

Preliminary results of SAM's microphysics with improved treatment of ice

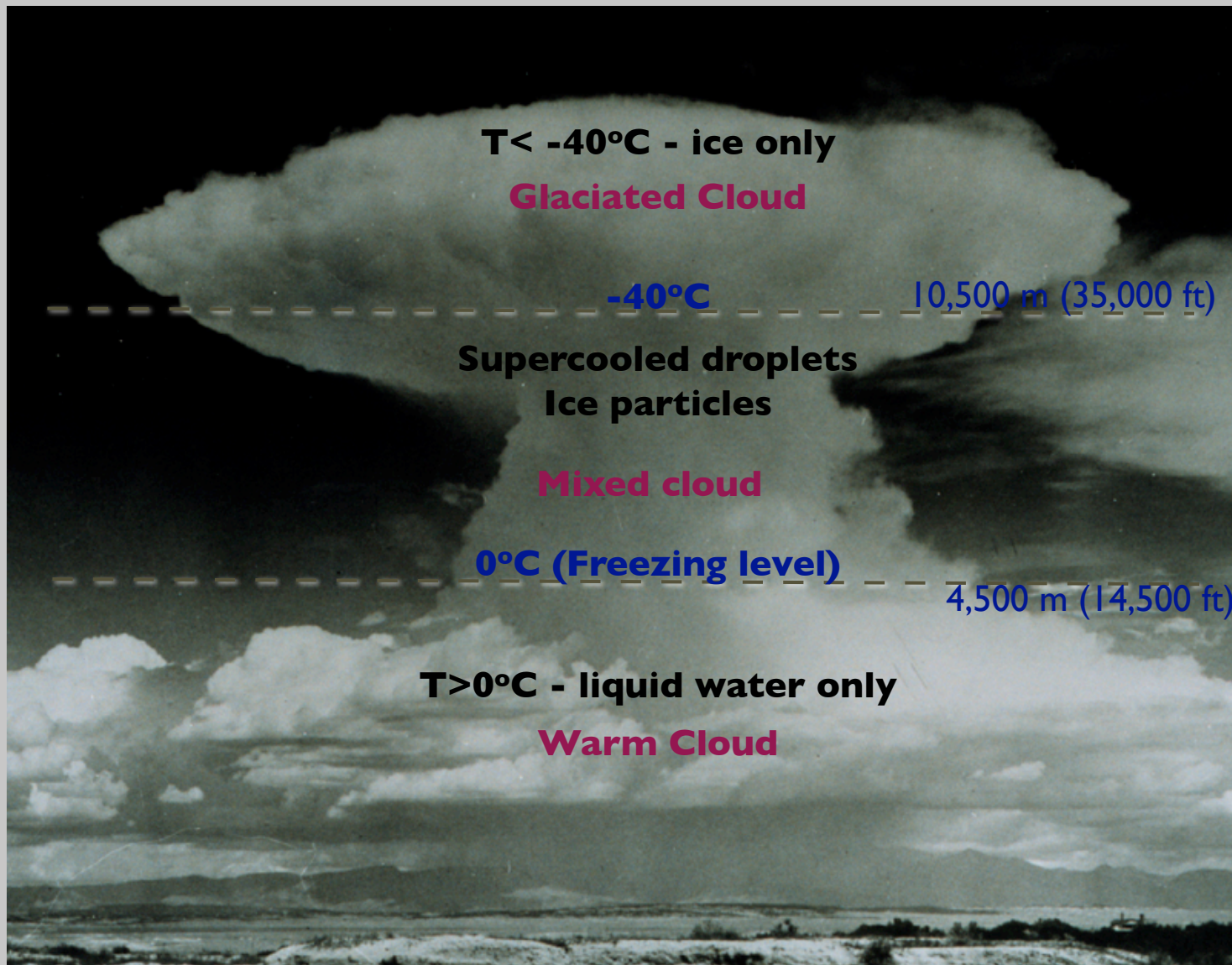
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Stony Brook University

Andrew Heysmfield
NCAR



Cold Clouds

If a cloud top extends above the 0°C level, it is called a *cold cloud*



Growth of Ice in Clouds

Growth from the vapor phase (deposition)

*The equation for the growth rate of mass of an ice crystal m is similar to the one for the mass of droplet except for introduction of the capacitance C (arising from analogy between electric field around an arbitrary shaped charged particle and stationary diffusion equation)

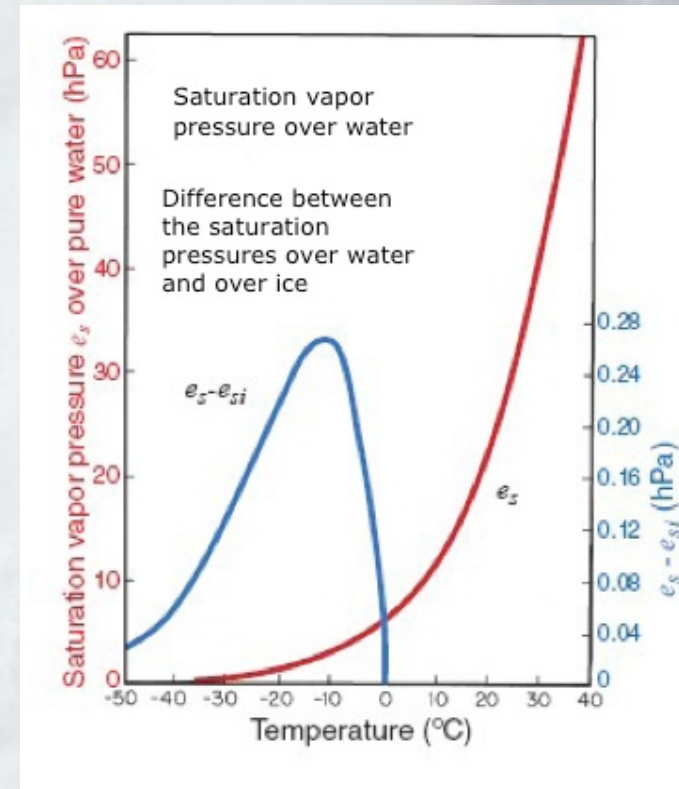
$$\left(\frac{dm}{dt}\right)_{dep} = \frac{4\pi C(S_i - 1)}{F(T)} f(D)$$

S_i - Supersaturation over ice

$C = r$ For spherical particles (drops; graupel; hail)

$C = 2r/\pi$ For plate-type particles (plates; dendrites)

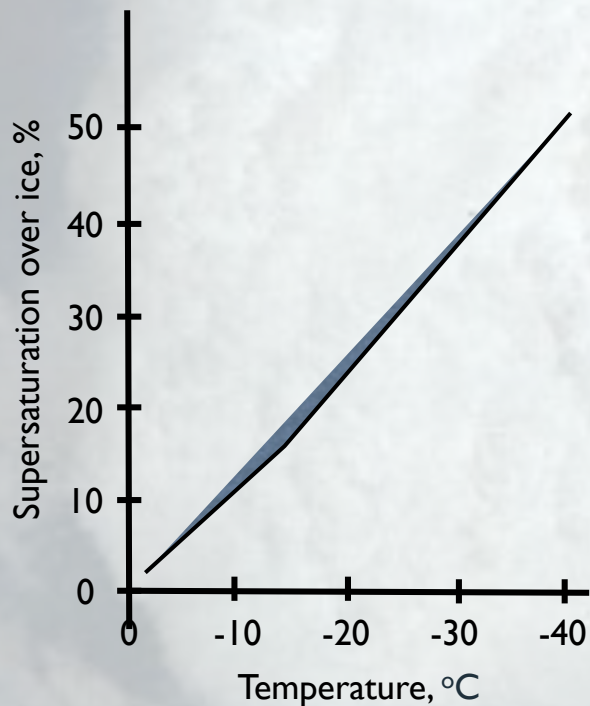
*Ice crystals grow most rapidly by vapor deposition in mixed clouds at temperatures around -12°C



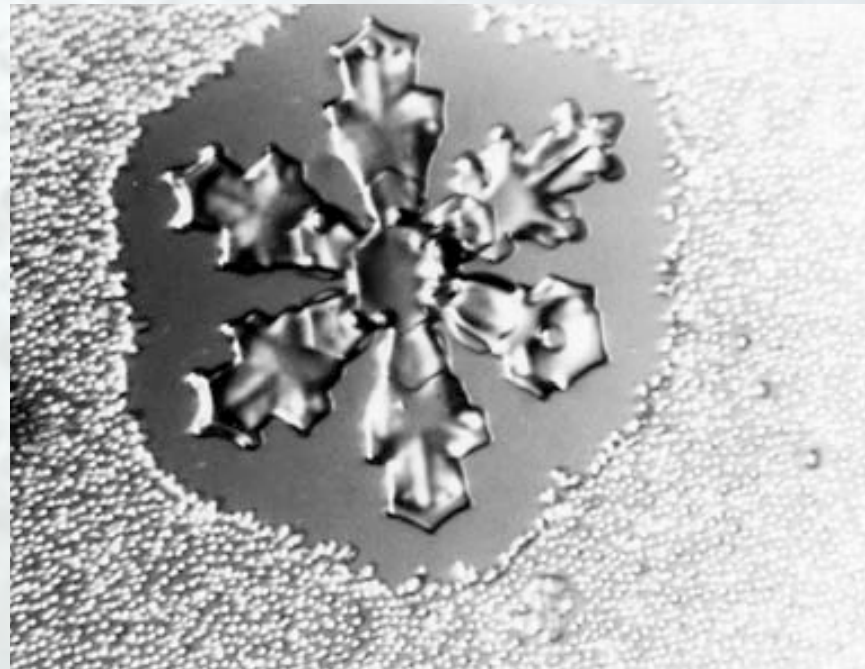
Growth of Ice in Clouds

Bergeron-Findeisen process

- * Saturation vapor pressure over ice is always lower than over liquid water;
- * In mixed-phase clouds, vapor is saturated with respect to liquid water; hence, supersaturated with respect to ice
- * So, in mixed clouds ice is growing at the expense of supercooled droplets.

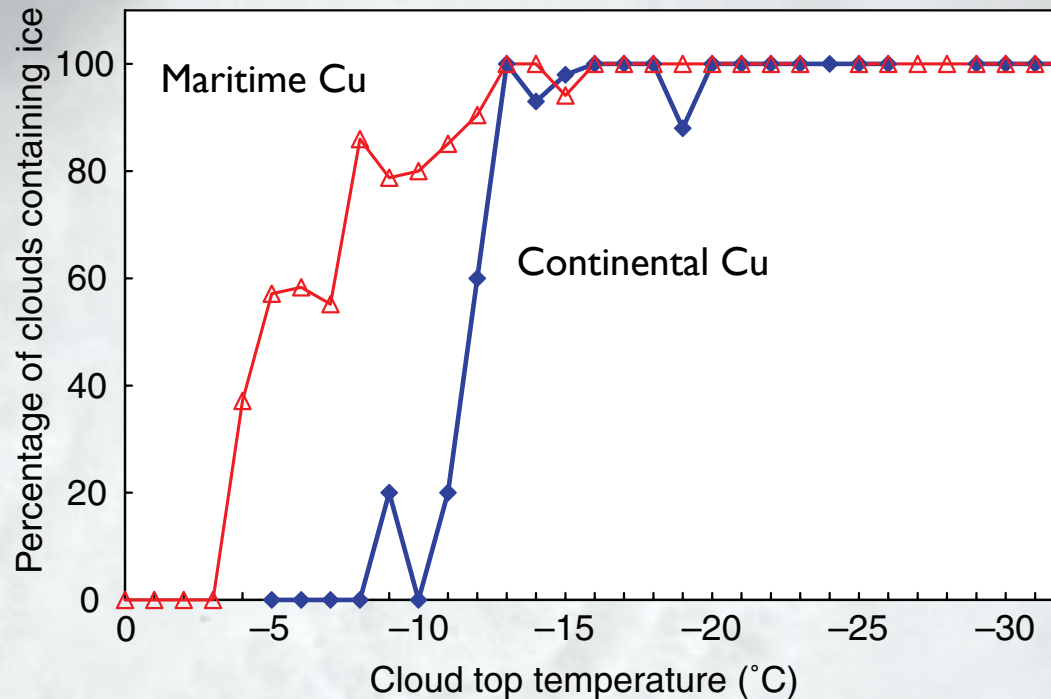


Supersaturation relative to ice when vapor is saturated relative to water (in mixed-phase clouds)



Fraction of Ice in Clouds

Dependence on Temperature

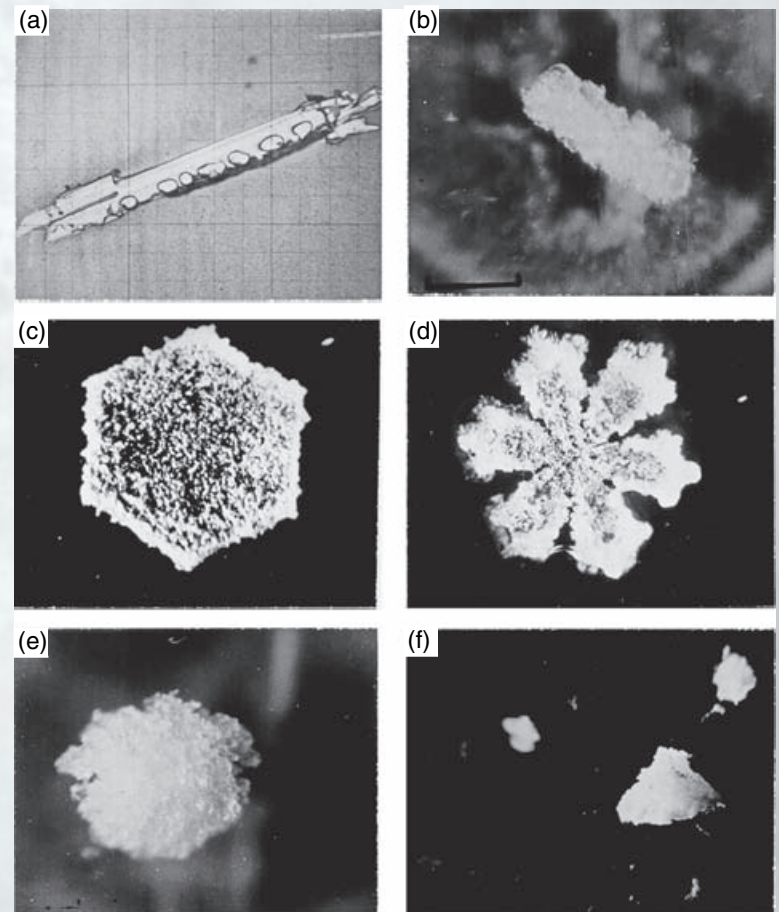
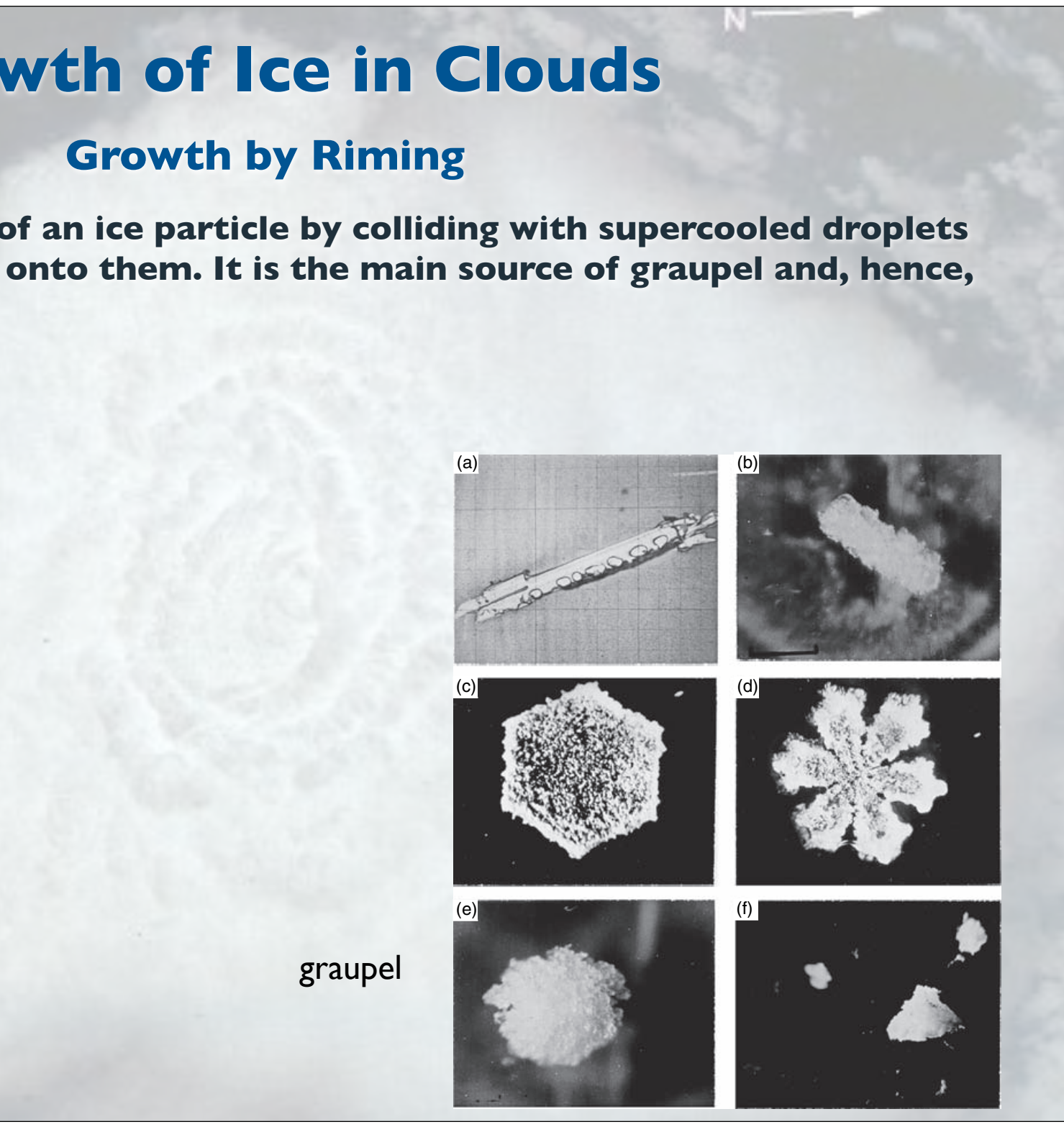


- * Fraction of ice particles in the liquid drop/ice mixture in clouds generally increases as temperature decreases
- * Clouds with the top temperatures lower than -15°C are usually glaciated (way warmer than -40°C homogeneous freezing threshold).

Growth of Ice in Clouds

Growth by Riming

***Riming:** Growth of an ice particle by colliding with supercooled droplets that then freeze onto them. It is the main source of graupel and, hence, precipitation.

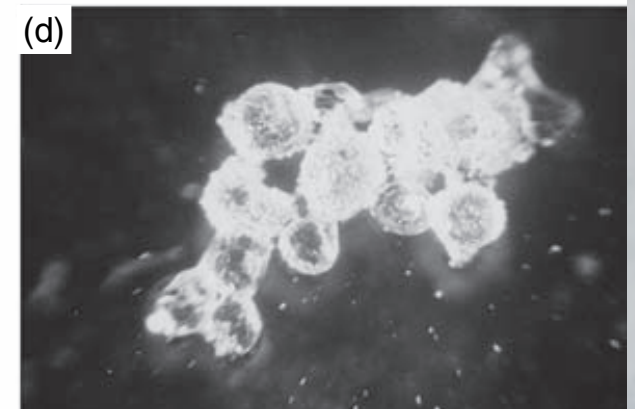
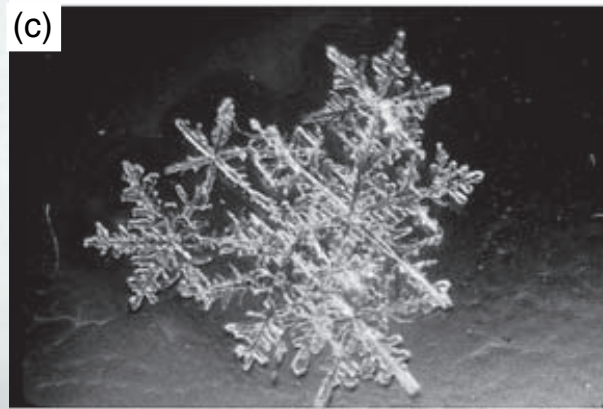
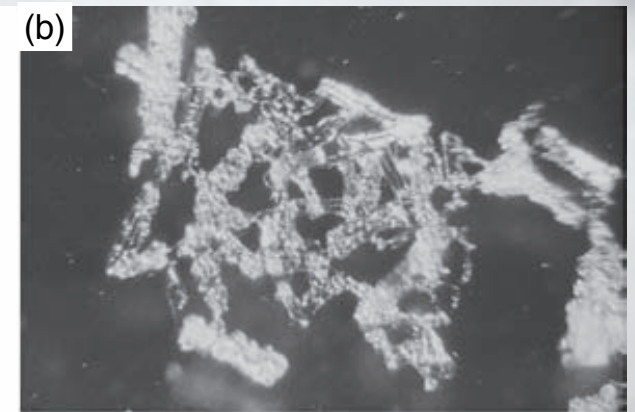
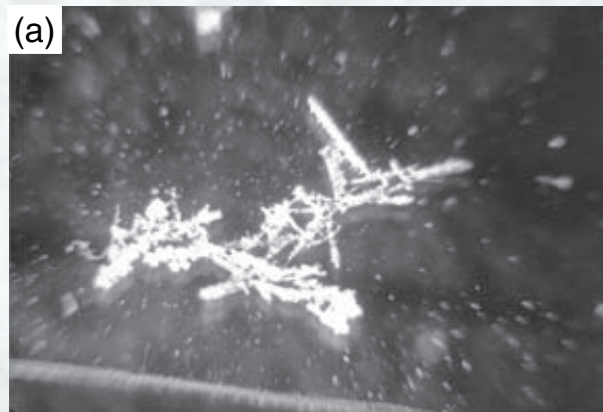


graupel

Growth of Ice in Clouds

Growth by Aggregation

***Aggregation:** Ice crystals can collide with each other (when they have slightly different fall speeds) and may stick together forming a bigger particle (like snow flakes)



Aggregates of (a) rimed needles; (b) rimed columns; (c) dendrites; (d) rimed frozen drops.

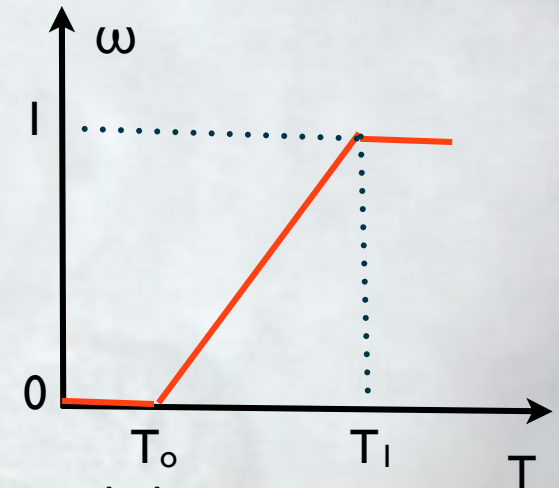
SAMIMOM Microphysics

3 prognostic variables (explicitly transported around the grid):

- 1) $h = c_p T + gz - Lq_{LIQ} - L_s q_{ICE}$ Liquid/ice static energy
- 2) $q_T = q_v + q_c + q_i$ Total non-precipitating water
- 3) $q_P = q_r + q_s + q_g$ Total precipitating water

Diagnostic variables :

- | | |
|--|------------------------|
| $q_c = \omega_{ci}(T)(q_c + q_i)$ | Cloud water |
| $q_i = (1 - \omega_{ci}(T))(q_c + q_i)$ | Cloud ice ("Pristine") |
| $q_v = \omega_{ci} q_s + (1 - \omega_{ci}) q_{si}$ | Saturation water vapor |
| $q_r = \omega_r(T)(q_r + q_s + q_g)$ | Rain |
| $q_g = (1 - \omega_r(T)) \omega_{gs}(T)(q_r + q_s + q_g)$ | Graupel/Hail |
| $q_s = (1 - \omega_r(T))(1 - \omega_{gs}(T))(q_r + q_s + q_g)$ | Snow |



- * No explicit condensation/evaporation/deposition/sublimation rates are needed
- * No explicit Bergeron-Findeisen processes
- * All other bulk processes like autoconversion-to-rain, ice-to-snow conversion, sedimentation, riming, accretion rates change the prognostic variables (but not T).

SAMIMOM Microphysics

Deficiencies

- Impossible to compute diabatic heating due to microphysics
- No link to aerosol (CCN)
- No Bergeron process
- Ice forms at 100% RH over ice, while observations suggest higher RH at very cold temperatures (cirrus)
- Mixed-phase clouds at narrow predefined temperature range (currently below -20°C all clouds are frozen)
- Artificial separation on pristine ice and snow
- ...

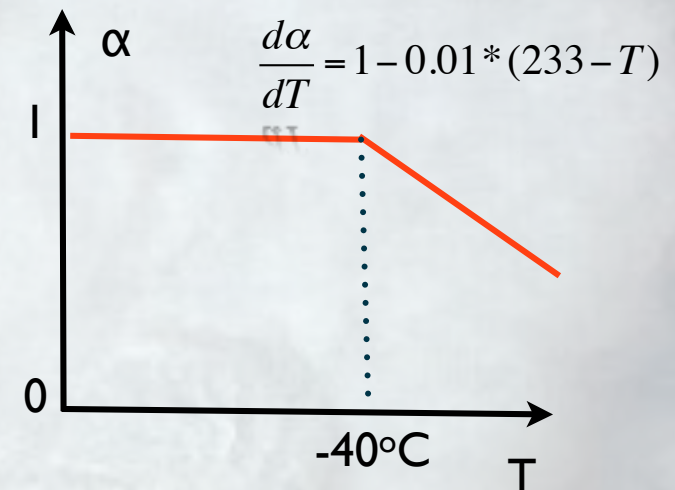
KH3 Microphysics

4 prognostic variables (explicitly transported around the grid):

- 1) $h = c_p T + gz - Lq_{LIQ} - L_s q_{ICE}$ Liquid/ice static energy
- 2) $q_T = q_v + q_c$ Total non-precipitating liquid water
- 3) q_i Ice (Pristine + Snow)
- 4) $q_P = q_r + q_g$ Precipitating water

4 diagnostic variables :

- $$q_c = q_T - q_*$$
- $$q_* = q_s \alpha(T)$$
- $$q_r = \omega_r q_P$$
- $$q_g = (1 - \omega_r) q_P$$
- $$N_i = f(T)$$
- Cloud water
 Saturation Vapor
 Rain
 Graupel/Hail
 Ice concentration



- * Explicit Bergeron-Findeisen process for mixed-phase clouds
- * Cirrus formation from “aerosol” at significant super-saturation over ice
- * Aggregation into snow is implicitly included
- * Riming of cloud water by ice creates graupel

Parameterization of ice concentration

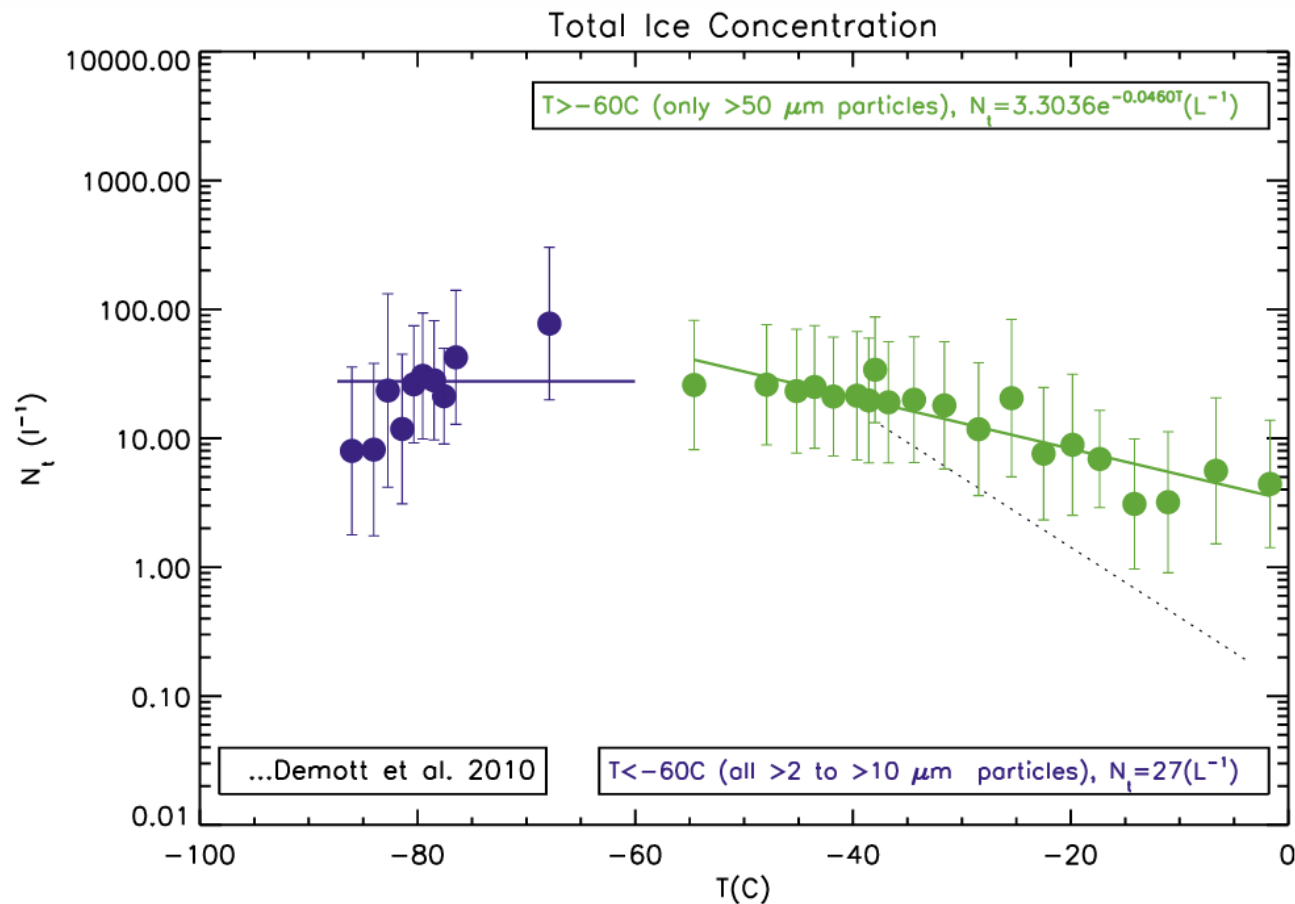


FIG. 4. Total ice number concentrations above sizes 2–10 μm for $T < -60^\circ\text{C}$ (blue), depending on the field program, and approximately 50 μm for $T > -60^\circ\text{C}$ (green). Median values of N_t in increments of equal numbers of data points are plotted through the data for each size range. The average curve developed by Demott et al. (2010) is shown by the dotted line.

Heimsfield et al 2013

$$N_i = 10^3 \min(54, 6.6e^{0.046(T-273.15)})$$

Assumed ice size-spectrum: Gamma-distribution

Size PDF:

$$n(D) = \frac{N_i \lambda^{\gamma+1}}{\Gamma(\gamma+1)} D^\gamma e^{-\lambda D}$$

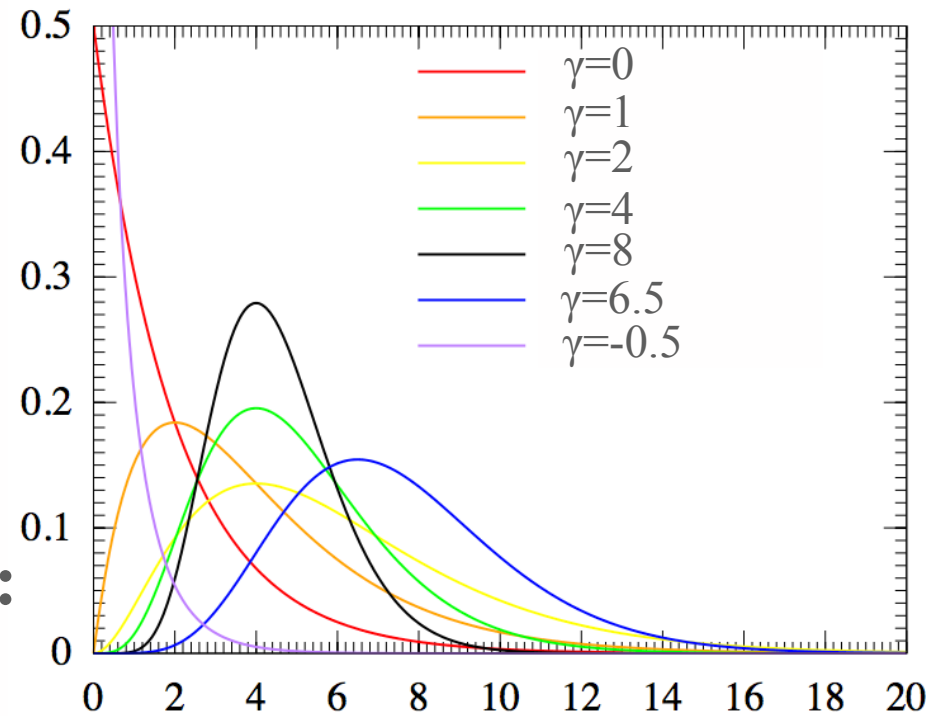
Ice mixing ratio:

$$q_i = \rho^{-1} \int_0^{\infty} m(D) n(D) dD$$

Assumed size-mass relationship:

$$m(D) = aD^b$$

$a=0.095$ $b=2.1$ (Heymsfield et al 2013)



$$\lambda = \left[\frac{aN_i \Gamma(b + \gamma + 1)}{\rho q_i \Gamma(\gamma + 1)} \right]^{1/b}$$

Parameterization of dispersion parameter γ

b: Temp. Dependence

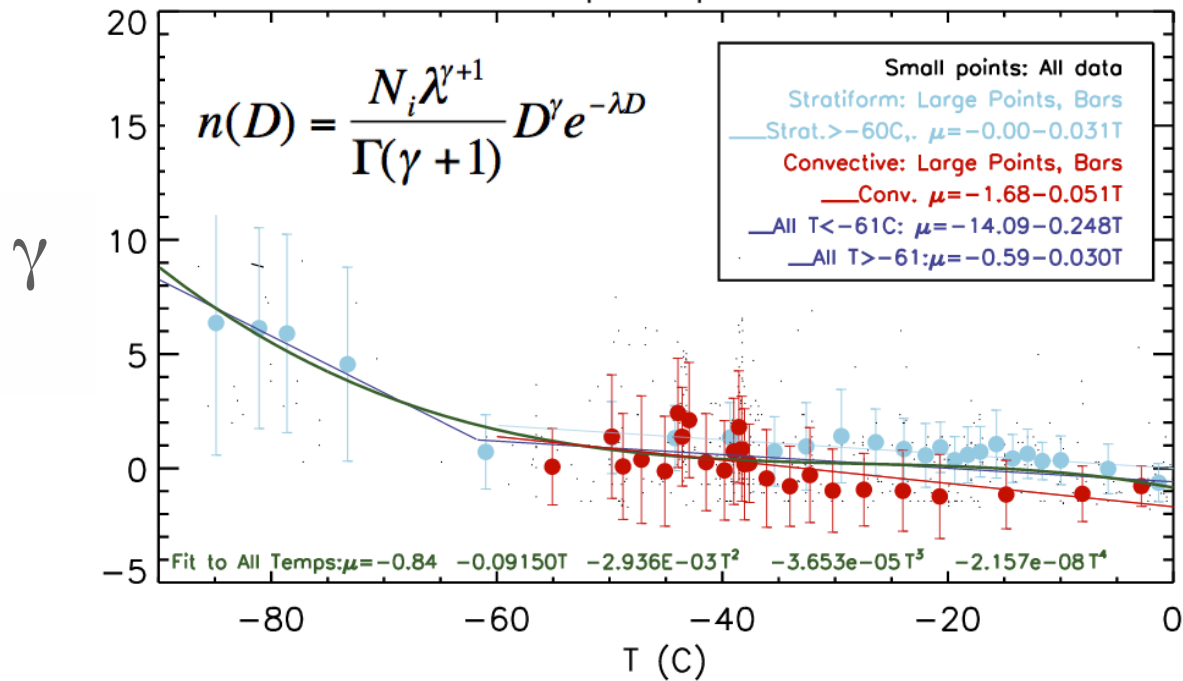


FIG. 9. PSD dispersion μ as a function of (a) slope and (b) temperature. In (a), note that the scale for μ adds a value of 3 to the derived value so that the plot can be made on a logarithm (y axis) scale, and the dashed horizontal line corresponds to an exponential PSD, where the gamma PSD has a value of $\mu = 0$. The term cc is the goodness of fit of the PSDs.

Heimsfield et al 2013

$$\gamma = \max(0, 16 + 0.27(T - 273.15))$$

Vapor deposition/sublimation

Bulk rate of change

$$\left(\frac{\partial q_i}{\partial t}\right)_{proc} = \rho^{-1} \int_0^{\infty} \frac{dm}{dt} n(D) dD$$

Deposition rate on a plate

$$\left(\frac{dm}{dt}\right)_{dep} = \frac{2D(S_i - 1)}{F} f(D)$$

$$F = \frac{L}{K_a T} \left(\frac{L}{R_v T} - 1 \right) + \frac{R_v T}{e_{si} D_v}$$

Ventilation factor

$$f(D) = a_f + b_f \left(\frac{\rho D v_T}{\mu} \right)^{1/2}$$

$$a_f = 0.65; \quad b_f = 0.44$$

Summary of V_t - D Relationships

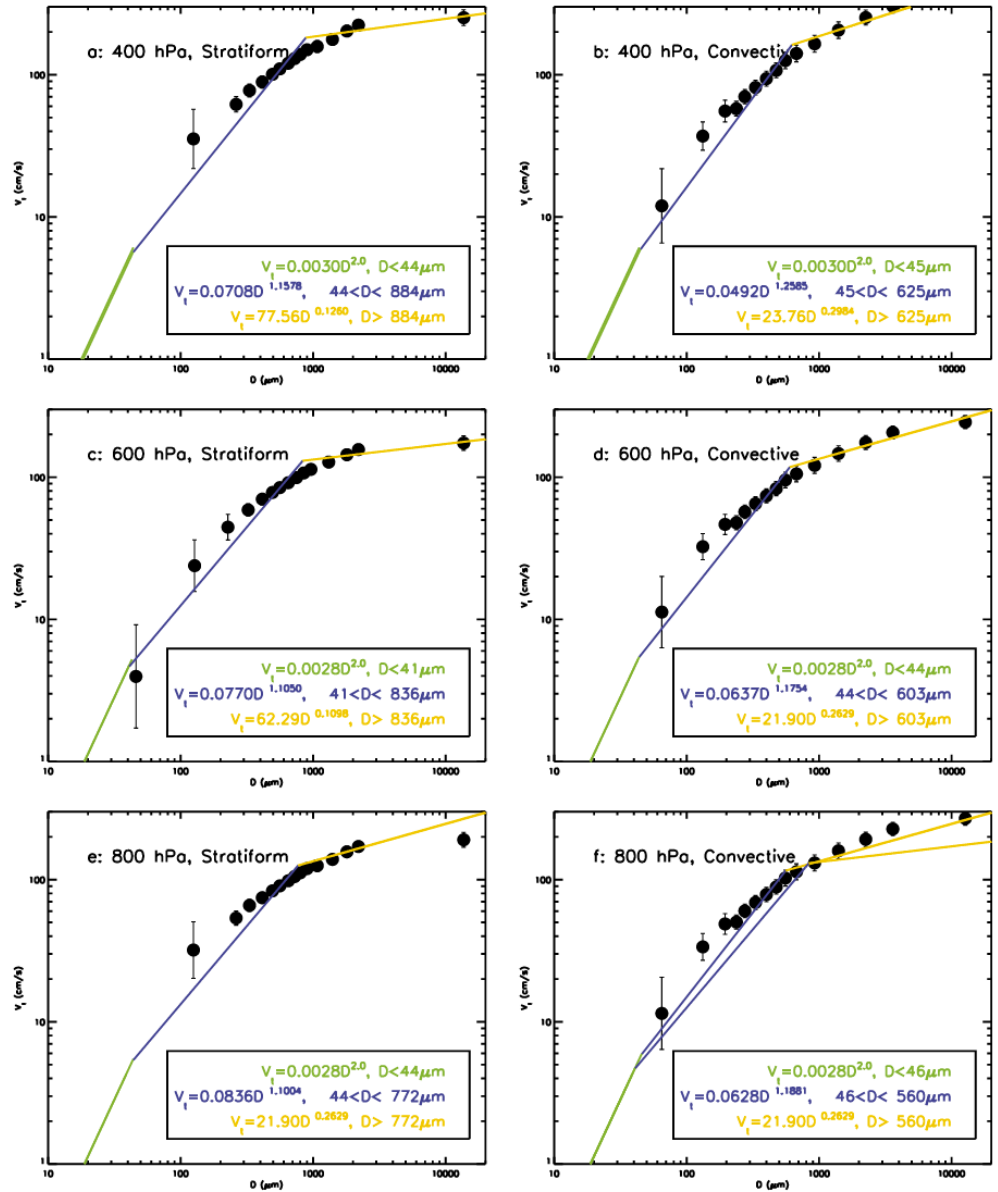


FIG. 16. Average terminal velocities as a function of particle diameter for (a),(c),(e) stratiform and (b),(d),(f) convectively defined ice clouds, and pressure levels (top) 400, (middle) 600, and (bottom) 800 hPa. Power-law relationships are fitted to the calculations in three intervals of particle size.

Ice sedimentation/deposition rates

Assumed dependence of terminal velocity on size (in m/s , D in m)

$$v_T = a_v D^{b_v}$$

Best fit to data (P in hPa):

$$a_v = 0.0603 \left(\frac{P}{1000} \right)^{0.315} 10^{6b_v} \quad b_v = 1.17 \left(\frac{1000}{P} \right)^{0.0783}$$

Deposition rate

$$\left(\frac{\partial q_i}{\partial t} \right)_{dep} = \frac{2N_i}{\rho F} \left[A q_i^{1/b} + B q_i^{\frac{3+b_v}{2b}} \right] (S_i - 1)$$

$$A = a_f \frac{\Gamma(\gamma + 2)}{\Gamma(\gamma + 1)} \left(\frac{\rho \Gamma(\gamma + 1)}{a N_i \Gamma(b + \gamma + 1)} \right)^{1/b} \quad B = b_f \left(\frac{\rho a_v}{\mu} \right)^{1/2} \frac{\Gamma(\gamma + \frac{5+b_v}{2})}{\Gamma(\gamma + 1)} \left(\frac{\rho \Gamma(\gamma + 1)}{a N_i \Gamma(b + \gamma + 1)} \right)^{\frac{3+b_v}{2b}}$$

Ice precipitation rate

$$P_i = \rho q_i V_i = \rho q_i a_v \frac{\int_0^{\infty} n(D) D^{b_v} D^b dD}{\int_0^{\infty} n(D) D^b dD}$$

$$P_i = a_v \frac{\Gamma(b + b_v + \gamma + 1)}{\Gamma(b + \gamma + 1)} [aN_i \Gamma(b + \gamma + 1)]^{-b_v/b} (\rho q_i)^{1+b_v/b}$$

Riming (production of graupel)

$$\left(\frac{dm}{dt}\right)_{rim} = \frac{\pi}{4} D^2 v_T E_r \rho q_c$$

$$\left(\frac{dq_i}{dt}\right)_{rim} = -\left(\frac{dq_p}{dt}\right)_{rim} = -C q_c q_i^{\frac{2+b_v}{b}}$$

$$C = a_v E_r N_i \rho \frac{\pi \Gamma(b_v + \gamma + 3)}{4 \Gamma(\gamma + 1)} \left(\frac{\rho \Gamma(\gamma + 1)}{a N_i \Gamma(b + \gamma + 1)} \right)^{\frac{2+b_v}{b}}$$

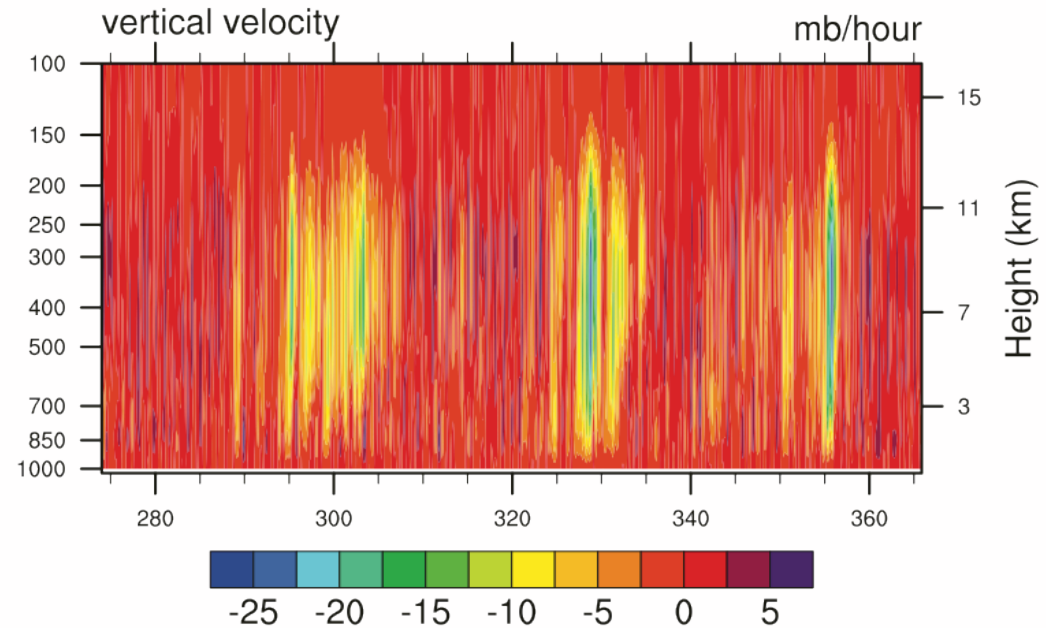


DYNAMO

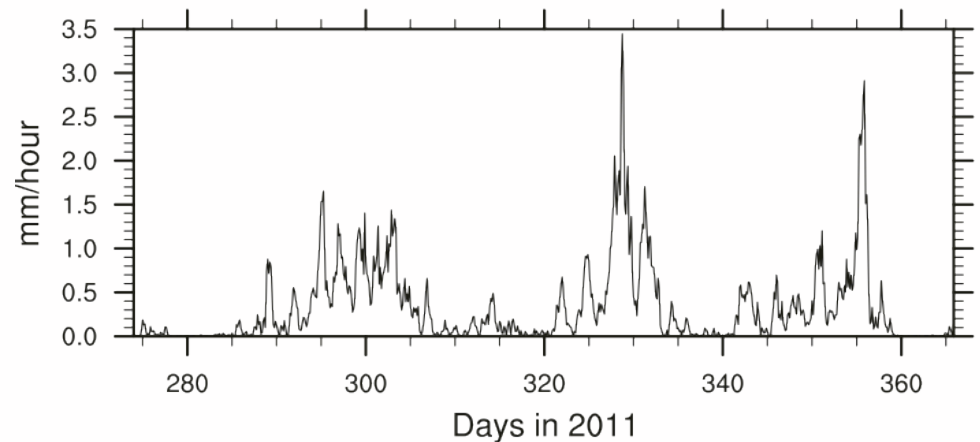
Dynamics of the Madden-Julian Oscillation

- SAM6.10.8
- 256x256x64 grid
- $\Delta x = \Delta y = 1$ km
- Domain top at 27 km
- Microphysics:
 - SAM1MOM
 - M2005
 - KH3
- Radiation: CAM3

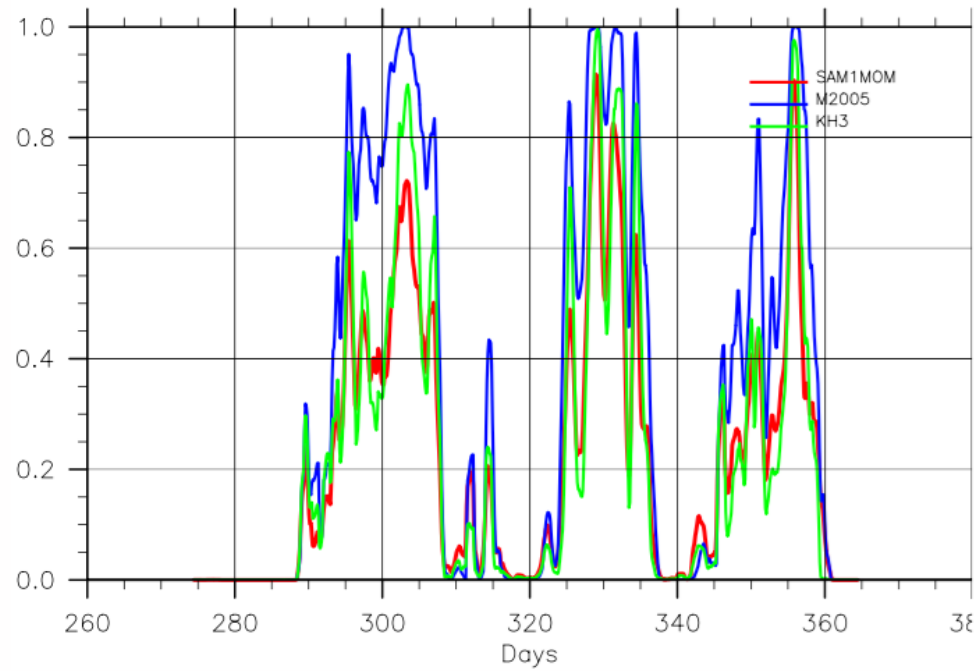
Omega



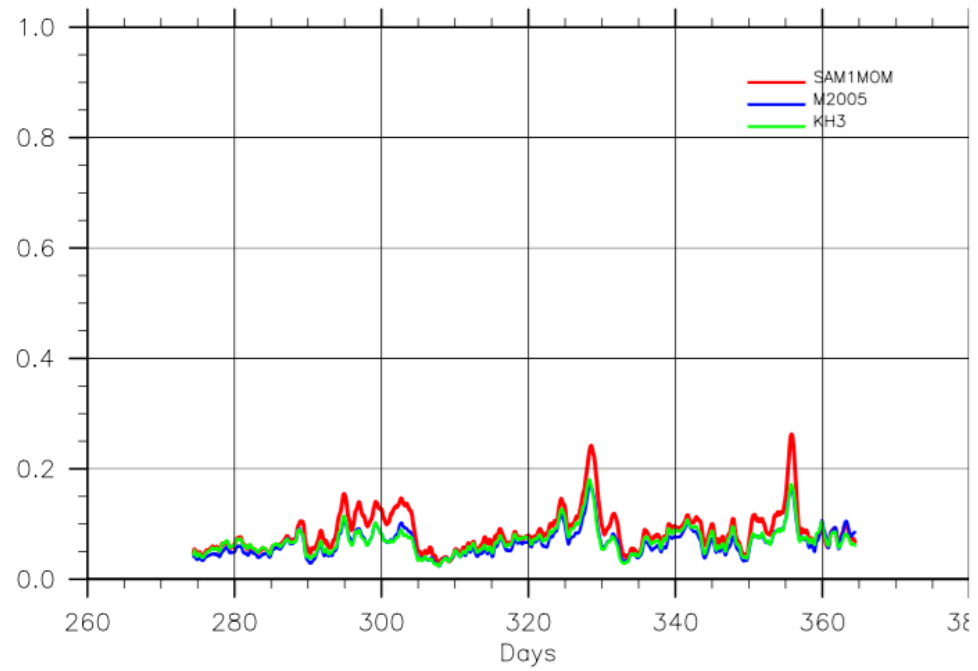
TRMM 3B42 Precipitation



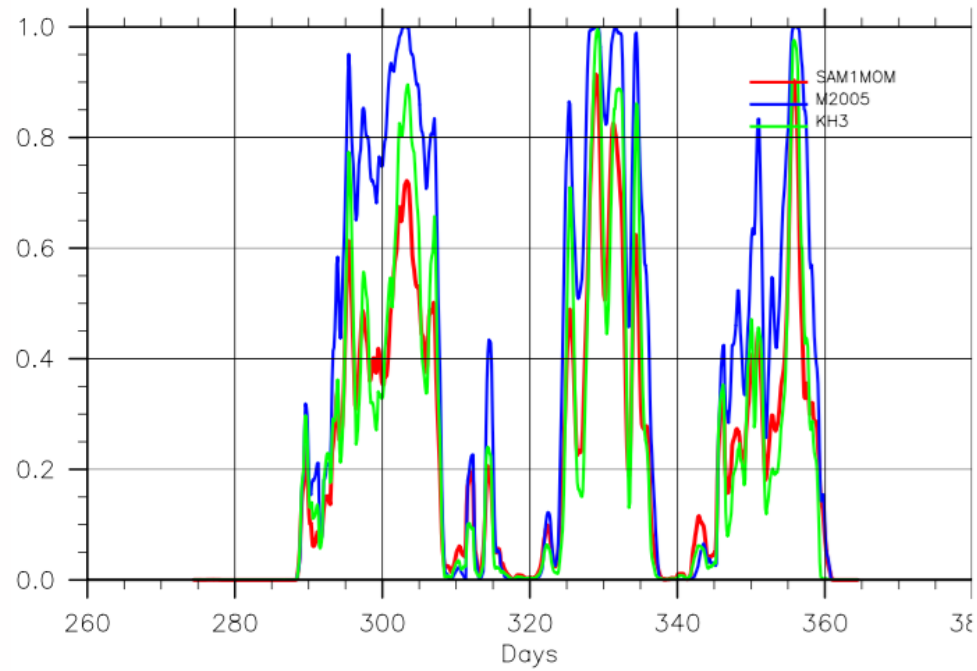
High Cloud Fraction



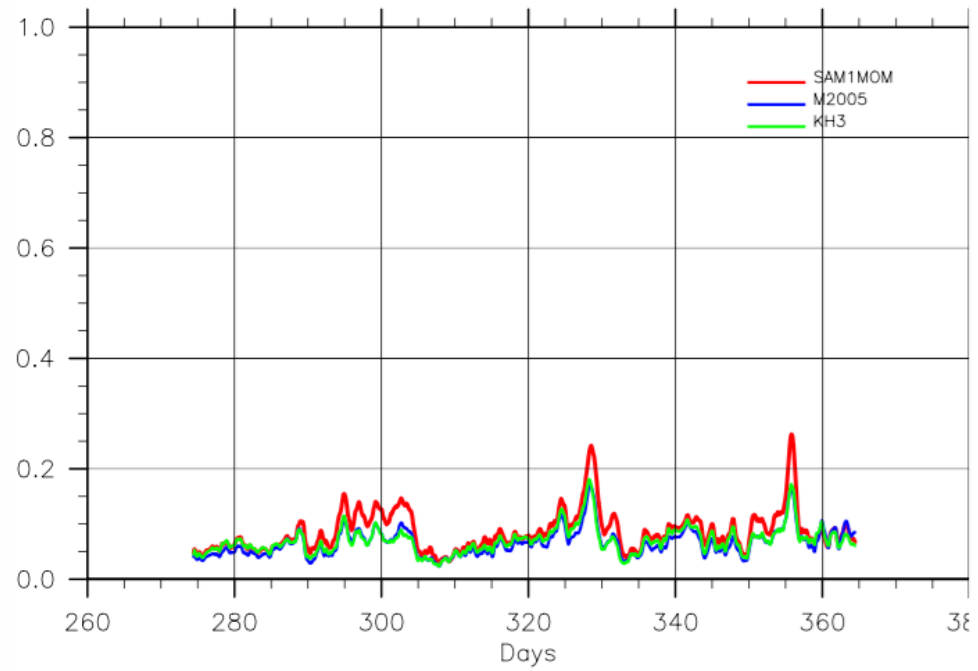
Low Cloud Fraction



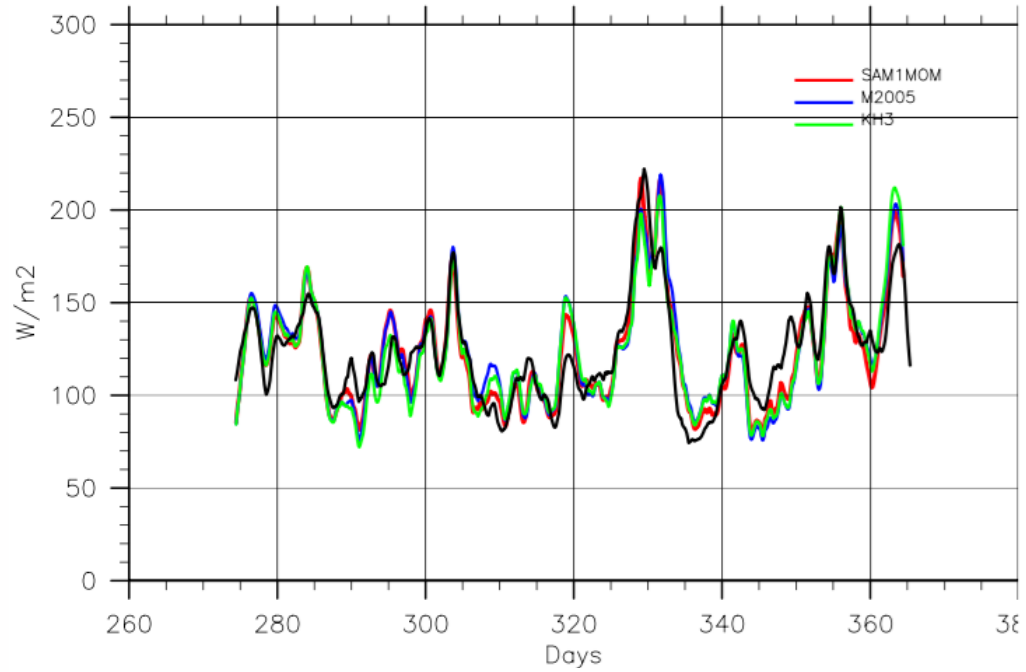
High Cloud Fraction



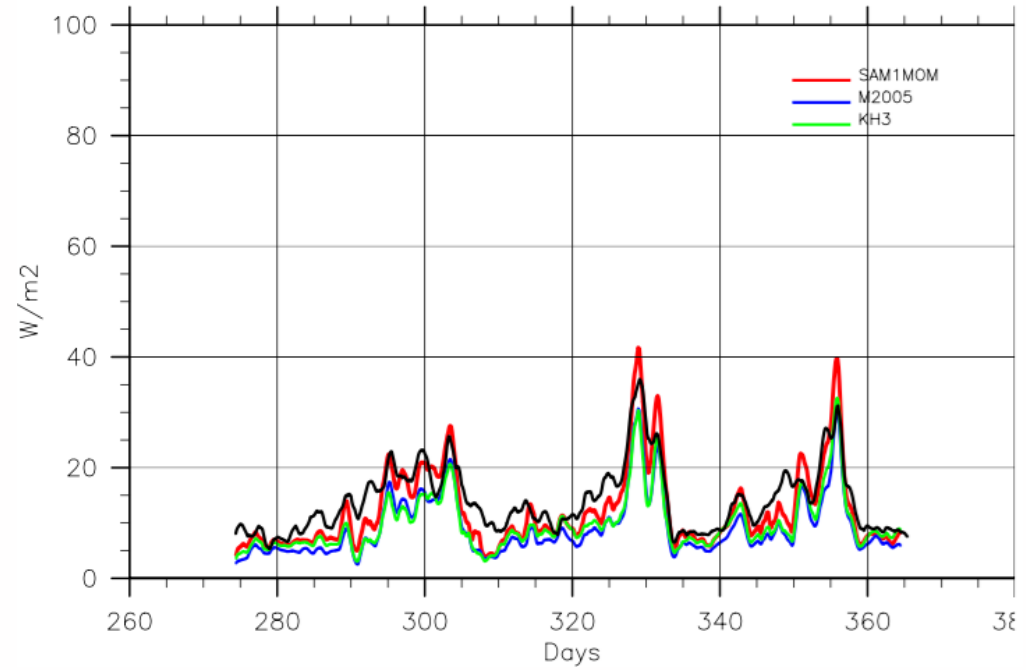
Low Cloud Fraction



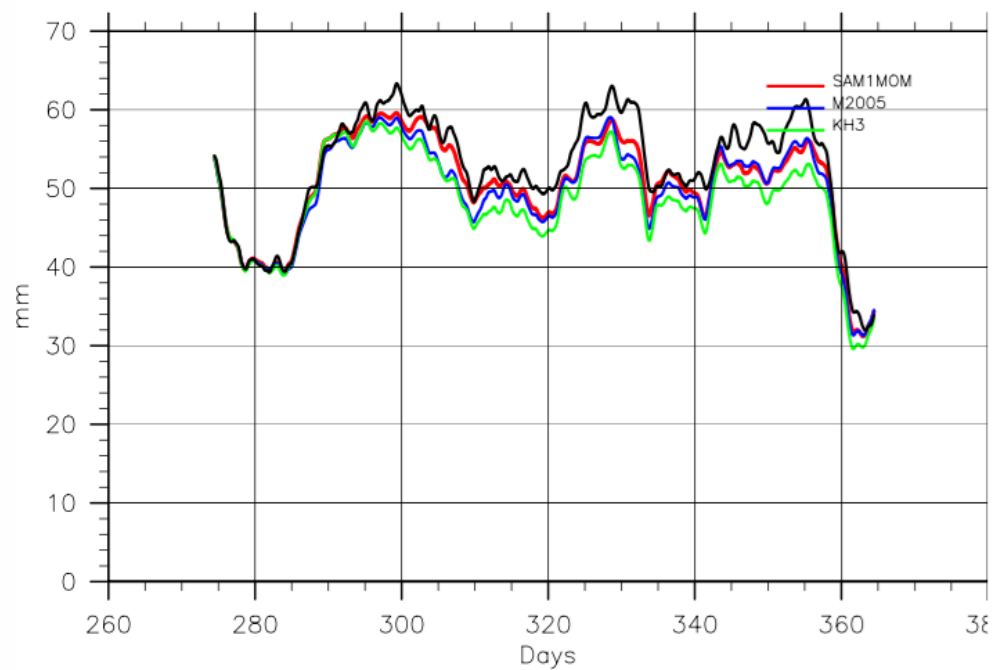
Latent Heat Flux



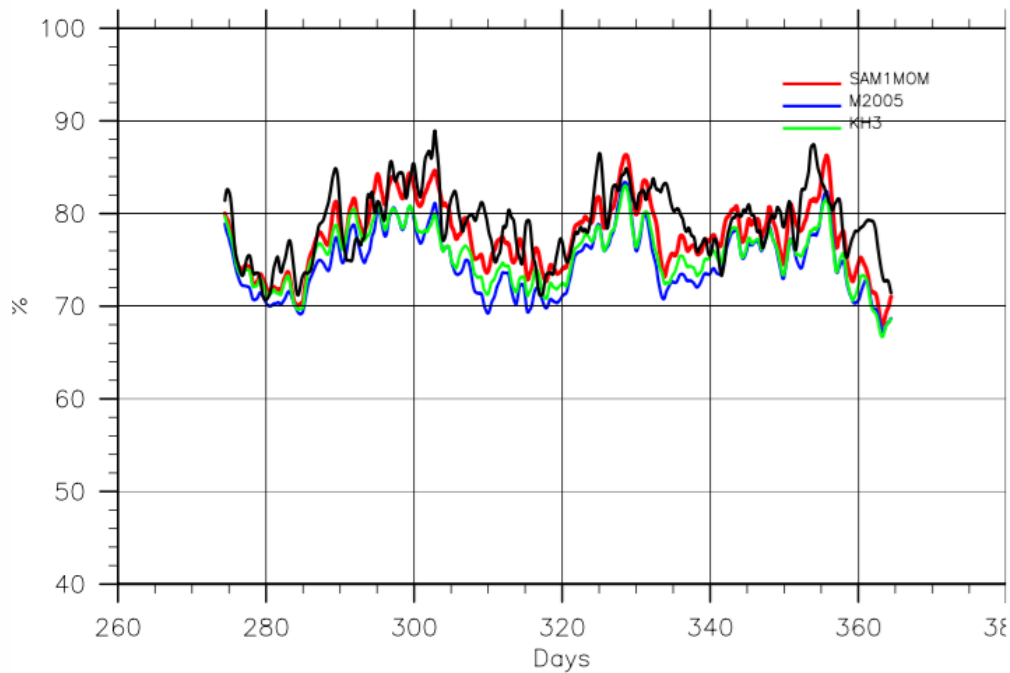
Sensible Heat Flux



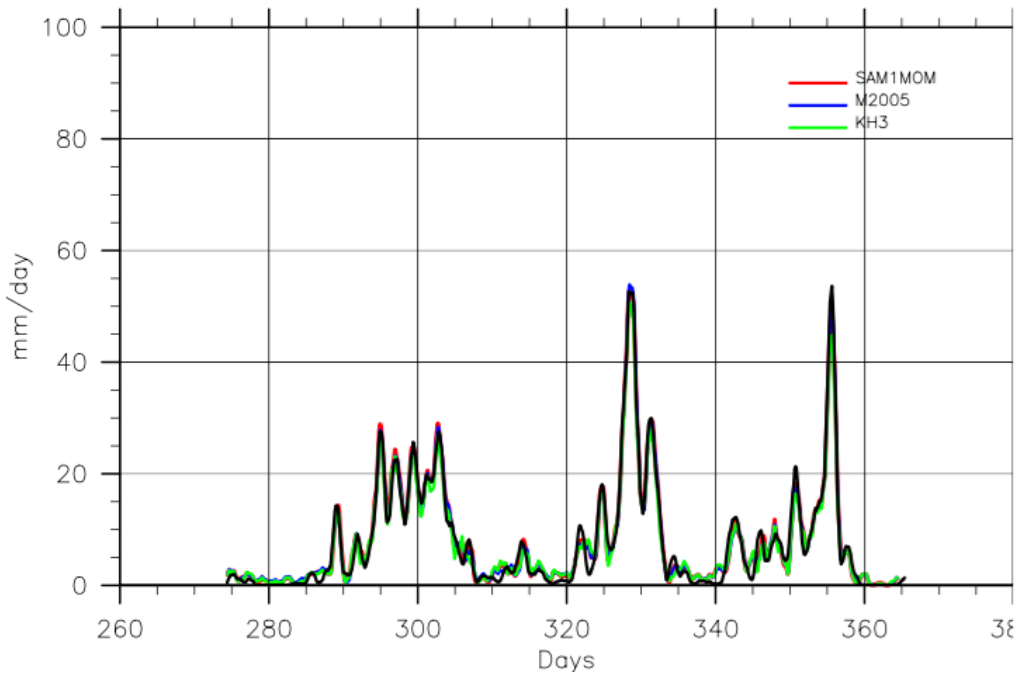
Precipitable Water



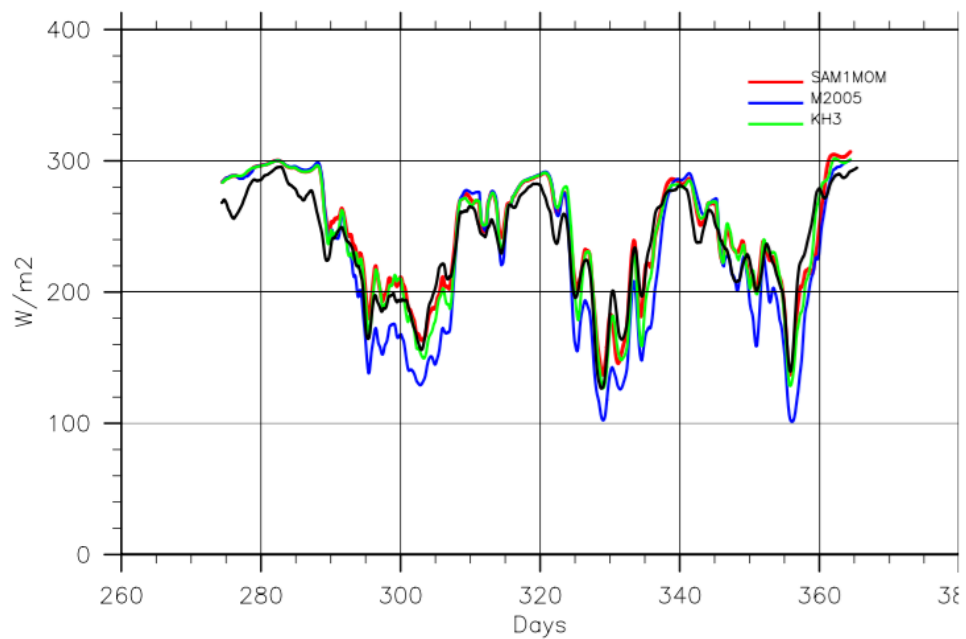
Surface Air RH



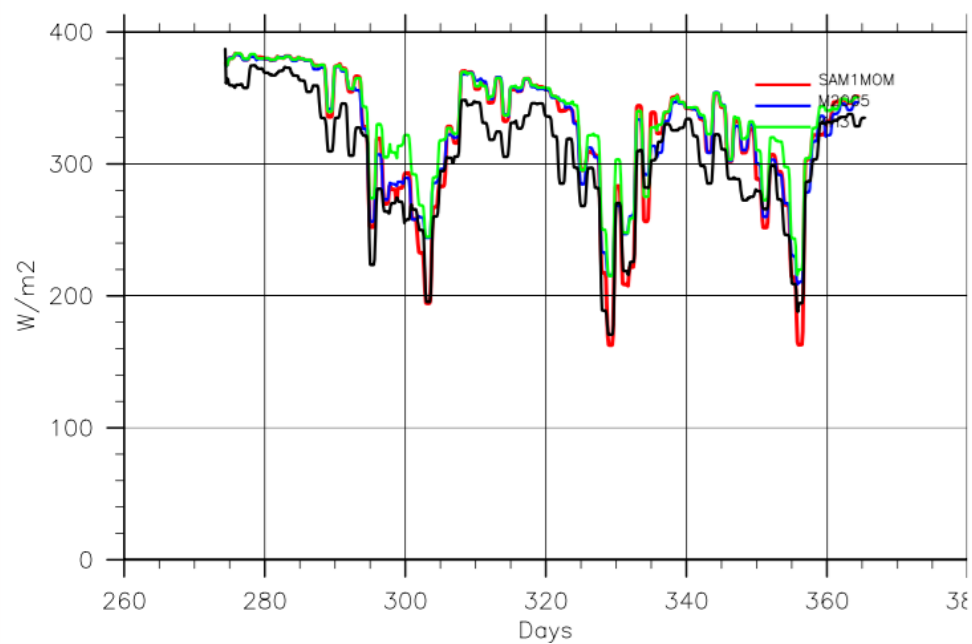
Surface Precipitation



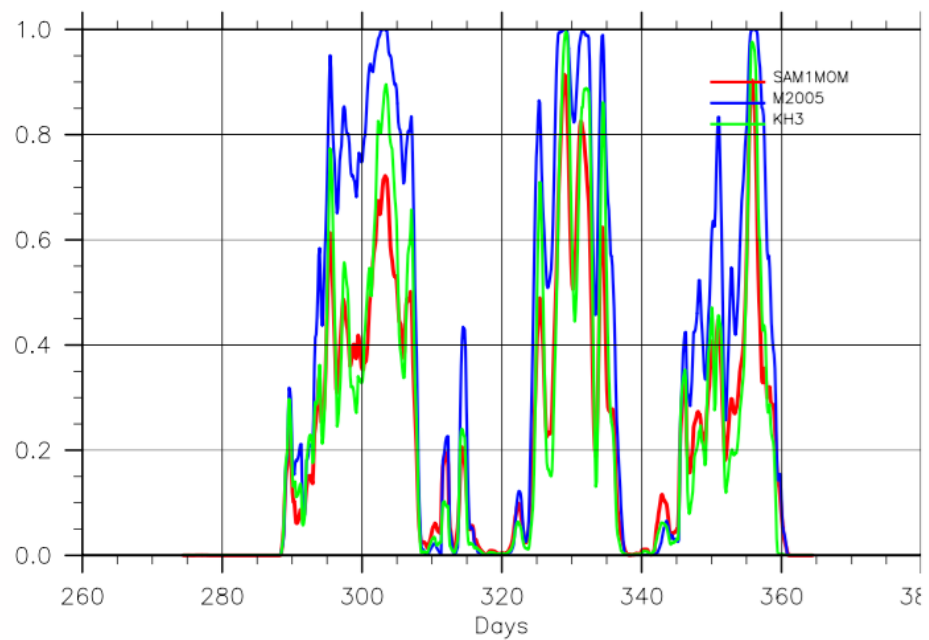
Net LW flux at Top-of-Model)



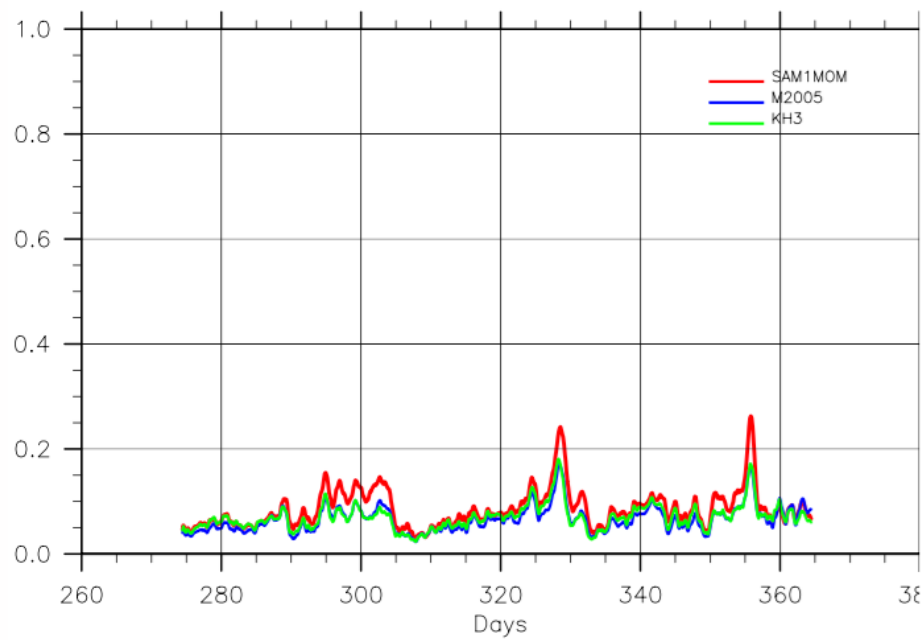
Net SW flux at Top-of-Model)



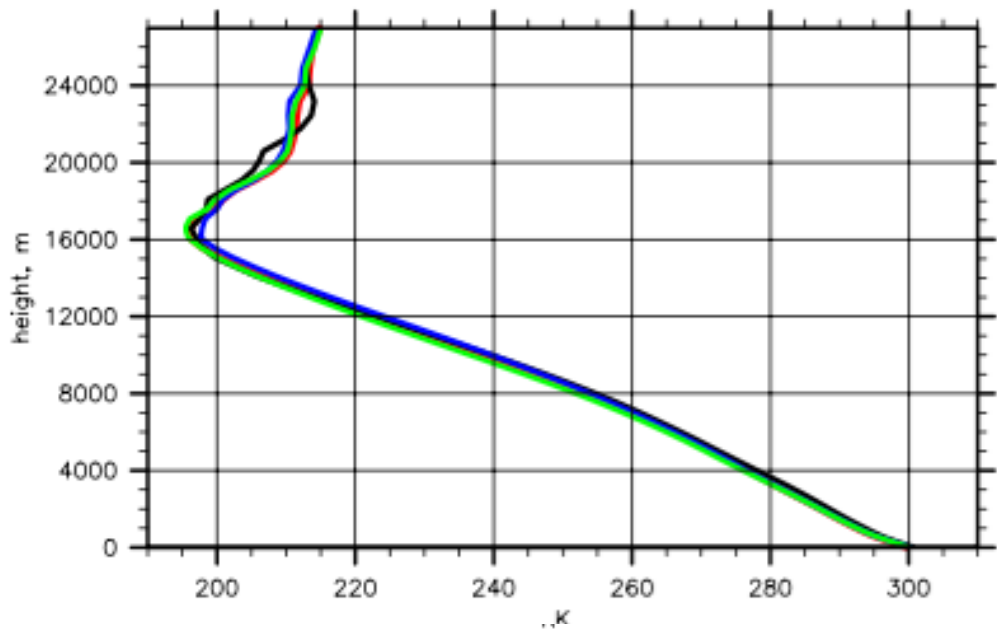
High Cloud Fraction



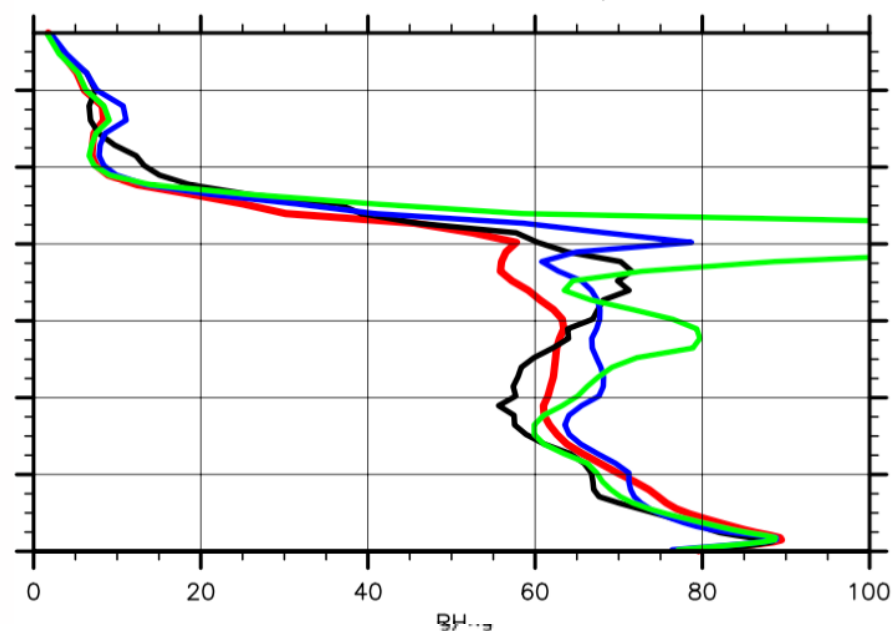
Low Cloud Fraction



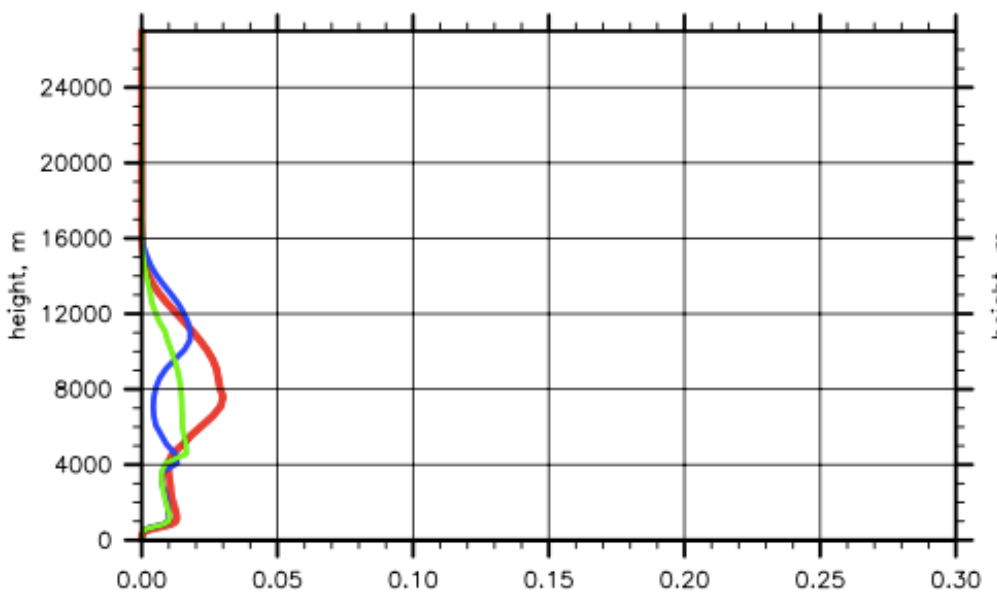
Absolute temperature



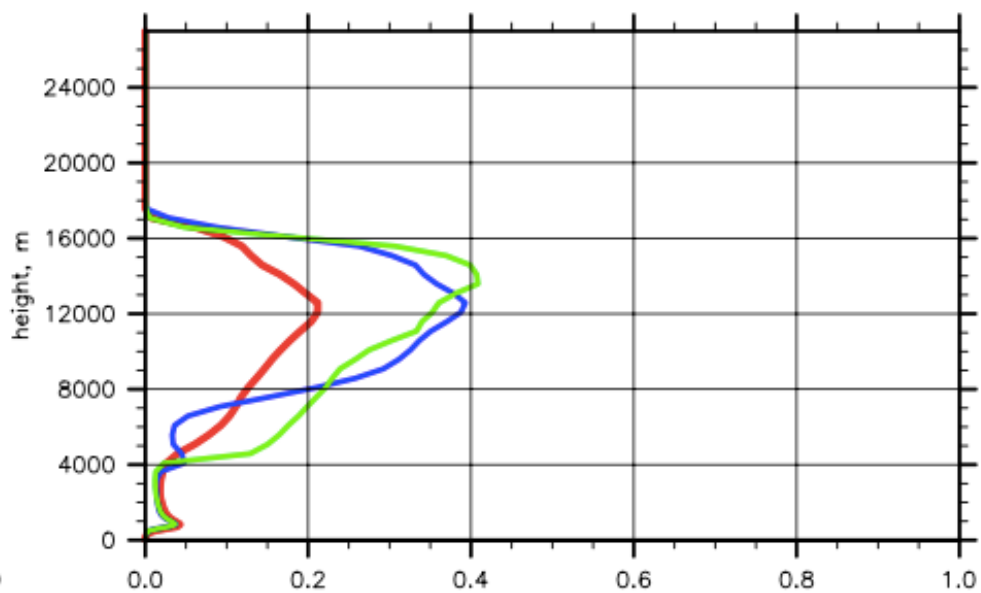
Relative Hum over Liq.W



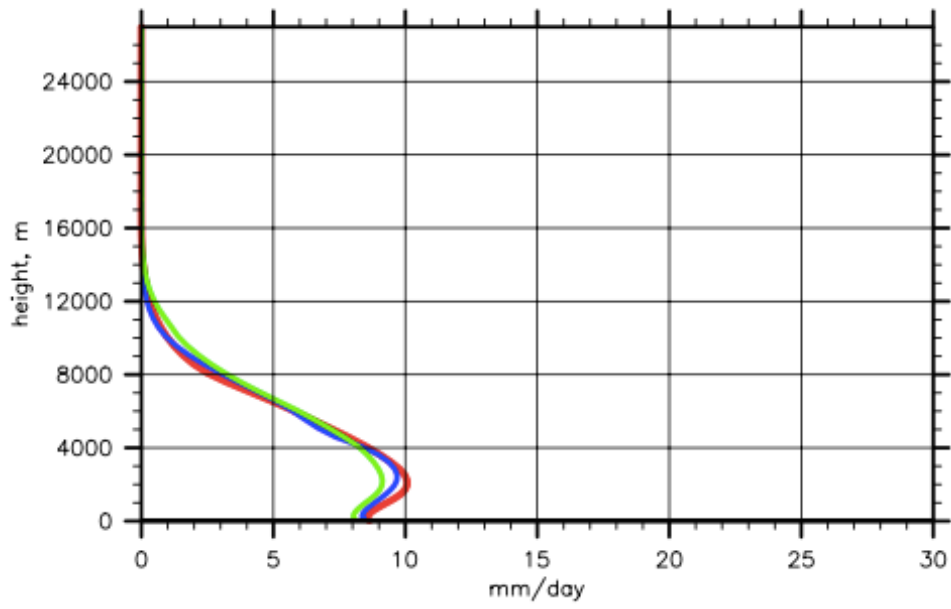
Cloud water and cloud ice



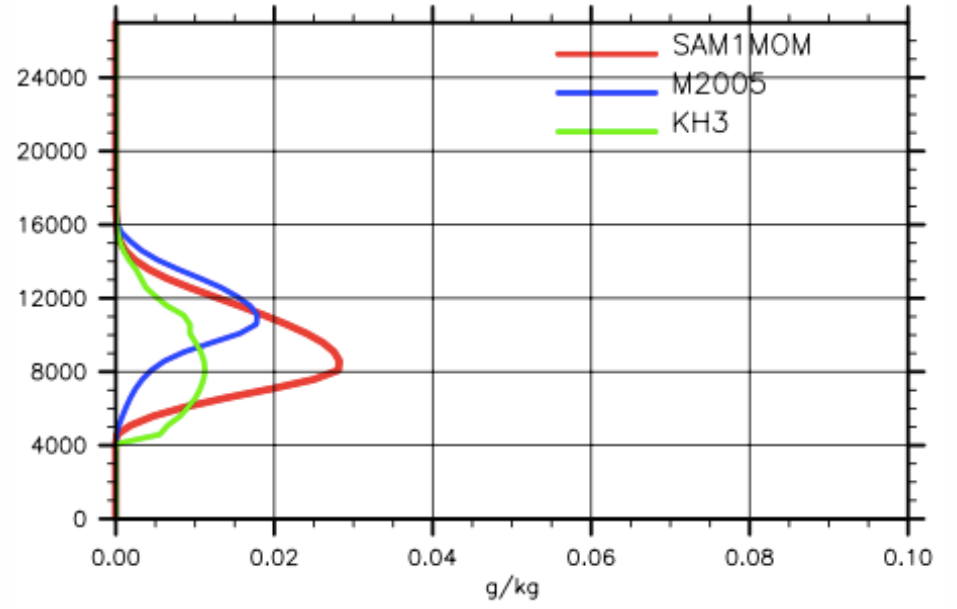
cloud Fraction



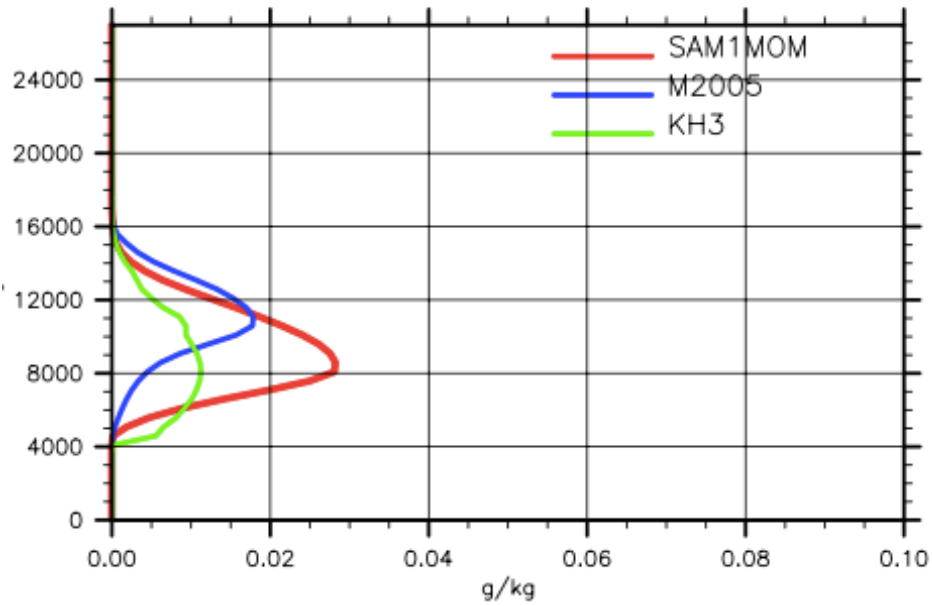
Precipitation flux



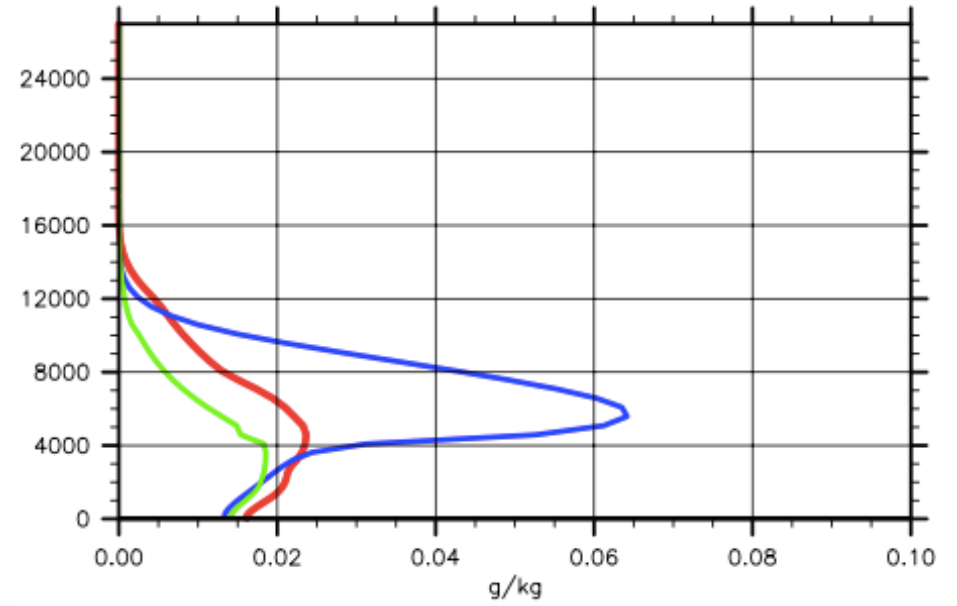
Icy cloud water



Icy cloud water

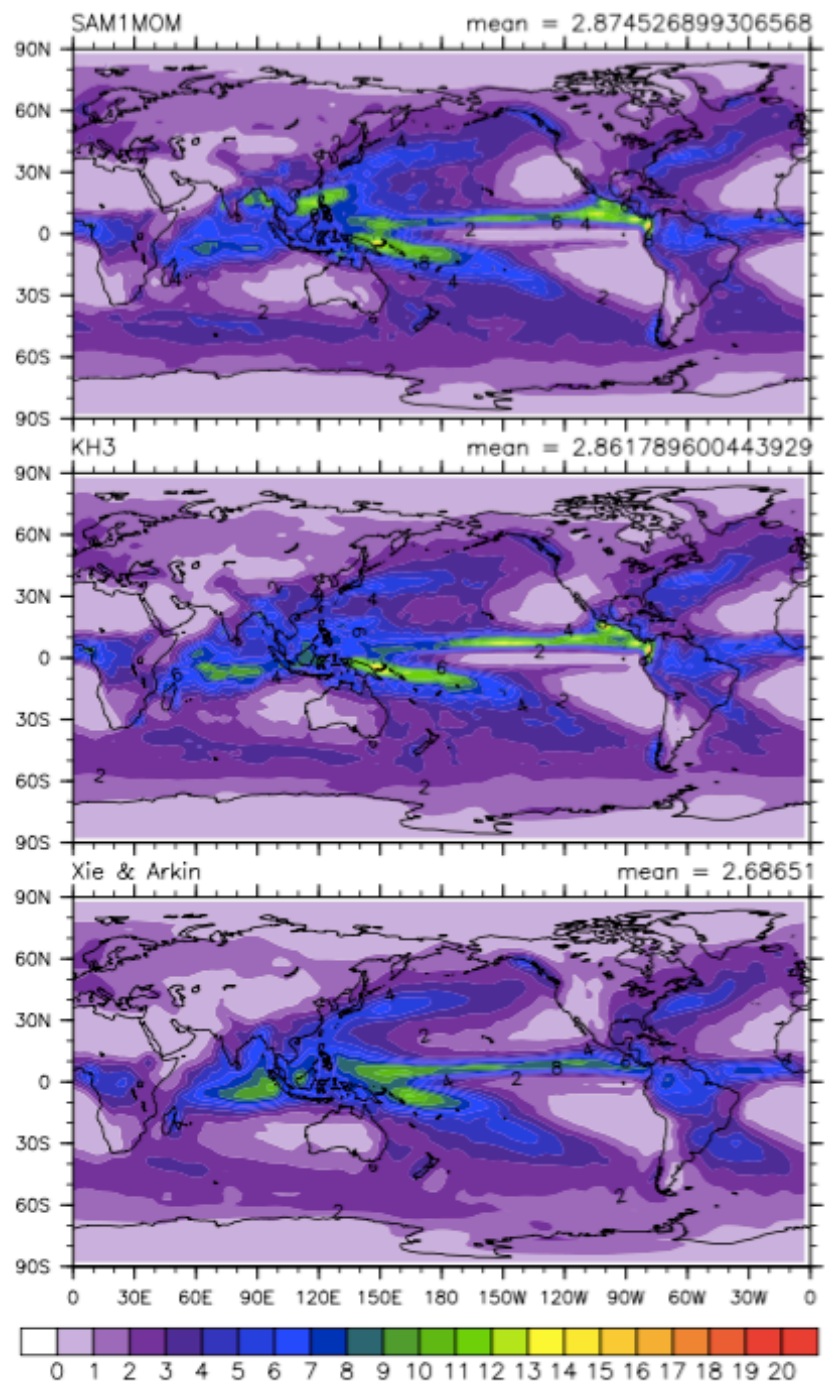


Rain and Snow

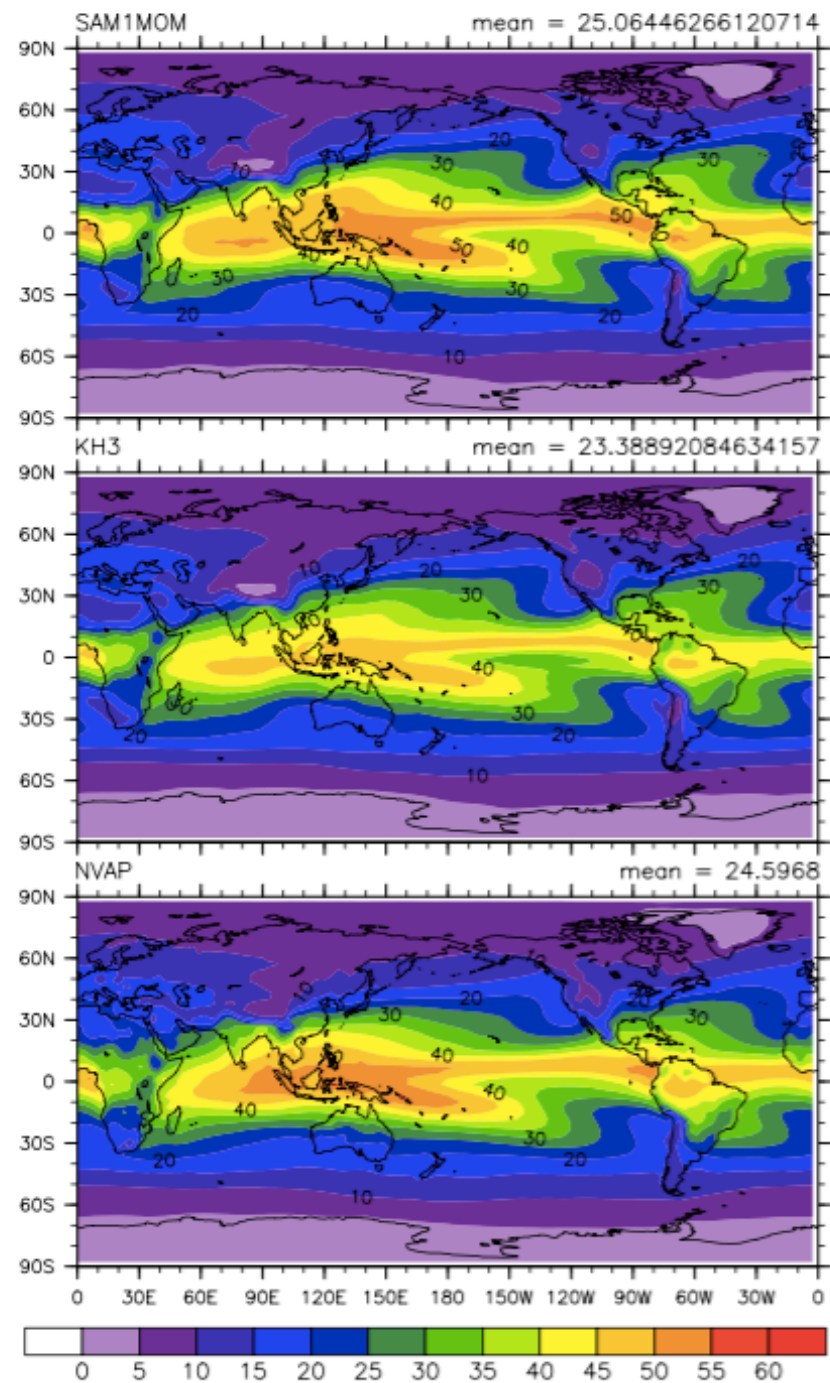


Preliminary Test in SP-CAM_{3.5}

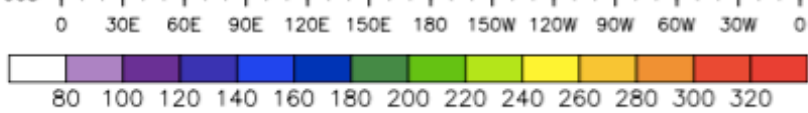
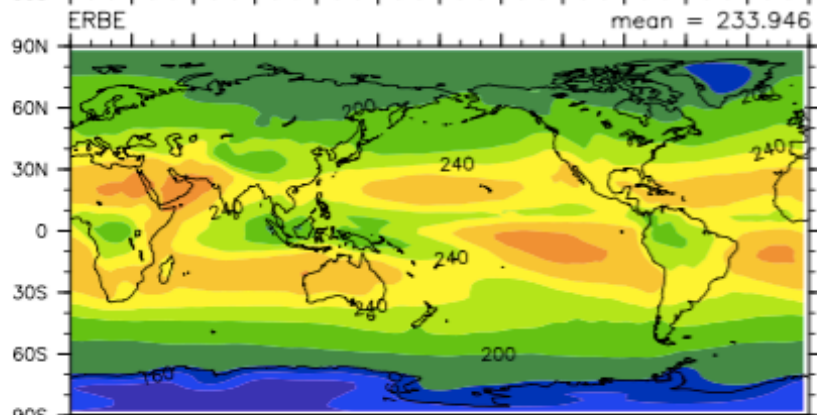
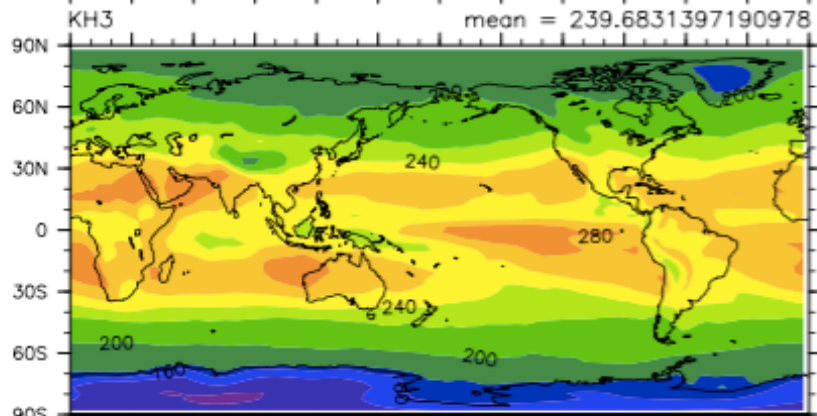
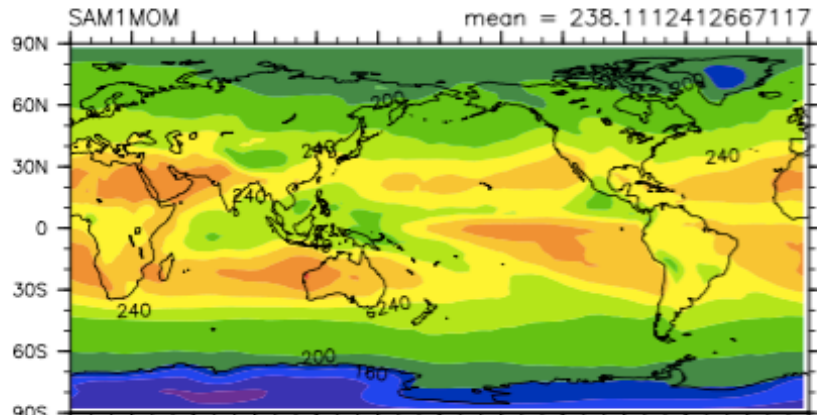
ANN Precipitation Rate, mm/day



ANN Precipitable Water, mm



ANN Outgoing Longwave Radiation, W/m^2



ANN Absorbed Shortwave Radiation, W/m^2

