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The global mesospheric sodium layer observed by Odin/OSIRIS in 2004–2009

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ABSTRACT

The source of the mesospheric sodium layer is the daily ablation of 10–100 tons of meteoric material in Earth's atmosphere. Global studies of this layer yield important information about the chemistry and dynamics of Earth's mesosphere and lower thermosphere (MLT). For nine years the Optical Spectrograph and Infra-Red Imager System (OSIRIS) on-board the Odin satellite has observed Earth's middle atmosphere by limb measurements of scattered sunlight from the ultraviolet to the infrared. In its aeronomy mode, Odin performs limb scans during 15 near-polar sun-synchronous orbits each day. The current measurement programme provides scans up to 110 km on about 300 days per year. Above 70 km, Na D resonance scattering at 589 nm results in a strong limb signal. Retrievals from this dayglow feature have provided a global database of the mesospheric sodium layer. We present an updated sodium climatology from the Odin mission, including latitudinal and seasonal dependence, and interannual variability. We find a weak seasonal variation at low latitudes and an annual variation at mid- and high-latitudes with a clear summer minimum. An interesting feature is an interhemispheric asymmetry in the global dataset with larger sodium abundances during fall in the northern hemisphere and during spring in the southern hemisphere.

1. Introduction

10–100 tons of meteoric material enters Earth's atmosphere globally each day (Love and Brownlee, 1993; Mathews et al., 2001). Ablation of this material at altitudes between 70 and 120 km in the mesosphere and lower thermosphere (MLT) is the source of the mesospheric metal atom layers including e.g. sodium, iron, potassium, calcium and magnesium (Plane, 2003). The strong Na D transition at wavelengths near 589 nm has long been an important tool for optical measurements of the sodium layer. Early measurements have been performed both by ground-based twilight measurements (Chamberlain et al., 1958) and rocket-borne dayglow photometry (Donahue and Meier, 1967). The invention of the tuneable laser and the development of the lidar technique in the late 1960s (Bowman et al., 1969) enabled the sodium layer to be observed with excellent spatial and temporal resolution over the full diurnal cycle, providing a tool for studying the chemistry and dynamics of the MLT region. Long-term observations made possible by a number of lidar systems have provided details about seasonal, latitudinal and diurnal variations (States and Gardner, 1999; She et al., 2000).

An obvious limitation of the above techniques is the geographic coverage. Global observations of the Na layer can only be provided by space-borne instruments. First reports of satellite observations of the sodium layer were from dayglow measurements by the OGO-6 satellite (Donahue et al., 1972) and from nightglow measurements by the DMSP satellite (Newman, 1988; Clemesha et al., 1990). The first global picture of the Na layer was reported from stellar occultation measurements by the GOMOS instrument on-board ENVISAT (Fussen et al., 2004). Recently a global GOMOS climatology of mesospheric sodium number densities was presented for the period 2002–2008 (Fussen et al., 2010). The first use of satellite-borne measurements of the Na dayglow to determine absolute sodium concentration profiles in the MLT was reported by Gumbel et al. (2007) and Fan et al. (2007). These authors processed global limb measurements by the OSIRIS instrument on-board the Odin satellite for the years 2003 and 2004. In the current paper we now present the available OSIRIS sodium dataset from 2004 to 2009 and discuss global and seasonal climatologies as well as interannual and diurnal variability.

The source of sodium in the upper atmosphere is the ablation of incoming meteoric material. Resulting Na abundances in the MLT are highly variable with time of day, season and latitude. In order to understand this variability it is important to understand the chemistry of mesospheric sodium and, in particular, its temperature dependence. A detailed review of the chemistry of meteoric metals has been given by Plane (2003). In the MLT, Na^+ ions and sodium bicarbonate ($NaHCO_3$) are the major reservoir species above and below the atomic sodium layer, respectively (Plane et al., 1999; Plane, 2004). The residence time of the ablated total sodium in the region between 80 and 100 km is of the order of days to weeks. This is long compared with the chemical turnover time of

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atomic Na, which is a few seconds, and the lifetime of atomic Na with respect to conversion to the reservoir species which is on the order of seconds to a few hours (Plane et al., 1998). Because of this, chemistry reaches a photochemical steady-state on the time-scales of vertical transport by eddy or molecular diffusion and thus, chemistry plays a key role in determining the atomic Na distribution. Na is converted to $NaHCO_3$ via the reactions (Plane, 2004)

$$Na+O_3 \rightarrow NaO+O_2 \quad (1)$$

$$NaO+H_2O \rightarrow NaOH+OH \quad (2)$$

$$NaOH+CO_2\ (+M) \rightarrow NaHCO_3\ (M=N_2 \text{ or } O_2) \quad (3)$$

All three reactions are fast with small temperature dependences. $NaHCO_3$ is converted back to Na by the reaction

$$NaHCO_3+H \rightarrow Na+H_2CO_3 \quad (4)$$

This reaction has a large activation energy (Cox et al., 2001), which leads to substantially faster conversion at higher temperatures and, thus, a shift in the steady-state balance from $NaHCO_3$ to Na. This temperature effect is further enhanced by the temperature dependence of the recombination of O and O_2, leading to smaller O_3 concentrations at higher temperatures and, hence, slowing down the conversion of Na to NaO at the same time as the larger O concentrations reduce NaO back to Na. The wave-driven general circulation of the middle atmosphere transports air upward in the high-latitude summer hemisphere. This upwelling cause adiabatic cooling of the air and result in very low temperatures in the polar mesosphere (well below 150 K) making the conversion from $NaHCO_3$ to Na very slow. The positive temperature dependence of Na is further reinforced by the removal of sodium species in the lower part of the sodium layer on the ice surfaces of noctilucent clouds (NLC) that form at these low temperatures. The upwelling also transports H_2O from the lower mesosphere, which further increases the rate at which Na is converted to $NaHCO_3$. The corresponding strong downward motion over the winter pole results in a temperature increase due to adiabatic heating and in a downward transport of sodium species.

Fan et al. (2007) investigated the temperature dependence of sodium number density. They found a strong positive correlation below 96 km at middle and high latitudes as expected in view of the above temperature effects on sodium chemistry. Above 96 km, on the other hand, Fan et al. (2007) suggested a strong anti-correlation between temperature and sodium atom abundance. Here, ion chemistry dominates and Na^+ ions are formed by charge transfer from ambient NO^+ and O_2^+ and by photo ionisation, both being essentially temperature-independent (Plane, 2004). The dominant path for neutralisation of Na^+ is clustering with N_2, CO_2 or H_2O, followed by dissociative electron recombination (Cox and Plane, 1998). The cluster formation gives rise to a negative temperature dependence, thus shifting the steady-state balance between Na^+ and Na towards the neutral atom at lower temperatures. At low latitudes, Fan et al. (2007) found no consistent strong correlation with temperature at any altitude. Instead there is a strong diurnal variation here apparently driven by the diurnal tide.

The next section describes the Odin/OSIRIS measurements and the sodium data retrieval. Section 3 presents global results from the years 2004–2009. Section 4 discusses these results and provides perspectives on upcoming studies with the database.

2. Method

The Odin satellite was launched in early 2001 by the Swedish National Space Board (SNSB) and the space agencies of Canada (CSA), Finland (TEKES) and France (CNES) (Murtagh et al., 2002). In the beginning Odin was a dual-mission satellite shared equally between aeronomy and astronomy, but since 2007 it is dedicated solely to aeronomy. The Optical Spectrograph and Infra-Red Imager System (OSIRIS) is one of two instruments on-board (Llewellyn et al., 2004). The Optical Spectrograph part of OSIRIS measures scattered solar radiance from the Earth's limb at wavelengths between 275 and 810 nm with a spectral resolution of about 1 nm. In its aeronomy mode Odin performs limb scanning during 15 near-polar sun-synchronous orbits each day. During the course of Odin's mission, the availability of limb scans covering the mesosphere and lower thermosphere up to 110 km has steadily increased, and comprises today more than 300 days per year. The vertical resolution of the limb measurement is typically 2 km as determined by the combination of vertical field of view and integration time. The limb measurement path through the sodium layer is typically 400 km and the cross-track field of view is 30 km.

OSIRIS' global coverage is determined by its orbit with an altitude of about 600 km and an inclination angle of 97.8°. Original equator-passing times were near 6:00 LT and 18:00 LT on the descending and ascending node, respectively. Over the years this has shifted towards 6:50 LT and 18:50 LT. As a consequence, an increasing number of evening scans do not provide useful data as they take place in darkness. The opposite is true for the morning scans. In total, 63% of the useful data in 2007–2009 comes from morning scans. In particular, equatorial measurements are today largely restricted to the morning hours. Neither evening nor morning measurements are available during the dark high-latitude winter season.

The retrieval method that converts OSIRIS limb radiances into sodium density profiles has been described in detail by Gumbel et al. (2007). At tangent altitudes above 70 km, Na D resonance scattering near 589 nm is a strong feature of the measured limb spectra. After subtracting the Rayleigh background of scattered solar radiation, vertical profiles of the pure Na D limb radiance are obtained. Optical Estimation (OEM) with a Gauss–Newton iteration is applied to retrieve vertical number density profiles (Rodgers, 2000; Gumbel et al., 2007). This includes detailed forward modelling of the Na D resonance radiative transfer. As radiative conditions are generally close to optically thin, simulations can be based on a single scattering model modified with Na D self-absorption along the incident and scattered optical path. The optimal estimation uses the seasonal lidar climatology by She et al. (2000) as a-priori input. Critical dependence on the a-priori is avoided by allowing for large a-priori variability and by verifying the consistency of converged simulated and measured limb radiance profile. 15% of the retrievals show a deviation of more than 3×10^8 ph cm^{-2} s^{-1} str^{-1} (root-mean-square) between measured and simulated limb radiance and are removed from the subsequent climatological analysis. Retrievals are also restricted to solar zenith angles (SZA) smaller than 92° in order to avoid uncertainties due to lower atmosphere influences on the optical paths. Fig. 1 shows a typical example of OSIRIS limb spectra, measured and simulated limb radiance, as well as retrieved sodium density profile.

While retrievals are based on the procedure originally described by Gumbel et al. (2007), some improvements have been added in the meantime. The calibration of the OSIRIS spectrograph applied to the sodium retrievals published earlier was preliminary as comprehensive re-calibration efforts were ongoing. Sodium retrievals reported by Gumbel et al. (2007) and Fan et al. (2007) were essentially validated by comparing with resonance lidar measurements at Fort Collins (40°N, 105°W) and at Urbana (41°N, 88°W). In the meantime, re-calibration efforts have been completed, based largely on measurements of atmospheric Rayleigh scattering and detailed radiative transfer simulations (Bourassa et al., 2008). This has confirmed the original OSIRIS calibration at 589 nm within 1%.