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LONGITUDINAL STRUCTURE IN ATOMIC OXYGEN CONCENTRATIONS OBSERVED WITH WINDII ON UARS

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Abstract. WINDII, the Wind Imaging Interferometer on the Upper Atmosphere Research Satellite, began atmospheric observations on September 28, 1991 and since then has been collecting data on winds, temperatures and emissions rates from atomic, molecular and ionized oxygen species, as well as hydroxyl. The validation of winds and temperatures is not yet complete, and scientific interpretation has barely begun, but the dominant characteristic of these data so far is the remarkable structure in the emission rate from the excited species produced by the recombination of atomic oxygen. The latitudinal and temporal variability has been noted before by many others. In this preliminary report on WINDII results we draw attention to the dramatic longitudinal variations of planetary wave character in atomic oxygen concentration, as reflected in the OI 557.7 nm emission, and to similar variations seen in the Meinel hydroxyl band emission.

Introduction

Ever since Lord Rayleigh's (1930) first absolute emission rate determination of the night airglow OI 557.7 nm emission, this airglow feature has been extensively studied. McLennan and Shrum (1925) showed that the emission was from atomic oxygen, and Chapman (1931) hypothesized that it was produced by the three-body recombination of atomic oxygen to molecular oxygen. Current formulations involving a two-step process (Murtagh et al., 1990), do provide realistic values of atomic oxygen concentration.

The variability of the emission was noted by McLennan, McLeod and Ireton (1928), and by Rayleigh (1931). Later detailed studies of the seasonal and diurnal variation were made by Barbier (1959) and by Christophe-Glaume (1965). Petitdidier and Teitelbaum (1977) were able to explain the diurnal variation on the basis of atmospheric tides and Teitelbaum et al. (1981) reported the observation of gravity waves and planetary waves in meteor winds and 557.7 nm airglow emission.

Satellite measurements have the advantage of achieving global measurements with a single instrument. The OGO 4 satellite employed nadir viewing to obtain global maps of the 557.7 nm emission, which showed large scale patchiness (Reed and Chandra, 1975). High latitude data were later interpreted in terms of the influence of a stratospheric warming (Walker and Reed, 1976). The OGO 6 satellite made limb scanning measurements, providing estimates of atomic oxygen density and eddy diffusion (Donahue et al., 1974). The ISIS-2 satellite yielded limb scanning data (Cogger et al., 1981), from which a mid-latitude equinoctial maximum of 557.7 nm emission was found. The Visible Airglow Experiment on the Atmospheric Explorer Satellites (Hays et al., 1973) provided further information on the processes that control the OI 557.7 nm emission.

The WINDII instrument on the Upper Atmosphere Research Satellite is the first capable of making extended aeronomical measurements of this emission on a truly global basis. This is because the orbit is circular, and data-taking is conducted 24 hours per day. In addition, the satellite has better attitude stability and knowledge than previous aeronomical satellites, providing altitude accuracy of better than 1 km.

The first WINDII measurements of the OI 557.7 nm emission confirm the temporal and latitudinal variability found in earlier studies, although there is much more localized structure than expected. What is new in the WINDII data is longitudinal structure having the appearance of planetary scale waves, of wavenumbers one and two, adding a new dimension to the problem of understanding atomic oxygen variations, the related airglow emissions, and the upper atmosphere dynamics that gives rise to these variations.

Brief Instrument Description

WINDII is basically a CCD imager that views the earth's limb through a Michelson interferometer set to an optical path difference of 4.49 cm at 557.7 nm. The Michelson is stepped to eight optical path difference values, each separated in phase by 45°, and an image is recorded at each step. WINDII has two fields of view, and acquires two images side by side on the CCD detector; one views at 45° to the velocity vector and the other at 135°. Since the UARS has an orbital inclination of 57°, this means that as the satellite passes its most northerly latitude of 57°N the fields of view sweep along a track at 42°N, and the latitude coverage is from 72°S to 42°N. How-

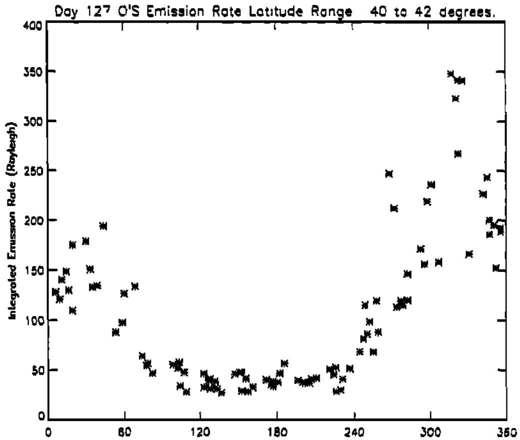

Fig. 1. Zenithal integrated emission rate for the atomic oxygen 557.7 nm emission as observed by WINDII on Jan. 16, 1992, plotted for the latitude band 40-42°N.

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ever, the satellite is rotated so as to fly "backwards" on alternate months, and in this configuration the coverage is from 42°S to 72°N. The bottom of the image varies around 70 km tangent height and the top around 300 km. For each bin in the image, the apparent emission rate, temperature and wind are derived from the sampled sinusoidal signal; the emission rate coming from the signal mean value, the temperature from the modulation depth of the signal and the wind from the phase. These quantities are then inverted to give true altitude profiles. For the atomic oxygen 557.7 nm emission the exposure time is normally 2 s at night, and for the hydroxyl emission it is 4 s. Other emissions are observed, but only these are reported upon in this paper. A more detailed description of the WINDII instrument is given by Shepherd et al. (1993).

Data Presentation

The inverted height profiles for the nighttime data for a 24-hour period were integrated along vertical paths over the altitude range 80 to 115 km in order to obtain the apparent E-region emission rate that would be seen by an observer on the ground. In Figure 1 we show these zenithal emission rates plotted versus longitude for the latitude range 40-42°N for Jan. 16, 1992. As explained above, for "forward" flight the fields of view have a most northerly latitude of 42°; there is thus a dense set of points in this narrow latitude band. Moreover, for one day all of these points correspond to essentially the same local time, as the orbit precesses by only about 20 min per day. We see a very strong wave-like pattern, with apparent zonal wave number 1, peaking at 320° longitude. The emission rate varies from about 30 R at the minimum to 300 R at the maximum.

To evaluate the long term stability of this pattern, we show in Figures 2 and 3 the zenithal emission rate plots for the same 40-42°N band for successive three day intervals, Jan. 19 and Jan. 22, 1992. There are missing data for some orbits due to calibrations, but there is a well-defined maximum at 240° on Jan. 19 (Figure 2), and on Jan. 22 there is a clear wavenumber 2 signature, with peaks at 180° and at 360° (Figure 3). It is tempting to conclude that the peak at 320° in Figure 1 has moved to 240° in Figure 2 and in Figure 3, a movement of about 25° per day, but with this limited dataset that is little more than speculation.

The same data can also be displayed as contours of volume emission rate versus altitude and longitude, as shown in Figure 4 for Jan. 22. We see here that the airglow layer is far from uniform, with the bottomside, as arbitrarily defined by 50 photon cm^{-3}s^{-1}, varying by more than 5 km. There is also a tendency for the regions of larger emission rate to be at lower altitude.

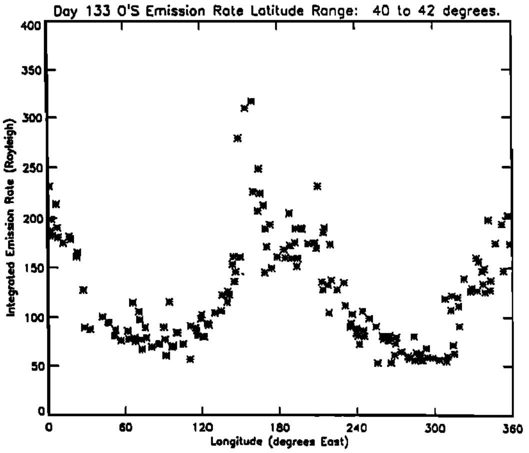

Fig. 3. Zenithal integrated emission rate for the atomic oxygen 557.7 nm emission as observed by WINDII on Jan. 22, 1992, plotted for the latitude band 40-42°N.

In Figure 5 the integrated zenithal emission rates for the latitude band 40-42° for Jan. 30 are presented. The longitudinal pattern is at first sight more complex than on Jan. 19 (Figure 2) owing to the presence of some shorter wavelength structure, but there is a maximum at 180° which is similar in magnitude and shape to the the 180° maximum in Figure 2. It is less prominent in Figure 5 because the maxima at 0° and 360° that also exist in Figure 2 are of larger amplitude in Figure 5.

In Figure 6 we show the peak apparent emission rate for the hydroxyl Meinel emission in the (8,3) band, plotted versus longitude for a latitude range 39-43°N for Jan. 12, 1992. Here we see a planetary wave structure with apparent zonal wavenumber 1. The longitudinal maximum is centered near 150°, far from the 320° maximum of Figure 1, for data taken four days later.

These emission rate variations indicate the presence of strong dynamical effects, to which the winds measured by WINDII will hopefully help provide an understanding. The wind measurements for WINDII are not finally validated, but as an example of the results obtained from the 557.7 nm emission at night we show in Figure 7 the meridional wind component at 97 km, plotted versus longitude for Jan. 22 expressed as the difference from the mean. Here we see a wave-like

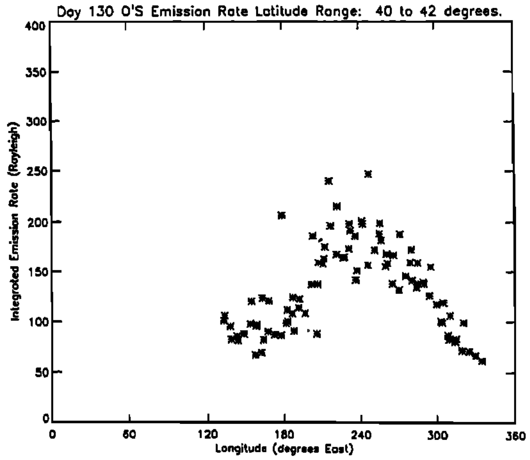

Fig. 2. Zenithal integrated emission rate for the atomic oxygen 557.7 nm emission as observed by WINDII on Jan. 19, 1992, plotted for the latitude band 40-42°N.

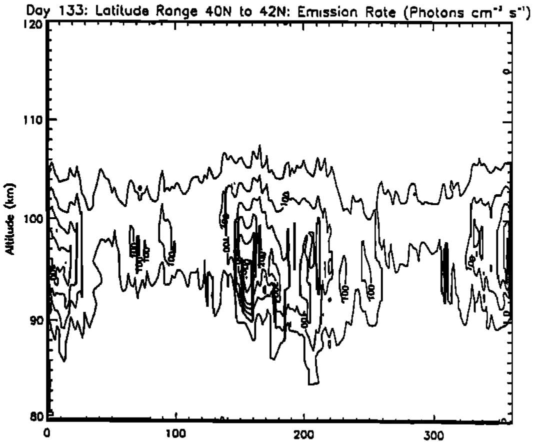

Fig. 4. Contours of volume emission rate for the atomic oxygen 557.7 nm emission as observed by WINDII on Jan. 22, 1992, plotted for the latitude band 40-42°N.

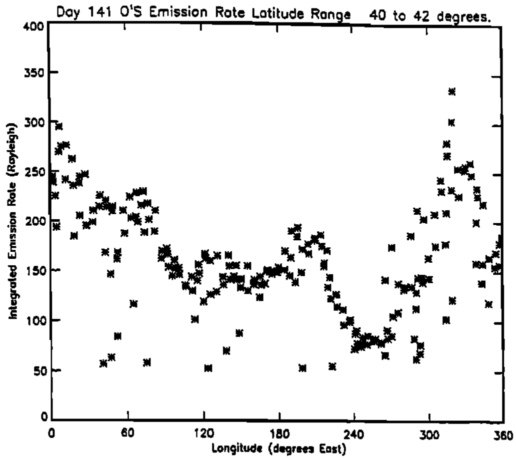

Fig. 5. Zenithal integrated emission rate for the atomic oxygen 557.7 nm emission as observed by WINDII on Jan. 30, 1992, plotted for the latitude band 40-42°N.

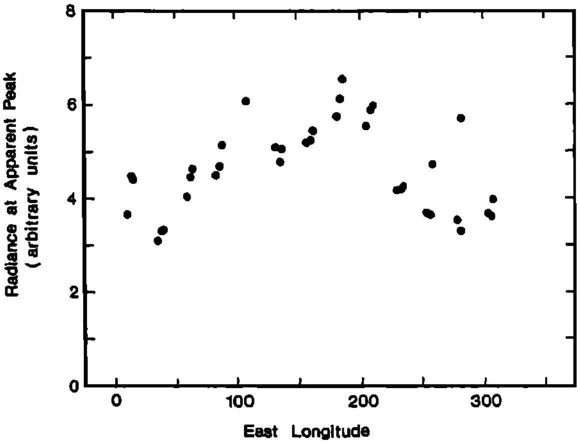

Fig. 6. Peak apparent emission rates observed at the limb for the (8,3) Meinel hydroxyl band on Jan. 12, 1992, plotted for the latitude band 39-43°N.

structure with two maxima, of about 100 ms^{-1} in amplitude. One maximum is located at the 180° emission rate maximum-for Jan. 22 and the other is located at the adjacent emission rate minimum.

Discussion

The results for the OI 557.7 nm emission and the hydroxyl emission during the month of January, 1992 show the presence, at mid-latitudes (40-42°), of planetary wave structure that appears to be a superposition of waves with apparent zonal wave numbers 1 and 2. We say apparent, because while WINDII views the whole longitude range each day, it views each longitude at a different universal time during that day. It is therefore possible that WINDII is sampling different points on a wave that is travelling with respect to the earth. However, we believe that these waves move relatively little from day to day, for two reasons. First, the emission rate at 0° on a given day tends to be the same as at 360°, as shown in Figures 1, 3 and 5, suggesting some measure of stability. Secondly, if such travelling waves routinely pass over ground stations during the course of a single night then all mid-latitude stations would regularly report airglow variations of a factor of four or more every night. Variations of the OI 557.7 nm emission observed at ground stations during the course of a single night are normally very much smaller, typically 30%; these are normally attributed to gravity waves, of much shorter wavelengths and smaller periods (for examples see Wiens et al. (1992) or Teitelbaum et al. (1981)). Variations of a factor of 4, or more, are infrequently seen at ground stations on a given night, that is, on a time scale of weeks rather than days. If the movement of 25° per day suggested above were typical, though we doubt that it is, it would take two weeks for a ground station to pass through a complete cycle. Our tentative hypothesis is thus that these waves have relative stability on a time scale of days, but from time to time, suffer a dramatic change in position or planetary wave pattern distribution that causes the large scale variations observed at ground stations. This supposition is based more on existing ground-based observations, which are extensive, than on the WINDII dataset provided here, which is insufficient to allow any firm conclusions. When a more extensive WINDII dataset is employed in conjunction with selected ground stations it will be possible to resolve temporal ambiguities and thus arrive at an accurate global description of the behavior of these planetary-scale waves.

The WINDII data raise the important question as to whether these airglow emission rate variations, and the associated atomic oxygen concentrations, are driven by processes associated with the earth (or the lower atmosphere), rather than by the sun. Historically, aeronomers have tended to interpret airglow variations in the framework of solar-driven photochemistry. On the basis of the evidence presented here for enormous airglow variations in longitude for data all at the same local time, we conclude that the earth, or the lower atmosphere, is the origin of these variations.

One piece of supporting evidence for this is in the middle atmosphere planetary waves incorporated in the CIRA 86 model (Barnett and Labitzke, 1990). For January, at 42°N, the geopotential altitude from this model is a combination of wavenumbers 1 and 2. We plotted this for the maximum altitude available, 83.3 km, and found the pattern to look similar to the waves shown in Figures 3 and 5. The 0.5 km amplitude is very much smaller than the variations seen in Figure 4, and presumably smaller than required to cause such large emission rate variations. But these planetary waves do not necessarily propagate upwards from below; an alternative possibility is that upward propagating gravity waves interact with the mean flow at airglow altitudes, creating these waves there.

We now briefly mention the mechanism for airglow emission rate variation. Up until now, such variations have in general been interpreted in terms of changes in atomic oxygen concentration at a fixed altitude. The WINDII data show that airglow layers are not idealized layers at a fixed altitude, but

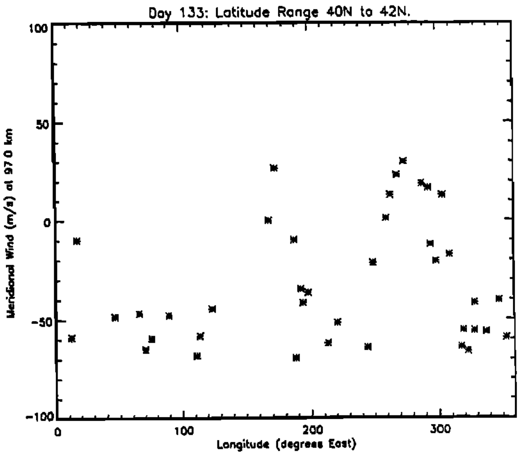

Fig. 7. The meridional wind observed by WINDII on Jan. 22, 1992 at an altitude of 97 km for the latitude band 40-42°N.

involve a good deal of horizontal and vertical structure. Airglow 557.7 nm enhancements may be caused by increasing the oxygen mixing ratio at a given pressure level or by increasing the total density in a given location. The latter mechanism explains the influence of gravity waves on airglow (Hines and Tarasick, 1987), with the 30% variations mentioned earlier, but the factor of four variations observed in these planetary waves would seem to require significant changes in mixing ratio.

Conclusions

We have observed planetary-scale waves in the atomic oxygen 557.7 nm airglow emission observed at night, in the associated meridional wind pattern. These waves are remarkable for their simple structure, dominantly consisting of wavenumbers 1 and 2, but more so for the very large peak to valley ratio, a factor of four or more. The observations are reported for a single latitude band 40-42°, during January, 1992 and so tell us only about winter mid-latitudes. Similar waves are observed for the hydroxyl emission. There are significant variations in the associated altitude distributions of the emissions, with a tendency for the more intense emission to be at lower altitude.

We hypothesize that the waves move relatively little on a time scale of a few days, but this response is based on the examination of a small amount of data, and a conclusive answer must await the study of the larger body of data that does exist.

The significance of these observations is that they demonstrate a strong coupling between the mesopause and the atmospheric regions below, including perhaps the earth's surface. In any case, the very existence of this planetary wave structure requires a major change in perspective regarding our present aeronomical knowledge of the mesosphere and lower thermosphere. With the development of the WINDII database we hope to contribute to the resolution of these fundamental questions.

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