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FORMATION CHARACTERISTICS OF SPORADIC Na LAYERS OBSERVED SIMULTANEOUSLY BY LIDAR AND AIRGLOW INSTRUMENTS DURING ALOHA-90

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Abstract: Sporadic Na (Na_s) layers were observed by the airborne lidar during ALOHA-90 on the 22, 25 and 27 March flight missions. Perturbations in the O_2 and OH nighttime airglow emission intensities and temperatures were also observed by instruments on the aircraft and at Haleakala Crater (20.8°N, 156.2°W) during these events. The most striking correlation between the airglow and lidar measurements occurred during the northbound flight leg of the 25 March mission. When the Na_s layer formed at 90.7 km, while the Electra aircraft was between 750 and 500 km south of Haleakala, the O_2 temperatures near 95 km above the Electra and Haleakala increased by approximately 45 K. The data for this night suggest a connection between Na_s and a large-scale wave, and suggest that the wave is tidal in nature. The data also suggest that some Na_s layers can form very quickly over large geographic areas. Fast chemical processes are required to generate the large amounts of atomic Na involved in some of these events.

Introduction

The sporadic Na (Na_s) layer phenomenon is characterized by large, sometimes rapid, enhancements in Na density in the mesopause region, typically over a limited height range (~ 1 km FWHM). A crucial Na_s layer parameter is the formation time. If the actual formation times are as short as several minutes, then fast chemical processes are required to generate the large amounts of atomic Na involved in some of these events. Unfortunately, it is not clear whether ground based lidars are observing the formation of Na_s layers or the advection of fully formed Na_s clouds through the lidar beam. Numerous Na_s events have been observed at Sao Paulo, Brazil (23°S, 46°W) [Batista et al., 1989], Andoya, Norway (69°N, 16°E) [Hansen and von Zahn, 1990] and Mauna Kea, Hawaii (20°N, 155°W) [Kwon et al., 1988]. At these sites the Na_s layers exhibit a strong tendency to form more quickly than they dissipate. This suggests that in many cases the lidars are observing the actual formation of the Na_s layers. However, because of diffusion effects, it can be argued that the leading edges of the Na_s clouds will be sharper than the trailing edges and so even when the clouds are advected through the lidar field-of-view, the dissipation times are expected to be longer than the formation times.

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Several mechanisms have been proposed to explain the formation of Na_s layers. Beatty et al. [1989] argued that the interaction of sporadic $E(E_s)$ layers with upper atmospheric dust particles containing Na could release the required Na. The Bonn group has also proposed mechanisms involving dust as well as several chemical processes to explain the formation of various classes of Na_s layers [Hansen and von Zahn, 1990]. The Brazilian group favors a common meteoric source for both Na_s and E_s events [Batista et al.,1989].

In this paper we examine the spatial and temporal characteristics of 3 Na_s layers observed during ALOHA-90 by the airborne lidar and by the airglow instruments on the Electra aircraft and at Haleakala Crater (20.8°N, 156.2°W). The combined data sets are used to characterize the formation times and spatial extents of the Na_s events observed during the 22, 25 and 27 March flights.

Experimental Data

The most striking similarities between the airglow measurements and the formation of an Na_s event were observed during the 25 March mission. On 25 March the Electra flew almost due south from Maui (see Figure 2 of introductory paper [Gardner, 1991]). On the return leg a Na_s layer began forming near 16.5°N at approximately 1515 UT. The layer reached maximum density (20,560 cm^{-3} at 90.7 km) at 1536 UT near 18.3°N. The Ebert-Fastie spectrometer on the Electra and the Fourier transform spectrometer and Aerospace imager at Haleakala all observed increases in the O_2 and OH intensities and temperatures during this period. The rms error in the temperature measurements ranged from 2.5 to 5.0 K depending on instrument type and integration time. Typically, the OH and O_2 emissions peak near 87 km and 95 km, respectively, and have a thickness of approximately 10 km FWHM. The Na_s layer abundance, airglow intensities and airglow temperatures are plotted versus time for the northbound flight leg in Figure 1.

A general increasing trend in O_2 temperature began above Haleakala at 1230 UT and continued throughout the remainder of the observation period. During this time temperatures increased from ~185 K to ~220 K. The O_2 temperatures above the Electra displayed a similar increase nearly in phase with the corresponding temperature increase above Haleakala. The OH temperatures above Haleakala began a rapid increase about the

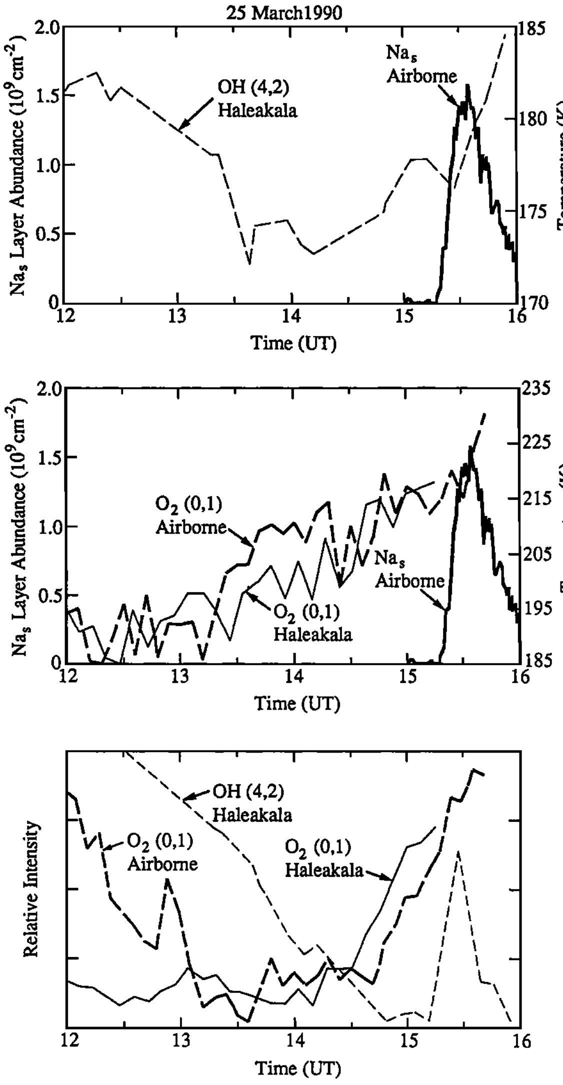

Fig. 1 Temporal variations of the Na$_s$ layer abundance, airglow temperatures and airglow intensities above the Electra aircraft and Haleakala Crater during the 25 March mission. Note each airglow intensity plot has been scaled differently to emphasize relative intensity variations.

time that the peak Na$_s$ layer abundance was recorded above the Electra and followed the O$_2$ temperatures in phase by about 2 hours. Above the Electra the intensity of the O$_2$(0,1) band increased rapidly beginning at 1442 UT and appeared to reach a maximum near the time the Na$_s$ layer was most intense. This behavior seems well-correlated with the increase in O$_2$ intensity observed by the Aerospace Imager on Haleakala. The intensity increase at Haleakala led the increase above the Electra by about 10 min.

Perturbations in the OH band temperatures were also observed at Haleakala during the Na$_s$ event. The OH temperature increased from approximately 175 K to 185 K between 1430 and 1600 UT. However, most of that increase occurred from 1530 to 1600 UT, at which time observations ended because of sunrise. Because temperature perturbations are observed to generally lead intensity variations [Hecht and Walterscheid,1991], the expected OH intensity increase was not observed because it would have occurred after shutdown.

The striking similarities between the O$_2$ temperatures and intensities observed above Haleakala and the Electra and the timing of their enhancements relative to the Na$_s$ event suggest that the phenomena are related. When the O$_2$ temperature began increasing near 1300 UT the Electra was more than 1000 km south of Maui. When the Na$_s$ layer began forming, the Electra was approximately 480 km south of Haleakala and when the layer reached maximum density near 1530 UT, the Electra was 290 km south of Maui. Because the Na$_s$ layer was still visible when the Electra passed over Haleakala at 1608 UT, we believe the layer formed nearly simultaneously above Maui and the Electra starting around 1515 UT when the Electra was 480 km south of Haleakala. The simplest explanation for the apparent correlation between the airglow and Na perturbations, consistent with all the observations, would be a large-scale propagating wave. The alternate explanation of a large Na cloud advected zonally, nearly simultaneously across the Electra flight path and Haleakala, is also possible but requires a fortuitous coincidence of unrelated events.

On 27 March the Electra flew west from Maui toward the International Date Line (see Figure 2 in Gardner [1991]). A Na$_s$ layer was already formed when data acquisition began at 0820 UT. However, at 1120 UT when the aircraft was 1500 km west of Haleakala, the Na$_s$ event began to intensify. The Na$_s$ layer reached its maximum density (10,500 cm^{-3} at 93.0 km) at 1155 UT when the aircraft was 1200 km west of Haleakala. The Na$_s$ layer completely dissipated by 1230 UT.

The Na$_s$ layer abundance, airglow intensities and airglow temperatures for the 27 March event are plotted versus time in Figure 2. Above Haleakala the O$_2$ intensity began increasing at approximately 1100 UT and reached a maximum at 1230 UT when the Na$_s$ layer dissipated. Although the O$_2$ temperature fluctuates considerably, the temperature does begin increasing at about 1045 UT, reaches a maximum just before 1200 UT when the Na$_s$ layer density is maximum and then decreases between 1200 and 1300 UT. The OH Meinel (6–2) band temperature and intensity above Haleakala begin increasing also near 1100 UT reaching maxima at 1245 UT (temperature) and 1310 UT(intensity). Hecht and Walterscheid [1991] attribute the time delay between the O$_2$ and OH intensity maxima to the vertical phase progression of a large amplitude gravity wave. The OH(4,2) band observations on Haleakala also exhibit an abrupt increase in temperature starting at ~1100 UT and reaching a maximum at ~1238 UT.

The airglow perturbations observed above the Electra are more subtle and it is not clear if they are related to the Na$_s$ layer enhancement. The maximum Na$_s$ layer density for the 27 March event was nearly half that of the 25 March event. Perhaps the 27 March event was much stronger near Haleakala, consistent with the stronger responses of the airglow emissions and temperatures. The time lag between the Haleakala airglow perturbations and the Na$_s$ enhancement above the Electra is at most 30 min. Zonal advection velocities exceeding 500 m/s would be required to transport a disturbance between Haleakala and the Electra. Of course, it is possible that the enhancement in Na and O$_2$ intensity was caused by the meridional advection of a large (~1500 km) Na$_s$ cloud across the Electra flight path and Haleakala.

The largest Na$_s$ event was observed on the 22 March mission [Kane et al., 1991]. The Na$_s$ abundance and airglow intensities are plotted in Figure 3. Only the OH airglow intensities appear to be reasonably well correlated with the formation of the Na$_s$ layer. The OH Meinel (3,1) and (7,3) band intensities above the Electra show a strong enhancement

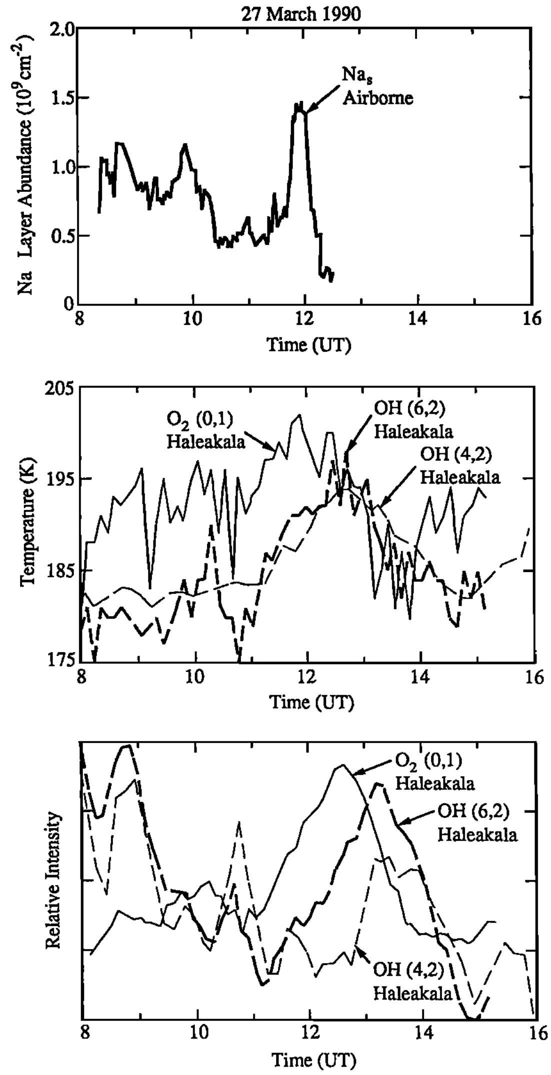

Fig. 2 Temporal variations of the Na_s layer abundance, airglow temperatures and airglow intensities above the Electra aircraft and Haleakala Crater during the 27 March mission. Note each airglow intensity plot has been scaled differently to emphasize relative intensity variations.

starting at about 0930 UT and continuing until about 1100 UT. The most intense period of the Na_s event was between 0900–1100 UT. On Haleakala the O_2 atmospheric band intensity exhibited a minor enhancement during this period. The O_2 observations on the Electra and the OH observations on Haleakala exhibited no unusual behavior during this Na_s event. When the most intense phase of the Na_s event ended at about 1100 UT, the aircraft was at approximately 11°N or about 1200 km south of Haleakala.

Discussion

The data show clearly that some of the airglow intensities and temperatures were highly perturbed during the Na_s events compared to other periods of the campaign. The most striking example occurred on 25 March when the O_2 Atmospheric band intensities and temperatures above the Electra and Haleakala increased substantially during the Na_s event. The connection between the O_2 emissions and the Na_s formation is unclear. The O_2 emission layer is believed to be about 10 km thick FWHM with the peak emissions occurring near 95 km. On 25 March, a Na_s layer formed on the bottomside of the O_2 layer near 90.7 km. Na_s events are known to be accompanied by E_s layers [e.g.Beatty et al., 1989]. A correlation between the intensity of the $O_2(0,1)$ emissions and the height of the E_s layer has been observed [Gorbunova et al., 1982]. If the Na_s layers are related to upper atmospheric dust as suggested by Beatty et al. [1989] and Hansen and von Zahn [1990], perhaps the observed increase in temperature facilitates the release of Na from upper atmospheric dust particles as well as increase the O_2 emissions. The OH(4,2) band temperatures increased above Haleakala during this event while the OH Meinel band intensities above Haleakala and the Electra were not perturbed. The OH emissions originate from a ~10 km FWHM thick layer centered near 87 km, well below the Na_s layer on this night.

The data for the night of 25 March suggest a connection between a pronounced increase in temperature in the Na layer and the occurrence of Na_s. The Na_s layer formed after the O_2 temperature observed from the Electra had increased by about 30 K from its value about three hours earlier. The O_2 temperature variation observed at Haleakala was strikingly similar to the variation observed from the Electra; the temperature increase was virtually the same, and essentially in phase at the two locations. The most likely explanation for the temperature increases occurring essentially simultaneously above the Electra and Haleakala is a large-scale zonally propagating wave. The temporal behavior shown in Figure 1 suggests that the period of the wave is ~12 hours or greater. The coherence of the wave over large distances and its period

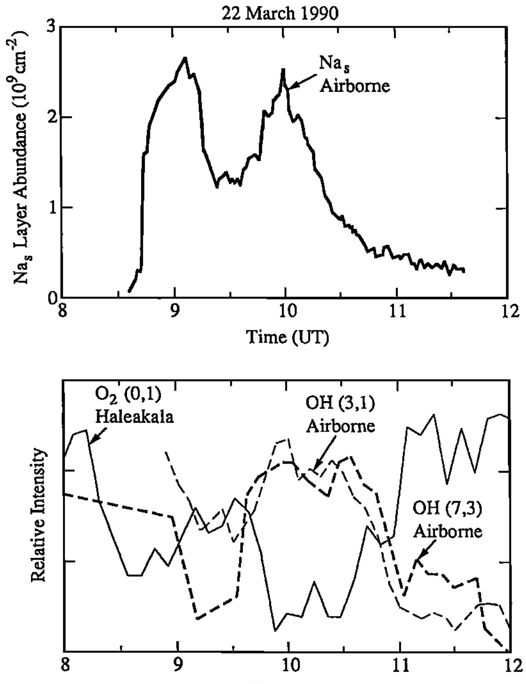

Fig. 3 Temporal variations of the Na_s layer abundance and airglow intensities above the Electra aircraft and Haleakala Crater during the 22 March mission. Note each airglow intensity plot has been scaled differently to emphasize relative intensity variations.

suggest that the temperature increase is tidal in origin. This suggestion is strengthened by the vertical propagation of the wave inferred from the phase difference between the OH and O_2 temperatures [Hecht and Walterscheid, 1991]. The analysis indicates a wave with downward phase propagation and a vertical wavelength, assuming a semidiurnal period, of ~40 km, which is more or less characteristic of the semidiurnal tide at mesopause altitudes [Walterscheid et al., 1981; Forbes, 1982]. If a Na_S layer is initiated when T exceeds some threshold value then the onset of a Na_S event indicates that the temperature has reached that value in the Na layer.

The relationships between the Na_S events and the airglow emissions are less convincing on 22 and 27 March. On 27 March the O_2 and OH temperatures above Haleakala increased by almost 20 K during the time period the Na_S event intensified above the Electra. O_2 emissions also increased during this period. However, the airglow intensities and temperatures above the Electra appear to be unaffected by the event. Although the vertical distribution of any constituent layer will be perturbed by atmospheric waves, the centroid height is influenced appreciably only by waves with vertical wavelengths larger than the layer thickness. Hence, the centroid heights of the relatively thick airglow and Na layers typically change by no more than 1 or 2 km, whereas the altitudes of thin Na_S layers have been observed to change by 5 km or more under the influence of strong atmospheric waves. Kane et al. [1991] show that on 27 March the Na_S layer is tilted systematically downward to the west. When the layer reached maximum intensity at 1155 UT above the Electra, its altitude was ~92.8 km. The model derived by Kane et al. [1991] for the Na_S layer altitude suggests that its altitude was ~94 km above Haleakala at 1155 UT. Thus, the Na_S layer was located near the peak of the O_2 emission layer at Haleakala and below the O_2 layer above the Electra when it reached maximum density. This altitude variation and the fact that this event was weaker than the 25 March event, may partially explain the lack of an airglow response above the Electra. We also note that this Na_S layer was formed when data acquisition began. The response near 1100 UT was an enhancement of an existing layer, not the formation of a new layer.

In conclusion, the data show that both O_2 and OH intensities and temperatures can increase substantially over large distances during an Na_S event. The observations during the 25 March event suggest that this Na_S layer formed almost simultaneously (within 30 min) above Haleakala and above the Electra (750 km south of Haleakala) and was tidally generated. We do not believe the Electra flew underneath a fully formed Na_S cloud on 25 March. Unrealistic meridional advection velocities of several hundred m/s are required to transport the Na_S cloud the 750 km between Haleakala and the Electra. Although zonal advection of a large cloud could explain the airglow perturbations observed above Haleakala and the Electra, it is difficult to explain the large difference in the sharpness of the leading and trailing edges of the Na_S cloud deduced from the observed difference in formation and decay times. The Na_S layer was observed for a total of 50 min over a north-south distance of ~460 km. Typical zonal wind speeds of 50 m/s would imply that the east-west extent of the layer was at most 150 km if we assume the layer was simply advected out of the lidar field-of-view. Thus if advection causes the observed spatial and temporal characteristics of this Na_S layer, the Na_S cloud must have an aspect ratio of at least 3 with the major axis oriented parallel to the flight path and the horizontal scale length of the trailing edge being 2 to 3 times the scale length of the leading edge. Because the temporal characteristics of this Na_S layer are similar to those of numerous events observed by ground based lidars [e.g. Kwon et al.,1988; Hansen and von Zahn,1990; Batista et al.,1989], we believe the data are consistent with the assumption that the lidar observed the actual formation of the 25 March layer.

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