Aerosol Direct and Indirect Forcing

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WRF-Chem Tutorial, July 23 2008, Boulder CO

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Background

First A Brief History …

- CBM-Z, Fast-J, and an early version of MOSAIC in WRF-chem originated from an off-line chemical transport model
- Then, aerosol-radiation-cloud-chemistry interactions were added
- We are currently adding more capabilities, making modules more generic, and trying to follow WRF coding guidelines
- Our overall motivation is to use the model to better understand the local to regional-scale evolution of particulates and their effect on radiation, clouds, and chemistry

For more information and updates:

- PNNL atmospheric sciences: www.pnl.gov/atmospheric
- PNNL modules: www.pnl.gov/atmospheric/research/wrf-chem, including capabilities, current research, and publications

Part 1: Aerosol Direct Forcing

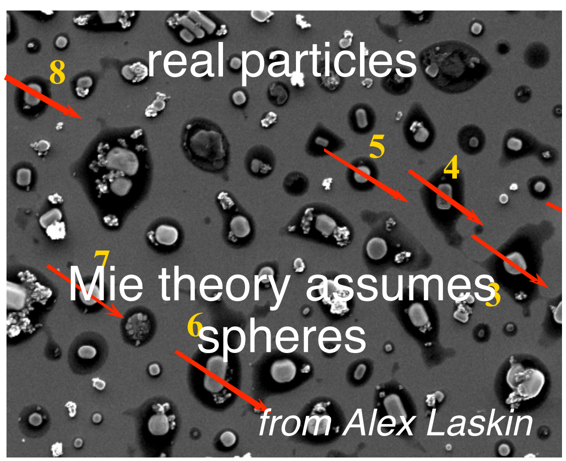
Aerosols – Radiation

Aerosol Properties

General Description and Assumptions

size and number distribution
composition
aerosol water
➡ refractive indices ➡ Mie theory ➡ layer optical depth, τ_λ
single scattering albedo, ω_o
asymmetry factor, g
➡ shortwave radiation

- τ, ω_o, and g function of wavelength, 300, 400, 600, 1000 nm
  - *τ = TAUAER1, TAUAER2, TAUAER3, TAUAER4 in Registry*
  - *ω_o = WAER1, WAER2, WAER3, WAER4 in Registry*
  - *g = GAER1, GAER2, GAER3, GAER4 in Registry*
- $\omega_o = k_s / (k_a + k_s)$, k_s and k_a = scattering and absorption coefficients
- various methods of obtaining refractive index



Mass, composition, and size distribution:

- *more mass ➡ bigger radiative impact*
- *amount of black carbon ➡ k_a*
- *aerosol size ➡ k_s*

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Aerosol Direct Radiative Effects

General Description and Assumptions

size and number distribution
composition
aerosol water
→ refractive indices → Mie theory → layer optical depth, τ_λ
single scattering albedo, ω_o
asymmetry factor, g
→ shortwave radiation

- Goddard shortwave scheme utilizes aerosol optical properties at 11 wavelengths, but the they are zero in default WRF / WRF-chem
- Use Angstrom relationship to interpolate between 4 wavelengths from optical property module to 11 wavelengths used in Goddard scheme
- Aerosols now account for scattering & absorption in Goddard scheme
- Effect of aerosols on longwave radiation not treated

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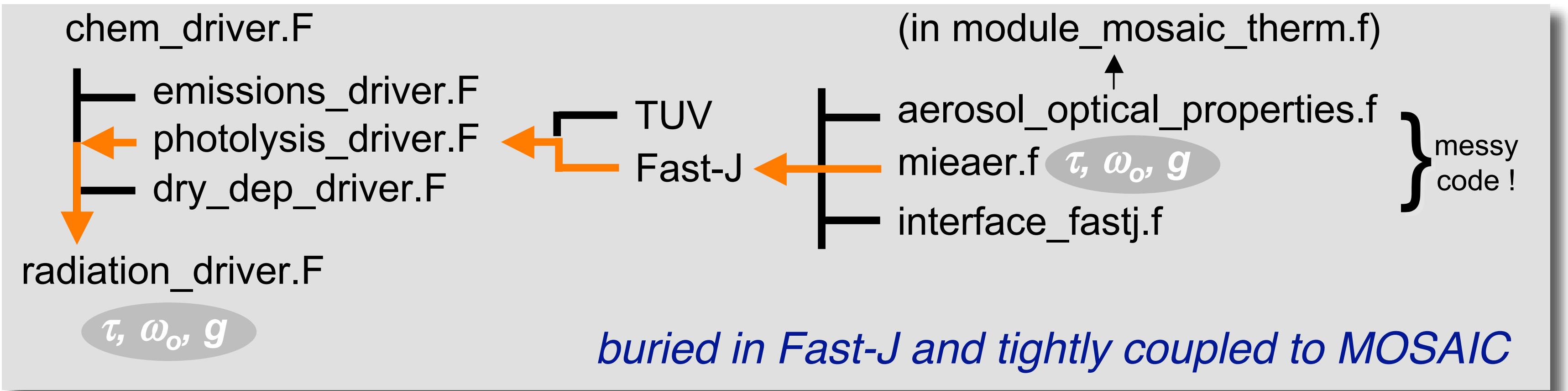
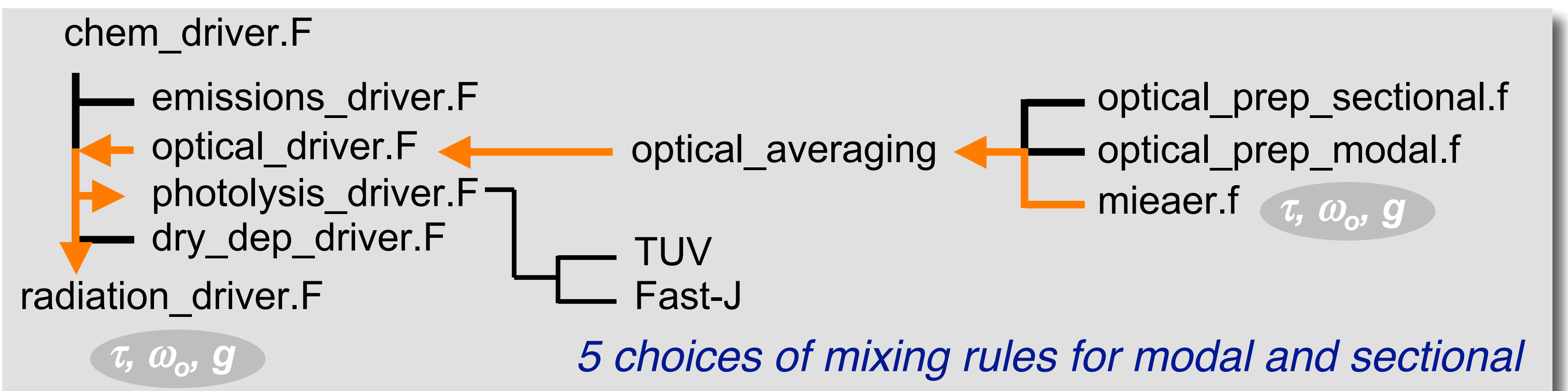
Coding Structure

Aerosol Optical Properties in WRF-chem v2.2



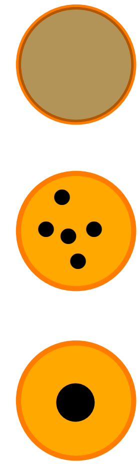
More Generic Aerosol Optical Properties for WRF-chem v3



Example of making the code more generic and interoperable

Choice of Mixing Rule

- **Volume Averaging**
  - averaging of refractive indicies based on composition
- **Maxwell-Garnett** [*Borhren and Huffman, 1983*]
  - small spherical randomly distributed in particle
- **Shell-Core** [*Ackermann and Toon, 1983; Borhren and Huffman, 1983*]
  - black carbon core and average of other compositions in shell



- Volume-Averaging and Maxwell-Garnett computed either exactly or approximately (faster)
- Shell-core the most expensive computationally, but presumably the most accurate
- All very sensitive to changes in the amount of black carbon
- *aer_op_opt* in namelist.input:
  - *1 = Volume-Averaging approximate*
  - *2 = Maxwell-Garnett approximate*
  - *3 = Volume-Averaging exact*
  - *4 = Maxwell-Garnett exact*
  - *5 = Shell-Core*

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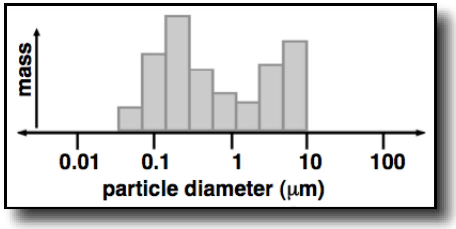
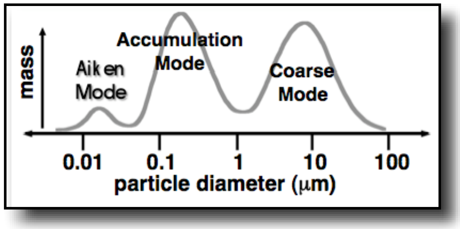
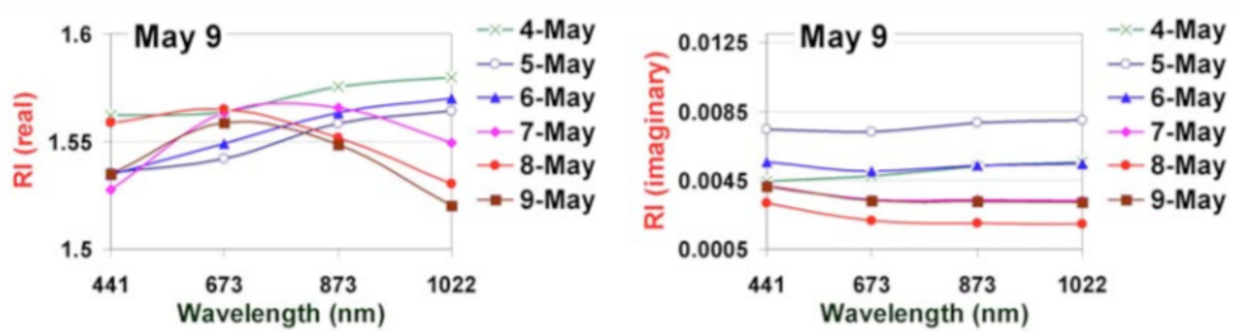
Assumptions

- Interfaces with MADE/SORGAM and MOSAIC only, but modifications needed for other aerosol models should be minor
- **Sectional (MOSAIC):** tested only with 4 and 8 size bins – should work if additional size bins are specified
- **Modal (MADE/SORGAM):** divides mass in modes into 8 sections - could divide into more sections to be more accurate
- Refractive indices may need updating
  - Range of values reported in the literature
  - Do not assume wavelength dependence of refractive indices







from Prasad and Singh, JGR, 2007

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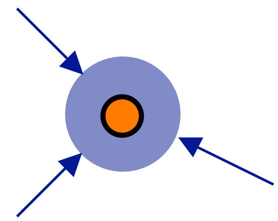
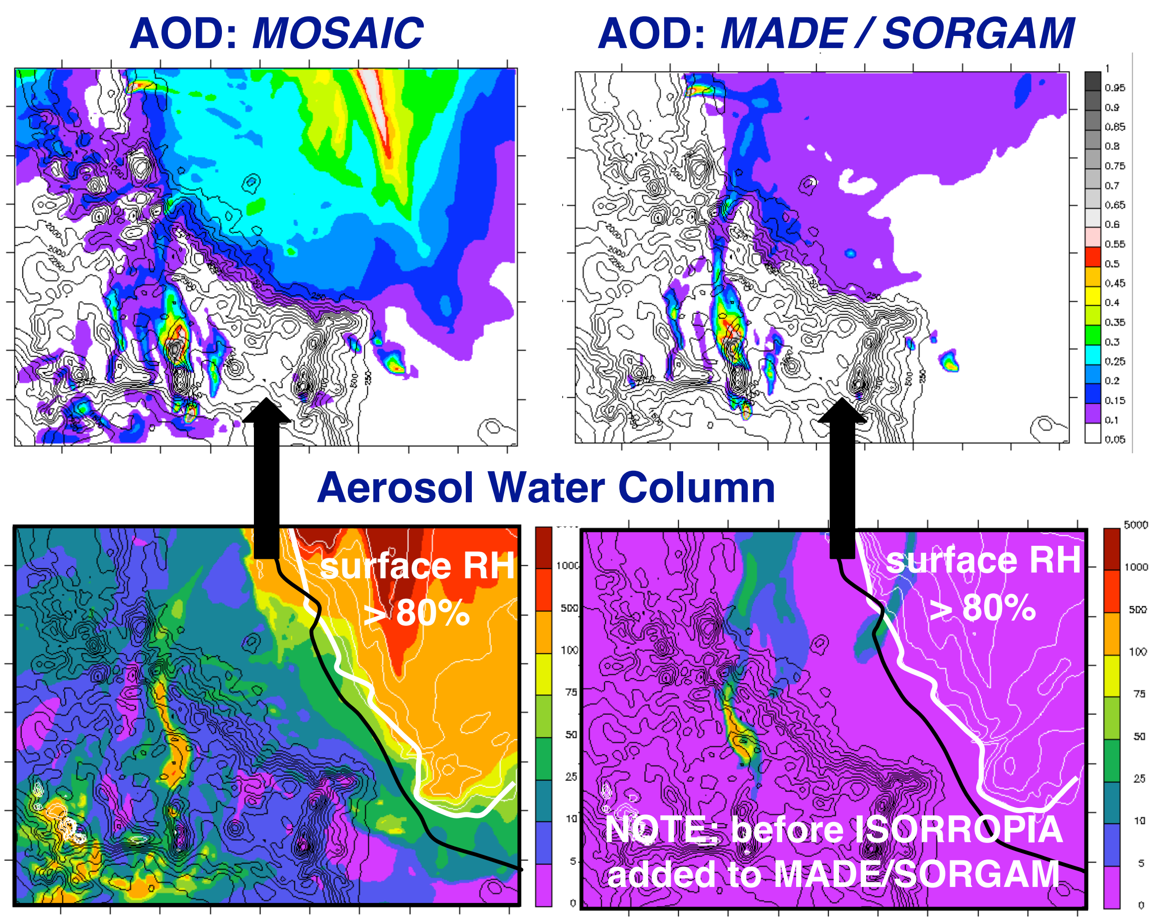
Importance of Aerosol Water

- Amount of aerosol water will have a big impact on τ, ω_o, *and g* that depends on the relative humidity (RH)
- Therefore, predictions of RH need to be monitored when evaluating aerosol direct radiative forcing

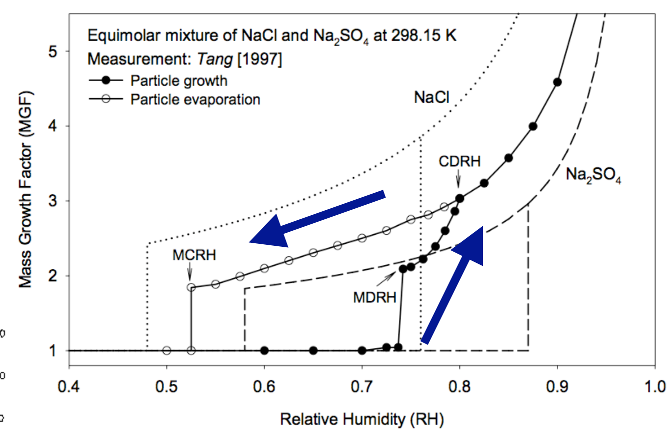




Aerosol Water

MADE / SORGAM: diagnosed

MOSAIC: prognostic specie



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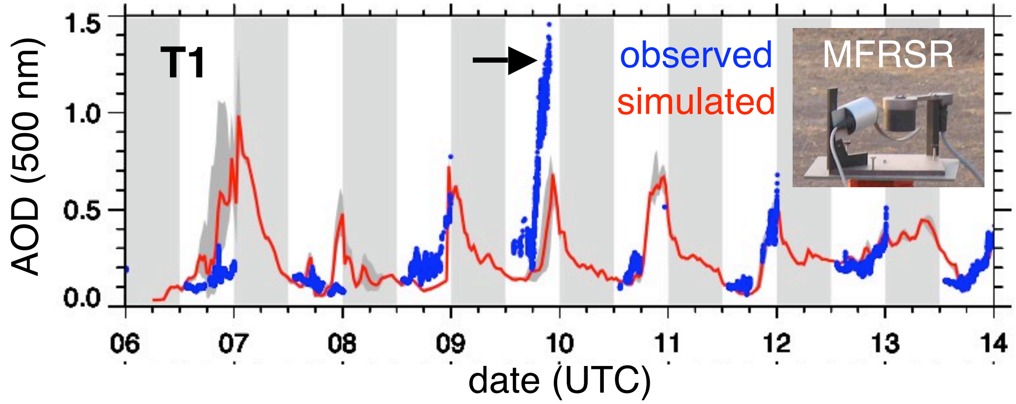
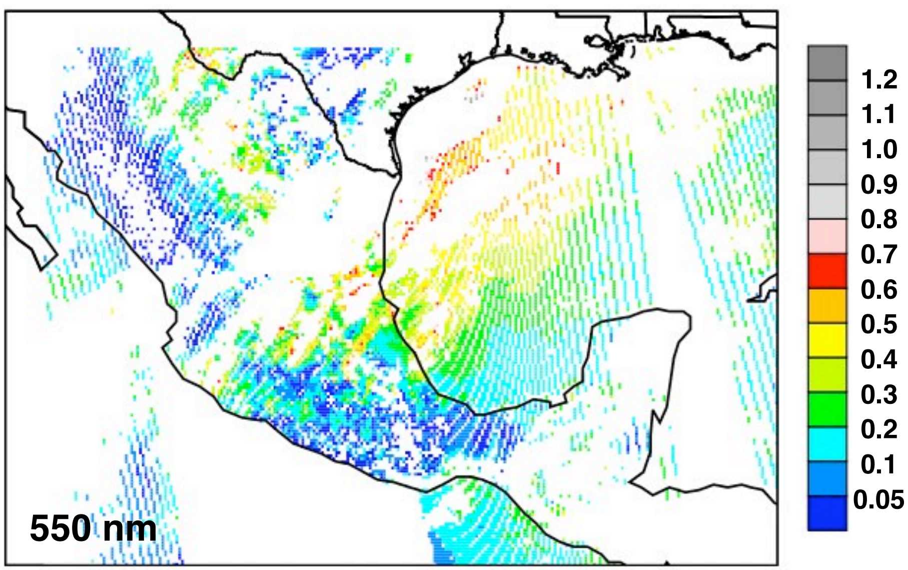
Example 1: AOD

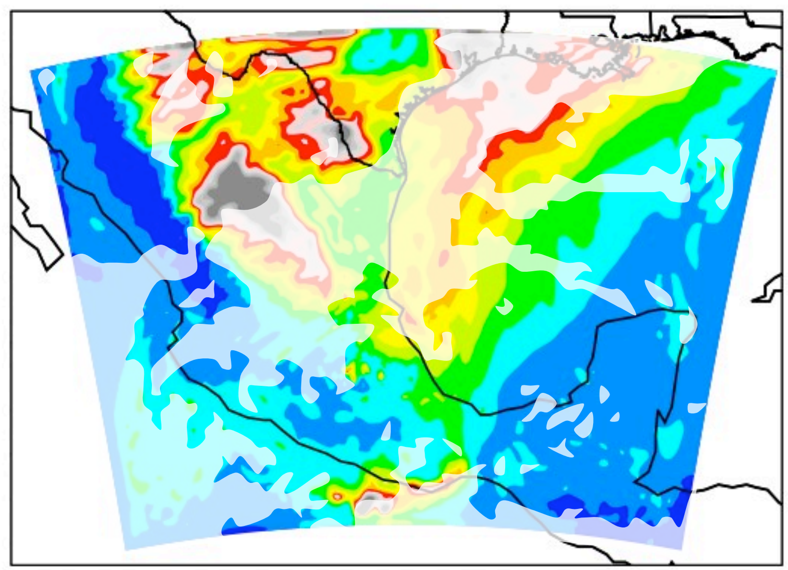
AOD during March 2006 for MILAGRO Field Campaign



MODIS AOD, ~1930 UTC March 10

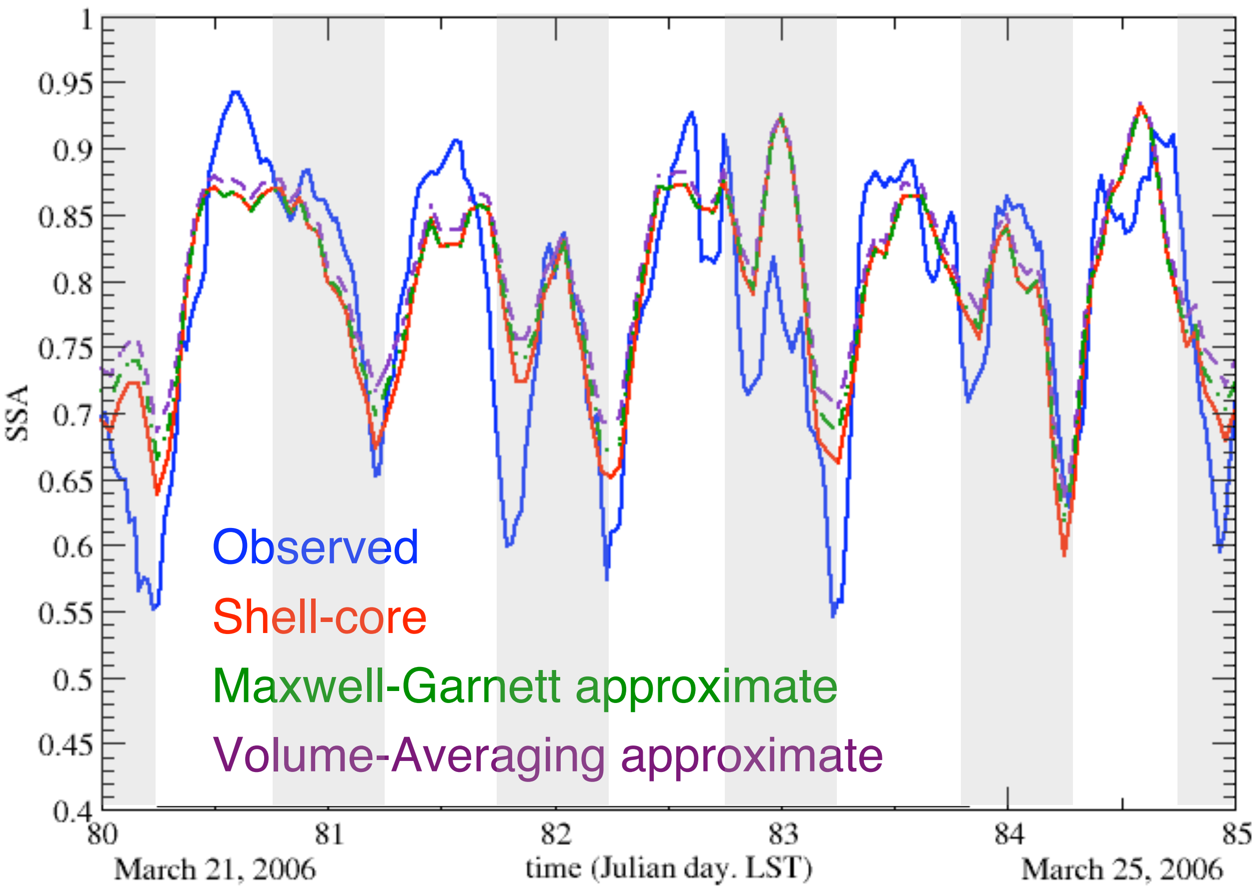


Simulated AOD, 20 UTC March 10



Example 2: SSA

SSA during March 2006 MILAGRO Field Campaign



Offline Version of Aerosol Optical Property Modules in WRF-chem

Aerosol optical property modules driven by measurements of particulate mass, composition, and size distribution

Some uncertainties in measured mass

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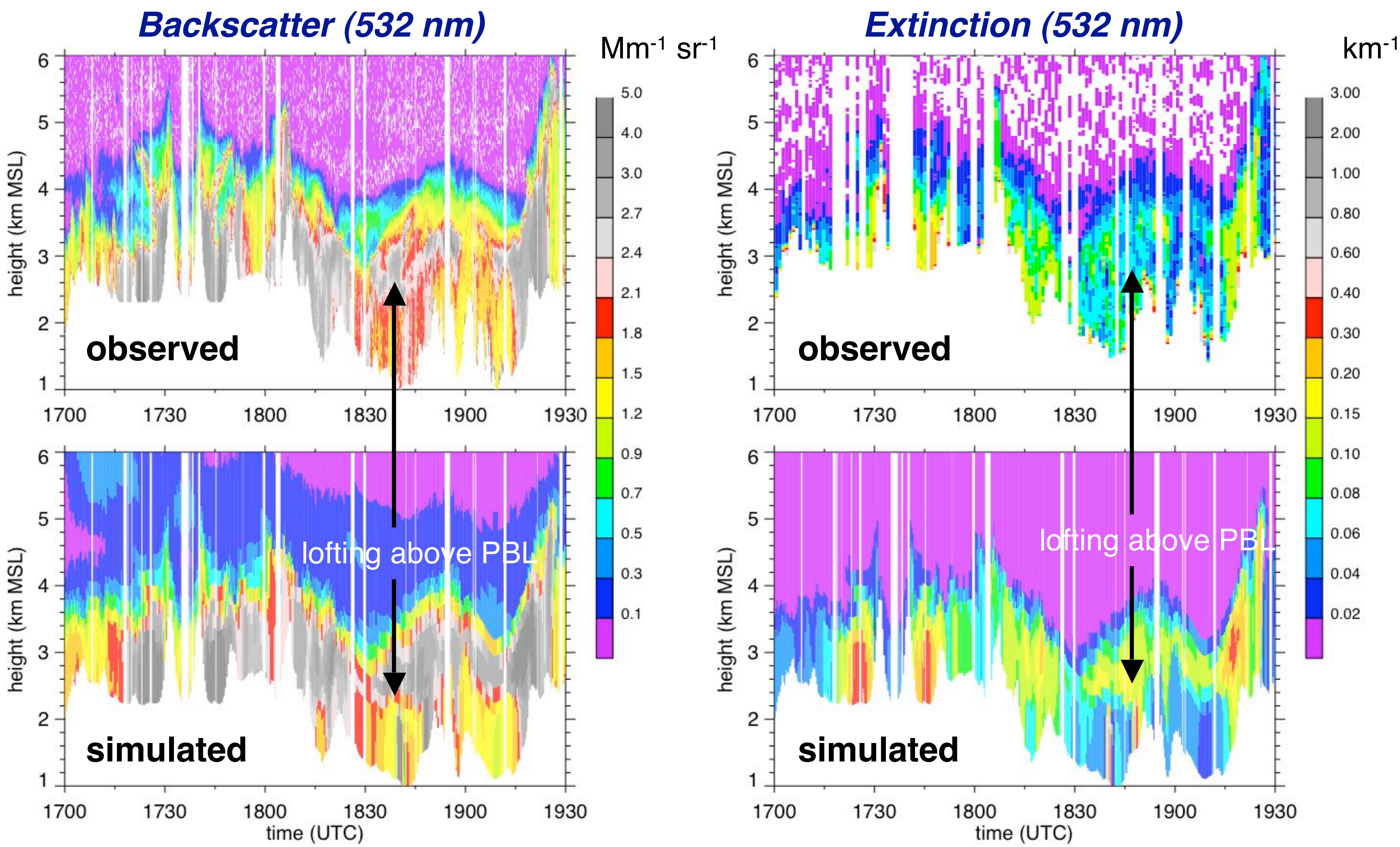
Example 3: Backscatter

NASA B200 Aircraft Flight Path 13 March 2006 during MILAGRO



- Backscatter output new to Version 3: BSCOEF1 – 4 in Registry

Settings in namelist.input

- *ra_physics* = 2, affects only radiation computed by Goddard scheme
- *aer_ra_feedback* = 1, turns on aerosol radiation feedback
- *aer_op_opt* = > 0, define the mixing rule for Mie calculations
- Works for either MADE/SORGAM and MOSAIC options

Coming Soon:

- Adapt CAM scheme (*ra_sw_physics = 3*) by replacing τ, ω_o, and g computed from off-line monthly averaged aerosols with on-line values
- Wavelength dependence of refractive indices

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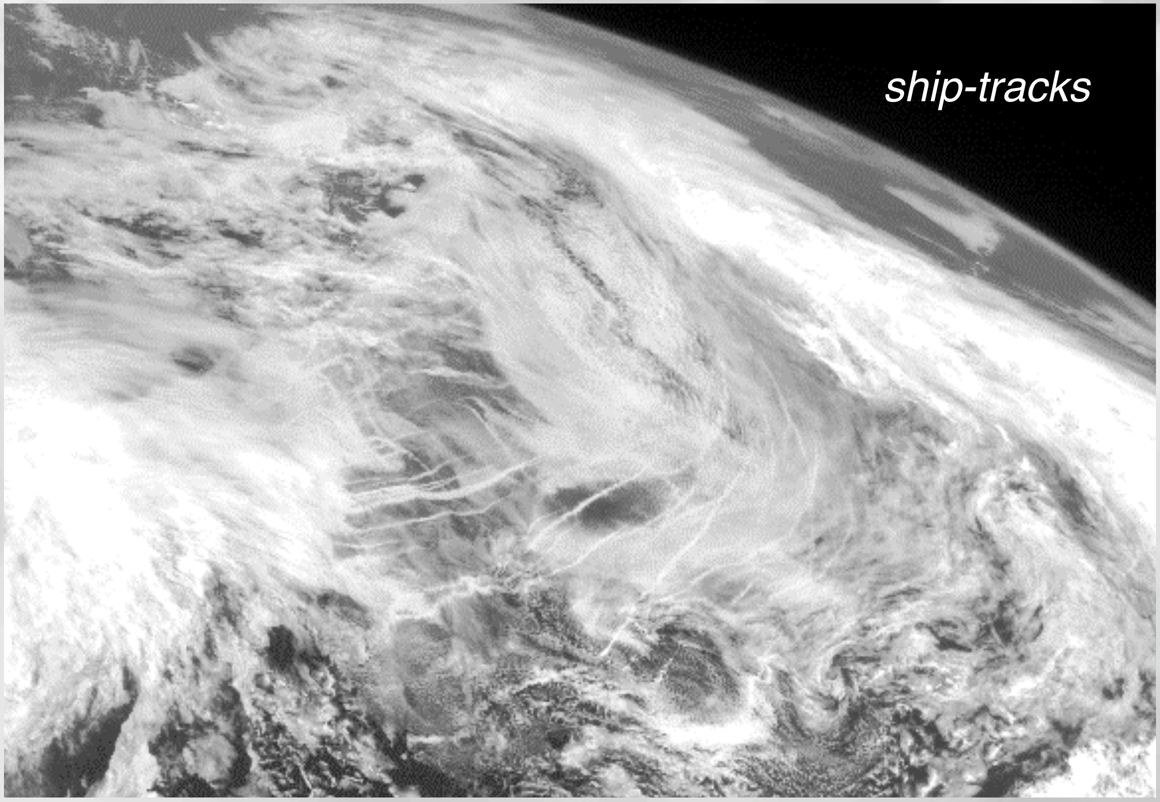
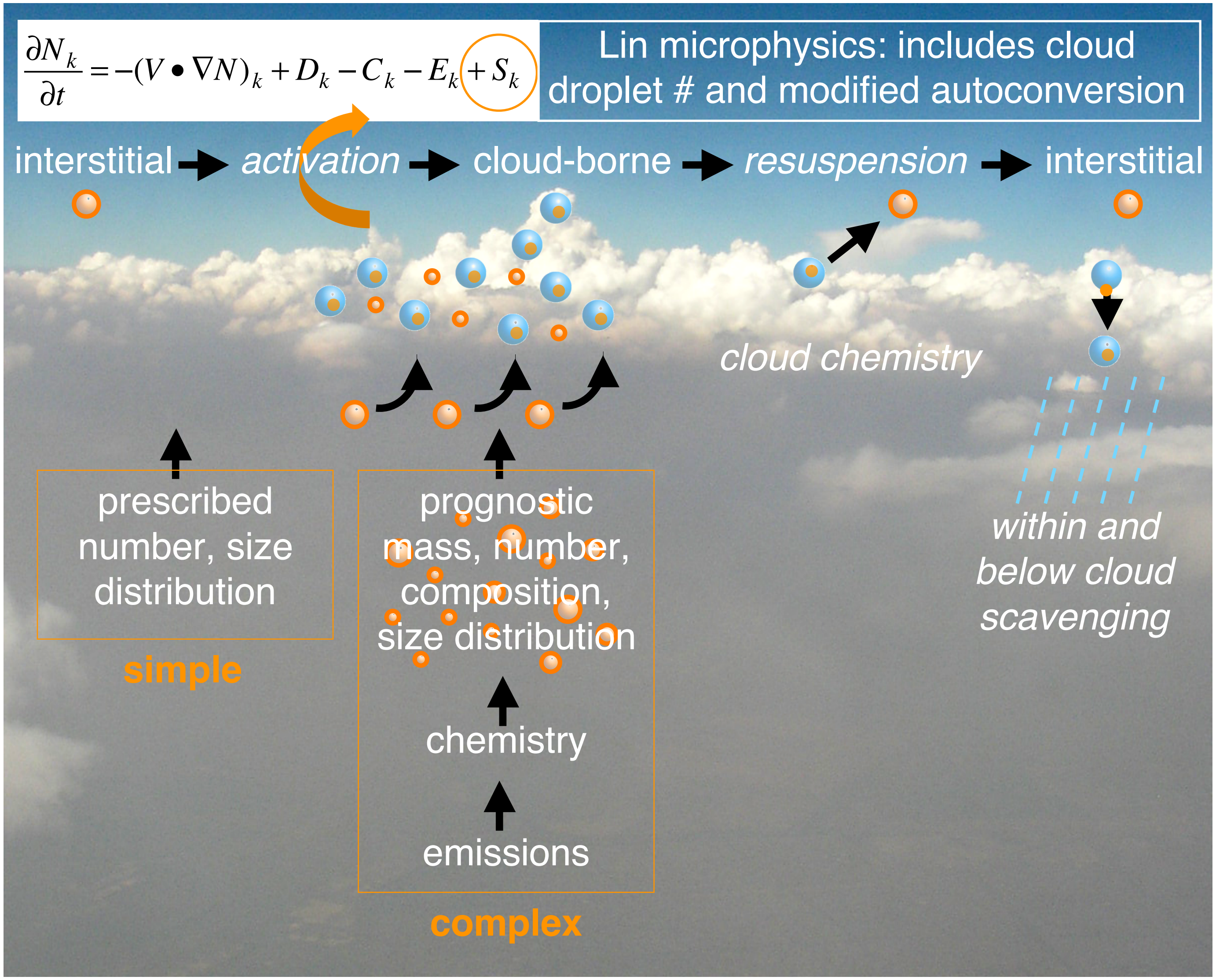
Part 2: Aerosol Indirect Forcing

Aerosols - Clouds - Radiation



Cloud-Aerosol Interactions

General Description and Assumptions



Simple:

- chem_opt = 0
- progn = 1
- naer = specified
- mp_physics = 2
- ra_sw_physics = 2

Complex:

- chem_opt = 9 or 10
- progn=1
- naer = ignored
- mp_physics = 2
- ra_sw_phycis = 2

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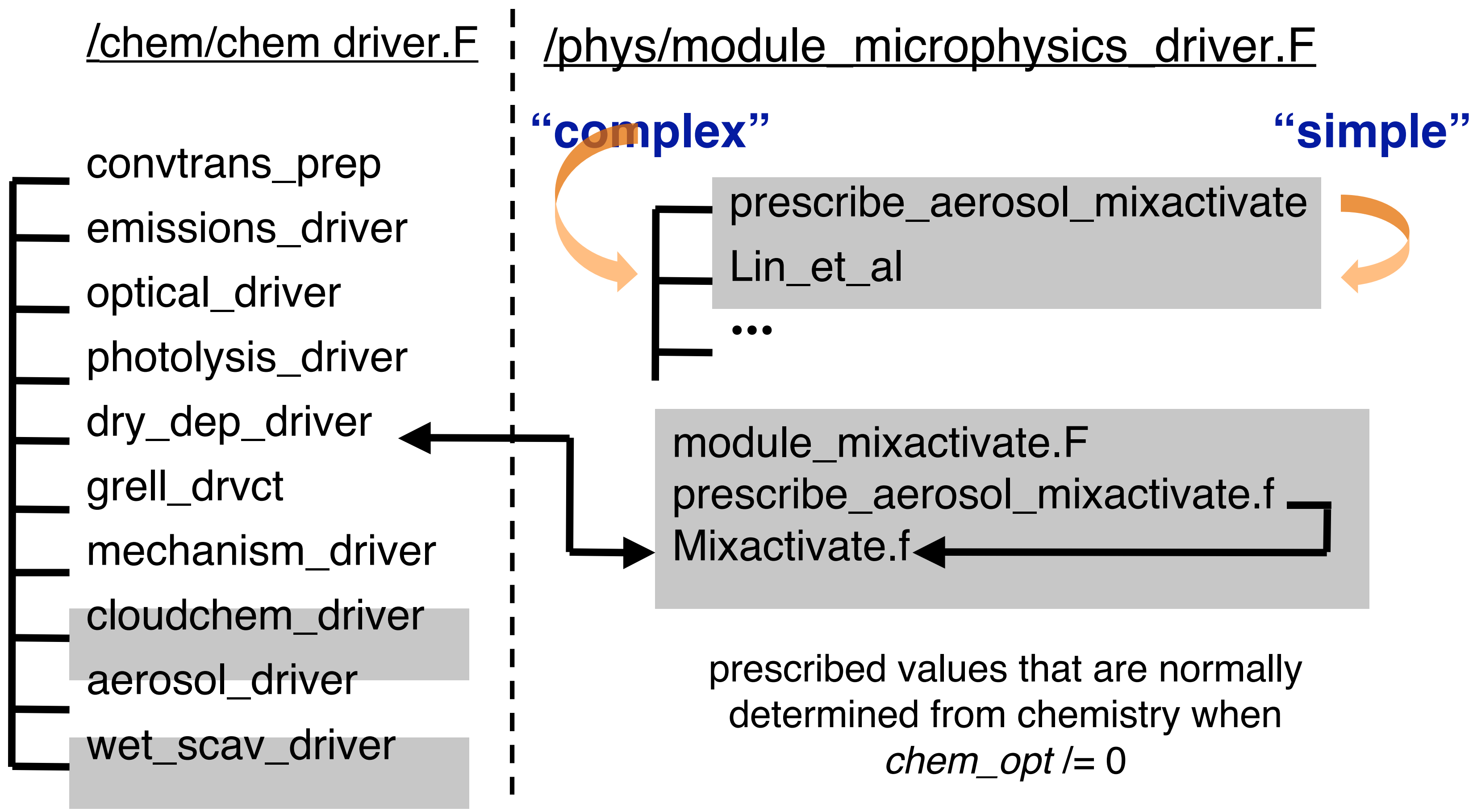
Flow chart



When chemistry turned on, arrays for cloud droplet number, cloud droplet number source, and CCN passed between /chem and /phys directories

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Cloud Droplet Number

- converted Lin et al. microphysics scheme (*mp_physics=2*) to a two-moment treatment (mass & number)

$$\frac{\partial N_k}{\partial t} = -(V \bullet \nabla N)_k + D_k - C_k - E_k + S_k$$

qndrop → N_k - grid cell mean droplet number mixing ratio in layer k

D_k - vertical diffusion

C_k - droplet loss due to collision/coalescence & collection

E_k - droplet loss due to evaporation

qndropsource (nsource) → S_k - droplet source due to nucleation (determined in mixactivate.f)

- cloud droplet number source determined by aerosol activation (for meteorology-only runs a prescribed background aerosol size distribution is used)
- droplet number and cloud water mixing ratio used to compute effective cloud-particle size for the cloud optical depth in Goddard shortwave radiation scheme (*ra_sw_physics=2*)

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Activation

- Hygroscopic properties depend on particulate composition:
  - hygro_so4_aer = 0.5
  - hygro_no3_aer = 0.5
  - hygro_nh4_aer = 0.5
  - hygro_oc_aer = 0.14 → *some OC is hygrophilic – subject of research*
  - hygro_bc_aer = 1.0e-6 *hygrophobic*
  - hygro_oin_aer = 0.14
  - hygro_ca_aer = 0.1
  - hygro_co3_aer = 0.1
  - hygro_msa_aer = 0.58
  - hygro_cl_aer = 1.16
  - hygro_na_aer = 1.16 *hygrophilic*
- Hygroscopicity used in activation determined by volume weighted bulk hygroscopicity, prior to the call to mixactivate.f, and total aerosol number
- For *chem_opt* = 0 and *nprog* = 1, hygroscopicity set to 0.5

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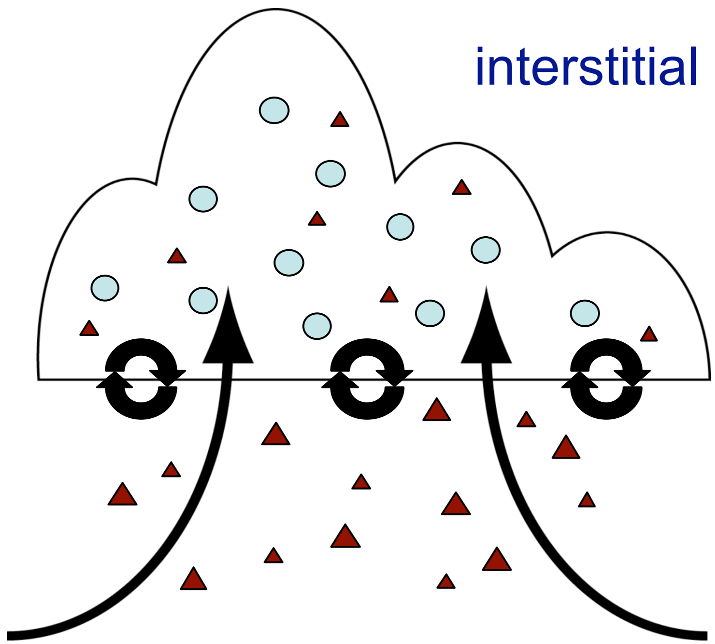
Activation and Resuspension (1)

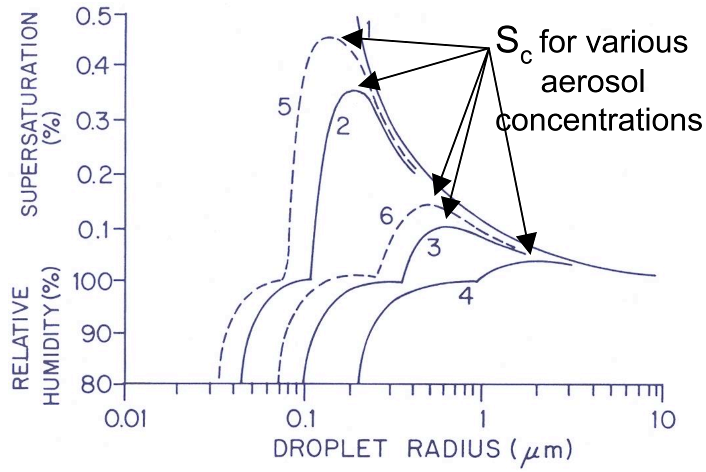
activation / *resuspension*

interstitial → cloud-borne → interstitial



Aerosol particles activated when the environmental supersaturation in the air "entering cloud", S, exceeds the aerosol particle's critical supersaturation, S_c

Köhler Curves



1: pure H_2O
2: 10^{-19} kg NaCl
3: 10^{-18} kg NaCl
4: 10^{-17} kg NaCl
5: 10^{-19} kg $(NH_4)SO_4$
6: 10^{-18} kg $(NH_4)SO_4$

S_c, depends on aerosol size and composition

Activation and Resuspension (2)

Aerosol Species

- interstitial and cloud-borne aerosol particles treated explicitly, nearly doubling the number of transported species

interstitial	*activation* →	cloud-borne	*resuspension* →	interstitial
so4_a01		so4_cw01		so4_a01
so4_a02		so4_cw02		so4_a02
…		…		…
no3_a01		no3_cw01		no3_a01
no3_a02		no3_cw02		no3_a02
…		…		…
num_a01		num_cw01		num_a01
num_a02		num_cw02		num_a02
8 bins x 12 species + hysw + water = 112		8 bins x 12 species = 96		

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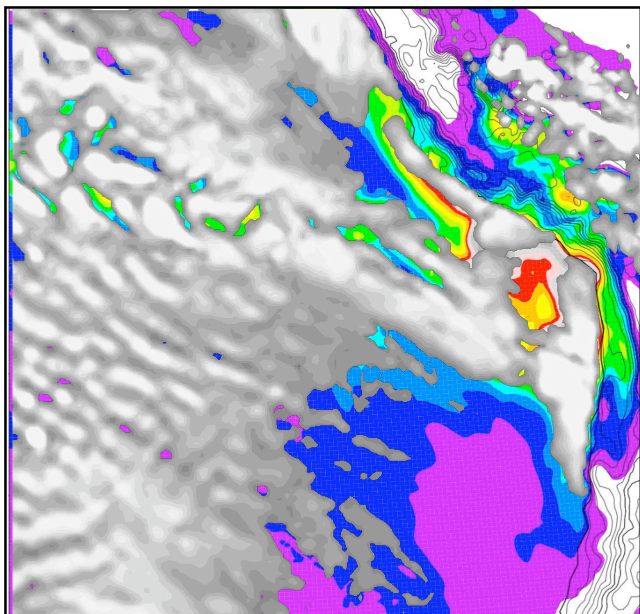
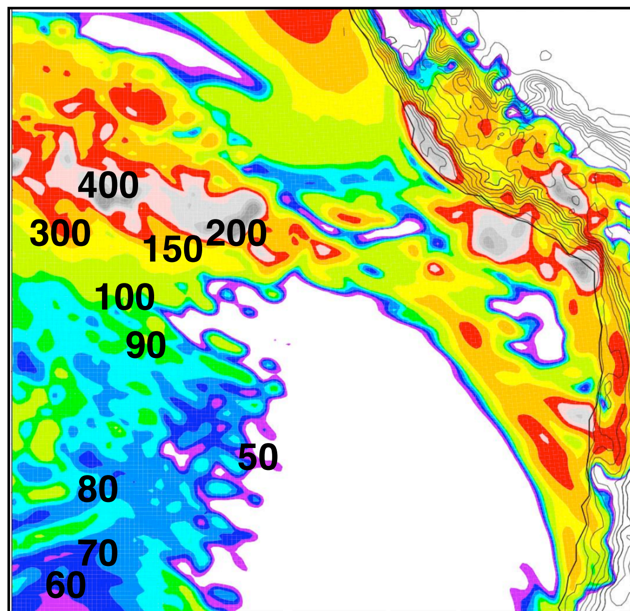
Cloud Condensation Nuclei

- CCN: number concentration of aerosols activated at a specified super-saturation
- Diagnostic quantity, but varies in space and time since particulates and humidity varies
- Computed at 6 super-saturations (.02, .05, .1, .2, .5, and 1%) that correspond to *CCN1, CCN2, CCN3, CCN4, CCN5, CCN6* in Registry
- Computed in module_mixactivate.F

AOD (600 nm) and COD



CCN at 0.1% SS (# cm^{-3})



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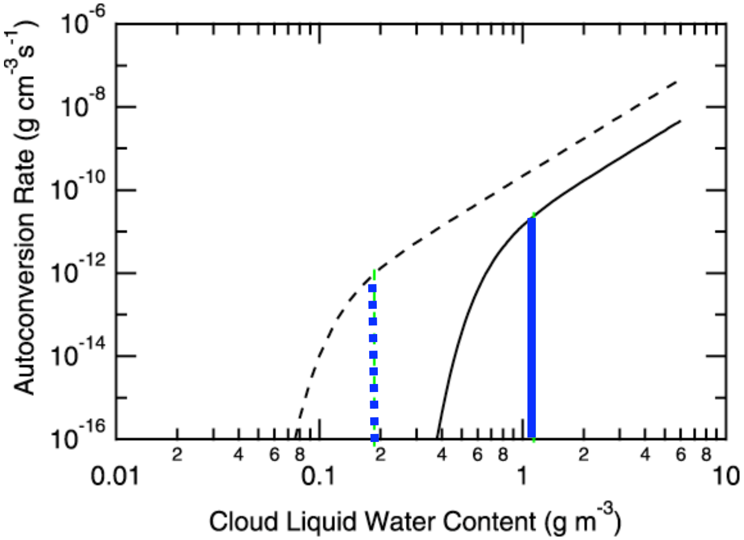
Autoconversion

- autoconversion = coalescence of cloud droplets to form embryonic rain drops
- replaced autoconversion parameterization employed by Lin et al. microphysics (*mp_physics=2*) with *Liu et al.* [2005] parameterization
  - adds droplet number dependence
  - physically based w/o tunable parameters



Black: New Liu et al. parameterization

Blue: Kessler-type parameterization, similar to default Lin et al. scheme

Dashed: N = 50 cm^{-3}

Solid: N = 500 cm^{-3}

Adapted from Fig. 3, Liu et al., 2005, GRL.

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Aqueous Chemistry

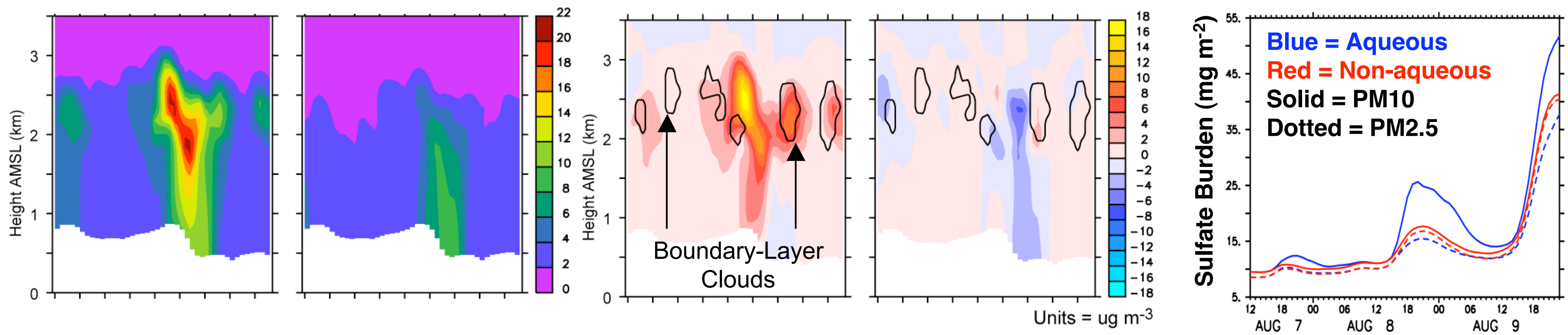
- Bulk cloud-chemistry module of *Fahey and Pandis* [2001]
- Oxidation of S(IV) by H_2O_2, O_3, trace metals, and radical species
- Non-reactive uptake of HNO_3, HCl, NH_3, and other trace gases
- Bulk mass changes partitioned among cloud-borne aerosol size bins, followed by transfer of mass & number between bins due to growth

Vertical Cross-Section Though Power Plant SO_2 Plume

SO_4, Aqueous Chemistry Simulation — **< 10 µm**, **< 2.5 µm**

SO_4 Difference (Aqueous - Non-Aqueous) — **< 10 µm**, **< 2.5 µm**

Average Sulfate Burden Over Domain



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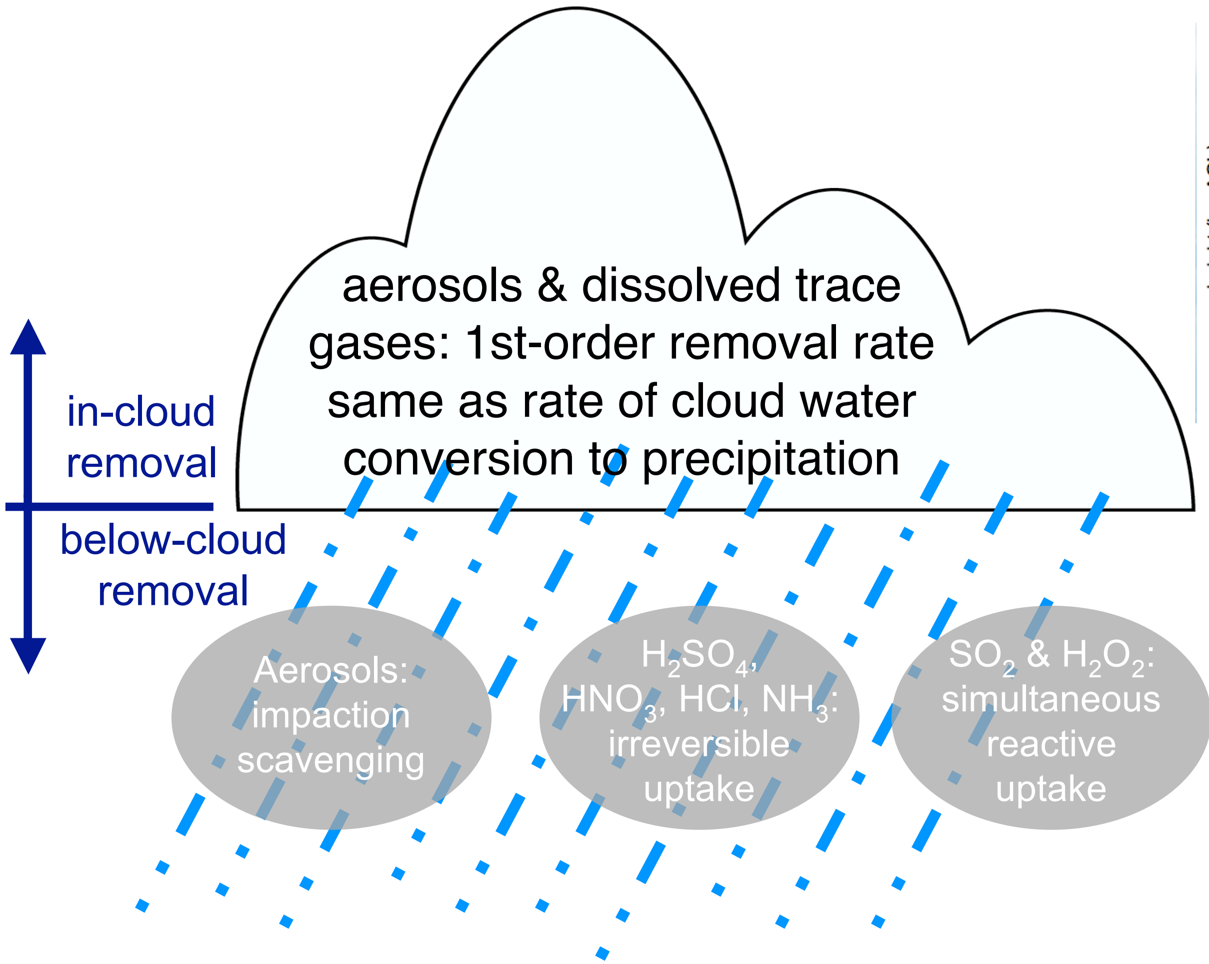
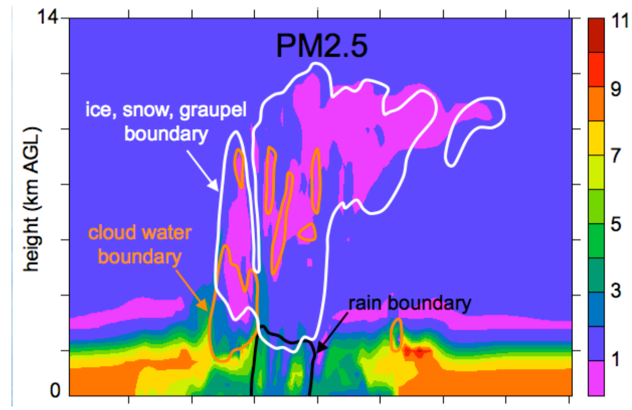
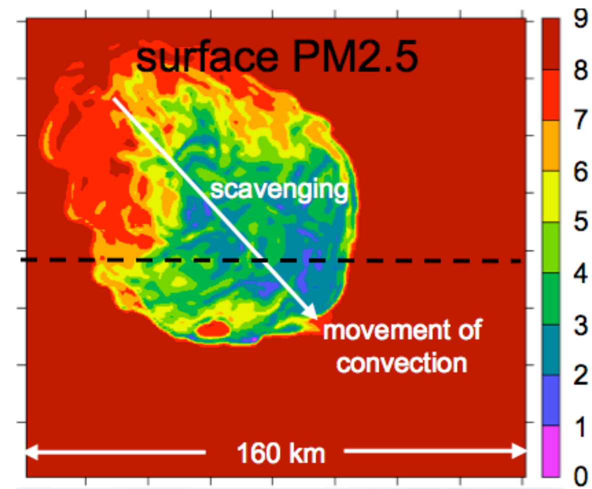
Scavenging



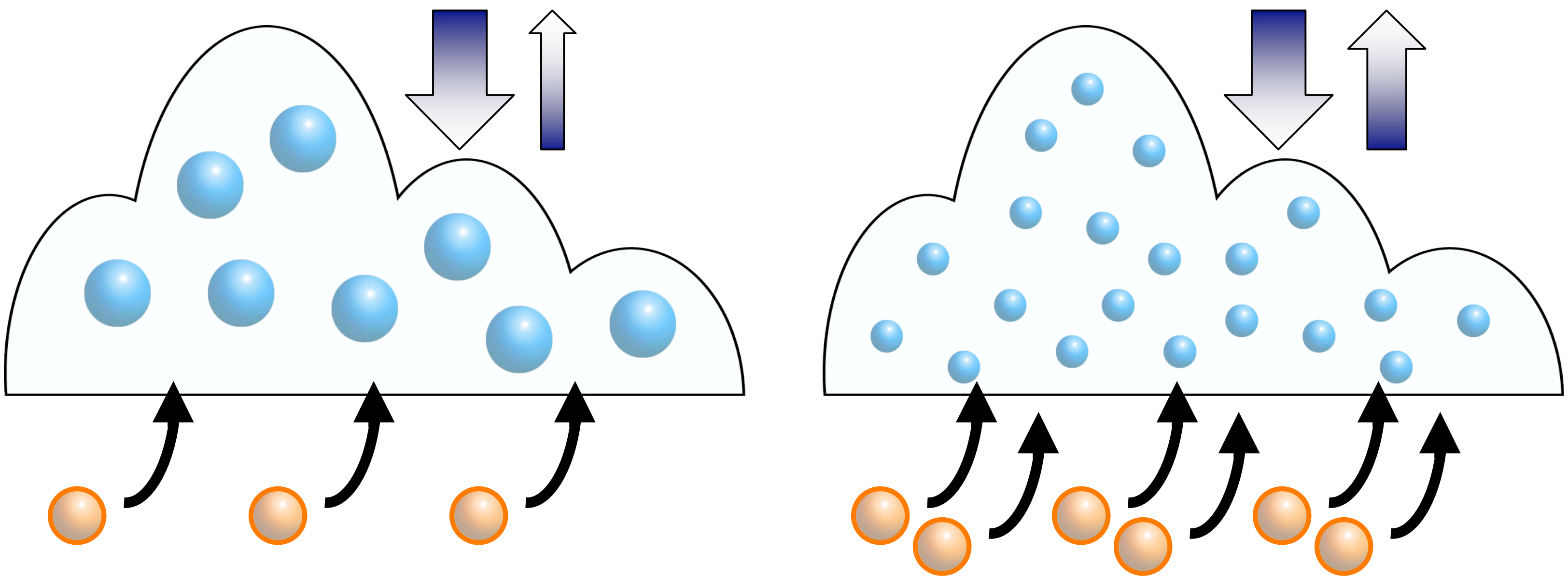




scavenged aerosols and gases are assumed to be instantly removed (wet deposited)

First Indirect Effect

- Influence of cloud optical depth through impact on effective radius, with no change in water content of cloud



'clean' **'polluted'**

qndrop → gsfcwrad.f → reff → sorad.f → taucld

module_ra_gsfcsw.F effective radius

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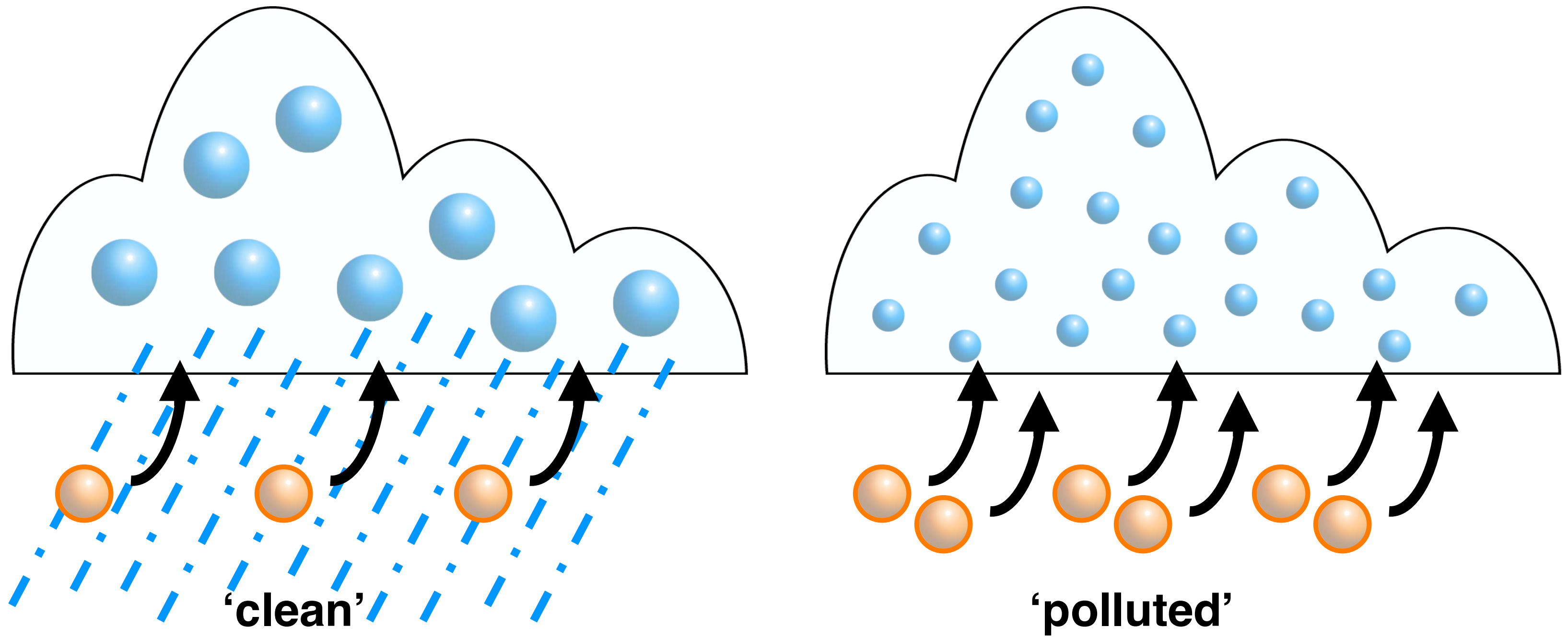
Second Indirect Effect

- Influence of cloud optical depth through influence of droplet number on mean droplet size and hence initiation of precipitation



qndrop → cldphy_1d.f → praut → qr → precr

module_mp_lin.F — autoconversion rate — rain mixing ratio — precipitation rate

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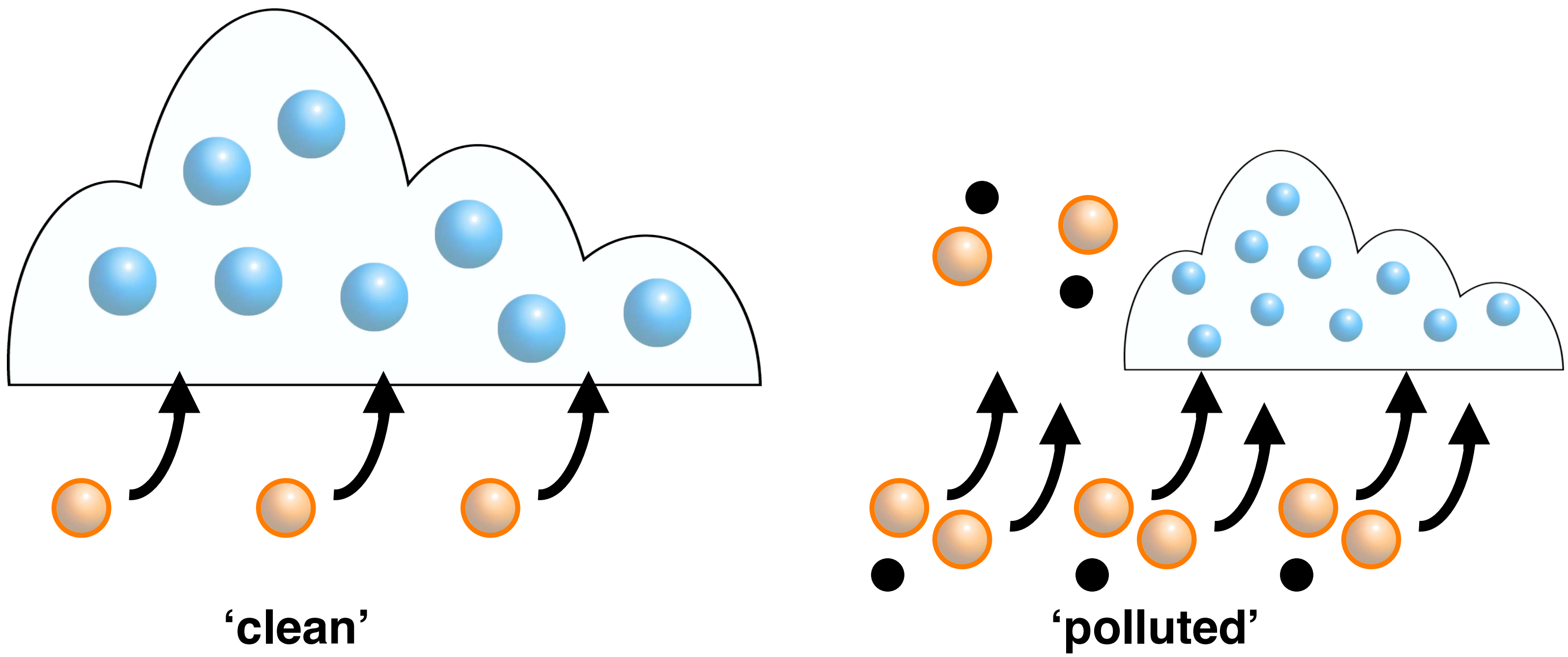
Semi-Direct Effect

- Influence of aerosol absorption of sunlight on cloud liquid water and hence cloud optical depth



τ, ω_o, g → gsfcwrad.f → sorad.f → flx → ttend2d → θ tendency

module_ra_gsfcsw.F (under gsfcwrad.f)

solar uv and ir fluxes (under flx)

heating rate (under ttend2d)

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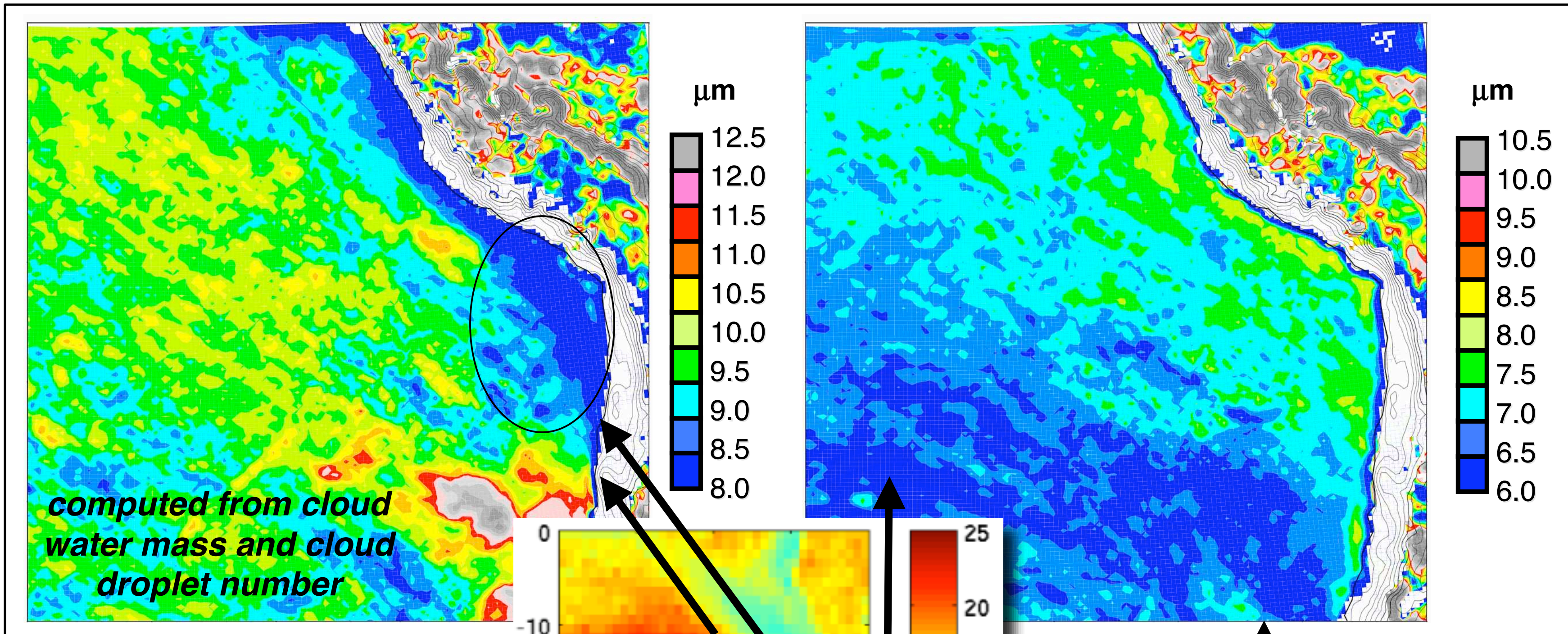
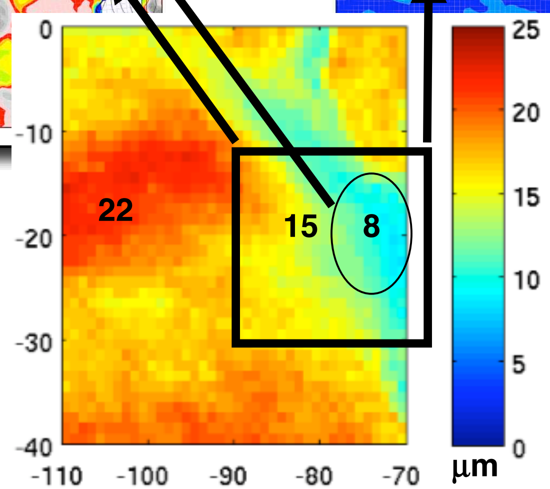
Example: Effective Radius

October 2006 Average at 12 UTC

Full Chemistry Simulation ***Prescribed Aerosol # Simulation***





depends on # chosen !

Mean MODIS Cloud Droplet Effective Radius October 2006

from Matthew Wyant (UW)

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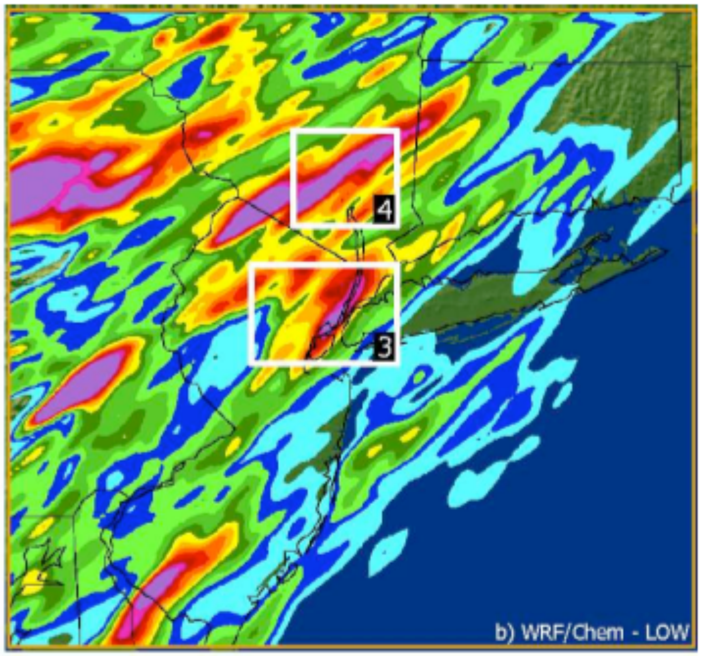
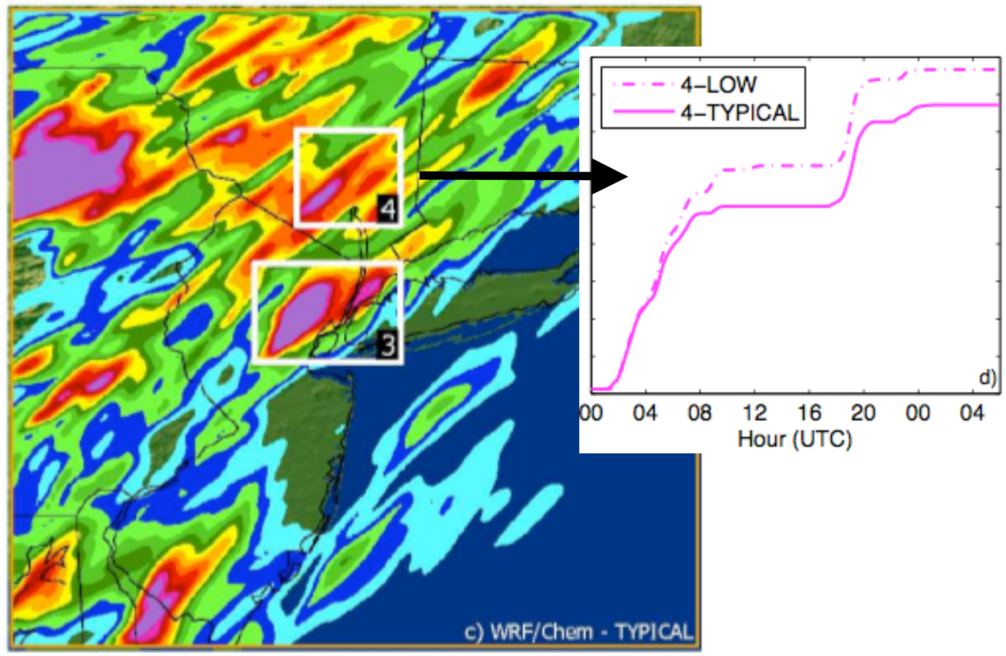
Example: Deep Convection

Impact of Particulates on Convective Precipitation Along the Urban East Coast Corridor

WRF-chem: low emissions



WRF-chem: typical emissions



- Ntelekos, A., J.A. Smith, L. Donner, J.D. Fast, E.G. Chapman, W.I. Gustafson Jr., and W.F. Krajewski, 2008: The Effects of aerosols on intense convective precipitation in the northeastern U.S. Submitted to *Q. J. Roy. Meteor. Soc.*

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Interactions not Treated

- **First Dispersion Effect:** Influence on cloud optical depth through influence of aerosol on dispersion of droplet size distribution, with no change in water content of cloud
- **Second Dispersion Effect:** Influence on cloud optical depth through influence of aerosol on dispersion and hence initiation of precipitation
- **Glaciation Indirect Effect:** Influence of aerosol on conversion of haze and droplets to ice crystals, and hence on cloud optical depth and initiation of precipitation

(Ice processes are a current research topic for PNNL team)

pointer system already in place to handle ice-borne species

so4_a01	so4_cw01	so4_ci01
so4_a02	so4_cw02	so4_ci02
…	…	…
num_a01	num_cw01	num_ci01
num_a02	num_cw02	num_ci02

Settings in namelist.input

Simple:

- *chem_opt* = 0
- *naer* = specified value

Complex:

- *chem_opt* = 9 or 10, cloud-phase aerosols only for MOSAIC
- *cldchem_onoff* = 1, turns on cloud chemistry
- *wetscav_onoff* = 1, turns on wet scavenging

Both:

- *mp_physics* = 2, cloud-aerosol interactions only for Lin scheme
- *progn* = 1, turns on prognostic cloud droplet number

Coming Soon:

- *chem_opt* = 11 or 12, cloud-phase aerosols for MADE/SORGAM
- *mp_physics* = 8, cloud-aerosol interactions for Thompson scheme

Comparing Options

Care must be taken in quantifying direct and indirect effects

- **Direct effect:**
  - Run with *aer_ra_feedback* on versus off
  - Add code to output clean-sky and dirty-sky from the same run
- **Indirect effects:**
  - Comparing a *chem_opt* = 8 with a *chem_opt* = 10 run <u>does not</u> quantify the indirect effect since the autoconversion scheme used in the Lin scheme will be different
  - Have to determine a prescribed aerosol scenario to compare with chem_opt=10 – see [*Gustafson et al.*, GRL, 2007]
  - An approach used with GCMs is to output dirty-cloudy, dirty-clear, clean-cloudy, and clean-cloudy radiation from the same run

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References

WRF-chem Papers Describing Aerosol-Radiation-Cloud Interactions

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<u>Additional details included in cited papers</u>

(More on the way regarding performance during MILAGRO field campaign)

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