Aerosol modeling with WRF-Chem

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WRF-Chem Tutorial, 29 January 2018

Part I - Introduction

- Overview of ...
  - Aerosol
  - Aerosol processes and life cycle
  - Model treatment of aerosol
  - WRF-Chem aerosol schemes

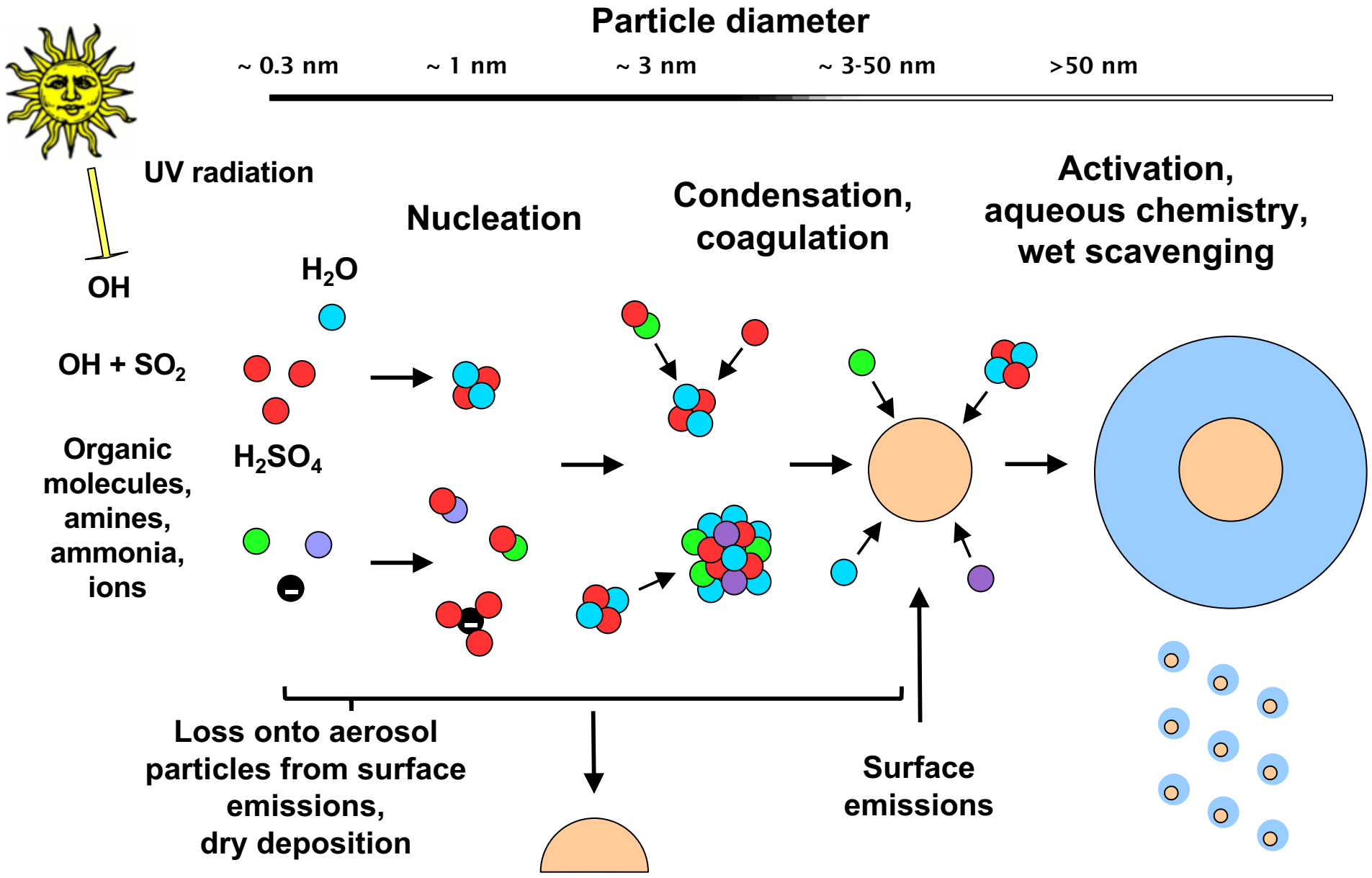
Part II – The details

- Representing the aerosol size distribution
- Walk through the WRF-Chem aerosol schemes
  - How they work and what they do
  - Coupling to other processes
    - Gas phase chemistry
    - Aqueous chemistry
    - ...
- Hint on how to tell WRF/Chem what to do
- Resources

Part I – Introduction

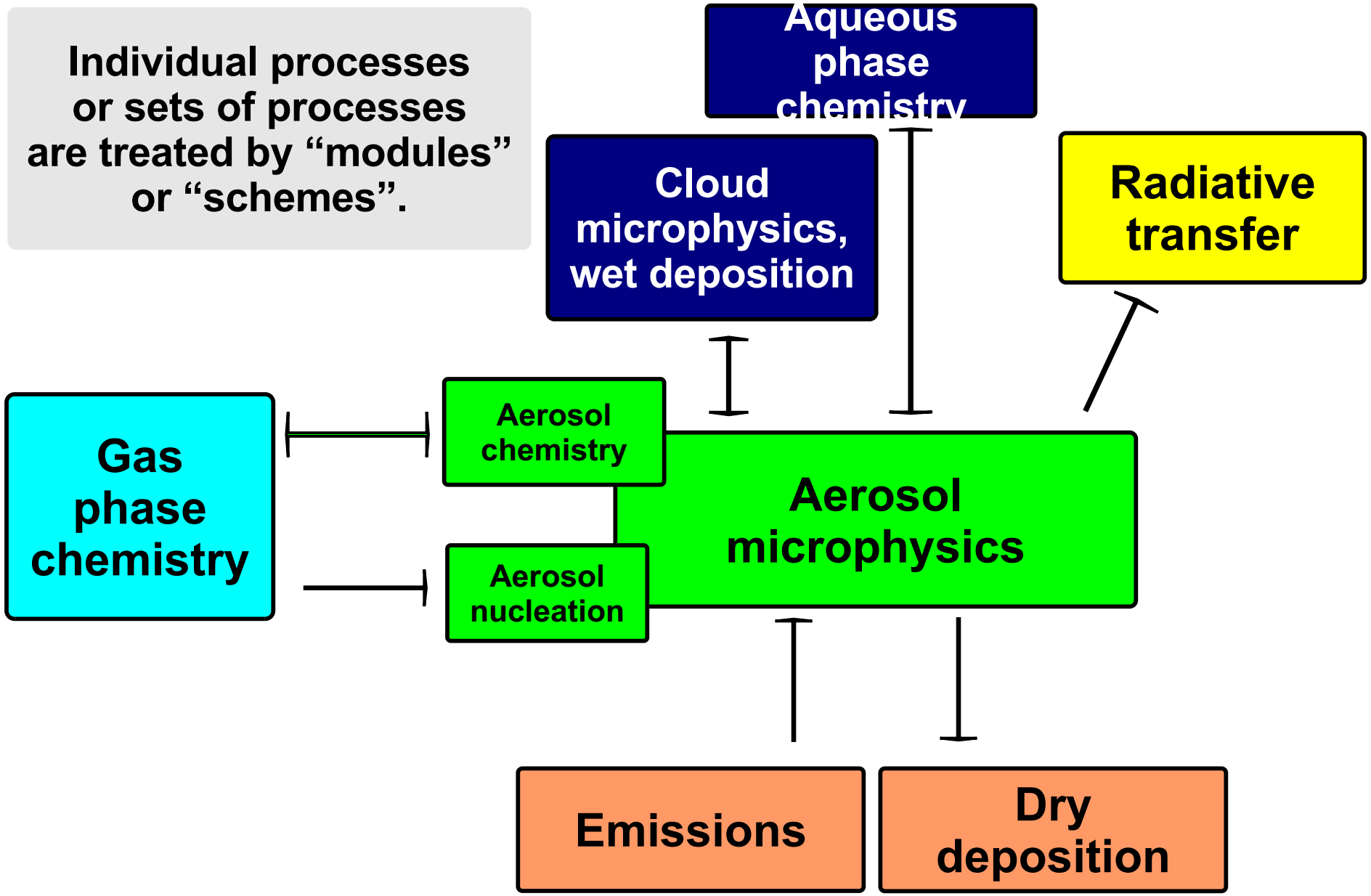
Aerosols

Aerosol life cycle and processes



Model treatment of aerosols

Individual processes or sets of processes are treated by "modules" or "schemes".



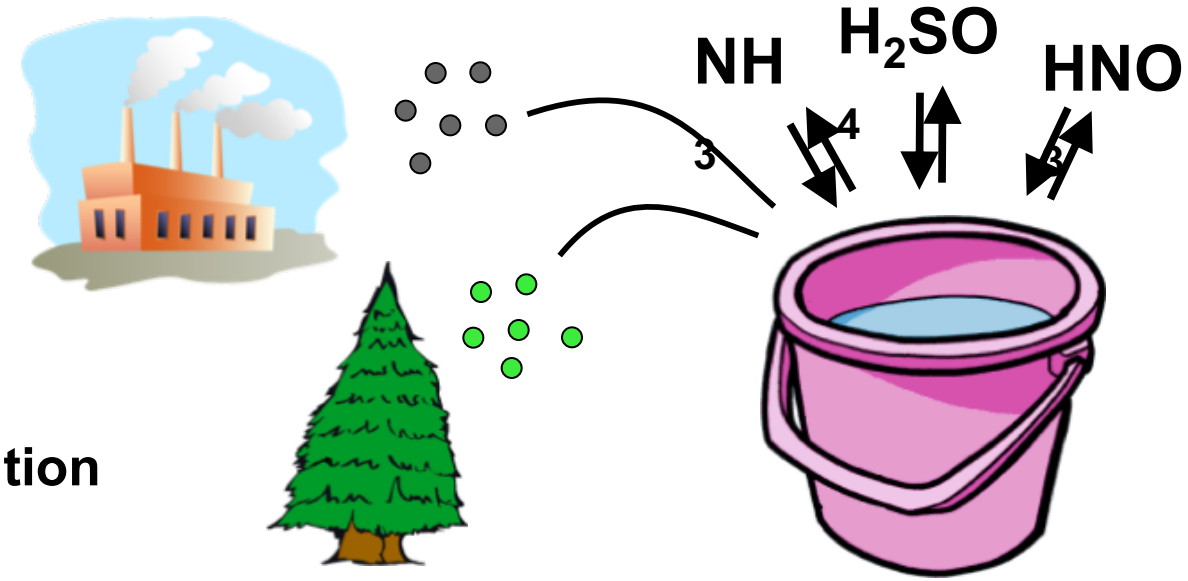
WRF/Chem aerosol schemes

- An efficient aerosol scheme from the GOCART model
  - No size information for sulfate, BC, OC
  - Size information for dust and sea salt
  - No secondary organic aerosol (SOA)
- Modal Aerosol Dynamics Model for Europe – MADE
  - 3 log-normal modes
  - Inorganic, organic aerosols, SOA
- Model for Simulating Aerosol Interactions and Chemistry (MOSAIC)
  - Sectional aerosol scheme, 4 or 8 bins
  - Inorganic, organic aerosols, SOA
- MAM – Modal Aerosol Model from CAM5
  - 3 or 7 log-normal modes
  - Inorganic, organic aerosols, SOA, sea salt, BC, mineral dust
- Simple sectional (bin) scheme for volcanic ash aerosol

Part II – The details

Bulk aerosol schemes

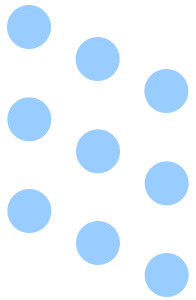
- Only total mass of aerosol compounds is known



- No information on
  - Particle number
  - Aerosol size distribution

Aerosol size distribution needs to be assumed for:

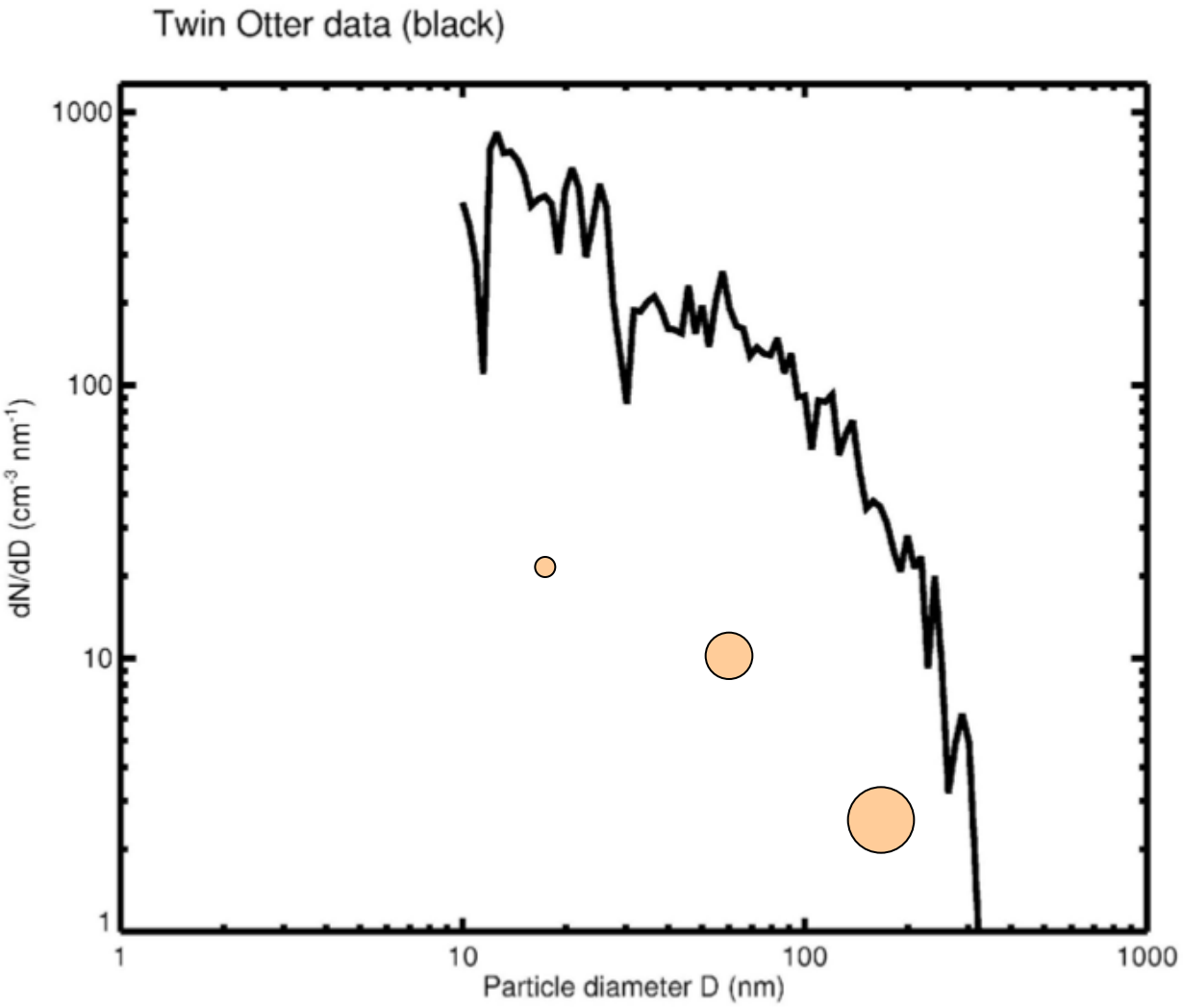
- radiative transfer
- response of cloud properties to aerosol number



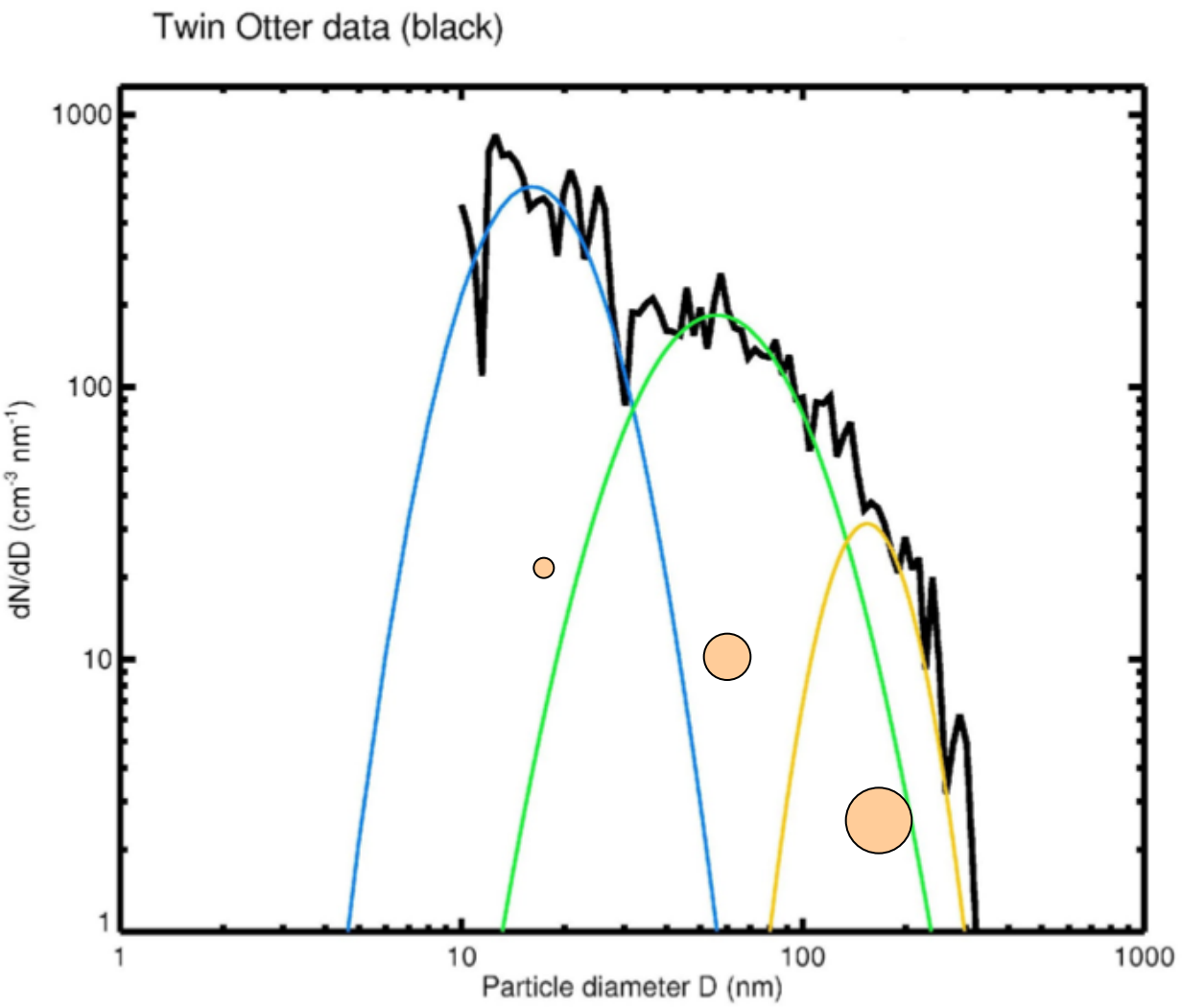
- Numerically efficient
- Useful when focus is on complex gas phase chemistry e.g.

→ **GOCART (+ size resolved dust and sea salt)**

Modal aerosol schemes



Modal aerosol schemes

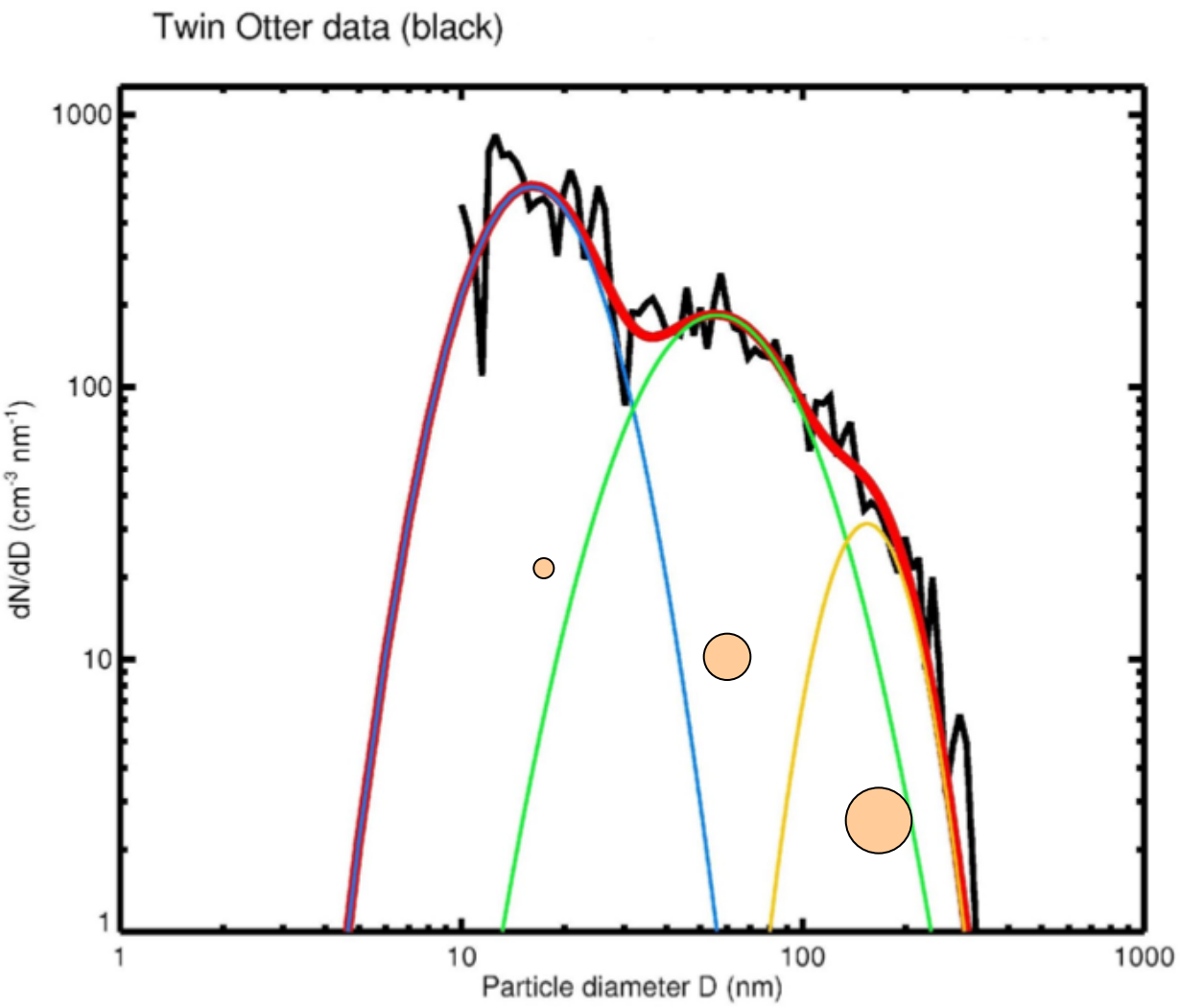


$\frac{dN}{dD}$ → $N = 8195\ cm^{-3}$
$\mu = 18.22\ nm$
$\sigma = 1.42$

$\frac{dN}{dD}$ → $N = 12732\ cm^{-3}$
$\mu = 68.44\ nm$
$\sigma = 1.57$

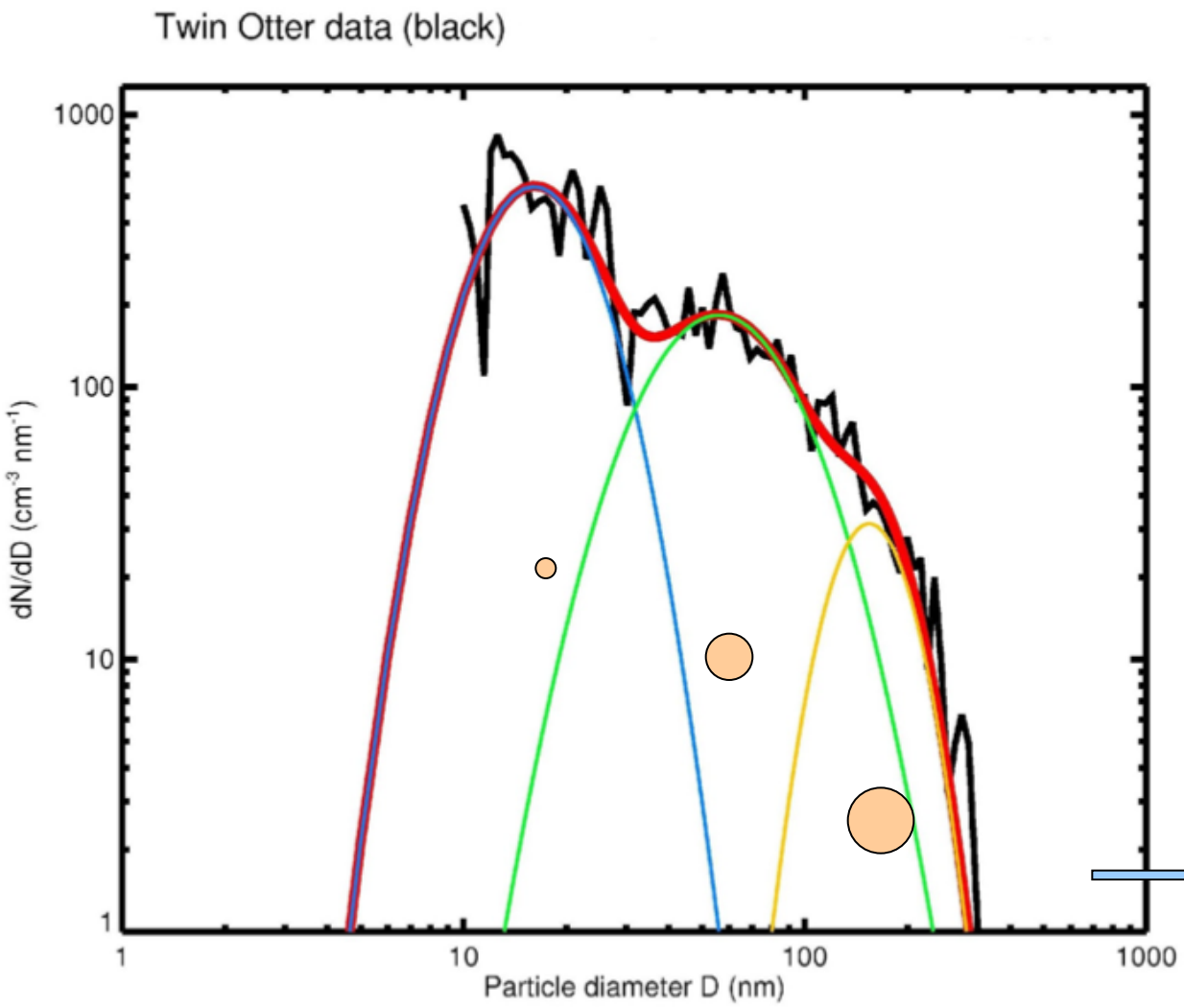
$\frac{dN}{dD}$ → $N = 3140\ cm^{-3}$
$\mu = 164.41\ nm$
$\sigma = 1.28$

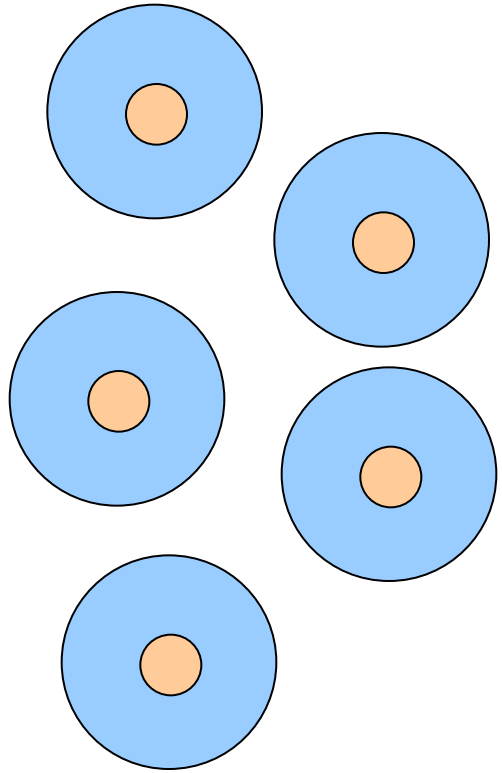
Modal aerosol schemes



$$\frac{dN}{dD} = \frac{dN}{dD} + \frac{dN}{dD} + \frac{dN}{dD}$$

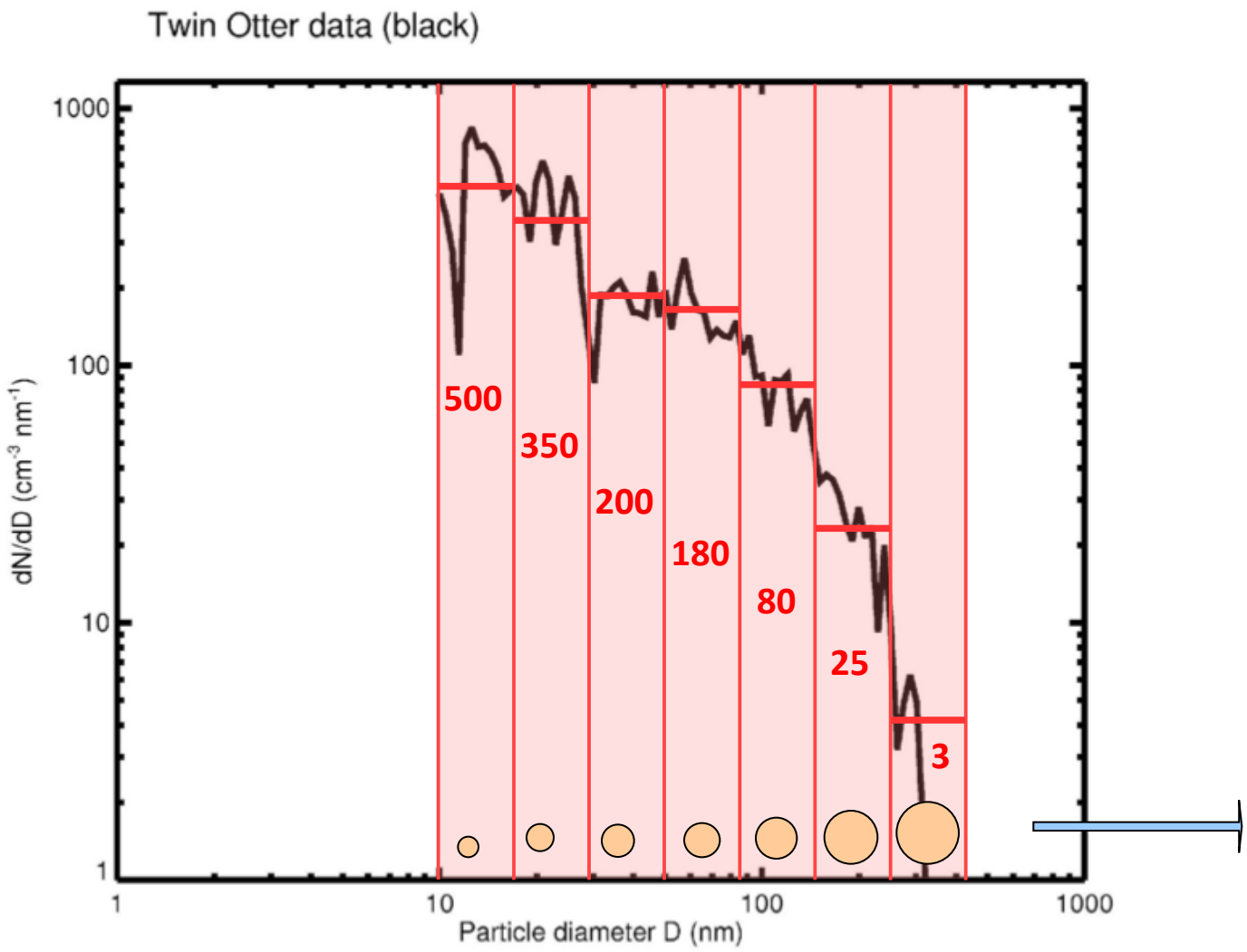
Modal aerosol schemes

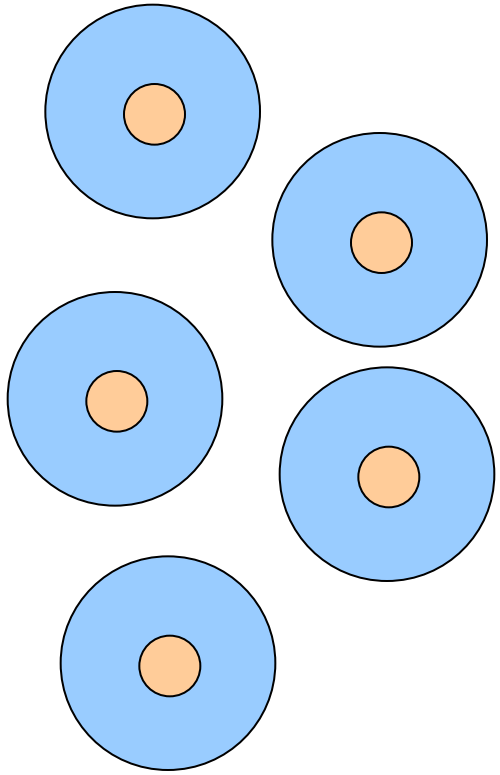




→ **MADE and MAM**

Sectional aerosol schemes





→ **MOSAIC, volcanic ash,**

GOCART aerosol module

- Georgia Tech/Goddard Global Ozone Chemistry Aerosol Radiation and Transport model (Chin et al., JGR, 2000)
  - **Bulk aerosol:**
    - Hydrophobic black carbon (fresh soot)
    - Hydrophilic black carbon (aged/coated soot)
    - Hydrophobic organic carbon (fresh burnt biomass)
    - Hydrophilic organic carbon (aged/coated burnt biomass)
      - Fresh → aged conversion time 2.5 days
    - Other GOCART primary PM2.5
    - Other GOCART primary PM10
    - Sulfate (only secondary aerosol species)
  - **Sectional scheme for dust and sea salt:**
    - Dust: 0.5, 1.4, 2.4, 4.5, 8.0 μm effective radius
    - Sea salt: 0.3, 1.0, 3.2, 7.5 μm effective radius

GOCART aerosol module

GOCART comes with sulfur gas phase chemistry:

- **DMS + OH → SO_2 + ...**
- **DMS + OH → MSA + ...**
- **DMS + NO_3 → SO_2 + ...**
- **SO_2 + OH → $SO_4^=$ + ...**

Extended gas phase chemistry can be used:

- **MOZART (with KPP)**
- **RACM (with KPP)**
- **RADM (with and without KPP)**

GOCART aerosol module

- **Interaction with radiation:**
  - Direct effect for some model setups
  - Effect on photochemistry
- **Interaction with clouds:**
  - Aqueous chemistry
    - $SO_2 + H_2O_2 \rightarrow SO_4^=$
    - $SO_2 + O_3 \rightarrow SO_4^=$
- **No secondary organic aerosol (SOA)**

MADE aerosol module

Modal Aerosol Dynamics Model for Europe

(Ackermann et al., Atm. Env., 1998)

- **3 log-normal aerosol modes: Aitken, accumulation, coarse**
- **Mode width σ is fixed**
- **Aerosol number and mass variable**
- **Interaction with radiation:**
  - **Direct aerosol effect**
  - **Effect on photolysis**
- **Interaction with clouds:**
  - **Aerosol number determines cloud drop number and size**
  - **Radiative response → 1st indirect aerosol effect**
    - **only for resolved clouds (Sc)**
  - **Aqueous chemistry**
  - **Wet removal (scavenging)**

MADE aerosol module

Aitken and accumulation modes:

- $SO_4^{=}$, NH_4^{+}, NO_3^{-}, H_2O
- NaCl (sea salt)
- Anthropogenic SOA from oxidation of ...
  - Alkanes
  - Aromatics
- Biogenic SOA from oxidation of ...
  - Alpha-pinene
  - Limonene
  - Isoprene
- Anthropogenic POA
- Elemental carbon (soot)
- Primary PM2.5

MADE aerosol module

Coarse mode:

- Anthropogenic primary aerosol – e.g. from
  - Coal combustion
  - Cement manufacturing
  - Metallurgy
  - Waste incineration
- Sea salt
- Soil derived particles (mineral dust)

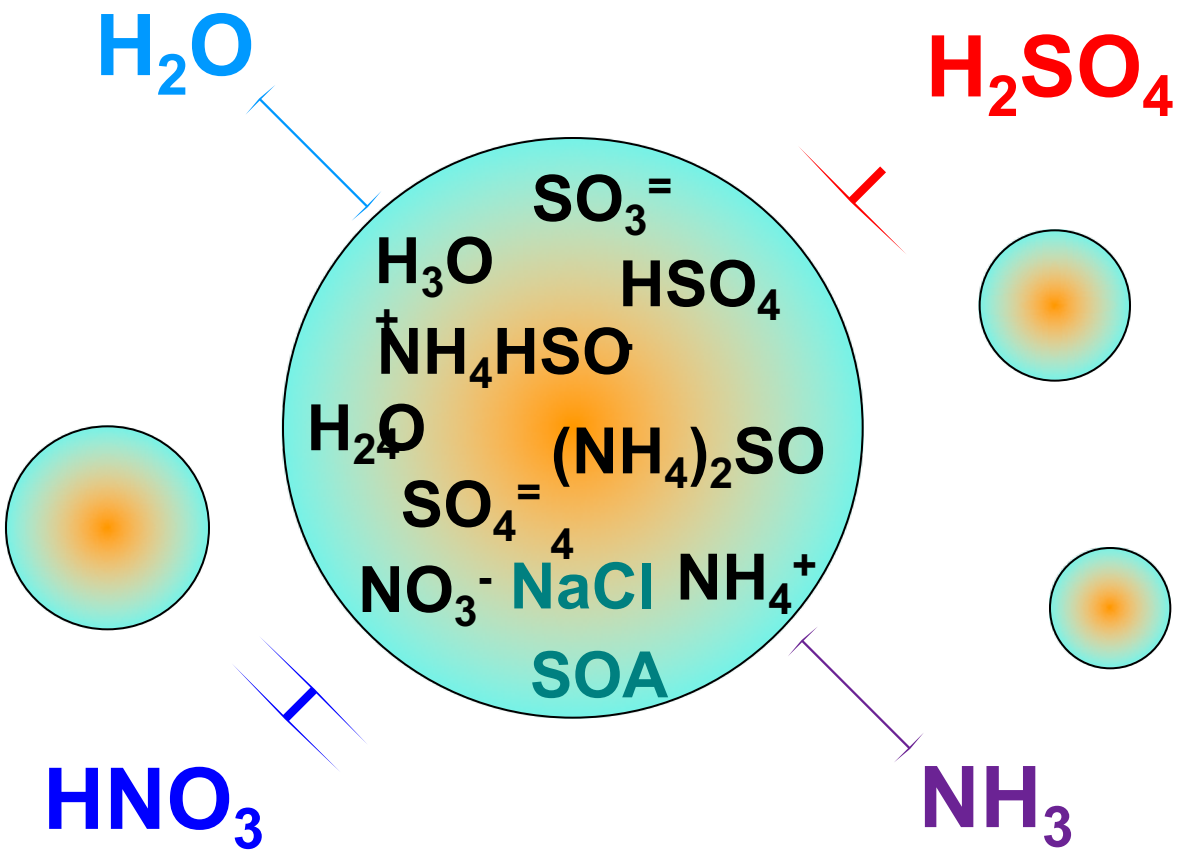
MADE aerosol coupling with chemistry

- **Gas phase chemistry:**
  - **RADM2 (Regional Acid Deposition Model version 2)**
  - **RACM (Regional Atmospheric Chemistry Mechanism)**
  - **RACM NOAA/ESRL version**
  - **CBMZ (Carbon-Bond Mechanism version Z)**

- **Gas phase/particle partitioning (aerosol chemistry):**
  - **MARS (Model for an Aerosol Reacting System)**
  - **SORGAM (Secondary Organic Aerosol Model)**
  - **VBS (Volatility Basis Set)**

- **Aqueous chemistry:**
  - **(CMU aqueous chemistry)**
  - **CMAQ aqueous chemistry (computationally more efficient)**
  - **Only for Aitken and accumulation mode**
  - **Only for selected gas phase chemistry options**

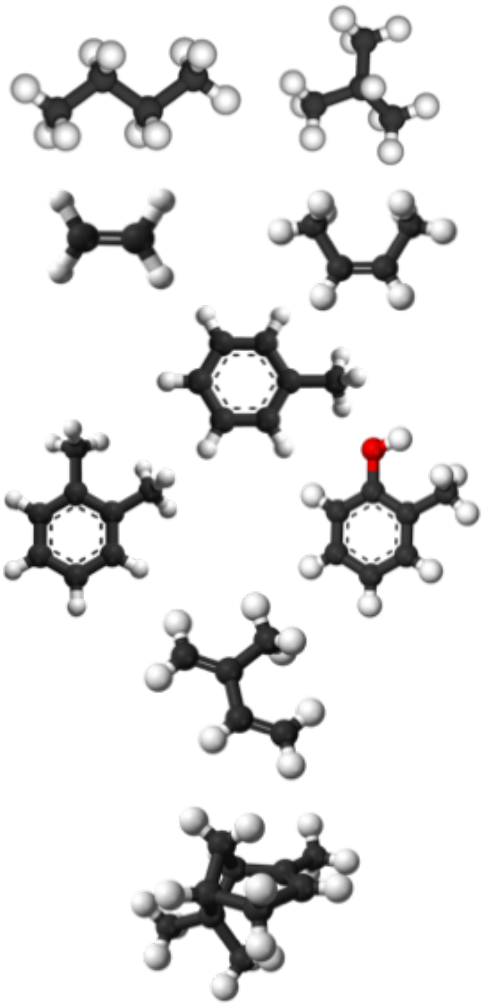
MADE and MARS: Inorganic aerosol chemistry



MARS (Model for an Aerosol Reacting System), Saxena et al., Atm. Env., 1986

MADE/SORGAM

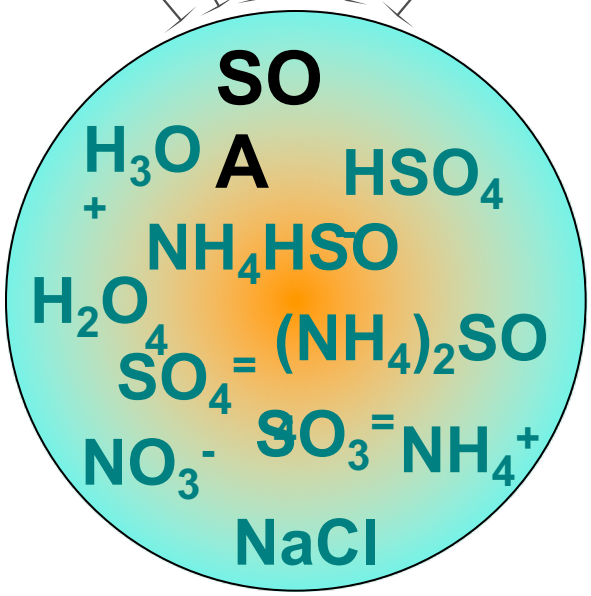
Gas phase scheme (RADM2, RACM)
Alkanes
Alkenes
Toluene
Xylene, cresole, ...
Isoprene
Sesquiterpene
Alpha-pinene, limonene



OH, O_3, NO_3

Semi-volatile organics

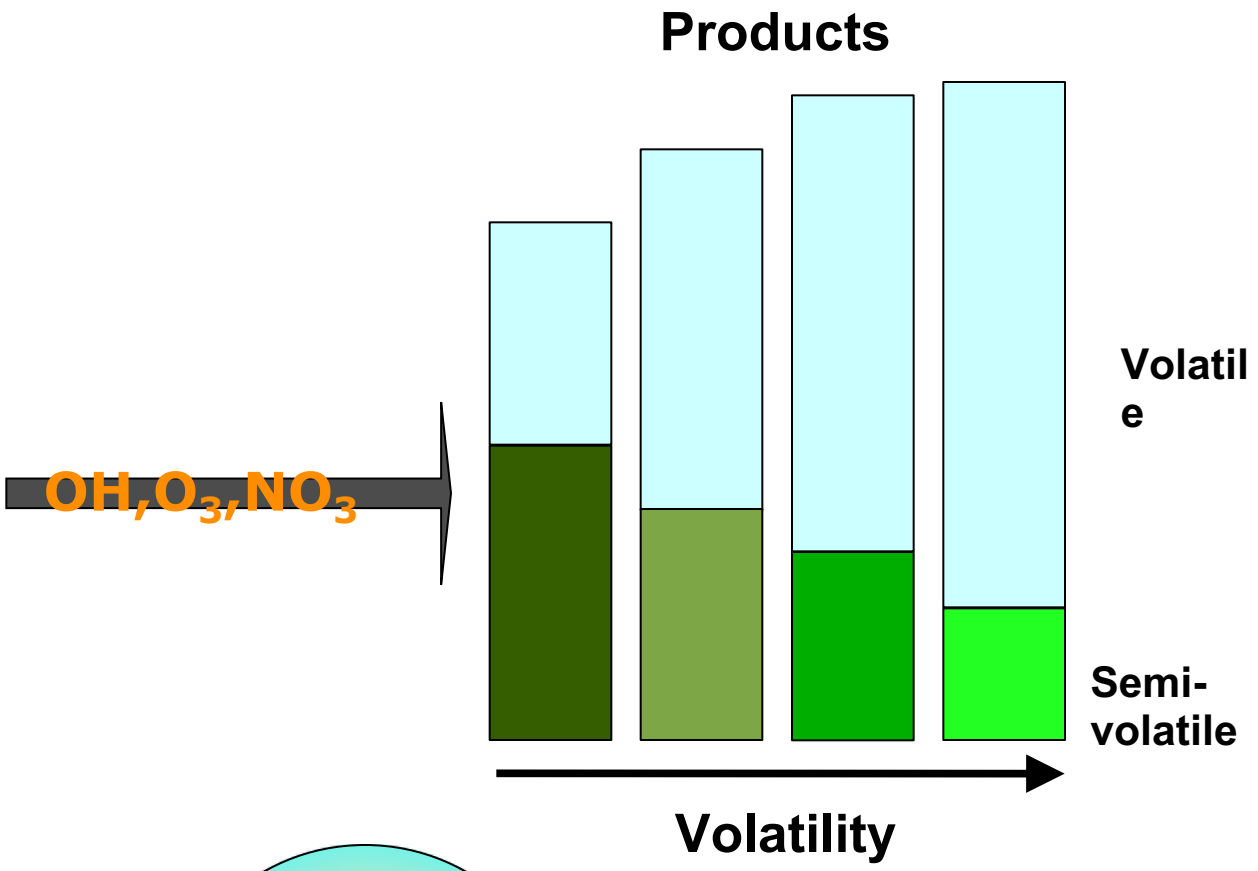
$X_1, X_2, X_3, X_4, X_5, \ldots, X_n$

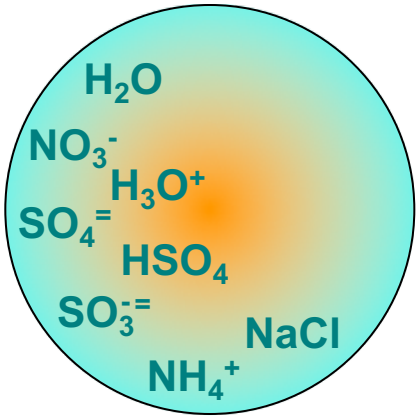


SORGAM (Secondary Organic Aerosol Model), Schell et al., JGR, 2001

MADE/VBS (Volatility Basis Set)

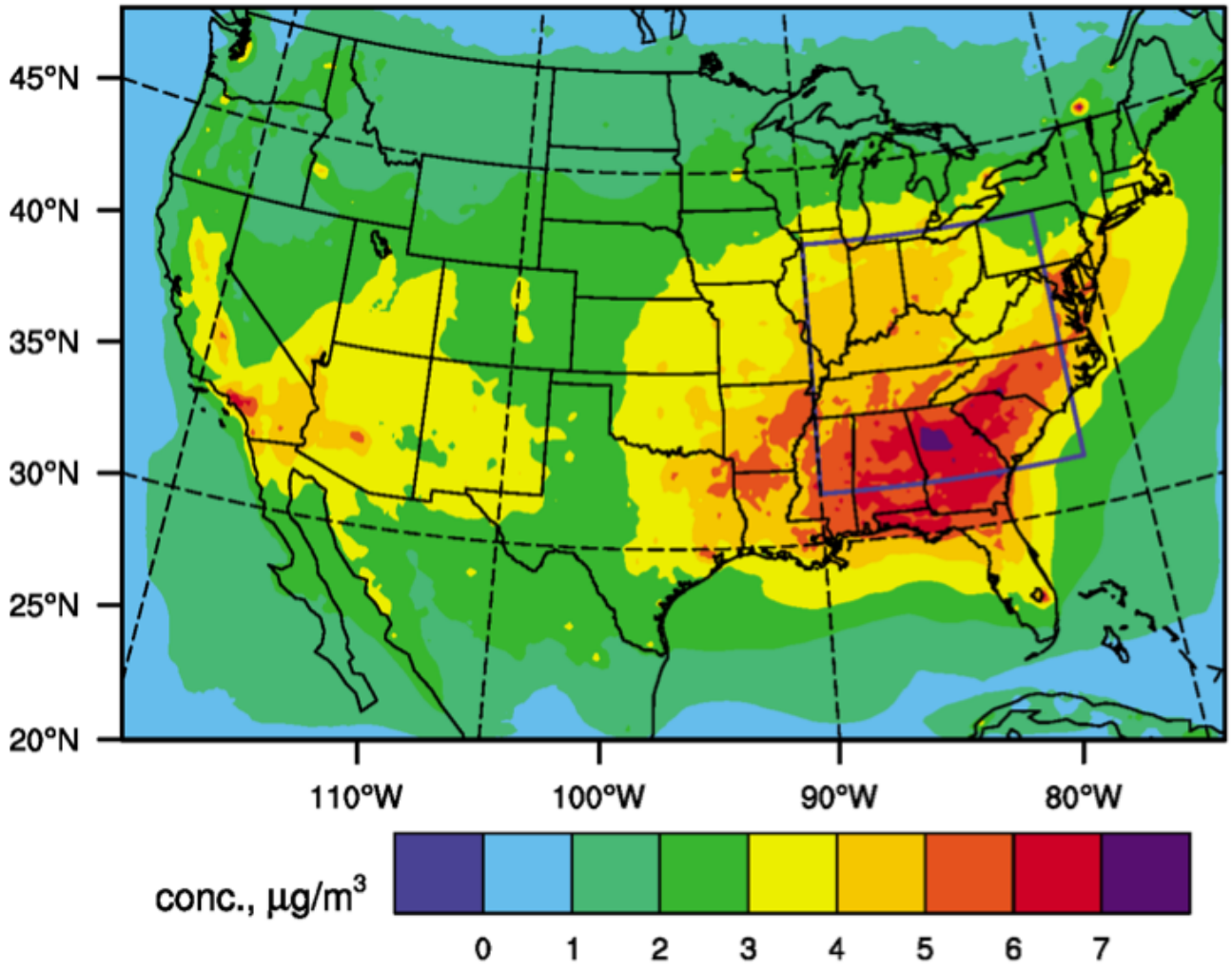
- Gas phase scheme (RACM)
- Alkanes
- Alkenes
- Toluene
- Xylene, cresole, ...
- Isoprene
- Sesquiterpene
- Alpha-pinene, limonene





Ahmadov et al., JGR 2012

MADE/VBS (Volatility Basis Set)

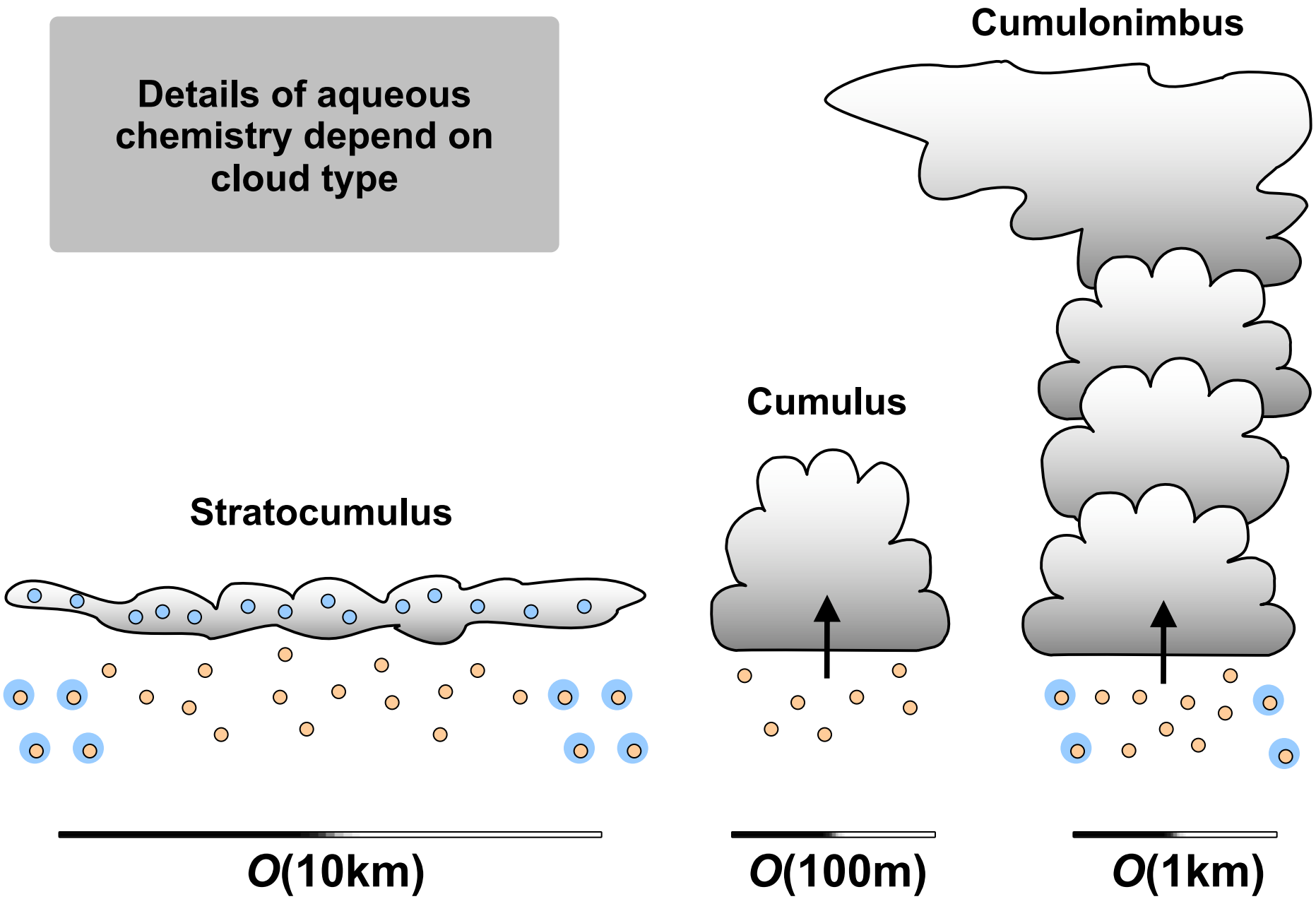


Organic aerosol mass in the surface layer (August - September 2006)

Ahmadov et al., JGR 2012

How clouds are simulated in WRF(Chem)

Details of aqueous chemistry depend on cloud type



MADE and aqueous chemistry

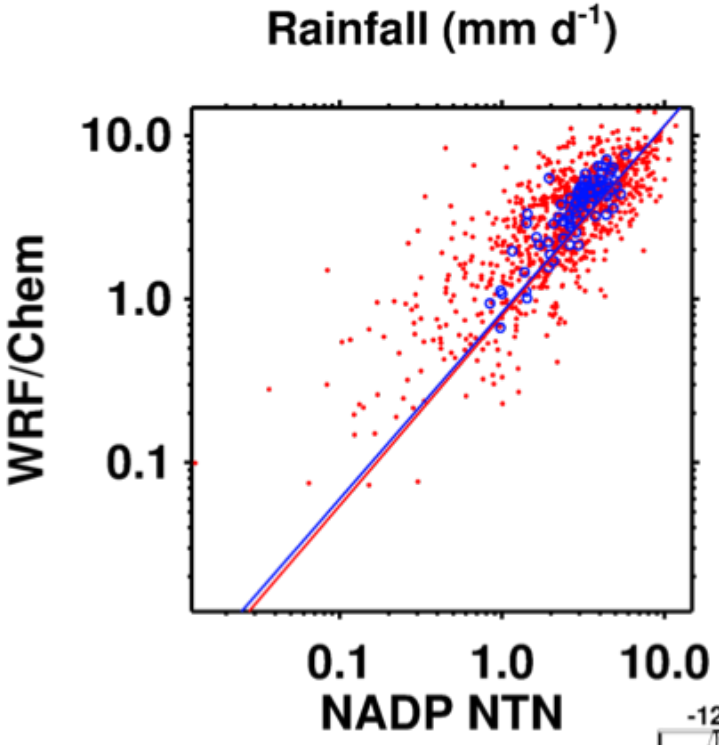
- **CMU aqueous chemistry**
  - (Fahey & Pandis, Atm. Env., 2001)
  - Slow, only for resolved clouds (Sc)
- **CMAQ aqueous chemistry**
  - (Walcek & Taylor, JAS, 1986)
  - Relatively fast
  - In both resolved (Sc) and parameterized (Cu) clouds
  - Can generate wet deposition of $SO_4^=$ and NO_3^-
  - Check in registry.chem:
    - wd_so4_sc, wd_so4_cu
    - wd_no3_sc, wd_no3_cu

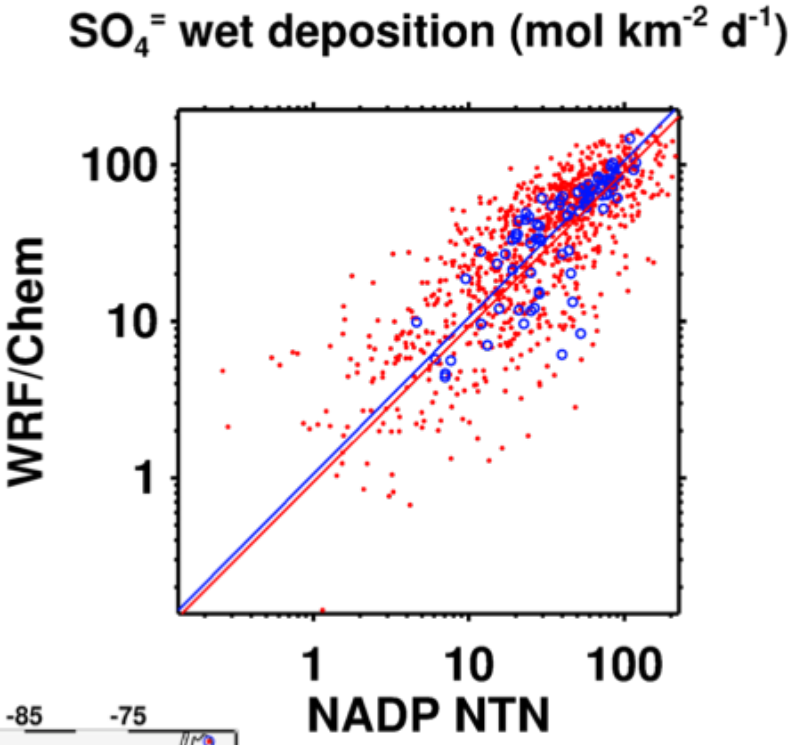
MADE and aqueous chemistry

CHEM_OPT	Stratocumulus	Cumulus
1		AQCHEM **
11	CMU *	AQCHEM **
12	CMU *	AQCHEM **
105		AQCHEM **
106		AQCHEM **
107		AQCHEM **
108		AQCHEM **
41	AQCHEM *	AQCHEM **
42	AQCHEM *	AQCHEM **
42	AQCHEM *	AQCHEM **

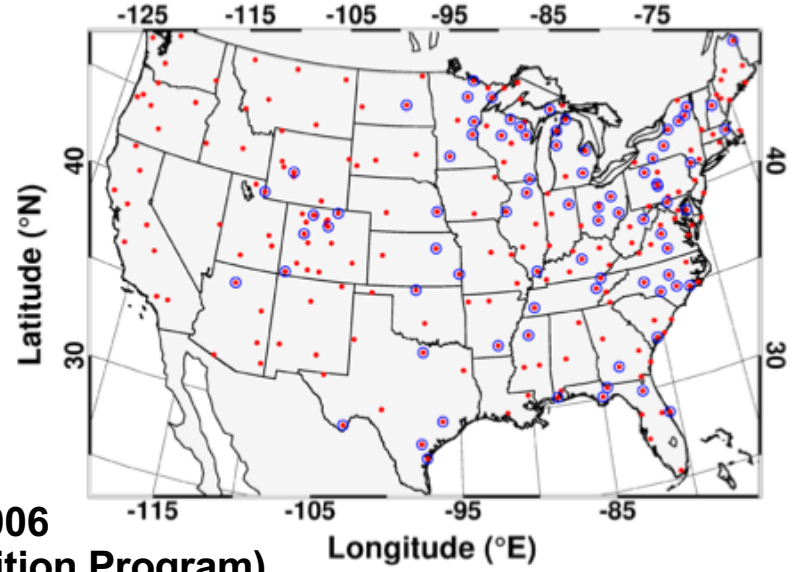
```
*  cloud_chem_onoff = 1 : Aqueous chemistry in Sc clouds on
** conv_tr_aqchem   = 1 : Aqueous chemistry in Cu clouds on
** wetscav_onoff    = 1 : Wet scavenging on in Sc clouds
** conv_tr_wetscav  = 1 : Wet scavenging in Cu clouds
```

Wet deposition example





Rainfall	
r	model/obs.
0.80	1.24



$SO_4^=$ wet dep.	
r	model/obs.
0.89	1.04

May-September 2006
(National Atmospheric Deposition Program)

MOSAIC aerosol module

Model for Simulating Aerosol Interactions and Chemistry (Zaveri et al., JGR, 2008)

- **Modern aerosol scheme in WRF/Chem**
- **4 or 8 aerosol size sections (bins) 39 nm – 10 μm**
- **Interaction with radiation:**
  - **Direct aerosol effect**
  - **Effect on photolysis**
- **Interaction with clouds:**
  - **Aerosol number determines cloud drop number and size**
  - **Radiative response → 1st indirect aerosol effect**
  - **Aqueous chemistry**
  - **Wet removal (scavenging)**

MOSAIC aerosol module

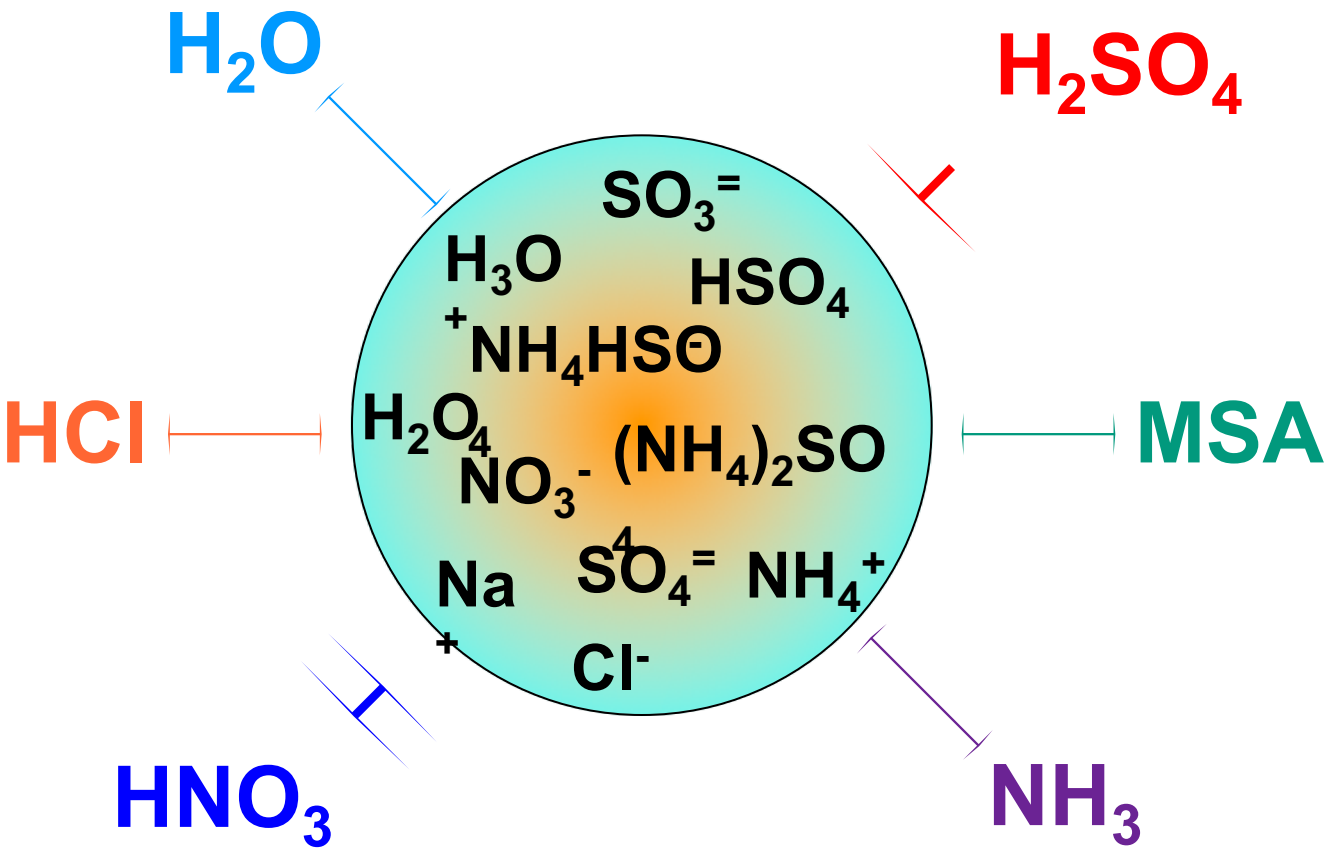
Aerosol composition

- $SO_4^=$, NH_4^+, NO_3^-, H_2O
- NaCl (sea salt)
- CH_3SO_3 (methanesulfonate)
- carbonate (CO_3)
- calcium (Ca)
- black carbon (BC)
- primary organic mass (OC)
- other inorganic mass (minerals, trace metals)

MOSAIC aerosol coupling with chemistry

- **Gas phase chemistry:**
  - **CBMZ (Carbon-Bond Mechanism version Z)**
    - **"Standard" gas phase chemical scheme for MOSAIC**
  - **SAPRC99 (extensive VOC chemistry)**
    - **Works with the VBS SOA scheme**
  - **MOZART (Model for Ozone and Related chem. Tracers)**
    - **Works with the VBS SOA scheme**
- **Gas phase/particle partitioning (aerosol chemistry):**
  - **MTEM (Multicomponent Taylor Expansion Method)**
  - **MESA (Multicomponent Equilibrium Solver for Aerosols)**
  - **VBS (Volatility Basis Set)**
- **Aqueous chemistry:**
  - **CMU aqueous chemistry, only for resolved clouds (Sc)**

MOSAIC, MTEM, and MESA



MTEM calculates activity coefficients
MESA solves ion-equilibria in the liquid phase
For SOA: VBS (Volatility Basis Set) scheme

MTEM (Multicomponent Taylor Expansion Method), Zaveri et al., JGR 2005a

MESA (Multicomponent Equilibrium Solver for Aerosols), Zaveri et al., JGR 2005b

MAM aerosol module

Modal Aerosol Model from CAM5

- 3 or 7 log-normal aerosol modes: MAM3 and MAM7
- Mode width σ is fixed
- Aerosol number and mass variable
- Liu et al., Geosci. Model Dev., 5, 709-739, 2012

MAM 3

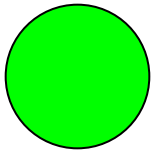
Aitken mode

- Sulfate ($SO_4^=$)
- SOA
- Sea salt

15 – 53 nm

Coagulation, condensation

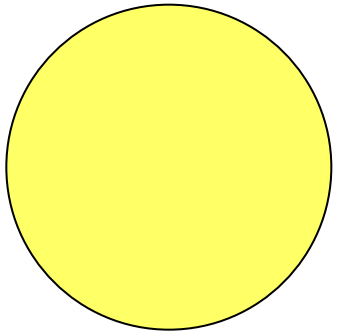
Accumulation mode



- Sulfate ($SO_4^=$)
- SOA
- Primary organic matter
- Black carbon
- Mineral dust
- Sea salt

58 – 270 nm

Coarse mode

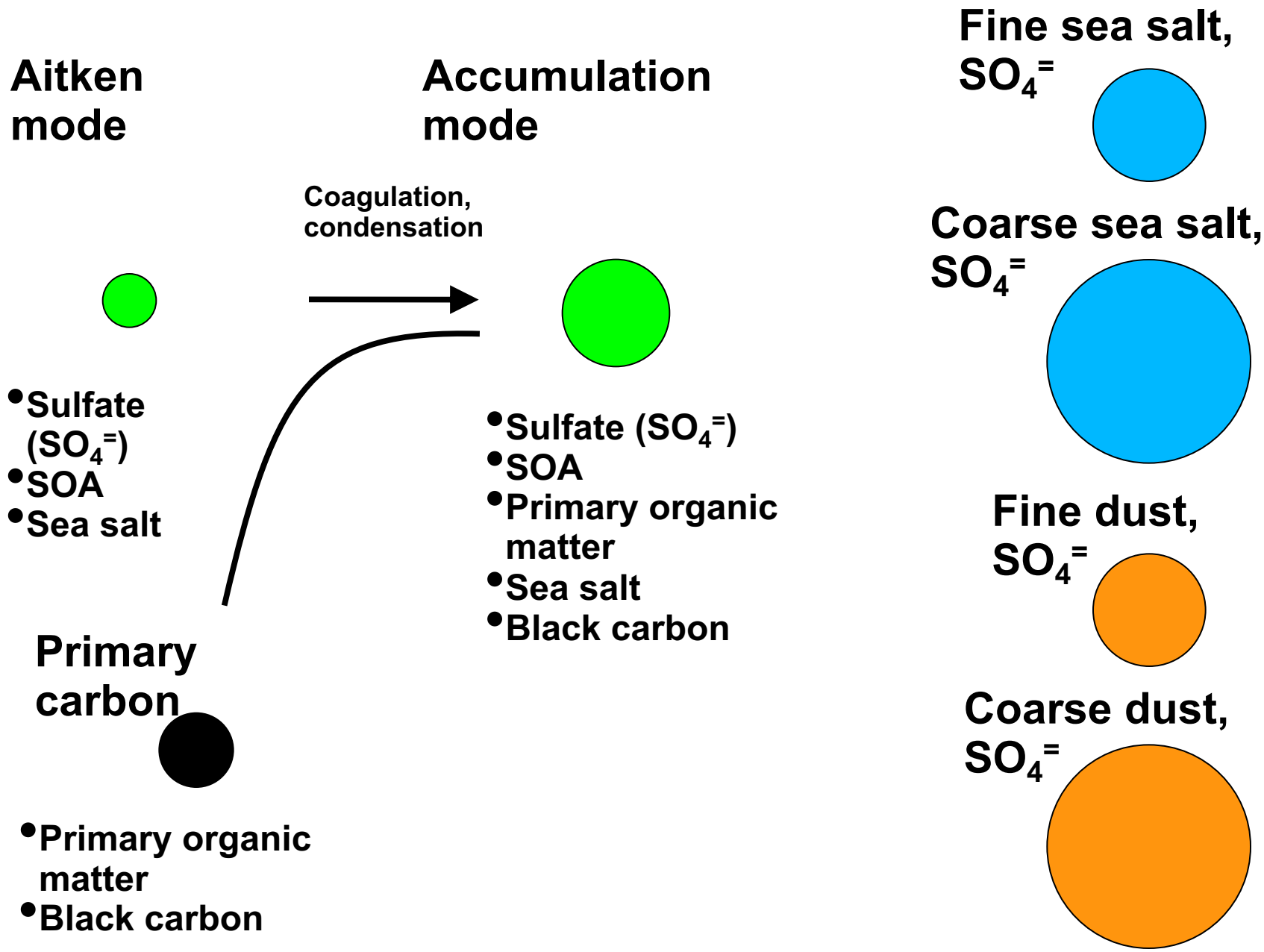


- Sulfate ($SO_4^=$)
- Mineral dust
- Sea salt

0.8 – 3.65 µm

Dry particle diameter

MAM 7


Aitken mode
Accumulation mode
Coagulation, condensation
•Sulfate ($SO_4^=$)
•SOA
•Sea salt
•Sulfate ($SO_4^=$)
•SOA
•Primary organic matter
•Sea salt
•Black carbon
Primary carbon
•Primary organic matter
•Black carbon
Fine sea salt, $SO_4^=$
Coarse sea salt, $SO_4^=$
Fine dust, $SO_4^=$
Coarse dust, $SO_4^=$

MAM aerosol module

- Currently only one gas phase chemistry scheme
  - CBMZ (Carbon-Bond Mechanism version Z)
- Interaction with radiation:
  - Coupled to RRTMG radiation → Direct aerosol effect

As in CAM5:

- Gas phase/particle partitioning (aerosol chemistry):
  - Condensation of water vapor and of the 4 inorganic trace gase species: NH_3, H_2SO_4, HNO_3, HCl
- Interaction with clouds only resolved clouds (Sc):
  - Coupled to Morrison & Gettelman cloud microphysics
  - Radiative response → 1st indirect aerosol effect
  - Wet removal (scavenging)
  - Aqueous chemistry
- Dry deposition

Volcanic ash

- 10 bins for volcanic ash aerosol
- Transport, settling, dry deposition
- Currently no other aerosol
- Single active volcano
- Database of 1535 volcanoes (latitude, longitude, height)

How to tell WRF-Chem what to do

../WRFV3/test/em_real/real.exe
../WRFV3/test/em_real/namelist.input
../WRFV3/test/em_real/...
../WRFV3/test/em_real/...

```
  ...
  ...
 &chem
 chem_opt         = 43
 photdt           = 0.25
 chemdt           = 0
  ...
aerchem_onoff     = 1
  ...
conv_tr_aqchem    = 1
```

MADE/SORGAM, RACM-ESRL, CMAQ aqueous chemistry

Switches all aerosol processes on/off

CMAQ aqueous chemistry on in Cu

Resources

- **WRF-Chem User's Guide**
  - Model options (namelist parameters)
  - Combinations of physical/chemical schemes
  - ...
- **Papers referenced in the WRF-Chem User's Guide**
- **WRF-Chem source code**

- **WRF-Chem Help (wrfchemhelp.gsd@noaa.gov)**