Before I start my presentation, let me put it briefly into context. Firstly, my presentation and the following one by Johann Feichter should be seen in context to give a picture on climate engineering.
In my talk I will make a survey over some of the proposed climate engineering schemes and introduce into the physical science while Johann will give a more detailed analysis of the climatic side effects of two of the most discussed options.

Secondly I would like to explain, why I encourage to discuss and research climate engineering concepts. This is certainly not because I want any of them being implemented (at least not in the foreseeable future). But on the other hand I am pessimistic that we as a whole will be able to limit our C02 emission in such a way as to avoid evident climate change by the middle of the century. By then, first dramatic consequences of climatic change might be evident and hopefully, effective legislation will be in place. It is very likely, that at least by then, the public pressure to implement effective countermeasures will be very high and on the other hand, financial incentives will attract all kind of people to sell concepts to save the climate or at least to extend our time for adaptation.
For me, it seems very important that the scientific community then has a deep understanding of the mechanism and side effects of such actions in order to give well founded and concrete advice to the politicians. Just saying that you should not fiddle around with the climate system might be not enough at a time when it becomes more than clear that we have been fiddling around for too long already.

# Engineering the climate – a review of aerosol approaches

*Thomas Leisner, Michael Höpfner*
*Institut für Meteorologie und Klimaforschung FZ Karlsruhe*

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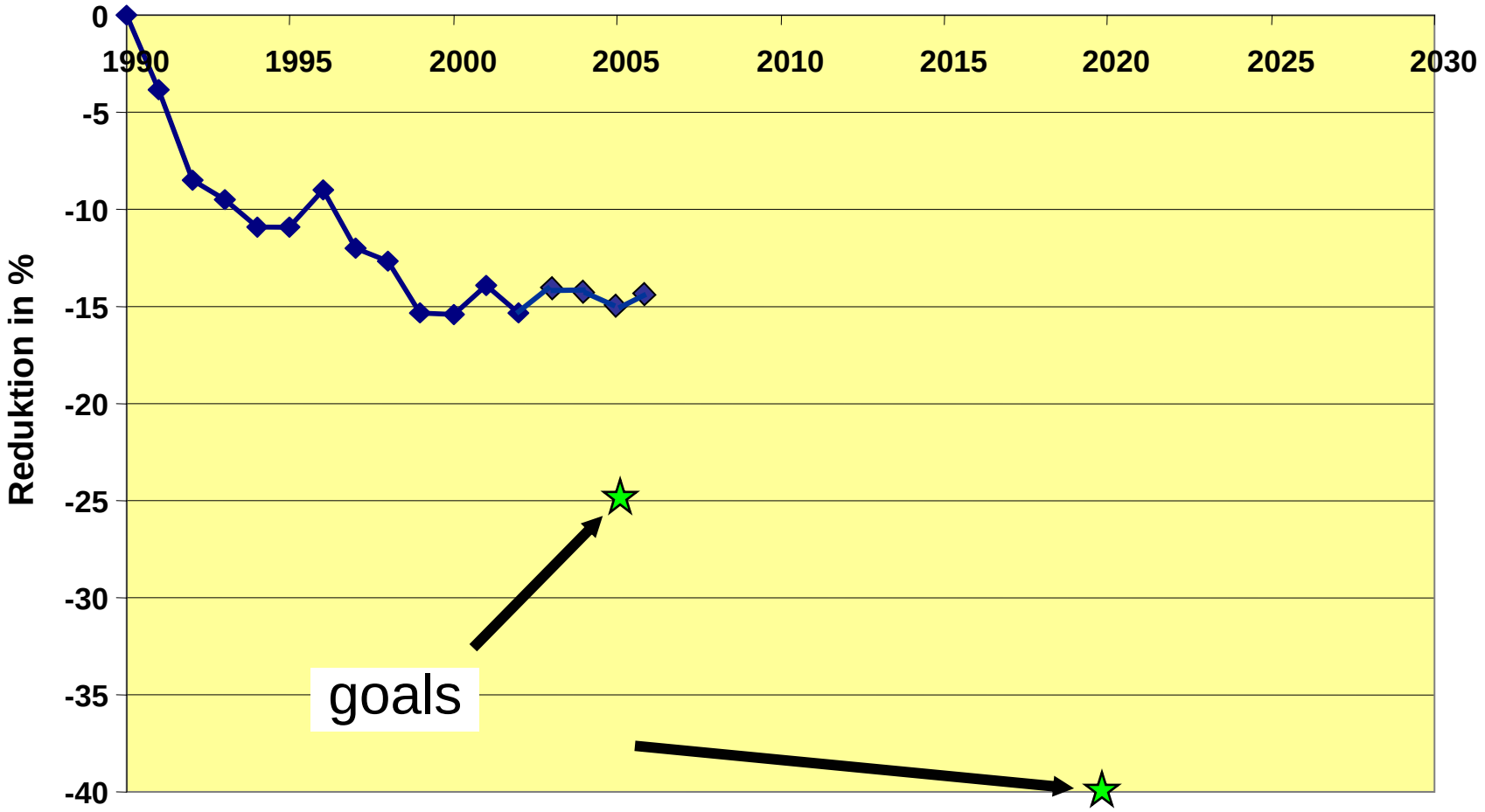
# $CO_2$-emissionen in Germany

Karlsruhe Institute of Technology




Datenquelle: BMU 3/2003 und Koalitionsvereinbarung Nov. 2005

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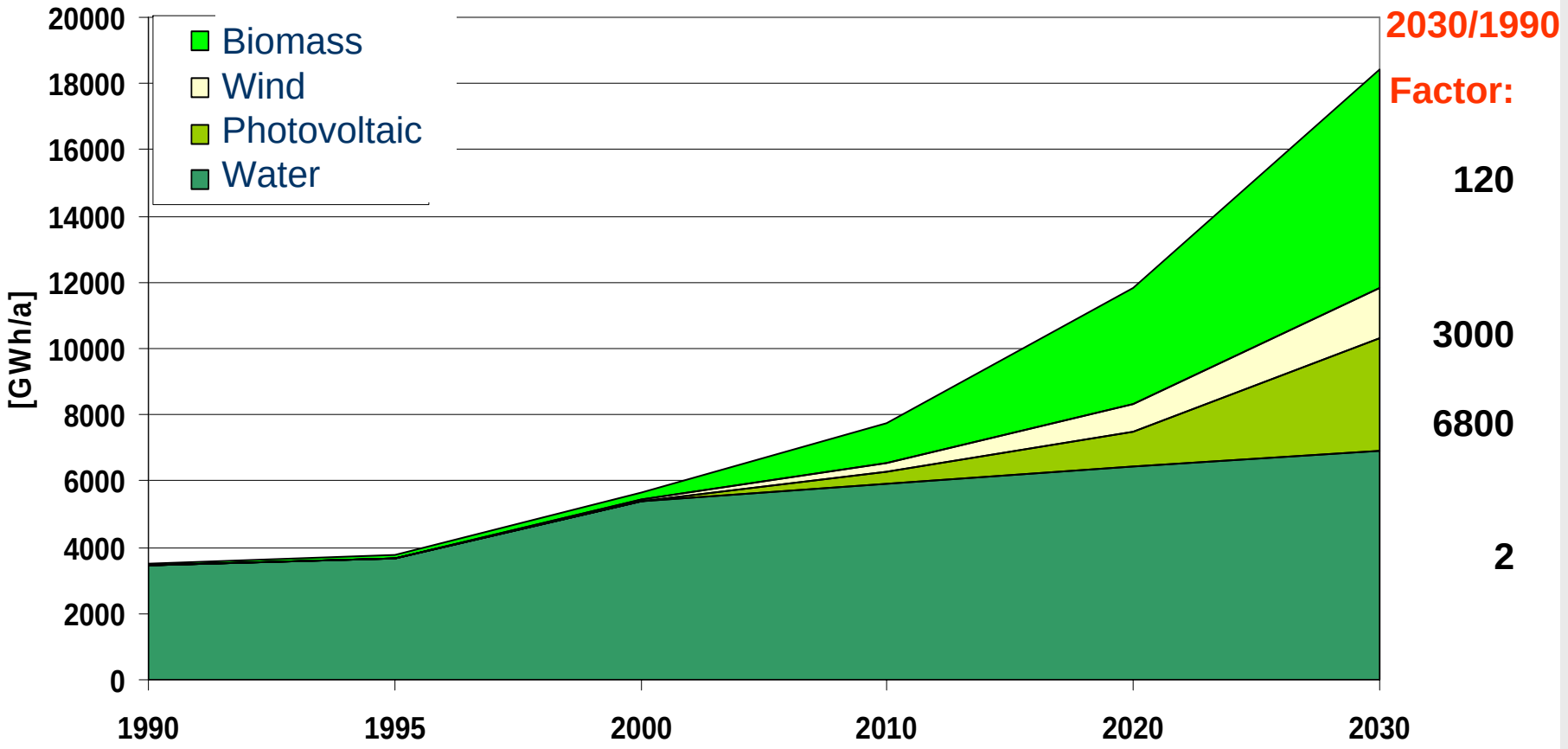
# Potential electricity from renewables, Federal state of Baden-Württemberg,

KIT
Karlsruhe Institute of Technology



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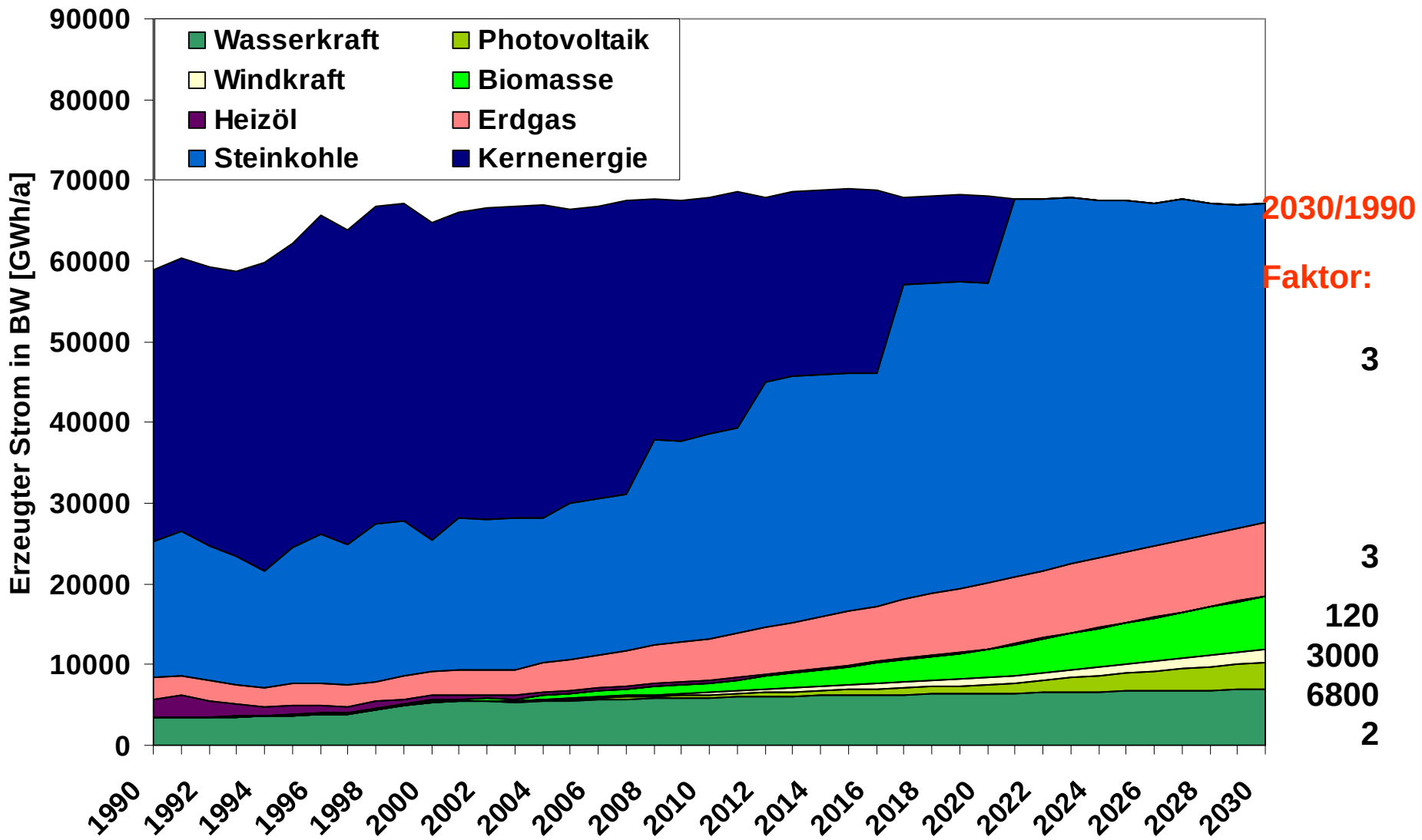
# Electricity in Baden Württemberg, optimistic scenario

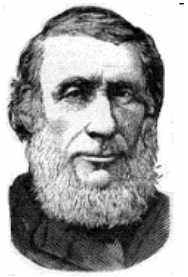
Karlsruhe Institute of Technology




Datenquelle: bis 2000: Energiebericht Baden-Württemberg 2001
ab 2010 Gutachten des IER im Auftrag der Landesregierung BW März 2001

# History of aerosol research: the 19th century

**John Tyndall:**



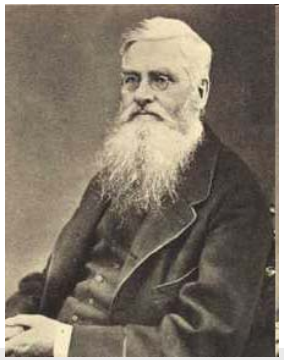
Absorption and scattering of radiation in the atmosphere: **„Without water vapor, the earth would be held fast in the iron grip of frost“ (1859)**

**John Aitken:**

(portrait wanted)

Cloud condensation nuclei: **„Without dust ... there would be neither fog nor rain“ (Trans. Roy. Soc. Edinb. 30, (1880))**

**Alfred R. Wallace:**



**The Importance of Dust: A Source of Beauty and Essential to Life, “The Wonderful Century” (1898)**

But in all densely-populated countries there is an enormous artificial production of dust… This superabundance of dust …. must almost certainly produce some effect on our climate; and the particular effect it seems calculated to produce is the increase of cloud and fog, but not necessarily any increase of rain.

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# Climate engineering: The historical perspective

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- Weather and precipitation control for commercial and military purpose (USA, USSR, China, 1950 ~ 1980)

**As our civilization steadily becomes more mechanized and as our population density grows the impact of weather will become ever more serious. ...The solution lies in ... intelligent use of more precise weather forecasts and, ideally, by taking the offensive through control of weather... I shudder to think of the consequences of a prior Russian discovery of a feasible method for weather control.**
*Henry Houghton, MIT, 1957*

- Geoforming, Geoengineering, „Improving the planet“
Melting the arctic ice cap and irrigating central asia by diverting the siberian rivers and by building a dam across the Bering Strait.
P.M. Borisov, *Bulletin of the Atomic Scientists*, March, 1969, pp. 43-48

*Earth-Science Reviews* – Elsevier Publishing Company, Amsterdam - Printed in The Netherlands

LAMB, H. H., 1971. Climate-engineering schemes to meet a climatic emergency. *Earth-Sci. Rev.*, 7: 87–95.

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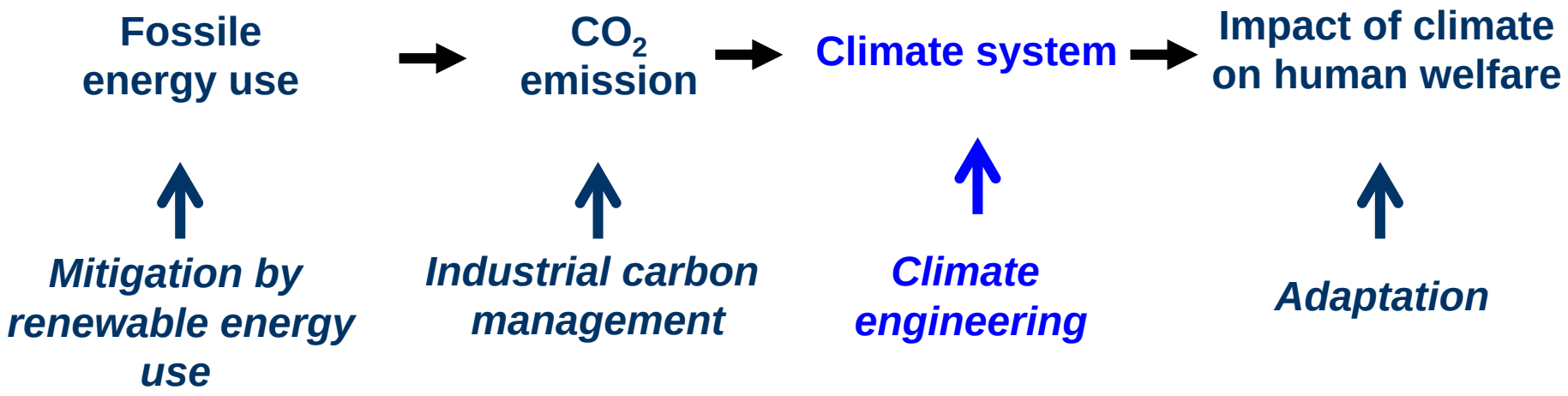
# Definition Climate engineering

Karlsruhe Institute of Technology

**intentional large-scale manipulation of the environment, with the goal of reducing undesired climate change caused by human influences (Keith, 2000)**




after Keith, 2000

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# Recent interest

Karlsruhe Institute of Technology

**Global Warming and Ice Ages:**
**I. Prospects for Physics-Based Modulation of Global Change**

E. Teller
L. Wood
R. Hyde

This paper was prepared for submittal to the
22nd International Seminar on Planetary Emergencies
Erice (Sicily), Italy
August 20-23, 1997

August 15, 1997

Lawrence Livermore National Laboratory

**ALBEDO ENHANCEMENT BY STRATOSPHERIC SULFUR INJECTIONS: A CONTRIBUTION TO RESOLVE A POLICY DILEMMA?**

*An Editorial Essay*

**P. Crutzen**
**Climatic Change, 2006**

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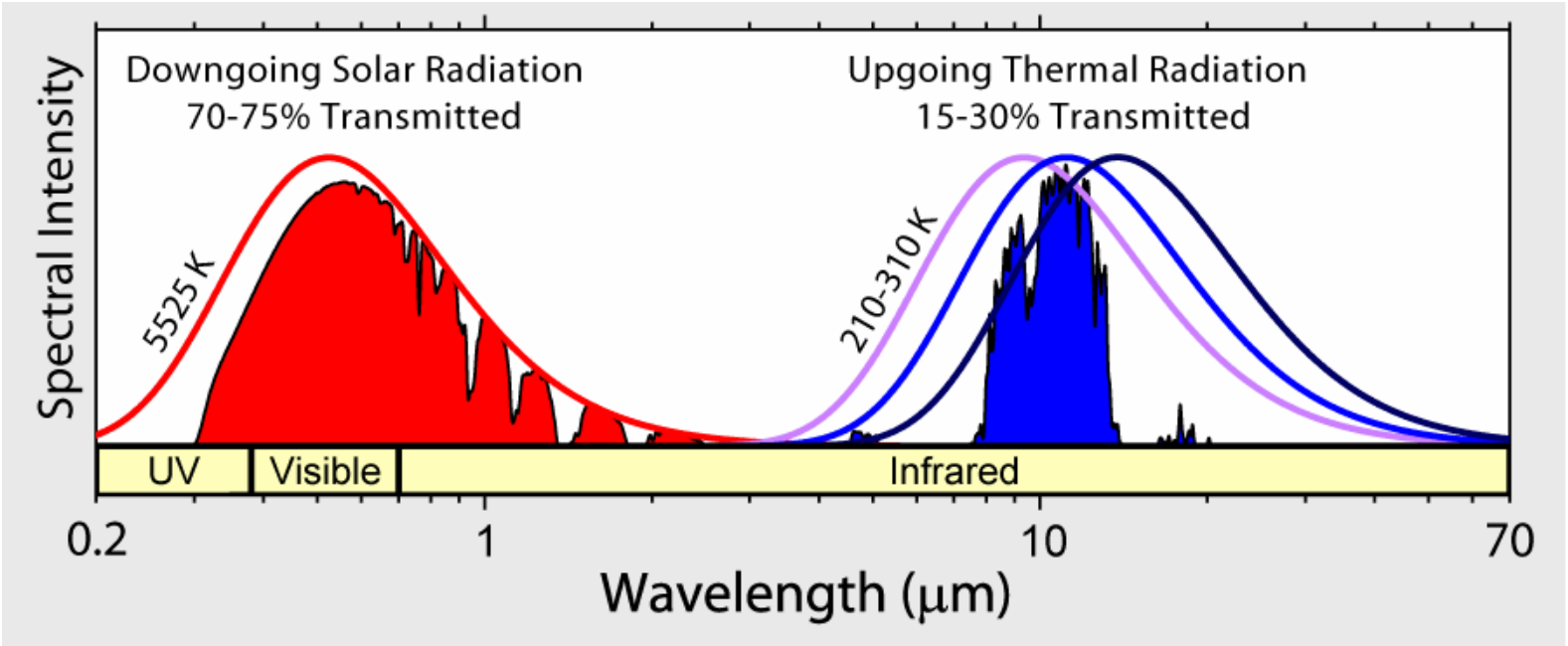
# The radiation budget of the earth
# The physical science base

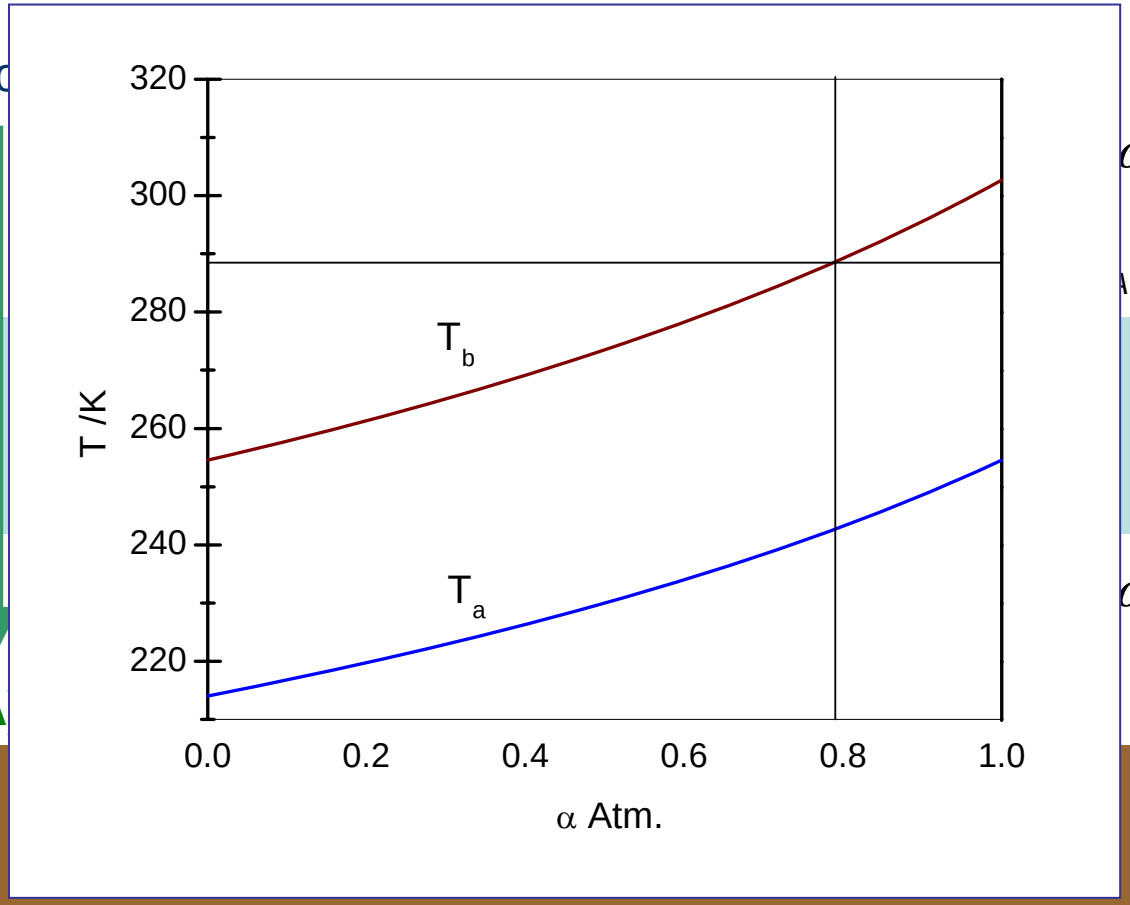
Karlsruhe Institute of Technology



# A zero-dimensional „radiation model“

$$\sigma T_B^4 = 2\sigma T_A^4 = 2\frac{L}{2-\alpha_A} = \frac{S_0/2(1-A)}{2-\alpha_A}$$

Visible (sho
radiation




$\alpha_A)\sigma T_B^4 + \alpha_A \sigma T_A^4$

$\sigma T_A^4$

**solar constant**
**(1360 W/m²)**

$\alpha_A \sigma T_A^4$

$L = S_0/4\ (1\text{-}A$

$= \sigma T_B^4 - \alpha_A \sigma T_A^4$

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# Cimate engineering Taxonomy

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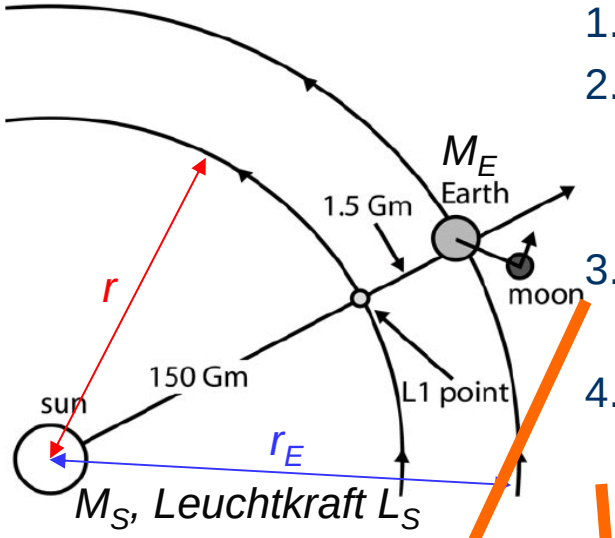
| Changing the solar constant | Increasing the planetary albedo | Reducing the atmospheric absorbtivity |
|---|---|---|
| • Scatterers in space | • Scatterers in the stratosphere<br>• Absorbers in the stratosphere<br>• Scatterers in the Troposphäre<br>• Changing the Albedo of Land or Sea- Surface | • Geochemical CO2 Sequestration by fertilization of the oceans<br>• $CO_2$ – extraction from air<br>• $CO_2$ – uptake by terrestrial ecosystems |

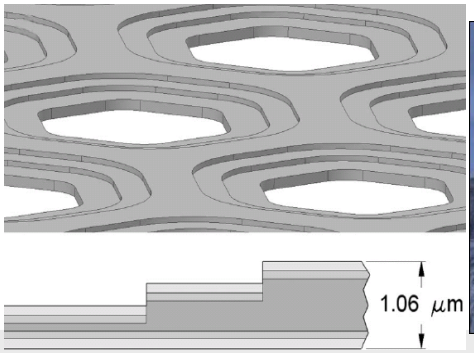
# Changing the solar constant: (Angel, PNAS, 2006)

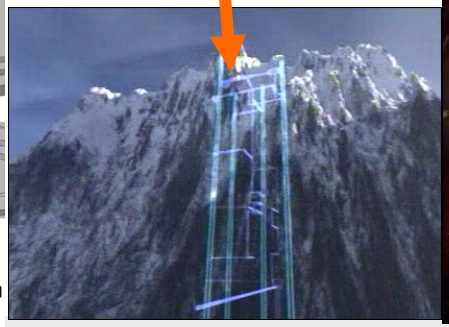


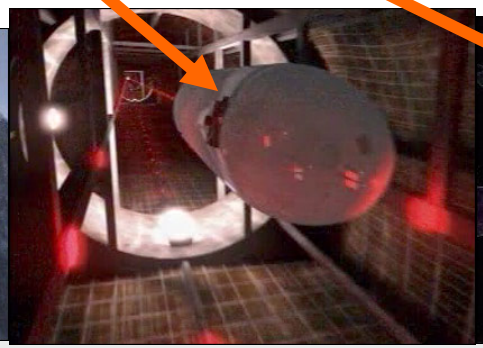


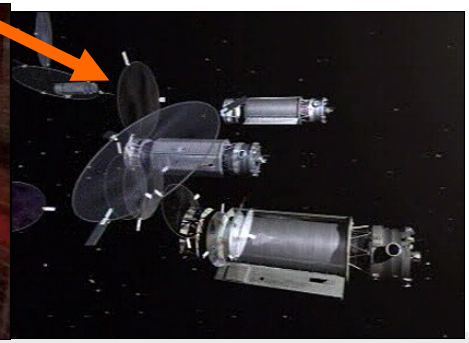

1. Location L1 point (weakly unstable)
2. Implementation: Cloud of thin fresnel lenses (SiN), stabilized by radiation pressure control, Dia: 1m, thickness 1 µm, weight 1g, $N_{tot}$ $1{,}6\times10^{13}$
3. Optical Design: Fresnel lens type of high reflective index material, only slight deviation of the light
4. Transportation : elektromagnetic launch (rail gun), Ionen propulsion. Cost 50 $/kg (currently 20000 $/kg)

**Total cost several Trillion US$**
**$(100 Mrd. $/a)**

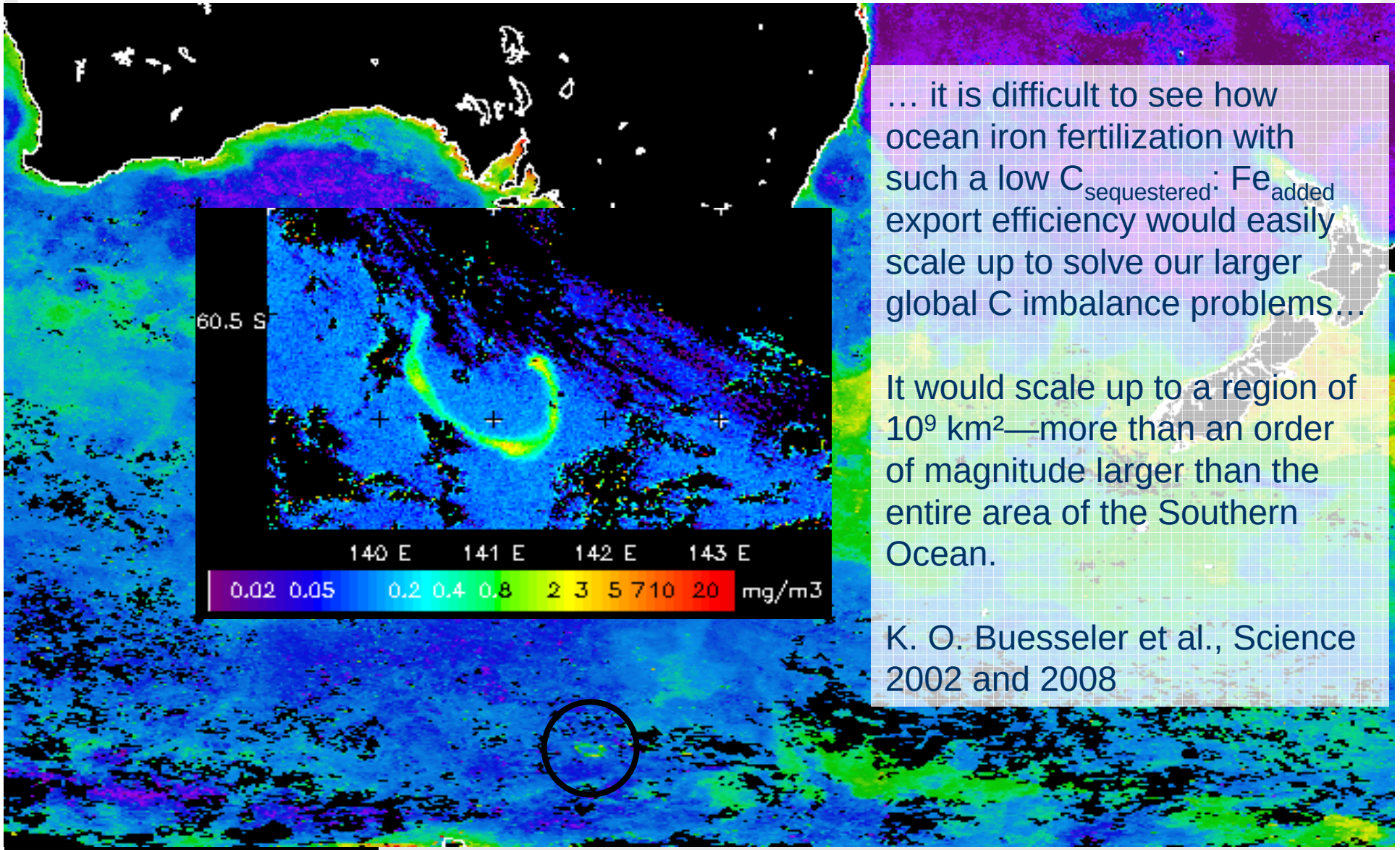






# $CO_2$ Sequestration by fertilization of nutrient deficient oceans




SOIREE experiment Boyd, 2007

… it is difficult to see how ocean iron fertilization with such a low $C_{sequestered}$: $Fe_{added}$ export efficiency would easily scale up to solve our larger global C imbalance problems…

It would scale up to a region of $10^9$ km²—more than an order of magnitude larger than the entire area of the Southern Ocean.

K. O. Buesseler et al., Science 2002 and 2008

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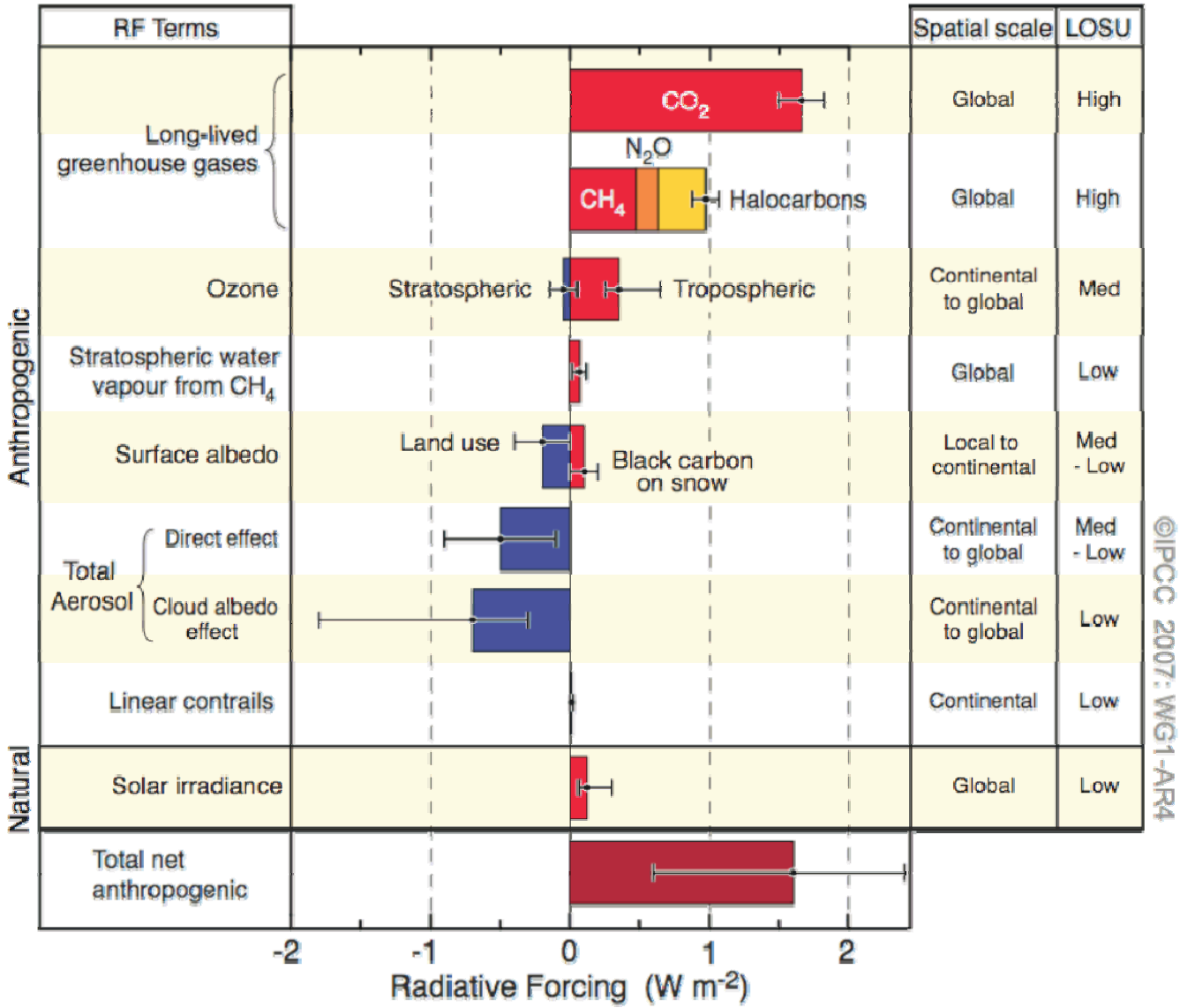
# Aerosol approaches, the physical science base

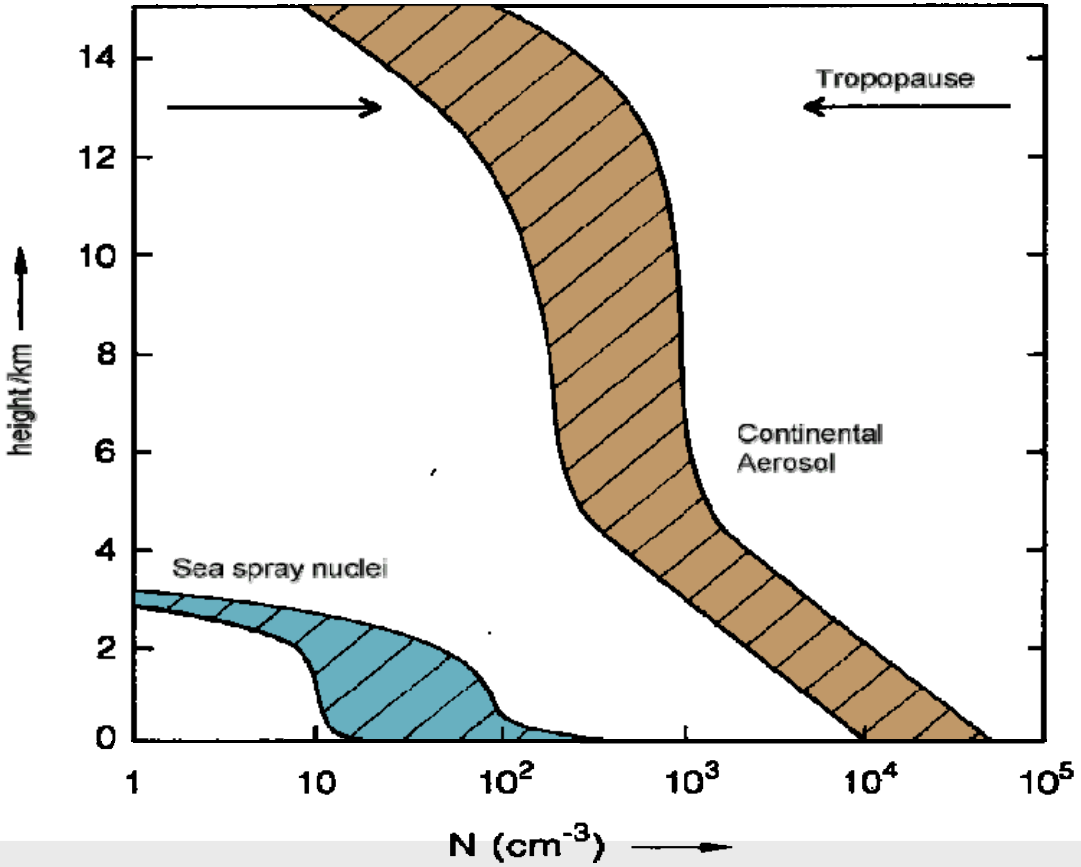
Karlsruhe Institute of Technology



# Aerosols

Airborne particles mainly from ammonium sulfate, sea salt, minerals, black carbon or high molecular weight organic matter

Concentration: 1000 - 100000 particles per $cm^3$ in the low atmosphere




adapted from: W. Rödel, Physik unserer Umwelt – die Atmosphäre, Springer

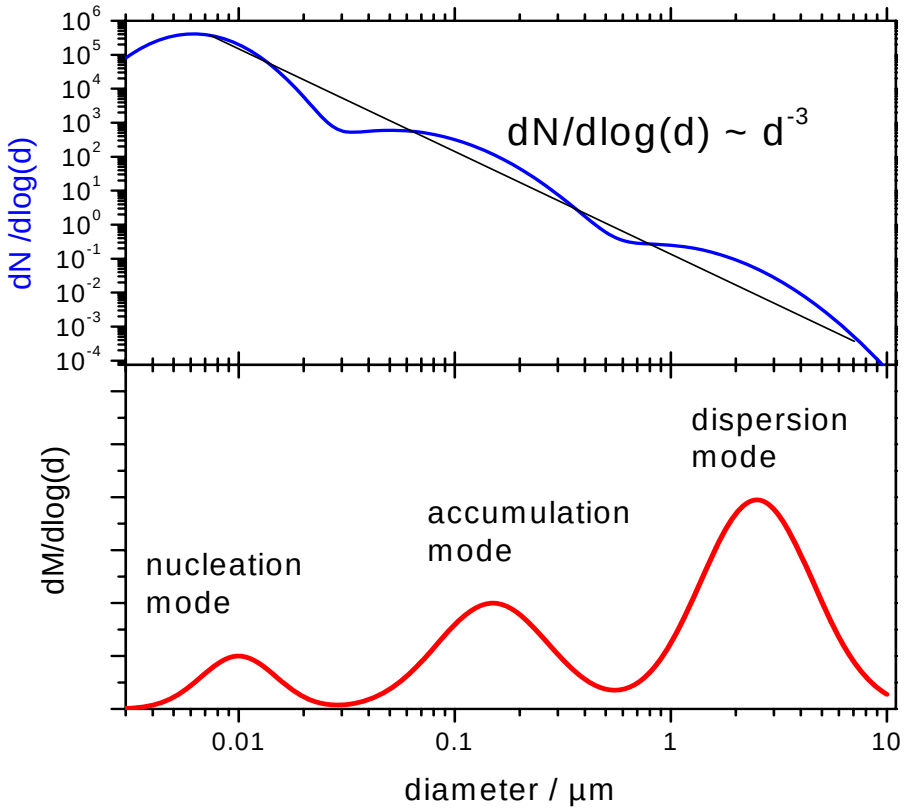
# Aerosol sources and processes

**Primary aerosol:**
Particles emitted from the surface
Wind blown mineral dust,
Seaspray, Biomass burning,
volcanic ashes

**Secondary aerosol:**
homogeneous condensation of
low volatility reaction products
from volatile precursor gases.

**Processes:**
coagulation, sedimentation, cloud
interaction

## Size distribution

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# optical properties

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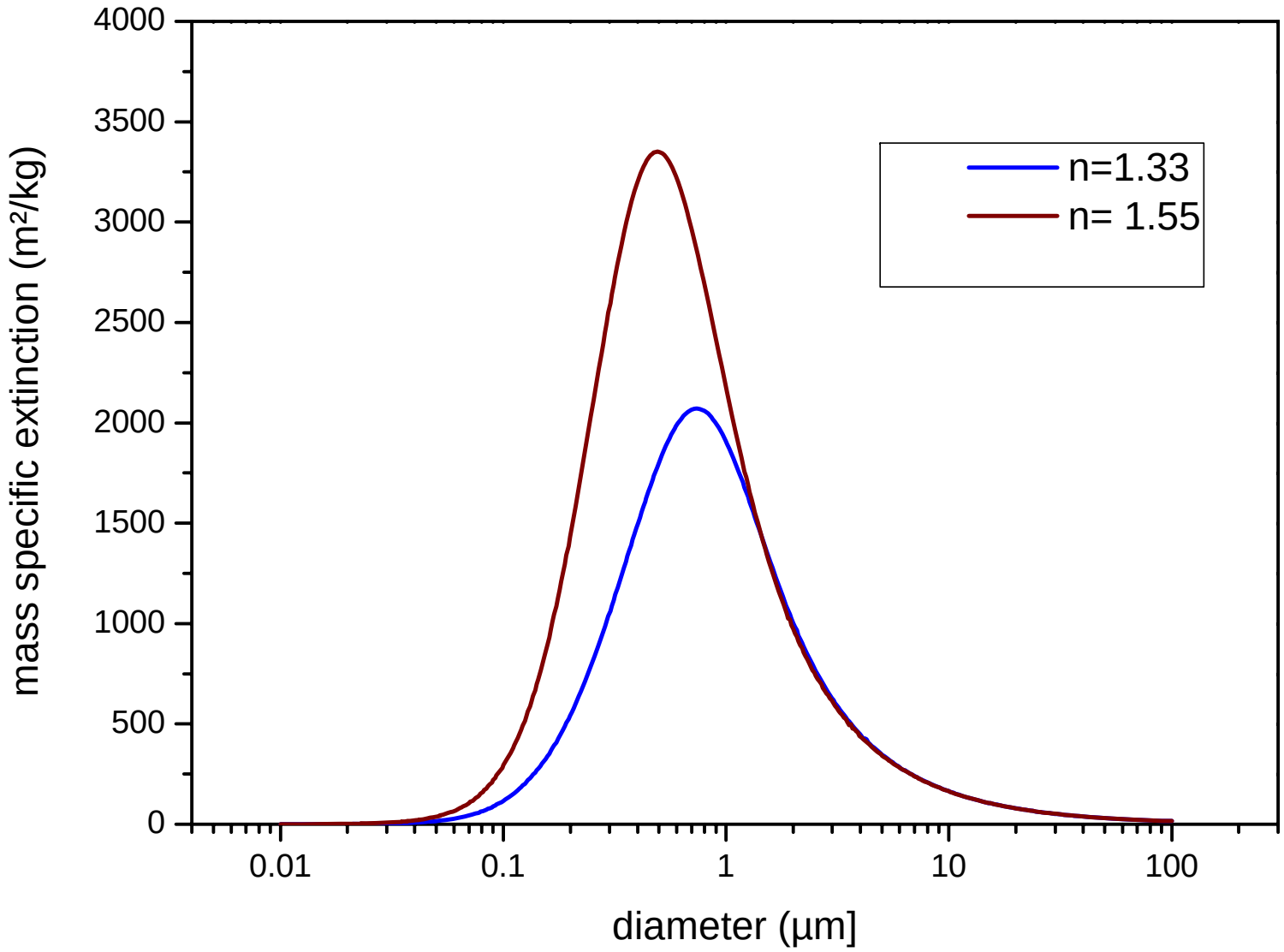

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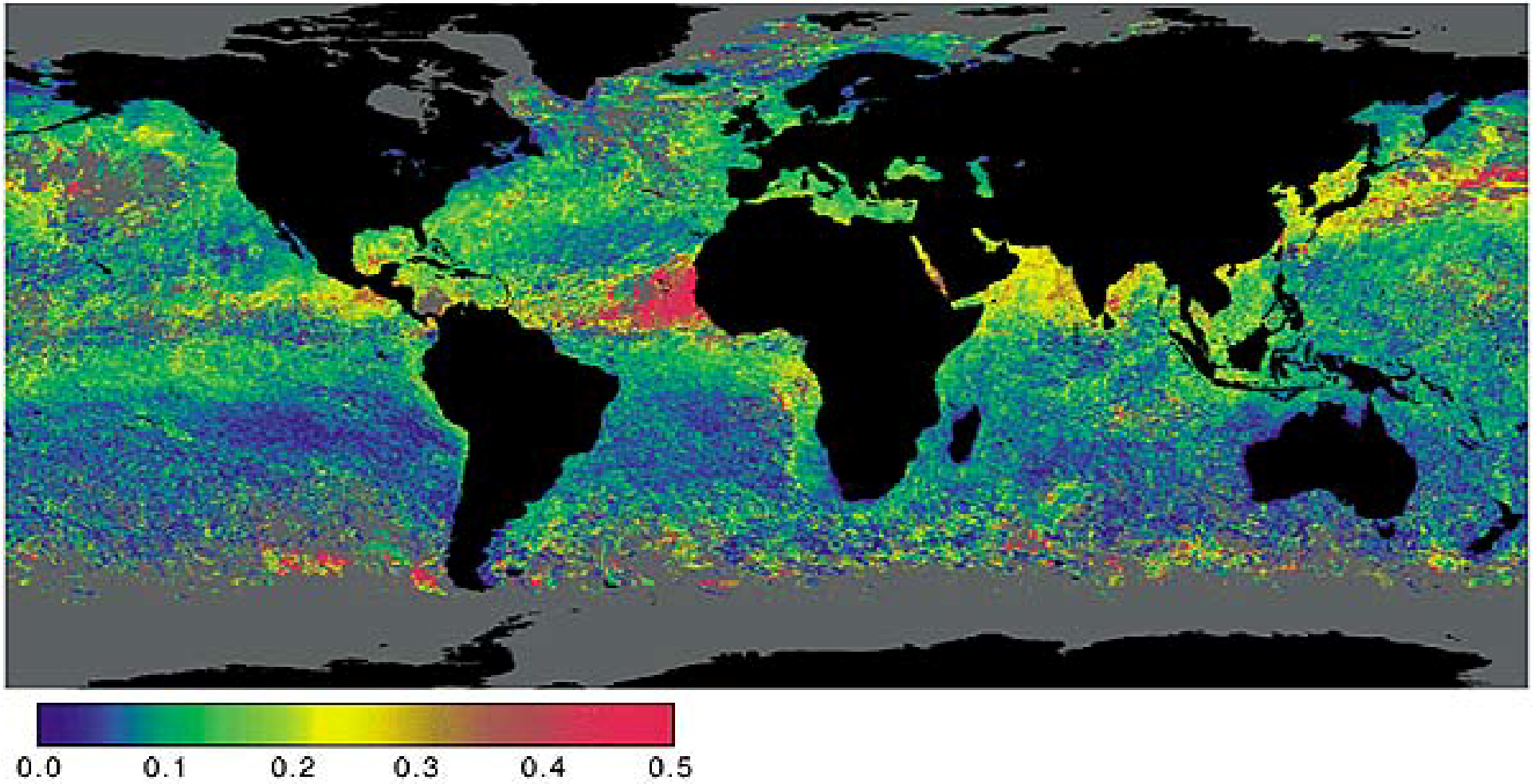
# Aerosol optical depth

Karlsruhe Institute of Technology

(a) May 1997 Aerosol optical depth at 865 nm from Polder on ADEOS



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# Aerosol- Cloud Interaction

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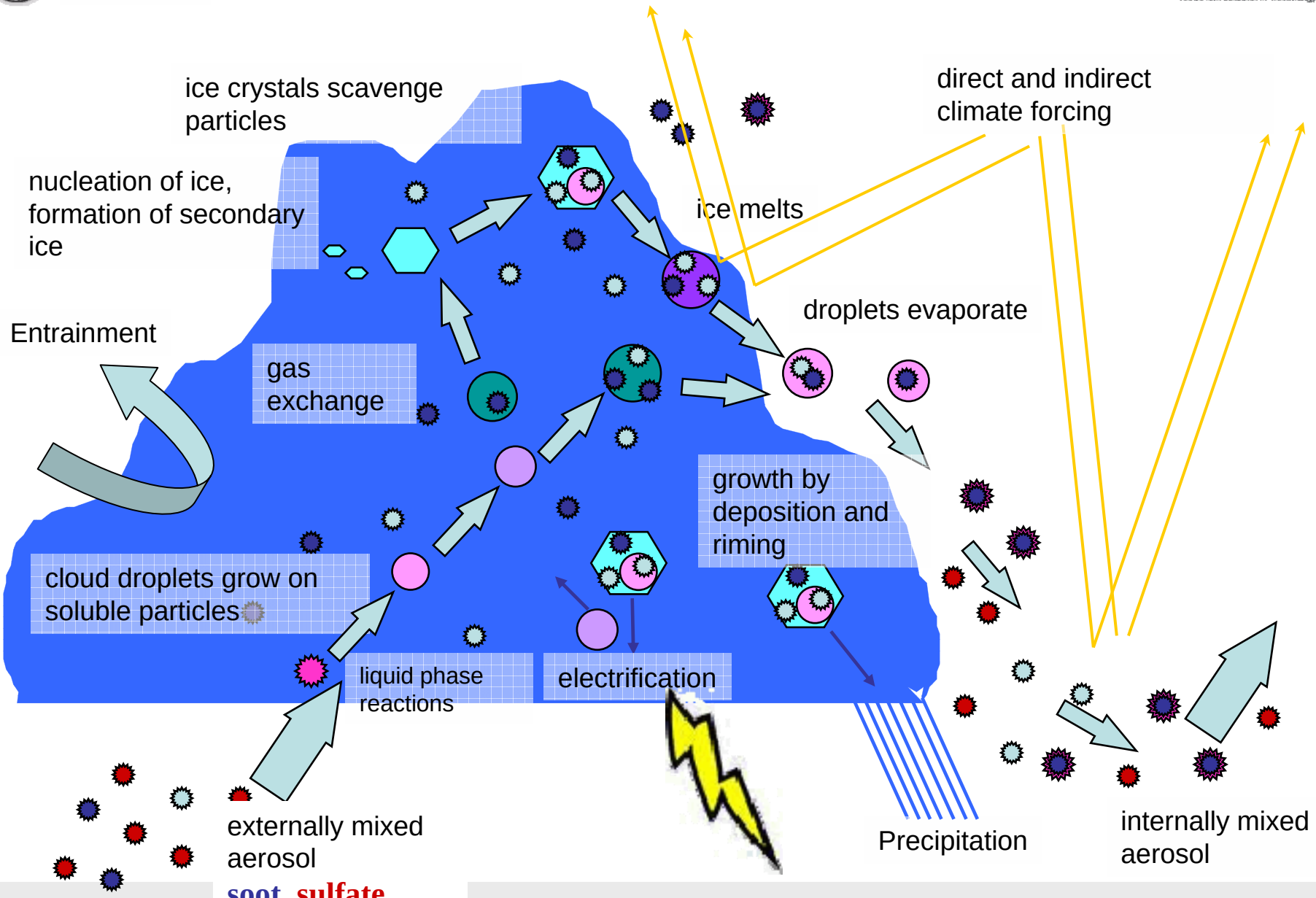
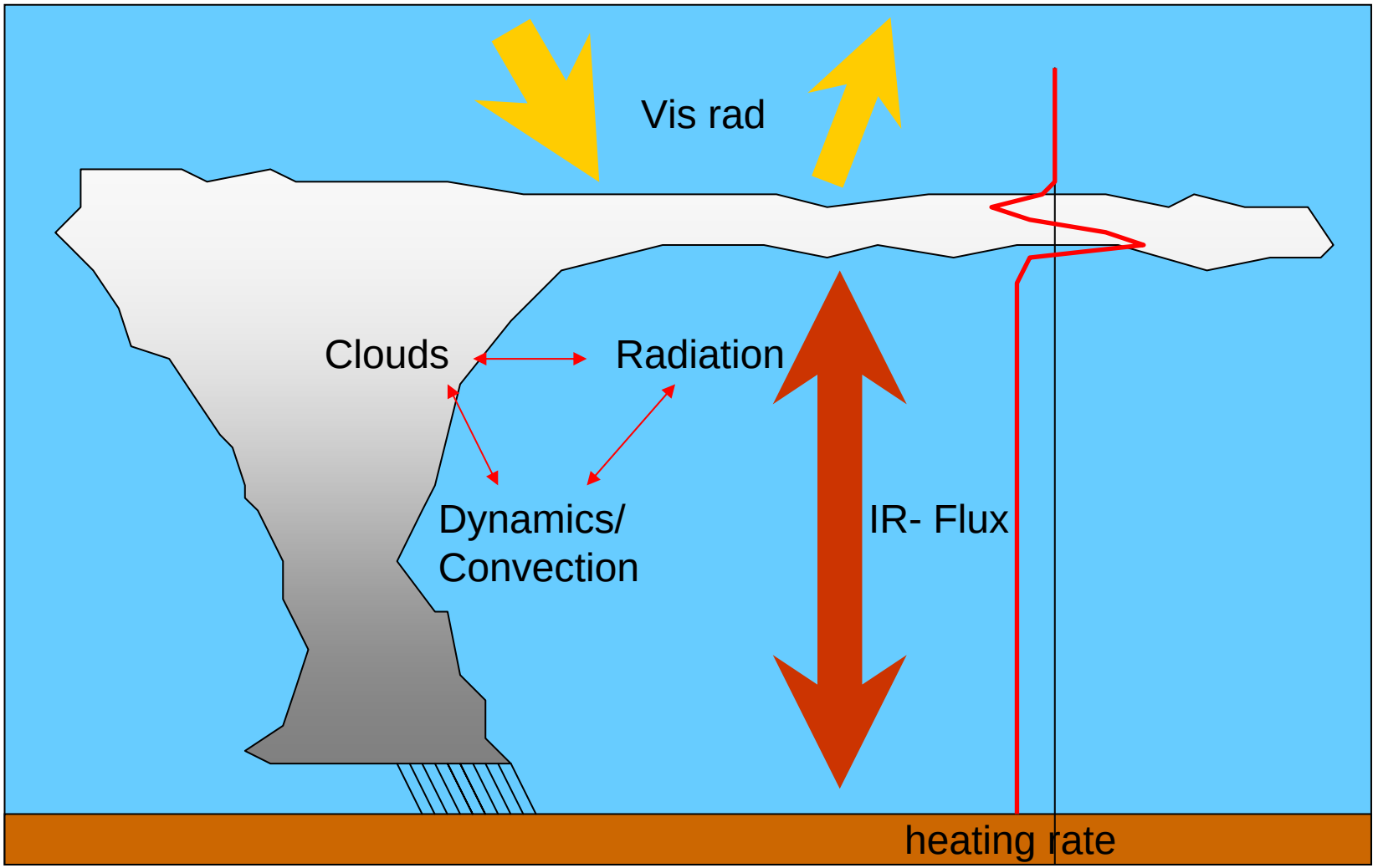
Karlsruhe Institute of Technology



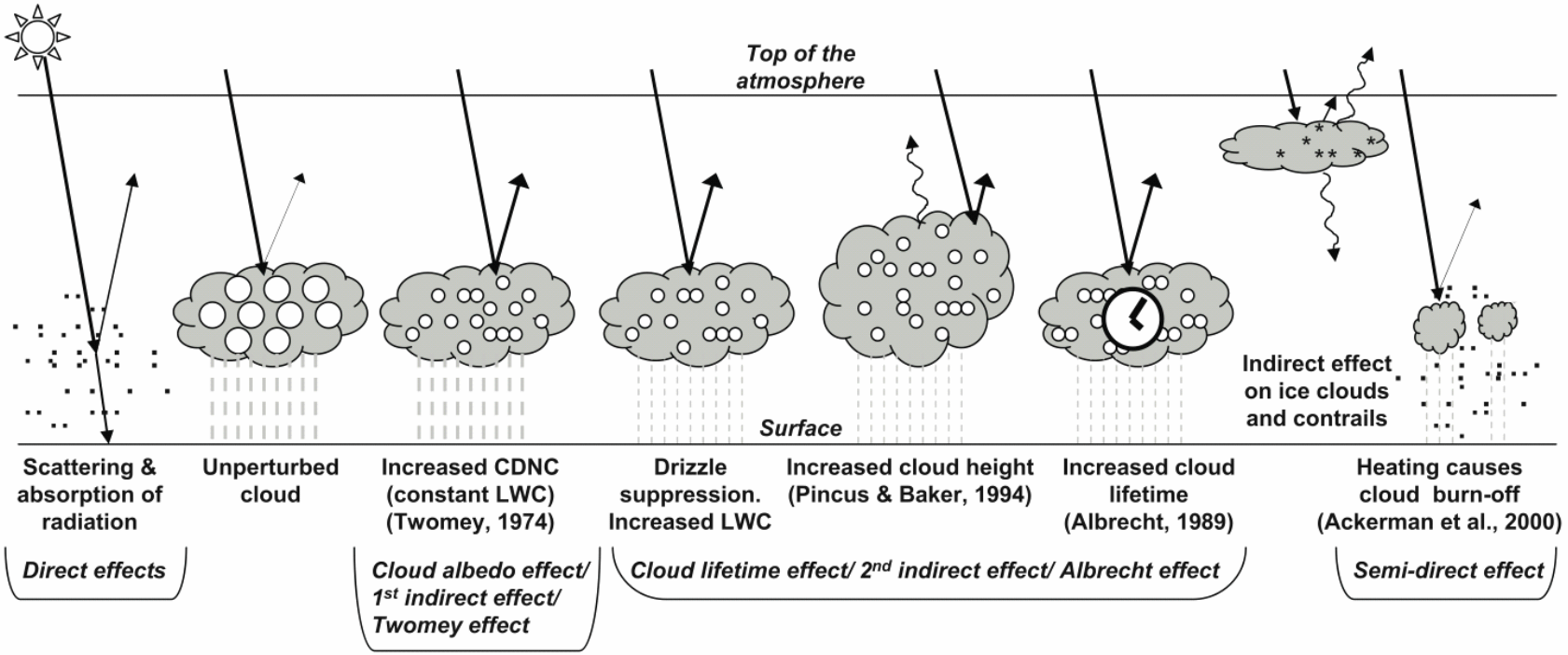

Adapted from Sabine Wurzler, IfT Leipzig

# Cloud radiative feedback





# Aerosol- Cloud Climate interaction




from IPCC AR 4

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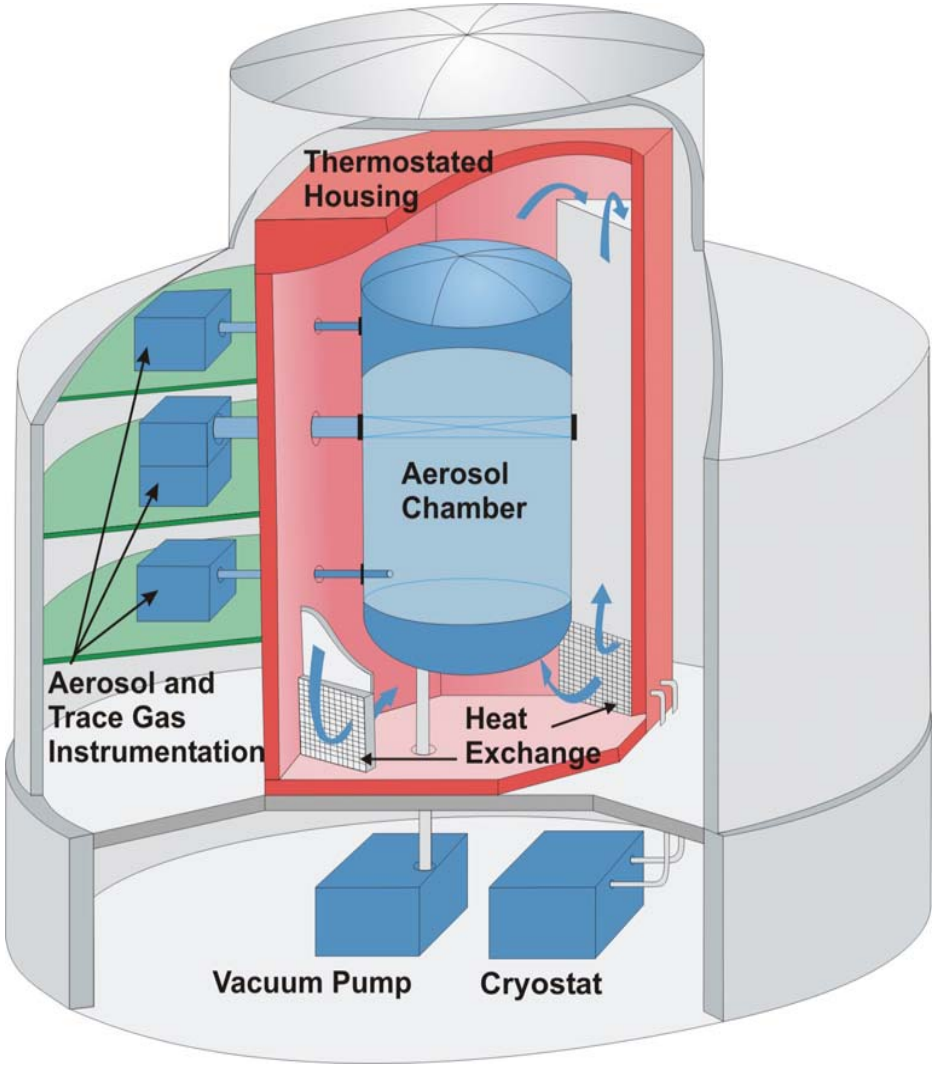
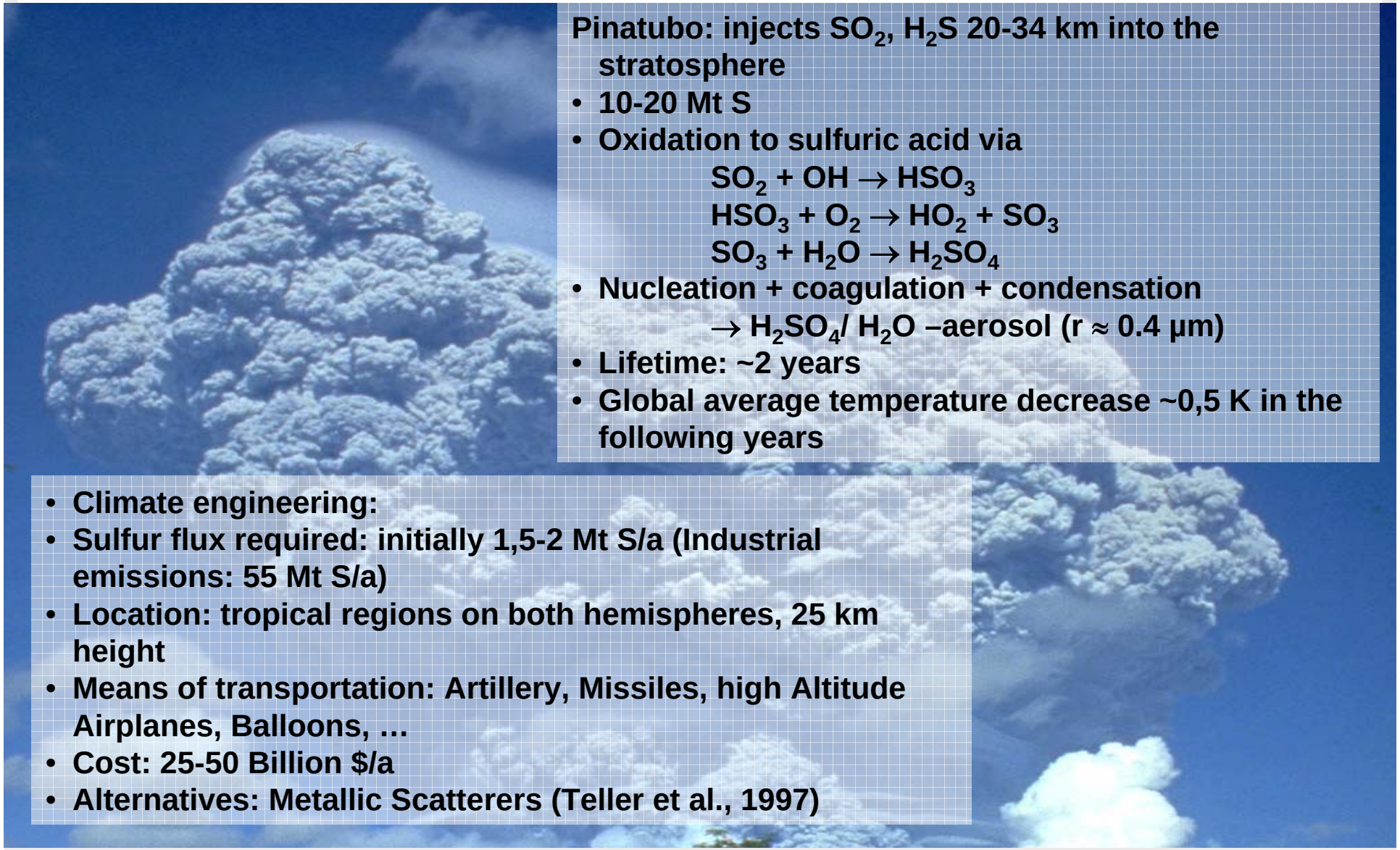
# AIDA: A large (84m³) simulation chamber for cloud- and aerosol processes esp. at low temperatures (180K)

KIT
Karlsruhe Institute of Technology




# Putting aerosols into the stratosphere
# Budyko, 1982, Crutzen, 2006





**Pinatubo: injects $SO_2$, $H_2S$ 20-34 km into the stratosphere**

- **10-20 Mt S**
- **Oxidation to sulfuric acid via**

$$SO_2 + OH \rightarrow HSO_3$$
$$HSO_3 + O_2 \rightarrow HO_2 + SO_3$$
$$SO_3 + H_2O \rightarrow H_2SO_4$$

- **Nucleation + coagulation + condensation**

$$\rightarrow H_2SO_4/\ H_2O \text{ –aerosol } (r \approx 0.4\ \mu m)$$

- **Lifetime: ~2 years**
- **Global average temperature decrease ~0,5 K in the following years**

- **Climate engineering:**
- **Sulfur flux required: initially 1,5-2 Mt S/a (Industrial emissions: 55 Mt S/a)**
- **Location: tropical regions on both hemispheres, 25 km height**
- **Means of transportation: Artillery, Missiles, high Altitude Airplanes, Balloons, …**
- **Cost: 25-50 Billion $/a**
- **Alternatives: Metallic Scatterers (Teller et al., 1997)**

**Mt.Pinatubo, 12.6.1991**

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# Effects of volcanic aerosols on the radiation budget

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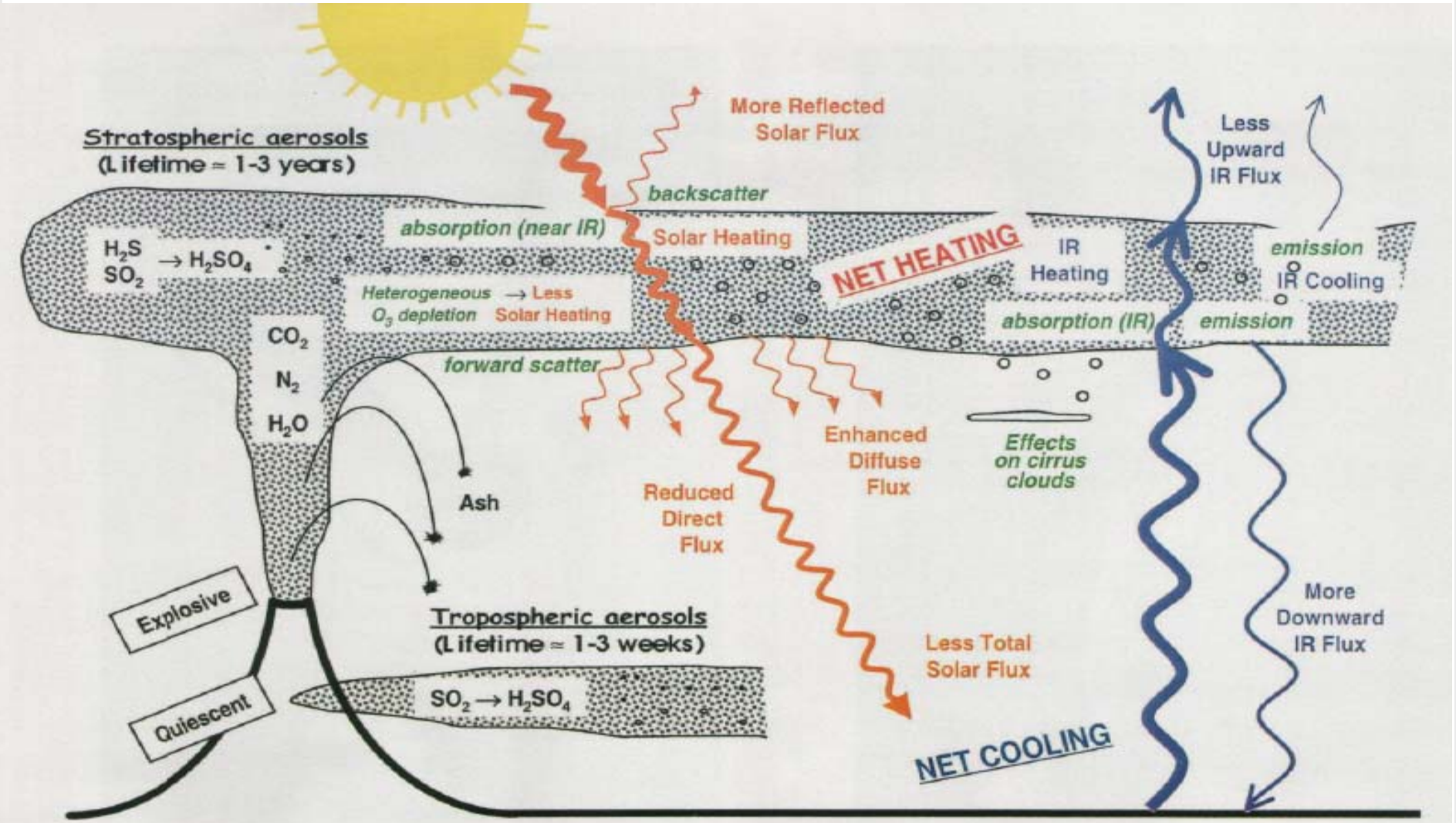


**Plate 1.** Schematic diagram of volcanic inputs to the atmosphere and their effects. This is an extended version of Figures 1 and 2 of *Simarski* [1992], drawn by L. Walter and R. Turco.

From Robock Reviews of Geophysics 38 (2000)

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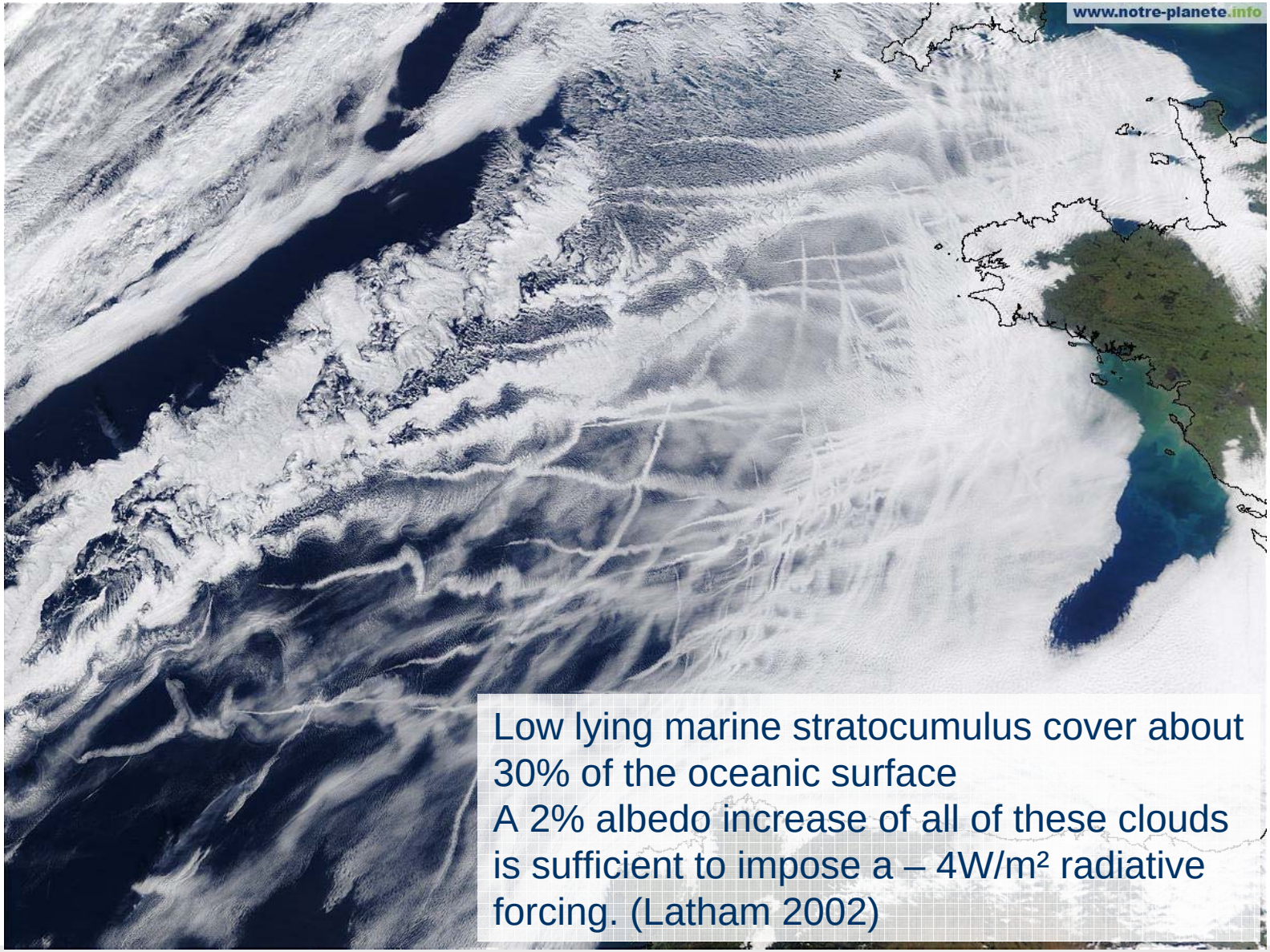
# Enhancing cloud albedo by seeding clouds over the southern oceans

Karlsruhe Institute of Technology




Low lying marine stratocumulus cover about 30% of the oceanic surface
A 2% albedo increase of all of these clouds is sufficient to impose a – 4W/m² radiative forcing. (Latham 2002)

# Cloud seeding with sea-salt particles (J. Latham)

Large albedo enhancement (~20%) can be obtained under favorable conditions
d=300nm (m=$10^{-16}$kg) NaCl particles optimal
works best in very pristine maritime air
more efficient to influence large areas to a small extend than vice-versa

Suggestions: Use unmanned wind-powered floats which are navigated to meteorologically promising positions.

Spray seawater droplets d~ 1 µm into rising air

Need thousands of these units deployed per year, costs and much of technical conceptare not yet clear.

K. Bower et al. Atmospheric Research 82 (2006)

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# Questions beyond technical feasibility and cost

Karlsruhe Institute of Technology

What are the meteorological consequences?

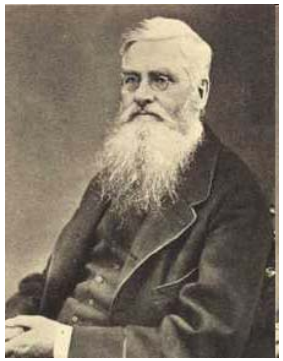
What effect has the increasing $CO_2$ on marine life?

Who makes the decisions, once first adverse effects become apparent?

Who can guarantee the operation of a climate engineering scheme for several thousand years?

What are the consequences, if for some reason the measures are not sustained beyond a certain point in time?

## Alfred R. Wallace:



### The Importance of Dust: A Source of Beauty and Essential to Life, “The Wonderful Century” (1898)

But in all densely-populated countries there is an enormous artificial production of dust… This superabundance of dust …. must almost certainly produce some effect on our climate; and the particular effect it seems calculated to produce is the increase of cloud and fog, but not necessarily any increase of rain.

(find complete article in material)