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 chemical structure of the middle atmosphere. Early transport by turbulent mixing leads to a net transport of constituents from regions of high concentrations to those of lower concentrations. Dynamical transport occurs when wind fluctuations associated with dissipating non-breaking waves impact a net vertical transport in the constituent that they propagate through a region. Chemically induced transport is only important for reactive species when vertical advection by wave-induced winds alters the chemical production and loss of the species. The coupling between the wave-induced currents and gravity waves also contribute 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. The Na lidar is used to measure the seasonal variations of the vertical flux of atomic Na through the mesosphere region. From theoretical considerations, we use the mean Na flux to infer the net displacement velocity associated with the dynamical transport by dissipating waves, and the chemically induced transport velocity associated with the Na bearing species by both dissipating and non-dissipating waves. We compare these measurements with the effective eddy transport velocity based on commonly measured values for the diffusion coefficient and with vertical drift velocities above SOR that were inferred from the measured Na vertical motions.

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 laser system at SOR (35N, 106W). The wave induced vertical fluxes of a constituent is defined as the expected value of the product of the fluctuations in vertical wind u and constituent density number N.

WIND, wind, temperature and Na density profiles were derived from the SOR lidar measurements at SOR of vertical and horizontal resolutions. Monthly mean profiles of Na density N and Na vertical velocity u were computed according to the procedures used in Gardner and Liu (2005) 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 seasonal Na density and vertical flux are shown in Figure 1.

3. Production Rate of Na Due to Flux Convergence
The production rate of Na due to vertical flux convergence is

\[ \dot{N}_a = -\frac{1}{\rho_N} \frac{\partial}{\partial z} \left( \rho_N w \right) \]

where \( \rho_N \) is the Na density and \( w \) is the vertical Na velocity. 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 km\(^{-2}\) at 92 km, based on the 2-5×10\(^{19}\) cm\(^{-2}\) average mesospheric Na density.

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

\[ \frac{\partial N}{\partial t} = -\nabla \cdot (\mathbf{N} \mathbf{V}) + \frac{\partial}{\partial z} \left( L_w \frac{\partial T}{\partial z} \right) + \frac{\partial}{\partial z} \left( \mathbf{N} \mathbf{C} \frac{\partial T}{\partial z} \right) + \frac{\partial}{\partial z} (\mathbf{N} \mathbf{w}) \]

The theoretical relationship between the chemical and constituent fluxes can also be derived:

\[ \frac{\partial N}{\partial t} = \alpha \frac{\partial w}{\partial z} \]

where \( \alpha \) is the scale height of the Na and 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:

\[ \mathbf{N} \mathbf{w} = \alpha \mathbf{N} \mathbf{V} = \alpha \mathbf{N} \left( \nabla \cdot (\mathbf{N} \mathbf{V}) \right) + \frac{\partial}{\partial z} \left( L_w \frac{\partial T}{\partial z} \right) + \frac{\partial}{\partial z} \left( \mathbf{N} \mathbf{C} \frac{\partial T}{\partial z} \right) \]

5. Wave-Induced Chemical Transport of Na
The difference between \( \dot{N}_w \) and \( \dot{N}_w \) 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 average annual 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 chemical transport is generally downward with a maximum of 8 cm\(^{-2}\) 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 advection and eddy transport velocities are calculated using the vertical mean velocities inferred from the measured Na vertical and eddy diffusion coefficients from WACCM. All four transport velocities are compared for their annual mean and vertical mean in Figure 7.

7. Conclusions
Extensive observations of winds, temperatures, and Na densities between 80 and 105 km at SOR are used to characterize the seasonal variations of the vertical fluxes of atomic Na and its impact on the Na layer. The largely downward Na flux and its correlation allow the transport of Na from mesospheric 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\(^{-}\) below 90 km in midsummer and when and when 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 approaches ~8 cm\(^{-}\)s\(^{-}\) 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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References