Development of Optical Mesosphere Thermosphere Imagers (OMTI)

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Abstract.

The Optical Mesosphere Thermosphere Imagers (OMTI) have been developed to investigate the dynamics of the upper atmosphere through nocturnal airglow emissions. The OMTI consist of an imaging Fabry-Perot interferometer, three all-sky cooled-CCD cameras, three tilting photometers, and a Spectral Airglow Temperature Imager (SATI) with two container houses to install them in. These instruments measure wind, temperature and 2-dimensional airglow patterns in the upper atmosphere at multi-wavelengths of OI (557.7nm and 630.0nm), OH(6-2) bands, O_2(0,1) bands, and Na (589.3nm), simultaneously. Examples of the data are shown for the cameras, the photometers, and the SATI based on the airglow observation at a mid-latitude station in Japan. Good correlation of the photometer and SATI observations is obtained. A comparison is shown for small- and large-scale wave structures in airglow images at four wavelengths around the mesopause region using four cooled-CCD cameras. We found an event during which large-scale bands, small-scale row-like structures, and large-scale front passage occur simultaneously.

1. Introduction

Nocturnal airglow emissions give useful information on the study of the dynamics and chemistry of the upper atmosphere. Rotational temperature of atmospheric molecular constituents can be obtained by photometric measurement of airglow band emissions (e.g., Meriwether, 1975; Takahashi *et al.*, 1989; Wiens *et al.*, 1991, 1995; Fagundes *et al.*, 1997). Doppler wind and temperature of the upper atmosphere are obtained by high-resolution interferometric measurements (e.g., Killeen and Roble, 1988, Rees *et al.*, 1990; Hernandez and Roble, 1995; Conde and Smith, 1995; Dyson *et al.*, 1997).

Furthermore, recent development of cooled-CCD detector makes it possible to detect spatial patterns in airglow emissions with a high-sampling rate of a few minutes per image. The images show various types of short-period wave structures which are probably caused by atmospheric gravity waves (e.g., Hecht and Walterscheid, 1991; Taylor and Hill, 1991; Taylor *et al.*, 1995a, 1997, 1998). Simultaneous imaging observations of several airglow layers are very important to study vertical propagation of these waves. Such observations have not been done sufficiently yet, since an all-sky camera takes airglow images at several wavelengths by changing filters. Moreover, simultaneous observations of wind, temperature, and airglow images are needed to study the dynamics of the short-period waves.

The Optical Mesosphere Thermosphere Imagers (OMTI) were introduced by the Solar-Terrestrial Environment Laboratory, Nagoya University in 1997 in order to measure airglow variation patterns, horizontal wind, and temperature at several airglow layers simultaneously using three all-sky cameras and several interferometers with cooled-CCD detectors. In this paper, we show details of the instrumentation and initial results of the mid-latitude airglow observations near the mesopause region.

2. Instrumentations

Figure 1 shows a schematic picture of the OMTI system. The OMTI consists of a Fabry-Perot interferometer, three all-sky cameras, three tilting photometers, and a Spectral Airglow Temperature Imager (SATI). These instruments are set in two air-conditioned container houses with several personal computers and a SUN workstation. Pictures of these instruments are shown in Figure 2. The operations of the cameras, photometers, and SATI are fully automated by the personal computers. The data from these instruments can be copied from remote stations through a computer network.

The imaging Fabry-Perot interferometer measures neutral wind vectors and temperatures at three different altitudes simultaneously. Three cooled-CCD cameras with liquid nitrogen dewars are used as detectors. An all-sky airglow image is divided into three wavelengths (557.7nm (OI), 630.0nm (OI), and 839.9nm (OH)) by two dichroic filters, passed through three band-pass filters, and detected by the cameras. The etalon has a clear aperture size of 116mm with a cavity spacing of 15mm (Queensgate ET116). It is set in a sealed cell to avoid fluctuation of the spacing due to the changes of pressure and humidity. Input light from a fish-eye lens passes through the etalon with a maximum angle of 0.7 (deg). Details of this instrument and its performance will be published elsewhere in the future.

The SATI measures intensities and rotational temperatures of O_2 Atmospheric (0-1) P branch and OH Meinel (6-2) Q branch emissions using the technique of interference filter spectral scanning with a cooled-CCD detector. The technique was firstly developed by the Mesopause Oxygen Rotational Temperature Imager (MORTI) and the present implementation is described by Wiens *et al.* (1997). The integration time for each emission is 2 min. By changing band-pass filters, the SATI measures the intensities and temperatures of O_2 and OH band emissions with a time resolution of 4 min. The SATI has an annular field-of-view in the sky with a radius of $30° \pm 3.5°$ zenith angle centered on the zenith. Temperature and intensity of each emission are obtained for twelve azimuthal sectors.

In the following two sections we describe the performance of the all-sky cameras and the tilting filter photometers.

2.1. All-Sky Cameras

Figure 3 is a schematic diagram showing one of the camera system. The fish-eye (f=24mm) lens at the head of the camera has a field of view of 180°. This front lens can be replaced by 45mm and 80mm lenses for narrower fields of view of 76° and 47°, respectively. The shutter is controlled by the personal computer, while it is designed to remain closed when daylight is detected by the CdS optical sensor as a fail-safe system. The filter wheel contains five 3-inch filters the characteristics of which are listed in Table 1. The incident light from the front lens passes through the telecentric optics made by KEO Consultants and is focused on the thinned and back-illuminated 512×512 cooled-CCD detectors (Hamamatsu C4880). The image data from the cameras are recorded on a 640MB optical disk through the computer and are also accessible through a computer network. The whole system is backed up by a power supply that can run for more than 10 min.

The absolute sensitivities at the (256,256) pixel (around the center of image) are also listed in Table 1. Details of the calibration to obtain these values are shown by Shiokawa *et al.* (1998). The sensitivities vary from 0.03 to 0.05 (counts/R/s) depending on the cameras and filters. For airglow emissions with an intensity of 100 R, a 100-s exposure provides 300-500 counts per pixel. This amount is enough to discuss airglow patterns, since the read-out noise and the dark noise of the CCD detector are 10 (counts (r.m.s.)) and far less than 1 (counts/pixel/s), respectively. The typical exposure time for each emission line is also shown in Table 1. The cameras are capable of detecting an airglow image by a 2-3 min exposure for OI, Na, and O_2-band emissions and by a 15 sec exposure for OH band emission. Simultaneous observation of at least three emission lines is possible using these cameras. One example of such an observation will be shown in Section 3.2. Coordinated multipoint observations are also possible using these cameras for 557.7nm (OI), 630.0nm (OI), and OH band emissions, since all the cameras have the same filters for these emissions.

2.2. Tilting Photometers

The meridian-scanning tilting photometers No.1 and 2 are built to measure mid-latitude airglow emissions of OI (557.7nm and 630.0nm) and OH bands with relatively narrower field of view, while the photometer No.3 is built to measure weak emissions caused by energetic heavy particle precipitation during magnetic storms (e.g., Tinsley *et al.,* 1984, 1986). Figure 4 is a schematic diagram showing one of the photometer system. The field of view of the 40 mm diameter front lens is 3° for photometer No.1 and 2 and 8° for No.3. The stepping motors for meridian scanning and filter tilting are controlled by the personal computer. The shutter is also controlled by the computer with a fail-safe system using the CdS optical sensor. The photomultipliers, Hamamatsu R636-10 (for No.1 and 2) and R268 (for No.3), are used as detectors. Low-pass filters with a cut-off period of 2 s (for No.1 and 2) and 10 s (for No.3) are used in the signal amplifier in order to reduce thermal noise from the photomultiplier. The temperature of the photometer is set at 20°C by the air conditioner. The whole system is backed up by a power supply that can run for more than 10 min.

Filter and tilting details and sensitivities of the photometers are listed in Table 2. The sensitivities were obtained using calibration facilities at the National Institute of Polar Research, Japan. The time resolution of photometers No.1 and 2 is 1 min (= 4 filter tilt $\times$ 5 meridian scan $\times$ 2.5 s + dark current detection), while that of the photometer No.3 is 10 min (= 20 filter tilt $\times$ 3 meridian scan $\times$ 10 s). Because the noise levels of the channels for the OH bands and the OI (630.0nm) line are relatively high compared to the airglow intensity, data are further averaged for 10 min for these channels. Examples of the observed data will be shown in the next section.

3. Observations

3.1. May 21–22, 1998

The meridian-scanning tilting photometers started automatic observation of the airglow at Shigaraki (35°N, 136°E), Japan in May 1998. Figure 5 shows intensity variations of OI (557.7nm) and OH Meinel (6-2) (846.5nm and 843.0nm) airglow emissions observed by photometer No.1 during the clear night of May 21–22, 1998. The meridian scan is in the north-south direction. The spectra of these emission lines obtained every hour by taking full-tilt data of the filters at the meridian scan angle of 0° (zenith) are also shown in the right side of Figure 5. The noise levels of the OI curves and 10-min averaged OH curves are small enough to discern hourly variation. It is clearly seen that the intensity of the 557.7nm emission increases with increasing local time, while that of the OH bands decreases.

Figure 6 shows the intensity variations of the O_2 Atmospheric (0-1) band and the OH Meinel (6-2) band emissions and rotational temperatures calculated from these emissions. These data are obtained by the SATI as an average over all azimuth angles at Shigaraki on the same night as that of Figure 5. The zenith photometer data in Figure 5 are also plotted in the bottom panel. It is interesting that the intensities of O_2 bands and 557.7nm line measured by the SATI and the photometer, respectively, show fairly consistent variations. The OH band intensities measured by these two instruments fit quite well, though that by the photometer fluctuates after 23LT. This fluctuation may be due to the different fields of view of the two instruments. The anti-correlation of the intensities of O_2 and OH emissions is not seen in the temperature data. Both O_2 and OH temperatures gradually increase from dusk to dawn.

Figure 7 shows intensity variations of the Doppler-shifted Hydrogen Balmer β line (485.1nm) and the N_2^+ First Negative line (427.8nm) measured by photometer No.3 on the same night as that of Figure 5 (May 21-22, 1998). Emissions of these lines at mid-latitudes are caused by energetic heavy particle precipitation during magnetic storms. Since a magnetic storm did not occur on this day, no significant emission is seen in the data. One can see that the noise level of the photometer is less than 5 R for both channels. The large negative intensities at the start of the observation around 20LT are due to intense background sunlight, while the following weak emission of $\sim$4 R for 20–21LT in Hβ is probably the geocorona.

3.2. March 4, 1998

During the first Japanese Planetary Scale Mesopause Observing System (PSMOS) campaign for January–March, 1998, we made a comprehensive observation of airglow emissions in the mesopause region. Four all-sky cameras (three from the OMTI and one from the Radio Atmospheric Science Center, Kyoto University) are used to obtain 3-dimensional structure of gravity waves through the airglow images.

Figure 8 shows an example of the observed airglow patterns in the four emissions OI (557.7nm, $\sim$96 km), O_2 Atmospheric (0-1) bands ($\sim$94 km), Na (589.3nm, $\sim$90 km, camera by the Kyoto University), and OH bands ($\sim$87 km) on March 4, 1998. Background intensities of Na emission decrease significantly during the observed interval. The OH image is taken every 30 s, while the images of other emissions are taken every 2 min. Note that these are the first simultaneous observations of these four emissions using four all-sky cameras.

Three kinds of wave structure are seen in these images. A schematic diagram of the wave structures seen in the OI image at 0021LT is shown in Figure 9. The first one is the large-scale "band" structure in the NNW-SSE direction which moves toward the ENE. The velocity of the motion is $\sim$160 m/s in the OI images assuming an emission altitude of 96 km. The horizontal wavelength of this structure is ∼100 km. This structure is clearly seen in the OI and O_2 images but is not clear in the Na and OH images.

The second one is the large-scale EW structure which moves northward with a velocity of ∼80 m/s in the OI images. This structure, which is more or less like a boundary between intense and weak emissions, is seen at the bottom edge of the OI and O_2 images at 0001LT and around the center of the images at 0031LT. This structure is relatively weak in the Na and OH images, but can be seen in the 0031LT images.

The third one is groups of small-scale waves which form row-like structures in the NW-SE direction. These row-like structures are seen in all four images around the center. The wavelength of the small-scale NE-SW waves in a row is ∼15 km. This structure is more distinct in the OH images than in the OI images.

4. Discussion

The noise levels of OH channels of the photometers No.1 and 2 (31–87 R as listed in Table 2) are relatively high. By averaging 10 data as plotted in Figure 5, the noise decreases to 1/3 ($\sim \sqrt{10}$) of these values. However, it is still difficult to calculate rotational temperature from the intensity data. Additional cooling will be needed for the photomultipliers.

On the other hand, the noise levels of the photometers are low enough to discuss diurnal intensity variations as shown in the comparison with data from the SATI. The good correlation observed between OI (557.7nm) and O_2 Atmospheric (0-1) bands (Figure 6) has been reported by previous researchers (e.g., Misawa and Takeuchi, 1977; Rodrigo *et al.*, 1985). The trends of increasing 557.7nm intensity and of decreasing OH band intensity are similar to those observed at Cachoeira Paulista (23°S, 45°W) in May (Takahashi *et al.* 1984). The gradual increase of O_2 rotational temperature is not similar to that observed at Bear Lake Observatory (42°N, 111°W), but our May data were acquired later in the year than any of the Bear Lake data reported (Wiens *et al.*, 1995).

The noise level of photometer No.3 is less than 5 R as shown in Figure 7. Emission intensities at mid- and low-latitudes by energetic heavy particle precipitation during magnetic storms are typically a few R for the Hβ line and a few hundred R for the N_2^+(1NG) band (Tinsley *et al.* 1984). Thus, the noise level is comparable to the typical intensity for Hβ, while it is low enough for N_2^+(1NG) detection.

The all-sky images shown in Figure 8 indicate that a variety of wave structures such as bands and row-like waves is observed at a mid-latitude of 35°N. The large-scale band structures are seen only in the OI and O_2 emissions. From the ALOHA-93 campaign observation at a tropical latitude of 21°N, Taylor *et al.* (1995a) pointed out that wave structures are detected in significantly higher amount at OI altitudes ($\sim$96 km) and suggested ducted wave motions in the lower thermosphere. Similar mechanism may play a role at this latitude.

On the other hand, the small-scale row-like structure is observed simultaneously at all altitudes. Similar wave structures are reported by Taylor *et al.* (1995a). They also noted that this pattern is seen at all four wavelengths. However, the small-scale row-like structures in Figure 8 are more prominent at the OH altitude than at the OI altitude, which is opposite to the observation by Taylor *et al.*

The northward moving EW boundary structure is similar to the spectacular front event reported by Taylor *et al.* (1995b). Dewan and Picard (1998) suggested that such front passage is caused by the mechanism of a tidal bore in the mesopause region. A decrease of 557.7nm intensity and an increase of OH intensity after the passage of the front is seen in the images of 0031LT, which is also consistent with the observation by Taylor *et al.* (1995b). Small-scale wave structures observed in their images after the front passage is not clear in our case.

The three kinds of wave structures in Figure 8 observed at the mid-latitude station is quite similar to those observed during the ALOHA-93 campaign at tropical latitudes.

It is very interesting to note, however, that these waves appear in the same images.

5. Summary

We have developed the OMTI system in the Solar-Terrestrial Environment Laboratory. The OMTI is capable of measuring wind, temperature, and 2-dimensional airglow pattern at multi-wavelengths simultaneously. Automated routine observations of airglow emissions by the cameras, the photometers, and the SATI were started from July 1998, May 1998, and December 1997, respectively, at Shigaraki, Japan. The operation of the Fabry-Perot interferometer has not been automated yet.

The OH rotational temperature from the photometer is still unreliable due to a high noise level, while diurnal variation of airglow intensity can be discussed from the photometer data. The photometer No.3 has a capability enough to measure mid-latitude atmospheric emissions by heavy particle precipitation during magnetic storms. The SATI measures intensities and rotational temperatures of OH and O_2 bands fairly well.

As shown in Figure 8, simultaneous observation of airglow images at several wavelengths give us useful information to study vertical propagation of gravity waves. Short-period wave structures similar to those observed in the equatorial latitude are seen from the mid-latitude observation. We found an event during which large-scale bands, small-scale row-like structures, and large-scale front passage occur simultaneously.

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Figure 1. Schematic diagram of the Optical Mesosphere Thermosphere Imagers (OMTI).

Figure 2. Pictures of the instruments of OMTI. Two container houses (top left) with three photometers and several transparent domes on the roof, an all-sky camera (middle left), a meridian-scanning tilting photometer (bottom left), an imaging Fabry-Perot interferometer (top right), and a Spectral Airglow Temperature Imager (SATI, bottom right).

Figure 3. Schematic diagram of the all-sky cooled CCD camera system with 5-position filter wheel. The camera operation is controlled by the personal computer. Image data are saved into the optical disk.

Figure 4. Schematic diagram of the meridian-scanning tilting photometer system. Two airglow lines are measured simultaneously by separating the incident light using a dichroic mirror. The whole system is controlled by the personal computer.

Figure 5. Intensity variations of OI (557.7nm) and OH Meinel (6-2) (846.5nm and 843.0nm) airglow emissions observed by the meridian-scanning tilting photometer No.1 at Shigaraki (35°N, 136°E), Japan on May 21–22, 1998. The meridian scanning is for five zenith angles from $-74.88°$ (northward) to $74.88°$ (southward). Line spectra obtained every hour by taking 1-min full-tilt data at the scan angle of $0°$ (zenith) are also shown in the right side.

Figure 6. Intensities and rotational temperatures of O_2 Atmospheric (0-1) band and OH Meinel (6-2) band emissions measured by the SATI (average of all azimuth angles) at Shigaraki on May 21–22, 1998. The zenith photometer data in Figure 5 are also plotted by dashed lines in the bottom panel.

Figure 7. Intensity variations of Doppler-shifted Hydrogen Balmer β line (485.1nm) and N_2^+ First Negative line (427.8nm) measured by the meridian scanning tilting photometer No.3 at Shigaraki on May 21–22, 1998. The meridian scanning is for three zenith angles from -74.88° (northward) to 74.88° (southward).

Figure 8. All-sky airglow images at OI (557.7nm, $\sim$96 km), O_2 Atmospheric (0-1) bands ($\sim$94 km), Na (589.3nm, $\sim$90 km), and OH bands ($\sim$87 km) observed at Shigaraki for 00:01–00:31LT on March 4, 1998. The OH image is taken every 30 s, while the images of other emissions are taken every 2 min. These images at four emission lines are taken at exactly a same time using four all-sky cameras. Upward is toward the north and leftside is toward the east. The images are deviations from the average image for 00:01–0031LT.

Figure 9. Schematic diagram showing three kinds of wave structure seen in the all-sky image of the OI emission at 0021LT in Figure 8. The arrows indicate directions of the wave motion.