Near InfraRed Imaging Spectrograph (NIRIS) for ground-based mesospheric OH(6-2) and O₂(0-1) intensity and temperature measurements

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This paper describes the development of a new Near InfraRed Imaging Spectrograph (NIRIS) which is capable of simultaneous measurements of OH(6-2) Meinel and O₂(0-1) atmospheric band nightglow emission intensities. In this spectrographic technique, rotational line ratios are obtained to derive temperatures corresponding to the emission altitudes of 87 and 94 km. NIRIS has been commissioned for continuous operation from optical aeronomy observatory, Gurushikhar, Mount Abu (24.6°N, 72.8°E) since January 2013. NIRIS uses a diffraction grating of 1200 lines mm⁻¹ and 1024×1024 pixels thermoelectrically cooled CCD camera and has a large field-of-view (FOV) of 80° along the slit orientation. The data analysis methodology adopted for the derivation of mesospheric temperatures is also described in detail. The observed NIRIS temperatures show good correspondence with satellite (SABER) derived temperatures and exhibit both tidal and gravity waves (GW) like features. From the time taken for phase propagation in the emission intensities between these two altitudes, vertical phase speed of gravity waves, c_z , is calculated and along with the coherent GW time period ' τ ', the vertical wavelength, λ_z , is obtained. Using large FOV observations from NIRIS, the meridional wavelengths, λ_y , are also calculated. We have used one year of data to study the possible cause(s) for the occurrences of mesospheric temperature inversions (MTIs). From the statistics obtained for 234 nights, it appears that *in situ* chemical heating is mainly responsible for the observed MTIs than the vertical propagation of the waves. Thus, this paper describes a novel near infrared imaging spectrograph, its working principle, data analysis method for deriving OH and O₂ emission intensities and the corresponding rotational temperatures at these altitudes, derivation of gravity wave parameters (τ , c_z , λ_z , and λ_y), and results on the statistical study of MTIs that exist in the earth's mesospheric altitudes.

Keywords. Near Infrared Imaging Spectrograph (NIRIS); nightglow emissions; mesospheric temperatures; mesospheric dynamics; gravity wave characteristics; mesospheric inversion layers; mesospheric temperature inversions.

1. Introduction

Airglow intensity and temperature variations in time and space have been used to understand

the complex upper atmospheric dynamics at their altitudes of emissions. It is now understood that the waves of different scales, such as planetary waves, tides, and gravity waves play an important

role in the transfer of energy and momentum between various atmospheric layers and thereby modulate density and temperature while passing through the airglow emitting altitudes (e.g., [Krassovsky and Shefov 1965](#); [Hines 1974](#)). Various observations and models over the years have provided some information on the gravity waves; however, their effects at mesospheric altitudes over low-latitudes is yet to be understood comprehensively. Here, we present a new in-house built instrument (Near InfraRed Imaging Spectrograph (NIRIS)), the results on the behaviour of OH(6-2) and O₂(0-1) intensities, and the corresponding temperatures obtained by it from the optical aeronomy observatory, Gurushikhar, Mount Abu (24.6°N, 72.8°E), in India. The OH and O₂(0-1) emission layers are normally located at altitudes of around 87 ([Baker and Stair 1988](#)) and 94 km ([Murtagh et al. 1990](#)). Hence, simultaneous measurements of variations in these two emissions provide an opportunity to investigate the wave features corresponding to vertical propagation of gravity waves.

Mesospheric OH and O₂ rotational temperature measurements using spectral line ratios is a well-established technique (e.g., [Meriwether 1984](#); [Greet et al. 1998](#); [Taylor et al. 1999](#); [French et al. 2000](#); [Bittner et al. 2002](#); [Taori et al. 2005](#); [Shiokawa et al. 2007](#)). We have used this method to derive the mesospheric temperatures as discussed in the following sections. NIRIS is a large field-of-view imaging spectrograph which is sensitive to fluctuation in intensities of less than around 2% for a 5 min integration time. Due to high spectral resolution (around 0.78 nm) and large spectral coverage, rotational temperatures from the OH(6-2) Meinel and O₂(0-1) atmospheric band emissions can be derived simultaneously. Using photometric techniques (e.g., [Taylor et al. 1999](#); [Taori et al. 2011](#)), temperature measurements have been carried out in which interference filters of different wavelengths are used in sequence to obtain the emission intensities of the desired rotational lines. In such methods, it is required that the filter bandwidths be narrow in order to discretely obtain the intensities of the two rotational lines. However, as the transmission from neighbouring spectral regions through such filters is non-zero, it might not be possible to avoid contamination of contribution from the neighbouring lines. This could contribute to over- or under-estimation of the mesospheric temperatures. In the spectrographic technique (NIRIS) described in this paper, however, as the spectral resolution is high it is possible to obtain not

only uncontaminated intensities from the desired rotational lines discretely, but also information on the background contribution from the night sky around these wavelengths of interest. Therefore, background subtraction is enabled before proceeding further for obtaining ratios of rotational line intensities by this technique and so it reduces the errors in the measurement of intensities and temperatures.

Owing to these capabilities of NIRIS, it has been possible to investigate the mesospheric wave dynamics during a tropical cyclonic event, Nilofar, which occurred in the western Indian coast during 25–31 October, 2014 ([Singh and Pallamraju 2016](#)). Further, high data cadence long term observation from NIRIS provides an opportunity to not only study both the large- and small-scale fluctuations in the O₂ and OH emission intensities and corresponding temperatures, but also to investigate statistical study of the GW characteristics in the mesosphere. Recently, using long term NIRIS data it was shown that both O₂ and OH intensities show variations similar to those of sunspot numbers indicating a strong solar influence on these mesospheric emissions along with the characteristic atmospheric semi-annual and annual variations ([Singh and Pallamraju 2017](#)).

Using NIRIS measured nocturnal intensity and temperature variations, wave period (τ) can be calculated and if this wave has propagated up to the O₂ emission altitude, its vertical wavelength (λ_z) can also be estimated with the knowledge of the phase delay in the fluctuations in intensities and temperatures at these two emission altitudes. Due to the imaging property of NIRIS, the meridional (λ_y) or zonal (λ_x) wavelength of the gravity waves can be estimated depending on the orientation of the instrument. In this paper, we will present the technical details of the instrument, data analysis methodology, and sample results on its capabilities in obtaining the characteristics of GW-induced fluctuations at the mesospheric altitudes. Such capability enabled us to ascertain the possible reasons for the phenomena of mesospheric temperature inversions, results from which are also described in this paper.

2. Instrumentation

NIRIS was designed and developed for the measurement of mesospheric nightglow emission intensities and corresponding rotational temperatures

using OH(6-2) vibrational and O₂(0-1) atmospheric band spectra. NIRIS is a high spectral and spatial resolution spectrograph which uses 1200 lines mm⁻¹ grating as the dispersing element and has a spectral resolution of 0.78 at 840 nm wavelength. A variant of NIRIS was used to derive daytime wave characteristics in the mesosphere lower thermosphere (MLT) region wherein ultra-violet measurements of OI 297.2 nm dayglow emission have

been obtained on-board a balloon in an earlier experiment (Pallamraju *et al.* 2014). The optical layout of NIRIS along with its photograph is shown in figure 1(a and b). The convex spherical primary mirror with 20 mm radius of curvature (labelled 1 in the figure) reflects the incident beam of light onto a concave spherical secondary mirror (2) which has a focal length of 600 mm. This secondary mirror focusses the light from a large FOV

Figure 1. (a) Optical layout of Near Infrared Imaging Spectrograph (NIRIS). Different components used in NIRIS are numbered, the details of which are given in table 1. (b) Photograph of NIRIS on a mounting platform at the time of installation for the field operations.

Table 1. Characteristics of Near Infrared Imaging Spectrograph (NIRIS).

1. Primary mirror	Convex; $R = 20$ mm
2. Secondary mirror	Concave; $f = 600$ mm, diameter = 150 mm
3. Slit	$45 \text{ mm} \times 1 \text{ mm}$
4. Collimator	Off-axis paraboloid; $f = 600$ mm, diameter = 130 mm
5. Diffraction grating	Plane; $120 \text{ mm} \times 100 \text{ mm}$; 1200 lines mm^{-1}
6. Converging optics	Schmidt telescope; $f = 139$ mm, diameter = 100 mm
7. CCD Detector	1024×1024 pixels deep depleted; $13 \mu\text{m}$ pixel size, QE at 840 nm = 90% Resolution = 0.78 nm at 840 nm wavelength.

($\sim 80^\circ$) onto the slit of a size of $45 \text{ mm} \times 1 \text{ mm}$ (3). A 600 mm focal length off-axis paraboloid (4) is used as a collimator which makes the reflected beam parallel and is allowed to fall onto a 1200 lines mm^{-1} reflection grating (5). The diffracted light from the grating is focussed by a Schmidt telescope (6) which has a focal length of 139 mm onto a charge-coupled device (CCD) detector (7). The 1024×1024 pixels deep depleted CCD detector used has a square pixel of size $13 \mu\text{m}$ and high quantum efficiency (more than 80% in the wavelength range 800–900 nm). The details of the optical components used in NIRIS are provided in table 1. NIRIS has been commissioned at the Optical Astronomy Observatory in Gurushikhar, Mount Abu (24.6°N , 72.8°E), in India and is in operation in an automated mode since January 2013. The slit of NIRIS is oriented along north–south meridian which yields around $150 \text{ km} \times 3 \text{ km}$ coverage of the sky at the height of O_2 emission layer ($\sim 94 \text{ km}$). NIRIS obtains several spectral images on each night at pre-defined camera settings such as, exposure time, on-chip binning, and CCD temperature which are enabled through in-house developed software. Each spectral image is subjected to a quality check and those images which suffer from glare due to stray light or moonlight are removed from further analysis. Therefore, the available duration of the data is greater during the two weeks centered on the new moon phase as compared to other times. The data cadence of NIRIS is 5 min.

Wavelength calibration of NIRIS has been performed in the laboratory using Argon spectral lamp (Newport model: 6030) as the source and a spectral image thus obtained is shown in figure 2(a). The x- and y-axes of figure 2(a and c) correspond to the wavelength and spatial directions, respectively. The spectral lines in figure 2(b) are obtained by taking a cut across the spectral image as shown in figure 2(a). Some of the strong ArI emission lines which have been used for the spectral calibration of the instrument are shown in this figure. The

dispersion achieved by NIRIS is $0.07 \text{ nm pixel}^{-1}$ in the wavelength range of 823–894 nm. The raw spectra obtained from NIRIS cannot be used directly as they are convolved with many effects, such as, incidences of cosmic rays, image curvature, vignetting, etc., which need to be corrected before further analysis. Each of the spectral images are passed through a sigma filter to remove the contribution of the noise that arises from the hot pixels caused by the incident cosmic rays, if any, onto the CCD detector. The sigma filter used here replaces pixels with intensities more than a specified level from its neighbours. The CCD uses thermoelectric air cooling technique which provides a typical sensor temperature of around -80°C . Even though the dark current generated at such low temperatures is very small, we do subtract this background. In order to do that, a dark frame is generated for every individual image by considering a portion of the image that is not illuminated by the incoming light. This dark frame is then subtracted from every spectral image to remove the contribution of dark current in it. Later, the images are corrected for flat-field in which the effects on the images caused by pixel-to-pixel variability across the chip, vignetting, and features on the optical components, if any, are removed. For large FOV optical instruments, it is a challenge to provide a Lambertian surface for equal intensity illumination across the field. However, diffused skylight during twilight is considered as a close approximation for this purpose (e.g., [Garcia et al. 1997](#)) and has been implemented in this work.

As this method involves taking ratios of intensities, it is important that the vignetting effect of transmission from one spectral region to the other be taken care of. This is achieved by using a non-spectral white light output from a low light level integrating sphere (Gooch and Housgo model: OL 426). The curvature effect in spectral lines arises due to the differences in the angles of the rays between the center of the

Figure 2. (a) NIRIS obtained spectral image using Argon lamp as the source. (b) Brightness of ArI spectral lines of the image shown in figure 2(a) which are represented in arbitrary units (AU). These show the emission lines at 826.5, 842.5, 852.1 and 866.8 nm which are used for wavelength calibration of the spectrum obtained from NIRIS. (c) A nocturnal spectral image obtained by NIRIS in which OH(6-2), O₂(0-1), and OH(7-3) bands are identified based on the wavelength calibration of the instrument. The x and y axes represent spectral and spatial coverage of NIRIS. (d) Spectral lines are obtained by taking a cut across the spectral image of figure 2(c). Three rotational lines of OH(6-2) band namely, P₁(2) at 840.0 nm, P₁(4) at 846.5 nm, and P₁(5) at 850.5 nm, respectively, are identified which are used for the OH rotational temperature derivation. Two regions of O₂(0-1) atmospheric band centered at 866.0 and 868.0 nm are also identified which are used for the determination of O₂ rotational temperatures.

slit and those coming from locations away from the slit onto the grating facet. This curvature effect in the image is removed by spline fitting of data at three locations along each spectral line. A typical nocturnal spectral image obtained by

NIRIS for a 5-min exposure and for an on-chip binning of 1×32 is shown in figure 2(c) which has been accomplished after performing all the treatments described above. The Meinel OH(6-2), OH(7-3), and O₂(0-1) atmospheric bands are identified

based on the wavelength calibration. For the determination of nightglow emission wavelengths, calibration of the spectra was carried out using 12 known spectral lines located within the spectral region of 823–894 nm. The spectral scale for each of the spectra is obtained by comparing the line positions with the identified lines by using a 3rd-order polynomial fit. So, also for the background level which is determined by fitting a 3rd-order polynomial fit at 12 identified regions where there are no airglow emissions in the wavelength range of 823–894 nm.

Owing to the imaging property of NIRIS, the vertical axis in figure 2(c) corresponds to different spatial locations in the sky along the slit orientation. The angle calibration of NIRIS has been carried out after mounting it for field operations. This is done by allowing diffused day light to fall onto the CCD chip only through a small portion along the slit orientation (by fully covering the light from other directions). For the next image, the light is allowed only through another small portion along the slit orientation. Using several of such images, the angular coverage of each pixel has been obtained. It is found that the 80° of the sky in N–S direction is imaged onto 15 vertical pixels from pixel number 8 to 22 onto the CCD chip for the 1×32 on-chip binning. After performing the wavelength calibration and removing background contribution as discussed above, the brightness of the resulting emission lines over zenith are obtained and are shown in figure 2(d) which corresponds to the spectral image shown in figure 2(c). In figure 2(d), centers of emissions at five different wavelengths that are used in this study are marked by I_1 – I_5 . These marked spectra show different regions of Meinel (6-2) and O_2 (0-1) atmospheric bands that have been used for the determination of OH and O_2 emission intensities and derivation of corresponding rotational temperatures. These emission intensities are determined by integrating the photons obtained over 1.2 nm centered at each of the spectral line.

3. Mesospheric temperature determination

The hydroxyl airglow band is formed by vibrational–rotational transitions between two levels of OH and was first identified by Meinel (1950). The production of OH^* ($v' \leq 9$) at around the mesopause altitudes is due to interaction of atomic hydrogen with ozone: $H + O_3 \rightarrow OH^*(v' \leq 9) + O_2 + 3.3 \text{ eV}$. This reaction is the main cause for the

destruction of ozone at night near the mesopause and the energy released is sufficient to excite the ground state OH to ninth vibrational state (Bates and Nicolet 1950). The hydroxyl emission layer is centered at $86.8 \pm 2.6 \text{ km}$ with a thickness of $8.6 \pm 3.1 \text{ km}$ (Baker and Stair 1988). The derivation of O_2 and OH rotational temperatures through the spectral line ratio method assumes that the underlying gas is in local thermodynamic equilibrium (LTE) (Meriwether 1984). The degree of thermalization depends upon the radiative lifetime of the excited OH^* molecule and the neutral collision frequency. For OH, the radiative lifetimes for vibrational states of $v = 9, 6$, and 1 are 3.62, 6.2, and 44 milliseconds, respectively (Turnbull and Lowe 1989). At 87 km altitude (for $T \sim 200 \text{ K}$ and $P \sim 3 \times 10^{-4} \text{ kPa}$), the neutral collision frequency is $\sim 3 \times 10^4 \text{ s}^{-1}$. Therefore, depending on the vibrational state to which the OH molecule is excited, it would undergo around 110–1320 number of collisions prior to radiative de-excitation, which are large enough to achieve thermalization. Therefore, population of the OH rotational states can be assumed to obey Boltzmann distribution and therefore the rotational temperatures determined by this spectrographic method can be taken to represent the ambient temperature of the region. Thus, the intensities of two OH lines from different rotational states of a single vibrational band are compared using the following equation (Mies 1974; Meriwether 1984) for estimating rotational temperatures:

$$T_{\text{rot}} = \frac{\frac{hc}{k} * [(F_{v'}(J_2) - (F_{v'}(J_1))]}{\ln \left[\frac{I_1(2J_2+1)A_2}{I_2(2J_1+1)A_1} \right]} \quad (1)$$

where $F(J_1)$ and $F(J_2)$ are the energy levels of the initial rotational states; I_1 and I_2 are the emission intensities of the OH lines from different upper states; A_1 and A_2 are the transition probabilities; J_1 and J_2 are the upper state total angular momentum quantum numbers. The OH(6-2) band $P_1(2)$, $P_1(4)$, and $P_1(5)$ rotational lines centered at 840.0, 846.5, and 850.5 nm, respectively, are used for the derivation of OH rotational temperatures. The values of Einstein coefficients A 's are taken from Mies (1974) and those of $F(J)$'s from Coxon and Foster (1982). The rotational temperatures are calculated by taking two sets of rotational lines of OH(6-2) band emission. After putting in the theoretical constants for $P_1(2)$ and $P_1(4)$ lines in equation (1), we get:

$$T(\text{OH1}) = \frac{228.59}{\ln [2.609 (I_1/I_2)]} \text{K}. \quad (2)$$

Similarly, after putting in the theoretical constants for $P_1(2)$ and $P_1(5)$ lines in equation (1), we get:

$$T(\text{OH2}) = \frac{401.10}{\ln [3.388 (I_1/I_3)]} \text{K}, \quad (3)$$

where I_1 is the intensity of $P_1(2)$ line at 840.0 nm, I_2 is the intensity of $P_1(4)$ line at 846.5 nm, and I_3 is the intensity of $P_1(5)$ line at 850.5 nm wavelengths, which are obtained by integrating the emissions over 1.2 nm wide window centered at each of the spectral lines mentioned above.

The O_2 atmospheric band emission is a two-step process with a three-body collision (Barth mechanism) required to place the O_2 in an excited state (e.g., Torr *et al.* 1985):

The atmospheric O_2 band emission results from de-excitation of the $\text{O}_2(b^1\Sigma_g^+)$ state

To calculate the temperature using $\text{O}_2(0-1)$ atmospheric band, similar procedure was applied in which we have considered PP and PQ pairs of rotational lines for $K''=7$ and $K''=15$ centered at 866.0 and 868.0 nm wavelengths, respectively. The spectroscopic constants and values of line strengths are taken from Schlapp (1937). The rotational temperature using $\text{O}_2(0-1)$ atmospheric band is given by the following equation:

$$T(\text{O}_2) = [(248.88 * (I_5/I_4)) + 77.7] \text{K}, \quad (7)$$

where I_4 and I_5 are the intensities of the $\text{O}_2(0-1)$ atmospheric band PP and PQ pairs of rotational lines obtained by integrating over each spectral line using a 1.2 nm wide window centered at 866.0 and 868.0 nm, respectively (figure 2d).

4. Results and discussions

NIRIS derived OH and O_2 nightglow emission intensities are calculated by taking averages of I_1 and I_2 and I_4 and I_5 , respectively. The variations in intensities over zenith for two representative nights of 16 April and 04 May 2013 are

shown in figure 3(a and c) along with the uncertainties in the measurements. On the night of 16 April 2013, the OH and O_2 intensities show out-of-phase variations from 19.5 (19:30 LT) to 25.5 hrs (01:30 LT) and in-phase variation after that time until 28.6 hrs (04:36 hrs). Whereas, on the night of 4 May, 2013, no such relationship was observed except for initial couple of hours when out-of-phase variations were seen. Although OH and O_2 intensities on these two nights show both in-phase and out-of-phase variations with time, it is not necessary that the phase differences should always be either 0 or 180 degrees. Such kind of variations in mesospheric airglow intensities are common and are due to the gravity wave effects. The temperatures corresponding to an altitude of 87 km are derived by considering two different rotational line ratios which have been calculated using equations (2 and 3). For OH band emissions they are shown for two line ratios $T(\text{OH1})$ and $T(\text{OH2})$ (blue and green colored lines) for these two nights in figure 3(b and d). The temperatures from O_2 emissions, $T(\text{O}_2)$, corresponding to an altitude of 94 km are calculated by using equation (7) and are also shown (magenta coloured lines) for these two nights in figure 3(b and d). The estimated uncertainty in the NIRIS derived mesospheric temperatures is approximately ± 3 K. The nocturnal mean values of $T(\text{OH1})$, $T(\text{OH2})$, and $T(\text{O}_2)$ are 194, 202, and 196 K, for the night of 16 April, 2013 and are 193, 201, and 194 K for the night of 4 May, 2013, respectively. These are shown along with their standard deviations by square boxes (towards the left in each plot). As can be clearly seen, variations in $T(\text{OH1})$ and $T(\text{OH2})$ are quite similar for both the nights and the nightly mean values are within the one-sigma variation. This is an added advantage in the spectroscopic technique over the photometric ones in which simultaneous derivation of mesospheric temperatures can be achieved by using different sets of rotational lines without any need to change the filters and hence can also be used to cross-verify the accuracy of the temperature values arrived at. This also yields a better temporal cadence as there is no movement of filters (on-band and off-band).

Unlike the OH and O_2 emission intensities, the mesospheric temperatures, $T(\text{OH1})$, $T(\text{OH2})$, and $T(\text{O}_2)$, derived for the night of 16 April, 2013 show out-of-phase variations for initial couple of hours and are in-phase for most of the time later. However, on the night of 4 May, 2013, no such distinct phase relationship has been noted

Figure 3. **(a)** Nocturnal variations in O_2 and OH intensities, and **(b)** their corresponding rotational temperatures on the night of 16 April, 2013 in which the O_2 and OH intensities showed both in-phase and out-of-phase variations. **(c and d)** Similar to figure 3(a and b), but on the night of 4 May, 2013. It may be noted that O_2 and OH intensities do not show any phase relationship on this night.

in the temperatures. Therefore, nightglow emission intensities seem to be more sensitive to the fluctuations caused by the gravity wave propagations in comparison to the temperatures since the density fluctuations at these altitudes due to any perturbation in the medium are reflected in the intensities almost instantaneously.

4.1 SABER and NIRIS temperatures

NIRIS derived mesospheric temperatures have been compared with independent satellite based observations. For that we have considered Level 2A data from the Sounding of the Atmosphere using Broadband Emission Radiometry (SABER) on-board Thermosphere, Ionosphere, Mesosphere Energetics and Dynamics (TIMED) satellite. SABER provides temperature profile with an estimated uncertainty of around ± 4 K in the altitude range of 80–100 km (Mertens *et al.* 2001). Figure 4 shows the vertical profile of SABER derived temperatures which is averaged over those obtained in the latitude and longitude range of 21.6° – 27.6° N and 69.8° – 75.8° E for the night of 4 May, 2013. The NIRIS derived

mesospheric temperatures, $T(O_2)$ and $T(OH1)$, for the same night are also shown at their representative altitudes. The NIRIS data show large range in temperatures, wherein $T(O_2)$ and $T(OH1)$ vary from 179 to 223 and 173 to 211 K with mean values of 193.5 and 193.4 K on this night. The large nocturnal variations in the NIRIS derived temperatures are due to mesospheric dynamics due to GW propagations which are captured due to high temporal resolution. On the other hand, the satellite-based observations have poor temporal resolution but carry information on spatial variations of a given parameter. Nevertheless, the temperature values from SABER (figure 4) corresponding to the observational station compare well with those of NIRIS observations. The combinations of ground- and satellite-based observations, thus, present complementary information on spatio-temporal variations in temperatures and provide an opportunity to study global phenomena. An example of such an investigation has been reported in an earlier study (Singh and Pallamraju 2015) wherein mesospheric temperature enhancement over low-latitudes has been shown to be

Figure 4. Vertical profile of SABER derived temperatures obtained by averaging over $\pm 3^\circ$ latitude and longitude of the observational station for the night of 4 May, 2013. The NIRIS derived temperatures for the same night are also shown at the respective altitudes which show large range in the nocturnal temperature variability at both the altitudes which are due to mesospheric dynamical variations.

developed as a consequence of sudden stratospheric warming events over high-latitudes.

4.2 Wave characteristics using NIRIS data

The derivation of various elements of mesospheric GW characteristics from O_2 and OH emission intensity variations are demonstrated for two representative nights of observations on 16 April, 2013 and 4 May, 2013. These nights have been chosen because they showed vertical propagation of GW across these two altitudes. In the following sections, details of the methodology adopted to derive these wave parameters will be described.

4.2.1 Derivation of wave period (τ)

The large nocturnal variability in the NIRIS derived mesospheric intensities and corresponding temperatures show short period oscillations embedded in it (figure 3). It is owing to high data cadence ground-based observations from NIRIS that these features could be obtained. As indicated before,

the data cadence of NIRIS is 5 min and the duration of data available on this night is around 9 hrs (19:30 LT in the evening to 04:40 LT on the following morning). Therefore, it is possible to derive the periods between 10 min and 9 hrs on these two nights. In general, the minimum frequency (maximum period) is given by total observational duration. However, we have put a more rigorous constraint in deriving the maximum periods in which we have considered that the data should contain at least two cycles. In order to obtain the periodicities that are smaller than half of the observational duration, residuals have been obtained by subtracting 4.5-hr running average from the original data. The residuals so obtained are represented in the form of zero mean unit variances which were calculated by subtracting the mean value from the residuals and then dividing them by their standard deviation. This process normalizes the relative power in each period in a given dataset and thereby inter-comparison can be made on the parameters on different nights (Pallamraju *et al.* 2010). The residuals thus obtained for O_2 and OH intensities, $I(O_2)$ and $I(OH)$, are shown in figure 5(a, b) and 5(d, e) for the nights of 16 April, 2013 and 4 May, 2013, respectively. The black dotted lines shown in these four subplots are six point (30 min) smoothing of the respective residuals. These residuals have been subjected to spectral analyses which provide information on the GW periodicities that are smaller than 4.5-hr duration in the data. To investigate the periodicities of fluctuations present in $I(O_2)$ and $I(OH)$, we have used Lomb-Scargle periodogram analysis (Lomb 1976; Scargle 1982). The result of this analysis is shown in figure 5(c and f) for these nights in which the dashed curves are the Red noise calculated using REDFIT (Schulz and Mudelsee 2002) with 95% false alarm limit (FAL). Statistically significant coherent periodicities (greater than FAL) of 1.85 and 1.8 hrs can be clearly seen in O_2 and OH nightglow intensities for these nights. In addition to the 1.8-hr period, a 3-hr period is also seen in $I(O_2)$ on the night of 4 May, 2013.

4.2.2 Derivation of vertical phase speed (c_z) and vertical wavelength (λ_z)

Since the residuals of the $I(O_2)$ and $I(OH)$ show a common periodicity and a downward phase propagation in the nightglow emission intensities on both these nights (as can be seen in figure 5(a and b) and (d and e)), it is apparent that the GW propagated

Figure 5. (a and b) Residuals obtained by subtracting the 4.5-hr running averaged data from the original nightglow intensities for both O₂ and OH emissions as shown in figure 3(a) and are represented by zero mean and unit variances on the night of 16 April, 2013. (c) Lomb–Scargle periodograms of these residuals showing 1.85 hrs common period in both the intensities that are greater than 95% false alarm level (FAL). As can be seen the phase is propagating downwards indicating an upwards propagation of gravity wave. (d and e) Similar to that in figure 5(a and b), but for another night (4 May, 2013) which also showed vertical propagation of gravity wave. (f) Lomb–Scargle periodograms of the residuals shown in figure 5(d and e) which showed 1.8 hrs common period in both the intensities which are above 95% FAL.

upwards (Hines 1960). These downward phase propagations seen in the residuals of the nightglow intensities are highlighted by green dashed lines in figure 5. By using cross correlation analysis between residuals of O₂ and OH intensities seen in figure 5, we have calculated the phase offset times (Δt) which are found to be 0.8 and 0.5 hrs for the nights of 14 April and 4 May, 2013. With the knowledge that the waves show common periodicities in I(O₂) and I(OH) and the time offsets in the residual intensity variations (Δt), the vertical phase speed, c_z , and vertical wavelength, λ_z , can be calculated using the following relations:

$$c_z = \frac{\Delta z}{\Delta t} \quad \text{and} \quad \lambda_z = \frac{\tau \cdot \Delta z}{\Delta t}, \quad (8)$$

where Δz is the difference between the heights O₂ and OH emission layers (7 km). Thus, using Δt and τ obtained experimentally as discussed above, the vertical phase speeds (c_z) are calculated to be 2.3 and 3.9 ms⁻¹ on these nights. The vertical wavelengths (λ_z) calculated using equation (8) is found to be 15.6 and 25.2 km for these nights. It is important to note that the derivation of vertical

wavelength can be done only if the GW period ' τ ' is coherent at both the altitudes and the wave shows vertical propagation (downward phase propagation). No coherency observed in τ is an indication that the GWs at these two altitudes could be of different origin.

4.2.3 Derivation of meridional wavelength (λ_y)

As mentioned above, NIRIS has a large FOV of 80° and is presently being operated in north–south orientation. To increase the signal collection 1×32 on-chip binning has been carried out. The on-chip binning reduces the time taken to read-out the image thereby increasing the data cadence. A sample image so obtained is shown in figure 2(c), in which the vertical axis represents the spatial coverage of the sky. Therefore, by using the airglow intensity variability from different directions along the meridian being imaged by NIRIS, it is possible to derive the neutral scale sizes in the meridional direction (λ_y). By operating NIRIS in the east–west orientation, it is possible to obtain neutral scale sizes in the zonal direction (λ_x). At the O₂ and OH emission altitudes (94 km and 87 km), the spatial

Figure 6. (a and c) Variations in the O_2 and OH intensities along N-S meridian throughout the night of 4 May, 2013 are shown. In both the figures, the scales shown on the vertical axis is for the bottom-most intensity variations and the subsequent plots are shifted by 0.15 arbitrary units. The GW meridional scale lengths along the north-south meridian are obtained by carrying out Lomb-Scargle analysis between direction and intensity variations for each observation obtained at a cadence of 5 minutes. (b and d) Statistically significant horizontal wavelengths are shown for O_2 and OH intensity variation throughout the night. A common 40–50 km horizontal wavelength is observed at both altitudes for most of the duration on this night.

extent being covered by NIRIS is 155 and 145 km. Since a total of 15 pixels on the CCD (for 1×32 binning) cover 80° of the sky in the y-direction, the meridional scale sizes which are discernible at O_2 and OH emission altitudes are 20.6–155 and 19.4–145 km. Meridional variations of O_2 and OH emission intensities for every individual observation (5 min cadence) throughout the night are shown in figure 6(a and c) for the night of 4 May, 2013. Here, the vertical scale is for the bottom-most intensity variation and the subsequent plots are shifted by 0.15 arbitrary units (AU) for a better visualization. The start and end times of the observations (19.5 hrs (19:30 LT) and 28.5 hrs (04:30 LT of 5 May)) are marked in figure 6. The horizontal axes in figure 6(a and c) show the meridional coverage (from south to north) at the respective emission altitudes and the dashed vertical lines indicate the position of zenith. The large scale structures in the

spatial intensity variations are evident throughout the night in both O_2 and OH intensities. Wave number spectral analyses on these spatial intensity variations thus provide information on the GW scale sizes along the north-south meridian (λ_y). Using Lomb-Scargle analysis statistically significant horizontal wavelengths are obtained which are above 90% FAL for every observation throughout the night. Nocturnal variations in λ_y for the night of 4 May, 2013 obtained from O_2 and OH intensities are shown in figure 6(b and d). It can be noted that the meridional wavelengths, λ_y , of larger scale sizes (90 and 110 km) are present only at the OH emission altitudes in comparison with the 60–80 km meridional scale sizes observed at O_2 emission altitudes. The scale sizes of 30–50 km are more in number at O_2 emission altitudes as compared to the OH emission altitudes. The observation of larger scale sizes at the OH emission

altitudes as compared to the O₂ emission altitudes seem most probably to be a signature of gravity wave breaking just above OH emission altitude.

4.3 Schematic of the wave propagation

Figure 7(a) shows the schematic of a propagating gravity wave of horizontal wavelength, λ_h , and vertical wavelength, λ_z . Here, the wave fronts of both crests and troughs are shown as filled and open loops (ellipses). The phase can be seen to be progressing downwards as it is the case for upward propagating wave (Hines 1960). The magenta and blue coloured horizontal lines in figure 7(a) represent the altitudes of peak O₂ and OH emissions. The nocturnal variations in O₂ and OH emission intensities as seen in figure 3 for both the nights are also due to convolution of the effect of wave propagation of similar kind as seen in figure 7(a) from lower to higher altitudes. As can be seen in figure 3, these variations in intensities and temperatures can have varying relationship (in-phase, out-of-phase or constant phase) depending on the GW vertical wavelengths and angles of propagation. Figure 7(b, c, and d) shows three representative possibilities. In the first scenario (figure 7b), if the vertical wavelength of the upward propagating wave is such that the crests of the wave overlap with the peak altitudes of emission of O₂ and OH, then, both the intensities show in-phase variations. In this case, the vertical wavelength is equal to the distance between the altitudes of emission. The higher harmonics of this scale size will also give rise to in-phase variations, however, the lower scale sizes will be limited by kinematic viscosity. The second scenario (figure 7c) could be when the crest/trough of the vertical wave falls at OH/O₂ emission altitudes or vice versa, then, both the intensities show out-of-phase variations. Thus, in this case, the vertical wavelength will be equal to twice the difference in the emission altitudes of OH and O₂. In the third scenario (figure 7d), the crest/trough of the waves occur either lower or higher than the peak height of the OH and O₂ emissions. In such cases, there could be in-phase/out-of-phase/constant-phase relationship between these two emissions. Also, depending on the vertical wavelength, angle of propagation, and the speed of propagation the in-phase relationship could change to out-of-phase with time. It should be noted that these three cases are not the only possibilities. There could be different harmonics of the wave that can show similar/dissimilar

variations in the emission intensities at both the altitudes. This schematic is drawn to provide a visualization of the wave dynamical influence at altitudes of emissions so that the results pertaining to the MLT wave dynamics could be understood better.

5. Anomalous increase in O₂ temperatures

From NIRIS observations of around one year it is seen that, in general, T(O₂) is lower than T(OH) which is the average behaviour of the mesospheric temperature structure. This also indicates that the height of mesopause is above that of the O₂ emission layer (~94 km). However, it was also observed that there are several occasions when T(O₂) is greater than T(OH) which can happen if (1) the altitude of mesopause is below that of O₂ emission layer (~94 km) (e.g., Venkat Ratnam *et al.* 2010), (2) mesospheric temperature inversions (MTIs) (e.g., Hauchecorne *et al.* 1987) also known as mesospheric inversion layers (MILs) (e.g., Meriwether and Gardner 2000), and (3) large scale circulation in the MLT region (e.g., Meriwether and Gerrard 2004). One or more of these processes can act in tandem as well to enhance temperature at O₂ emission altitude regions in comparison with that of OH. The mesospheric temperatures inversions are the regions of enhanced temperatures above normal values of temperature. They can have a thickness of several kilometres and appear in MLT region of the low- and mid-latitude at any time of the year (e.g., Meriwether and Gerrard 2004). MTIs/MILs are mainly attributed to energy deposition of upward propagating tides and gravity waves (e.g., Hauchecorne *et al.* 1987; Meriwether and Gardner 2000) and chemical heat released *in-situ* by several exothermic reactions (e.g., Meriwether and Mlynczak 1995; Meriwether and Gardner 2000; Meriwether and Gerrard 2004; Ramesh *et al.* 2013). The mean location of the mesopause over Gadanki (13.5°N, 79.2°E), in the Indian region is around 98 km (varying between 87 and 105 km; Venkat Ratnam *et al.* 2010). That study also found that there is a secondary minimum in the temperature profile at 75–80 km. In between these two regions there is an increase in temperature (inversion) up to 85–90 km which are more prominent during equinoxes (March/April and September/October). These MTIs/MILs show small seasonal variation, but they do show pronounced short-term variations. These satellite-based measurements present

Figure 7. (a) A schematic of the propagation of gravity wave in which the phase is shown to be progressing downwards (upward propagating wave). λ_h and λ_z represent the horizontal and vertical wavelength of the gravity wave. (b–d) Possibilities for the nature of vertical wavelength which can show three different scenarios. Under these scenarios, the nocturnal variations in O₂ and OH intensities can show in-phase, out-of-phase, and random variations.

Figure 8. The difference in $T(O_2)$ and $T(OH)$ on the night of (a) 16 April, 2013 and (b) 6 May, 2013. Temperature inversion on both nights can be noted mainly in the pre-midnight hours.

an average picture of the MLT region but do not describe their dynamics in shorter time scales. In order to understand short-time fluctuation in the MLT temperatures, high data cadence observations are required.

The differences in $T(O_2)$ and $T(OH)$ on the night of 16 April and 6 May, 2013 are shown in figure 8(a and b). It can be seen that the difference in temperatures is positive for around 2.5 hrs after the sunset (19:30 to 22:00 LT) on the night of 16 April, 2013 and for around 3.5 hrs (19:30 to 23:00 LT) on the night of 4 May, 2013. The peak temperature difference observed on these two nights is around 30 K. We have seen vertical propagation of wave on these two nights which is confirmed by the downward phase propagation in the residuals of O₂ and OH emission intensities (figure 5). Hence, the cause for the observed temperature inversions on these nights can be attributed to

upward propagating gravity waves as discussed above.

In order to assess the general behaviour of such temperature inversions in the mesosphere, we have considered all the data obtained in the year 2013 to characterize the different possibilities that exists. Some new developments in terms of mesospheric temperature dynamics have come to light owing to the high cadence simultaneous measurement of $T(O_2)$ and $T(OH)$.

Case 1: Difference between the temperatures at O₂ and OH emission altitudes [$T(O_2) - T(OH)$] is positive and vertical propagation is seen in the O₂ and OH emissions (as shown for the nights of 16/04/2013 and 04/05/2013). The source of such temperature enhancements (MTIs) could be attributed to the vertical propagation of waves.

Figure 9. The five rows in the different subplots represent the differences in $T(\text{O}_2)$ and $T(\text{OH})$, $I(\text{O}_2)$ and $I(\text{OH})$, residuals of O_2 and OH emission intensities, and the periodicities present in the O_2 and OH emission intensities, respectively. These nights are chosen to show three cases (2, 3, and 4). (Column 1) represents Case 2 in which observation on the night of 15/04/2013 is shown and on this night both temperature inversion and vertical propagation are not seen. (Column 2) represents Case 3 in which temperature inversion is not seen but the vertical propagation is observed. (Column 3) represents Case 4 in which temperature inversion is seen but the vertical propagation is not seen. It should be noted that to determine the periodicities that are present at O_2 and OH emission altitudes, we have used the same method as described for generating figure 5.

Case 2: Difference between the temperatures at O_2 and OH emission altitudes [$T(\text{O}_2) - T(\text{OH})$] is negative and vertical propagation not seen in the O_2 and OH emissions (as seen for night of 15/04/2013; figure 9, left column). This would be an ‘unperturbed’ quiet time mesospheric behaviour.

Case 3: Difference between the temperatures at O_2 and OH emission altitudes [$T(\text{O}_2) - T(\text{OH})$] is negative and vertical propagation can be seen in the O_2 and OH emissions (as seen for night of 01/05/2013; figure 9, middle column). Such type of cases would negate the argument (Case 1) of source for observed MTIs to be the vertically propagating gravity waves from below.

Case 4: Difference between the temperatures at O_2 and OH emission altitudes [$T(\text{O}_2) - T(\text{OH})$] is positive and vertical propagation is not seen in the O_2 and OH emissions (as seen for night of 03/05/2013; figure 9, right column). Such behaviour has been considered as a signature of *in-situ* chemical heating as the source for MTIs.

The mesospheric temperatures on two nights of 16/04/2013 and 04/05/2013 discussed in earlier paragraph and shown in figures 3, 5, and 8 represent the behaviour as in Case 1. In figure 9, we have shown the other three cases as defined above in which the nights of 15/04/2013, 01/05/2013, and 03/05/2013 represent the cases 2, 3, and

4, respectively, and are shown in three different columns. The subplots in rows of figure 9 represent the differences in $T(O_2)$ and $T(OH)$, O_2 and OH emission intensities, residuals of O_2 and OH emissions (as obtained by similar method shown in figure 5), and the periodicities in O_2 and OH emissions. As can be seen from figure 9(a), $T(O_2)$ is less than $T(OH)$ for most of the duration which means that no temperature inversion is seen on the night of 15 April, 2013. Also, this night does not show common periods in $I(O_2)$ and $I(OH)$ and hence, no vertical propagation seems to exist. Such scenario describes the quiet time mesospheric behaviour. However, on the night of 01/05/2013, no temperature inversion is seen but this night does show signatures of vertical propagation of GW as they show common wave periodicities of around 1.5 hrs in O_2 and OH emissions and their residual show downward phase propagation. Such observations indicate that vertical propagation in waves need not be responsible for MTIs. The night of 03/05/2013 does show the temperature inversion wherein the difference between the temperatures [$T(O_2) - T(OH)$] is positive for around 3.5 hrs (from 19:30–23:00 LT) with peak value of around 32 K. This night, however, does not show the common periods in O_2 and OH emissions and hence, no vertical propagation of wave seems to exist. Such cases have been interpreted as the signature of chemical heating to be the cause of observed MTI. These different cases shown above indicate that the temperature inversions in the O_2 emission altitude could most probably be either due to the effect of upward propagating waves or due to chemical heating when the vertical propagation is not seen. It is also possible that even when vertical propagation is seen the source of chemical heat might also be operative to form the MTIs.

NIRIS was running on a continuous mode from Gurushikhar throughout the year 2013 wherein a total of 234 nights of observations were possible excluding monsoon and moonlit periods. We have carried out statistical distribution of all four cases defined above. Similar plots as shown in figure 9 were made for all nights of observation in the year of 2013. Out of 234 nights of observations, those nights which belongs to cases 1, 2, 3, and 4 are 17, 154, 23, and 40, respectively. The nights on which the temperature inversion and the vertical propagation both are not seen are maximum in number (Case 2, 65.8%), followed by the nights in which temperature inversion is seen but not the vertical propagation (Case 4, 17.1%). Those nights

in which temperature inversion is not seen, but vertical propagation is seen (Case 3) are around 9.8% followed by those nights in which both temperature inversion and vertical propagation are observed (Case 1, 7.3%). Based on the present statistics it appears that chemical heating in the mesosphere could be a more probable cause for the observed MTIs in comparison to vertical propagation. Moreover, the cases for and against vertical propagation as the cause for MTI are nearly equal (Case 1 and Case 3). Therefore, at this stage it is difficult to ascertain if the excess energy carried upwards to the mesosphere is not deposited there but transported to altitudes higher above. This could explain the absence of MTIs on the night of the existence of vertical propagation. Answers to all these aspects require supporting simulation studies. These will be attempted in the future.

6. Summary and conclusions

Development of a new Near Infrared Imaging Spectrograph (NIRIS) has been discussed which is a major step forward towards passive remote sensing of the mesospheric dynamics. NIRIS provides simultaneous nocturnal spectra of OH(6-2) Meinel and $O_2(0-1)$ atmospheric bands with a resolution of 0.78 nm in the wavelength range of 823–894 nm region. NIRIS has been commissioned at the Optical Aeronomy Observatory, Gurushikhar, Mount Abu (24.6°N, 72.8°E), in India for continuous observations from January 2013. Theory of the determination of mesospheric temperatures using the ratio method from different sets of OH(6-2) rotational lines and $O_2(0-1)$ band spectra has been discussed. Data analysis methodology is developed to derive the intensities of these rotational lines from NIRIS obtained raw images and these intensities are further used to derive mesospheric temperatures. The NIRIS derived mesospheric temperatures match well with the temperatures obtained from SABER for the passes close to the observational station.

The nocturnal variations in OH and O_2 emission intensities and temperatures show signatures of vertical propagation of GW as downward phase propagation is seen in the residuals of intensities. With the help of simultaneous high data cadence measurement of OH and O_2 nightglow emission intensities, it was possible to experimentally obtain intrinsic GW parameters, such as, wave period (τ), vertical phase speed (c_z), and vertical wavelength (λ_z). These GW parameters

can be derived for all those nights on which the wave periods at both the altitudes are coherent and show vertical wave propagation (downward phase propagation) indicating the influence of the same gravity wave at both these altitudes. The values of τ on two such nights of 16 April, 2013 and 4 May, 2013 (obtained from OH and O₂ emission intensity variations) are 1.85 and 1.8 hrs. The values of c_z are found to be 2.3 and 3.9 ms⁻¹, and λ_z is calculated as 15.6 and 25.2 km on these two nights. Large FOV ($\sim 80^\circ$) observations from NIRIS also made it possible to calculate the meridional wavelength (λ_y) since the slit orientation is kept along N–S meridian. For OH nightglow intensity variations for a sample night of 4 May, 2013, the λ_y values were found to be around 90 and 110 km, which was not present at O₂ emission altitudes. λ_y in the range of 60–80 km are observed only at O₂ emission altitudes. The smaller scale waves of the range of 30–50 km are found to be more in number at O₂ emission altitudes as compared to the OH emission altitudes. Nocturnal variations in OH and O₂ intensities show different kind of variations on different/same night, e.g., they show in-phase, out-of-phase, and constant variations. A schematic is drawn to suggest the possible vertical wavelength characteristics that can show these different kinds of observed variations.

From the high data cadence simultaneous measurement of OH and O₂ rotational temperatures, four different cases are defined based on the difference in O₂ and OH temperatures and the vertical propagation of the waves. Possible causes for the mesospheric temperature inversion are discussed. Using a total of 234 nights of observations carried out in the year 2013 statistical distribution of all four cases are investigated. It is found that the number of nights on which temperature inversion is seen, but not the vertical propagation (40, 17.1%) are more than those on which both temperature inversion and vertical propagation are observed (17, 7.3%). This indicates that chemical heat release in the mesosphere on some nights to be a more probable cause for the MTIs. NIRIS is a field proven, and rugged instrument which has been automated to operate from remote places successfully. Other than the above-mentioned applications to derive the GW parameters to understand the nocturnal dynamics, this technique also enables study of mesospheric dynamics of various time-scales using these mesospheric nightglow emission variabilities. Thus, the newly developed NIRIS is

an extremely useful and powerful tool to obtain simultaneous large FOV (80°) high data cadence O₂ and OH emission intensity variations and their corresponding temperatures for the investigation of mesospheric dynamics.

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