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

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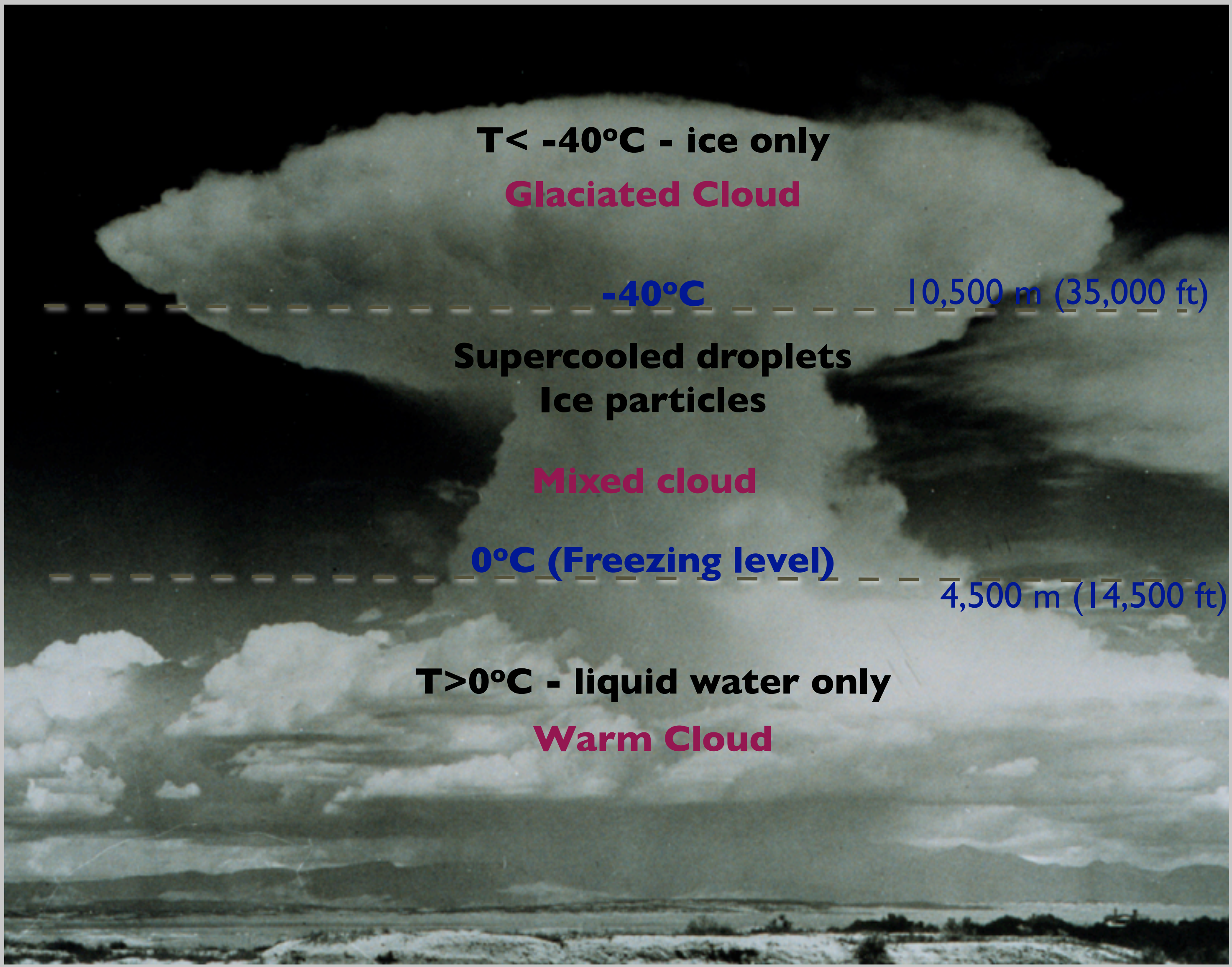
Cold Clouds

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)

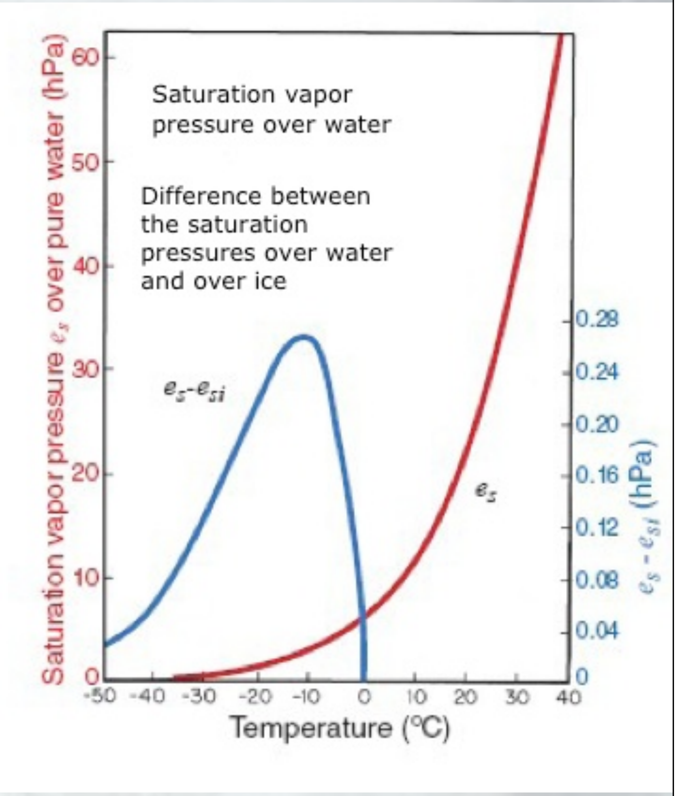
- **The equation for the growth rate of mass of an ice crystal *m* is similar to the one for the mass of droplet except for introduction of the capacitance C (arising from analogy between electric field around an arbitrary shaped charged particle and stationary diffusion equation)**

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

S_i - Supersaturation over ice

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

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

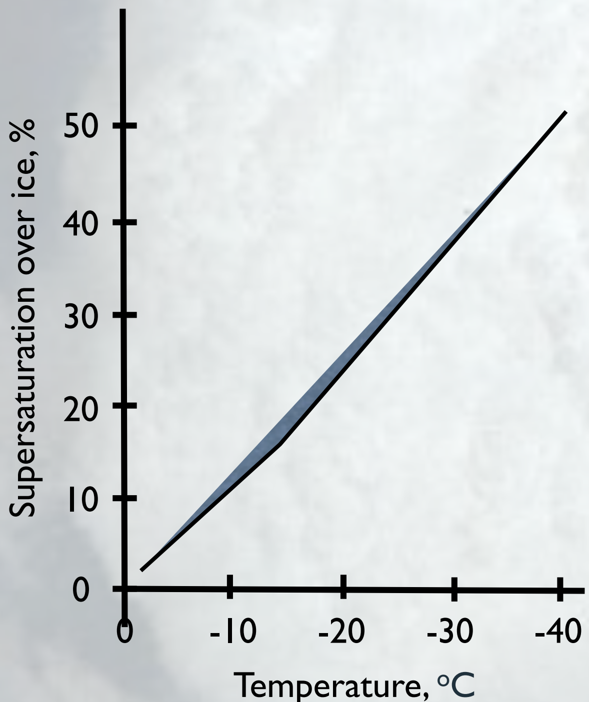


- **Ice crystals grow most rapidly by vapor deposition in mixed clouds at temperatures around -12°C**

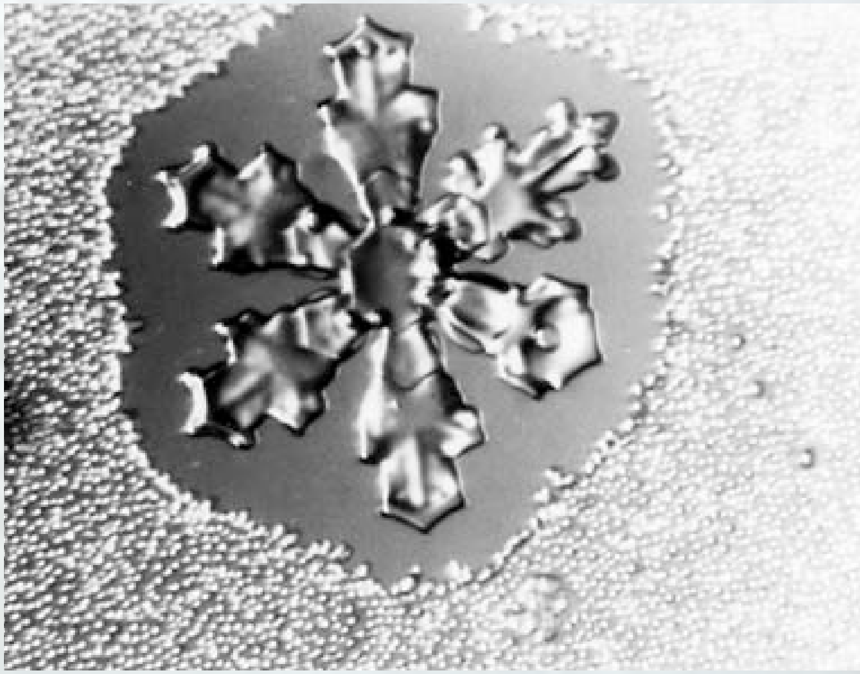
Growth of Ice in Clouds

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.

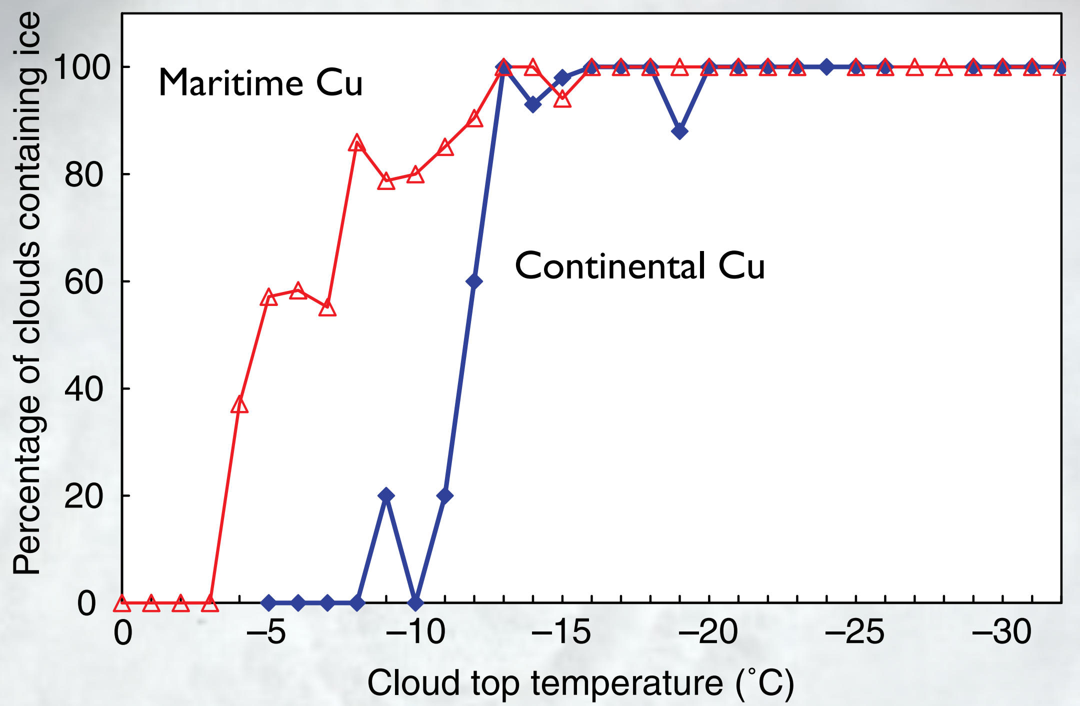


Supersaturation relative to ice when vapor is saturated relative to water (in mixed-phase clouds)



Fraction of Ice in Clouds

Dependence on Temperature



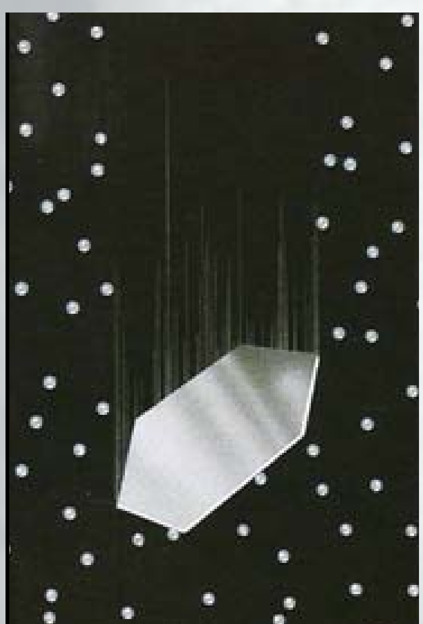
- ✻ **Fraction of ice particles in the liquid drop/ice mixture in clouds generally increases as temperature decreases**

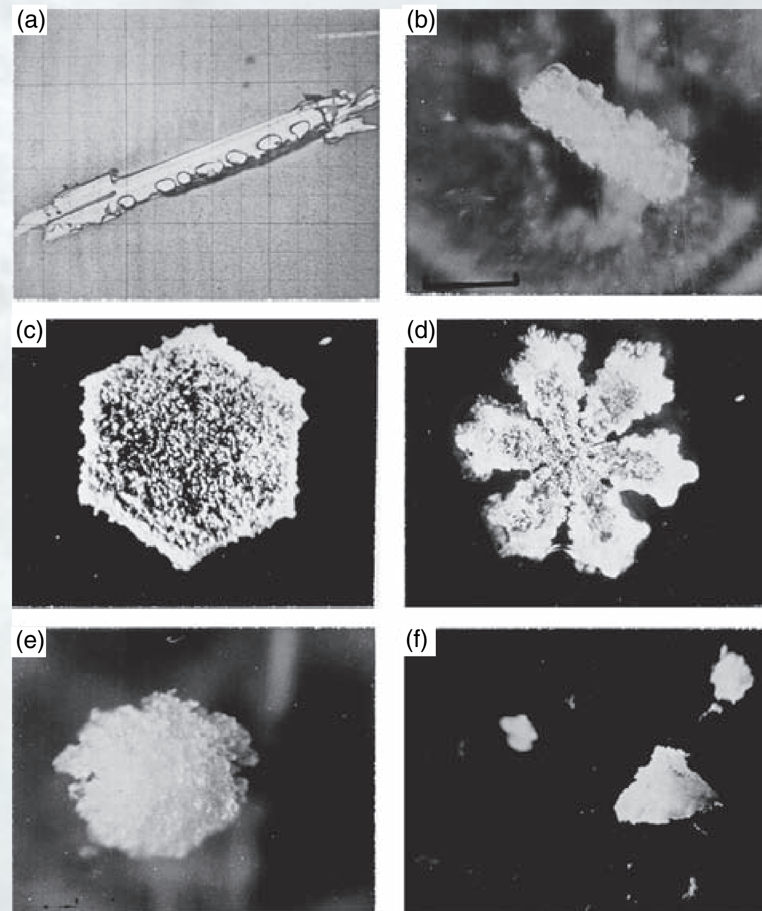
- ✻ **Clouds with the top temperatures lower than -15ºC are usually glaciated (way warmer than -40ºC homogeneous freezing threshold).**

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.



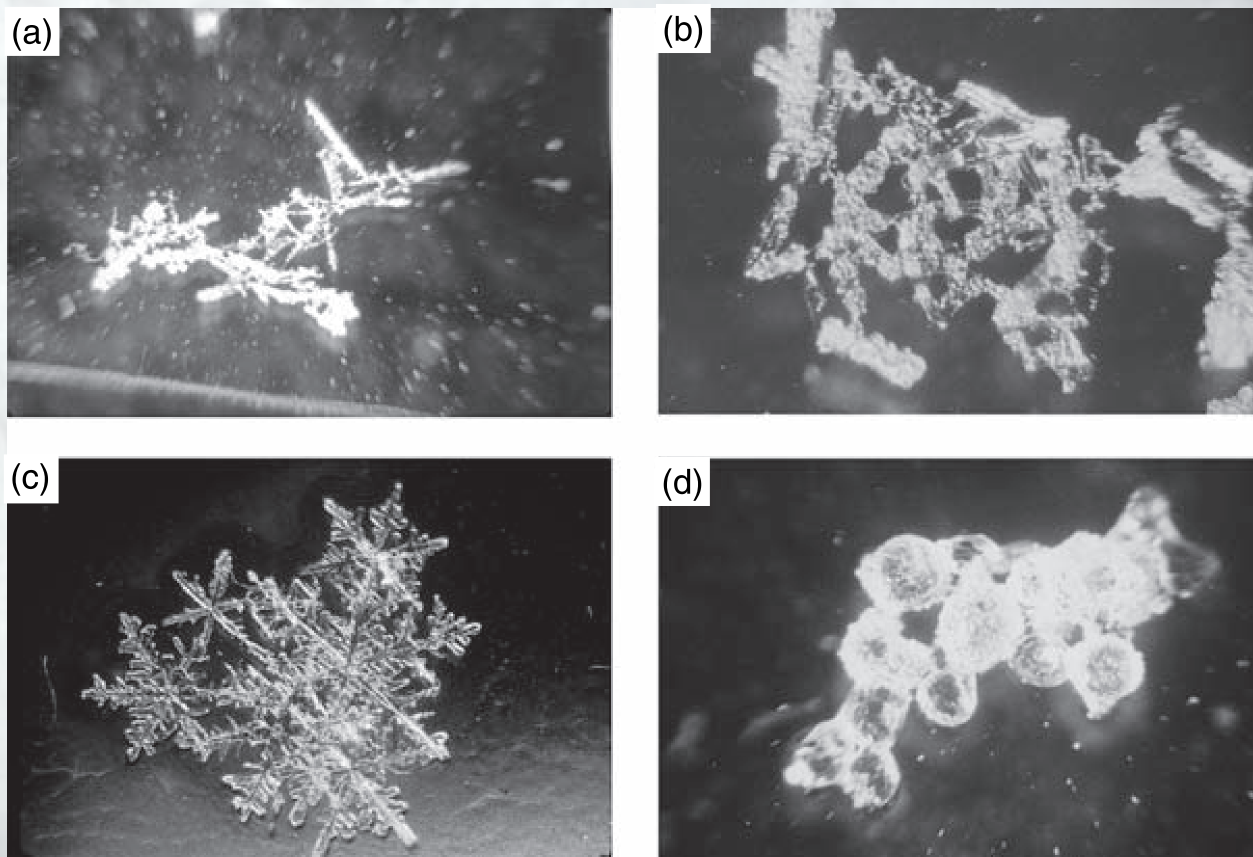


graupel

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.

SAM1MOM Microphysics

3 prognostic variables (explicitly transported around the grid):

1) $h = c_p T + gz - L q_{LIQ} - L_s q_{ICE}$ 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

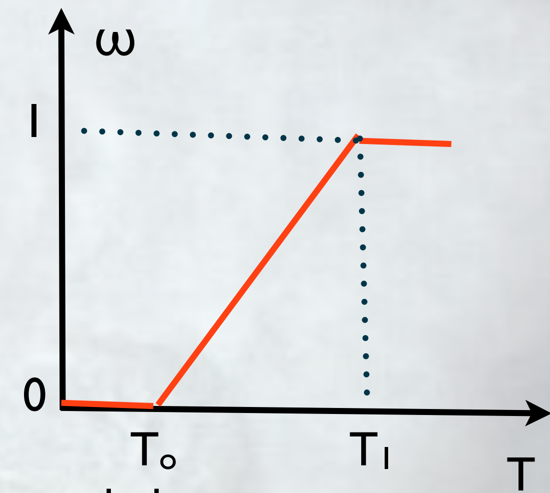
$q_i = (1 - \omega_{ci}(T))(q_c + q_i)$ Cloud ice ("Pristine")

$q_v = \omega_{ci} q_s + (1 - \omega_{ci}) q_{si}$ 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).

SAM1MOM 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 prestine 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 :

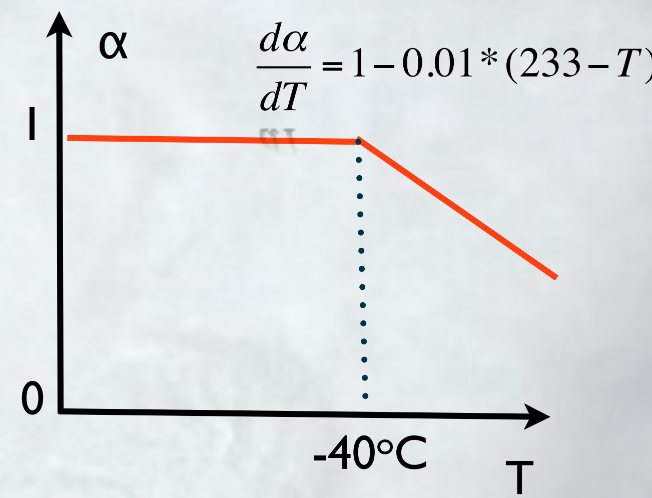
$q_c = q_T - q_*$ Cloud water

$q_* = q_s \alpha(T)$ Saturation Vapor

$q_r = \omega_r q_P$ Rain

$q_g = (1-\omega_r) q_P$ Graupel/Hail

$N_i = f(T)$ 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

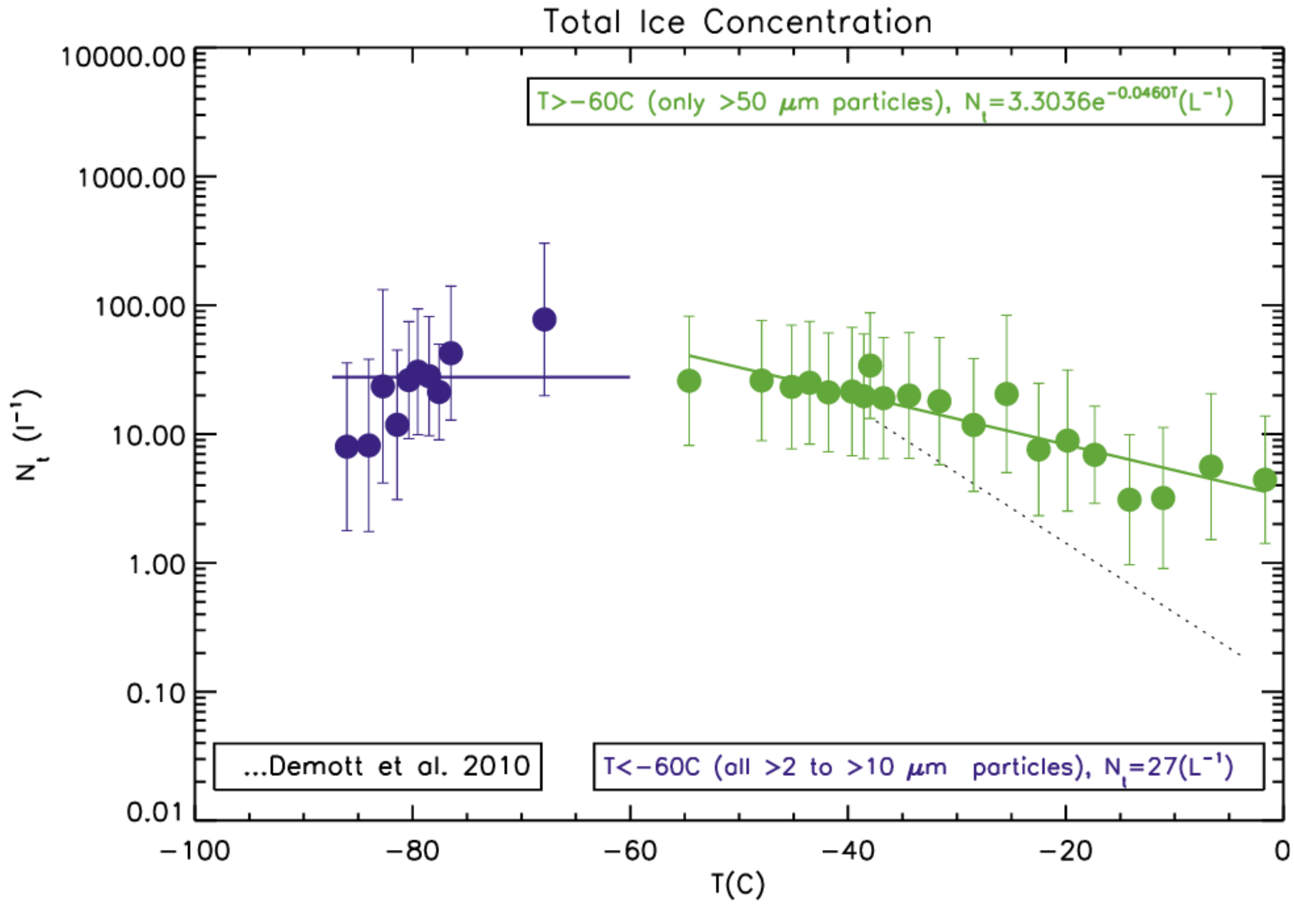


FIG. 4. Total ice number concentrations above sizes 2–10 μm for $T < -60°C$ (blue), depending on the field program, and approximately 50 μm for $T > -60°C$ (green). Median values of N_t in increments of equal numbers of data points are plotted through the data for each size range. The average curve developed 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:

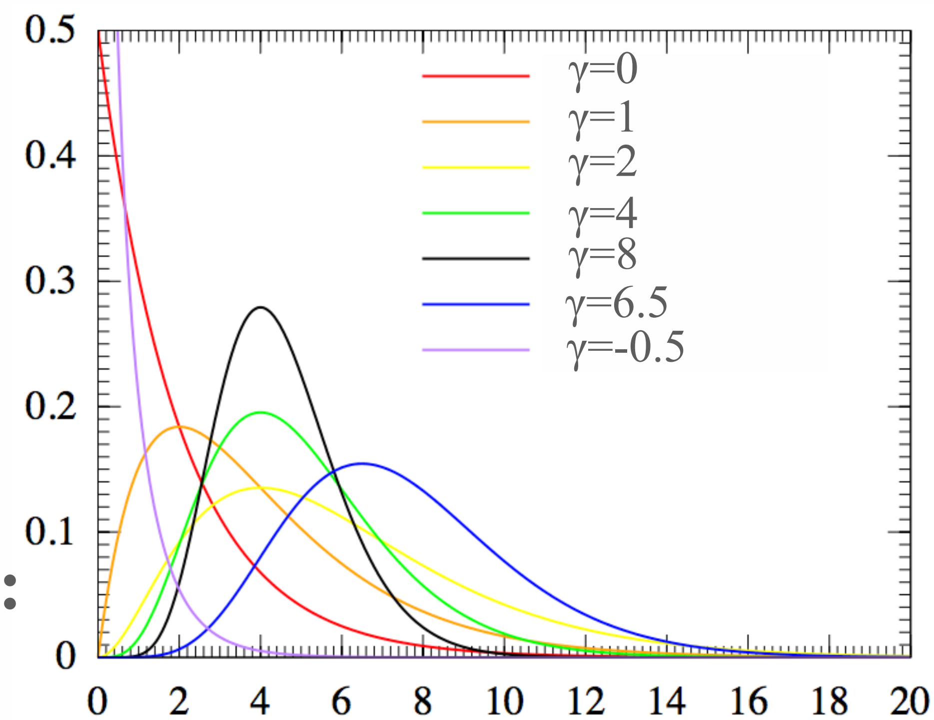
$$q_i = \rho^{-1} \int_{o}^{\infty} m(D) n(D) dD$$

Assumed size-mass relationship:

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

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

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



Parameterization of dispersion parameter γ

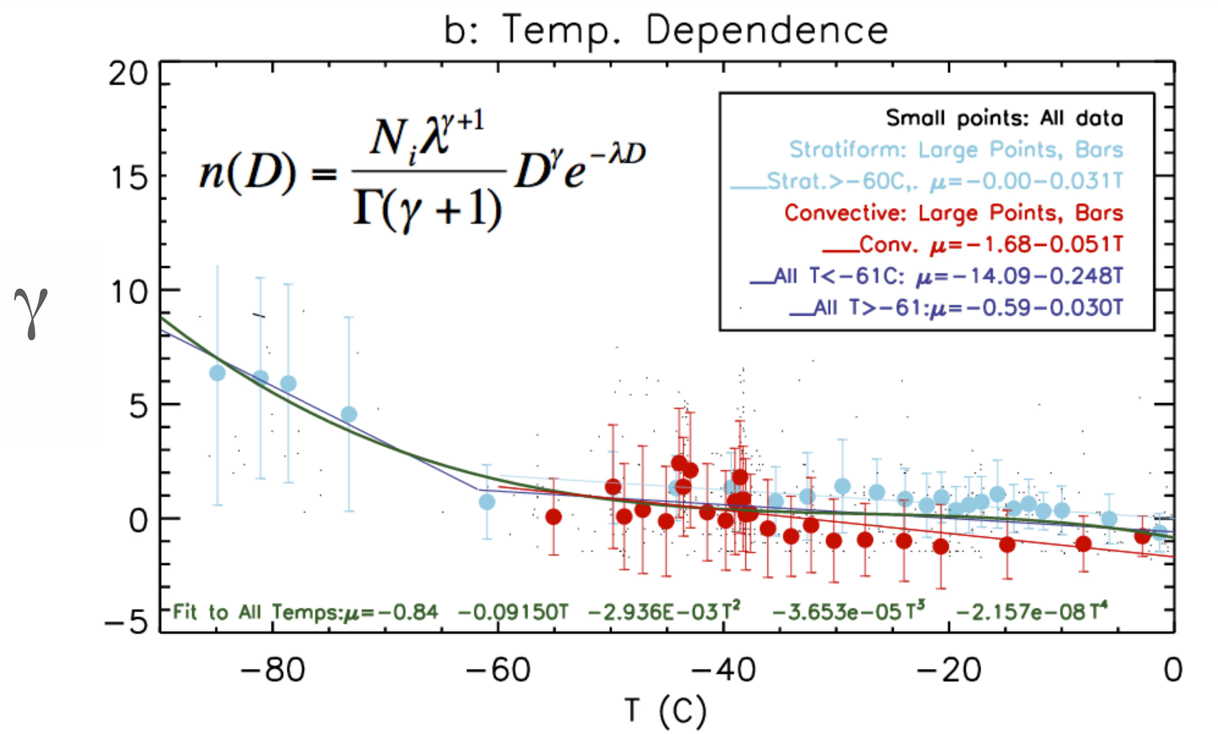


FIG. 9. PSD dispersion μ as a function of (a) slope and (b) temperature. In (a), note that the scale for μ adds a value of 3 to the derived value so that the plot can be made on a logarithm (y axis) scale, and the dashed horizontal line corresponds to an exponential PSD, where the gamma PSD has a value 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

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

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, b_f =0.44

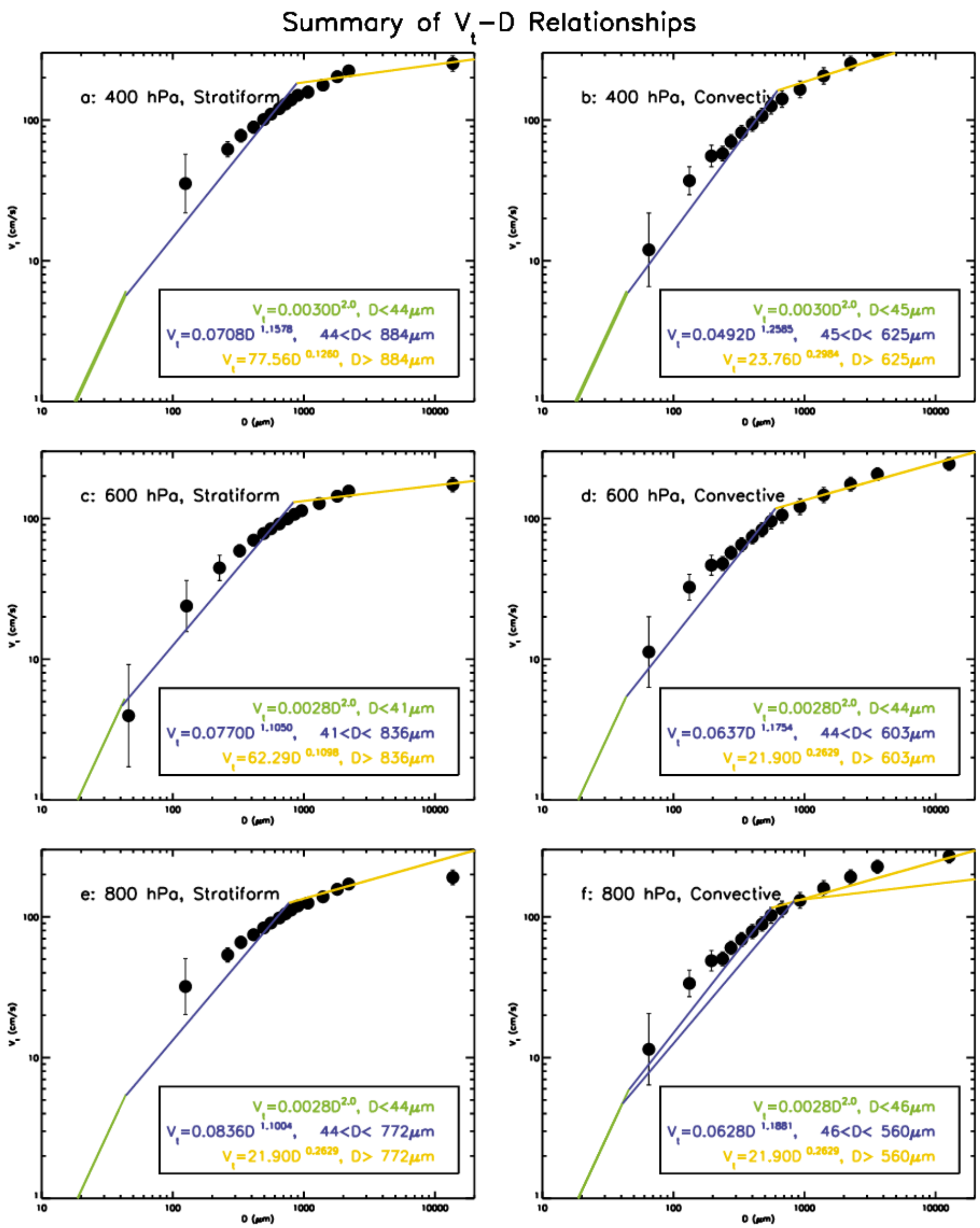


FIG. 16. Average terminal velocities as a function of particle diameter for (a),(c),(e) stratiform and (b),(d),(f) convectively defined ice clouds, and pressure levels (top) 400, (middle) 600, and (bottom) 800 hPa. Power-law relationships are fitted to the calculations in three intervals of particle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

Heimsfield et al 2013

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):

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

Deposition rate

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

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

Ice precipitation rate

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

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

Riming (production of graupel)

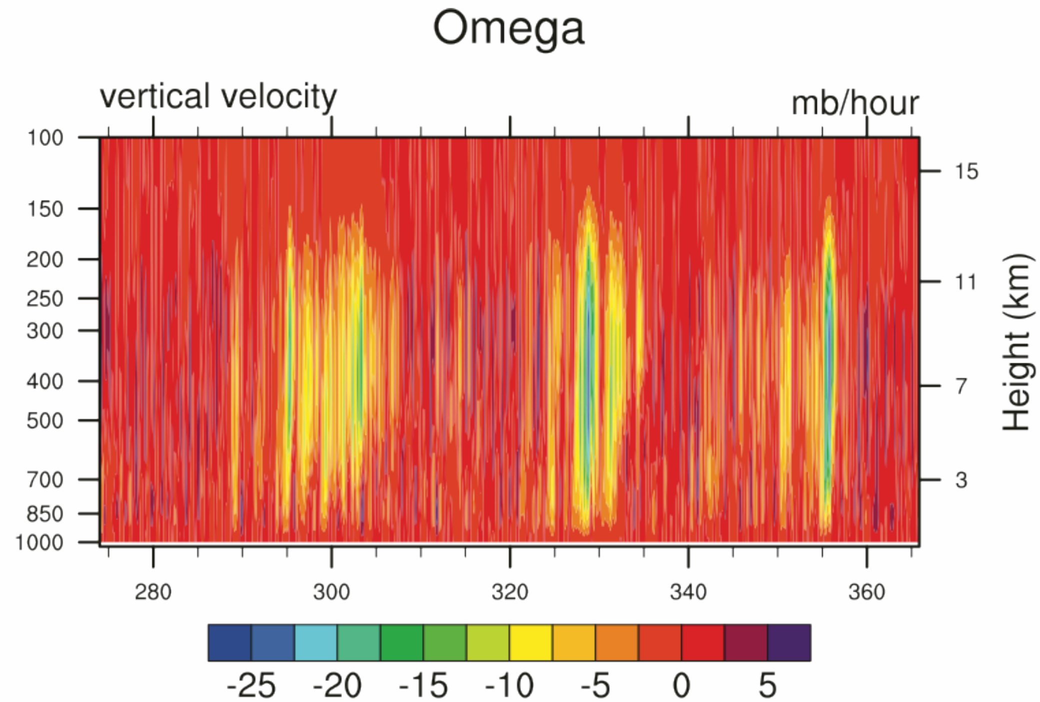
$$\left(\frac{dm}{dt}\right)_{rim} = \frac{\pi}{4} D^2 v_T E_r \rho q_c$$

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

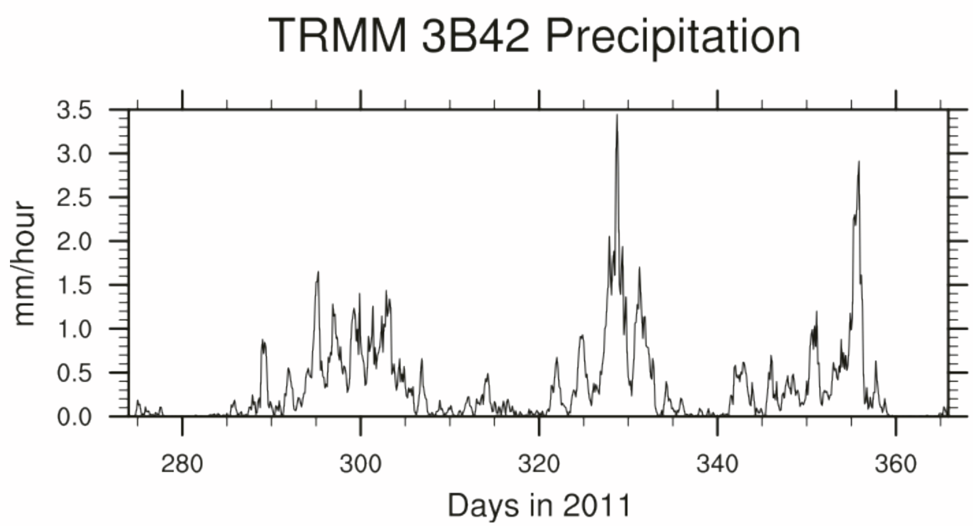
$$C = a_v E_r N_i \rho \frac{\pi \Gamma(b_v + \gamma + 3)}{4\Gamma(\gamma + 1)} \left(\frac{\rho \Gamma(\gamma + 1)}{a N_i \Gamma(b + \gamma + 1)}\right)^{\frac{2+b_v}{b}}$$

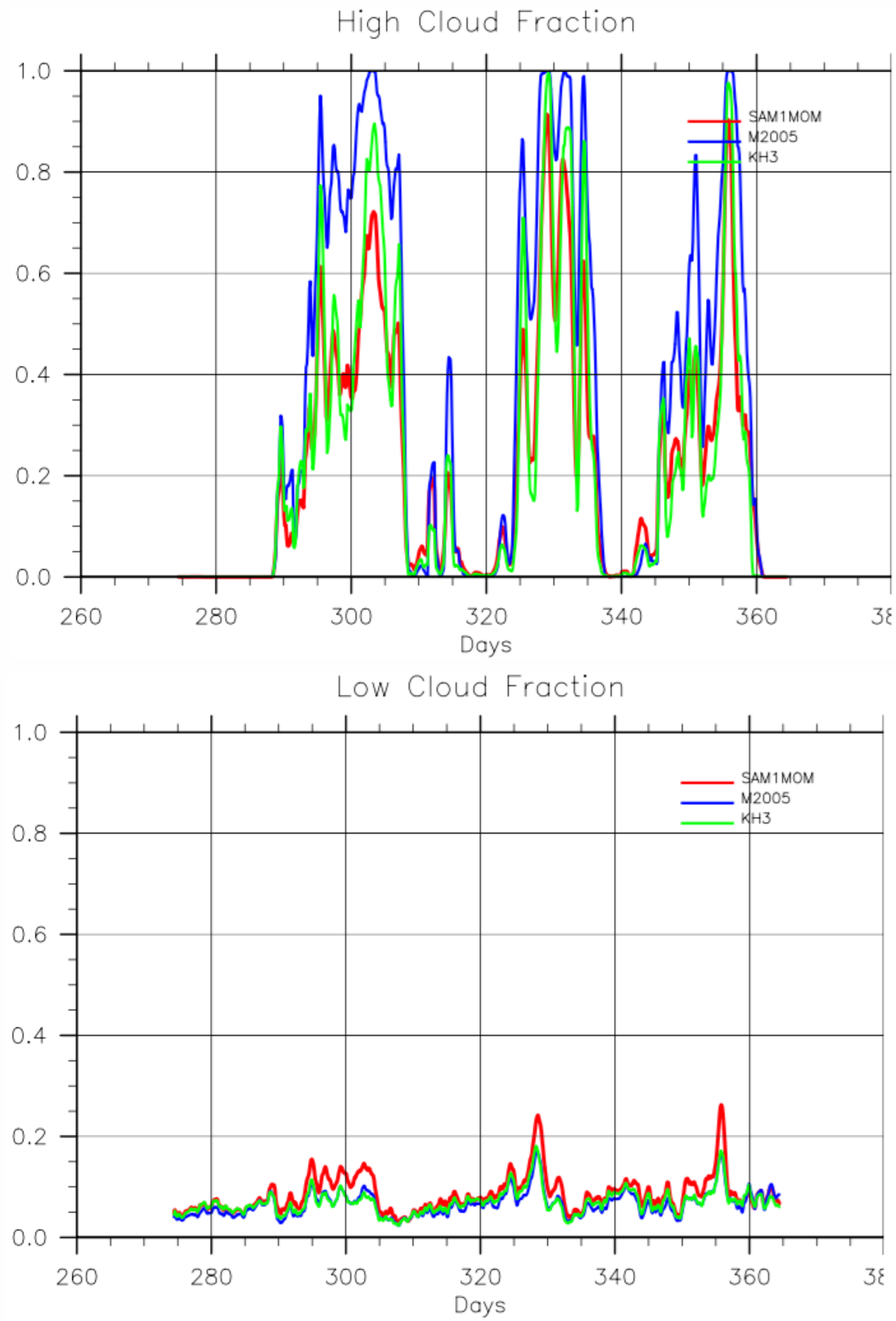
DYNAMO

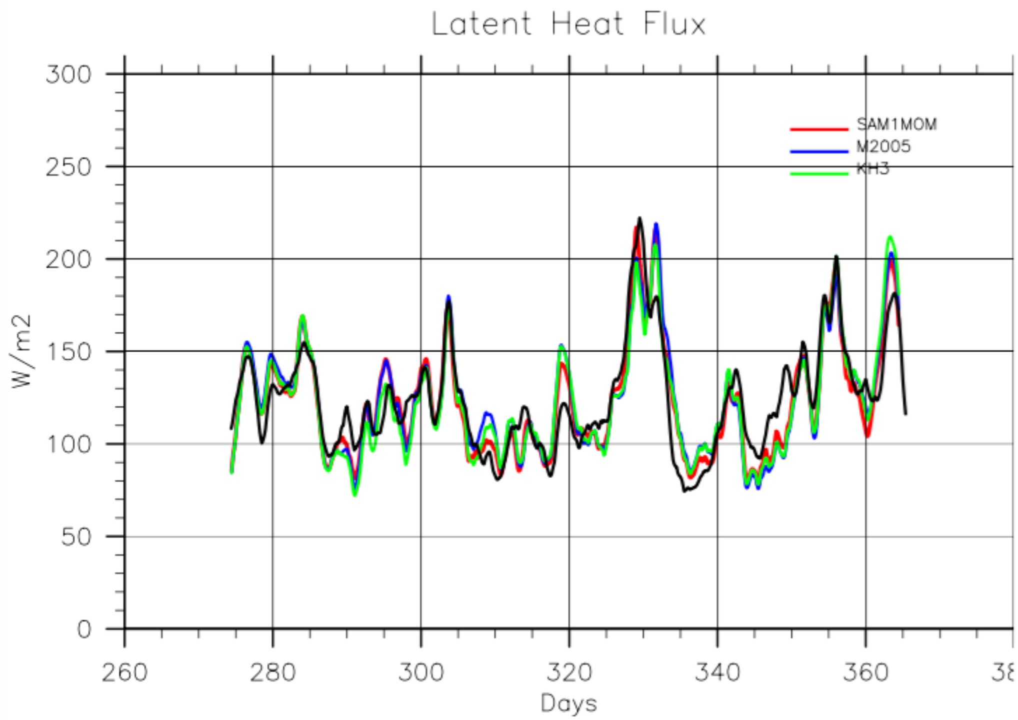
Dynamics of the Madden-Julian Oscillation

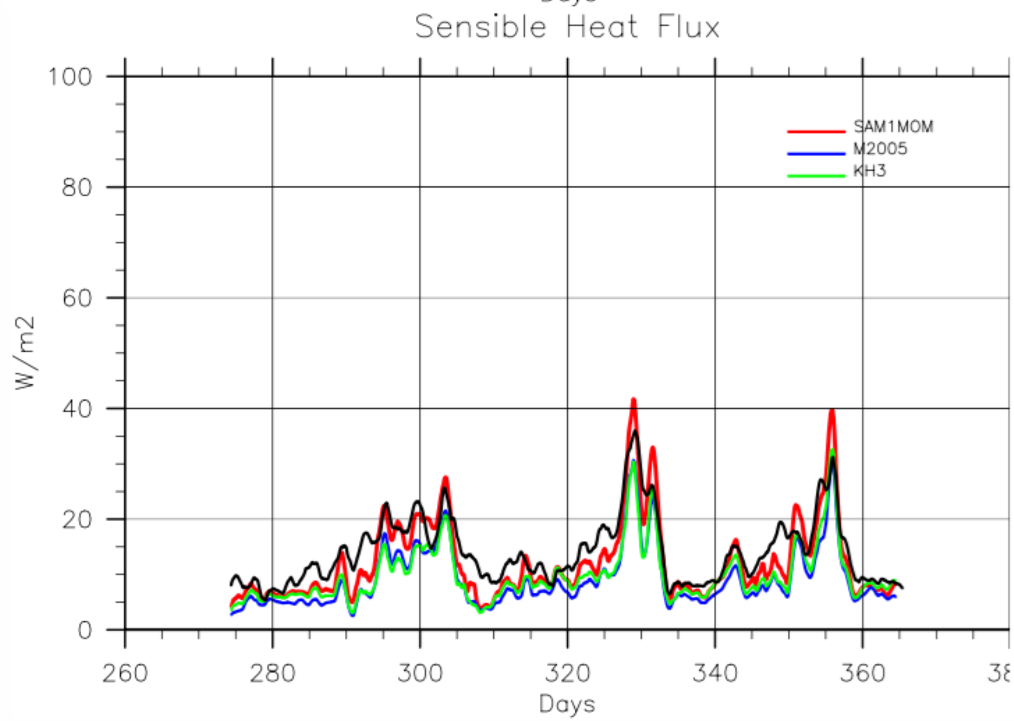


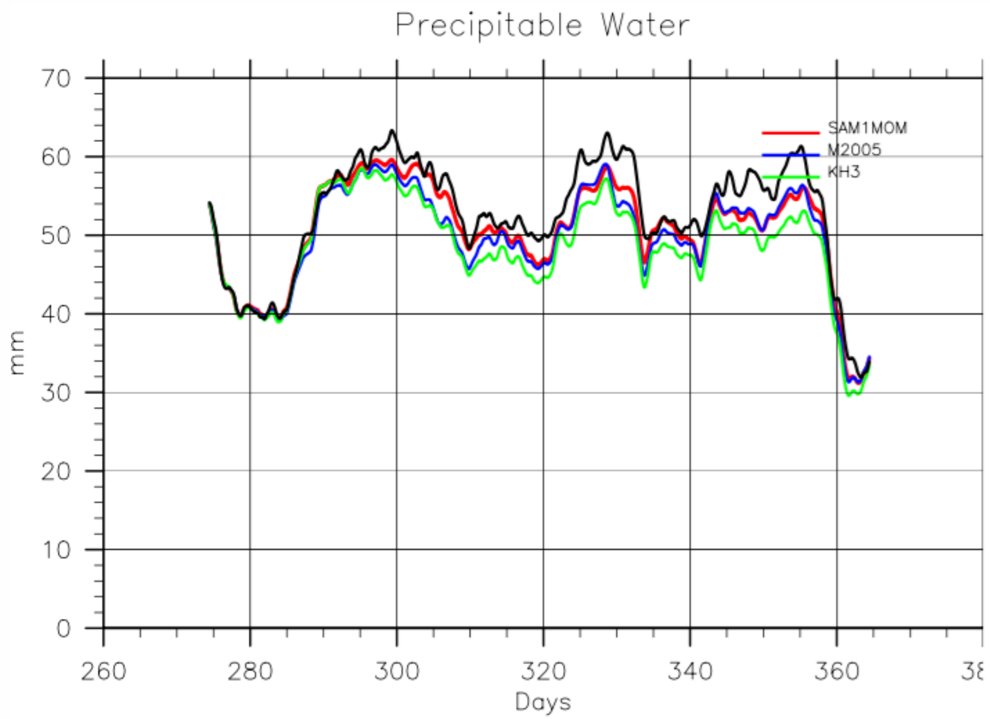
- SAM6.10.8
- 256x256x64 grid
- $\Delta x = \Delta y = 1$ km
- Domain top at 27 km
- Microphysics:
  - SAM1MOM
  - M2005
  - KH3
- Radiation: CAM3

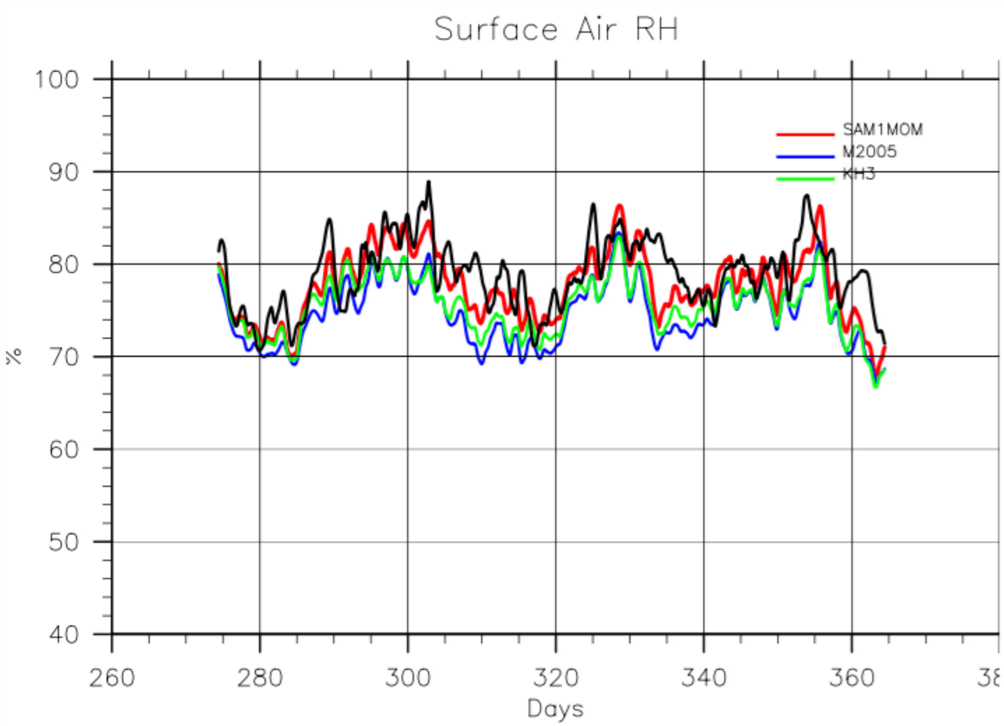


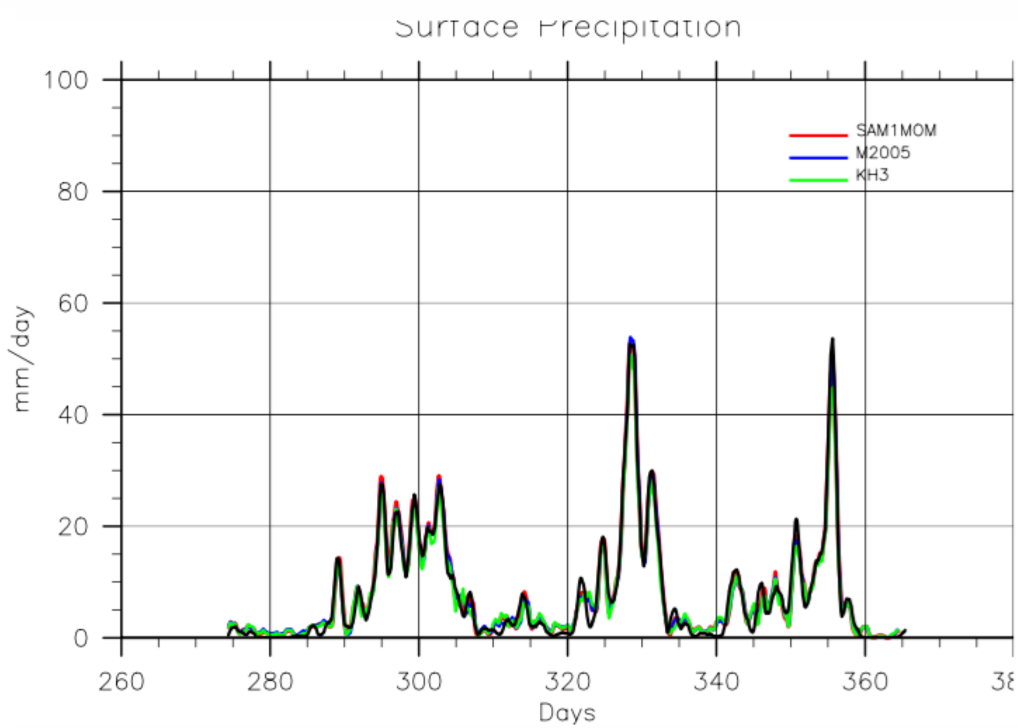

High Cloud Fraction
1.0
0.8
0.6
0.4
0.2
0.0
260
280
300
320
340
360
SAM1MOM
M2005
KH3
Days
Low Cloud Fraction
1.0
0.8
0.6
0.4
0.2
0.0
260
280
300
320
340
360
SAM1MOM
M2005
KH3
Days

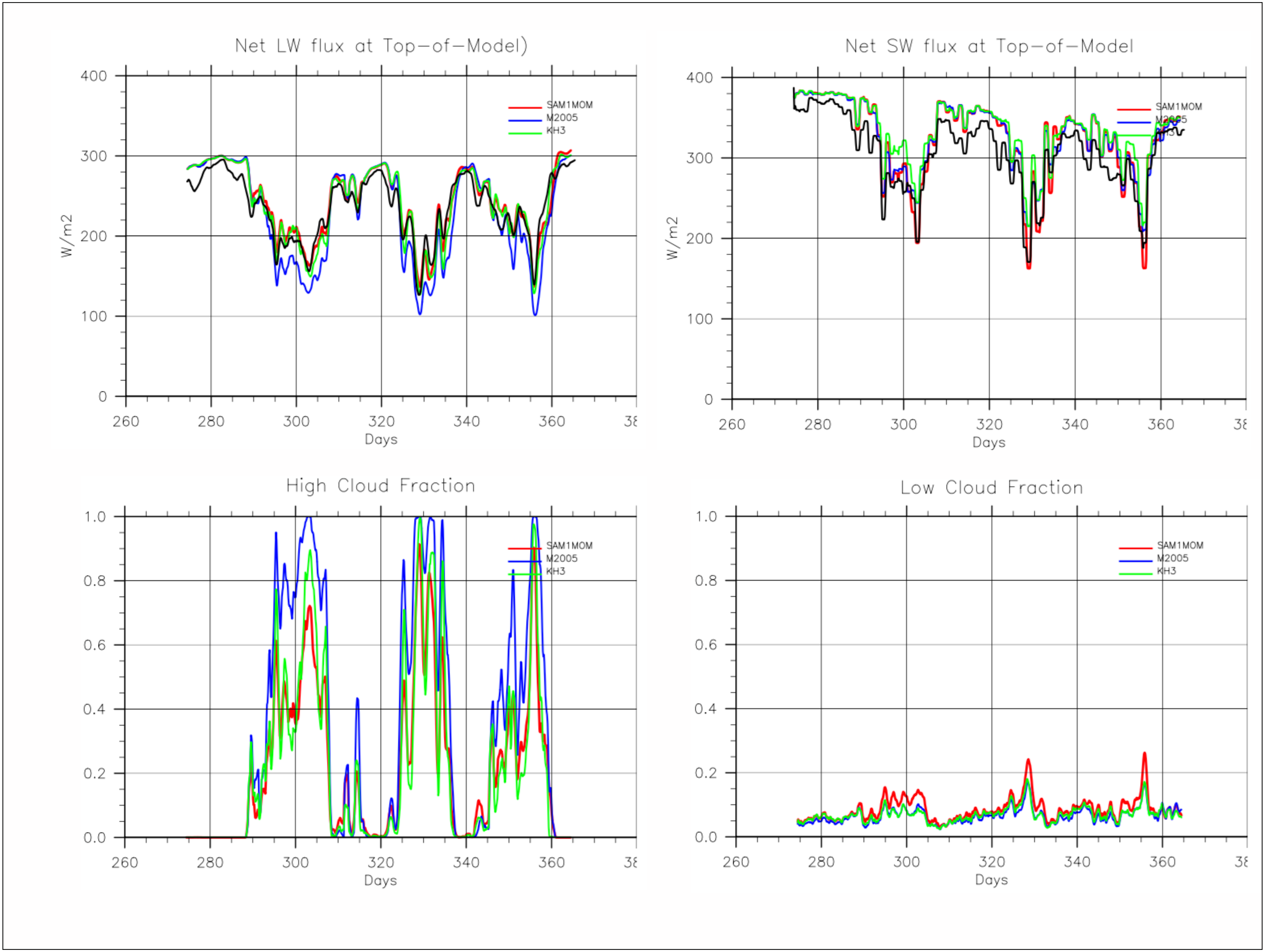

Latent Heat Flux
W/m2
Days
SAM1MOM
M2005
KH3
0
50
100
150
200
250
300
260
280
300
320
340
360


Sensible Heat Flux
W/m2
Days
SAM1MOM
M2005
KH3
0
20
40
60
80
100
260
280
300
320
340
360

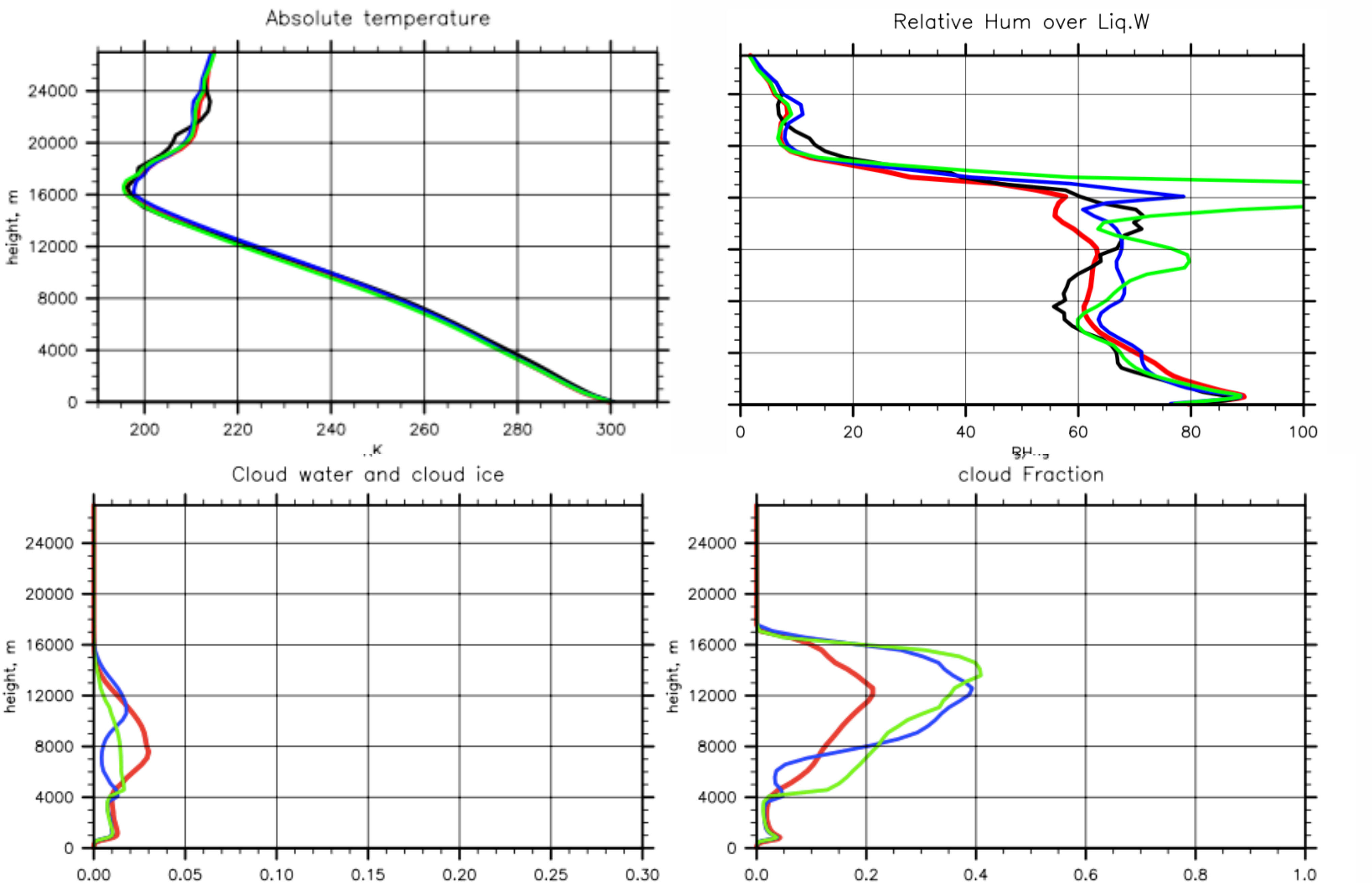

Precipitable Water
SAM1MOM
M2005
KH3
mm
70
60
50
40
30
20
10
0
260
280
300
320
340
360
Days


Surface Air RH
SAM1MOM
M2005
KH3
%
100
90
80
70
60
50
40
260
280
300
320
340
360
Days

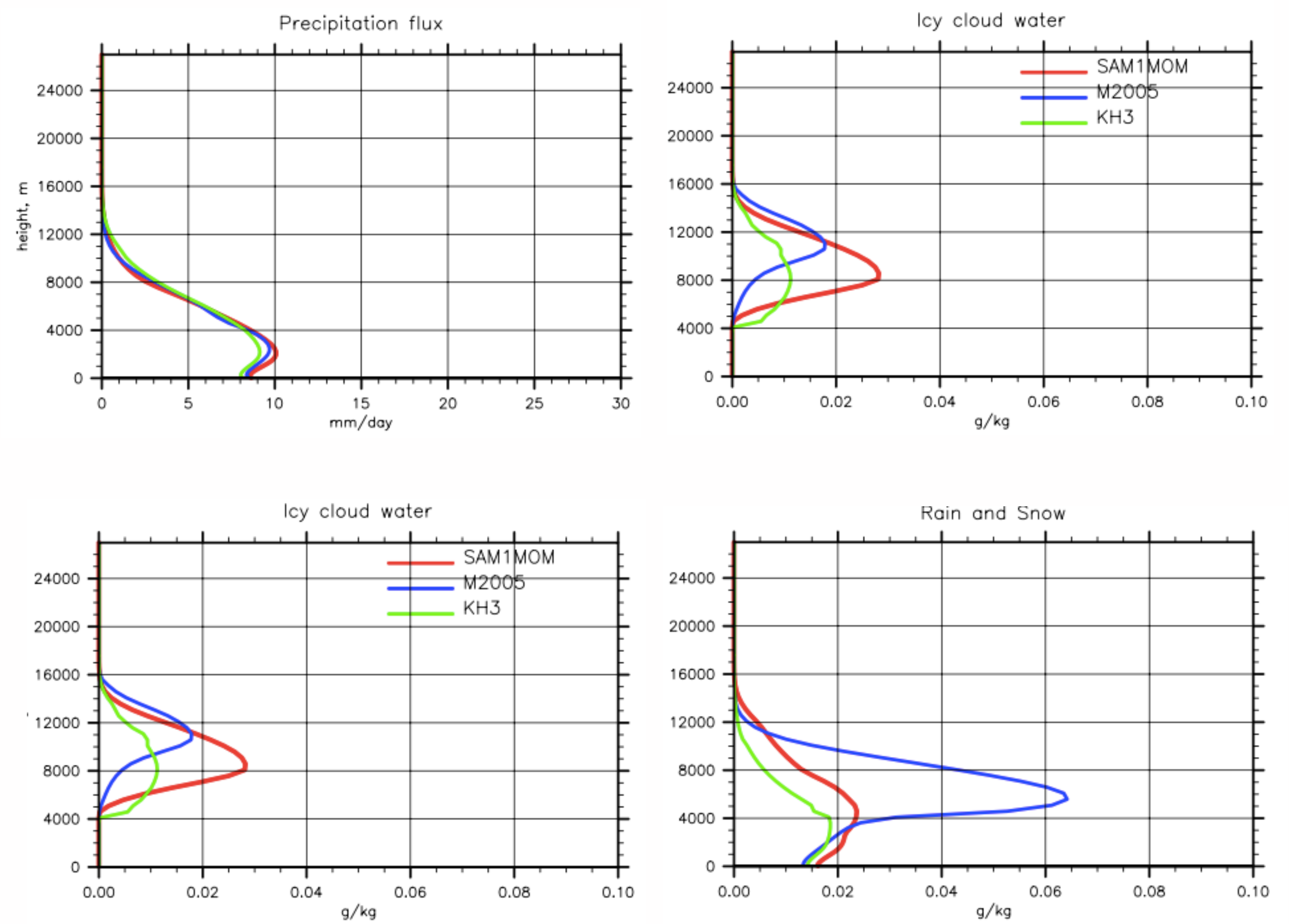

SAM1MOM
M2005
KH3
mm/day
100
80
60
40
20
0
260
280
300
320
340
360
Days



Net LW flux at Top-of-Model)
Net SW flux at Top-of-Model
High Cloud Fraction
Low Cloud Fraction
W/m2
Days
SAM1MOM
M2005
KH3

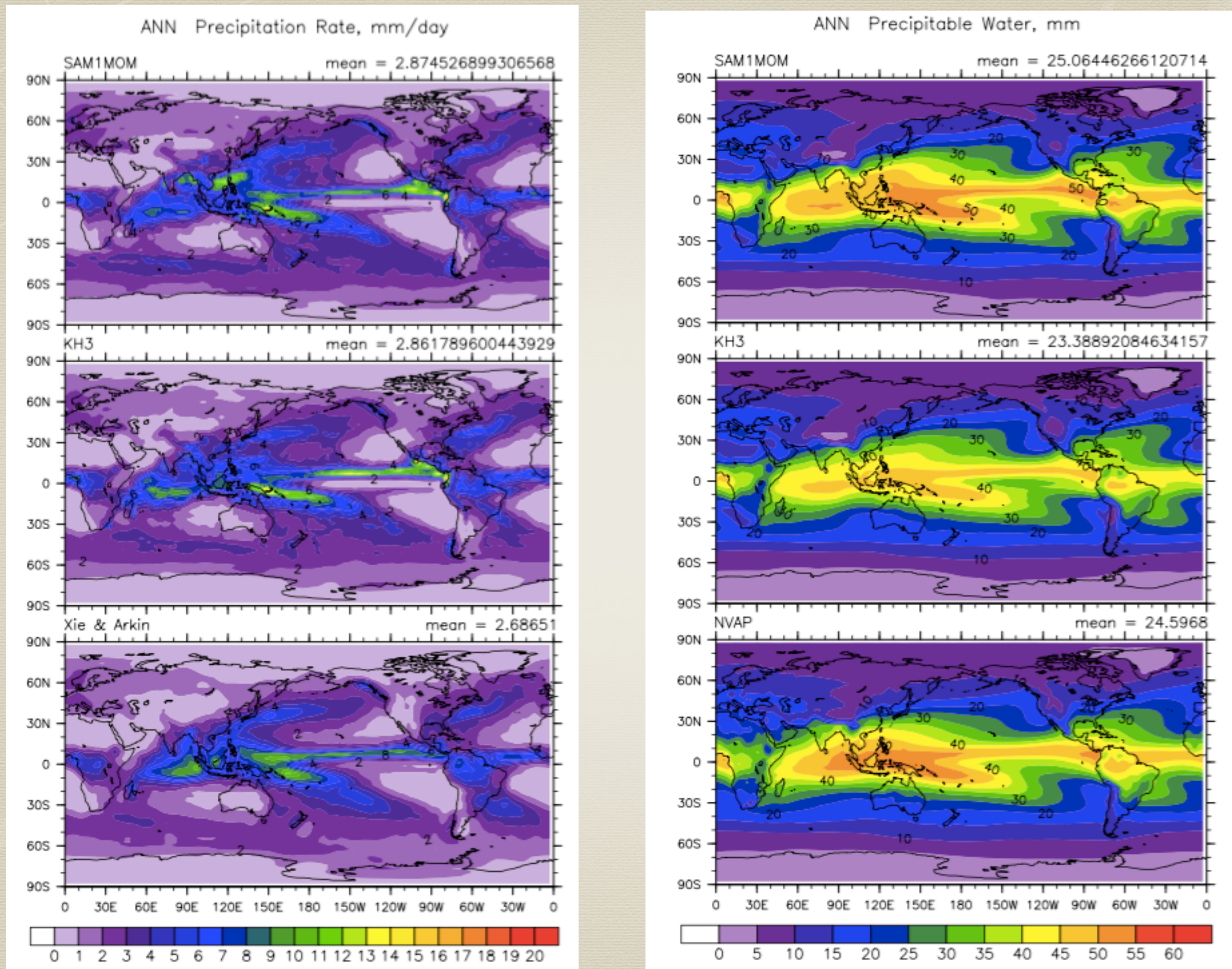


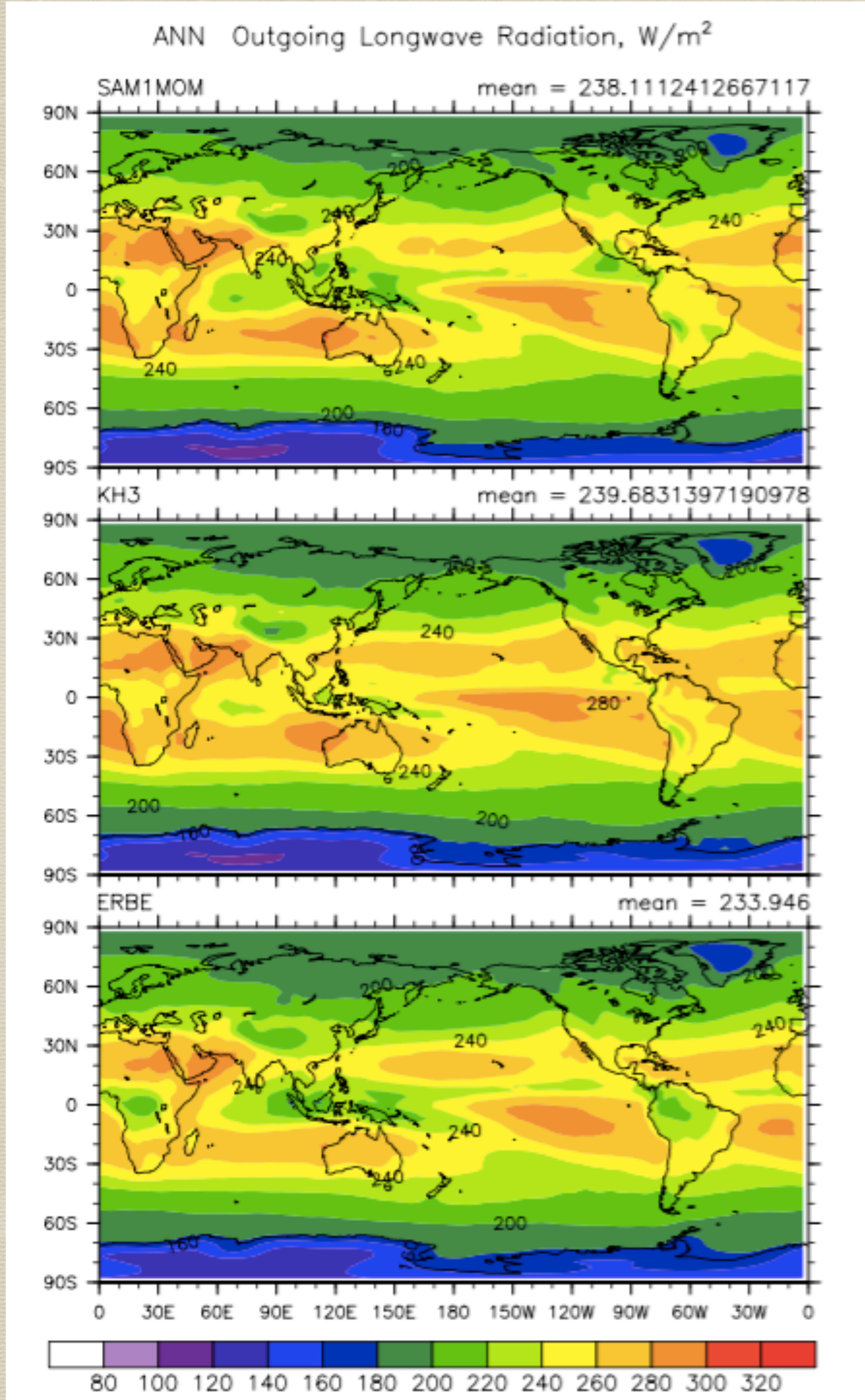
Absolute temperature
height, m
24000
20000
16000
12000
8000
4000
0
200
220
240
260
280
300
Relative Hum over Liq.W
0
20
40
60
80
100
Cloud water and cloud ice
height, m
0.00
0.05
0.10
0.15
0.20
0.25
0.30
cloud Fraction
height, m
0.0
0.2
0.4
0.6
0.8
1.0

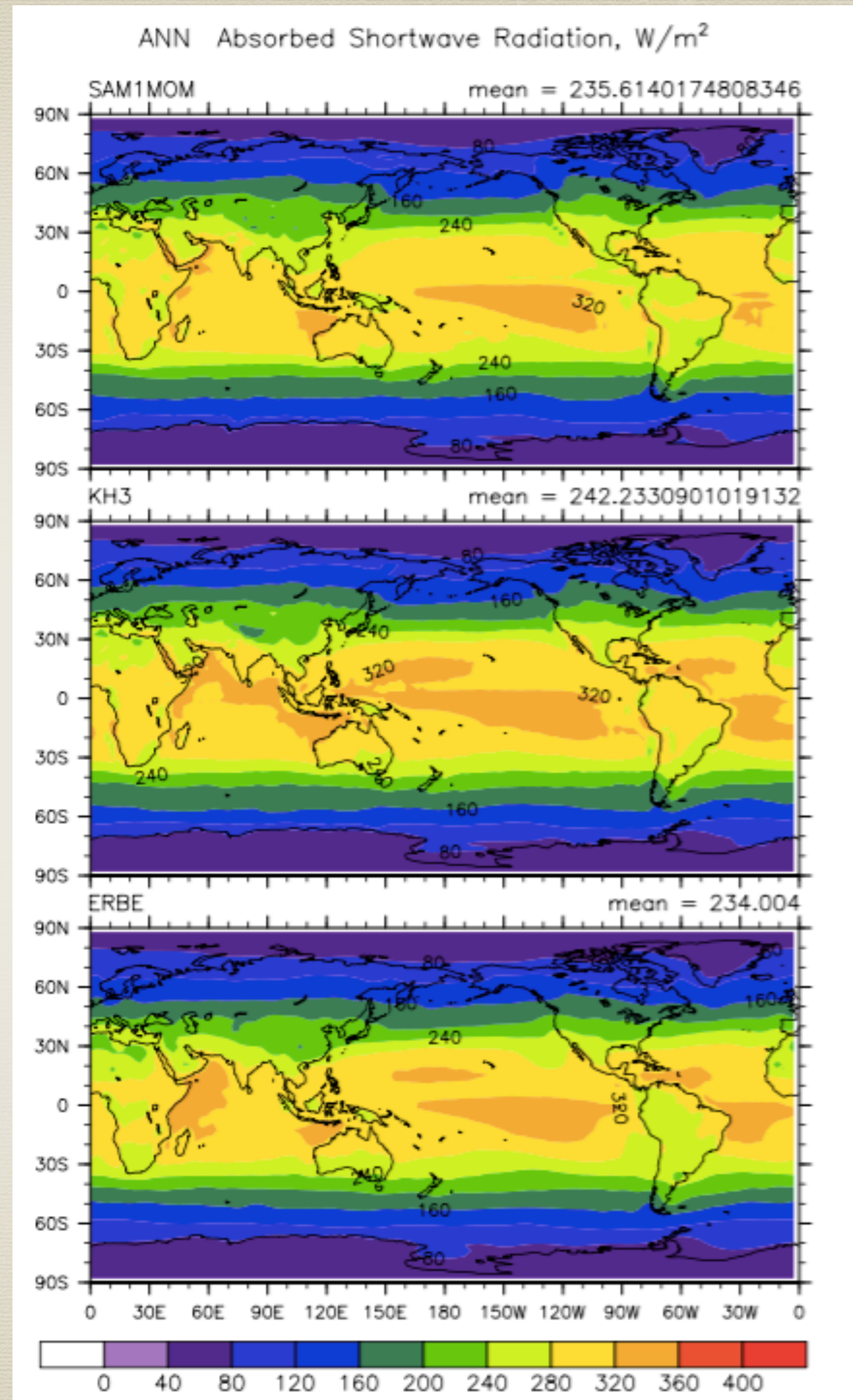


Precipitation flux
height, m
24000
20000
16000
12000
8000
4000
0
0
5
10
15
20
25
30
mm/day
Icy cloud water
SAM1MOM
M2005
KH3
0.00
0.02
0.04
0.06
0.08
0.10
g/kg
Icy cloud water
SAM1MOM
M2005
KH3
g/kg
Rain and Snow
g/kg

Preliminary Test in SP-CAM3.5


ANN Precipitation Rate, mm/day
SAM1MOM
mean = 2.874526899306568
KH3
mean = 2.861789600443929
Xie & Arkin
mean = 2.68651
ANN Precipitable Water, mm
SAM1MOM
mean = 25.06446266120714
KH3
mean = 23.38892084634157
NVAP
mean = 24.5968
90N 60N 30N 0 30S 60S 90S
0 30E 60E 90E 120E 150E 180 150W 120W 90W 60W 30W 0
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20
0 5 10 15 20 25 30 35 40 45 50 55 60


ANN Outgoing Longwave Radiation, W/m²
SAM1MOM
mean = 238.1112412667117
KH3
mean = 239.6831397190978
ERBE
mean = 233.946
90N
60N
30N
0
30S
60S
90S
0
30E
60E
90E
120E
150E
180
150W
120W
90W
60W
30W
0
80
100
120
140
160
180
200
220
240
260
280
300
320


ANN Absorbed Shortwave Radiation, W/m²
SAM1MOM
mean = 235.6140174808346
KH3
mean = 242.2330901019132
ERBE
mean = 234.004
90N
60N
30N
0
30S
60S
90S
0
30E
60E
90E
120E
150E
180
150W
120W
90W
60W
30W
0
0
40
80
120
160
200
240
280
320
360
400