MGS Observations and Modeling of Martian Lee Wave Clouds. S. E. Wood[1], D. C. Catling[1], S. C. R. Rafkin[2], E. A. Ginder[1], C. G. Peacock[1], [1]*Dept. of Atmospheric Sciences, University of Washington, Seattle WA*, [2]*Dept. of Space Studies, Southwest Research Institute, Boulder CO.*

Introduction: Lee wave clouds form when stable air is deflected vertically by a topographic obstacle and undergoes a wave-like oscillation in the lee of the obstacle. Condensation occurs at the adiabatically-cooled crest of the waves, usually leaving a regular train of clouds aligned orthogonal to the prevailing wind and/or a "ship's wake" divergent pattern. The existence of lee waves in the Martian atmosphere has been known since Mariner 9 [1]. Craters varying in size from a few to hundreds of kilometers commonly generate lee waves on Mars (i.e., **Figure 1**). For larger craters, waves can extend up to nearly 1000 km downstream of their source [1-5]. The wavelength and propagation characteristics of lee waves are determined by the temperature (stability) and wind profiles of the atmosphere, as well as moisture in the impinging flow, so they allow us to make inferences about the atmospheric structure and dynamics. Also the statistical occurrence of lee wave clouds in preferred seasons and locations allows us to tie lee wave incidence to the general climatic state of the Martian atmosphere. In previous missions, coverage has not been systematic. Mars Global Surveyor (MGS) provides an opportunity to systematically look at the occurrence of lee waves and correlate this with meteorological predicaments. The only significant limitation from MGS is lack of local time coverage.

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Fig. 1. Lee wave clouds generated by Milankovic crater (55N, 148W, diam~110 km) on L_s=234. (MOC-WA image M08/07249).

MOC wide-angle (WA) images have a better footprint for observing clouds than the narrow-angle MOC images. The red- and blue-filtered WA images allows us to distinguish ice clouds (bright in the blue) from dust clouds (bright in the red), at least where paired images of the same scene were taken. Radio Science (RS) data can provide vertical temperature profile context in principle, but there is scant overlap in local time with the relevant images. The Thermal Emission Spectrometer (TES) has better coverage in space and time than RS; it can provide context for cloud and vapor distribution, but temperature profiles have insufficient vertical spatial resolution for direct application to lee waves. MOLA provides excellent surface topography for models, as well as some direct cloud observations. However, direct cloud observations are biased towards CO_2-ice clouds, which are reflective, rather than H_2O-ice clouds, which are absorptive.

Observations and Interpretation: We are currently compiling a cloud catalog from MOC WA images of condensate clouds. Consistent with the results of [5], which is based on global swath images, lee wave clouds are found to occur in the mid-latitude and polar regions in fall and winter of the respective hemisphere, with wavelengths of up to 50 km. Unlike [5], our study also includes all of the regional-scale WA images, which allows detection of lee wave clouds with smaller wavelengths (i.e., **Figure 2**) as well as a more detailed analysis of their shape and structure. In some cases we observe shadows that can be used to derive cloud heights.

Two particular questions come to mind: (1) Why is the Martian atmosphere apparently prone to a large amount of lee wave activity (2) What determines the seasonal trends?

We find that the occurrence of lee waves has less to do with the water vapor abundance and more to do with the dynamical state of the atmosphere. Northern hemisphere water vapor peaks at ~L_s 120 and yet there is little occurrence of lee wave clouds before L_s=170. The reason can be deduced from understanding the conditions required for lee wave occurrence, as follows.

Conditions for trapped lee waves: The horizontal (k) and vertical wavenumbers (m) of the wave are coupled through the Scorer Parameter (l), given by:

$$l^2 = \frac{N^2}{U^2} - \frac{1}{U}\frac{\partial^2 U}{\partial z^2}, \text{ where } l^2 = m^2 + k^2 \qquad (1)$$

where U is the wind speed and N is the Brunt-Vaisala frequency [e.g., 6]. The horizontal propagation of the wave, and the presence of clouds, is strongly controlled by the atmospheric structure. For example, if $k < l$, then the lee wave is vertically propagating (does not damp with height). Such a wave can result in the appearance of a single wave disturbance directly over the obstacle through a depth of the atmosphere where l remains greater than k. When $k > l$, the wave is damped with height (m is imaginary). In the simplest "two layer" idealization for trapped waves in the lee of a ridge, the lower layer has conditions such that the intrinsic frequency of the wave, Uk, is less than N and in the upper layer has $Uk > N$. Under these conditions, the wave is not damped in the lower layer, while it is evanescent (dying away in amplitude) in the upper layer. The wave is thus trapped. Thus if the vertical variations of N and U are such that the Scorer Parameter decreases significantly with height, then cross-topographic flow is prone to give rise to a lee waves.

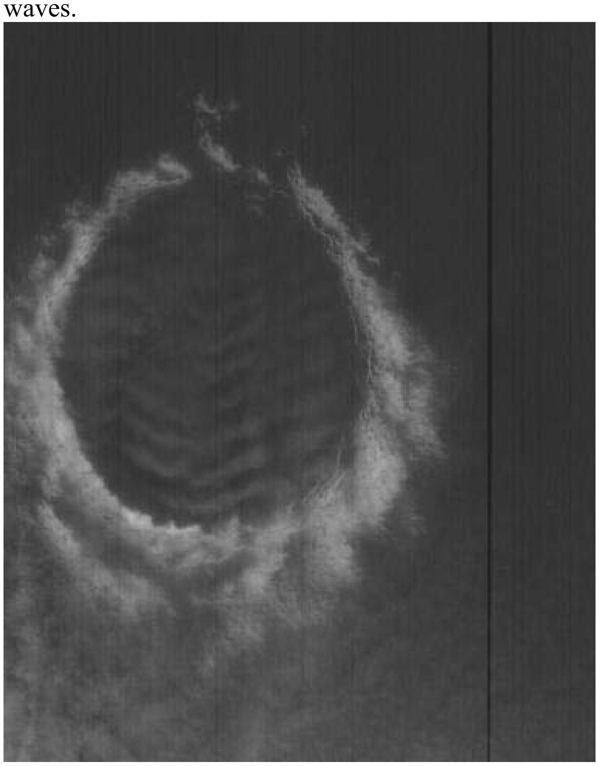

Fig. 2. Small wavelength (~7km) lee wave clouds inside Lomonosov crater (65N, 9W, diam~150km) on L_s=53. (MOC-WA image M19/01563).

Values of N(z) can be obtained from RS temperature profiles typical of a particular season or GCM output. Values of U(z) must generally be obtained from GCM output for a particular location. From these values we can derive l(z) as a function of time and space. We can also calculate an effective "Scorer wavelength" ($\lambda_s = 2\pi/l$) as a function of height This λ_s parameter must increase with altitude z for waves to exist, and if so, it provides an upper limit to their wavelength. **Figure 3** shows profiles for a location near Korolev crater (73N, 196W) at three different seasons showing development of conditions conducive to leewaves.

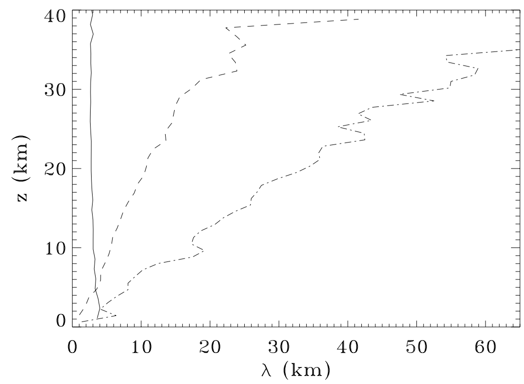

Fig. 3. Vertical profiles of the "Scorer wavelength" in the atmosphere at high northern latitudes derived from Radio Science occultation profiles taken on L_s=100 (*solid line*), L_s=166 (*dashed line*), and L_s=180 (*dot-dash line*).

This shows that lee waves are not expected for the summer season, as indeed is observed. Only as summer progresses to fall does the Scorer parameter become liable to decrease significantly with height (or equivalently λ_s increases with altitude z). This gives rise to the conditions for trapped lee waves.

Consequently, the answer to why Mars has significant autumn and winter lee wave activity in midlatitudes is that the wind shear is very large, with wind speeds increasing greatly with height because of the winter midlatitude jet stream. For a linear velocity profile, Eqn. (1) becomes $l^2 \approx N^2 / U^2$, which is dominated by the denominator term in zonal wind. The answer to why lee waves are prevalent in the autumn and winter is that the strong variation of wind with height is only set up during these seasons.

We are also undertaking more detailed modeling using linear models that can predict the horizontal wavelength (which is the main feature observed in images), and shapes of the waves. A particular trait of crater lee waves on Mars that often occurs is a pattern of diverging cloud trains as seen in a "ship's wake". This is in contrast to transverse clouds, which are orthogonal to the wind direction in the lee of the crater. More comprehensive and less idealized simulations can be obtained from the MRAMS mesoscale model [7].

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