be derived from the latter via vertical winds. The same problem arises for all the profiles obtained before midnight. The time-series shown in Figs. 1 and 2 were filtered with a 1-hr cut-off. It should be mentioned here that profiles averaged over short time periods show even greater deviations from the nightly mean. It should also be noted that the main wave peak does not appear to suffer the phase reversal predicted by the mixing ratio mechanism as it passes through the height of maximum mixing ratio.

Another example of a sequence of profiles which appears to show the propagation of a gravity wave is given in Figure 3. In this case the apparent vertical wavelength is 2.7 km and the apparent period is just less than 2 hours. In Figure 4 the same data is re-plotted in terms of mixing ratio. Again we see that the wave modulation of the layer can not be explained solely by the mixing ratio gradient mechanism. In the profile for 2330 LT the mixing ratio at 105 km would require an upward displacement of around 4 km for it to be produced by vertical winds, as compared to the vertical wavelength of only 2.7 km. Later in the night the peak mixing ratio is considerably greater than the maximum mixing ratio for the average profile.

The foregoing examples, one for a long period wave, probably tidal in origin, and the other for a short period gravity wave, leave it clear that wave propagation observed in the sodium layer is not always explicable in terms of the mixing ratio gradient mechanism. To explain the observations we need production and loss mechanisms which can be influenced by wave propagation. In view of the observed relationship between Na_s layers and atmospheric waves, it seems quite probable that the same mechanisms are involved in both phenomena. We do, in fact, observe cases where wave modulation of the sort described above appears to lead to the formation of an Na_s layer. It would also be true to say that, in some cases, there is no clear distinction between Na_s layers and the enhanced wave modulation of the topside of the sodium layer described in this paper. An example of a Na_s layer which develops from a wave is shown in Figure 5, which shows a



Figure 4. As for Fig. 2, but for May 30-31, 1996

six-minute average profile centered on 2340 LT on June 13. 1996, the same night as is shown in Figure 1. The Na, layer started to develop at around 2300, reached its maximum at 2340, and continued to exist until about 0115. The Na, layer formed at exactly the same height as that of the descending wave maximum. Returning to the subject of production and loss mechanisms, neutral chemistry is an unlikely candidate. Modeling studies of the sodium layer, such as that of Helmer and Plane [1993], show that the concentrations of neutral sodium compounds should be much smaller than that of free sodium atoms on the topside of the layer, so there is little scope for major changes in sodium density in via neutral chemistry. At first sight the same objection can be raised against ion chemistry, again the models suggest rather low concentrations for sodium ions, and most rocket-borne ion mass spectrometer measurements also show low Na⁺ concentrations. On the other hand, the possibility of production and loss via ions is attractive, because ions can easily be transported by electrodynamical forces associated with atmospheric wave motions, thus providing the required link with waves and a mechanism for concentrating the ions into a thin layer.

In the case of Na_s, the fact that rather low sodium ion concentrations are observed at heights around 100 km has led to a number of suggestions for alternative formation mechanisms, most of which are related to sodium-bearing aerosols. von Zahn et al. (1987) suggested that the sporadic sodium layers which they observed at Andoya could be caused by the liberation of sodium from aerosol particles by auroral particle bombardment. Two problems with this mechanism are that it will only work for auroral latitudes, and that Es and Nas layer formation is not well correlated with particle precipitation (Kirkwood & Collis, 1989). A variation on the aerosol mechanism, proposed by Beatty et al. (1989), is that Na_s layers could be produced via the formation of cluster ions generated by collisions between Es ions and dust particles. In yet another variation on this theme, Kirkwood & von Zahn (1991) have suggested that charged dust particles could be lifted to Es layer heights by electric fields, and that the interaction between the high-density plasma in the Es layer and the aerosol particles would result in the release of free sodium. Although the liberation of sodium from aerosols might, in principle, explain the observed large-amplitude wave modulation of the layer, there is no direct evidence for the existence of dust particles at the heights in question, and the mechanism whereby free metal atoms could be liberated from these particles is poorly understood.

Returning to the subject of ion recombination, the two major objections which have been raised to this as a mechanism for the production of Na_s layers are the low concentrations of Na⁺ observed in rocket experiments and the inadequate rate at which such ions would be converted to free sodium. Estimates of Na⁺ concentration are based on a fairly small number of rocket-borne ion mass spectrometer experiments. Many of the reports of mass spectrometer measurements give only the total concentration of metallic ions. Of a total of 11 experiments for which Na⁺ concentrations have been reported [Aikin and Goldberg, 1973; Alpers et al., 1993; Kopp and Hermann, 1984; Kopp, 1997], 2 showed concentrations around 10⁴ cm⁻³ [Alpers et al., 1993 (see their Table 3); Kopp, 1997 (see their Figure 3)] and the rest gave values between 30 and 1000 cm⁻³. It may be significant that the early measurements [Aikin and Goldberg, 1973] all showed sodium ion concentrations of less than 100 cm⁻³, whereas the later studies [Alpers et al., 1993; Kopp and Hermann, 1984; Kopp, 1997] showed values greater than 100 cm⁻³. It could be that the measuring technique used in the early measurements was inadequate for measuring such low ion concentrations.

Both Nas layers and strong wave modulation of the topside of the sodium layer are sporadic phenomena. The fact that only two out of eleven rocket measurements have detected Na⁺ concentrations high enough for ions to be considered as a possible source for the formation of strong Na, layers is not surprising. At São José dos Campos, for example, Nas layers are observed in only about 6% of the lidar observations of the sodium layer. It appears possible, then, that the sodium ion concentrations encountered on the topside of the layer could sometimes be sufficient to form a source for the excess sodium required to explain both the formation of Nas layers and the observed wave-modulation. With respect to the rate of conversion from ions to neutral sodium, the requirements for production of the effects discussed here are less exacting than in the case of Na_s, which has been discussed by various workers in the literature (see, for example, Hansen and von Zahn, 1990). Although the direct radiative recombination of Na^{+} is very slow, the formation of cluster ions such as NaN_{2}^{+} , followed by dissociative recombination with electrons should result in fast recombination at heights below 100 km [Hansen and von Zahn, 1990; Cox et al., 1993]. In this respect, Cox and Plane, [1998] have shown that the lifetime of Na⁺ ions above 90



Figure 5. Sporadic sodium layer observed at 2340 LT on June 13, 1996.

km is strongly influenced by atomic oxygen, which recycles molecular ions back to Na⁺. Without this process Na⁺ would be almost inexistent below 100 km. According to *Cox and Plane*, [1998] the main cluster ion formed will be NaN_2^+ , which will then ligand switch with O or CO_2 , either producing stable $NaCO_2^+$ ions or reverting to Na⁺. The $NaCO_2^+$ ions would have a lifetime against dissociative recombination of only about 100 s, and 97% of the clusters would be recycled to Na⁺ at 100 km. As a result of this mechanism, although the main recombination of Na⁺ occurs via cluster ions, the actual concentration of such ions would be very small. This would explain why rocket-borne ion mass spectrometer measurements have not, in general, identified such cluster ions.

Despite the foregoing, it must be confessed that there continue to exist serious difficulties in explaining descending structures in the topside Na layer, including Na_s layers, as being produced by the recombination of ions. Not the least of these is the fact that, in a modelling study, *Cox and Plane* [1998] found it necessary to start with a Na⁺ concentration of $5x10^4$ cm⁻³, 5 times greater than ever measured, in order to produce an Na_s layer with a reasonable peak Na concentration. It is clear that our understanding of the processes at work is still inadequate. Nevertheless, our understanding of the alternative mechanisms proposed so far is so poor that ion recombination would still appear to be the least improbable candidate.

Conclusions

The existence of wavelike structures in the upper part of the sodium layer, with amplitudes too large to be explained in terms of wave-associated vertical winds in the presence of mixing ratio gradients, leads us to suggest that such structures could be the result of neutralization of windshear concentrated sodium ion layers. This would explains why such wave-modulation sometimes appears to lead to the formation of Nas layers. The latter frequently appear to grow out of the former, although it must be admitted that we also observe Nas layers where there is no obvious relationship with waves. Although sporadic neutral layers are relatively infrequent at our location, descending wavelike structures with amplitudes similar to that of the example shown in Figure1 occur often. Whether or not these structures result in the formation of what would conventionally be called a sporadic layer would depend on the amplitude and, perhaps more importantly, the coherence of the wave responsible. In summary, we suggest that the following process takes place: sodium ions, trapped at the descending nodes in the winds associated with tides and/or gravity waves, are neutralized by processes of the sort described by Cox and Plane [1998], leading to the formation of descending peaks in sodium density. When the amplitude and coherence of the waves are appropriate, this process can lead to the formation of the narrow layers of very high density known as sporadic layers.

Regardless of the mechanisms involved in the formation of the enhanced wavelike structures observed on the topside of the sodium layer, the fact that these structure cannot be explained solely on the basis of the mixing ratio gradient mechanism implies that care must be taken in deriving atmospheric wave parameters from lidar observations of the sodium layer. Acknowledgments. The authors would like to acknowledge the financial support of the Fundação de Amparo a Pesquisa do Estado de São Paulo - FAPESP, and the Conselho Nacional de Desenvolvimento Científico e Tecnológico - CNPq.

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