Earth System Modelling and specific challenges

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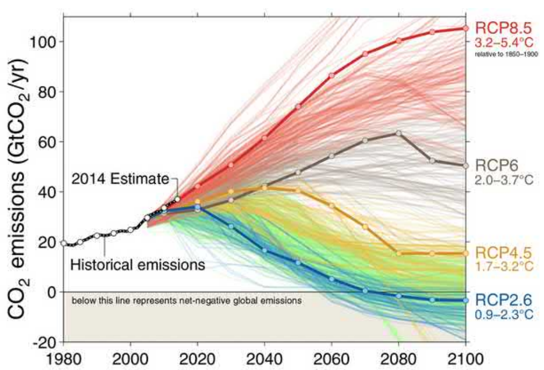
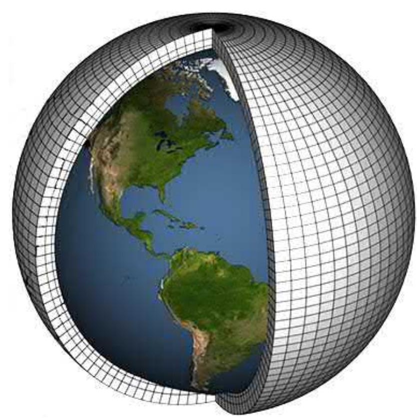
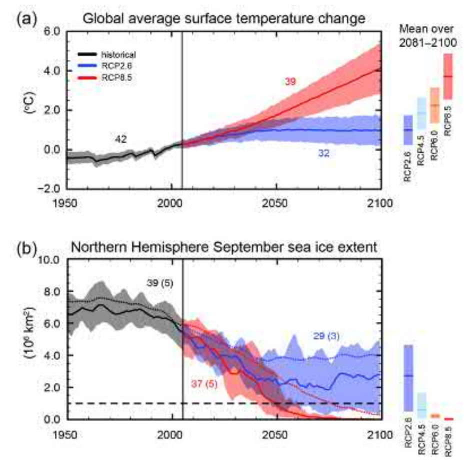
Input
(e.g. greenhouse gas emission)



Earth System Model



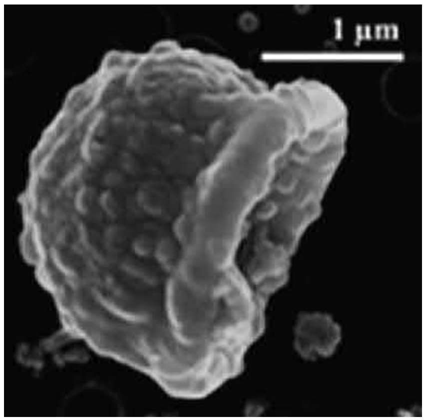
Climate prediction



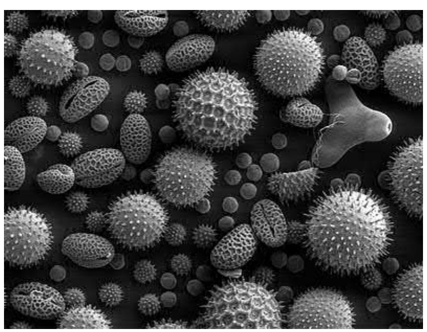
What are atmospheric aerosols?

Solid or liquid particles suspended in air

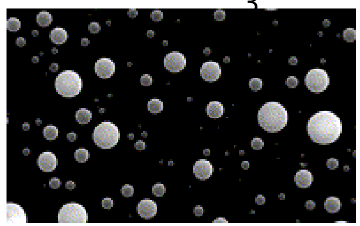
Spores



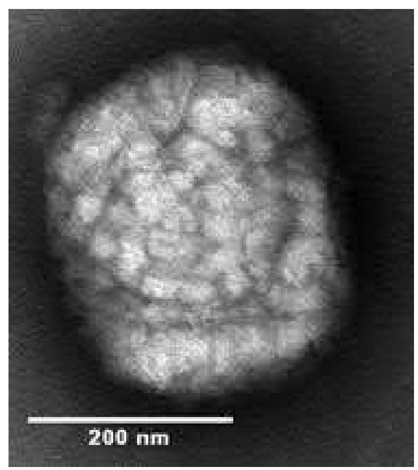
Pollen



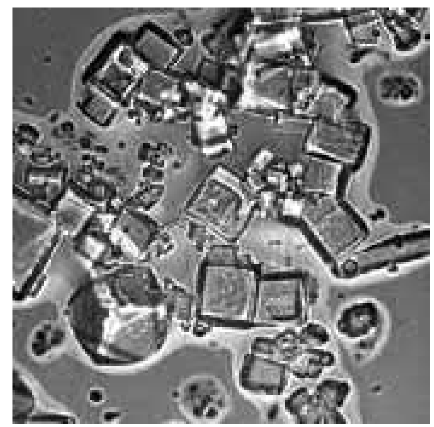
$NaNO_3$



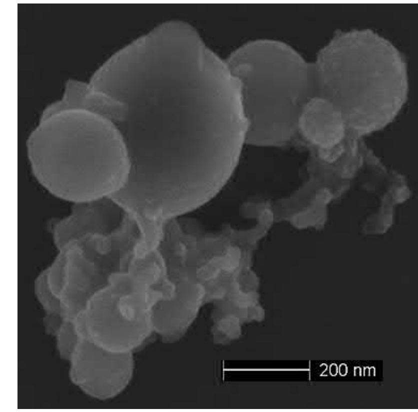
Virus



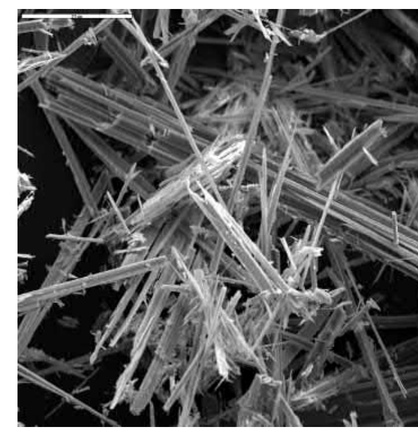
Sea salt



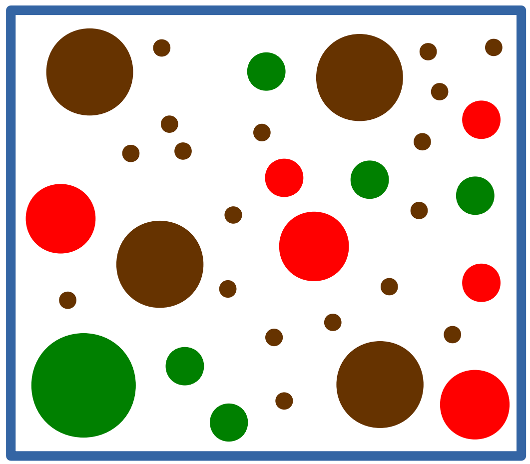
Wood smoke

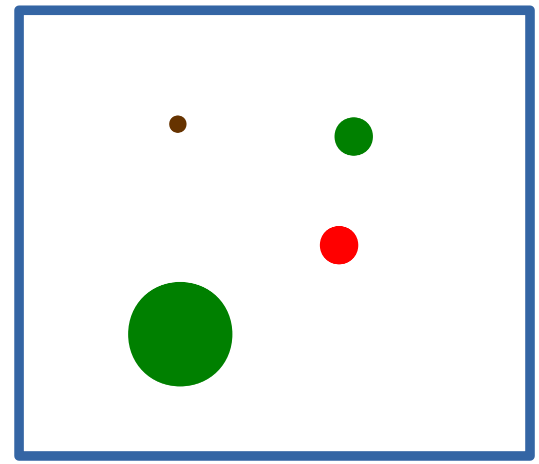


Fibres



	Urban atmosphere	**Remote atmosphere**
Aerosol number conc.	10^4-10^8 # /cm^3	even < 50 # /cm^3
Aerosol mass	10-200 µg / m^3	< 1 µg / m^3

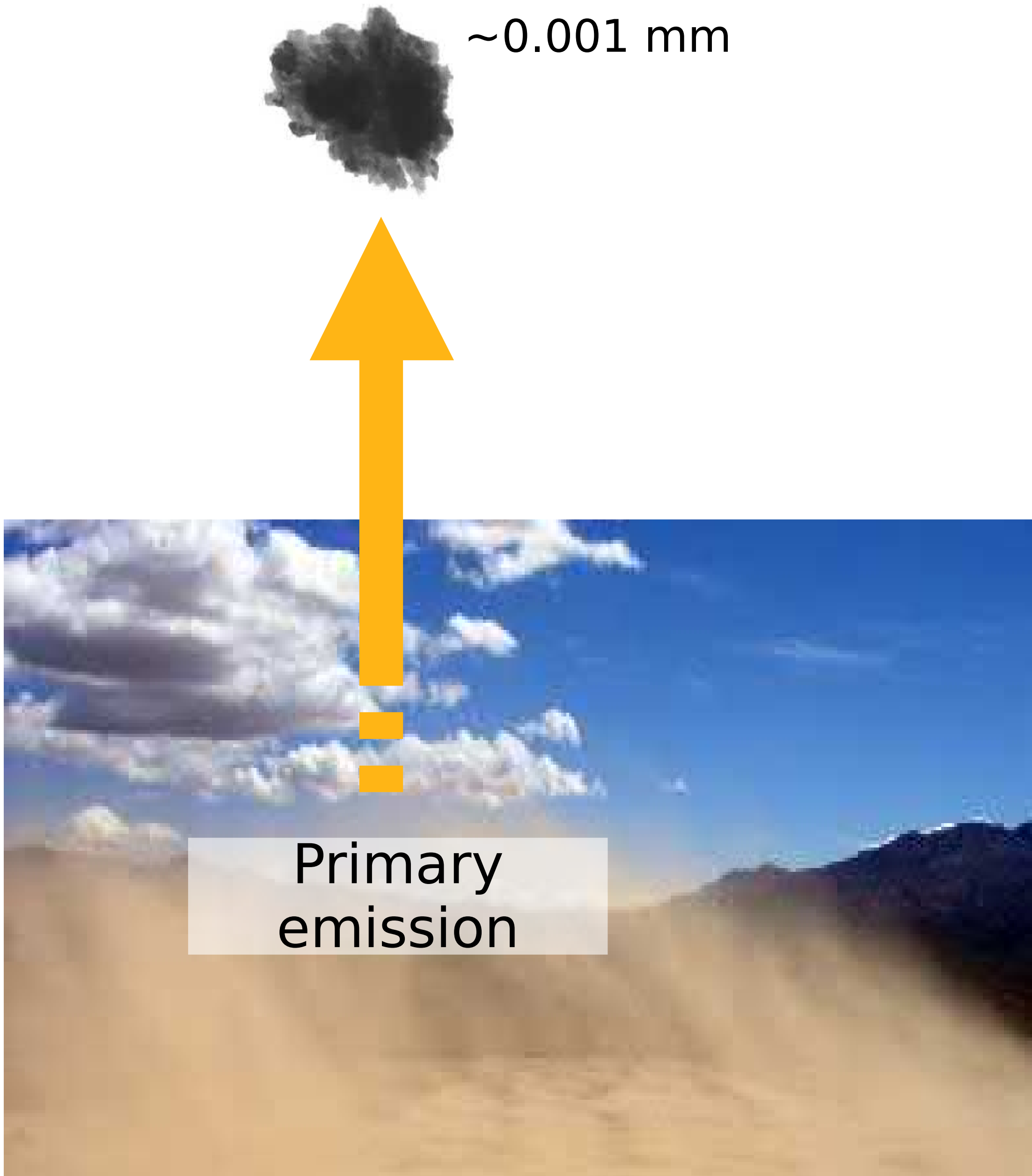




Aerosols reduce visibility

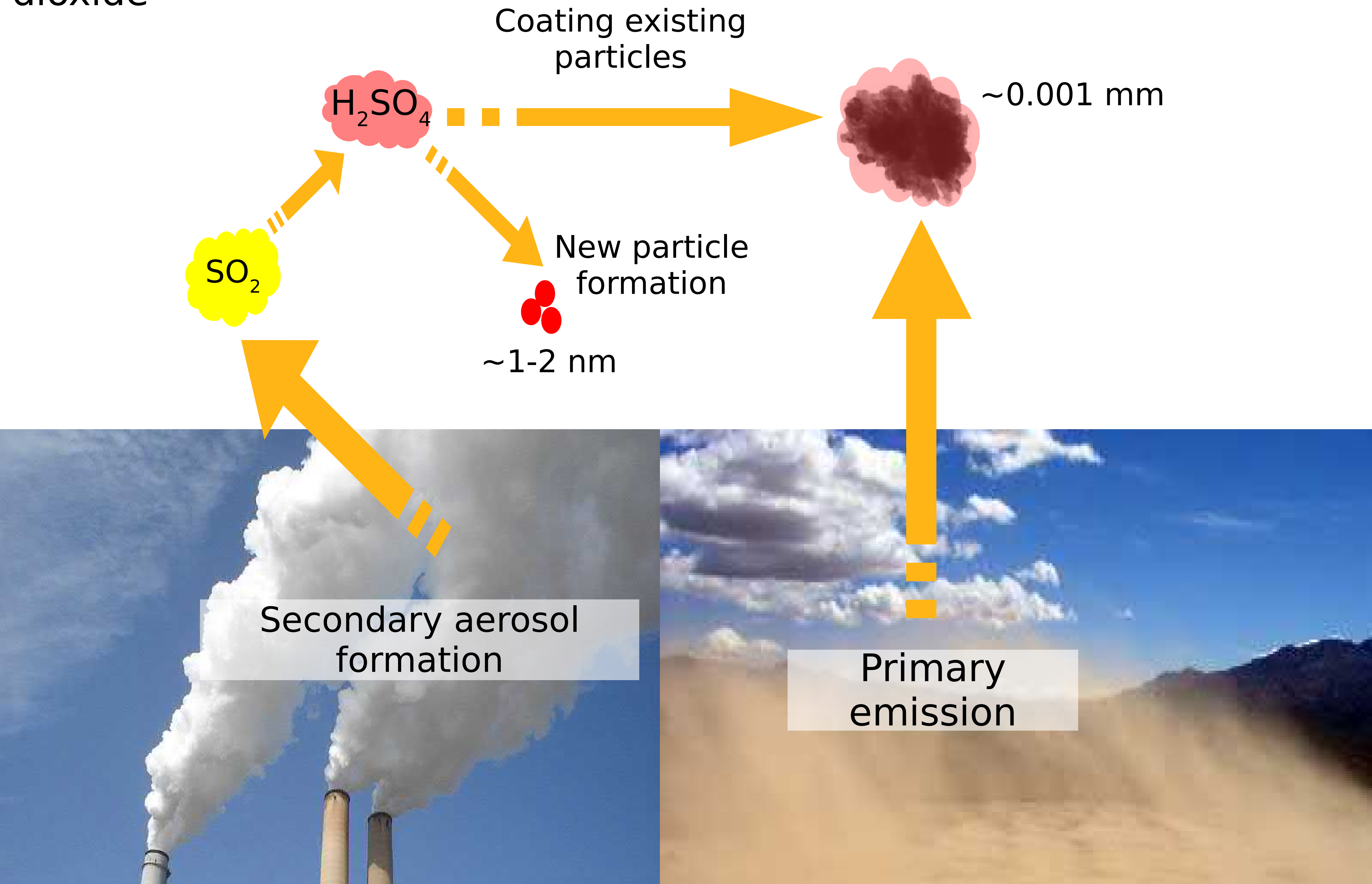
How do aerosols enter the atmosphere?

Example: wind-blown dust



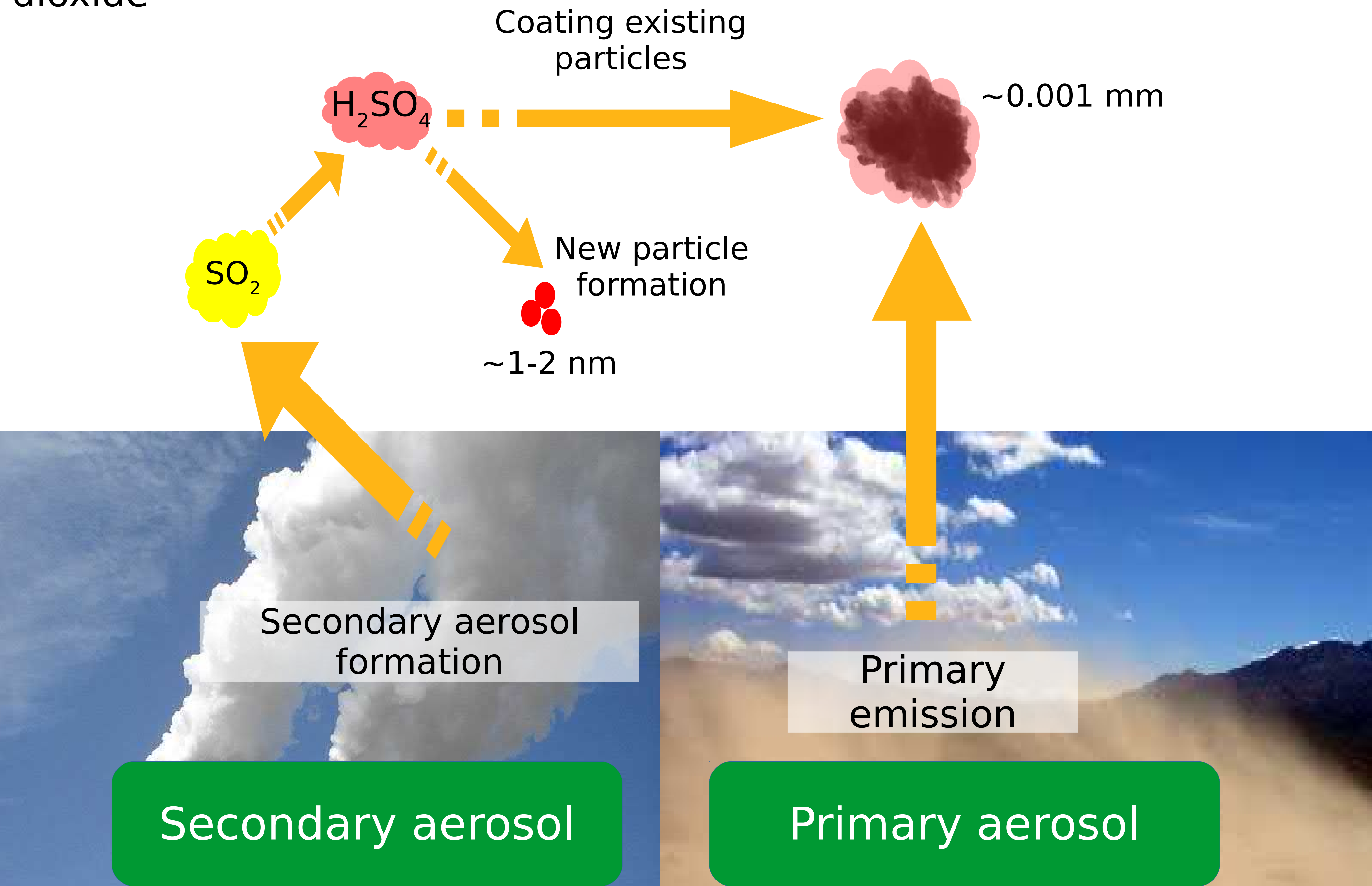
How do aerosols enter the atmosphere?

Example: wind-blown dust and secondary formation from sulfur dioxide

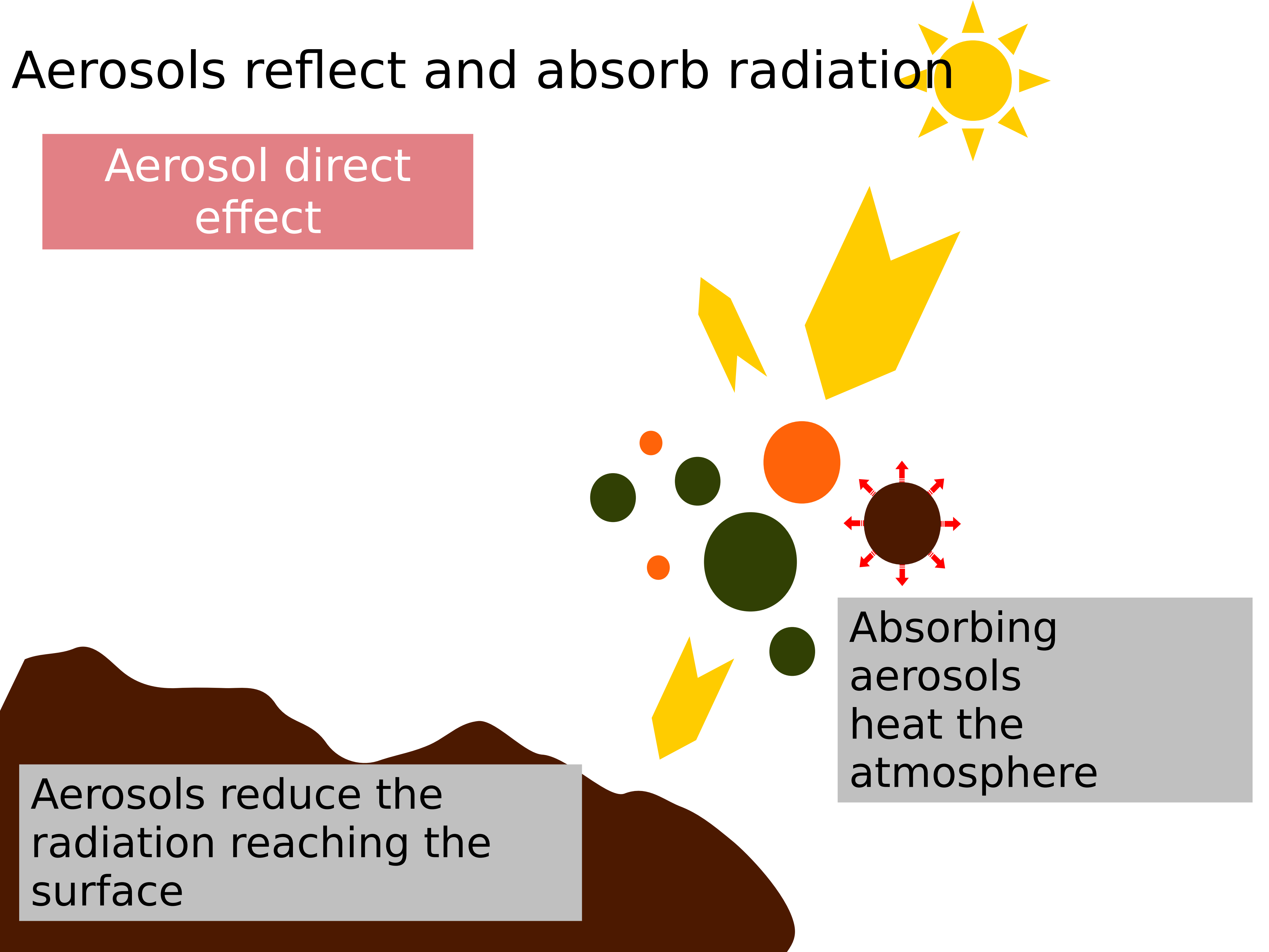


How do aerosols enter the atmosphere?

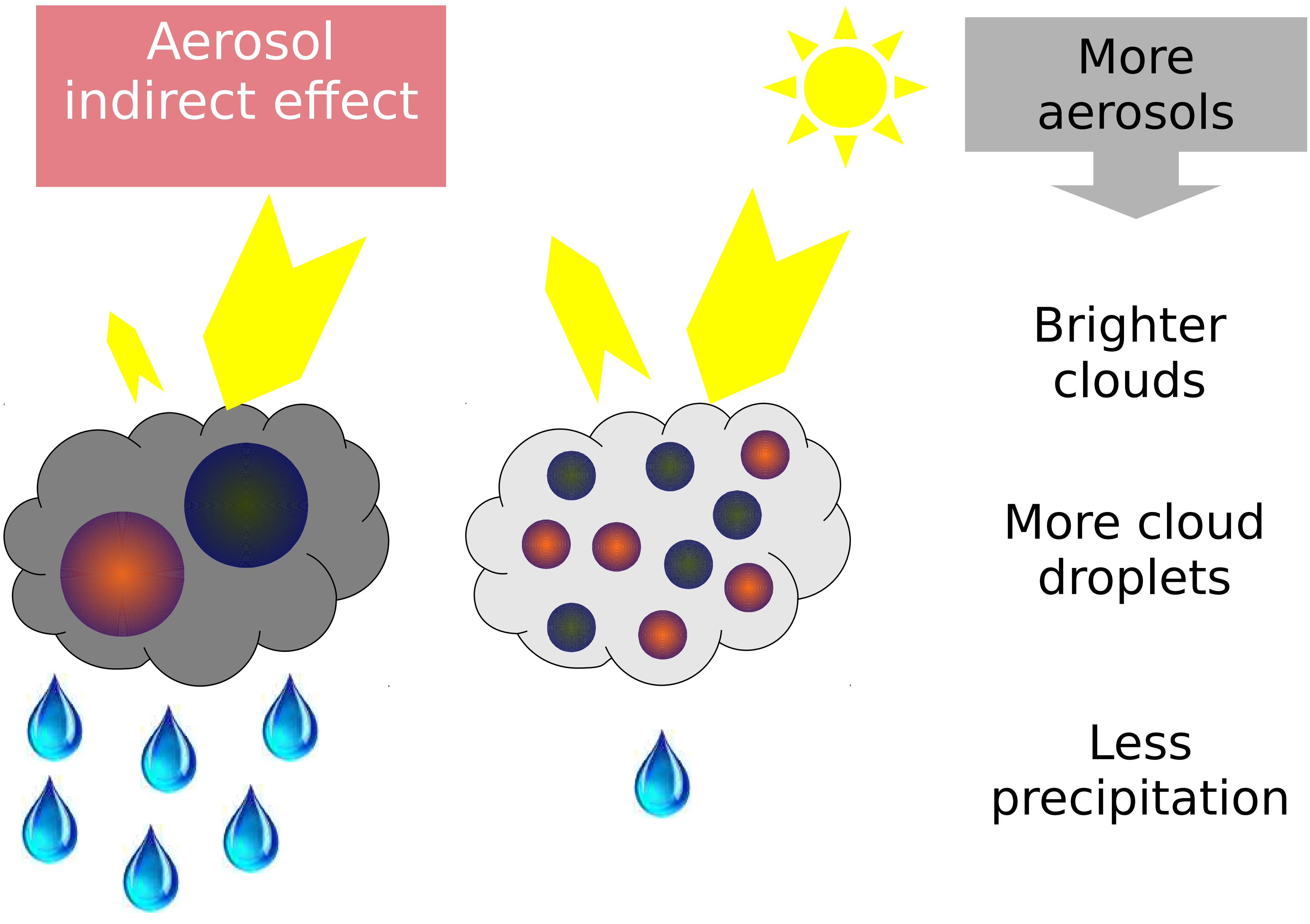
Example: wind-blown dust and secondary formation from sulfur dioxide



Why would we want to include aerosols/chemistry in a climate model?


Aerosols reflect and absorb radiation
Aerosol direct effect
Absorbing aerosols heat the atmosphere
Aerosols reduce the radiation reaching the surface

Aerosols act as cloud condensation nuclei



Role of clouds in the atmosphere

Radiation budget and climate: Clouds reflect effectively incoming sunlight back to space. Similarly, clouds absorb and re-emit infrared radiation emitted by the Earth's surface

Hydrological cycle: Clouds turn water vapor into precipitating hydrometeors (rain drops, snow flakes, hail etc), thereby wetting land surfaces and filling rivers and lakes.

Cleaning of the atmosphere: Precipitating clouds scavenge both gaseous and particulate pollutants from the atmosphere

Atmospheric chemistry: Clouds serve as a medium for aqueous-phase chemical reactions. By this way, clouds influence the concentrations of many soluble trace gases and modify the chemical composition (and size) of atmospheric aerosol particles.

Vertical transportation: Vertical motion of air in the atmospheric is often associated with clouds. These include i) cycling of turbulent eddies in the boundary layer, ii) exchange of moisture, trace gases and aerosol particles between the boundary layer and free troposphere, iii) transportation material from the free troposphere to the stratosphere.

Aerosols and clouds

In addition to making the existence of clouds possible, aerosol particle modify many cloud properties, including

cloud albedo (higher aerosol number concentrations make clouds more reflective)

cloud lifetime (many clouds live longer at higher aerosol concentrations)

cloud precipitating efficiency (aerosol particle may either suppress or accelerate precipitation)

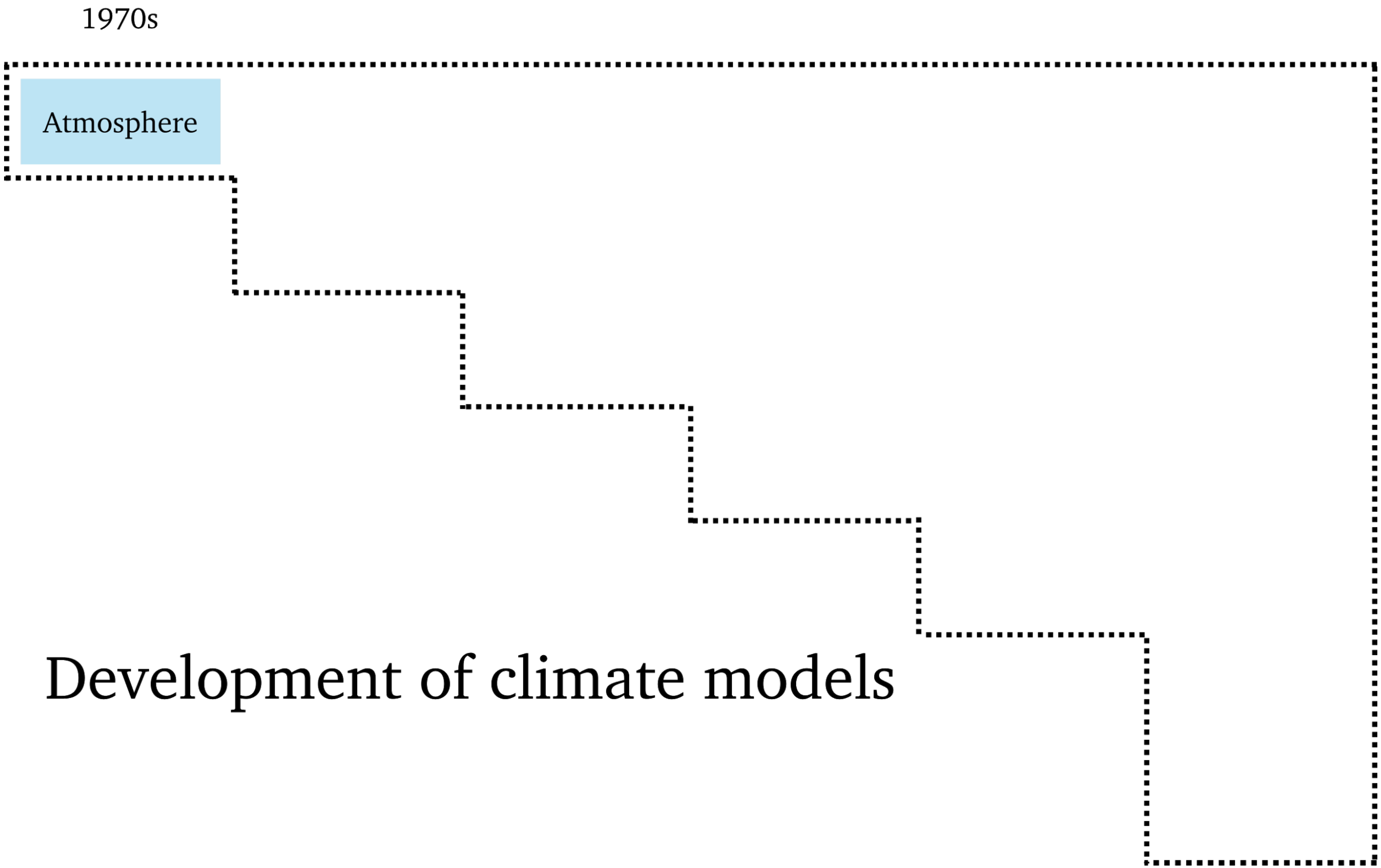
cloud formation probability (large concentrations of absorbing aerosol may inhibit cloud formation altogether)

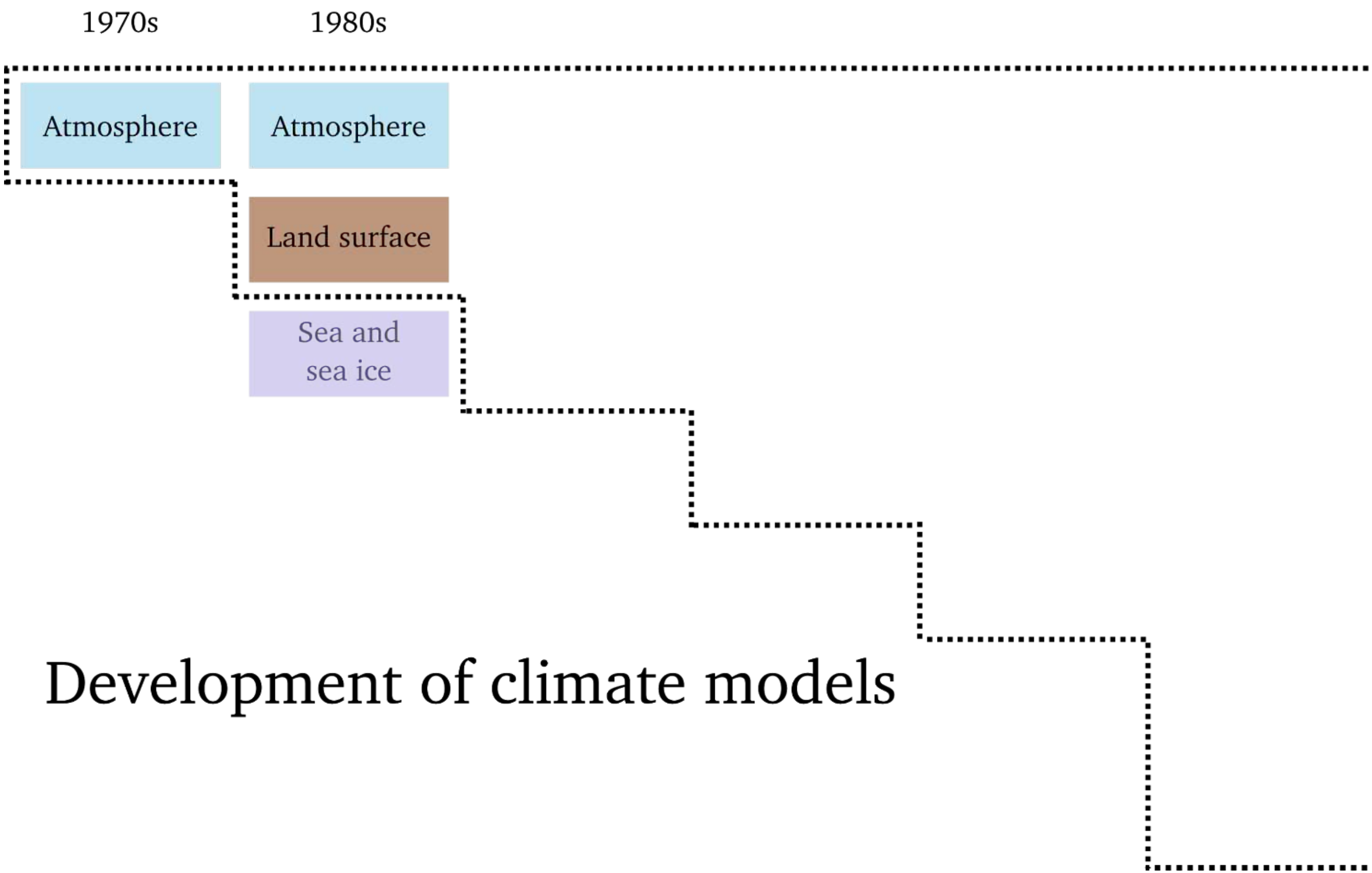
Why add aerosols in Earth System / Climate models?

- Aerosol-radiation interactions
- Aerosol-cloud interactions
- Health effects
- Environmental effects
  - Deposition
  - Long-range nutrient dispersion
- Anthropogenic climate forcing
- Natural Earth System feedbacks via aerosols

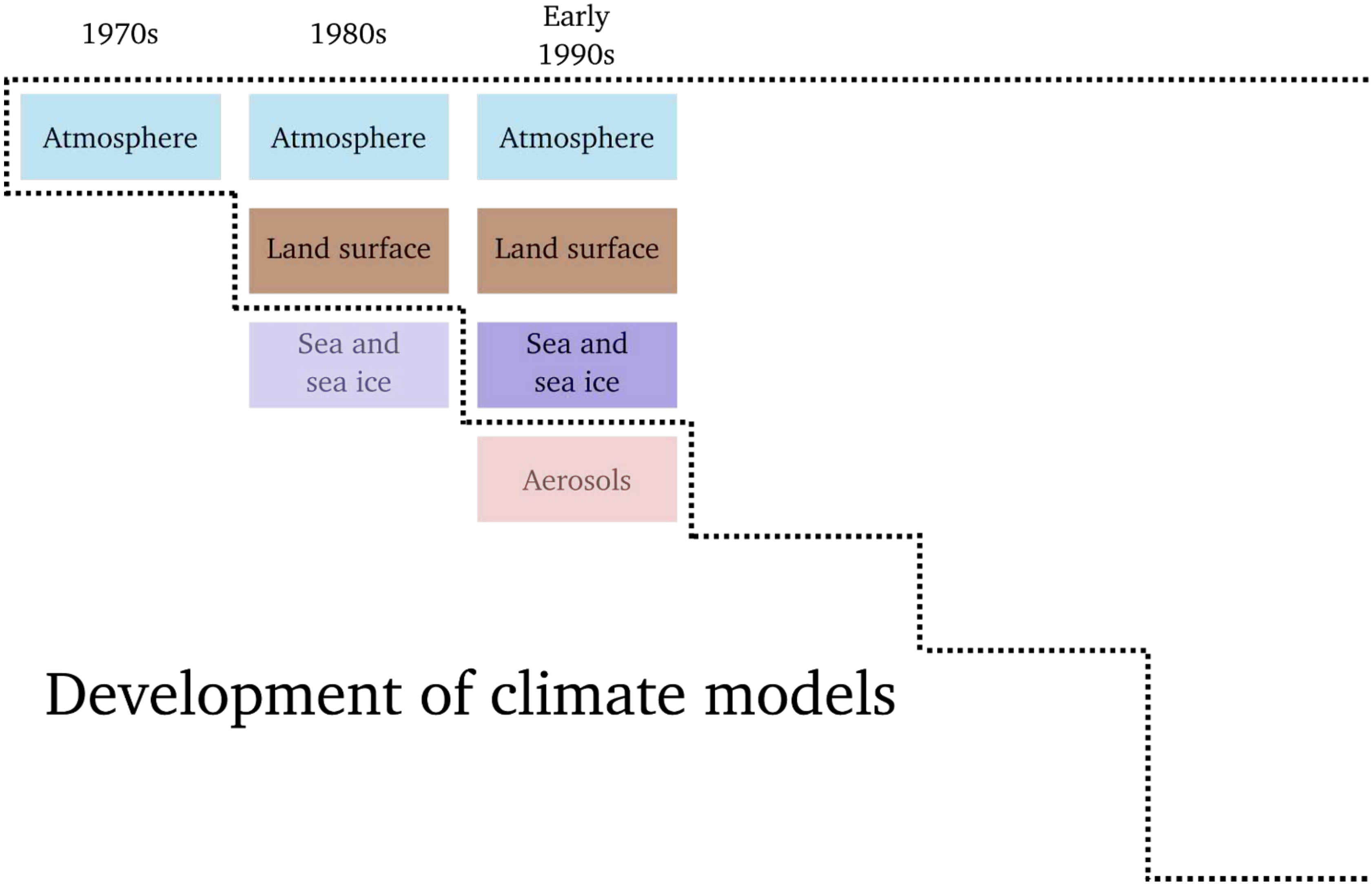
Development of climate models

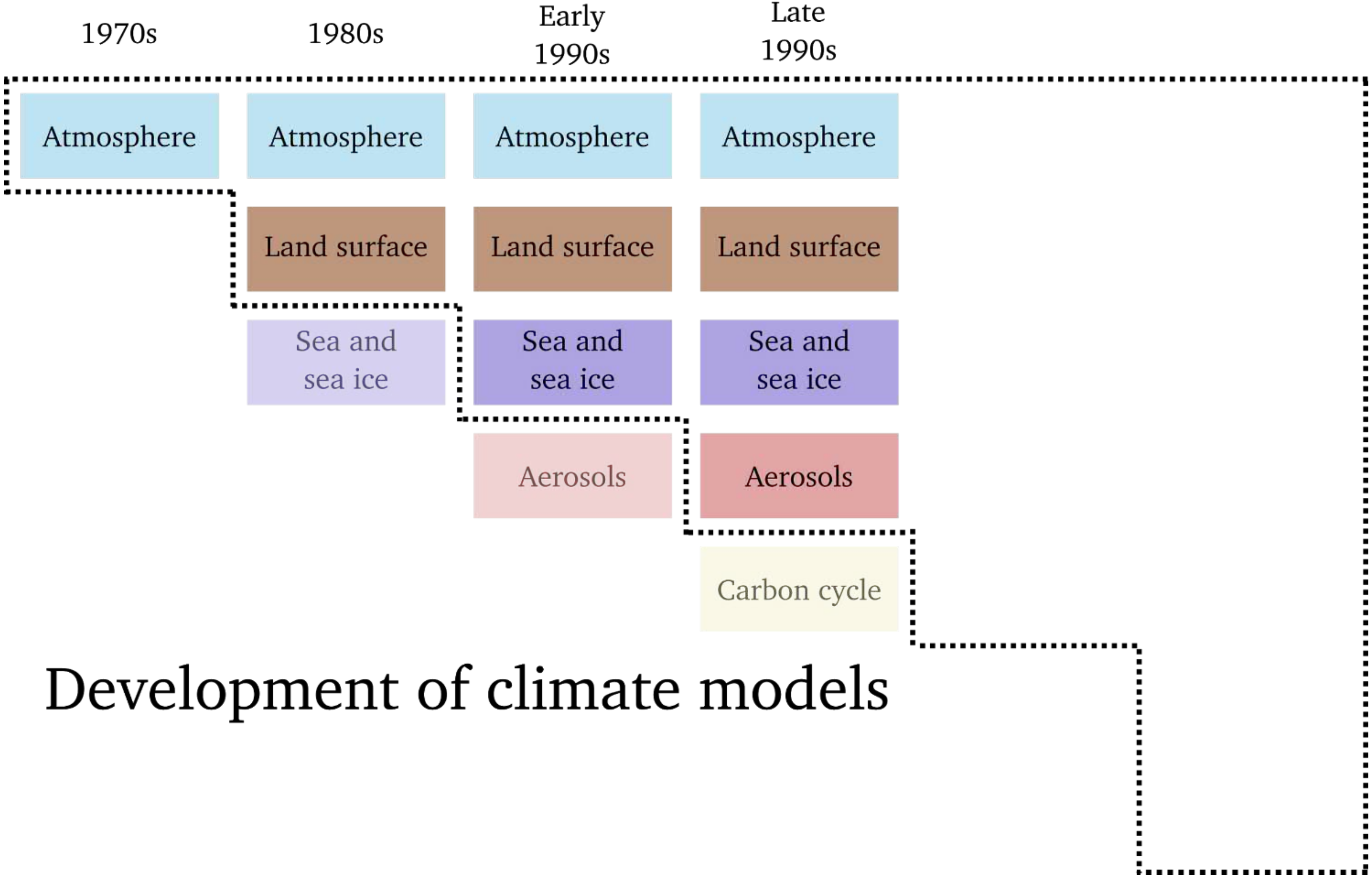
Development of climate models



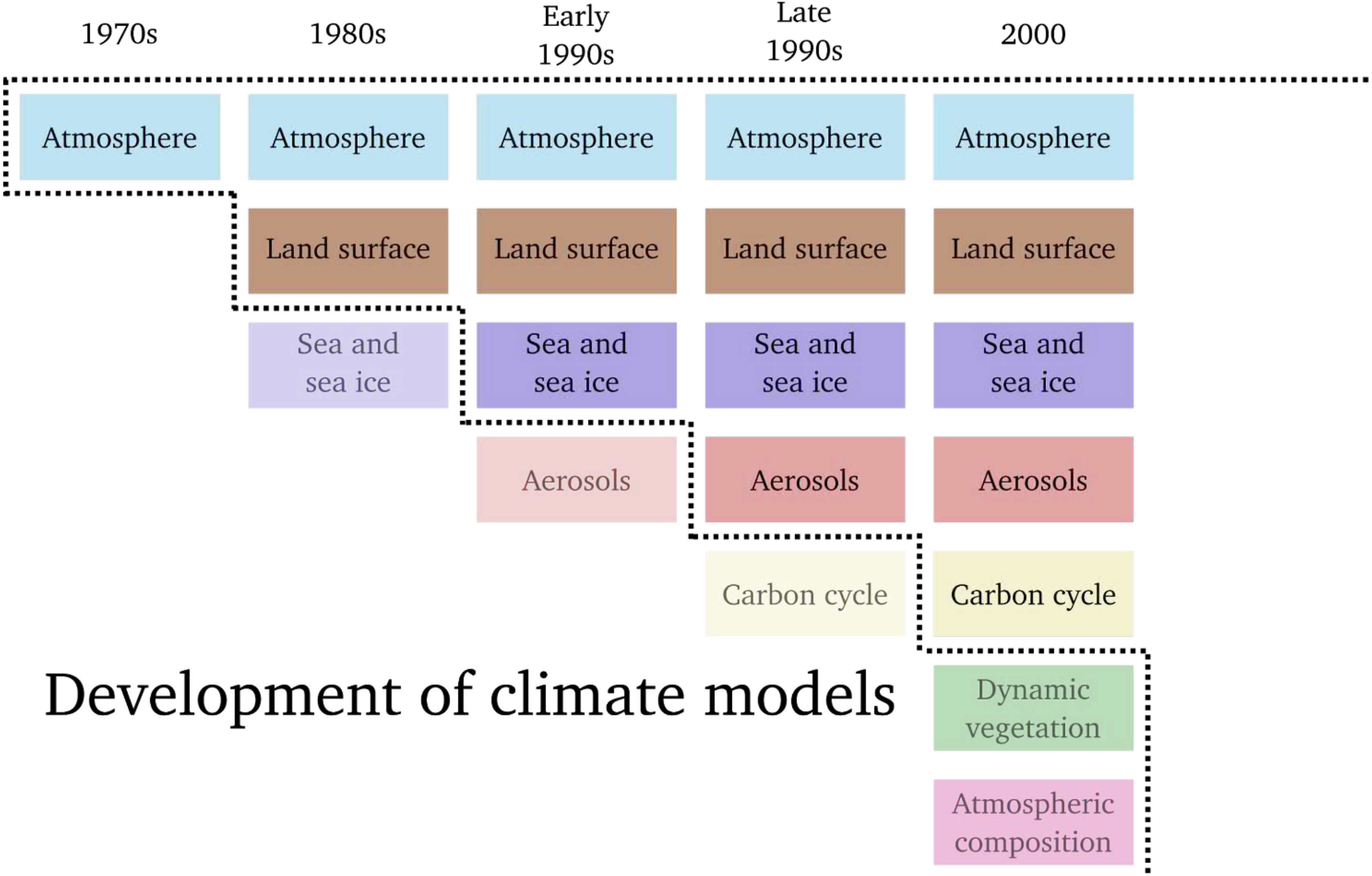

1970s
1980s
Atmosphere
Atmosphere
Land surface
Sea and sea ice
Development of climate models

Development of climate models

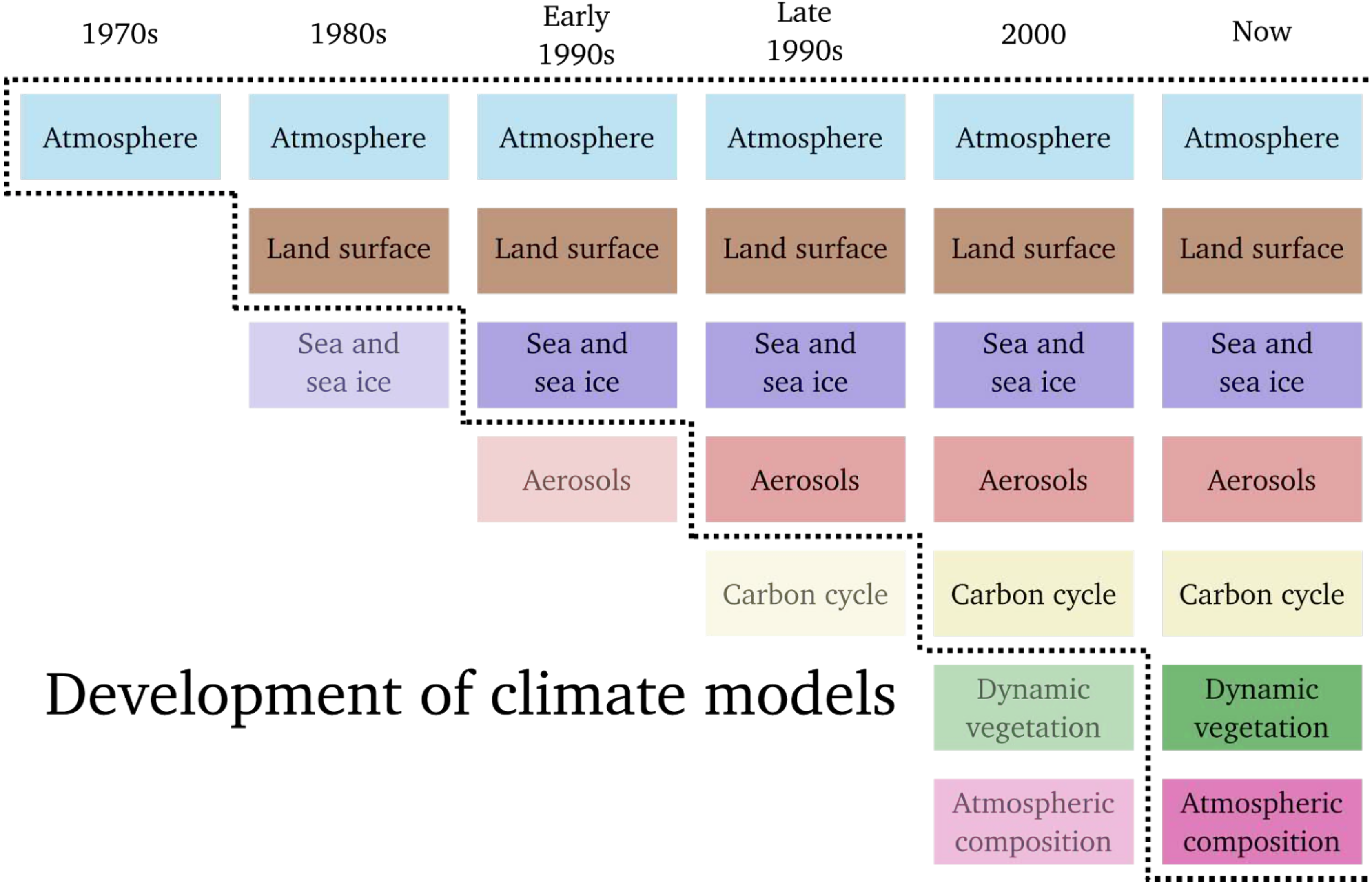


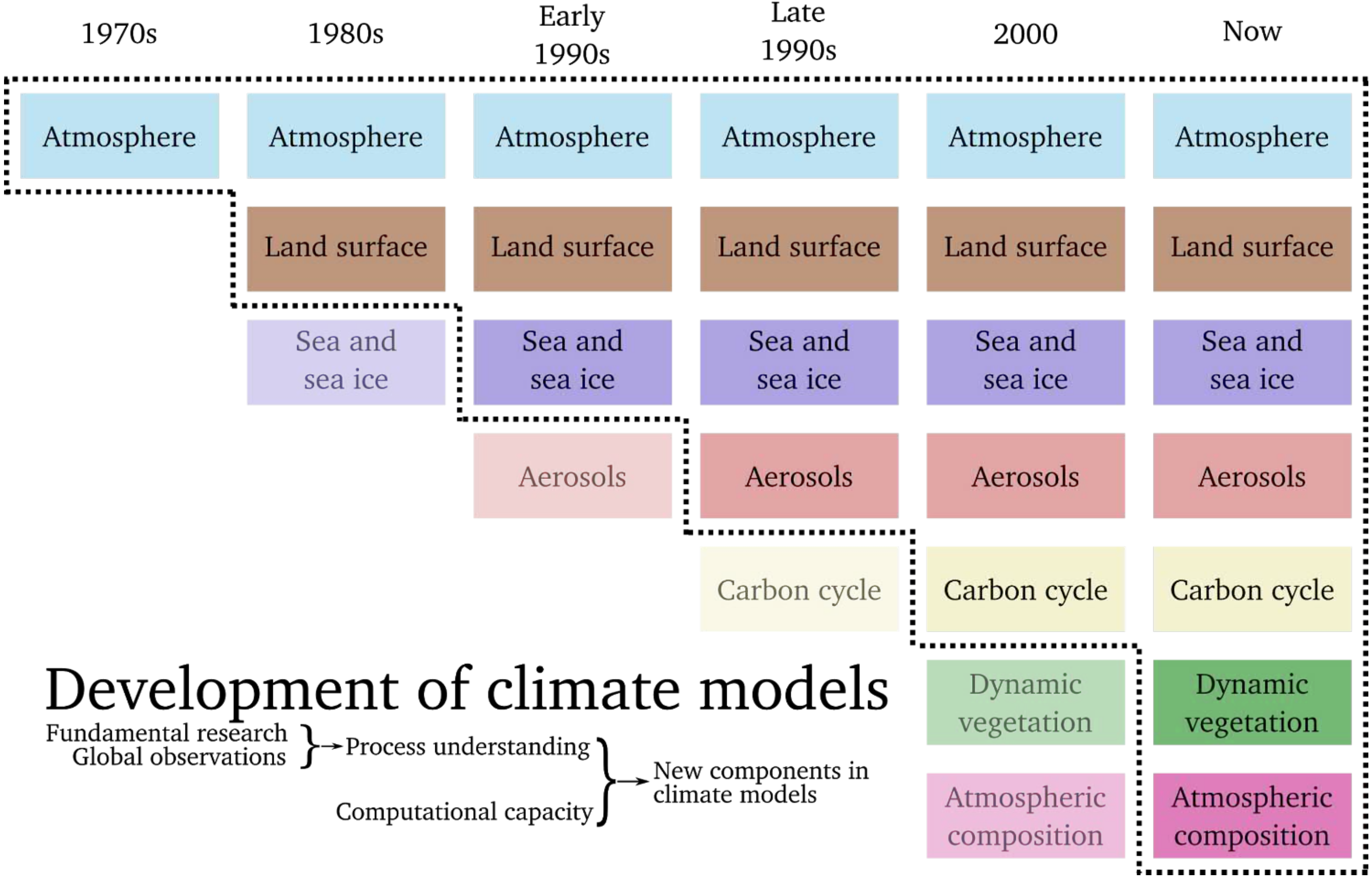


Development of climate models



Development of climate models


1970s
1980s
Early 1990s
Late 1990s
2000
Now
Atmosphere
Land surface
Sea and sea ice
Aerosols
Carbon cycle
Dynamic vegetation
Atmospheric composition
Development of climate models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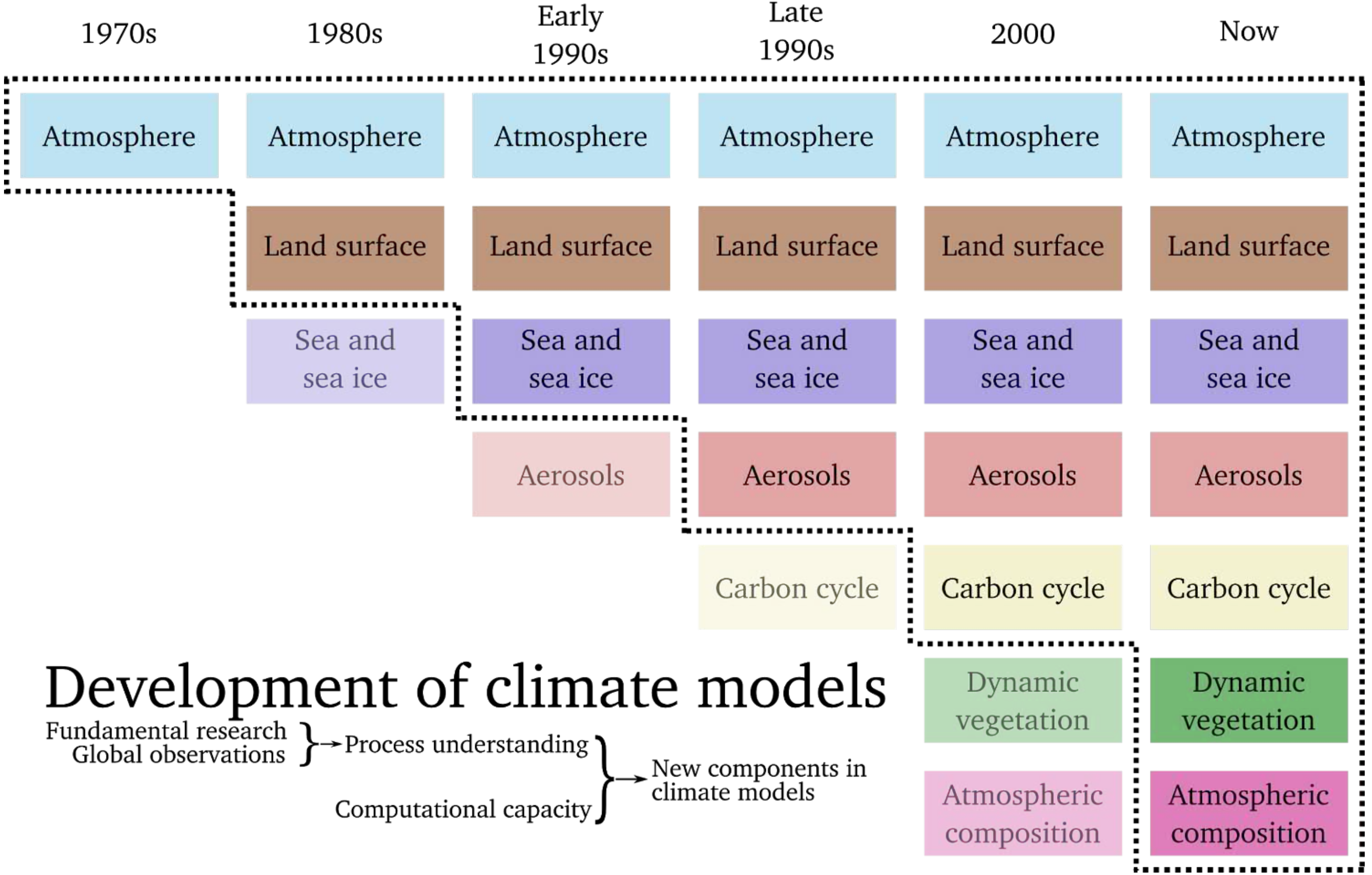
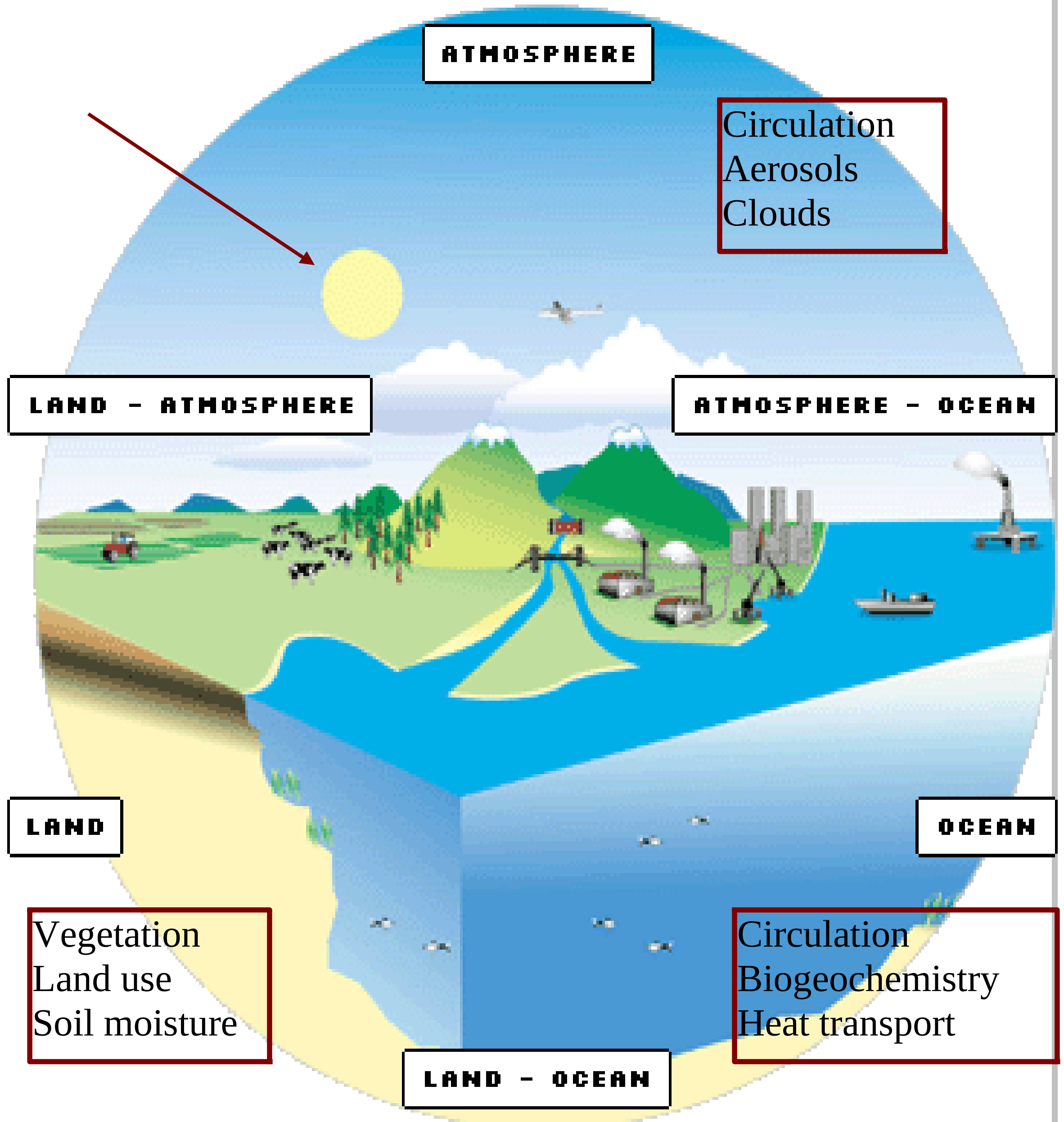
Development of climate models
Fundamental research
Global observations
Process understanding
Computational capacity
New components in climate models



Climate models are already several millions lines of code, with scientific domains competing for computational resources

Earth System (Model)

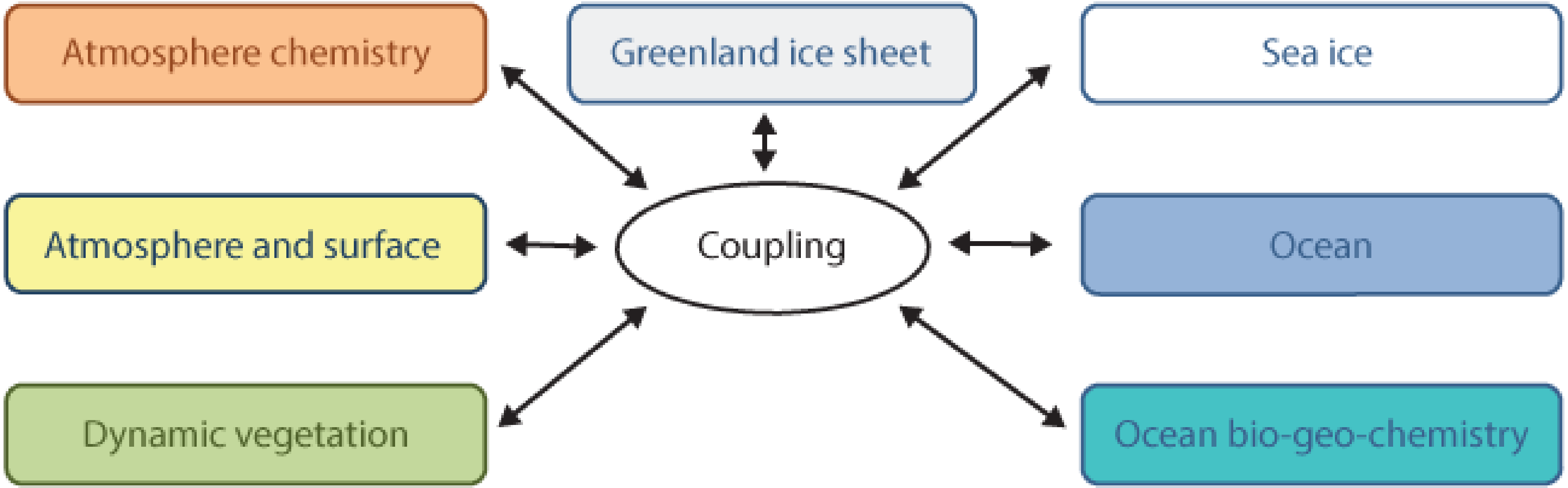
Aerosol emissions
Gaseous emissions
Deposition



Heat transfer
Momentum flux
Aerosol emissions

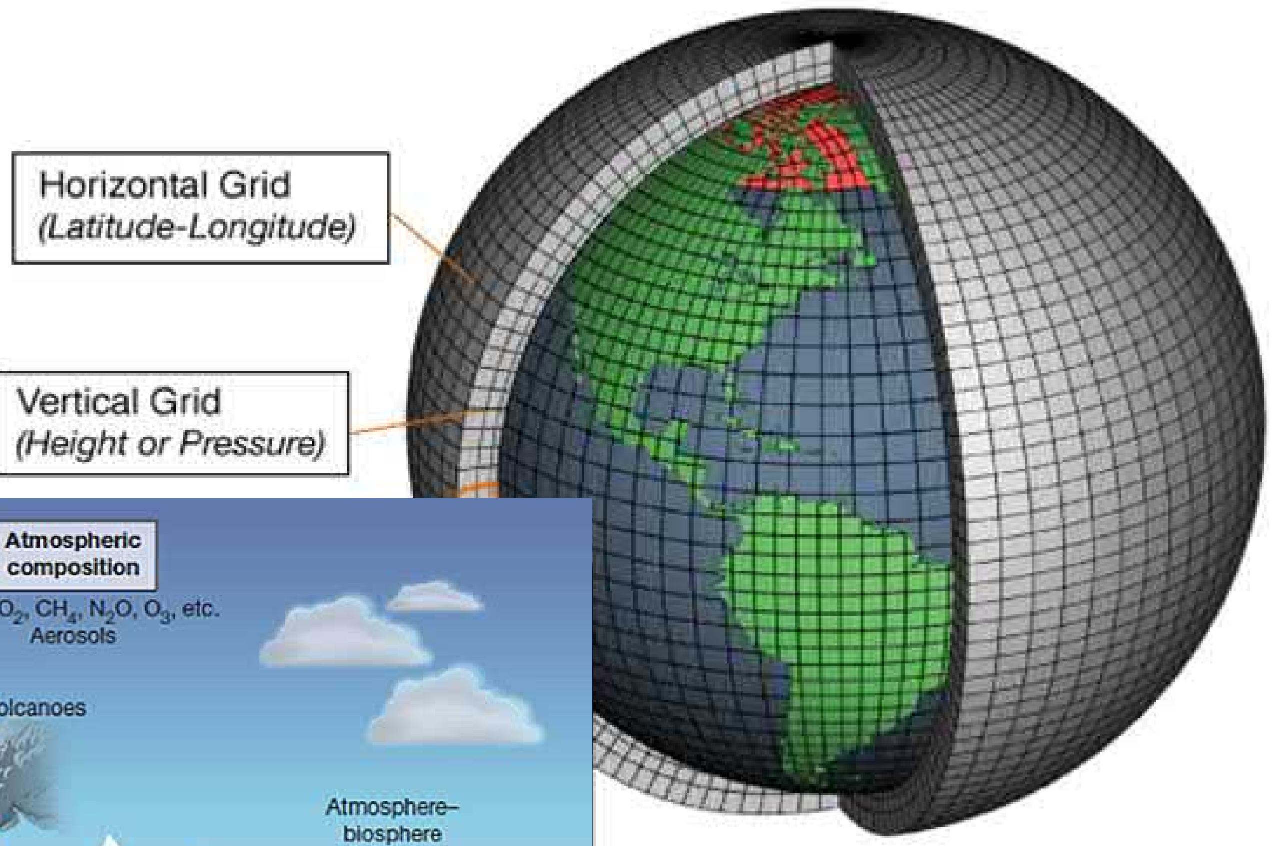
Example: EC-Earth3

- **Atmosphere**: IFS
- **Atmospheric transport and chemistry**: TM5
  - Carbon bond (CB05) mechanism (51 species,156 reactions)
- **Ocean**: NEMO, **sea-ice**: LIM, **biogeochemistry**: PISCES
- **Dynamic vegetation**: LPJ-GUESS
- **Ice sheets**: PISM

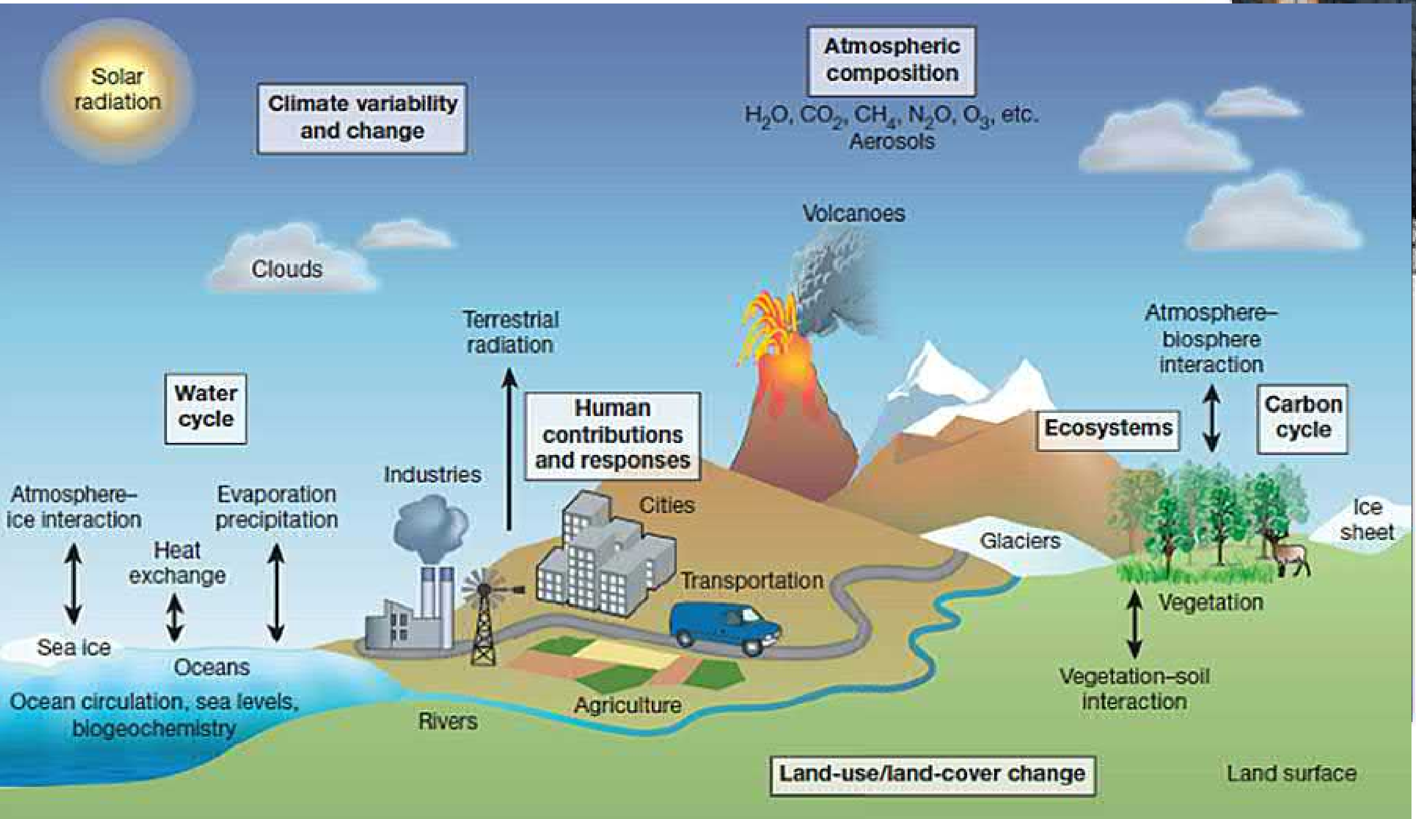


How to describe aerosols/chemistry in a global climate model?

Earth System Models

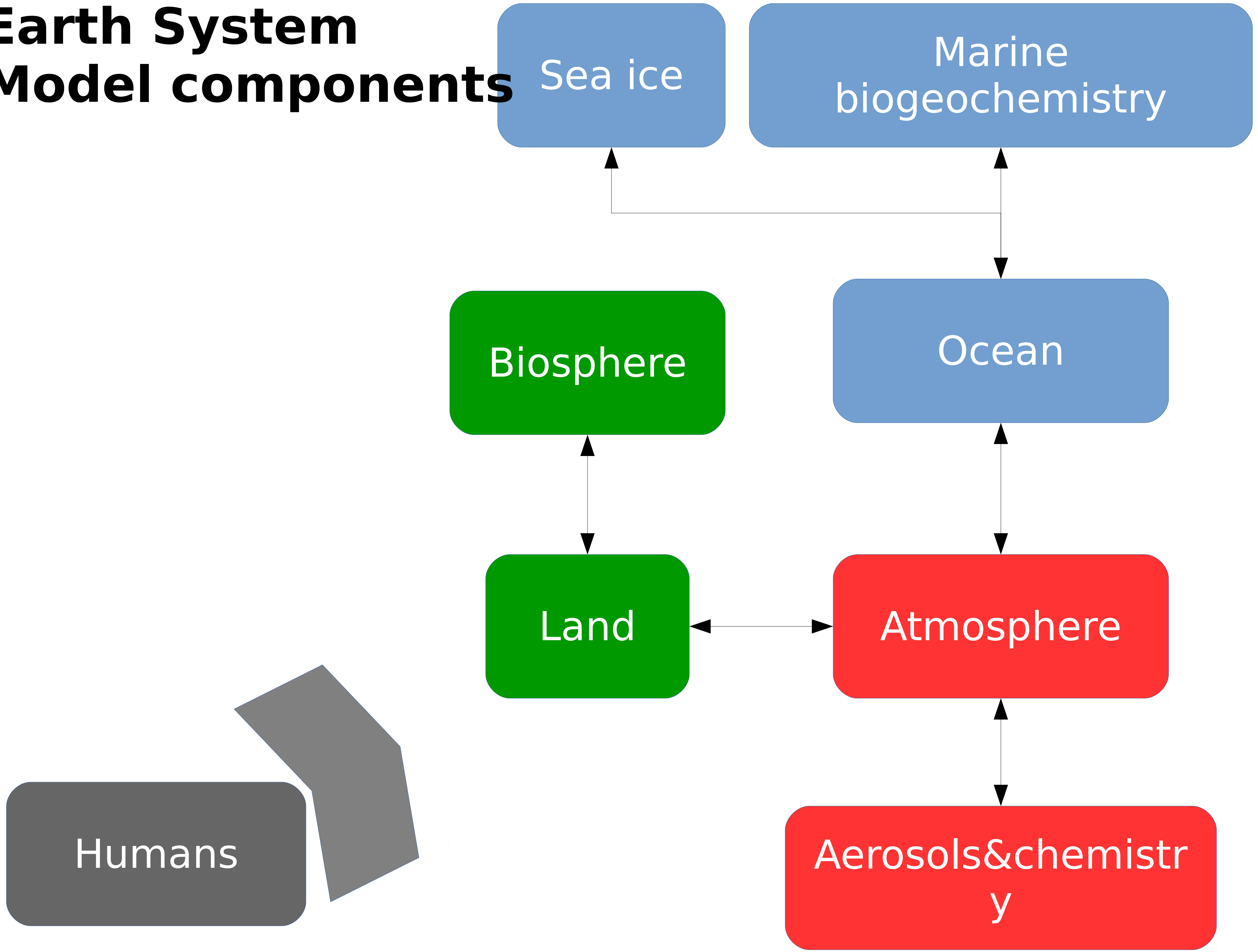


Princeton.edu



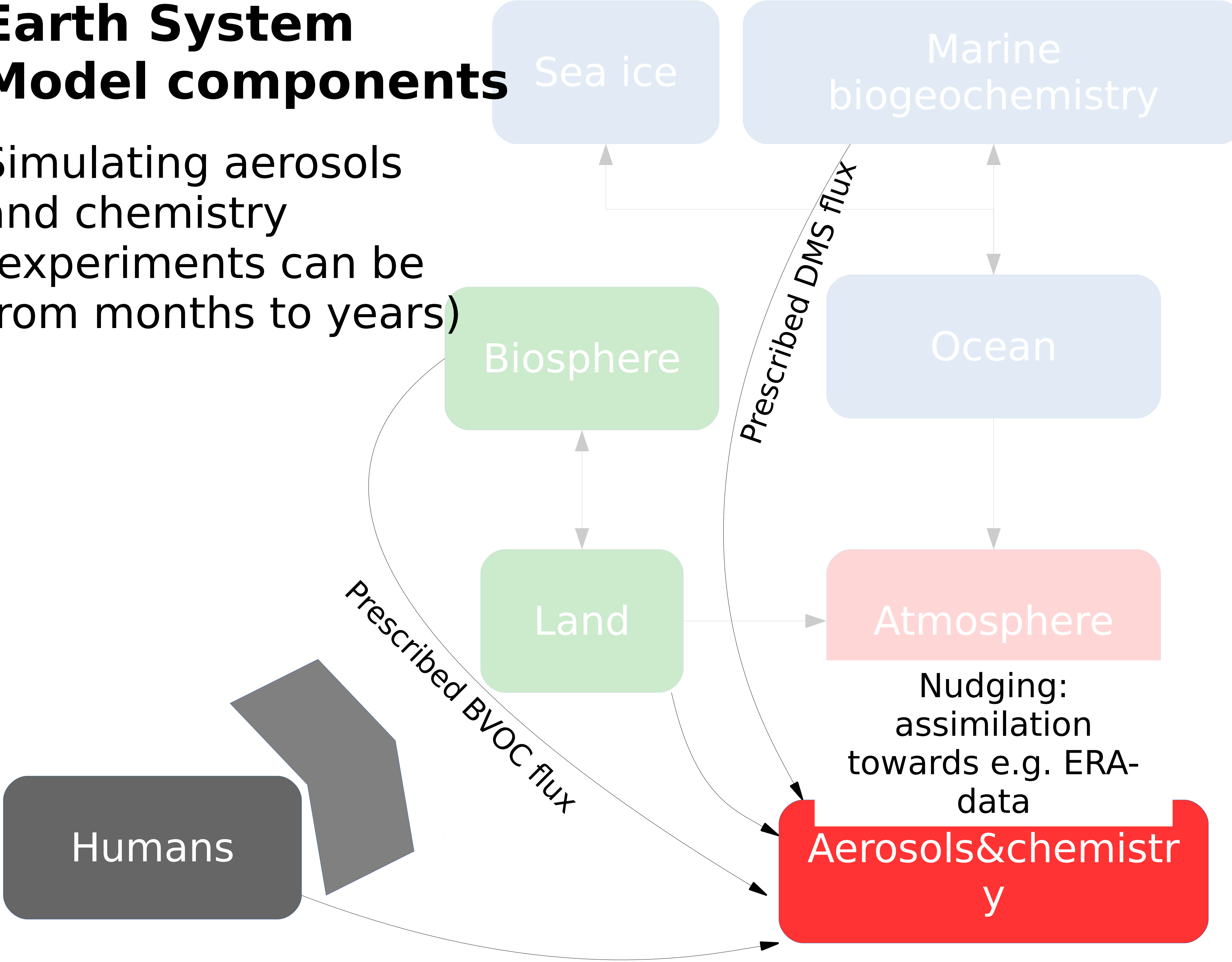
U.S. Climate Change Science Program

Earth System Model components



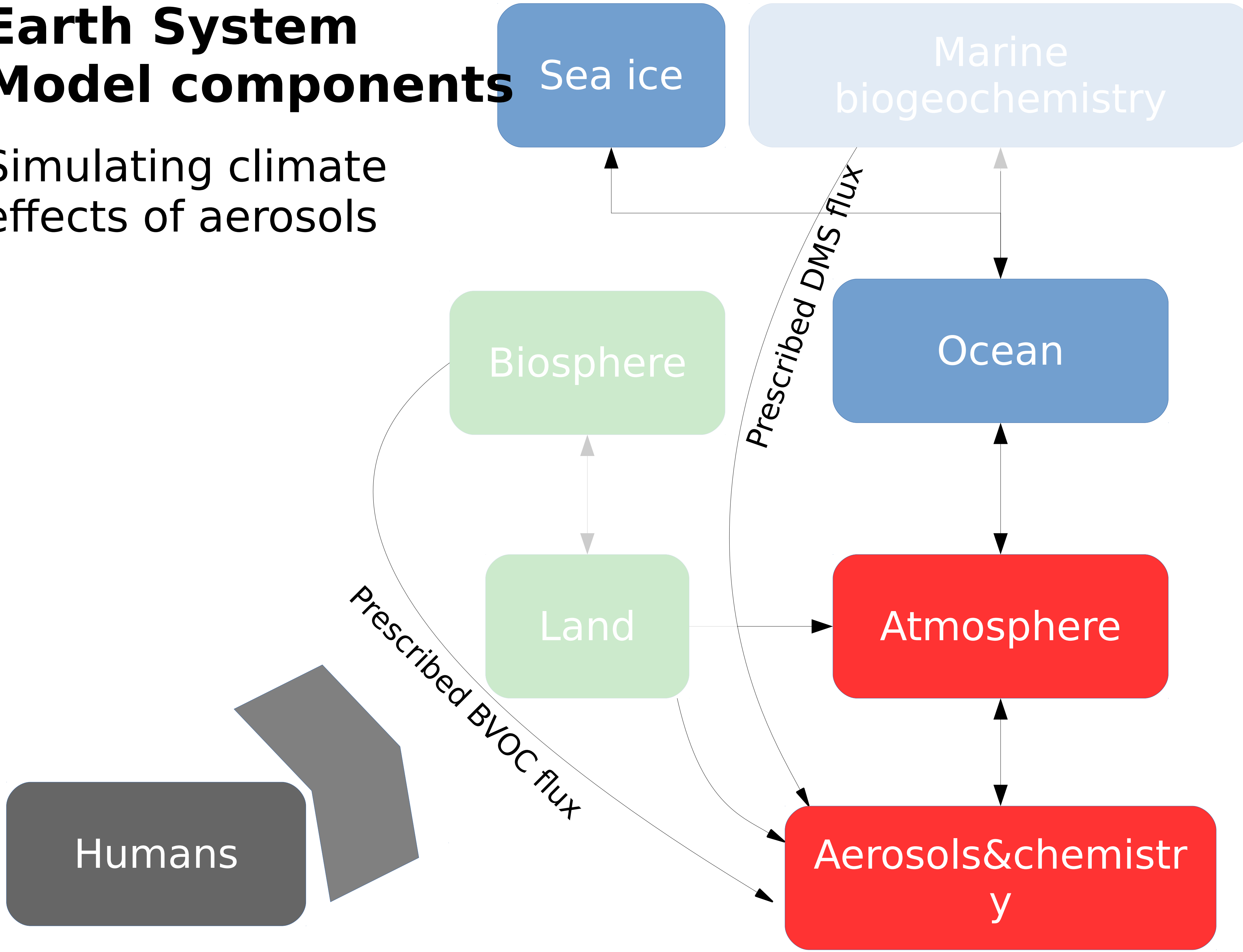
Earth System Model components

Simulating aerosols and chemistry (experiments can be from months to years)



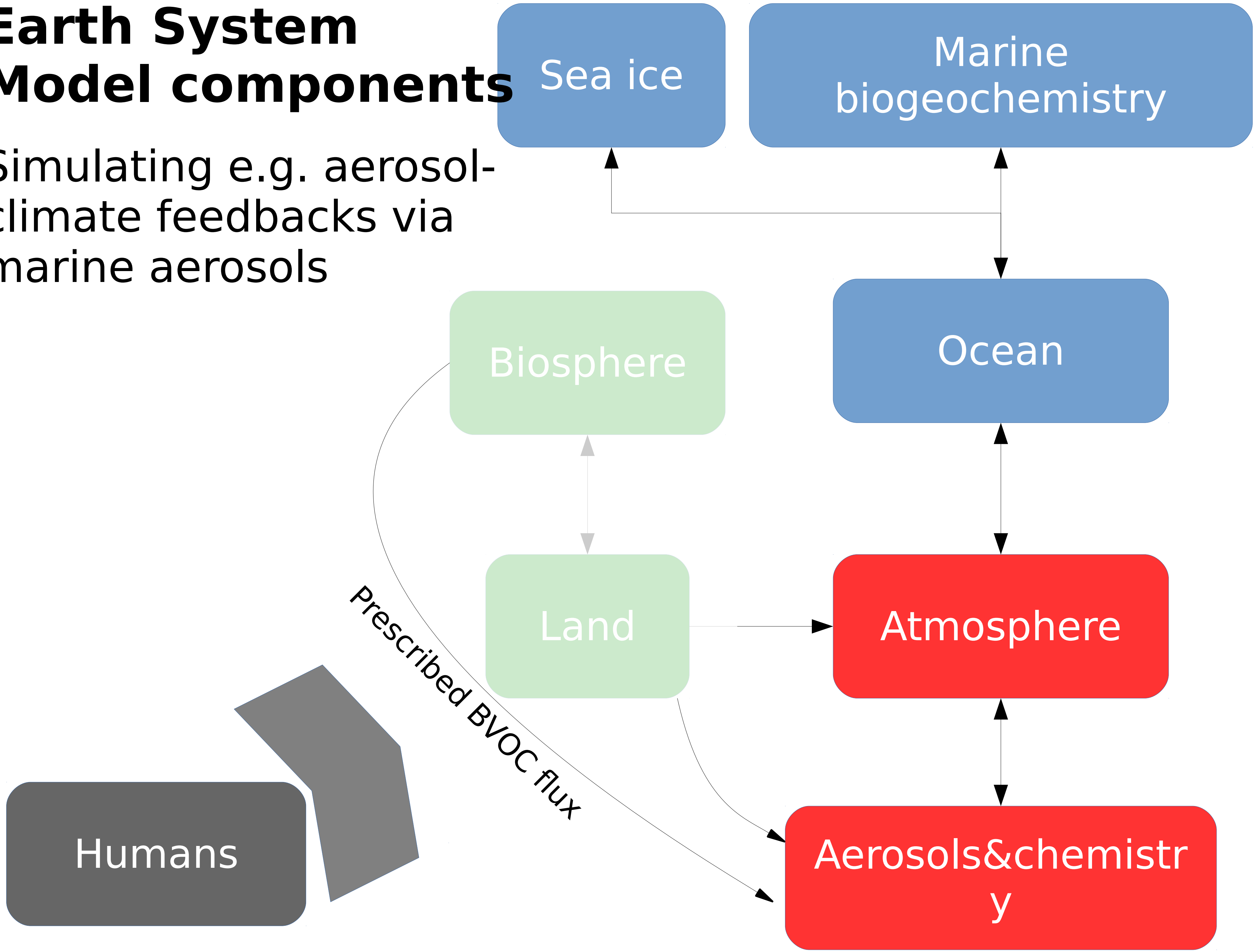
Earth System Model components

Simulating climate effects of aerosols



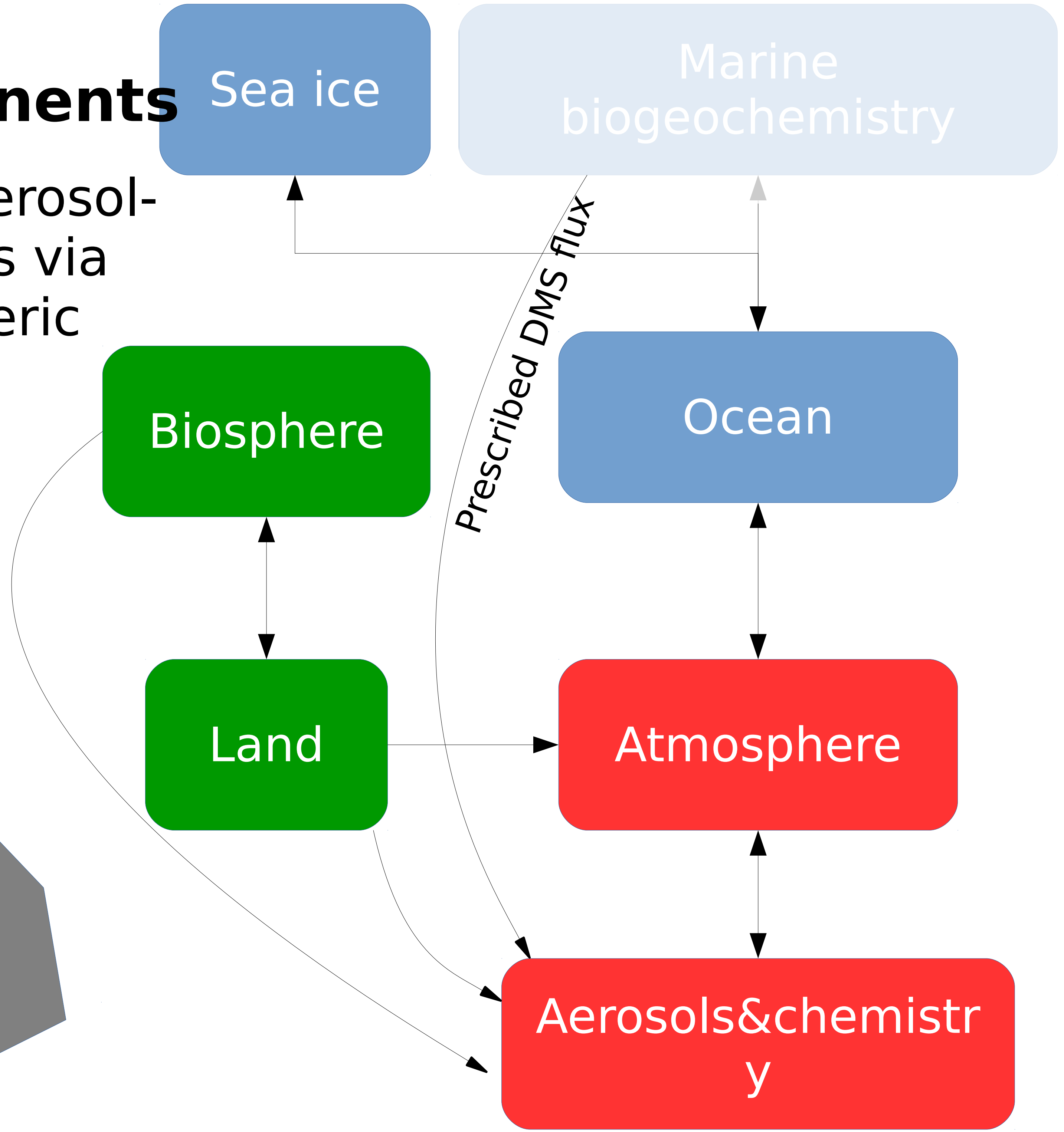
Earth System Model components

Simulating e.g. aerosol-climate feedbacks via marine aerosols



Earth System Model components

Simulating e.g. aerosol-climate feedbacks via terrestrial biospheric aerosols



Earth System Model: choice of components

Choice of ESM components is based on

- timescale of the experiment: years, decades or millenia
- variables of interest: air quality, climate change, process study
- computational resources

Model of everything related to Earth

Population model

Dynamic vegetation model

Ocean circulation model

Prescribed vegetation (type, LAI)

Mixed layer ocean

Cloud microdynamics

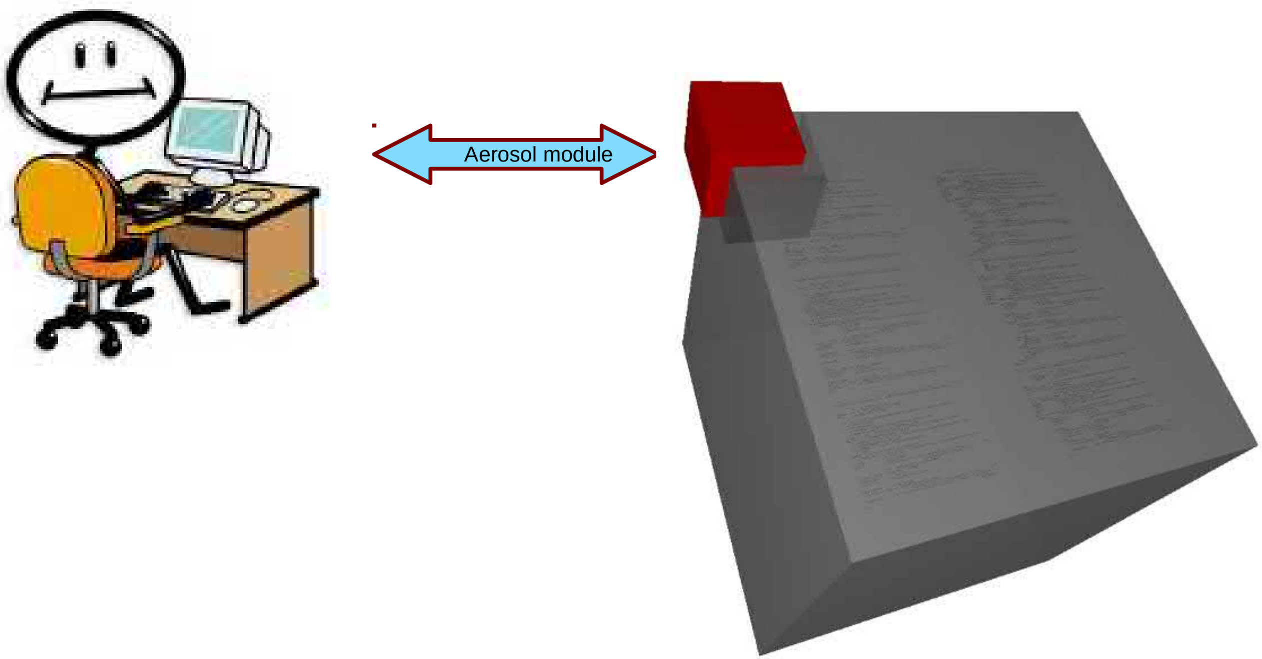
Prescribed sea surface temperatures and sea ice

Prescribed meteorology

Complexity
Computational expense
Simulated noise

Earth System Model: black box modeling

- ESM can easily have millions of lines of code
- A single researcher usually contributes only to a single module
  - Rest of the model is considered black box (“need to know” basis)



What details do we need for global aerosol modeling?

- Spatial distribution
  - unlike long-lived greenhouse gases, aerosols have a highly inhomogeneous spatial distribution
  - climate effect of an aerosol concentration (change) depends strongly on the location

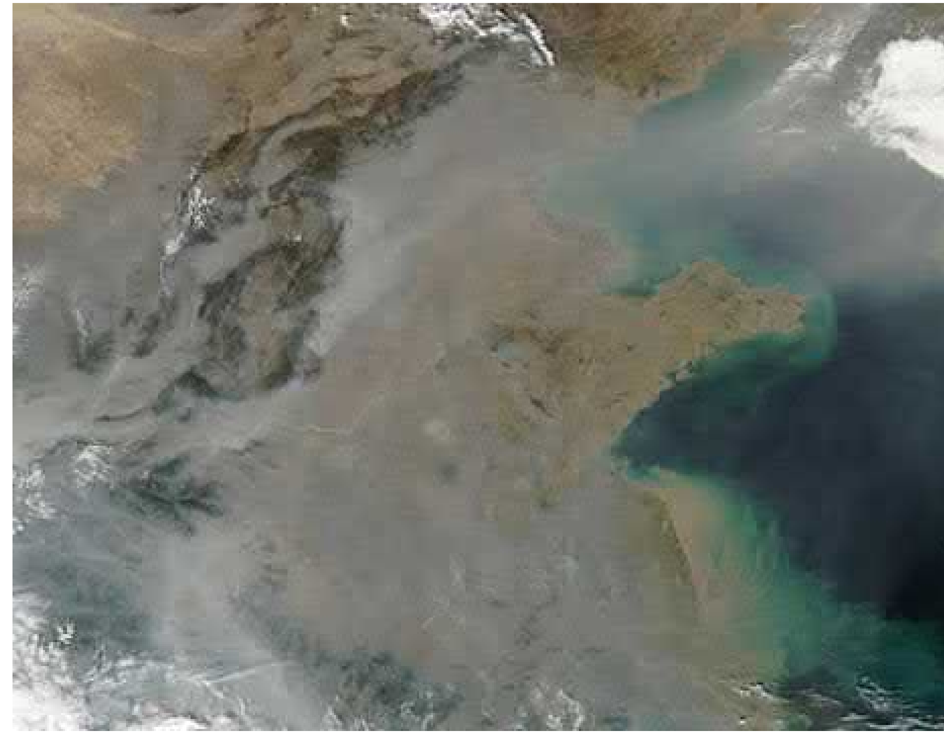
  → **need to describe the spatial distribution**
- Composition
  - different aerosol types induce distinct climate effects (e.g. scattering, absorbtion)

  → **need to describe aerosols species composition**
- Size distribution
  - aerosol size determines e.g. potential to act as cloud condensation nuclei (CCN)

  → **need to describe aerosol size distribution**
- Processes
  - Aerosols enter atmosphere either by direct emission or atmospheric formation (chemistry)
  - Particle size distribution is changing rapidly via aerosol microphysics

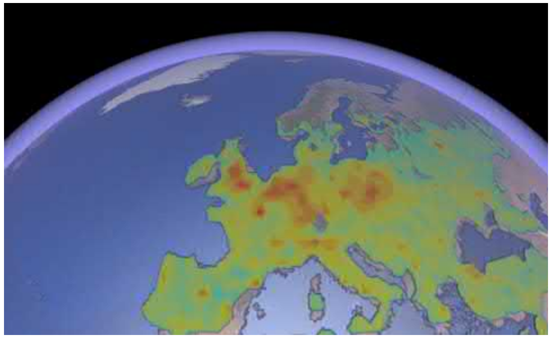
  → **need to describe atmospheric chemistry and aerosol microphysics**

What aerosol (and gas-phase) components need to be considered in a climate model?

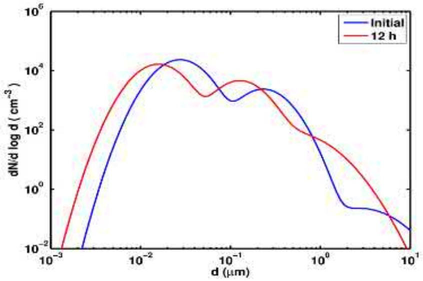





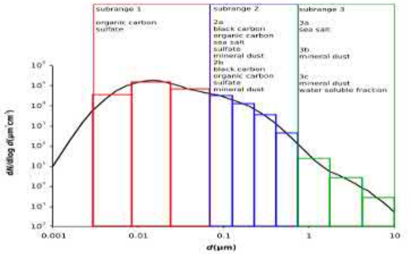

Global aerosol models



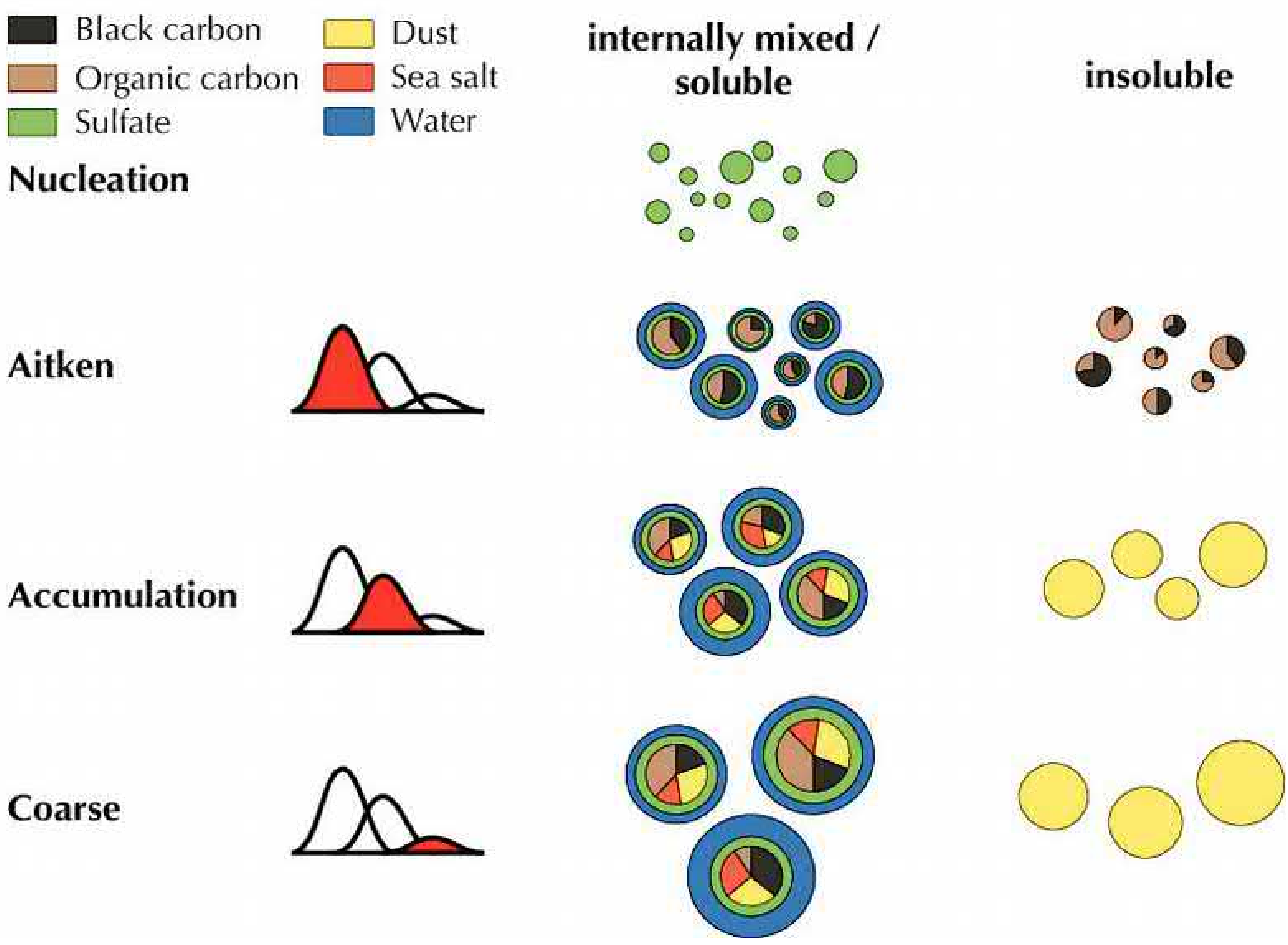
- First approximations use fixed aerosol climatologies
  - Monthly/yearly average radiative properties of aerosol
  - Based on previous simulations and satellite observations
- Aerosol mass-only models (Bulk-models)
  - No (or very limited) aerosol microphysical processes
- Modal size-resolved aerosol microphysics models
  - Aerosol distribution is represented with superposition of several log-normal modes



- Sectional size-resolved aerosol microphysics models
  - Better representation of aerosol processes, especially for growth and cloud processes



Example of global aerosol microphysics: M7   (used in e.g. ECHAM and EC-Earth)



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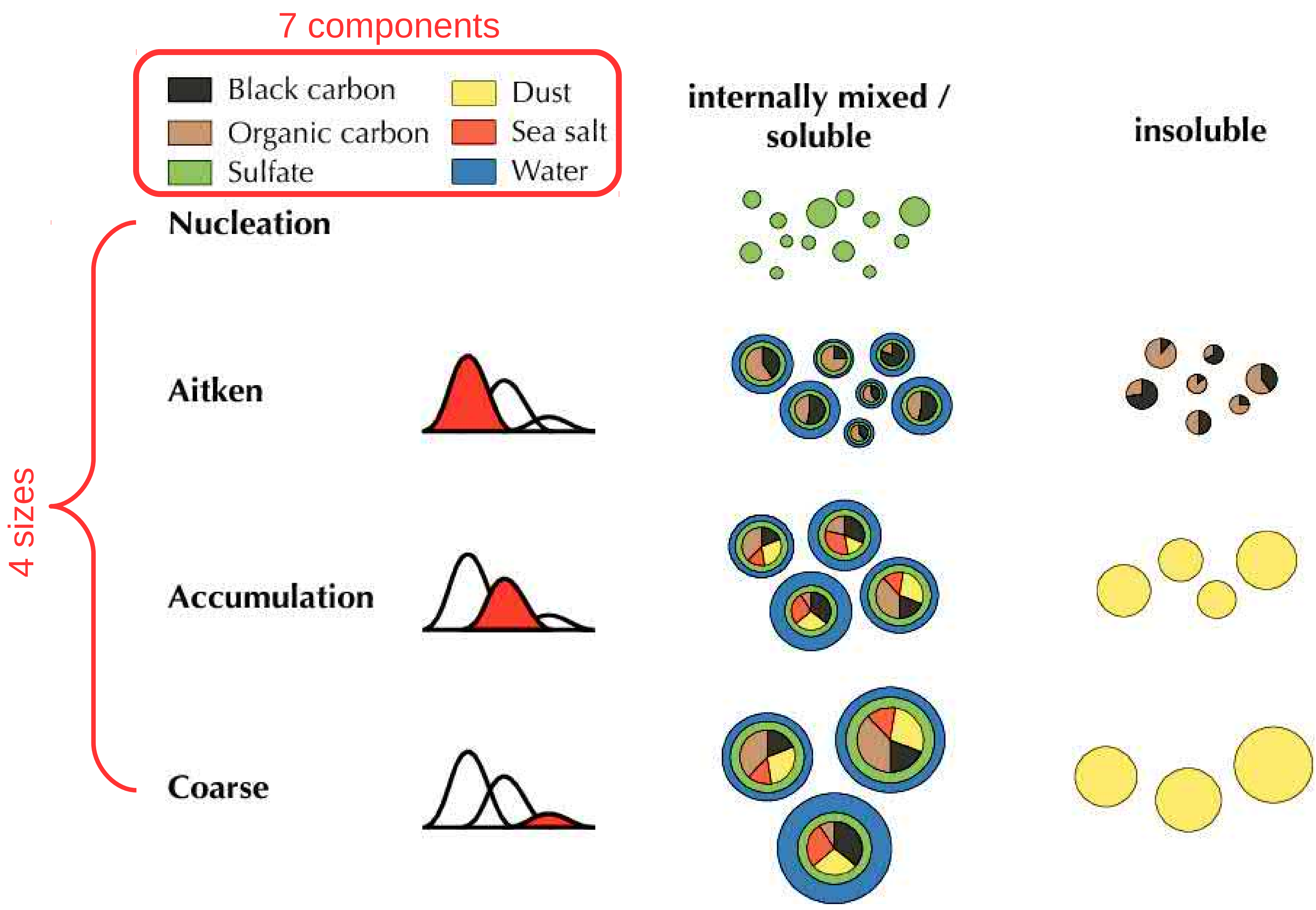
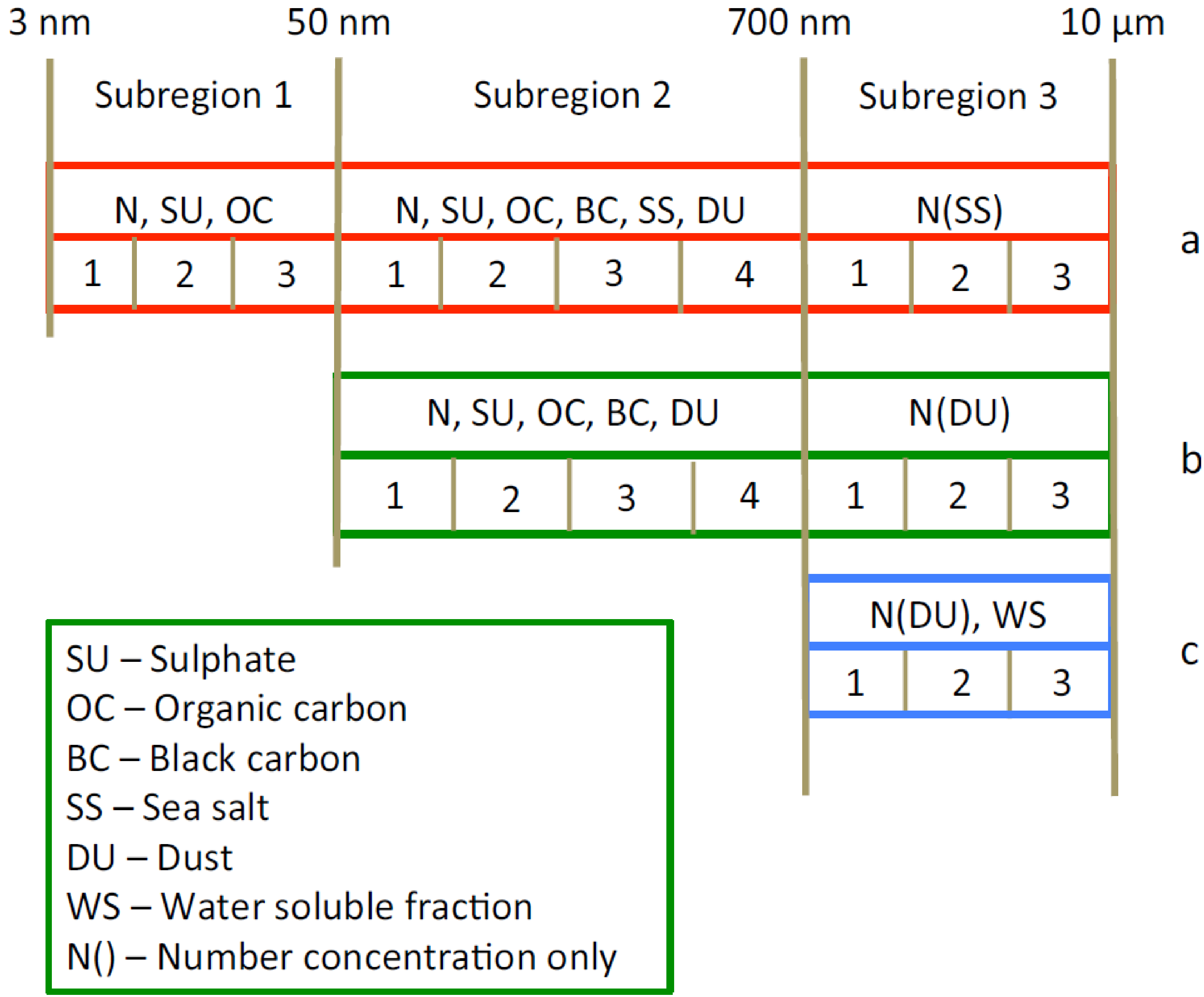
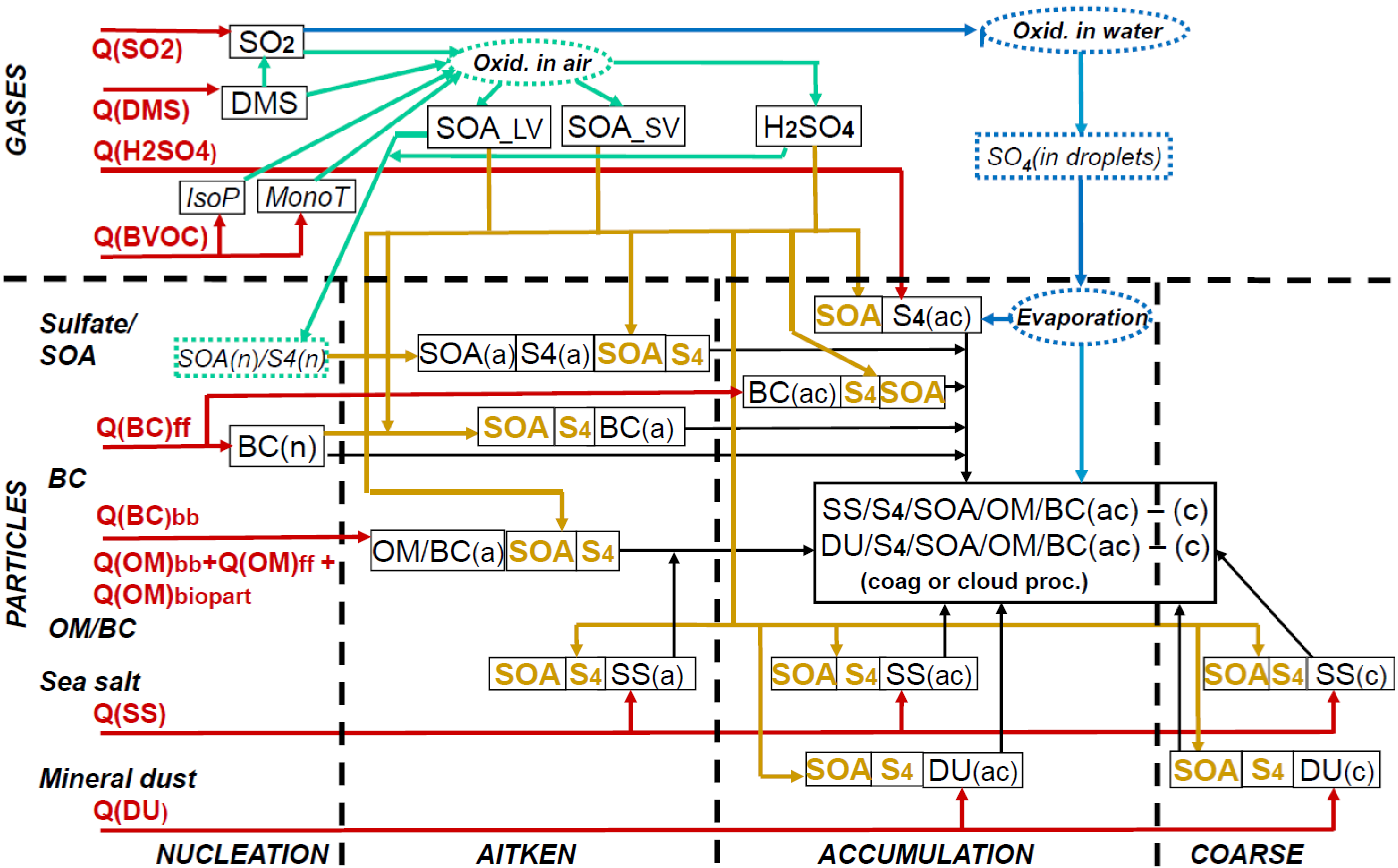


Example of global aerosol microphysics: SALSA (used in ECHAM)



Example of global aerosol microphysics: NorESM

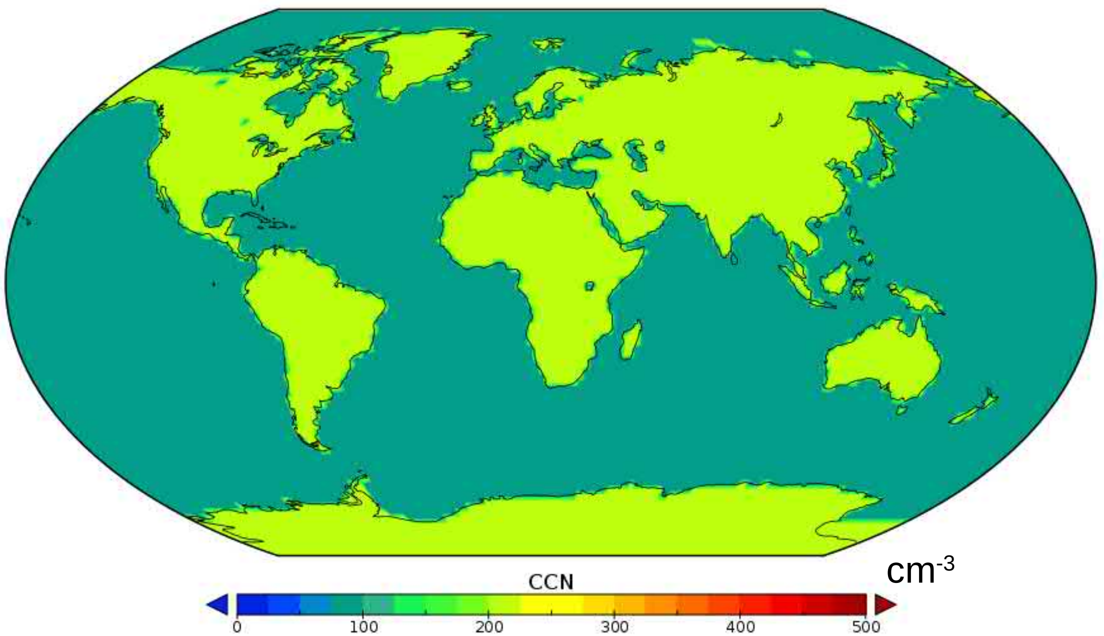


Kirkevåg et al., 2018

No aerosol information

If aerosols are not simulated, model needs to assume a prescribed monthly/annual distribution which can vary in vertical and horizontal

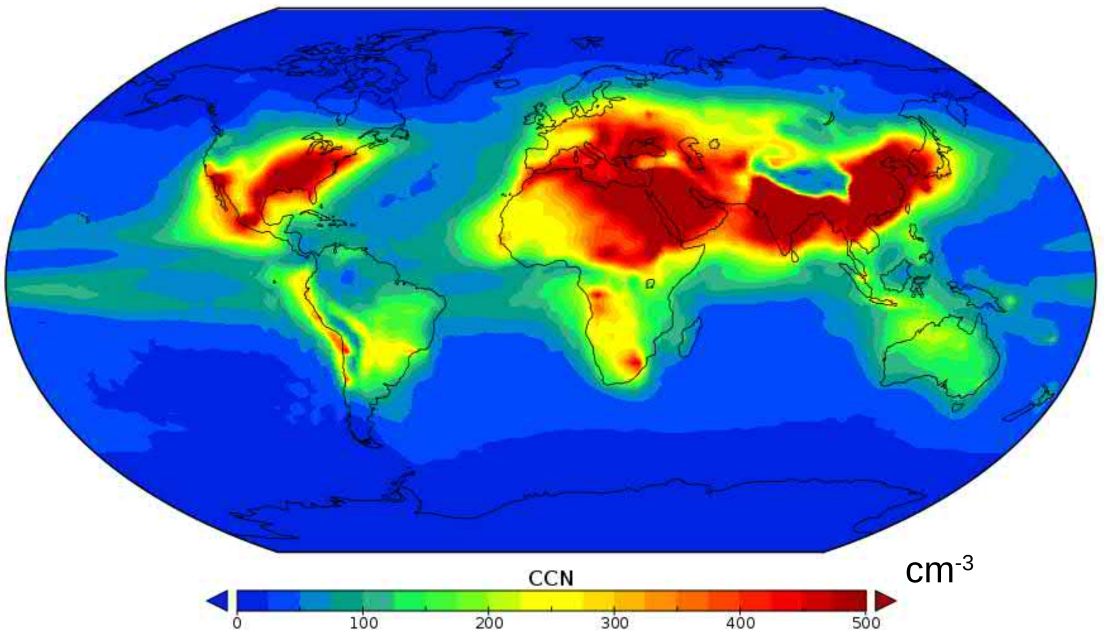
Example: ECHAM5 assumes aerosol concentrations of 80 cm-3 over ocean and 220 cm-3 over land (for cloud activation)



Interactive aerosol model

If aerosol size distribution and chemical composition is prognosted by the model, cloud condensation nuclei (CCN) can be diagnosed as $N(d_p > d_{limit})$ or at different supersaturations with (kappa-)Köhler.

Example: ECHAM5-HAM CCN(0.2%) annual average supersaturation



Atmospheric chemistry

Atmospheric chemistry in climate models

- Complete atmospheric chemistry is impossible to model
  - E.g. Master Chemical Mechanism (near-explicit chemical mechanism for VOC degradation): 142 primary compounds, >6000 resulting species, over 13500 reactions
- Tracers are expensive
- Typically 2+ options for chemistry

1) Fixed oxidant fields, basic sulfur chemistry, limited organic chemistry – FAST
2) Extended (“full”) chemistry, 30-80 chemical species, 100-200 reactions – EXPLICIT

   (Examples: MOZART, CB05 chemical mechanisms)

Atmospheric chemistry in climate models

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For example, chemistry mechanism in EC-Earth:

27 transported species
15 non-transported species

Chemical trace species	(continued)	(continued)
O_3	ORGNTR[5]	OH
NO_x	ISOP	NO_2
H_2O_2	SO_2	NO_3
CH_4	DMS	N_2O_5
CO	NH_3	HNO_4
HNO_3	NH_4^{+}[8]	CH_3COCHO
CH_3OOH	MSA	C_2O_3
CH_2O	SO_4^{2-}[6]	ROR[9]
PAR[1]	NO_3^{-}[7]	RXPAR[10]
C_2H_4	^{222}Rn	XO_2 [11]
OLE[2]	^{210}Pb	XO_2N[12]
ALD2[3]	NO	NH_2
PAN	HO_2	
ROOH[4]	CH_3O_2	

Atmospheric chemistry in climate models

Reactants	Products	Rate expression	Reference
$NO + O_3$	NO_2	3.0E-12*exp(−1500/T)	[1]
$NO + HO_2$	$NO_2 + OH$	3.5E−12*exp(250/T)	[1]
$NO + CH_3O_2$	$CH_2O + HO_2 + NO_2$	2.8E-12*exp(300/T)	[1]
$NO_2 + OH\ (+ M)$	HNO_3	K_0 = 1.8E-30*(300/T)$^{3.0}$ K_∞ = 2.8E−11	[1]
$OH + HNO_3$	NO_3	K_0 = 2.41E−14*(460/T) K_2 = 6.51E−34*(1335/T) K_3 = 2.69E−17*(2199/T)	[1]
$NO_2 + O_3$	NO_3	1.2E−13*exp(-2540/T)	[1]
$NO + NO_3$	$NO_2 + NO_2$	1.5E−11*exp(170/T)	[1]
$NO_2 + NO_3$	N_2O_5	K_0 = 2.0E−30*(300/T)$^{4.4}$ K_∞ = 1.4E−12*(300/T)$^{0.7}$	[1]
N_2O_5	$NO_2 + NO_3$	2.7E−27*exp(11 000/T)	[1]
$OH + HNO_4$	NO_2	1.3E−12*exp(380/T)	[1]
$NO_2 + HO_2$	HNO_4	K_0 = 2.0E−31*(300/T)$^{3.4}$ K_∞ = 2.9E−12*(300/T)$^{1.1}$	[1]
$HNO_4\ (+ M)$	$NO_2 + HO_2$	2.1E−27*exp(10900/T)	[1]
$O(^1D)\ (+ M)$		3.3E−11*exp(55/T)*[O_2] + 2.15E11*exp(110/T)*[N_2]	[1]
$O(^1D) + H_2O$	$OH + OH$	1.63E−10*exp(60/T)	[1]
$O_3 + HO_2$	OH	1.0E-14*exp(−490/T)	[1]

Example, chemistry mechanism in EC-Earth

Example, chemistry mechanism in EC-Earth

Reactants	Products	Rate expression	Reference
$CO + OH$	HO_2	$K_0 = 5.9E{-}33*(300/T)^{1.4}$	[1]
		$K_\infty = 1.1E{-}12*(300/T)^{-1.3}$	
		$K_0 = 1.5E{-}13*(300/T)^{-0.6}$	
		$K_\infty = 2.1E9*(300/T)^{-6.1}$	
$O_3 + OH$	HO_2	$1.7E{-}12*exp(-940/T)$	[1]
$OH + H_2O_2$	HO_2	$1.8E{-}12$	[1]
$OH + CH_2O$	$CO + HO_2$	$5.5E{-}12*exp(125/T)$	[1]
$OH + CH_4$	CH_3O_2	$2.45E{-}12*exp(-1775/T)$	[1]
$OH + CH_3OOH$	$0.7\ CH_3O_2 + 0.3\ CH_2O + 0.3\ OH$	$3.8E{-}12*exp(200/T)$	[1]
$OH + ROOH$	$0.7\ XO_2 + 0.3\ OH$	$3.01E{-}12*exp(190/T)$	[2]
$CH_3O_2 + HO_2$	CH_3OOH	$4.1E{-}13*exp(750/T)$	[1]
$CH_3O_2 + CH_3O_2$	$1.33\ CH_2O + 0.67\ HO_2$	$9.5E{-}14*exp(390/T)$	[1]
$OH + HO_2$		$4.8E{-}11*exp(250/T)$	[1]
$HO_2 + HO_2$	H_2O_2	$3.5E{-}13*exp(430/T)$	[1]
		$1.77E{-}33*exp(1000/T)$	
		$1.4E{-}21*exp(2200/T)$	
$OH + H_2$	HO_2	$2.8E{-}12*exp(-1800/T)$	[1]
$NO_3 + CH_2O$	$HNO_3 + CO + HO_2$	$5.8E{-}16$	[1]
ALD2 + OH	C_2O_3	Average of :	[3]
		$4.4E{-}12*exp(365/T)$	[3]
		$5.1E{-}12*exp(405/T)$	
ALD2 + NO_3	$C_2O_3 + HNO_3$	Average of :	[3]
		$1.4E{-}12*exp(-1860/T)$	[3]
		$6.5E{-}15$	
$NO + C_2O_3$	$CH_2O + XO_2 + HO_2 + NO_2$	$8.1E{-}12*exp(270/T)$	[1]
$NO_2 + C_2O_3$	PAN	$K_0 = 2.7E{-}28*(300/T)^{7.1}$	[3]
		$K_\infty = 1.2E{-}11*(300/T)^{0.9}$	

Reactants	Products	Rate expression	Reference
PAN	$NO_2 + C_2O_3$	$K_0 = 4.9E{-}3*\exp(-12100/T)$	[3]
		$K_\infty = 5.4E16*\exp(-13\,830/T)$	
$C_2O_3 + C_2O_3$	$2\ CH_2O + 2\ XO_2 + 2\ HO_2$	$2.9E{-}12*\exp(500/T)$	[1]
$C_2O_3 + HO_2$	$CH_2O + XO_2 + HO_2 +$	$4.3E{-}13*\exp(1040/T)$	[1]
	$0.79\ OH + 0.21\ ROOH$		
OH + PAR	$0.87\ XO_2 + 0.76\ ROR + 0.11\ HO_2 +$	$8.1E{-}13$	[4]
	$0.11\ ALD2 + 0.11\ RXPAR + 0.13\ XO_2N$		
ROR	$1.1\ ALD2 + 0.96\ XO_2 + 0.04\ XO_2N +$	$1E15*\exp(-8000/T)$	[4]
	$0.02\ ROR + 2.1\ RXPAR + 0.94\ HO_2$		
ROR	HO_2	1600.0(*)	[4]
OH + OLE	$CH_2O + ALD2 + XO_2 + HO_2 + RXPAR$	Average of :	[3]
		$1.86E{-}11*\exp(175/T)$	[3]
		$8.12E{-}12*\exp(610/T)$	[3]
		$2.6E{-}12*\exp(610/T)$	
O_3 + OLE	$0.44\ ALD2 + 0.64\ CH_2O + 0.25\ HO_2 + 0.29\ XO_2 +$	Average of :	[3]
	$0.37\ CO + 0.9\ RXPAR +$	$8.5E{-}16*\exp(-1520/T)$	[3]
	$0.4\ OH$	$1.4E{-}15*\exp(-2100/T)$	[3]
		$1.0E{-}17$	
NO_3 + OLE	$0.91\ XO_2 + CH_2O + 0.09\ XO_2N + NO_2 + ALD2$	Average of :	[3]
	+ RXPAR	$4.0E{-}14*\exp(-400/T)$	[3]
		$6.0E{-}16$	[3]
		$3.5E{-}15$	
$OH + C_2H_4\ (+M)$	$HO_2 + 1.56\ CH_2O + 0.22\ ALD2 + XO_2$	$K_0 = 1.0E{-}28*(300/T)^{4.5}$	
		$K_\infty = 8.8E{-}12*(300/T)^{0.85}$	
$O_3 + C_2H_4$	$CH_2O + 0.26\ HO_2 + 0.12\ OH + 0.43\ CO$	$1.2E{-}14*\exp(-2630/T)$	[1]
$OH + CH_3COCHO$	$XO_2 + C_2O_3$	$1.5E{-}11$	[3]

Example, chemistry mechanism in EC-Earth

Reactants	Products	Rate expression	Reference
OH + ISOP	0.85 XO_2 + 0.61 CH_2O + 0.58 OLE + 0.85 HO_2 + 0.15 XO_2N + 0.03 CH_3COCHO + 0.63 PAR	2.7E−11*exp(390/T)	[3]
O_3 + ISOP	0.9 CH_2O + 0.55 OLE + 0.36 CO + 0.15 C_2O_3 + 0.63 PAR + 0.3 HO_2 + 0.18 XO_2 + 0.03 CH_3COCHO + 0.28 OH	1.04E−14*exp(−1995/T)	[3]
NO_3 + ISOP	0.9 HO_2 + 0.9 ORGNTR + 0.45 OLE + 0.12 ALD2 + 0.08 CH_3COCHO + 0.1 NO_2 + 0.03 CH_2O	3.15E−12*exp(−450/T)	[3]
NO + XO_2	NO_2	2.6E−12*exp(365/T)	[2]
XO_2 + XO_2		6.8E−14[KC81]	[2] [3]
NO + XO_2N	ORGNTR	2.6E−12*exp(365/T)[KC79]	[2]
HO_2 + XO_2	ROOH	7.5E−13*exp(700/T)[KC82]	[2]
PAR + RXPAR		8E−11	[4]
OH + ORGNTR	NO_2 + XO_2	5.9E−13*exp(−360/T)	[2]
HO_2 + XO_2N	ROOH	(KC81*KC82)/KC79	[5]
DMS + OH	SO_2	1.1E−11*exp(−240/T)	[1]
DMS + OH	0.75 SO_2 + 0.25 MSA	1.0E−39*exp(5820/T) 5.0E−30*exp(6280/T)	[1]
DMS + NO_3	SO_2	1.9E−13*exp(520/T)	[6]
OH + SO_2	SO_4^{2-}	K_0 = 3.3E−31*$(300/T)^{4.3}$ K_∞ = 1.6E−12*(300/T)	[1]
OH + NH_3	NH_2	1.7E−12*exp(−710/T)	[1]
NO + NH_2		4.0E−12*exp(450/T)	[1]
NO_2 + NH_2		2.1E−12*exp(650/T)	[1]
HO_2 + NH_2		3.4E−11	[1]
O_2 + NH_2		6.0E−21	[1]
O_3 + NH_2		4.3E−12*exp(−930/T)	[1]

Example, chemistry mechanism in EC-Earth

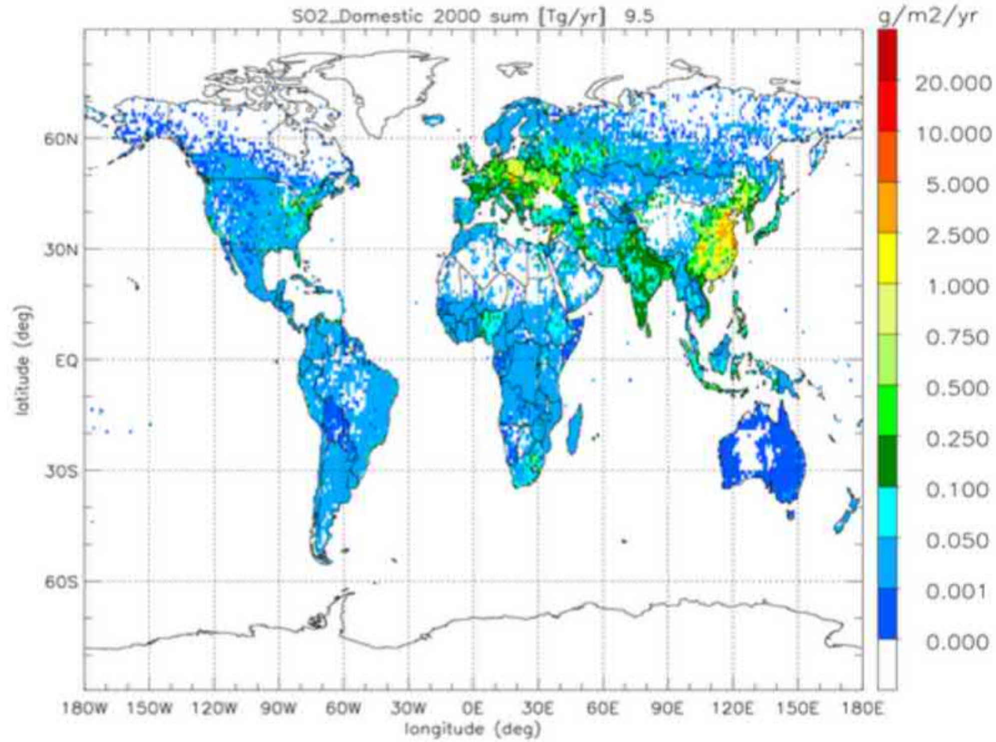
Atmospheric chemistry in climate models

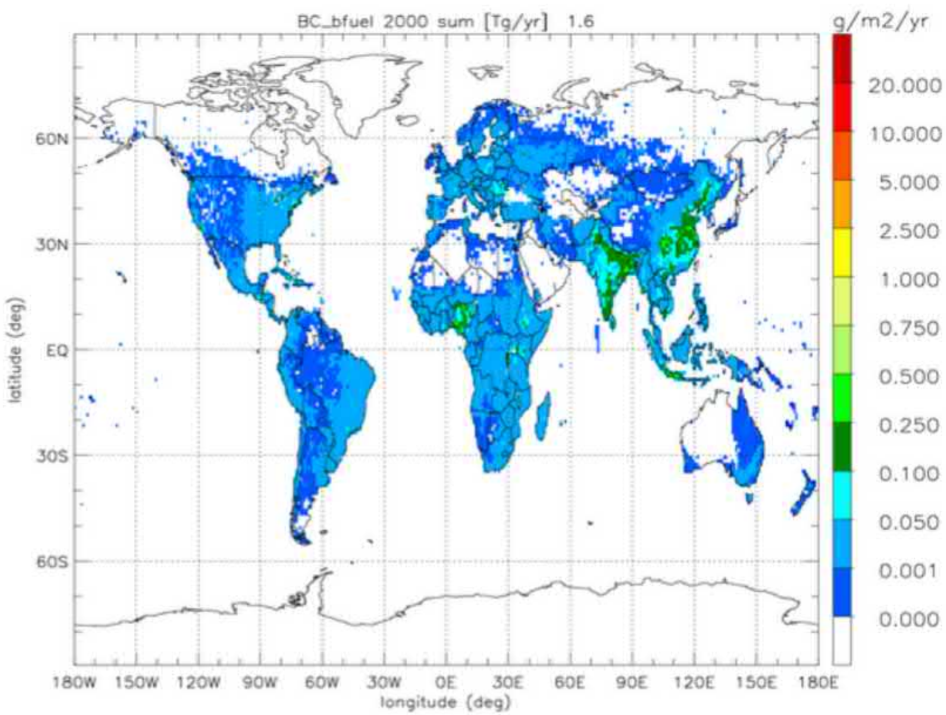
- In addition to gas-phase reactions, there is heterogeneous and aqueous-phase chemistry
  - e.g. oxidation of SO_2 by H_2O_2 and O_3 in cloud-phase and aerosol-phase (aqueous)
  - Conversion of N_2O_5 to HNO_3 on cloud droplets
  - Organic reactions and formation of secondary organic aerosol in aqueous-phase

How to include sources of aerosols?

Anthropogenic aerosol and precursor sources

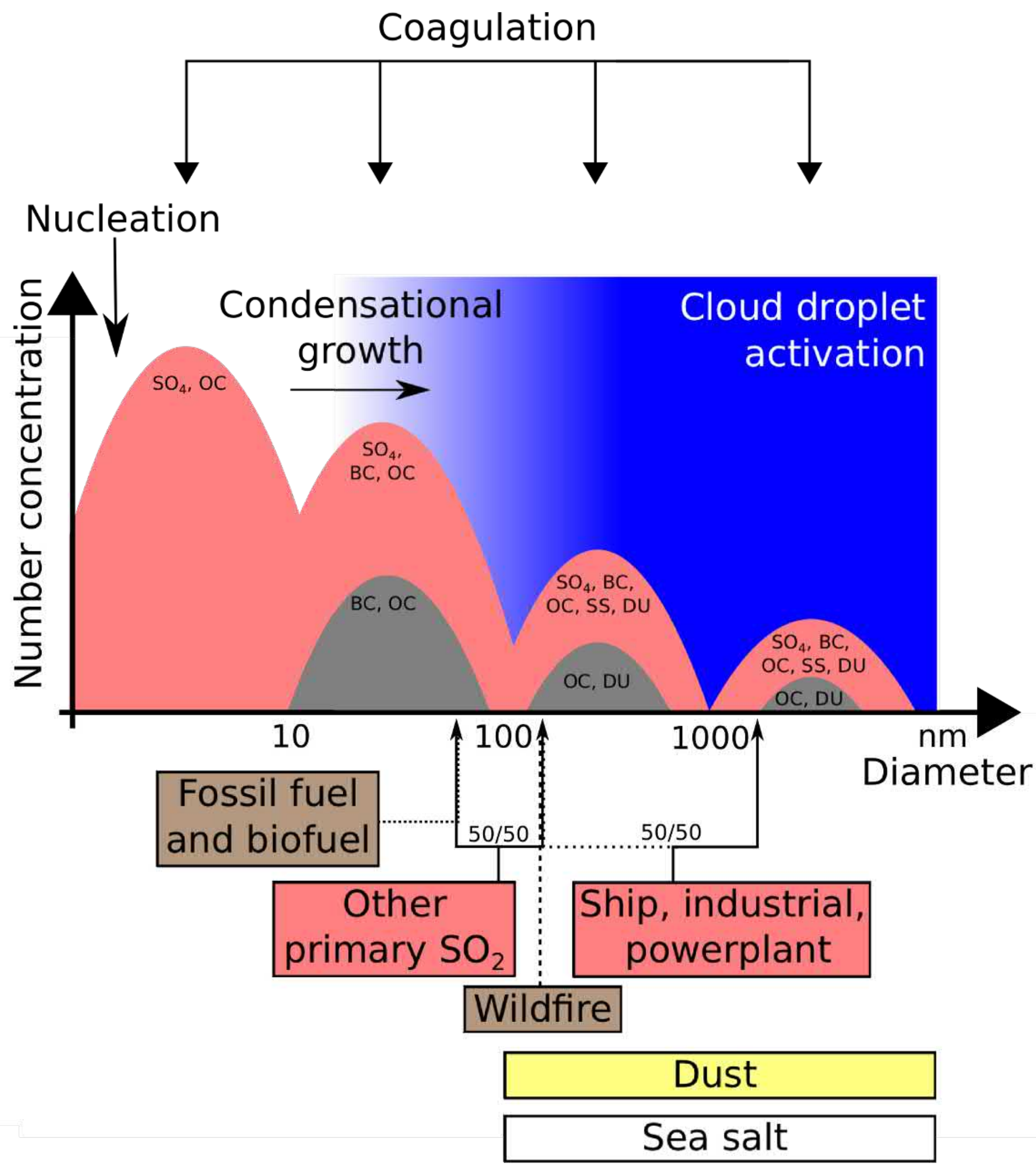
- Typically, anthropogenic emissions are
  - Prescribed annual or monthly maps
  - Primary aerosols: black carbon, organic carbon
  - Precursors: SO_2, NH_3, aromatics, …
  - Sectoral information (industry, power generation, traffic, …)
  - Limited vertical profiles: typically low (surface) and high (e.g. stack) emissions
  - No size information: model-specific assumptions for emission size-distribution, typically log-normal distribution





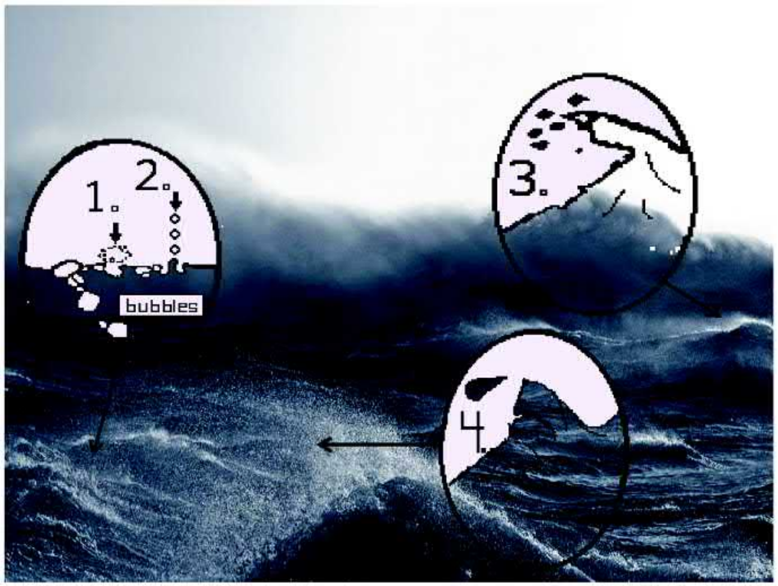
Dentener et al., 2006

What size is assumed for aerosol emissions: M7 (used in e.g. ECHAM and EC-Earth)

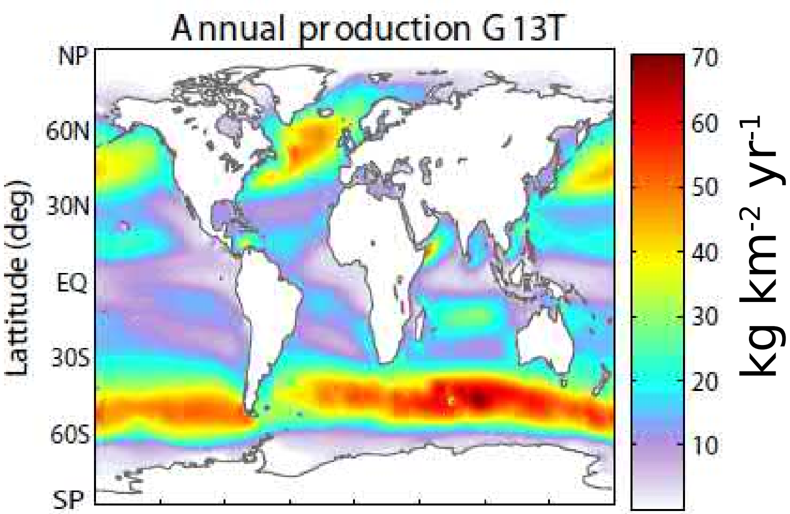


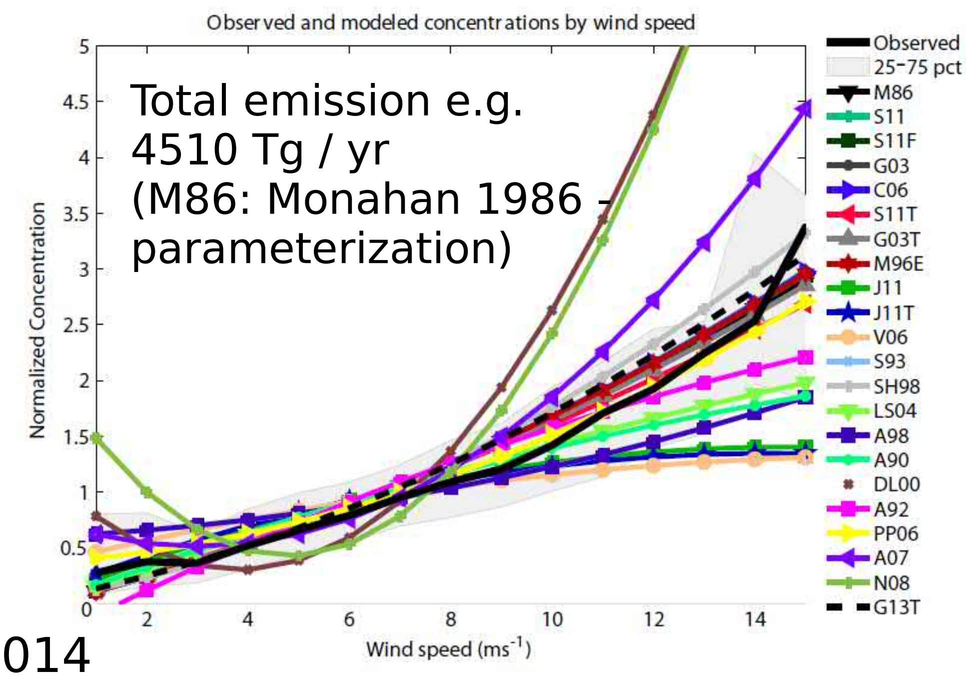
Sea spray sources

$$\frac{\mathrm{d}F(D_\mathrm{p},U_{10},T,S,O)}{\mathrm{d}D_\mathrm{p}} = W(U_{10},D_\mathrm{p})\cdot\frac{\mathrm{d}F_N D_\mathrm{p}}{\mathrm{d}D_\mathrm{p}}\cdot T_\mathrm{W}(T,D_\mathrm{p})\cdot S_\mathrm{W}(S,D_\mathrm{p})\cdot O_\mathrm{W}(O,D_\mathrm{p}).$$



D_p = dry diameter
W = white-cap fraction
U_{10} = 10m wind speed
F_N = shape function
T = ocean temperature
S = ocean salinity
O = sea state

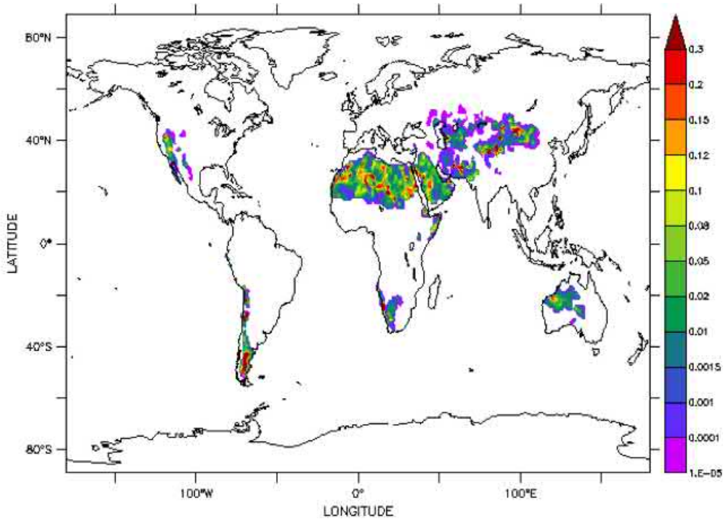




Grythe et al., 2014

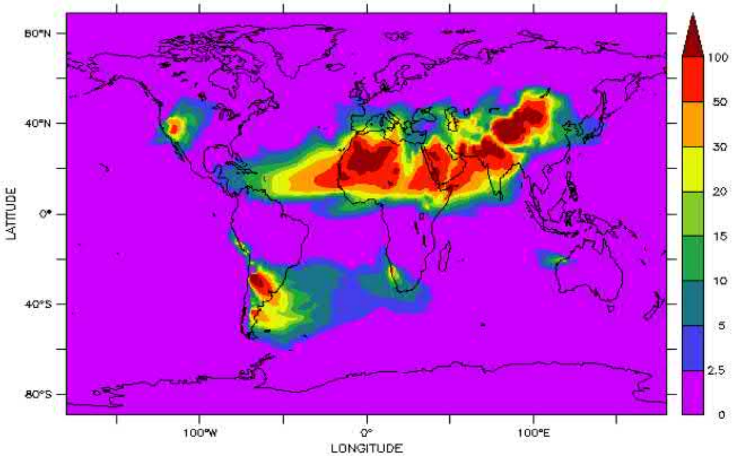
Dust sources

Dust emission



$kg\ km^{-2}\ yr^{-1}$

Dust loading



$ug\ cm^{-2}$

Model	Emission $[\mathrm{Tg\,yr^{-1}}]$
CAM	4313
GISS	1507
GOCART	3157
SPRINTARS	3995
MATCH	981
MOZGN	2371
UMI	1688
ECMWF	514
LOA	1276
UIO_CTM	1572
LSCE	1158
ECHAM5-HAM	664
MIRAGE	2066
TM5	1683
AEROCOM_MEDIAN	1123

Huneeus et al., 2011

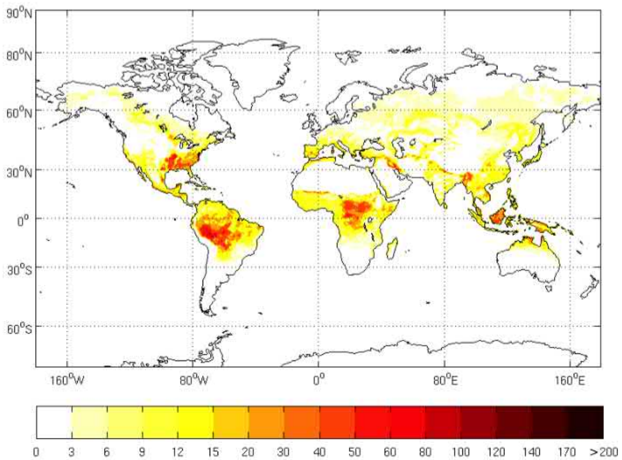
Dust emission flux F:
friction velocity
threshold friction velocity
clay content in the soil
bare soil fraction
source erodibility

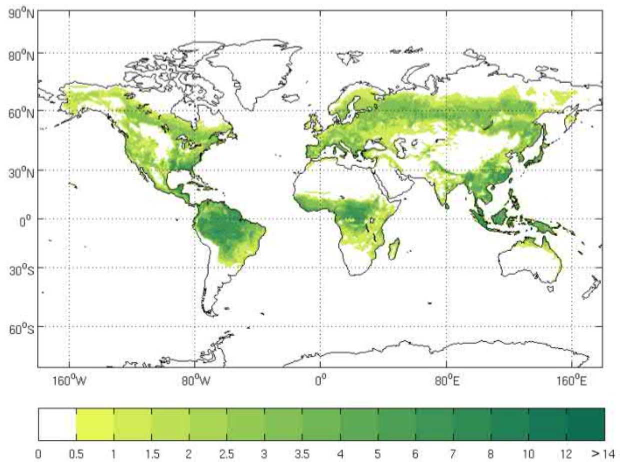
Biogenic sources

Sindelarova et al., 2014

Biogenic Volatile Organic Compounds (BVOCs)

mg m^{-2} day^{-1}





Emission activity factor:

$$\gamma = C_{ce} \cdot \mathrm{LAI} \cdot \gamma_P \cdot \gamma_T \cdot \gamma_A \cdot \gamma_{SM} \cdot \gamma_{CO_2}$$

normalization

Leaf Area Index

Light

Temperature

Leaf age

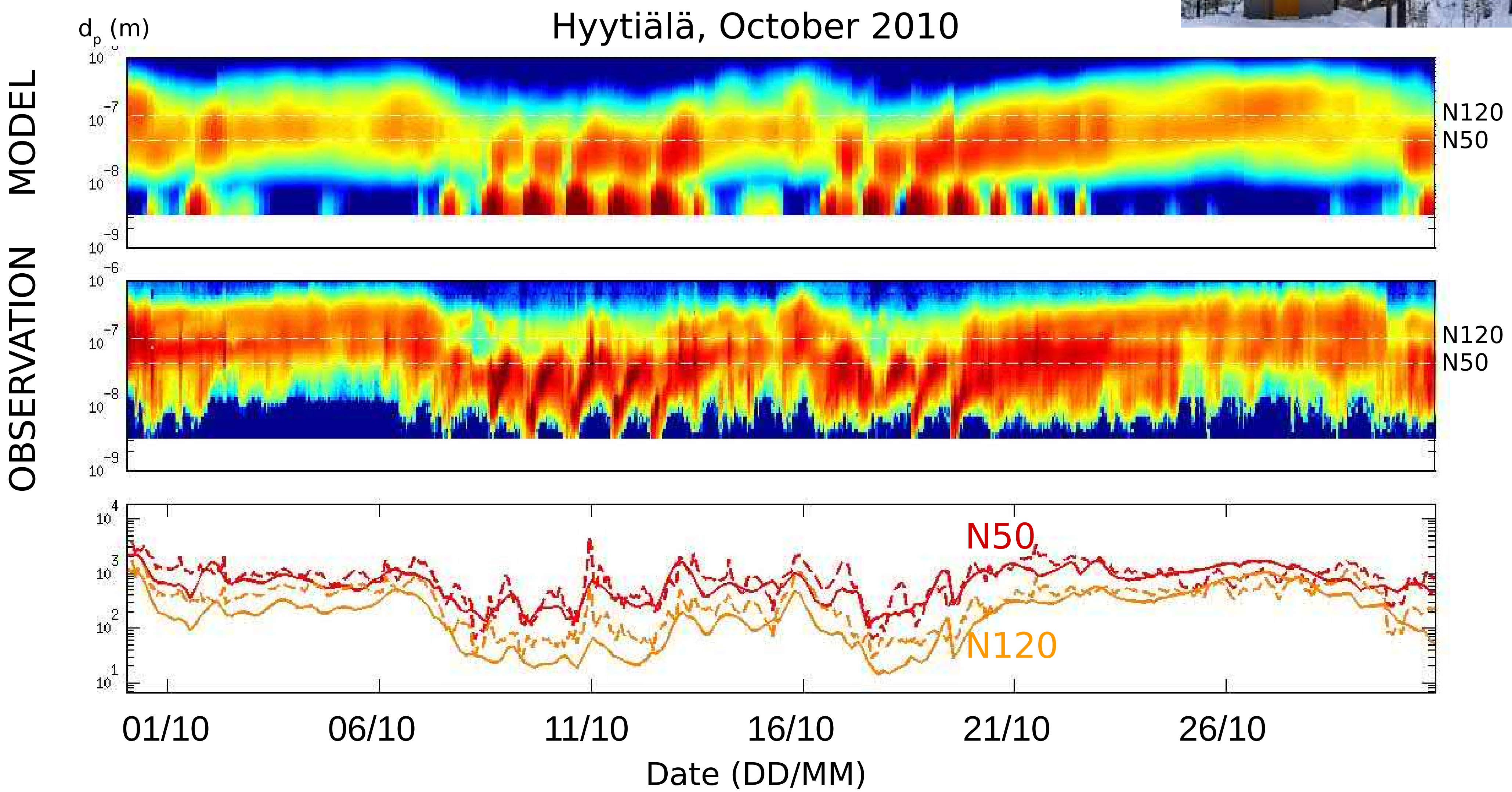
Soil moisture

CO_2 inhibition

Other aerosol and precursor sources

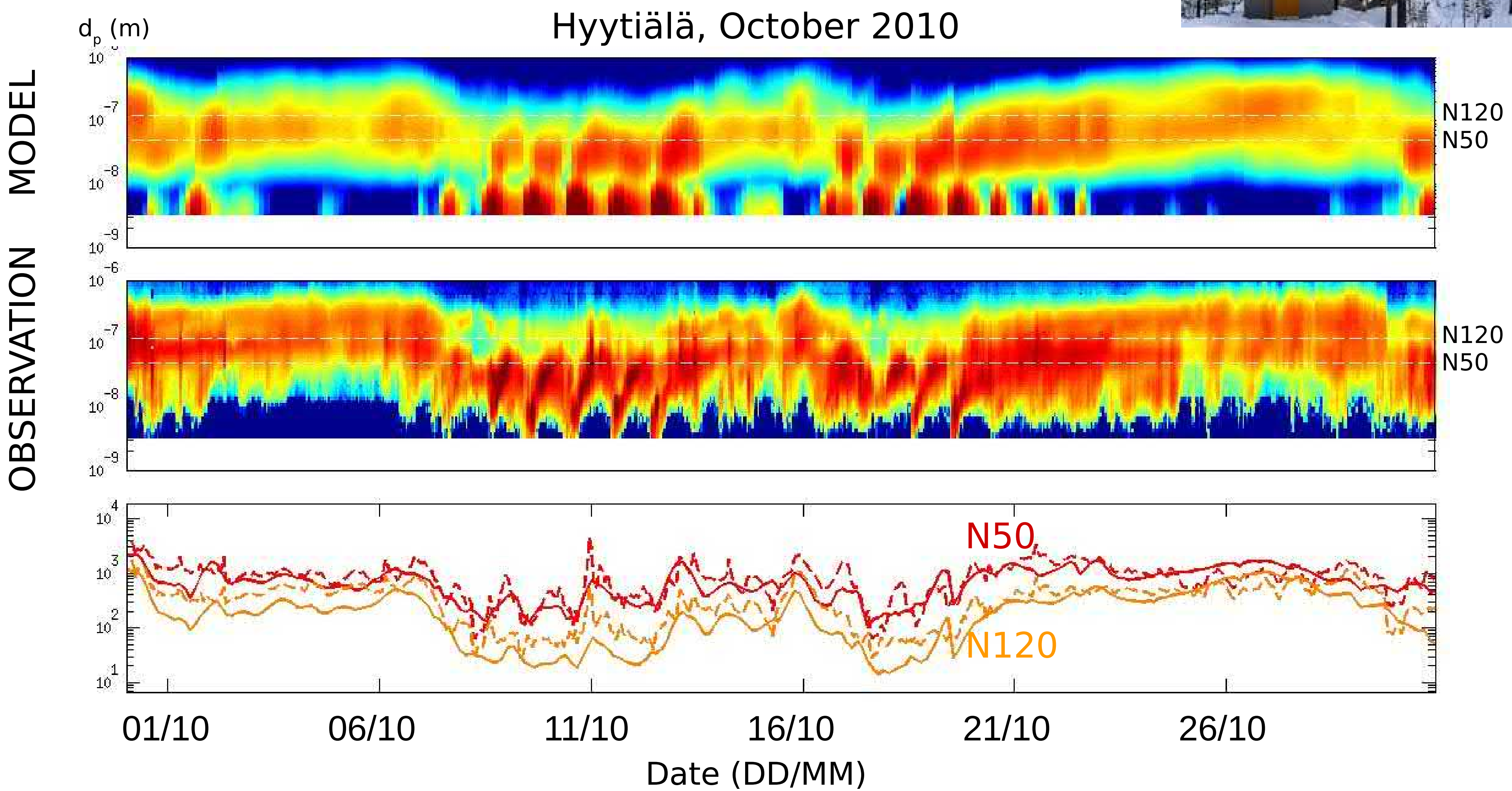
- Volcanic sources: SO_2, typically annual-mean for each source, with simplified vertical profile
- Wildfires
- Marine organics
- Primary biological aerosol particles (PBAPs)

Evaluation of model against in-situ DMPS observations

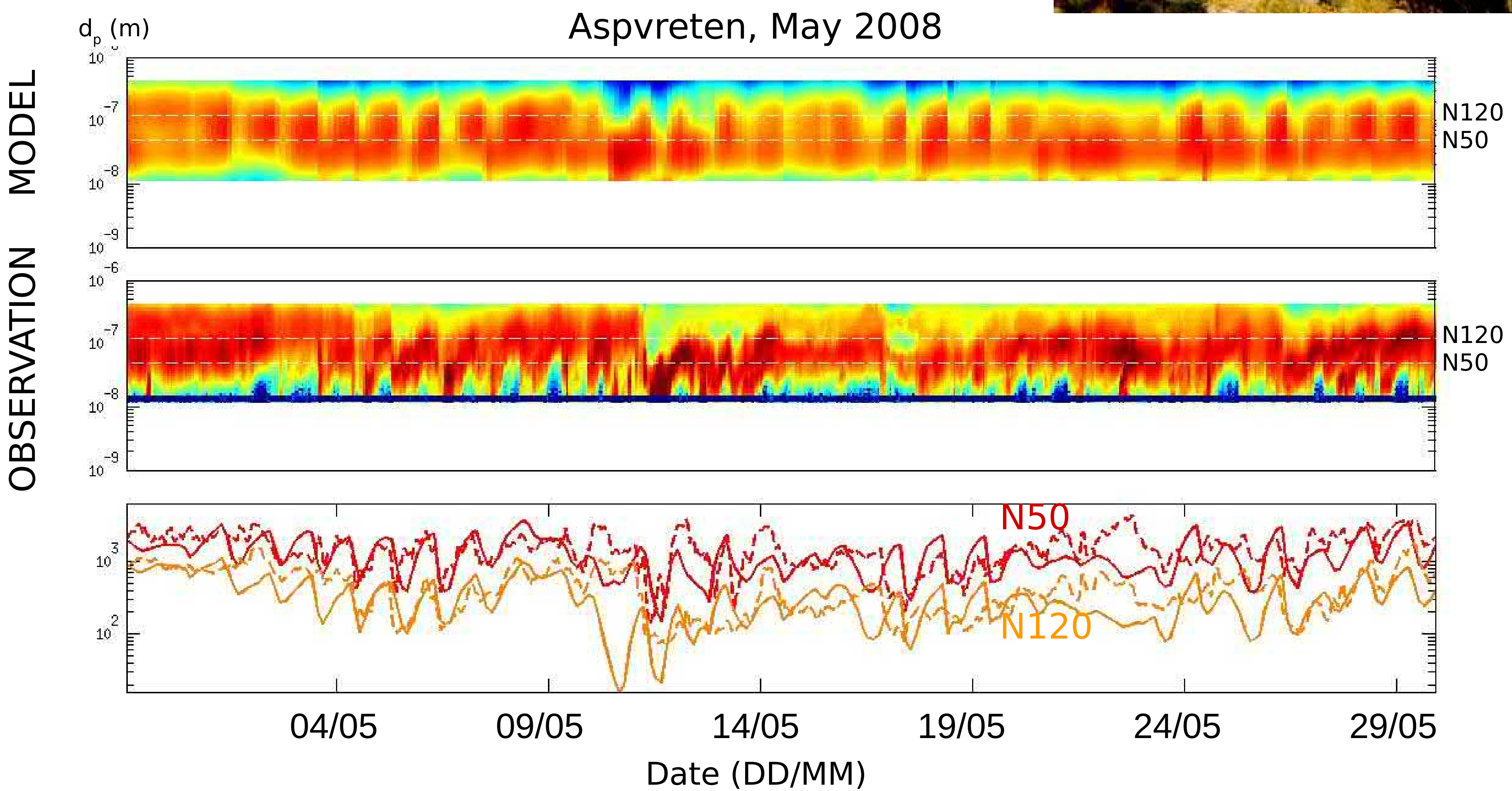


Evaluation of model against in-situ DMPS observations

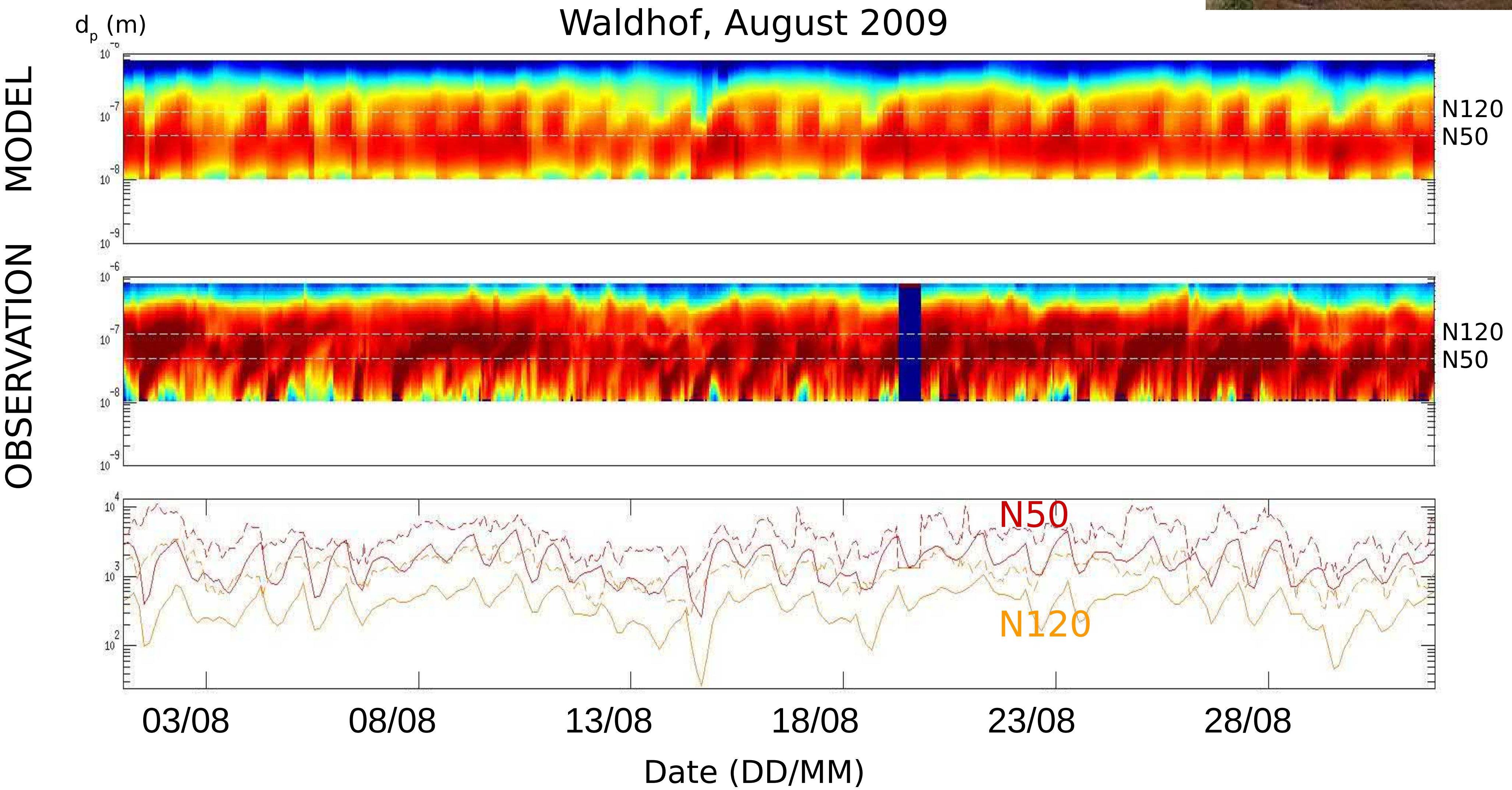
Even a global model with 200 km grid-size can predict events in Hyytiälä!



Evaluation of model against in-situ DMPS observations

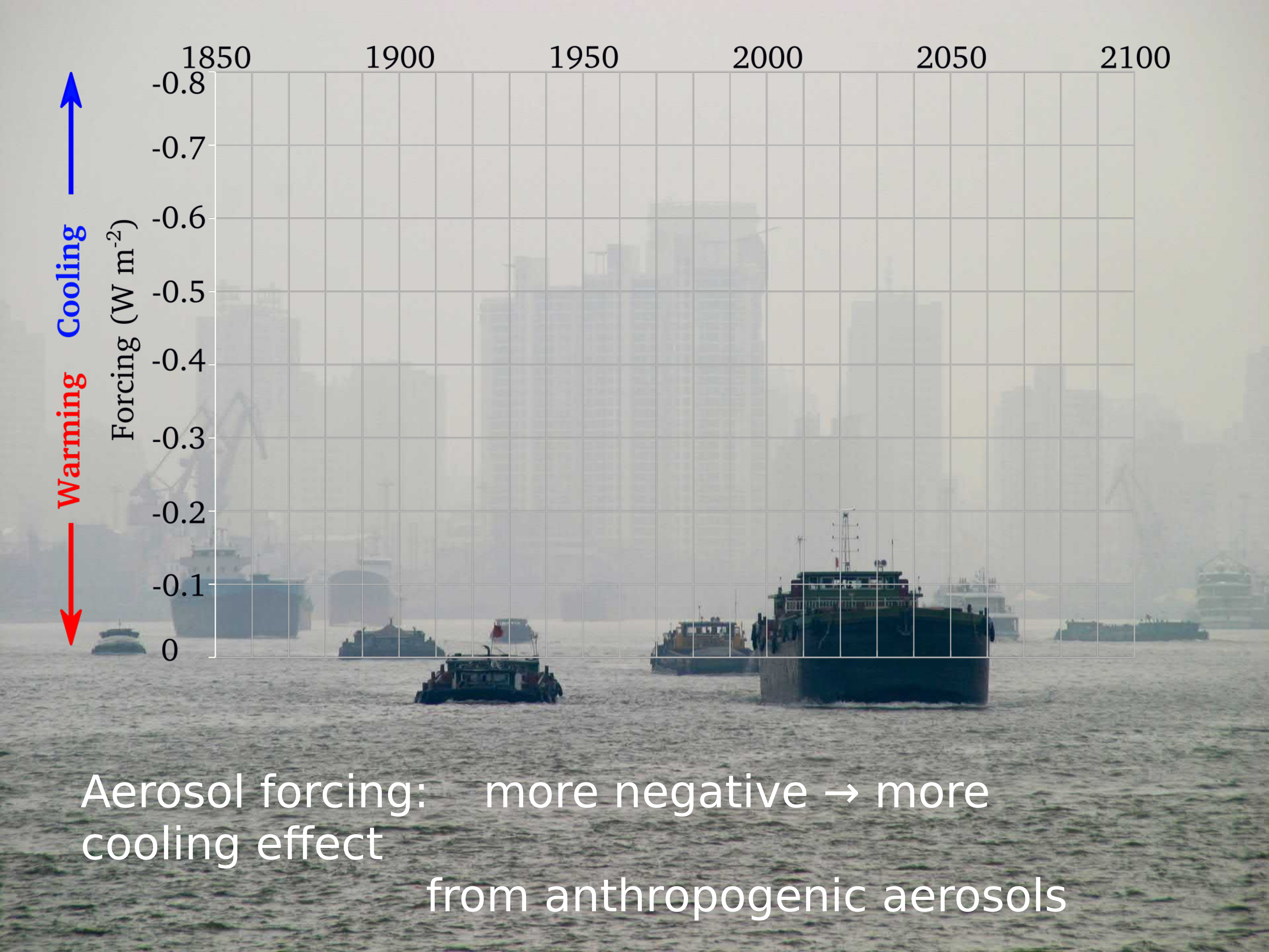


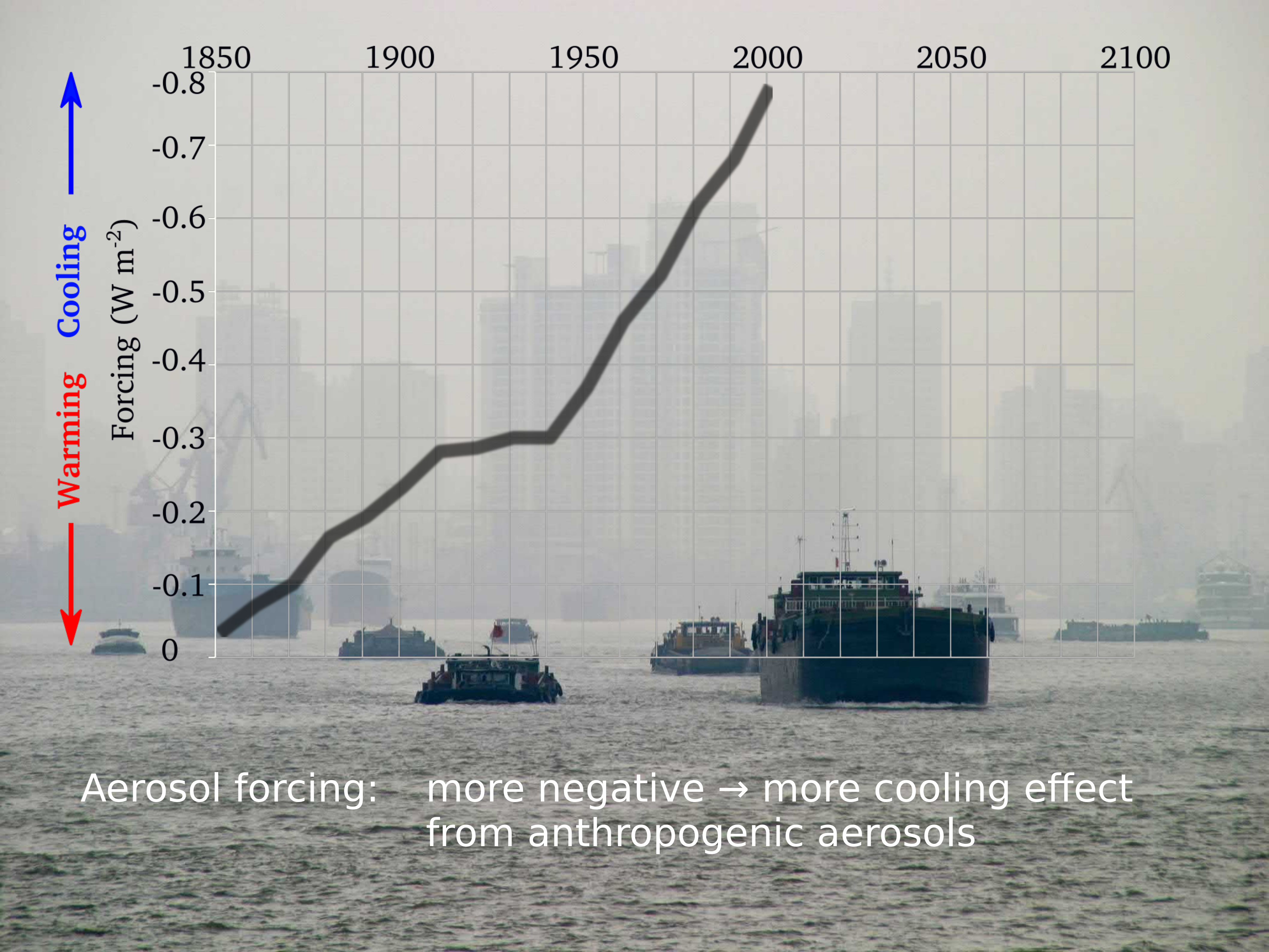
Evaluation of model against
in-situ DMPS observations

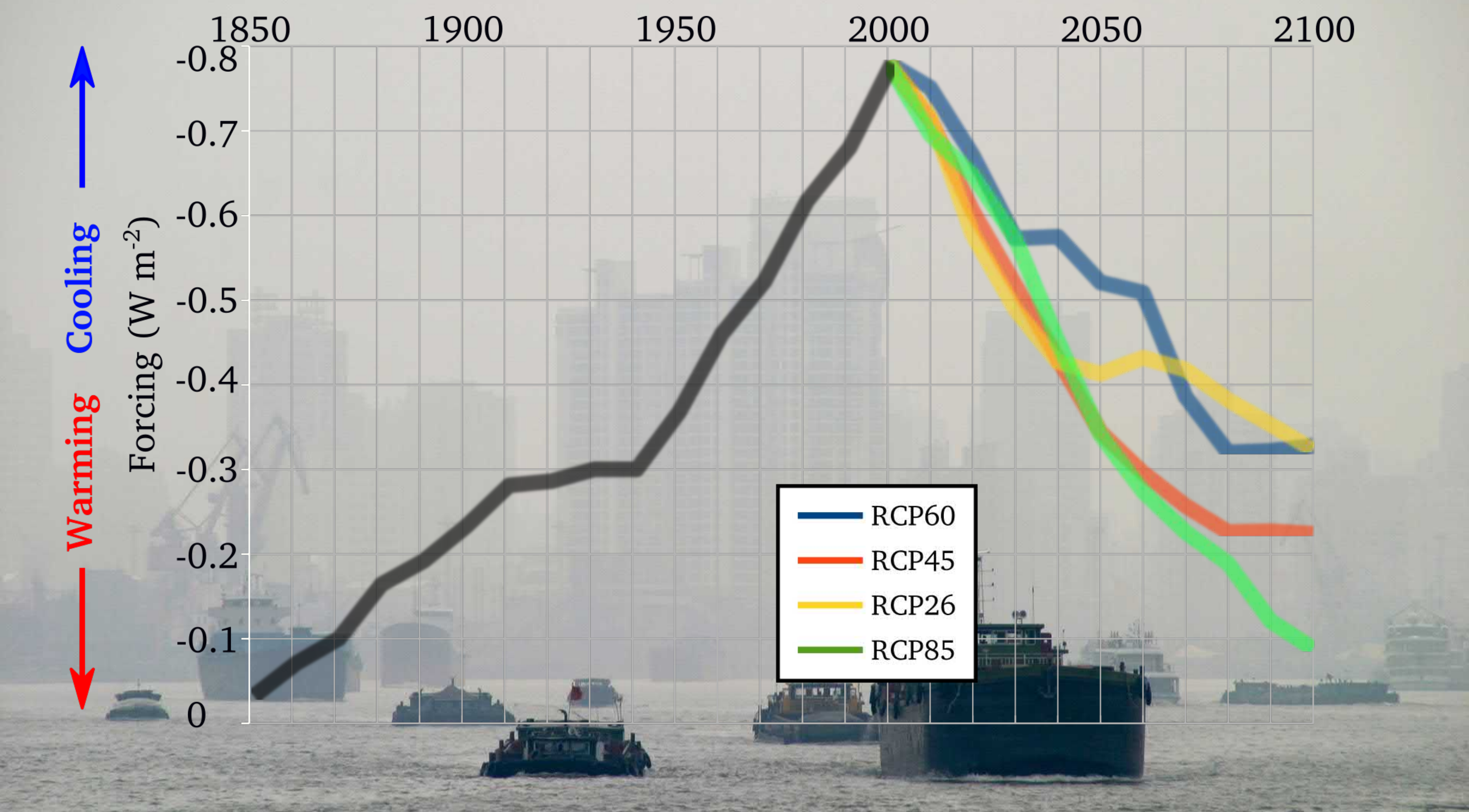


Aerosol forcing

How are anthropogenic aerosols influencing climate?


1850
1900
1950
2000
2050
2100
-0.8
-0.7
-0.6
-0.5
-0.4
-0.3
-0.2
-0.1
0
Cooling
Warming
Forcing (W m^{-2})
Aerosol forcing: more negative → more cooling effect
from anthropogenic aerosols

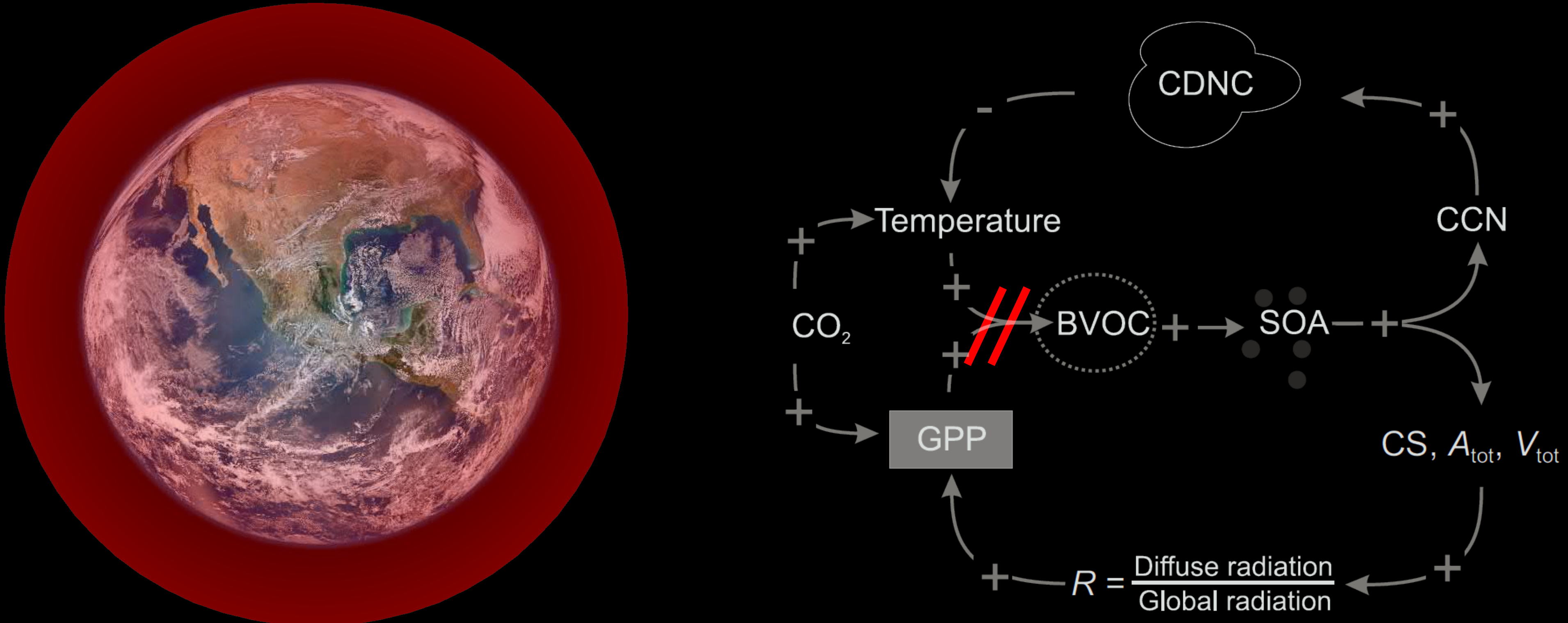

1850
1900
1950
2000
2050
2100
-0.8
-0.7
-0.6
-0.5
-0.4
-0.3
-0.2
-0.1
0
Forcing (W m-2)
Cooling
Warming
Aerosol forcing: more negative → more cooling effect from anthropogenic aerosols

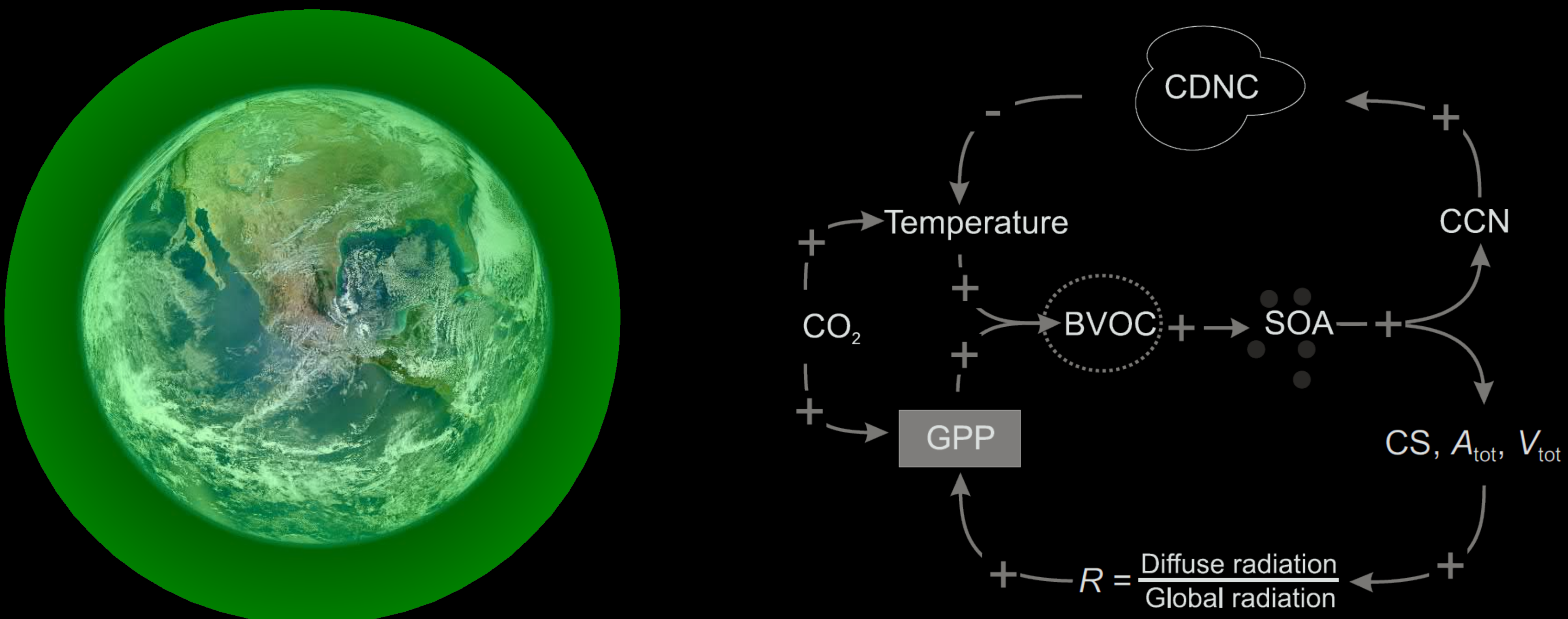


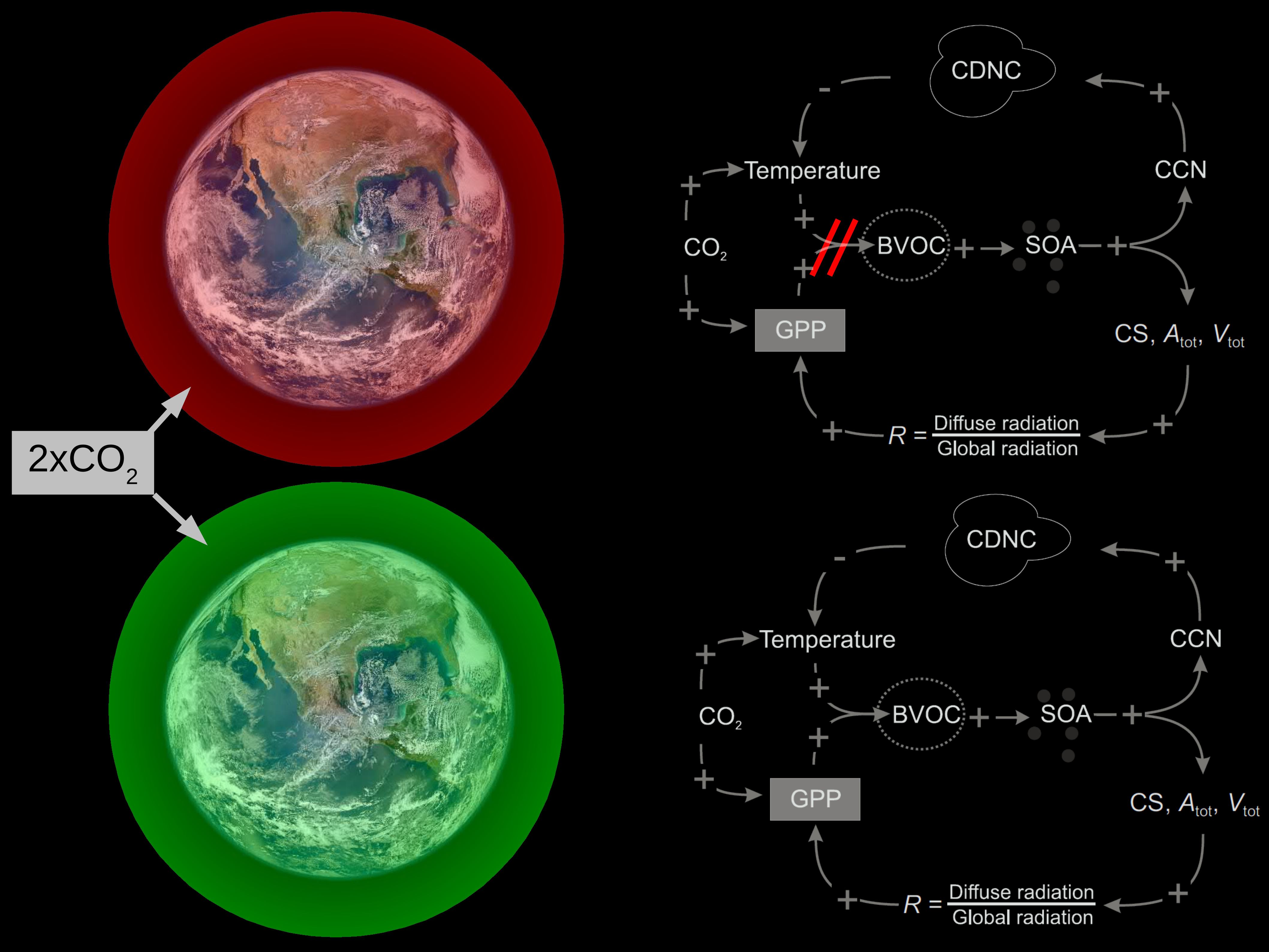
Aerosol forcing: more negative → more cooling effect from anthropogenic aerosols

Aerosol-climate feedbacks

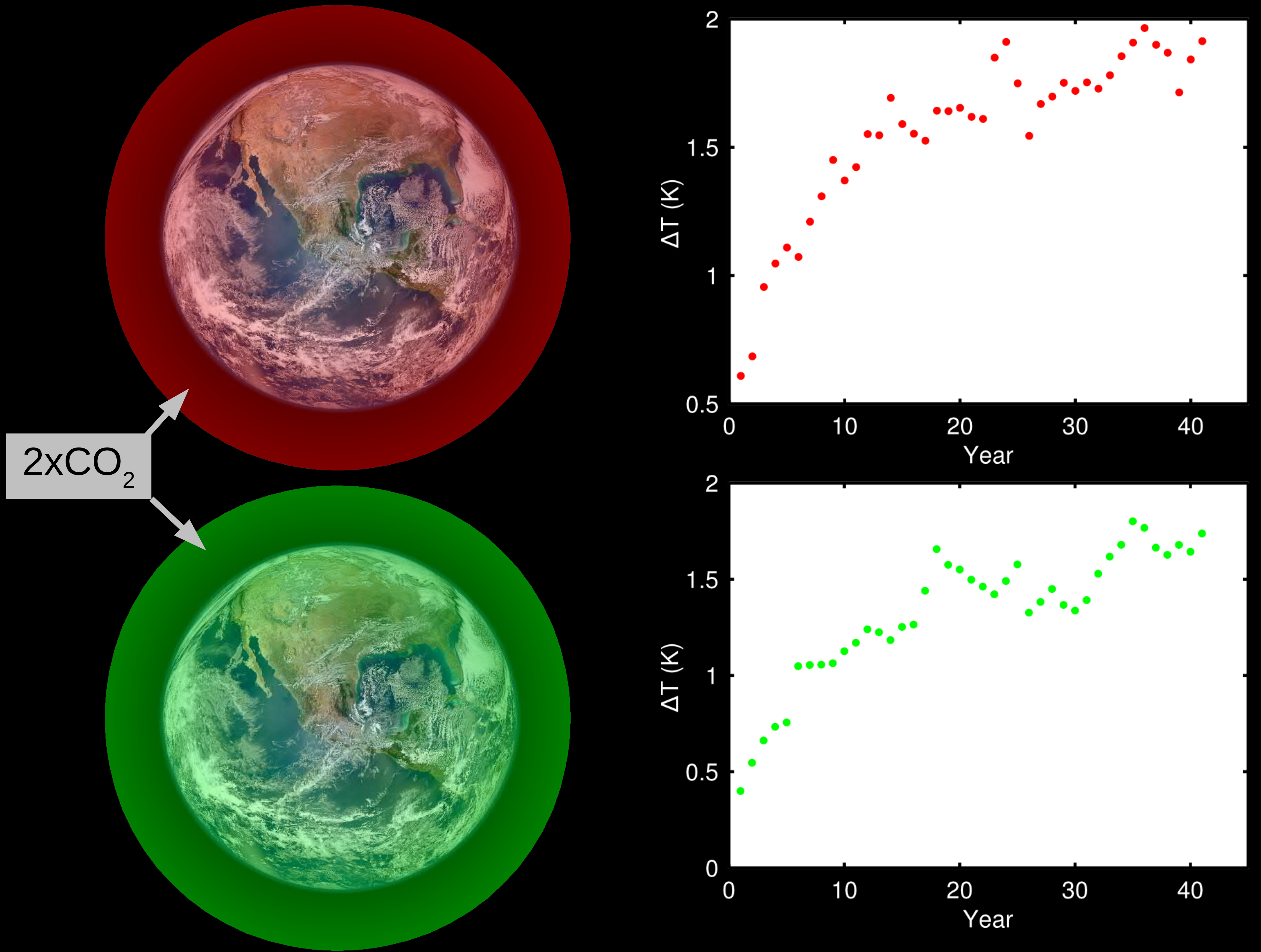
How does climate change modify aerosol sources or aerosol-climate effects?

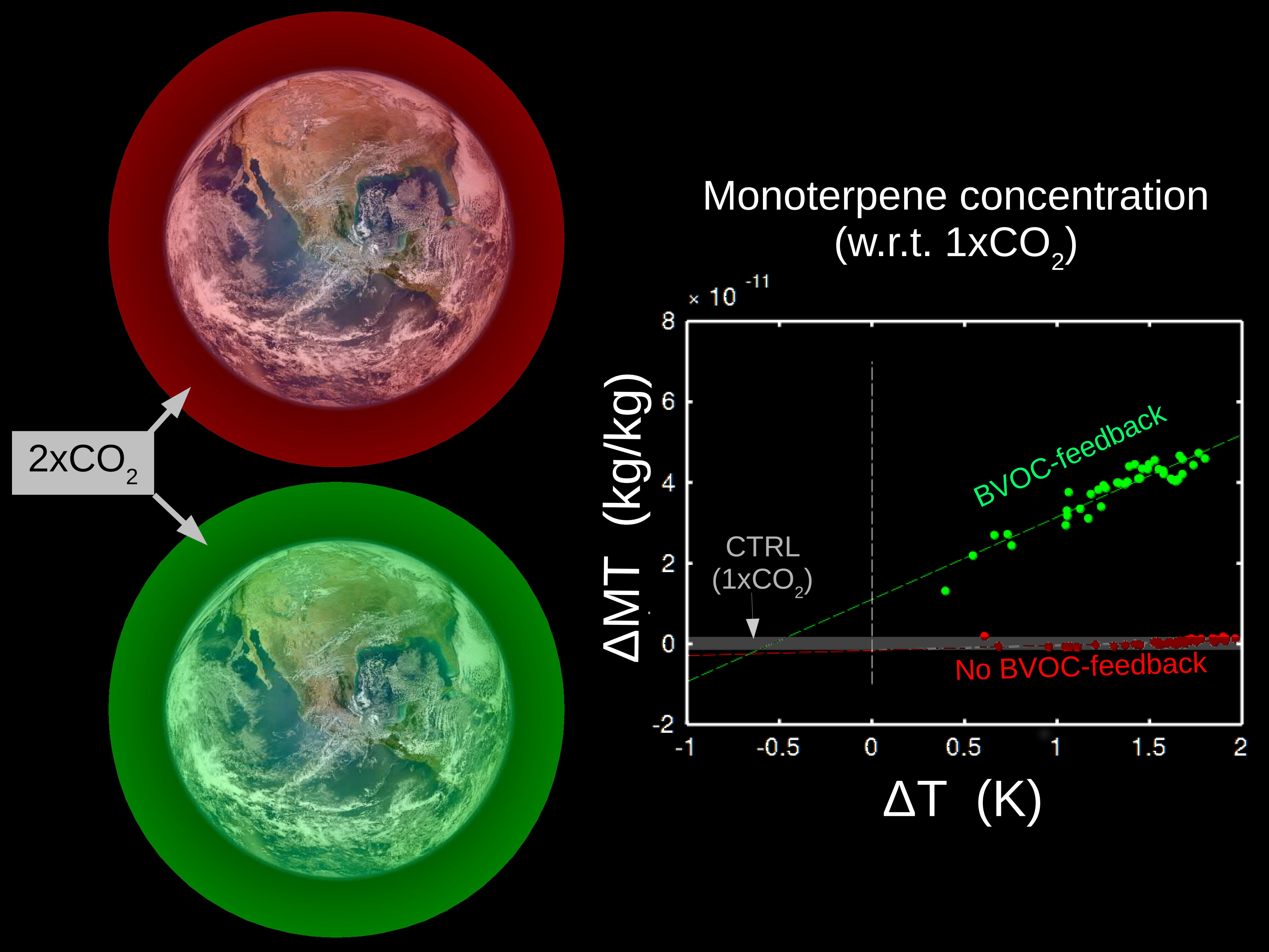

CDNC
Temperature
CCN
CO_2
BVOC
SOA
GPP
CS, A_{tot}, V_{tot}
$R = \frac{\text{Diffuse radiation}}{\text{Global radiation}}$


CDNC
Temperature
CCN
CO_2
BVOC
SOA
GPP
CS, A_{tot}, V_{tot}
$R = \frac{\text{Diffuse radiation}}{\text{Global radiation}}$

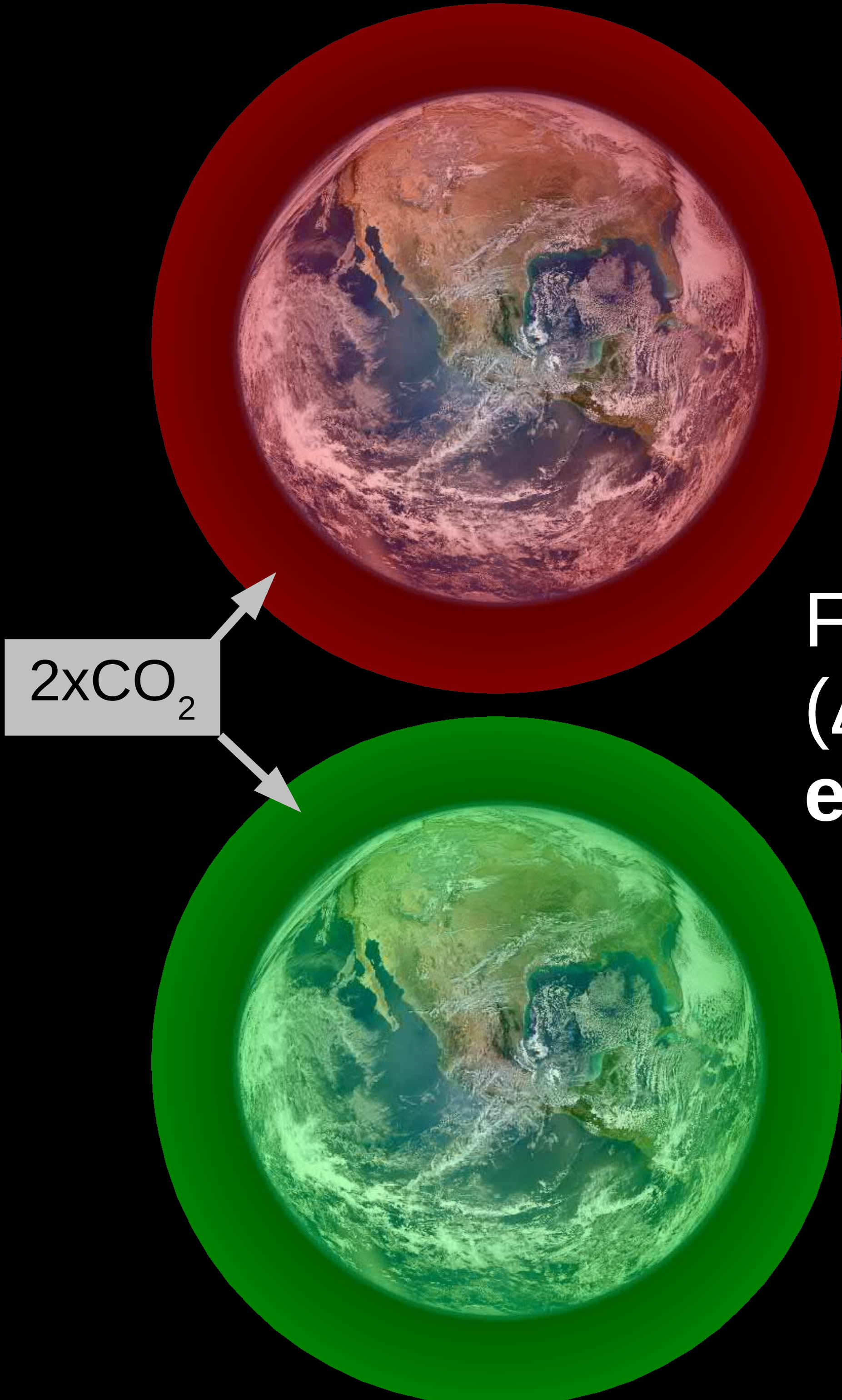


$2xCO_2$
CDNC
Temperature
CCN
CO_2
BVOC
SOA
GPP
CS, A_{tot}, V_{tot}
$R = \frac{\text{Diffuse radiation}}{\text{Global radiation}}$
CDNC
Temperature
CCN
CO_2
BVOC
SOA
GPP
CS, A_{tot}, V_{tot}
$R = \frac{\text{Diffuse radiation}}{\text{Global radiation}}$


2xCO2
ΔT (K)
Year
ΔT (K)
Year



Monoterpene concentration
(w.r.t. 1xCO2)
2xCO2
× 10 -11
ΔMT (kg/kg)
ΔT (K)
BVOC-feedback
No BVOC-feedback
CTRL
(1xCO2)
8
6
4
2
0
-2
-1
-0.5
0
0.5
1
1.5
2

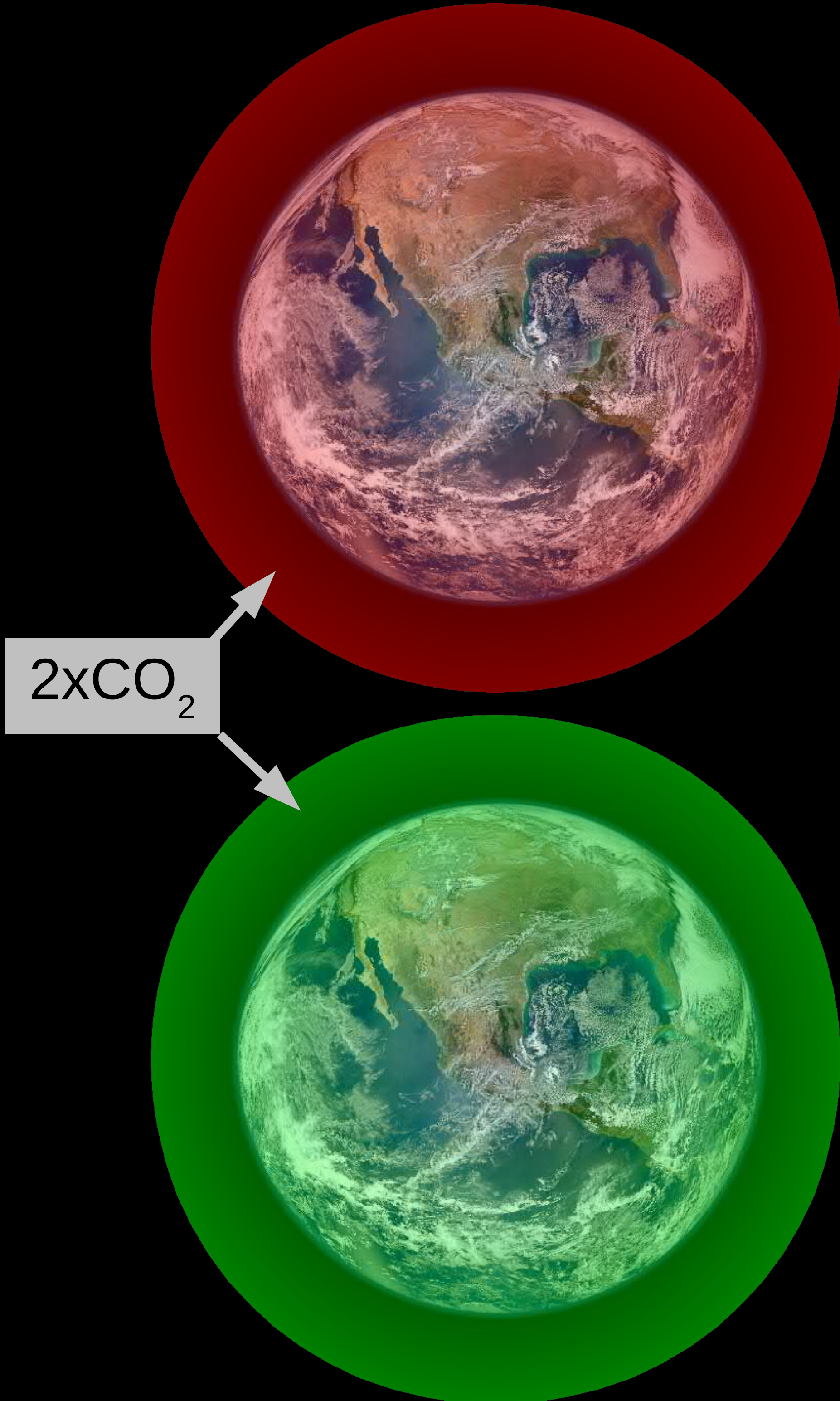


76 Tg yr^{-1}

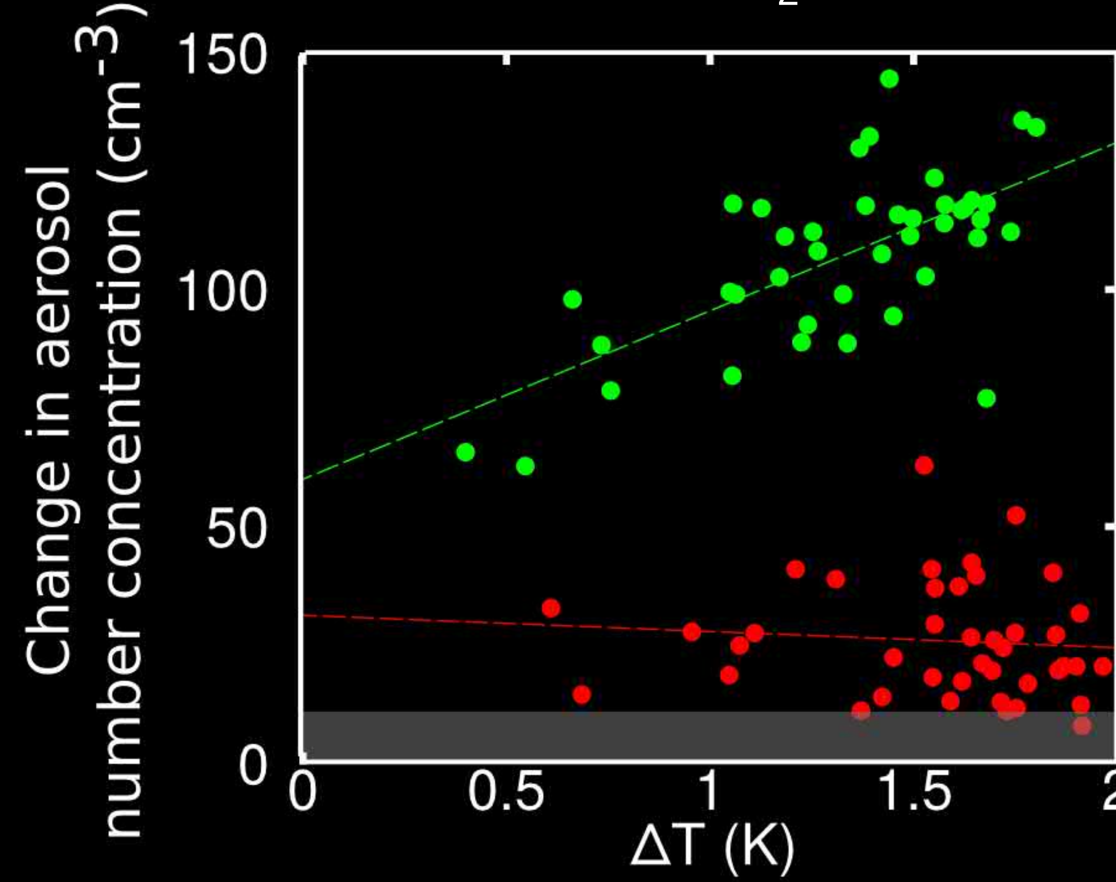
For equilibrium climate change ($\Delta T \approx 3.2$ K) **monoterpene emission** increases by 32%

100 Tg yr^{-1}

Heald et al. (2008): +19% (1.8K)
Liao et al. (2006): +58% (4.8K)

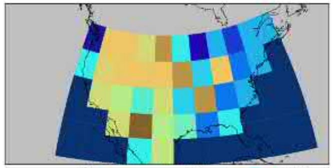


Aerosol number concentration (w.r.t. 1xCO_2)

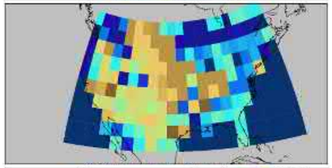


Climate model resolution has improved significantly in last decades

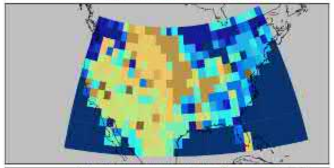
IPCC Assessment report (year)



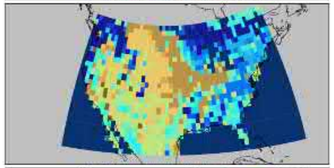
FAR (1990)
Resolution ~500 km



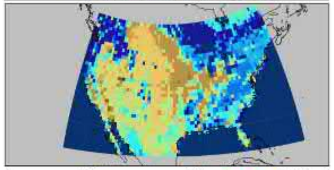
SAR (1995)
Resolution ~250 km



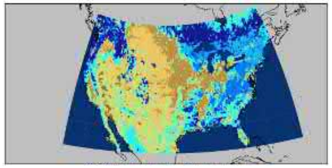
TAR (2001)
Resolution ~180 km



AR4 (2007)
Resolution ~150 km



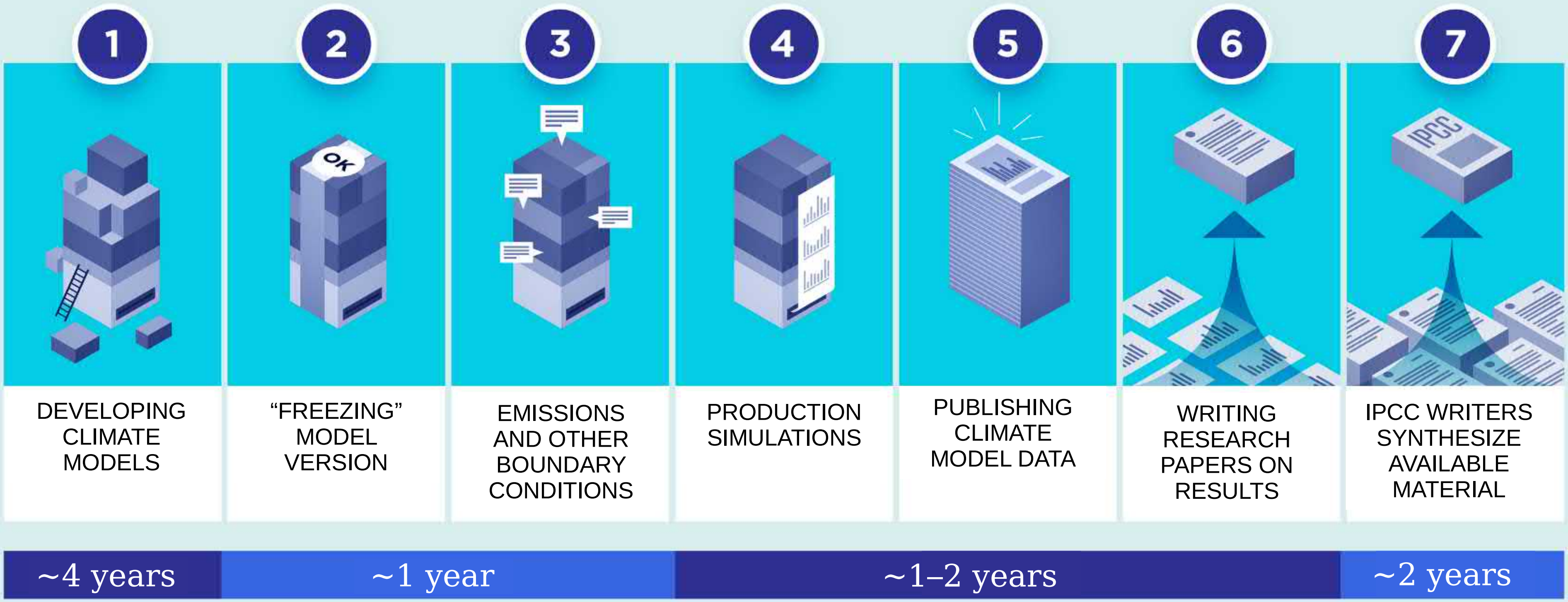
AR5 (2013)
Resolution ~80 km



AR6 (2021)
Resolution ?

From climate simulations to IPCC reports

Coupled Model Intercomparison Project (CMIP)



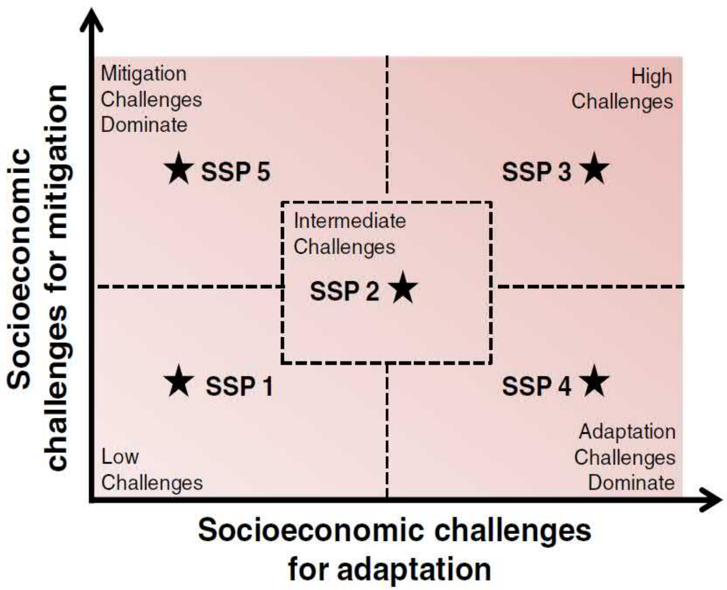
Coupled Model Intercomparison Project Phase 6

From socio-economic pathways to climate projections

Model input

Shared Socioeconomic Pathways

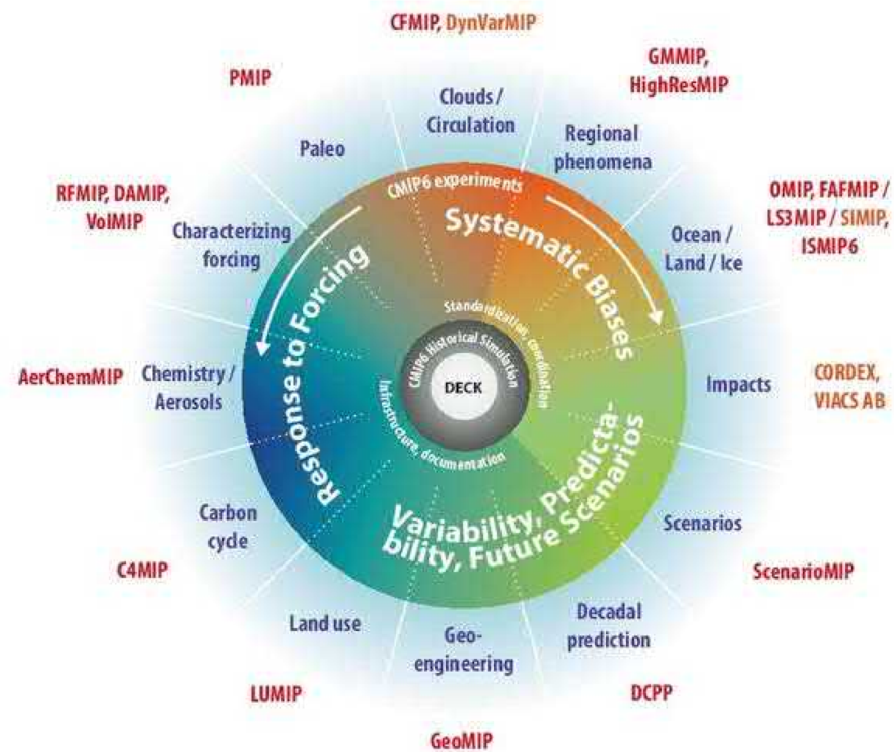
SSP/RCP matrixes



Experimental design

DECK-simulations (control, historical, 4xCO_2, 1%CO_2)

23 endorsed Model Intercomparison Projects (MIPs)



Mitigation challenges

Socioeconomic dimension

Climate dimension (Increasing mitigation ↓)	SSP1 sustainability	SSP4 inequality	SSP2 middle of the road	SSP3 regional rivalry	SSP5 fossil fueled development
8.5					4/4
6.0	6/6	3/3	6/6	4/4	4/4
4.5	6/6	3/3	6/6	4/4	4/4
3.4	6/6	3/3	6/6	4/4	4/4
2.6	6/6	3/3	6/6	0/4	3/4
1.9	6/6	1/3	4/6	0/4	2/4

SSP = Shared Socioeconomic Pathway. Source: Rogelj et al (2018). CB

Amount of CMIP data has increased roughly by a factor of 50

CMIP Phase	Models	Data amount
CMIP1 (TAR)	<20	1 Gb
CMIP2 (TAR)	>20	500 Gb
CMIP3 (AR4)	~35	30–40 Tb
CMIP5 (AR5)	>50	2–3 Pb
CMIP6 (AR6)	109	20–70 Pb

- More models
- Higher resolution
- More components
- More experiments

Summary

- Using highly coupled Earth System Models (ESMs) in studying history and future pathways of chemistry-climate-biosphere-atmosphere-ocean system
- Limitations due to technical implementations (computer and data resources), fundamental understanding, and unavailable globally applicable parameters
- Big data allows from tens of models allows novel steps towards enhanced understanding of underlying uncertainties in processes, interactions and feedbacks