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Lidar Observational Study of Sodium Transport Induced by Gravity Wave Dissipation at the Mesopause (Postprint)

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Abstract

Utilizing approximately 82 hours of observational data on sodium atom number density and vertical wind obtained with a sodium temperature and wind lidar at Langfang station (40.0° N, 116.3° E) from 2011 to 2013, we present the first analysis of sodium atom transport induced by atmospheric gravity wave dissipation in the mesopause region over Langfang. The analysis reveals that the average vertical flux of sodium atoms caused by gravity wave dissipation is overall negative at 90-100 km, with sodium atoms being transported downward, reaching a maximum negative value of -1.47×10^8 m^-3 m/s at 93 km. At 85-90 km, the average vertical flux of sodium atoms is positive, indicating upward transport, but the flux value decreases with altitude. The direction of the vertical flux of sodium atoms transitions at 90 km. The variation of vertical flux with altitude causes convergence of sodium atoms, and the maximum average sodium atom production rate induced by this convergence effect reaches 1.4×10^8 m^-3/h at 91 km, a value that exceeds the peak sodium atom production rate caused by meteoric ablation injection as predicted by theoretical simulations at the same altitude, indicating that it makes an important contribution to the formation of the sodium layer structure. Compared with observational results from the United States, the peak average sodium atom production rate is similar in magnitude but occurs at a different altitude, suggesting that material transport induced by atmospheric gravity wave dissipation exhibits significant regional variations. The research results can provide observational evidence for reference to improve atmospheric material transport theory and atmospheric metal layer physical models.

Full Text

Preamble

Lidar Observations of Atmospheric Gravity Wave Dissipation-Induced Sodium Atom Transport in the Mesopause Region at Langfang, China

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Abstract

Using approximately 82 hours of sodium atom density and vertical wind observations from the sodium fluorescence Doppler lidar at Langfang station (40.0° N, 116.3° E) between 2011 and 2013, we present the first analysis of sodium atom transport induced by atmospheric gravity wave dissipation in the mesopause region over Langfang. The results show that the mean vertical sodium flux induced by gravity wave dissipation is predominantly negative between 90 and 100 km, indicating downward transport of sodium atoms, with a maximum negative value of -1.47×10 m ^{3} m/s at 93 km. Between 85 and 90 km, the mean vertical sodium flux is positive, indicating upward transport, though the flux magnitude decreases with altitude. The direction of vertical flux reverses at approximately 90 km.

The height variation of vertical flux leads to convergence of sodium atoms. The maximum mean sodium production rate resulting from this convergence effect reaches 1.4×10 m ^{3}/h at 91 km, which exceeds the peak sodium production rate from meteoric ablation injection predicted by theoretical models at the same altitude. This demonstrates that gravity wave dissipation makes a significant contribution to the formation of the sodium layer structure. Compared with observational results from the United States, the peak mean sodium production rate is similar in magnitude but occurs at a different altitude, indicating substantial geographic variability in material transport induced by atmospheric gravity wave dissipation. These findings provide observational evidence to improve atmospheric material transport theory and refine physical models of the atmospheric metal layer.

Keywords: Sodium fluorescence Doppler lidar; Atmospheric gravity wave dissipation; Sodium layer structure; Sodium atom vertical flux; Sodium atom production rate

1 Introduction

The mesopause region is characterized by particularly significant atmospheric gravity wave activity and dissipation (Gardner et al., 2002; Zhao Y et al., 2003).

Atmospheric gravity waves cause atmospheric particles to oscillate near their equilibrium positions. When gravity waves dissipate, these oscillating particles cannot return to their equilibrium positions, resulting in net transport of the particles (Walterscheid and Hocking, 1991; Walterscheid, 2001). Additionally, if particles undergo chemical reactions after leaving their equilibrium positions, this also produces transport effects (Xu Jiyao et al., 2001). Such transport represents a coupling between atmospheric waves and chemical processes (Walterscheid and Schubert, 1989). Vertical transport of atmospheric constituents is a frontier topic in research on mesopause region atmospheric structure and dynamics.

Currently, global atmospheric models such as WACCM consider only turbulent mixing mechanisms for vertical material transport and do not account for vertical transport induced by gravity wave dissipation (Liu and Gardner, 2004). Consequently, model simulations of the mesopause sodium layer differ substantially from observations (Plane, 2003). The contribution of gravity wave dissipation to the vertical transport of various atmospheric constituents remains a poorly understood problem requiring solution and parameterization.

Sodium fluorescence Doppler lidar provides an observational means to reveal the effects of gravity wave dissipation on material transport. This lidar can simultaneously measure atmospheric three-dimensional wind fields, temperature, and sodium atom number density in the mesopause region (80-110 km). Sodium atoms in the mesopause region, with their relatively long lifetime and stable state, serve as effective tracers for analyzing transport by gravity wave dissipation (Bowman et al., 1969). Liu and Gardner (2004) first used sodium lidar observations from the Starfire Optical Range (SOR) station (35.0°N, 106.5°W) to estimate the significant effects of gravity wave dissipation on sodium transport and compared these with eddy transport results, finding comparable contributions from both mechanisms. Liu and Gardner (2005) conducted comparative studies of sodium lidar data from SOR and Maui (20.7°N, 156.3°W), revealing that transport induced by gravity wave dissipation varies with geographic location. Gardner and Liu (2010) used long-term observations from SOR to characterize the seasonal variations in sodium transport and various transport velocities induced by gravity waves.

While these results have greatly advanced our understanding of gravity wave-constituent coupling processes in the mesopause region, we remain far from comprehensively grasping the transport effects of gravity wave dissipation, their global variability, and appropriate parameterization schemes. Additional observational analyses from more stations are needed to support this research. This paper presents the first results analyzing sodium transport induced by gravity wave dissipation using observations from the Langfang Near-Space Environment Observatory (40.0° N, 116.3° E) in the Eastern Hemisphere, operated by the National Space Science Center, Chinese Academy of Sciences, and compares these with observations from SOR and Maui in the United States.

2 Observation Equipment and Data Source

The sodium fluorescence Doppler lidar at Langfang station is an advanced instrument independently developed by the National Space Science Center, Chinese Academy of Sciences (Yan et al., 2009; Hu et al., 2011; Xu et al., 2010). Its detection principle is identical to similar lidars in the United States (Bills et al., 1991; She and Yu, 1994; Gardner and Yang, 1998). The lidar emits three laser beams directed toward the zenith, 20° east of zenith, and 20° north of zenith, with three telescopes receiving backscatter signals from these directions to simultaneously measure atmospheric three-dimensional wind fields, temperature, and sodium atom number density between 80 and 105 km. System parameters are listed in .

The lidar has conducted routine observations since the end of 2010, and its temperature, wind field, and sodium atom density data have been used in studies of mesopause temperature structure (Hu et al., 2011), quasi-monochromatic gravity wave characteristics (Wang et al., 2016), sporadic sodium layer analysis (Chen et al., 2016), and atmospheric model validation. This study selects 82 hours of nighttime vertical wind and sodium atom number density observations from 2010-2013 for statistical analysis of vertical transport characteristics induced by gravity wave dissipation. The observation data have a temporal resolution of 15 minutes, vertical resolution of 1 km, maximum observation duration of 8 hours in a single day, and average observation duration of 4.5 hours.

Table 1 System parameters of sodium fluorescence Doppler lidar

Parameter	Value
Laser average power	589.158 nm ±630 MHz
Laser repetition frequency	30 Hz
Laser pulse length	~7 ns
Laser divergence angle	~1 mrad
Telescope aperture	1 m

3 Analysis Methods

To statistically derive atmospheric gravity wave dissipation-induced sodium transport from the observational data, we first extract vertical wind perturbations and sodium atom number density perturbations caused by gravity waves, then use these perturbations to calculate the mean vertical sodium flux, mean sodium production rate, and their uncertainties at each altitude. The relevant analysis methods are described below.

3.1 Extraction of Atmospheric Gravity Wave Perturbations

For each night' s observations, we construct time series of vertical wind and sodium atom number density at each altitude. The linear trend of each time series is subtracted from the raw data, and the residuals are taken as the vertical wind perturbations and sodium atom number density perturbations. Given the observation data have a vertical resolution of 1 km, temporal resolution of 15 minutes, and average observation duration of 4.5 hours, the perturbation values contain information about atmospheric gravity waves with periods of approximately 30 minutes to 9 hours and vertical wavelengths greater than 2 km. All data are first subjected to a three-sigma test to remove outliers. [Figure 1: see original paper] shows an example of vertical wind perturbation extraction for December 28, 2010.

3.2 Validation of Atmospheric Gravity Wave Perturbation Data

To verify the reliability of the extracted gravity wave perturbations, we examine their statistical distributions. Atmospheric gravity wave activity can be considered a random atmospheric phenomenon, with induced geophysical variations exhibiting random distribution characteristics. According to the Central Limit Theorem, the distribution of random variables approaches a Gaussian distribution, and the cumulative distribution of numerous random variables converges pointwise to a Gaussian distribution. The vertical wind and sodium atom number density perturbations extracted from the observations represent the sum of true values and measurement errors. While photon noise follows a Poisson distribution, it tends toward a normal distribution for large photon counts. Therefore, the lidar gravity wave perturbation values (including measurement errors) conform to a Gaussian random process. In the real atmosphere, when a sufficiently large number of independent waves are present, vertical wind perturbations, sodium atom number density perturbations, and measurement errors should follow a Gaussian random distribution model with zero mean.

We fit Gaussian distributions to the extracted vertical wind perturbations and sodium atom number density perturbations, as shown in [Figure 2: see original paper]. Both perturbations follow normal distributions, with sodium atom number density perturbations concentrated primarily within ±3×10 m ^{3} and vertical wind perturbations mainly within ±10 m/s. The Gaussian fit for vertical wind perturbations is better than that for sodium atom perturbations because atmospheric waves are the direct dynamic source of vertical wind perturbations, whereas sodium atom number density variations are influenced by more complex factors, including not only wave effects but also meteoric injection, photochemical reactions, and neutral chemical reactions. Overall, both perturbation distributions conform well to the Gaussian model, indicating that the sodium atom number density and vertical wind perturbation data are reliable.

3.3 Vertical Sodium Flux Induced by Atmospheric Gravity Wave Dissipation

Theoretically, the vertical sodium flux is the product of vertical wind and sodium atom number density, as shown in equation (1). The first term on the right represents the vertical sodium flux caused by the mean background vertical wind, while the second term represents the mean vertical flux induced by atmospheric waves, with w' and Na' denoting vertical wind perturbations and sodium atom number density perturbations, respectively. The term induced by atmospheric gravity waves is the focus of this study. Notably, for non-dissipative gravity waves, the relationship between w' and Na' is orthogonal, resulting in a zero mean flux. However, when gravity waves dissipate, the originally orthogonal phase relationship between w' and Na' is altered, making the mean flux non-zero and enabling gravity wave dissipation to induce vertical transport.

Since the gravity wave perturbations extracted from the observational data in the previous section contain measurement errors, the statistical estimation of gravity wave-induced vertical sodium flux using observations is given by equation (2), where F_{GW} represents the gravity wave-induced sodium flux and Δw and ΔNa represent measurement errors in vertical wind and sodium atom number density. Equation (3) gives the mean vertical sodium flux induced by gravity waves. The mean values of gravity wave perturbations and measurement errors for each night' s observations are zero, i.e., $\overline{w'} = 0$ and $\overline{Na'} = 0$, so equation (3) shows that the statistical results for vertical sodium flux are not affected by lidar measurement errors.

For each night' s continuous lidar observations, the variance estimate of the mean vertical sodium flux is given by equation (4), where τ is the observation duration, $L = 1$ km is the vertical height resolution, $\Delta z_{GF} = 1$ km is the vertical correlation scale of sodium flux, and $\Delta t_{GF} = 15$ min is the temporal correlation scale of sodium flux (parameter values and variance derivation details are provided in Gardner and Yang, 1998). The mean squared vertical wind perturbation is denoted as $\overline{w'^2}$.

Based on the extracted vertical wind and sodium density perturbation data for each night, we use equation (3) to calculate the gravity wave-induced vertical sodium flux at each altitude. Using the observation duration τ for each night, we employ equation (4) to estimate the variance of the mean vertical sodium flux at each altitude. Equation (5) yields the variance of the mean vertical sodium flux across all nights at each altitude, and taking the square root of the equation (5) results gives the standard deviation of the mean vertical sodium flux, which serves as the uncertainty parameter at each altitude.

3.4 Sodium Production Rate Induced by Vertical Flux

Gravity wave dissipation in the mesopause region causes vertical sodium flux to vary with height, and the gradient of this flux leads to convergence or depletion of sodium atoms at different altitudes. The increase or decrease in sodium atom number density caused by gravity wave dissipation can be expressed as a local sodium production rate, as shown in equation (6), where P_{Na} represents the sodium production rate. A positive P_{Na} indicates accumulation of local sodium atoms and increased number density due to gravity wave dissipation, while a negative value indicates a depletion rate and reduced number density (Gardner and Liu, 2010). Equation (7) gives the variance of the mean sodium production rate for each night at each altitude, where τ is the observation duration, L is the vertical height range, H is the scale height, Δz_{GF} is the vertical correlation scale of sodium flux, and Δt_{GF} is the temporal correlation scale of sodium flux.

Based on the nightly mean vertical sodium flux results from equation (3), we use equation (6) to calculate the mean sodium production rate at each altitude for each night. Equation (7) yields the variance of the nightly mean sodium production rate at each altitude. Equation (8) gives the variance of the mean sodium production rate across all nights at each altitude, and taking the square root of the equation (8) results provides the standard deviation of the mean sodium production rate, which serves as the uncertainty parameter at each altitude.

3.5 Effects of Measurement Errors

Lidar measurements of vertical wind velocity and sodium atom number density both contain measurement errors. The magnitude of these errors' influence on the estimates is crucial to the reliability of the mean vertical sodium flux and production rate statistics. From the mean vertical sodium flux estimation equation (3) and the mean sodium production rate estimation equation (6), measurement errors do not affect these estimated values. Therefore, the estimated mean vertical sodium flux and mean production rate are reliable.

However, equations (4) and (7) show that the variance of the nightly mean vertical sodium flux and sodium production rate is influenced not only by measurement errors Δw and ΔNa but also by geophysical variations in the atmospheric gravity wave perturbations w' and Na' (Fritts, 2000). To reduce the statistical variance and ensure that the mean vertical flux and mean production rate have clear physical meaning, we increase the temporal and spatial scales of the observational data. In this study, we use 82 hours of data on a temporal scale and 1 km vertical spatial scale to produce statistically meaningful results.

4 Results

4.1 Sodium Layer Structure

Averaging all sodium atom density profiles yields the mean sodium atom number density profile over Langfang, shown in [Figure 3: see original paper]. The mean vertical profile of sodium atom number density over Langfang exhibits a quasi-Gaussian distribution, with a sodium layer peak height of 90 km, centroid height of 91 km, and maximum mean number density of 3.17×10 m ^{3}. The source of mesopause metal sodium is meteoric ablation in the atmosphere, and sodium atom number density variations are also influenced by the ionosphere, photochemical reactions, and atmospheric wave effects (Hedin and Gumbel, 2011). Solar radiation directly affects photochemical reactions involving sodium ions in the upper mesopause (Mcneil et al., 2002). Changes in active species concentrations such as O and OH in the mesopause region influence neutral chemical reactions involving sodium atoms and their compounds (Plane and Helmer, 1994), with notable effects on sodium atoms and compounds in the middle and lower portions of the sodium layer. Gravity waves, tides, and other atmospheric waves along with small-scale eddies provide energy for sodium atom motion and transport, causing vertical transport and mixing of sodium atoms (Fritts and Alexander, 2003). These factors interact and collectively shape the quasi-Gaussian distribution of the sodium layer structure.

4.2 Vertical Sodium Transport Induced by Atmospheric Gravity Wave Dissipation

[Figure 4: see original paper] shows the mean vertical sodium flux profile and its error bars, smoothed with a 5 km Hamming window. Positive values indicate upward transport, negative values indicate downward transport, and error bars represent uncertainties expressed as the standard deviation of the mean vertical sodium flux. The error bar magnitude does not affect the determination of positive or negative values for flux maxima and minima. The figure clearly shows that the sodium flux reverses direction near the 90 km sodium layer peak height (see [Figure 3: see original paper]). Below 90 km, the sodium flux is positive (upward transport); above 90 km, it is negative (downward transport), reaching a minimum value of -1.47×10 m^{3} m/s at 93 km. Near 97 km, the sodium flux approaches zero.

[Figure 5: see original paper] presents the sodium production rate profile and its error bars, also smoothed with a 5 km Hamming window. Error bars represent uncertainties expressed as the standard deviation of the mean sodium production rate. Below 93.5 km, the sodium production rate is positive, indicating a net increase in sodium atom number density per unit time due to gravity wave dissipation. The maximum mean sodium production rate reaches 1.47×10 m^{3}/h at 91 km. The sodium layer centroid height coincides with the height of maximum sodium production rate, demonstrating that gravity wave dissipation-induced transport causes sodium atom accumulation near the 91 km centroid height and likely plays an important role in forming the peak structure characteristics near the sodium layer centroid.

compares the statistical results from Langfang station (40.0°N, 116.3°E) with those from the SOR (35.0°N, 106.5°W) and Maui (20.7°N, 156.3°W) stations (Liu and Gardner, 2005). The table shows that the minimum vertical sodium flux and maximum sodium production rate are comparable across the three regions, but the mean profile trends differ. At SOR and Maui, the vertical sodium flux is predominantly negative between 85 and 100 km, with maximum negative values near 87 km and 88 km, respectively, and maximum sodium production rates near 86 km. At Langfang, the sodium flux is positive between 85 and 90 km, with the maximum negative value near 93 km and the maximum production rate near 91 km. These differences likely arise from geographic and other conditional variations. Currently, global observations of vertical sodium transport remain limited, and further data analysis is needed to understand these differences.

Table 3 Comparison of vertical sodium flux and sodium production rate among Langfang, SOR, and Maui stations

Station	Minimum Vertical Flux & Height	Maximum Production Rate & Height
Langfang (40.0°N, 116.3°E)	-1.5×10 m ^{3} m/s ~93 km	1.4×10 m ^{3}/h ~91 km
SOR (35.0°N, 106.5°W)	-2.6×10 m ^{3} m/s ~87 km	2.8×10 m ^{3}/h ~86 km
Maui (20.7°N, 156.3°W)	-0.8×10 m ^{3} m/s ~88 km	1×10 m ^{3}/h ~86 km

4.3 Discussion

The quasi-Gaussian structure of the sodium layer is generally considered to be influenced by five primary factors. First, meteoric ablation injection effects: since the sodium layer altitude coincides with meteoric ablation altitudes, sodium atoms produced by meteoric ablation are directly injected near the 90 km sodium layer peak (Plane, 2004). Second, ion chemistry processes: above 90 km, ion chemistry dominates, with some Na undergoing ion reactions with NO and O to become Na , and some Na being directly ionized by solar radiation to Na , with Na number density peaking near 100 km (Mcneil et al., 2002). Third, neutral chemistry processes: below 85-90 km, neutral chemical reactions dominate, with Na atoms reacting with O , H , and CO to form stable NaHCO that deposits to lower altitudes, with NaHCO number density peaking near 85 km. Model calculations show that Na and NaHCO number densities are 0.2-0.3 times the Na atom number density peak, indicating limited contributions from ion and neutral chemistry processes to the sodium layer peak (Plane, 2004). Fourth, eddy transport processes: between 85 and 95 km, eddies produce uniform mixing that transports sodium atoms to lower altitudes, negatively affecting the formation of the quasi-Gaussian peak structure (Liu and Gardner, 2004). Fifth, atmospheric gravity wave transport: gravity wave dissipation-induced vertical sodium flux causes accumulation or depletion of sodium atoms in the vertical direction, with the sodium production rate from gravity wave dissipation at 92 km being comparable to that from meteoric ablation injection (Gardner and Liu, 2010). Thus, the accumulation effect from gravity wave dissipation and the injection effect from meteoric ablation both play important roles in forming the sodium layer peak structure.

Our results show that gravity wave dissipation-induced transport over Langfang causes sodium atom convergence near the centroid height of 91 km. Plane (2004) used the NAMOD model and LDEF (Long Duration Exposure Facility) observational data to analyze meteoric ablation altitudes, efficiencies, and injection rates of sodium atoms in the MLT region, finding that meteors with average velocities of 18 km/s produce a peak sodium production rate of 2.5×10 m ^{3}/h at 92 km through ablation injection. The Langfang results show a peak production rate of 1.4×10 m ^{3}/h at 91 km, exceeding the peak production rate from meteoric ablation injection. These observations further demonstrate that the contribution of gravity wave dissipation to sodium layer distribution and peak formation cannot be neglected, and atmospheric models that currently omit this transport mechanism require improvement.

5 Conclusion

This study presents the first analysis of sodium atom vertical transport induced by mesopause gravity wave dissipation and its impact on sodium layer structure using sodium atom number density and vertical wind observations from the sodium fluorescence Doppler lidar at Langfang station, National Space Science Center, Chinese Academy of Sciences. Over Langfang, the mean vertical sodium flux induced by gravity wave dissipation is positive below 90 km (upward transport) and negative above 90 km (downward transport), reaching a maximum negative value of -1.47×10 m ^{3} m/s at 93 km. The sodium production rate at the 91 km sodium layer centroid reaches a maximum value of 1.47×10 m ^{3}/h, exceeding the peak sodium production rate from theoretical calculations of meteoric ablation injection, indicating that gravity wave dissipation-induced transport significantly influences the formation of the entire sodium layer structure.

Compared with observations from SOR and Maui in the United States, the Langfang results are generally consistent, but the altitude of flux direction reversal and the peak production rate differ, demonstrating that gravity wave dissipation-induced transport exhibits geographic characteristics.

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