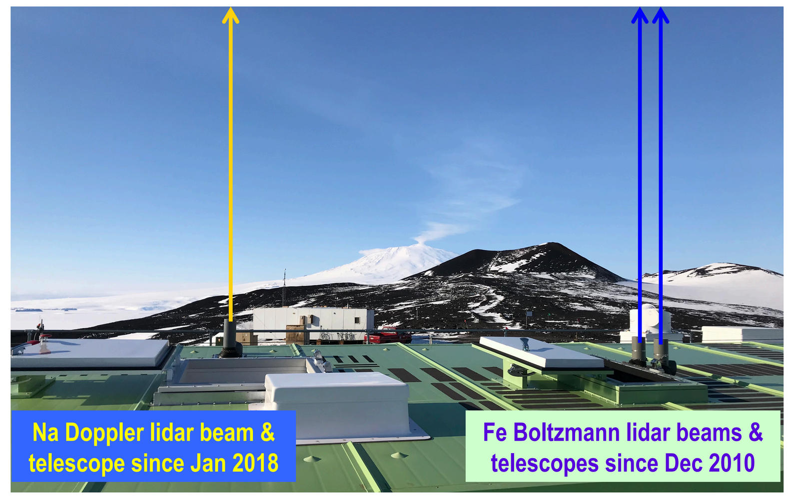

Surprising Results of Sensible Heat and Meteoric Na Fluxes in the Mesosphere and Lower Thermosphere Measured by Lidar at McMurdo, Antarctica

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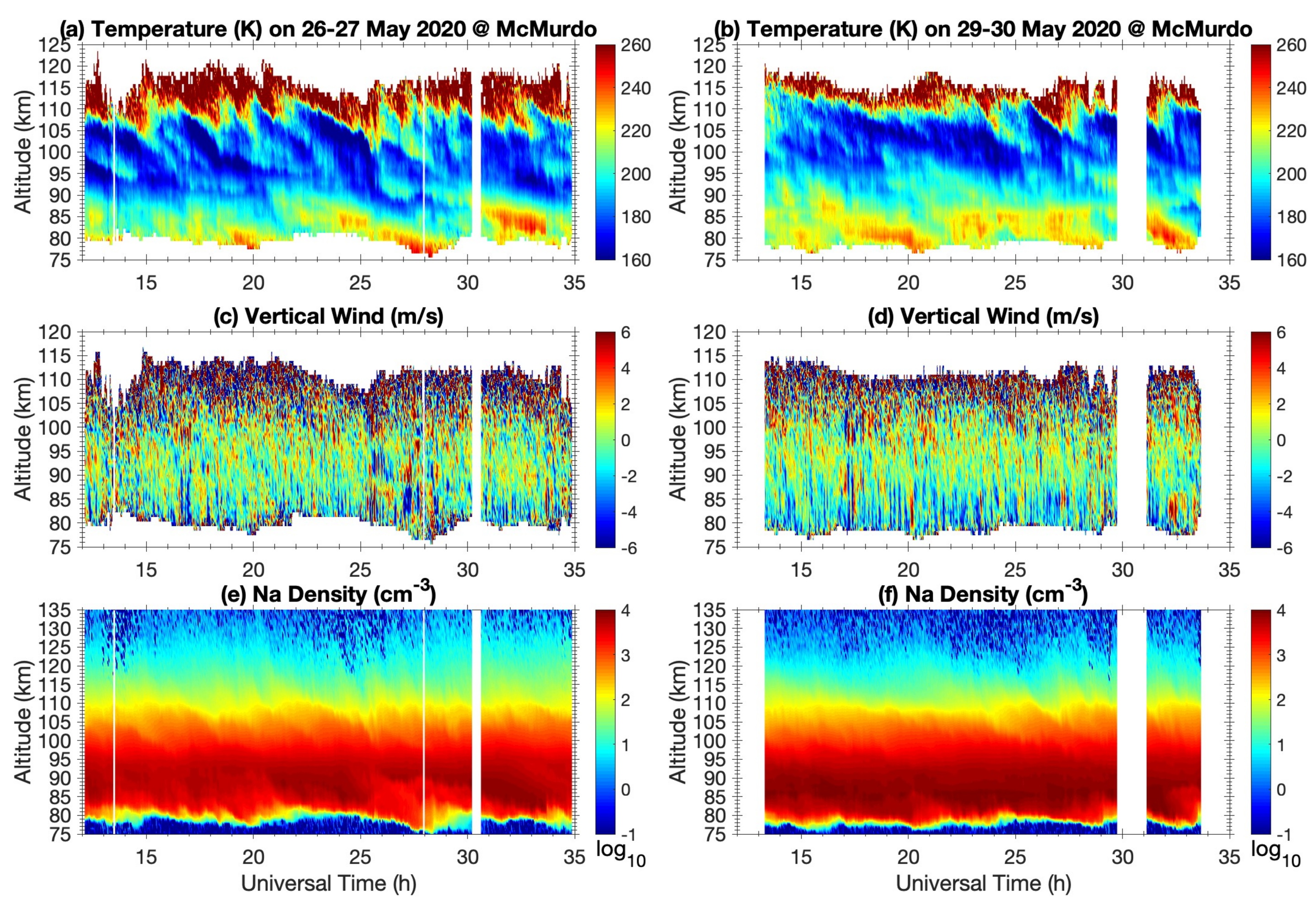
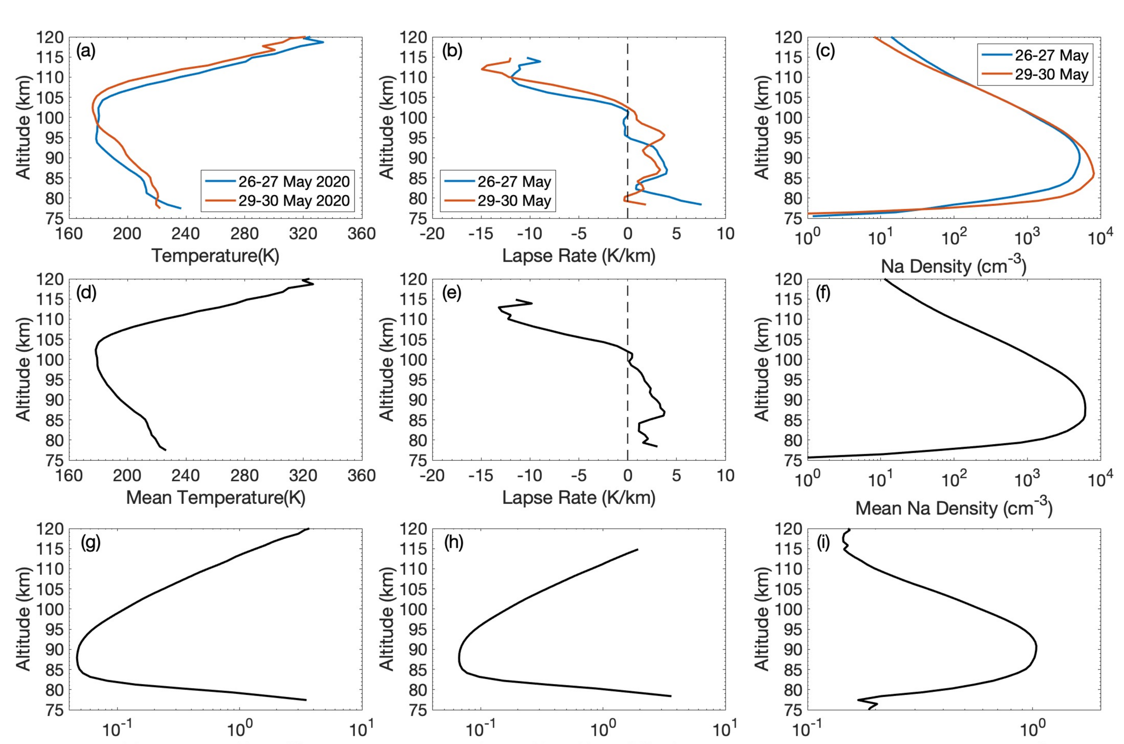
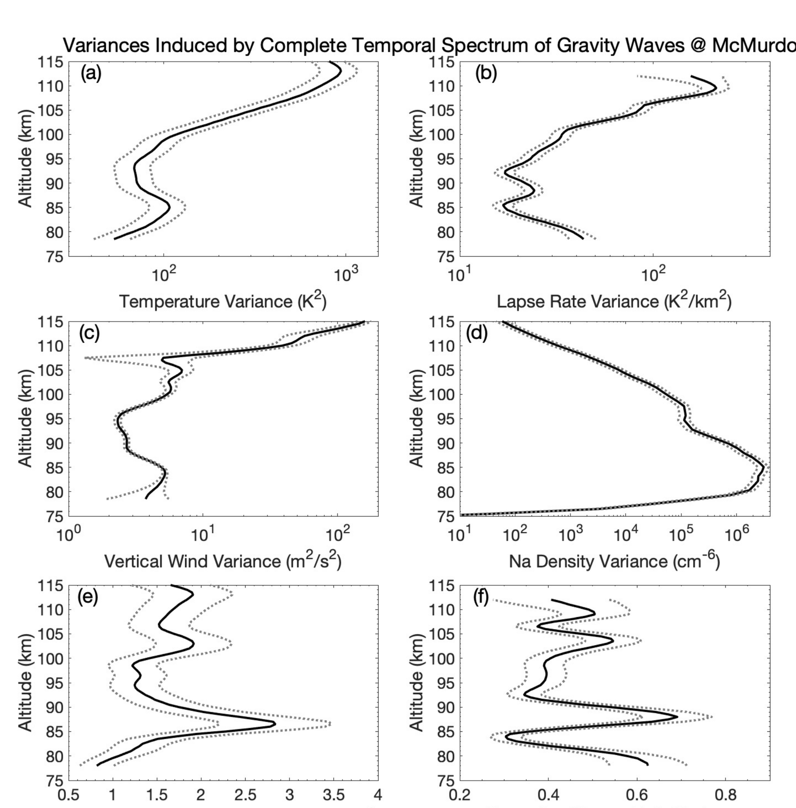
Abstract We report the first lidar observations of vertical fluxes of sensible heat and meteoric Na from 78–110 km in late May 2020 at McMurdo, Antarctica. The measurements include contributions from the complete temporal spectrum of gravity waves and demonstrate that wave-induced vertical transport associated with atmospheric mixing by non-breaking gravity waves, Stokes drift imparted by the wave spectrum, and perturbed chemistry of reactive species, can make significant contributions to constituent and heat transport in the mesosphere and lower thermosphere (MLT). A surprising discovery is the positive heat flux in the lower thermosphere (97–106 km), which contradicts conventional thinking but demonstrates the importance of the fully compressible solutions of polarization relations for mesoscale gravity waves. The measured sensible heat and Na fluxes exhibit downward peaks at 84 km that are lower by ~4 km than the peak fluxes observed at midlatitudes. This is likely caused by the strong downwelling over McMurdo in late May. The Na flux magnitude is double the maximum at midlatitudes, which we believe is related to strong inertial-period waves that are persistent in the MLT at McMurdo. To achieve good agreement between the measured Na flux and theory, it was necessary to assume that ~40% of gravity wave energy was propagating downward, especially between 80 and 90 km where the Na flux and wave dissipation were largest. These downward propagating waves are likely secondary waves generated in-situ by the dissipation of primary waves that originate from lower altitudes. The sensible heat flux transitions from downward below 90 km to upward from 97–106 km. The observations are explained with the fully compressible solutions for polarization relations of gravity waves dominated by mesoscale vertical wavelengths ($\lambda_z > 10\ km$).

Fundamental Atmospheric Observations



Raw data: $\Delta t = 4.5\ s$, $\Delta z = 24\ m$ T, w, [Na] retrieved at $\Delta t = 2.5\ min$, $\Delta z = 0.96\ km$



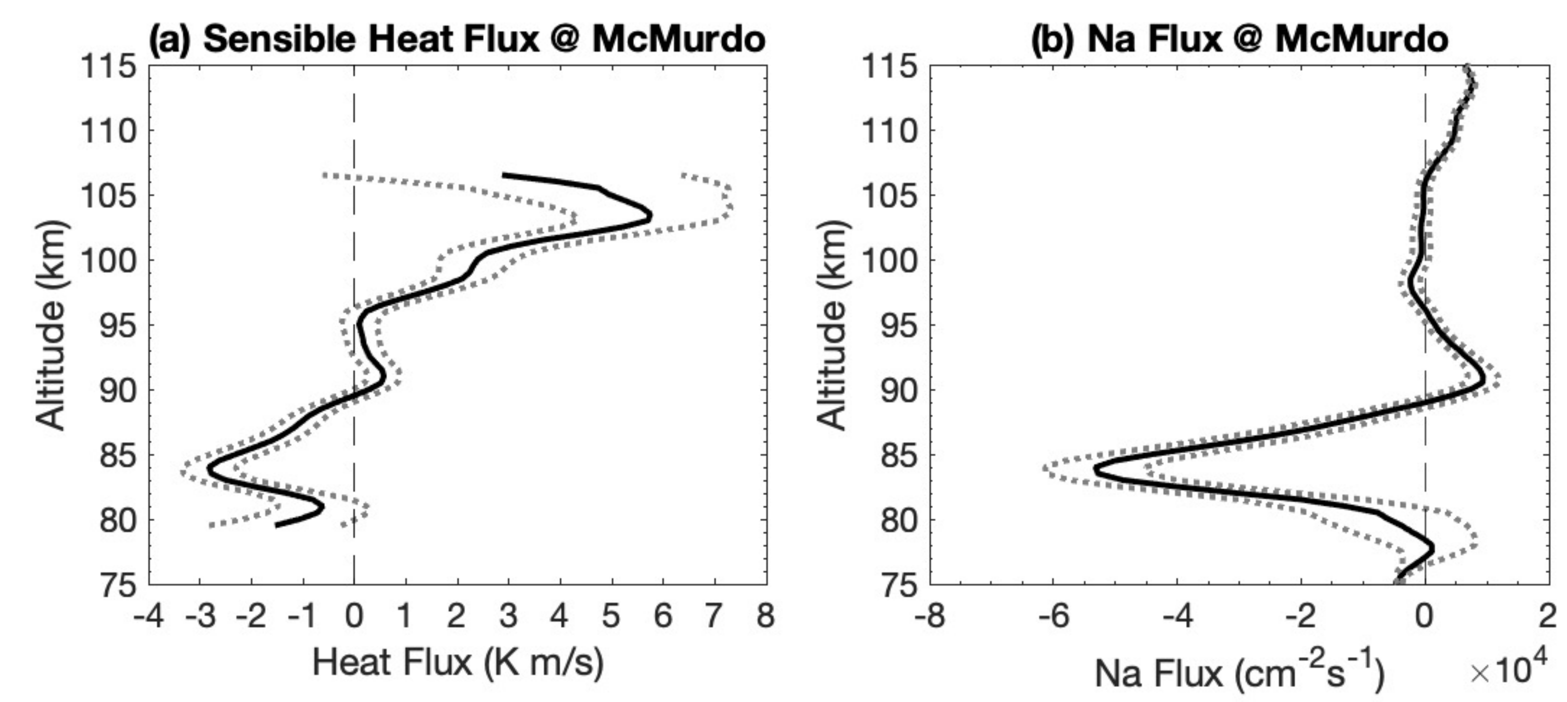


(Top) Measurements of temperature, vertical wind, and Na density in the MLT at McMurdo, Antarctica during 26–27 and 29–30 May 2020 with the University of Colorado STAR Na Doppler lidar. The Na density is plotted in log-10 scale. The upward wind is positive.

(Middle) Mean temperature, lapse rate, and Na density.

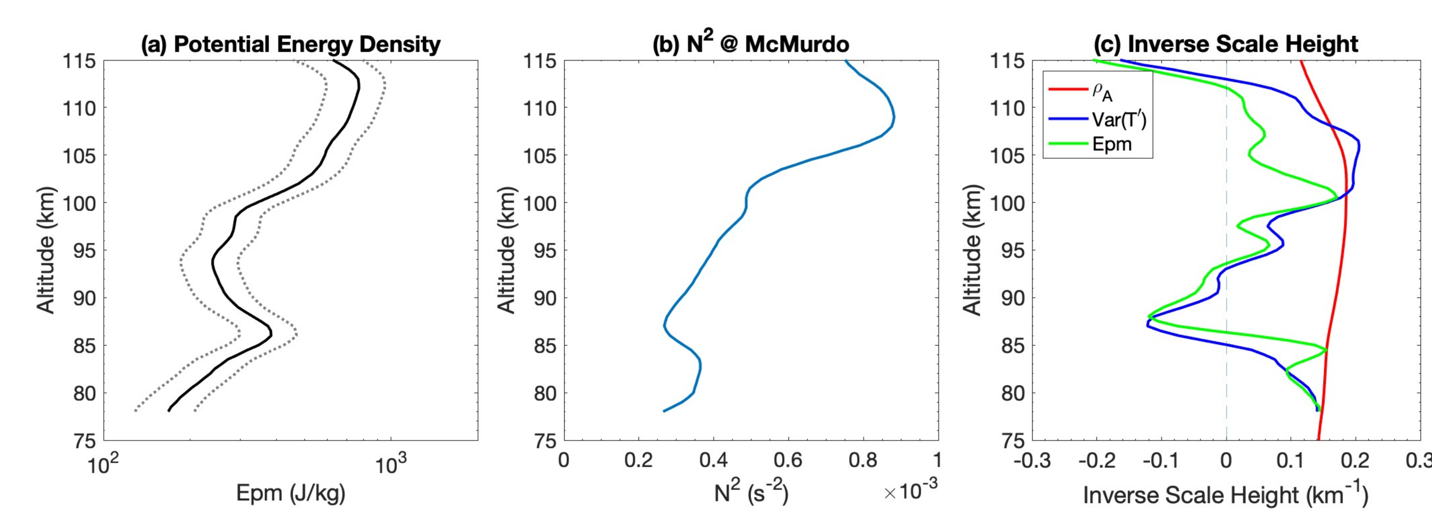
(Bottom) Computed fluctuation variances of (a) temperature $Var(T') = \overline{(T')^2}$, (b) lapse rate $Var(-\partial T'/\partial z) = \overline{(\partial T'/\partial z)^2}$, (c) vertical wind $Var(w') = \overline{(w')^2}$, and (d) Na density $Var(\rho_{Na}') = \overline{(\rho_{Na}')^2}$ induced by the complete temporal spectrum of gravity waves.

First Flux Measurements in Antarctica Show Surprising Results

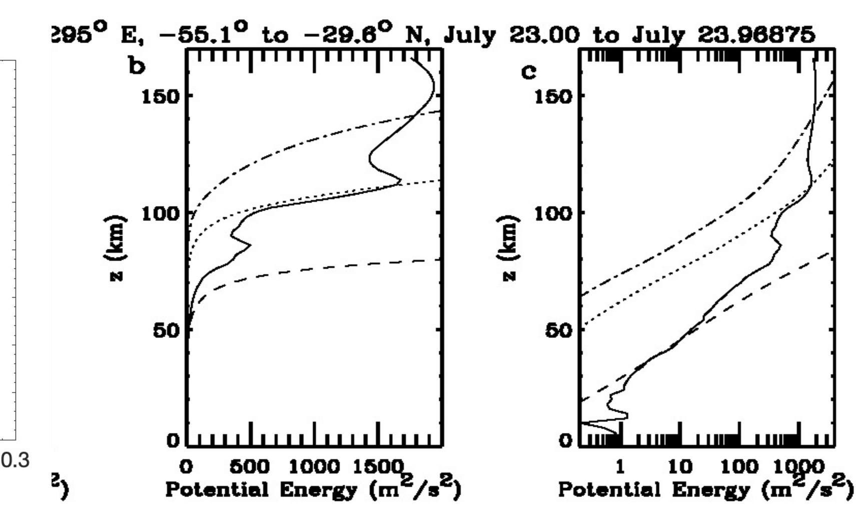


A surprising discovery is the positive heat flux in the lower thermosphere (97–106 km), which contradicts conventional thinking but demonstrates the importance of the fully compressible polarization relations of primary and secondary gravity waves.

By comparing the measured Na transport with theory, we also show that many of the waves between 80 and 95 km are propagating downward, which are likely generated in this region when upward propagating waves become unstable and break, much like ocean waves behave when breaking over a shoal.



[Chu, Gardner, et al., JGR, under review]



[Vadas and Becker, 2019]

The E_{pm} profile by lidar exhibits a striking similarity in shape to the E_{pm} profile published in Figure 20 of Vadas and Becker (2019). These authors used numerical modeling to explore secondary and tertiary gravity wave generation over the Southern Andes. Such similarities suggest that secondary and tertiary gravity waves are also generated in the MLT above McMurdo via the multistep vertical coupling process that was proposed by Vadas and Becker (2018 & 2019). Because the secondary and tertiary waves propagate both upward and downward, this mechanism could potentially lead to substantial fractions of downwardly propagating gravity waves throughout the MLT region at McMurdo.

$$w' = \frac{-ig\omega}{N^2}\frac{\left[1-\frac{i}{mH}\left(\frac{1}{2}-\frac{1}{\gamma}\right)\right]}{\left[1+\frac{i}{mH}\left(\frac{1}{2}-\frac{\gamma-1}{\gamma}\frac{\omega^2}{N^2}\right)\right]}\frac{T'}{\bar{T}}' \simeq \frac{-ig\omega}{N^2}\frac{T'}{\bar{T}}$$

$$\phi_w - \phi_T = \frac{\pi}{2} + \tan^{-1}\left[\frac{1}{mH}\left(\frac{1}{2}-\frac{1}{\gamma}\right)\right] + \tan^{-1}\left[\frac{1}{mH}\left(\frac{1}{2}-\frac{\gamma-1}{\gamma}\frac{\omega^2}{N^2}\right)\right]$$

$$\overline{w'(t)T'(t)} = \frac{1}{2}A_w A_T \cos(\phi_w - \phi_T) = -\frac{(\gamma-1)}{2\gamma H}\frac{g}{N^2}\frac{A_T^2}{\bar{T}}\frac{\frac{\omega}{m}\left(1-\frac{\omega^2}{N^2}\right)}{\left[1+\frac{1}{(mH)^2}\left(\frac{1}{2}-\frac{\gamma-1}{\gamma}\frac{\omega^2}{N^2}\right)^2\right]} \simeq -\frac{A_T^2}{2\bar{T}}\frac{\omega}{m}$$

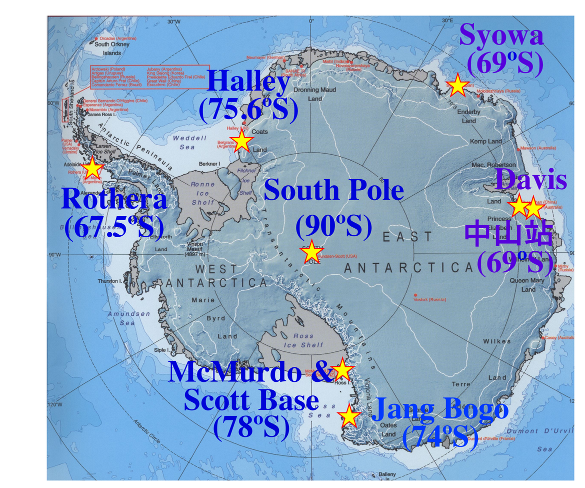
Derived directly from the full polarization relation, the phase difference between w' and T' differs from 90°. That is, $\phi_w - \phi_T < 90°$ for an upward-propagating, non-dissipative gravity wave with $\omega < N$, and $\phi_w - \phi_T > 90°$ for a downward-propagating wave. Consequently, the sensible heat flux is expected to be positive and negative for upward and downward propagating, non-dissipative gravity waves, respectively.

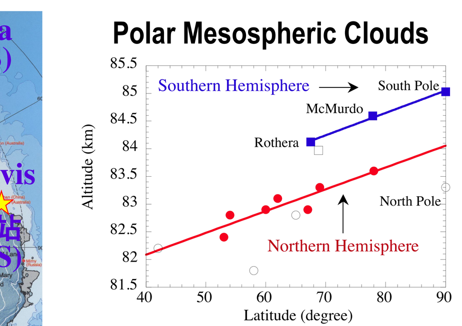
Upward-propagating gravity waves with fast vertical phase speeds (-ω/m) and relatively large temperature amplitudes (A_T) or with relatively slow vertical phase speeds but large temperature amplitudes, induce large, positive, sensible heat fluxes. In fact, the sensible heat flux can be quite large and positive in the lower mesosphere at McMurdo where dissipation is weak and mesoscale (~15–30 km) vertical wavelength waves are common. For example, for a vertical wavelength of 20 km and an intrinsic period of 16.7 min, the intrinsic vertical phase speed (ω/m) is 20 m/s. The mean temperature was about 175 K at 103 km at McMurdo during our observations, so if the temperature amplitude of the upward-propagating wave is 5 K, then the wave would induce a positive heat flux of about $+1.4\ Kms^{-1}$. This corresponds to a phase shift of about -8.6° from 90°. If there are on average 3–5 upward-propagating waves present simultaneously in the lower thermosphere at McMurdo with these average characteristics, then the total heat flux would be $+4\ to + 6\ Kms^{-1}$, similar to the value observed.

Lu et al. (2017) measured the phase differences between w' and T' for 184 mesoscale waves observed between 85 and 100 km at Table Mt., CO. They found that the mean phase difference $\phi_w - \phi_T = 84.2°$ was 2.6° larger than the phase difference 81.6° predicted by equation (7), which they showed was likely caused by dissipation associated with damping by eddy and molecular viscosity (Lu et al., 2017).

Dissipation could lead to larger phase difference, making it to approach or exceed 90°. Can wave amplification reduce the phase difference?

McMurdo Lidar Campaign

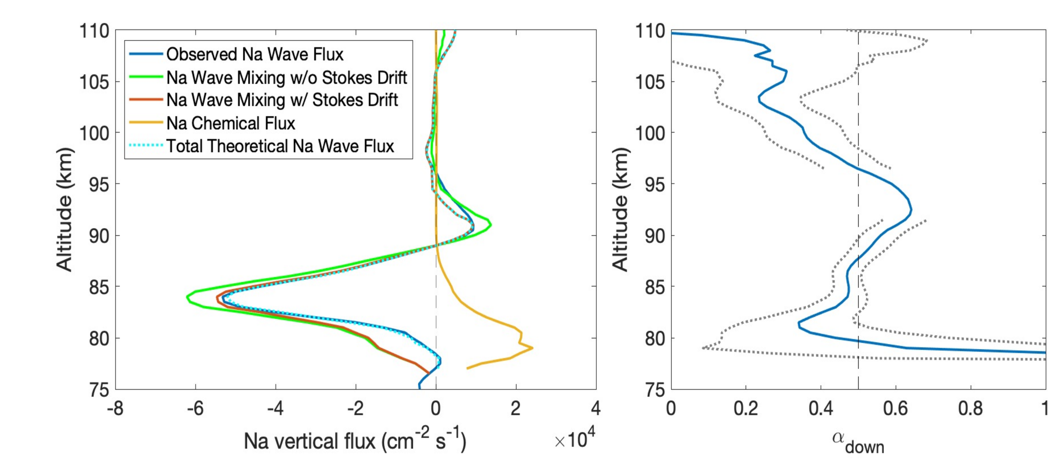




[Chu et al., JGR, 2003, 2006; GRL, 2001, 2011a]

McMurdo at high geographic (78°S) and geomagnetic (80°S) latitudes

Many discoveries from McMurdo lidar observations are eye-opening or transformative to advancing space-atmosphere sciences and to addressing fundamental science questions.



$$\overline{w'T'} = (\Gamma_{ad} + \partial\bar{T}/\partial z)(K_E - K_H)$$

$$\overline{w'\rho_C'} = \bar{\rho}_C\frac{\overline{w'\rho_A'}}{\bar{\rho}_A} - \bar{\rho}_C\left(\frac{g}{R\bar{T}} + \frac{1}{\bar{T}}\frac{\partial\bar{T}}{\partial z} + \frac{1}{\bar{\rho}_C}\frac{\partial\bar{\rho}_C}{\partial z}\right)K_{Wave} + \overline{w'\rho_C'}_{Chemical}$$

Stokes Drift Wave-induced Mixing Chemical Flux

$$K_{Wave} = \frac{g}{N^2}\frac{\overline{w'\rho_A'}}{\bar{\rho}_A} = -\frac{g}{N^2}\left(\frac{\overline{w'T'}}{\bar{T}} - \frac{\overline{w'p'}}{\bar{p}}\right) = K_H + \left(\frac{C_p}{R}-1\right)K_E$$

Conclusions and Future Work

First, the downward Na flux peak is located at 84 km, which is about 4 km lower than observed at midlatitudes, and the magnitude is double the maximum at midlatitudes

Second, to achieve good agreement between the predicted and measured Na flux, we needed to assume that a significant fraction (~40% or even over 50%) of the gravity wave energy was propagating downward, especially near 85 km where the Na flux and wave dissipation were largest.

Third, the measured sensible heat flux exhibits a downward peak at 84 km that is comparable to the peak values at midlatitudes but lower by about 4 km, while the sensible heat and potential temperature fluxes are directed upward (positive) in the lower thermosphere from 97 to 106.5 km.

The observed profiles of sensible heat flux (transitioning from downward below 90 km to upward from 97 to 106 km) and meteoric Na flux along with the profiles of E_{pm}, inverse scale heights, and variances depict a coherent picture of heat and constituent transport in the MLT by primary and secondary gravity waves.

It is speculated that $\overline{w'\theta'}$ could become positive if there is wave amplification, which may be driven by external heat sources.

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