Overview

We discuss a correction to the calculation of cloud density in equilibrium cloud condensation models (ECCMs) based on Weidenschilling and Lewis (1973). All other quantities, such as lapse rate and gas mixing ratios, are not affected by this correction.

Although more complex 2D and 3D simulations are preferred to model planetary and exoplanetary atmospheres, ECCMs are still used by many researchers to quickly estimate wet adiabatic atmospheric structures, saturated vapor profiles, and cloud base levels. With the conceptual corrections presented here, cloud densities can also be estimated.

Numerical revisions

Weidenschilling and Lewis (1973) showed that Eqn. 1 gives a relation for cloud density, based on defining the condensate column density between adjacent model layers:

$$D = \frac{1}{\rho} \left[ \frac{X_x - X_o}{3} \right]$$  \[1\]

This equation gives a result in units of density, which is mass/volume. However, for the volume calculation has unit area and a height of $H$. We derive a similar relation, which differs from the WL73 formula by a factor of $1/2$, with $l$ unit length, which gives a standard density based on the mass per unit volume (see Fig. 1):

$$D = \frac{1}{\rho} \left[ \frac{X_x - X_o}{2} \right]$$  \[2\]

Conceptual revisions

We call densities calculated by ECOM, "equilibrium condensate densities," to distinguish from actual cloud densities. Conceptually, the equilibrium condensate density $\rho_{\text{eq}}$ describes the amount of condensate produced when a unit volume of saturated air rises a unit distance upward, wet adiabatically (Fig. 2). But real clouds do not form in a perturbed closed system; the actual displaced volume depends on the duration and velocity of the updraft, and is modified by microphysical processes such as precipitation and evaporation.

Maintaining the concept from WL73, that condensed material remains at the altitude where it condenses out, we can calculate first order cloud densities by multiplying $\rho_{\text{eq}}$ by the updraft speed and duration, and dividing by the unit length to convert time-integrated mass flux to mass density:

$$\rho = \frac{\rho_{\text{eq}} \cdot t \cdot v}{l}$$  \[3\]

Validation

We attempt to validate the cloud density algorithm by comparing model data with cloud observations on Jupiter and Earth.

Jupiter: In Atreya et al. (1999), we compared equilibrium cloud densities to the Galileo Probe nephelometer measurements of cloud mass loading (Ragent et al. 1998) in the probe-entry site (PES) on Jupiter. Table 1 compares the new and old model cloud mass loading with the PES measurements. Old model mass loadings calculated with Eqn. 1 are much greater than observations, so precipitation or other processes would need to be invoked, which may not be reasonable considering the thin clouds thought to be present in Jovian hot spots. But the new algorithm gives much smaller densities, that could be consistent with observations depending on updraft characteristics. Simulations of Jupiter-like atmospheres have vertical velocities in the range of 100–1000 cm s$^{-1}$, where observed plans (Shupe et al. 2002, Mansell et al. 2005, Hueso and Sánchez-Lavega 2001), cm s$^{-1}$ for parameterized convection. Numerical revisions presented here, cloud densities can also be estimated. Conclusions and future work will be presented at the 2013 Fall Meeting.

Table 1: Observed and modeled Jupiter cloud properties. Observed cloud properties are from Ragent et al. (1998) for the Galileo Probe Entry Site (PES). Model output columns are integrated either over the same pressure ranges as the observed clouds (where labeled “PES height”) or over the full model height. Values labeled “old model” are for $\rho_{\text{eq}}$ calculated with Eqn. 1, “new model” is $\rho_{\text{eq}}$ calculated with Eqn. 2. Units are g cm$^{-3}$.

<table>
<thead>
<tr>
<th>Cloud Type</th>
<th>PES Height</th>
<th>New model</th>
<th>Old model</th>
<th>New model</th>
<th>Old model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water ice</td>
<td>2.9 x 10$^{-2}$</td>
<td>1.3 x 10$^{-2}$</td>
<td>1.3 x 10$^{-2}$</td>
<td>1.3 x 10$^{-2}$</td>
<td>1.3 x 10$^{-2}$</td>
</tr>
<tr>
<td>NH$_4$SH solid</td>
<td>3.0 x 10$^{-3}$</td>
<td>3.0 x 10$^{-3}$</td>
<td>3.0 x 10$^{-3}$</td>
<td>3.0 x 10$^{-3}$</td>
<td>3.0 x 10$^{-3}$</td>
</tr>
<tr>
<td>Equilibrium condensation</td>
<td>1.1 x 10$^{-2}$</td>
<td>1.1 x 10$^{-2}$</td>
<td>1.1 x 10$^{-2}$</td>
<td>1.1 x 10$^{-2}$</td>
<td>1.1 x 10$^{-2}$</td>
</tr>
<tr>
<td>Condensed vapor</td>
<td>3.0 x 10$^{-3}$</td>
<td>3.0 x 10$^{-3}$</td>
<td>3.0 x 10$^{-3}$</td>
<td>3.0 x 10$^{-3}$</td>
<td>3.0 x 10$^{-3}$</td>
</tr>
<tr>
<td>Condensate gas</td>
<td>1.1 x 10$^{-2}$</td>
<td>1.1 x 10$^{-2}$</td>
<td>1.1 x 10$^{-2}$</td>
<td>1.1 x 10$^{-2}$</td>
<td>1.1 x 10$^{-2}$</td>
</tr>
<tr>
<td>NH$_4$SH cloud</td>
<td>1.4 x 10$^{-3}$</td>
<td>1.4 x 10$^{-3}$</td>
<td>1.4 x 10$^{-3}$</td>
<td>1.4 x 10$^{-3}$</td>
<td>1.4 x 10$^{-3}$</td>
</tr>
<tr>
<td>Equilibrium condensation</td>
<td>1.5 x 10$^{-2}$</td>
<td>1.5 x 10$^{-2}$</td>
<td>1.5 x 10$^{-2}$</td>
<td>1.5 x 10$^{-2}$</td>
<td>1.5 x 10$^{-2}$</td>
</tr>
<tr>
<td>Condensed vapor</td>
<td>3.0 x 10$^{-3}$</td>
<td>3.0 x 10$^{-3}$</td>
<td>3.0 x 10$^{-3}$</td>
<td>3.0 x 10$^{-3}$</td>
<td>3.0 x 10$^{-3}$</td>
</tr>
<tr>
<td>Condensate gas</td>
<td>1.5 x 10$^{-2}$</td>
<td>1.5 x 10$^{-2}$</td>
<td>1.5 x 10$^{-2}$</td>
<td>1.5 x 10$^{-2}$</td>
<td>1.5 x 10$^{-2}$</td>
</tr>
</tbody>
</table>

References/symbols

Lawson, P. et al. (2009) CRYSTAL-FACE team meeting, Feb. 24-28, Salt Lake City, UT.
Soto, P. et al. (2009) CRYSTAL-FACE team meeting, Feb. 24-28, Salt Lake City, UT.
Shupe, M. et al. (2002) CRYSTAL-FACE team meeting, Feb. 24-28, Salt Lake City, UT.
Zuchowski, L.O. et al. (2009a,b) J. Geophys. Res. 114, D12101 (24 pp.).
Zuchowski, L.O. et al. (2009a,b) J. Geophys. Res. 114, D12101 (24 pp.).