Development of the Multilayer Cloudy Radiative Transfer Model for GOES-R Advanced Baseline Imager (ABI)

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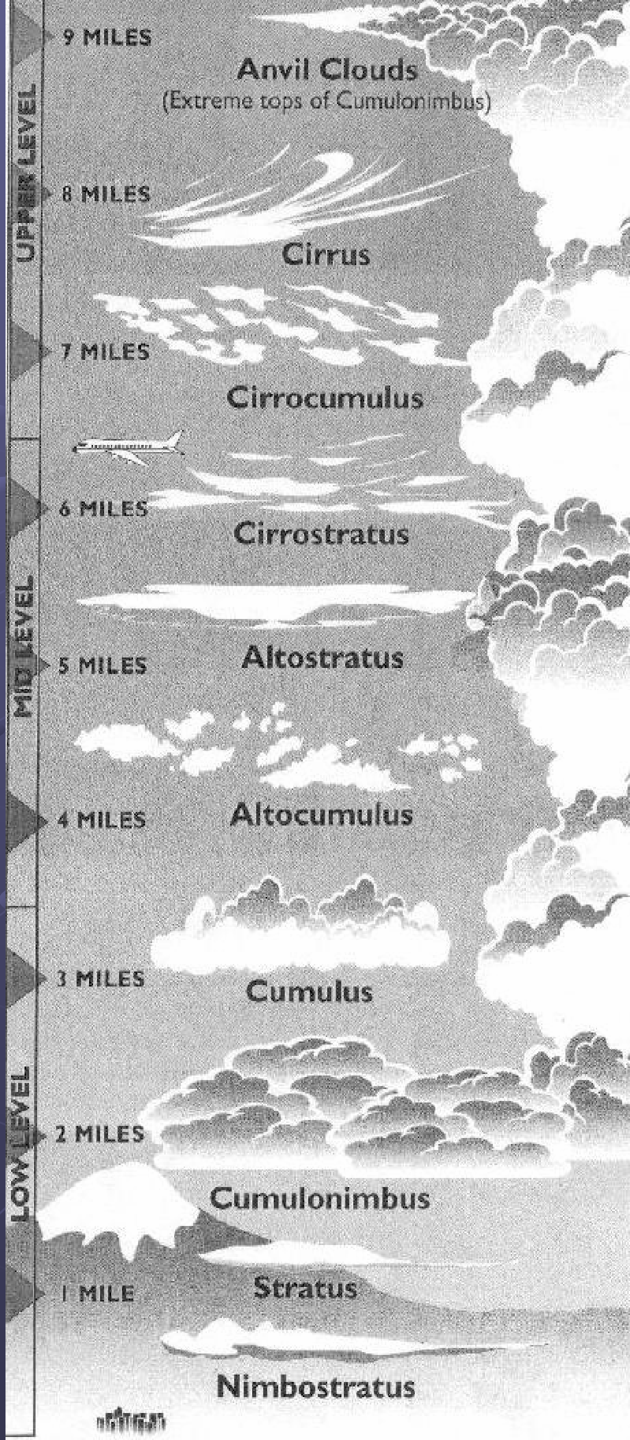
Outline

- Multilalyer Clouds – Observation, Modeling & Retrieval Issues
- Generalized Radiative Transfer Equation for Multilayer Clouds
- Applications to GOES-R Advanced Baseline Imager (ABI)
- Summary and Future Work

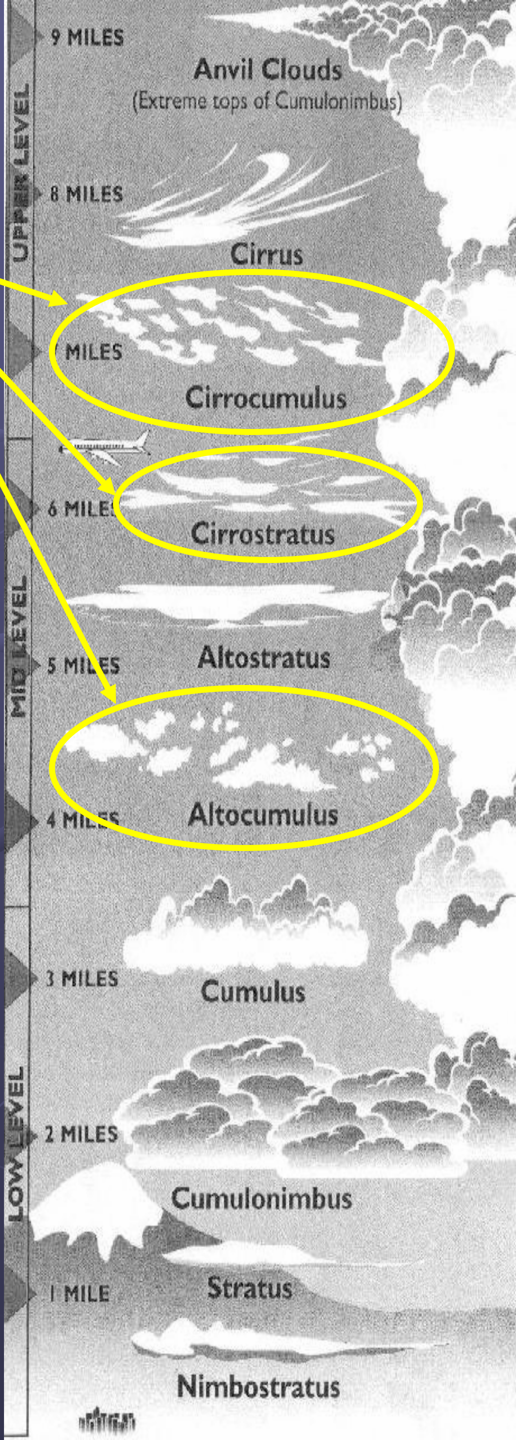
Observations of Multilalyer Clouds

- Multilalyer clouds frequently occur in frontal areas where cirrus clouds overlie boundary layer convective clouds or stratus clouds (Hahn et al. 1982, 1984).
- The probability of cirrus clouds overlying low stratus or altostratus clouds was higher than 50% (Tian 1989).
- Field experiments such as FIRE-I (1986), FIRE-II-Cirrus (1991), UAV-ARESE (1995) and SUCCESS (1996) have also observed multiple cloud layers involving cirrus overlying lower-layer clouds.
- For a given location, it is common for two or more cloud types to occur simultaneously but at different altitudes in the atmosphere (Baum et al. 1995) .
- A generalized radiative transfer model to include multilayer clouds is needed for remote sensing!



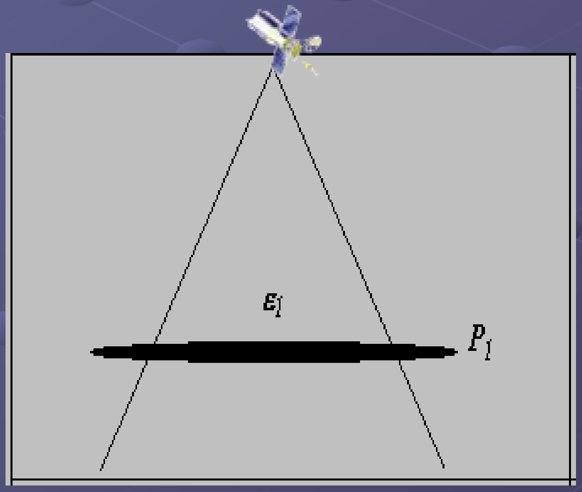
Broken Cloud & Partial Cloud Cover

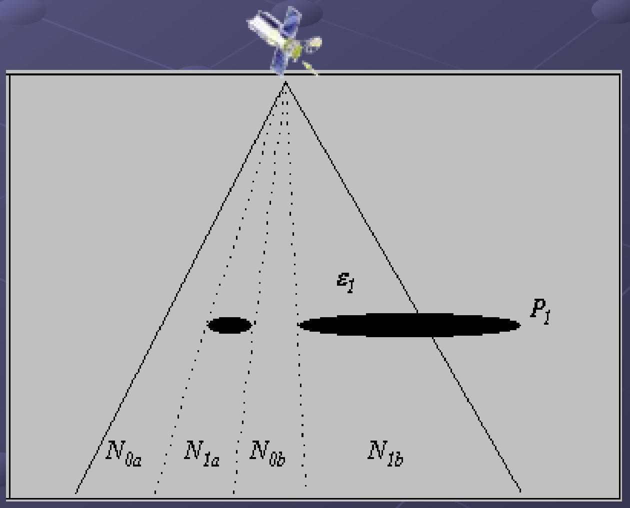
- Broken clouds exist in the real world.
- Partial cover of broken or continuous cloud within a sensor's field of view (FOV) may exist.



Indistinguishable Observations

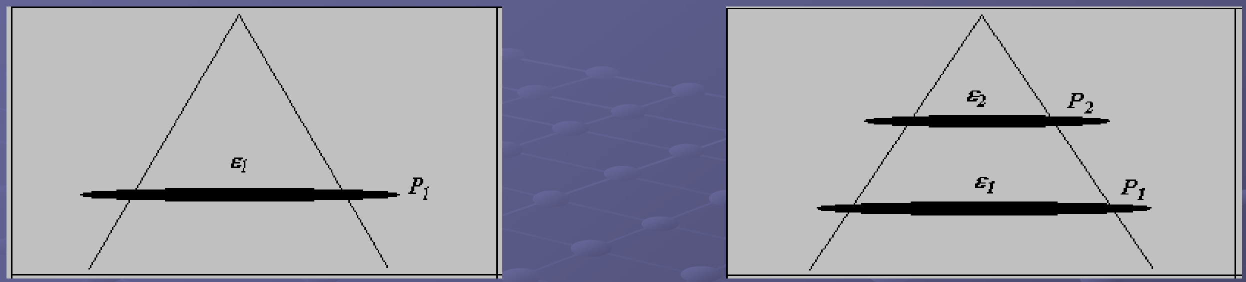
- The radiance observations from the following two FOVs may be indistinguishable to the sensor if both FOVs have the same amount of cloud fractions ($N_1 = N_{1a} + N_{1b}$), given the same atmosphere and cloud properties.



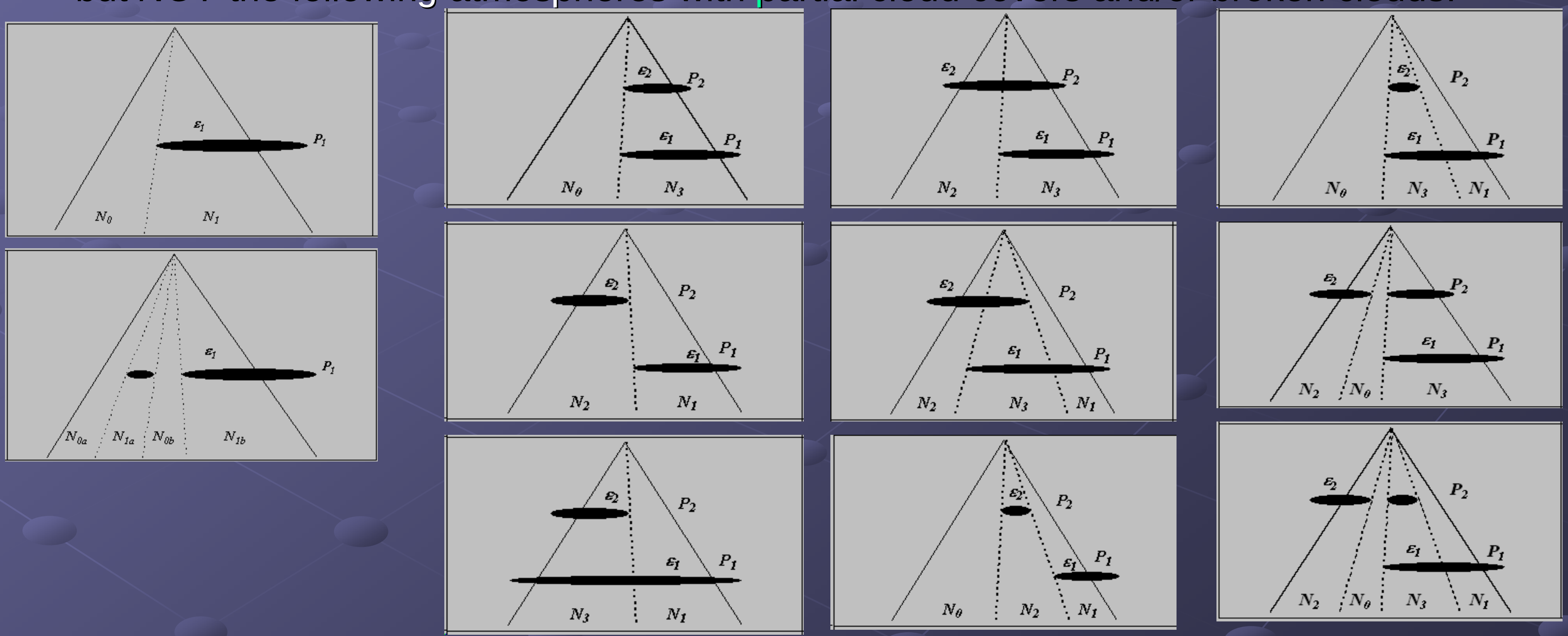


Limitation of the Plane-Parallel Radiative Transfer Equation

- The plane-parallel radiative transfer models (e.g. DISORT, SBDART) can simulate the following overcast cloudy atmospheres:



but *NOT* the following atmospheres with partial cloud covers and/or broken clouds:



- Again, a generalized radiative transfer equation (RTE) for multilayer clouds is desired !

Generalized RTE for the *M*-Layer Cloud System

- **We are developing a multilayer cloudy forward model which is not too complicated that it makes the cloudy inverse problem unmanageable, while generalized enough to include multilayer clouds.**

- For a nonscattering atmosphere with *M*-layer clouds at most, a sensor's FOV has up to 2^M sub-FOVs. We showed that the observed radiance can be described by:

$$R_{obs} = \sum_{K=0}^{2^M-1} N_K \sum_{i=0}^{M} \prod_{j=i+1}^{M+1} \left(1 - k_j \varepsilon_j\right) k_i \varepsilon_i R_i$$

with

$$R_i = B_\nu\left[T_c(p_i)\right]\tau_\nu(p_i) + \int_{p_i}^{0} B_\nu\left[T(p)\right] d\tau_\nu(p) \,,$$

$$\sum_{K=0}^{2^M-1} N_K = 1 \,, \qquad K = \left[k_M k_{M-1} \cdots k_1\right]_2 \,,$$

where R_i is the radiance from the *i*-th layer cloud (as if it were opaque) and the atmosphere above it, N_k is the FOV fraction corresponding to the *k*-th sub-FOV. If an *i*-th layer cloud exists within a sub-FOV, then k_i =1, otherwise k_i = 0.

Example 1: The Generalized RTE for 1-Layer Cloud System.

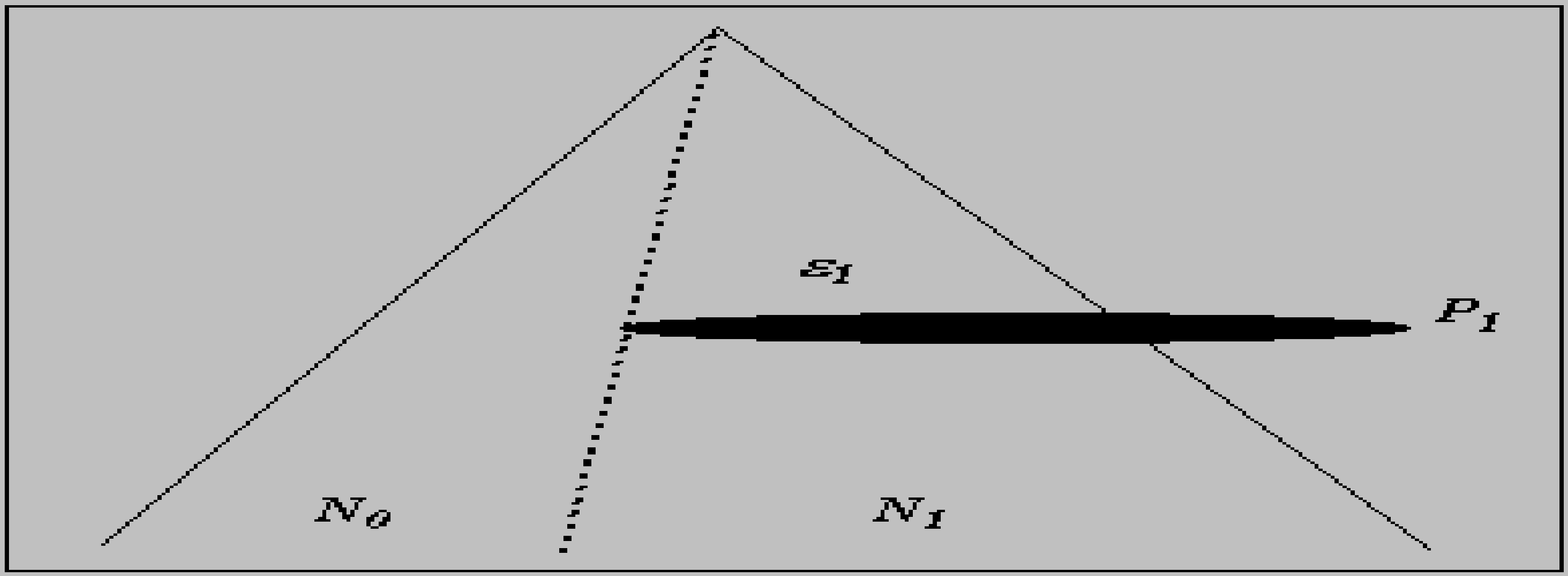


Figure 2. The generalized one-level cloud system with two sub-FOVs.

$$R_{obs} = N_0 R_0 + N_1 \left[(1 - \varepsilon_1) R_0 + \varepsilon_1 R_1 \right]$$
$$= (1 - N_1 \varepsilon_1) R_0 + N_1 \varepsilon_1 R_1.$$

When applied to two adjacent FOVs, it yields the *N method for cloud clearing.**

When applied to two close CO_2 channels, it yields the CO_2-slicing method for cloud top pressure retrieval.

Example 2: The Generalized RTE for 2-Layer Cloud System.

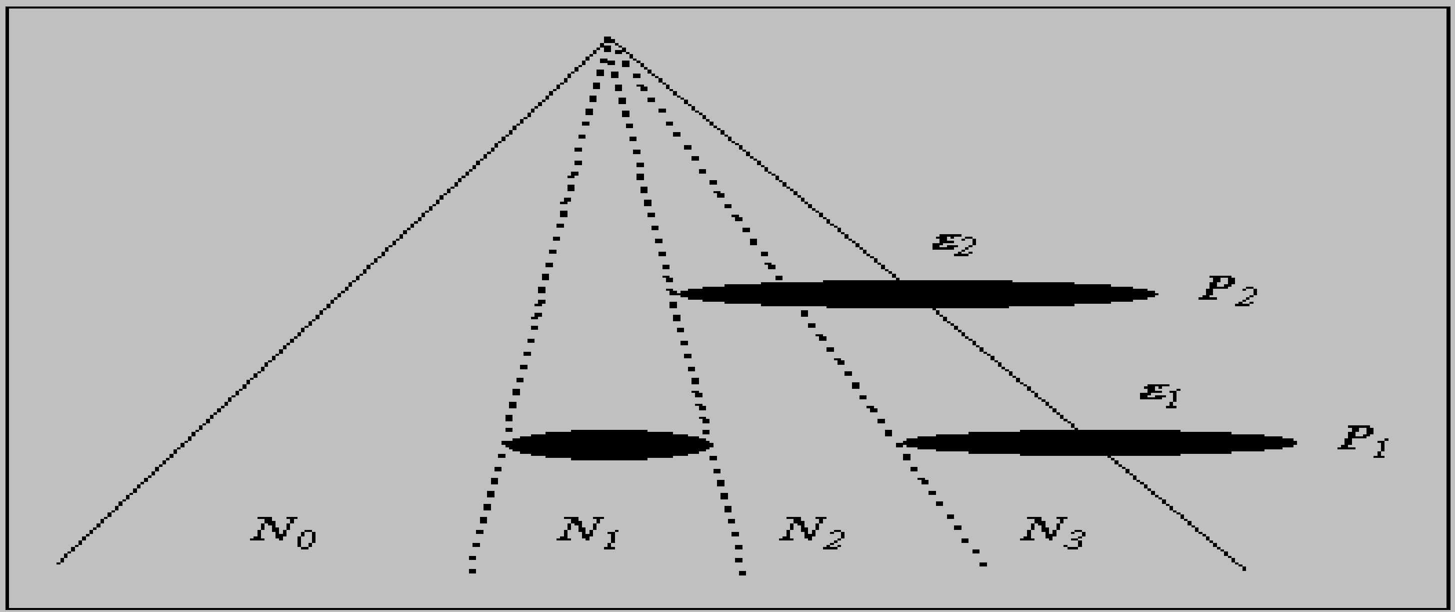
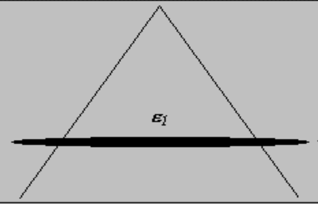


Figure 3. The generalized two-level cloud system with four sub-FOVs.

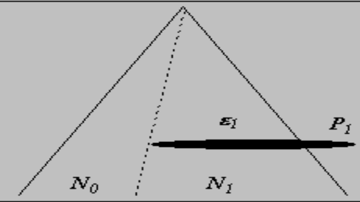
$$R_{obs} = [N_0 + N_1 (1 - \varepsilon_1) + N_2 (1 - \varepsilon_2) + N_3 (1 - \varepsilon_1)(1 - \varepsilon_2)]\, R_0 + [N_1 \varepsilon_1 + N_3 (1 - \varepsilon_2)\, \varepsilon_1]\, R_1 + (N_2 \varepsilon_2 + N_3 \varepsilon_2)\, R_2 .$$

Both the *N and CO_2-slicing methods are not applicable to a system with multilayer clouds!**

2 ways to form a one-layer cloud system:

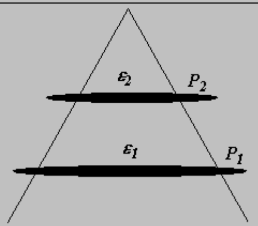


$$R_{obs} = (1-\varepsilon_1)R_0 + \varepsilon_1 R_1$$

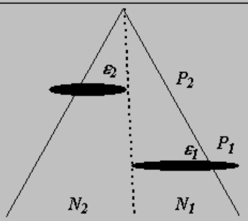


$$R_{obs} = (1-N_1\varepsilon_1)R_0 + N_1\varepsilon_1 R_1$$

10 ways to form a two-layer cloud system:

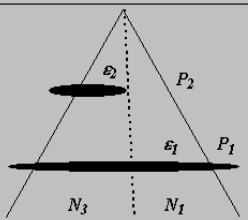


$$R_{obs} = (1-\varepsilon_1-\varepsilon_2+\varepsilon_1\varepsilon_2)R_0 + \varepsilon_1(1-\varepsilon_2)R_1 + \varepsilon_2 R_2,$$



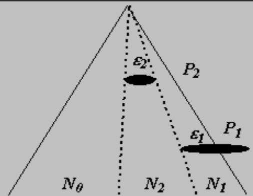
$$R_{obs} = (1-N_1\varepsilon_1-N_2\varepsilon_2)R_0 + N_1\varepsilon_1 R_1 + N_2\varepsilon_2 R_2,$$

$$N_1+N_2=1$$



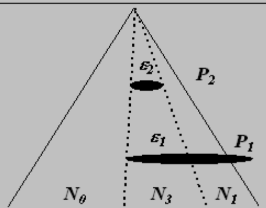
$$R_{obs} = [1-N_1\varepsilon_1-N_3(\varepsilon_1+\varepsilon_2-\varepsilon_1\varepsilon_2)]R_0 + [N_1\varepsilon_1+N_3\varepsilon_1(1-\varepsilon_2)]R_1 + N_3\varepsilon_2 R_2,$$

$$N_1+N_3=1.$$



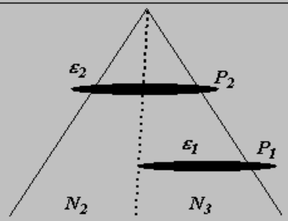
$$R_{obs} = (1-N_1\varepsilon_1-N_2\varepsilon_2)R_0 + N_1\varepsilon_1 R_1 + N_2\varepsilon_2 R_2$$

$$N_0+N_1+N_2=1$$



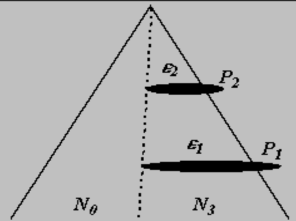
$$R_{obs} = [1-N_2\varepsilon_2-N_3(\varepsilon_1+\varepsilon_2-\varepsilon_1\varepsilon_2)]R_0 + [N_3\varepsilon_1(1-\varepsilon_2)]R_1 + (N_2\varepsilon_2+N_3\varepsilon_2)R_2,$$

$$N_0+N_1+N_3=1.$$



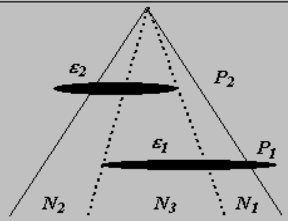
$$R_{obs} = [1-N_2\varepsilon_2-N_3(\varepsilon_1+\varepsilon_2-\varepsilon_1\varepsilon_2)]R_0 + N_3\varepsilon_1(1-\varepsilon_2)R_1 + (N_2\varepsilon_2+N_3\varepsilon_2)R_2,$$

$$N_2+N_3=1.$$



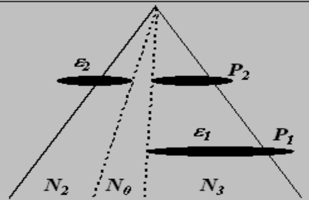
$$R_{obs} = [1-N_3(\varepsilon_1+\varepsilon_2-\varepsilon_1\varepsilon_2)]R_0 + N_3\varepsilon_1(1-\varepsilon_2)R_1 + N_3\varepsilon_2 R_2,$$

$$N_0+N_3=1.$$



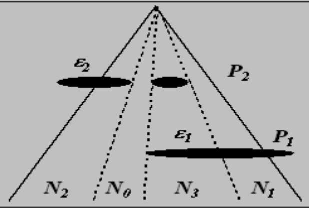
$$R_{obs} = [1-N_1\varepsilon_1-N_2\varepsilon_2-N_3(\varepsilon_1+\varepsilon_2-\varepsilon_1\varepsilon_2)]R_0 + [N_1\varepsilon_1+N_3\varepsilon_1(1-\varepsilon_2)]R_1 + (N_2\varepsilon_2+N_3\varepsilon_2)R_2,$$

$$N_1+N_2+N_3=1.$$



$$R_{obs} = [1-N_2\varepsilon_2-N_3(\varepsilon_1+\varepsilon_2-\varepsilon_1\varepsilon_2)]R_0 + (N_3\varepsilon_1(1-\varepsilon_2))R_1 + (N_2\varepsilon_2+N_3\varepsilon_2)R_2,$$

$$N_0+N_2+N_3=1.$$

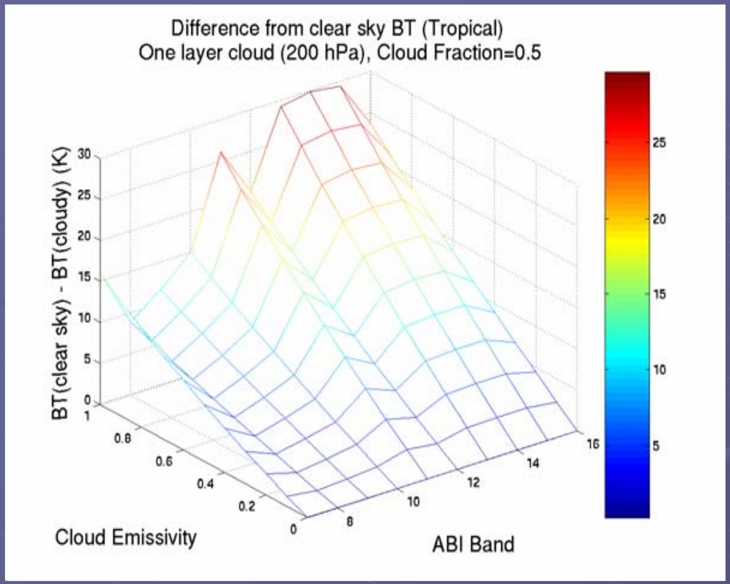


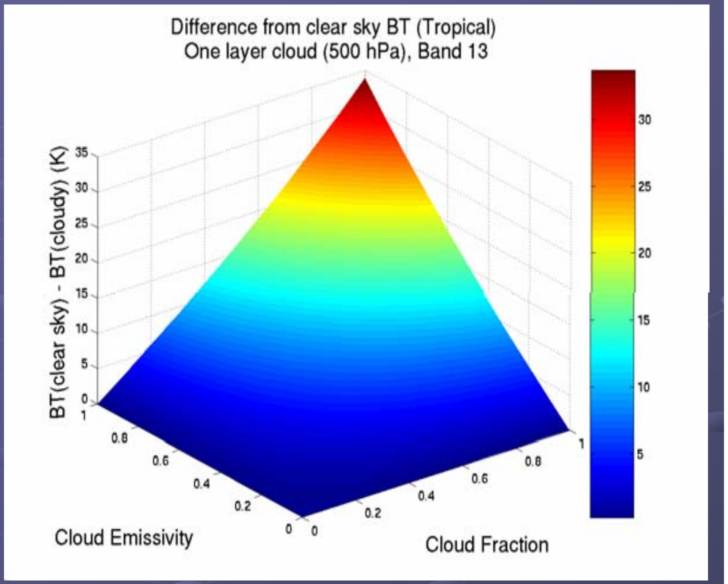
$$R_{obs} = [1-N_1\varepsilon_1-N_2\varepsilon_2-N_3(\varepsilon_1+\varepsilon_2-\varepsilon_1\varepsilon_2)]R_0 + [N_1\varepsilon_1+N_3\varepsilon_1(1-\varepsilon_2)]R_1 + (N_2\varepsilon_2+N_3\varepsilon_2)R_2,$$

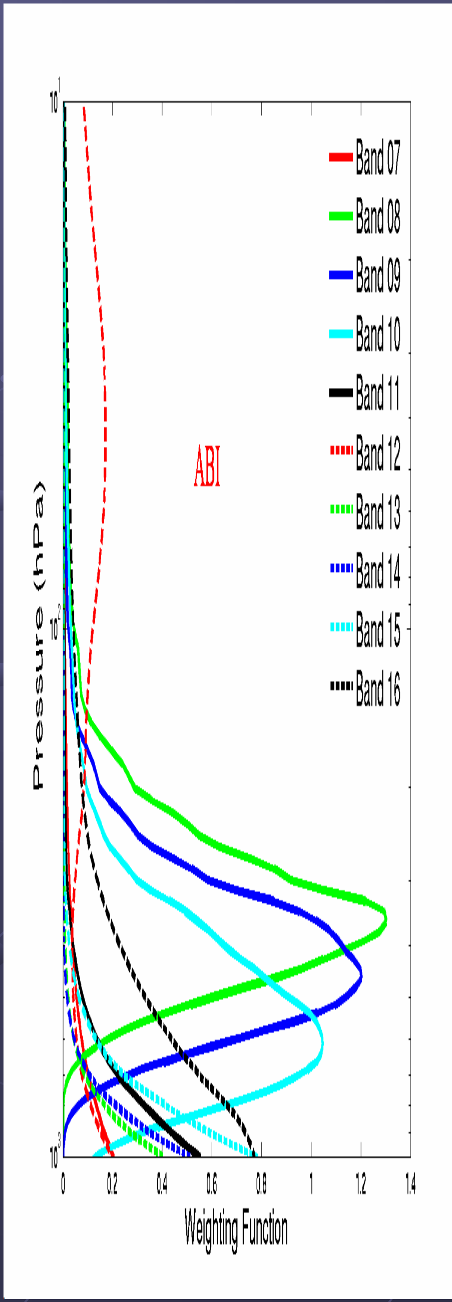
$$N_0+N_1+N_2+N_3=1.$$

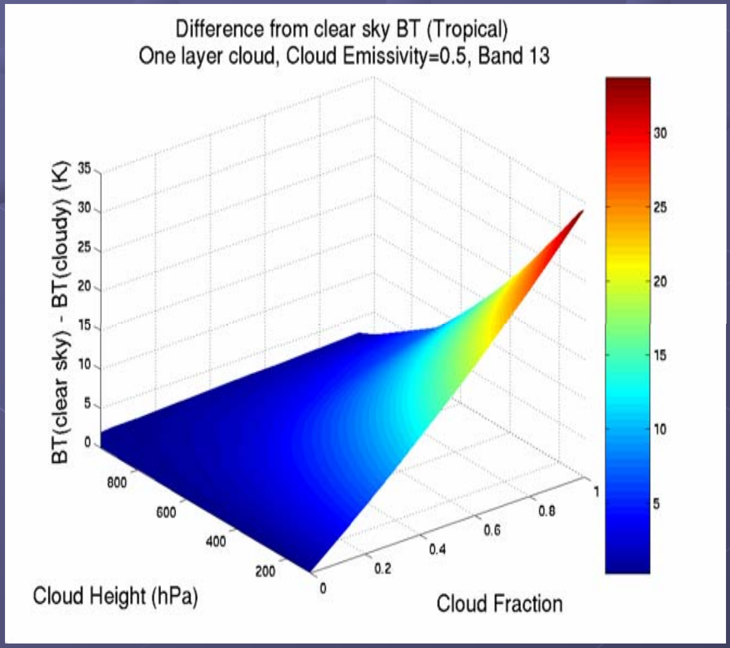
GOES-R ABI Multilayer Cloudy Forward Model

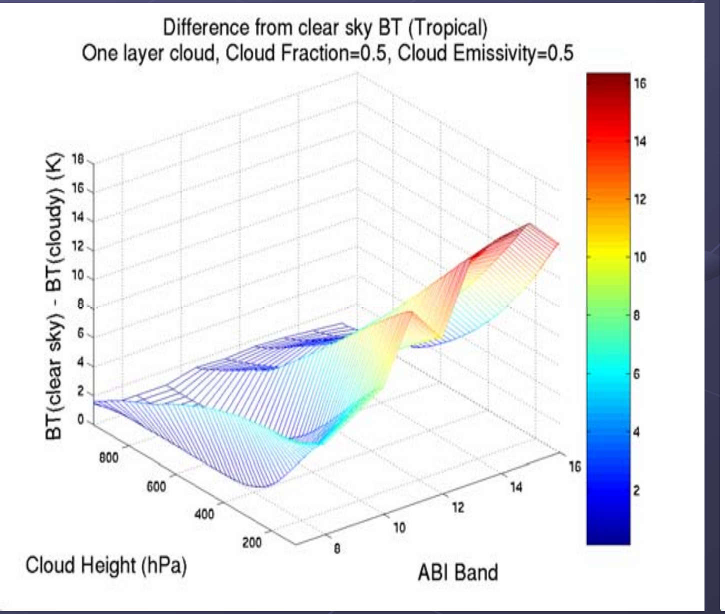
One-layer cloud system studies





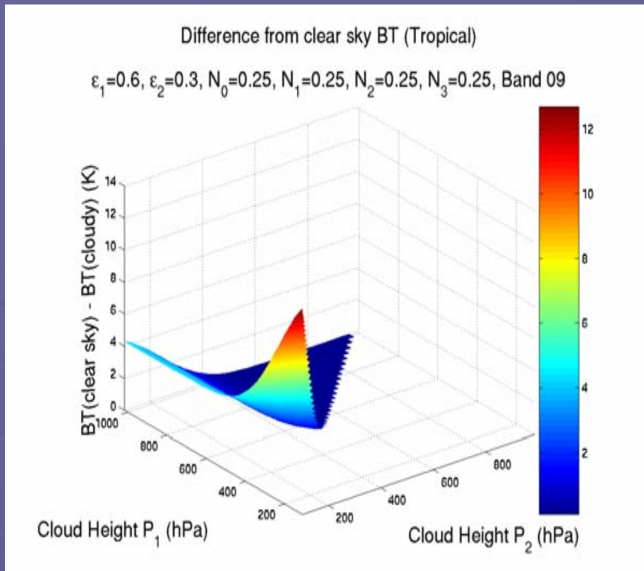


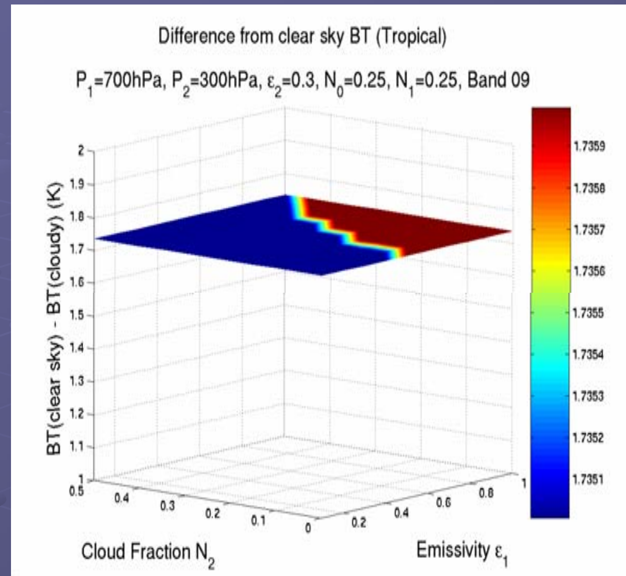


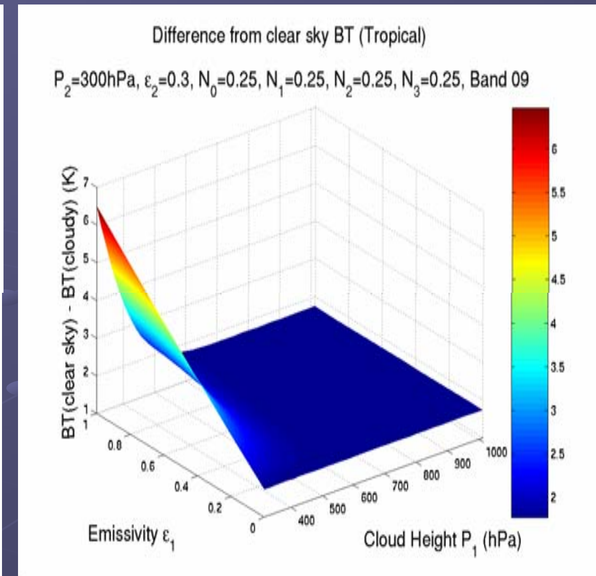


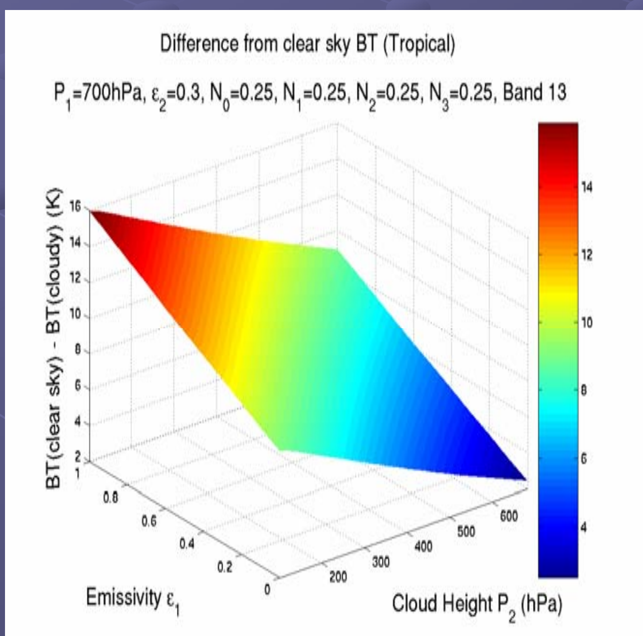
ABI Multilayer Cloudy Forward Model

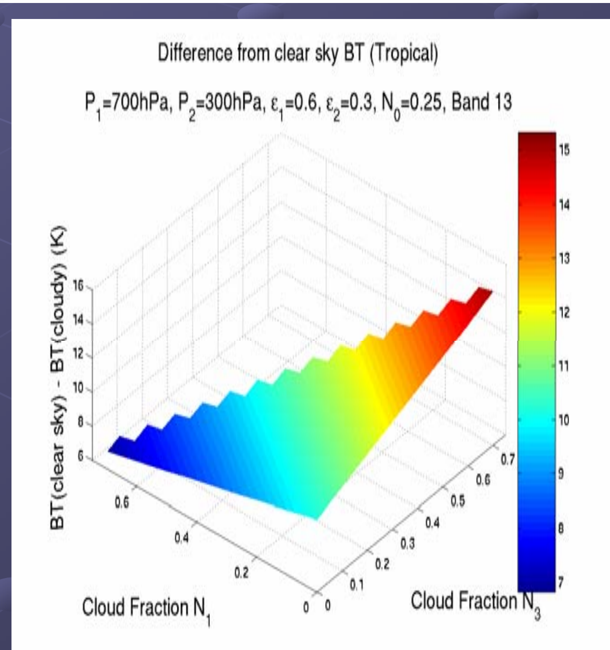
Two-layer cloud system studies

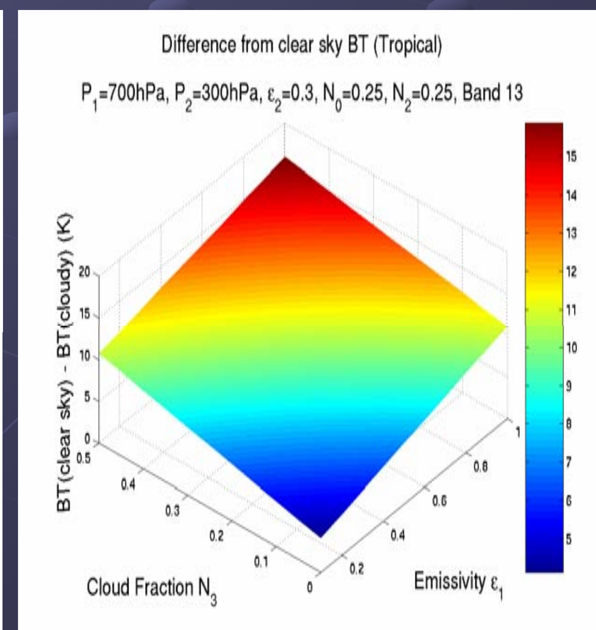




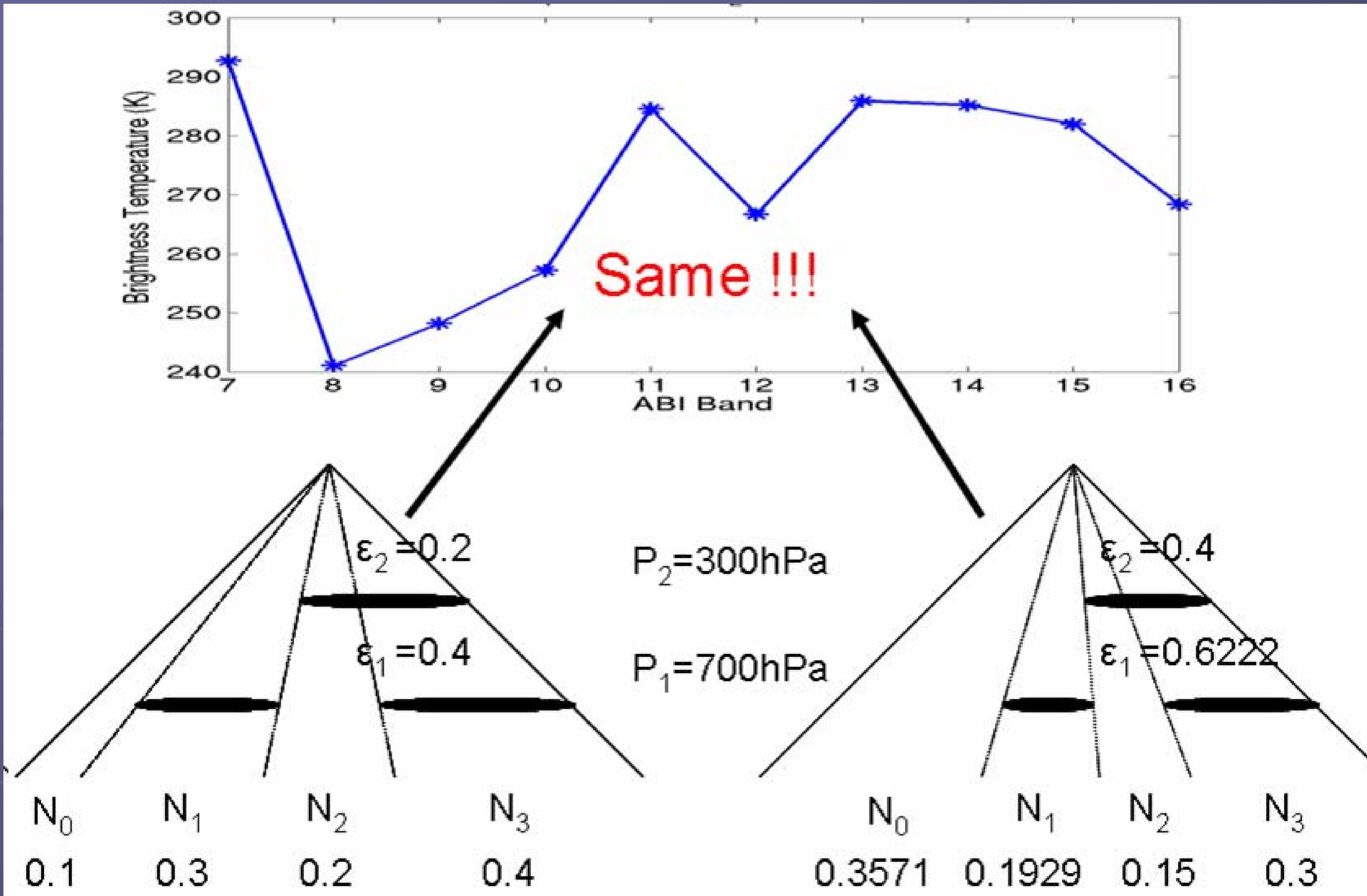








Multiple Solutions Exist for the Multilayer Cloudy Retrieval!



Summary

- The generalized radiative transfer equation for multilayer clouds is developed.

- The clear-sky atmosphere is its special case when cloud fractions are zero.

- Both the *N** and CO_2-slicing methods are not applicable to multilayer cloud cases.

- The GOES-R ABI multilayer cloudy forward model is implemented.

- The ABI case studies show some correlations among cloud parameters.

Future Work

- **Implementation of the multilayer cloudy forward model for hyperspectral sounders (e.g. IASI, CrIS, AIRS)**

- **Multilayer cloudy retrieval for the multispectral sensors (e.g. ABI).**

Not enough bands? Can be done in a "MOPPIT" way, i.e. atmospheric temperature and moisture profiles are supplied from the weather forecast model.

Only retrieve cloud parameters with some inter-correlations in mind for parameterized simplification.

- **Multilayer cloudy retrieval for the hyperspectral sensors.**

Much easier with thousands of channels for simultaneous retrieval of atmospheric variables and cloudy parameters!