THE DOE ATMOSPHERIC SCIENCE PROGRAM

WHERE WE ARE AND WHERE WE NEED TO BE GOING

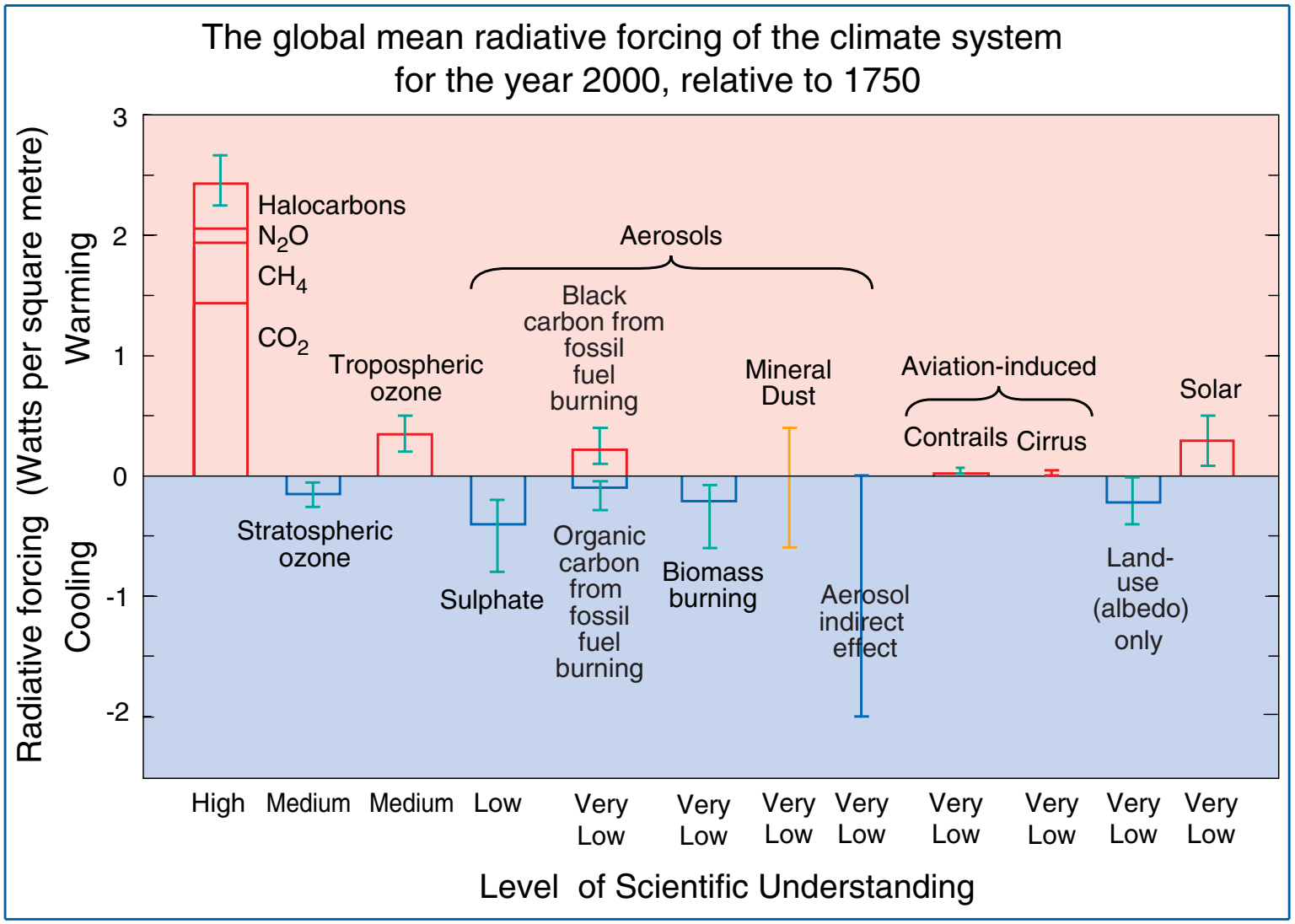
Stephen E. Schwartz

ASP Chief Scientist

ASP Science Team Annual Meeting

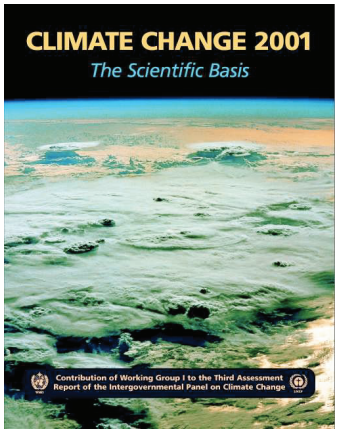
Charleston SC Jan 25-27, 2005

RADIATIVE FORCING OVER THE INDUSTRIAL PERIOD
IPCC (2001)



Summary for Policymakers

A Report of Working Group I of the Intergovernmental Panel on Climate Change



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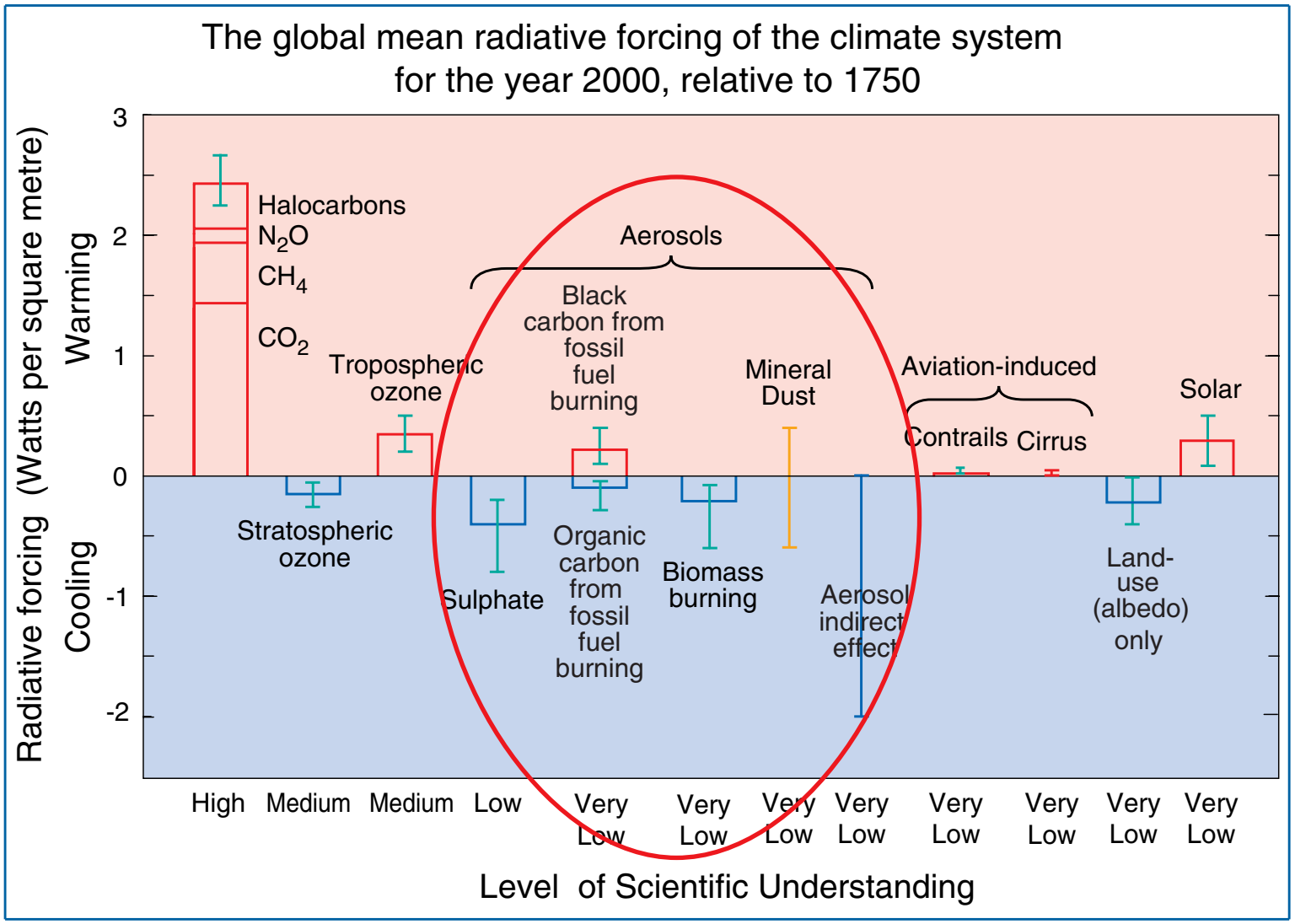

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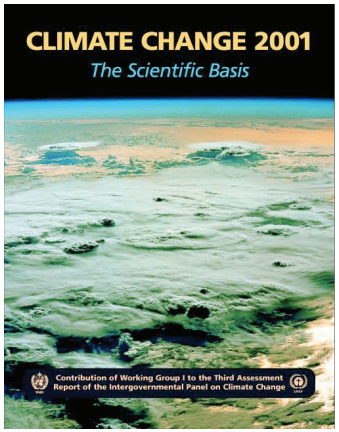


AEROSOL INFLUENCES ON RADIATION AND CLIMATE

Direct Shortwave Radiative Effects (Clear sky)

Light scattering → Cooling influence

Light absorption → Warming influence, depending on surface

Indirect Shortwave Radiative Effects–Aerosols influence cloud properties

More droplets → Brighter clouds (Twomey)

More droplets → Enhanced cloud lifetime (Albrecht)

More droplets → Broadening of drop distribution -- warming (Liu)

Semi-Direct Shortwave Radiative Effect

Absorbing aerosol heats air and evaporates clouds (Hansen)

Longwave Radiative Effect (Clear sky)

Greenhouse effect of aerosol particles (Vogelmann)

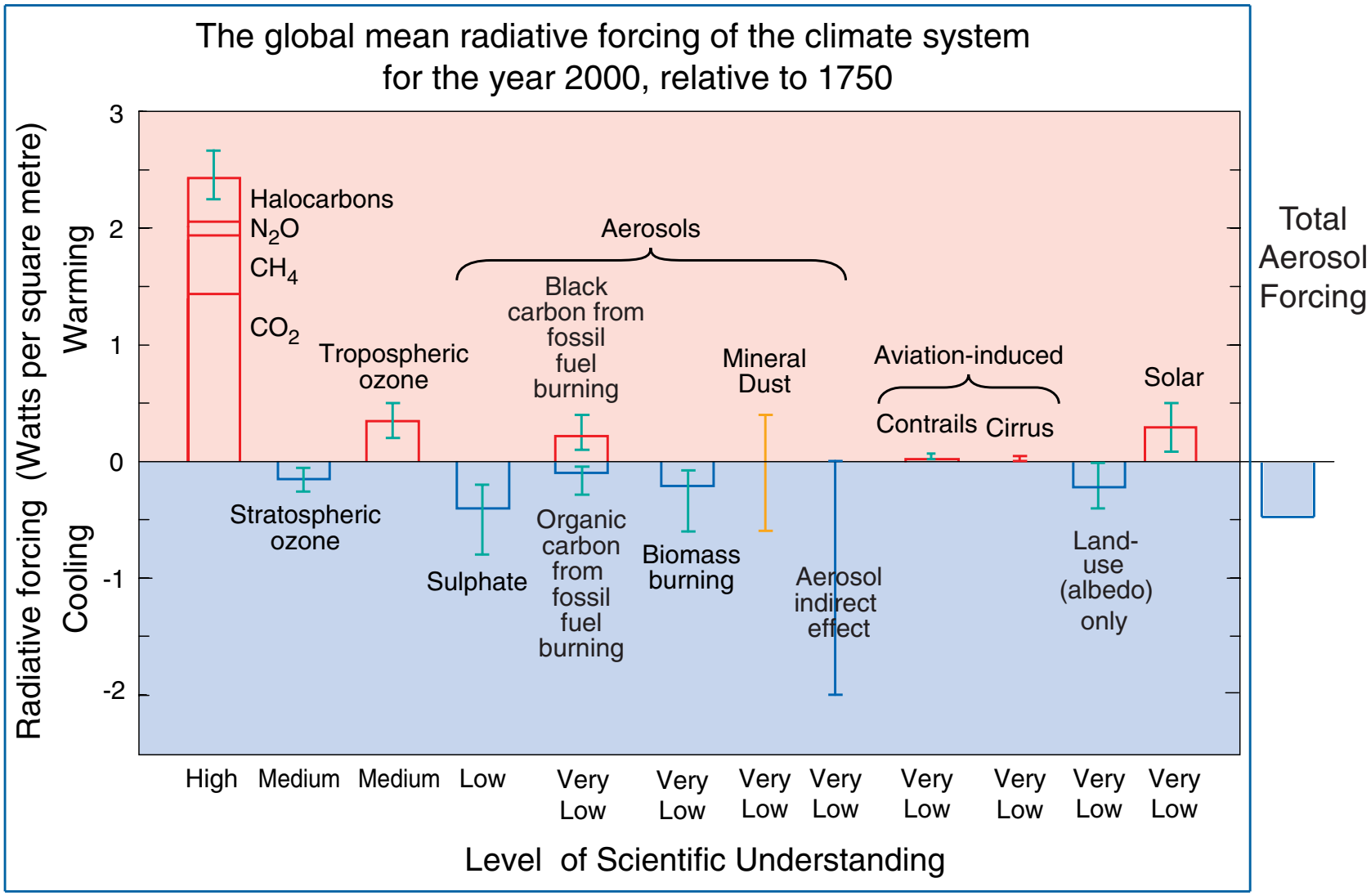
Hydrological Effects

Suppressed surface evaporation -- Spinning down the water cycle

Displaced precipitation -- Clouds last longer or evaporate (Rosenfeld)

RADIATIVE FORCING OVER THE INDUSTRIAL PERIOD
IPCC (2001)

With total aerosol forcing



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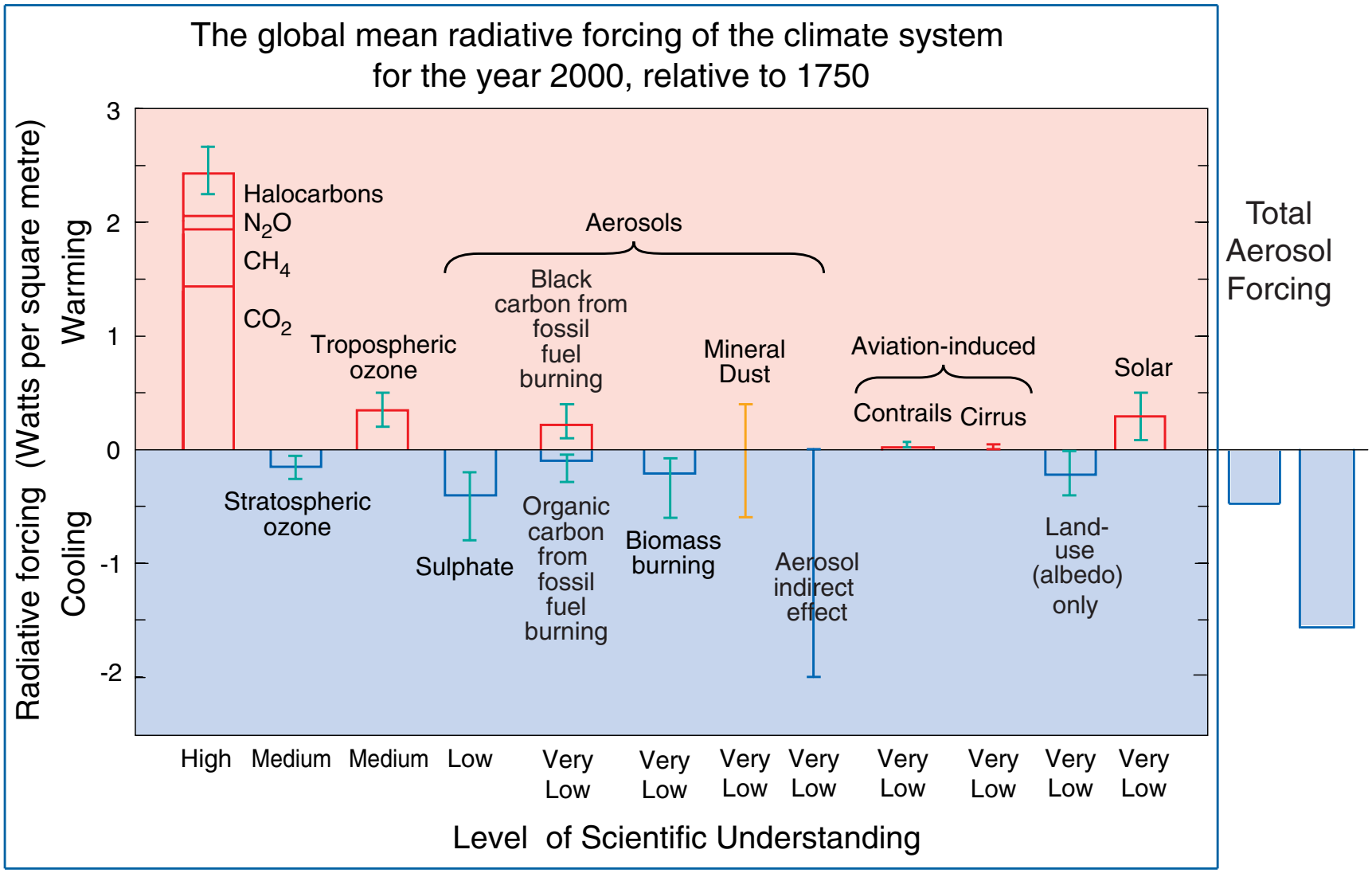

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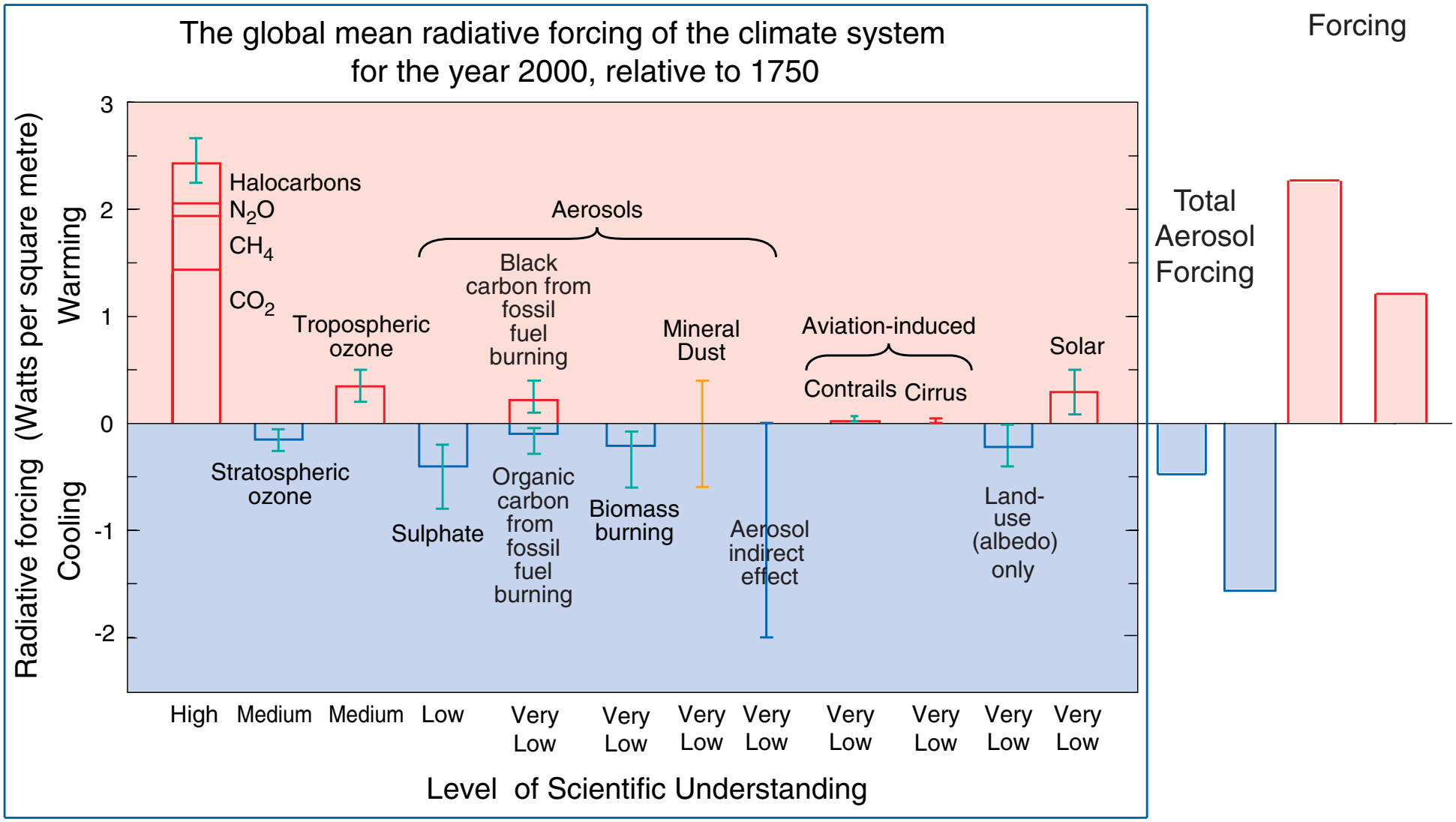
RADIATIVE FORCING OVER THE INDUSTRIAL PERIOD
IPCC (2001)

With total aerosol forcing and total forcing



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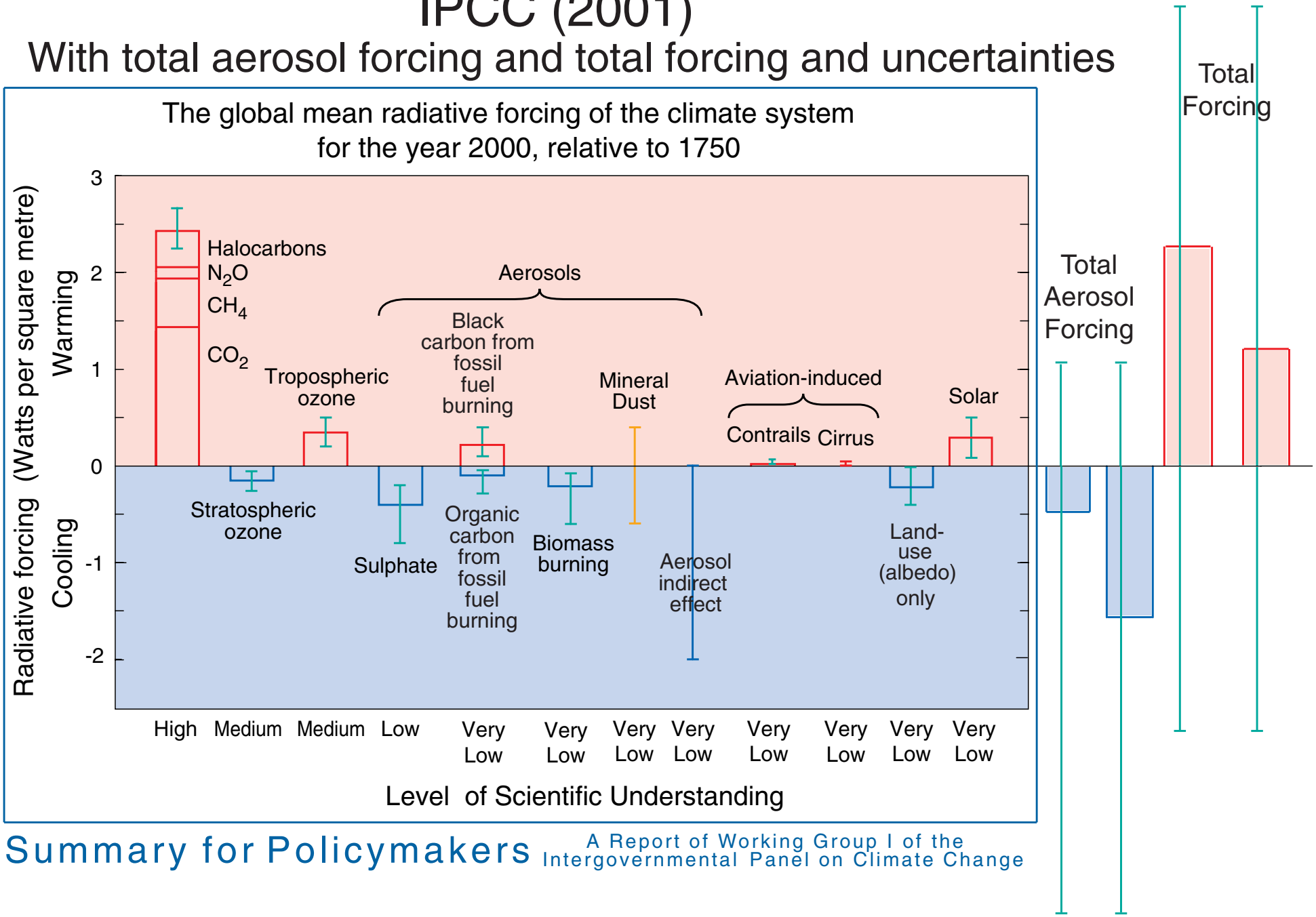
RADIATIVE FORCING OVER THE INDUSTRIAL PERIOD
IPCC (2001)
With total aerosol forcing and total forcing and uncertainties



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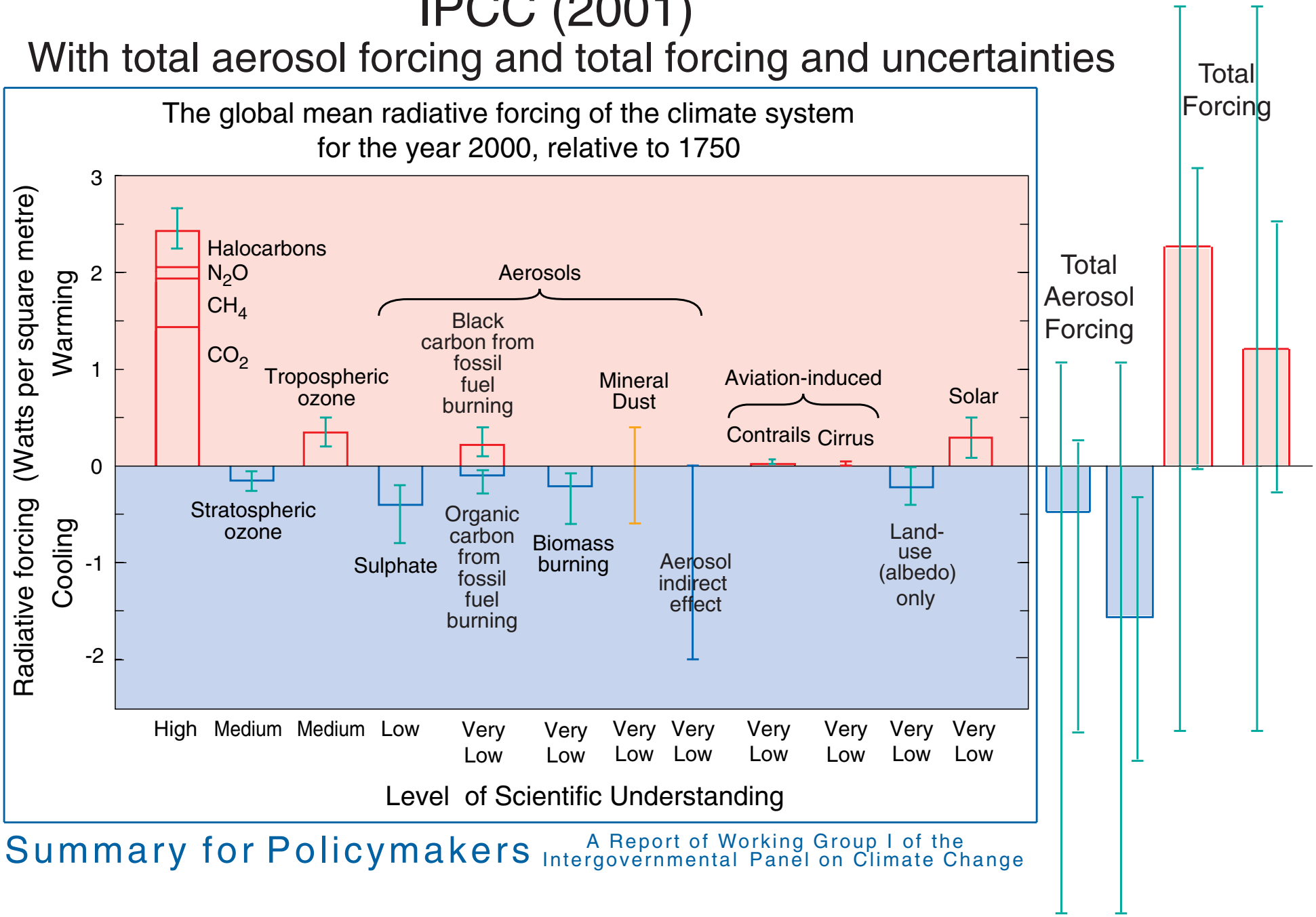


Summary for Policymakers

A Report of Working Group I of the Intergovernmental Panel on Climate Change

WHY SO LARGE UNCERTAINTY IN AEROSOL FORCING?

- ***Uncertainties in knowledge of atmospheric composition***

  Mass loading and chemical and microphysical properties and cloud nucleating properties of anthropogenic aerosols, and geographical distribution.

  At present and as a function of secular time.

- ***Uncertainties in knowledge of atmospheric physics of aerosols***

  Relating direct radiative forcing and cloud modification by aerosols to their loading and their chemical and microphysical properties.

BERAC RECOMMENDATIONS

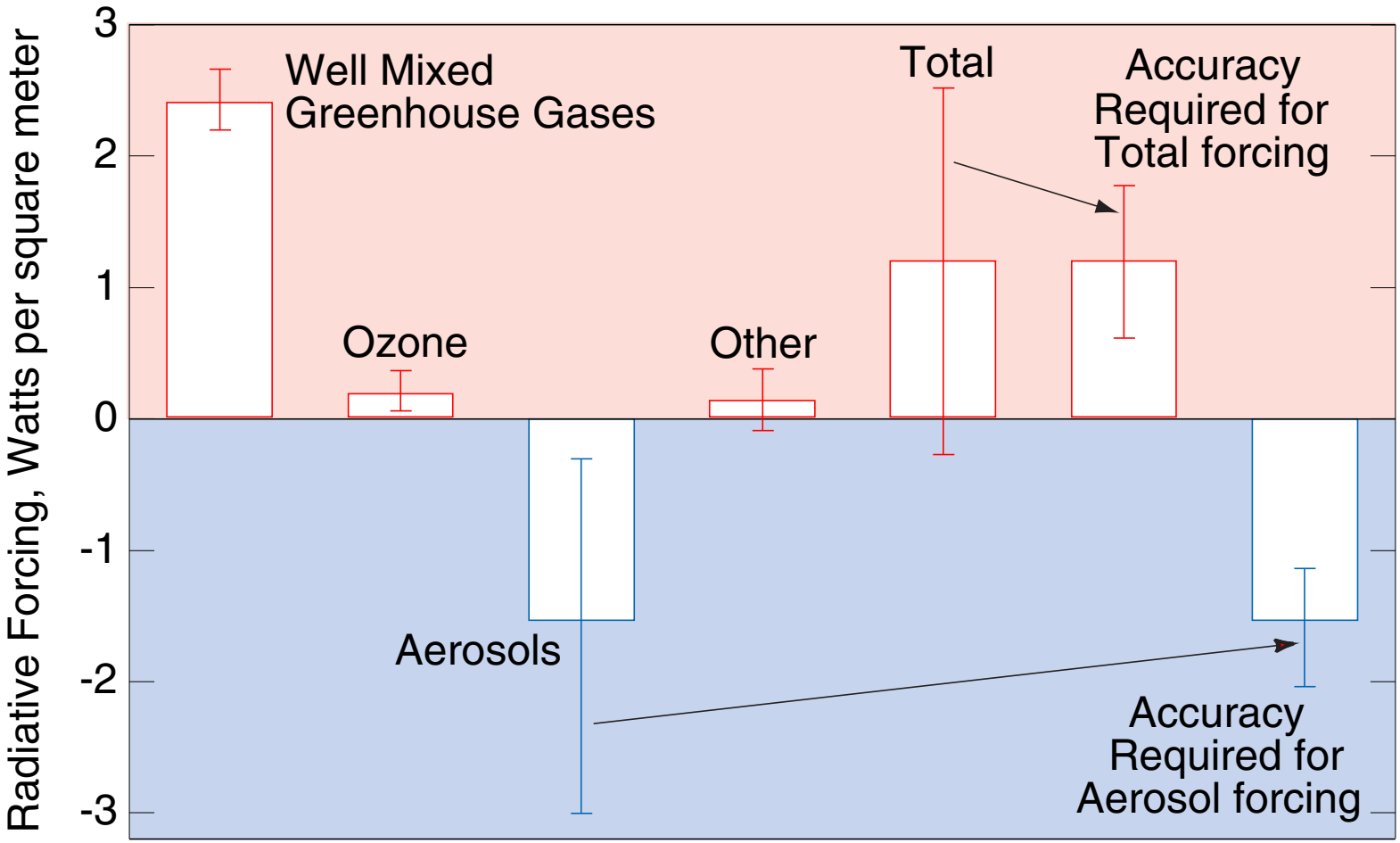
- Reconfiguring the ASP to a program emphasizing ***radiative forcing of climate from aerosols*** has great merit in contributing to the CCSP goals and as such should be implemented as soon as practical.
- The reconfigured ASP should have as its goal the reduction of uncertainties in two specific gap areas. These are (1) the ***indirect effects of aerosols on clouds*** and (2) the role of ***black carbon and organic carbon aerosols*** on climate forcing.
- A well-balanced program consisting of ***field*** measurements, ***laboratory*** experiments, ***theoretical*** analysis with process ***modeling***, and development and application of new ***instrumentation*** will be required.
- The reconfigured ASP needs to be ***closely coordinated*** with the DOE Atmospheric Radiation Program (ARM) program and vice-versa as well as collaboration with other stakeholder programs in order to make most effective use of limited resources.
- The reconfigured ASP should look to the climate modeling program within DOE and the larger Climate Change Science Program (CCSP) as a test bed for ***applying knowledge and parameterizations*** gleaned both from the reconfigured ASP and the ARM programs.

-- *A Reconfigured Atmospheric Science Program*

DOE Biological and Environmental Research Advisory Committee, April 2004

ASP

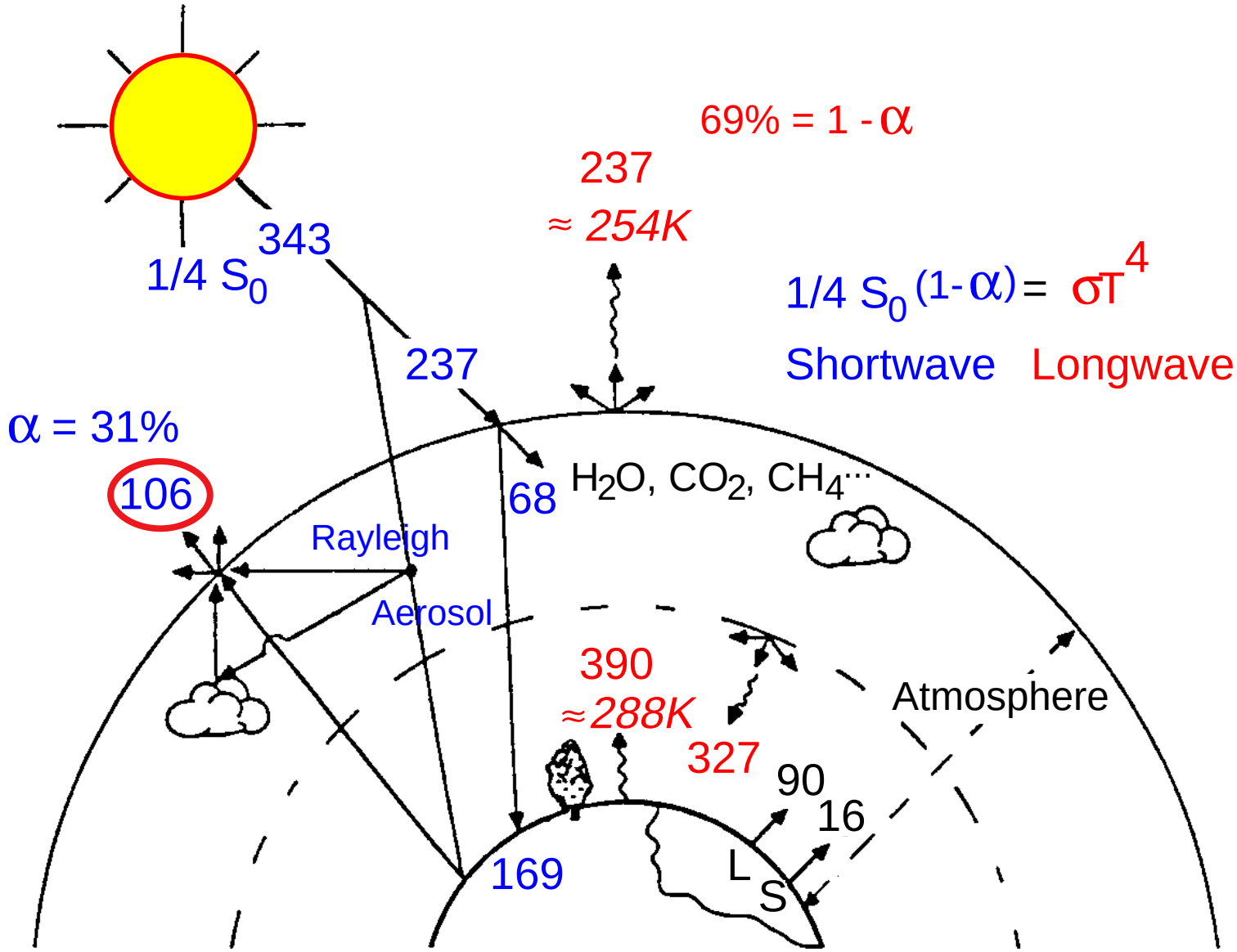
ACCURACY REQUIREMENT FOR AEROSOL FORCING



Uncertainty in aerosol forcing must be reduced by at least a factor of 3.

GLOBAL ENERGY BALANCE

Global and annual average energy fluxes in watts per square meter



Modified from Ramanathan, 1987

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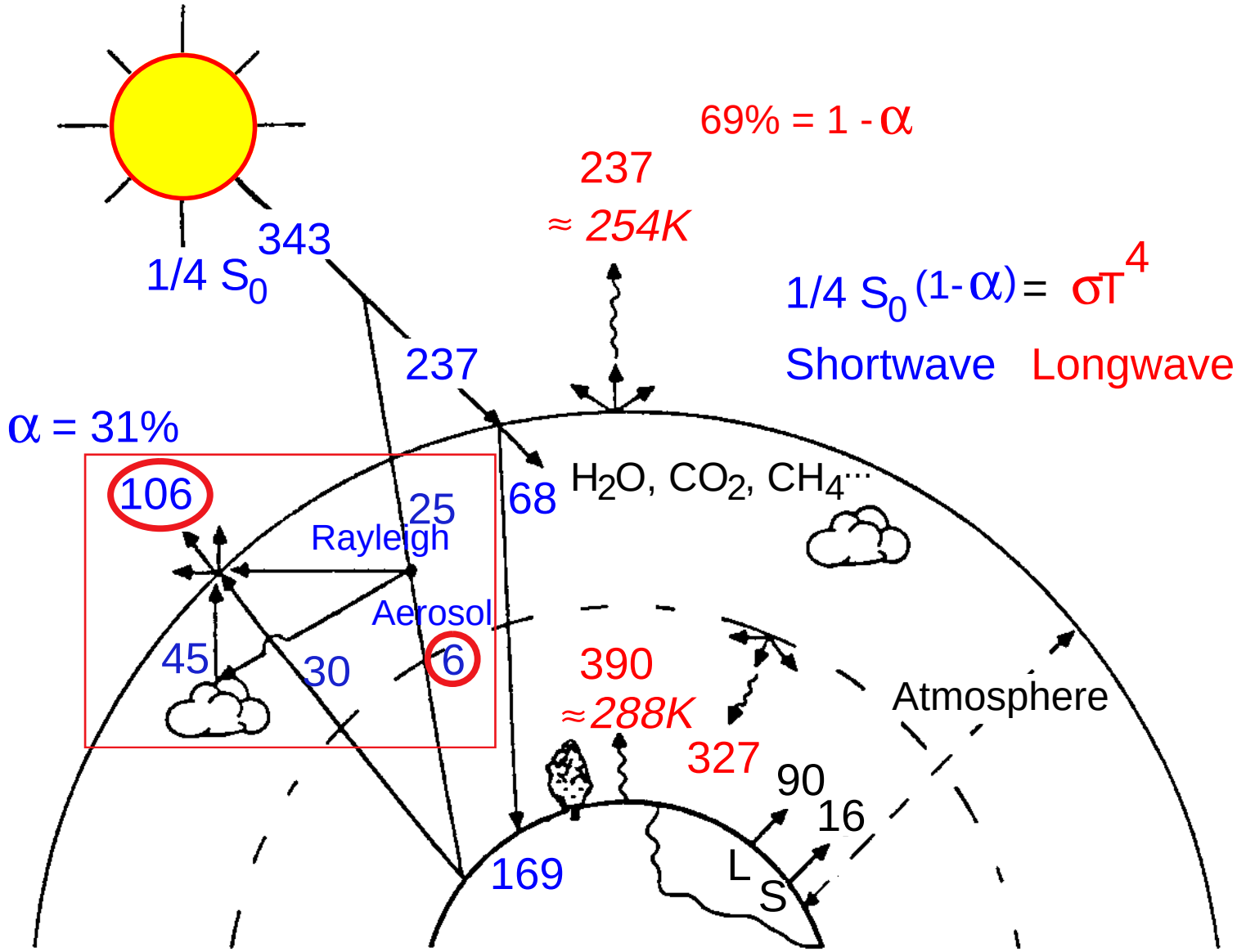


Modified from Ramanathan, 1987

REQUIREMENTS FOR DETERMINING AEROSOL RADIATIVE FORCING OF CLIMATE CHANGE

Perturbation of net irradiance at the top of the atmosphere (TOA) due to ***anthropogenic*** aerosols.

Requirement:

Determine anthropogenic aerosol radiative flux perturbation as a function of space ($360^\circ \times 180^\circ$) and time ($24 \times 365$).

Accuracy ***better than ± 0.5 W m^{-2}***
(*Schwartz, AGU, Fall, 2003; JAWMA, 2004*).

Based on determining climate sensitivity to ± 30%.

Challenges:

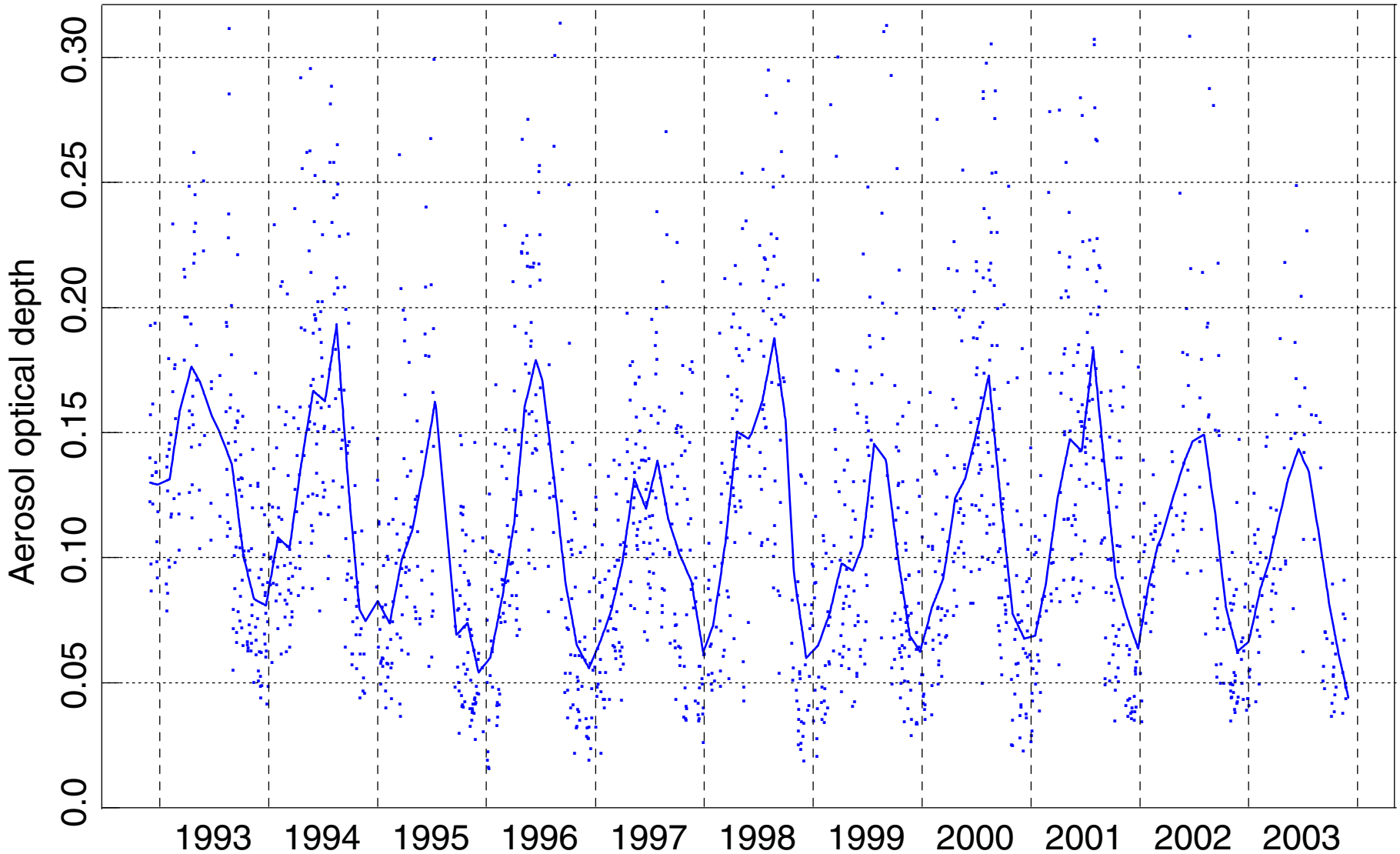
Aerosol forcing is highly variable in space and time.

Total upwelling shortwave irradiance is highly variable in space and time.

AEROSOL OPTICAL DEPTH

Determined by sunphotometry

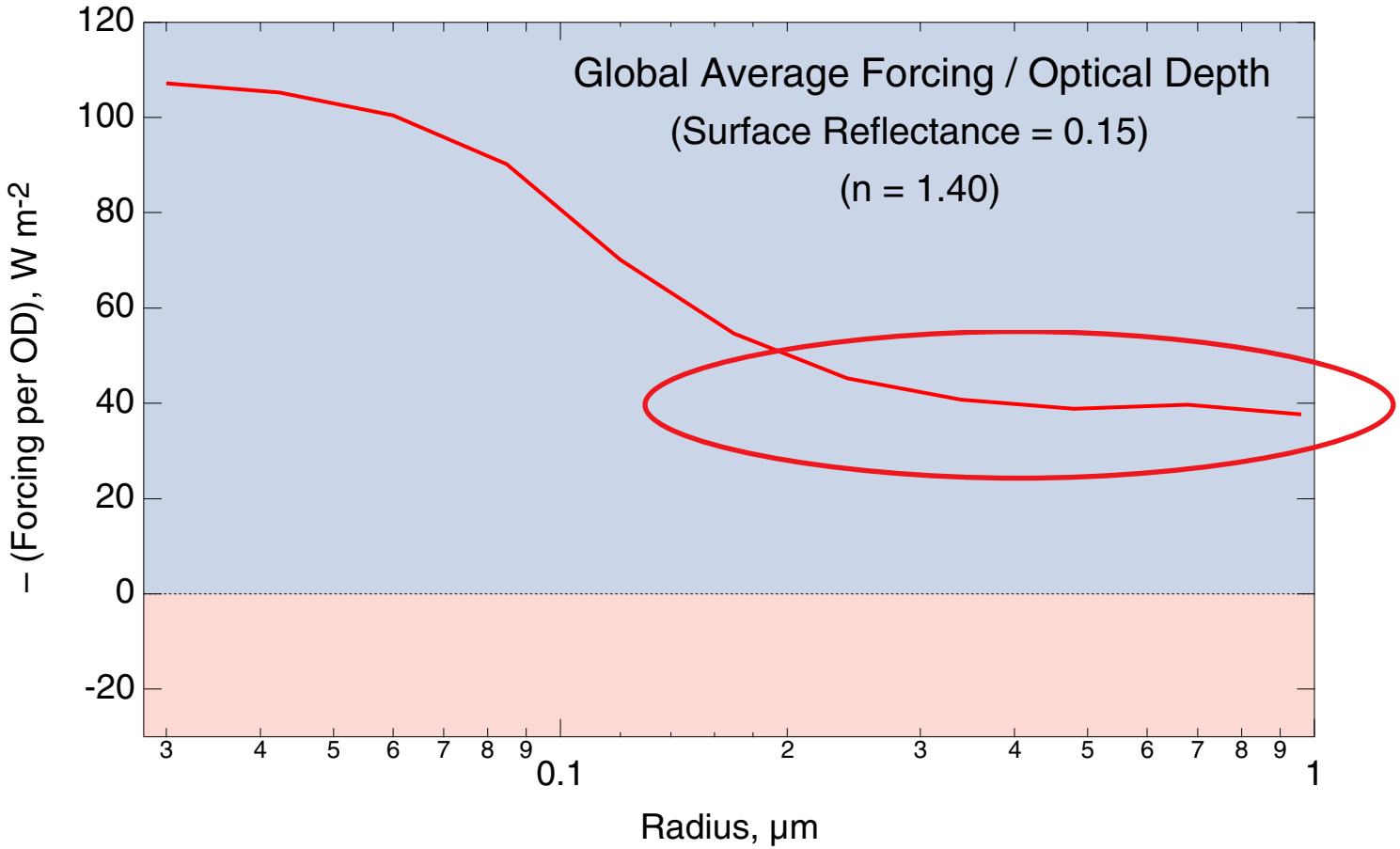
North central Oklahoma - Daily average at 500 nm



J. Michalsky et al., JGR, 2001

FORCING PER OPTICAL DEPTH

Global average, cloud-free sky - Scattering aerosol

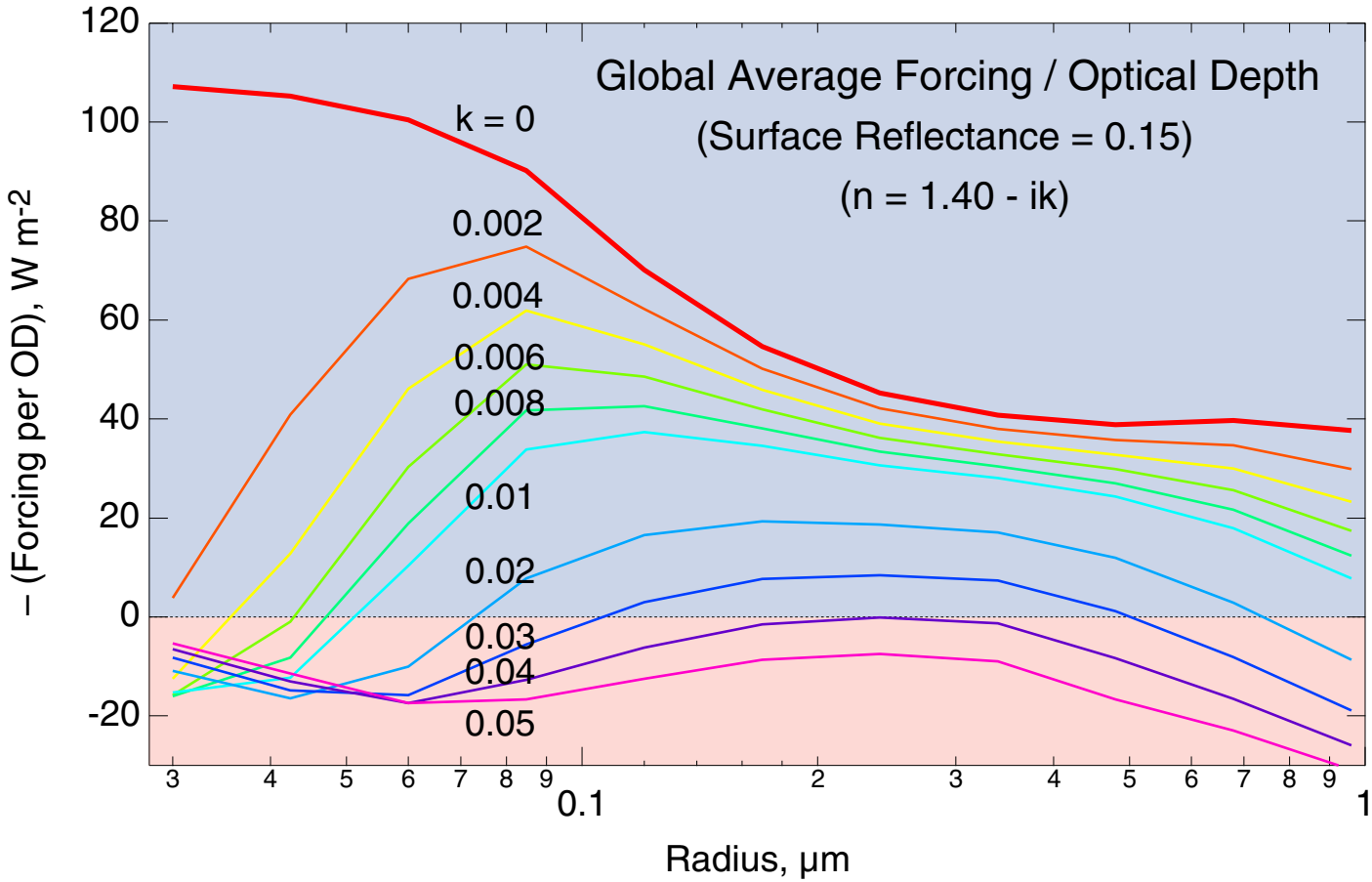


Forcing per optical depth depends rather strongly on particle size.

Forcing accuracy 0.5 W m^{-2} requires optical depth accuracy ~0.01 (~0.02 for 60% cloud cover).

FORCING PER OPTICAL DEPTH

Global average, cloud-free sky - Absorbing aerosol



Forcing per optical depth depends rather strongly on particle size – and also rather strongly on aerosol absorption.

APPROACHES TO DETERMINE AEROSOL **DIRECT** RADIATIVE FORCING

(*Schwartz, AGU, Fall, 2004*).

1. Satellite Irradiance Method
2. Satellite AOT Method
3. Ground-based AOT Method
4. Surface Forcing Method
5. *In-situ* Measurements Method
6. Chemical Transport Modeling Method

CHEMICAL TRANSPORT MODELING METHOD

Chemical-microphysical modeling of aerosol loading $f(x,y,z,t)$ and chemical and microphysical properties

Modeling of aerosol optical properties σ_{ep}, ω, g, as $f(x,y,z,t,RH,\lambda)$

Radiation transfer modeling of forcing

STRENGTHS	LIMITATIONS/CONCERNS
Spatial coverage	Accuracy of modeled aerosol loading and properties
Temporal coverage	Requires knowledge of Sources Transformation Removal
Account for cloudiness and f(RH)	
Accurate forcing estimates	
Attribution to anthro	
	Need to evaluate model

AEROSOL INFORMATION REQUIRED TO DETERMINE DIRECT FORCING

Time-dependent 3-D map of size-dependent particle concentration, composition, and morphology.

Needed for computation of optical properties, cloud-nucleating properties, and radiative and hydrological influences.

This can be obtained only by chemical transport modeling of aerosols . . .

Based on ***understanding*** of the controlling processes.

Evaluated by comparison with observations.

Concentrations
Rates

REPRESENTING AEROSOL PROCESSES IN CTMs

Sources of primary particles and precursor gases

3-D transport as controlled by governing meteorology

Gas to particle conversion (clear air and cloud)
New particle formation
Accretion onto existing particles

Particle size evolution (clear air and cloud)

Particle ***morphology*** and intra-particle structure

Removal of particles and precursor gases, controlled by meteorology

Aerosol properties as ***bivariate functions of particle size and composition***

Aerosol optical properties (extinction coefficient, single scatter albedo, asymmetry parameter) as integrals over single particle properties (Mie)

All as a function of ***3-D location and secular time***

Quantities and processes governing aerosol *direct* forcing of climate change and the quantities on which their dependence must be known

Quantity/Process	Symbol	Dependence on
Particle and gaseous precursor emissions	$e(\boldsymbol{x}, t, r_{\mathrm{ap}}, \chi)$	Radius r_{ap}, composition χ, 2-D location
Transport, chemical reaction, microphysical evolution	$\downarrow$	Concentrations of precursors and other reagents, solar intensity; size dependent concentrations of other aerosol species; 3-D winds, clouds . . .
Aerosol particle number concentration	$n_{\mathrm{ap}}(\boldsymbol{x}, t, r_{\mathrm{ap}}, \chi)$	Radius, composition, shape, 3-D location
Index of refraction (real, imaginary components)	$n(\lambda) + ik(\lambda)$	Radius, composition, wavelength, RH
Mie scattering theory	$\downarrow$	
Optical properties: extinction coefficient, single scatter albedo, asymmetry parameter	$\sigma_{\mathrm{ep}}(\boldsymbol{x}, t, \lambda)$ $\omega(\boldsymbol{x}, t, \lambda)$ $g(\boldsymbol{x}, t, \lambda)$	RH
Radiation transfer (3*D*)	$\downarrow$	Cloud geometry, surface reflectance
Net spectral flux at top of atmosphere	$F_{\mathrm{toa}}(\boldsymbol{x}, t, \lambda)$	

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UNCERTAINTY

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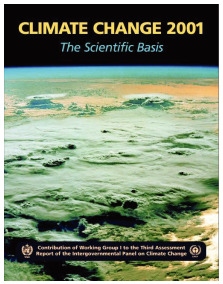
UNCERTAINTY BUDGET FOR *DIRECT* FORCING BY ANTHROPOGENIC SULFATE AEROSOL

Quantity	Central Value	2/3 Uncertainty Range
Total emission of anthropogenic sulfate from fossil fuel burning (Tg/yr)	69	57.5 to 82.8
Atmospheric burden of sulfate from fossil fuel burning (Tg S)	0.525	0.35 to 0.79
Fraction of light scattered into upward hemisphere, $\bar{\beta}$	0.23	0.17 to 0.29
Aerosol mass scattering efficiency ($m^2 g^{-1}$), α_s	3.5	2.3 to 4.7
Aerosol single scattering albedo, co-albedo (dry), ω_0, $1-\omega_0$	1	
T_a, atmospheric transmittance above aerosol layer	0.87	0.72 to 1.00
Fractional increase in aerosol scattering efficiency due to hygroscopic growth at RH=80%	2.0	1.7 to 2.3
Fraction of Earth not covered by cloud	0.39	0.35 to 0.43
Mean surface albedo, co-albedo	0.15	0.08 to 0.22
Result: Central value of forcing is $-0.5\ Wm^{-2}$; the uncertainty range is from -0.25 to -1.0 Wm^{-2}.		

Modified from Penner et al., IPCC, 2001



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Quantity	Central Value	2/3 Uncertainty Range	Uncertainty Factor
Total emission of anthropogenic sulfate from fossil fuel burning (Tg/yr)	69	57.5 to 82.8	1.4
Atmospheric burden of sulfate from fossil fuel burning (Tg S)	0.525	0.35 to 0.79	**2.3**
Fraction of light scattered into upward hemisphere, $\bar{\beta}$	0.23	0.17 to 0.29	1.7
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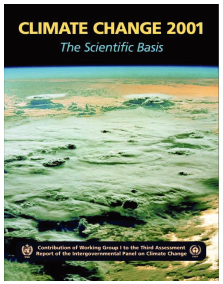
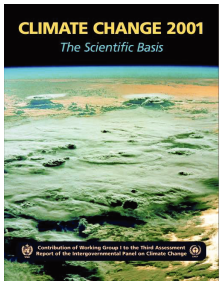


Principal uncertainties in chemistry and microphysics

UNCERTAINTY BUDGET FOR *DIRECT* FORCING BY INDUSTRIAL AEROSOLS

Quantity	Central Value	2/3 Uncertainty Range
Total emission of anthropogenic OC from fossil fuel burning (Tg/yr)	20	10 to 30
Atmospheric burden of OC from fossil fuels (Tg)	0.48	0.33 to 0.70
Total emission of anthropogenic BC from fossil fuel burning (Tg/yr)	7	4.67 to 10.5
Atmospheric burden of BC from fossil fuel burning (Tg)	0.133	0.11 to 0.16
Total emission of anthropogenic sulfate from fossil fuel burning (Tg/yr)	69	57.5 to 82.8
Atmospheric burden of sulfate from fossil fuel burning (Tg S)	0.525	0.35 to 0.79
Fraction of light scattered into upward hemisphere, $\bar{\beta}$	0.23	0.17 to 0.29
Aerosol mass scattering efficiency (m^2g^{-1}), α_s	3.5	2.3 to 4.7
Aerosol single scattering albedo, co-albedo (dry), ω_0, $1-\omega_0$	0.92	0.85 to 0.97
T_a, atmospheric transmittance above aerosol layer	0.87	0.72 to 1.00
Fractional increase in aerosol scattering efficiency due to hygroscopic growth at RH=80%	2.0	1.7 to 2.3
Fraction of Earth not covered by cloud	0.39	0.35 to 0.43
Mean surface albedo, co-albedo	0.15	0.08 to 0.22
Result: If central value is –0.6 Wm^{-2} the 2/3 uncertainty range is from -0.1 to -1.0 W m^{-2}.		

Modified from Penner et al., IPCC, 2001



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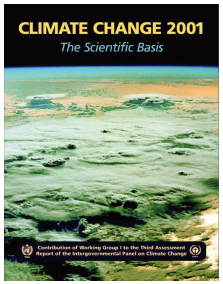
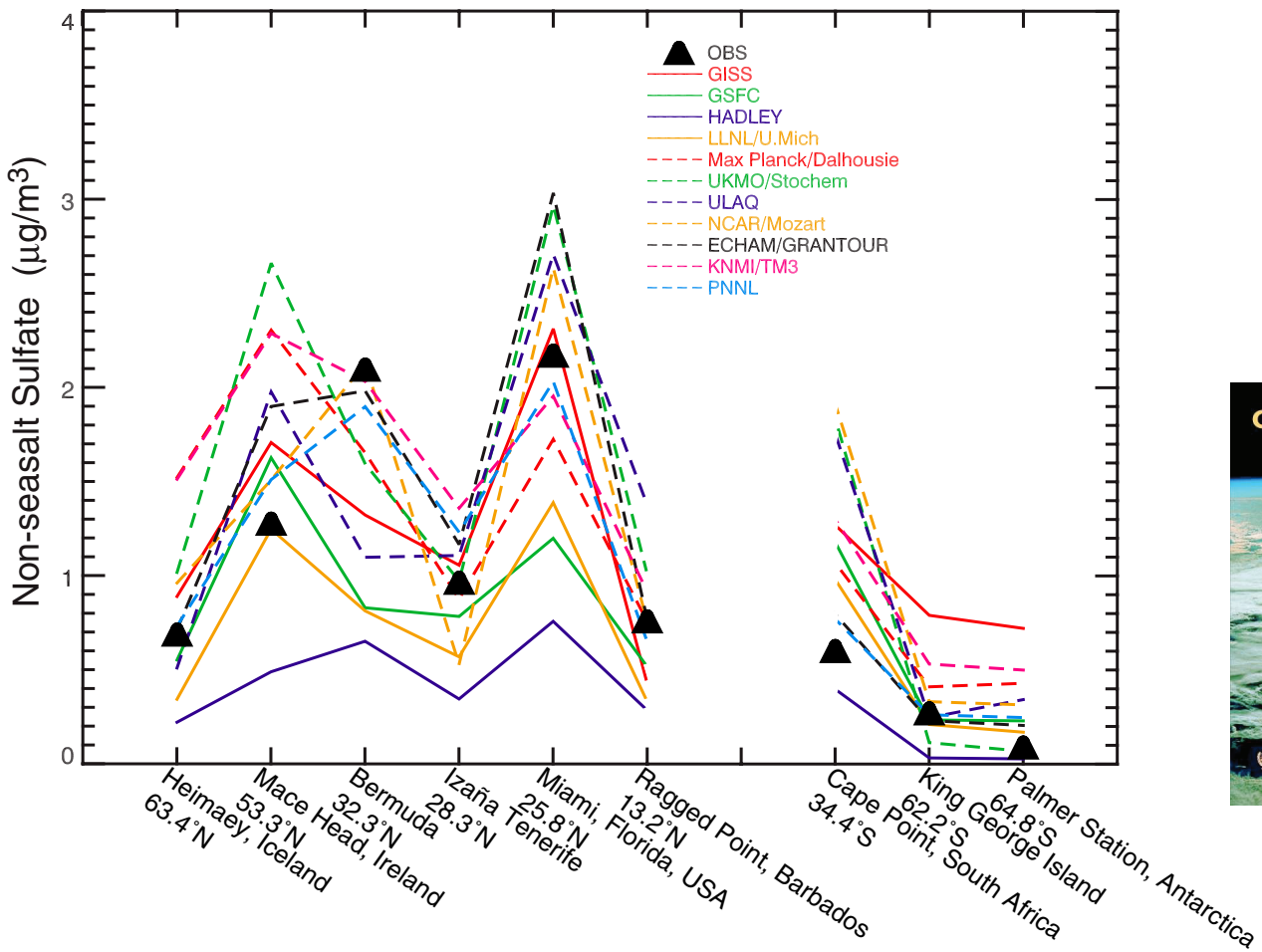
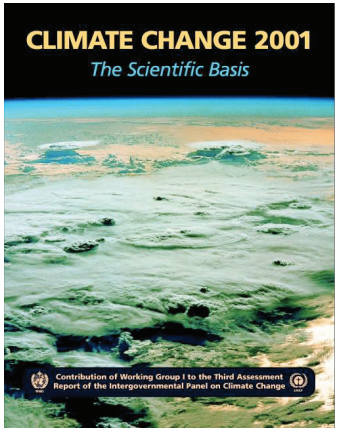


Principal uncertainties in chemical, microphysical, and optical properties.

SULFATE MODEL INTERCOMPARISON

Annual average non-seasalt sulfate in 11 chemical transport models and comparison with observations at nine stations





Penner et al., IPCC, 2001

"Most models predict surface-level seasonal mean sulphate aerosol mixing ratios to within 20%."

"We cannot be sure that these models achieve reasonable success for the right reasons."

STATISTICS OF SEVERAL SULFATE CTMs

Model	F96	L97	R98	K99	R00	C00	B97	B04
SO_2 Sink Rate (%/day)								
Dry Deposition	26	10	8	17	16	26	12	24
Wet Deposition	5	0	0	0	1	7	0	4×10^{-4}
Gas Conversion	11	7	8	6	6	9	8	14
Aqueous Conversion to sulfate	22	26	27	15	29	15	16	30
Oxidation & immediate wet dep								21
Sulfate Sink Rate (%/day)								
Dry Deposition	3	5	5	4	2	2	3	2
Wet Deposition	20	14	17	14	23	15	18	13
Inverse Lifetime (%/day)								
SO_2	63	43	42	38	53	56	36	90
Sulfate	23	19	21	18	25	17	21	15
Sulfate yield, %								
	51	76	82	55	68	43	66	50
Burden (Tg S)								
SO_2	0.33	0.56	0.61	0.56	0.4	0.43		0.20
Sulfate	0.43	1.05	0.96	0.73	0.60	0.63		0.60
Sulfate Potential (days)								
	2.1	4.4	3.7	3.4	2.5	2.7		3.3

Benkovitz & Schwartz, 2004

ISSUES IN DETERMINING AEROSOL INDIRECT FORCING

1. Enhancement in aerosol particle concentration (and size, composition, etc.) between preindustrial and present, as function of location.
2. Relation between aerosol particle concentration (and size, composition, etc.) and cloud droplet concentration.
3. Relation between cloud drop concentration and cloud reflectance.
4. Aerosol influences on LWP, cloud lifetime, etc., in addition to reflectance.

These requirements can be met only by models – models that are evaluated by comparison with observation

Emissions models

Chemical transport and transformation models

Cloud drop activation and microphysics models

Radiation transfer models

Quantities and processes governing aerosol *indirect* forcing of climate change and the quantities on which their dependence must be known

Quantity/Process	Symbol	Dependence on
Particle and gaseous precursor emissions	$e(\boldsymbol{x}, t, r_{\mathrm{ap}}, \chi)$	Radius r_{ap}, composition χ, 2-D location
Transport, chemical reaction, microphysical evolution	$\downarrow$	Concentrations of precursors and other reagents, solar intensity; size dependent concentrations of other aerosol species; 3-D winds, clouds . . .
Aerosol particle number concentration	$n_{\mathrm{ap}}(\boldsymbol{x}, t, r_{\mathrm{ap}}, \chi)$	Radius, composition, 3-D location
Supersaturation spectrum	$n_{\mathrm{ccn}}(s)$	Radius, composition, supersaturation$s$
Cloud formation and dissipation	$\downarrow$	$n_{\mathrm{ccn}}(s)$, updraft velocity, turbulent intensity, precipitation development, heating rate, entrainment . . .
Cloud drop number concentration and properties	$n_{\mathrm{cd}}(\boldsymbol{x}, t, r_{\mathrm{cd}}, \omega(\lambda)$	Radius, single scatter albedo ω, wavelength λ
Cloud optics	$\downarrow$	Cloud drop size distribution, Mie scattering
Cloud drop scattering and absorption coefficients	$\{\sigma_{\mathrm{sc}}, \sigma_{\mathrm{ac}}\}(\boldsymbol{x}, t, \lambda)$	Absorption by dissolved and suspended materials
Vertical integral	$\downarrow$	Updrafts, entrainment
Cloud scattering and absorption optical depth	$\{\tau_{\mathrm{sc}}, \tau_{\mathrm{ac}}\}(\boldsymbol{x}, t, \lambda)$	Cloud physical depth, liquid water path
Radiation transfer (3D)	$\downarrow$	Cloud geometry, surface reflectance
Net spectral flux at top of atmosphere	$F_{\mathrm{toa}}(\boldsymbol{x}, t, \lambda)$	

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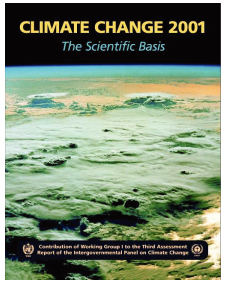
UNCERTAINTY BUDGET FOR *INDIRECT* FORCING BY INDUSTRIAL AEROSOLS

Quantity	Central Value	2/3 Uncertainty Range
Background N_d for Northern Hemisphere marine (cm^{-3})	140	66 to 214
Perturbed N_d for Northern Hemisphere marine (cm^{-3})	217	124 to 310
Cloud mean liquid water content (LWC) ($g\ m^{-3}$)	0.225	0.125 to 0.325
Background sulfate concentration ($g\ m^{-3}$)	1.5	0.85 to 2.15
Cloud layer thickness (m)	200	100 to 300
Perturbed sulfate concentration ($g\ m^{-3}$)	3.6	2.4 to 4.8
Susceptible cloud fraction, f_c	0.24	0.19 to 0.29
Atmospheric transmission above cloud layer, T_a	0.92	0.78 to 1.00
Mean surface albedo	0.06	0.03 to 0.09
Result: If central value is -1.4 Wm^{-2} the 2/3 uncertainty range is from 0 to -2.8 Wm^{-2}.		

Modified from Penner et al., IPCC, 2001



UNCERTAINTY BUDGET FOR *INDIRECT* FORCING BY INDUSTRIAL AEROSOLS

Quantity	Central Value	2/3 Uncertainty Range	Uncertainty Factor
Background N_d for Northern Hemisphere marine (cm^{-3})	140	66 to 214	**3.2**
Perturbed N_d for Northern Hemisphere marine (cm^{-3})	217	124 to 310	**2.5**
Cloud mean liquid water content (LWC) ($g\ m^{-3}$)	0.225	0.125 to 0.325	2.6
Background sulfate concentration ($\mu g\ m^{-3}$)	1.5	0.85 to 2.15	**2.5**
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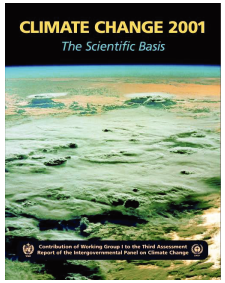
The greatest uncertainties are in aerosol and cloud microphysics properties, such as dependence of cloud drop concentration on ***aerosol composition, loading, and microphysical properties.***



These uncertainties are not well quantified.

QUANTIFYING UNCERTAINTIES

- Propagation of input uncertainties in measurements or models

  - Sensitivity studies

- Comparison of multiple measurements or models
- Comparison of models with measurements
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UNQUANTIFIABLE UNCERTAINTIES

- Underdetermined quantities (inversion problems)
- Assumptions
- Omitted processes

ASP

ASP TIMELINE AND MILESTONES

2004

March 2	Chief Scientist selected
April 29	BERAC approval of Reconfiguration Report
May 4	Federal Register announcement
June 21	Proposals due; ~154 proposals received
September 21	Proposal reviews completed
November 4	Recommended projects announced

2005

January 25	Science Team meeting
July ?	In the field!

ASP

CRITERIA OF SUCCESS IN ASP

- Development and application of ***new methods*** for the study of aerosol processes controlling aerosol radiative forcing of climate and climate change
  - Instruments, models, lab studies
  - Major field campaigns, on our own or with others
  - Special issues, symposia at national meetings
- ***Improved understanding*** of these processes
- ***Model-based representation*** of these processes with ***known and reasonable uncertainty***
- ***Deliverables that are useful and used*** and lead to better CCSP products
- A whole that ***greatly*** exceeds the sum of the parts

ASP

This is not the end.

It is not even the beginning of the end.

But it is, perhaps, the end of the beginning.