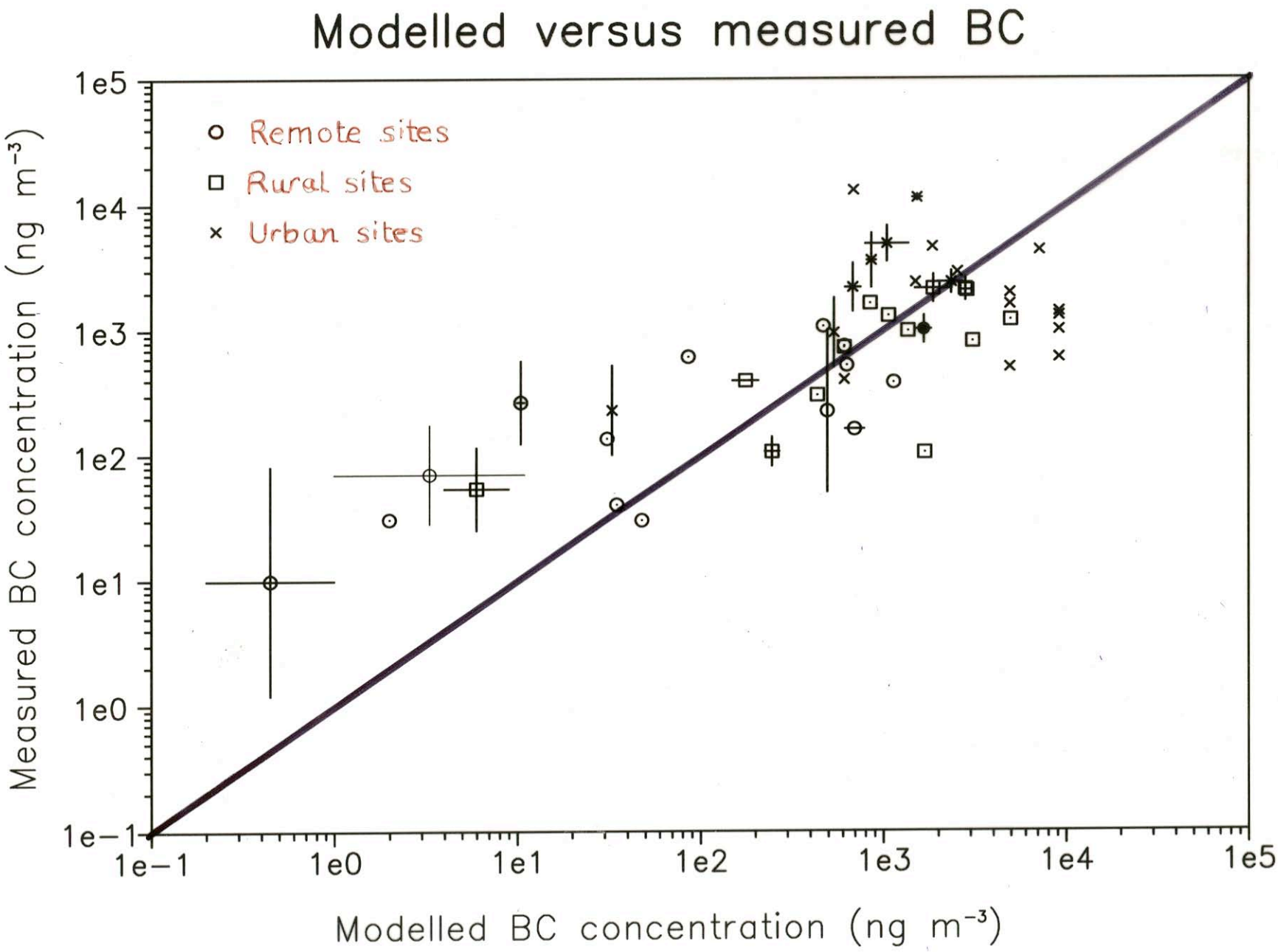
Calculation of Aerosol Forcing in Coupled Models

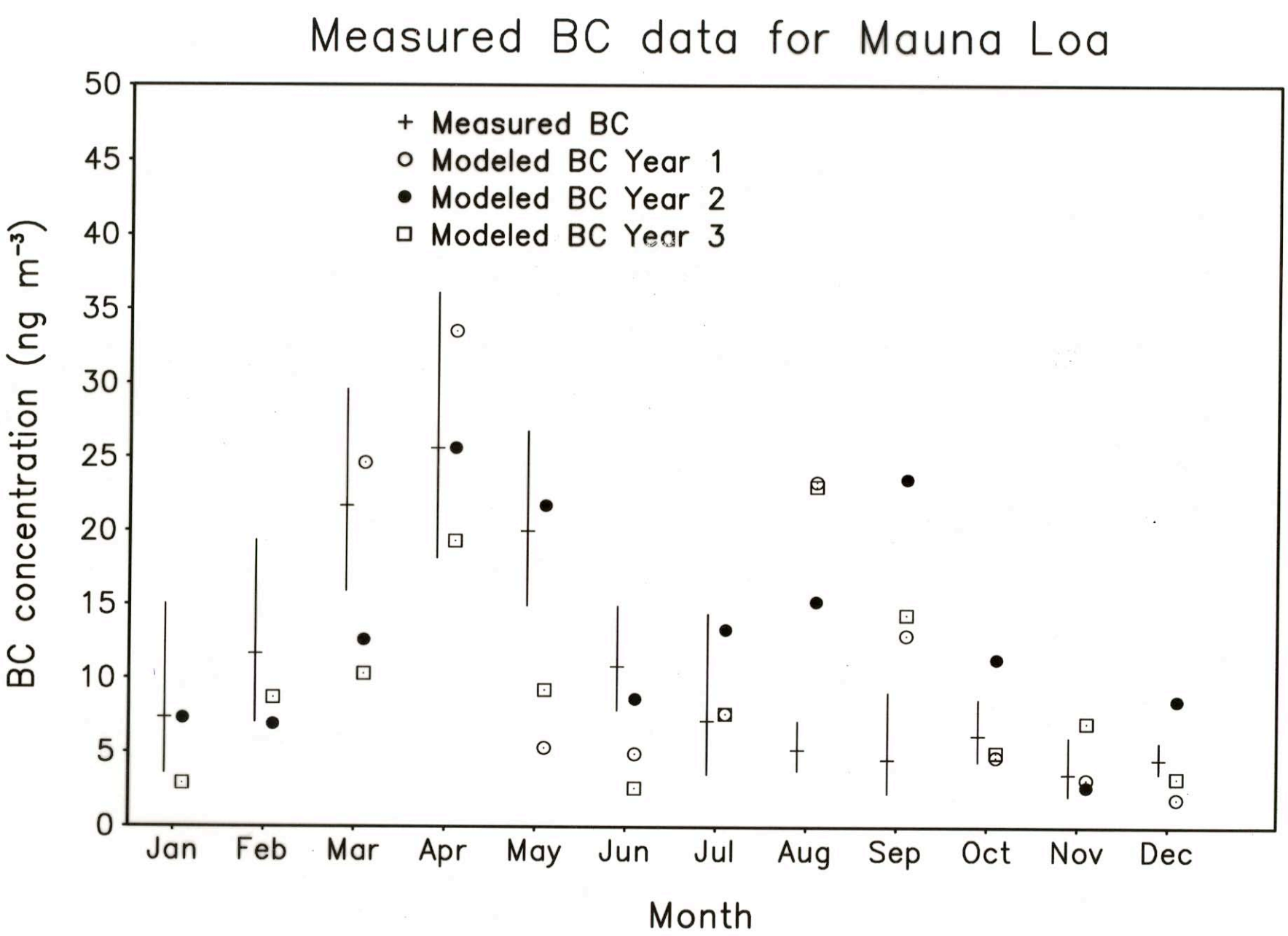
V. Ramaswamy

NOAA/ Geophysical Fluid Dynamics Laboratory, Princeton University

Sensitivity of simulated BC concentrations

(Cooke, Ramaswamy, Kasibhatla, JGR 2002)


Modelled versus measured BC
Remote sites
Rural sites
Urban sites
Measured BC concentration (ng m⁻³)
Modelled BC concentration (ng m⁻³)
1e5
1e4
1e3
1e2
1e1
1e0
1e−1
1e−1
1e0
1e1
1e2
1e3
1e4
1e5


Measured BC data for Mauna Loa
Measured BC
Modeled BC Year 1
Modeled BC Year 2
Modeled BC Year 3
BC concentration (ng m⁻³)
0
5
10
15
20
25
30
35
40
45
50
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Month

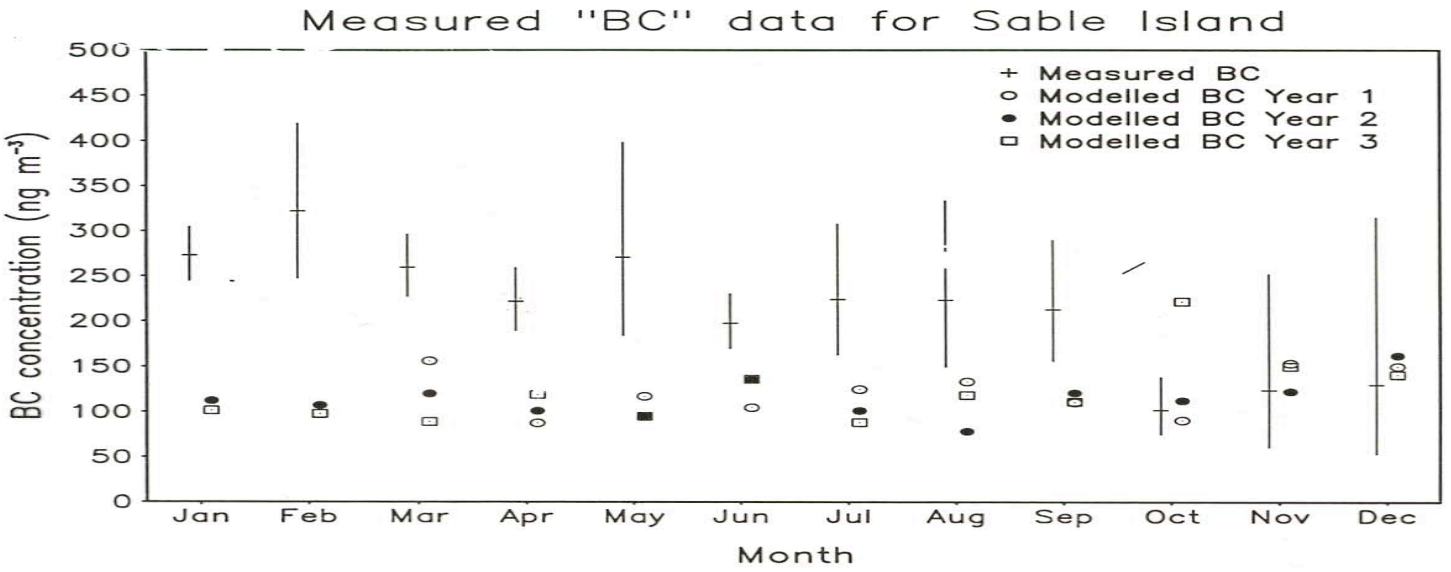


Figure 2. Comparison of modeled (3 years of data) and measured black carbon at Sable Island (60°W, 43.9°N). The mean and geometric deviation of the observations is shown, while , for the model, the values for each of the 3 years of simulation are plotted.

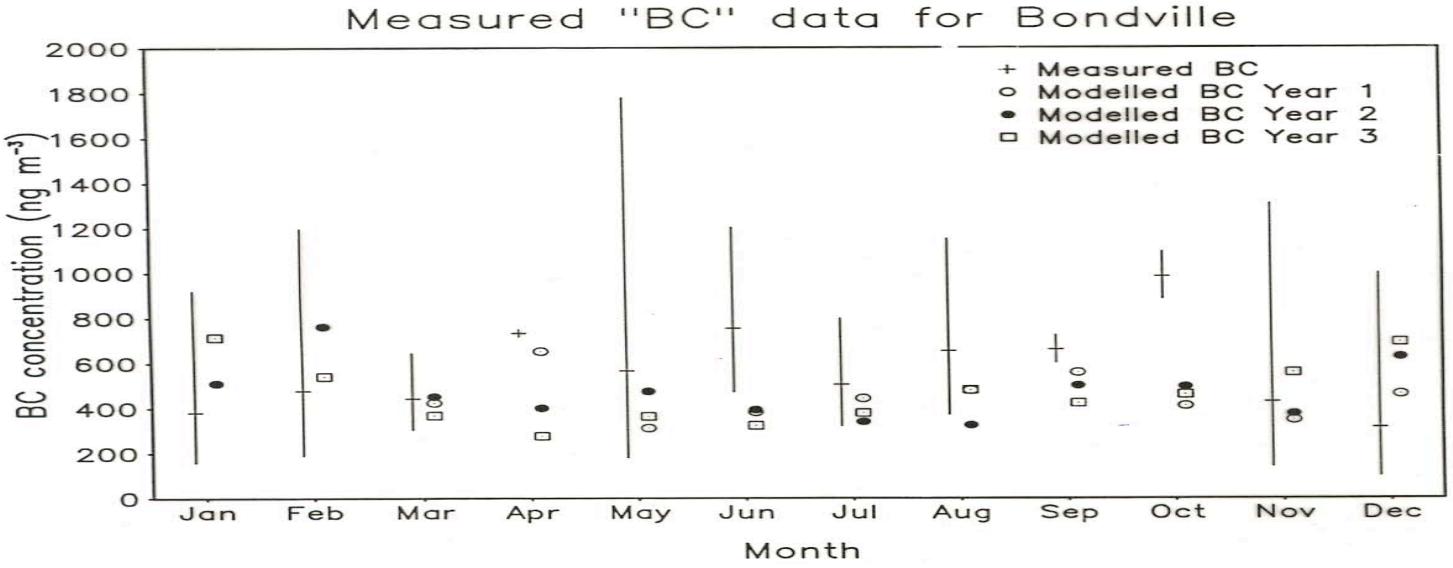


Figure 3. Same as Figure 2 except at Bondville (88.4°W, 40.1°N).

Figures

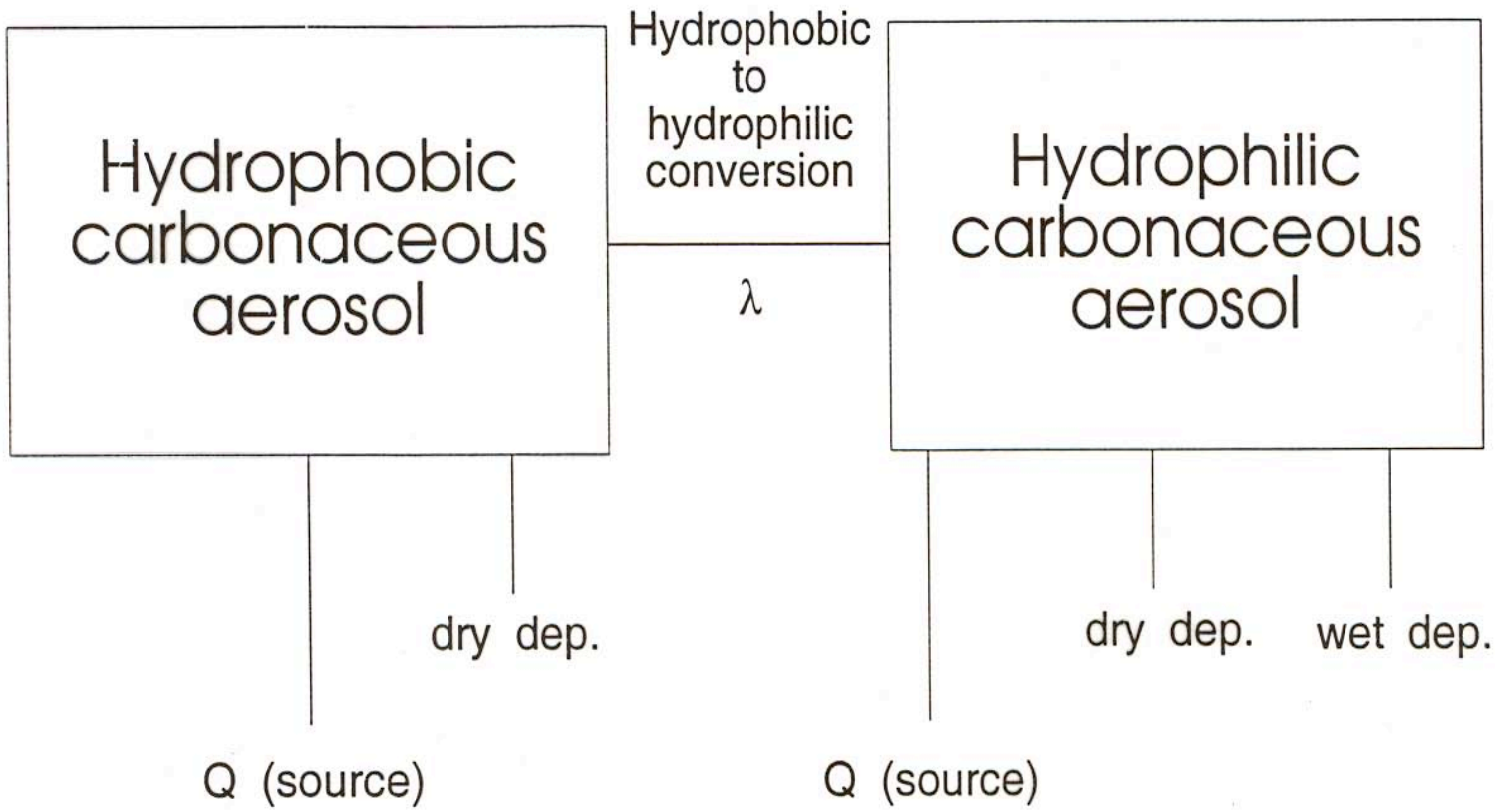


Figure 1. Emission and transformation scheme for carbonaceous aerosol as implemented in the GCM.

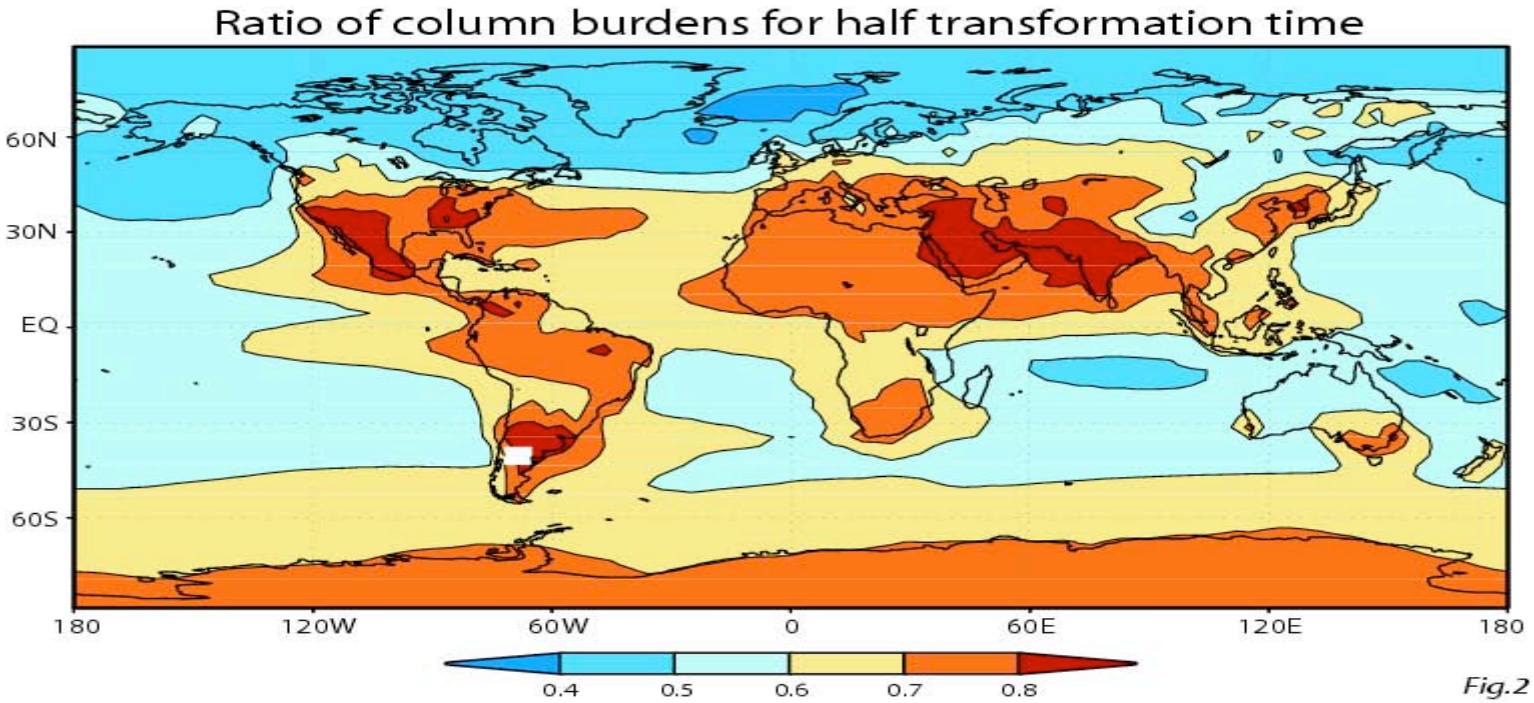

Ratio of column burdens for half transformation time
60N
30N
EQ
30S
60S
180
120W
60W
0
60E
120E
180
0.4
0.5
0.6
0.7
0.8

Fig.2

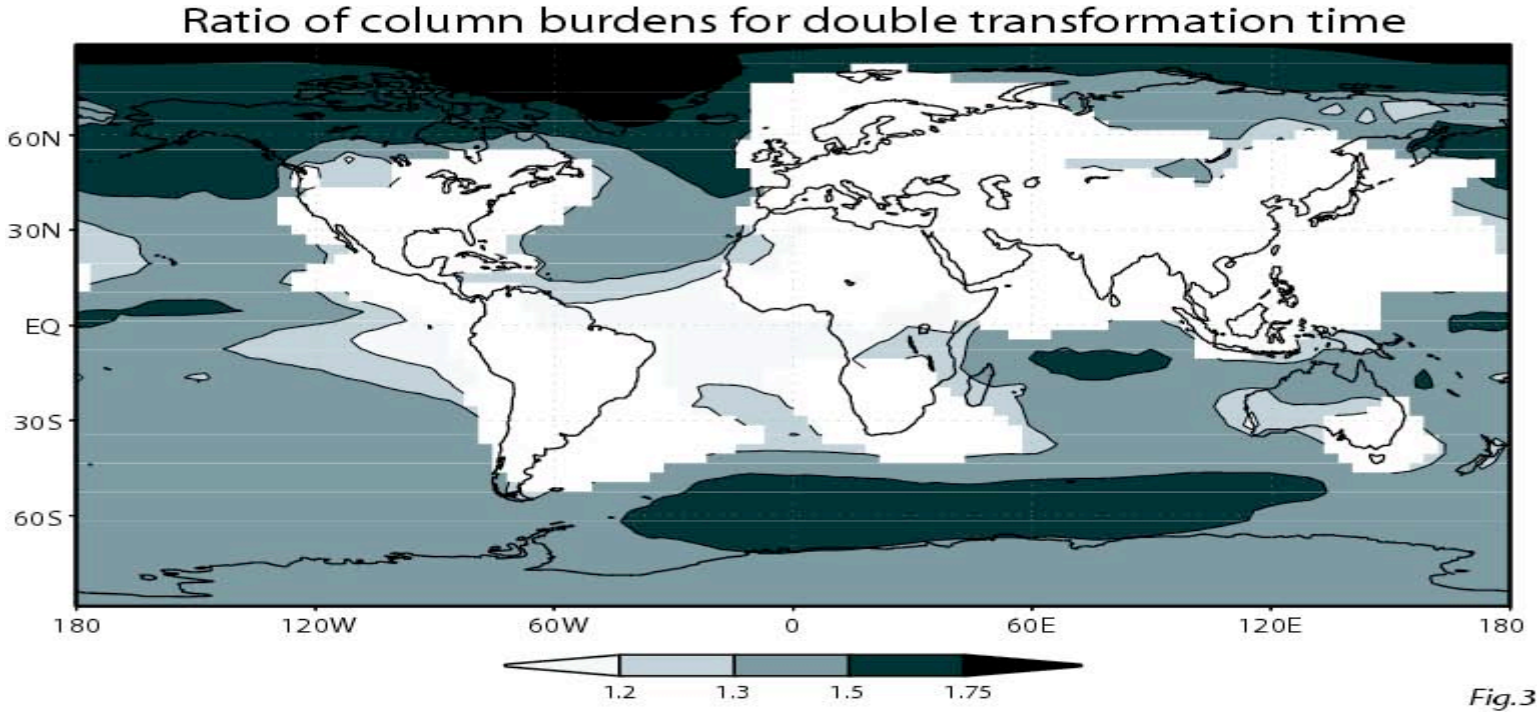

Ratio of column burdens for double transformation time
60N
30N
EQ
30S
60S
180
120W
60W
0
60E
120E
180
1.2
1.3
1.5
1.75

Fig.3

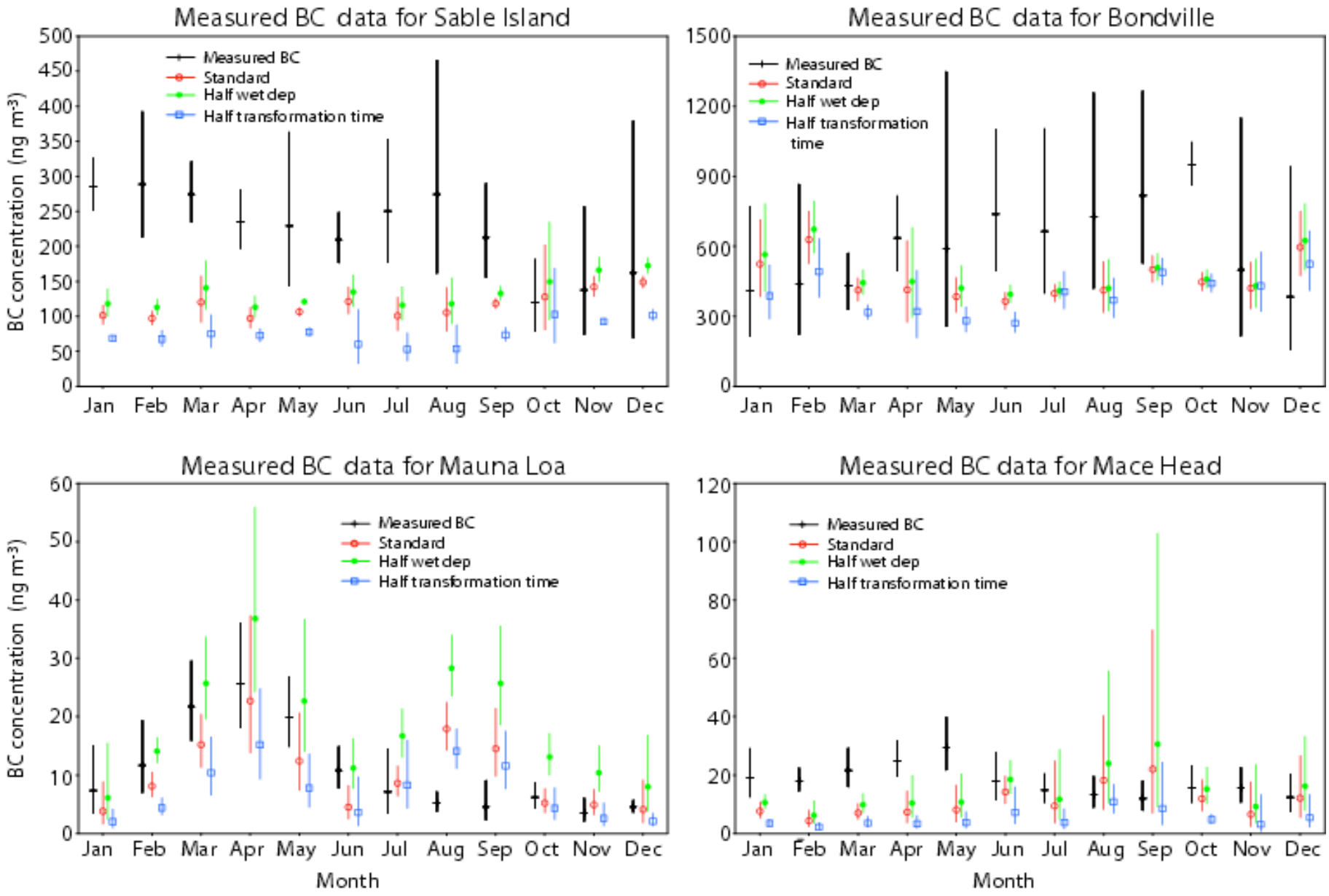

Measured BC data for Sable Island
Measured BC data for Bondville
Measured BC data for Mauna Loa
Measured BC data for Mace Head
Measured BC
Standard
Half wet dep
Half transformation time
BC concentration (ng m-3)
Month
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec

Fig.4

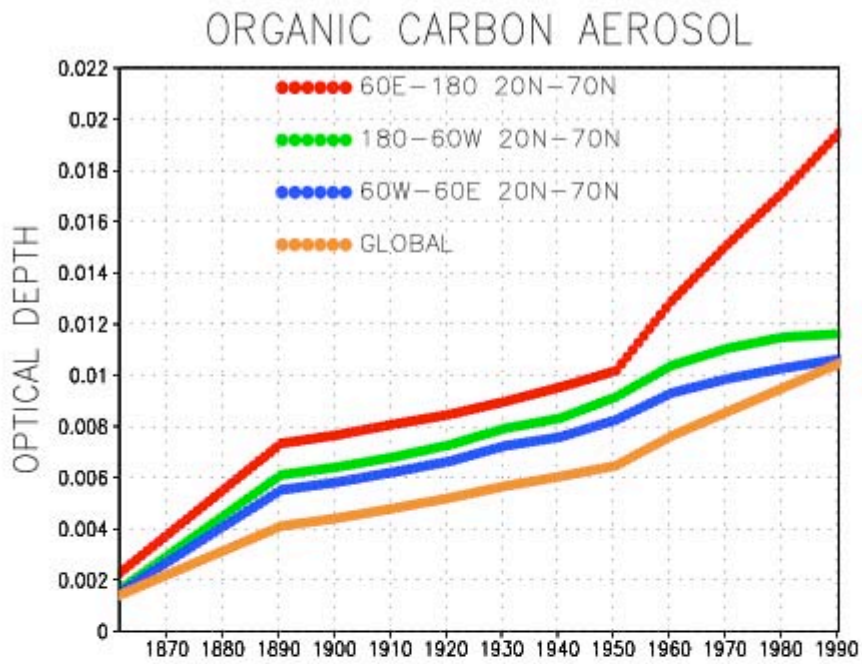
Sensitivity of global-mean forcing of black carbon aerosol from fossil-fuel combustion to aerosol microphysics.

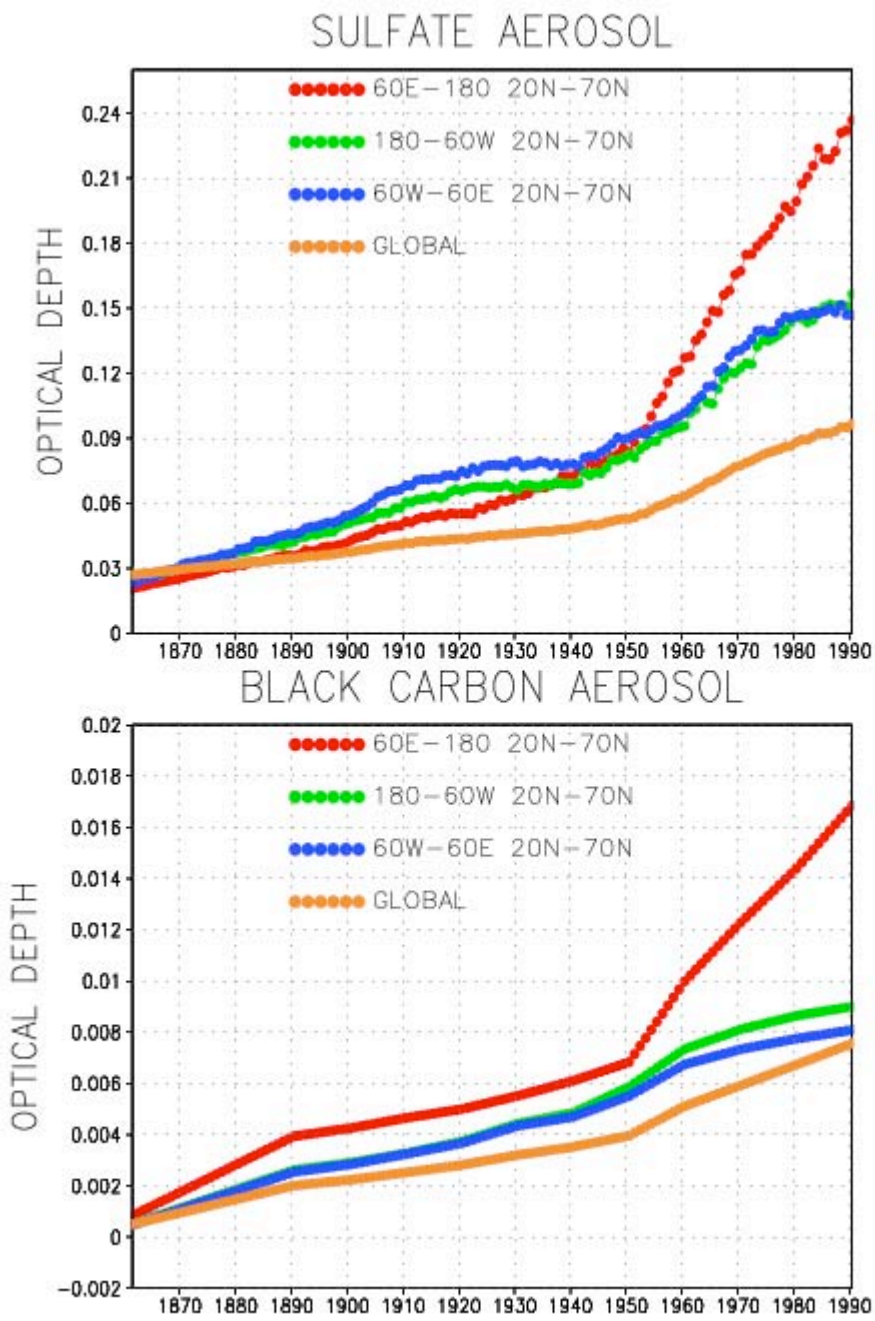
Parameter	FACTOR DIFFERENCE
STANDARD	1
Transformation time halved	0.8
Transformation time doubled	1.1
100% hydrophobic emission	1.2
100% soluble aerosol	0.6
Wet deposition rate halved	1.3

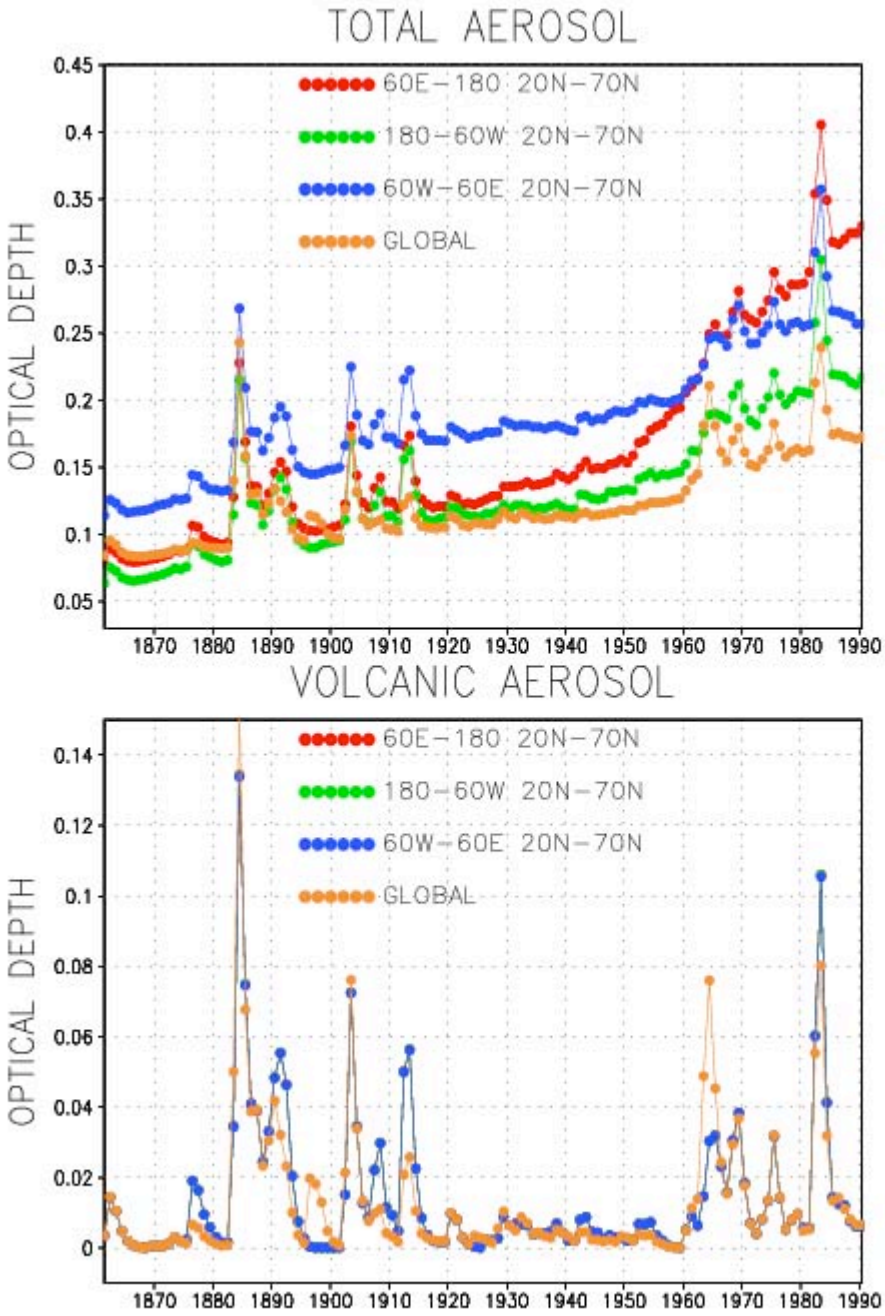
OVERALL SENSITIVITY

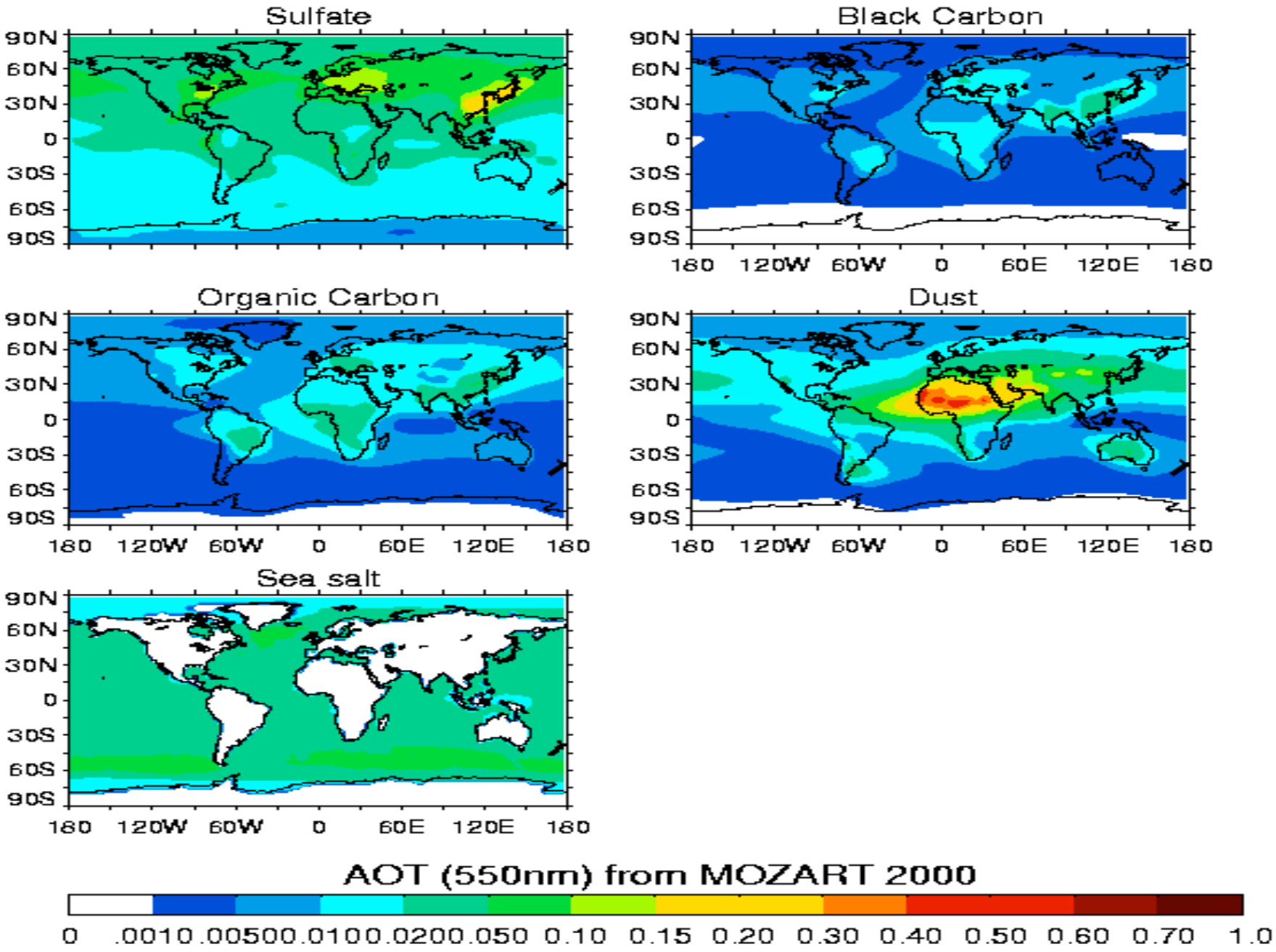
~2x

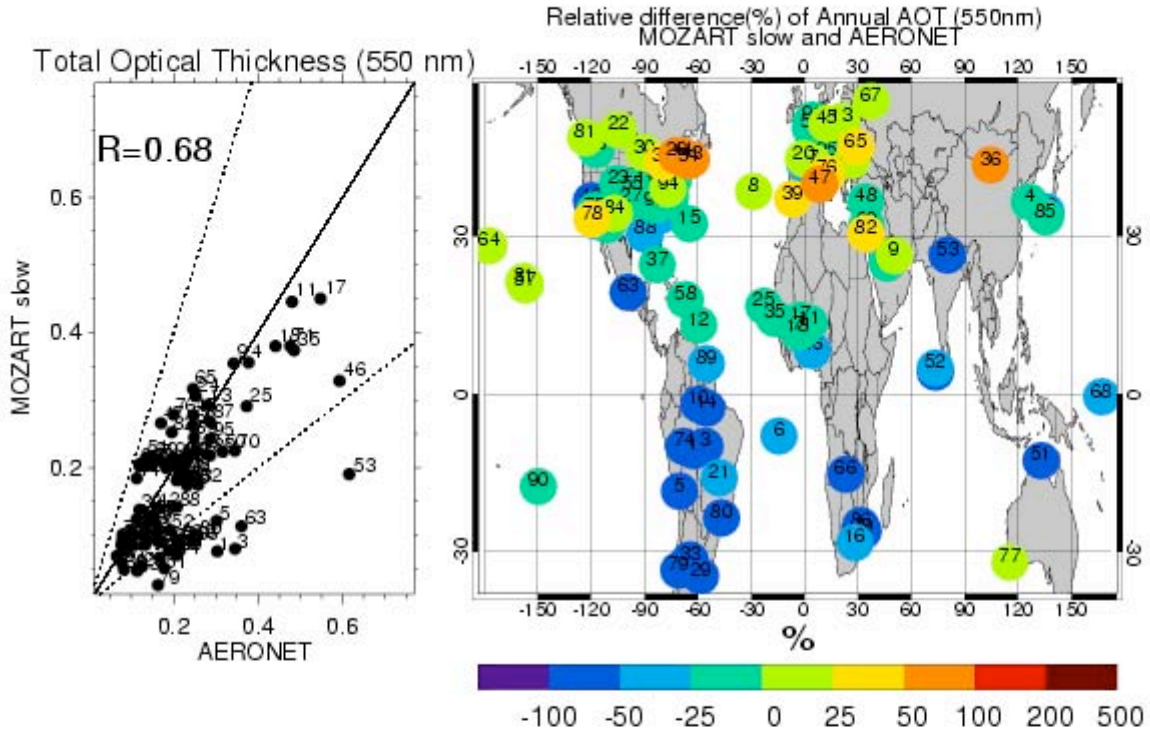
Aerosol Forcing for the GFDL IPCC simulations

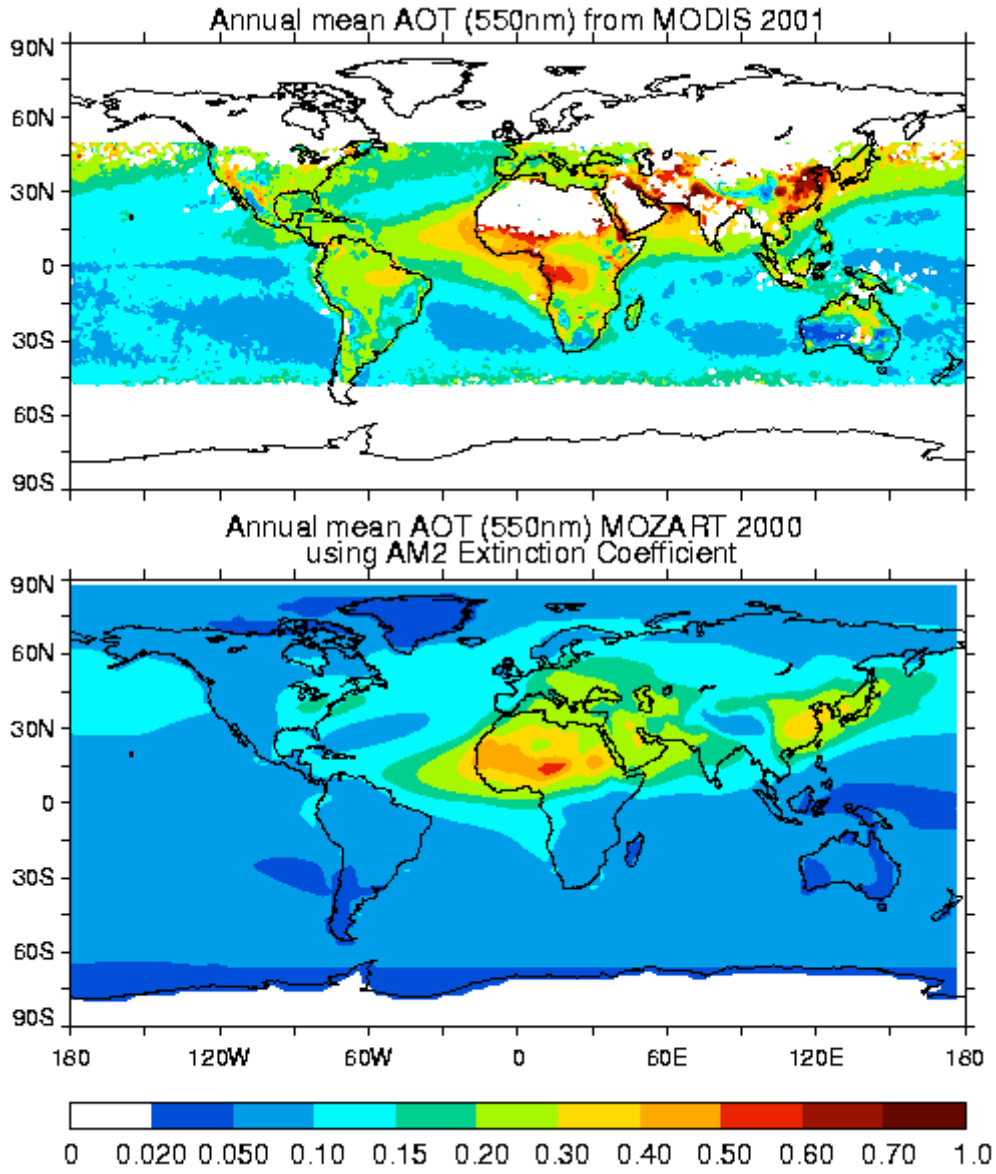

ORGANIC CARBON AEROSOL
OPTICAL DEPTH
0.022
0.02
0.018
0.016
0.014
0.012
0.01
0.008
0.006
0.004
0.002
0
60E-180 20N-70N
180-60W 20N-70N
60W-60E 20N-70N
GLOBAL
1870 1880 1890 1900 1910 1920 1930 1940 1950 1960 1970 1980 1990

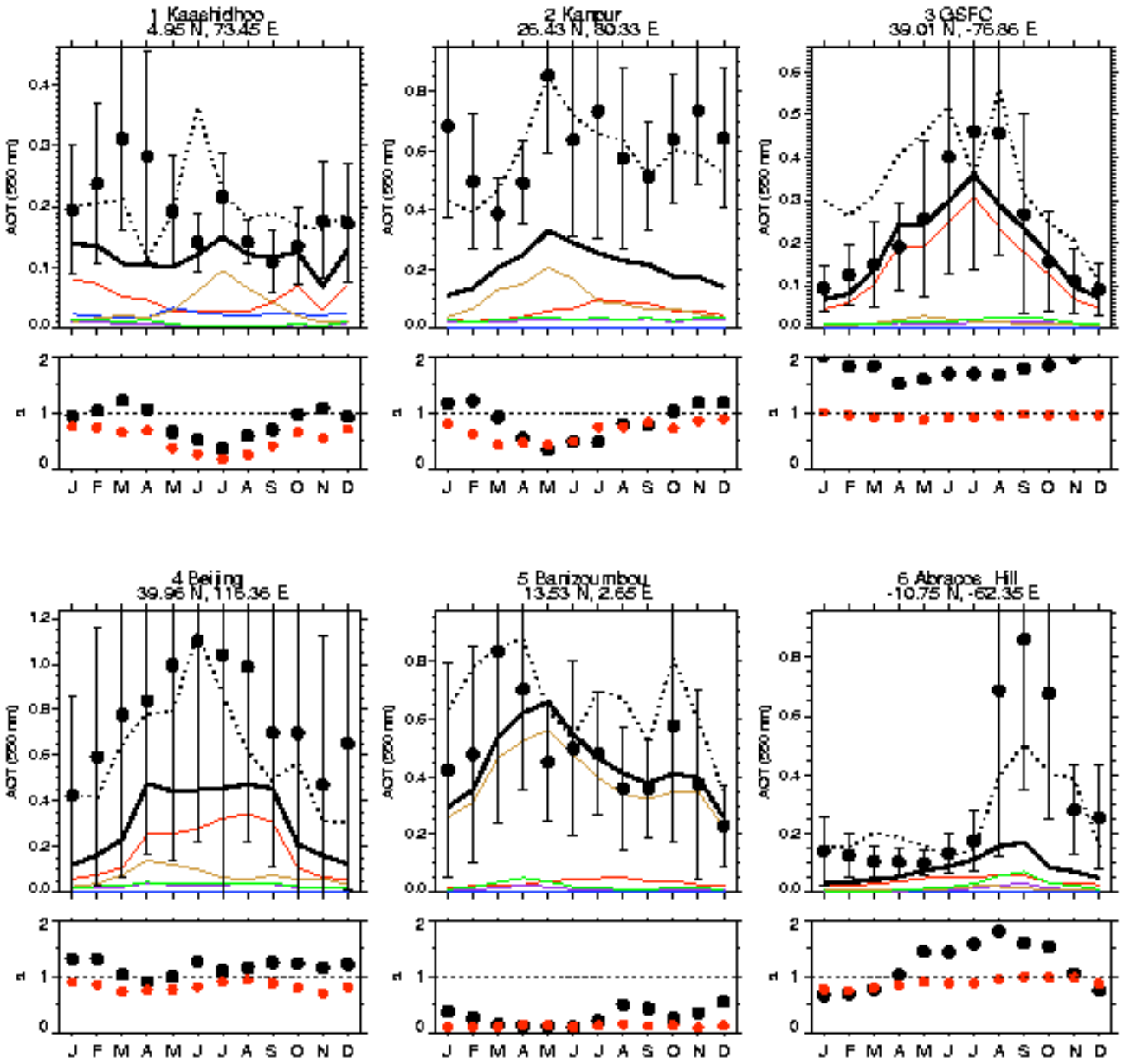

SULFATE AEROSOL
60E–180 20N–70N
180–60W 20N–70N
60W–60E 20N–70N
GLOBAL
OPTICAL DEPTH
0.24
0.21
0.18
0.15
0.12
0.09
0.06
0.03
0
1870 1880 1890 1900 1910 1920 1930 1940 1950 1960 1970 1980 1990
BLACK CARBON AEROSOL
60E–180 20N–70N
180–60W 20N–70N
60W–60E 20N–70N
GLOBAL
OPTICAL DEPTH
0.02
0.018
0.016
0.014
0.012
0.01
0.008
0.006
0.004
0.002
0
−0.002
1870 1880 1890 1900 1910 1920 1930 1940 1950 1960 1970 1980 1990

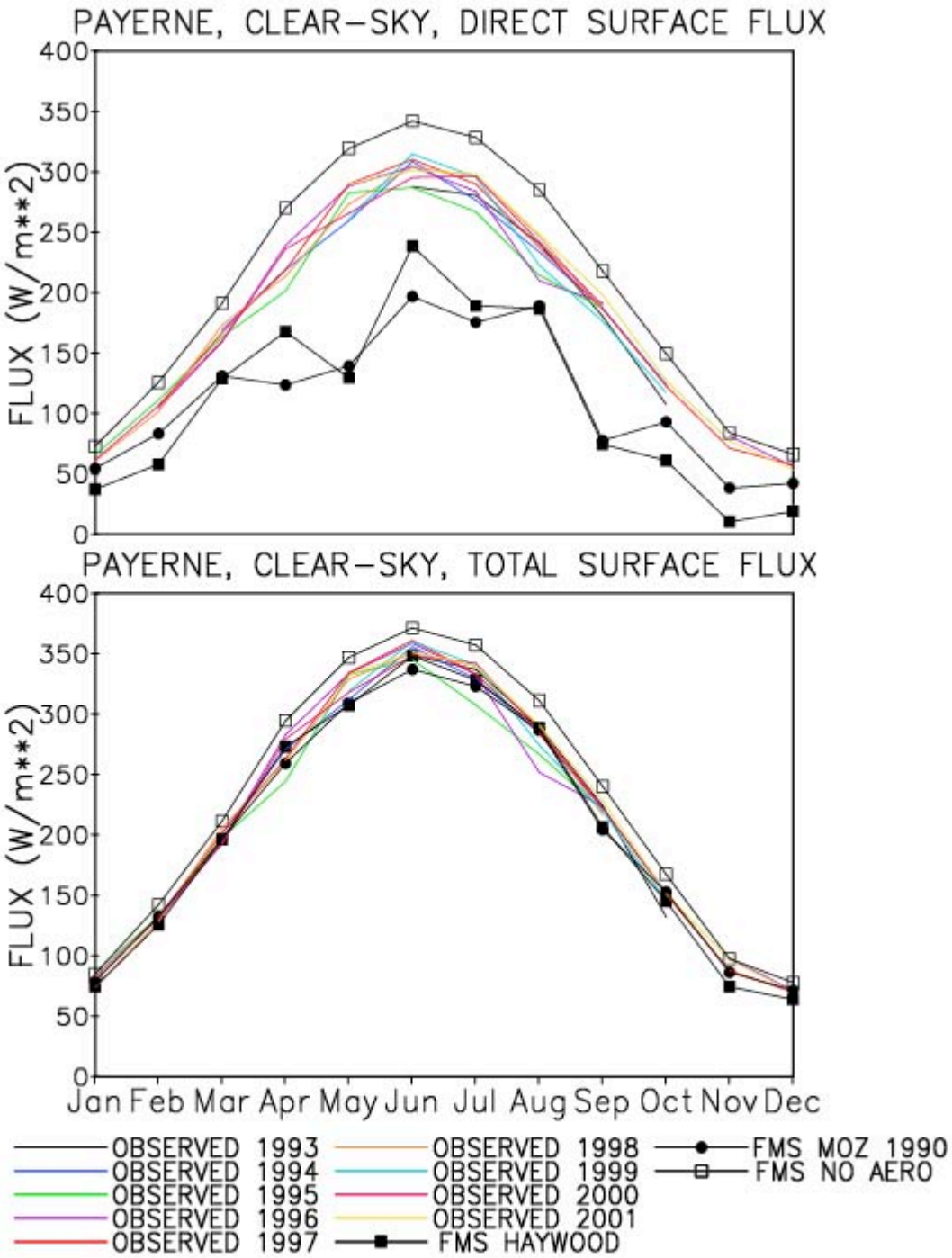

TOTAL AEROSOL
OPTICAL DEPTH
60E-180 20N-70N
180-60W 20N-70N
60W-60E 20N-70N
GLOBAL
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
1870 1880 1890 1900 1910 1920 1930 1940 1950 1960 1970 1980 1990
VOLCANIC AEROSOL
OPTICAL DEPTH
60E-180 20N-70N
180-60W 20N-70N
60W-60E 20N-70N
GLOBAL
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
1870 1880 1890 1900 1910 1920 1930 1940 1950 1960 1970 1980 1990

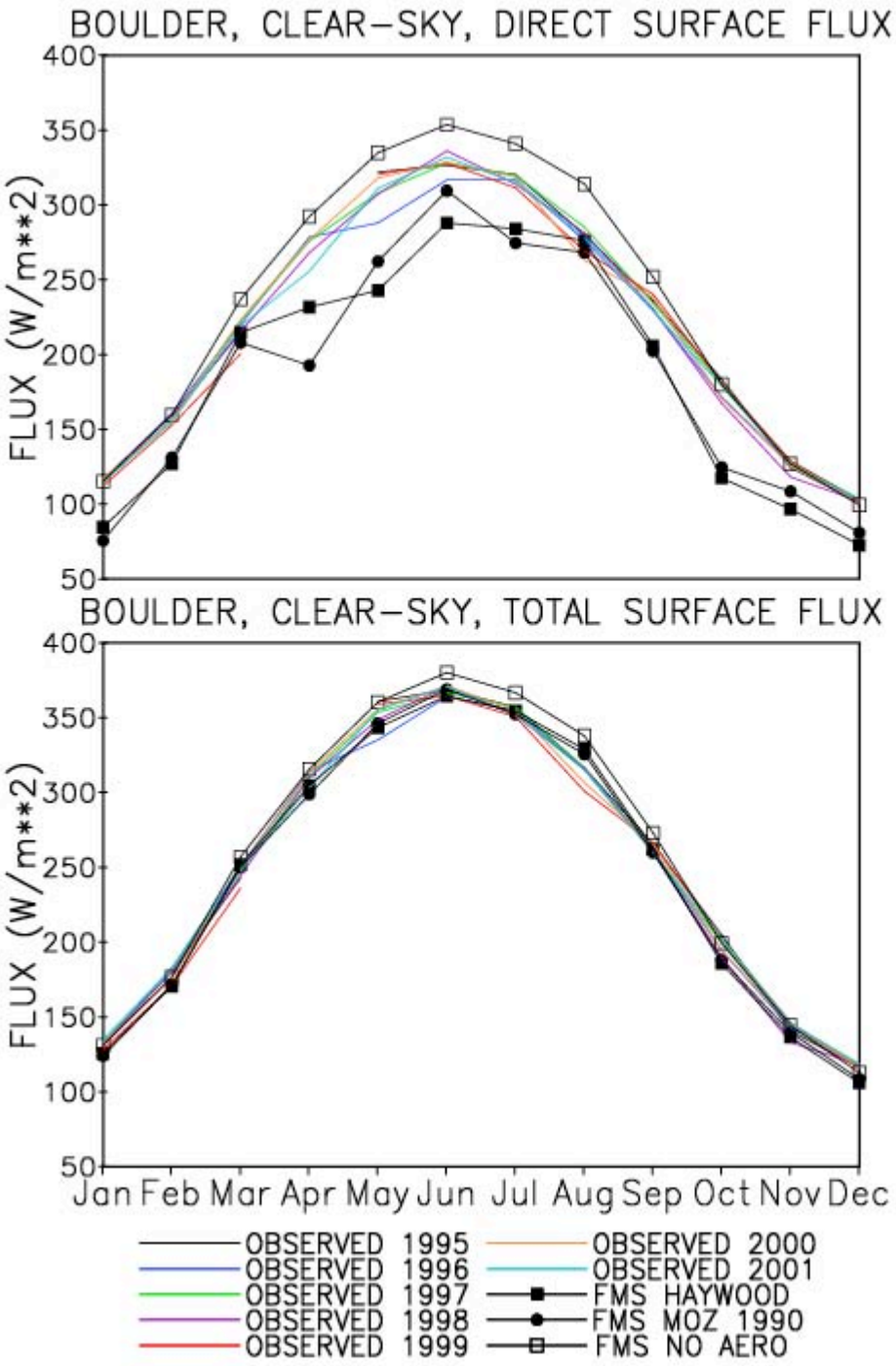

Sulfate
Black Carbon
Organic Carbon
Dust
Sea salt
90N
60N
30N
0
30S
60S
90S
180
120W
60W
0
60E
120E
180
AOT (550nm) from MOZART 2000
0
.001
0.005
0.01
0.02
0.05
0.10
0.15
0.20
0.30
0.40
0.50
0.60
0.70
1.0

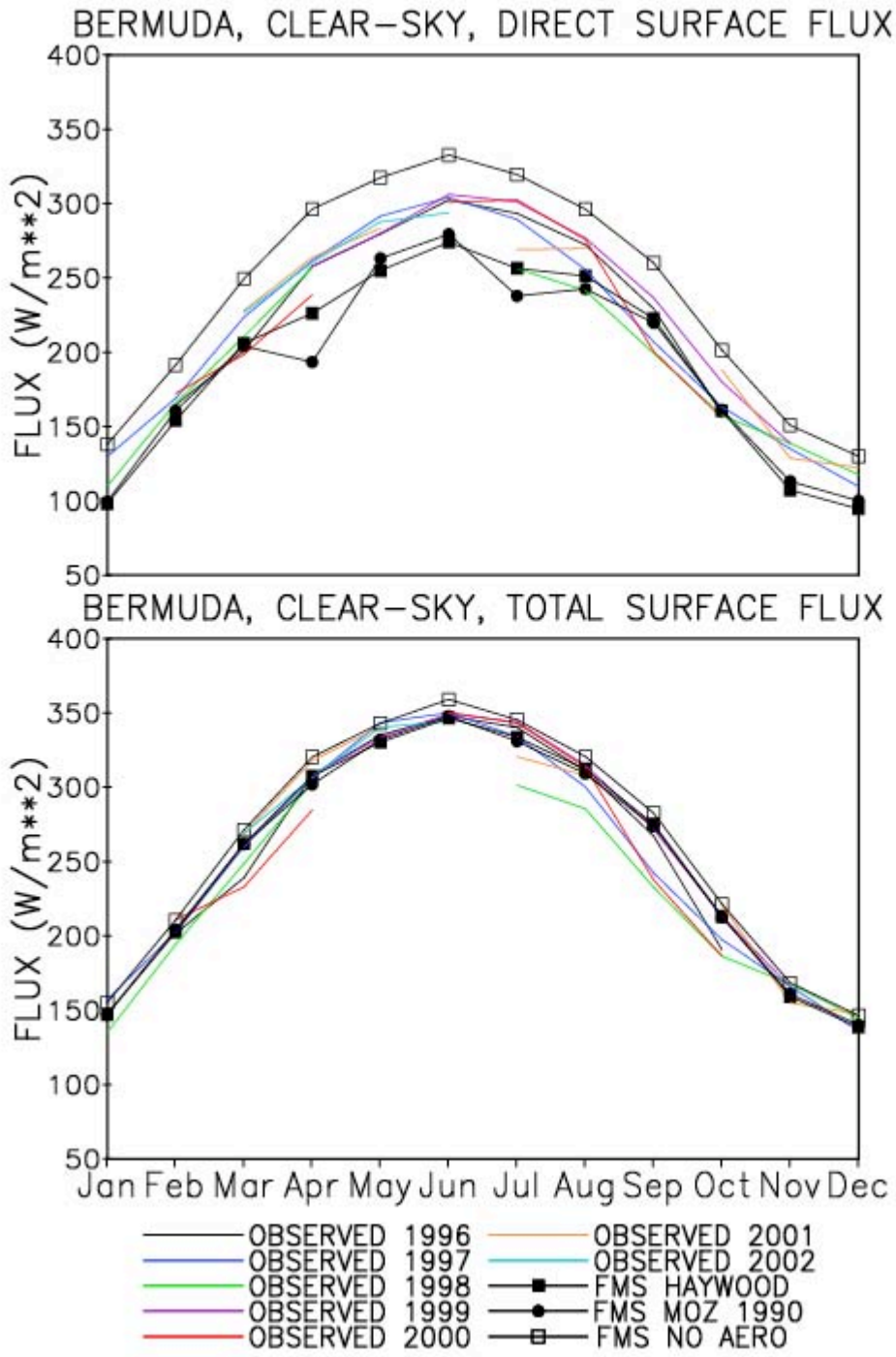

Total Optical Thickness (550 nm)
R=0.68
MOZART sbw
AERONET
0.2
0.4
0.6
Relative difference(%) of Annual AOT (550nm)
MOZART slow and AERONET
-150 -120 -90 -60 -30 0 30 60 90 120 150
30
0
-30
%
-100 -50 -25 0 25 50 100 200 500

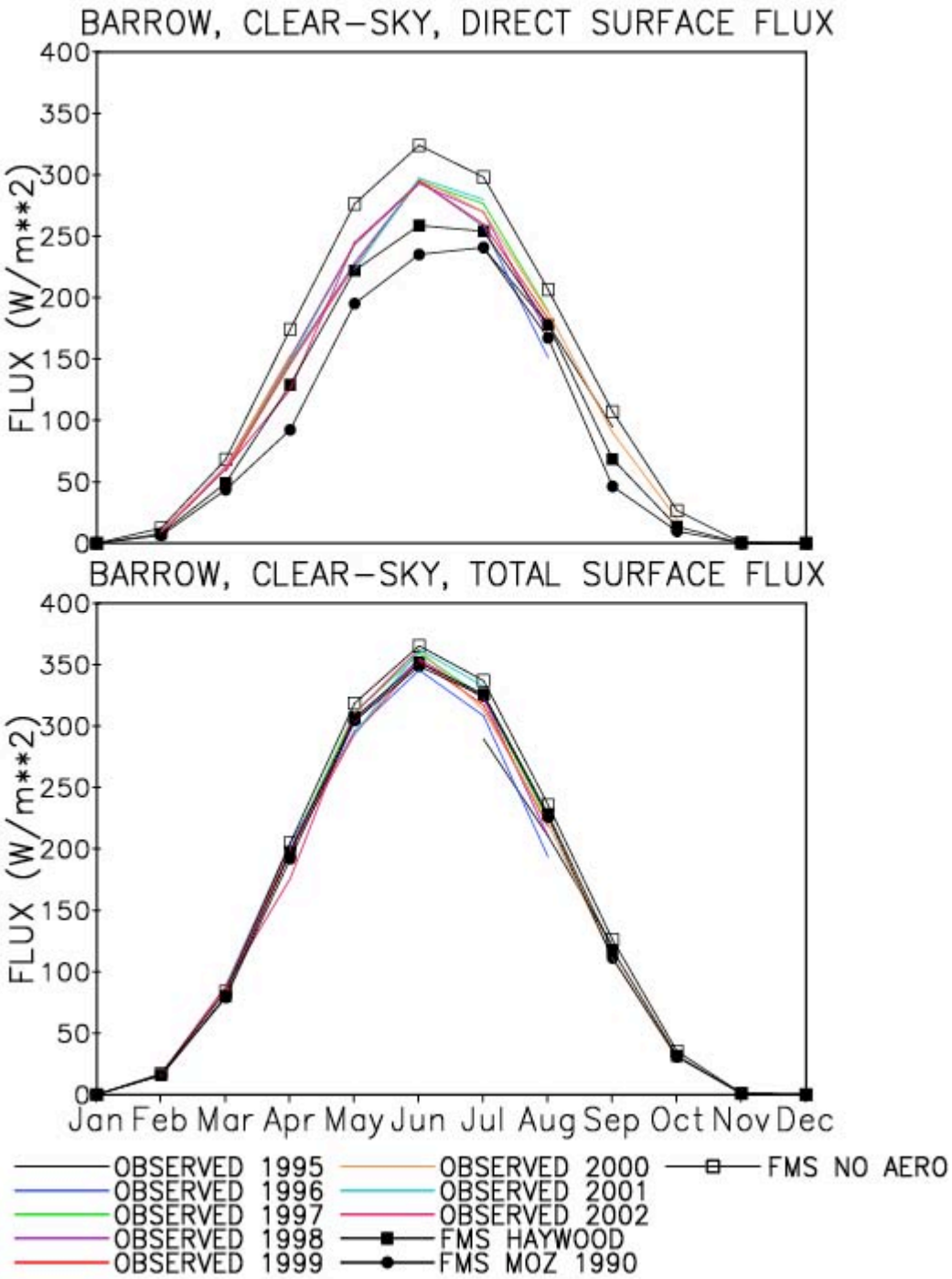

Annual mean AOT (550nm) from MODIS 2001
90N
60N
30N
0
30S
60S
90S
Annual mean AOT (550nm) MOZART 2000
using AM2 Extinction Coefficient
90N
60N
30N
0
30S
60S
90S
180
120W
60W
0
60E
120E
180
0
0.020
0.050
0.10
0.15
0.20
0.30
0.40
0.50
0.60
0.70
1.0

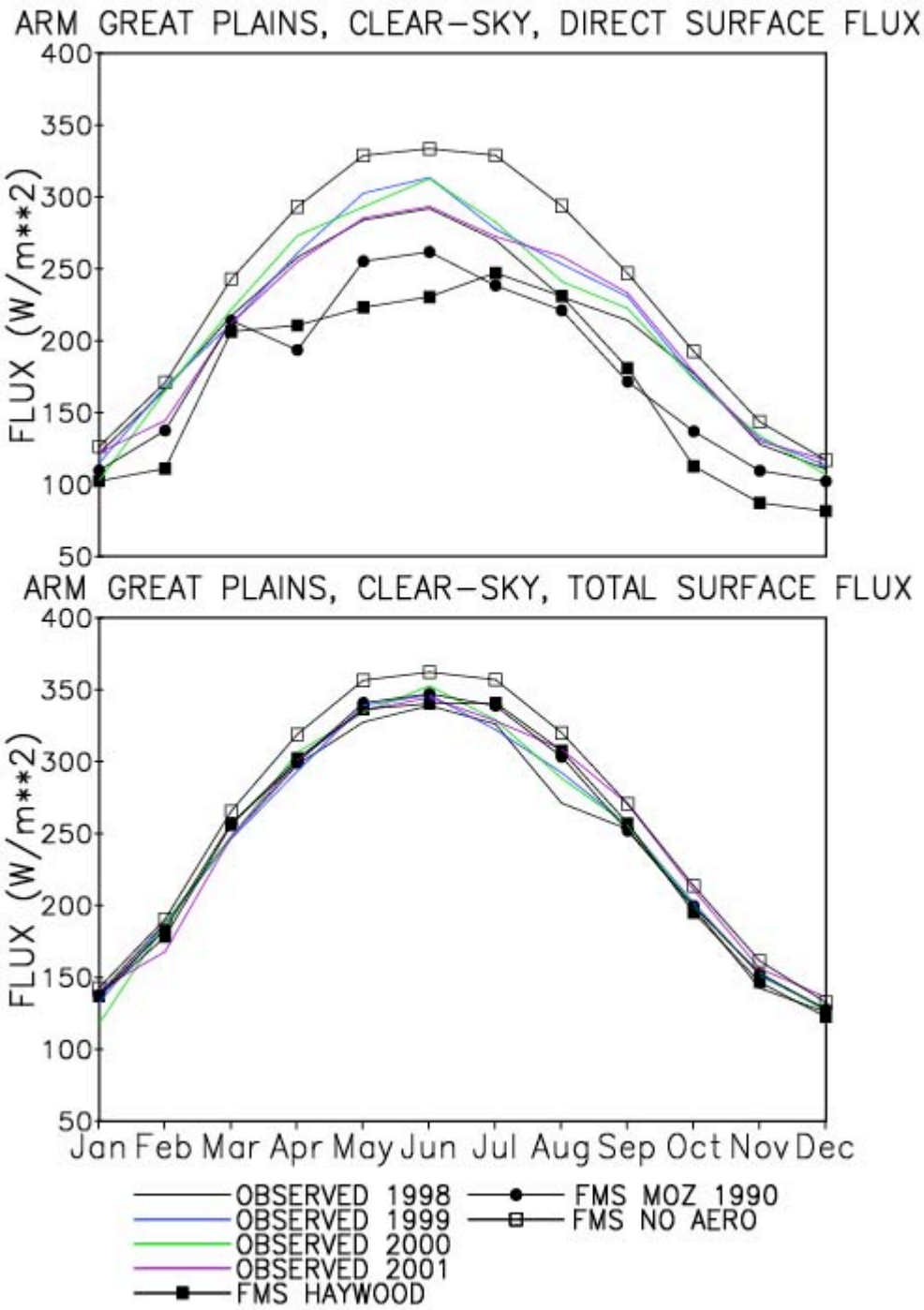

1 Kaashidhoo
4.95 N, 73.45 E
2 Kanpur
26.43 N, 80.33 E
3 GSFC
39.01 N, -76.86 E
4 Beijing
39.96 N, 116.36 E
5 Banizoumbou
13.53 N, 2.65 E
6 Abracos_Hill
-10.75 N, -62.35 E
AOT (550 nm)
α
J F M A M J J A S O N D

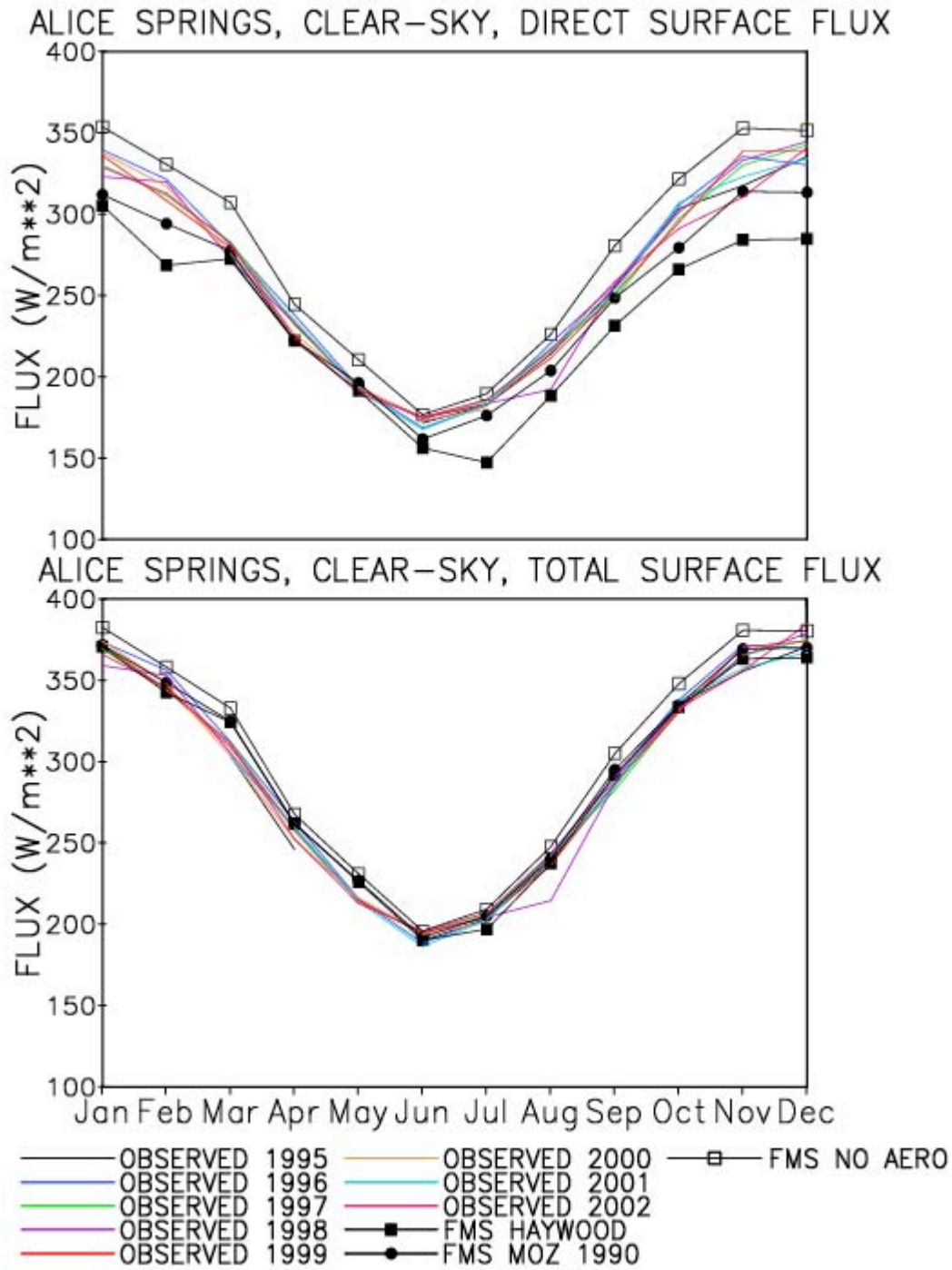

PAYERNE, CLEAR-SKY, DIRECT SURFACE FLUX
FLUX (W/m**2)
0
50
100
150
200
250
300
350
400
PAYERNE, CLEAR-SKY, TOTAL SURFACE FLUX
FLUX (W/m**2)
0
50
100
150
200
250
300
350
400
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec
OBSERVED 1993
OBSERVED 1994
OBSERVED 1995
OBSERVED 1996
OBSERVED 1997
OBSERVED 1998
OBSERVED 1999
OBSERVED 2000
OBSERVED 2001
FMS HAYWOOD
FMS MOZ 1990
FMS NO AERO


BOULDER, CLEAR-SKY, DIRECT SURFACE FLUX
FLUX (W/m**2)
400
350
300
250
200
150
100
50
BOULDER, CLEAR-SKY, TOTAL SURFACE FLUX
FLUX (W/m**2)
400
350
300
250
200
150
100
50
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec
OBSERVED 1995
OBSERVED 1996
OBSERVED 1997
OBSERVED 1998
OBSERVED 1999
OBSERVED 2000
OBSERVED 2001
FMS HAYWOOD
FMS MOZ 1990
FMS NO AERO


BERMUDA, CLEAR-SKY, DIRECT SURFACE FLUX
FLUX (W/m**2)
400
350
300
250
200
150
100
50
BERMUDA, CLEAR-SKY, TOTAL SURFACE FLUX
FLUX (W/m**2)
400
350
300
250
200
150
100
50
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec
OBSERVED 1996
OBSERVED 1997
OBSERVED 1998
OBSERVED 1999
OBSERVED 2000
OBSERVED 2001
OBSERVED 2002
FMS HAYWOOD
FMS MOZ 1990
FMS NO AERO

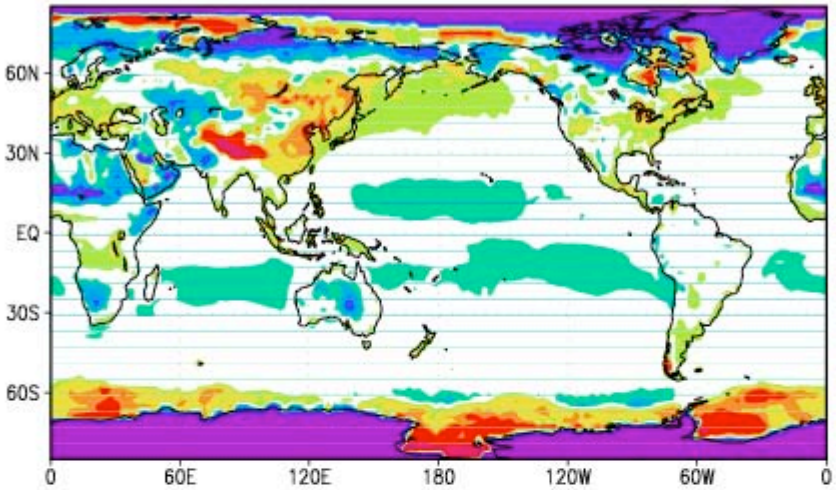

BARROW, CLEAR-SKY, DIRECT SURFACE FLUX
FLUX (W/m**2)
400
350
300
250
200
150
100
50
0
BARROW, CLEAR-SKY, TOTAL SURFACE FLUX
FLUX (W/m**2)
400
350
300
250
200
150
100
50
0
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec
OBSERVED 1995
OBSERVED 1996
OBSERVED 1997
OBSERVED 1998
OBSERVED 1999
OBSERVED 2000
OBSERVED 2001
OBSERVED 2002
FMS HAYWOOD
FMS MOZ 1990
FMS NO AERO


ARM GREAT PLAINS, CLEAR-SKY, DIRECT SURFACE FLUX
FLUX (W/m**2)
400
350
300
250
200
150
100
50
ARM GREAT PLAINS, CLEAR-SKY, TOTAL SURFACE FLUX
FLUX (W/m**2)
400
350
300
250
200
150
100
50
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec
OBSERVED 1998
OBSERVED 1999
OBSERVED 2000
OBSERVED 2001
FMS HAYWOOD
FMS MOZ 1990
FMS NO AERO


ALICE SPRINGS, CLEAR-SKY, DIRECT SURFACE FLUX
FLUX (W/m**2)
400
350
300
250
200
150
100
ALICE SPRINGS, CLEAR-SKY, TOTAL SURFACE FLUX
FLUX (W/m**2)
400
350
300
250
200
150
100
Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec
OBSERVED 1995
OBSERVED 1996
OBSERVED 1997
OBSERVED 1998
OBSERVED 1999
OBSERVED 2000
OBSERVED 2001
OBSERVED 2002
FMS HAYWOOD
FMS MOZ 1990
FMS NO AERO

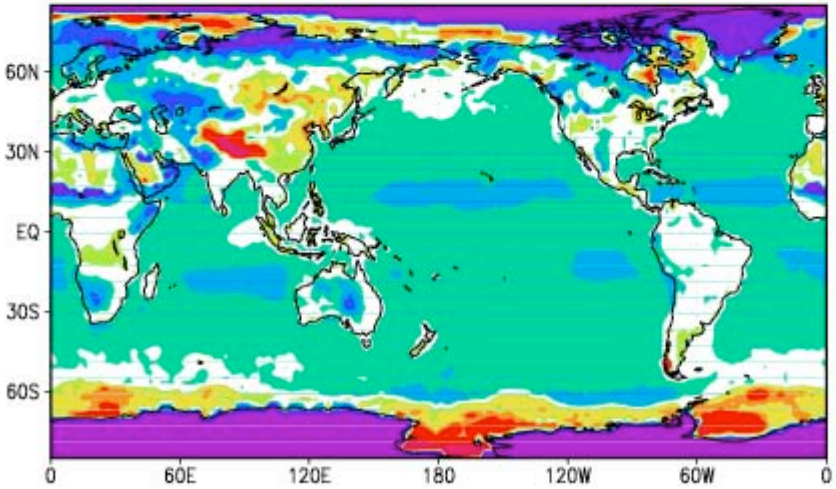
CLEAR−SKY REFLECTED AT TOA, MODEL−ERBE

WITH AEROSOLS (MOZART 1990, SLOW WET DEP)

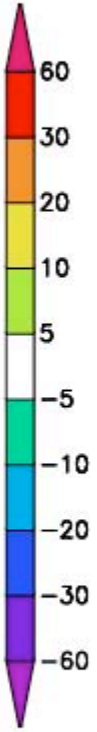


GLOBAL = −2.86 W/m2

WITHOUT AEROSOLS

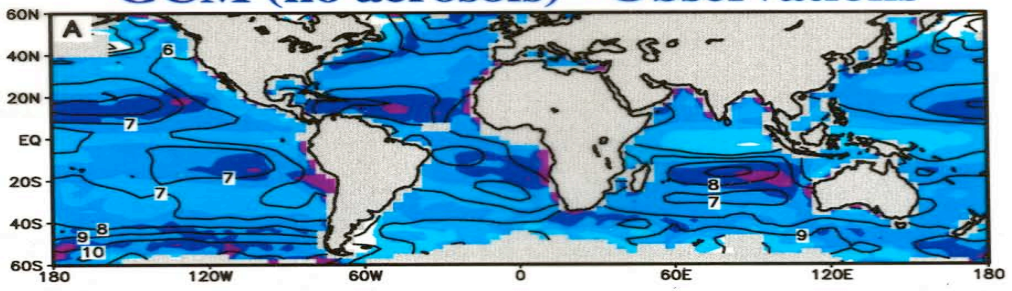


GLOBAL = −7.63 W/m2

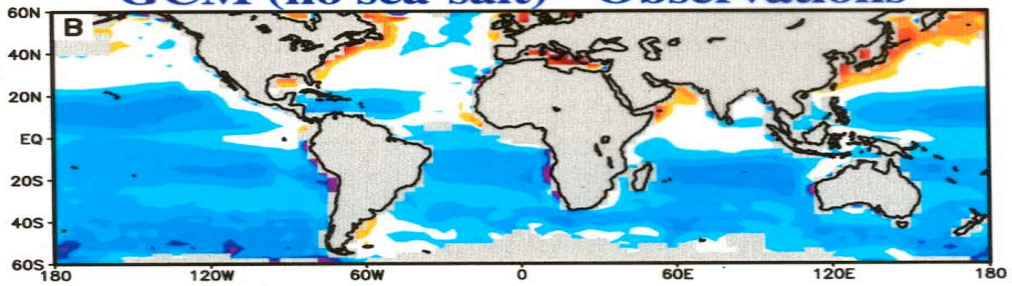


Tropospheric Aerosol Climate Forcing in Reflected Solar Radiation: A Comparison of Observations and GCM Simulations

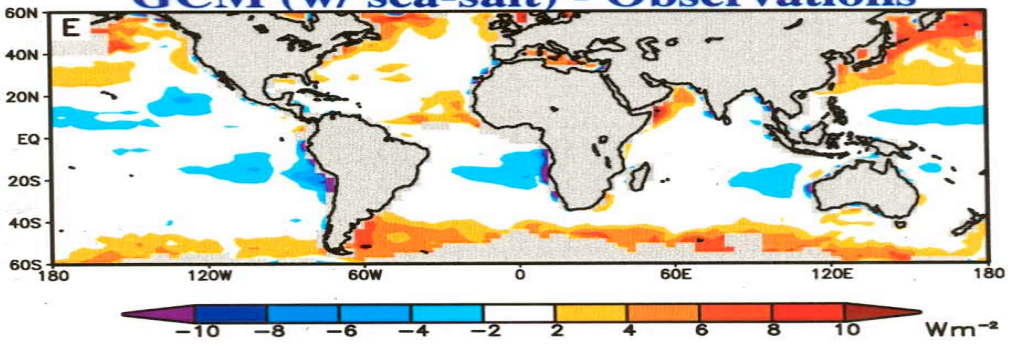
GCM (no aerosols) - Observations



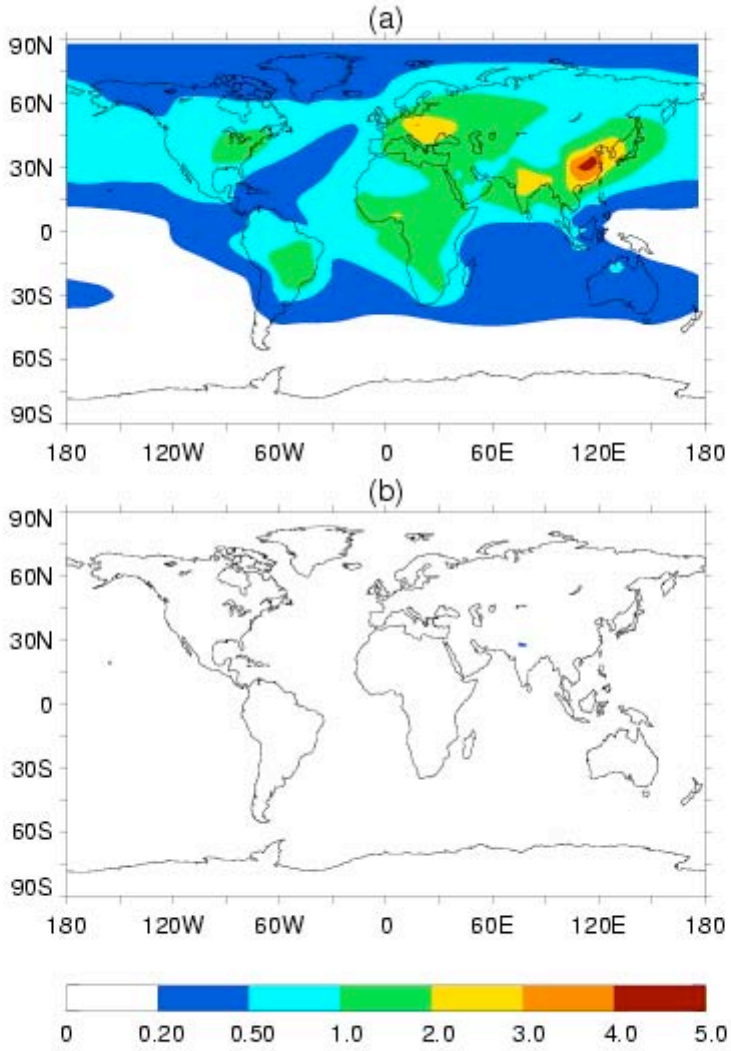
GCM (no sea-salt) - Observations

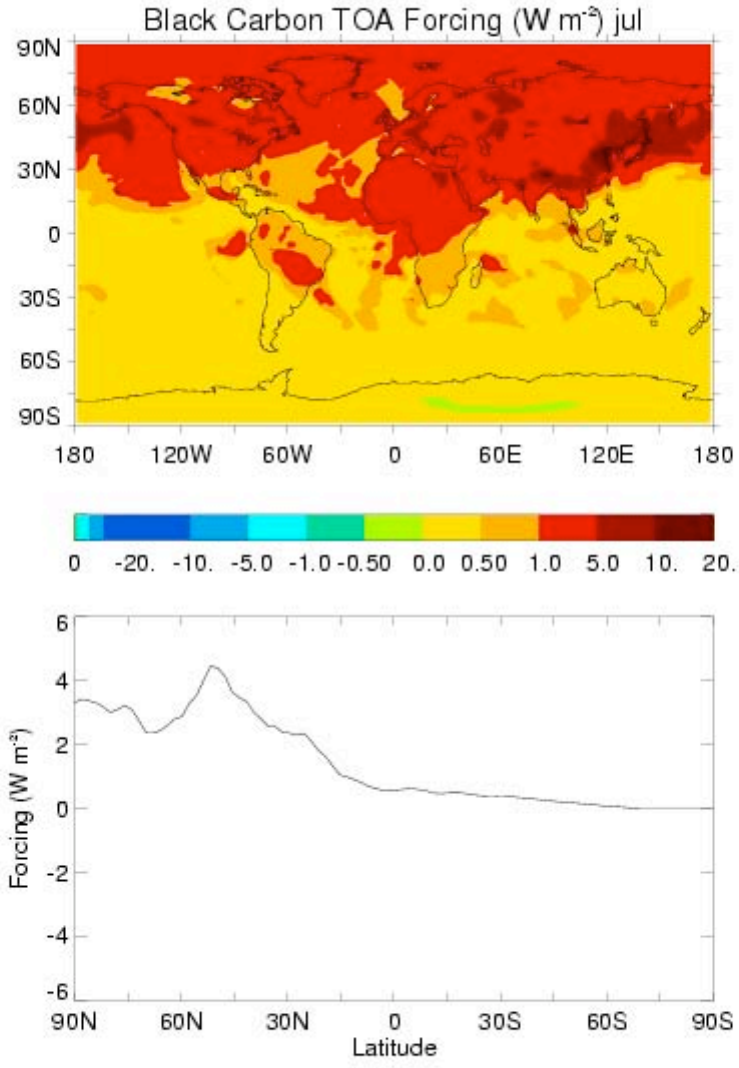


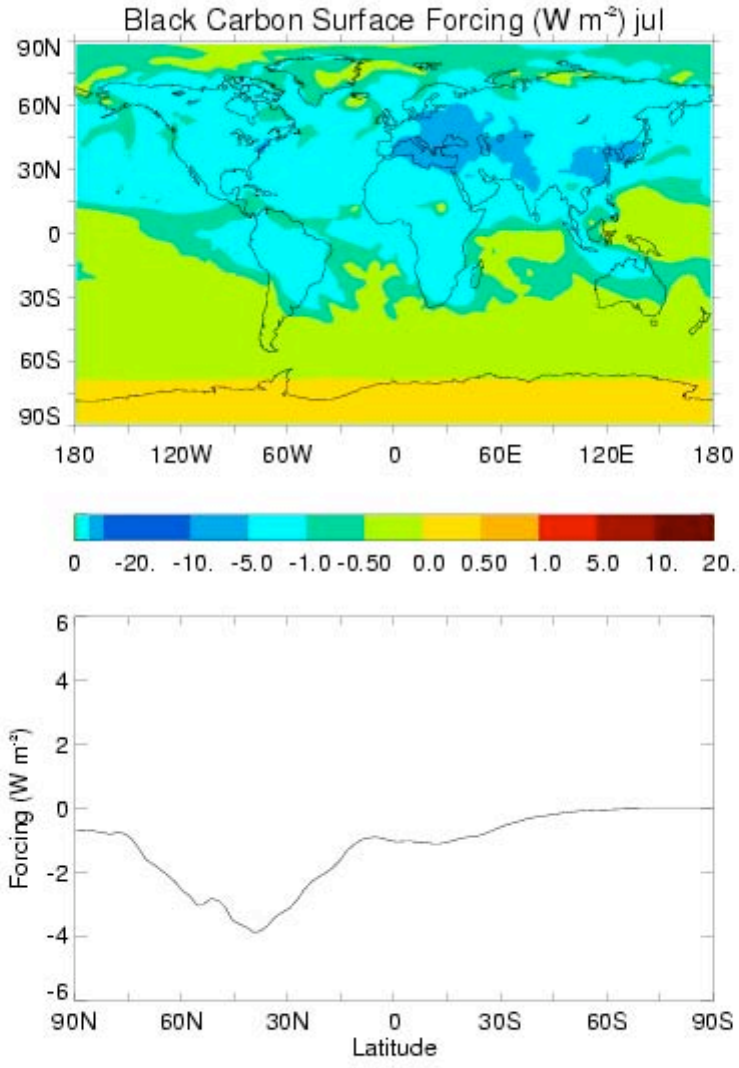
GCM (w/ sea-salt) - Observations

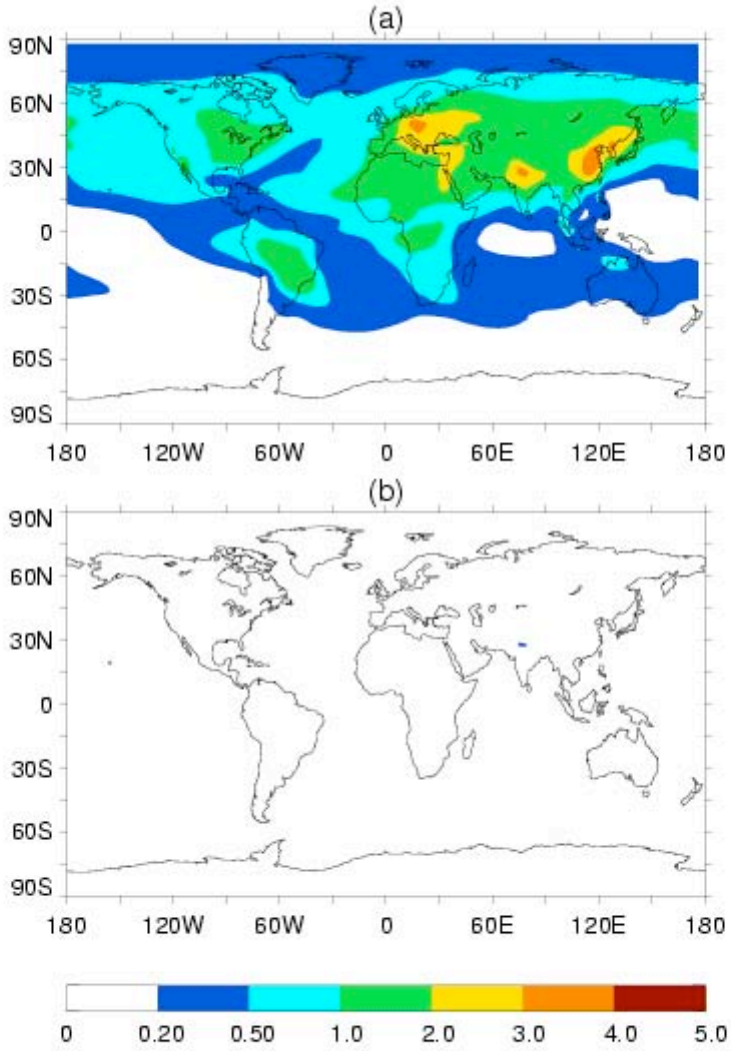


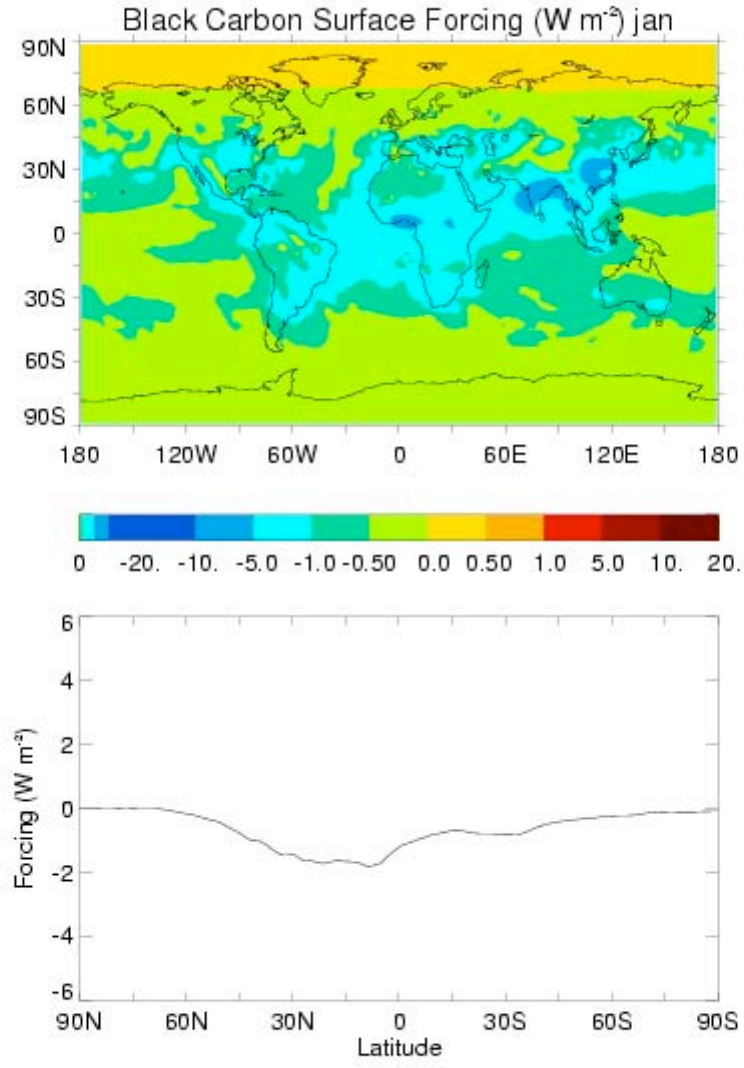
☛ Spatial signatures and magnitude of clear-sky aerosol radiative forcing identified through satellite/model comparison. Sea-salt is a leading contributor.

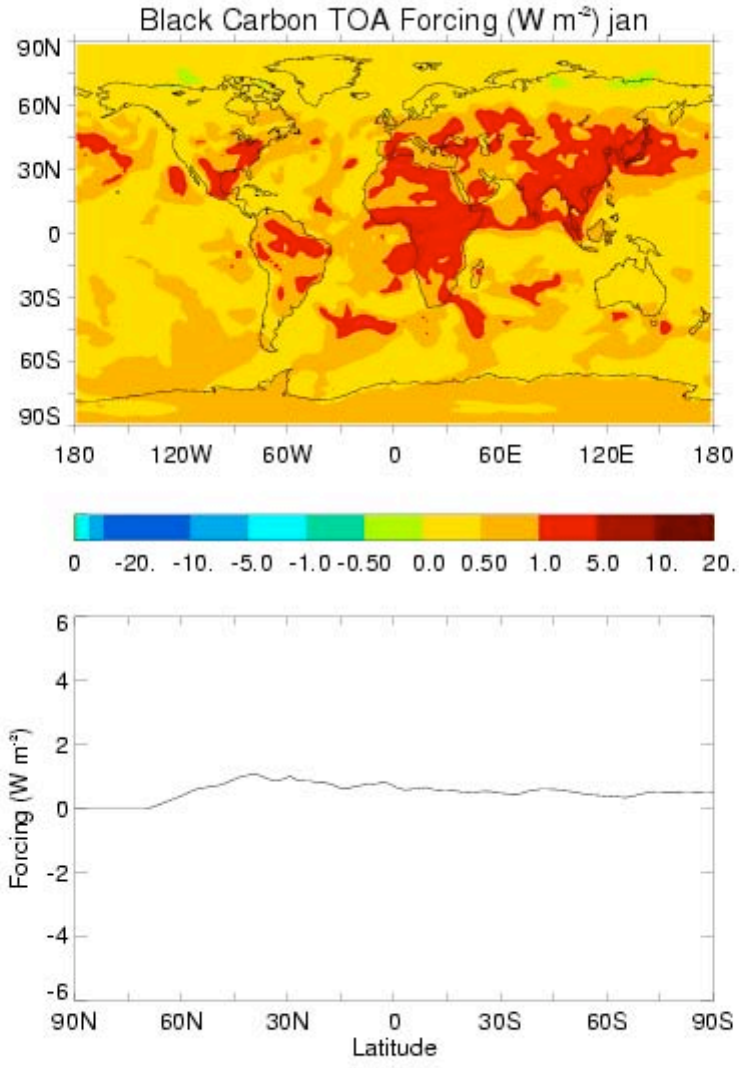

(a)
90N
60N
30N
0
30S
60S
90S
180
120W
60W
0
60E
120E
180
(b)
90N
60N
30N
0
30S
60S
90S
180
120W
60W
0
60E
120E
180
0
0.20
0.50
1.0
2.0
3.0
4.0
5.0


Black Carbon TOA Forcing (W m-2) jul
90N
60N
30N
0
30S
60S
90S
180
120W
60W
0
60E
120E
180
0
-20.
-10.
-5.0
-1.0
-0.50
0.0
0.50
1.0
5.0
10.
20.
6
4
2
0
-2
-4
-6
Forcing (W m-2)
90N
60N
30N
0
30S
60S
90S
Latitude

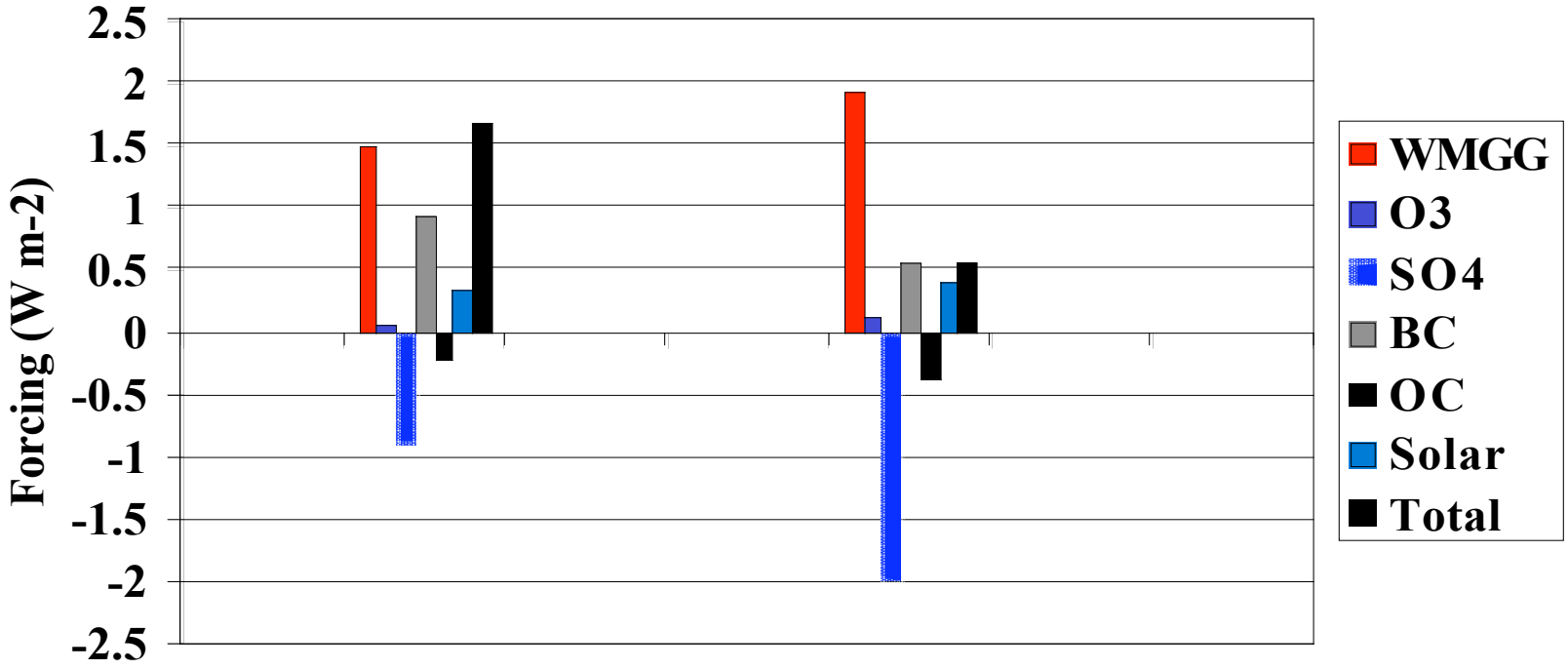

Black Carbon Surface Forcing (W m-2) jul
90N
60N
30N
0
30S
60S
90S
180
120W
60W
0
60E
120E
180
0
-20.
-10.
-5.0
-1.0
-0.50
0.0
0.50
1.0
5.0
10.
20.
6
4
2
0
-2
-4
-6
Forcing (W m-2)
90N
60N
30N
0
30S
60S
90S
Latitude

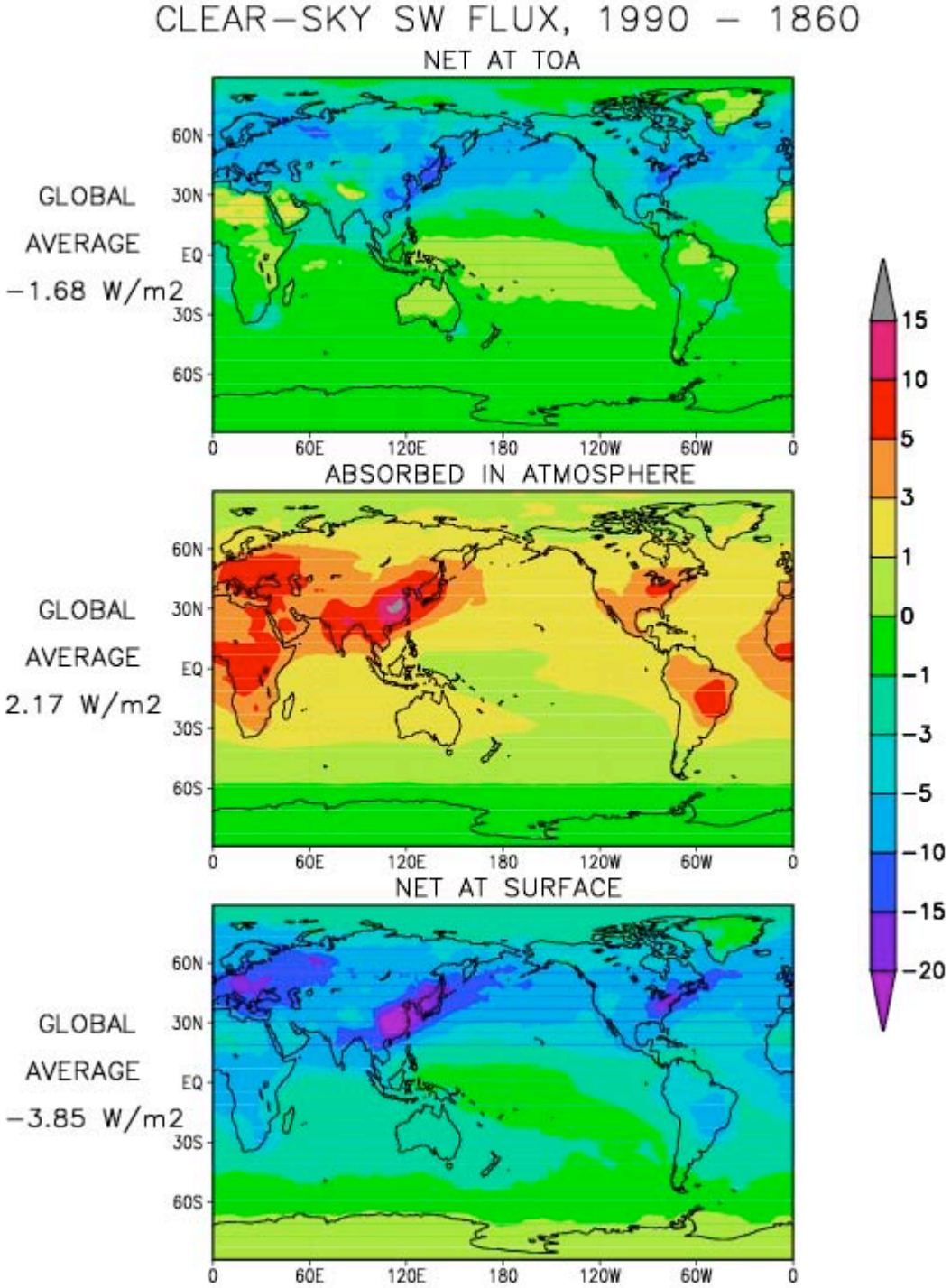

(a)
90N
60N
30N
0
30S
60S
90S
180
120W
60W
0
60E
120E
180
(b)
90N
60N
30N
0
30S
60S
90S
180
120W
60W
0
60E
120E
180
0
0.20
0.50
1.0
2.0
3.0
4.0
5.0

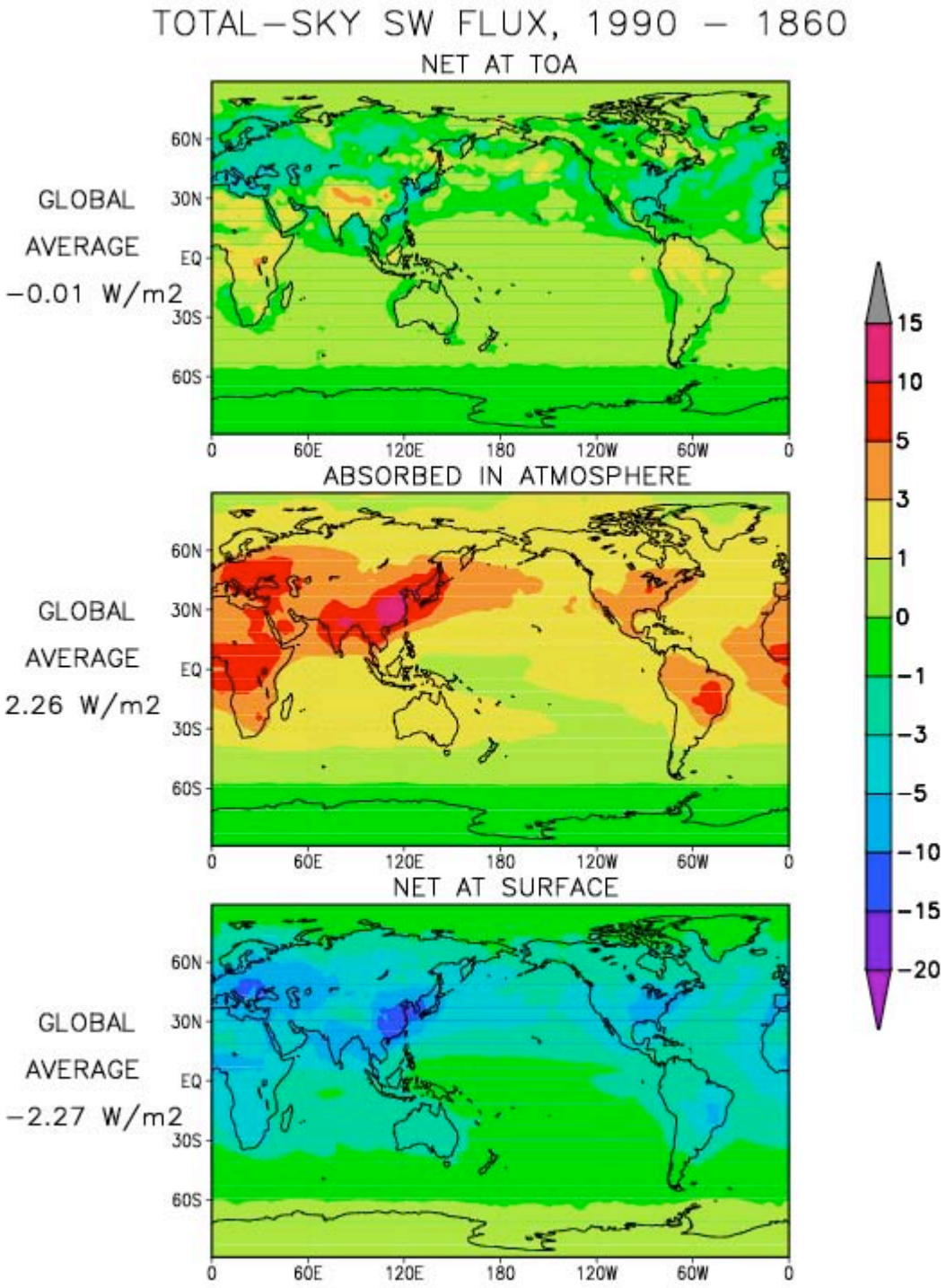

Black Carbon Surface Forcing (W m-2) jan
90N
60N
30N
0
30S
60S
90S
180
120W
60W
0
60E
120E
180
0
-20.
-10.
-5.0
-1.0
-0.50
0.0
0.50
1.0
5.0
10.
20.
6
4
2
0
-2
-4
-6
Forcing (W m-2)
90N
60N
30N
0
30S
60S
90S
Latitude

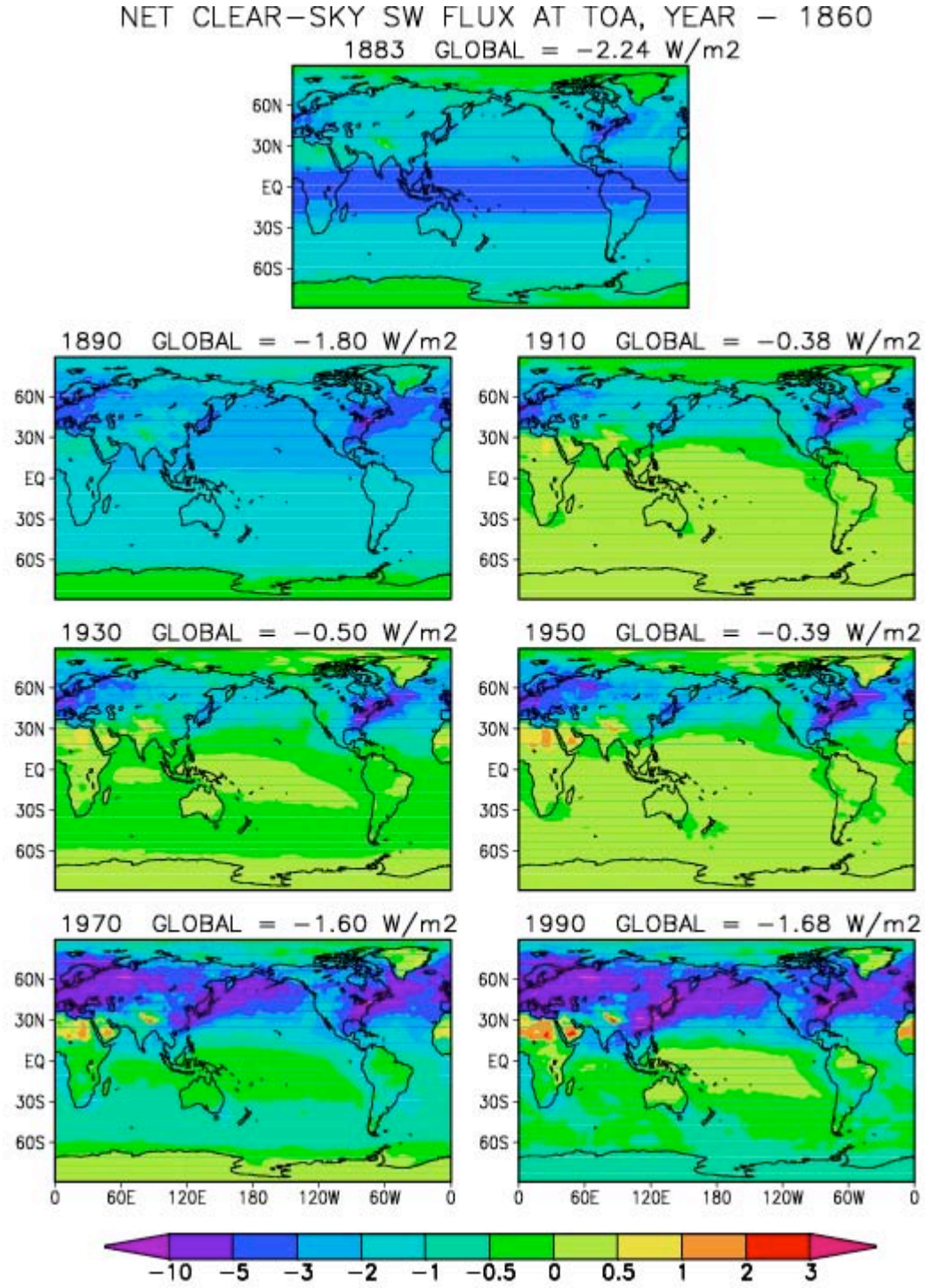

Black Carbon TOA Forcing (W m-2) jan
90N
60N
30N
0
30S
60S
90S
180
120W
60W
0
60E
120E
180
0
-20.
-10.
-5.0
-1.0
-0.50
0.0
0.50
1.0
5.0
10.
20.
6
4
2
0
-2
-4
-6
Forcing (W m-2)
90N
60N
30N
0
30S
60S
90S
Latitude

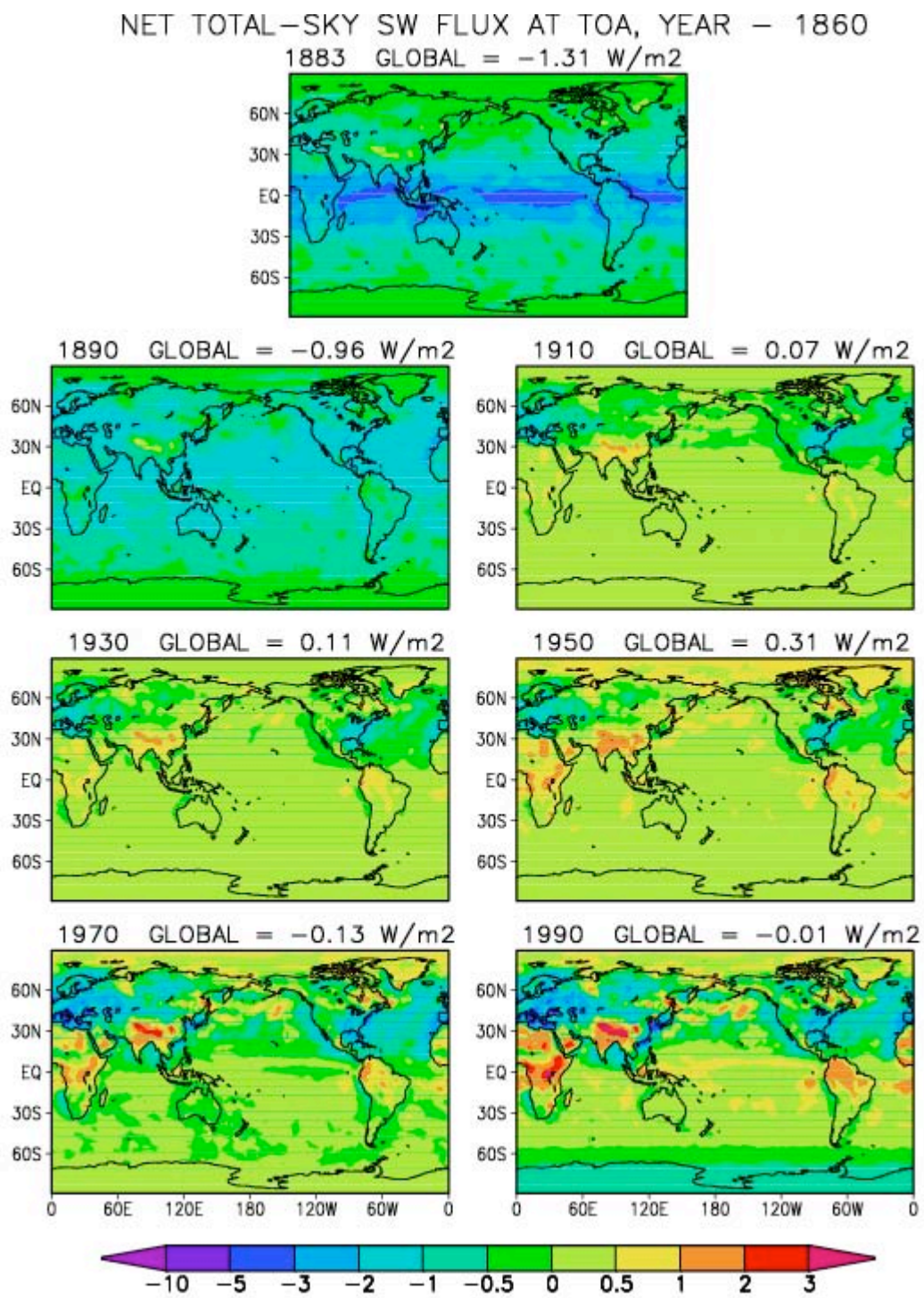
Global-annual-mean forcing TOA [1990 – 1860]

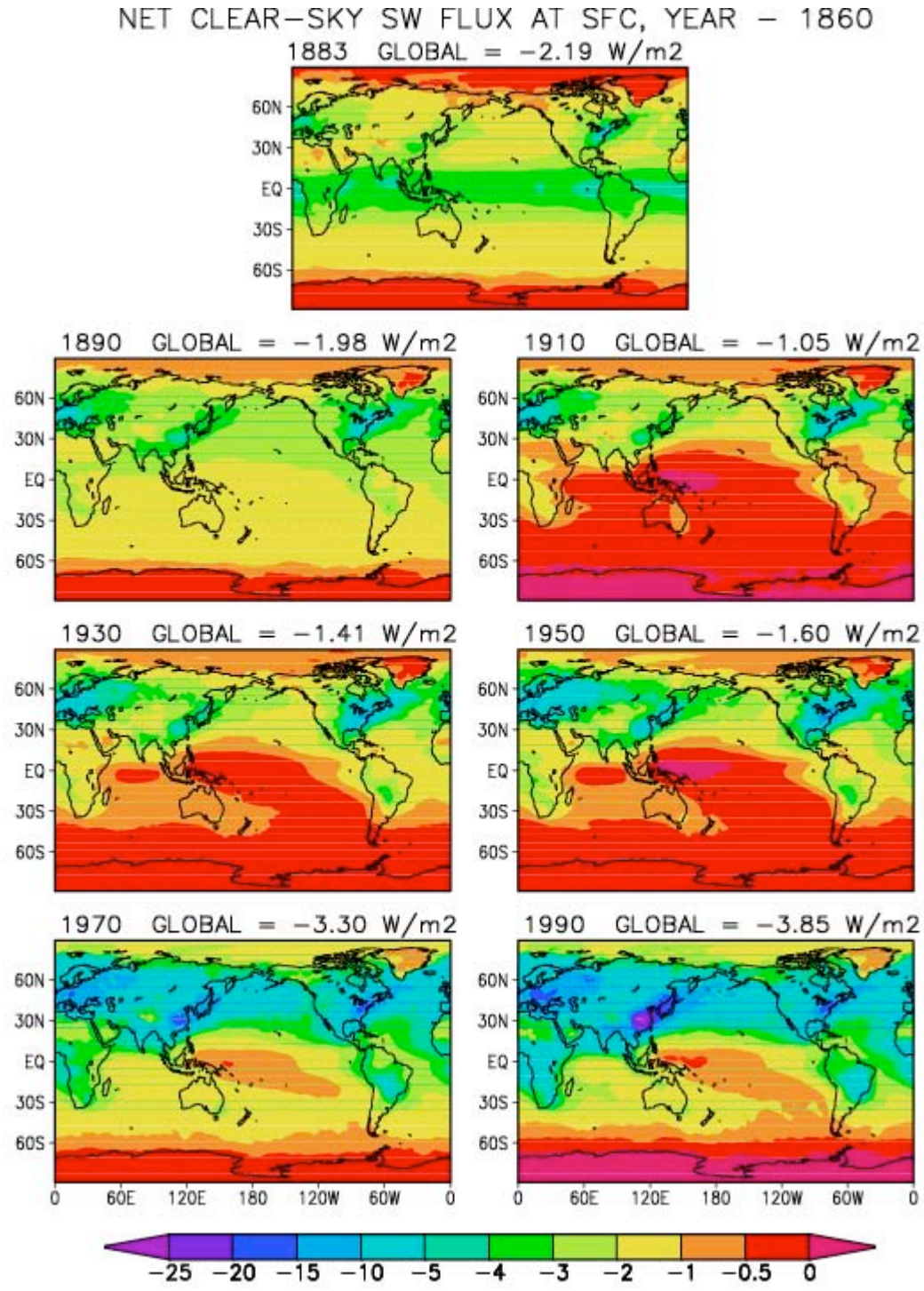


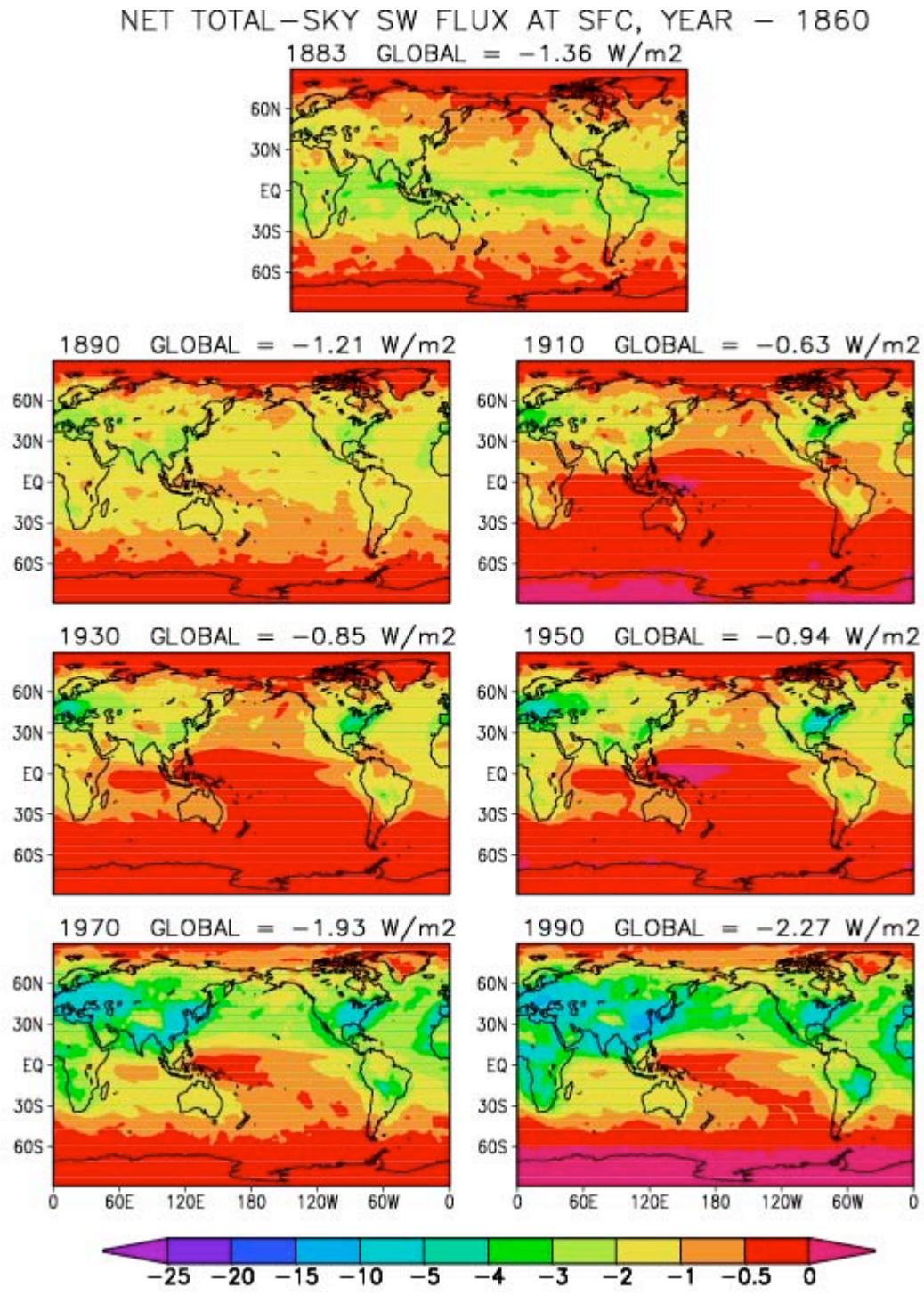

CLEAR–SKY SW FLUX, 1990 – 1860
NET AT TOA
GLOBAL
AVERAGE
–1.68 W/m2
ABSORBED IN ATMOSPHERE
GLOBAL
AVERAGE
2.17 W/m2
NET AT SURFACE
GLOBAL
AVERAGE
–3.85 W/m2
60N
30N
EQ
30S
60S
0
60E
120E
180
120W
60W
15
10
5
3
1
0
–1
–3
–5
–10
–15
–20

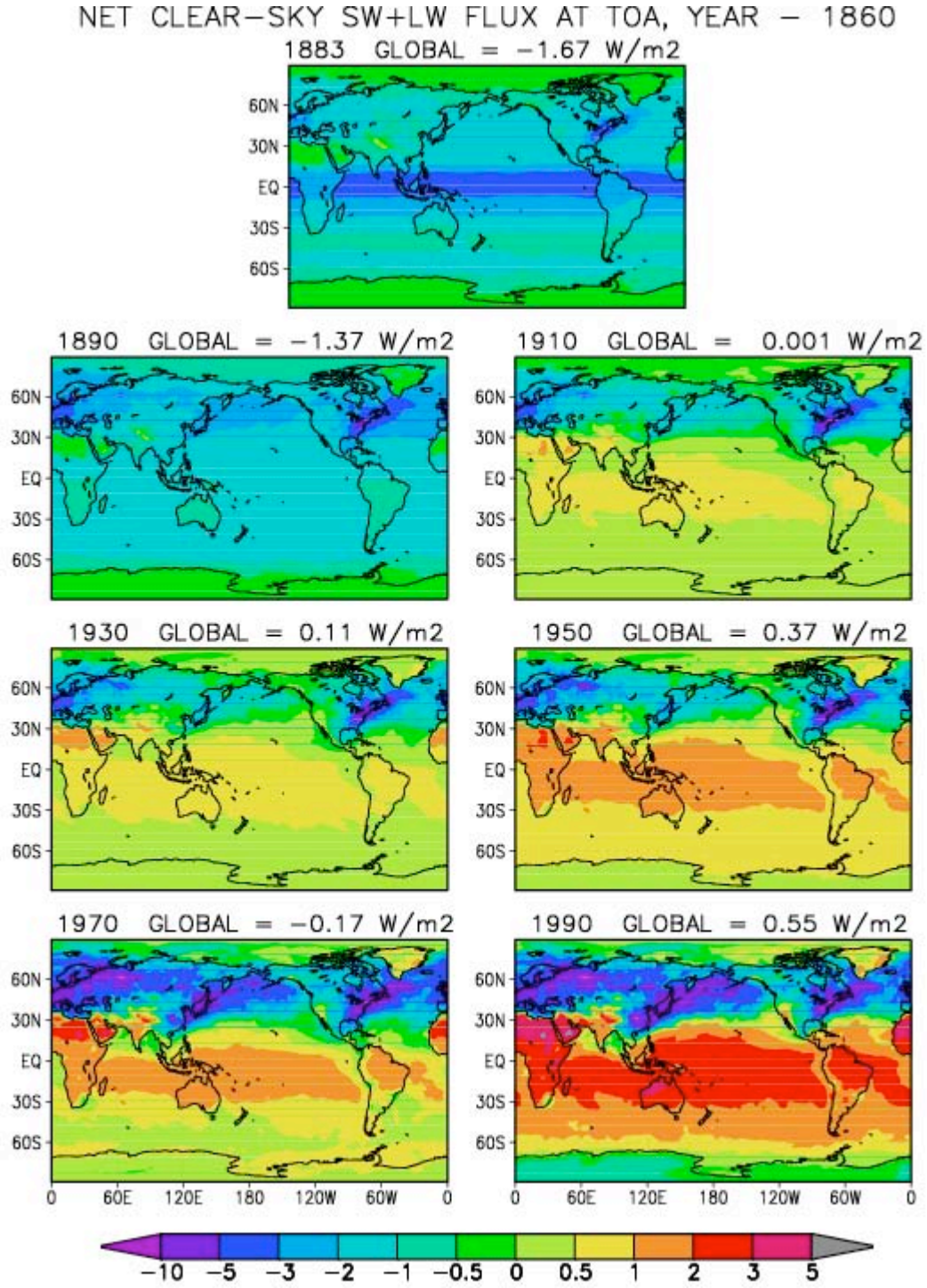

TOTAL−SKY SW FLUX, 1990 − 1860
NET AT TOA
GLOBAL
AVERAGE
−0.01 W/m2
ABSORBED IN ATMOSPHERE
GLOBAL
AVERAGE
2.26 W/m2
NET AT SURFACE
GLOBAL
AVERAGE
−2.27 W/m2
60N
30N
EQ
30S
60S
0
60E
120E
180
120W
60W
15
10
5
3
1
0
−1
−3
−5
−10
−15
−20

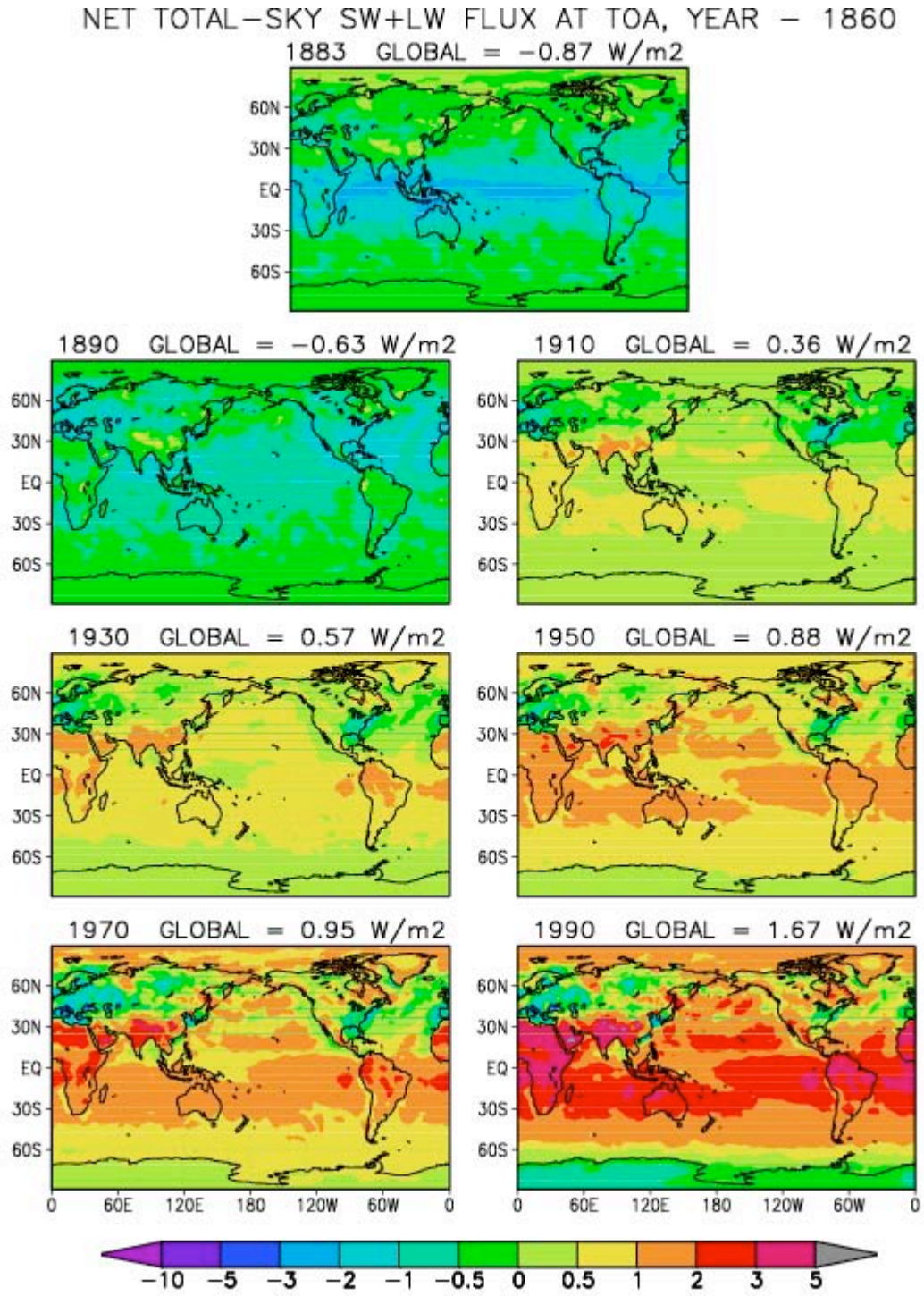

NET CLEAR-SKY SW FLUX AT TOA, YEAR - 1860
1883 GLOBAL = -2.24 W/m2
1890 GLOBAL = -1.80 W/m2
1910 GLOBAL = -0.38 W/m2
1930 GLOBAL = -0.50 W/m2
1950 GLOBAL = -0.39 W/m2
1970 GLOBAL = -1.60 W/m2
1990 GLOBAL = -1.68 W/m2
60N
30N
EQ
30S
60S
0
60E
120E
180
120W
60W
-10 -5 -3 -2 -1 -0.5 0 0.5 1 2 3

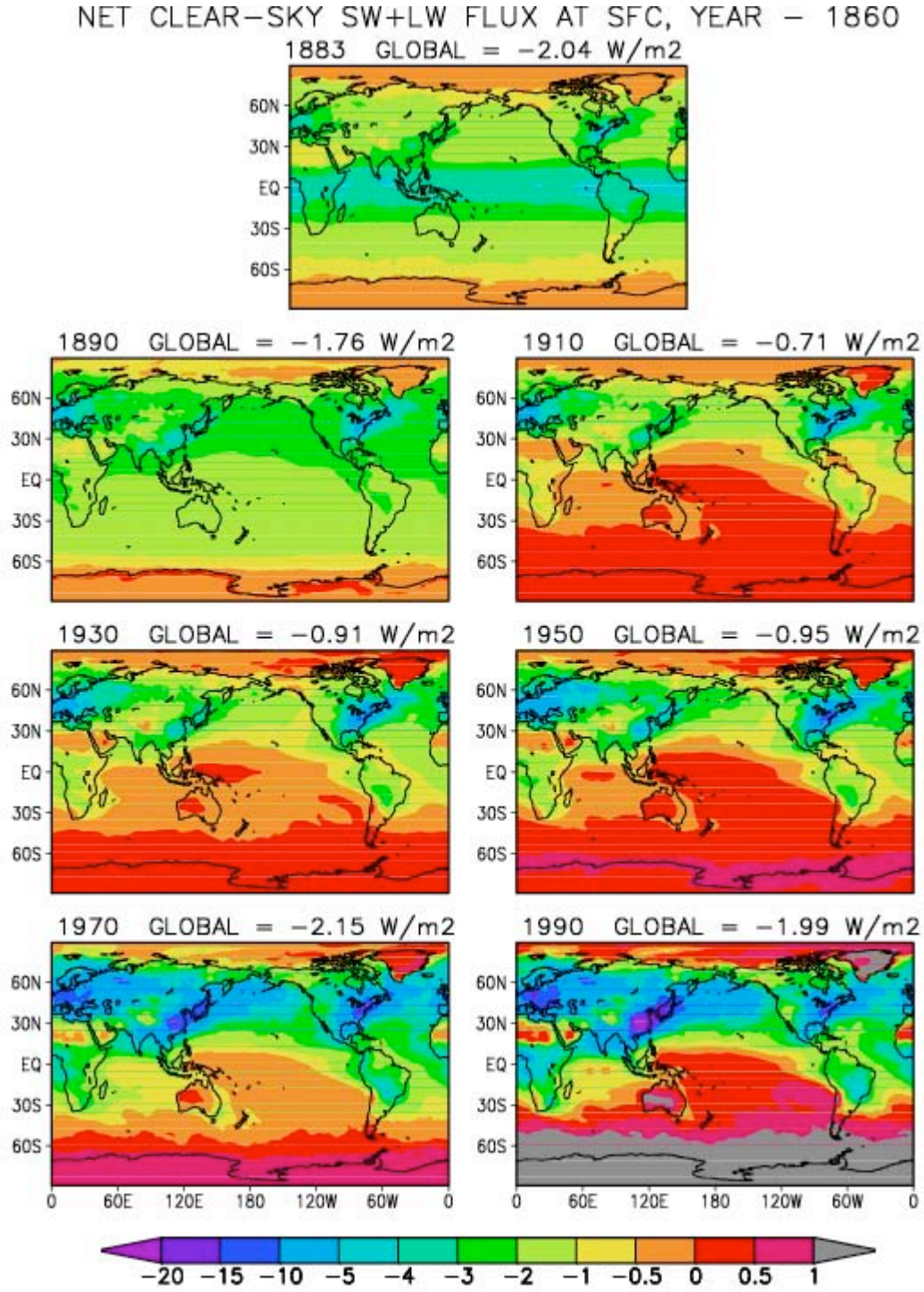

NET TOTAL−SKY SW FLUX AT TOA, YEAR − 1860
1883 GLOBAL = −1.31 W/m2
1890 GLOBAL = −0.96 W/m2
1910 GLOBAL = 0.07 W/m2
1930 GLOBAL = 0.11 W/m2
1950 GLOBAL = 0.31 W/m2
1970 GLOBAL = −0.13 W/m2
1990 GLOBAL = −0.01 W/m2
60N
30N
EQ
30S
60S
0
60E
120E
180
120W
60W
−10
−5
−3
−2
−1
−0.5
0
0.5
1
2
3

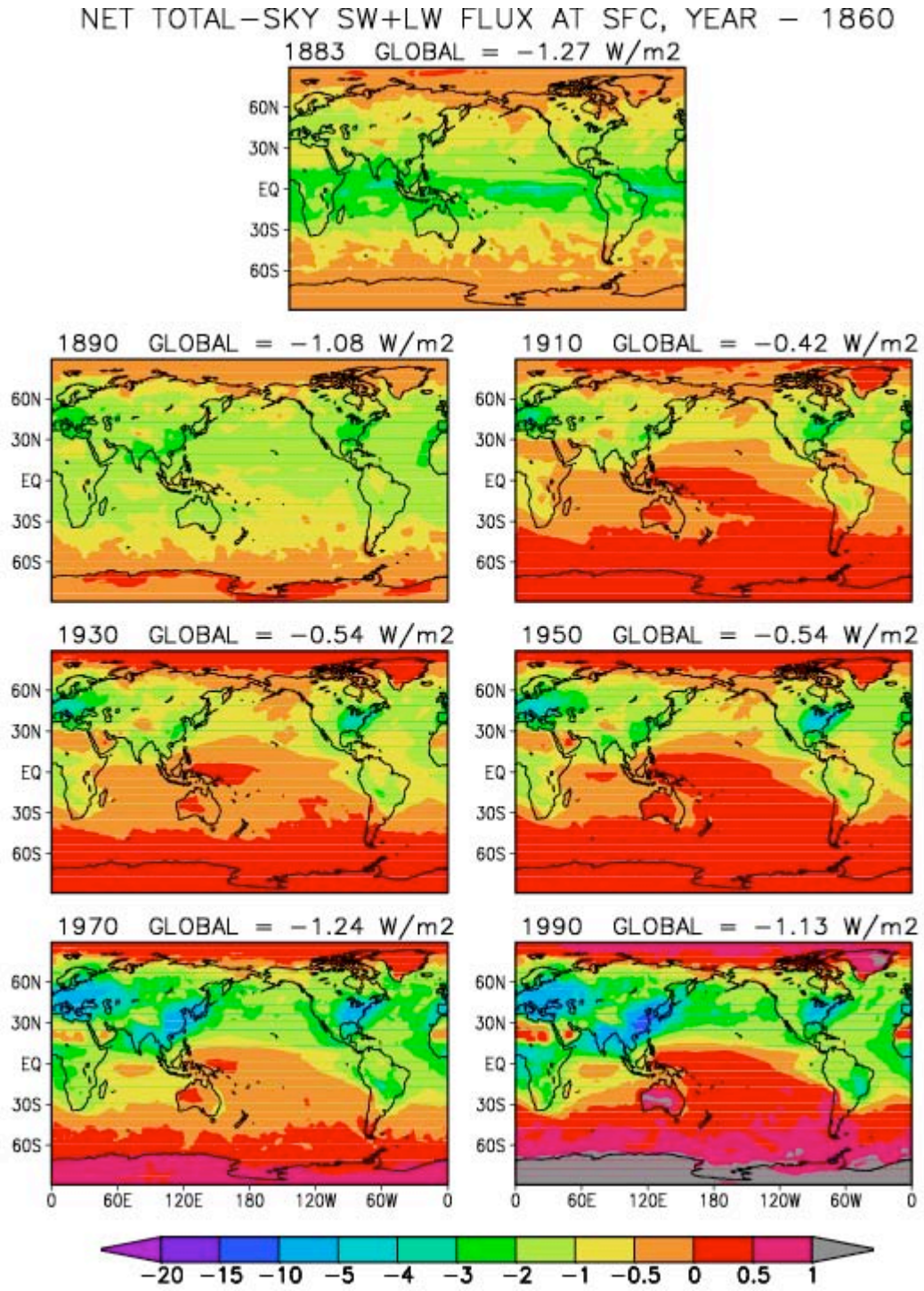

NET CLEAR-SKY SW FLUX AT SFC, YEAR - 1860
1883 GLOBAL = -2.19 W/m2
1890 GLOBAL = -1.98 W/m2
1910 GLOBAL = -1.05 W/m2
1930 GLOBAL = -1.41 W/m2
1950 GLOBAL = -1.60 W/m2
1970 GLOBAL = -3.30 W/m2
1990 GLOBAL = -3.85 W/m2
60N
30N
EQ
30S
60S
0
60E
120E
180
120W
60W
-25 -20 -15 -10 -5 -4 -3 -2 -1 -0.5 0


NET TOTAL−SKY SW FLUX AT SFC, YEAR − 1860
1883 GLOBAL = −1.36 W/m2
1890 GLOBAL = −1.21 W/m2
1910 GLOBAL = −0.63 W/m2
1930 GLOBAL = −0.85 W/m2
1950 GLOBAL = −0.94 W/m2
1970 GLOBAL = −1.93 W/m2
1990 GLOBAL = −2.27 W/m2
60N
30N
EQ
30S
60S
0
60E
120E
180
120W
60W
−25 −20 −15 −10 −5 −4 −3 −2 −1 −0.5 0

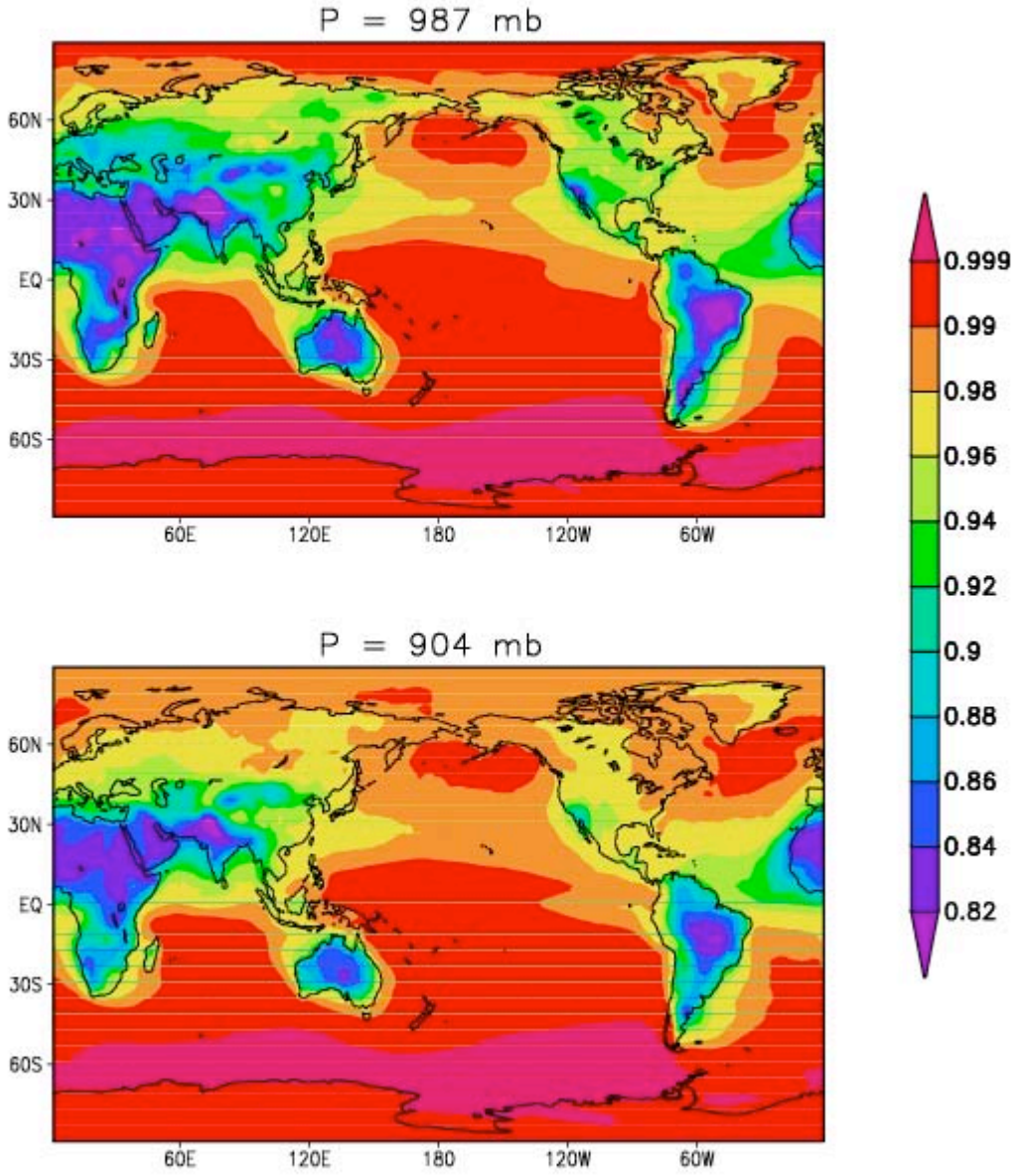

NET CLEAR−SKY SW+LW FLUX AT TOA, YEAR − 1860
1883 GLOBAL = −1.67 W/m2
1890 GLOBAL = −1.37 W/m2
1910 GLOBAL = 0.001 W/m2
1930 GLOBAL = 0.11 W/m2
1950 GLOBAL = 0.37 W/m2
1970 GLOBAL = −0.17 W/m2
1990 GLOBAL = 0.55 W/m2
60N
30N
EQ
30S
60S
0
60E
120E
180
120W
60W
−10 −5 −3 −2 −1 −0.5 0 0.5 1 2 3 5

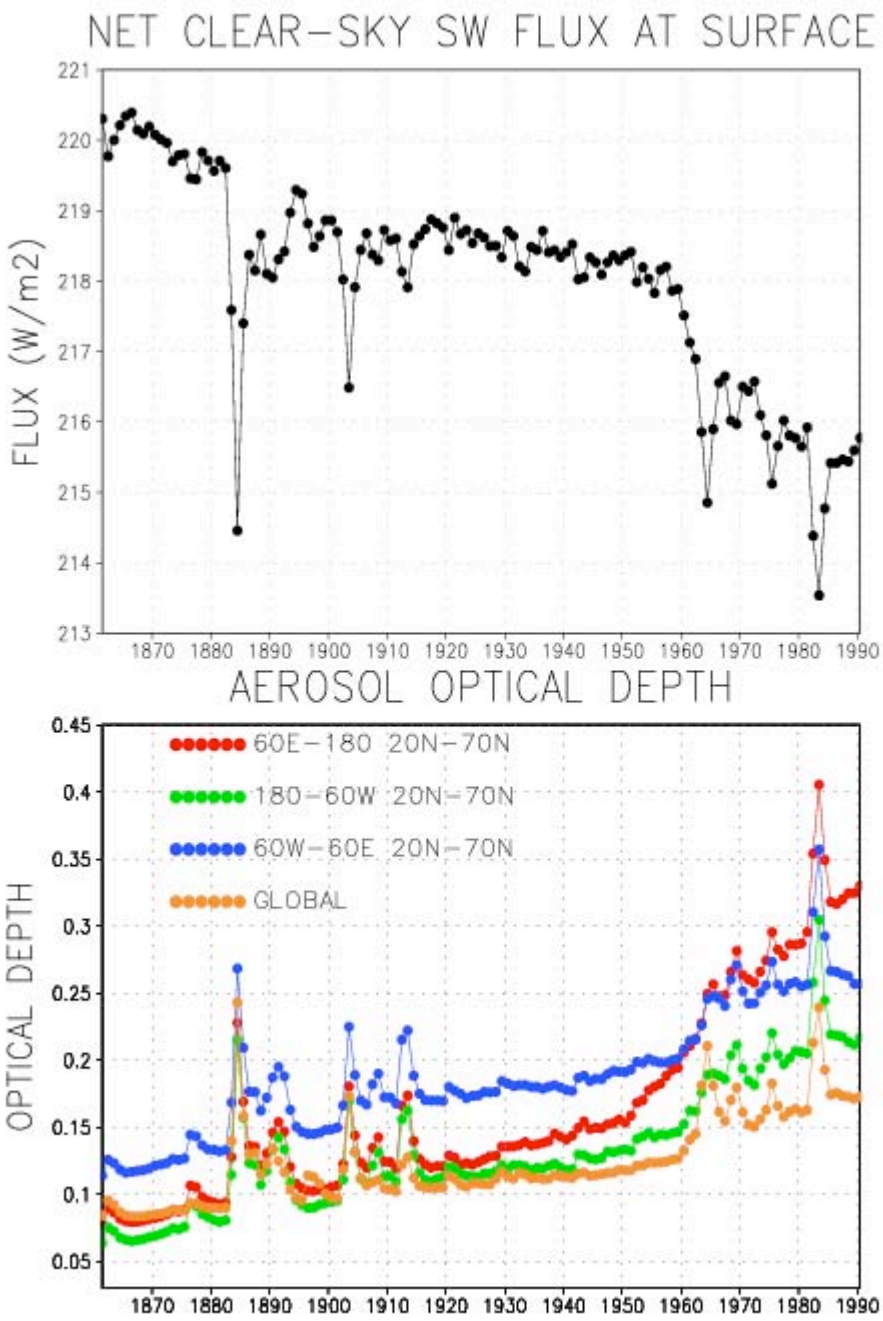

NET TOTAL−SKY SW+LW FLUX AT TOA, YEAR − 1860
1883 GLOBAL = −0.87 W/m2
1890 GLOBAL = −0.63 W/m2
1910 GLOBAL = 0.36 W/m2
1930 GLOBAL = 0.57 W/m2
1950 GLOBAL = 0.88 W/m2
1970 GLOBAL = 0.95 W/m2
1990 GLOBAL = 1.67 W/m2
60N
30N
EQ
30S
60S
0
60E
120E
180
120W
60W
−10 −5 −3 −2 −1 −0.5 0 0.5 1 2 3 5

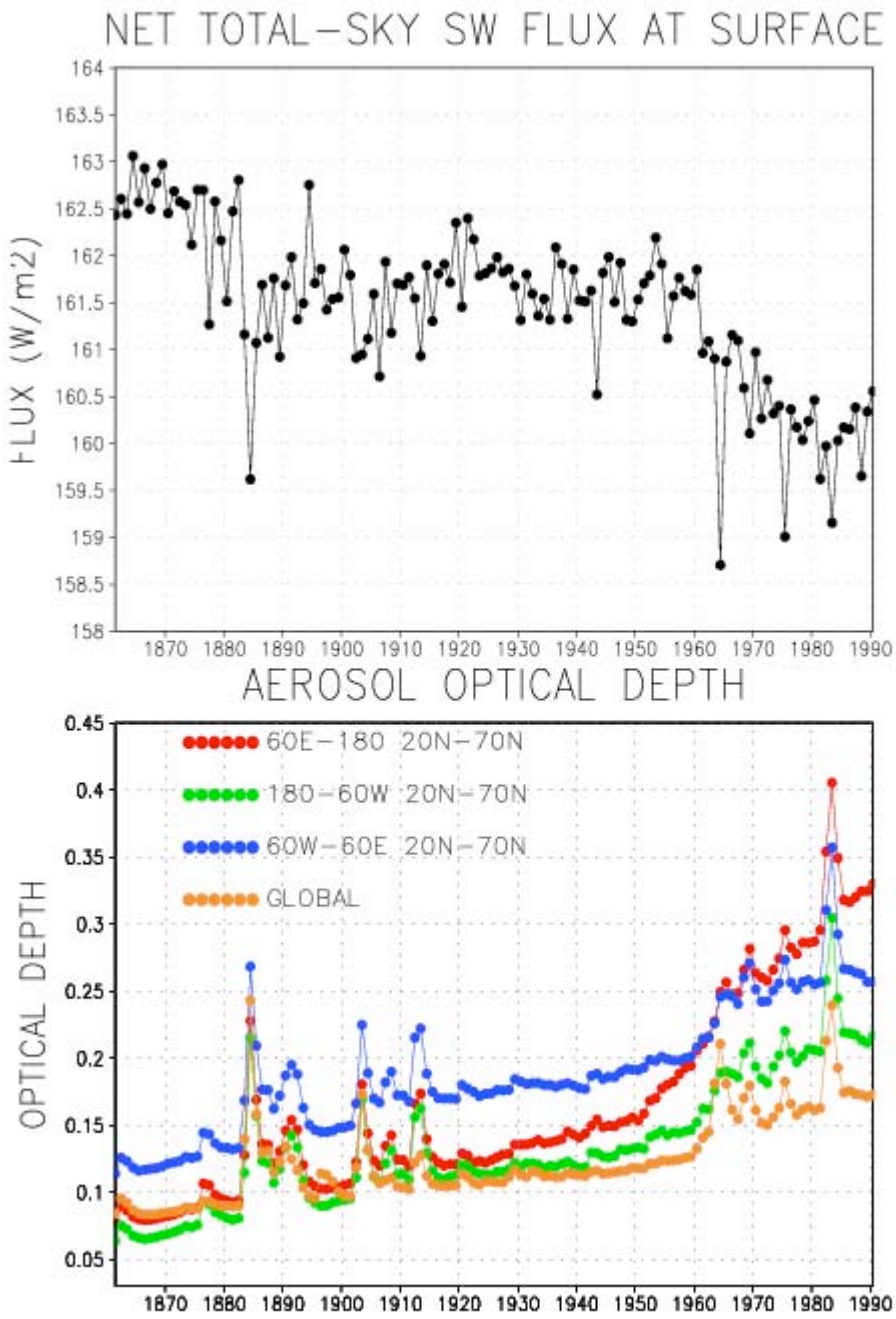

NET CLEAR-SKY SW+LW FLUX AT SFC, YEAR - 1860
1883 GLOBAL = -2.04 W/m2
1890 GLOBAL = -1.76 W/m2
1910 GLOBAL = -0.71 W/m2
1930 GLOBAL = -0.91 W/m2
1950 GLOBAL = -0.95 W/m2
1970 GLOBAL = -2.15 W/m2
1990 GLOBAL = -1.99 W/m2
60N
30N
EQ
30S
60S
0
60E
120E
180
120W
60W
-20 -15 -10 -5 -4 -3 -2 -1 -0.5 0 0.5 1


NET TOTAL−SKY SW+LW FLUX AT SFC, YEAR − 1860
1883 GLOBAL = −1.27 W/m2
1890 GLOBAL = −1.08 W/m2
1910 GLOBAL = −0.42 W/m2
1930 GLOBAL = −0.54 W/m2
1950 GLOBAL = −0.54 W/m2
1970 GLOBAL = −1.24 W/m2
1990 GLOBAL = −1.13 W/m2
60N
30N
EQ
30S
60S
0
60E
120E
180
120W
60W
−20 −15 −10 −5 −4 −3 −2 −1 −0.5 0 0.5 1

MODEL TOTAL AEROSOL SINGLE SCATTERING ALBEDO



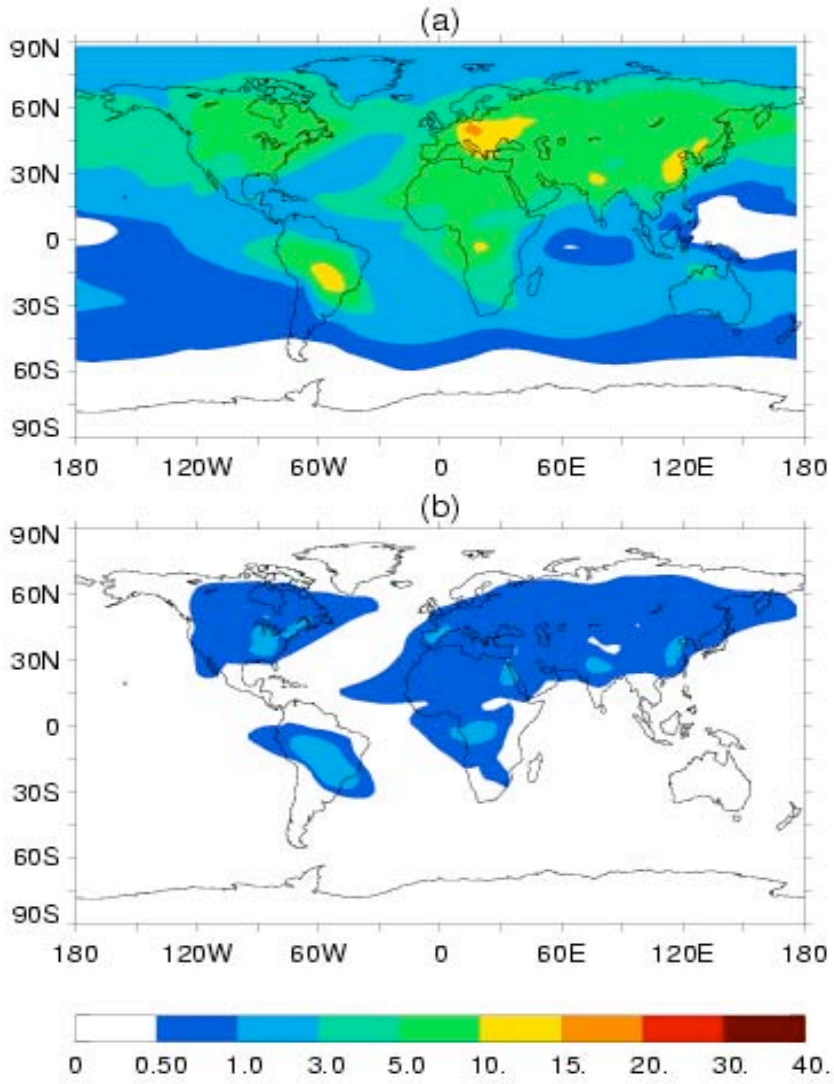

NET CLEAR-SKY SW FLUX AT SURFACE
FLUX (W/m2)
221
220
219
218
217
216
215
214
213
1870 1880 1890 1900 1910 1920 1930 1940 1950 1960 1970 1980 1990
AEROSOL OPTICAL DEPTH
OPTICAL DEPTH
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
60E-180 20N-70N
180-60W 20N-70N
60W-60E 20N-70N
GLOBAL
1870 1880 1890 1900 1910 1920 1930 1940 1950 1960 1970 1980 1990

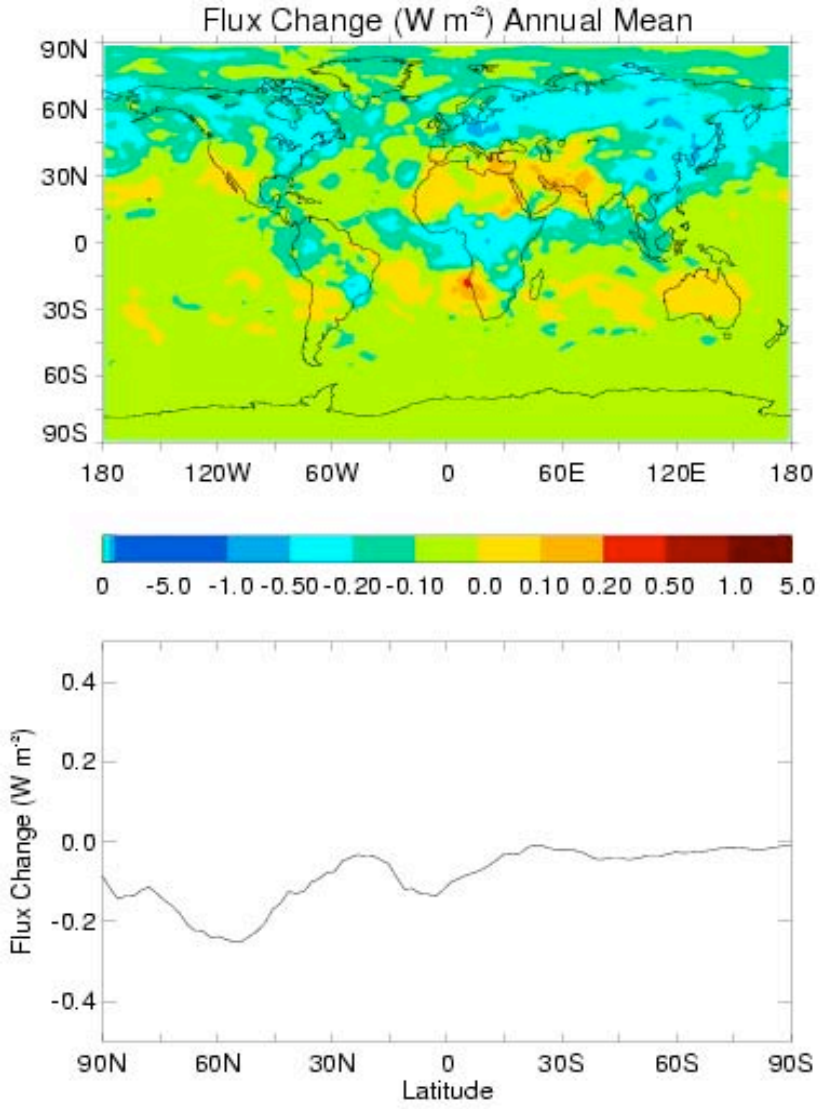

NET TOTAL-SKY SW FLUX AT SURFACE
FLUX (W/m2)
164
163.5
163
162.5
162
161.5
161
160.5
160
159.5
159
158.5
158
1870 1880 1890 1900 1910 1920 1930 1940 1950 1960 1970 1980 1990
AEROSOL OPTICAL DEPTH
OPTICAL DEPTH
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
60E-180 20N-70N
180-60W 20N-70N
60W-60E 20N-70N
GLOBAL
1870 1880 1890 1900 1910 1920 1930 1940 1950 1960 1970 1980 1990

SUMMARY

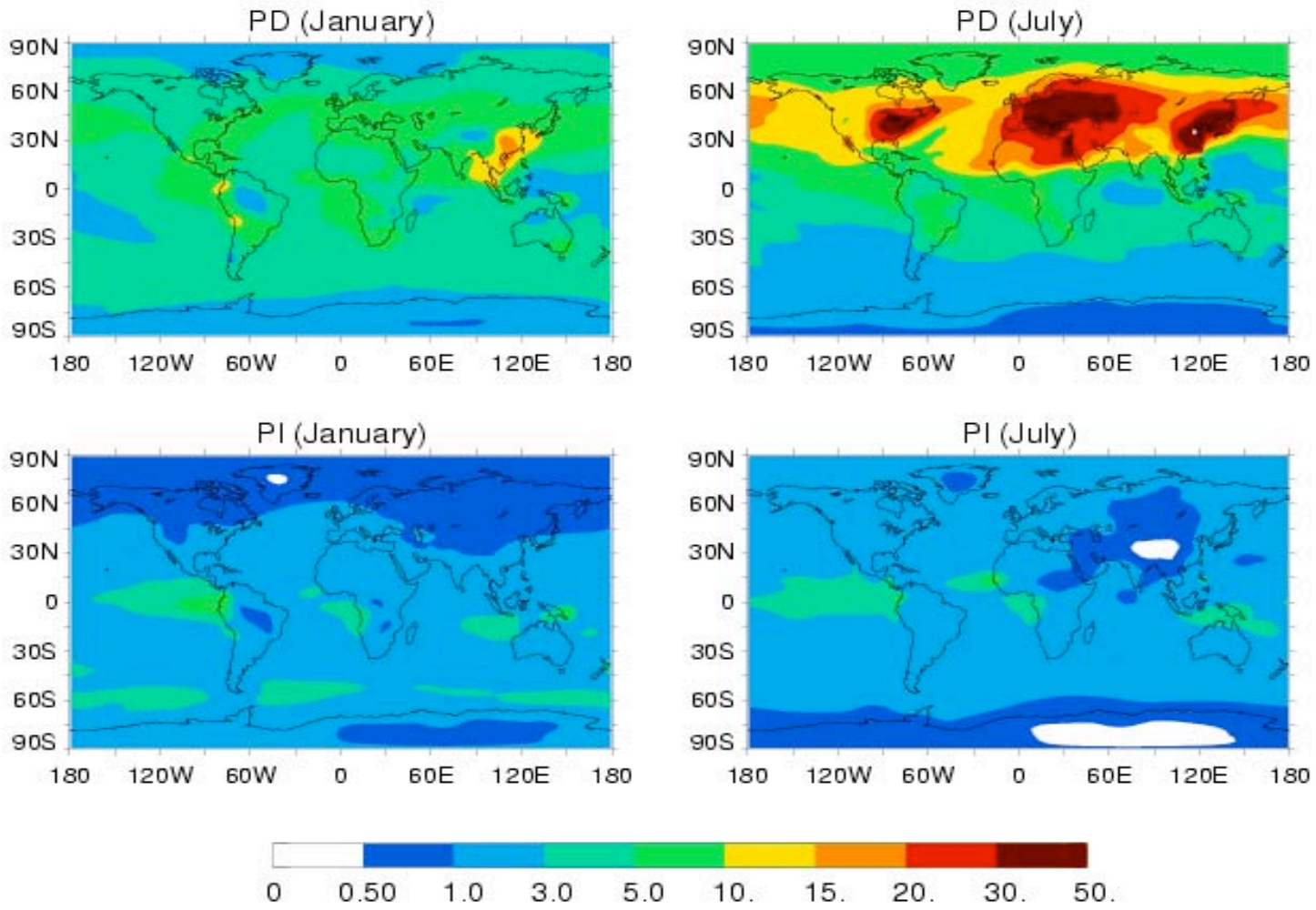
- Sensitivity of BC burden to microphysics and transport. Both are significant.
- BC surface concentration observations can have a substantial interannual variability.
- Sensitivity of BC burden to frequency and intensity of precipitation especially in the travel to distant regions.

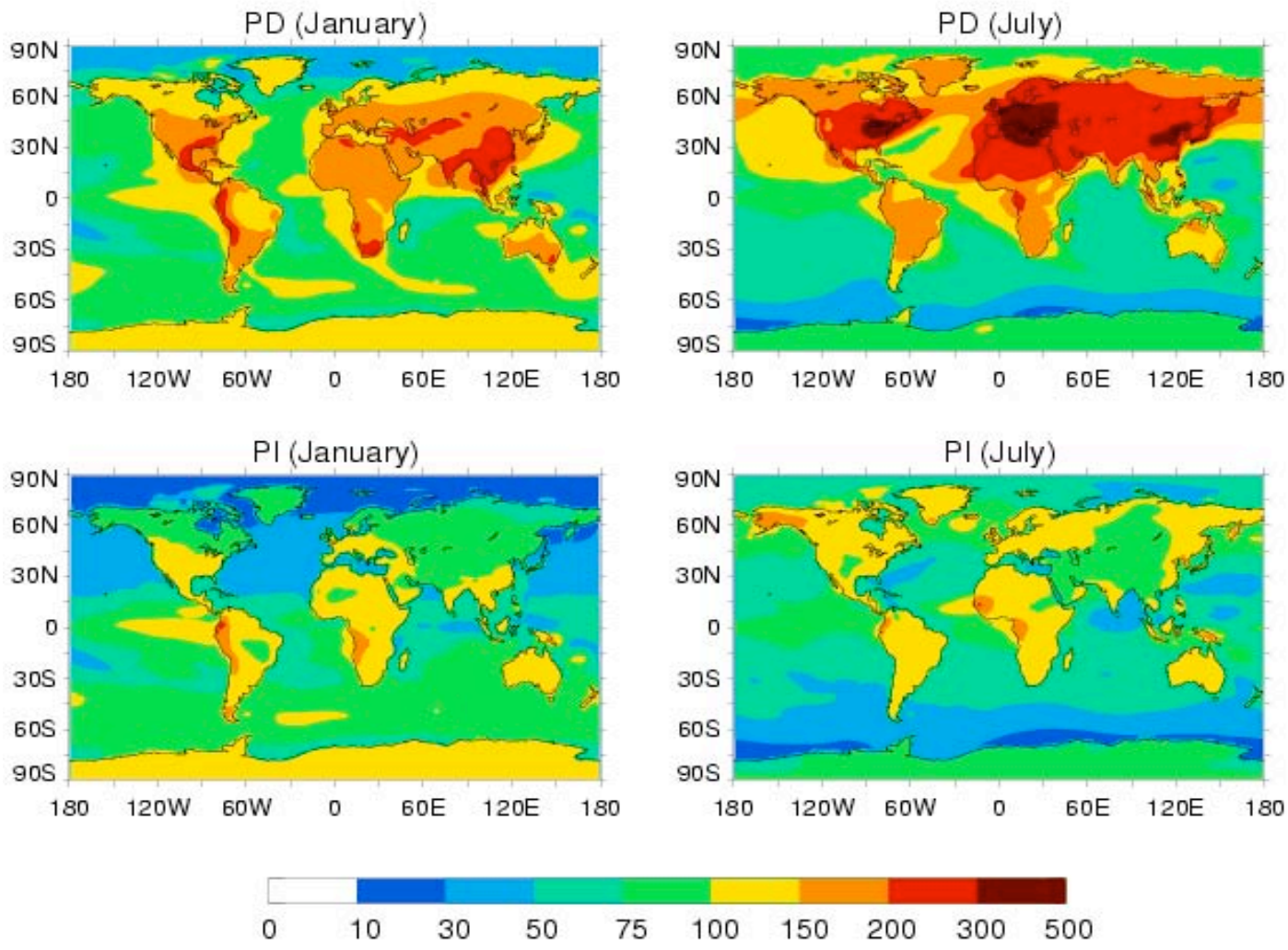
- Aerosol properties for GFDL IPCC runs simulated using MOZART-2. Comparisons with observed surface concentrations, optical depths, TOA and surface fluxes indicate a reasonable basis for use in historical forcing runs

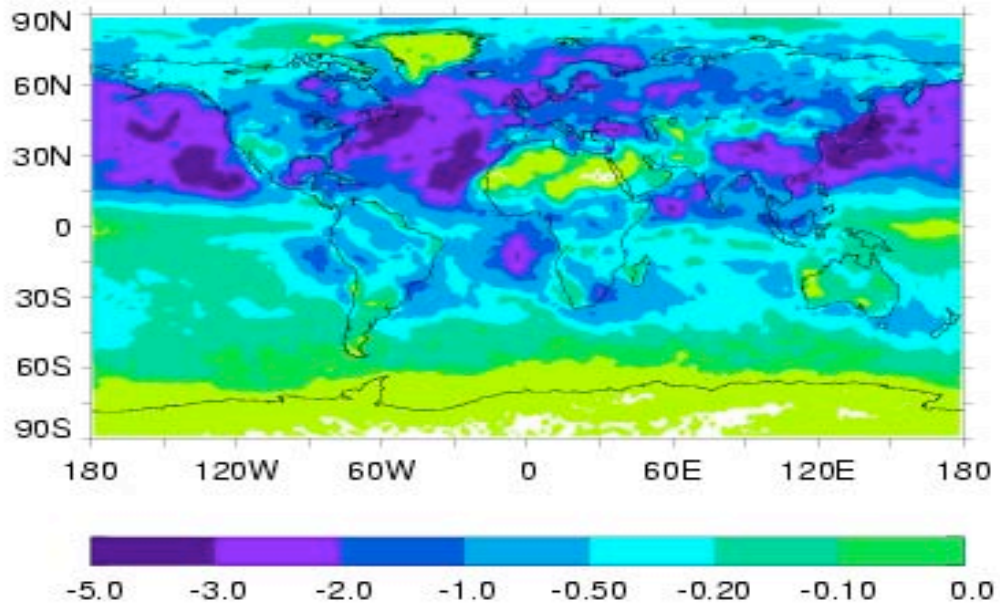

(a)
90N
60N
30N
0
30S
60S
90S
180
120W
60W
0
60E
120E
180
(b)
90N
60N
30N
0
30S
60S
90S
180
120W
60W
0
60E
120E
180
0
0.50
1.0
3.0
5.0
10.
15.
20.
30.
40.

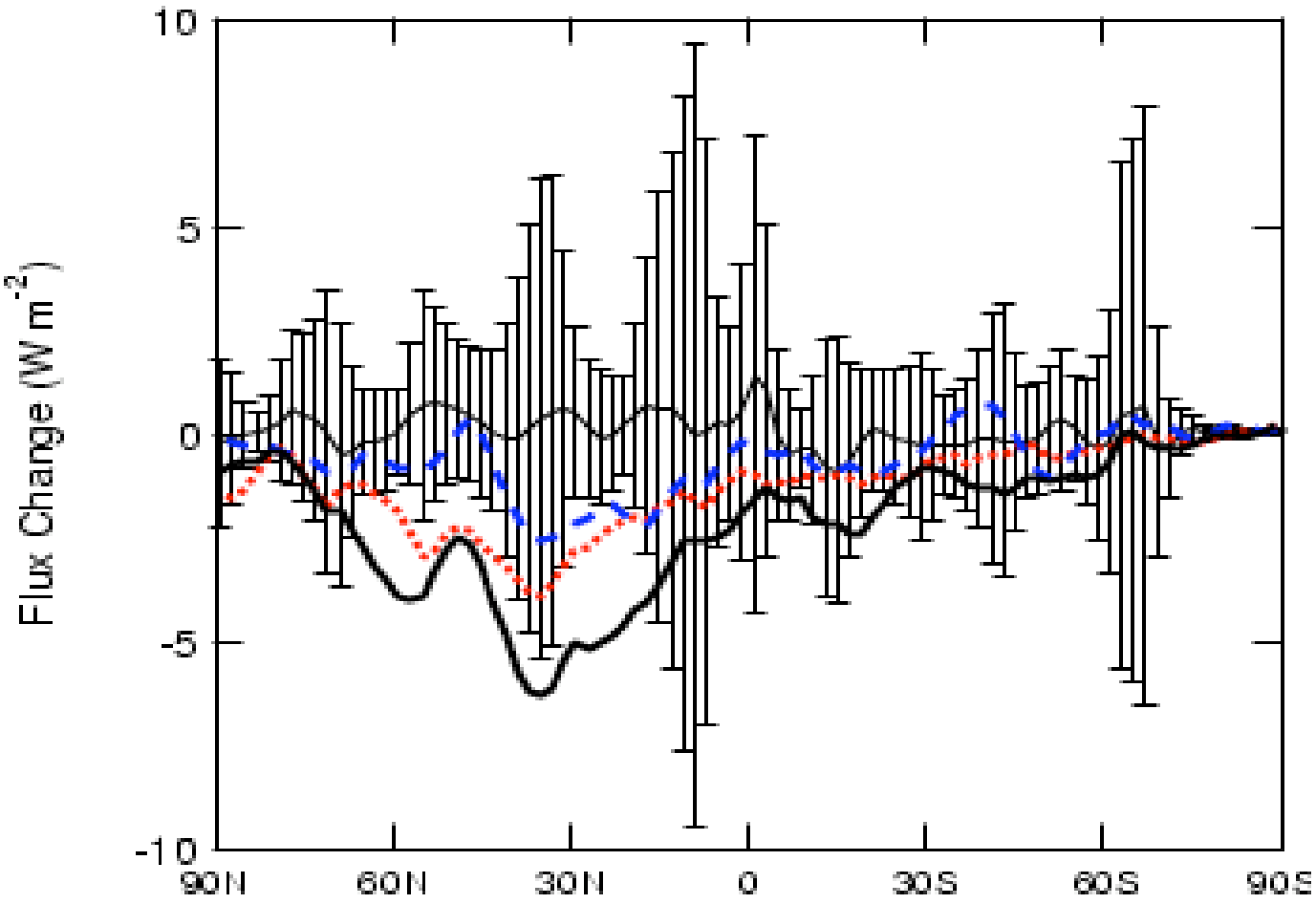

Flux Change (W m-2) Annual Mean
90N
60N
30N
0
30S
60S
90S
180
120W
60W
0
60E
120E
180
0
-5.0
-1.0
-0.50
-0.20
-0.10
0.0
0.10
0.20
0.50
1.0
5.0
0.4
0.2
0.0
-0.2
-0.4
Flux Change (W m-2)
90N
60N
30N
0
30S
60S
90S
Latitude

Flux changes due to aerosol-cloud interactions
(anthropogenic sulfate aerosols)


PD (January)
PD (July)
PI (January)
PI (July)
90N
60N
30N
0
30S
60S
90S
180
120W
60W
0
60E
120E
180
0
0.50
1.0
3.0
5.0
10.
15.
20.
30.
50.

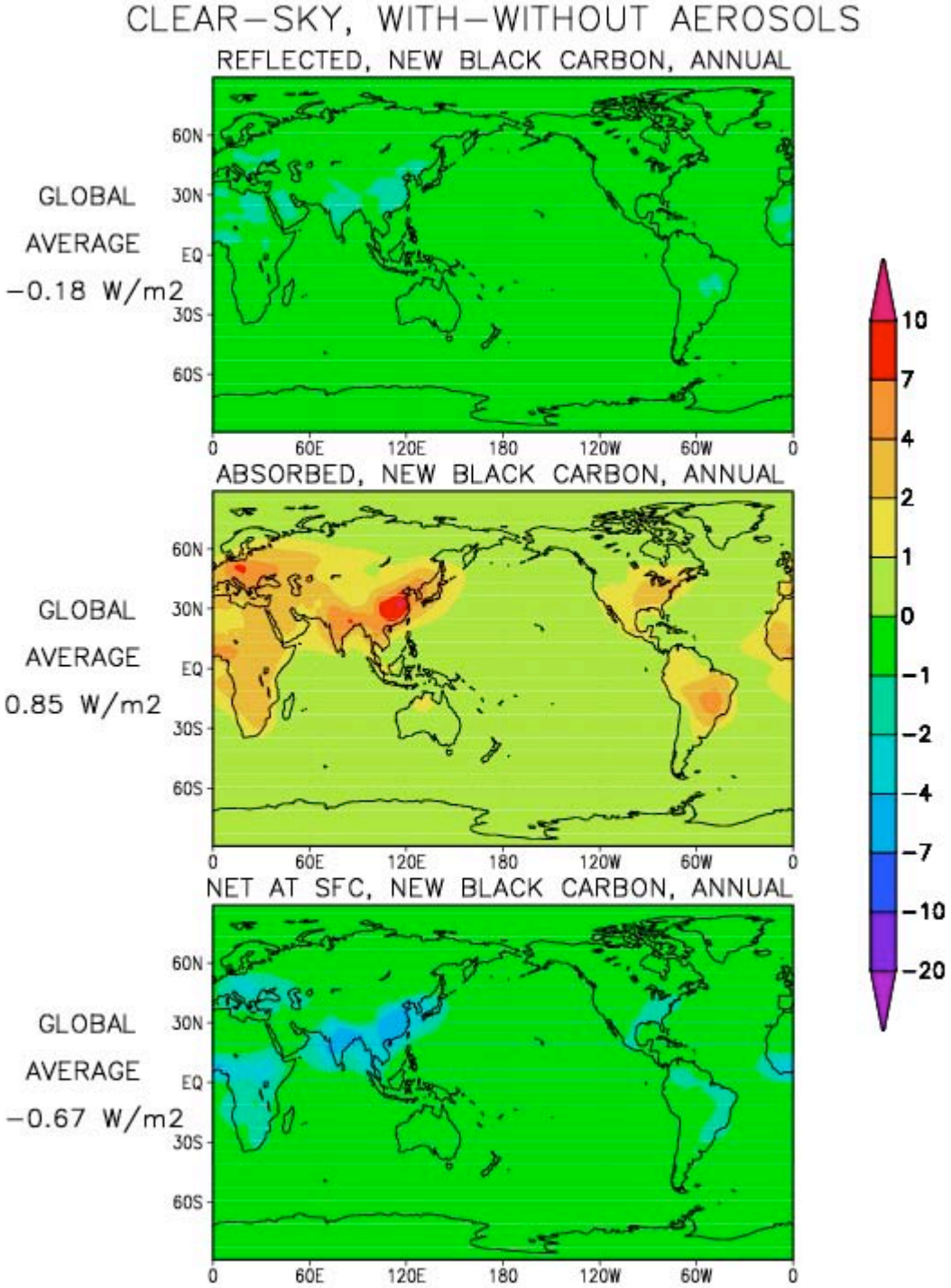

PD (January)
PD (July)
PI (January)
PI (July)
90N
60N
30N
0
30S
60S
90S
180
120W
60W
0
60E
120E
180
0
10
30
50
75
100
150
200
300
500

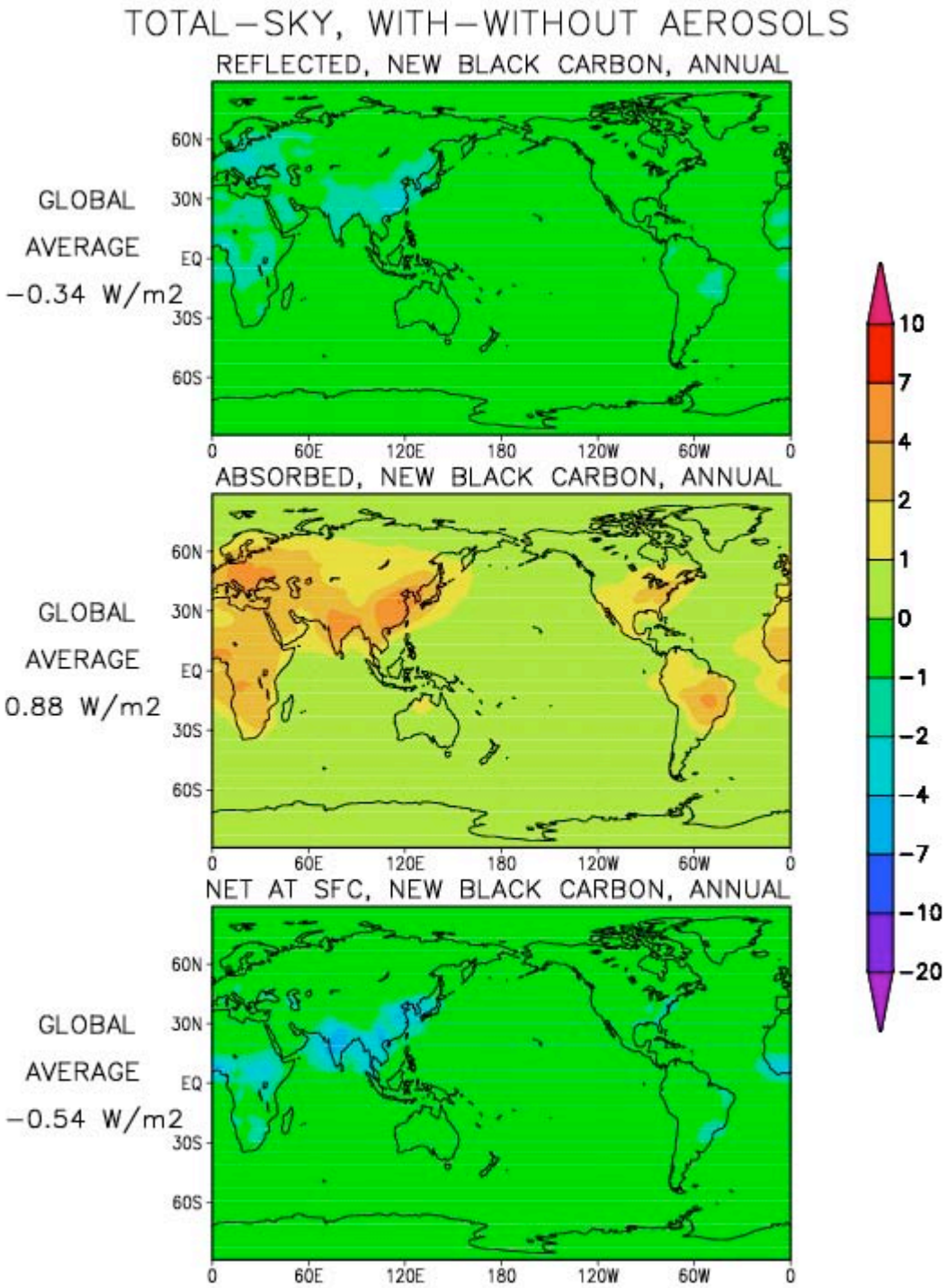

90N
60N
30N
0
30S
60S
90S
180
120W
60W
0
60E
120E
180
-5.0
-3.0
-2.0
-1.0
-0.50
-0.20
-0.10
0.0

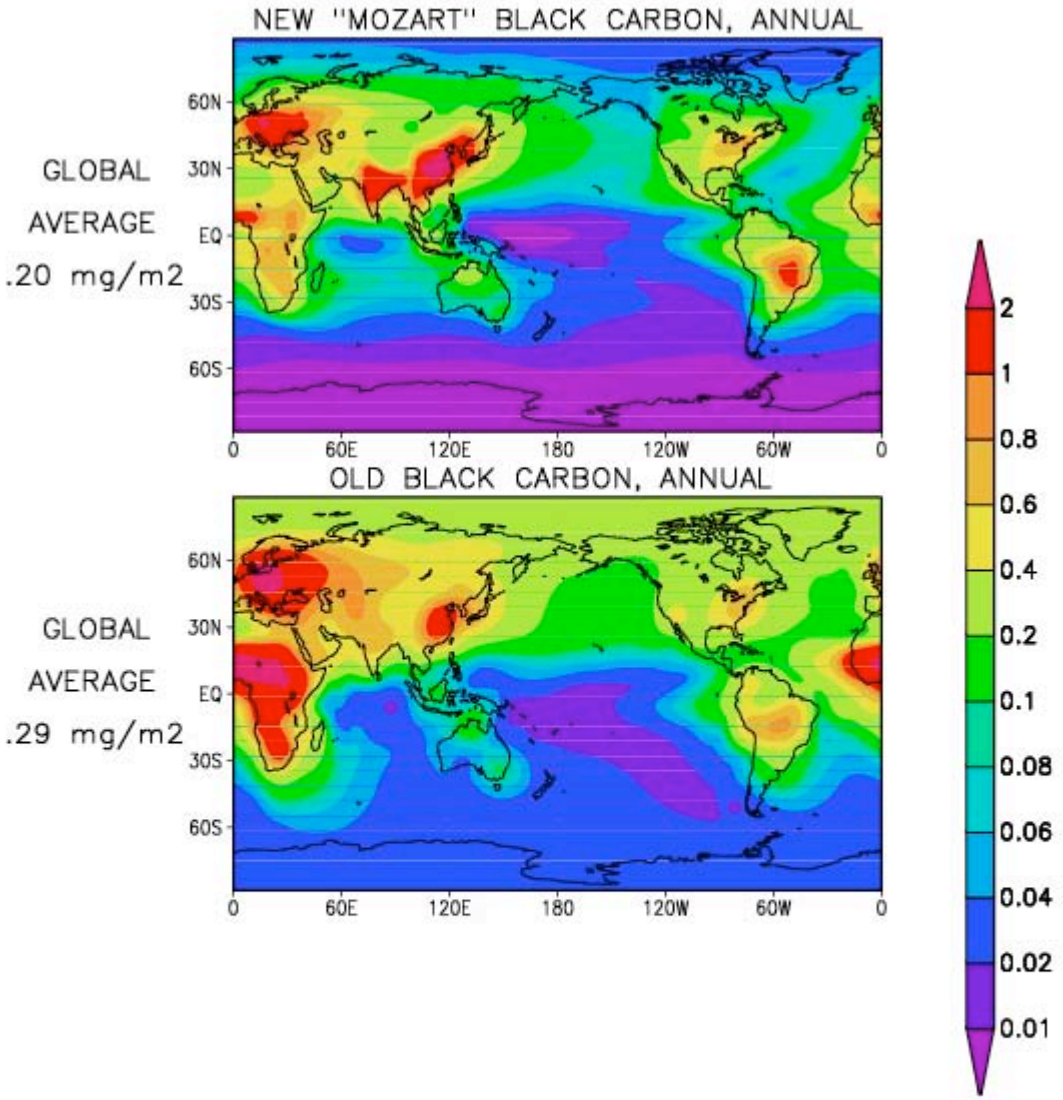

10
5
0
-5
-10
Flux Change (W m-2)
90N
60N
30N
0
30S
60S
90S

SUMMARY (contd.)

- Change in global-mean forcing due to consideration of OC hygroscopicity and mild absorption effects small, but regional effects can be notable.
- 1st and 2nd indirect effects arising due to aerosol-cloud interactions = -1.6 W/m2.

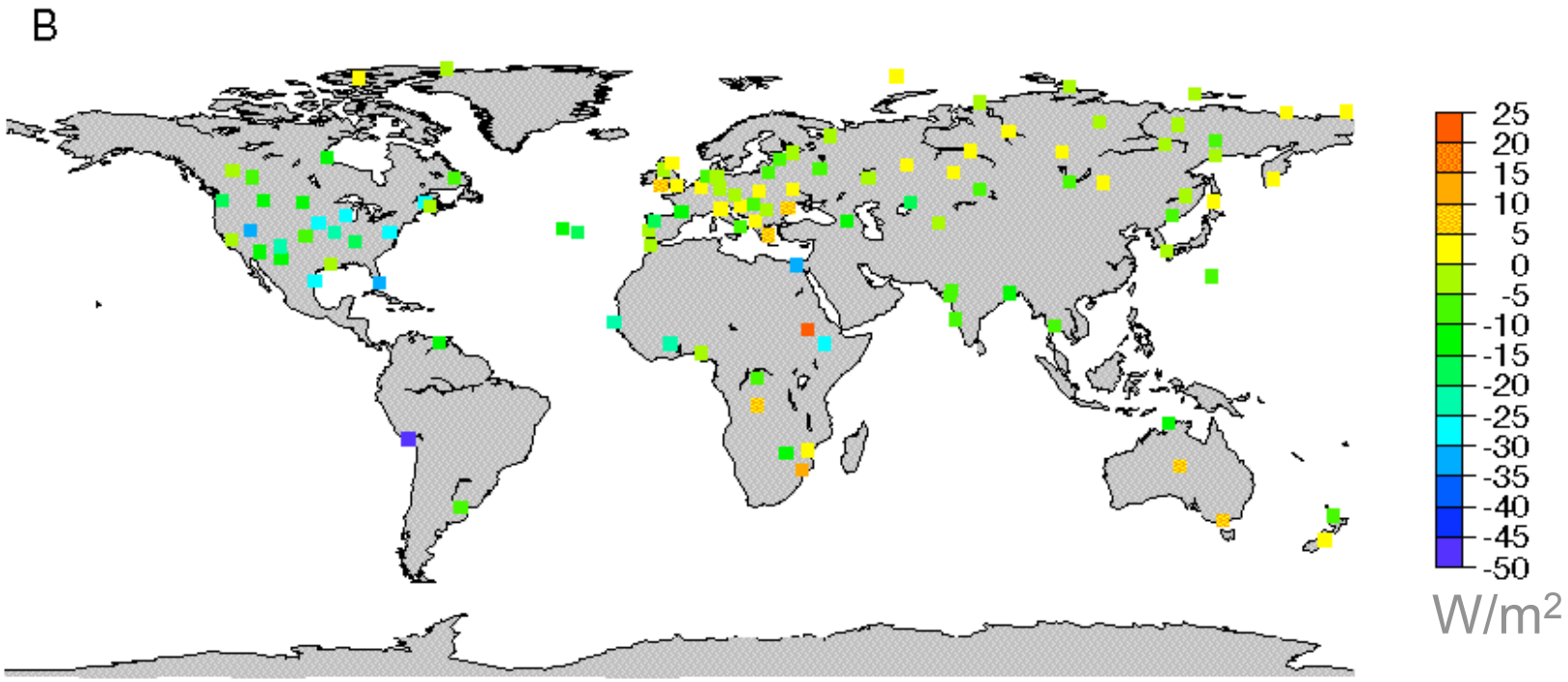

CLEAR−SKY, WITH−WITHOUT AEROSOLS
REFLECTED, NEW BLACK CARBON, ANNUAL
GLOBAL AVERAGE −0.18 W/m2
ABSORBED, NEW BLACK CARBON, ANNUAL
GLOBAL AVERAGE 0.85 W/m2
NET AT SFC, NEW BLACK CARBON, ANNUAL
GLOBAL AVERAGE −0.67 W/m2
60N
30N
EQ
30S
60S
0
60E
120E
180
120W
60W
10
7
4
2
1
0
−1
−2
−4
−7
−10
−20

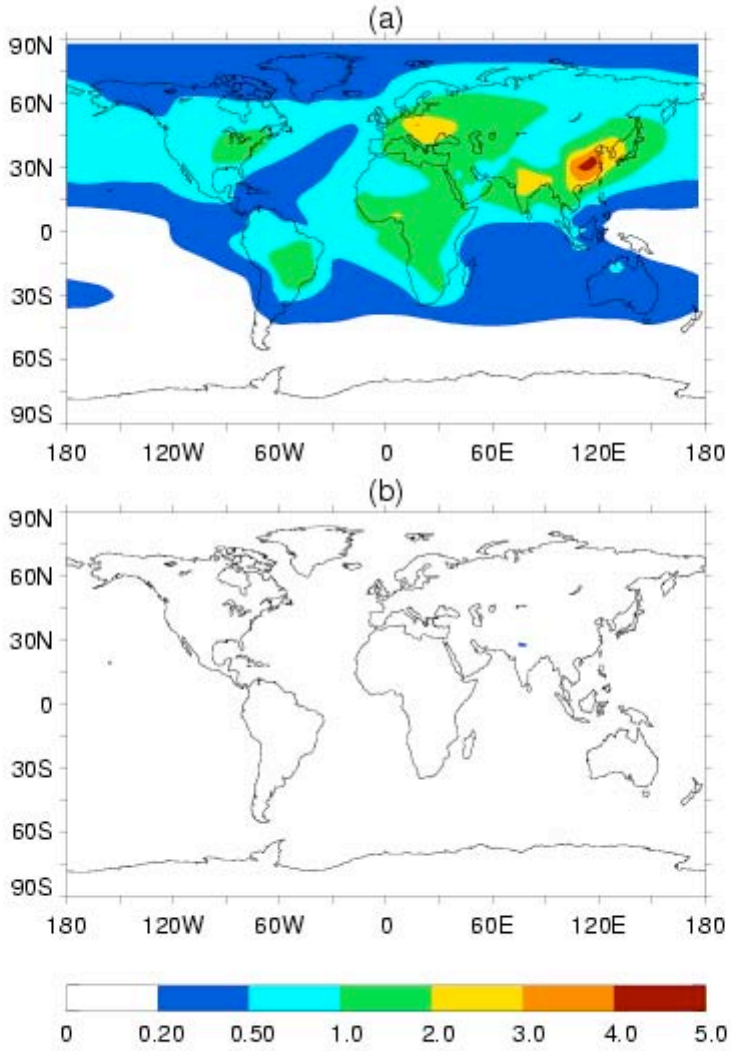

TOTAL−SKY, WITH−WITHOUT AEROSOLS
REFLECTED, NEW BLACK CARBON, ANNUAL
GLOBAL AVERAGE −0.34 W/m2
ABSORBED, NEW BLACK CARBON, ANNUAL
GLOBAL AVERAGE 0.88 W/m2
NET AT SFC, NEW BLACK CARBON, ANNUAL
GLOBAL AVERAGE −0.54 W/m2
60N
30N
EQ
30S
60S
0
60E
120E
180
120W
60W
10
7
4
2
1
0
−1
−2
−4
−7
−10
−20

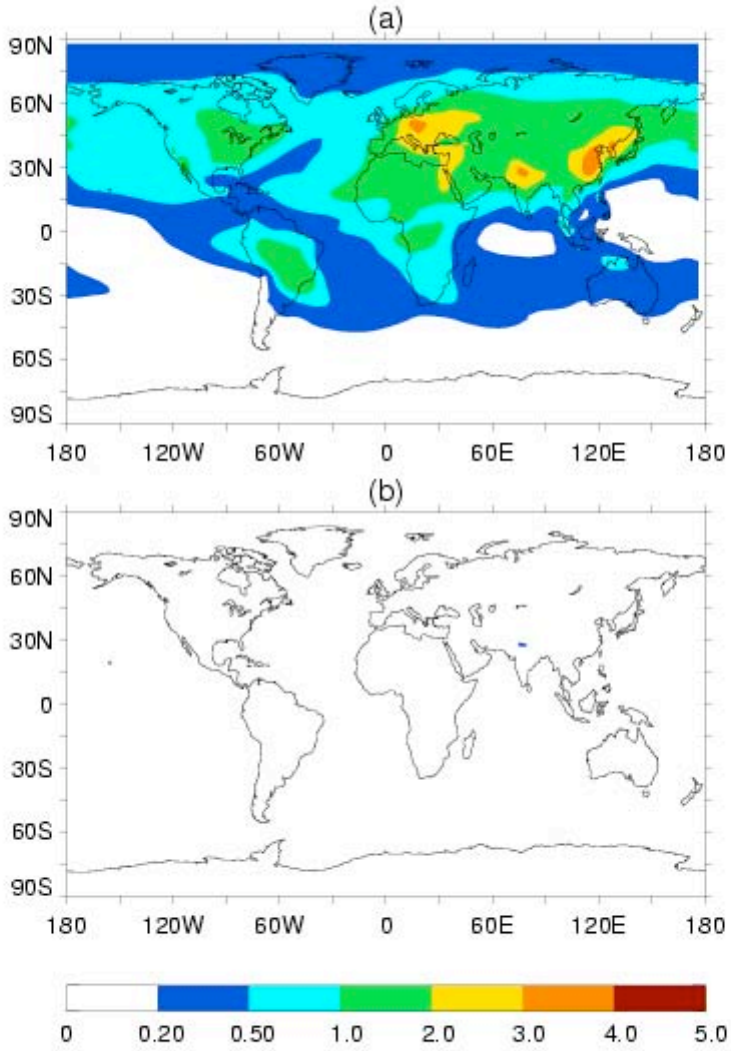

NEW "MOZART" BLACK CARBON, ANNUAL
GLOBAL
AVERAGE
.20 mg/m2
60N
30N
EQ
30S
60S
0
60E
120E
180
120W
60W
0
OLD BLACK CARBON, ANNUAL
GLOBAL
AVERAGE
.29 mg/m2
60N
30N
EQ
30S
60S
0
60E
120E
180
120W
60W
0
2
1
0.8
0.6
0.4
0.2
0.1
0.08
0.06
0.04
0.02
0.01

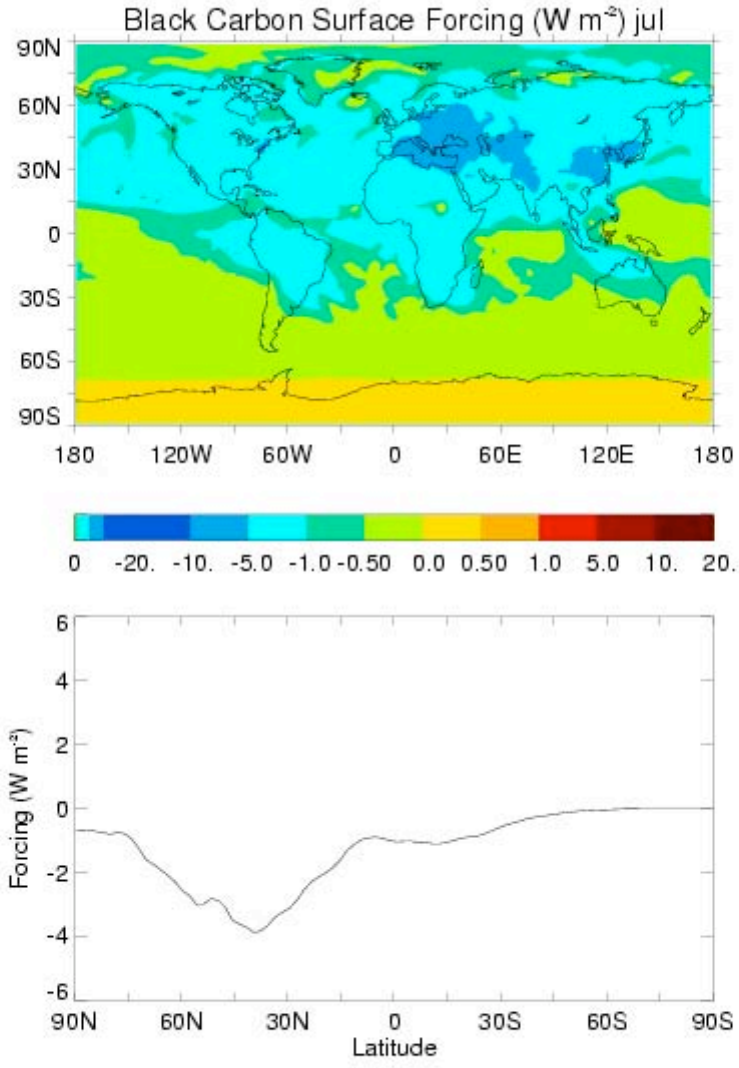
Changes of Decadal Mean Surface Solar Radiation: 1981 - 1990 minus 1961-1970 (Liepert, *GRL*, 2002)

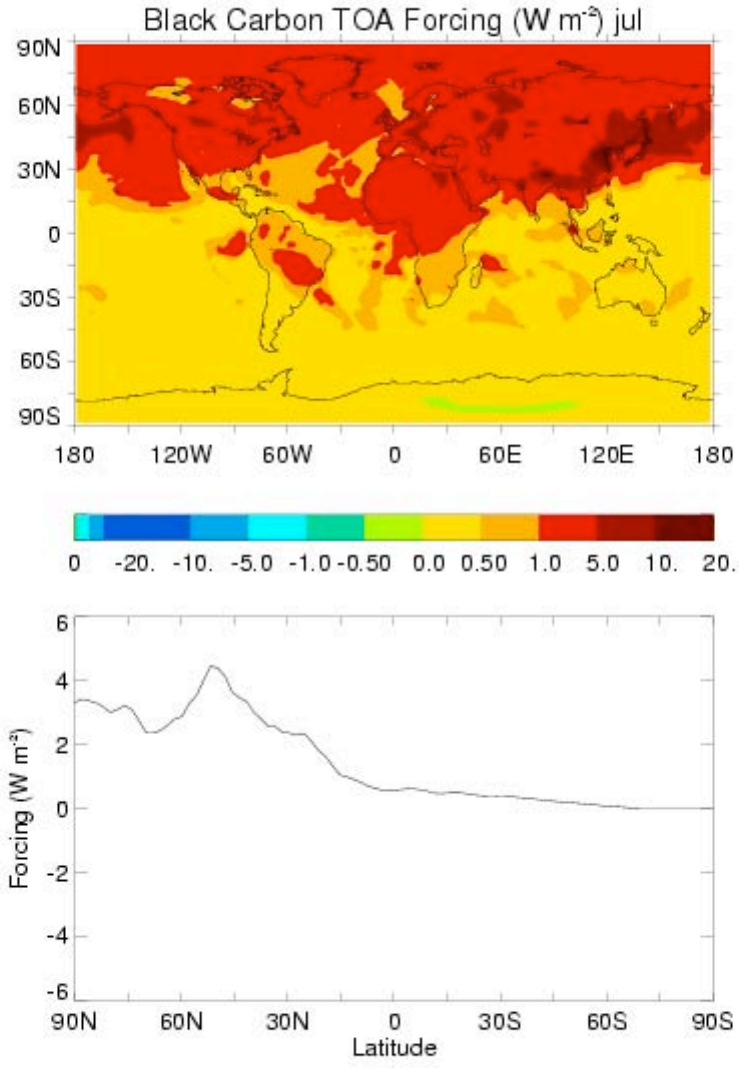
Stanhill and Cohen, 2001: -10% ; 1950 to 1990
Ohmura and Gilgen: 5% to 10%; 1960 to 1990
Liepert , GRL, : -4%

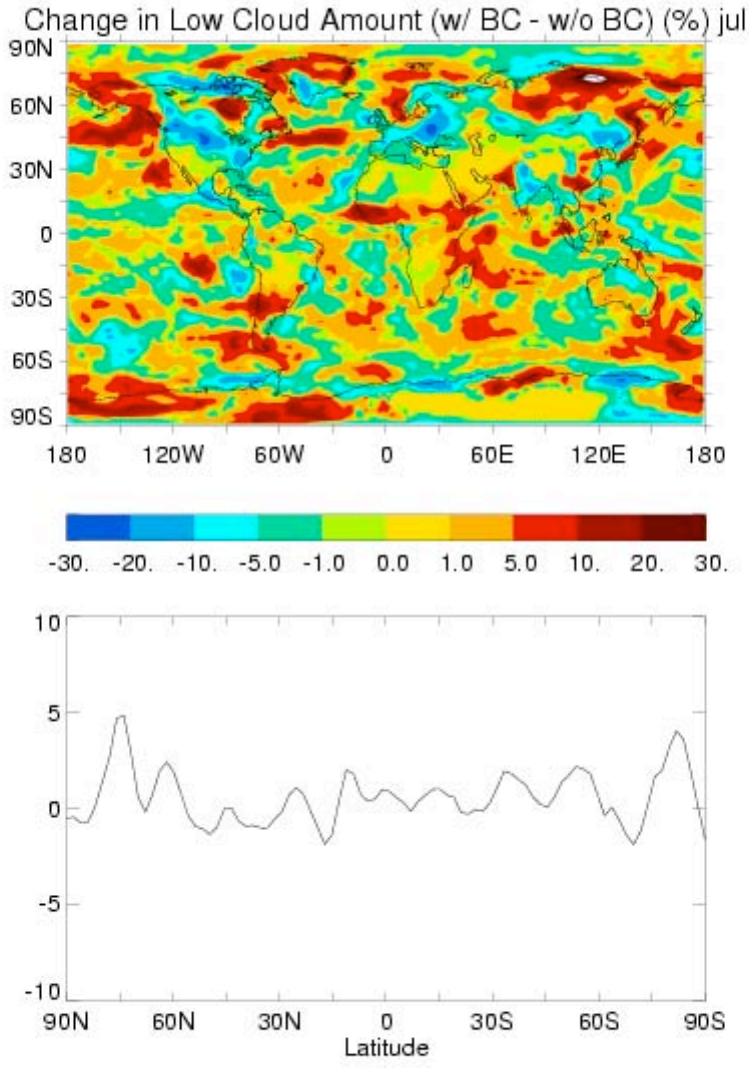


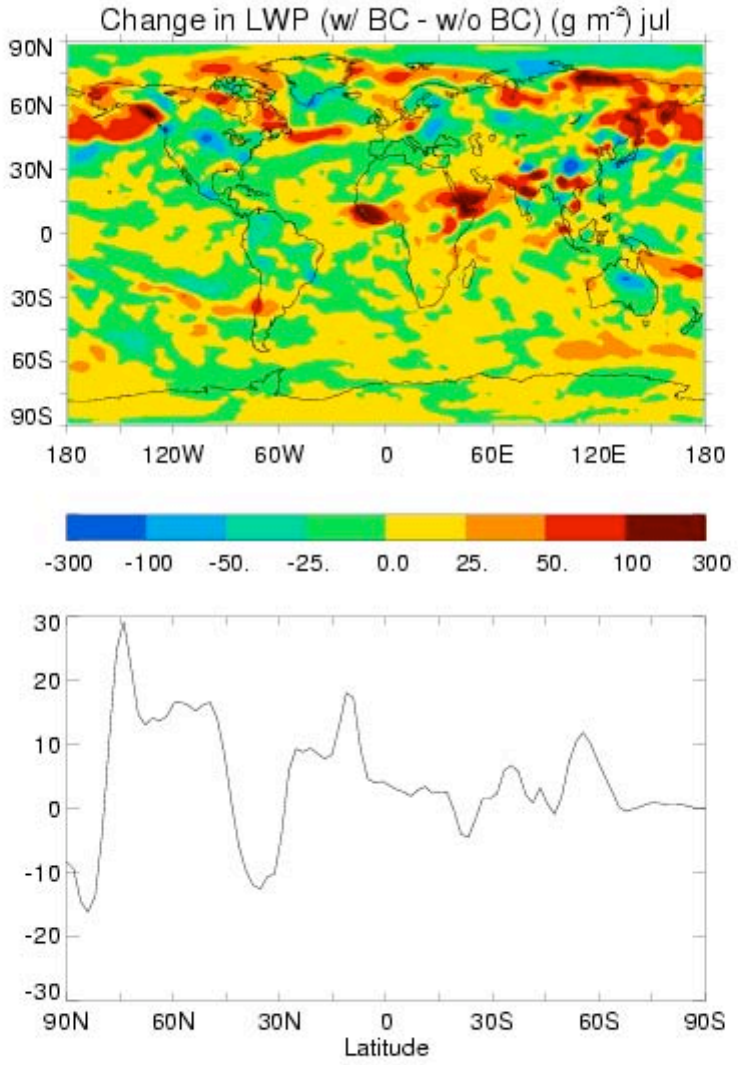

(a)
90N
60N
30N
0
30S
60S
90S
180
120W
60W
0
60E
120E
180
(b)
90N
60N
30N
0
30S
60S
90S
180
120W
60W
0
60E
120E
180
0
0.20
0.50
1.0
2.0
3.0
4.0
5.0

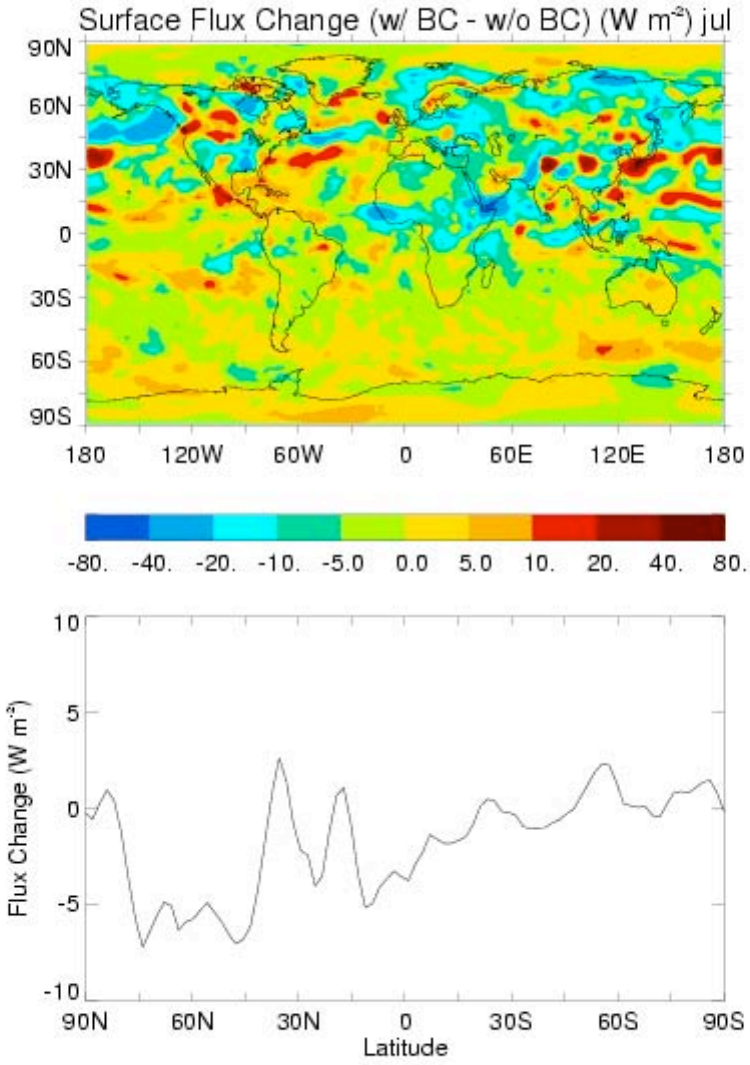

(a)
90N
60N
30N
0
30S
60S
90S
180
120W
60W
0
60E
120E
180
(b)
90N
60N
30N
0
30S
60S
90S
180
120W
60W
0
60E
120E
180
0
0.20
0.50
1.0
2.0
3.0
4.0
5.0

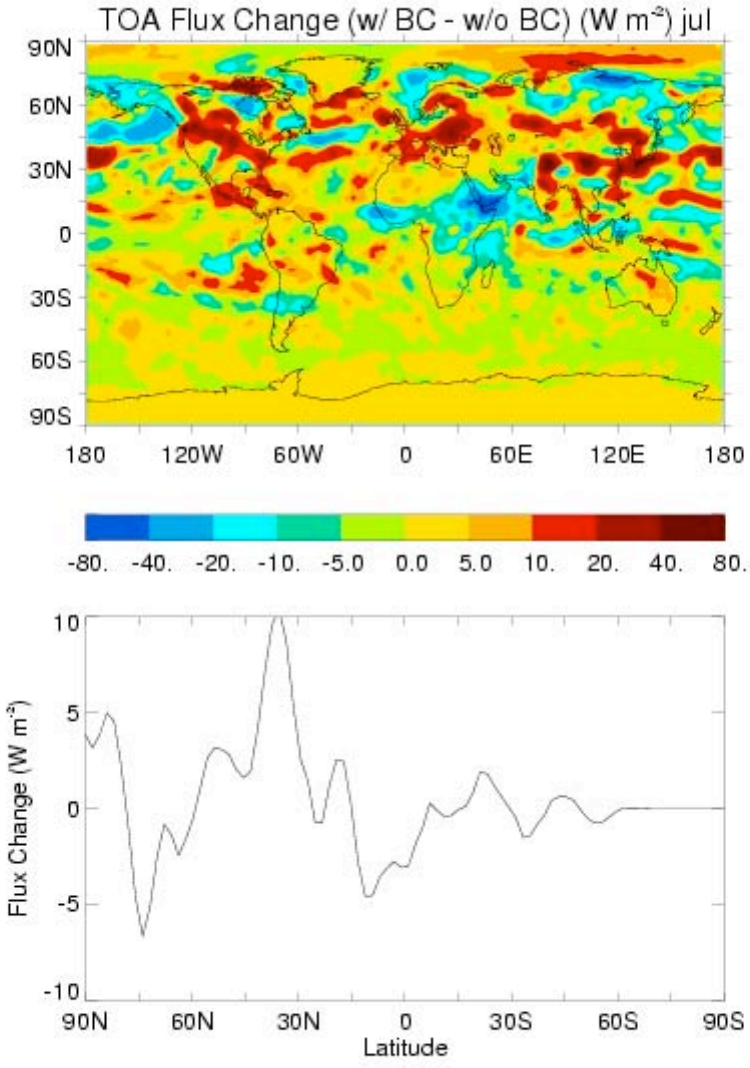

Black Carbon Surface Forcing (W m-2) jul
90N
60N
30N
0
30S
60S
90S
180
120W
60W
0
60E
120E
180
0
-20.
-10.
-5.0
-1.0
-0.50
0.0
0.50
1.0
5.0
10.
20.
6
4
2
0
-2
-4
-6
Forcing (W m-2)
90N
60N
30N
0
30S
60S
90S
Latitude

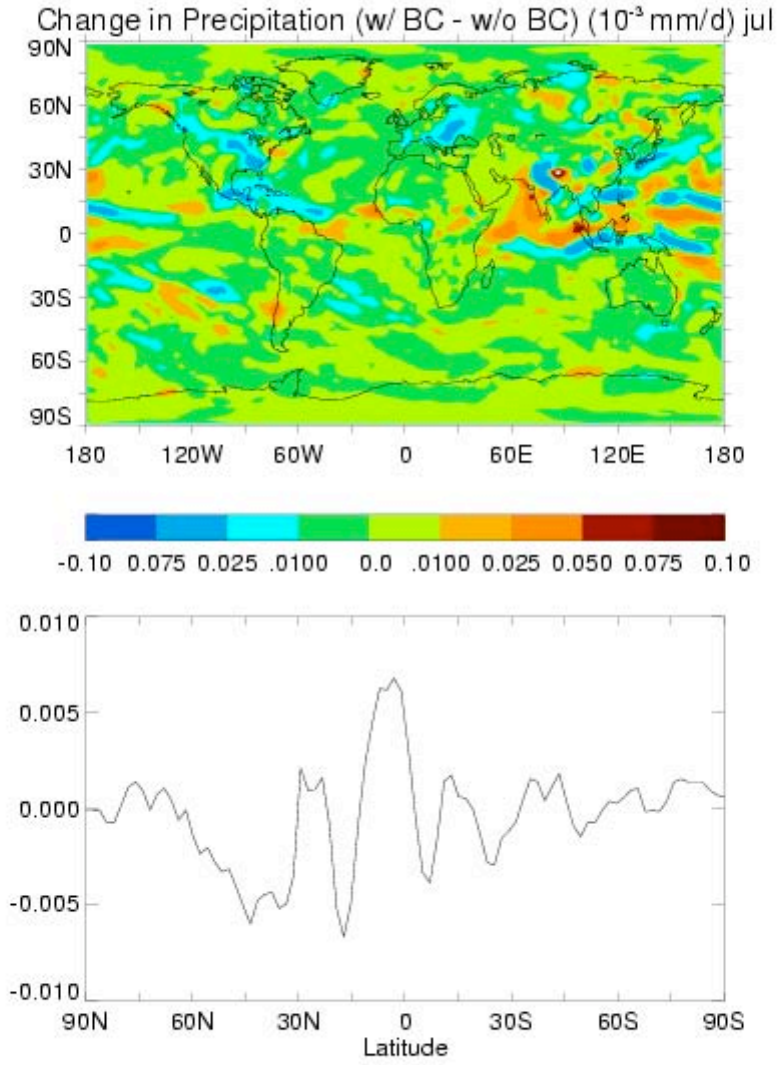

Black Carbon TOA Forcing (W m-2) jul
90N
60N
30N
0
30S
60S
90S
180
120W
60W
0
60E
120E
180
0
-20.
-10.
-5.0
-1.0
-0.50
0.0
0.50
1.0
5.0
10.
20.
6
4
2
0
-2
-4
-6
Forcing (W m-2)
90N
60N
30N
0
30S
60S
90S
Latitude

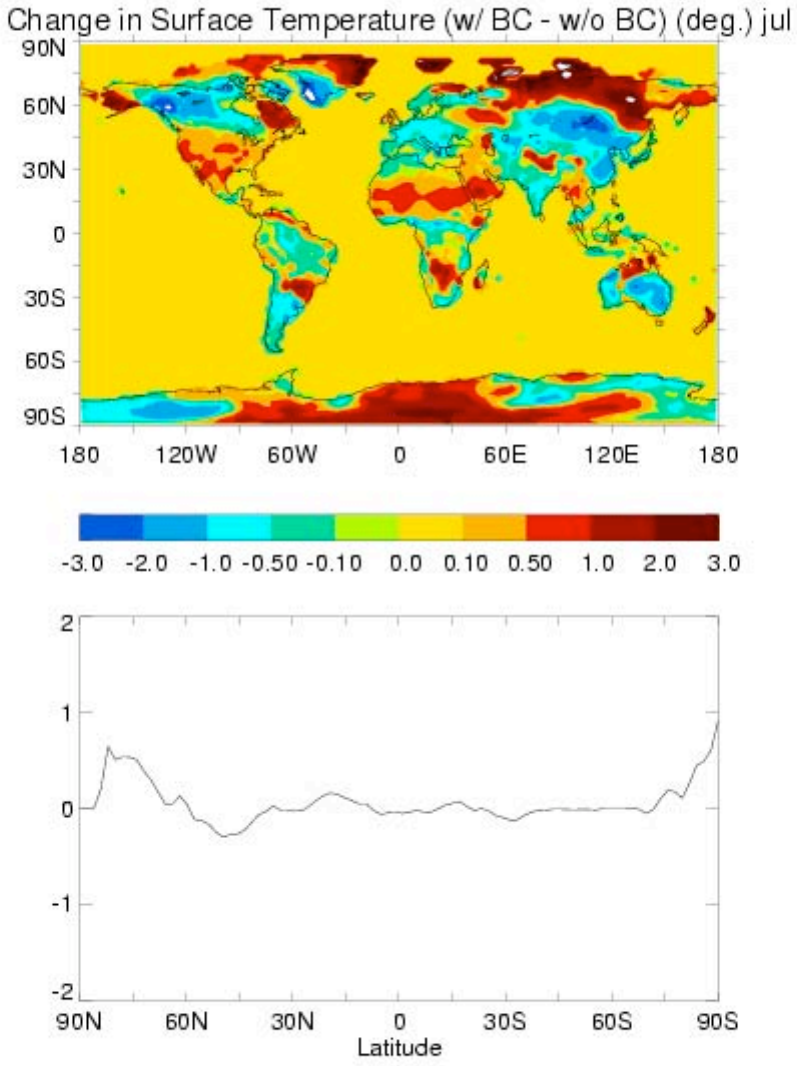

Change in Low Cloud Amount (w/ BC - w/o BC) (%) jul
90N
60N
30N
0
30S
60S
90S
180
120W
60W
0
60E
120E
180
-30.
-20.
-10.
-5.0
-1.0
0.0
1.0
5.0
10.
20.
30.
10
5
0
-5
-10
90N
60N
30N
0
30S
60S
90S
Latitude

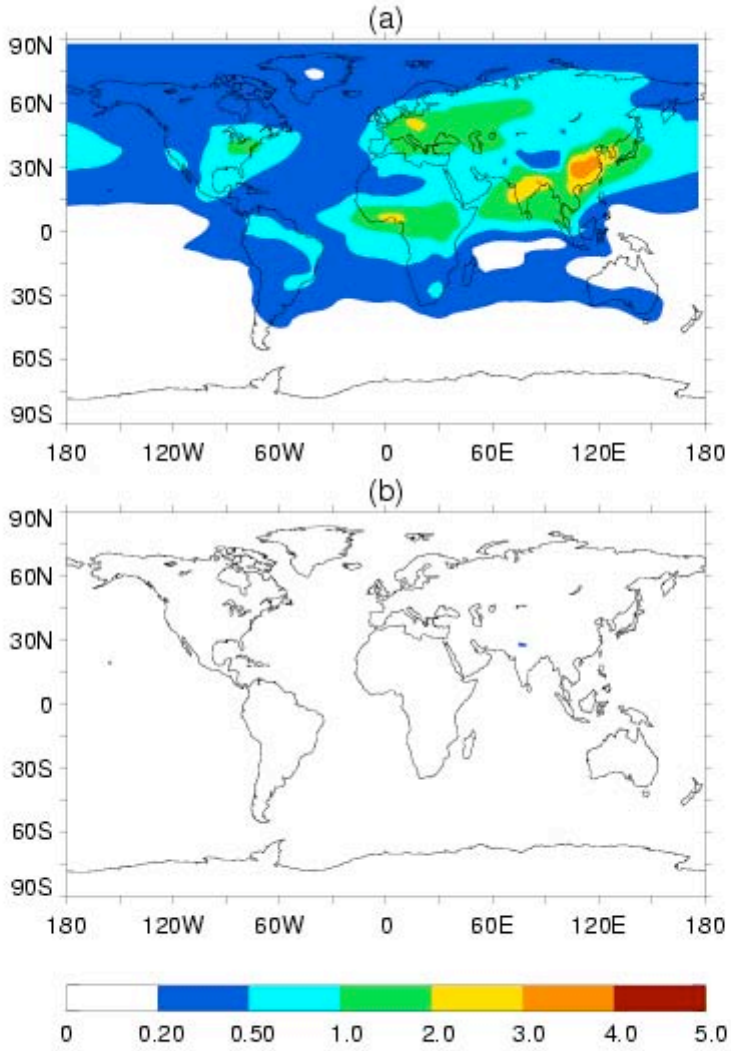

Change in LWP (w/ BC - w/o BC) (g m-2) jul
90N
60N
30N
0
30S
60S
90S
180
120W
60W
0
60E
120E
180
-300
-100
-50.
-25.
0.0
25.
50.
100
300
30
20
10
0
-10
-20
-30
90N
60N
30N
0
30S
60S
90S
Latitude

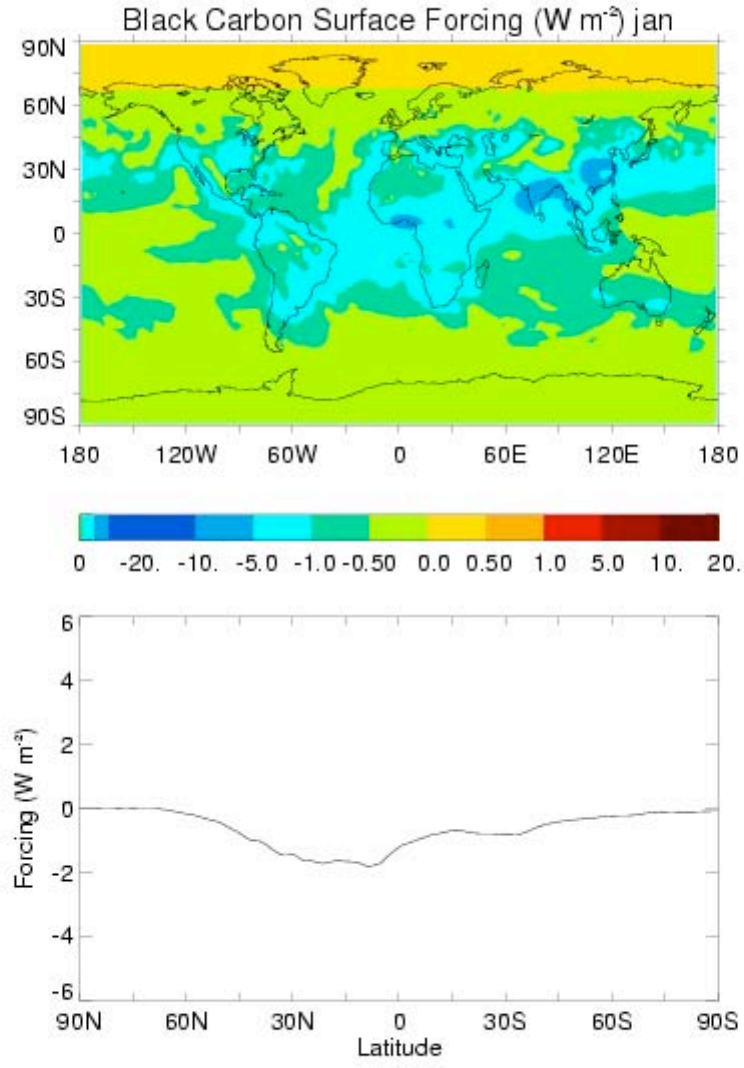

Surface Flux Change (w/ BC - w/o BC) (W m-2) jul
90N
60N
30N
0
30S
60S
90S
180
120W
60W
0
60E
120E
180
-80.
-40.
-20.
-10.
-5.0
0.0
5.0
10.
20.
40.
80.
10
5
0
-5
-10
Flux Change (W m-2)
90N
60N
30N
0
30S
60S
90S
Latitude

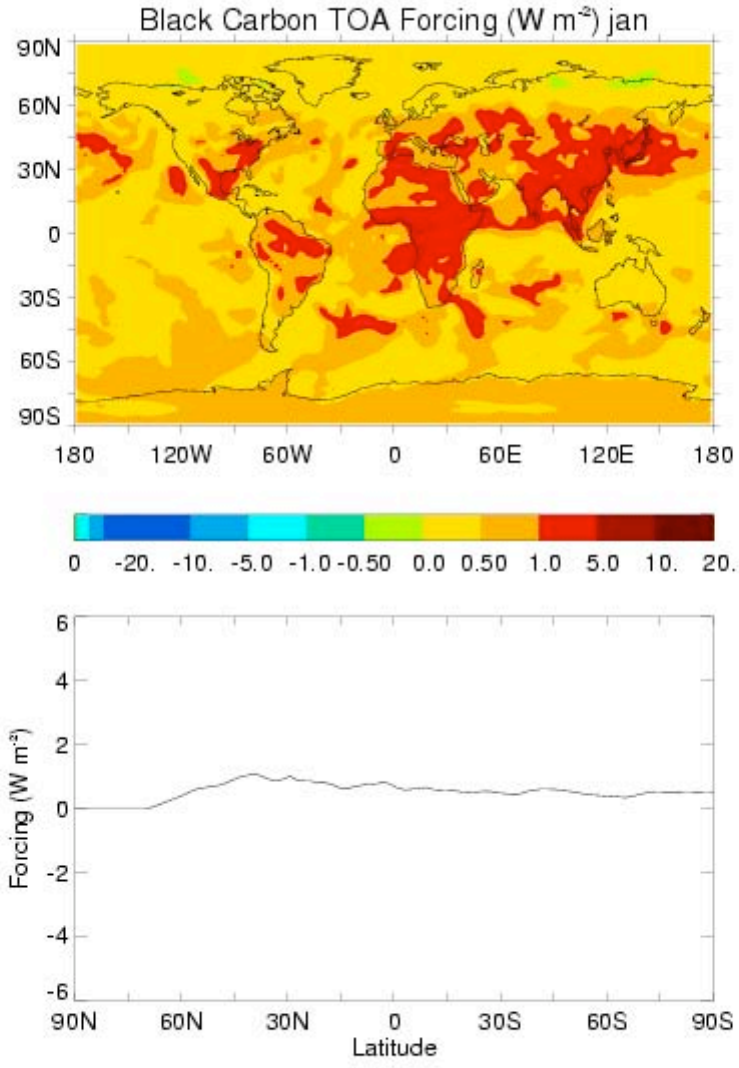

TOA Flux Change (w/ BC - w/o BC) (W m-2) jul
90N
60N
30N
0
30S
60S
90S
180
120W
60W
0
60E
120E
180
-80.
-40.
-20.
-10.
-5.0
0.0
5.0
10.
20.
40.
80.
10
5
0
-5
-10
Flux Change (W m-2)
90N
60N
30N
0
30S
60S
90S
Latitude

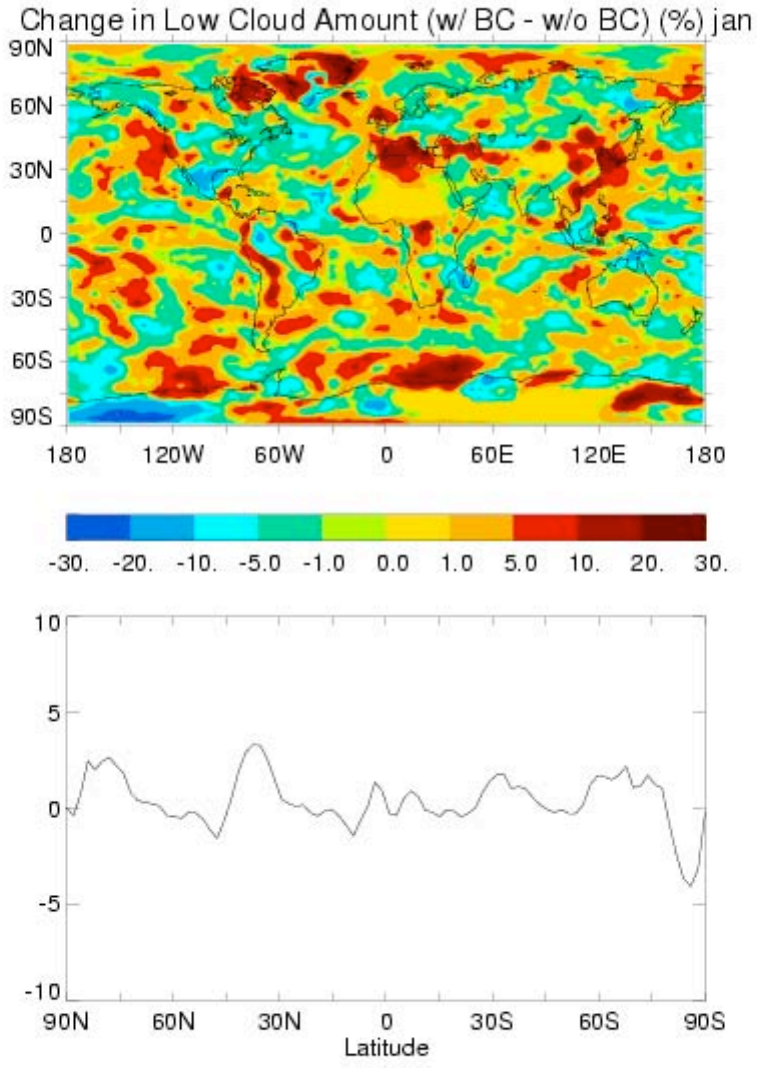

Change in Precipitation (w/ BC - w/o BC) (10-3 mm/d) jul
90N
60N
30N
0
30S
60S
90S
180
120W
60W
0
60E
120E
180
-0.10 0.075 0.025 .0100 0.0 .0100 0.025 0.050 0.075 0.10
0.010
0.005
0.000
-0.005
-0.010
90N
60N
30N
0
30S
60S
90S
Latitude

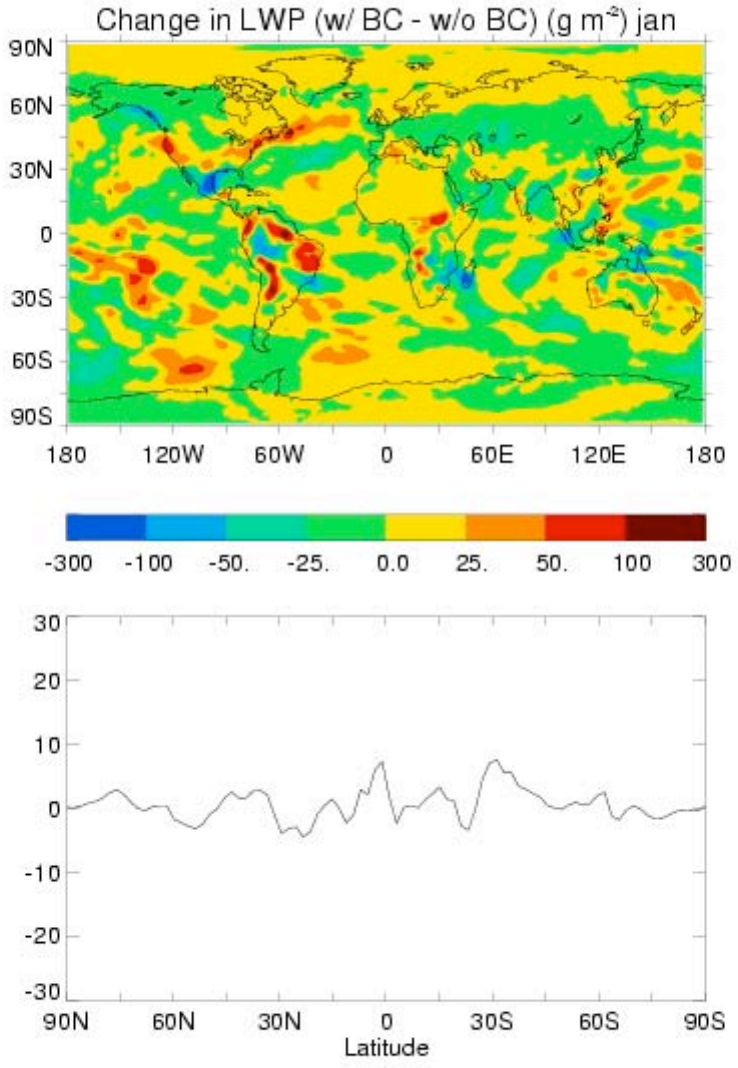

Change in Surface Temperature (w/ BC - w/o BC) (deg.) jul
90N
60N
30N
0
30S
60S
90S
180
120W
60W
0
60E
120E
180
-3.0 -2.0 -1.0 -0.50 -0.10 0.0 0.10 0.50 1.0 2.0 3.0
2
1
0
-1
-2
90N
60N
30N
0
30S
60S
90S
Latitude

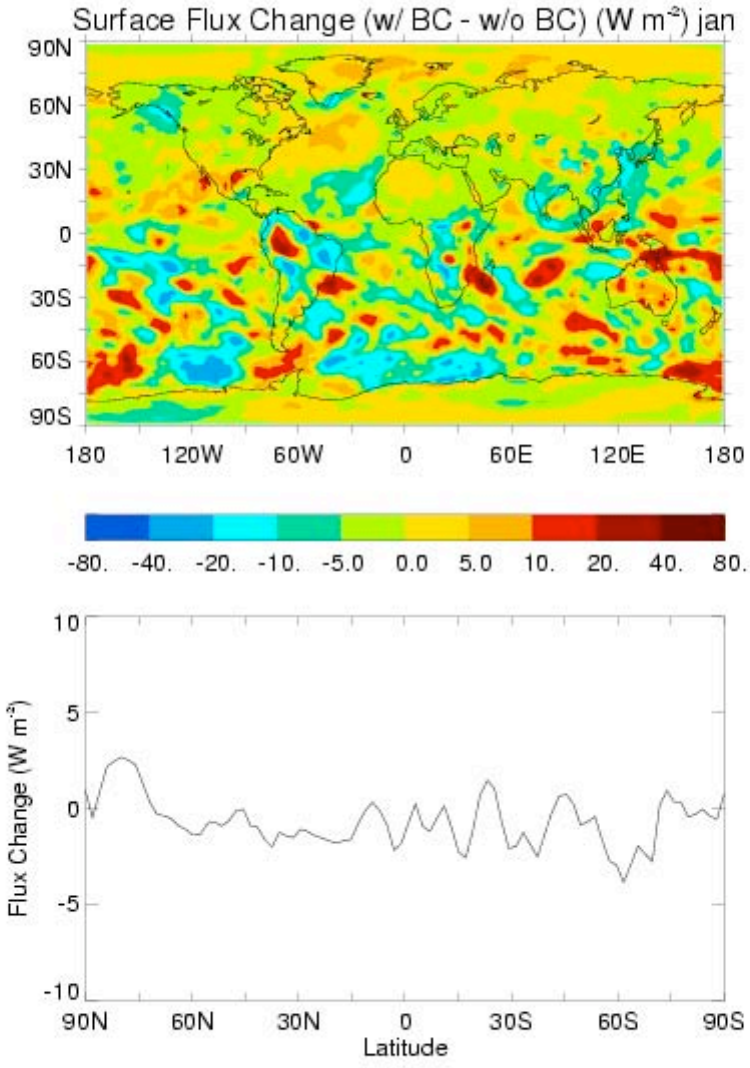

(a)
90N
60N
30N
0
30S
60S
90S
180
120W
60W
0
60E
120E
180
(b)
90N
60N
30N
0
30S
60S
90S
180
120W
60W
0
60E
120E
180
0
0.20
0.50
1.0
2.0
3.0
4.0
5.0

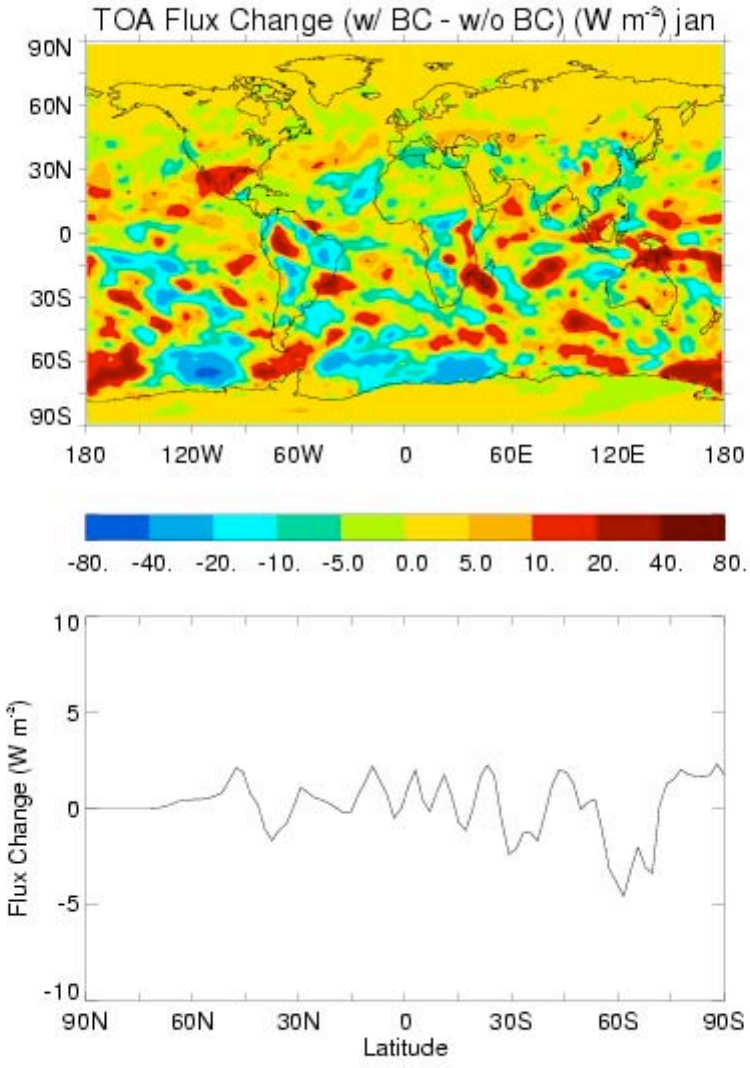

Black Carbon Surface Forcing (W m-2) jan
90N
60N
30N
0
30S
60S
90S
180
120W
60W
0
60E
120E
180
0
-20.
-10.
-5.0
-1.0
-0.50
0.0
0.50
1.0
5.0
10.
20.
6
4
2
0
-2
-4
-6
Forcing (W m-2)
90N
60N
30N
0
30S
60S
90S
Latitude

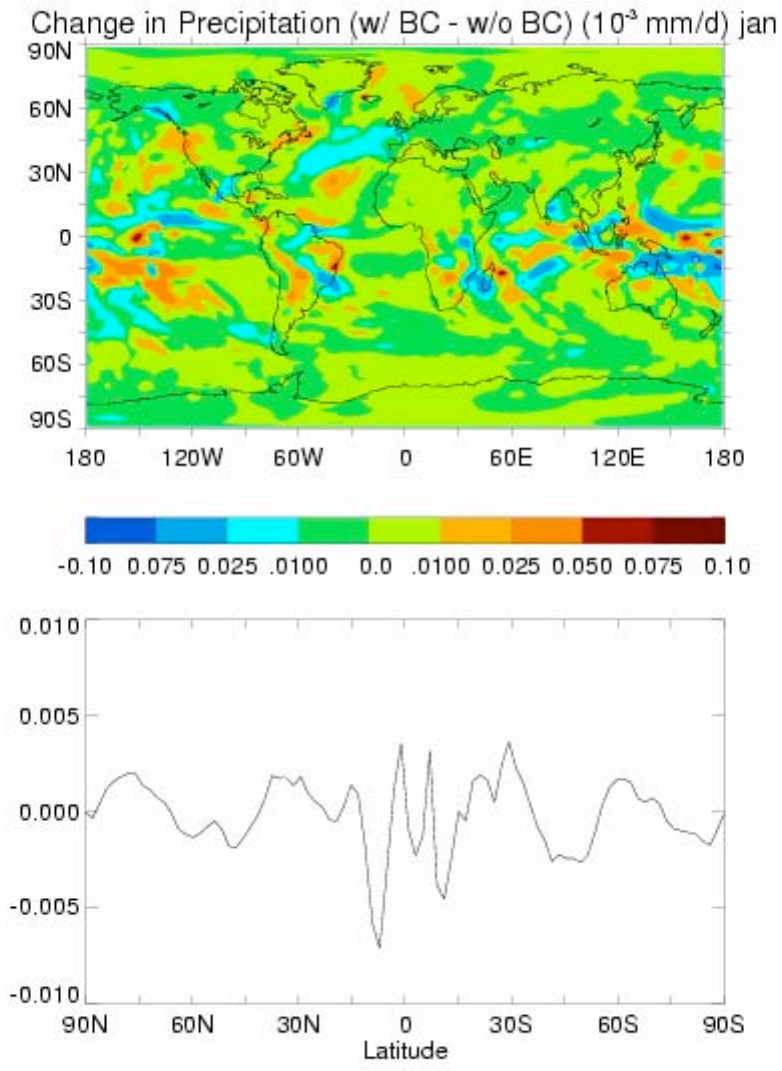

Black Carbon TOA Forcing (W m-2) jan
90N
60N
30N
0
30S
60S
90S
180
120W
60W
0
60E
120E
180
0
-20.
-10.
-5.0
-1.0
-0.50
0.0
0.50
1.0
5.0
10.
20.
6
4
2
0
-2
-4
-6
Forcing (W m-2)
90N
60N
30N
0
30S
60S
90S
Latitude

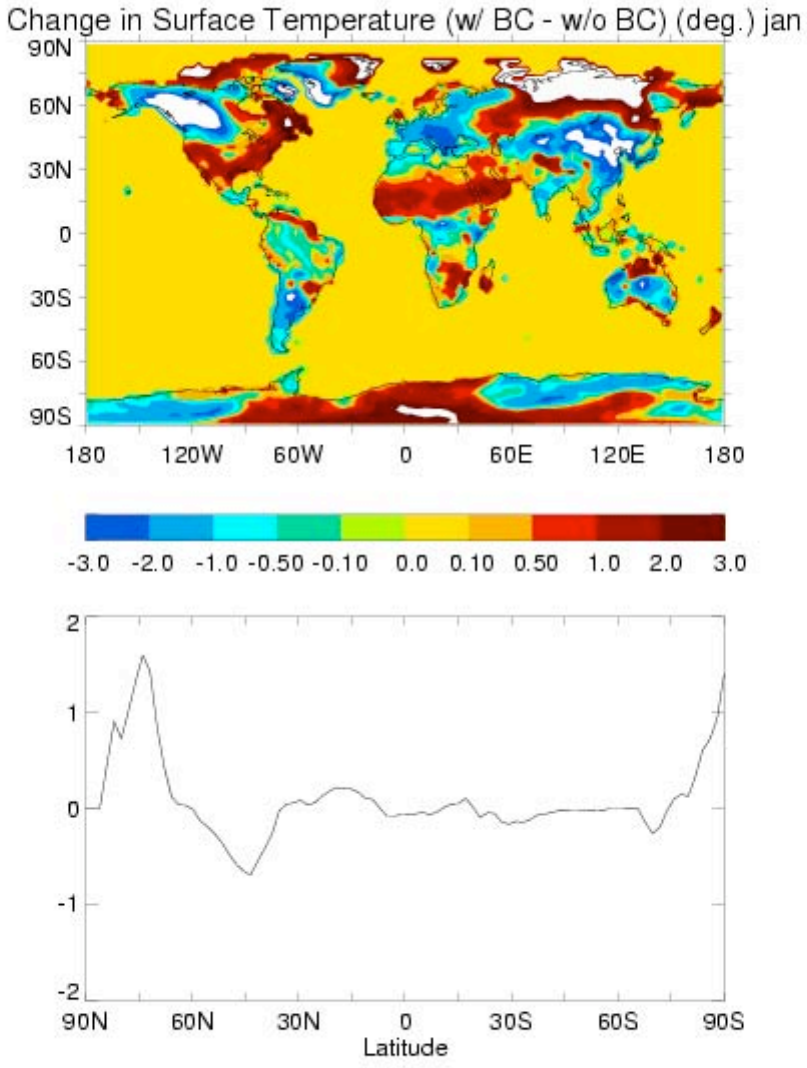

Change in Low Cloud Amount (w/ BC - w/o BC) (%) jan
90N
60N
30N
0
30S
60S
90S
180
120W
60W
0
60E
120E
180
-30.
-20.
-10.
-5.0
-1.0
0.0
1.0
5.0
10.
20.
30.
10
5
0
-5
-10
90N
60N
30N
0
30S
60S
90S
Latitude


Change in LWP (w/ BC - w/o BC) (g m-2) jan
90N
60N
30N
0
30S
60S
90S
180
120W
60W
0
60E
120E
180
-300
-100
-50.
-25.
0.0
25.
50.
100
300
30
20
10
0
-10
-20
-30
90N
60N
30N
0
30S
60S
90S
Latitude


Surface Flux Change (w/ BC - w/o BC) (W m-2) jan
90N
60N
30N
0
30S
60S
90S
180
120W
60W
0
60E
120E
180
-80.
-40.
-20.
-10.
-5.0
0.0
5.0
10.
20.
40.
80.
10
5
0
-5
-10
Flux Change (W m-2)
90N
60N
30N
0
30S
60S
90S
Latitude


TOA Flux Change (w/ BC - w/o BC) (W m-2) jan
90N
60N
30N
0
30S
60S
90S
180
120W
60W
0
60E
120E
180
-80.
-40.
-20.
-10.
-5.0
0.0
5.0
10.
20.
40.
80.
10
5
0
-5
-10
Flux Change (W m-2)
90N
60N
30N
0
30S
60S
90S
Latitude


Change in Precipitation (w/ BC - w/o BC) (10-3 mm/d) jan
90N
60N
30N
0
30S
60S
90S
180
120W
60W
0
60E
120E
180
-0.10 0.075 0.025 .0100 0.0 .0100 0.025 0.050 0.075 0.10
0.010
0.005
0.000
-0.005
-0.010
90N
60N
30N
0
30S
60S
90S
Latitude


Change in Surface Temperature (w/ BC - w/o BC) (deg.) jan
90N
60N
30N
0
30S
60S
90S
180
120W
60W
0
60E
120E
180
-3.0 -2.0 -1.0 -0.50 -0.10 0.0 0.10 0.50 1.0 2.0 3.0
2
1
0
-1
-2
90N
60N
30N
0
30S
60S
90S
Latitude