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1986-9

WCRP and ICTP Interpreting Climate Change Simulations: Capacity Building for Developing Nations Seminar

26 - 30 November 2007

IPCC WGI
Radiative forcing of climate change.

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IPCC WGI

Radiative forcing of climate change

V. Ramaswamy

NOAA/ Geophysical Fluid Dynamics Laboratory

Presentation at ICTP, Trieste; November 27, 2007

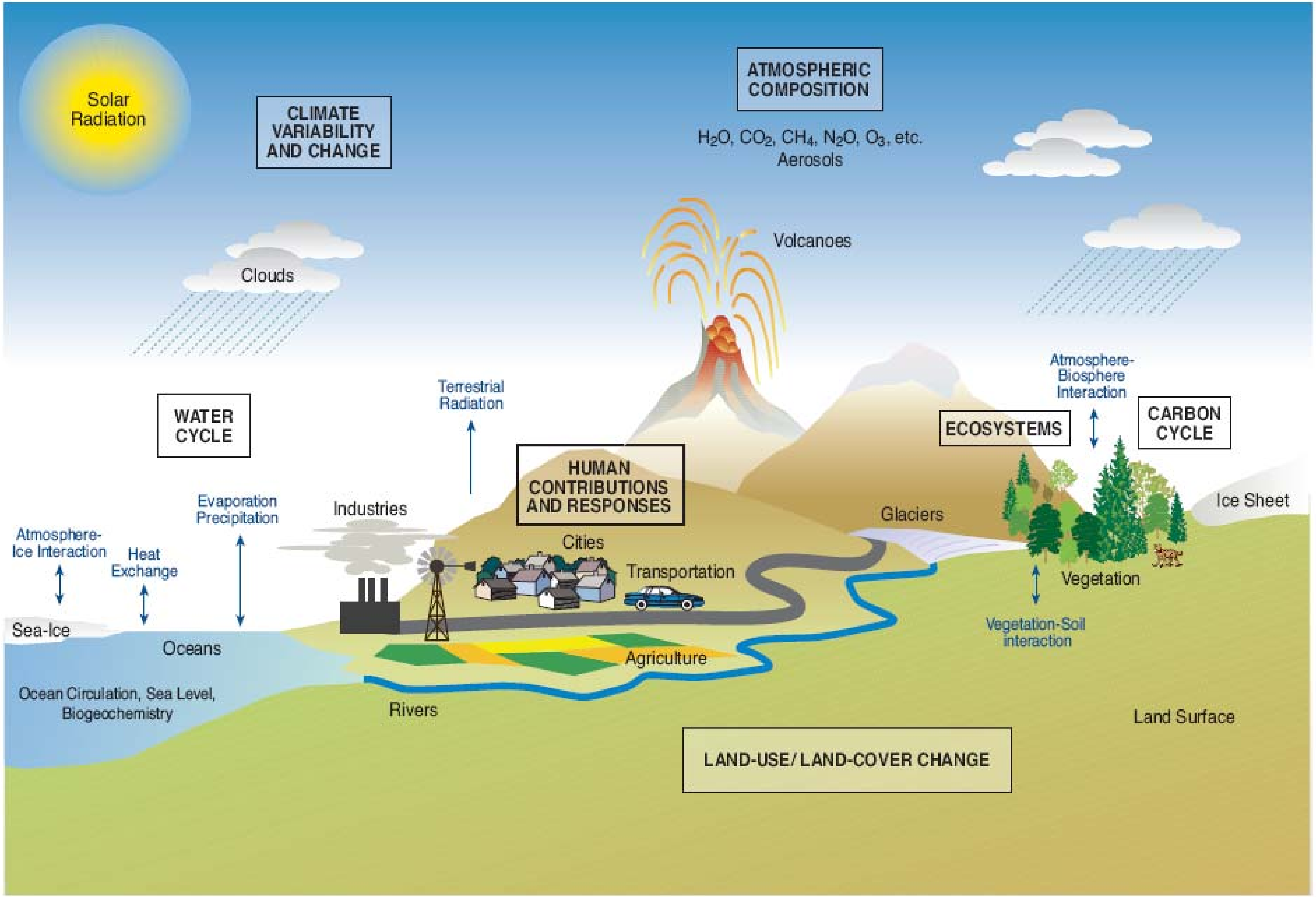


Figure 1: Major components needed to understand the climate system and climate change.

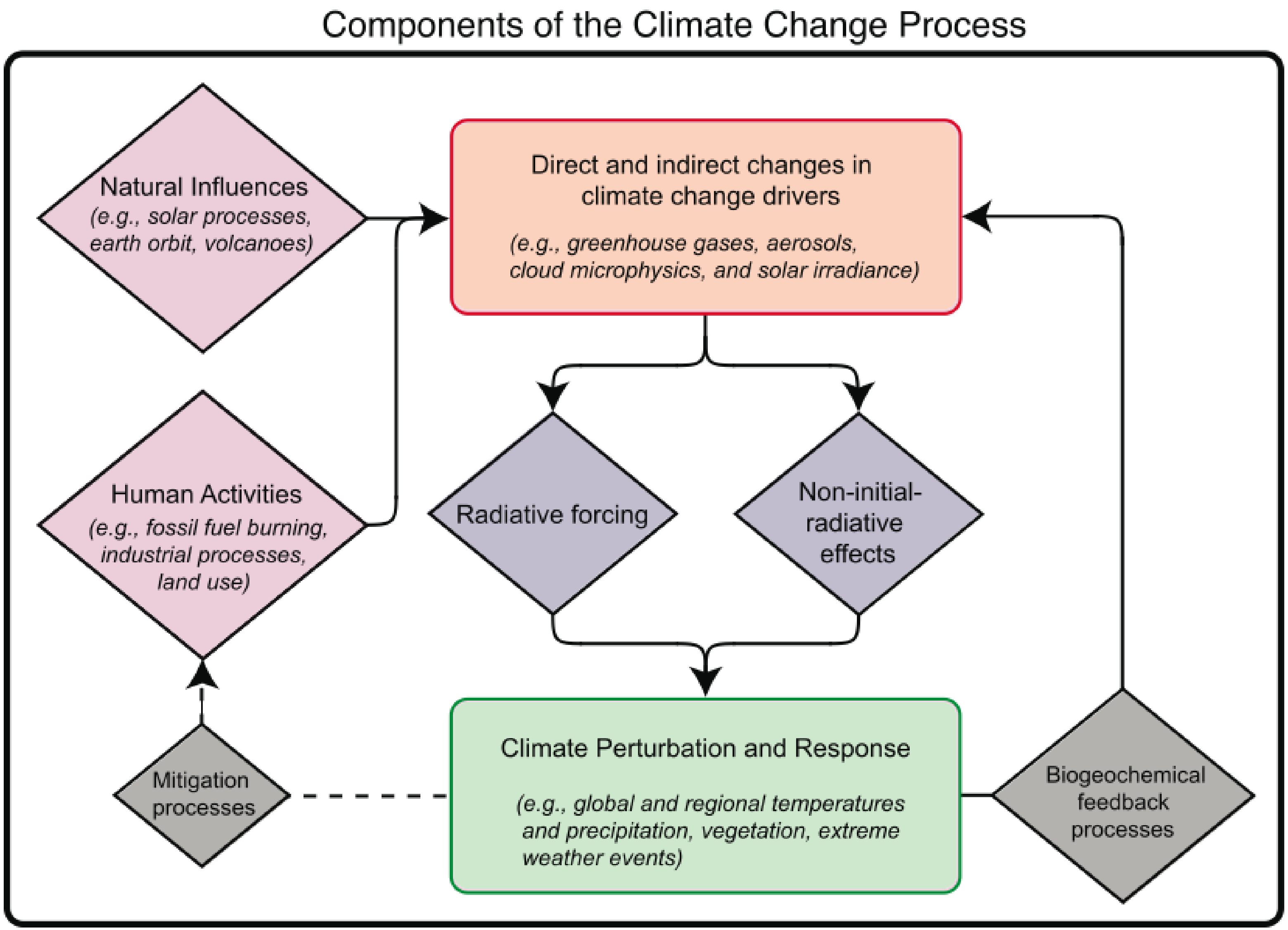
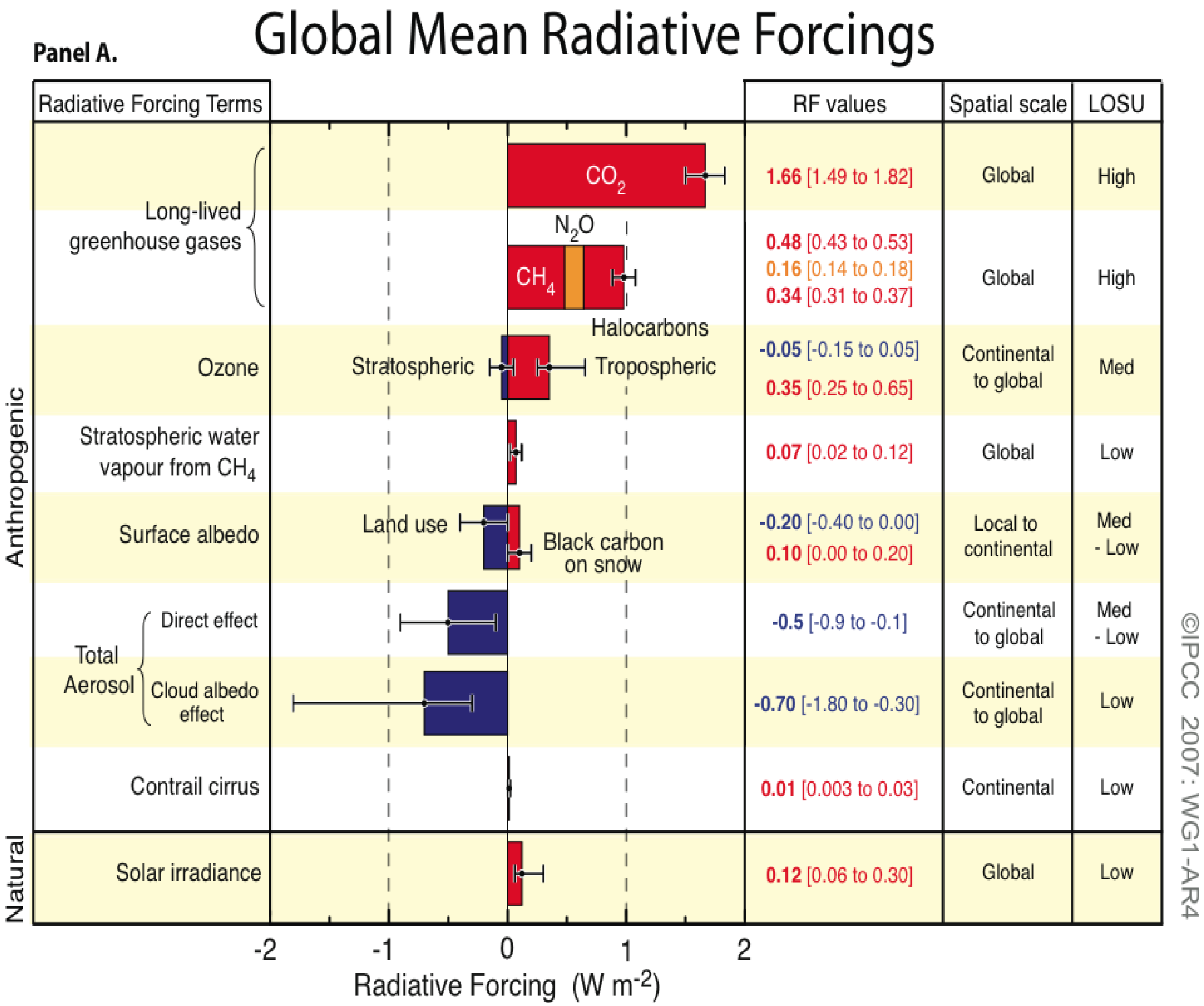

Components of the Climate Change Process
Natural Influences
(e.g., solar processes, earth orbit, volcanoes)
Direct and indirect changes in climate change drivers
(e.g., greenhouse gases, aerosols, cloud microphysics, and solar irradiance)
Human Activities
(e.g., fossil fuel burning, industrial processes, land use)
Radiative forcing
Non-initial-radiative effects
Mitigation processes
Climate Perturbation and Response
(e.g., global and regional temperatures and precipitation, vegetation, extreme weather events)
Biogeochemical feedback processes

Figure 2.1

Radiative Forcing of Climate [1750 to 2005]



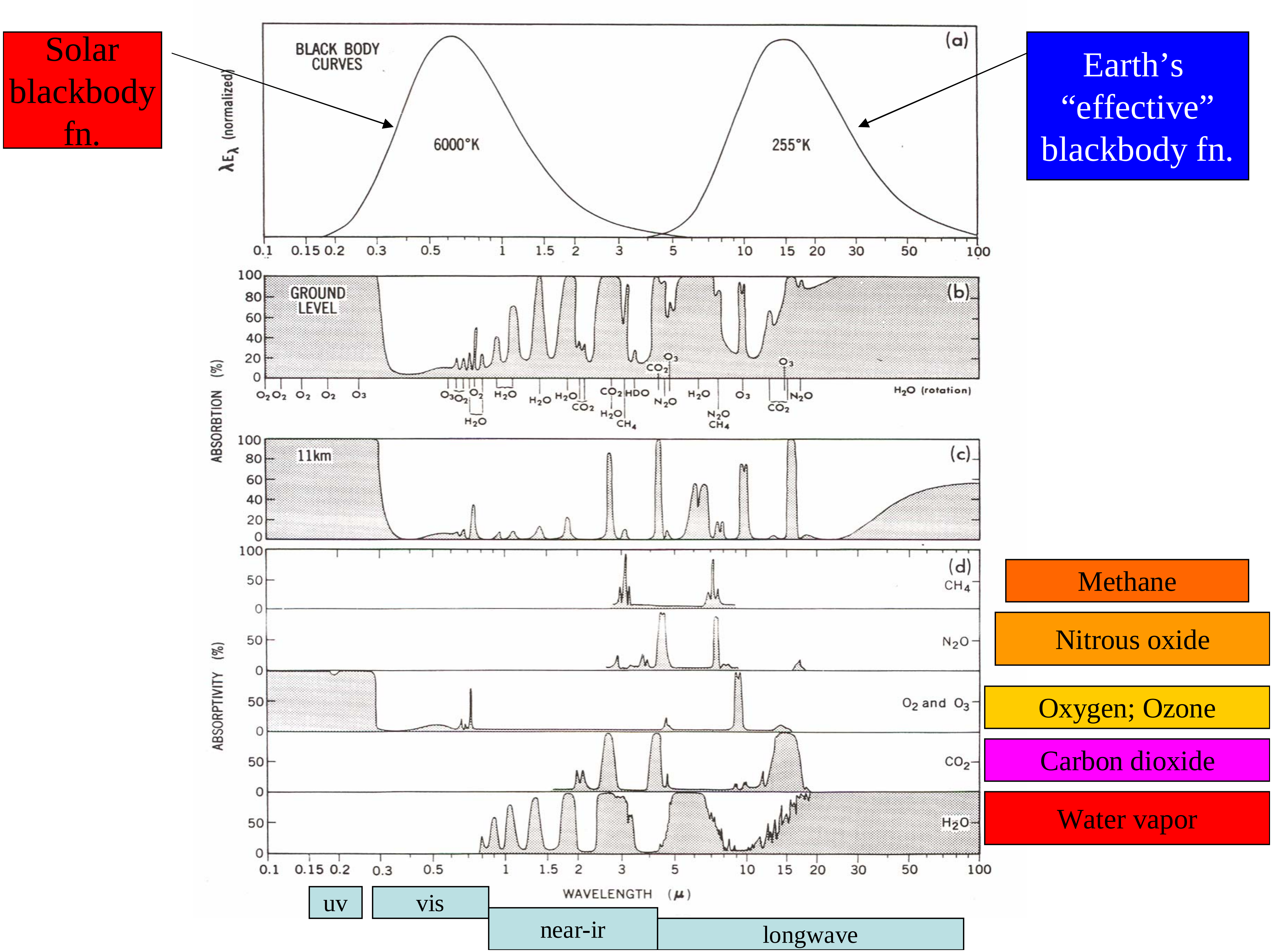
Best estimate and range for individual terms; ranges given by 90% confidence interval.

Note differences in spatial scale

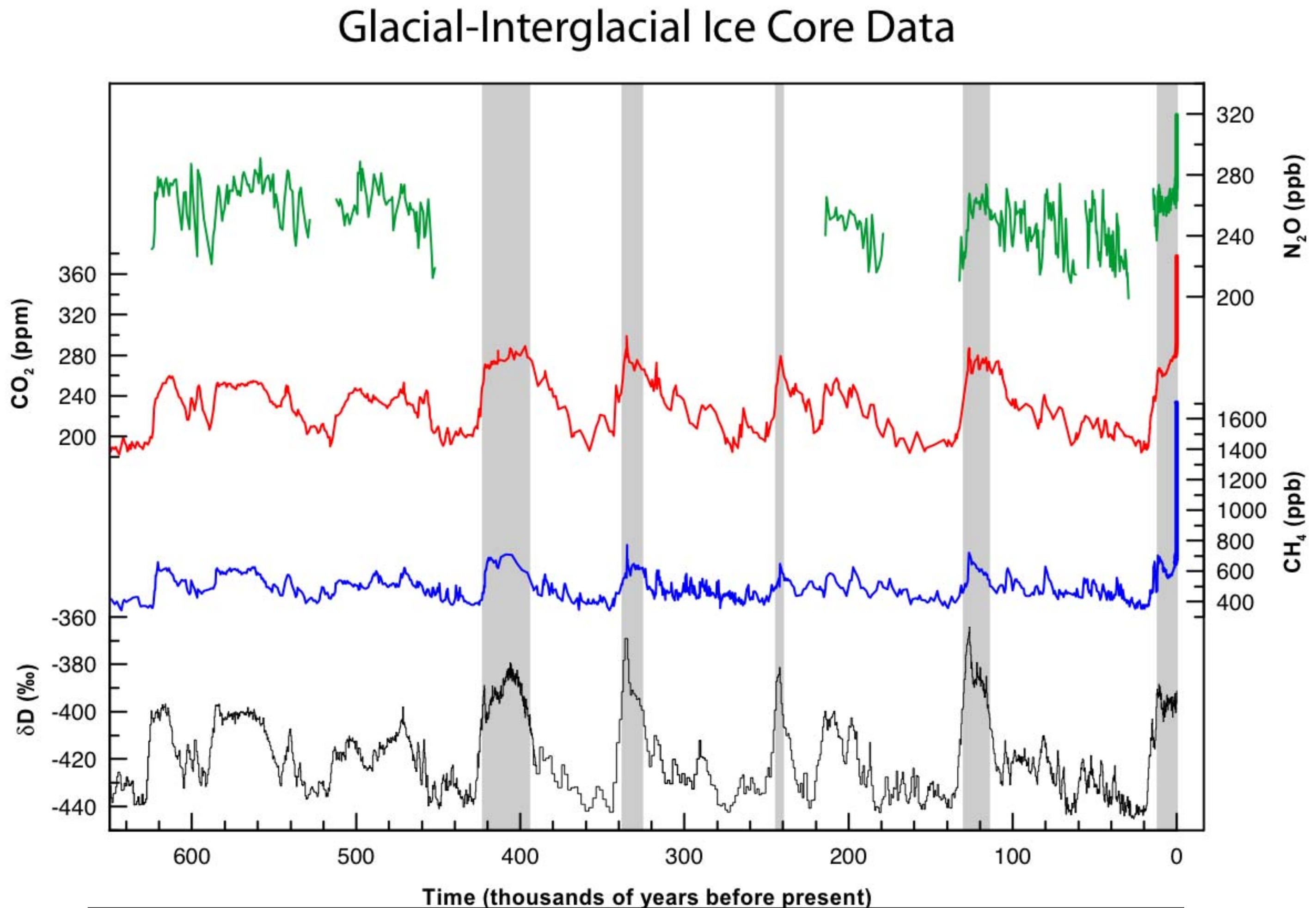
Time-scale: varies between mechanisms;

difficult to characterize CO_2's lifetime by a single value.

Figure TS-5
(Panel A)


Solar blackbody fn.
Earth's "effective" blackbody fn.
BLACK BODY CURVES
6000°K
255°K
(a)
GROUND LEVEL
(b)
11km
(c)
(d)
ABSORBTION (%)
ABSORPTIVITY (%)
CH4
N2O
O2 and O3
CO2
H2O
H2O (rotation)
Methane
Nitrous oxide
Oxygen; Ozone
Carbon dioxide
Water vapor
WAVELENGTH (μ)
uv
vis
near-ir
longwave

Molecule	Spectral Range cm^{-1}	Band Strength $cm^{-2} atm^{-1}$ at 296K
CO_2	550-800	220
O_3	950-1200	312
N_2O	1200-1350	218
CH_4	950-1650	134
$CFCl_3$ (CFC11)	800-900	1828
CF_2Cl_2 (CFC12)	875-950	1446
CF_3Cl (CFC13)	1075-1125	1758



Change in carbon dioxide, methane and nitrous oxide concentrations over last 650,000 years, from Antarctic ice cores, and recent atmospheric measurements. Two temperature proxy timeseries are also shown.
[Figure 6.3]

Points

Long-term record, esp. CO_2, CH_4

N_2O record not as continuous

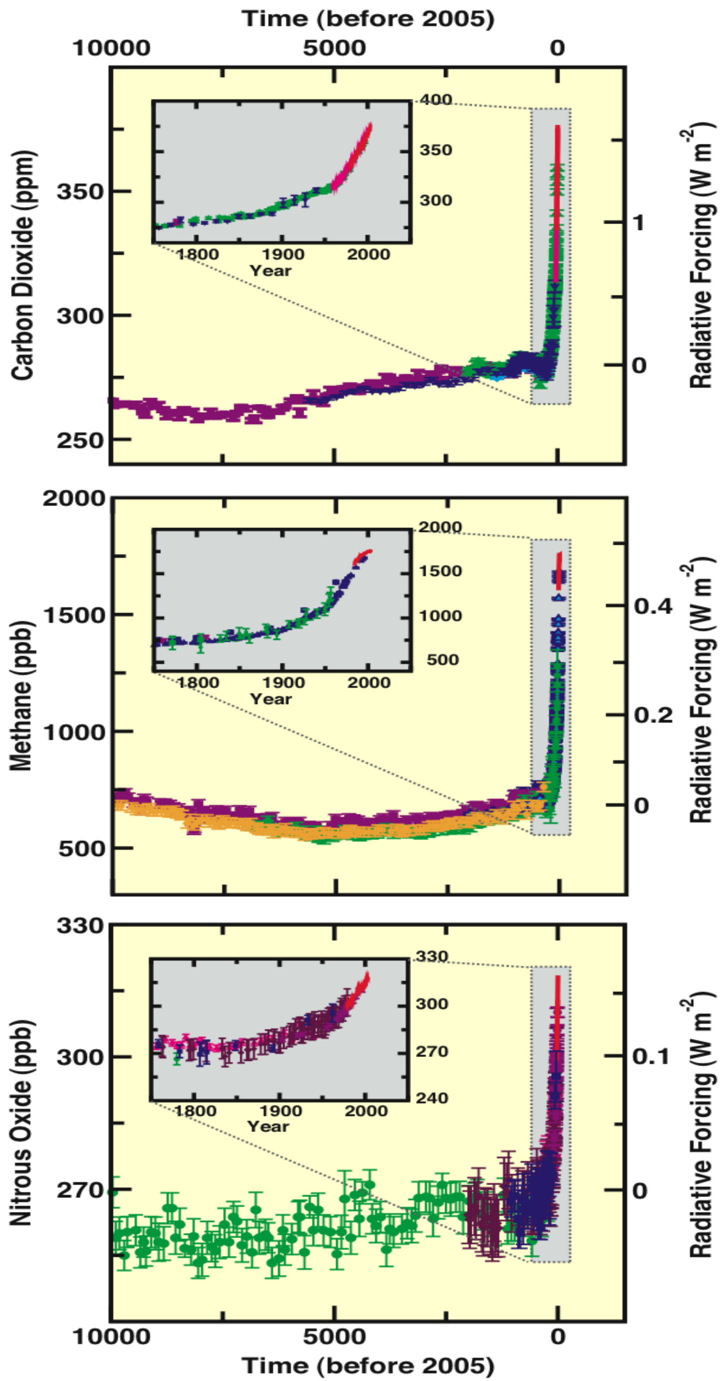
Long-lived greenhouse gas records approximately equivalent to global mixing ratio values

Temperature record is more local to Antarctica

CO_2

CH_4

N_2O



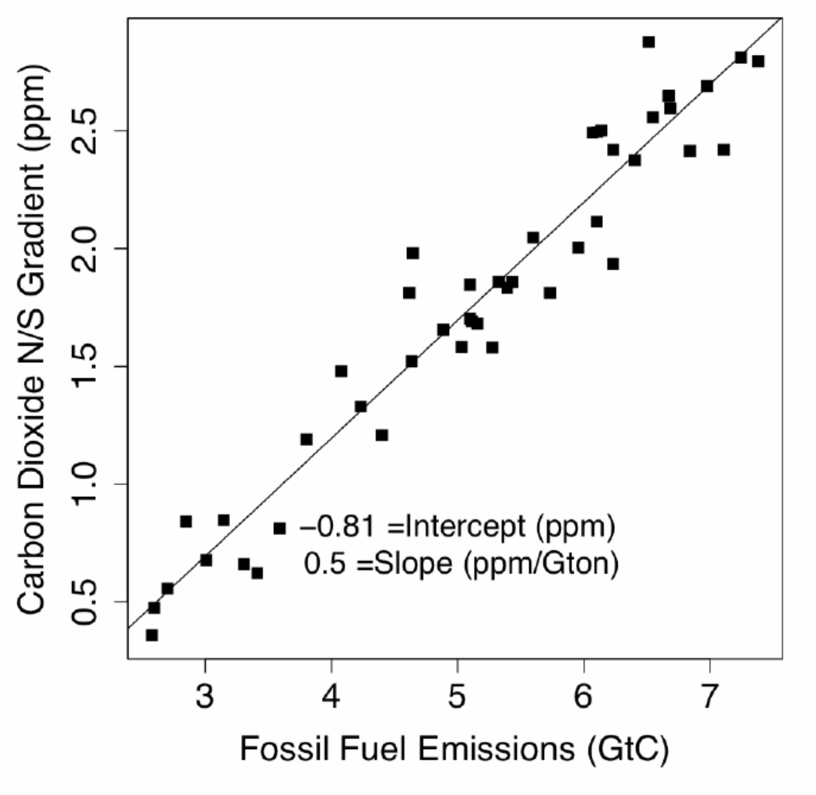
Change in carbon dioxide, methane and nitrous oxide concentrations and radiative forcing
over last 10,000 years,
and (inset) from 1750-2005
[Figure SPM-1].

Increase since 1750 is unprecedented in record

CO_2 radiative forcing has increased by 20% in last 10 years

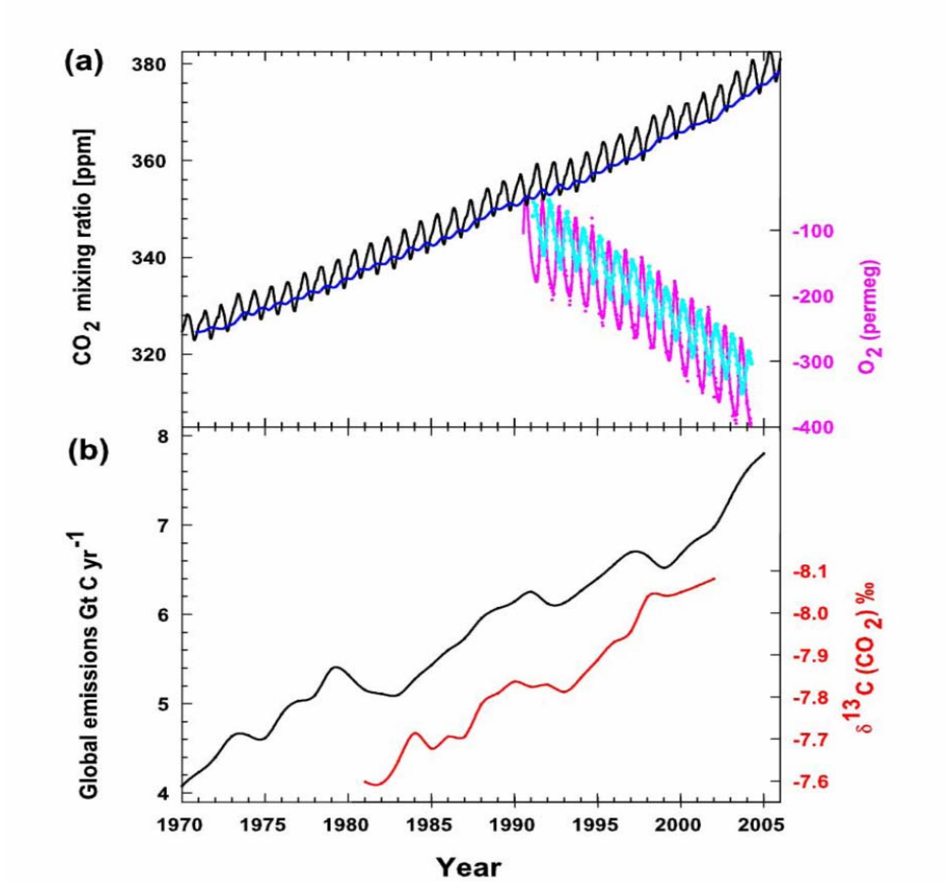
Carbon dioxide increases are due to anthropogenic emissions

North-South CO_2 gradient is related to fossil fuel emissions [Figure 7.5]



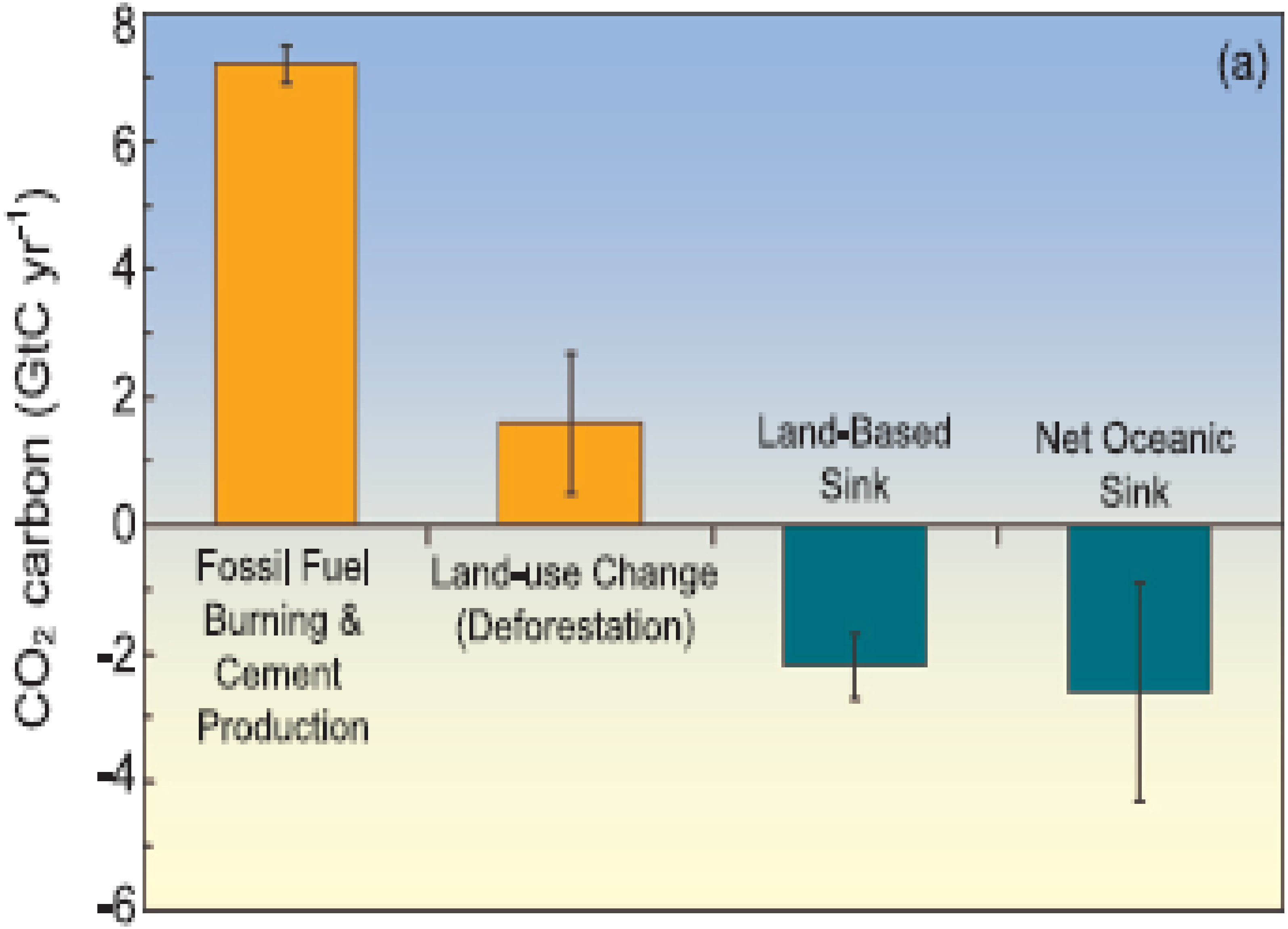
CO2 → chemically stable → long-lived → well-mixed

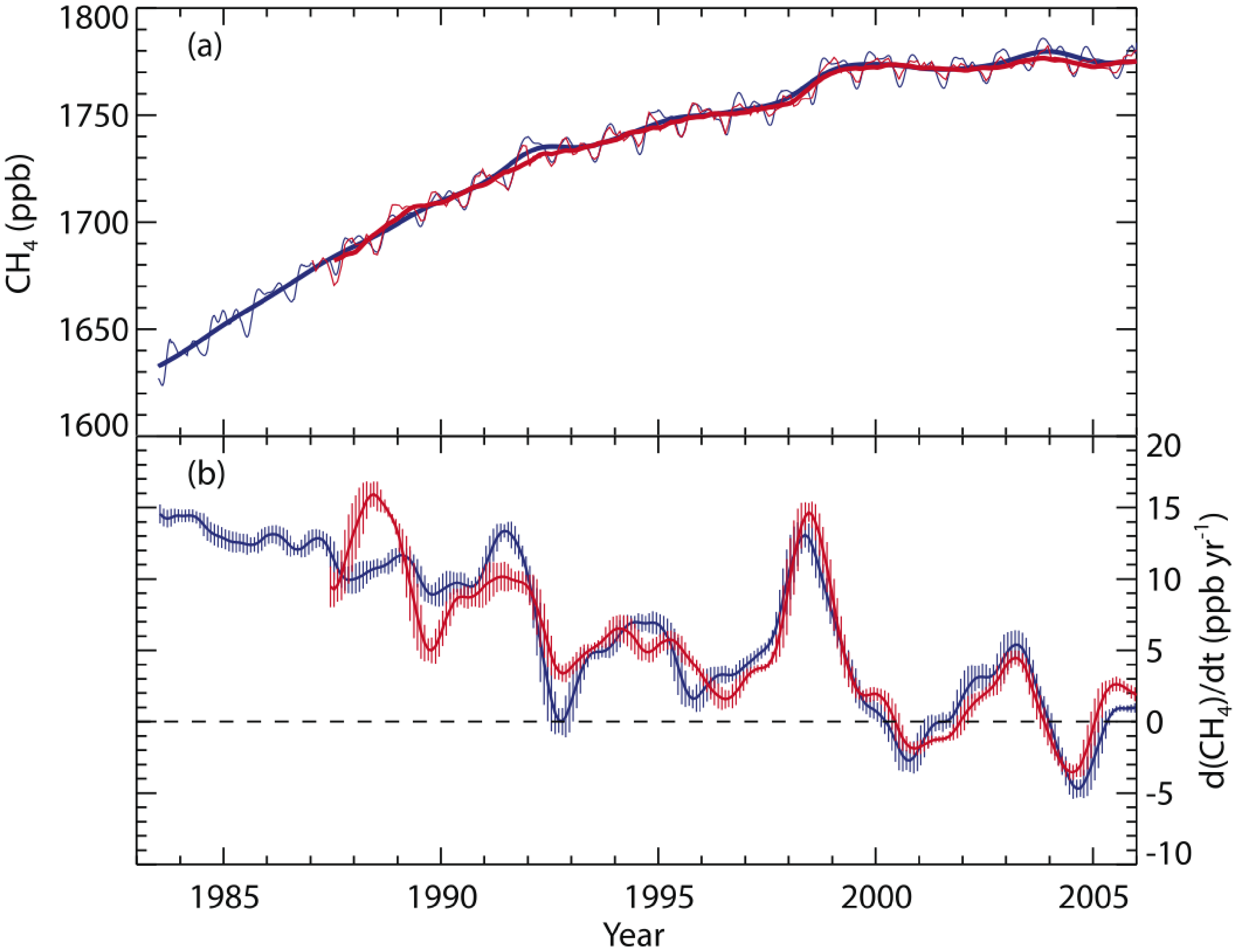
Oxygen and carbon isotope record show anthropogenic cause [Figure 2.3]



Global fossil fuel CO_2 emissions are increasing

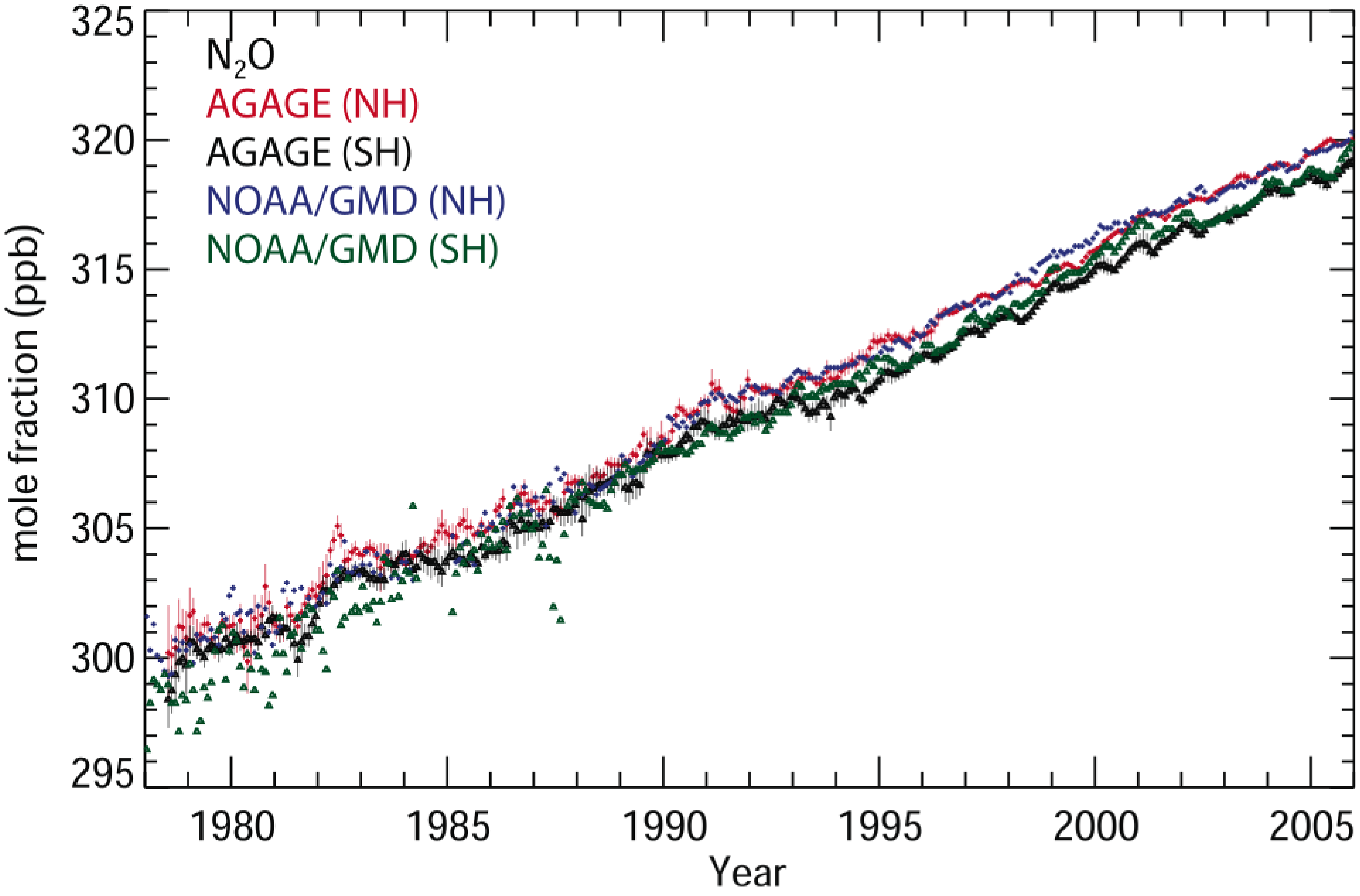
IPCC AR4 Chapter 7





(a)
(b)
1800
1750
1700
1650
1600
CH_4 (ppb)
20
15
10
5
0
-5
-10
$d(CH_4)/dt$ (ppb yr^{-1})
1985
1990
1995
2000
2005
Year

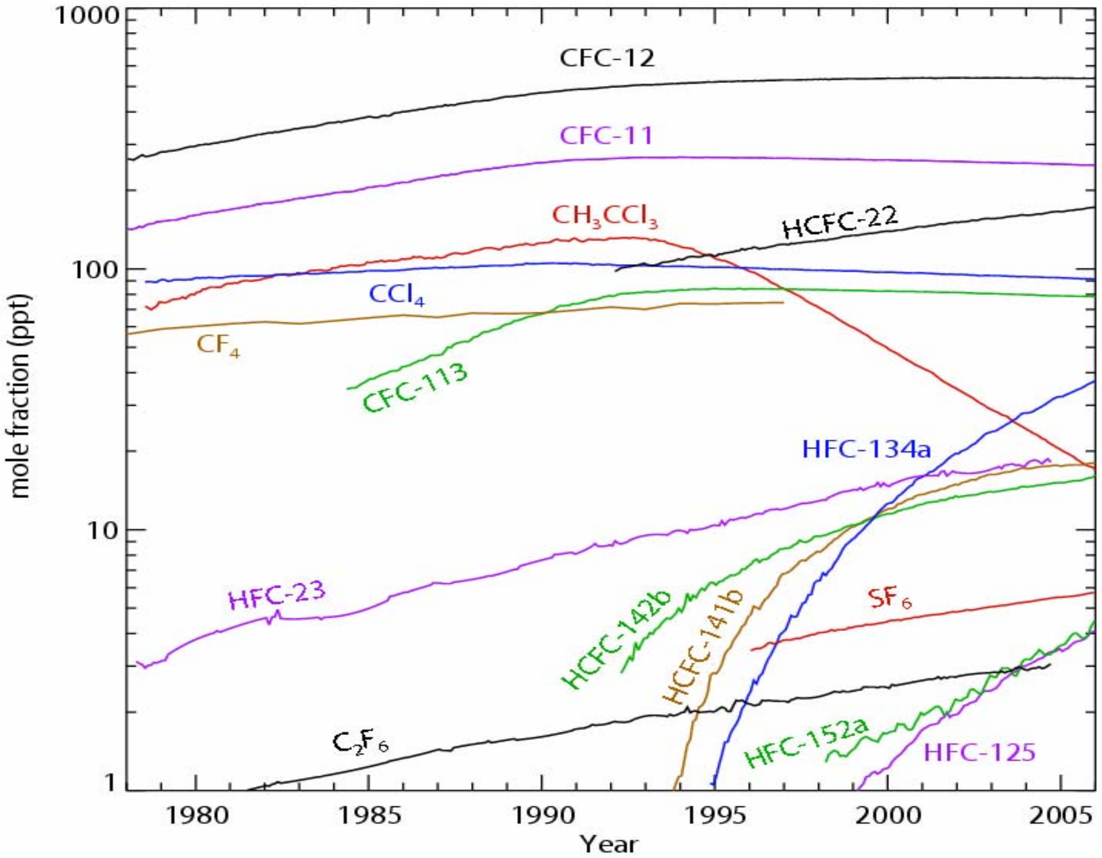
Figure 2.4



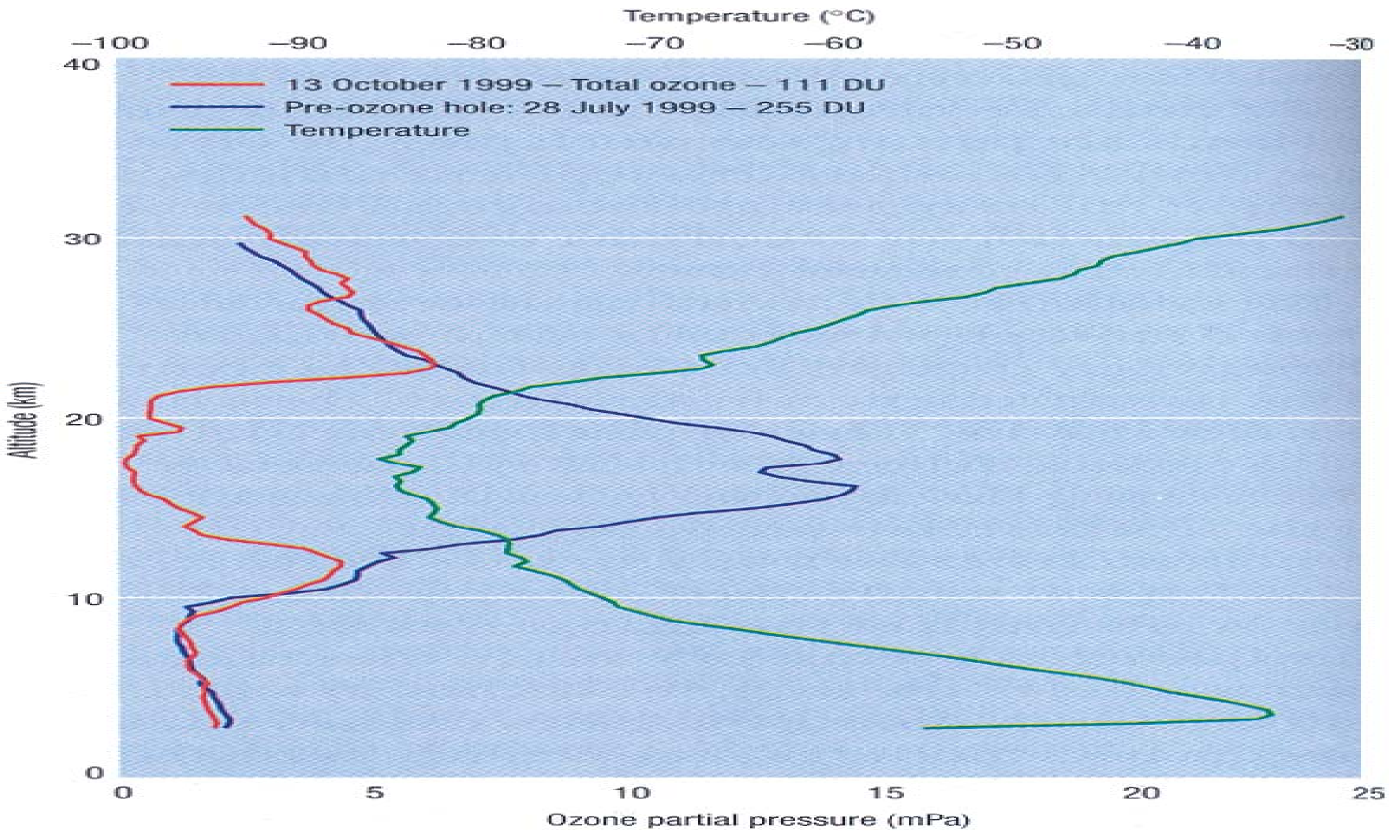
N2O
AGAGE (NH)
AGAGE (SH)
NOAA/GMD (NH)
NOAA/GMD (SH)
mole fraction (ppb)
325
320
315
310
305
300
295
1980
1985
1990
1995
2000
2005
Year

Figure 2.5

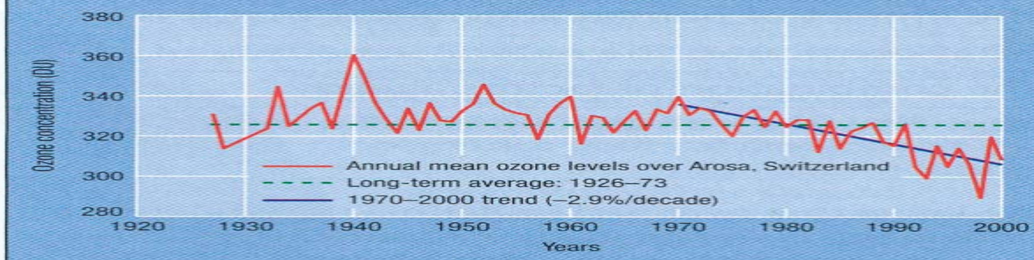
Temporal evolution of the major Halocarbons [Figure 2.6]



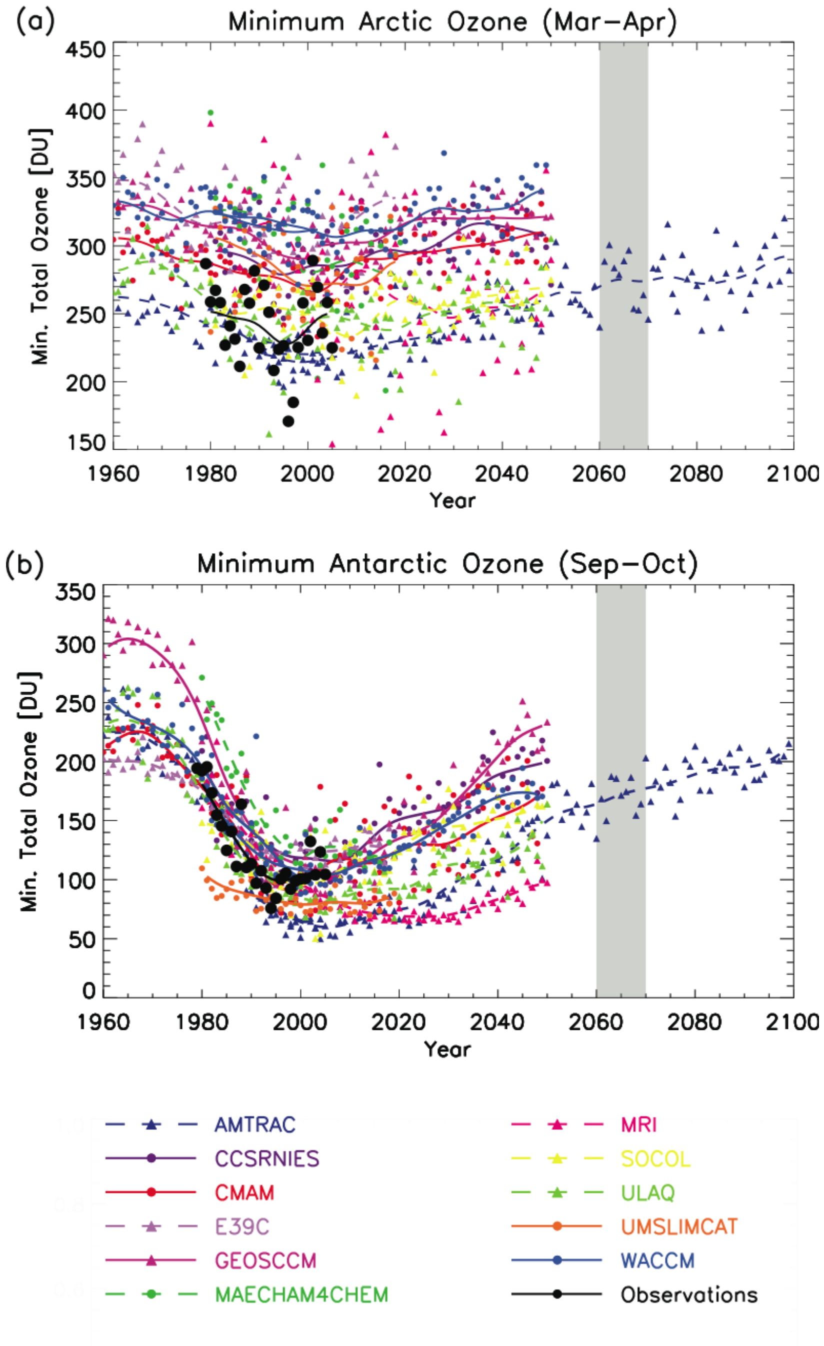
Some species (CFC-11, CFC-12) flattening or going down because of Protocols
Some species (HCFC-22, SF6) increasing
Overall slight increase in halocarbon radiative forcing since the time of the TAR
Not elucidated on in SPM, as recently evaluated in IPCC/TEAP (2005) report



Measurement of atmospheric ozone

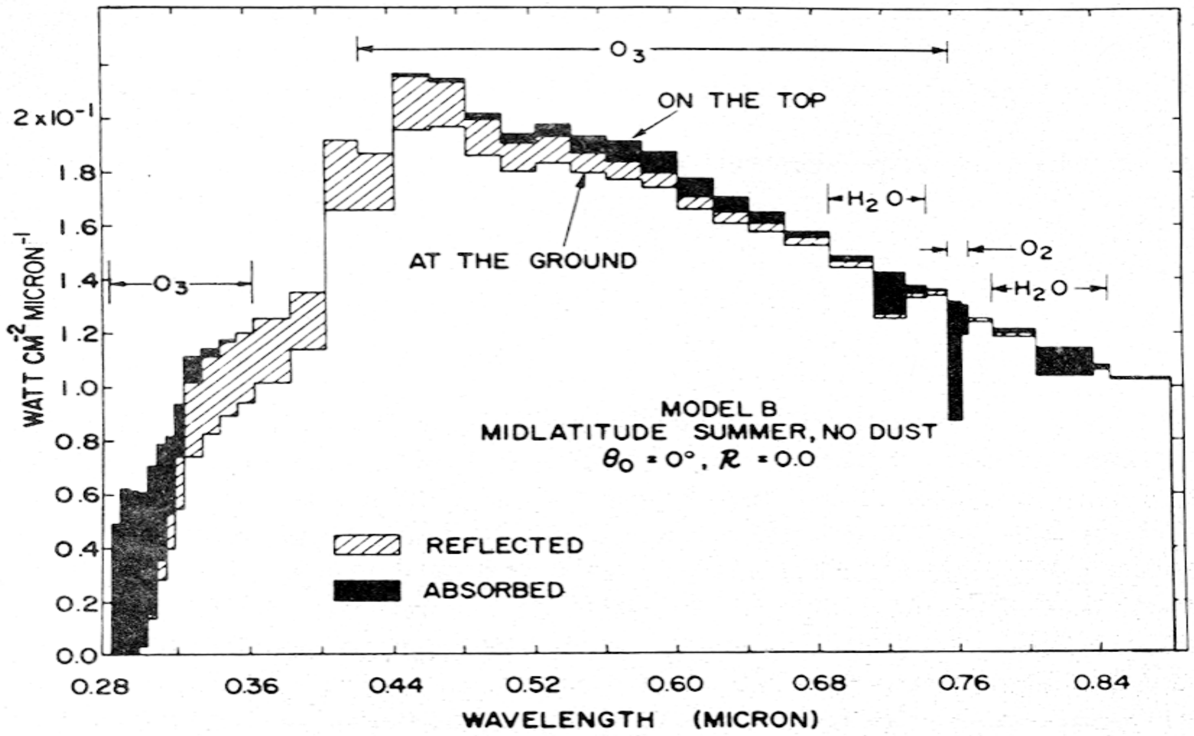


In 1922, G.M.B. Dobson, an English physicist at Oxford, developed an operational spectrophotometer for routine measurement of total ozone in the overhead air column. The Dobson photospectrometer, as shown above, was the standard instrument for more than 50 years and more than 100 were constructed and deployed around the world for ozone measurement. The systematic observations from Arosa, Switzerland show nearly steady amounts of ozone until the early 1970s, and a significant decline thereafter.



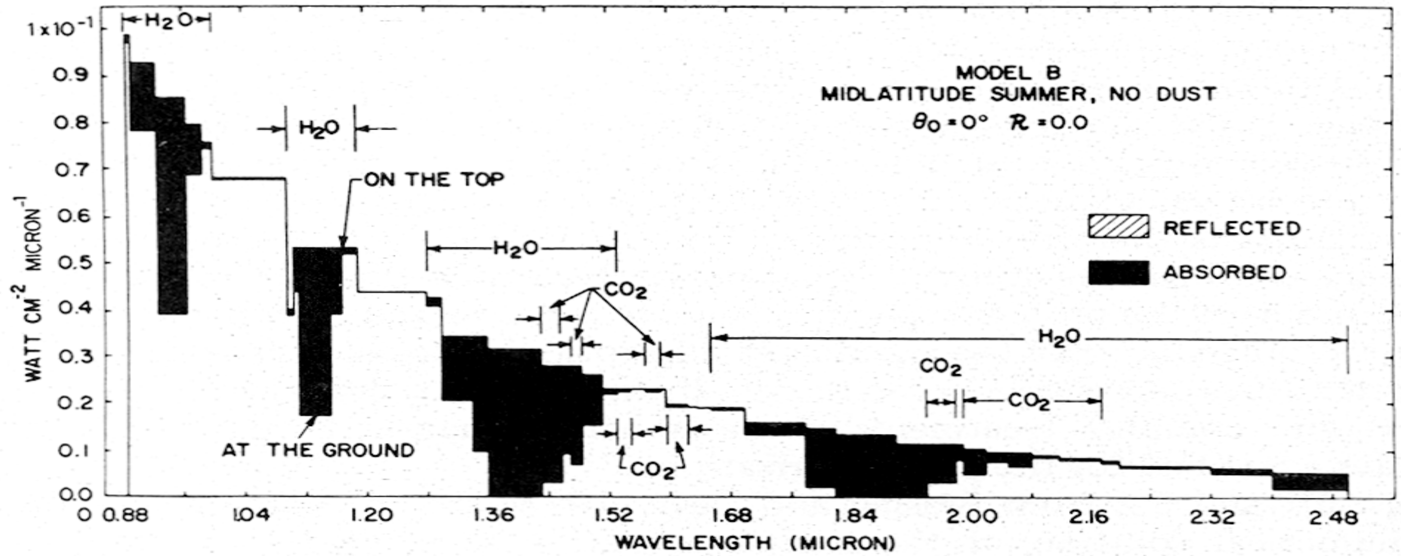
(a)
Minimum Arctic Ozone (Mar–Apr)
Min. Total Ozone [DU]
450
400
350
300
250
200
150
1960
1980
2000
2020
2040
2060
2080
2100
Year
(b)
Minimum Antarctic Ozone (Sep–Oct)
Min. Total Ozone [DU]
350
300
250
200
150
100
50
0
1960
1980
2000
2020
2040
2060
2080
2100
Year
AMTRAC
CCSRNIES
CMAM
E39C
GEOSCCM
MAECHAM4CHEM
MRI
SOCOL
ULAQ
UMSLIMCAT
WACCM
Observations

Figure 7.18



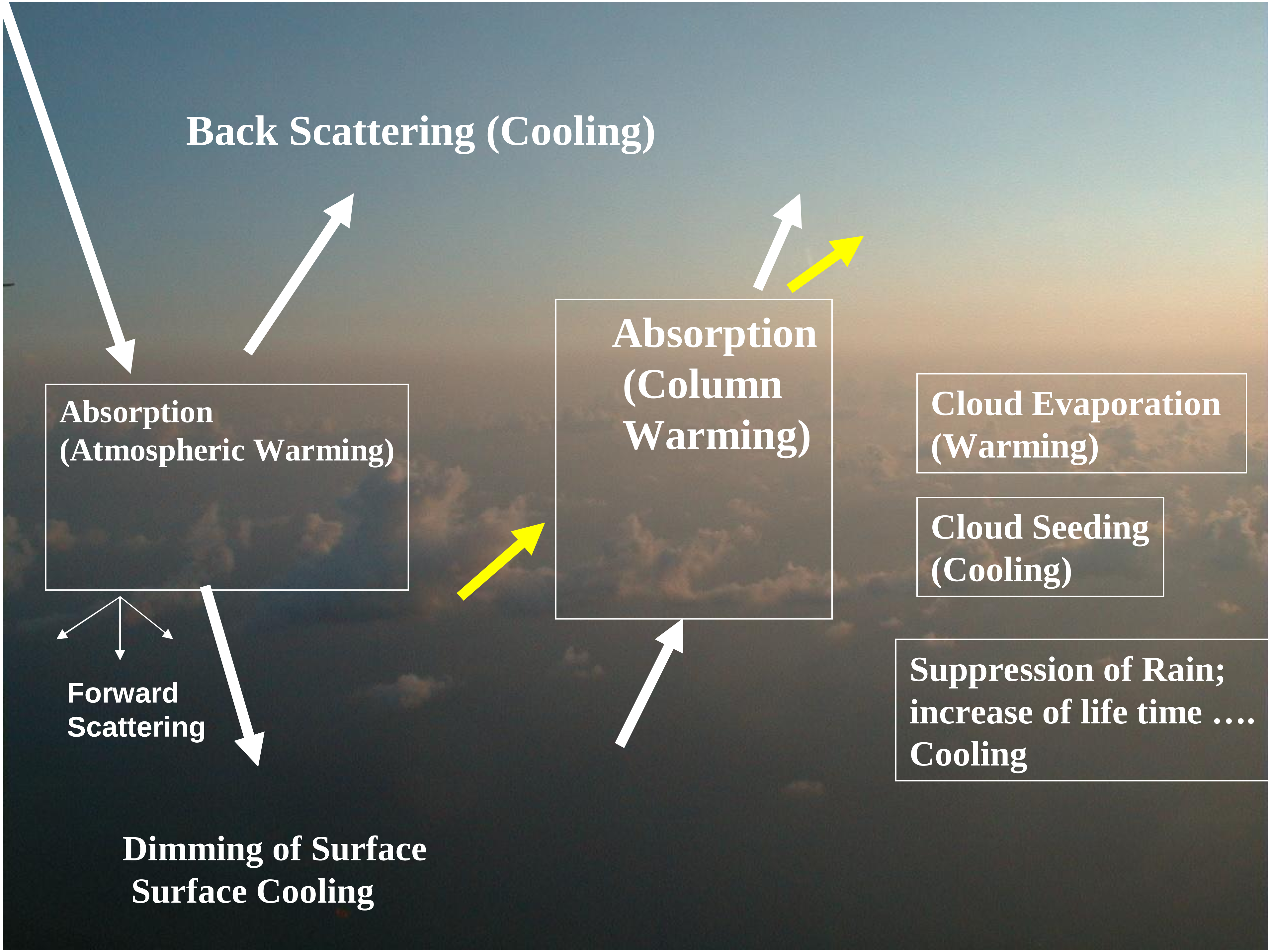
O3
ON THE TOP
2 x10-1
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
WATT CM-2 MICRON-1
AT THE GROUND
H2 O
O2
H2 O
MODEL B
MIDLATITUDE SUMMER, NO DUST
θ0 = 0°, R = 0.0
REFLECTED
ABSORBED
0.28
0.36
0.44
0.52
0.60
0.68
0.76
0.84
WAVELENGTH (MICRON)

VIS

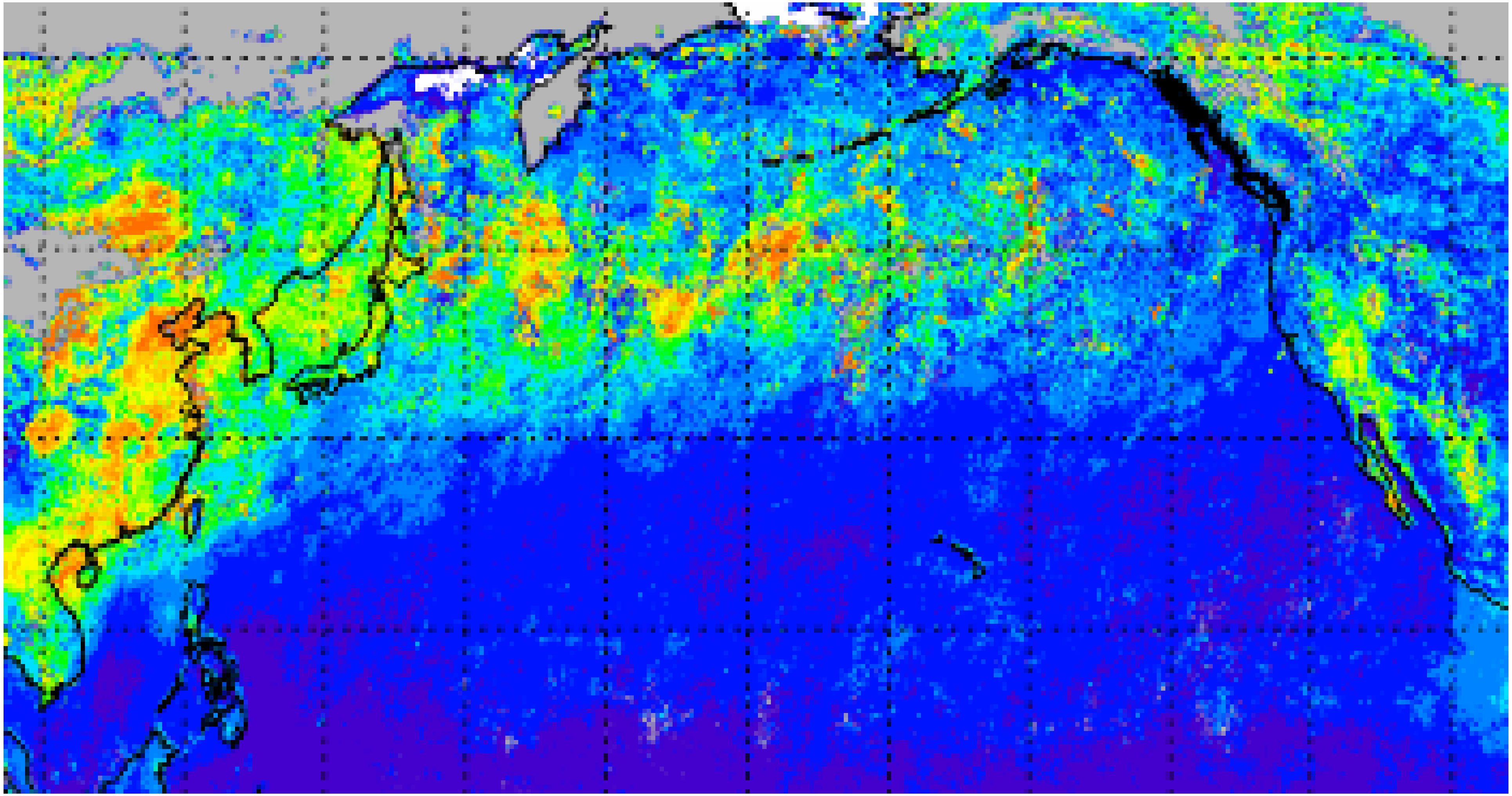


H2O
1 x10-1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
WATT CM-2 MICRON-1
MODEL B
MIDLATITUDE SUMMER, NO DUST
θ0 = 0° R = 0.0
H2O
ON THE TOP
REFLECTED
ABSORBED
H2O
CO2
H2O
CO2
CO2
CO2
AT THE GROUND
0 0.88
1.04
1.20
1.36
1.52
1.68
1.84
2.00
2.16
2.32
2.48
WAVELENGTH (MICRON)

Near-IR


Back Scattering (Cooling)
Absorption
(Atmospheric Warming)
Forward
Scattering
Dimming of Surface
Surface Cooling
Absorption
(Column
Warming)
Cloud Evaporation
(Warming)
Cloud Seeding
(Cooling)
Suppression of Rain;
increase of life time ….
Cooling

MODIS AOD: April 2003



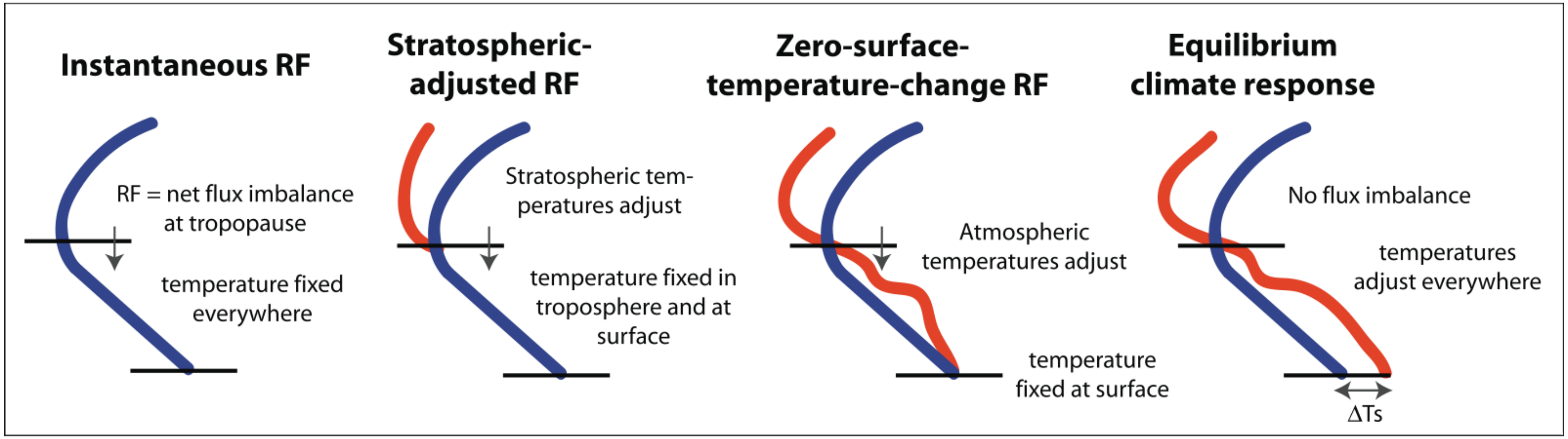

Instantaneous RF
Stratospheric-adjusted RF
Zero-surface-temperature-change RF
Equilibrium climate response
RF = net flux imbalance at tropopause
temperature fixed everywhere
Stratospheric temperatures adjust
temperature fixed in troposphere and at surface
Atmospheric temperatures adjust
temperature fixed at surface
No flux imbalance
temperatures adjust everywhere
ΔTs

Figure 2.2

FORCING - RESPONSE RELATION

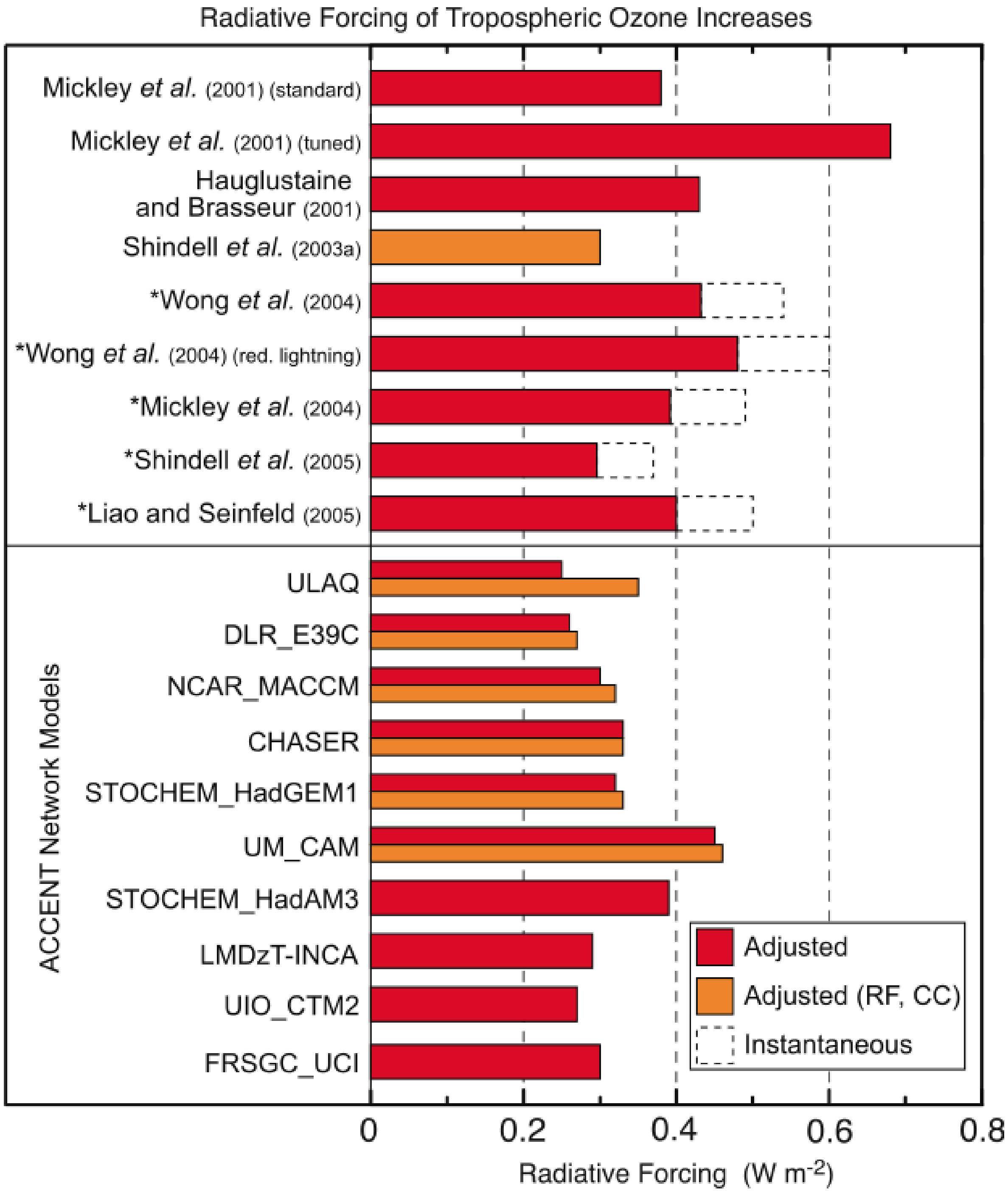
{at equilibrium}

$$\Delta T_s = \lambda * (\Delta F)$$

T_s = global-mean, annual-mean surface temperature

ΔF = global-mean, annual-mean radiative forcing evaluated at tropopause after equilibration of stratosphere

λ = global-mean climate sensitivity factor (parameter)



Radiative Forcing of Tropospheric Ozone Increases
Mickley et al. (2001) (standard)
Mickley et al. (2001) (tuned)
Hauglustaine and Brasseur (2001)
Shindell et al. (2003a)
*Wong et al. (2004)
*Wong et al. (2004) (red. lightning)
*Mickley et al. (2004)
*Shindell et al. (2005)
*Liao and Seinfeld (2005)
ACCENT Network Models
ULAQ
DLR_E39C
NCAR_MACCM
CHASER
STOCHEM_HadGEM1
UM_CAM
STOCHEM_HadAM3
LMDzT-INCA
UIO_CTM2
FRSGC_UCI
Adjusted
Adjusted (RF, CC)
Instantaneous
0
0.2
0.4
0.6
0.8
Radiative Forcing (W m-2)

Figure 2.9

- Long-Lived Greenhouse Gases (LLGHGs):

  Use the observed record, together with radiative transfer calculations, to determine the Radiative Forcing.

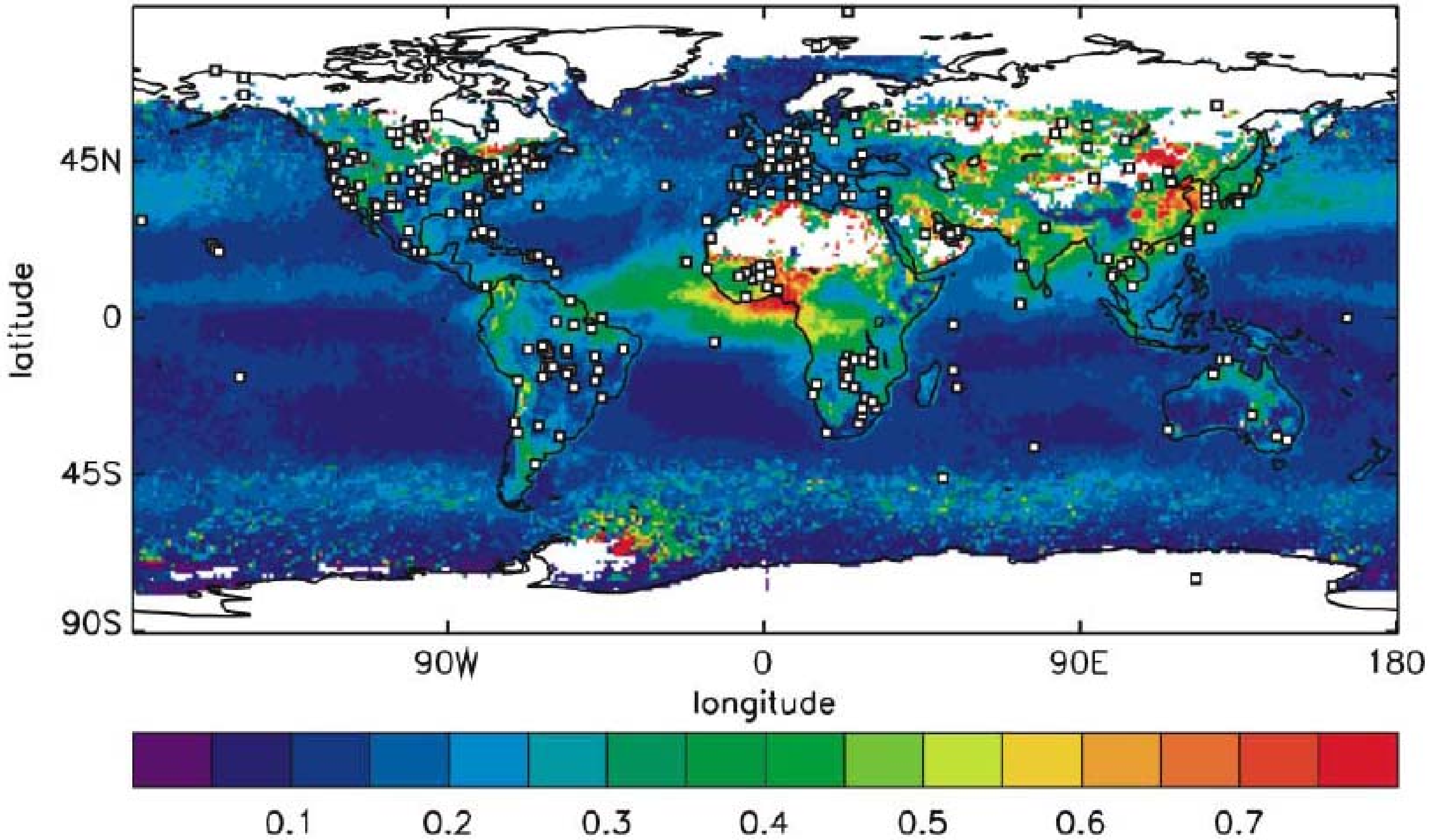
- For other species e.g., aerosols, tropospheric ozone, observations are less extensive, there is more spatial inhomogeneity.

  Other methods e.g., three-dimensional chemistry-transport models, together with relevant observations, used to determine the Radiative Forcing.

Since the TAR, improved understanding and better quantification of the forcing mechanisms

Total aerosol optical depth (natural+anthropogenic components) at mid-visible wavelength, from satellite instruments, and complemented by two different kinds of ground-based measurements [Figure TS-4 (top)]

January to March, 2001



- **Observations reveal the presence and provide quantitative aspects.**
- **Aerosol transport-forcing models better tested and constrained.**

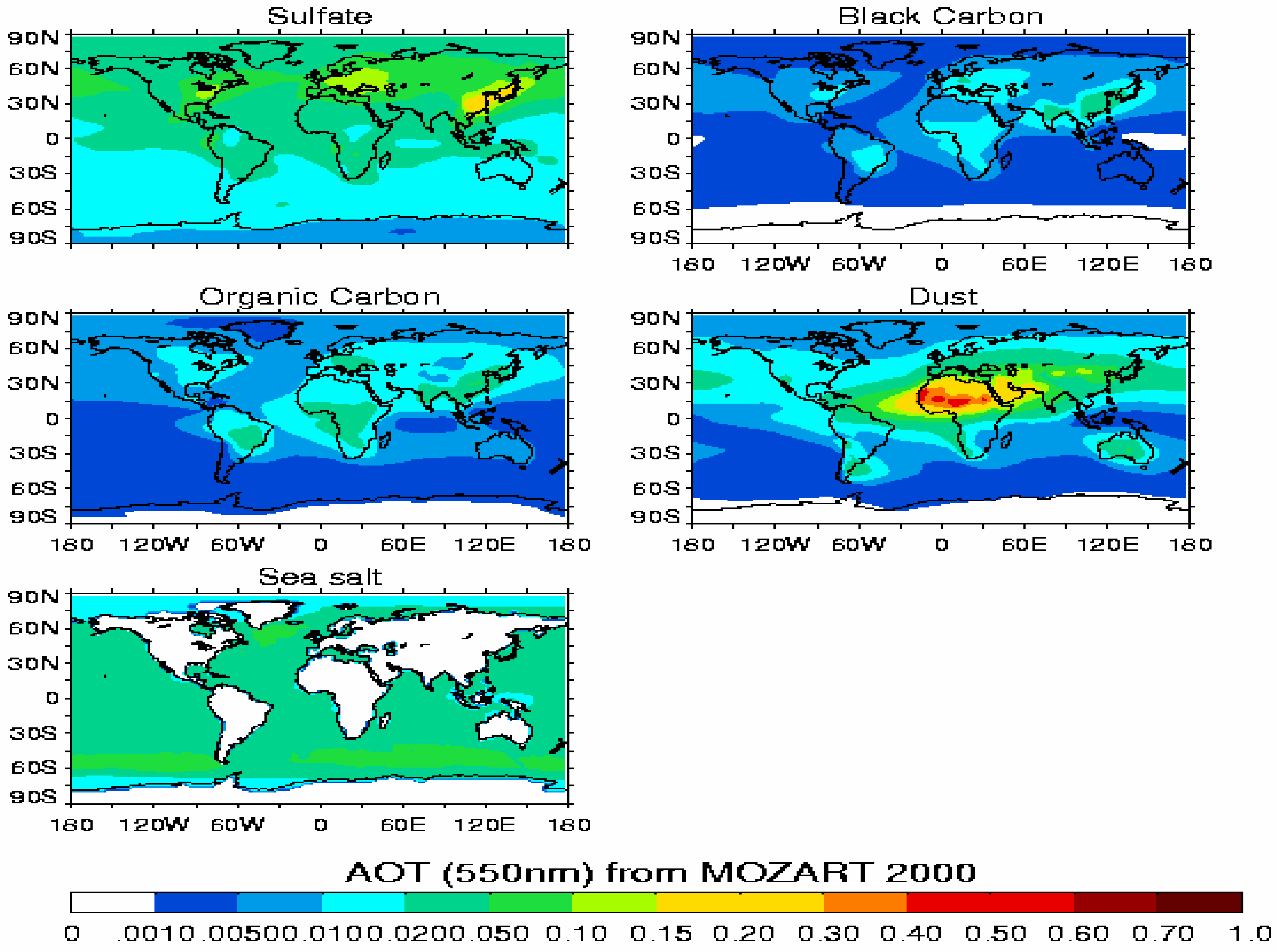
➔ More improved estimate of the Aerosol Direct Radiative Forcing.

- Global observations available only over the past approximately 25 years.
- Models used that describe the transport and distribution of aerosols based on natural and anthropogenic emissions.

Aerosol species:

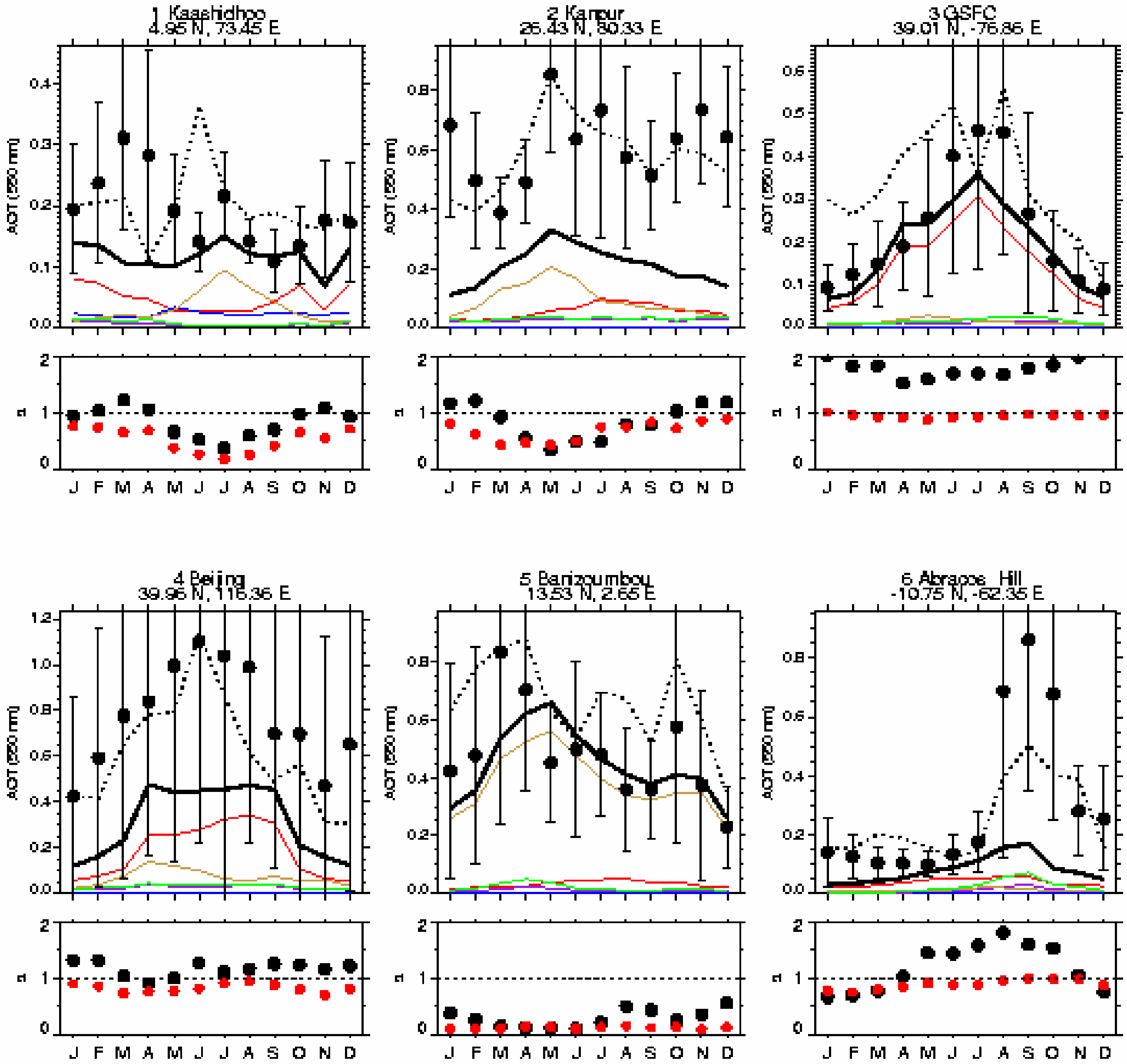
Sulphate, nitrate, fossil fuel organic carbon, fossil fuel black carbon, biomass burning, mineral dust, sea salt

(‘red’ = significant anthropogenic component)



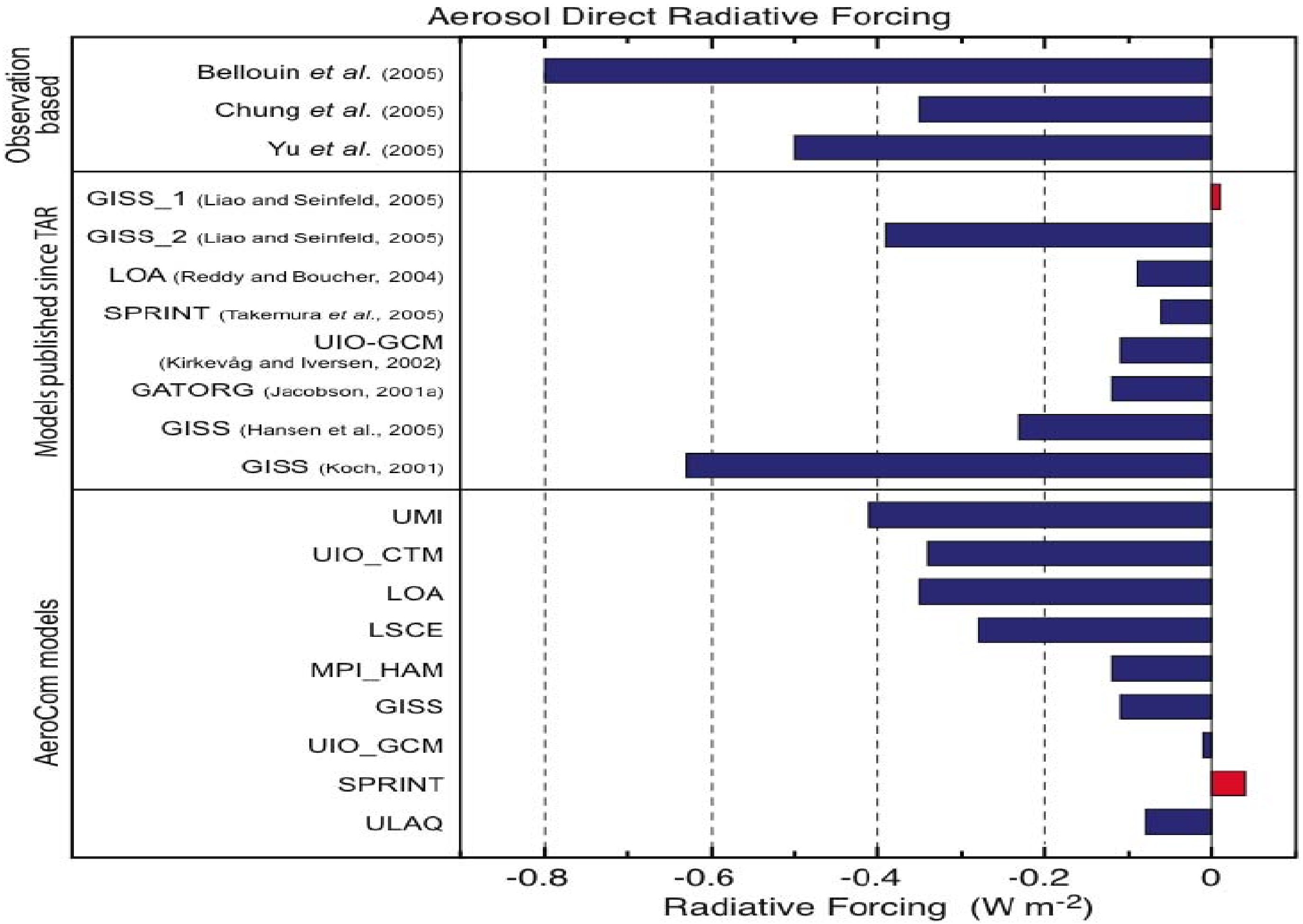
Sulfate
Black Carbon
Organic Carbon
Dust
Sea salt
90N
60N
30N
0
30S
60S
90S
180
120W
60W
0
60E
120E
180
AOT (550nm) from MOZART 2000
0
.0010
.0050
.0100
.0200
.050
0.10
0.15
0.20
0.30
0.40
0.50
0.60
0.70
1.0

Aerosol Optical Depth: Simulation vs. AERONET, MODIS



Ginoux et al. (2006)

Estimates of the Aerosol Direct Radiative Forcing (sulphate, fossil fuel black and organic carbon, biomass burning, dust and nitrate) from different models [Fig. 2.13]



Best estimate
-0.5 W/m^2

Range:
-0.9 to -0.1 W/m^2

More models that contain aerosol species beyond sulphate

Observations used to apply constraints to combined aerosol direct radiative forcing

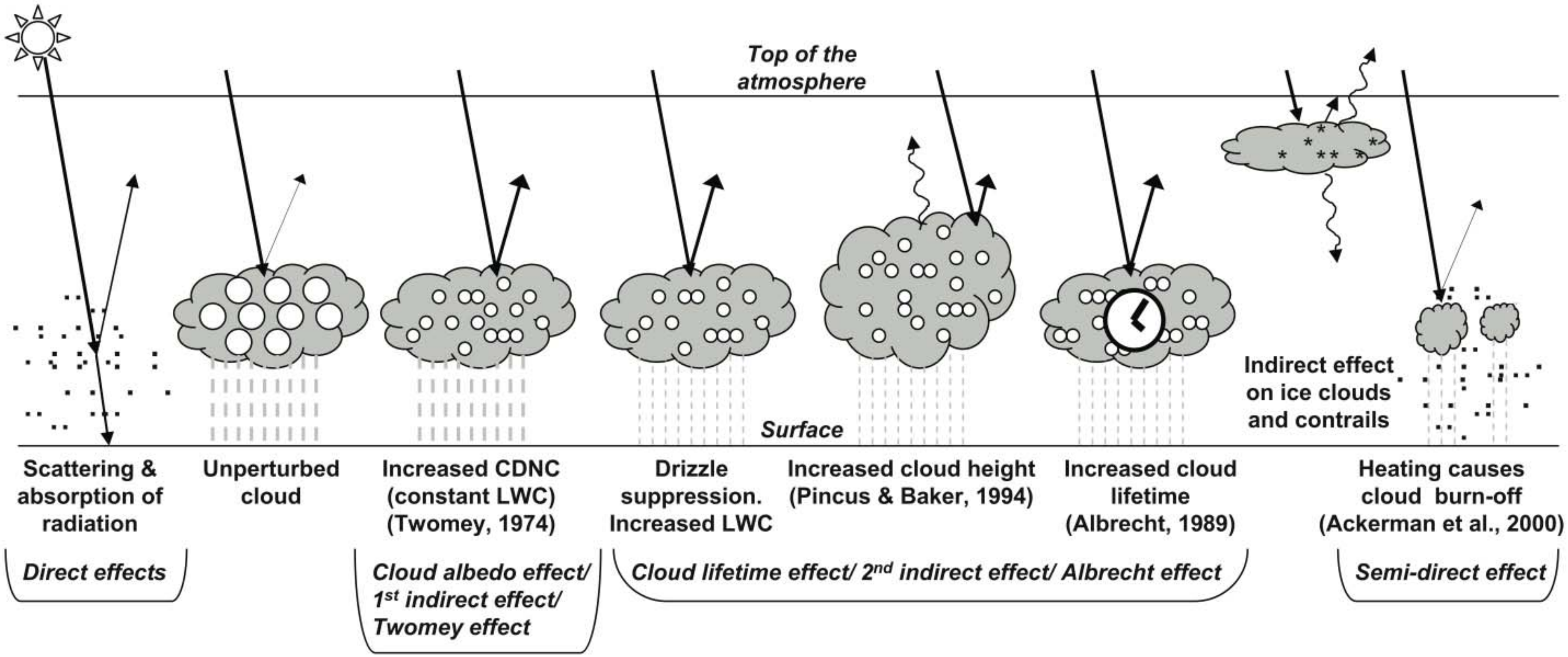
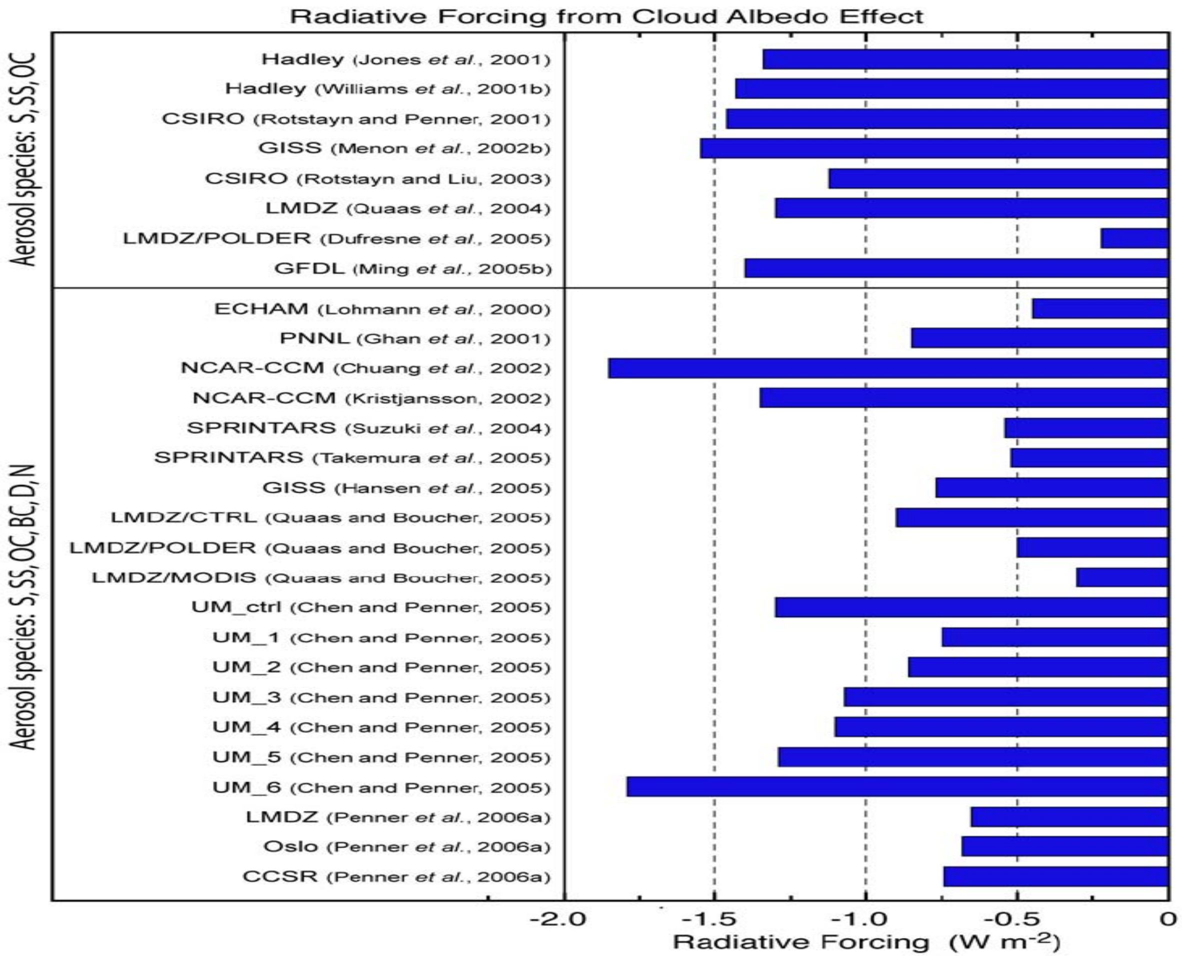

Top of the atmosphere
Surface
Indirect effect on ice clouds and contrails
Scattering & absorption of radiation
Unperturbed cloud
Increased CDNC (constant LWC) (Twomey, 1974)
Drizzle suppression. Increased LWC
Increased cloud height (Pincus & Baker, 1994)
Increased cloud lifetime (Albrecht, 1989)
Heating causes cloud burn-off (Ackerman et al., 2000)
Direct effects
Cloud albedo effect/ 1st indirect effect/ Twomey effect
Cloud lifetime effect/ 2nd indirect effect/ Albrecht effect
Semi-direct effect

Figure 2.10

Estimates of the Cloud Albedo radiative forcing due to aerosols from different models [Figure 2.14]

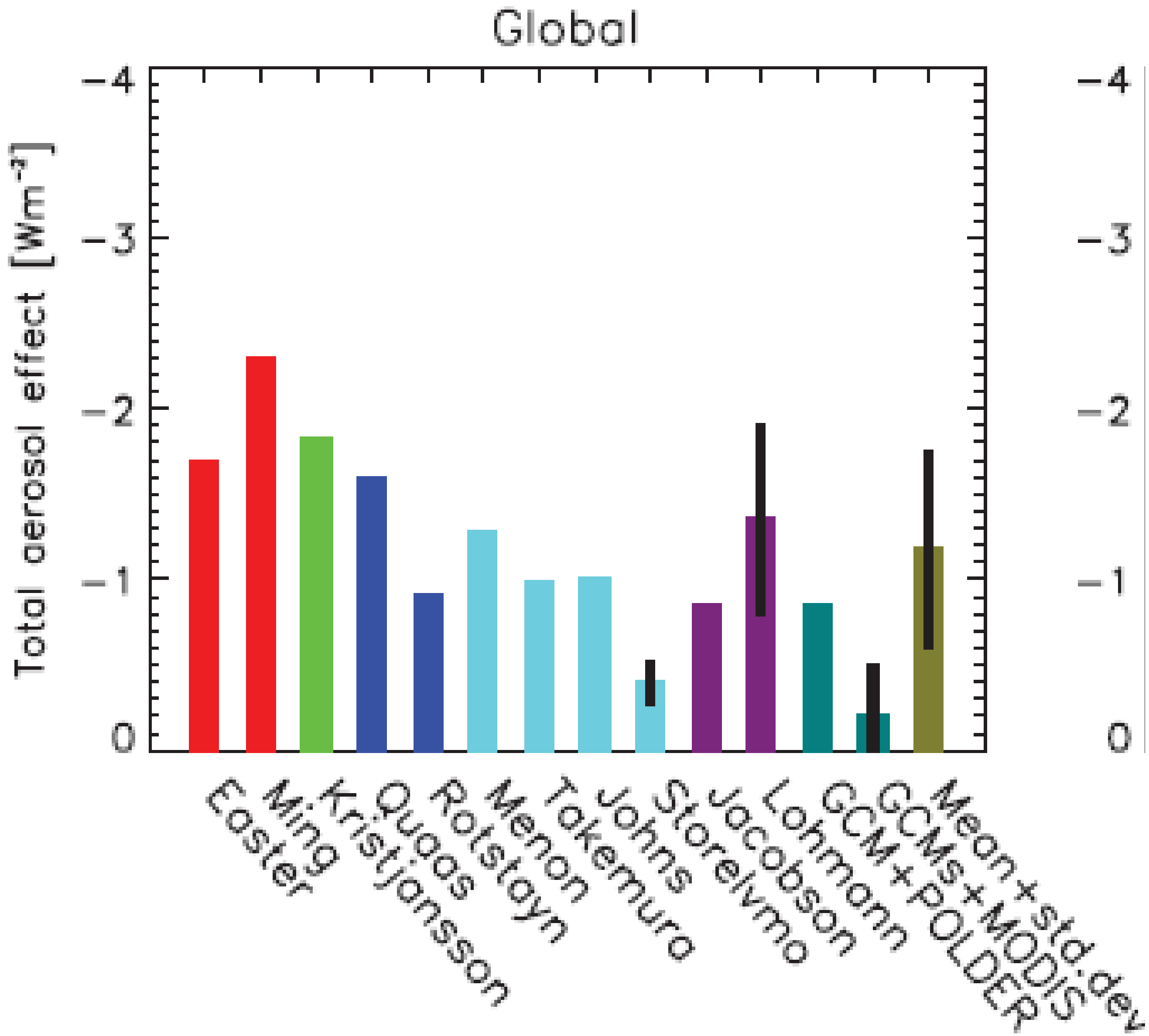


Best estimate:
-0.7 W/m^2

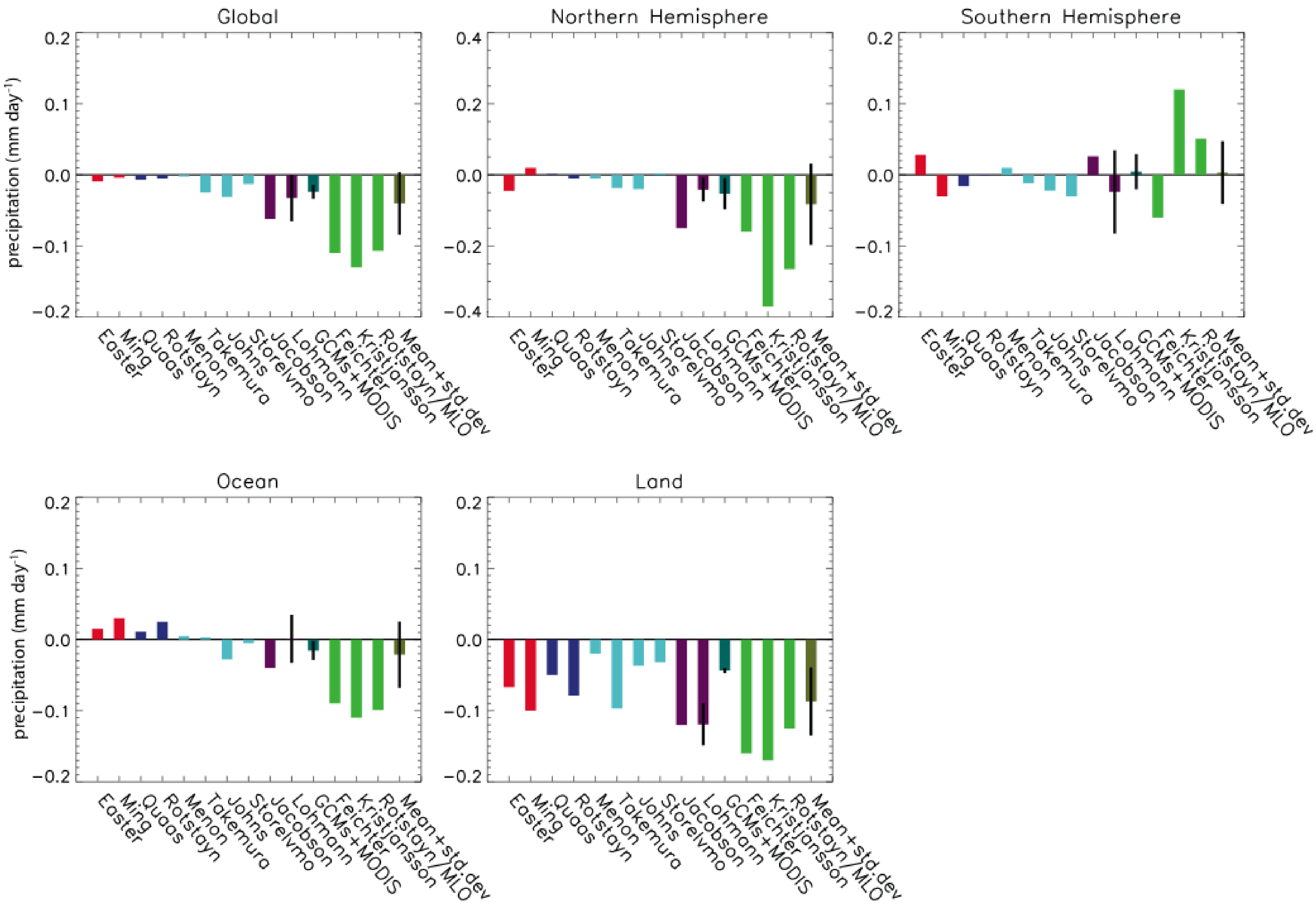
Range:
-1.8 to -0.3 W/m^2

More model studies since the TAR, many include more species

Those with more aerosol species or constrained by satellite observations have a weaker radiative forcing



Global
Total aerosol effect [Wm⁻²]
-4
-3
-2
-1
0
Easter
Ming
Kristjansson
Quaas
Rotstayn
Menon
Takemura
Johns
Storelvmo
Jacobson
Lohmann
GCM+POLDER
GCMs+MODIS
Mean+std.dev



Global
Northern Hemisphere
Southern Hemisphere
Ocean
Land
precipitation (mm day⁻¹)
0.2
0.1
0.0
−0.1
−0.2
0.4
−0.4
Easter
Ming
Quaas
Rotstayn
Menon
Takemura
Johns
Storelvmo
Jacobson
Lohmann
GCMs+MODIS
Feichter
Kristjansson
Rotstayn/MLO
Mean+std.dev

Figure 7.22

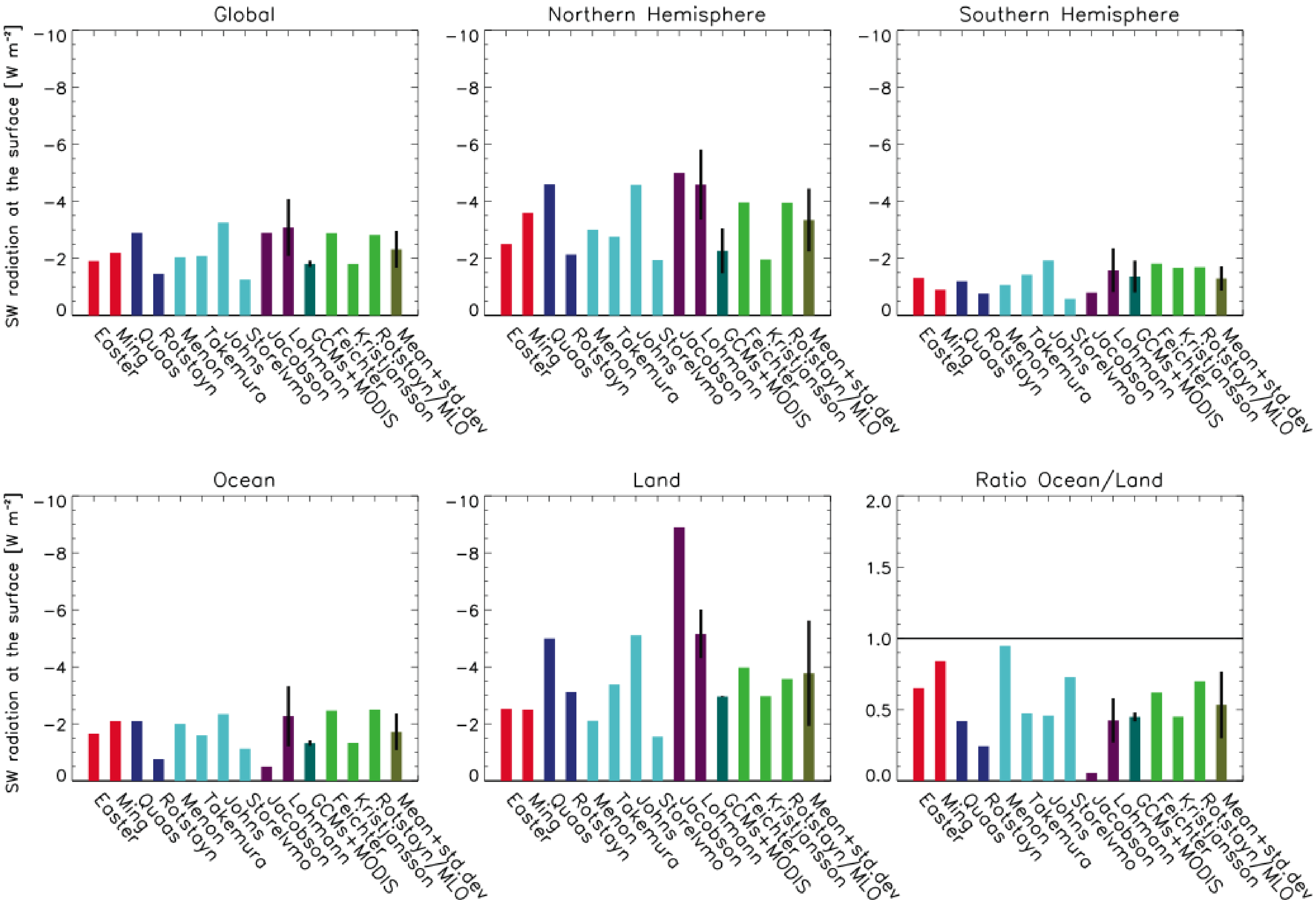

Global
Northern Hemisphere
Southern Hemisphere
Ocean
Land
Ratio Ocean/Land
SW radiation at the surface [W m⁻²]
Easter
Ming
Quaas
Rotstayn
Menon
Takemura
Johns
Storelvmo
Jacobson
Lohmann
GCMs+MODIS
Feichter
Kristjansson
Rotstayn/MLO
Mean+std.dev

Figure 7.23

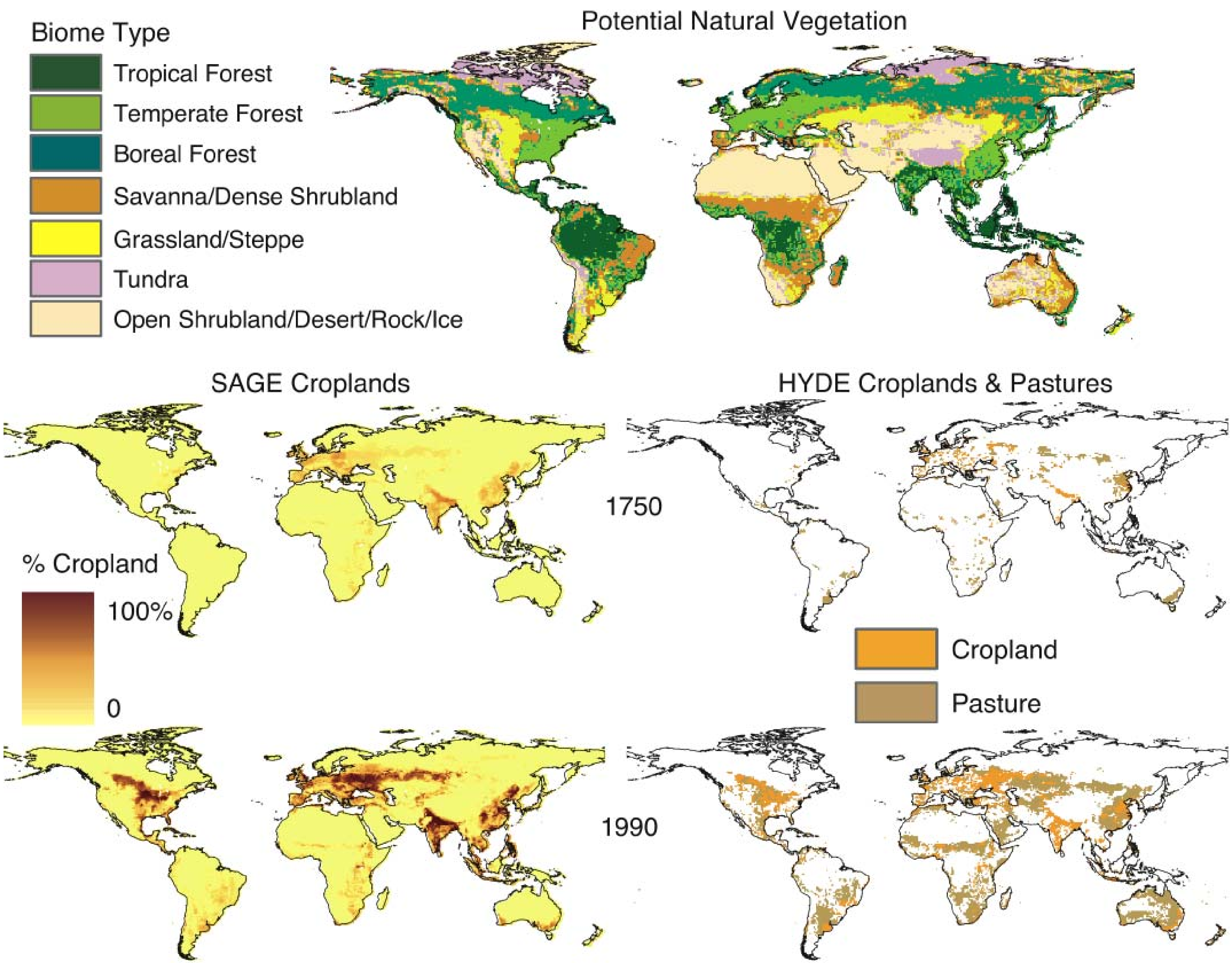

Potential Natural Vegetation
Biome Type
Tropical Forest
Temperate Forest
Boreal Forest
Savanna/Dense Shrubland
Grassland/Steppe
Tundra
Open Shrubland/Desert/Rock/Ice
SAGE Croplands
HYDE Croplands & Pastures
1750
% Cropland
100%
0
Cropland
Pasture
1990

Figure 2.15

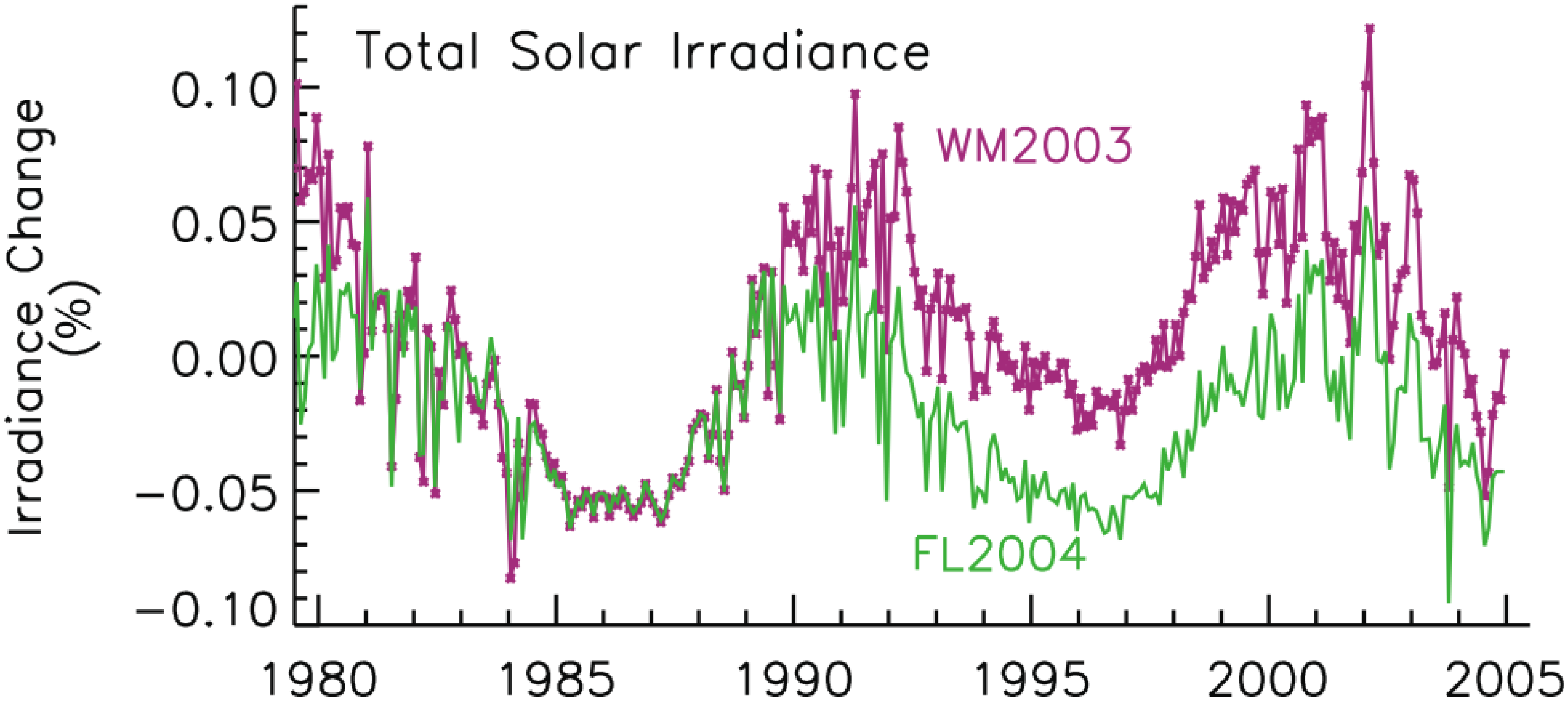
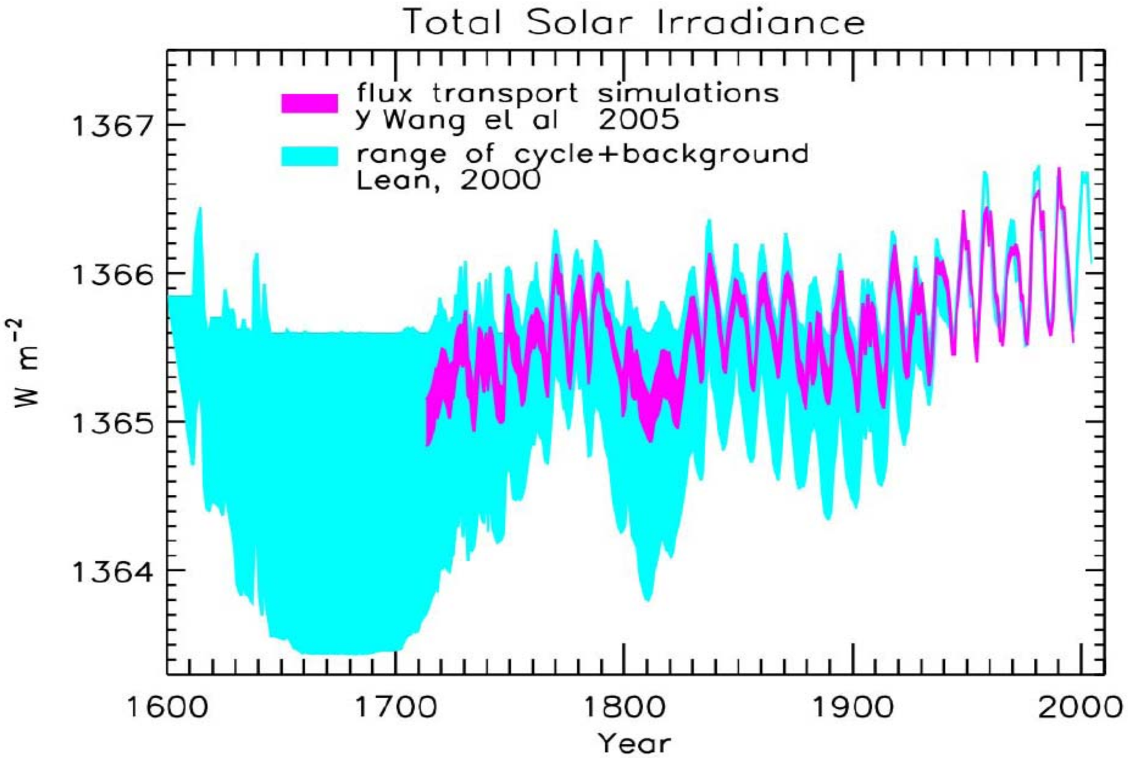

Total Solar Irradiance
WM2003
FL2004
Irradiance Change
(%)
0.10
0.05
0.00
−0.05
−0.10
1980
1985
1990
1995
2000
2005

Figure 2.16

Reconstruction of the Total Solar Irradiance [Figure 2.17]



Best estimate: 0.12 W/m^2

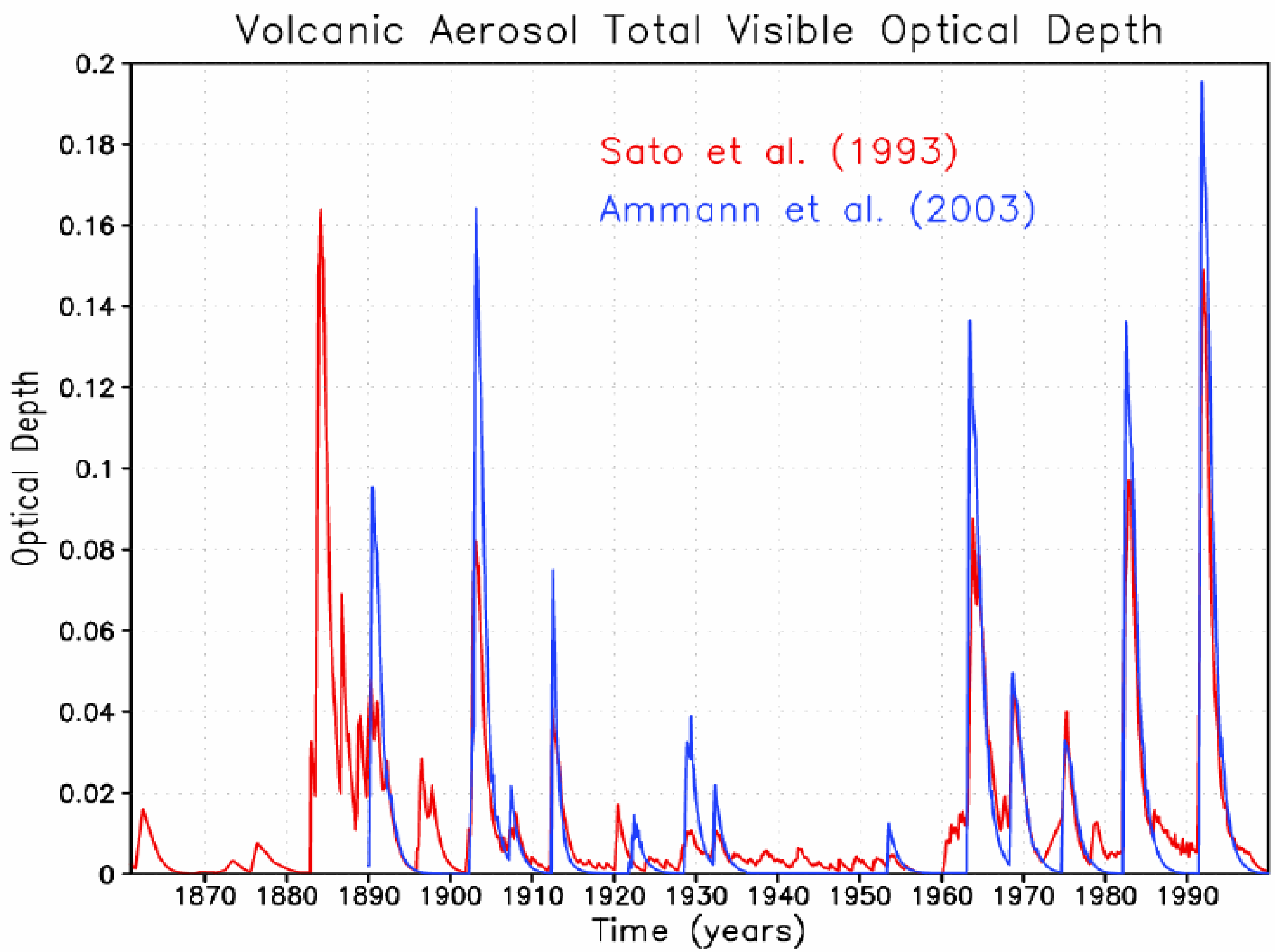
Range: 0.06 to 0.30 W/m^2

New reconstruction yields smaller solar radiative forcing estimate than in the TAR - based on: a) solar magnetic flux model rather than proxy data; b) better understanding of recent variations; c) re-evaluation of variations in Sun-like stars

Revised solar radiative forcing much smaller than long-lived greenhouse gas forcing since pre-industrial times

Solar indirect effects on stratospheric ozone not included

Visible optical depth from stratospheric sulphate aerosols in the aftermath of explosive volcanic eruptions [Fig. 2.18]



➔ Explosive volcanic eruptions are episodic.

➔ Aerosols from an explosive volcanic eruption are transitory (lasting ~1-2 years).

- **Galactic cosmic rays:** Not-evaluated - no proven physical mechanism, and studies comparing with changes in global cloud cover are inconsistent.

- **Aviation:** Linear contrails radiative forcing only evaluated. Aviation induced cirrus too uncertain to quantify. Other aviation effects implicitly included in other radiative forcing terms.

- **Water vapour** is a powerful greenhouse gas, but changes are associated with the climate response/feedback and not included on the *forcing "bar-plot" [Fig. SPM-2].* Climate models include this feedback in their evaluation of temperature changes

Other points raised for clarity

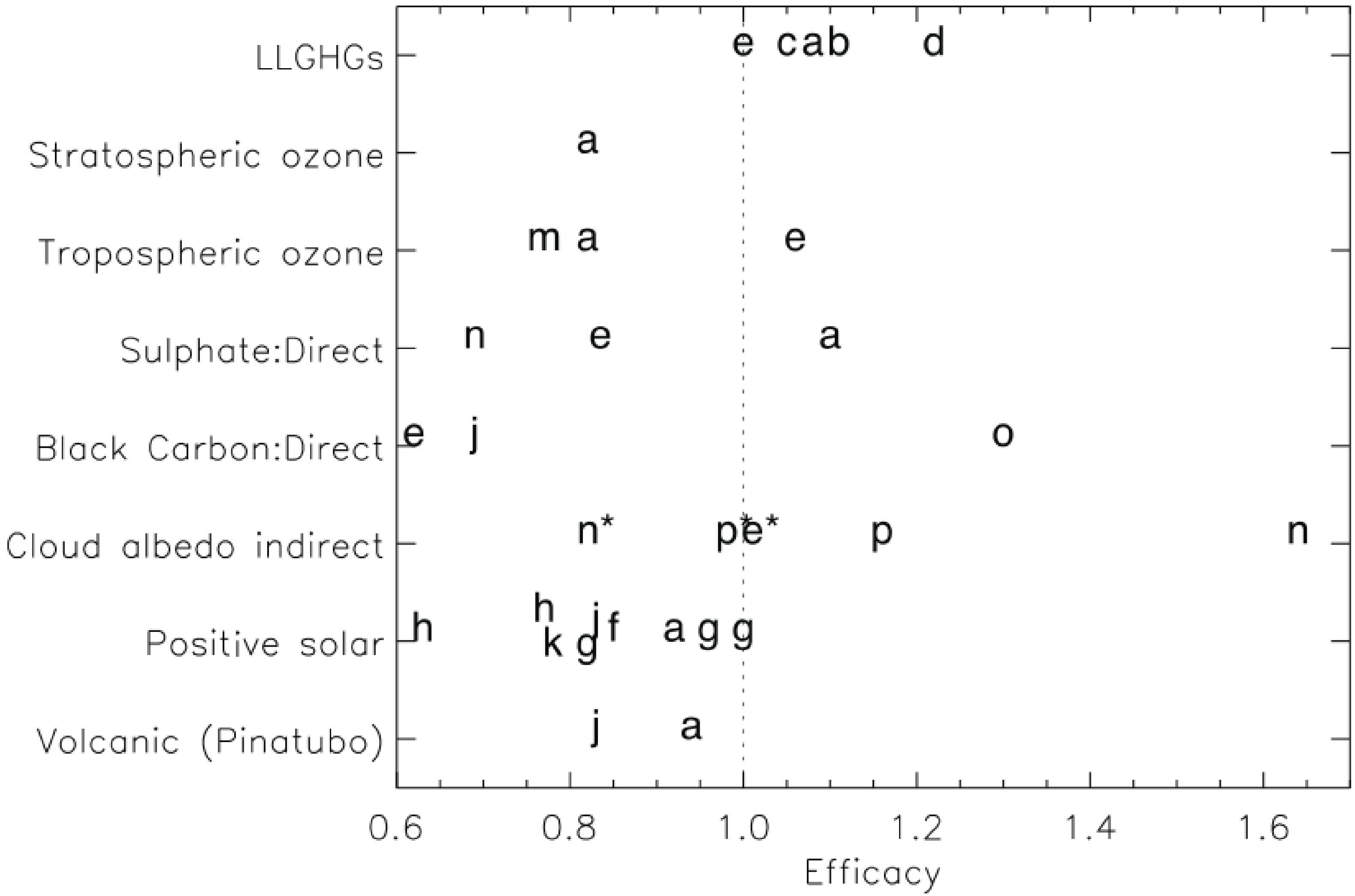

LLGHGs
Stratospheric ozone
Tropospheric ozone
Sulphate:Direct
Black Carbon:Direct
Cloud albedo indirect
Positive solar
Volcanic (Pinatubo)
e cab d
a
m a e
n e a
e j o
n* pe* p n
h h j f a g g k g
j a
0.6
0.8
1.0
1.2
1.4
1.6
Efficacy

Figure 2.19

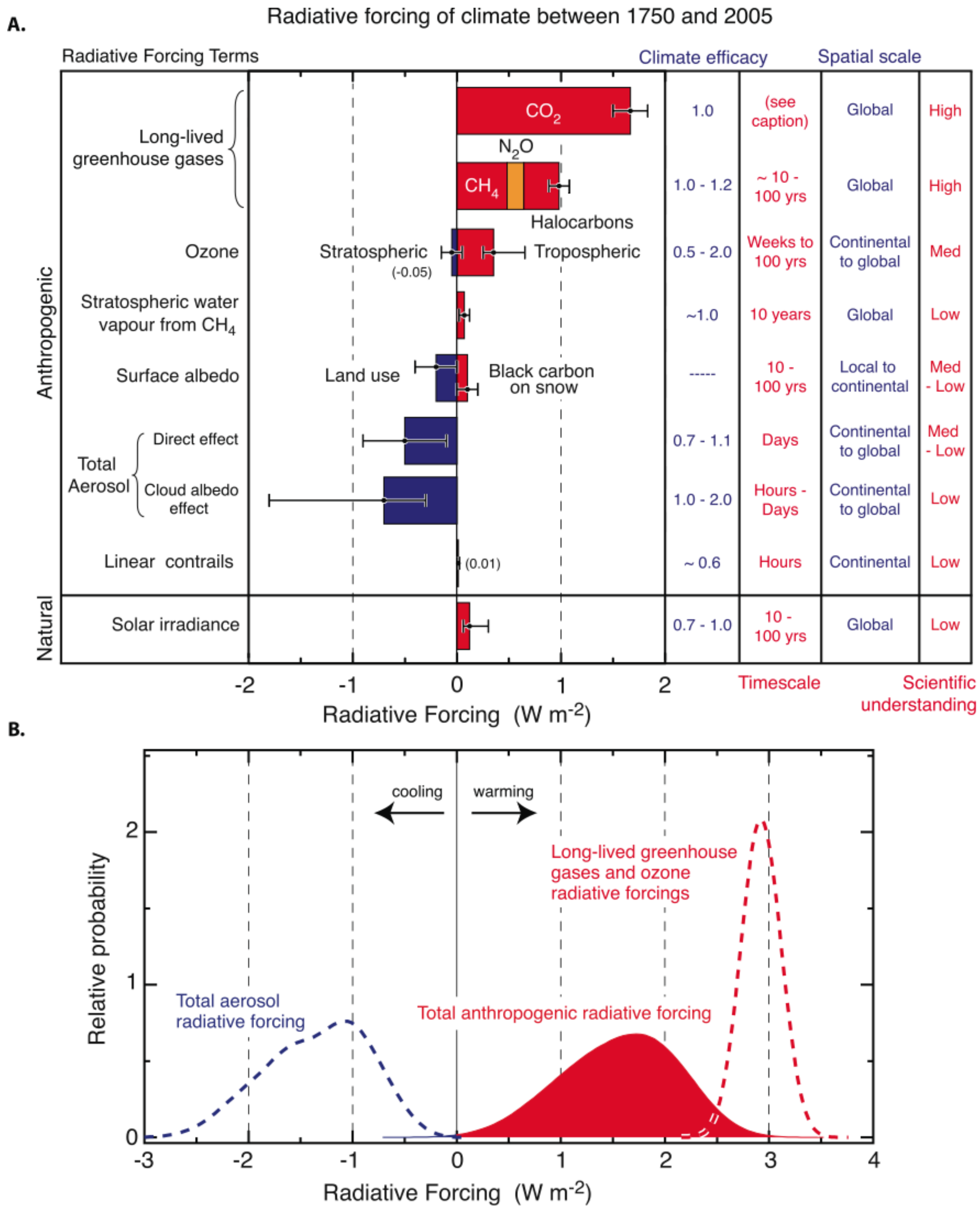

A.
Radiative forcing of climate between 1750 and 2005
Radiative Forcing Terms
Climate efficacy
Spatial scale
Long-lived greenhouse gases
CO2
1.0
(see caption)
Global
High
N2O
CH4
Halocarbons
1.0 - 1.2
~ 10 - 100 yrs
Global
High
Ozone
Stratospheric
(-0.05)
Tropospheric
0.5 - 2.0
Weeks to 100 yrs
Continental to global
Med
Stratospheric water vapour from CH4
~1.0
10 years
Global
Low
Surface albedo
Land use
Black carbon on snow
-----
10 - 100 yrs
Local to continental
Med - Low
Total Aerosol
Direct effect
0.7 - 1.1
Days
Continental to global
Med - Low
Cloud albedo effect
1.0 - 2.0
Hours - Days
Continental to global
Low
Linear contrails
(0.01)
~ 0.6
Hours
Continental
Low
Solar irradiance
0.7 - 1.0
10 - 100 yrs
Global
Low
Anthropogenic
Natural
-2
-1
0
1
2
Radiative Forcing (W m-2)
Timescale
Scientific understanding
B.
cooling
warming
Long-lived greenhouse gases and ozone radiative forcings
Total aerosol radiative forcing
Total anthropogenic radiative forcing
Relative probability
0
1
2
-3
-2
-1
0
1
2
3
4
Radiative Forcing (W m-2)

Figure 2.20

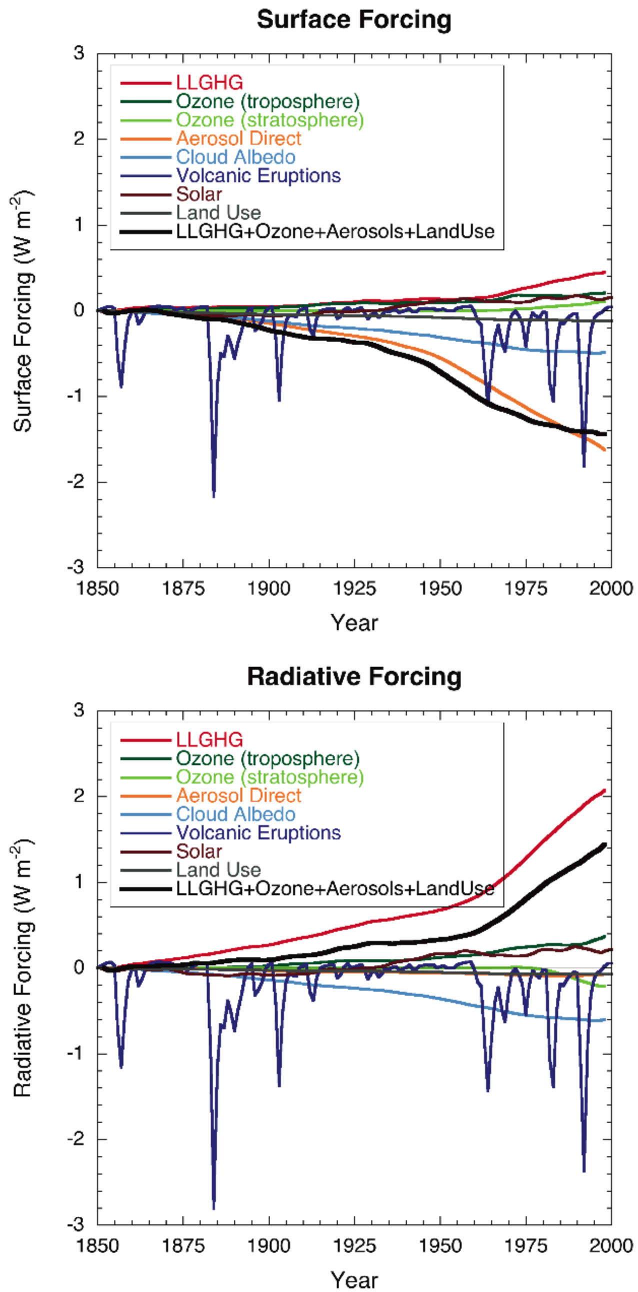
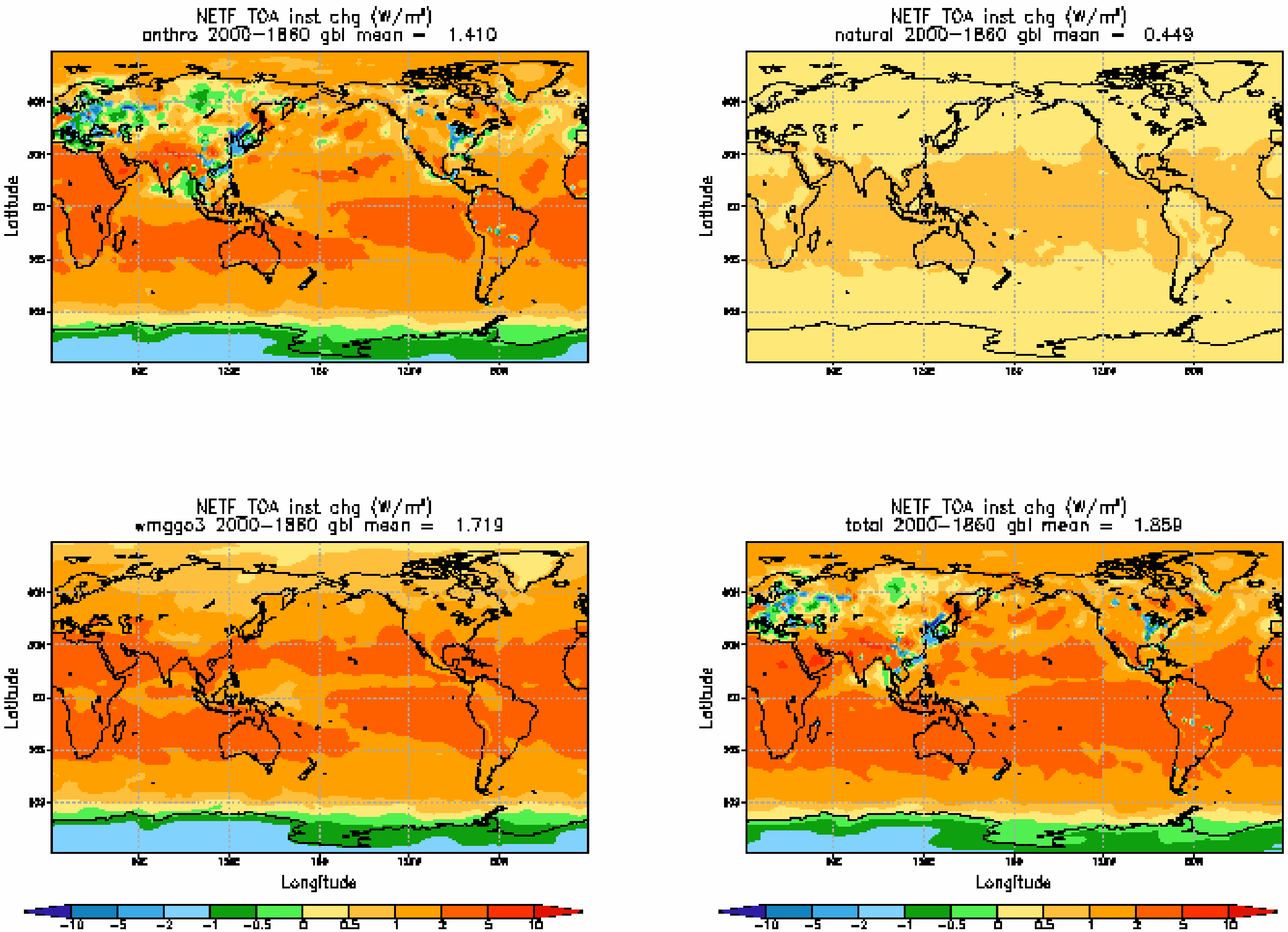
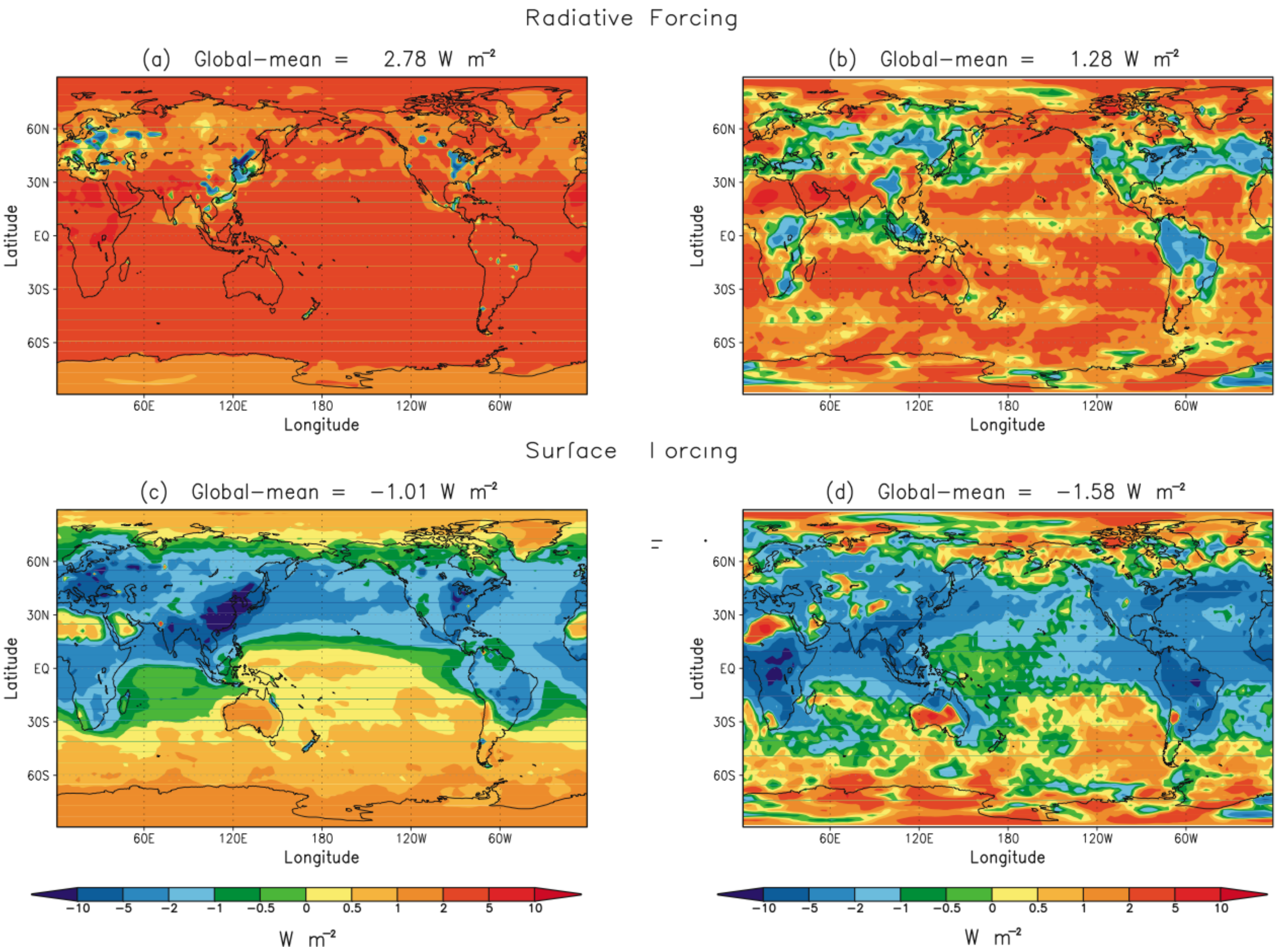

Surface Forcing
LLGHG
Ozone (troposphere)
Ozone (stratosphere)
Aerosol Direct
Cloud Albedo
Volcanic Eruptions
Solar
Land Use
LLGHG+Ozone+Aerosols+LandUse
Surface Forcing (W m-2)
Year
Radiative Forcing
LLGHG
Ozone (troposphere)
Ozone (stratosphere)
Aerosol Direct
Cloud Albedo
Volcanic Eruptions
Solar
Land Use
LLGHG+Ozone+Aerosols+LandUse
Radiative Forcing (W m-2)
Year

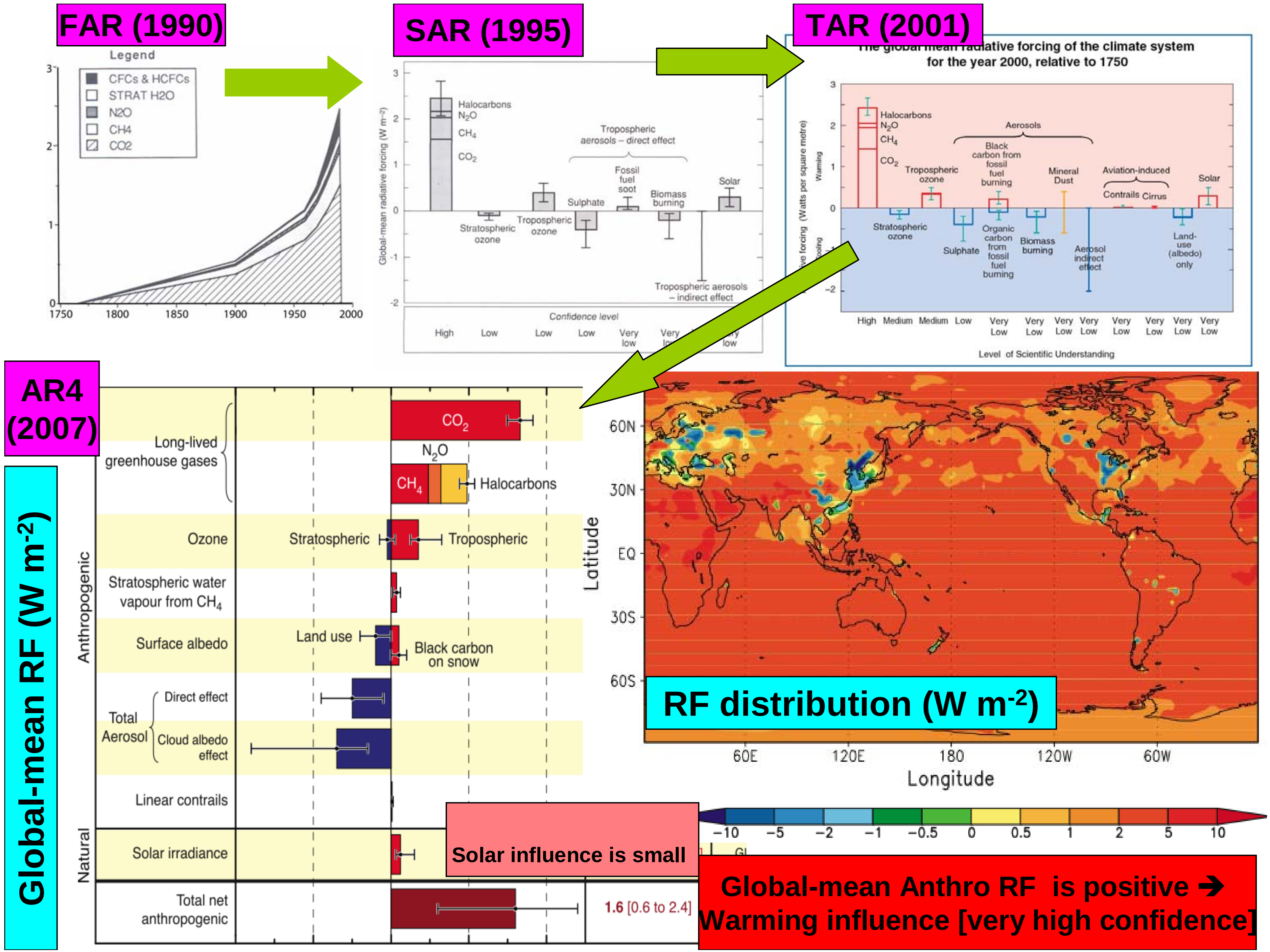
Figure 2.23


NETF_TOA inst chg (W/m²)
anthro 2000–1860 gbl mean = 1.410
Latitude
NETF_TOA inst chg (W/m²)
natural 2000–1860 gbl mean = 0.449
Latitude
NETF_TOA inst chg (W/m²)
wmggo3 2000–1860 gbl mean = 1.719
Latitude
Longitude
NETF_TOA inst chg (W/m²)
total 2000–1860 gbl mean = 1.859
Latitude
Longitude
−10 −5 −2 −1 −0.5 0 0.5 1 2 5 10
−10 −5 −2 −1 −0.5 0 0.5 1 2 5 10



Radiative Forcing
(a) Global-mean = 2.78 W m⁻²
(b) Global-mean = 1.28 W m⁻²
Surface Forcing
(c) Global-mean = −1.01 W m⁻²
(d) Global-mean = −1.58 W m⁻²
Latitude
Longitude
60N
30N
EQ
30S
60S
60E
120E
180
120W
60W
−10 −5 −2 −1 −0.5 0 0.5 1 2 5 10
W m⁻²

Figure 2.24



FAR (1990)
Legend
CFCs & HCFCs
STRAT H2O
N2O
CH4
CO2
1750
1800
1850
1900
1950
2000
SAR (1995)
Global-mean radiative forcing (W m⁻²)
Halocarbons
N2O
CH4
CO2
Tropospheric aerosols – direct effect
Fossil fuel soot
Biomass burning
Solar
Sulphate
Stratospheric ozone
Tropospheric ozone
Tropospheric aerosols – indirect effect
Confidence level
High
Low
Very low
TAR (2001)
The global mean radiative forcing of the climate system for the year 2000, relative to 1750
Halocarbons
N2O
CH4
CO2
Aerosols
Black carbon from fossil fuel burning
Mineral Dust
Aviation-induced
Contrails
Cirrus
Solar
Tropospheric ozone
Stratospheric ozone
Sulphate
Organic carbon from fossil fuel burning
Biomass burning
Aerosol indirect effect
Land-use (albedo) only
High
Medium
Low
Very Low
Level of Scientific Understanding
AR4 (2007)
Global-mean RF (W m-2)
Anthropogenic
Natural
Long-lived greenhouse gases
CO2
N2O
CH4
Halocarbons
Ozone
Stratospheric
Tropospheric
Stratospheric water vapour from CH4
Surface albedo
Land use
Black carbon on snow
Total Aerosol
Direct effect
Cloud albedo effect
Linear contrails
Solar irradiance
Total net anthropogenic
1.6 [0.6 to 2.4]
Solar influence is small
60N
30N
EQ
30S
60S
Latitude
60E
120E
180
120W
60W
Longitude
RF distribution (W m-2)
−10
−5
−2
−1
−0.5
0
0.5
1
2
5
10
Global-mean Anthro RF is positive ➔ Warming influence [very high confidence]

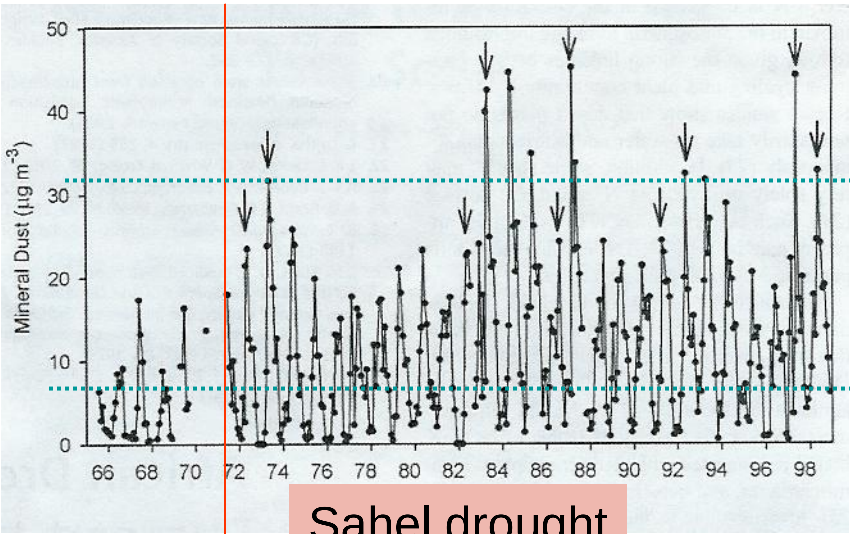
Key Issues

.....Urgent progress needed.....

- Causes of recent changes in methane growth rates
- Roles of different factors in tropospheric ozone increase
- Aerosol distributions
- Aerosol-cloud interactions
- Water vapor increases in the stratosphere
- Land-surface properties and land-atmosphere interactions.
- Solar irradiance changes on decadal-to-centuries scales.
- Emissions, concentrations and forcings in future ➔ GHGs and aerosols

Observed Variability of Dust for the last 50 Years

Dust concentration at Barbados (Prospero and Lamb, 2003)

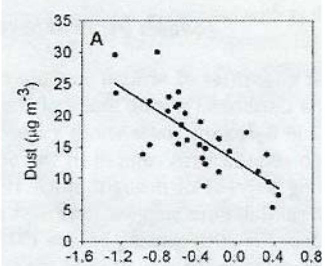


Factor 4 increase

Sahel drought

Correlation at Barbados (Prospero and Lamb, 2003)

Barbados Dust



Sahel Precipitation Index (previous year)

Since 1970ies dust concentration in Caribbean (Prospero and Lamb, 2003) and dust deposition in French Alps (De Angelis and Gaudichet, 1991) have increased by a factor 4-5

Aerosol Indirect Effects (1^{st} and 2^{nd})

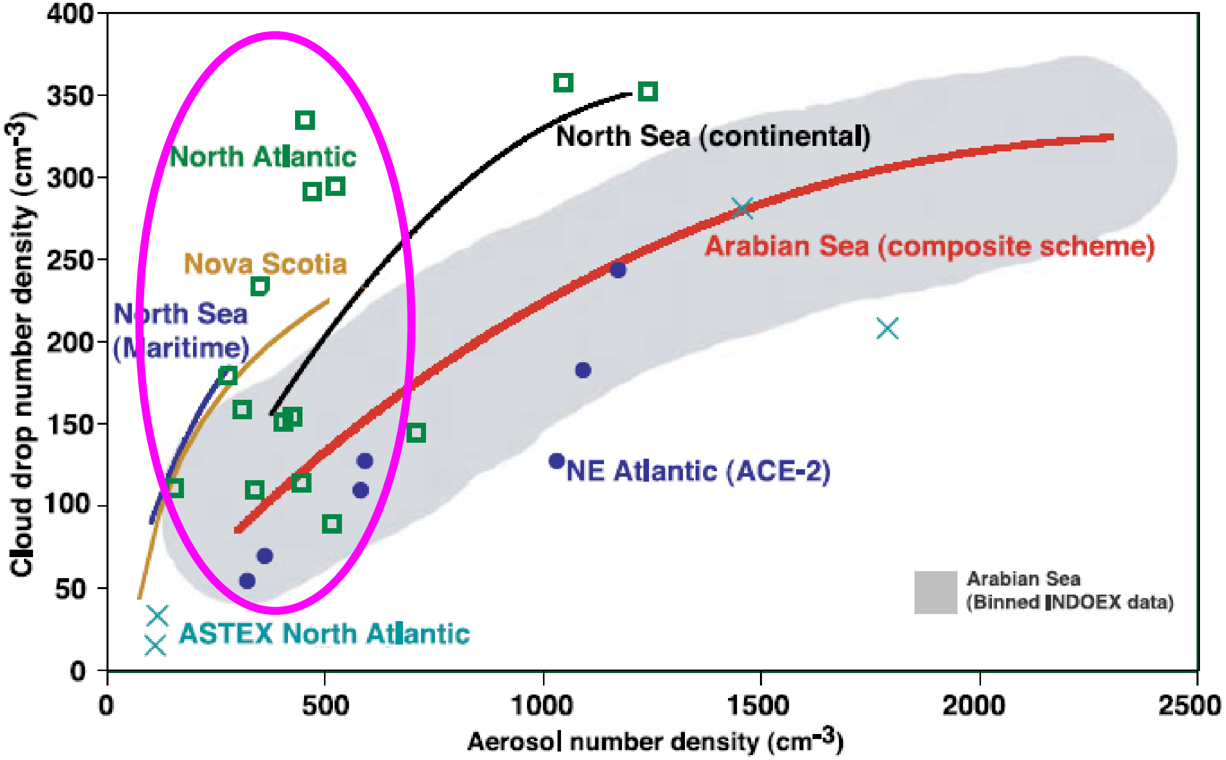
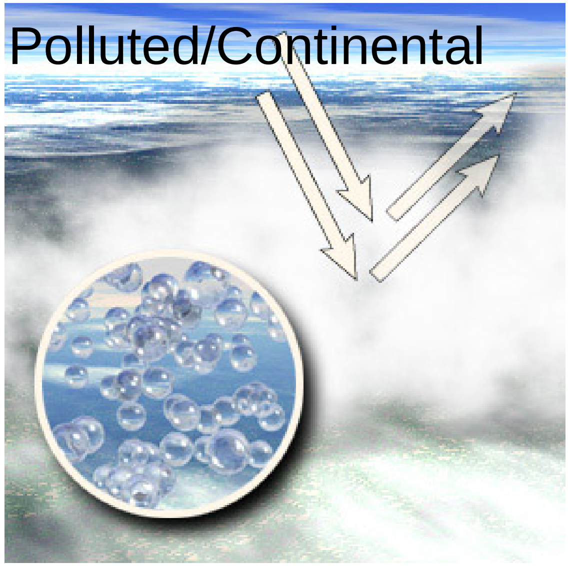


Fig. 5. Aircraft data illustrating the increase in cloud drops with aerosol number concentration. References for the data are as follows: North Sea (*28*), Nova Scotia and North Atlantic (*29*), ACE-2 (*30*), Astex (*31*), the thick red line is obtained from a composite theoretical parameterization that fits the INDOEX aircraft data for the Arabian Sea (*23*). The gray-shaded region is the INDOEX aircraft data for the Arabian Sea (*32*).



Ramanathan et al. (2001)

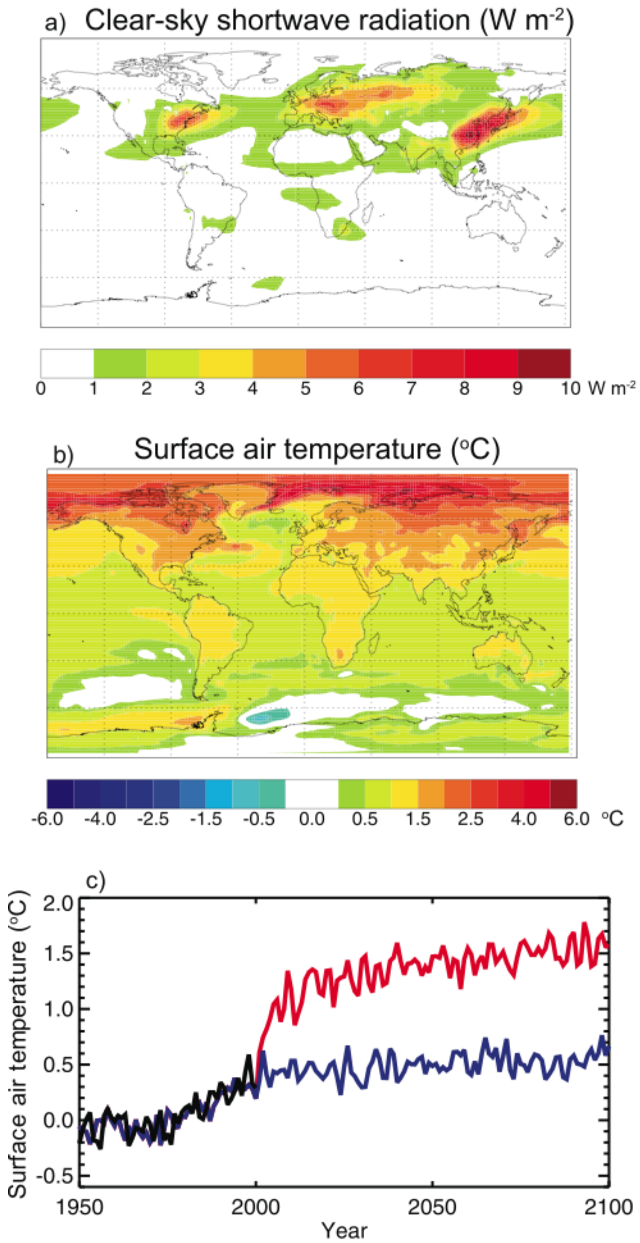
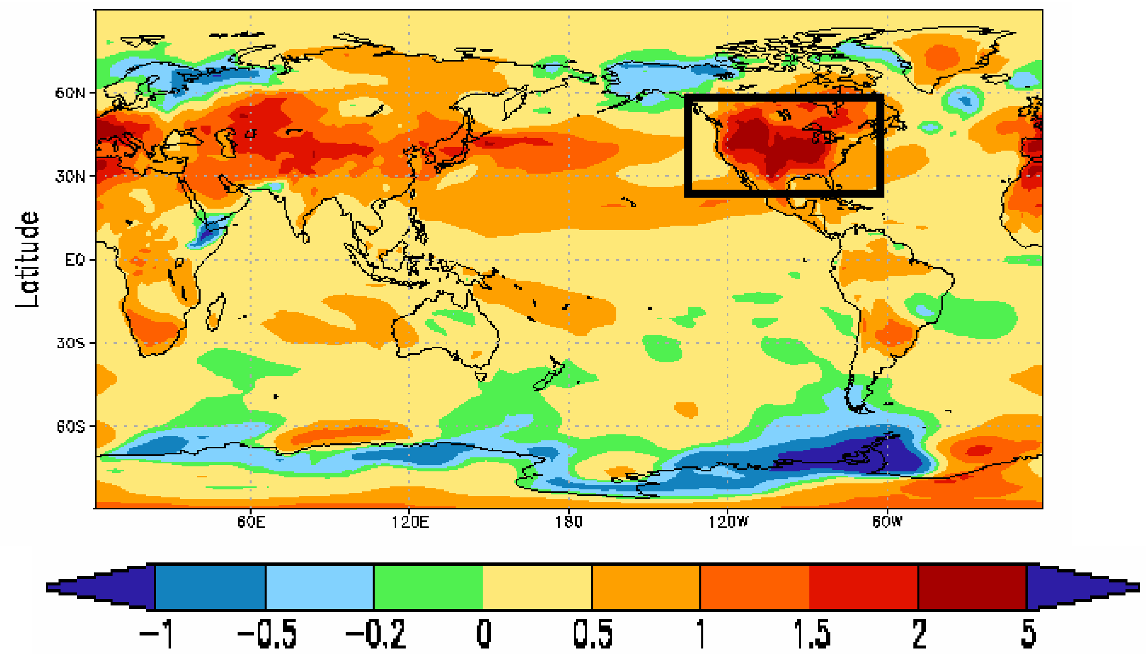

a) Clear-sky shortwave radiation (W m-2)
0 1 2 3 4 5 6 7 8 9 10 W m-2
b) Surface air temperature (°C)
-6.0 -4.0 -2.5 -1.5 -0.5 0.0 0.5 1.5 2.5 4.0 6.0 °C
c)
Surface air temperature (°C)
2.0 1.5 1.0 0.5 0.0 -0.5
1950 2000 2050 2100
Year

Figure 7.24

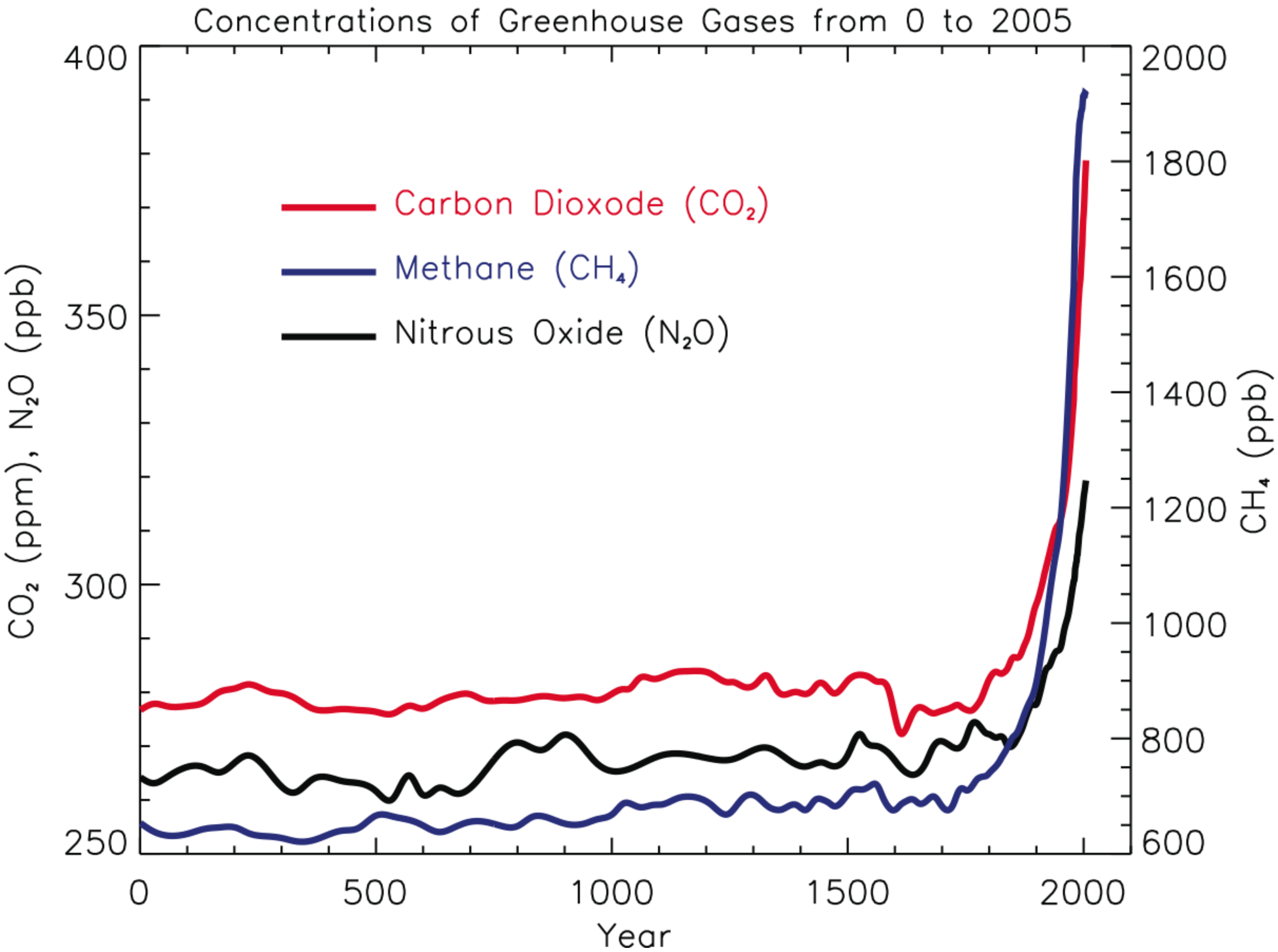
A “WIN-LOSE” CASE:
Global decreases in sulfate aerosol contribute to warmer U.S. summers

Change in Summer Temperature from 2000 to 2090 (^{0}C) resulting from projected changes in air pollutants

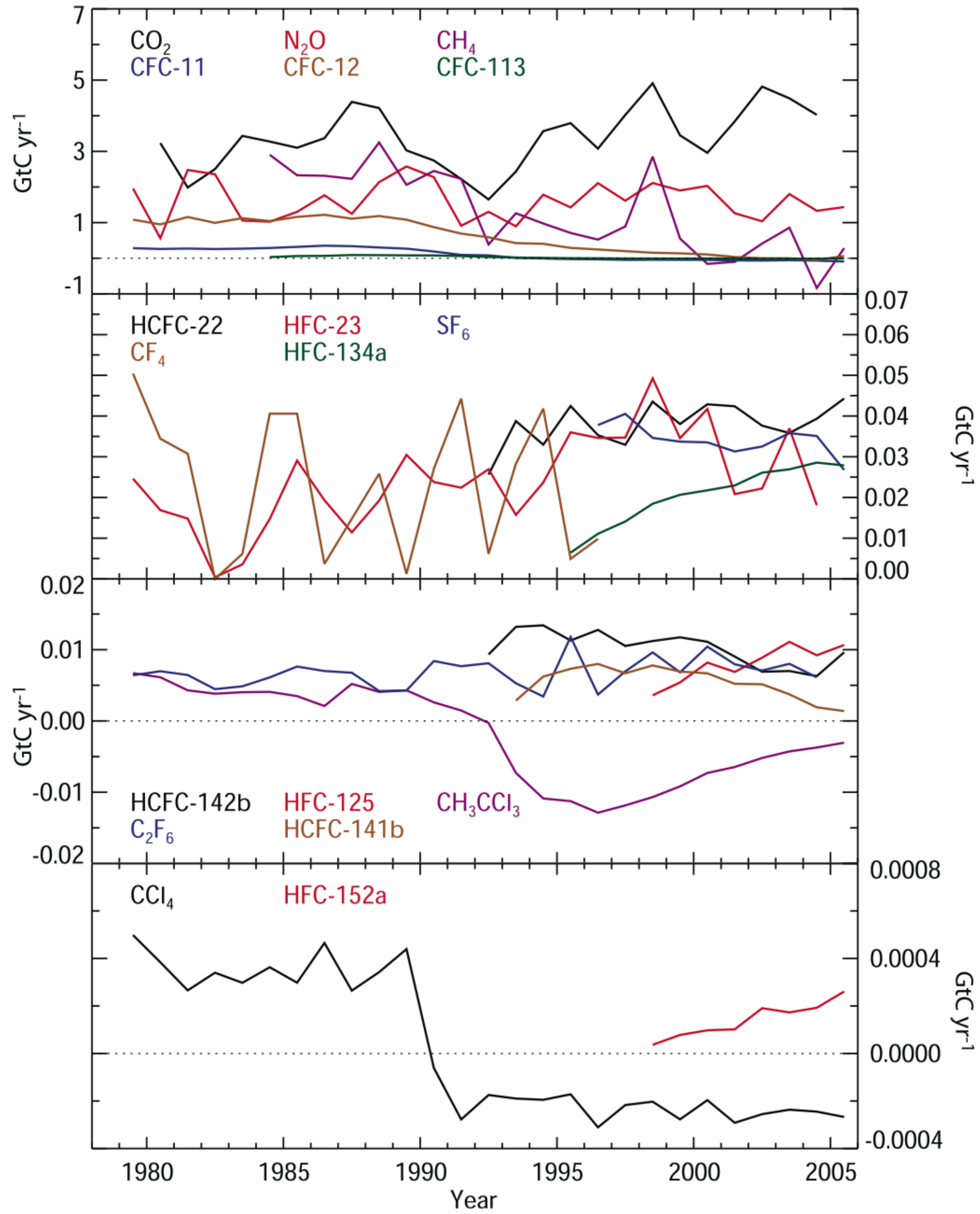


Warming over U.S. is due in part to decreases in sulfate driven by pollution control efforts (better air quality; not so for climate)

in GFDL Climate Model [Levy *et al*., JGR 2007, *in press*]



FAQ 2.1, Figure 1



CO2
N2O
CH4
CFC-11
CFC-12
CFC-113
HCFC-22
HFC-23
SF6
CF4
HFC-134a
HCFC-142b
HFC-125
CH3CCl3
C2F6
HCFC-141b
CCl4
HFC-152a
GtC yr-1
Year

Figure 2.7

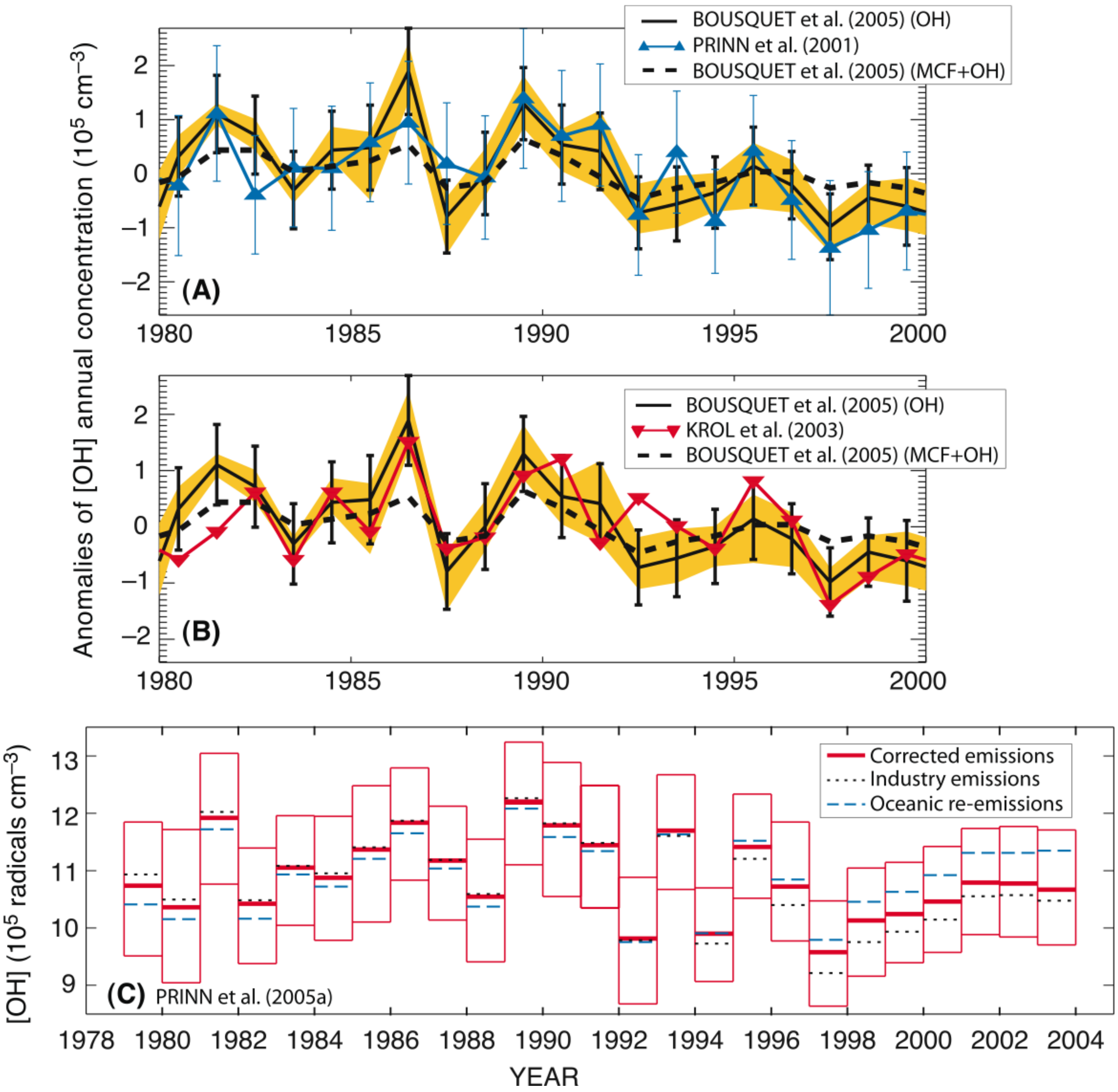
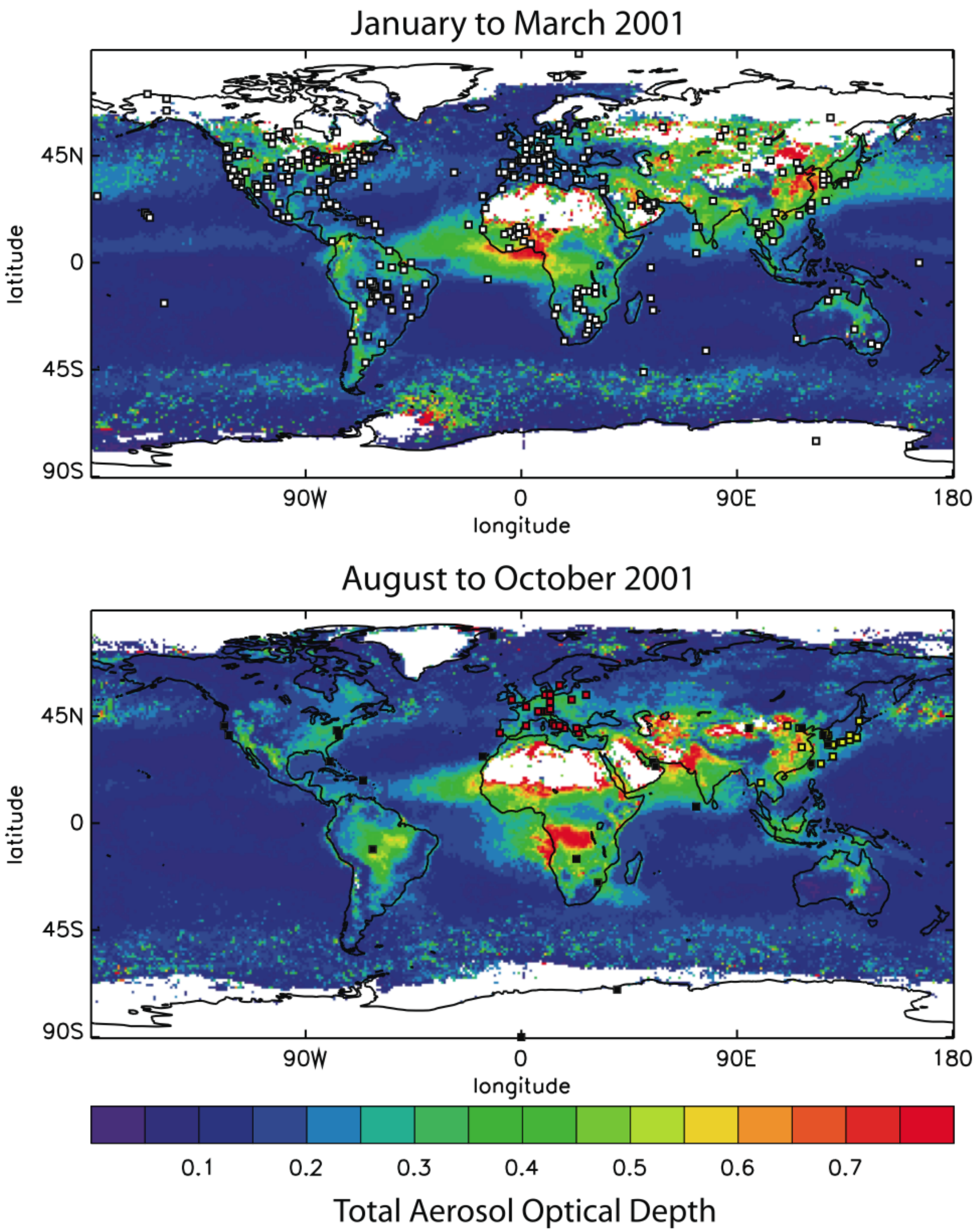

BOUSQUET et al. (2005) (OH)
PRINN et al. (2001)
BOUSQUET et al. (2005) (MCF+OH)
(A)
BOUSQUET et al. (2005) (OH)
KROL et al. (2003)
BOUSQUET et al. (2005) (MCF+OH)
(B)
Anomalies of [OH] annual concentration (10^5 cm^{-3})
1980
1985
1990
1995
2000
Corrected emissions
Industry emissions
Oceanic re-emissions
(C) PRINN et al. (2005a)
[OH] (10^5 radicals cm^{-3})
YEAR

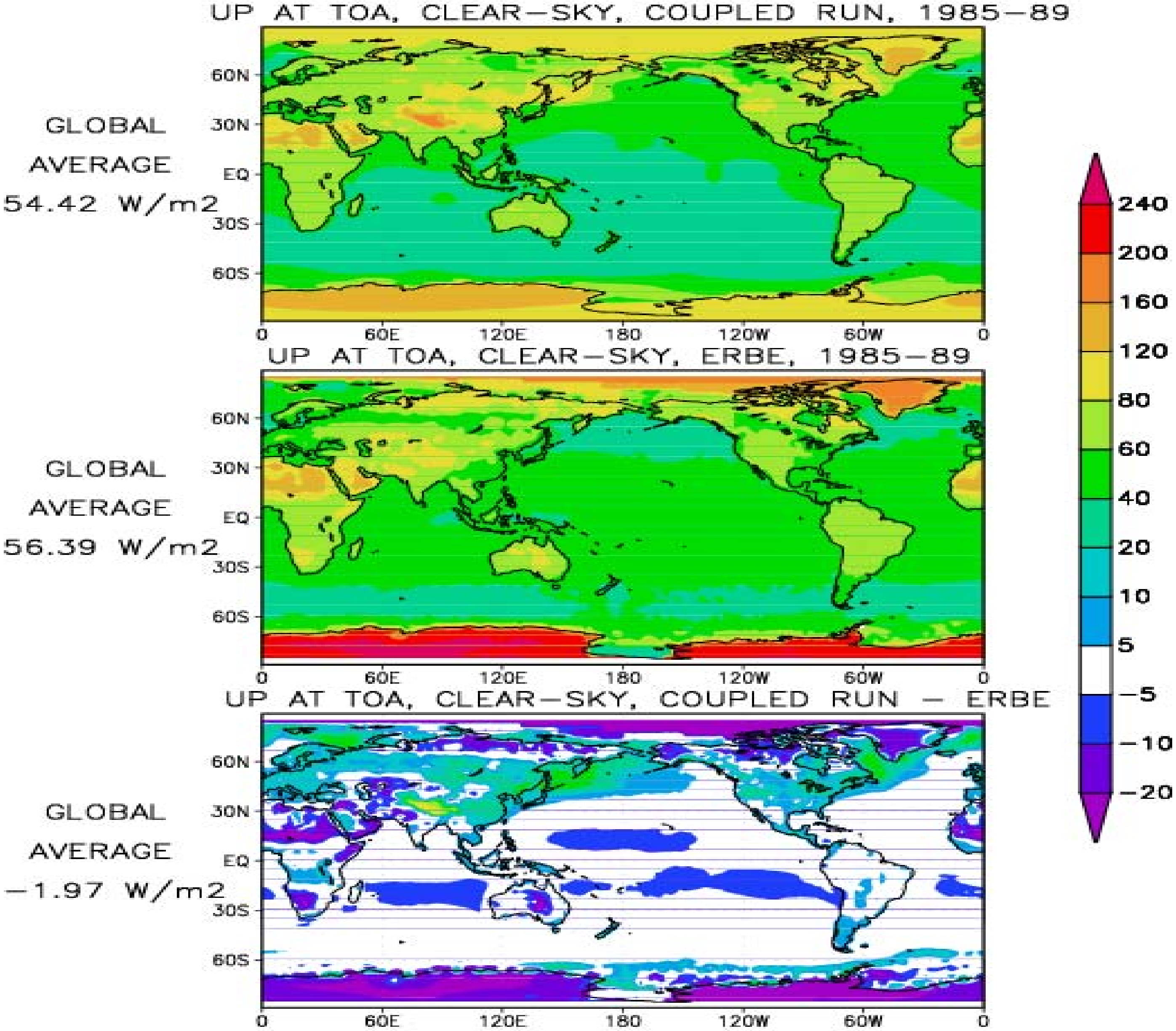
Figure 2.8

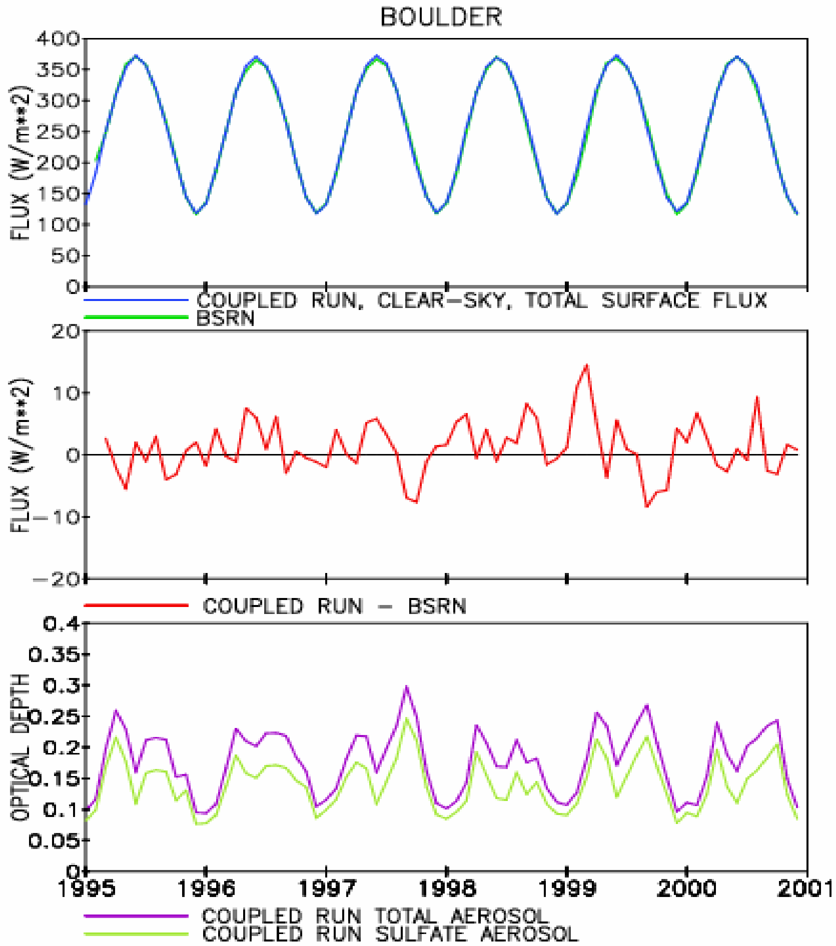


January to March 2001
45N
0
45S
90S
latitude
90W
0
90E
180
longitude
August to October 2001
45N
0
45S
90S
latitude
90W
0
90E
180
longitude
0.1
0.2
0.3
0.4
0.5
0.6
0.7
Total Aerosol Optical Depth

Figure 2.11

Comparison of Clear-Sky SW @ TOA





BOULDER
FLUX (W/m**2)
400
350
300
250
200
150
100
50
0
COUPLED RUN, CLEAR-SKY, TOTAL SURFACE FLUX
BSRN
20
10
0
−10
−20
COUPLED RUN − BSRN
OPTICAL DEPTH
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
1995
1996
1997
1998
1999
2000
2001
COUPLED RUN TOTAL AEROSOL
COUPLED RUN SULFATE AEROSOL

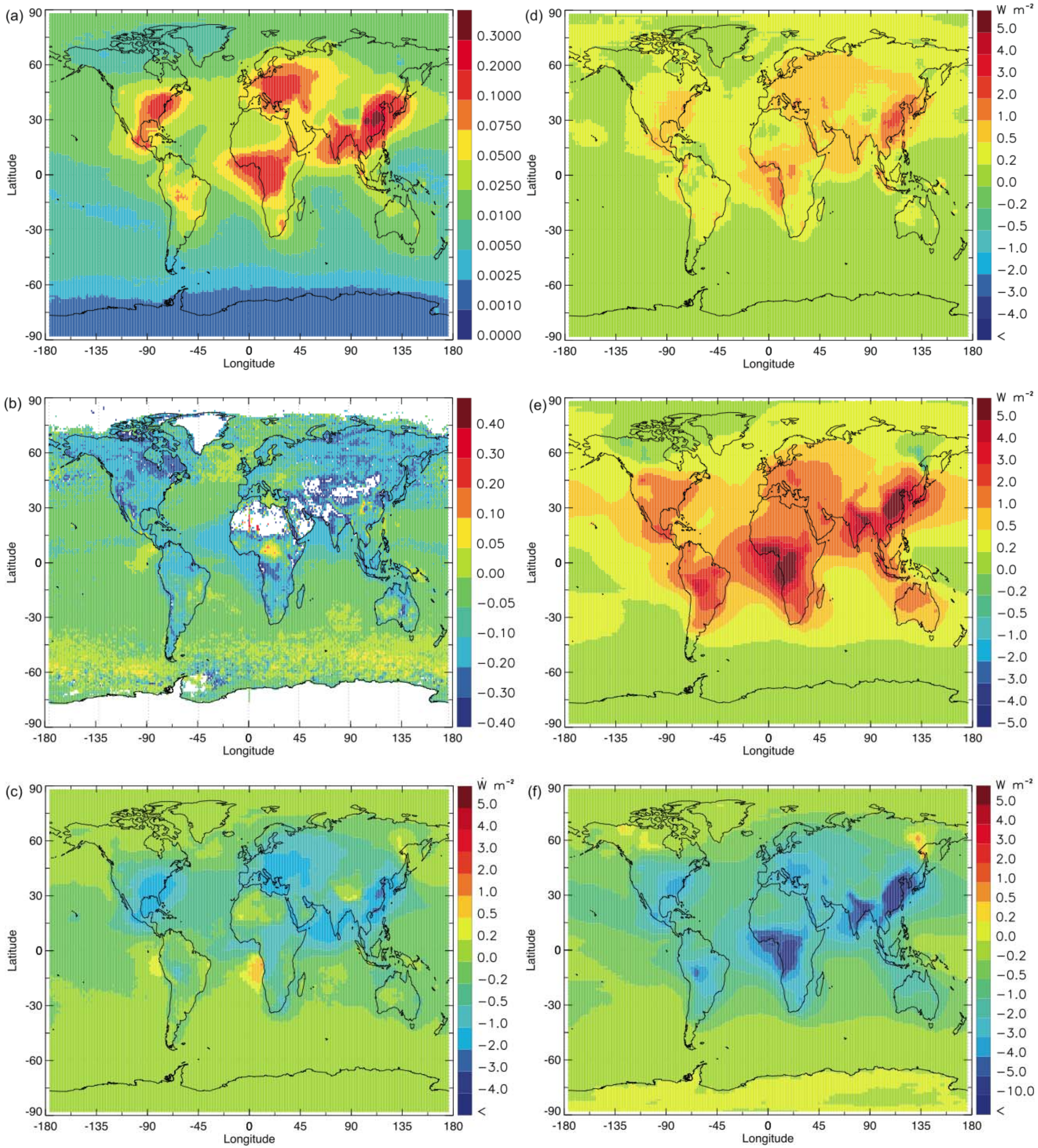
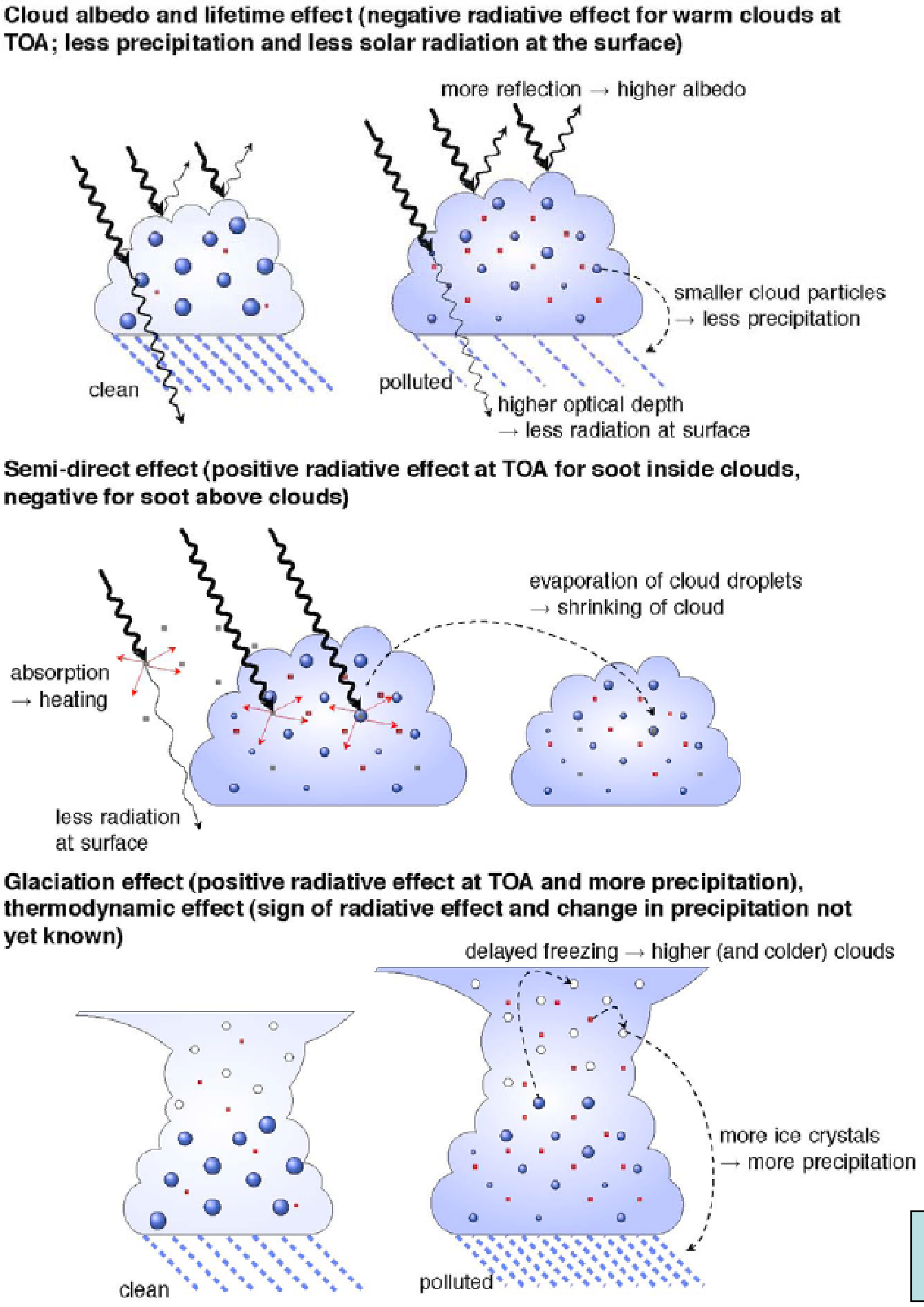

(a)
(b)
(c)
(d)
(e)
(f)
Latitude
Longitude
W m⁻²
0.3000
0.2000
0.1000
0.0750
0.0500
0.0250
0.0100
0.0050
0.0025
0.0010
0.0000
0.40
0.30
0.20
0.10
0.05
0.00
−0.05
−0.10
−0.20
−0.30
−0.40
5.0
4.0
3.0
2.0
1.0
0.5
0.2
0.0
−0.2
−0.5
−1.0
−2.0
−3.0
−4.0
−5.0
−10.0
<

Figure 2.12



Only the change of cloud albedo induced by aerosols in the context of liquid water clouds, is considered to be radiative forcing

Other processes are not considered as radiative forcings. However, they are included in climate models that explicitly consider the relevant processes

Aerosol effects on ice clouds are poorly understood, and are not quantified.

Aerosol cloud interactions [Figure 7.20]

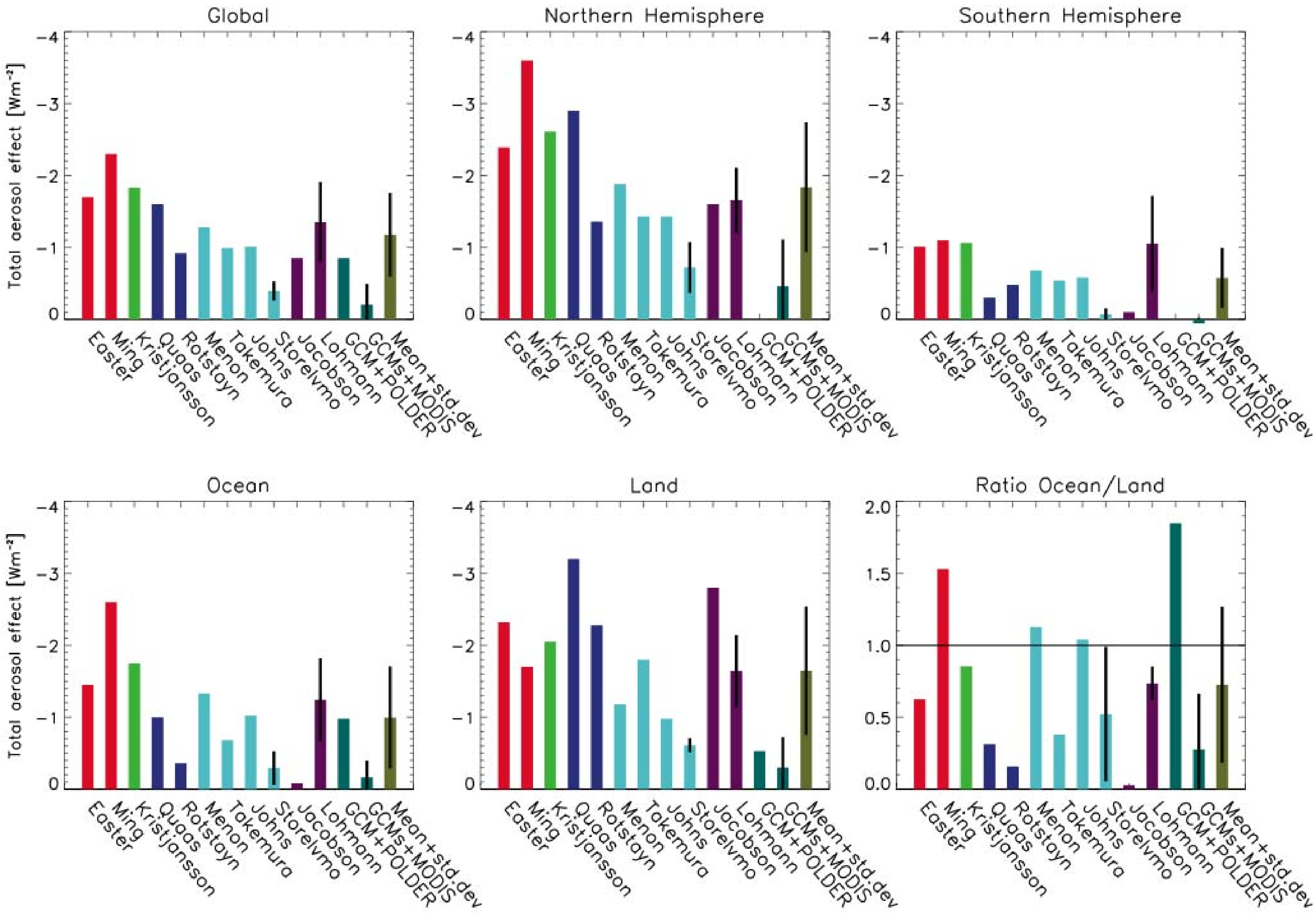
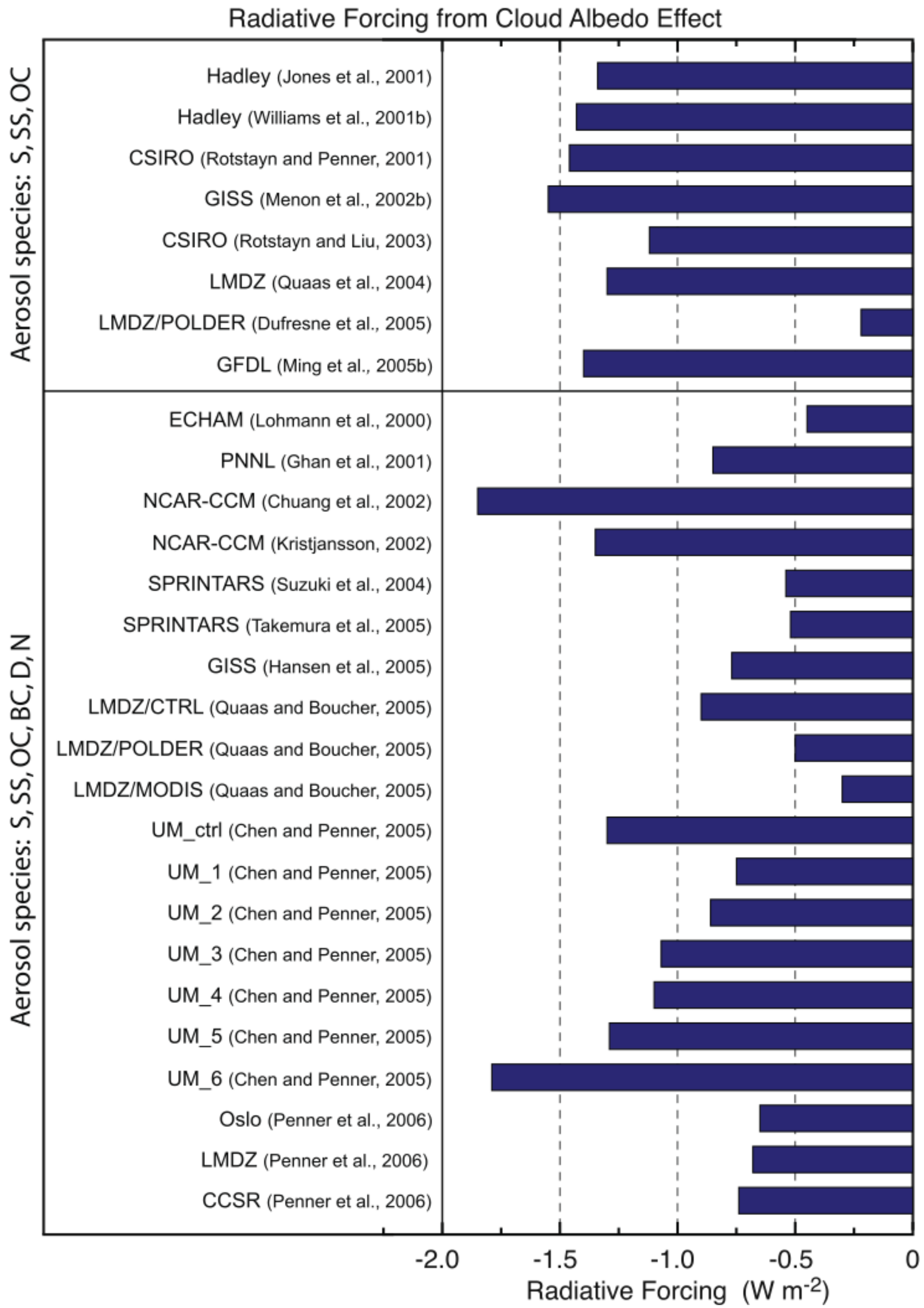

Global
Northern Hemisphere
Southern Hemisphere
Ocean
Land
Ratio Ocean/Land
Total aerosol effect [Wm⁻²]
-4
-3
-2
-1
0
2.0
1.5
1.0
0.5
0.0
Easter
Ming
Kristjansson
Quaas
Rotstayn
Menon
Takemura
Johns
Storelvmo
Jacobson
Lohmann
GCM+POLDER
GCMs+MODIS
Mean+std.dev

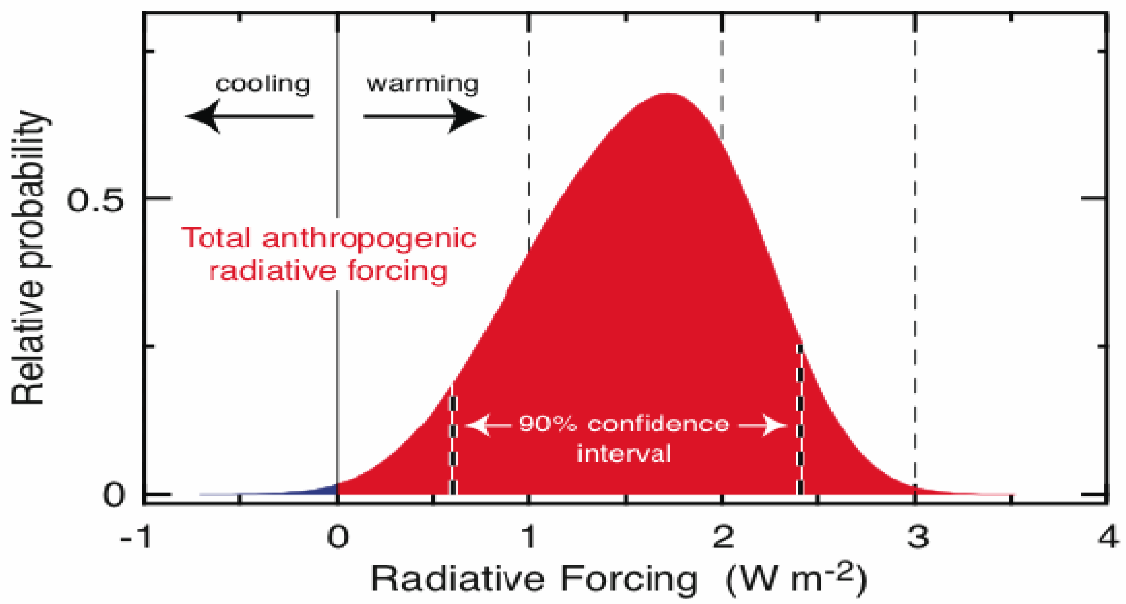
Figure 7.21



Radiative Forcing from Cloud Albedo Effect
Aerosol species: S, SS, OC
Hadley (Jones et al., 2001)
Hadley (Williams et al., 2001b)
CSIRO (Rotstayn and Penner, 2001)
GISS (Menon et al., 2002b)
CSIRO (Rotstayn and Liu, 2003)
LMDZ (Quaas et al., 2004)
LMDZ/POLDER (Dufresne et al., 2005)
GFDL (Ming et al., 2005b)
Aerosol species: S, SS, OC, BC, D, N
ECHAM (Lohmann et al., 2000)
PNNL (Ghan et al., 2001)
NCAR-CCM (Chuang et al., 2002)
NCAR-CCM (Kristjansson, 2002)
SPRINTARS (Suzuki et al., 2004)
SPRINTARS (Takemura et al., 2005)
GISS (Hansen et al., 2005)
LMDZ/CTRL (Quaas and Boucher, 2005)
LMDZ/POLDER (Quaas and Boucher, 2005)
LMDZ/MODIS (Quaas and Boucher, 2005)
UM_ctrl (Chen and Penner, 2005)
UM_1 (Chen and Penner, 2005)
UM_2 (Chen and Penner, 2005)
UM_3 (Chen and Penner, 2005)
UM_4 (Chen and Penner, 2005)
UM_5 (Chen and Penner, 2005)
UM_6 (Chen and Penner, 2005)
Oslo (Penner et al., 2006)
LMDZ (Penner et al., 2006)
CCSR (Penner et al., 2006)
-2.0
-1.5
-1.0
-0.5
0
Radiative Forcing (W m-2)

Figure 2.14

Combining anthropogenic forcing estimates



Panel B.

Figure TS-5
(Panel B)

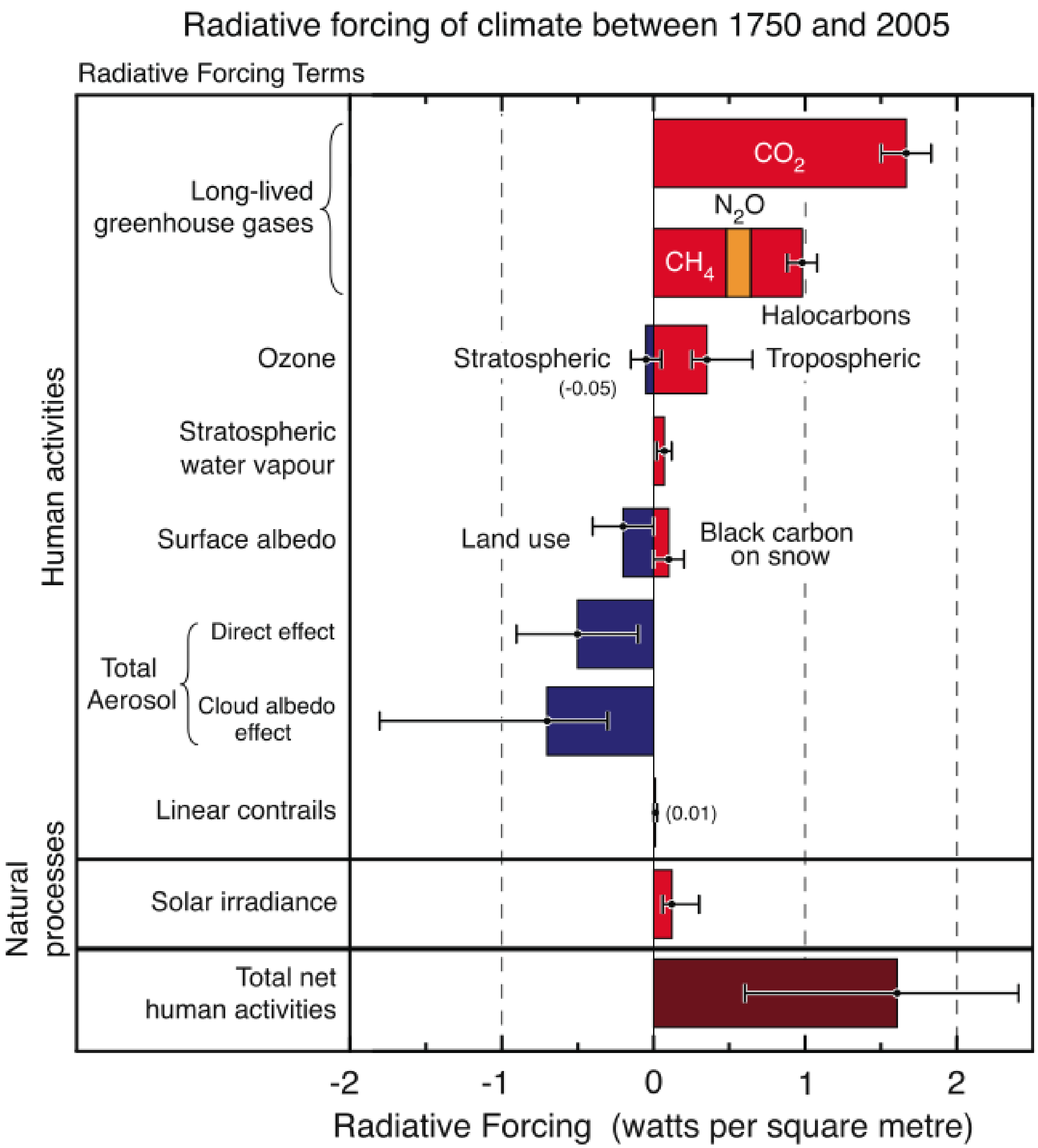
Combined anthropogenic forcing **is not straight sum of individual terms.**

Tropospheric ozone, cloud-albedo, contrails → asymmetric range about the central estimate

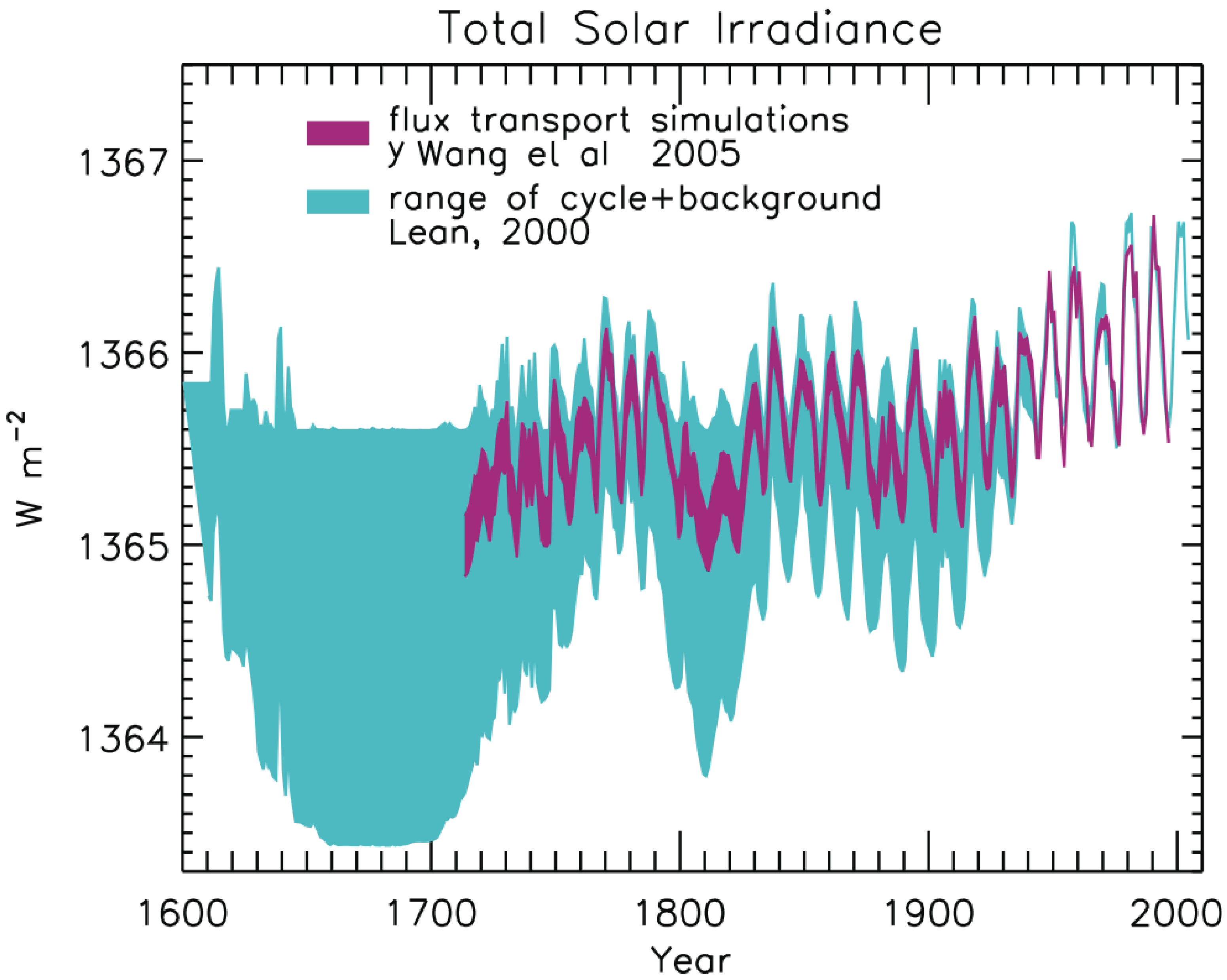
Uncertainties for the agents represented by normal distributions except: contrail (lognormal); discrete values → trop. ozone, direct aerosol (sulphate, fossil fuel black and organic carbon, biomass burning), cloud albedo

Monte Carlo calculations to derive probability density functions for the combined effect

Only derived for the global-mean



FAQ 2.1, Figure 2



Total Solar Irradiance
flux transport simulations
y Wang el al 2005
range of cycle+background
Lean, 2000
1367
1366
1365
1364
W m^{-2}
1600
1700
1800
1900
2000
Year

Figure 2.17

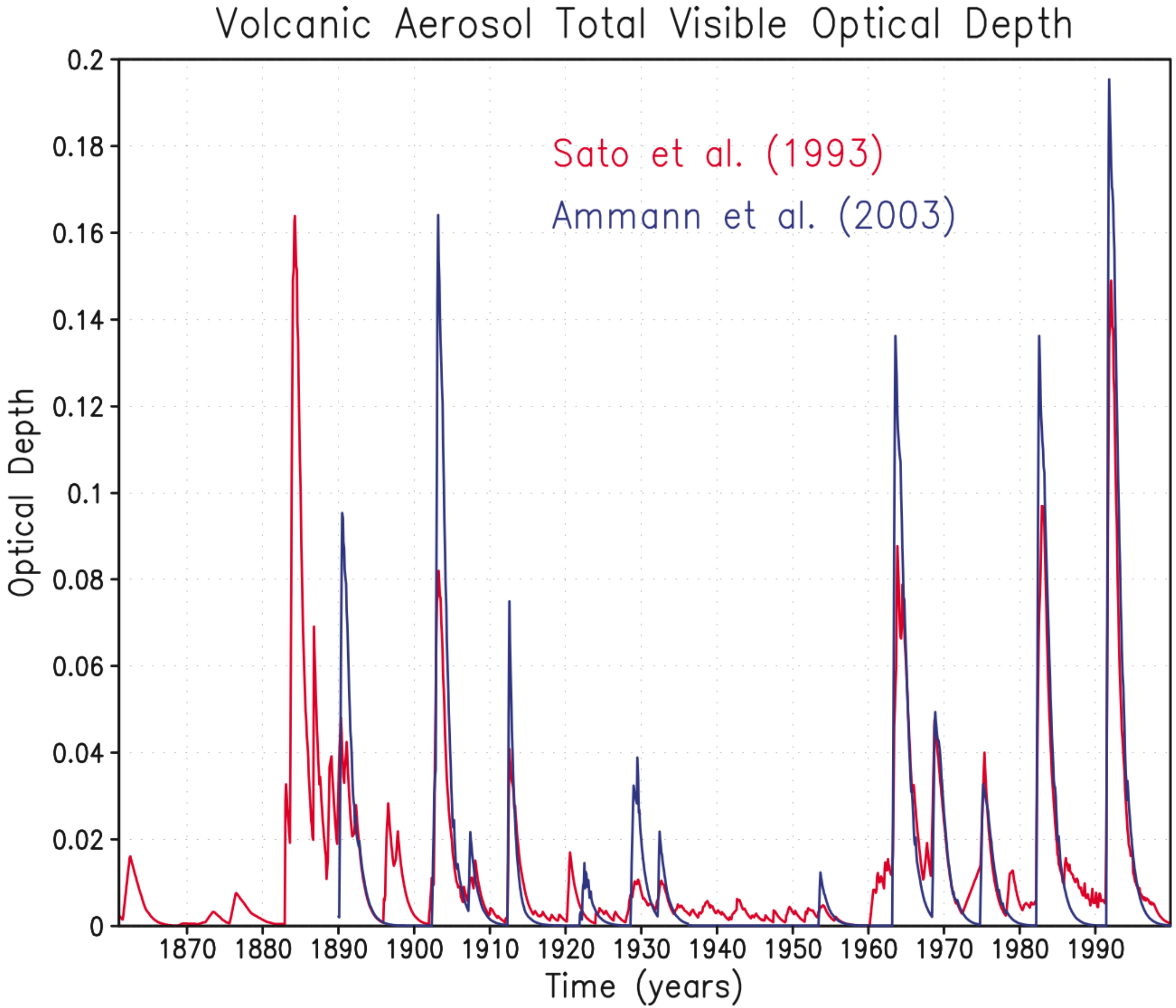
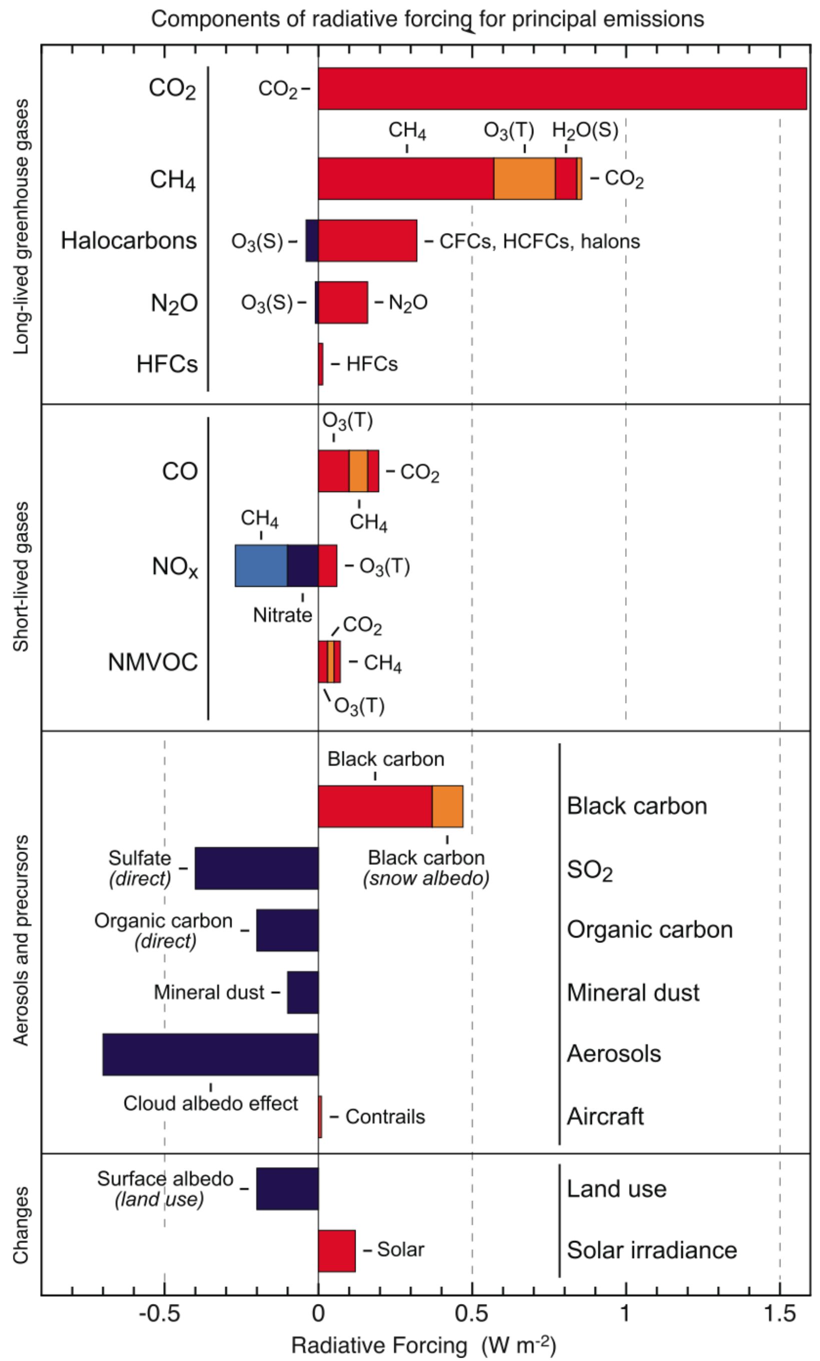
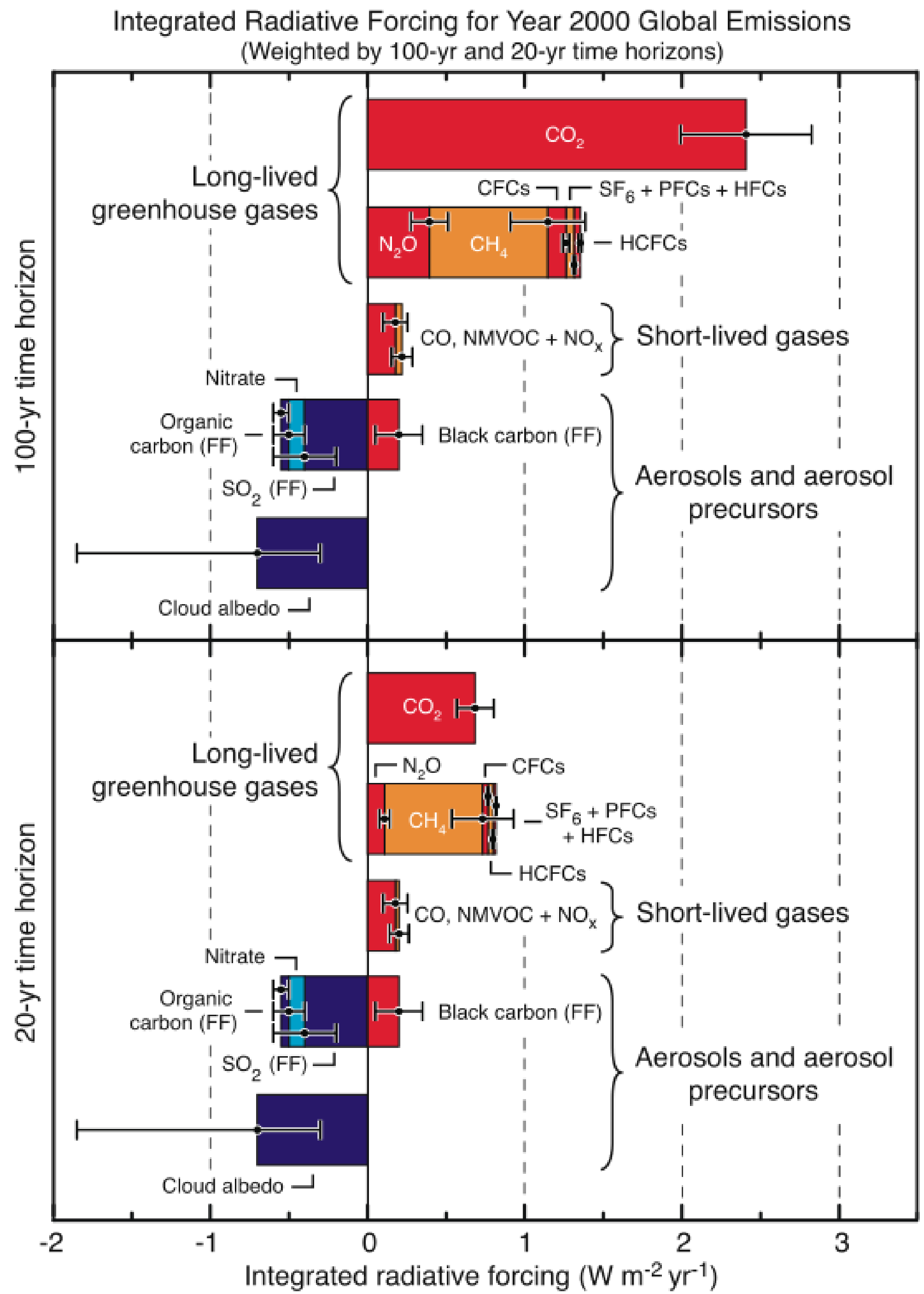

Volcanic Aerosol Total Visible Optical Depth
Sato et al. (1993)
Ammann et al. (2003)
Optical Depth
0.2
0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
1870
1880
1890
1900
1910
1920
1930
1940
1950
1960
1970
1980
1990
Time (years)

Figure 2.18



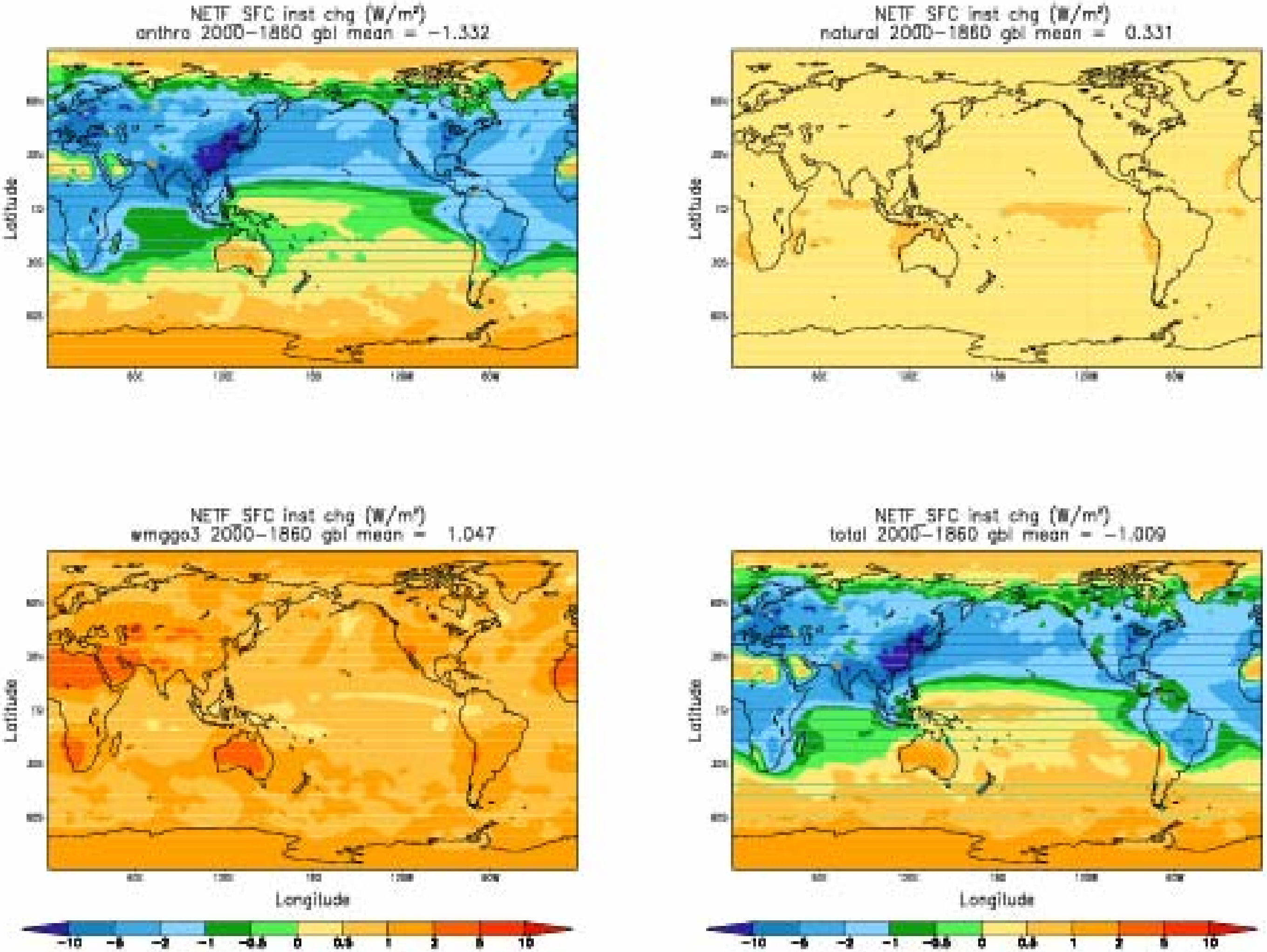
Components of radiative forcing for principal emissions
Long-lived greenhouse gases
CO2
CO2
CH4
CH4
O3(T)
H2O(S)
CO2
Halocarbons
O3(S)
CFCs, HCFCs, halons
N2O
O3(S)
N2O
HFCs
HFCs
Short-lived gases
O3(T)
CO
CO2
CH4
CH4
NOx
O3(T)
Nitrate
CO2
NMVOC
CH4
O3(T)
Aerosols and precursors
Black carbon
Black carbon
Sulfate (direct)
Black carbon (snow albedo)
SO2
Organic carbon (direct)
Organic carbon
Mineral dust
Mineral dust
Aerosols
Cloud albedo effect
Contrails
Aircraft
Changes
Surface albedo (land use)
Land use
Solar
Solar irradiance
-0.5
0
0.5
1
1.5
Radiative Forcing (W m-2)

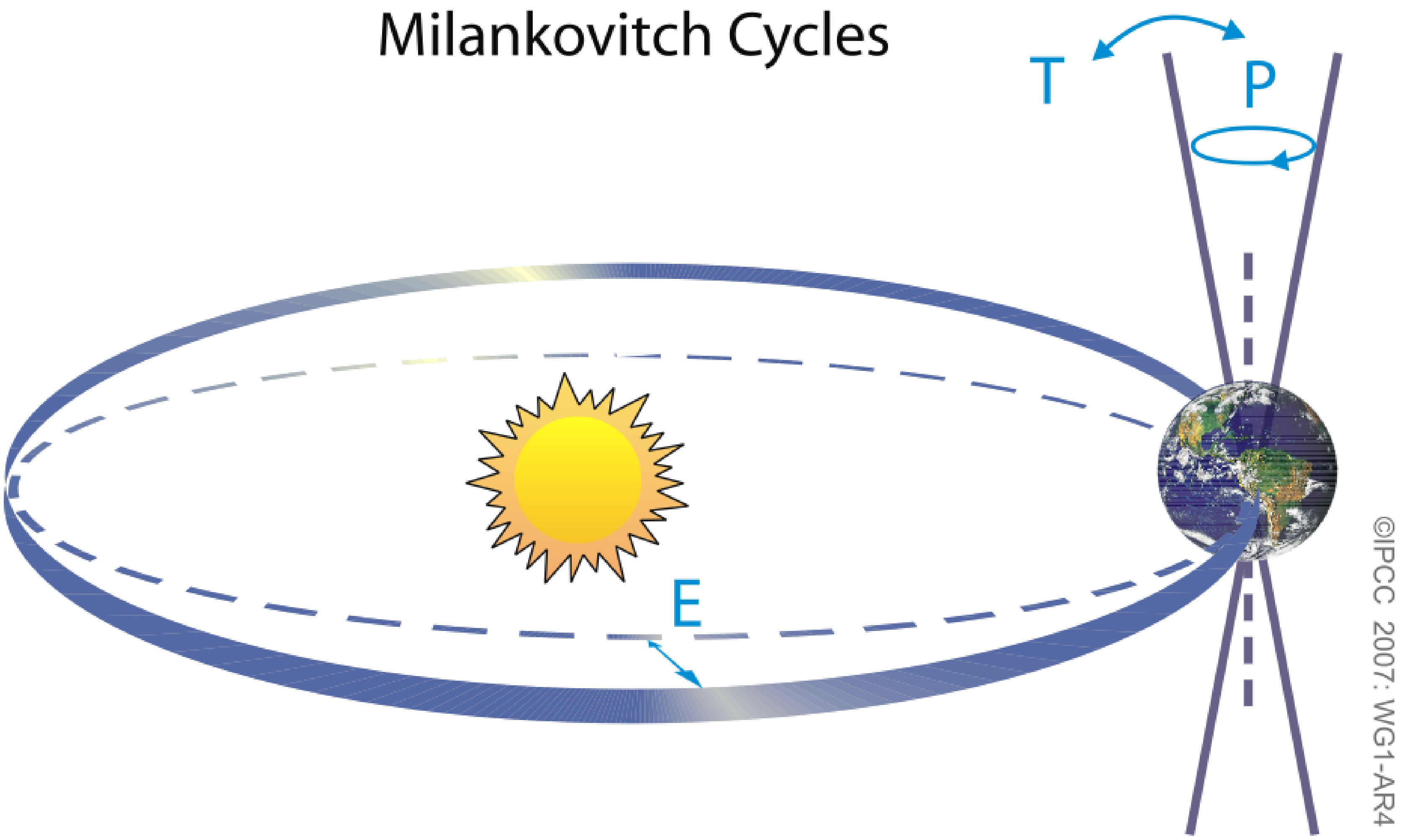
Figure 2.21



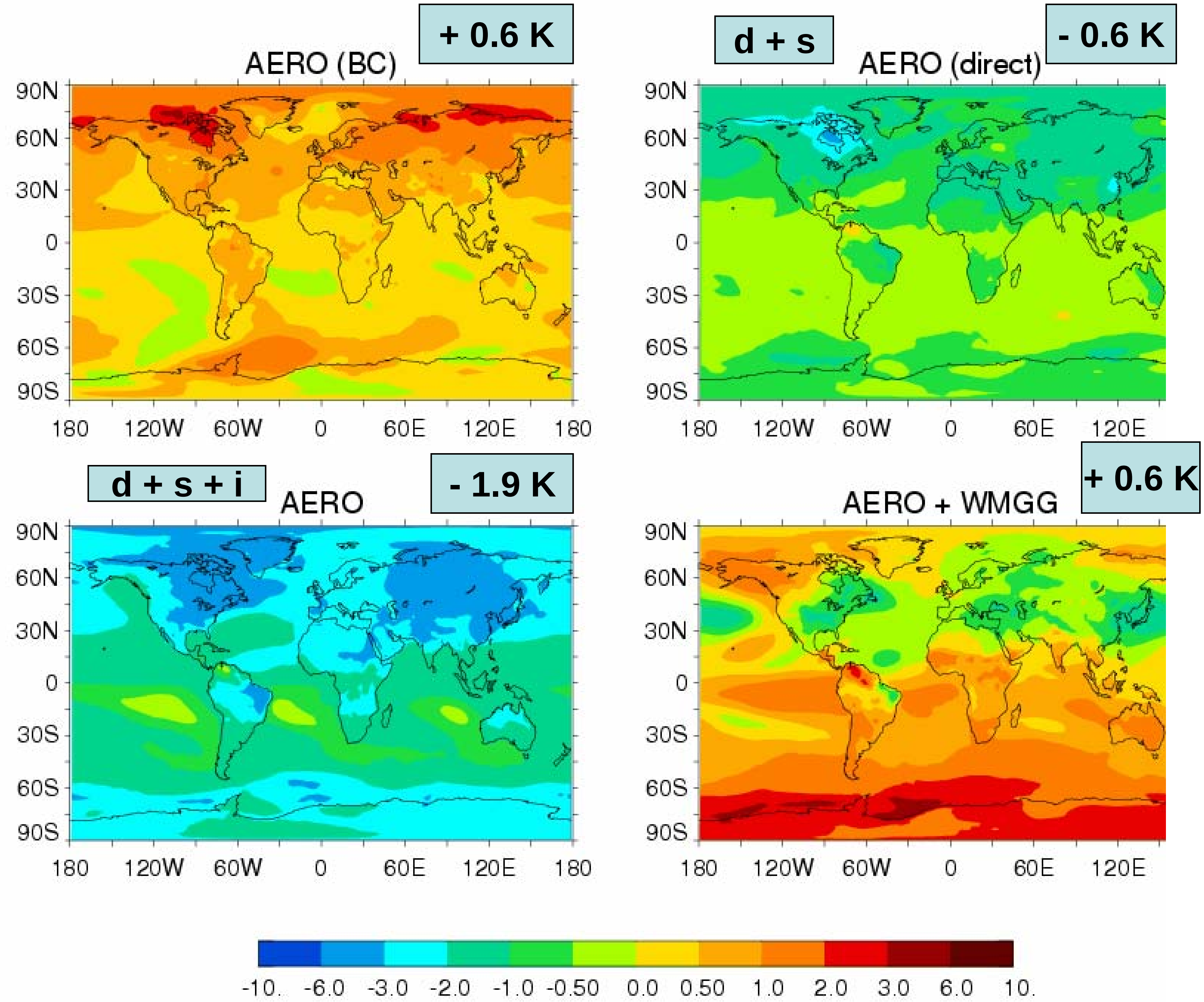
Integrated Radiative Forcing for Year 2000 Global Emissions
(Weighted by 100-yr and 20-yr time horizons)
100-yr time horizon
20-yr time horizon
Long-lived greenhouse gases
CO2
CFCs
SF6 + PFCs + HFCs
N2O
CH4
HCFCs
CO, NMVOC + NOx
Short-lived gases
Nitrate
Organic carbon (FF)
SO2 (FF)
Black carbon (FF)
Aerosols and aerosol precursors
Cloud albedo
-2
-1
0
1
2
3
Integrated radiative forcing (W m-2 yr-1)

Figure 2.22

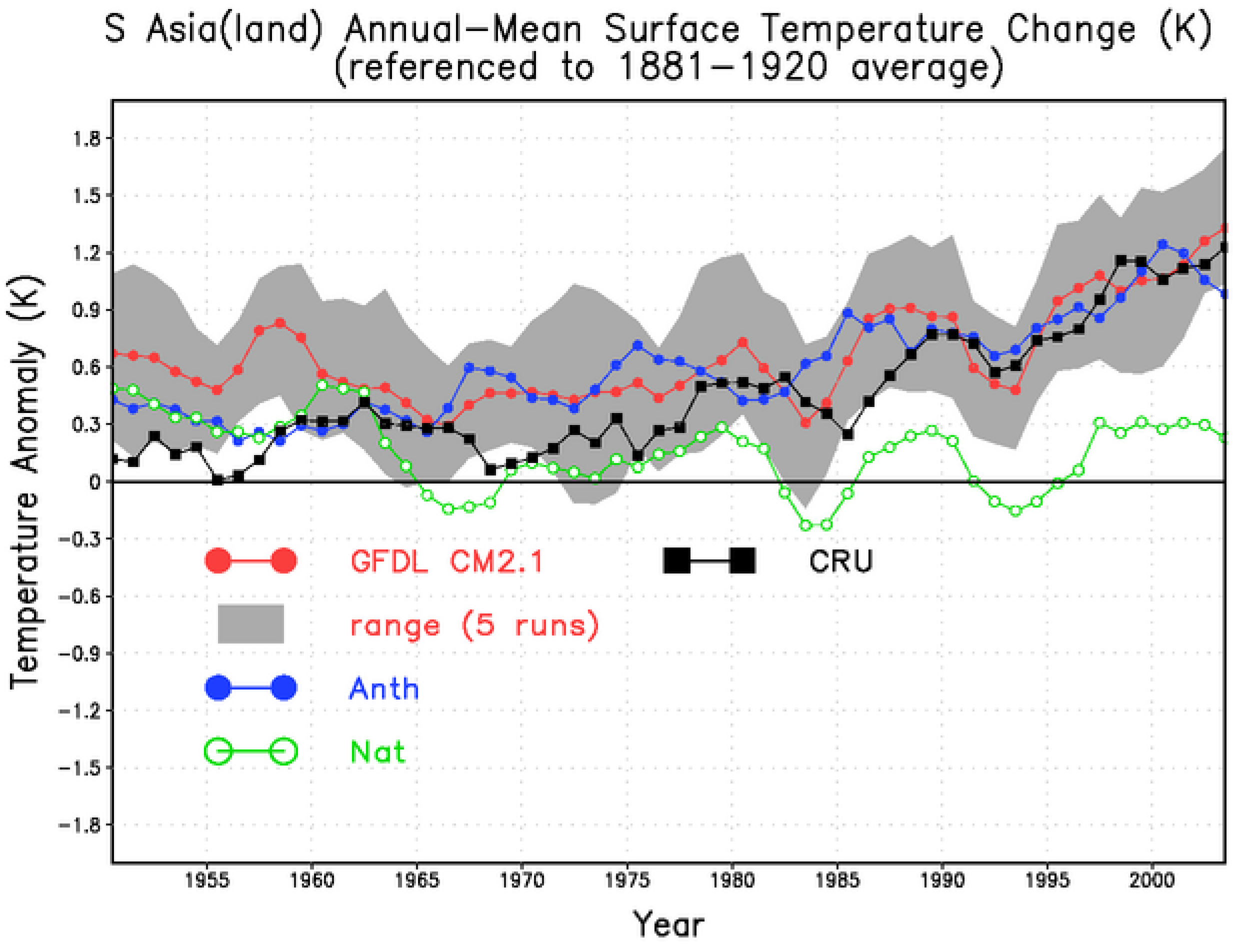

NETF_SFC inst chg (W/m²)
anthro 2000-1860 gbl mean = -1.332
NETF_SFC inst chg (W/m²)
natural 2000-1860 gbl mean = 0.331
NETF_SFC inst chg (W/m²)
wmggo3 2000-1860 gbl mean = 1.047
NETF_SFC inst chg (W/m²)
total 2000-1860 gbl mean = -1.009
Latitude
Longitude

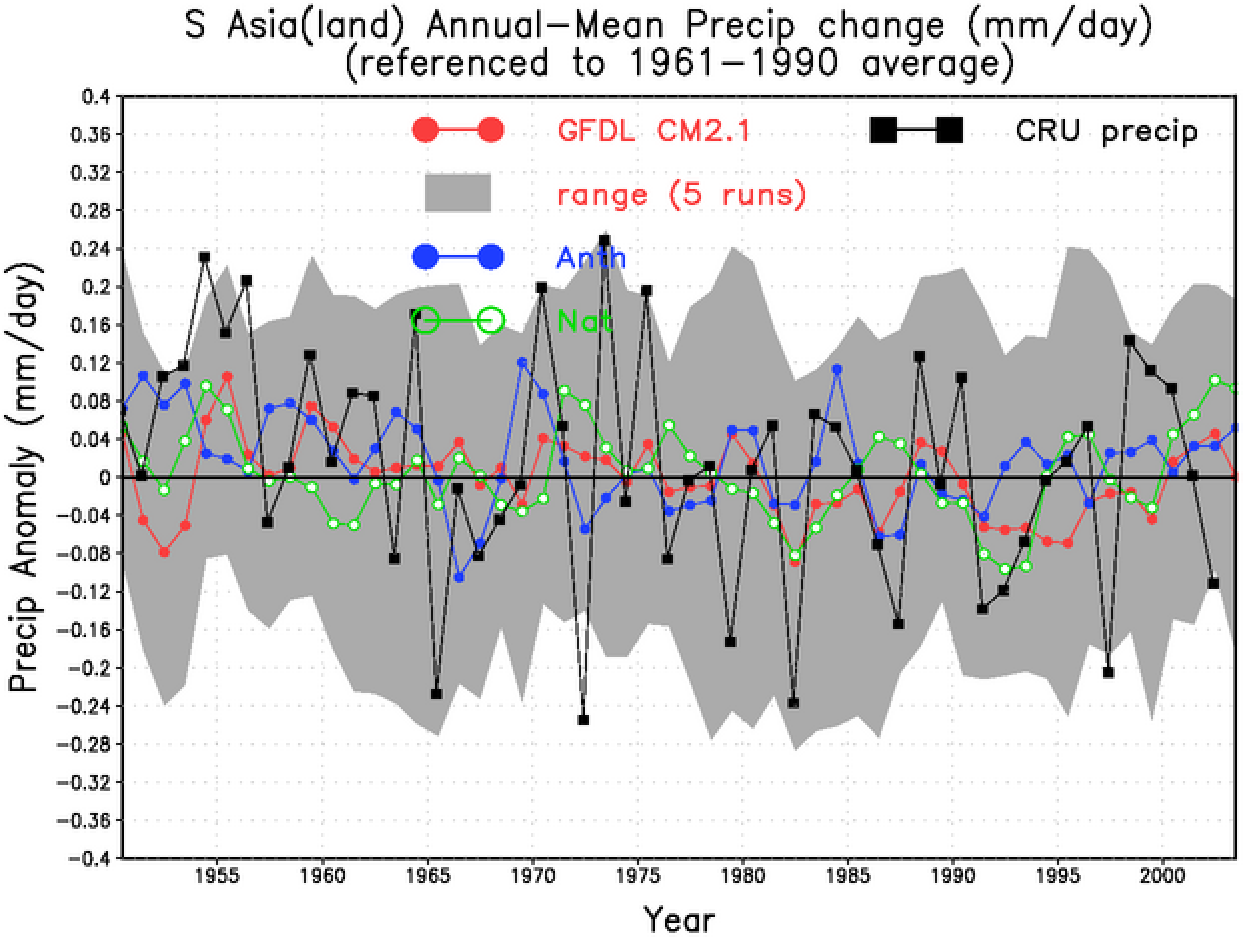


Box TS.6



+ 0.6 K
AERO (BC)
d + s
AERO (direct)
- 0.6 K
d + s + i
AERO
- 1.9 K
AERO + WMGG
+ 0.6 K
90N
60N
30N
0
30S
60S
90S
180
120W
60W
0
60E
120E
180
-10.
-6.0
-3.0
-2.0
-1.0
-0.50
0.0
0.50
1.0
2.0
3.0
6.0
10.


S Asia(land) Annual-Mean Surface Temperature Change (K)
(referenced to 1881-1920 average)
Temperature Anomaly (K)
1.8
1.5
1.2
0.9
0.6
0.3
0
-0.3
-0.6
-0.9
-1.2
-1.5
-1.8
1955
1960
1965
1970
1975
1980
1985
1990
1995
2000
Year
GFDL CM2.1
CRU
range (5 runs)
Anth
Nat



S Asia(land) Annual-Mean Precip change (mm/day)
(referenced to 1961-1990 average)
GFDL CM2.1
range (5 runs)
Anth
Nat
CRU precip
Precip Anomaly (mm/day)
0.4
0.36
0.32
0.28
0.24
0.2
0.16
0.12
0.08
0.04
0
-0.04
-0.08
-0.12
-0.16
-0.2
-0.24
-0.28
-0.32
-0.36
-0.4
1955
1960
1965
1970
1975
1980
1985
1990
1995
2000
Year