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Undulating wave front of mesospheric bore; Space-borne observations by ISS-IMAP/VISI

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Abstract. Large-scale spatial structures of mesospheric bores were observed by Visible and near Infrared Spectral Imager (VISI) of the ISS-IMAP mission (Ionosphere, Mesosphere, upper Atmosphere and Plasmasphere mapping mission from the International Space Station) in the mesospheric O_2 airglow at 762 nm wavelength. Two mesospheric bore events are reported in this paper; one event was observed over the south of African continent (48ºS–54ºS and 10ºE–25ºE) on 9 July 2015, and the other event over the south Atlantic Ocean (35ºS–43ºS and 24ºW–1ºE) on 7 May 2013. For the first event, the temporal evolution of the mesospheric bore was investigated from the difference of two observations in consecutive paths. The estimated eastward speed of the bore is 100 m/sec. The number of trailing waves increased with a rate of 3.5 wave/hour. Anti-clockwise rotation with a speed of 20º/hour was also recognized. These parameters are similar to those reported by previous studies based on ground-based measurements, and the similarity supports the validity of VISI observation for mesospheric bores. For the second event, VISI captured a mesopshric bore having a large-scale and undulating wave front. The horizontal extent of the wave front was 2,200 km. The long wave front undulated with 1,000 km wave length. The undulating wave front is a new feature of mesospheric bore revealed by the wide FOV of VISI. We suggest that non-uniform bore propagating speed due to inhomogeneous background ducting structure might be a cause of the undulation of the wave front. Temperature measurements from the Sounding of the Atmosphere using Broadband Emission Radiometry (SABER) of the Thermosphere, Ionosphere, Mesosphere, Energetics and Dynamics (TIMED) satellite indicated that bores of both events were ducted in a temperature inversion layer.

1 Introduction

Mesospheric bore is a propagating sharp front in the upper mesosphere. The front is often followed by undulations or turbulence, and called as an undular bore or a turbulent bore, respectively. The mesospheric bore has been observed as a sharp brightness jump or drop of airglow by ground-based imagers at various longitudes from low latitude to high latitude (e.g., Taylor et al., 1995; Smith et al., 2003, 2017; Fechine et al., 2005; Nielsen et al., 2006; Li et al., 2013).

Dewan and Picard (1998) proposed an explanation of mesospheric bore as propagating discontinuity in a stable layer or a duct in varicose mode. By solving conservation of mass and momentum, they calculated the speed of a bore as follows;

$$U = \sqrt{g' \frac{h_1(h_1 + h_0)}{2h_0}} \quad (1)$$

Here, h_0 and h_1 are half width of a ducting layer upward and downward of a bore, respectively. g' is gravitational acceleration corrected for buoyancy force. This mesospheric bore model has been examined and validated using simultaneous lidars and airglow imagers observations (Smith et al., 2003, 2005; She et al., 2004). Dewan and Picard (2001) tried to explain the generation of mesospheric bore with critical level interaction of gravity wave to the mean flow. Seyler (2005) and Laughman et al. (2009) demonstrated by using a numerical simulation that a wave front of a long-wavelength gravity wave in a duct can steepen and become a bore-like sharp front. Such a formation of mesospheric bore from a large-scale gravity waves was reported by Yue et al. (2010) with ground-based observations. However, the generation mechanism and origin of mesospheric bores are still not fully understood.

Since ground-based imagers have often observed only a portion of bore's wave front, the typical horizontal spatial scale of mesospheric bore seems to be larger than the field-of-view (FOV) of ground-based imagers. Previous studies based on ground-based observations have provided limited information on the large-scale horizontal structure of bores. Space-borne airglow imaging is a strong tool to study mesospheric bores with a wide FOV and global observational coverage, and can overcome the limitations of ground-based observations. Miller et al. (2015) reported two space-borne observations of mesospheric bore events by Day/Night Band (DNB) onboard the NOAA/NASA Suomi National Polar-orbiting Partnership environmental satellite. Although there are successful observations of mesospheric bores by DNB, a lot of works are left to do on the mesospheric bore study with space-borne imaging.

Visible and near Infrared Spectral Imager (VISI) of the Ionosphere, Mesosphere, upper Atmosphere and Plasmasphere mapping mission from the International Space Station (ISS-IMAP mission) is another instrument that has a capability to image mesospheric airglow from space with a wide FOV. While Miller et al. (2015) simply presented bore events to show DNB's potential for bore observation, we report two successful bore events from VISI with further detailed analyses in this paper. As event #1, we will report a mesospheric bore observed in the southern mid-latitude. We report this event because of two reasons. First, this is a bore observed in the southern mid-latitude, where few observations of bore reported. While a lot of bores have been reported in the northern mid-latitude, there are few reports of bore in the southern mid-latitude. Second, the bore was captured in two consecutive paths by VISI in this event, thus, the temporal evolution of the structure can be investigated. By comparing the obtained parameters with previous ground-based observations, we can validate the VISI observations. After the variation, we report a mesospheric bore having a very long wave front exceeding 2,200 km as Event #2. With a benefit of VISI's wide FOV, a new feature of undulating wave front was captured.

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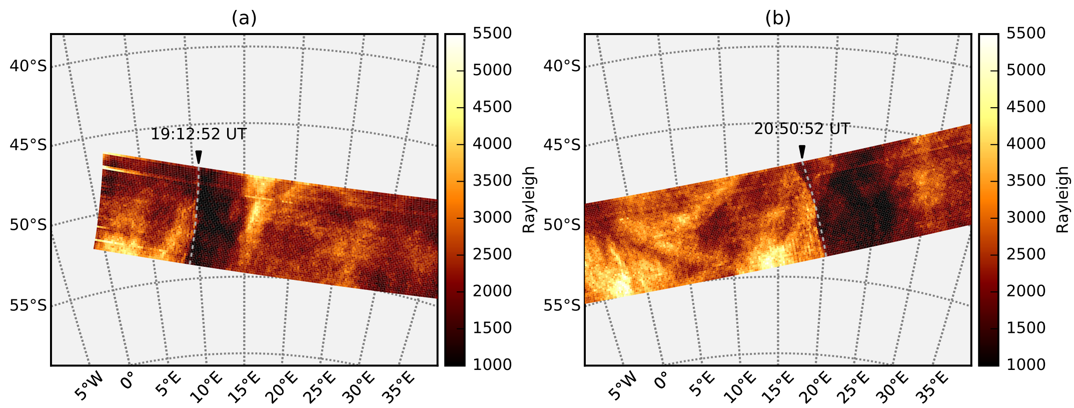

Figure 1. O_2 (762 nm) airglow images obtained by VISI with the backward FOV in two consecutive paths on 9 July 2015. Airglow images were mapped to the altitude of 95 km. The observation time when the FOV was crossed the bore front is indicated with black wedge in each figure.

2 Observations

VISI is a visible and near infrared spectral imager that was installed on the International Space Station (ISS), and made observations from September 2012 to August 2015 (Sakanoi et al., 2011). It has two slit-shape FOVs that are perpendicular to the ISS orbit track and 45° forward/backward to nadir. Data of O_2 (0-0) airglow at 762 nm is utilized in this study. A swath of data obtained every 1.9 sec with an exposure time of 1.0 sec. The nominal altitude of the emission is 95 km so that data were mapped to the altitude of 95 km. At the mapping altitude, the horizontal width of FOV is 670 km. The spatial resolutions are 13 km and 12-15 km along and across the ISS orbit track, respectively. The speed of the ISS, 7.4 km/sec, is much higher than the typical phase speed of mesospheric bores, 20–100 m/sec. Therefore, it is reasonable to consider that VISI observes snapshots of bore induced airglow structure.

Temperature profile obtained by the Sounding of the Atmosphere using Broadband Emission Radiometry (SABER) instrument onboard the Thermosphere, Ionosphere, Mesosphere, Energetics and Dynamics (TIMED) satellite is employed as supporting data to assess the background thermal structure. Vertical profile of kinetic temperature can be retrieved from SABER measurements of CO_2 1.5 μm earth rim emission (Mertens et al., 2001). The v2.0 level 2A data downloaded from http://saber.gats-inc.com was used in this study.

3 Results and Discussion

3.1 Event #1

A sharp front followed by undulations was observed by VISI on 9 July 2015 over the south of African continent. The front was captured in two consecutive paths so that the temporal evolution of the structure can be investigated from the observations. The airglow images obtained by the backward FOV of VISI are shown in Figure 1. The center of the backward FOV crossed the front at 19:12:52 UT in the first path, and crossed it again at 20:50:52 UT in the second path.

In the first observation (Figure 1a), a sharp brightness jump of airglow followed by wave structures can be seen around 10ºE longitude with S-N elongation of the front. The morphological feature is exactly same as bore induced airglow structures reported by previous studies. Since the undulations are seen on the western side of the front, the mesospheric bore is expected to propagate eastward. Two crests are identified on the southern part of the western side of the front, and the wavelength is 30 km. The O_2 airglow brightness on the western side of the front is 2,500–3,000 Rayleigh, which is 250-300 % brighter than that on the eastern side.

In the second observation (Figure 1b), the front moved eastward, and was observed at 16ºE–25ºE. The amplitude of the brightness jump is almost same as that in the first path, but both sides of the wave front are slightly brighter than previous, respectively; 3,000–3,500 in the western (bright) side, and 1,300 Rayleigh in the eastern (dark) side. Assuming a pure westward propagation, the bore speed is 100 m/sec at 50ºS. This value is close to the bore speeds reported by previous studies that are typically 60 – 80 m/s. The undulations are identified on the southern part in the second path as well as in the first path. The number of wave crests increased to seven, therefore, wave adding rate is expected to 3.5 wave/hour. This value is also similar to the wave adding rates reported previously: that ranged from 1.3 to 7 wave/hour.

The orientation of the wave front was NNW-SSE direction in the second path, while it was almost N-S direction in the first path. The azimuthal angle of the wave front was expected to rotate anti-clockwise from 12º (angle from north to east) to -18º within one orbital period of the ISS; thus, the rotation speed is -20º/hour. Smith et al. (2003) reported 6º/hour clockwise rotation of a bore front over North America. Li et al. (2013) reported 8º/hour clockwise rotation over northern China. While these bores in the northern mid-latitude showed clockwise rotation, the current bore in the southern mid-latitude showed anti-clockwise rotation. The rotation of wave fronts might be caused by background wind variations. Background wind in the mesopause region is largely dominated by atmospheric tide. Upward propagating tide makes clockwise wind variation in the northern hemisphere, and anti-clockwise wind variation in the southern hemisphere due to the Coriolis force. Rotation directions of this event in the southern hemisphere and the events in the northern hemisphere reported by previous studies are consistent with the background tidal wind variation. In the past studies, there were few reports of mesospheric bore in the southern mid-latitudes, where the ground-based observation sites are not dense. VISI can provide the southern mid-latitude data, and show the hemispheric difference clearly.

TIMED/SABER made an observation 2.3 hour after the second observation of VISI, at 23:10 UT on 9 July 2015, at (52.1ºS, 24.8ºE) for 95 km altitude (Figure 2a). Figure 2b presents the vertical temperature profile showing a 30 K temperature inversion at 95-100 km altitude. The vertical profile of Brunt-Väisälä Frequency derived from SABER temperature measurement is

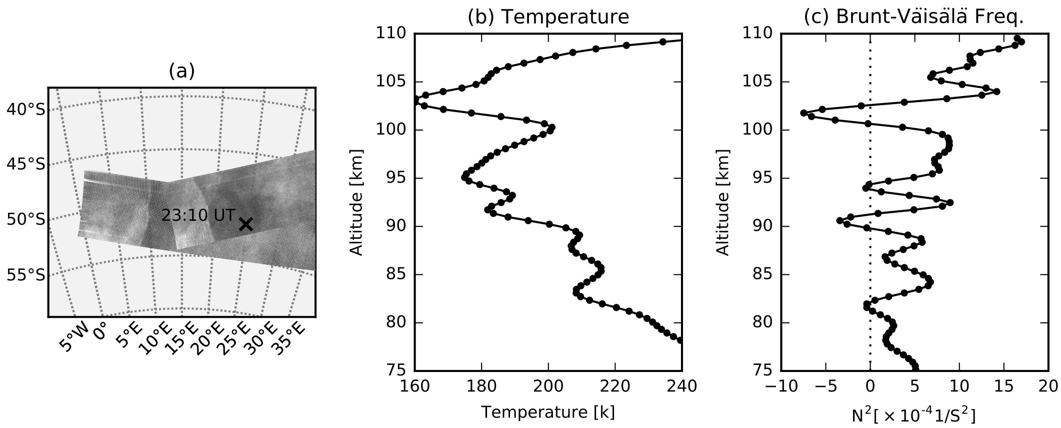

Figure 2. SABER measurements obtained 2.3 hours after the bore event #1. (a) The measurement point at 95 km altitude is indicated by black cross. (b) The altitude profile of temperature showing a 30 K temperature inversion at 95-100 km altitude. (c) The altitude profile of resulting Brunt-Väisälä frequency showing a stable layer at 95-100 km.

presented in Figure 2c. A stable layer surrounded by unstable region corresponding to the temperature inversion is recognized at 95-100 km altitude that is just slightly higher than the typical emission peak of 762 nm O_2 emission. Mesospheric bore is thought to require a ducting region created by a temperature inversion or a wind shear. Since temperature inversions are thought to be long-lived phenomena (Meriwether and Gardner, 2000; Meriwether and Gerrard, 2004), the stable layer due to the inversion layer observed by SABER is expected to exist during the VISI observation, 2.3 hours before the SABER observation. The mesospheric bore of this event is likely to propagate in the ducting region created by a temperature inversion.

The bore parameters, such as phase speed, wavelength of trailing waves, and wave adding rate, are similar to those reported by previous studies based on ground-based measurements. These similarities support the validity of VISI observation for mesospheric bores. Next, we will report a large-scale spatial structure of mesospheric bore revealed by the wide FOV of VISI.

3.2 Event #2

A mesospheric bore having a very long wave front was observed on 7 May 2013 over the south Atlantic Ocean (35ºS–43ºS, 24ºW–1ºE) as shown in Figure 3. A front of brightness jump with WNW-ESE elongation is captured from 20:55:01 UT to 20:59:57 UT with the forward FOV, and from 20:55:51 UT to 21:01:26 UT with the backward FOV. The O_2 airglow brightness on the SSW side of the front is 4,200–5,000 Rayleigh, that is 130-160 % brighter than that on the NNE side. Within the VISI's FOV, the wave front has a large horizontal extent exceeding 2,200 km. An interesting feature of this event is the undulating wave front. The wave front of the bright jump was not straight; it undulated with a wavelength of ~1,000 km. The crests of the modulation are at (18ºW, 27ºS) and (6ºW, 40ºS). The small wavy structures parallel to the wave front are seen at 8ºE–0ºE on

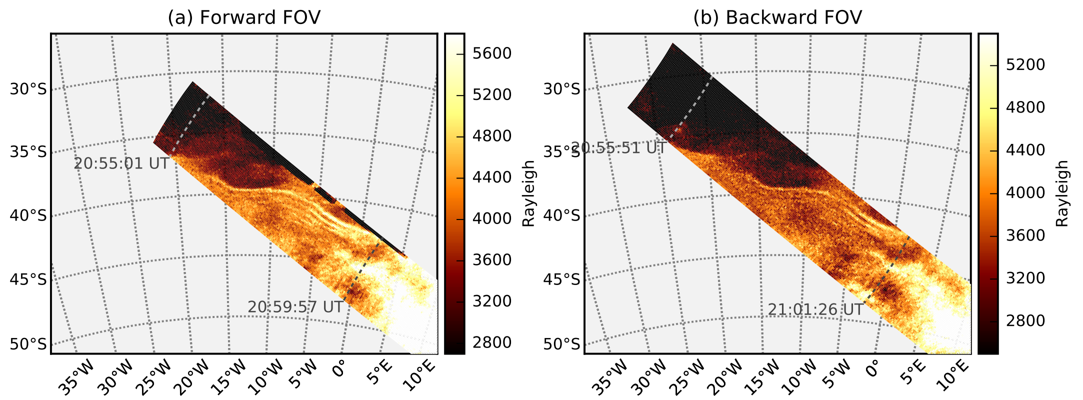

Figure 3. O_2 (762 nm) airglow images obtained by VISI with the forward and backward FOV on 7 May 2013. The starting and ending times of capturing the bore front are indicated with dashed lines.

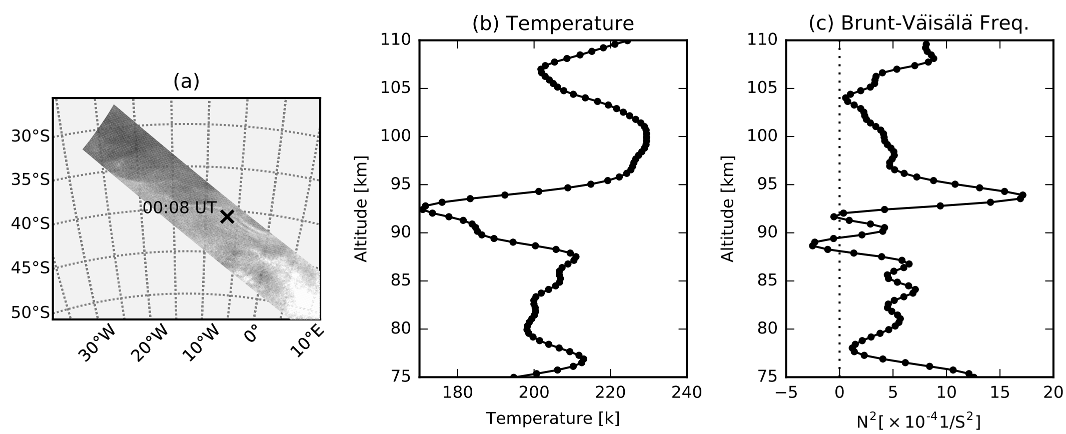

Figure 4. SABER measurements obtained 3 hours after the bore event #2 on 8 May 2013. The figure format is same as Figure 2. (b) and (c) indicate a large 60 K temperature inversion and a corresponding stable layer at 93–100 km altitude.

the SSE (bright) side of the wave front, thus, the bright front is expected to propagate NNE-ward. The wavelength of trailing waves is 50 km.

Figure 4 shows the result of SABER measurement 3 hours after the VISI observation. The measurement was made at (25ºE, 40ºS) for 95 km altitude at 23:10 UT on 7 May 2013. A large 60 K temperature inversion layer is recognized at 93–100 km altitude. Figure 2c indicates the existence of corresponding stable layer at 93–97 km favorable for ducting mesospheric bore. Therefore, as same as event #1, the mesospheric bore of event #2 seems to be ducted in a stable region induced by a temperature inversion.

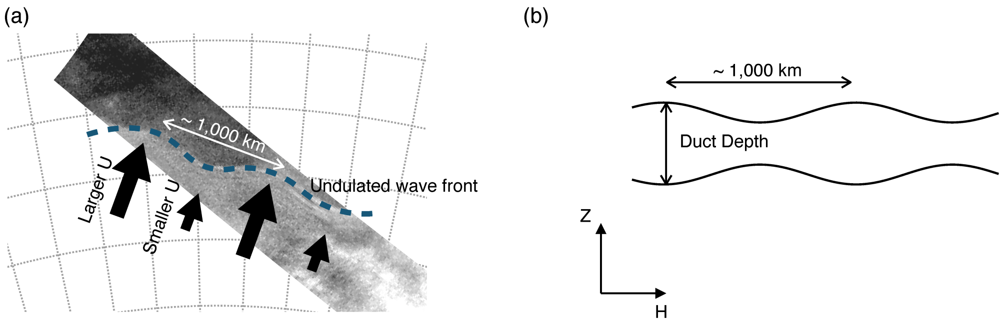

Figure 5. (a) Possible interpretation of the modulating wave front. (b) Schematic picture of a proposed modulating duct structure.

In this event, VISI captured a very large spatial extent of mesospheric bore exceeding 2,200 km. The result indicates that the ducting region due to a mesospheric inversion layer has similar or larger spatial extent. Smith et al. (2003) reported a mesospheric bore propagating for 1,000 km and a concurrent measurement of an inversion layer at a separated observation site, and showed that inversion layers with horizontal scale-sizes of 1,000–1,500 km can exist. Suzuki et al. (2013) demonstrated that ducting gravity wave can propagate over 1,800 km at mesopause height by using a network of ground-based imagers. These previous studies showed the horizontal extents along the propagating direction of waves. Our result shows that the horizontal extents perpendicular to the propagating direction can be also large as it exceeds 2,200 km.

While a curved or bent wave front of mesospheric bore has been reported (Brown et al., 2004; Smith et al., 2017), to our knowledge, an undulating wave front of mesospheric bore has never been reported. The undulating wave front seen in Figure 3 is a new feature of mesospheric bore that was revealed by the wide FOV of space-borne imaging. A possible explanation of the undulated wave front is non-uniform bore speed along the wave front. As illustrated in Figure 5a, periodically modulating propagating speed can make an undulating wave front. According to equation (1), propagating speed of bore is dependent on the depth of the ducting layer ($U \propto \sqrt{\text{duct depth}}$) and surrounded temperature structure (via g'). Therefore, a spatial inhomogeneity in the ducting structure, such as duct depth or thermal structure, can cause an inhomogeneity of bore speed in space. Figure 5b shows schematic picture of possible modulating duct structure. For example, a gravity wave whose vertical wavelength is about duct depth, and horizontal wavelength is 1,000 km can make a such a modulation of duct depth. Since bore speed is proportional to the square root of duct depth, larger bore speed is expected where duct depth is large, and smaller bore speed is expected where duct depth is small. Thus, if there is a modulating duct as shown in Figure 5b, it can yield non-uniform bore speed, and resultant modulating wave front.

Sometimes a source location of disturbance is estimated from a curvature of wave front in airglow with an assumption that the disturbance propagates radially from its source (Suzuki et al., 2007; Smith et al., 2017). An implication from the discussion of the undulated wave front is that such a method for source identification using a curvature of wave front would be misleading in case the bore speed is non-uniform.

4 Summary

Two mesospheric bore events observed by VISI were reported. For event #1, the temporal evolution of bore was estimated from two consecutive VISI observations. Estimated bore parameters, such as phase speed, wavelength of trailing waves, and wave adding rate, were consistent with previous studies. It is a proof of VISI validity in the bore observations. This event provided information on the temporal evolution of the azimuth angle of bore front in the southern mid-latitude, where few previous studies were reported. The bore was rotated anti-clockwise with a speed of 20º/hour, while past studies reported clockwise rotating bore in the northern mid-latitude. The rotating directions are consistent with upward propagating tide suggesting that the bore was affected by tidal backward tidal wind variation. From event #2, with the benefit of the wide FOV of VISI, we found that 1), wave front of mesospheric bore can be long as it exceeds 2,200 km, 2), wave front of mesospheric bore is not always straight or simply curved in a large-scale view, it can periodically undulate. The undulating wave front of bore suggests that the bore speed in the duct is not uniform in space. The space-borne imaging has a wide FOV and global observation coverage, and it can be utilized to study mesospheric bore in synoptic scale. As a future work, we plan to conduct a statistical study on the global characteristic of mesospheric bore with VISI data.

Data availability. ISS-IMAP/VISI data are available via e-mail inquiry to Akinori Saito at Kyoto University (saitoua@kugi.kyoto-u.ac.jp). TIMED/SABER v2.0 level 2A data were downloaded from http://saber.gats-inc.com.

Competing interests. The authors declare that they have no conflict of interest.

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