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On the role of non-LTE effects for variations in OH rotational temperatures

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Time series of rotational temperatures from OH lines with low rotational quantum numbers are an important resource for studies of short-term and long-term variations in the Earth's mesopause region. For this purpose, it is usually assumed that these measurements coincide with the effective kinetic temperature of the OH emission layer. However, this might not be true due to deviations from the local thermodynamic equilibrium (LTE) for the population distribution over the considered rotational levels. The non-LTE effects can vary if the ratio of collisions with air molecules contributing to the rotational relaxation and those with atomic oxygen contributing to the multi-quantum vibrational level deactivation or chemical removal of OH significantly changes.

In order to better understand these processes, we have investigated the variability of OH rotational temperatures and the corresponding contributions of non-LTE effects for different OH bands. We have done this for time scales up to 15 years based on data from the astronomical echelle spectrographs UVES and X-shooter at the Very Large Telescope at Cerro Paranal in Chile. In order to link the measured rotational temperatures with the structure of the OH emission layer, we have also studied OH emission and kinetic temperature profiles from the multi-channel radiometer SABER on the TIMED satellite.

The results show that non-LTE contributions can significantly affect the OH rotational temperatures. Their variations can be especially strong during the night and for high upper vibrational levels of the transitions, where amplitudes of several Kelvins can be measured. They appear to be weak if long-term variations such as those caused by the solar cycle are investigated. These differences in the response depend on the amplitude of the changes in the effective height of the OH emission layer. Indeed, stronger non-LTE effects are related to a lower layer-weighted air density but a higher effective atomic oxygen density.

Study of UV airglow for purposes of JEM-EUSO mission

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A night time observation of Extensive Air Showers (EAS) that are induced by Ultra High Energy Cosmic Rays (UHECR) from Space by optical telescopes will require a precise characterization of the background, the diffuse UV light. The main component of such UV light is well known as airglow and understanding of its dynamics is essential for missions like JEM-EUSO (Extreme Universe Observatory on-board Japanese Experiment Module). To study airglow variations, we have analyzed data of JEM-EUSO pathfinder missions and specified expectations for the future ones. To estimate absolute values of airglow in the UV spectral band, we have developed relatively simple and inexpensive ground-based one-pixel detector. The state-of-art of the JEM-EUSO airglow study will be presented and possible connections to the NDMC mission will be discussed.

Effect of magnetospheric disturbances on UV nightglow

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It was proved, in previous decades, that magnetospheric disturbances affect nightglow of upper atmosphere. We realized calculations of nightglow response in UV (range form 300 to 500 nm) to magnetospheric disturbances, for selected places at period from 1970 till 2012, to obtain quantitative estimation of influence. Calculations was obtained by AURIC CPI code. The evaluated responses are presented. Such estimations are used to obtain insight to nightglow dynamics, which affect measurements of highly sensitiv detectors like JEM-EUSO and his precursors.

The effect of the geomagnetic activity at temperature of the sub-auroral mesopause over Yakutia

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Regular observations of the hydroxyl emission band (6,2) were carried out at the Maimaga station (63° N, 129,5° E) since 1999. Measurements were conducted with an infrared spectrograph. The monthly average residuals of OH(6,2) temperature after the subtraction of the mean seasonal variation were studied earlier. The residual temperature maximum follow peak of Ottawa 10.7 cm flux with 25 months delay was found. The effect of geomagnetic activity on the subauroralmesopause temperature was evaluated to find the possible reasons for the time lag. The rotational temperature data set comprises 2864 nightly averages, which pass selection criteria. For the analysis was used Ap index. The correlation analyses showed connection between OH(6,2) rotational temperature with the geomagnetic activity. The correlation coefficient R = 0.44 with a value 0.18 of 95% confidence interval level.

For the geomagnetic forcing, we divide the data into high geomagnetic activity (Ap>8) and low geomagnetic activity (Ap$\leq$ 8) years. The winter temperature of OH excitation heights in active years is approximately 10 K higher, than in years with low Ap. Monthly averaged temperatures in August-September and in March-May have not significant differences. A possible mechanism is precipitation of energetic particles into the atmosphere during geomagnetic activity years. Numerous models show that during geomagnetic active periods the particle precipitations significantly increase the amount of NOx and HOx in the polar winter mesosphere, resulting in local ozone decreases of up to stratosphere. These changes are followed by an intensification of the polar night jet, as well as mesospheric warming and stratospheric cooling.

Altitude of the hydroxyl layer over the Observatory of Sierra Nevada (37N,3W), Granada, Spain

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Based on the empirical model suggested by Liu and Shepherd (2006) and further exploited by Mulligan et al. (2009), we have derived a formula that predicts the altitude of the layer peak at 37N by using SABER OH nighttime emission measurements from 2002 to 2016. The prediction reproduces the altitude with an accuracy better than 250m. After expressing measurements from the Spectral Airglow Temperature Imager (SATI) located in Granada in terms of co-located SABER measurements, we have used the formula to infer the OH peak altitude. We will discuss its inter-annual, seasonal and daily variability at our location.

Chemical heating rates derived with the developed Multiple Airglow Chemistry model

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The photochemistry of the identified and coupled electronic states of molecular oxygen was reflected in the developed Multiple Airglow Chemistry (MAC) model based on more than 60 aeronomical reactions. The MAC model was applied in the upper mesosphere and lower thermosphere (MLT) region to retrieve atomic oxygen concentration ([O]) profiles and to calculate heating rate profiles. The MAC model was validated with rocket in-situ measurements and Sounding of the Atmosphere using Broadband Emission Radiometry (SABER) infrared radiometer data of nightglow. The reference heating rate profiles extracted from SABER represent chemical heating rates of seven reactions governing the energy budget of the mesopause region. The MAC model was applied to estimate the contribution of these seven reactions and the contribution of other considered processes at night. The obtained heating rate profiles were compared with those ones extracted from SABER infrared radiometer data. The chemical heating in the MLT is prevailed by odd hydrogen and odd oxygen species. Particularly, the contribution of hydroxyl radical, atomic and molecular oxygen as well as ozone is significant in the quenching heating.

Characterizing variability in OH^* emissions during the last solar cycle retrieved from SCIAMACHY nightglow observations

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We present our results on the variability in emission rate and centroid emission altitude of the OH(3-1) and OH(6-2) Meinel bands in the terrestrial nightglow based on spaceborne nightglow measurements with the SCIAMACHY (SCanning Imaging Absorption spectroMeter for Atmospheric CHartographY) instrument on the Envisat satellite. The SCIAMACHY observations cover the time period from August 2002 to April 2012 and the nighttime observations used in this study are performed at 10:00 p.m. local solar time. Satellite measurements give us the opportunity to have observations of the vertical OH volume emission rate profile.

OH emission altitude and vertically integrated emission rate time series with daily resolution for the OH(3-1) band and monthly resolution for the OH(6-2) band were analyzed using a standard multilinear regression approach allowing for seasonal variations, QBO-effects (Quasi-Biennial Oscillation), solar cycle (SC) variability and a linear long-term trend. The analysis focuses on low latitudes, where SCIAMACHY nighttime observations are available all year. The dominant sources of variability for both OH emission rate and altitude are the semi-annual and annual variations, with emission rate and altitude being highly anti-correlated. There is some evidence for a 11-year solar cycle signature in the vertically integrated emission rate and in the centroid emission altitude of both the OH(3-1) and OH(6-2) bands.

Additionally, we used the OH(3-1) band nightglow data set with daily resolution and applied a Superposed Epoch Analysis to investigate solar 27-day effects in emission altitude as well as in emission rate and derived kinetic temperature. We find a clear 27-day signature in all three parameters. The sensitivity of the equatorial mesopause temperatures to the 27-day solar cycle is comparable to earlier studies. We also find emission rate and altitude generally to be highly anticorrelated. The larger sensitivity of emission altitude, emission rate and temperature to the 27-day solar cycle at the time of a solar-minimum, compared to solar maximum, is not fully understood.

Empirical model of the spatio-temporal distribution of the intensity of the infrared emissions of atomic oxygen (63 μm) and carbon dioxide (15 μm) in the upper atmosphere

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We present the results of systematization and analysis of long-term data of rocket and satellite measurements of the infrared (IR) radiation of atomic oxygen O (^{3}P) and carbon dioxide CO_2 in the upper atmosphere. This radiation, appearing at the height of the upper mesosphere and lower thermosphere (MLT), is of fundamental importance in the formation of the thermal state of the upper atmosphere and the energy balance at these heights. The significance of research of spatio-temporal variations in the infrared O (^{3}P) and CO_2 radiation is due to the necessity of considering the features of the regional variations in the upper atmosphere temperature at prognostic estimations of a global picture of the processes of its cooling at different latitudes at different time intervals during the year (diurnal and seasonal variation, etc.). Photochemical atmospheric processes, leading to the origin of the 63 μm O(^{3}P) and 15 μm CO_2 emissions, are analyzed. Based on statistical analysis of published data of rocket and satellite measurements of the 63 μm and 15 μm emissions characteristics, performed in the last 30 years, analytical expressions (empirical model) are obtained. This model allow us to describe the character of the altitude distribution of the O(^{3}P) and CO_2 emissions intensities, their seasonal and latitudinal behavior, as well as their dependency on the solar activity.

It is shown, that the dependence of the behavior of the 63 μm and 15 μm emissions intensities on the solar activity has non-linear character. It was revealed, that the height profile of the 63 μm volume emission rate, which maximum is about 100 km, also depends on the solar activity level. The seasonal variations in the O (^{3}P) and CO_2 emissions intensities were analyzed. It was found a slight (about 10%) increase in the intensity of the 63 μm atomic oxygen emission in summer. The seasonal variation in the 15 μm emission intensity has a minimum in summer and maximum in winter. Latitudinal behavior of the CO_2 emission intensity was investigated. Analysis of dependency of the annual mean CO_2 emission intensity on the geographical latitude revealed, that the intensity increases in both hemispheres with increasing latitude. In the equatorial region there is a small maximum in the CO_2 emission intensity.

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Studying metals in the MLT using astronomical facilities

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Metals in the mesopause region, such as Na, Fe or Ni, originate from meteoric ablation in the upper atmosphere. Through reactions with ozone they emit airglow. In the case of Fe and Ni the airglow originates from their oxidised form which unlike the atomic line emission from Na results in a pseudo-continuum emission. This pseudo-continuum emission is difficult to observe since it is a broad but weak spectral feature compared to the line emissions arising from sodium.

For this study on metals in the mesopause region we use astronomical data taken with the Very Large Telescope (VLT, 24° S, 70° W) operated by the European Southern Observatory (ESO) in Chile, and the Apache Point Observatory (APO, 32° N, 105° W) in New Mexico/USA. The ESO spectrographs X-shooter and UVES as well as the APO MaNGA survey instrument were utilised. The already studied X-shooter data cover 3.5 years, the UVES sample comprises 15 years, whereas MaNGA was recently started and encompasses 2.5 years so far.

X-shooter allows for detailed studies on the diurnal and seasonal behaviour of FeO and Na. We found a semi-annual amplitude of 27% and 30% with respect to the annual mean for FeO and Na, respectively. This compares to 17% and 25% in the amplitude of the annual oscillation for FeO and Na, respectively. In addition, simulations with WACCM (Whole Atmosphere Community Climate Model) allowed us to quantify the reaction rates in the MLT. We find a quantum yield of 13% for FeO and 11% for Na, which is in reasonable agreement with laboratory results. The investigation at the VLT site is complemented by a longterm study on sodium using UVES data.

The MaNGA sample offers the possibility to extend our investigation of FeO and Na also to the northern hemisphere. Especially, a comparison between the VLT and APO site with respect to latitude is of interest. Furthermore, the instrumental setup allows for a more detailed study on the contribution of NiO to the night-sky emission.

Retrieval of horizontally resolved winds from a multi-static multi-frequency meteor radar network

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Meteor radars have been proven to provide continuous and valuable measurements of mean winds in the mesosphere and lower thermosphere (MLT). Recently, a new concept was introduced called MMARIA – Multi-static Multi-frequency Agile Radar for Investigation of the Atmosphere, which shows that multi-static meteor observations are suitable to resolve the spatial characteristics of MLT winds.

During the last three years we built a new network consisting of two active meteor radars at Juliusruh (54.6° N, 13.4° E) and Collm (51.3° N, 13.0° E) and up to 5 passive multi-static links distributed in Northern Germany. The systems are located in such a way that the observation volumes are overlapping. Thus, there is a diversity of viewing geometries through the whole common domain area reaching from the Baltic coast down to Leipzig covering the Northeastern part of Germany.

Here we present some preliminary results from a newly developed wind retrieval algorithm to obtain horizontally resolved wind fields within the domain area. We demonstrate that such a meteor radar network is capable to investigate the spatial and temporal variability of gravity waves in the MLT. Further we apply new diagnostics by estimating horizontal wavelength spectra and horizontal divergence maps using the obtained 2D wind fields.

Using the Optimal Estimation Method to Retrieve Middle Atmospheric Temperature from Rayleigh-scatter lidar measurements

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Optimal estimation methods (OEMs) are an extremely powerful technique for the retrieval of information from measurements. These methods are extremely robust. In fact, if you can mathematically write a well-posed description of your measurements in terms of parameters that you know and parameters you want to retrieve, OEM will likely successfully retrieve those parameters. In atmospheric sciences, this powerful technique has been used to retrieve atmospheric parameters from passive instruments since the 1970s, particularly in the context of space-based spectroscopic measurements. More recently OEMs are used in weather forecasting to choose a "best" forecast from an ensemble of possible forecasts.

We have applied OEMs to lidar measurements of temperature and water vapour, and our group is developing new retrievals for rotational temperature and ozone. These studies, along with work done by Dr. A. Povey (Cambridge) for aerosols, have opened up new applications of OEMs for high spatial-temporal resolution active remote sensing measurements. These methods address several long-standing problems regarding systematic uncertainties and parameter resolution, knowledge of which is critical for using these measurements for scientific studies such as Atmospheric Change. The OEM allows a full uncertainty budget to be obtained on a per profile basis that includes, in addition to the statistical uncertainties, systematic uncertainties for a large number of parameters. The vertical resolution of the retrieved is found at each height, and a quantitative determination is made of the maximum height to which the retrieval is valid. A single retrieval profile can be found from measurements with multiple detection channels that cover different height ranges, vertical resolutions and even different detection methods.

We will show specific examples of how using OEM for temperature retrievals offers the ability to improve NDMC's measurements, both in terms of the range of available retrievals, comparisons with other ground and space-based sensors and the detailed uncertainty budgets necessary to determine atmospheric change.

A new middle atmosphere Rayleigh-scatter temperature climatology using the Optimal Estimation Method

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Rayleigh-scatter lidar measurements from the Purple Crow Lidar (PCL) facility located near The University of Western Ontario have been used to develop an atmospheric temperature climatology using measurements from 1994 to the present. Temperatures have previously been calculated using the algorithm given by Hauchecorne and Chanin (1980; henceforth HC). The HC method requires the assumption of a "seed" pressure at the highest altitude, typically taken from a model. Geophysical variation in the lower thermosphere is sufficiently large to cause temperature retrievals to be unreliable for the top 10 or more kilometers. Thus, without ancillary measurements, it is prudent to remove the top two scale heights of temperatures from each profile. Recently Sica and Haefele (2015) have presented an Optimal Estimation Method (OEM) to retrieve atmospheric temperature profiles and found that it had many advantages over other techniques. OEM produces a complete uncertainty budget for all retrieved and model parameters in the retrieval. Also, OEM determines a quantitatively determined cut-off height in the retrieval procedure.

The PCL consists of two Rayleigh channels able to measure temperature from 24 km to 110 km. These channels overlap with each other. To create a single temperature profile from multiple lidar channels using the HC method requires either count or temperature profiles to be merged, making assigning uncertainties difficult. The OEM provides a natural scheme to incorporate data from multiple sources, such as combining lidar measurements from multiple measurement channels. This presentation will show the PCL temperature climatology using the OEM for 500+ nights of Rayleigh measurements, including the quantitative determination of the top altitude of the retrieval and the evaluation of the various systematic and random uncertainties. When comparing techniques, the OEM climatology allows retrieving temperature to a higher altitude than the traditional method, and shows a colder mesopause region due to the ability to estimate the affect of the a priori profile on the retrieval.

Lidar observations of gravity waves and tides in the middle atmosphere above Kühlungsborn (54° N): An update

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Since summer 2010 the daylight capable RMR lidar at Kühlungsborn/Germany (54° N, 12° E) routinely probes the stratosphere and mesosphere. Temperature profiles cover an altitude range of 30 – 75 km during the day and 3 – 85 km during the night. Temporal coverage is only limited by clouds. Continuous multi-hour soundings allow for an effective separation between gravity waves and tides depending on wave periods and/or vertical wavelengths. Especially long soundings, covering 100 h or even more without interruption reveal the variability of tidal amplitudes that is often underestimated in observations. We will show climatological data for our mid-latitude site as well as case studies for single periods with excellent data coverage. Recently, gravity waves parameters like potential energy density are calculated from density variations. This allows integration times of 10 min and less, and by this also analysis of short-period gravity waves. Comparisons with longer-period gravity waves reveal different propagation conditions and damping. The high temporal resolution is especially important for NDMC since it provides good overlap with waves observed in airglow.

Meridional net of stations measuring the temperature of the mesopause in the North East of Siberia

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Meridional chain of stations are created within the framework of an international research program of mesopause changes NDMC (Network for the Detection of Mesopause Change, since 2007, continues). Meridional chain will consist of a mid-latitude station in Neryungri (56.39° N, 124.43° E) high-latitude stations Maimaga (63.04° N, 129.51° E) and Tiksi (71.58° N, 128.77° E). Each station will be equipped with the new infrared spectrograph (Andor) recording temperature for 1 min by OH (3.1) band of hydroxyl molecule and with all-sky camera which registers movement of internal gravity waves by night airglow emissions. At the present time spectrographs installed in Tiksi and Maimaga. Two all-sky cameras work in Maimaga. All devices run offline. The following year, the spectrograph will be installed in Neryungri. The network will be fully completed in a year or two.

A radiometric traceability concept for the Network of Mesospheric Change (NDMC)

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The NDMC is an international network of currently 55 ground-based experiments with emphasis on observing the airglow emissions from excited OH and O radicals as well as excited O2 molecules in the mesopause region. About one third of these instruments are of the so-called GRIPS type (Ground-based Infrared P-branch Spectrometer) determining the rotational temperature of the OH(3-1) vibrational transition.

We focus on giving radiometric traceability to measurements of theses GRIPS instruments to determine the mesopause temperature with sufficiently low uncertainty to identify temperature changes at the level of 1 K per decade. By Monte-Carlo simulations we determined the required uncertainty in terms of the relative radiance responsivity calibration of the applied instrument to achieve this goal. It needs to be better than 0.5%. Furthermore, an absolute radiance responsivity calibration of the GRIPS instruments within the NDMC would allow the determination of the OH* radical concentration which is directly correlated to the concentration of atomic oxygen in the mesopause.

The emission measurements of the OH* radicals are performed in the wavelength range from 1500 nm to 1600 nm, at very low radiance levels (around 350 $\mathrm{Wm^{-1}sr^{-1}m^{-2}}$) caused by their low density in the mesopause. At these radiance levels and wavelengths the required radiance uncertainty is currently just achievable for laboratory-based calibration procedures at the National Metrology Institutes. To obtain this low level of uncertainty for the NDMC in the field we propose a traceability concept based on a radiometrically well characterized Traveling Radiance SOurce (TRSO) and a likewise characterized Traveling Reference SPectrometer (TRSP). The applicability of the concept will be shown in a case study by the calibration of three GRIPS measurement sites. We identified two suitable instruments for the concept: a commercially available infrared plate radiator as the TRSO and a GRIPS instrument as the TRSP. For the transfer of the spectral radiance scale from the primary radiance standards of the PTB to the TRSO with lowest possible uncertainty a dedicated Near InfraRed Transfer Radiometer (NIRTR) has been developed by the VSL which matches closely the optical imaging properties of the GRIPS instruments.

We will present results of the characterization of the TRSO, TRSP and the NIRTR, i.e. their long-term stability, size-of-source effect, spectral responsivity and noise analysis. The results obtained in the first term required modifications of the TRSP instrument to achieve the intended uncertainty. A baffle system to suppress out of field stray light and

a dedicated thermally controlled housing to reach the necessary thermal stability of the instrument had to be developed. Finally, we will show the results of the first exemplary calibration of the GRIPS instrument at the DLR site in Oberpfaffenhofen with the TRSP and TRSO and the proposed radiometric traceability concept.

Development of a near-infrared filter radiometer as part of the traceability chain for ground-based P-branch spectrometers

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In this contribution we will present the development of a Near- InfaRed Transfer Radiometer (NIRTR) that is part of the radiometric traceability chain that provides SI traceability to Ground-based Infrared P-branch Spectrometers (GRIPS). These GRIPS instruments are part of the NDMC network and provide, among others, measurement data on the mesopause temperature. When calibrated for absolute radiance, also the atomic oxygen concentration can be derived. The work presented here complements the work submitted by Reiniger et al. Here we focus on the development of the NIRTR. Furthermore we will discuss some future plans for an alternative calibration method of infrared spectrometers, like GRIPS.

The NIRTR is a filter radiometer that is used to calibrate a traveling reference source (TRSO) to a primary black body radiator. The TRSO will subsequently be used for on site calibration of GRIPS instruments. The NIRTR requirements are based on the radiance level to be measured and on the measurement range and view angle of the GRIPS instrument. Furthermore, the NIRTR should be transportable and it should be possible to put it close to a black body radiator (about 120° C, 60 mm diameter), without affecting the NIRTR performance due to possible heat-up. To generate a typical radiance level of 350 $Wm^{-1}sr^{-1}m^{-2}$, the reference black body and the TRSO will operate at a temperature of 120° C.

In the optical design of the NIRTR, the light is collected with an objective lens with a diameter of 50 mm and a focal length of 80 mm. The field stop, having a diameter of 4 mm, is inserted to restrict the image size on the detector. Since the field stop is imaged 1 to 1 on the photodiode surface, having a sensitive area with a diameter of 5 mm, the photodiode will be underfilled. The field of view of the system is limited by a Lyot stop that is inserted between the two collimating lenses. The Lyot stop is inserted such that size of source effects are minimized. The filter is also inserted in the collimated beam between the lenses. The filter is centered around 1.55 μm, with a bandwidth of 65 nm. As a detector a thermo-electrically cooled InGaAs detector (Hamamatsu G112180) has been selected. The detector spectral responsivity and the filter transmission have been calibrated by PTB. The whole instrument is shielded with an insulated housing. The front panel and bottom plate are temperature stabilized by an embedded water cooling system. We will show that we have succesfully applied the NIRTR to transfer the radiance scale from primary black body to the TRSO within the required uncertainty of 0.5%.

As an alternative route to provide traceability to GRIPS instruments and other spectroradiometers, we will also discuss a method that will be developed in a new project starting mid 2017. Here we will develop a spectrally narrow, large aperture radiance source based on a tunable laser operating in the 1.5-1.6 μm range. The radiance source will be created by sending the laser light into an integrating sphere (or alternatively by using a diffuser). The radiance source will be calibrated via a detector based route, i.e. without the need for a black body reference source. In contrast to the broad band methods, this new approach also allows for stray light analysis of the spectrometers under calibration.

Results of reverse ray-tracing short-period gravity waves and ripples observed at Davis Station Antarctica (68° S, 78° E) during the period 1999-2013

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A scanning radiometer deployed at Davis Station, Antarctica (68° S, 78° E) has been recording infrared (1.0 - 1.6 μm) images of a small region (24 km x 24 km) of the zenith night sky once per minute each austral winter since the year 1999. These images have been processed to extract information on the passage of gravity waves (wavelength $>$ 15 km) and ripples (wavelength $\leq$ 15 km) over the observing station. Phase speeds, periods, wavelengths, and predominant propagation directions have been deduced from the observations. Reverse ray-tracing has been applied to the results in an effort to understand the origins of the waves and ripples. On average only 20% of waves detected can be traced back to the troposphere, and a large proportion (40%) were not successfully reverse traced substantially below the airglow layer. Two smaller groups were found to reach a termination condition for reverse ray-tracing at altitudes near 55 km and 75 km. Of those that reached the termination altitude (10 km) in the troposphere, most of the points fell within a radius of 300 km of the station. They show a very pronounced concentration of wave initiation to the north west of the station at approximately 100-200 km from the observing point. The predominant direction of propagation was southward, and they are observed throughout the year. Recent reports suggest the interaction of planetary waves with the background wind field as a potential source for these waves.

Derivation of horizontal and vertical wavelengths using a scanning OH(3-1) airglow spectrometer

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OH(3-1) spectrometer measurements allow the analysis of gravity wave periods, but spatial information cannot necessarily be deduced. To obtain this information, we therefore use a scanning spectrometer and the harmonic analysis to derive horizontal wavelengths at the mesopause above Oberpfaffenhofen, Germany for 22 nights in 2015. The approximation of the dispersion relation for gravity waves of low and medium frequency allows calculating the vertical wavelength horizontal wind information provided.

The nearest mesopause wind measurements to Oberpfaffenhofen are conducted at Leipzig, Germany, ca. 400 km northeastern of it by a meteor radar. They are used for the estimation of the vertical component of the wave vector.

In order to check our results, vertical temperature profiles of TIMED-SABER (Thermosphere Ionosphere Mesosphere Energetics Dynamics, Sounding of the Atmosphere using Broadband Emission Radiometry) overpasses are de-trended and the height range between 60 and 80 km is analysed with respect to the dominating vertical wavelength. With a mean difference of ca. 32% and 4 km between the vertical wavelengths based on SABER and the spectrometer-radar combination, the agreement can be judged as very good.

Comparison of atmospheric and ionospheric variabilities from measurements of OH(6-2) rotational temperature and F2 peak electron density

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We analyzed and compared variability in the neutral upper atmosphere and ionosphere parameters over Eastern Siberia. The analysis is based on 2008-2015 dataset of mesopause temperature (Tm) obtained from spectrometric measurements of the OH emission (834.0 nm, band (6-2)) at the ISTP Geophysical Observatory (51.8° N, 103.1° E, Tory), and the data of F2 peak electron density (NmF2) from Irkutsk DPS-4 Digisonde (52.3° N, 104.3° E). Day-to-day and diurnal variations of Tm and NmF2 were analysed. The period range included day-to-day (periods $T > 24$ hrs) and tidal (8 hrs $\leq T \leq$ 24 hrs) variations as well as variations in the internal gravity wave period range ($T < 8$ hrs). Comparative analysis of these variations revealed manifestation of wave activity of various time scales over a wide height range of the upper atmosphere. We revealed significant seasonal changes of Tm and NmF2 variabilities within a year. The comparison revealed both common features and distinctions in the seasonal patterns of the ionospheric and atmospheric variability. In both Tm and NmF2, winter variability is higher than summer one for all the considered period ranges. The largest variability is seen in winter or near-equinox months. High winter variability may be caused by impact of sudden stratospheric warmings on the upper neutral atmosphere and ionosphere. Maxima around the equinoxes may be explained by manifesting of seasonal (springtime/fall) transition of the atmospheric circulation. The revealed similarities in the seasonal behaviors may indicate that planetary waves propagating from the lower atmosphere layers have a significant impact on the mesopause temperature regime and ionospheric day-to-day variations.

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Comparison of temperature of the mesopause measured by ground-based and satellite instruments

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The work presents a comparison of the kinetic temperature of the emissive layers of O2 (90 km) and OH (87 km) measured with a SABER radiometer on the TIMED satellite, and rotational temperatures of the first atmospheric infrared O2(0-1) band and OH(6-2) band measured with a ground spectrograph installed on the optical station Maimaga (63° N, 129.5° E). For comparison SABER measurements obtained in 2002-2013 were selected within the area (55° N-70° N)×(115° E-135° E). The angle of view of the ground-based spectrograph isnearly in the center of the selected area. Analysis of the 4612 profiles obtained for 12 years showed that the seasonal temperature variations have approximately the same type. The temperature of the OH layer measured by satellite is 4.5K more than temperature measured by ground-based spectrograph and 20K higher for O2 layer correspondingly. It was found that the difference between the measurements from satellite and ground-based instrument has inter-annual variability. In 2002-2003, the temperature difference in the two emissive layers does not exceed 5K. In 2009-2010, the temperature difference reaches 40K for the O2 and 20K for the OH. In 2013, the temperature of OH layer measured by two devices is almost the same, but for O2 difference decreases to 10K.

Seasonal fluctuations of internal gravity waves in the mesopause region by measurements at Tiksi and Maimaga

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Standard deviations σ of average nighttime temperature in the mesopause region (87 km) are investigated by measurements at the station Maimaga (63.04° N, 129.51° E) and Tiksi (71.58° N, 128.77° E). Recording of the spectra at both stations is carried out using identical light-sensitive infrared spectrographs Shamrok (Andor) which register OH (3.1) band in the far infrared (1.5 microns). There are data for the seasons 2013-2014, 2014-2015, 2015-2016 for Maimaga station and data for the season 2015-2016 for Tiksi station.

Standard deviations of internal gravity waves (IGW) σ_{gw} are derived. There is a seasonal variation of σ_{gw} which remains after division by the average nighttime temperature $T_{\mathrm{averag}}(\sigma_{\mathrm{gw}}/T_{\mathrm{averag}})$ for both stations. Also in season 2015-2016 the standard deviations of IGW σ_{gw} at Tiksi and Maimaga have a similar appearance. At present work is underway on spectral analysis (Scargle-Lomb method) of temperature fluctuations per night.

Vortical perturbations and their possible transformation into short-period AGWs by nightglow observations

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Mesopause-lower thermosphere (MLT) region nightglow is an indicator of propagation of the atmospheric waves and their in situ evolution as well. The hydroxyl OH bands and the oxygen green 557.7 nm line intensities emitted from the MLT region shows the presence of short-period atmospheric gravity waves (AGWs), which can be result of the vortical type perturbation evolution in the inhomogeneous horizontal wind. An example of nightglow observations from Abastumani (41.75 N; 42.82 S) of possible transformation of AGWs and vortical perturbation into short-period oscillations (with periods about 4-8 min) are shown. The numerical results of similar temporal evolution of the AGWs and shear excited vortical perturbations (shear waves) are demonstrated.

Small-scale gravity waves in the Alpine region observed in OH-airglow - comparison of measurements at Oberpfaffenhofen, Germany, and Sonnblick, Austria

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The OH-airglow layer in about 87 km altitude is well-suited for the investigation of atmospheric dynamics, allowing continuous observations of the night-sky throughout the year. Especially, atmospheric gravity waves are prominent features in the data of airglow imaging systems.

Our imaging system FAIM 1 (Fast Airglow IMager 1) focusses on small-scale wave-like structures in the horizontal wavelength range of 1 km to 50 km at mesopause heights. This range covers small-scale gravity waves as well as larger scale instability structures and is rarely investigated in literature beyond case studies.

For FAIM 1 three years of measurements are available at present in a high temporal and spatial resolution. For the first year the instrument was located at Oberpfaffenhofen, Germany (48.087° N, 10.280° E) and for another 1.5 years it was set-up at Sonnblick Observatory, Austria (47.054° N, 12.958° E). To analyse the massive amount of image data, the two-dimensional FFT is used for extracting the wave parameters. For both stations, the dominant horizontal wavelengths and main propagation directions are retrieved; the similarities and differences are presented and discussed as well as a potential relation to the topography.

This work received funding from the Bavarian State Ministry of the Environment and Consumer Protection.

High resolution observations of small scale gravity waves and turbulence features in the OH airglow layer

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A new version of the Fast Airglow Imager (FAIM) for the detection of atmospheric waves in the OH airglow layer has been set up at the German Remote Sensing Data Centre (DFD) of the German Aerospace Centre (DLR) at Oberpfaffenhofen (48.09° N, 11.28° E), Germany. The spatial resolution of the instrument is 17 m/pixel in zenith direction with a field of view (FOV) of 11.1 km x 9.0 km at the OH layer height of ca. 87 km. Since November 2015, the system has been in operation in two different setups (zenith angles 46° and 0°) with a temporal resolution of 2.5 to 2.8 s.

In a first case study we present observations of two small wave-like features that might be attributed to gravity wave instabilities. In order to spectrally analyse harmonic structures even on small spatial scales down to 550 m horizontal wavelength, we made use of the Maximum Entropy Method (MEM) since this method exhibits an excellent wavelength resolution. MEM further allows analysing relatively short data series, which considerably helps to reduce problems such as stationarity of the underlying data series from a statistical point of view. We present an observation of the subsequent decay of well-organized wave fronts into eddies, which we tentatively interpret in terms of an indication for the onset of turbulence.

Another remarkable event which demonstrates the technical capabilities of the instrument was observed during the night of 4th to 5th April 2016. It reveals the disintegration of a rather homogenous brightness variation into several filaments moving in different directions and with different speeds. It resembles the formation of a vortex with a horizontal axis of rotation likely related to a vertical wind shear. This case shows a notable similarity to what is expected from theoretical modelling of Kelvin-Helmholtz instabilities (KHIs).

The comparatively high spatial resolution of the presented new version of the FAIM airglow imager provides new insights into the structure of atmospheric wave instability and turbulent processes. Infrared imaging of wave dynamics on the sub-kilometre scale in the airglow layer supports the findings of theoretical simulations and modellings. Parts of this research received funding from the Bavarian State Ministry of the Environment and Consumer Protection.

High-Resolution Airborne Airglow Imaging during the Gravity Wave Life Cycle Campaign in Northern Scandinavia

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Gravity waves play a central role in driving the mean meridional circulation, which is important in understanding the thermal structure of the mesopause-lower thermosphere (MLT) region. In frame of the GW-LCYCLE (Investigation of the life cycle of gravity waves) project a comprehensive field campaign was conducted in Northern Scandinavia in January/ February 2016. Concerning the MLT-region, the region of enhanced gravity wave breaking and momentum deposition, airglow observations constitute an important part of this field campaign.

Therefore, the new infrared camera system FAIM 2 (Fast Airglow IMager) has been installed aboard DLR's research aircraft "Falcon" together with a multitude of other scientific instruments probing the the atmosphere both in-situ as well as above and below the airplane. FAIM 2 carried out observations during six flights under varying meteorological conditions between 14th January and 1st February 2016. The high spatial resolution of approximately 150 m at mesopause heights make this instrument especially suited for studying small scale structures, thought to be associated with gravity wave breaking.

The airborne airglow observations are supported by ground-based airglow observations in ALOMAR (Arctic Lidar Observatory for Middle Atmosphere Research), Norway (69.28° N, 16.01° E) and Kiruna, Sweden (67.86° N, 20.24° E). These are used to determine the large scale behavior of the MLT region during the time of the campaign.

First results of the observations reveal that small scale instability structures, so-called "ripples", are rather common in the high-latitude winter mesopause. These quasi-periodic structures show unexpected variety with their scales ranging from only 1.2 km wavelength to more than 100 km^2 covered by a single structure, from more than 20 wave trains to less than two.

Observations of OH–airglow from ground, aircraft, and satellite during the GW-LCYCLE campaign: investigation of different wave types

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During the GW–LCYCLE campaign from January to February 2016 in Northern Scandinavia, we operated four instruments: two ground–based OH^* IR–spectrometers (scanning and non–scanning mode at ALOMAR (69° N), Norway, and Kiruna (68° N), Sweden) and one ground-based OH^* IR all–sky camera (at Kiruna) as well as one OH^* IR–camera on board the research aircraft FALCON (field of view ca. 30°, spatial resolution 150 m x 150 m). Due to the differing spatial and temporal resolution of the instruments, this equipment allows the investigation of temporal and spatial gravity wave parameters in a wide spectral range. The flights of the research aircraft provide the opportunity to investigate gravity waves in between both measurement sites. During the campaign period, the dynamical situation changed due to a minor stratospheric warming. The effect of this warming on the OH^*–layer is investigated using TIMED-SABER data. We provide an overview of the development of planetary and gravity wave parameters and energy density at mesopause height during the campaign period and present first results of the airborne measurements. Finally, we discuss possible wave sources and the influence of the stratospheric warming on wave parameters, and propagation.

Very high resolution observations of waves in the OH airglow at low latitudes

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Remote sensing of perturbations in the hydroxyl (OH) Meinel airglow have often been used to observe gravity, tidal and planetary waves travelling through the 8 km think OH layer near 87 km. However, insight into the shortest scale waves and instabilities are limited by the spatial and temporal resolution of the available observations.

Here we present a series of spectral observations of the OH Meinel (9,7) transition that were executed with the Nordic Optical Telescope on La Palma (18° W, 29° N). The telescope observes a 100 m area of the OH layer with an array detector, and the spatial resolution along the slit height used for these measurements was 10 m. With this resolution, spectra taken with 24 and 34 s repetition rates could resolve small-scale instabilities and evanescent wave instabilities in the OH layer. We will present the observations of these wave-like instabilities, their wavelengths (where appropriate), phase velocities, and lifetimes.

Trends and variability of planetary wave activity in the lower and middle atmosphere during the last 37 years

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Planetary waves are global scale waves in the lower and middle atmosphere. They lead to a more or less periodic change of weather patterns in the middle latitudes. Consequently they can contribute to the emergence of extreme weather events. This underlines the relevance of understanding the variability and long term changes of the planetary wave activity.

Based on European Centre for Medium-Range Weather Forecasts (ECMWF) Re-Analysis Interim (ERA-Interim) temperature data (0 – 65 km) and Ground based p-branch spectrometer (GRIPS) observations of the OH rotational temperature at mesopause heights (ca. 87 km), we derive a dynamical activity index (DAI) that serves as a measure for the planetary wave activity. The comparatively long time series spanning the last three decades show the characteristics of planetary waves, e.g. their annual cycle, wave damping with height etc. They are thus suited for the analysis of long-term variability and trends.

We find that the planetary wave activity has already changed, but significantly only in the stratosphere. The change of the planetary waves with higher wavenumbers turns out to be strongest. Furthermore, multi-decadal periodic oscillations (QBO, ENSO, solar cycles) have a noticeable impact on the wave activity.

We tentatively interpret our findings as a result of a weakening of the meridional temperature gradient due to comparatively strong temperature increases in high latitudes (arctic amplification).

Are self-sustained oscillations part of the climate problem?

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Long- term temperature observations (e.g. GLOTI, LOTI data) show a strong increase in recent decades ("climate effect"). Long- term oscillations appear to be included to these data. The IPCC AR5 report suggests that long period variations may play a role in the climate effect.The amplitudes in the LOTI and GLOTI data are decreased by the spatial averaging. The oscillations show up much clearer in long-term temperature measurement series at a local station. Such a series is available at the Hohenpeißenberg Observatory since 1781. We have simulated these data by superimposing three self-sustained periods taken from the ECHAM6 model (346yr, 78yr, 48yr). Amplitudes and phases were determined by a fit to the measured data (in the time interval 1783-1980). This fit curve is believed to approximate the non-anthropogenic variation of the atmospheric temperatures. It is not influenced by variations of the sun, the ocean, nor the trace gases.

In the recent decades the (extrapolated) fit curve deviates substantially from the measured data: it is much smaller. The measured "excess" is believed to be the anthropogenic climate effect. It is about twice as high as the fit curve, i.e. the non-anthropogenic part of the recent temperature increase is about one third. This result was checked by long-term data from three other stations in Europe (Innsbruck, Vienna, Stockholm), and was essentially confirmed. This suggests further studies in other parts of the world.

An update on ozone and temperature trends in the stratosphere.

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Over the last decades, changing concentrations of ozone depleting substances (ODS) and greenhouse gases (especially CO2) have had substantial effects on the stratosphere. Increases in CO2 have resulted in cooling of the stratosphere, because upwelling infrared radiation from the troposphere is reduced, and outgoing radiation to space is enhanced. Increasing ODS have resulted in substantial ozone depletion in the last millennium, both in the column and in the upper stratosphere. Thanks to the 1987 International Montreal Protocol and its amendments, however, world-wide ODS production has been stopped. Ozone is not declining anymore. First signs of ozone recovery are observed. This seems to have also halted the previous cooling of the lower stratosphere. Upper stratospheric cooling, however, is continuing. This has impacts on chemical reaction rates and will increase ozone in the upper stratosphere. In the presentation I will give an update on observed and modelled ozone and temperature trends in the stratosphere. Temperature trends in the stratosphere will also affect the mesosphere, as can be seen from the large inverse correlation between the annual cycles of geopotential heights (e.g. for the 0.4 hPa pressure surface) and mesopause temperature.

Investigation of the filtering effect of gravity waves by planetary waves based on a three decadal time series of mesopause temperatures at mid-latitudes

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A nearly three decadal time series (1987 - 2017) of mesopause temperatures has been obtained by combining data of two GRIPS (Ground-based Infrared P-branch Spectrometer) instruments, derived from OH*(3-1) emissions at the airglow layer. Both instruments are operated within the Network for the Detection of Mesospheric Change, NDMC. Measurements have been performed at Wuppertal (51.3° N, 7.2° E), Germany and Oberpfaffenhofen (48.09° N, 11.28° E), Germany.

In order to quantify atmospheric gravity wave activity, we developed suitable indicators which are based on both the spectral distribution of observed temperature fluctuations and the estimation of the potential energy density.

We find an overall and clear anti-correlation of gravity and planetary wave activity. It is interesting to note that the respective variabilities show characteristic variations even on decadal scales. Our results also reveal that gravity wave filtering depends significantly on the gravity wave spectrum. This suggests a period-dependent filtering mechanism between gravity and planetary waves. The longer periodic gravity wave activity exhibits an annual variation, being maximum in winter, which agrees well with previous research, while shorter periodic gravity wave activity tends towards a semi-annual pattern showing maximum gravity wave activity around the equinoxes. We will discuss the impact of these findings on the larger circulation patterns in the atmosphere.

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