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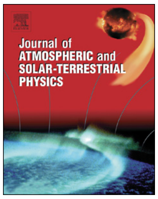

Vertical and horizontal transport of mesospheric Na: Implications for the mass influx of cosmic dust

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ABSTRACT

The mesospheric metal layers are formed by the vaporization of high-speed cosmic dust particles as they enter the Earth's upper atmosphere. We show that the downward fluxes of these metal atoms, induced locally by waves and turbulence, are related in a straightforward way to the meteoric influxes of the metals, their chemical losses and their advective transport by the large-scale vertical and horizontal motions associated with the meridional circulation system. Above the peak of the metal layers where chemical losses and large-scale vertical motions are small, the wave-induced flux is insensitive to changes in local wave activity. If the downward transport velocity increases, because wave activity increases, then in response, the metal densities will decrease to maintain a constant vertical flux. By fitting the theoretical Na flux profile to the annual mean vertical flux profile measured during the night at the Starfire Optical Range, NM, we derive improved estimates for the global influxes of both Na and cosmic dust. The mean Na influx is 22,500 ± 1050 atoms/cm^2/s, which equals 389 ± 18 kg/d for the global input of Na vapor. If the Na composition of the dust particles is identical to CI chondritic meteorites (4990 ppm by mass), then the global influx of cosmic dust is 176 ± 38 t/d. If the composition is identical to ordinary chondrites (7680 ppm), the global dust influx is 107 ± 22 t/d.

1. Introduction

Fe, Mg and Na are the most abundant gas-phase metal species in the mesosphere and lower thermosphere (MLT). During the last two decades our understanding of the chemistry and physics of these metal layers has improved significantly, in large part because of extensive lidar and satellite observations, chemical modeling and laboratory studies of key reactions (e.g. McNeil et al., 1995, 2002; Plane, 2003; Marsh et al., 2013; Plane et al., 2015). The metal layers are formed by meteoric ablation between about 70 and 120 km. Various dynamical processes transport the vaporized atoms and ions downward to chemical sinks below 90 km, where they form stable compounds, which then polymerize to form meteoric smoke particles. This meteoric debris is advected to the winter pole by the prevailing winds where it eventually settles onto the surface. Although the ablation and sputtering processes and the metal chemistry in the upper atmosphere, are reasonably well understood, there is still considerable uncertainty in the absolute influx of the metals and their transport downward and poleward (Vondrak et al., 2008; Plane, 2012; Plane et al., 2015; Carrillo-Sánchez et al., 2015; Gardner and Liu, 2016).

Between 80 and 100 km, the chemical loss rates of Fe, Mg and Na, due to their reactions with O_3, are significant. However, this reaction produces the metal oxide, which reacts with O, to quickly recycle the metals back to their atomic forms. Because of this recycling, these metals behave much like inert species above 90 km, where the meteoric influx is balanced by downward transport to maintain the steady state layer profiles. Below 90 km, where the O density decreases rapidly with decreasing altitude, while the atmospheric density and the densities of CO_2, H_2O and H_2 increase, this recycling is inhibited as the metals are tied up in the more stable compounds FeOH, Mg$(OH)_2$ and $NaHCO_3$. When these compounds form dimers or polymermize with other meteoric constituent molecules, the metals are permanently removed from the gas phase. Above about 95 km, reactions of all three metals with O_2^+ and NO^+

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create metals ions. Of course, during the day, photo-ionization is an additional loss process for these metals. In this way, Fe, Mg and Na are slowly depleted between 80 and 100 km as they are transported downward and converted, at least temporarily, to Fe^+, Mg^+, Na^+, FeOH, $Mg(OH)_2$, and $NaHCO_3$. These losses influence both the metal atom densities and their vertical fluxes.

In this paper we focus on the vertical and horizontal transport of mesospheric Na. By assuming that Na is in chemical and dynamical equilibrium (i.e. the steady state Na density is constant), we show how the vertical flux of atomic Na, induced by waves and turbulence, is related in a straightforward way, to the meteoric influx of Na, its chemical loss and the effects of large-scale vertical and horizontal motions. The results are used to infer the global meteoric influx of Na vapor from the extensive lidar measurements of Na flux and other key atmospheric parameters made at the Starfire Optical Range (SOR), NM (35.0°N, 106.5°W) (Gardner and Liu, 2007 and 2010).

2. Na chemistry, transport and continuity

The rate of change of Na density is governed by the continuity equation. We assume that Na is in chemical and dynamical equilibrium so that in the steady state, the mean Na density is constant with respect to time, in which case the continuity equation is given by

$$\nabla \bullet \left(\overline{\underline{V}[Na]} \right) = \bar{\mu}_{Na} + (\bar{P}_{Na} - \bar{L}_{Na})$$

where

$[Na] = Na$ density (cm^{-3})

$\underline{V}$ = wind velocity vector (cm/s)

$\underline{V}[Na]$ = total Na flux $(cm^{-2}s^{-1})$

μ_{Na} = meteoric influx rate of Na $(cm^{-3}s^{-1})$

P_{Na} = chemical production rate of Na $(cm^{-3}s^{-1})$

L_{Na} = chemical loss rate of Na $(cm^{-3}s^{-1})$, (1)

where the overbar denotes the mean quantity. The total flux divergence, expressed in the Earth's spherical coordinates, is

$$\nabla \bullet \left(\underline{V}[Na] \right) = \frac{1}{(r_E + z)\cos\phi} \left[\frac{\partial}{\partial\theta}\left(u[Na]\right) + \frac{\partial}{\partial\phi}\left(v[Na]\cos\phi\right) \right] + \frac{\partial}{\partial z}\left(w[Na]\right), \tag{2}$$

where r_E=6371 km is the mean Earth radius, θ is the longitude, ϕ is the latitude (negative in the southern hemisphere) and u, v and w, are respectively the zonal, meridional and vertical wind velocities. The flux divergence is dominated by global scale variations in wave and solar forcing of the meridional circulation system and by wind fluctuations induced locally by waves and turbulence. We simplify (2) by averaging the flux divergence zonally, which eliminates the zonal wind term. In this case, the mean flux divergence is

$$\nabla \bullet \left(\overline{\underline{V}[Na]} \right) = \frac{1}{(r_E + z)\cos\phi} \frac{\partial}{\partial\phi}\left(\bar{v}[\overline{Na}]\cos\phi + \overline{v'[Na]'}\cos\phi \right) + \frac{\partial}{\partial z}\left(\bar{w}[\overline{Na}] + \overline{w'[Na]'} \right)$$

where

$\bar{v}(\phi, z)$ = zonal mean meridional wind velocity $(cm\ s^{-1})$

$\bar{w}(\phi, z)$ = zonal mean vertical wind velocity $(cm\ s^{-1})$

$[\overline{Na}]$ = zonal mean Na density (cm^{-3})

$\bar{v}[\overline{Na}]$ = *meridional* advective flux of Na induced by large –scale horizontal motions $(cm^{-2}s^{-1})$

$\overline{v'[Na]'}$ = *meridional* flux of Na induced locally by waves and turbulence $(cm^{-2}s^{-1})$

$\bar{w}[\overline{Na}]$ = vertical advective flux of Na induced by large –scale vertical motions $(cm^{-2}s^{-1})$

$\overline{w'[Na]'}$ = vertical flux of Na induced locally by waves and turbulence $(cm^{-2}s^{-1})$, (3)

where the prime denotes the perturbed quantity. Several studies have suggested that meridional transport by planetary waves and tides in the lower thermosphere can be significant [e.g. Liu, 2007; Yue and Liu, 2010). However to simplify (3), we assume that the meridional gradient of the wave-induced meridional Na flux is sufficiently small

$$\left| \frac{1}{(r_E + r)\cos\phi} \frac{\partial}{\partial\phi}\left(\overline{v'[Na]'}\cos\phi \right) \right| \ll \left| \bar{\mu}_{Na} \right| + \left| \bar{P}_{Na} - \bar{L}_{Na} \right|, \tag{4}$$

that this term can be neglected.

By substituting (3) in (1), noting (4), rearranging terms and integrating over z, we find that total vertical Na flux is

$$\bar{w}[\overline{Na}] + \overline{w'[Na]'} = -\int_z^\infty \bar{\mu}_{Na}dr - \int_z^\infty \left(\bar{P}_{Na} - \bar{L}_{Na} \right)dr + \int_z^\infty \frac{1}{(r_E + r)\cos\phi} \frac{\partial}{\partial\phi}\left(\bar{v}[\overline{Na}]\cos\phi \right)dr. \tag{5}$$

The influx and outflow contributions associated with meridional transport depend on the latitudinal variations of the large-scale (zonal mean) meridional wind field and Na density, while the vertical advective flux depends on the large-scale (zonal mean) vertical motions. The meridional and vertical winds are related through the continuity equation for an incompressible fluid

$$\nabla \bullet \underline{V} = \frac{1}{(r_E + z)\cos\phi} \left[\frac{\partial u}{\partial\theta} + \frac{\partial(v\cos\phi)}{\partial\phi} \right] + \frac{\partial w}{\partial z} = 0, \tag{6}$$

which for zonal mean quantities can be expressed as

$$\frac{\partial\bar{w}(\phi, z)}{\partial z} = \frac{-1}{(r_E + z)\cos\phi} \frac{\partial}{\partial\phi}\left[\bar{v}(\phi, z)\cos\phi \right]$$

or

$$\bar{w}(\phi, z) = \int_z^\infty \frac{1}{(r_E + r)\cos\phi} \frac{\partial}{\partial\phi}\left[\bar{v}(\phi, r)\cos\phi \right]dr. \tag{7}$$

By applying (7) to the last term in (5), we obtain

$$\begin{aligned} &\int_z^\infty \frac{1}{(r_E + r)\cos\phi} \frac{\partial}{\partial\phi}\left(\bar{v}[\overline{Na}]\cos\phi \right)dr \\ &= \int_z^\infty \frac{[\overline{Na}]}{(r_E + r)\cos\phi} \frac{\partial}{\partial\phi}\left(\bar{v}\cos\phi \right)dr + \int_z^\infty \frac{\bar{v}}{(r_E + r)} \frac{\partial[\overline{Na}]}{\partial\phi}dr \\ &= -\int_z^\infty [\overline{Na}] \frac{\partial\bar{w}}{\partial r}dr + \int_z^\infty \frac{\bar{v}}{(r_E + r)} \frac{\partial[\overline{Na}]}{\partial\phi}dr = \bar{w}[\overline{Na}] \\ &+ \int_z^\infty \bar{w} \frac{\partial[\overline{Na}]}{\partial r}dr + \int_z^\infty \frac{\bar{v}}{(r_E + r)} \frac{\partial[\overline{Na}]}{\partial\phi}dr. \end{aligned} \tag{8}$$

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