CLIMATE FEEDBACKS OF THE INDIRECT EFFECT CAUSED BY ANTHROPOGENIC AEROSOLS

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OVERVIEW

- **The indirect effect of anthropogenic sulfate**

1) **The droplet radius effect:** smaller and more numerous droplets ➔brighter low-level clouds➔negative forcing
2) **The cloud lifetime effect**: slower autoconversion in warm clouds ➔less precipitation and more abundant low-level clouds➔negative forcing

- **Climate system feedbacks:**

– Response without altering aerosols: ”**geophysical feedback**”
– Response-contribution by aerosol-changes: ”**chemical feedback**”

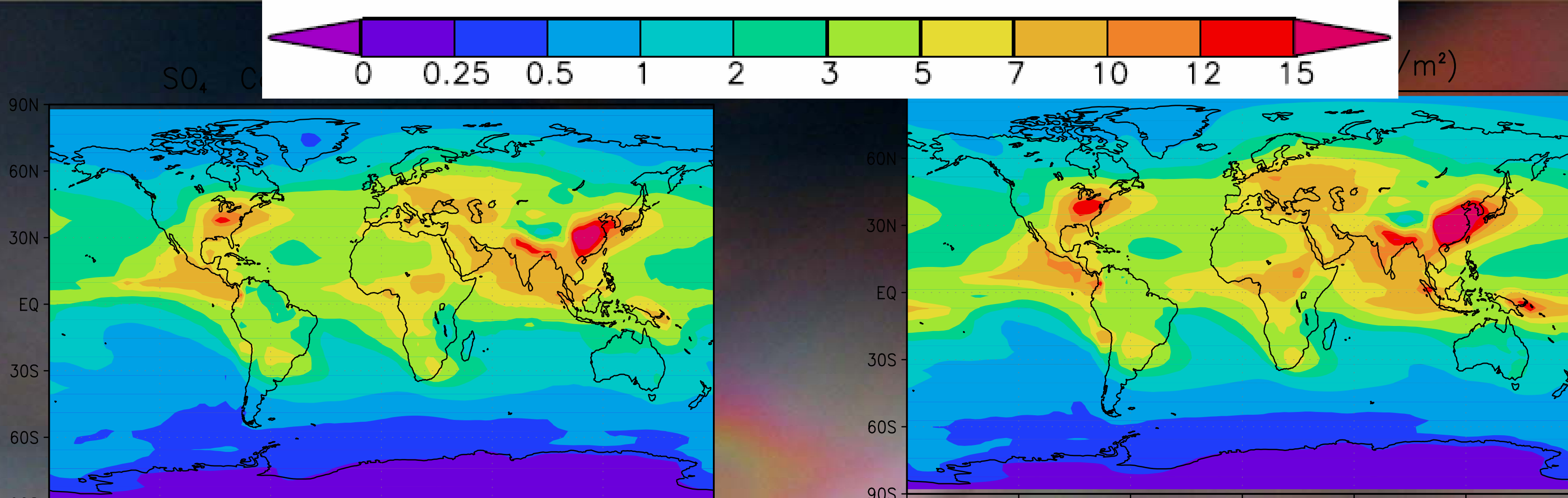
- **Tools and Methods:**

– **Oslo-GCM**: NCAR CCM3.2 extended with aerosol life-cycles coupled to clouds, precipitation, and radiation
– **30-years long equilibrium runs** with Oslo-GCM coupled to slab ocean
– **Emissions**: IPCC TAR for year 2000, natural and total

TWO TWIN EXPERIMENTS

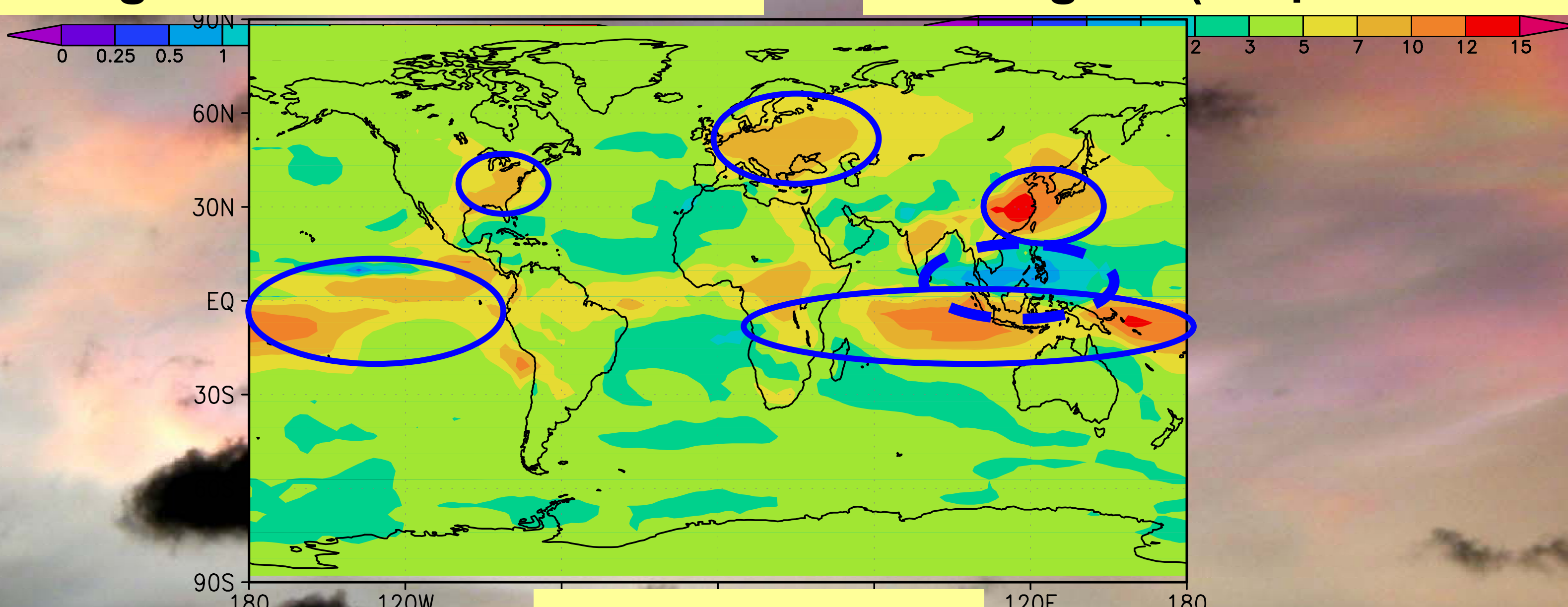
Each twin: natural & total 2000 emissions in Oslo-GCM with slab ocean for equilibrium climate response

- **Twin 1: off-line aerosols:**
  - Monthly averaged SO4 (and BC) prescribed.
  - No life-cycle scheme in the model
  - geophysical parameters influenced by indirect effect but not v.v.
- **Twin 2: on-line aerosols:**
  - SO4 (and BC) calculated by life-cycle scheme simultaneous with geophysical parameters
  - geophysical parameters influenced by indirect effect
  - SO4 (and BC), and thus CCN, influenced by changes in geophysical parameters.

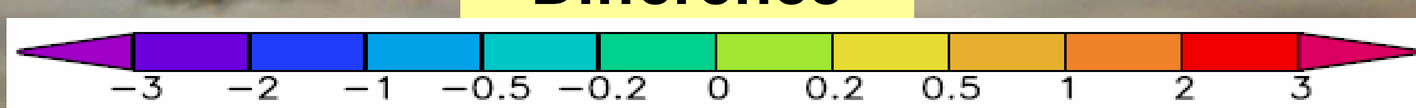


Off-line SO4 Column Burden, 3.01 mg/m2

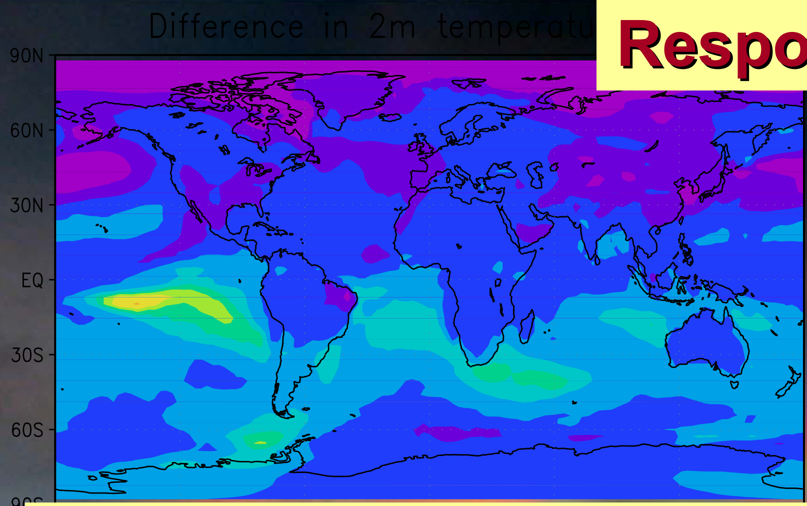
On-line SO4 Column Burden 3.51 mg/m2 (Response: Year 11-30)



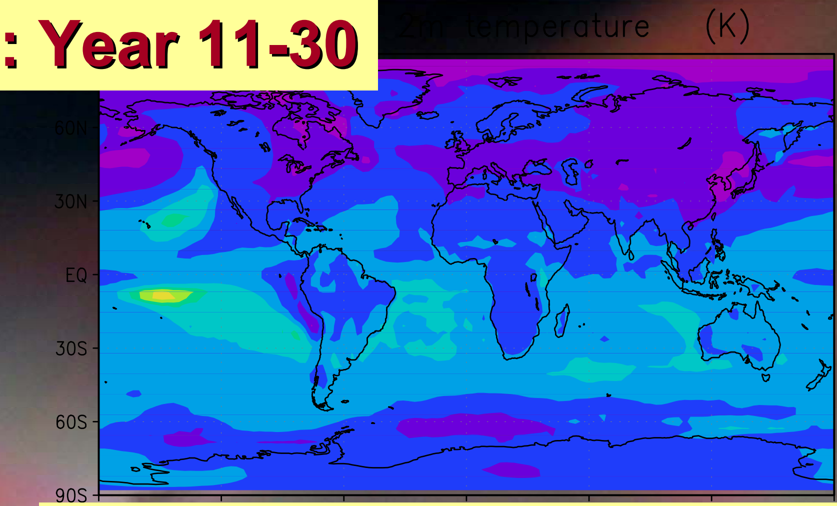
Difference



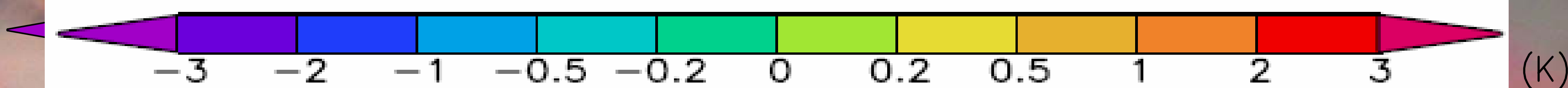
Response: Year 11-30

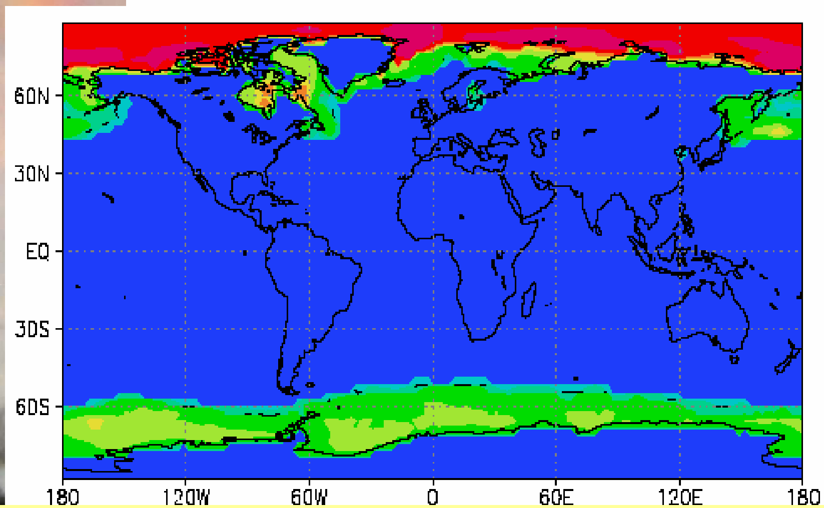


Off-line Anthropogenic
Surface Temp.-increment: - 1.35 K

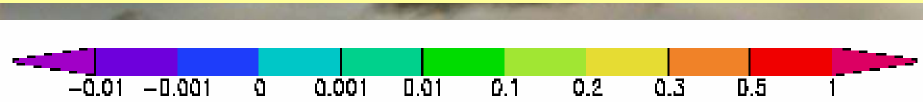


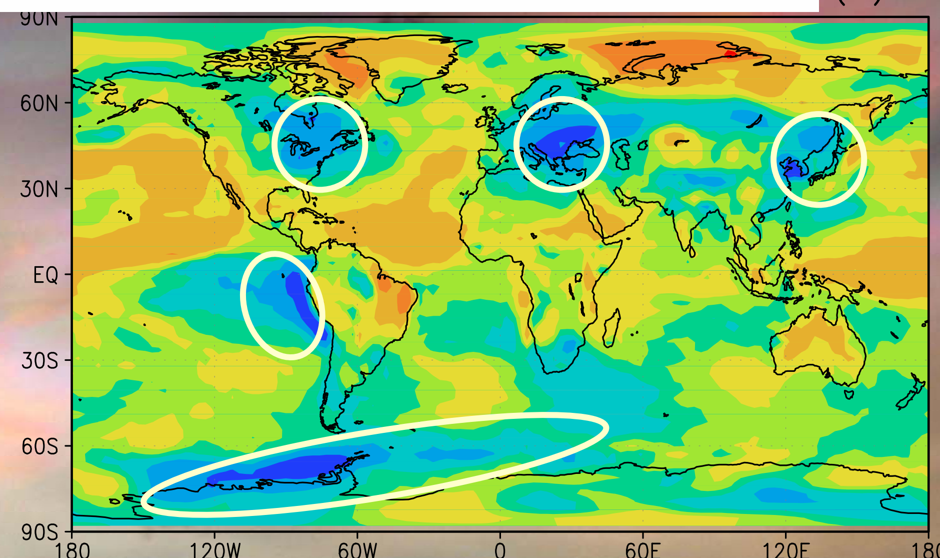
On-line Anthropogenic
Surface Temp.-increment: - 1.25 K





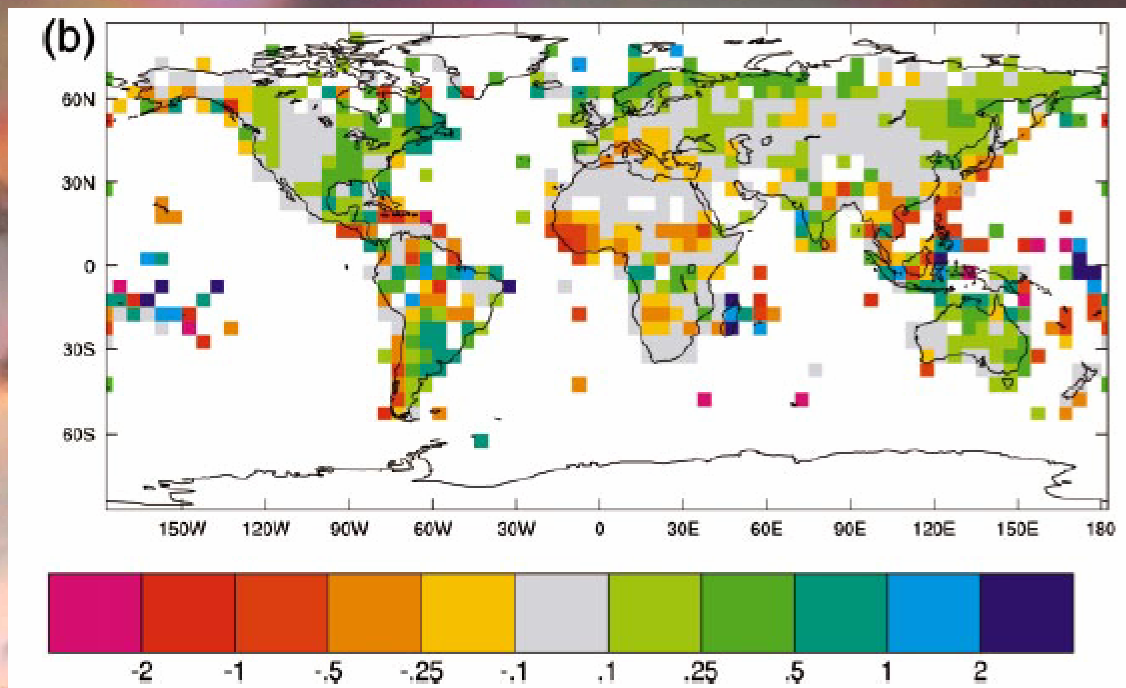
Off-line change in sea-ice thickness (m)





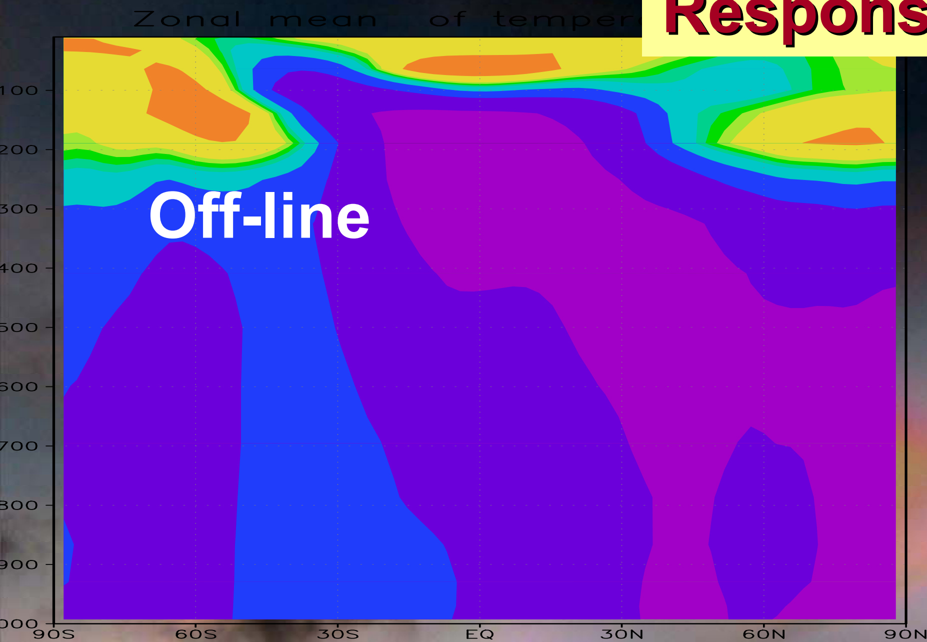
Surf. T. Difference (on-line – off-line)

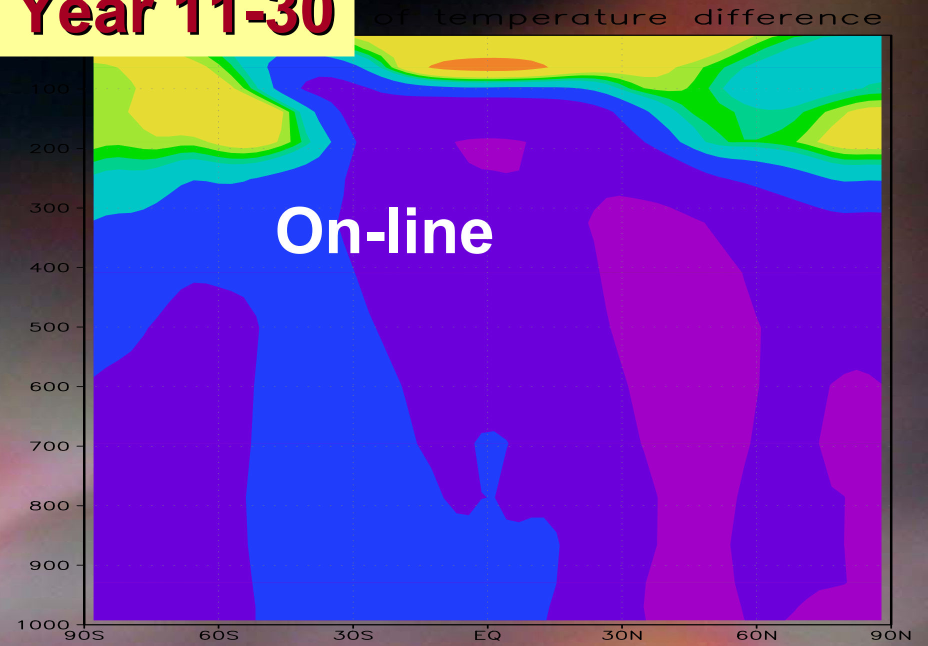
Observed changed in precipitation [Rotstayn and Lohmann, 2002]

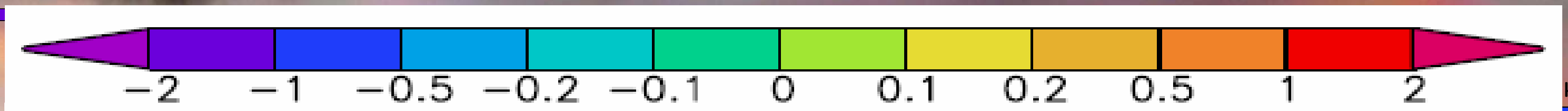


(b) Trend in observed annual-mean precipitation over the period 1901–98 in mm day^{-1} century^{-1}.

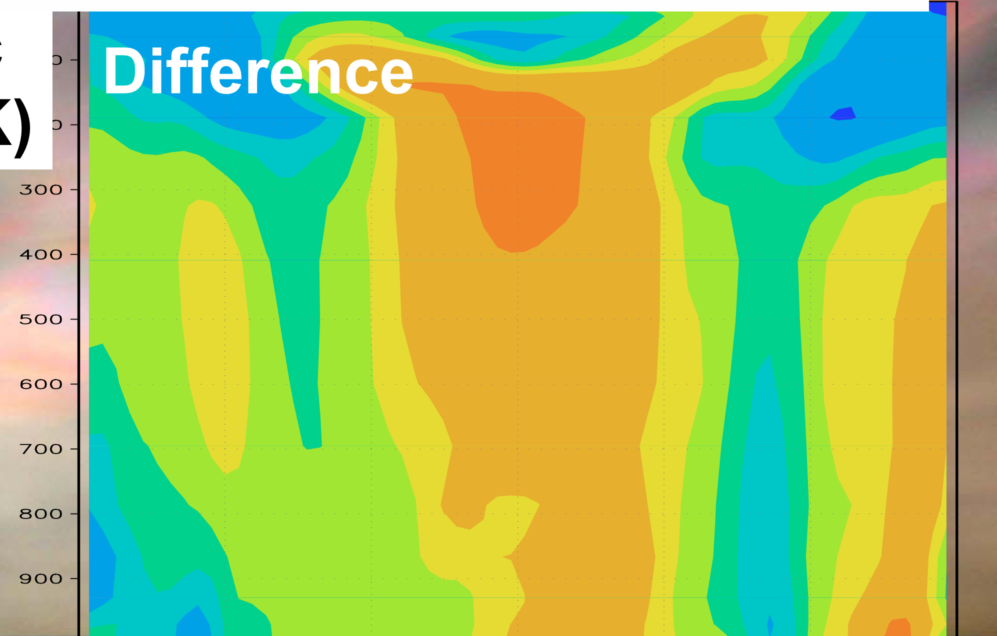
Response: Year 11-30



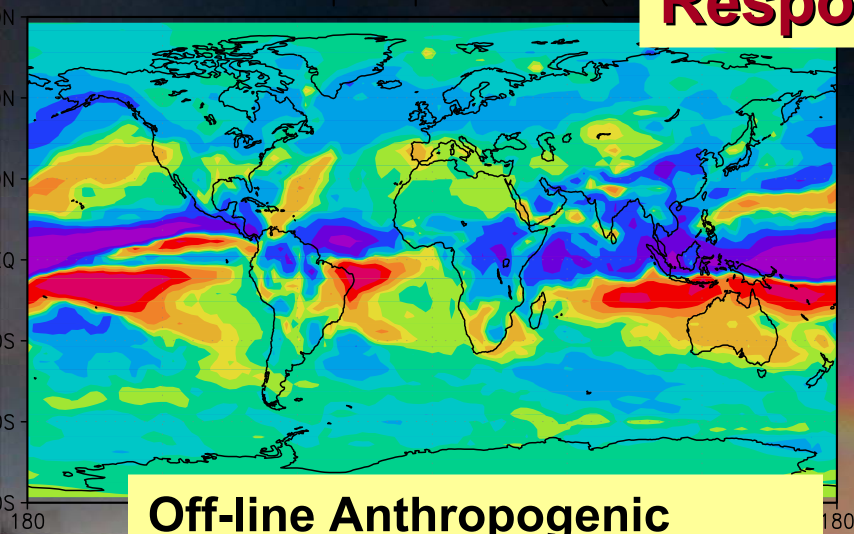




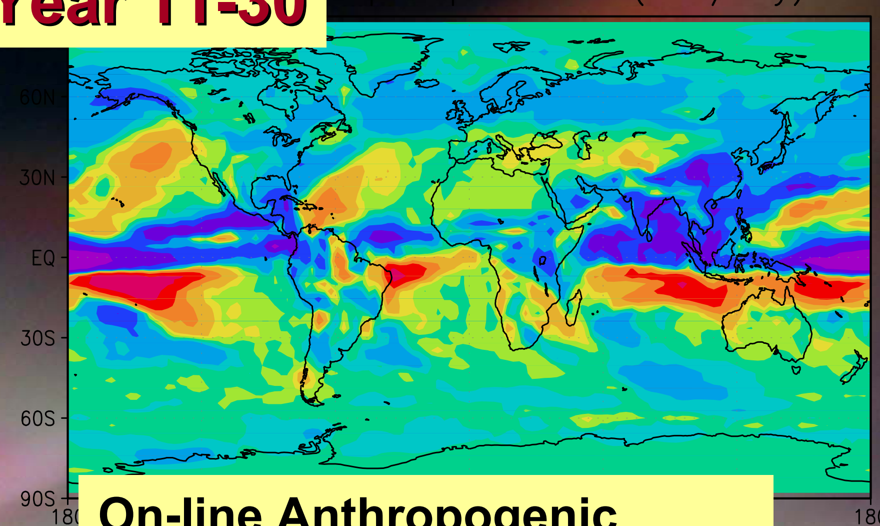
Zonal Mean Anthropogenic Temperature Increments (K)



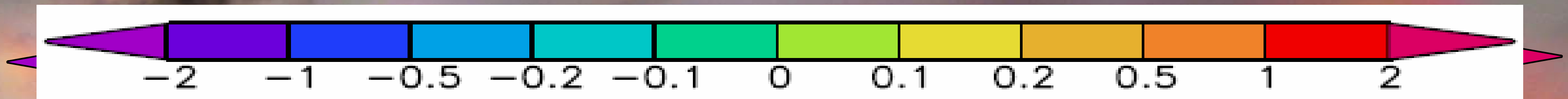
Response: Year 11-30

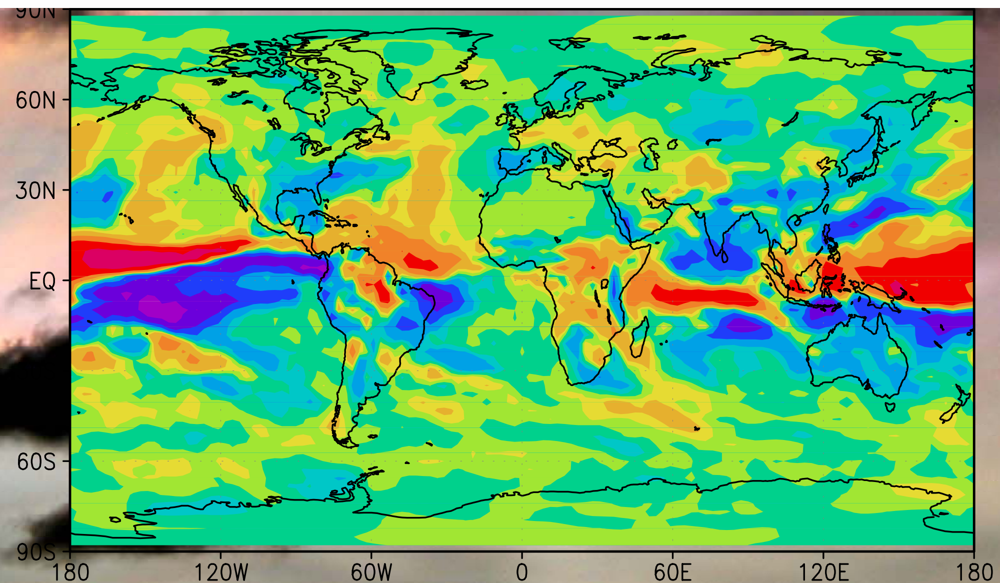


Off-line Anthropogenic
Prec.-increment: - 0.11 mm/d



On-line Anthropogenic
Prec.-increment: - 0.10 mm/d





Difference (on-line – off-line)

Results Summary

Geophysical feedback:

- **Cooling enhanced by sea-ice and snow cover albedo feedback**
- **Cooling wide-spread in the Troposphere**
- **Northern hemisphere cooled more than Southern**
- **ITCZ displaced to the south.**

Chemical feedback

- **Sulfate burden increases**
- **In major NH-source regions and a few SH oceanic areas, the indirect cooling increases, in expected (?) agreement with the sulfate burden increase**
- **However, contra-intuitively (?):**
  - **Global cooling is reduced**
  - **ITCZ-displacement is slighly reversed**

Discussion

Indirect effects are produced by anthropogenic increase of CCN due to sulfate.

Chemical feedback yields more sulfate but smaller climate impacts.

How can this come about?

1. **Why more sulfate?**
2. Why smaller indirect effect when sulfate increases?

SO_2 and SO_4 budgets

Total sources	SOx Source Tg(S)/a	SO2 dep (%)	SO4 Aq. prod (%)	SO4 Gas-prod (%)	SO2 burden Tg(S)	SO2 Res.-time (days)	SO4 source Tg(S)/a	SO4 wet dep (%)	SO4 burden Tg(S)	SO4 Res.-time (days)	SO4 Prod.-eff. (days)
Off-line	90.4	**40.7**	**44.8**	**13.2**	**0.37**	**1.5**	**54.0**	**85**	**0.51**	**3.4**	2.1
On-line	90.4	**37.7**	**47.3**	**13.4**	**0.38**	**1.6**	**56.5**	**81**	**0.60**	**3.8**	2.4

Discussion II

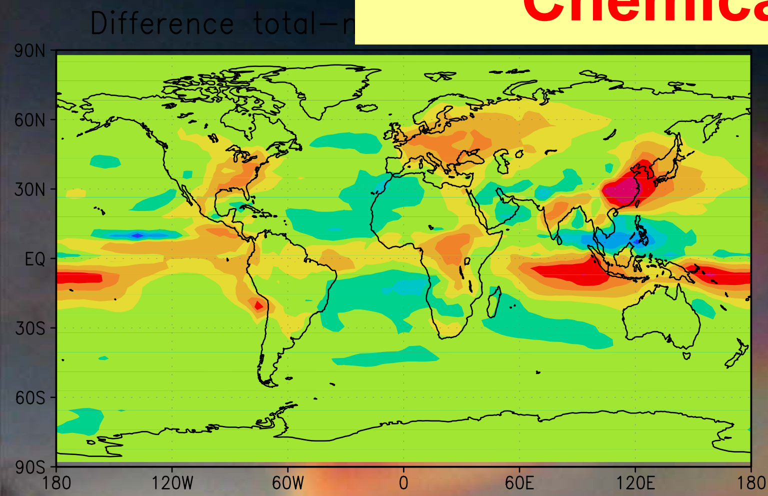
1. **Why more sulfate?**

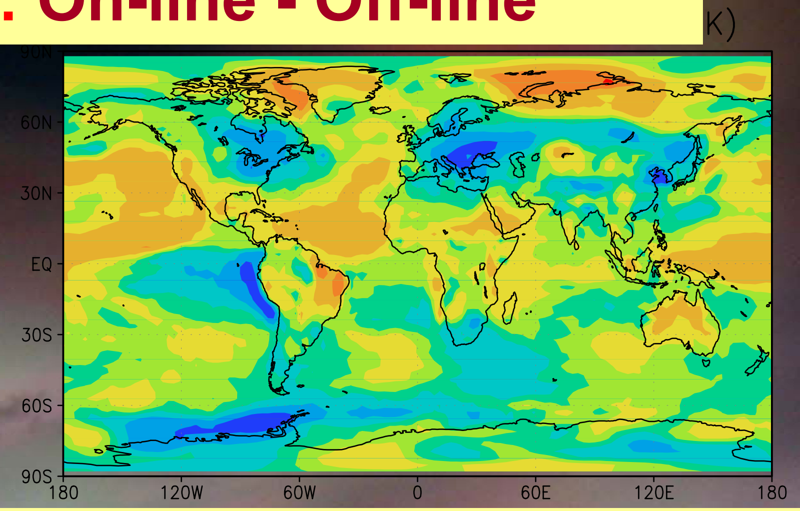
- More clouds → More aqueous phase SO_4.
- Less precipitation → Longer atmospheric residence time
- Colder climate → further reduced precip.

  → even more sulfate

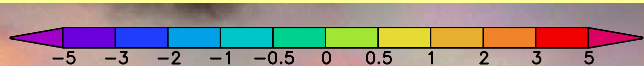
2. **Why smaller indirect effect when sulfate increases?**

Chemical Feedback: On-line - Off-line





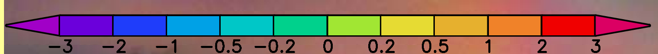
Feedback on SO4-column

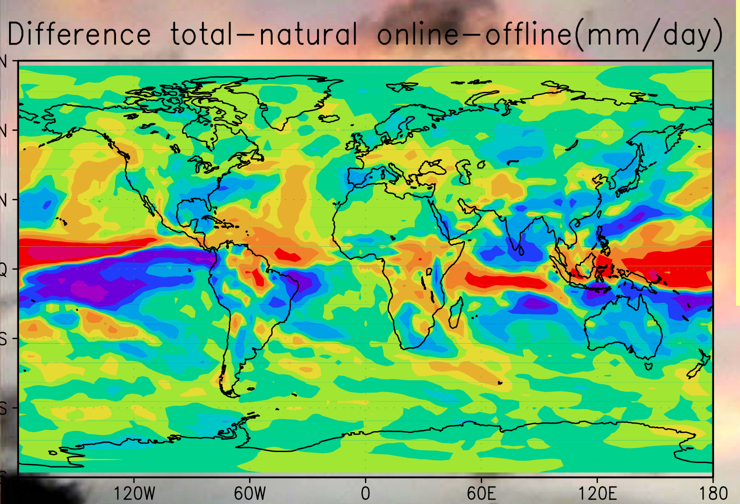


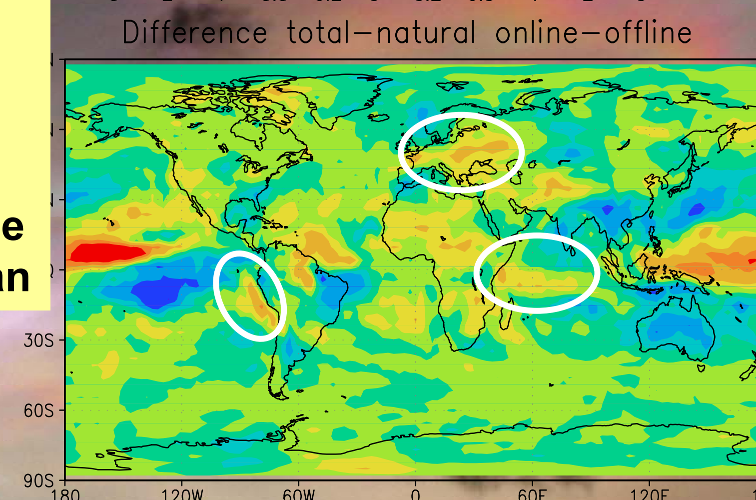
anticorrelations with SO4-feedback

Exceptions incl. cloudiness in Europe, Pacific off Peru/Chile Parts of Indian Ocean

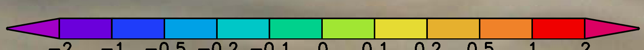
Feedback on 2-meter Temp



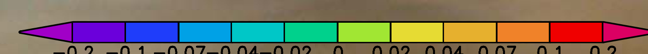




Feedback on Precipitation



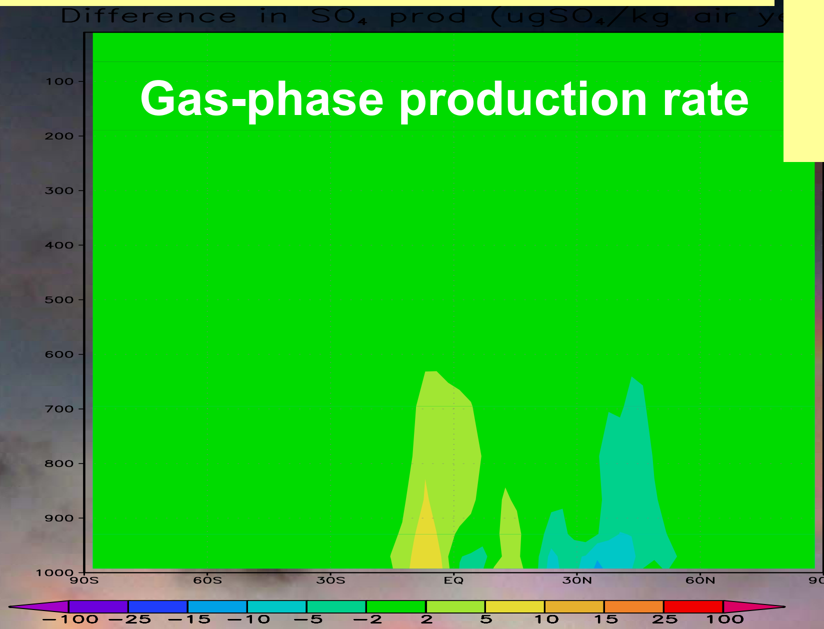
Feedback on cloudiness

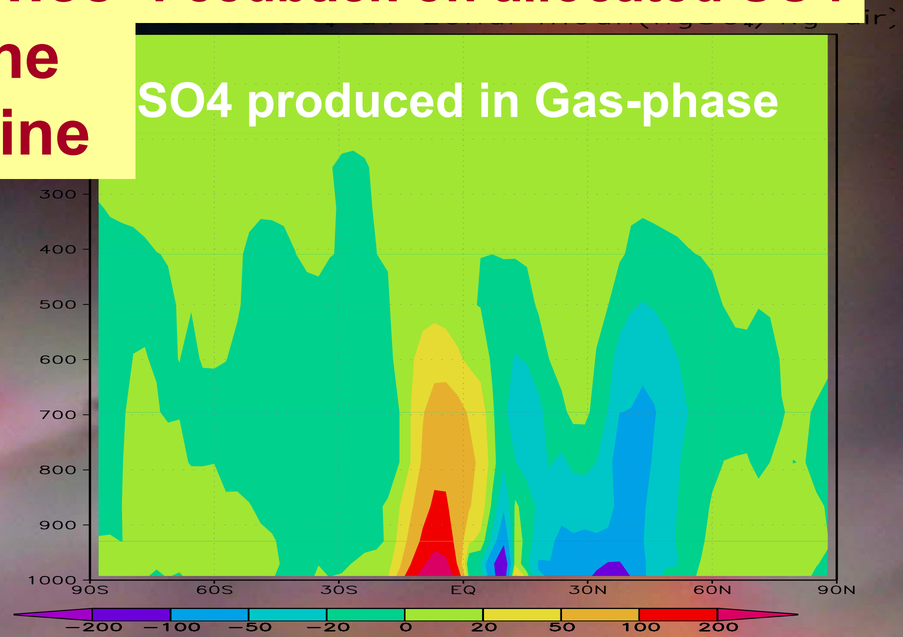


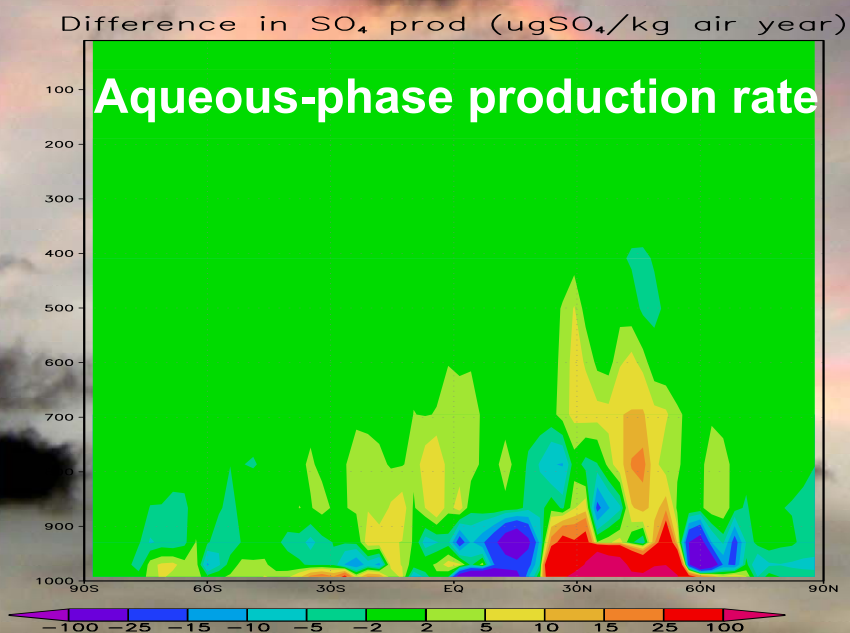
Feedback on SO4-production

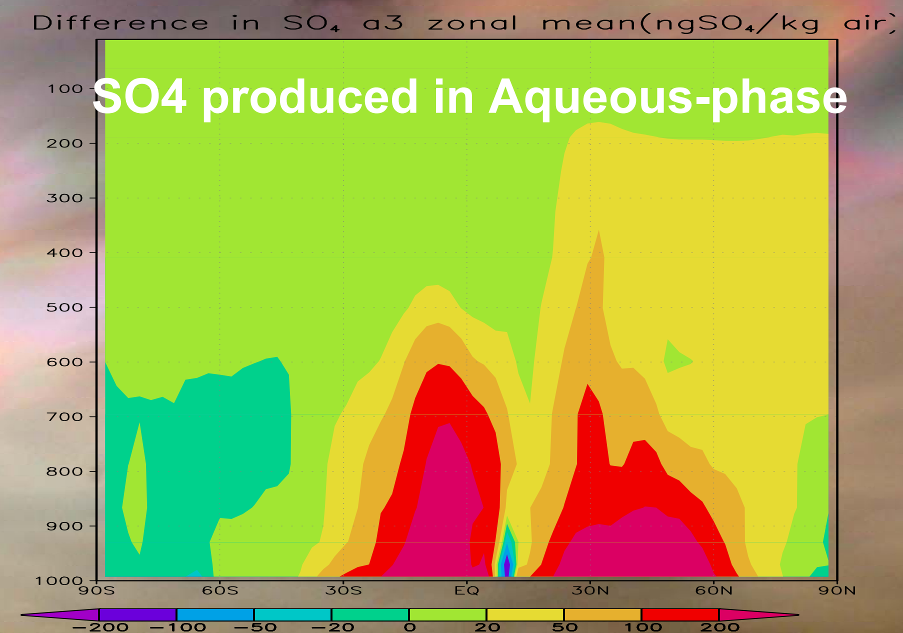
Difference On-line - Off-line

Feedback on allocated SO4



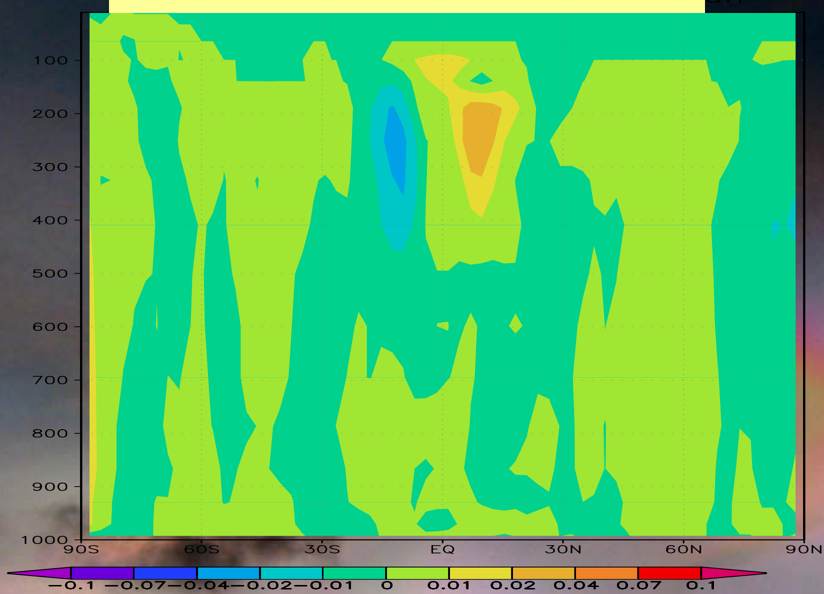


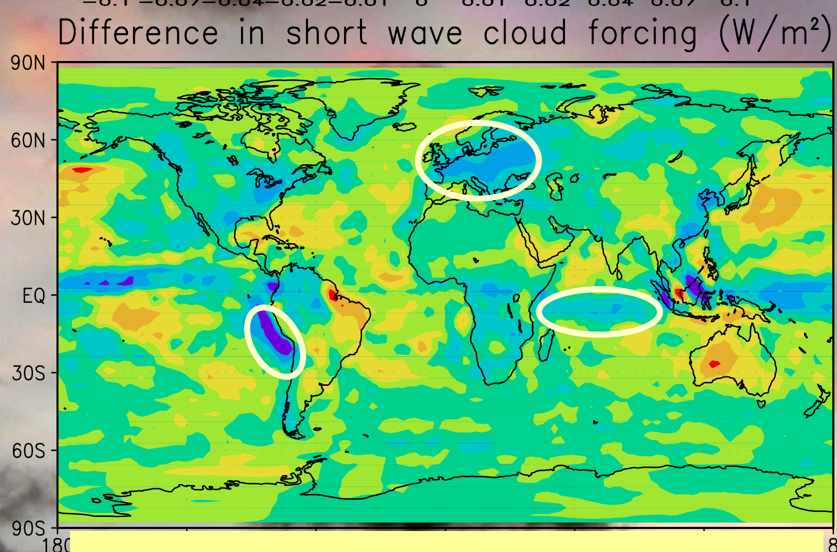




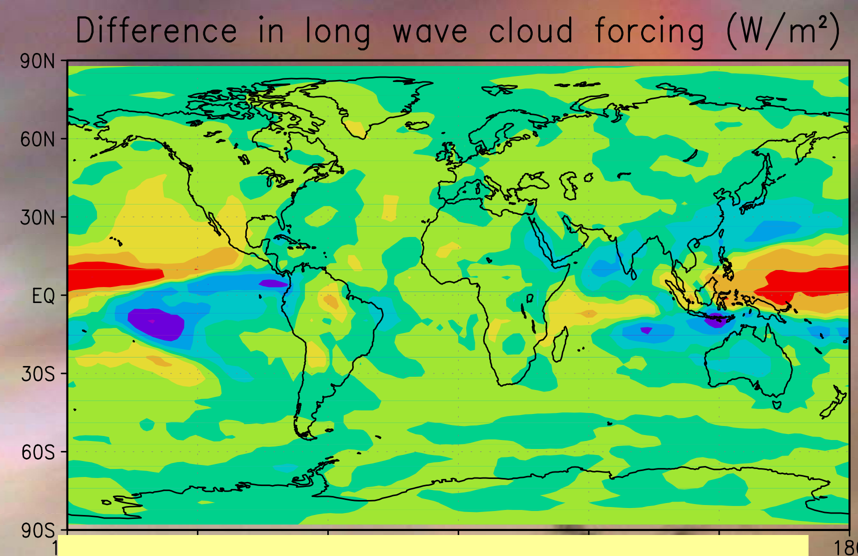
Difference On-line - Off-line

Feedback on cloudiness





Feedback on SW cloud forcing
- 0.14 W/m^2



Feedback on LW cloud forcing
+ 0.21 W/m^2

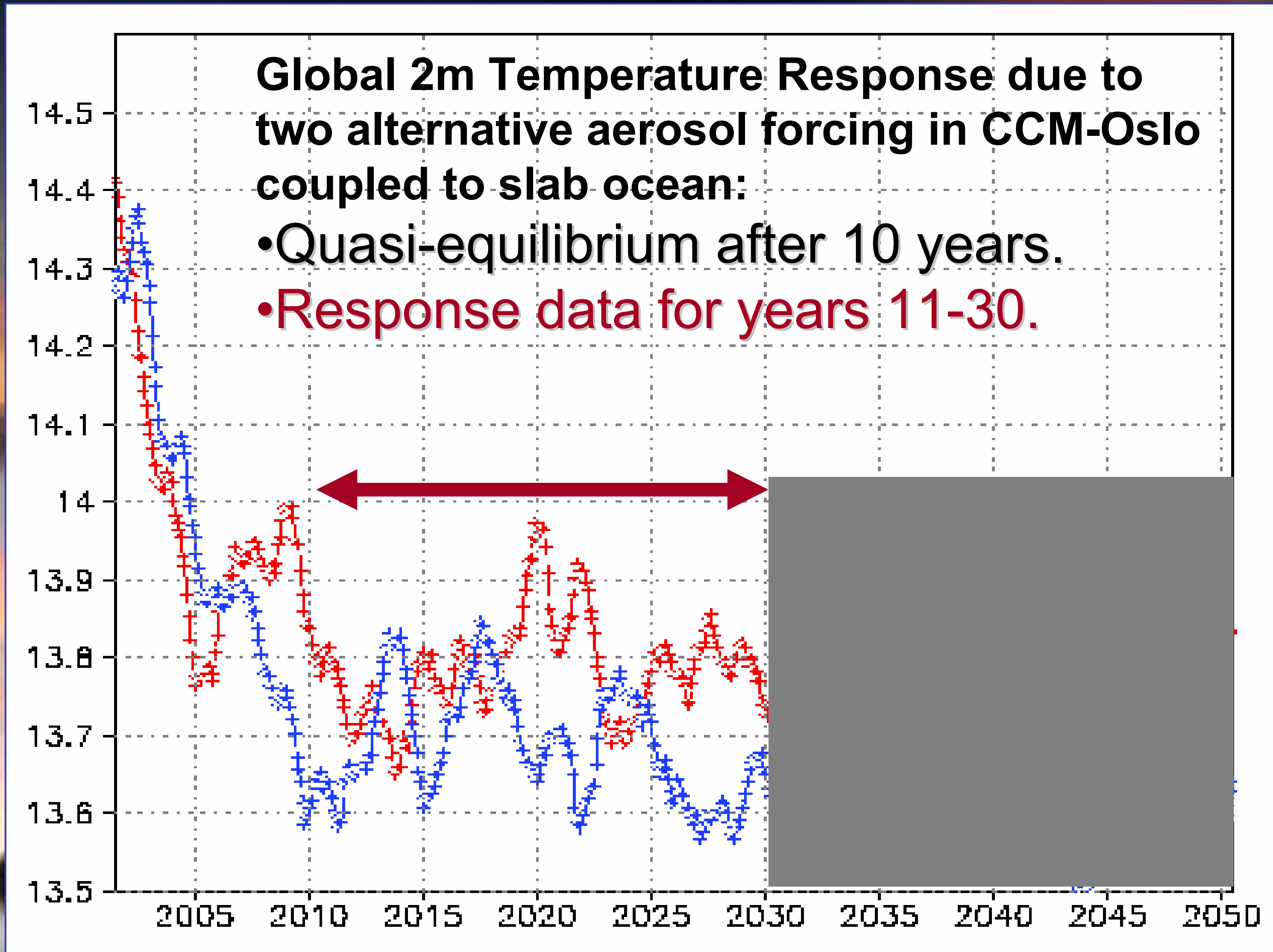
Discussion III

2. Why reduced indirect effect when sulfate increases?

Some elements of an explanation:

- **Sulfate increases predominantly in areas where clouds become less abundant and precipitation decreases**
- **Increased sulfate is predominantly produced in cloud droplets, implying minimal impacts on indirect effect**
- **Sulfate decreases slightly in areas normally sensitive to indirect effects (e.g. Atlantic sub-tropics)**
- **As ITCZ-displacements are reversed, clouds become more abundant in the upper tropical troposphere where LW cloud forcing warms more than SW cloud forcing cools**

Mother-of-Pearl clouds, Oslo, January 2003. © Michael Gauss


Global 2m Temperature Response due to two alternative aerosol forcing in CCM-Oslo coupled to slab ocean:
•Quasi-equilibrium after 10 years.
•Response data for years 11-30.
14.5
14.4
14.3
14.2
14.1
14
13.9
13.8
13.7
13.6
13.5
2005
2010
2015
2020
2025
2030
2035
2040
2045
2050

CCM-Oslo: Extensions of CCM3.2:

- **Prognostic cloud water**
  (Rasch and Kristjansson, 1998, *J. Climate,* **11**, 1587);

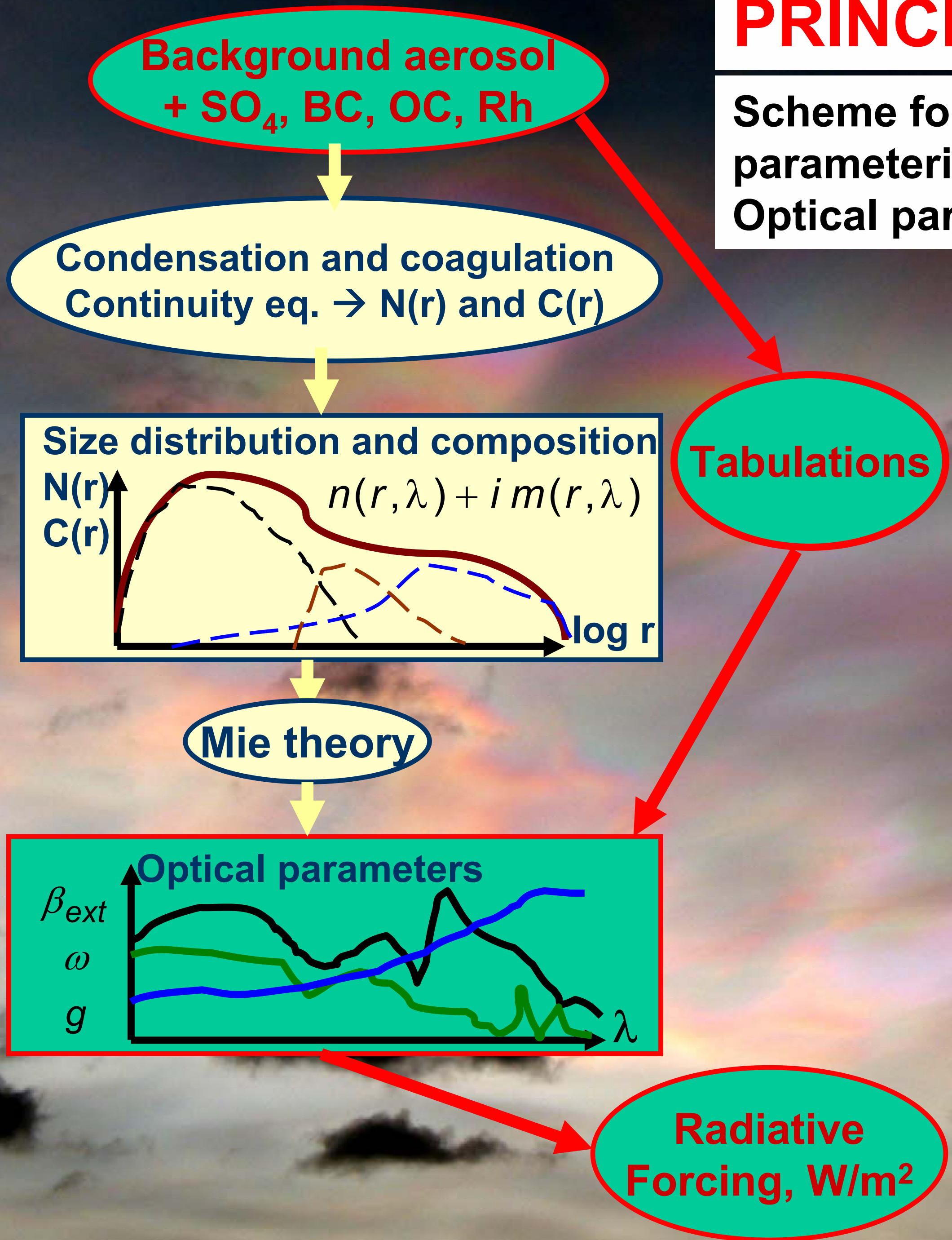
- **Life-cycle module for Sulphate and BC aerosols**
  (Iversen and Seland, 2002. *J. Geophys. Res*., **107** D24, 4751)

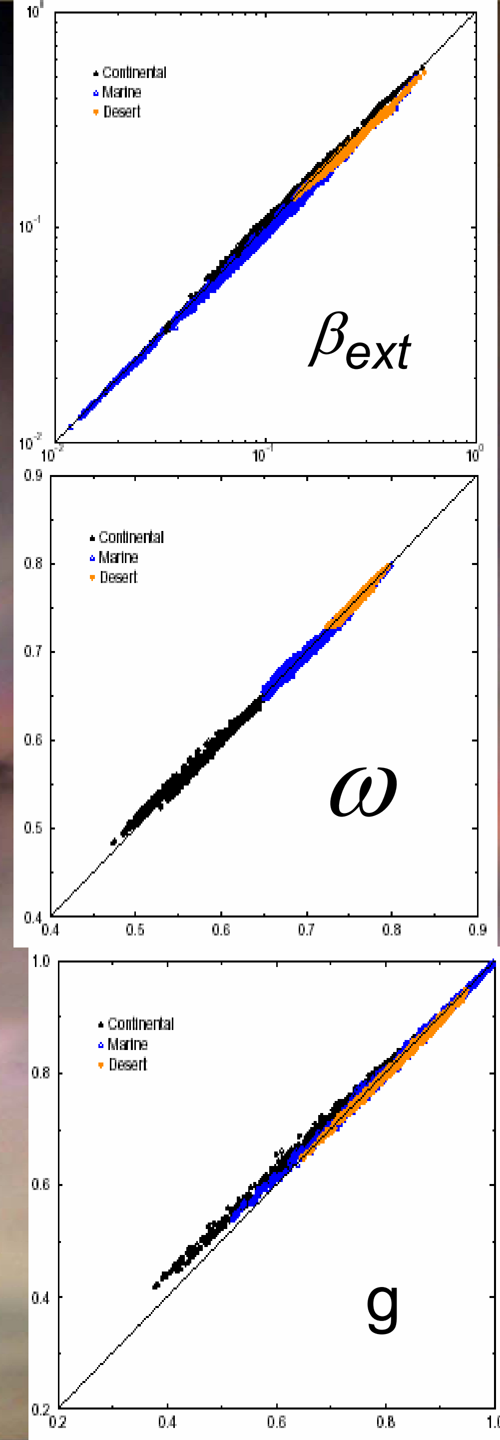
- **Parameterisation of aerosol size-distribution, optical properties, and CCN**
  Kirkevåg and Iversen, 2002, *J. Geophys. Res*., **107** D20, 4433.

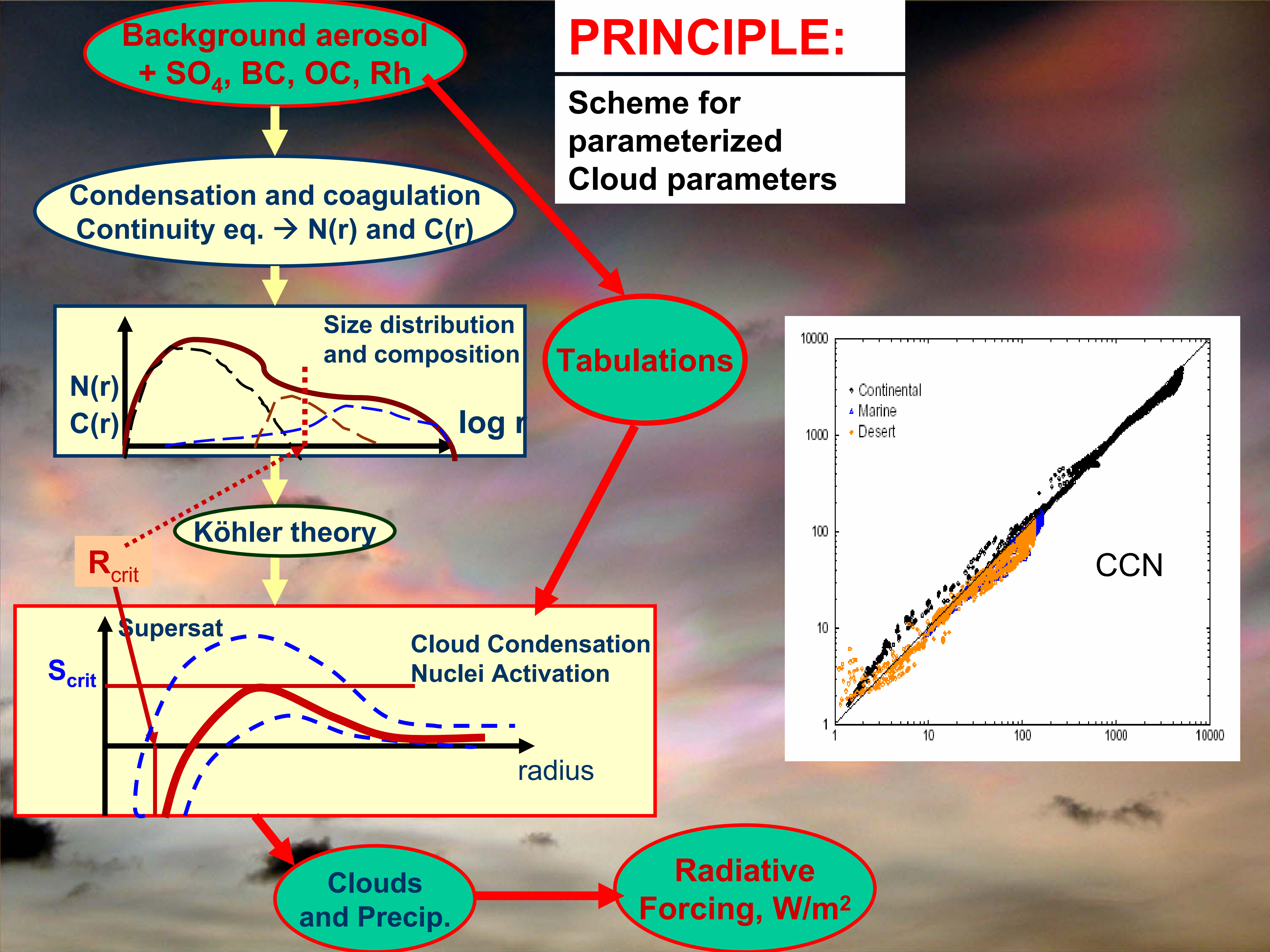
- **Parameterisation of aerosol-cloud-precipitation interactions for the Indirect aerosol effects**
  Kristjánsson, 2002. *J. Geophys. Res*., **107** D15, 4246.

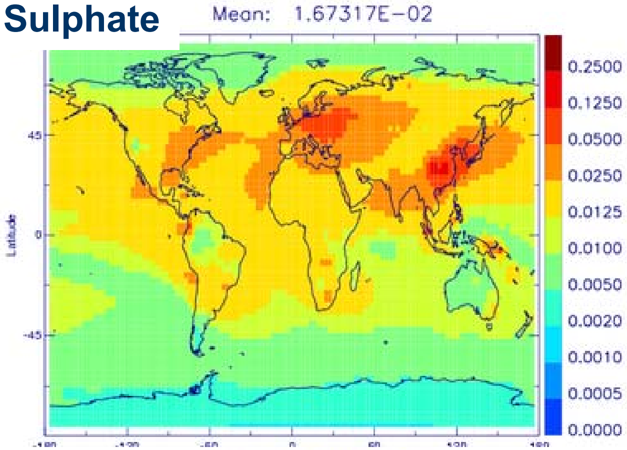
PRINCIPLE:

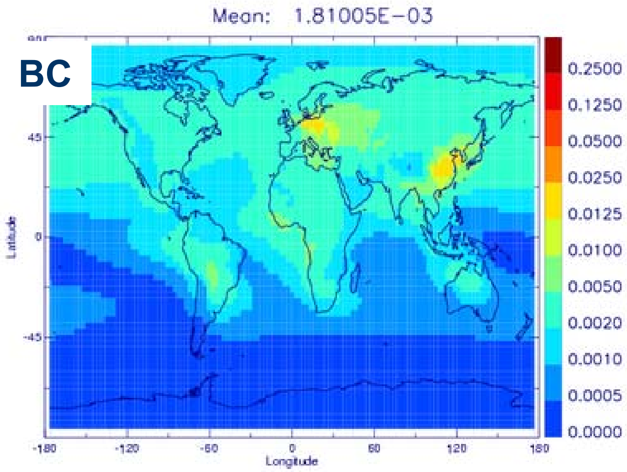
Scheme for parameterized Optical parameters

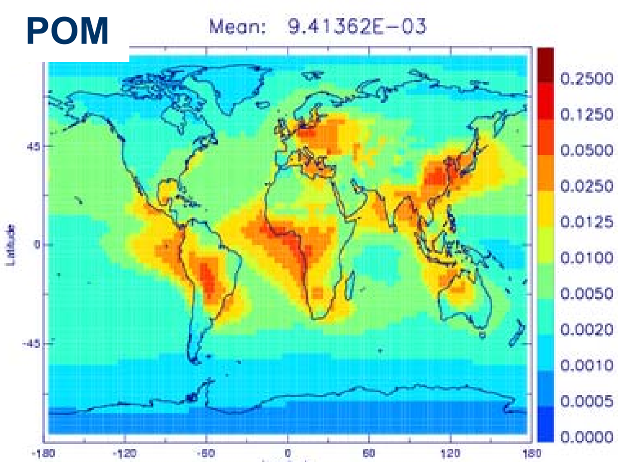


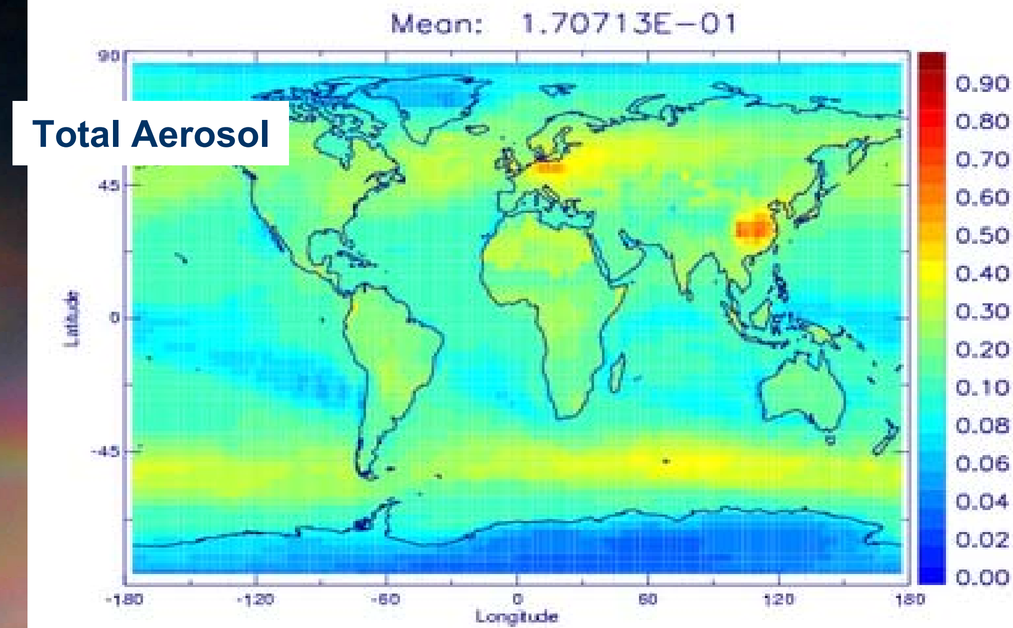


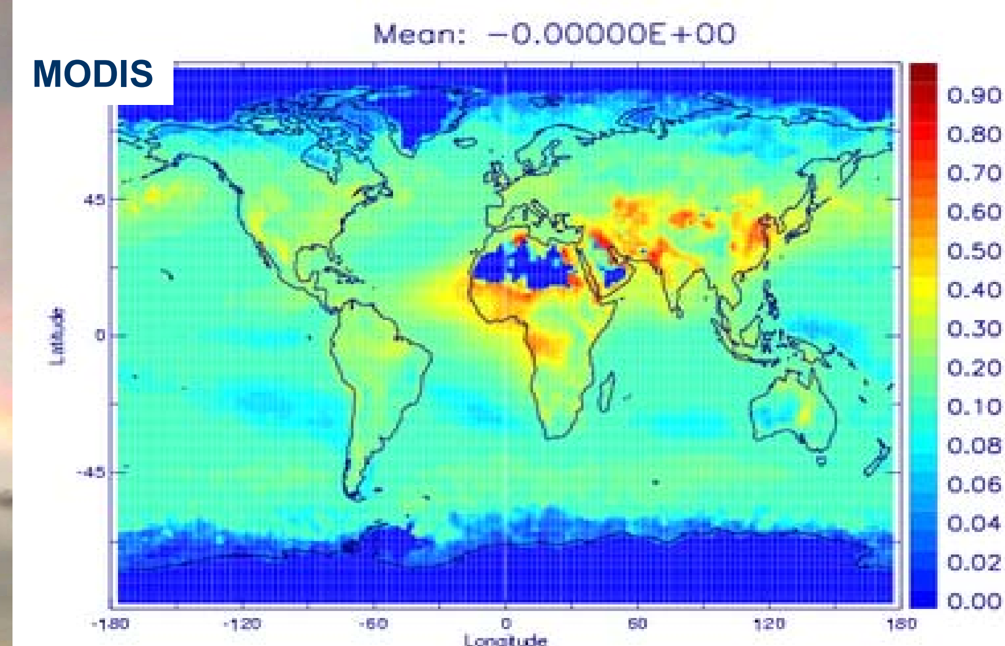

PRINCIPLE:
Scheme for parameterized Cloud parameters
Background aerosol + SO_4, BC, OC, Rh
Condensation and coagulation
Continuity eq. → N(r) and C(r)
Size distribution and composition
N(r)
C(r)
log r
Köhler theory
R_{crit}
Supersat
S_{crit}
Cloud Condensation Nuclei Activation
radius
Tabulations
Continental
Marine
Desert
10000
1000
100
10
1
1
10
100
1000
10000
CCN
Clouds and Precip.
Radiative Forcing, W/m²


Sulphate
Mean: 1.67317E-02
0.2500
0.1250
0.0500
0.0250
0.0125
0.0100
0.0050
0.0020
0.0010
0.0005
0.0000
Latitude

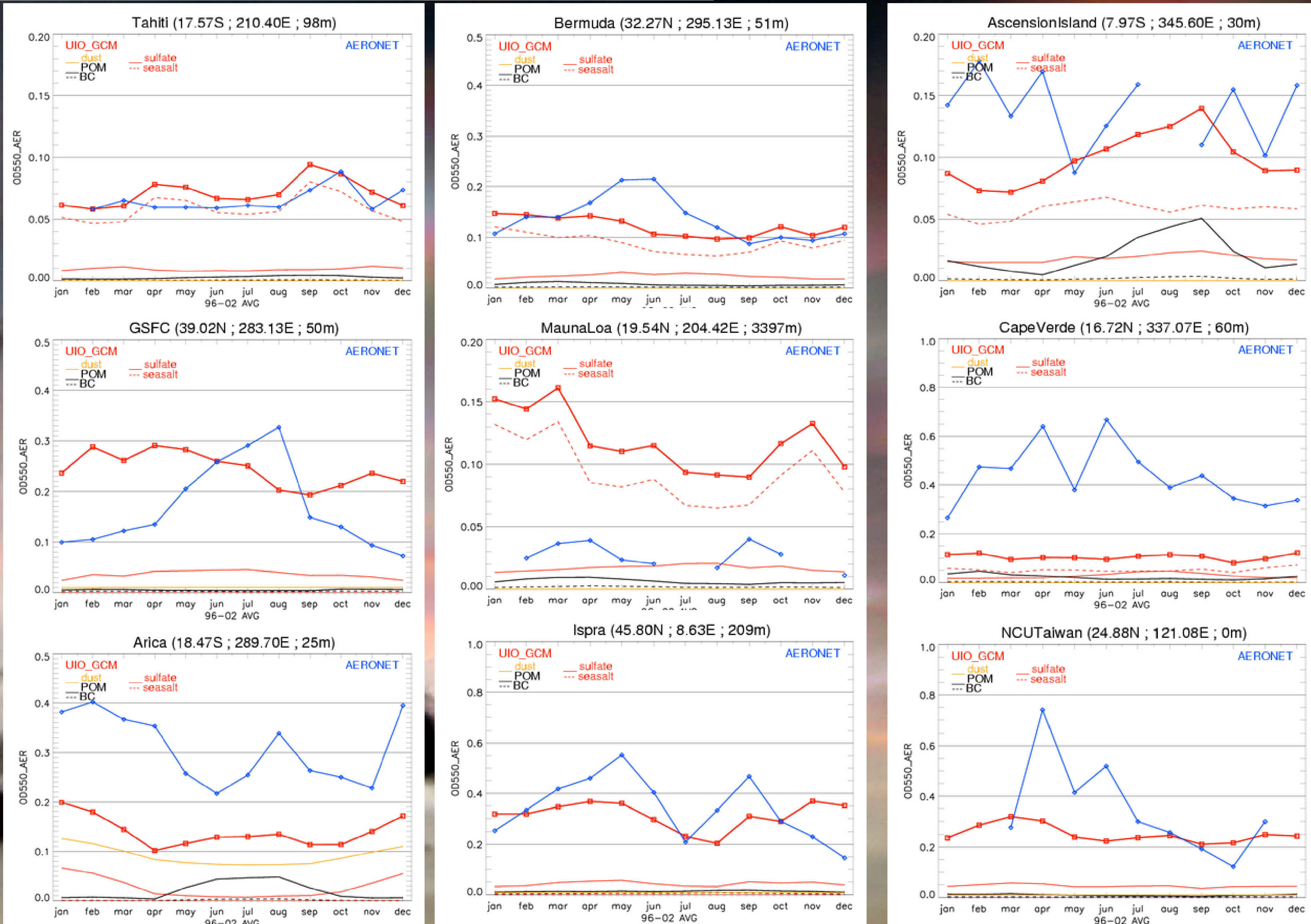

BC
Mean: 1.81005E-03
0.2500
0.1250
0.0500
0.0250
0.0125
0.0100
0.0050
0.0020
0.0010
0.0005
0.0000
Latitude
Longitude


POM
Mean: 9.41362E-03
0.2500
0.1250
0.0500
0.0250
0.0125
0.0100
0.0050
0.0020
0.0010
0.0005
0.0000
Latitude
Longitude


Total Aerosol
Mean: 1.70713E-01
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.08
0.06
0.04
0.02
0.00
Latitude
-180 -120 -60 0 60 120 180
Longitude

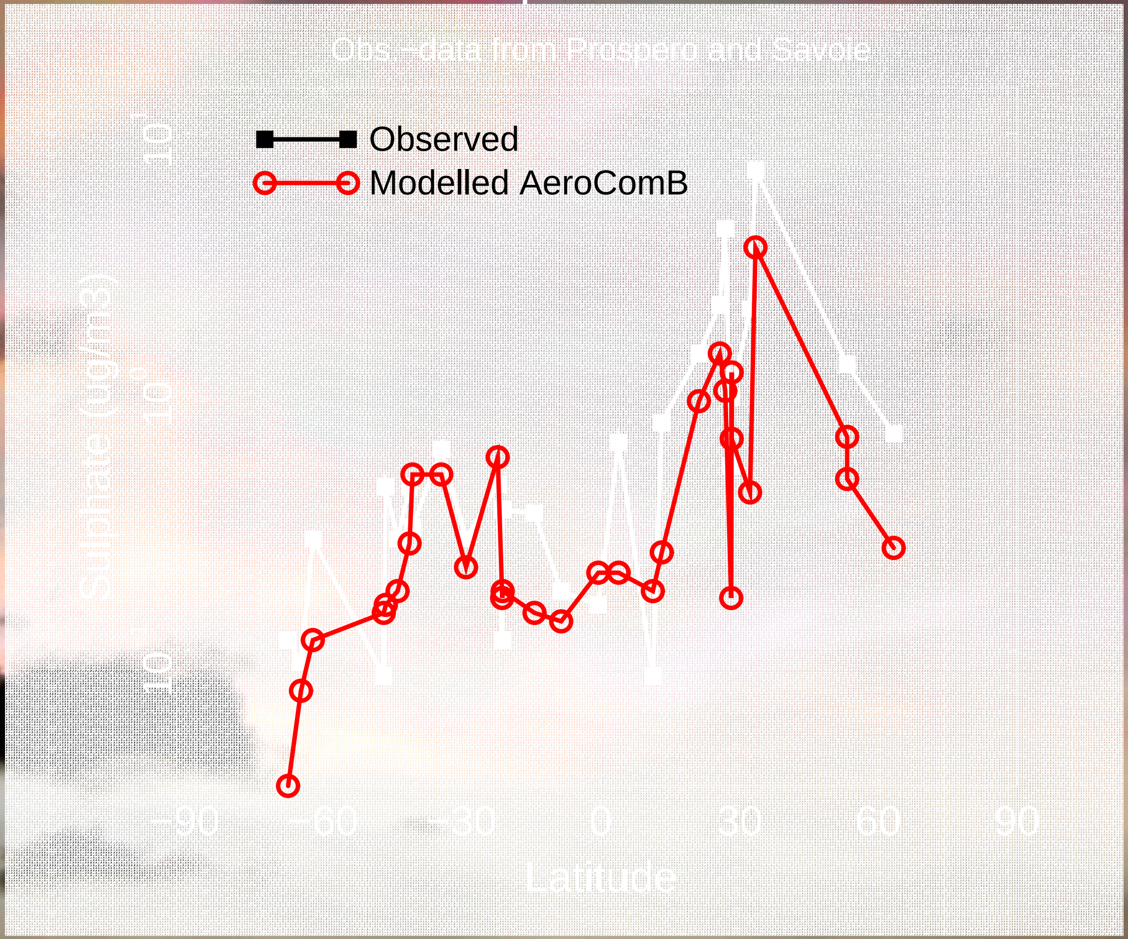

MODIS
Mean: -0.00000E+00
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.08
0.06
0.04
0.02
0.00
Latitude
-180 -120 -60 0 60 120 180
Longitude

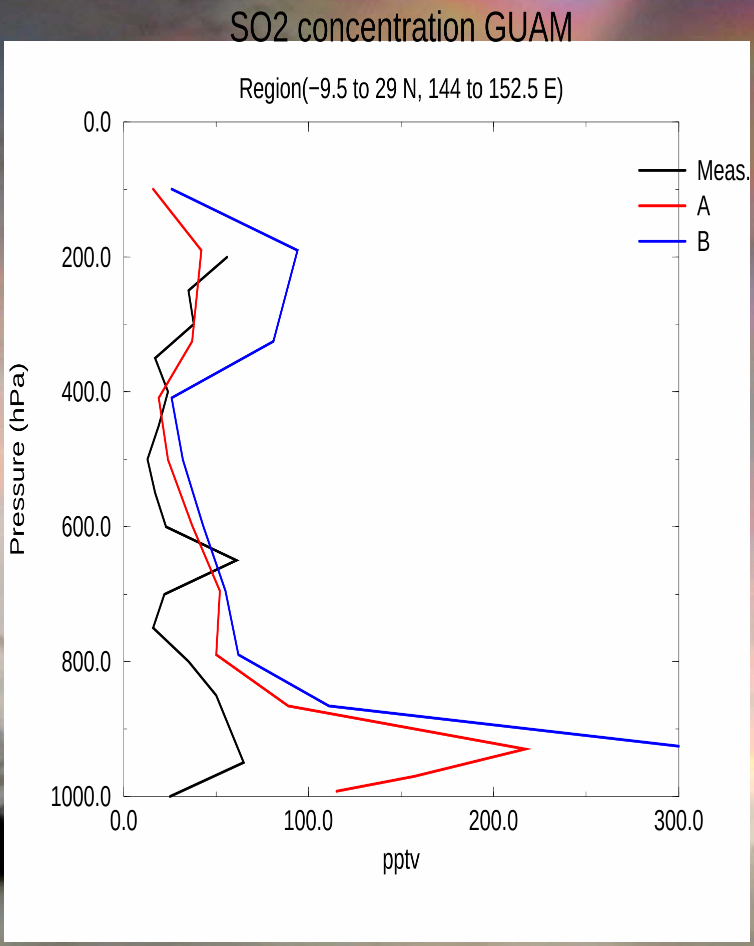
AEROCOM – RESULTS: ODE550



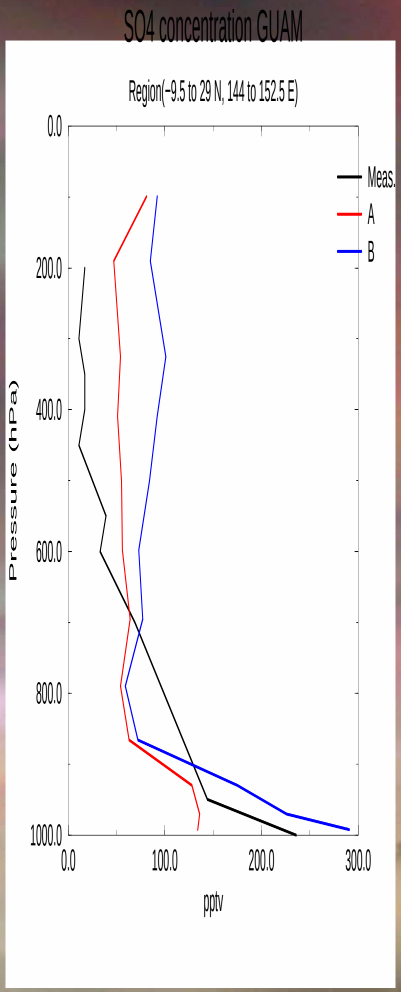
Sulphate in Oceanic areas

Annual nss−sulphate in oceanic areas

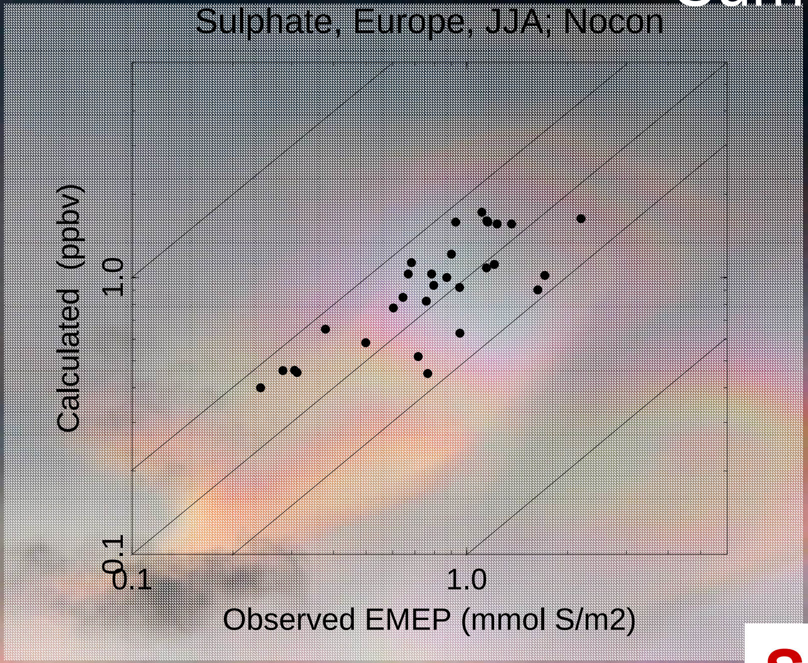




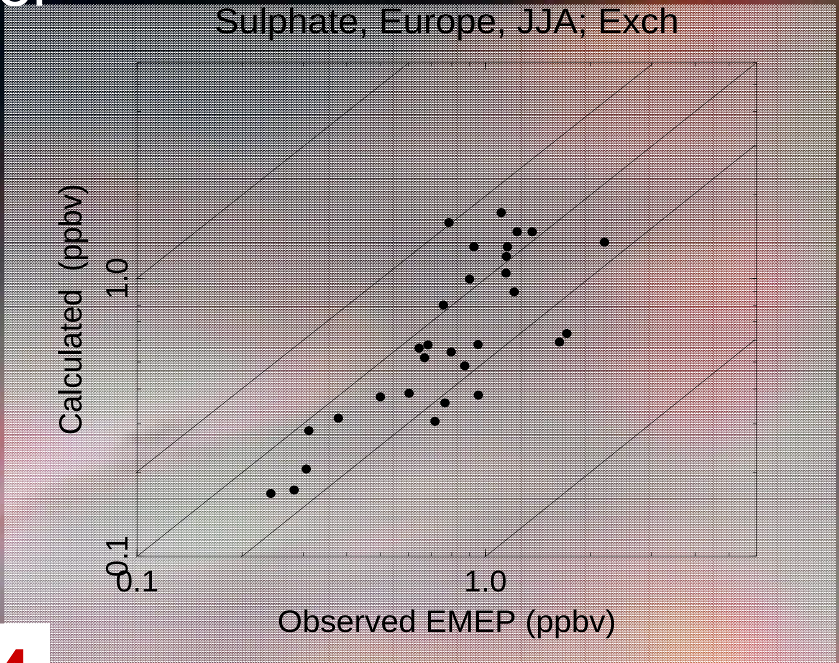
Guam:
Measured
AeroComA
AeroComB



Summer

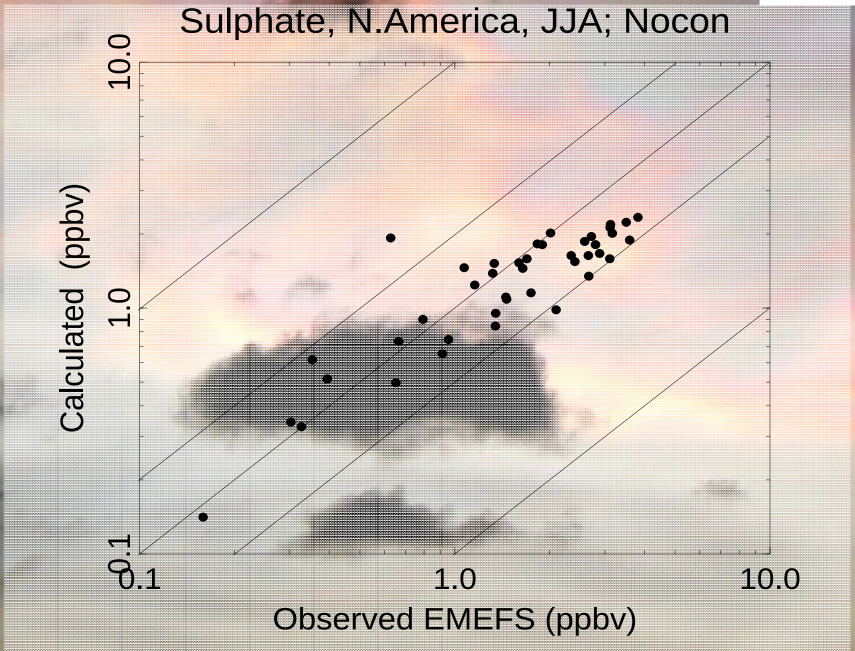


Sulphate, Europe, JJA; Nocon
Calculated (ppbv)
1.0
0.1
0.1
1.0
Observed EMEP (mmol S/m2)

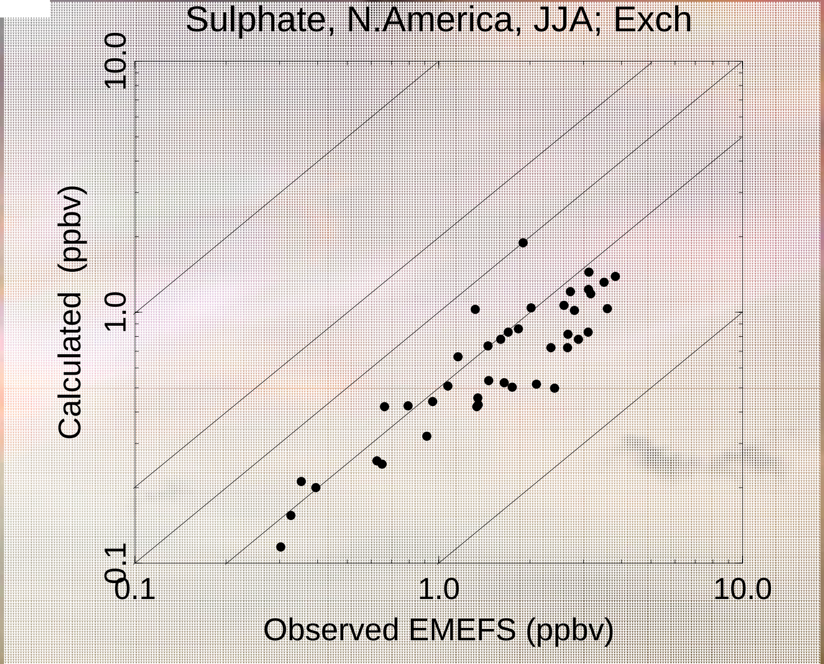


Sulphate, Europe, JJA; Exch
Calculated (ppbv)
1.0
0.1
0.1
1.0
Observed EMEP (ppbv)

SO4



Sulphate, N.America, JJA; Nocon
Calculated (ppbv)
10.0
1.0
0.1
0.1
1.0
10.0
Observed EMEFS (ppbv)



Sulphate, N.America, JJA; Exch
Calculated (ppbv)
10.0
1.0
0.1
0.1
1.0
10.0
Observed EMEFS (ppbv)