Cloud-Aerosol Interactions in the MMF

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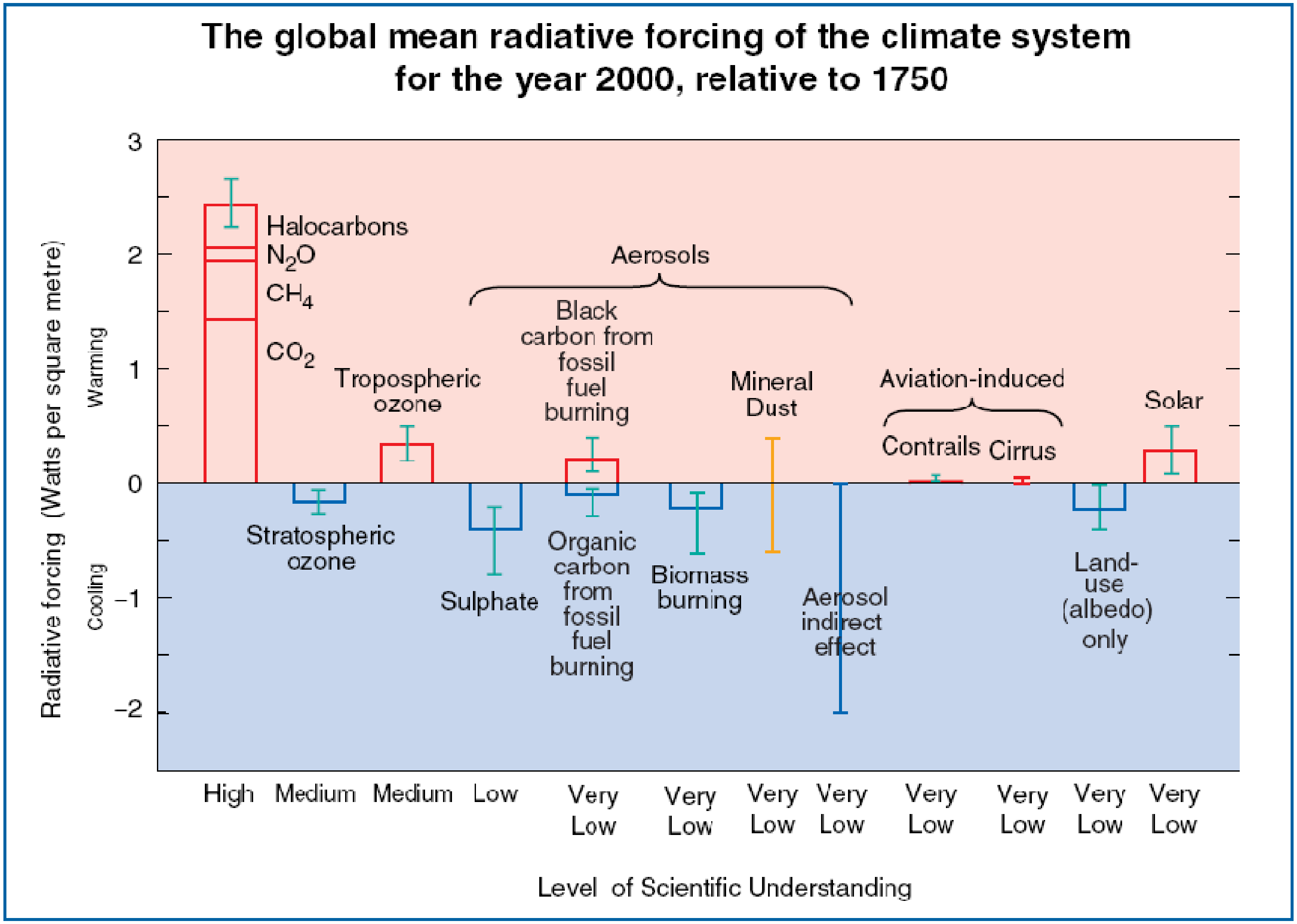
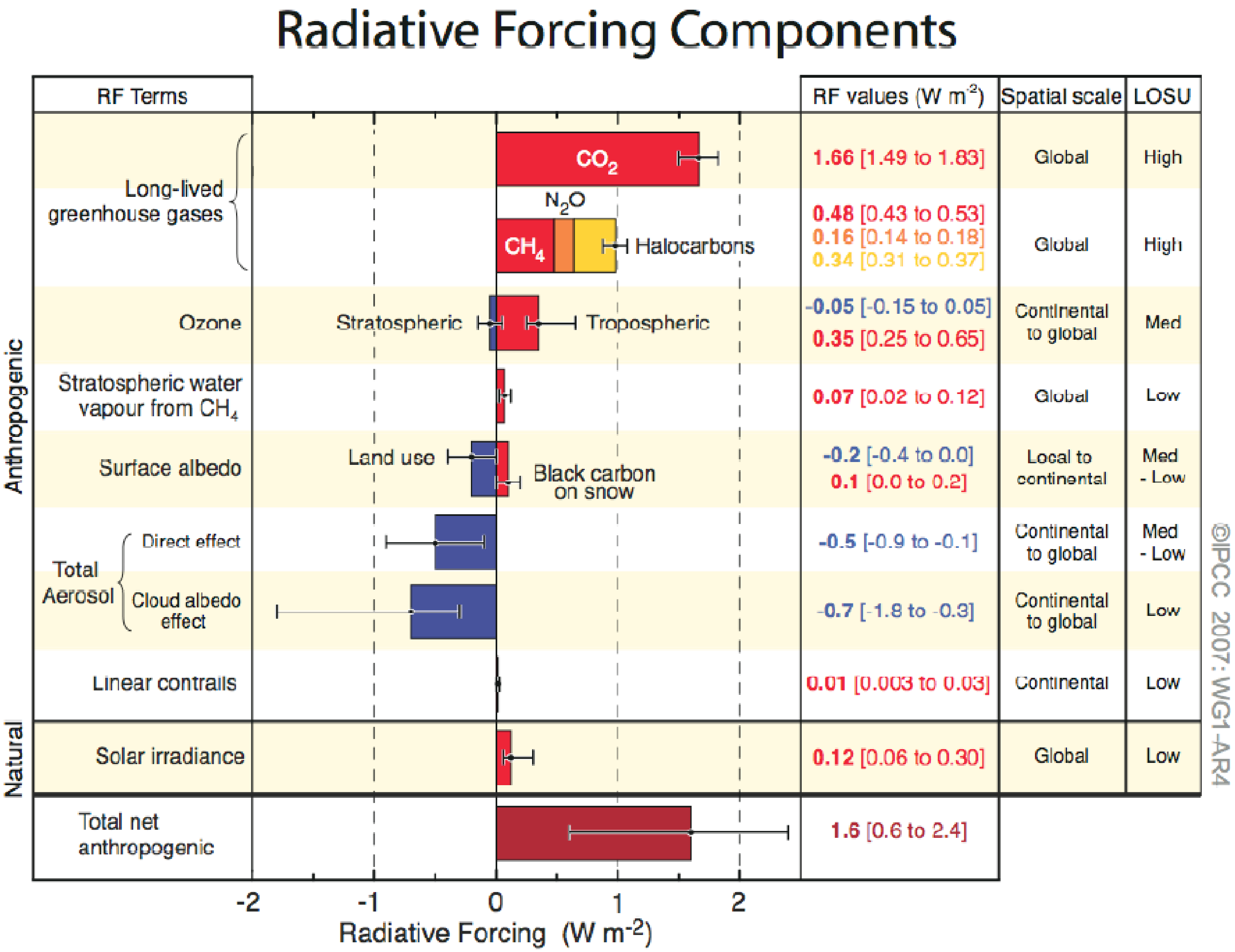
IPCC 2001


The global mean radiative forcing of the climate system
for the year 2000, relative to 1750
Radiative forcing (Watts per square metre)
Warming
Cooling
3
2
1
0
−1
−2
Halocarbons
N_2O
CH_4
CO_2
Stratospheric ozone
Tropospheric ozone
Aerosols
Sulphate
Black carbon from fossil fuel burning
Organic carbon from fossil fuel burning
Biomass burning
Mineral Dust
Aerosol indirect effect
Aviation-induced
Contrails
Cirrus
Land-use (albedo) only
Solar
High
Medium
Medium
Low
Very Low
Very Low
Very Low
Very Low
Very Low
Very Low
Very Low
Very Low
Level of Scientific Understanding

IPCC 2007



Radiative Forcing Components

RF Terms		RF values (W m^{-2})	Spatial scale	LOSU
Long-lived greenhouse gases	CO$_2$	1.66 [1.49 to 1.83]	Global	High
	CH$_4$ N$_2$O Halocarbons	0.48 [0.43 to 0.53] 0.16 [0.14 to 0.18] 0.34 [0.31 to 0.37]	Global	High
Ozone	Stratospheric Tropospheric	-0.05 [-0.15 to 0.05] 0.35 [0.25 to 0.65]	Continental to global	Med
Stratospheric water vapour from CH$_4$		0.07 [0.02 to 0.12]	Global	Low
Surface albedo	Land use Black carbon on snow	-0.2 [-0.4 to 0.0] 0.1 [0.0 to 0.2]	Local to continental	Med - Low
Total Aerosol	Direct effect	-0.5 [-0.9 to -0.1]	Continental to global	Med - Low
	Cloud albedo effect	-0.7 [-1.8 to -0.3]	Continental to global	Low
Linear contrails		0.01 [0.003 to 0.03]	Continental	Low
Solar irradiance		0.12 [0.06 to 0.30]	Global	Low
Total net anthropogenic		1.6 [0.6 to 2.4]		

Needed MMF/SAM extensions

- Aerosol distributions and properties.

  Treatment must:
  - Address both the first and second indirect effects
  - Account for cloud effects on aerosols
  - Be applicable to MMF (efficient computationally and take advantage of resolved large convection)

- Aerosol effects on cloud properties

  Treatment must:
  - Include both liquid and ice phases
  - Be applicable to MMF

Developing a double moment scheme.
Step 1: Diagnosing supersaturation within the interior of deep convective clouds

- Predicting droplet number requires treatment of **nucleation**, collision/coalescence, sedimentation, mixing
- In the current CAM approach (Ghan et al., JGR 1997) nucleation is diagnosed at cloud base only.
- Droplet nucleation in updraft cores can be important for deep convection.
- Predicting supersaturation (e.g., Phillips et al. 2007) requires solution for equations for T and q_v using small sub-steps in time and may not be very practical for MMF.
- We are testing a method to diagnose supersaturation.

Diagnosing supersaturation

- Equation for supersaturation

$$\frac{1}{S_w+1}\frac{dS_w}{dt} = A(T)w - C(T)\frac{dq_l}{dt} \qquad \frac{dq_l}{dt} = b(T,p)N\,\bar{r}\,S_w$$

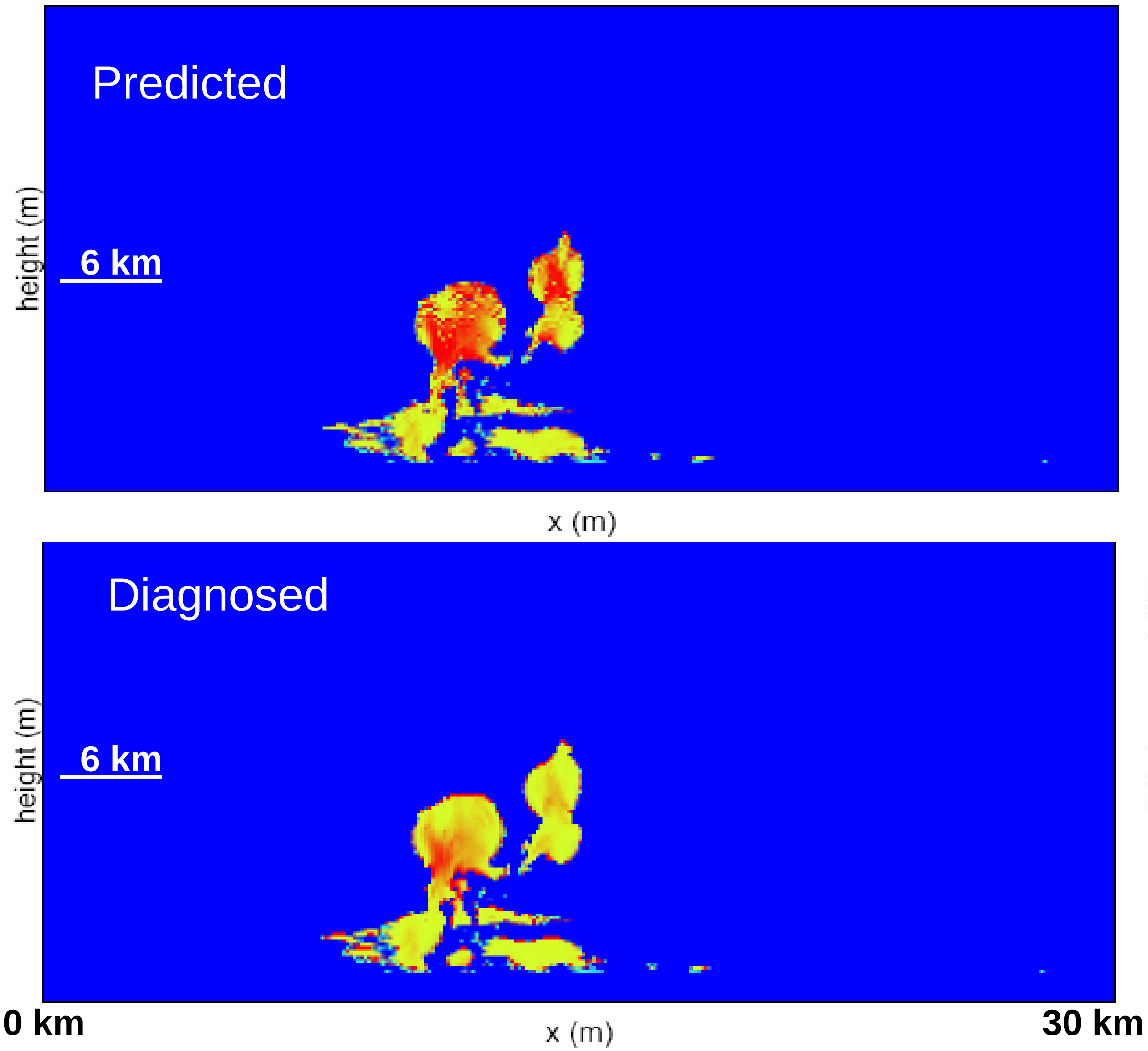
$$\frac{1}{S_w+1}\frac{dS_w}{dt} = A(T)w - B(T,p)N\,\bar{r}\,S_w$$

- Quasi-steady supersaturation

$$0 = A(T)w - B(T,p)N\,\bar{r}\,S_w \qquad S_{w,qs} = \frac{A(T)w}{B(T,p)N\,\bar{r}}$$

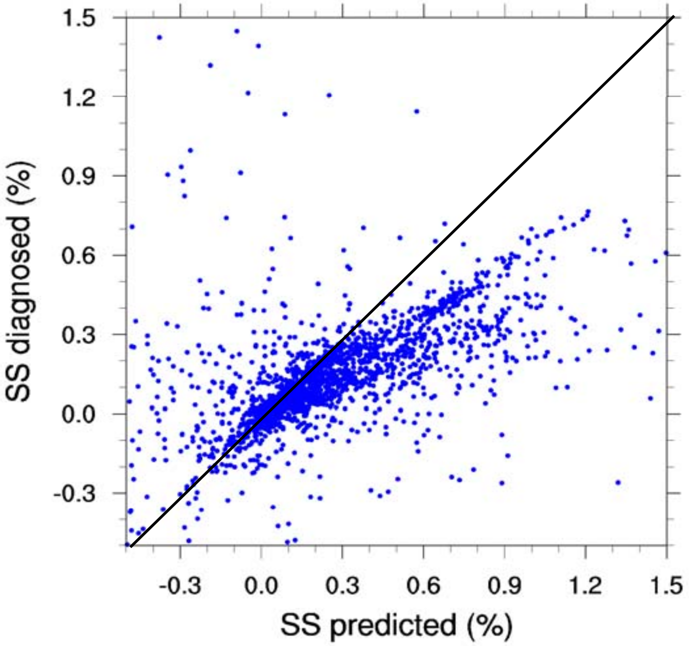
Horizontal advection and turbulent mixing of T and Q_v, and diabatic (radiative) changes in T are neglected

Diagnosed supersaturation (off line test)

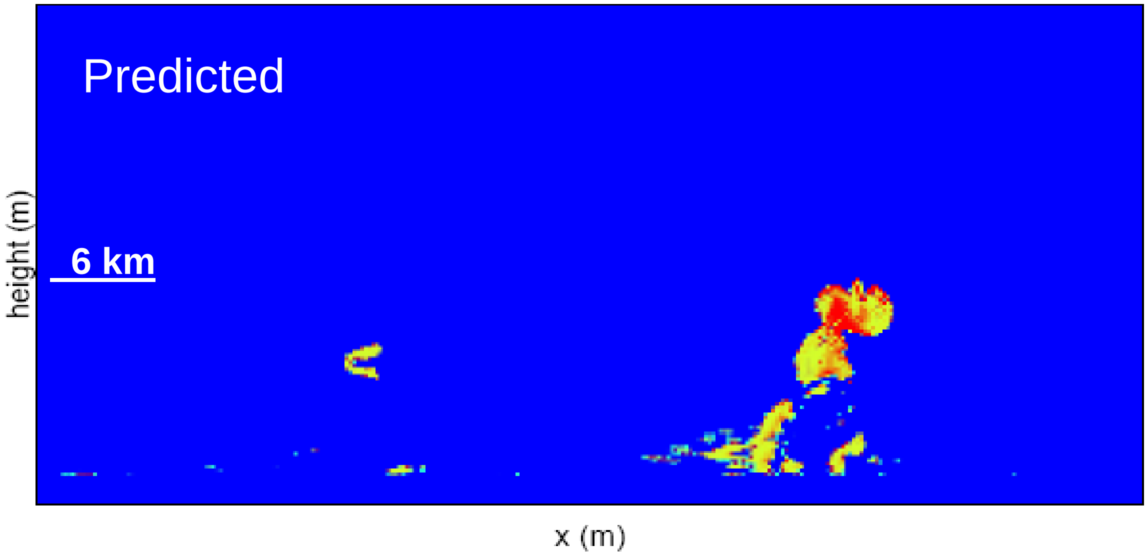


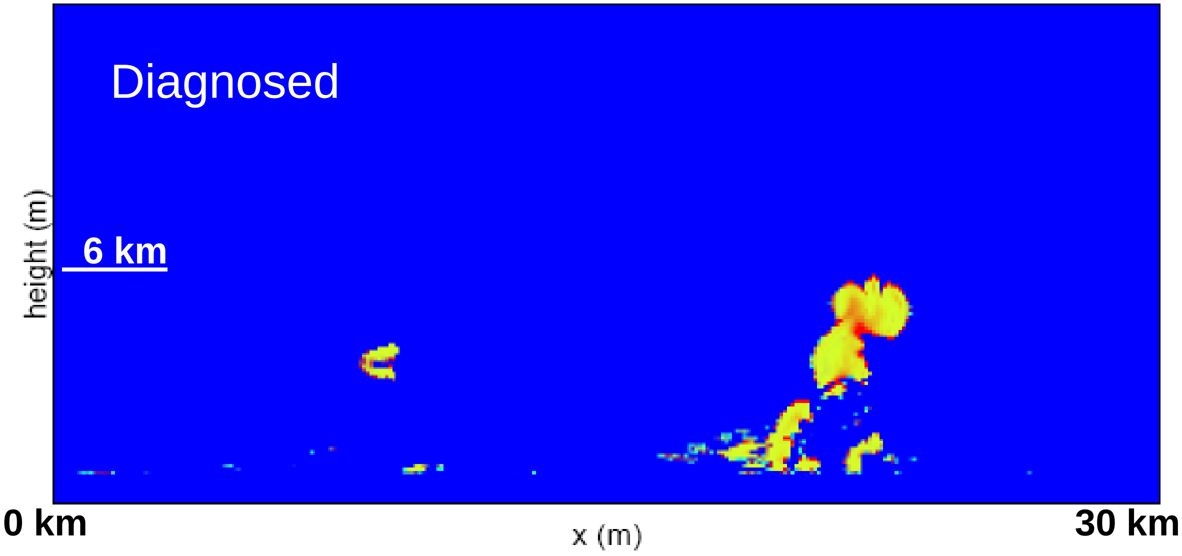
Use SAM coupled with size-resolved liquid-phase microphysics to obtain supersaturation (predicted), droplet spectra, w, T, and q_v.

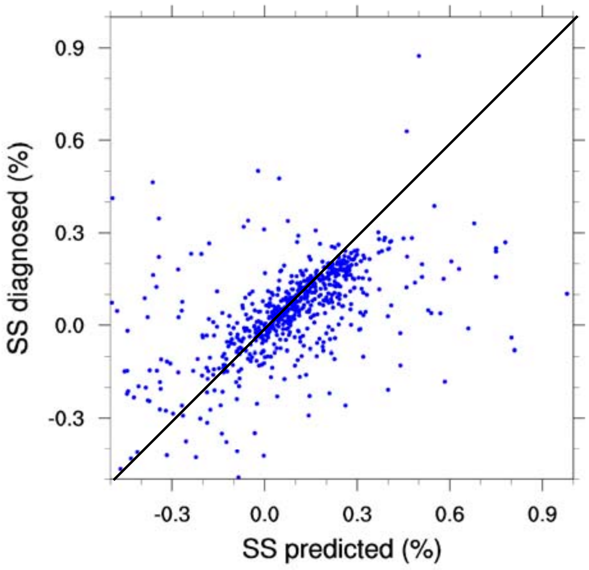
Compare predicted and diagnosed supersaturations within clouds.



Diagnosed supersaturation (off line test)



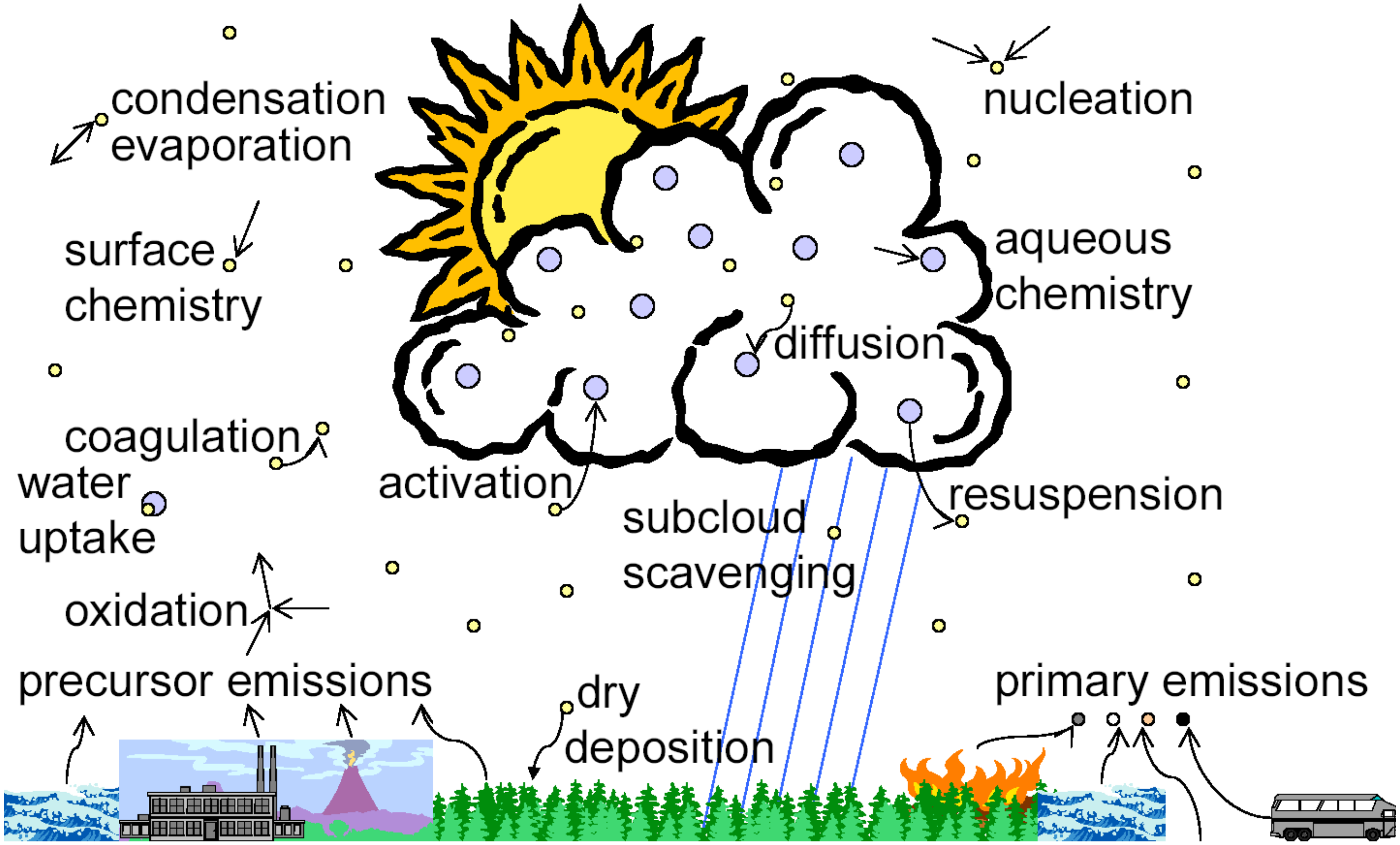




Superparameterization of Aerosol Transport, Transformation, and Removal by Clouds

Steven Ghan, Larry Berg, Richard Easter, …

Pacific Northwest National Laboratory

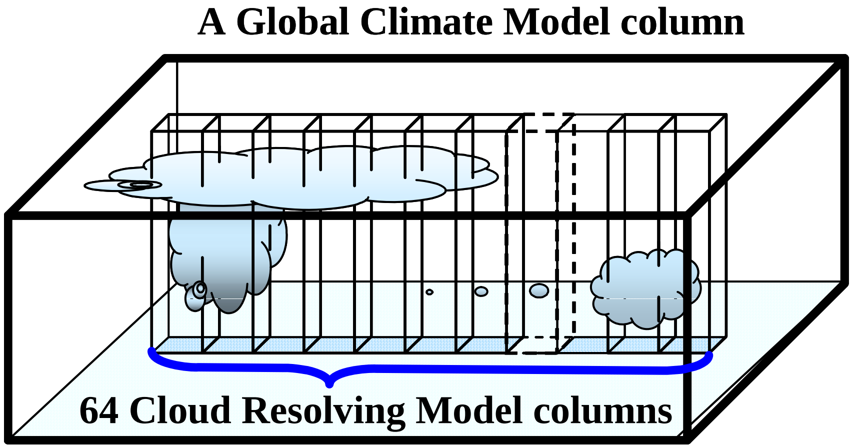


Motivation

- Uncertainty in estimates of direct and indirect effects by anthropogenic aerosols is comparable to the forcing by anthropogenic greenhouse gases.
- Direct effects are a highly nonlinear function of RH
- Indirect effects are a nonlinear function of
  - Updraft velocity
  - Aerosol concentration
  - Cloud thickness
- Aerosol concentration is strongly influenced by vertical transport, aqueous production, and precipitation scavenging by clouds that are poorly resolved or parameterized in global climate models

One Solution

- The Cloud Resolving Models embedded within the Multiscale Modeling Framework provide a powerful framework for translating improved process understanding into improved global-scale models.
- Embedding pollutant transport, transformation, and removal within the CRMs in each global model grid cell would provide a much more reliable physically-based subgrid treatment of cloud processing of pollutants and of direct and indirect effects of aerosols.

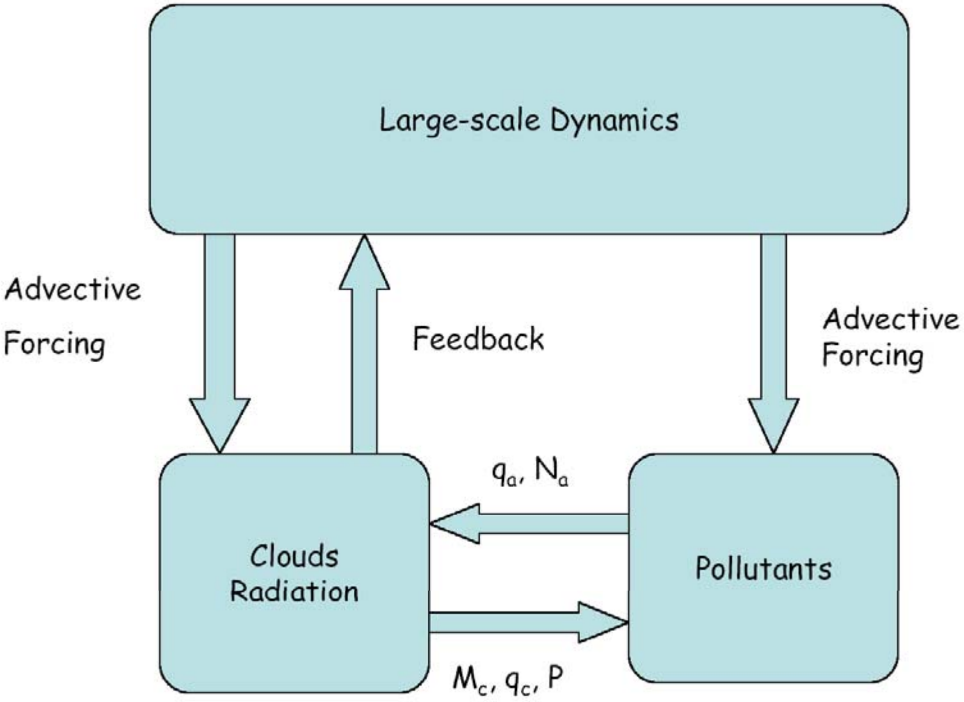


But Too Time-Consuming

- The MMF currently runs about 200 times slower than climate models with conventional cloud parameterizations.
- Plans for future MMF simulations will cost even more:
  - Six-fold for Δx=1 km instead of 4 km
  - Three-fold for quasi-3D on geodesic grid
  - Hundred-fold for full 3D
- Chemistry and aerosol physics can cost 2-10 times as much as typical climate physics.
- Adding chemistry and aerosol physics to embedded CRMs would produce a computational monster.

Explicit Clouds – Parameterized Pollutants (ECPP)

- Use grid cell mean statistics from the CRM simulation to drive a physically-based treatment of pollutant processing by clouds and of direct and indirect effects
  - use mean cloud mass flux to treat vertical transport of pollutants
  - use mean updraft velocity to determine the aerosol activation and droplet nucleation
  - use mean cloud fraction and in-cloud water content to treat aqueous chemistry
  - use mean precipitation fraction and precipitation rate to treat precipitation scavenging
  - use CRM RH to calculate water uptake and direct effects
  - use CRM droplet number and cloud water for indirect effects.



Explicit Clouds – Parameterized Pollutants (ECPP)

(1) Classify each CRM grid cell as updraft ($w > w_{up\text{-}thresh}$), downdraft ($w < -w_{dn\text{-}thresh}$), or quiescent environment. Calculate profiles of mass flux (M_J, J = up, dn, env) and fractional area (A_J) by averaging over the appropriate grid cells.

(2) Diagnose up- and downdraft entrainment (E_J) and detrainment (D_J) mass tendencies from

$$\frac{\partial(\rho A_J)}{\partial t} + \frac{\partial M_J}{\partial z} = E_J - D_J$$

by assuming that at each level, both are ≥ 0 and only one is > 0.

(3) Solve continuity equations for trace-species mixing ratios in the updraft, downdraft, and environment subareas ($q_{J,L}$). For updraft and downdraft subareas,

$$\frac{\partial(\rho A_J q_{J,L})}{\partial t} = -\frac{\partial(M_J q_{J,L})}{\partial z} + \left(E_J q_{env,L} - D_J q_{J,L}\right) + S_J$$

ECPP, continued

For the environment subarea,

$$\frac{\partial(\rho A_{env} q_{env,L})}{\partial t} = -\frac{\partial(M_{env} q_{env,L})}{\partial z} + \left(D_{up} q_{up,L} - E_{up} q_{env,L}\right) + \left(D_{dn} q_{dn,L} - E_{dn} q_{env,L}\right) + S_{env}$$

(4) The updrafts and downdrafts can be assumed steady-state, as is often done in convective cloud parameterations. In this case, the updraft and downdraft entrainment and detrainment are diagnosed using

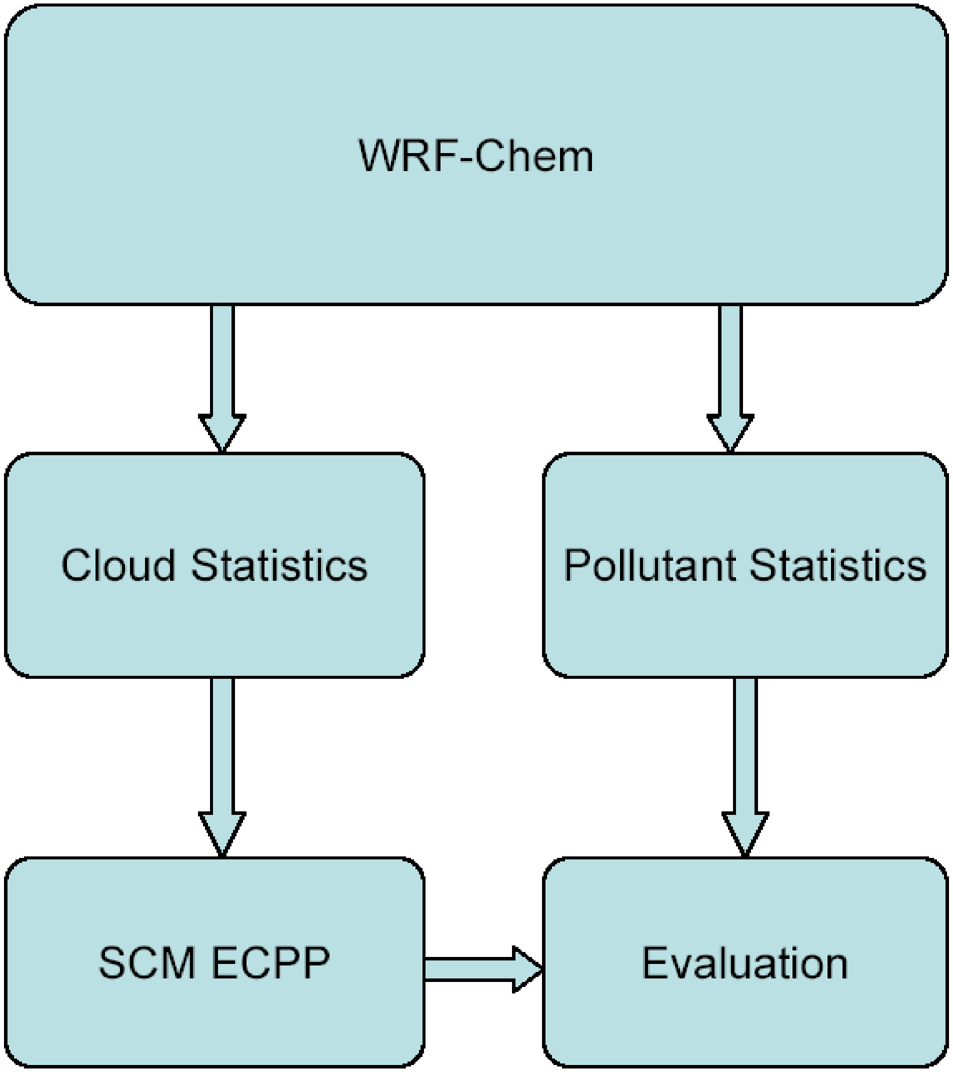
$$\frac{\partial M_J}{\partial z} = E_J - D_J$$

and the updraft and downdraft trace-species mixing ratios are computed using

$$\frac{\partial(M_J q_{J,L})}{\partial z} = \left(E_J q_{env,L} - D_J q_{J,L}\right) + S_J$$

Testing the Concept

- Perform cloud-resolving pollution simulations with WRF-Chem
- From model history calculate domain averaged cloud statistics
- Use cloud statistics to drive SCM with ECPP
- Evaluate SCM pollutant simulation using domain averaged pollutant statistics from WRF-Chem simulation


WRF-Chem

Cloud Statistics

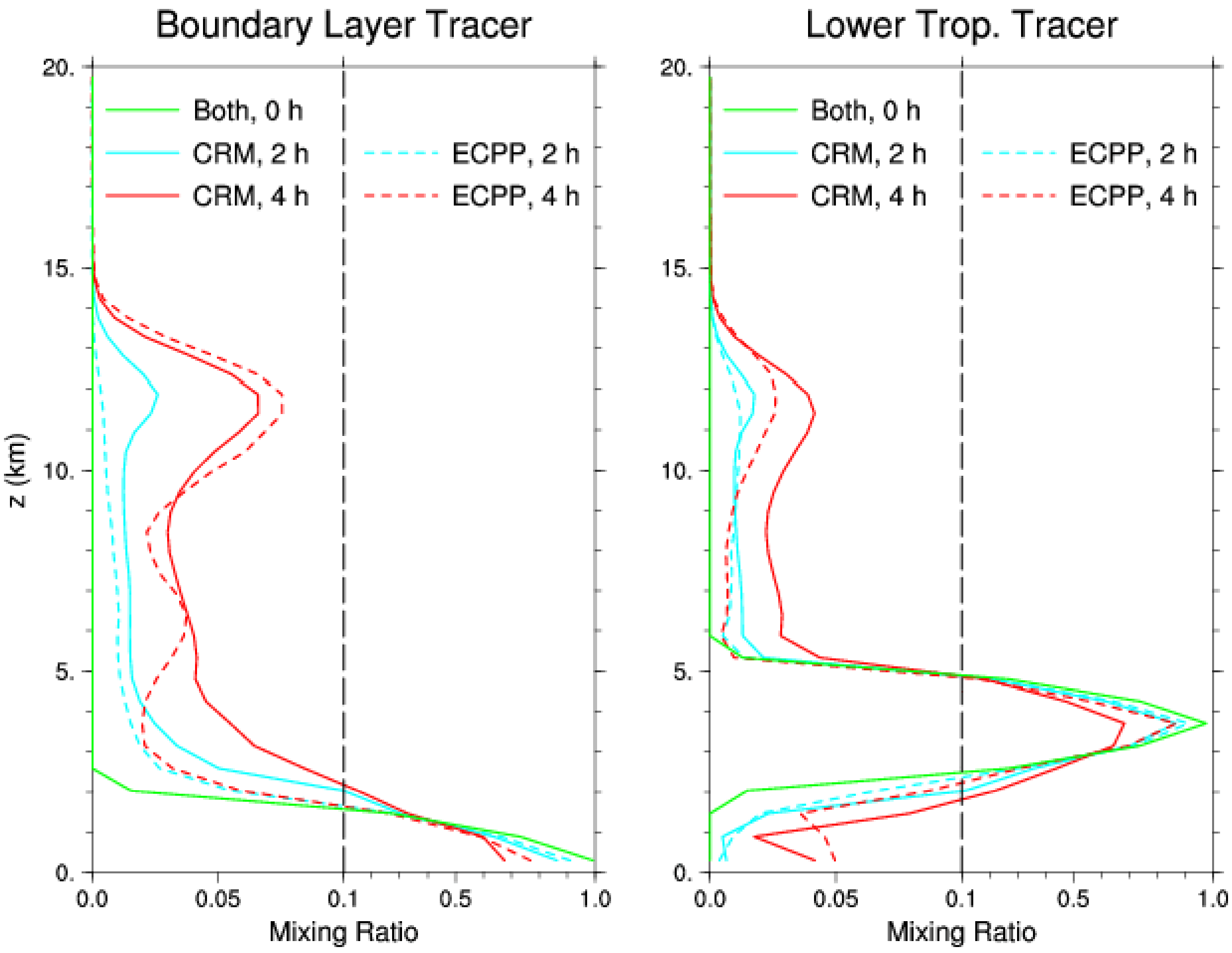
Pollutant Statistics

SCM ECPP

Evaluation

Testing Transport Only

KWAJEX case (set up by Vaughan Phillips)



Testing Transport Only

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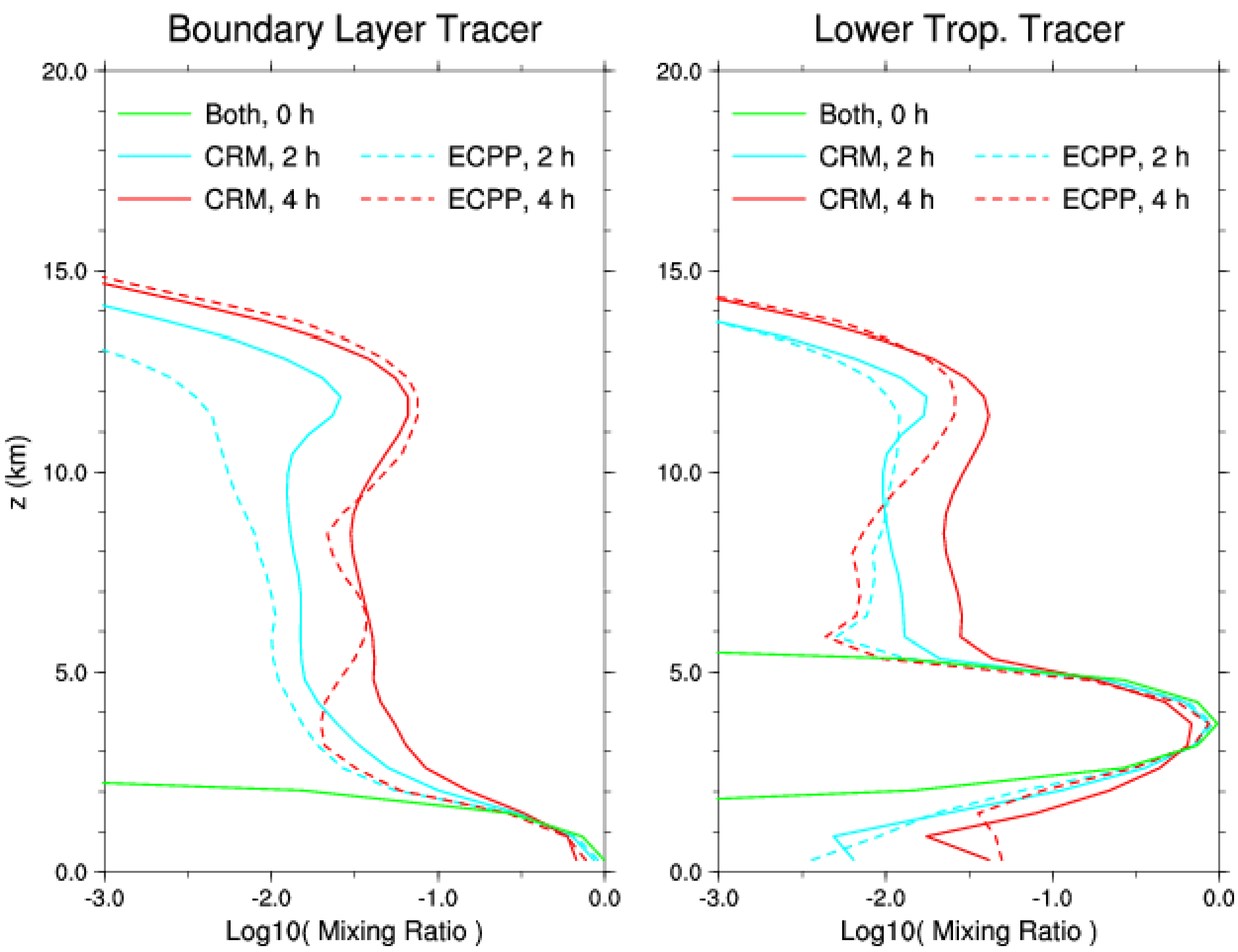

The Feedback of the Aerosol on the Clouds

- Testing the feedback of the aerosol on the clouds would require a Multiscale Modeling Framework.
- We have a global MMF, but it would be far too expensive to run with chemistry and aerosol physics embedded within it.
- Testing options:
  - Use an MMF version of WRF to test the feedback
    - Proposal to develop an MMF version of WRF
  - Evaluate the aerosol in a global MMF
    - Proposal to apply ECPP to MMF version of CAM3

Next steps