Wave Induced Transport of Atmospheric Constituents and Its Effect on the Mesospheric Na Layer

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1. Introduction

Wave induced vertical transport of atmospheric species through mixing, displacement, chemistry and advection, plays a crucial role in establishing the constituent structure of the middle atmosphere. Eddy transport by turbulent mixing leads to a net transport of constituents from regions of higher concentrations to those of lower concentrations. Dynamical transport arises when wind fluctuations associated with dissipating, non-breaking waves impart a net vertical displacement in the constituent as they propagate through a region. Chemically induced transport of reactive species occurs when vertical advection by wave-induced winds alters the chemical production and loss of the species. The upwelling/downwelling associated with the meridional circulation forced by gravity waves also contributes to the vertical transport of constituents.

We explore the transport of atomic Na and its effect on the mesospheric Na layer using extensive observations conducted at the Starfire Optical Range (SOR), Albuquerque, New Mexico with a Na wind/temperature lidar system. The data are used to characterized the seasonal variations of the vertical flux of atomic Na through the mesopause region. From theoretical considerations, we use the measurements to infer the net displacement velocity associated with the dynamical transport by dissipating waves, and the chemically induced transport velocity associated with the advection of Na bearing species by both dissipating and non-dissipating waves. We compare these measurements with the effective eddy transport velocity based upon commonly assumed values for the diffusion coefficient and with vertical drift velocities above SOR that were inferred from the mean meridional winds.

2. Wave Induced Vertical Flux of Na

We employ 370 hours of mesopause region vertical and horizontal winds, temperature and Na density measurements conducted throughout the year with a steerable lidar system at SOR (35N, 106.5W). The wave induced vertical flux of a constituent is defined as the expected value of the product of the fluctuations in vertical wind w' and constituent number density ρ_C'. Wind, temperature and Na density profiles were derived from the SOR lidar measurements at 500 m vertical and 90 s temporal resolutions. Monthly mean profiles of Na density $\overline{\rho}_{Na}$ and the vertical flux of Na $\overline{w'\rho_{Na}'}$ were computed according to the procedures used in *Gardner and Liu* [2007] for computing the heat and momentum fluxes. All the Na density and flux profiles measured during a given month were averaged and then smoothed vertically using a Hamming window of 2.5 km FWHM.

The measured flux profiles include important short vertical-scale, high-frequency waves that are most susceptible to dissipation and make the largest contributions to the vertical constituent fluxes. The measurements include the effects of the dynamical and chemical transport by non-breaking gravity waves. However, the flux measurements do not include the effects of eddy mixing or advective transport.

The dominant seasonal variations were determined by fitting the monthly mean densities and vertical fluxes to a model that includes the annual mean plus 12- and 6-month oscillations. The fitted seasonal variations of Na density and vertical flux are shown in Figure 1.

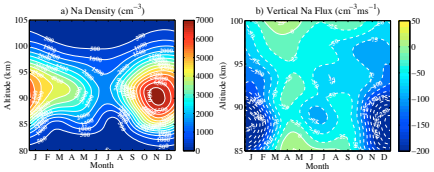


Figure 1. Seasonal variations of the a) mesospheric Na density and b) vertical flux of Na measured at the SOR.

The Na densities exhibit strong seasonal variations with minimum in mid-summer and maximum in November. This is driven primarily by temperature dependent chemistry and to a lesser extent by the meteoric input [*McNeil et al.*, 1995]. The Na flux also exhibits strong seasonal variations, which arise in part because of the seasonal variations of the Na densities. The largest downward Na fluxes (~ -280 ms^{-1}cm^{-3} at 88 km) occur just below the peak of the Na layer in mid winter when the densities are also largest.

The vertical structure and seasonal variations of the Na fluxes are consistent with the observed behavior in gravity wave activities reported by *Gardner and Liu* [2007]. Figure 2 shows the gravity wave variance in temperature and wind. It is clear that both temperature and wind variances are large during solstices and small during equinoxes.

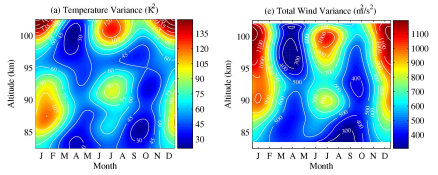


Figure 2. Seasonal variation of the temperature variance (left) and total wind variance (right) due to gravity waves at SOR.

3. Production Rate of Na Due to Flux Convergence

The production rate of Na due to vertical flux convergence is

$$P_{Na} = -\frac{\partial \overline{w'\rho_{Na}'}}{\partial z}$$

The seasonal variations of the Na production rate at SOR are shown in Figure 3. The production rates are significant compared with the primary source of mesospheric Na, meteoric ablation, which is estimated to be about 25 cm^{-3}hr^{-1} at 92 km, based on the 2.5×10^7 cm^{-2}hr^{-1} average meteoric input of Na.

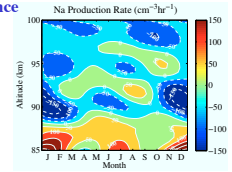


Figure 3. Seasonal variations of Na production rate associated with Na flux by gravity waves.

4. Theoretical Relationship Between Heat and Constituent Fluxes

The density response of the neutral atmosphere or of an atmospheric layer composed of a neutral constituent is

$$\frac{\partial \rho_C}{\partial t} + \nabla \cdot \left(\rho_C \mathbf{V}\right) = P - L$$

Gardner and Shelton [1985] have shown that the density response to wind fluctuations may be written in the form

$$\rho_C(\mathbf{p},t) = e^{-z}\rho_{C0}(z-\zeta)$$

where the parameters $\chi(\mathbf{p},t)$ and $\zeta(\mathbf{p},t)$ are solutions to the equations

$$\frac{\partial \chi}{\partial t} = \nabla \cdot \mathbf{V} - \mathbf{V} \cdot \nabla \chi \qquad \frac{\partial \zeta}{\partial t} = w - \mathbf{V} \cdot \nabla \zeta$$

Assuming that the perturbations are Gaussian distributed, the mean vertical wind and divergence of the mean wind are negligible, we find that the dynamical constituent flux is directly proportional to the heat flux

$$\left\langle w'\rho_C' \right\rangle = \frac{g/R - \Gamma_{ad}}{\Gamma_{ad} + \partial\langle T\rangle/\partial z} \frac{\langle \rho_C \rangle}{\langle T \rangle} \langle w'T' \rangle$$

The theoretical covariance between the temperature and constituent fluctuations can also be derived:

$$\left\langle T'\rho_C' \right\rangle = \frac{g/R - \Gamma_{ad} - \langle T\rangle/H_C}{\Gamma_{ad} + \partial\langle T\rangle/\partial z} \frac{\langle \rho_C \rangle}{\langle T \rangle} \langle T'^2 \rangle$$

where H_C is the scale height of the mean constituent density profile.

The dynamical flux can be expressed as the product of the mean constituent density and an effective vertical transport velocity, which depends only on the heat flux and temperature profiles:

$$w_{Dyn} = \frac{\left\langle w'\rho_C' \right\rangle}{\langle \rho_C \rangle} = \alpha_T w_{Heat}, \quad w_{Heat} = \frac{\langle w'T' \rangle}{\langle T \rangle}, \quad \alpha_T = \frac{g/R - \Gamma_{ad}}{\Gamma_{ad} + \partial\langle T\rangle/\partial z}$$

In an isothermal atmosphere, the constituent transport is about 2.5 times as fast as the heat transport.

Like the dynamical flux, the eddy flux can also be expressed as

$$w_{Mix} = \alpha_C w_{Diff}, \quad w_{Diff} = -\frac{K_{zz}}{H}, \quad \alpha_C = 1 - H\left(\frac{1}{H_C} - \frac{1}{\langle T\rangle}\frac{\partial\langle T\rangle}{\partial z}\right)$$

The scale factor α_C depends on the constituent scale height. It can reach 2-5 where the constituent volume mixing ratio exhibits steep vertical gradients.

In addition, the observed Na transport velocity was computed by $w_{Na} = \left\langle w'\rho_{Na}' \right\rangle / \langle \rho_{Na} \rangle$

The dynamical flux depends only on the constituent density profile, while the eddy flux depends on both the density profile and its vertical gradient. While the dynamical flux is generally downward, the eddy flux can have strong upward components in regions where the constituent scale height is small and positive, such as the topside of the Na layer. The seasonal variations of the three transport velocities are shown in Figure 4.

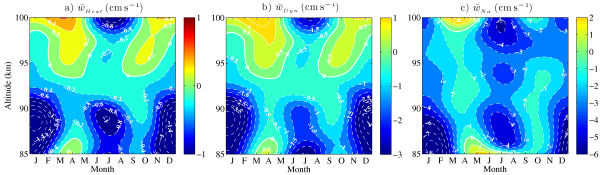


Figure 4. Seasonal variation of the wave induced transport velocities for (a) heat, (b) inert constituents, and (c) Na.

All three measured transport velocities are generally downward through the mesopause region. They vary strongly with altitude and exhibit prominent annual and semiannual oscillations. Weakest transport occurs at the equinoxes when the average values of all three velocities between 85 and 100 km are nearly zero.

The largest heat transport velocities, in excess of -1 cms^{-1}, occur in midwinter and midsummer between 85 and 90 km where convective instabilities dominate [*Gardner and Liu*, 2007]. The inferred dynamical transport velocities exhibit a similar pattern but average about 3 times as large. The directly measured Na transport velocities also exhibit the same general altitude and seasonal behavior but average about 3 times as large as w_{Dyn} and 9 times as large as w_{Heat}.

5. Wave-Induced Chemical Transport of Na

The difference between w_{Dyn} and w_{Na} are primarily related to Na chemistry. Figure 5 shows the theoretical correlation between the temperature and constituent fluctuations for an inert species with a Gaussian shaped density profile that is similar to the annual mean Na density, and the measured correlation between the temperature and Na fluctuations. Their differences suggest that the chemical effects altered the simple linear relationships between the Na and temperature fluctuations. The observed chemically induced transport velocity for Na is $w_{ChemNa} = w_{Na} - w_{Dyn}$, which is shown in Figure 6.

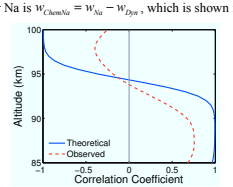


Figure 5. Theoretical (solid) and observed (dashed) correlation between the temperature and constituent fluctuations.

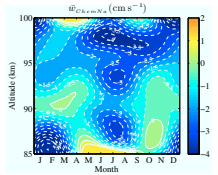


Figure 6. Seasonal variations of the chemically induced transport velocities for atomic Na.

The chemical transport is generally downward with a maximum of 8 cms^{-1} in February near 85 km. It is especially strong during summer throughout the 85-100 km region when the vertical wind variance is also the strongest [*Gardner and Liu*, 2007].

6. Comparison of Transport Velocities

The advective and eddy transport velocities are calculated using the vertical mean velocities inferred from the measured meridional wind and the eddy diffusion coefficients from WACCM. All four transport velocities are compared for their annual mean and vertical mean in Figure 7.

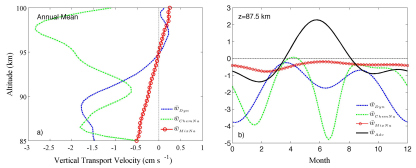


Figure 7. (a) Annual mean profiles of the dynamical (blue), chemical (green), and eddy (red) transport velocities for atomic Na. (b) Seasonal variations of the Na transport velocities at 87.5 km, including the advective transport (black) derived from the vertical drift velocity. Zero velocities are denoted by dotted lines.

7. Conclusions

Extensive observations of winds, temperatures, and Na densities between 80 and 105 km at the SOR are used to characterize the seasonal variations of the vertical flux of atomic Na and its impact on the Na layer. The largely downward Na flux and its convergence enhance the transport of Na from meteoric sources above 90 km to chemical sinks below 85 km, altering the height, width, and abundance of the Na layer. It is shown that the effective vertical velocity associated with dynamical transport by dissipating waves is the same for all species and is about 3 times faster than the effective heat transport velocity. Dynamical transport is generally downward with velocities as high as −5 cm s^{-1} below 90 km in midwinter when and where gravity wave activity and dissipation are strongest. Chemically induced transport of atomic Na by both dissipating and non-dissipating waves is also significant so that the total effective transport velocity for Na below 90 km approaches −8 cm s^{-1} in midwinter. The observations show that at the solstices, dynamical and chemical transport play far more important roles than turbulent mixing in transporting Na downward, while at the equinoxes the impacts of all three wave-induced transport mechanisms are comparable. These results have important implications for chemical modeling of the mesopause region.

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