Factors governing the ice cloud particle size

— analysis using Aura and other satellite observations —

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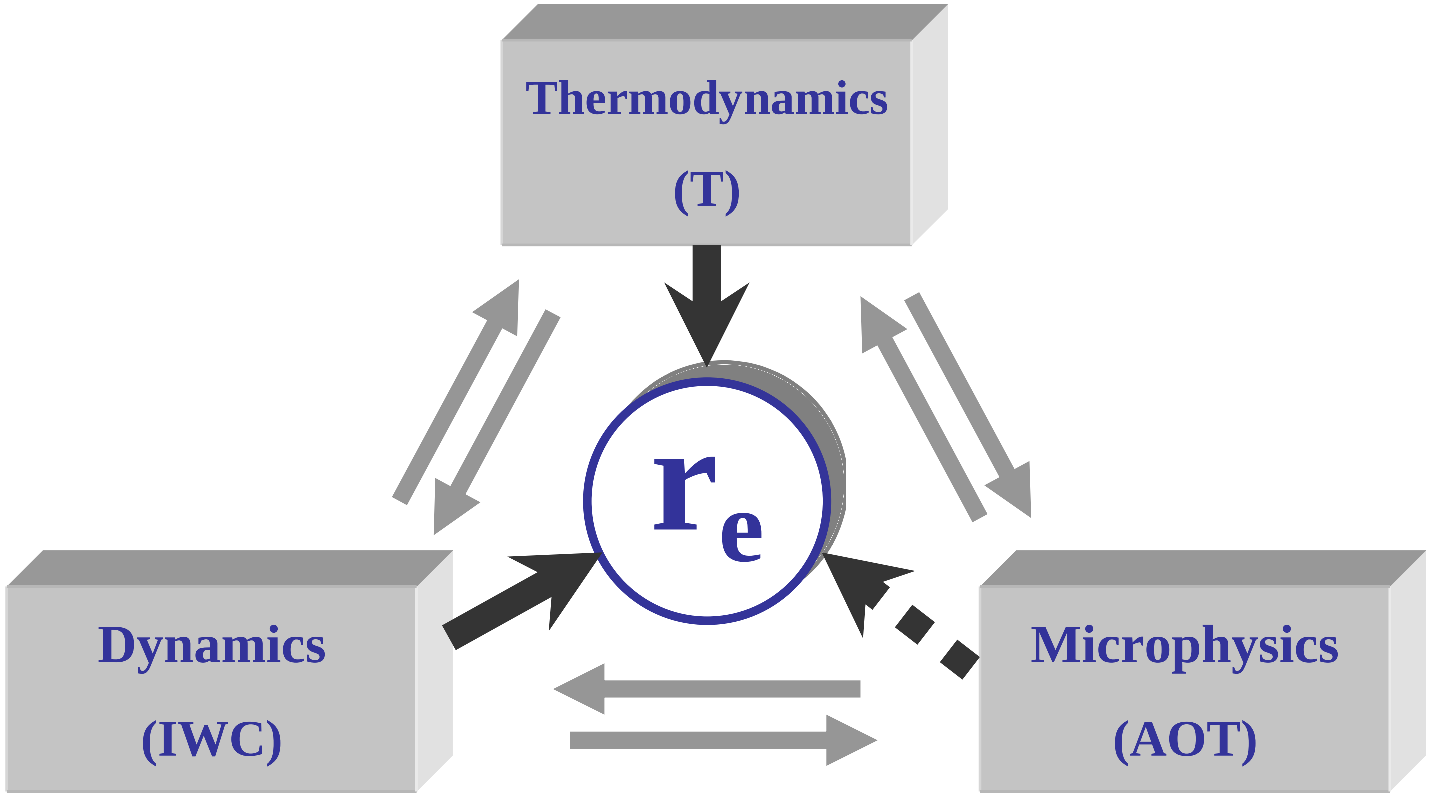
Objective

Aerosols can cause changes in cloud number concentration and therefore cloud effective particle size, which will result in changes of condensation and evaporation rates, latent heat release, collision coalescence efficiency, cloud particle fall speed, cloud lifetime, reflectance, and precipitation, etc.

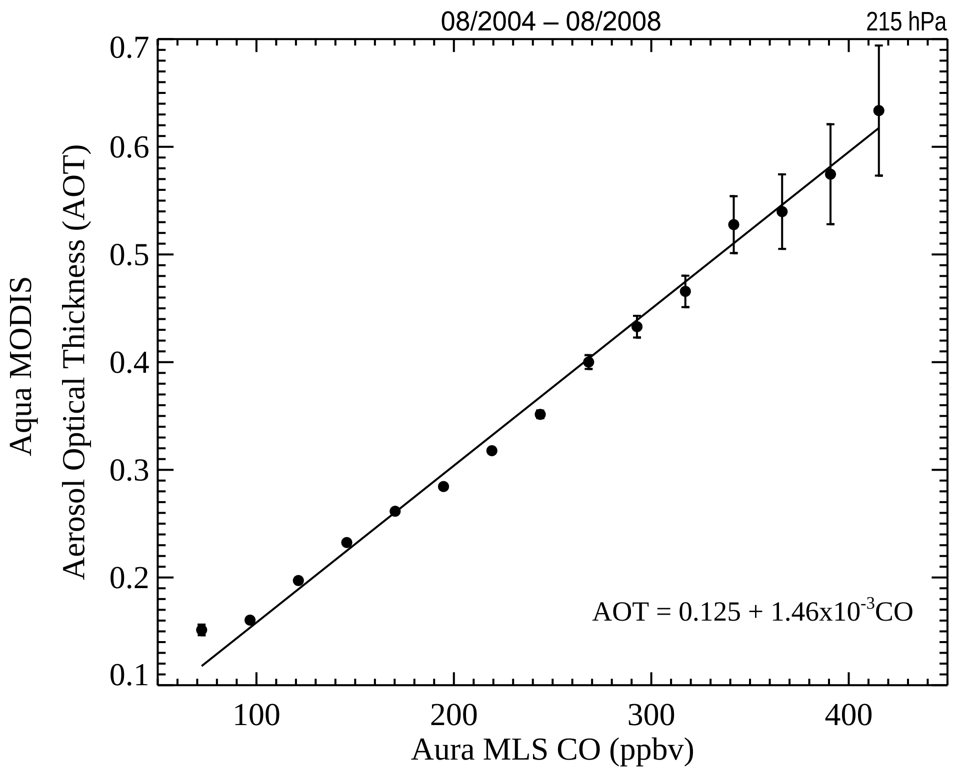
- **Use satellite observations to identify empirical relations of ice cloud effective radius (r_e) with ice water content (IWC) and aerosol loading.**
- **Understand interactions among aerosols, clouds, and dynamics.**
- **Provide a parameterization of the aerosol first indirect effect for climate models.**

Factors that control r_e



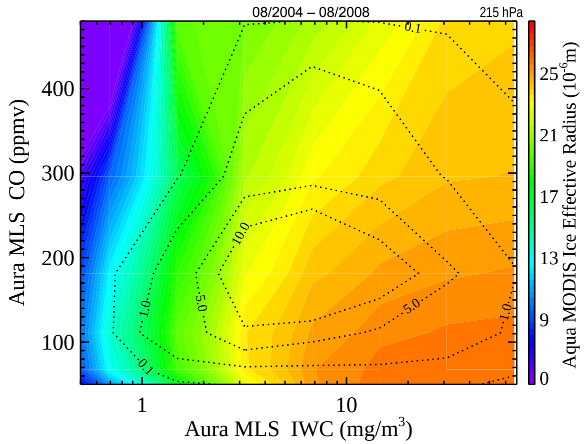
- **Thermodynamics:** temperature can influence cloud particle nucleation/growth.
- **Dynamics:** cloud particles size distribution is influenced by updrafts (IWC).
- **Microphysics:** aerosol can alter cloud particle size (e.g. Twomey effect).

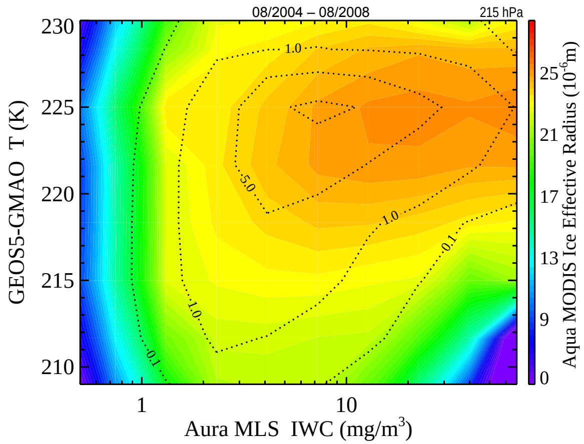
Aura MLS CO as an index of aerosol

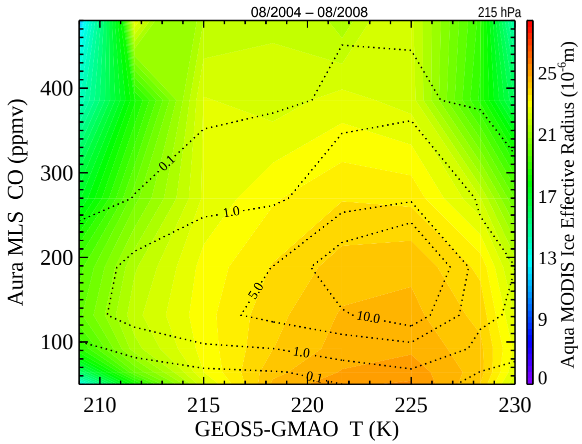


- MLS CO at 215 hPa is approximately linear with aerosol optical thickness (AOT) measured by Aqua MODIS and thus can be used as an index for aerosol loading.
- Using CO has an advantage over using AOT because it is difficult to measure AOT in cloudy regions, but simultaneous CO and IWC measurements are provided by Aura MLS.

Bi-Variate Composite (BVC) analysis

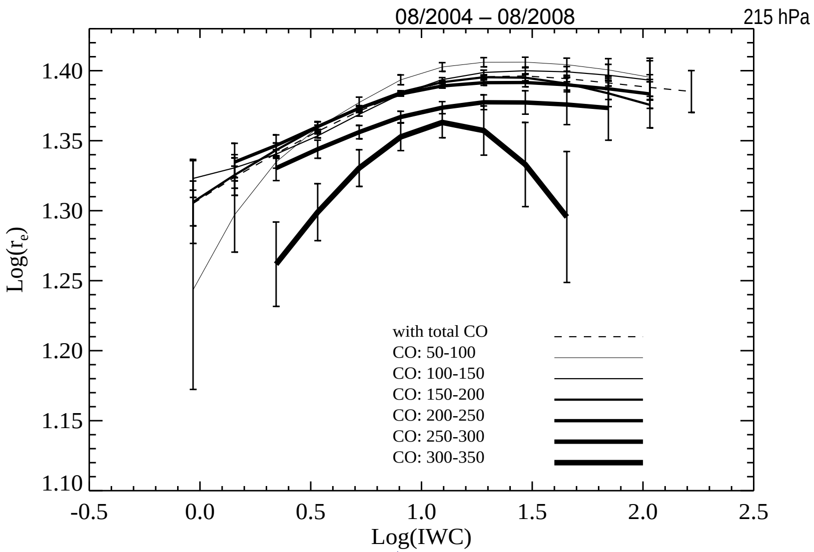




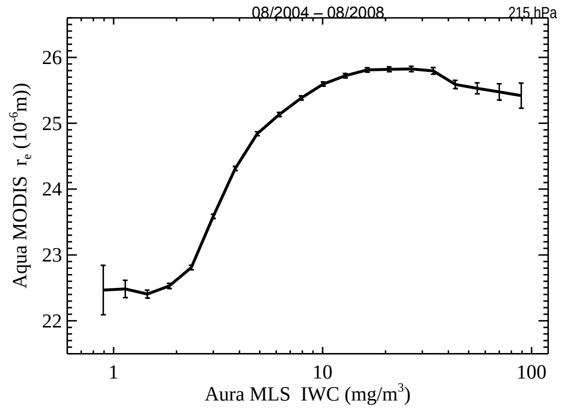


- r_e increases with IWC but decreases with AOT/CO: the largest r_e resides where convection (IWC) is largest and AOT/CO is lowest, i.e. strong convection in clean environment.
- r_e also has a temperature dependence → it has a maximum at ~225 K, and is smaller at low and high temperatures.

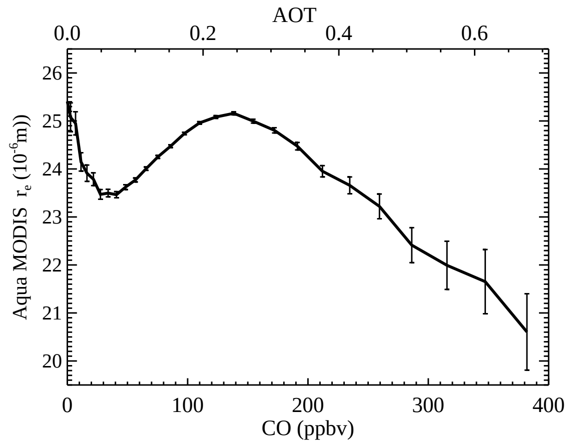
Dependence of r_e on IWC and CO



r_e vs. IWC for different CO (AOT)



r_e vs. IWC



r_e vs. AOT/CO

- When IWC is small, r_e increases with IWC, approximately following a power law.
- When IWC is larger, the increase of r_e with IWC becomes slower or even decreases with IWC as the maximum r_e is limited by settling velocity of ice particle.
- r_e increases with aerosol loading until it reaches maximum at AOT ~0.25 (CO ~140 ppbv).
- When AOT>~0.25, r_e decreases with AOT.

Empirical r_e, IWC, CO/AOT relation

We use least-squares fitting to fit the observed data with an expression:

$$\min_{\alpha,\beta,\gamma,r_e,IWC^0,CO^0} \sum_i \left[r_e^i - R_e(IWC^i, CO^i, \alpha, \beta, \gamma, R_e^0, IWC^0, CO^0) \right]^2$$

where r_e^i, IWC^i, CO^i **represent the observed** r_e, IWC **and** CO, **and** $\alpha, \beta, \gamma\ldots$ **are the fitting parameters. The function** R_e **is assumed to have the following empirical form:**

$$R_e(\alpha,\beta,\gamma,R_e^0,IWC^0,CO^0) = \frac{R_e^0}{(IWC/IWC^0)^{-\alpha}+1} \cdot \frac{(CO/CO^0)^{\gamma}}{(CO/CO^0)^{\beta}+1} \qquad (1)$$

The fitting is done for IWC^i (mg/m3) **and** CO^i (ppbv) **measured by MLS from 08-2004 to 08-2008 and yields:**

$$\alpha = 1.436, \quad \beta = 0.586, \quad \gamma = 0.282$$

$$R_e^0 = 56.029, \quad IWC^0 = 1.384, \quad CO^0 = 84.679$$

Also, a linear fitting gives the relation between CO and AOT:

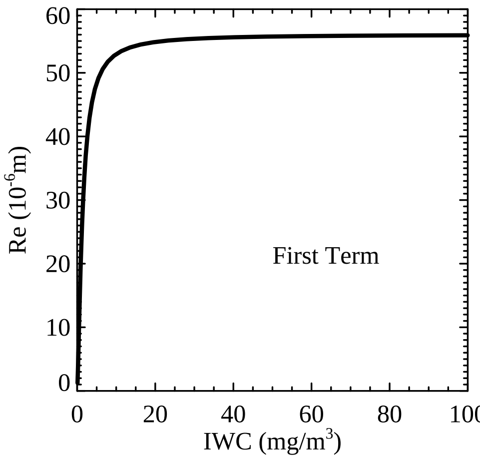
$$AOT = 0.125 + 1.46 \times 10^{-3} CO \qquad (2)$$

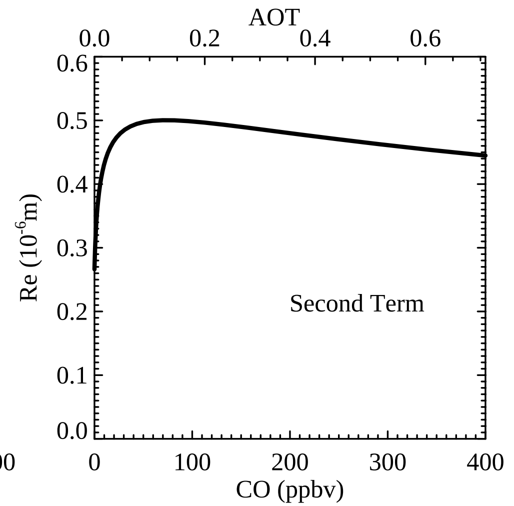
Substitute (1) and (2), we obtain r_e(μm), as a function of IWC (mg/m^3) and AOT as:

$$R_e = \frac{R_e^0}{\left(IWC / IWC^0\right)^{-\alpha} + 1} \cdot \frac{(\varepsilon \cdot AOT - \tau)^{\gamma}}{(\varepsilon \cdot AOT - \tau)^{\beta} + 1} \qquad (3)$$

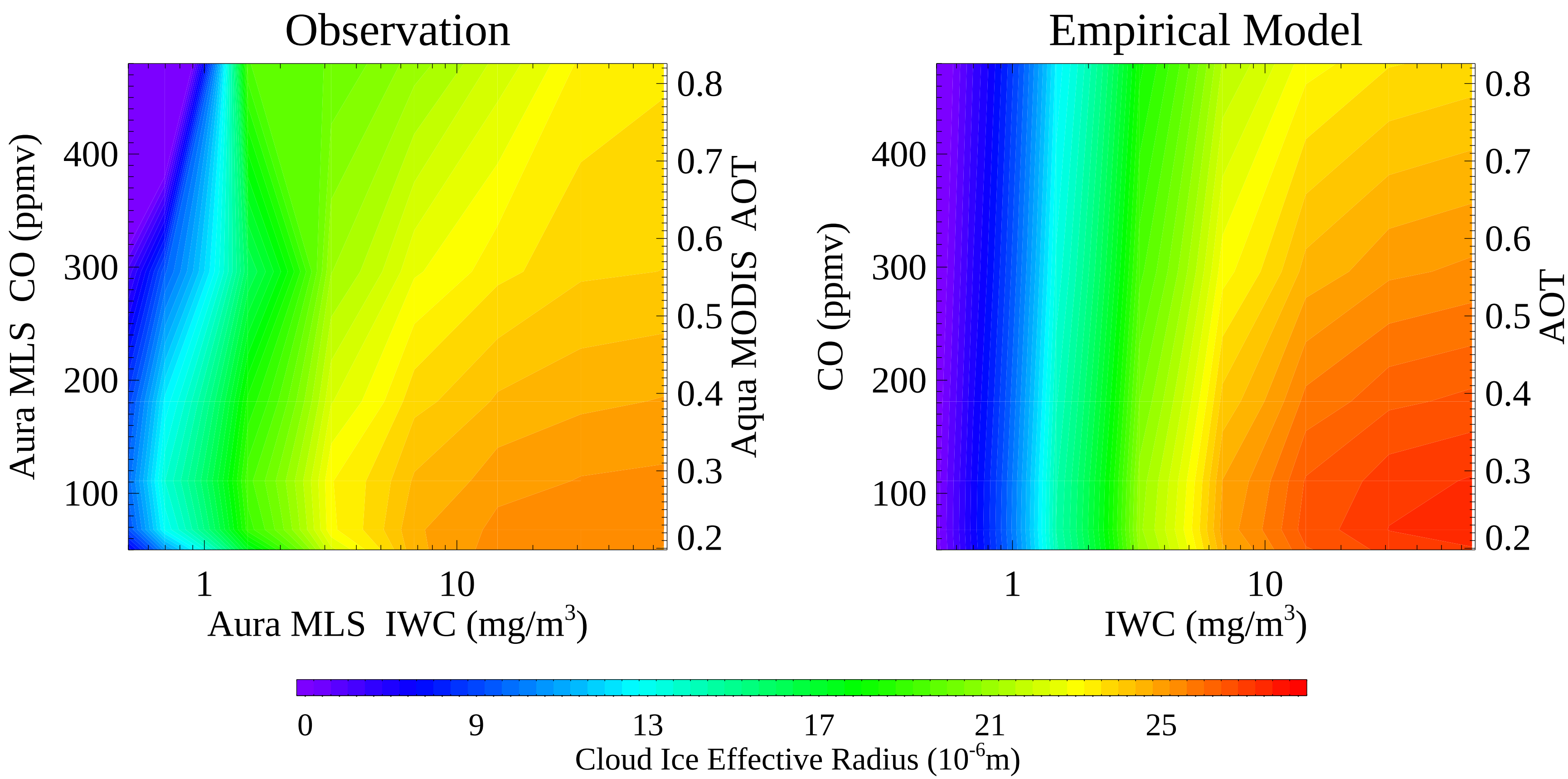
where $\varepsilon = 8.09,\ \tau = 1.11$

- The first term represents the power-law growth of r_e as IWC.
  - IWC $\rightarrow 0$, $r_e \rightarrow 0$.
  - As IWC increases, r_e grows, following a power law.
  - At large IWC, r_e approaches a limit largely determined by cloud particle fall speed.
- The second term represents the modulation of AOT on r_e.
  - Aerosol loading changes particle size distribution and reduces r_e.





Fitted IWC-r_e-AOT relations



The fitted empirical model approximately captures the observed IWC-r_e-AOT relationship. r_e is largest when convection (IWC) is strongest and pollution (AOT) is lowest, i.e., strong convection under clean condition.

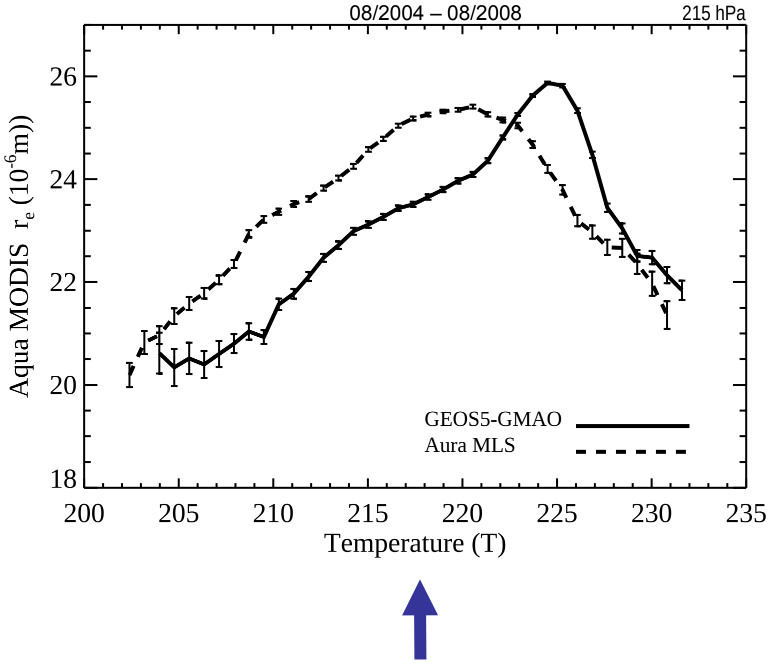
Conclusions

- **Based on the analysis of 4 years** (08-2004 to 08-2008**) collocated Aura MLS and Aqua MODIS observations, we found that ice particle size (r_e) generally increases with IWC but decreases with aerosol loading.**
- **Using least-squares fitting, we obtained an empirical formula for r_e as a function of IWC and AOT. This function broadly captures the variation of r_e with IWC and AOT.**
- **This empirical relationship of r_e with IWC and AOT can serve as a first-order parameterization of the first indirect effect of aerosol on ice clouds for climate models.**
- **Model simulations are underway to explore the role of the aerosol first indirect effect in affecting global hydrological cycle and climate.**

Future Work

1. Improve the empirical modeling by adding temperature dependence term, and further exam its regional and seasonal differences.

2. Complementary analysis using $r_{e,}$ IWC/LWC and aerosol from CloudSat and CALIPSO data.



r_e vs. Temperature

Acknowledgements

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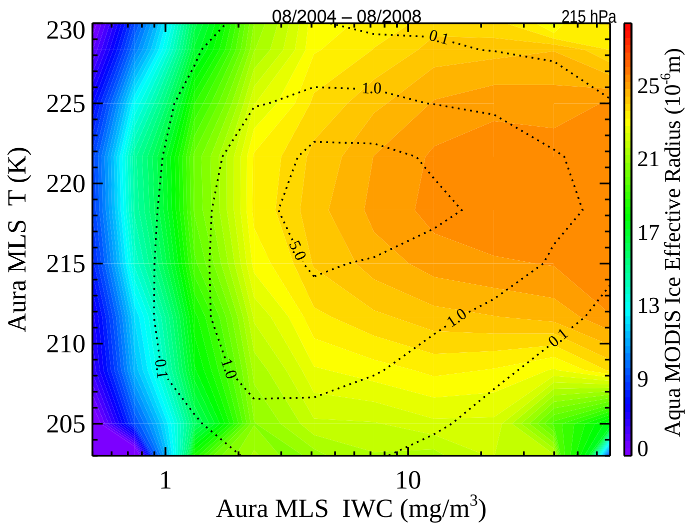
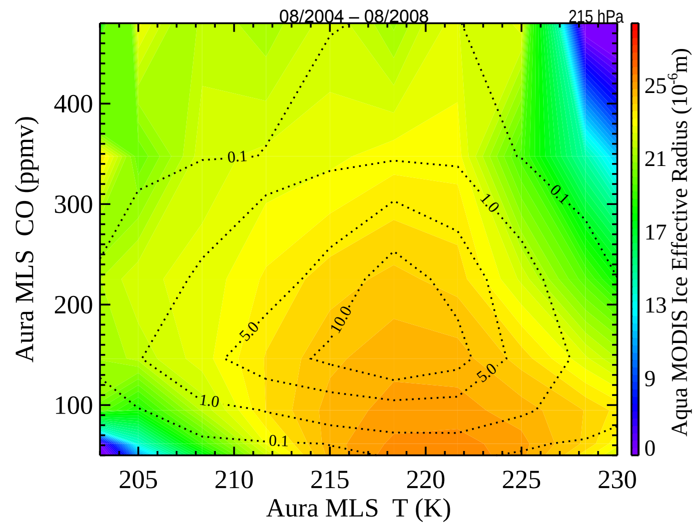
- Aqua MODIS Science Team.

Back-up slide





We used GEOS5-GMAO temperature on page 5 due to concern that MLS temperature at 215hPa has -2K bias. The MLS temperature, shown here, does not show significant differences, however.