Can Science Save the Earth? – Radiation balance and climate

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Ministero dell'Università e della Ricerca
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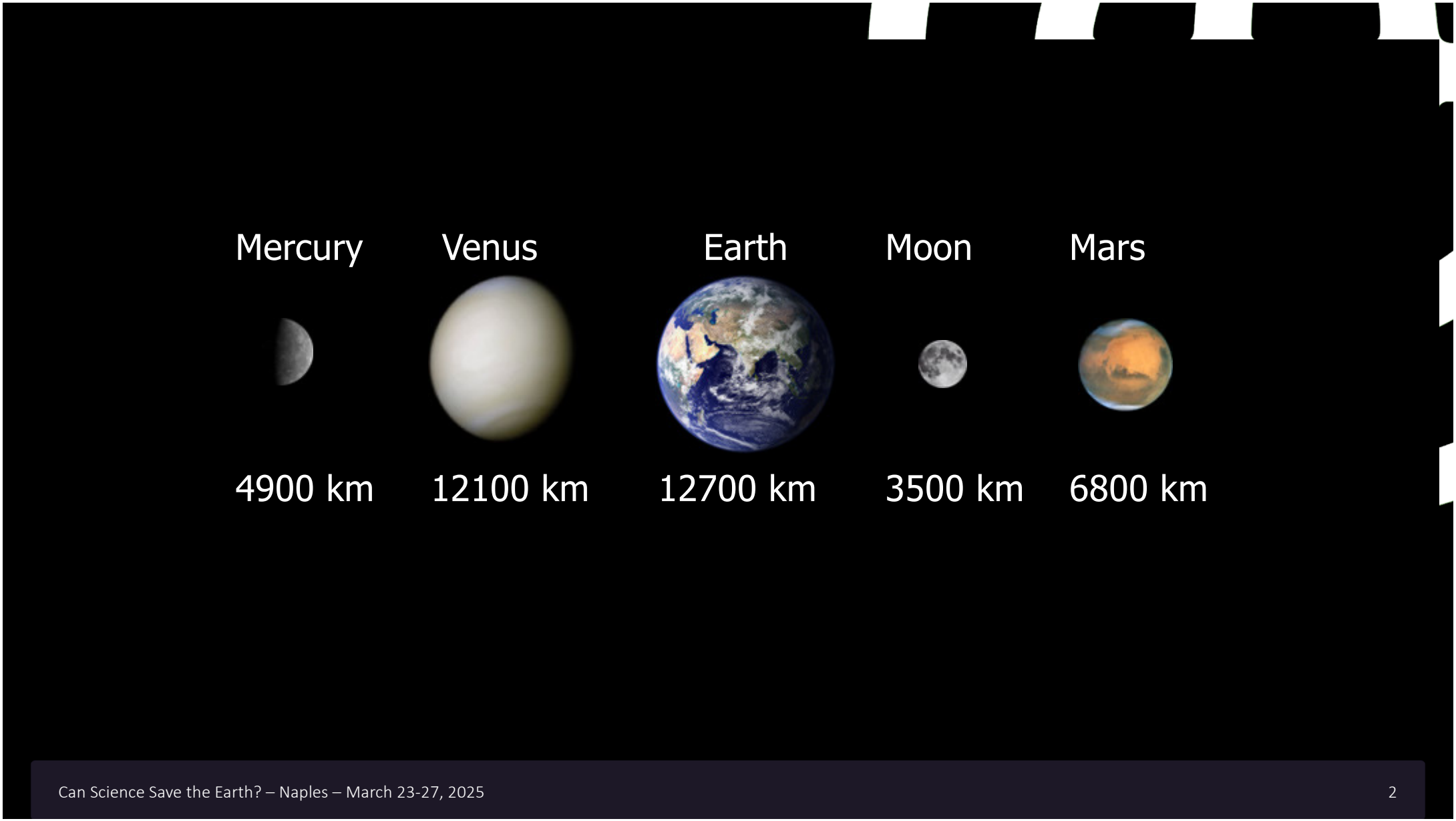
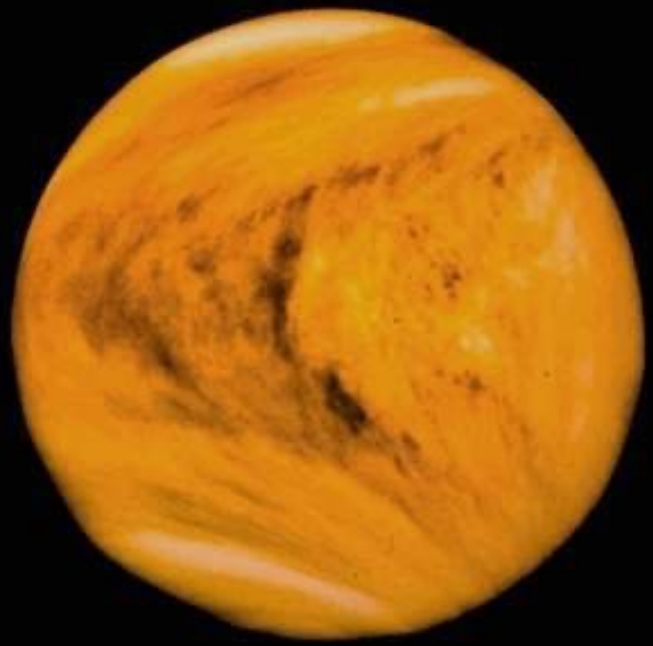
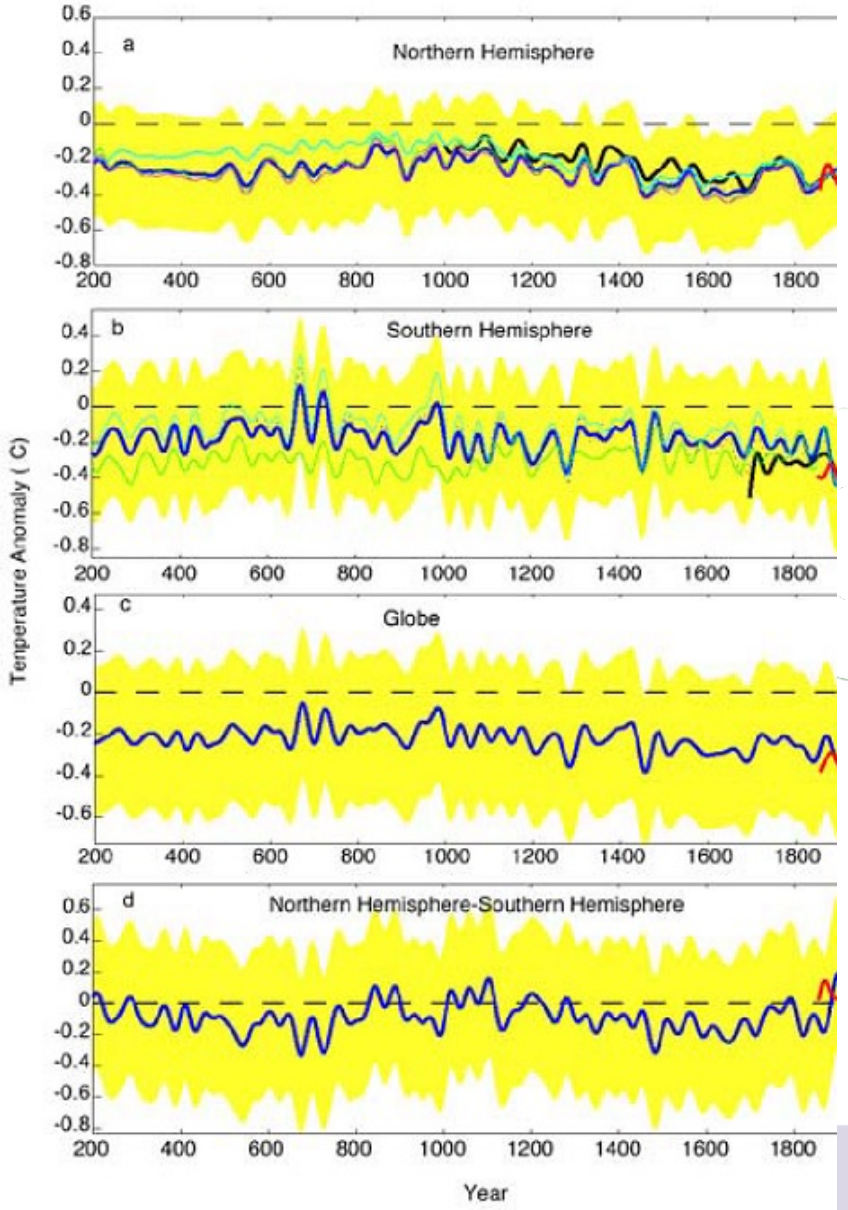
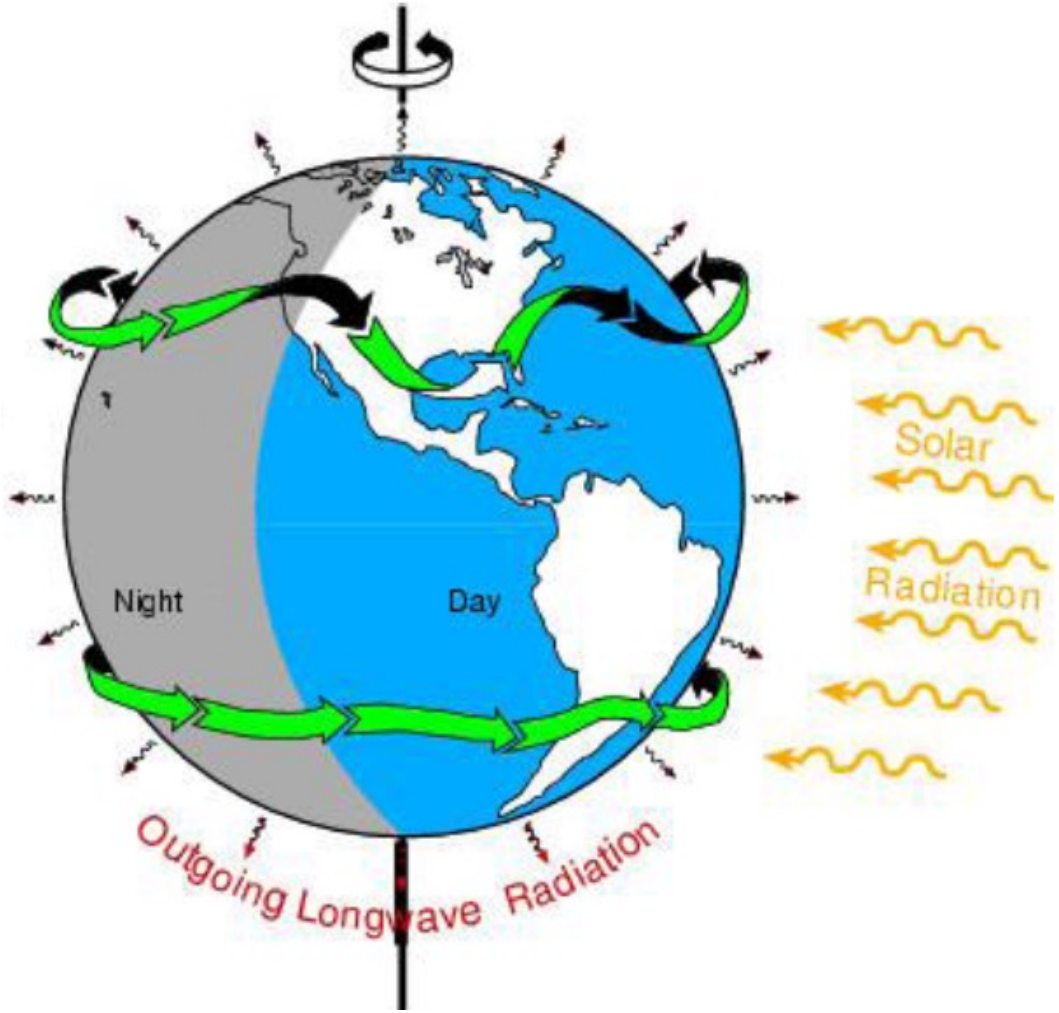

Mercury
Venus
Earth
Moon
Mars
4900 km
12100 km
12700 km
3500 km
6800 km

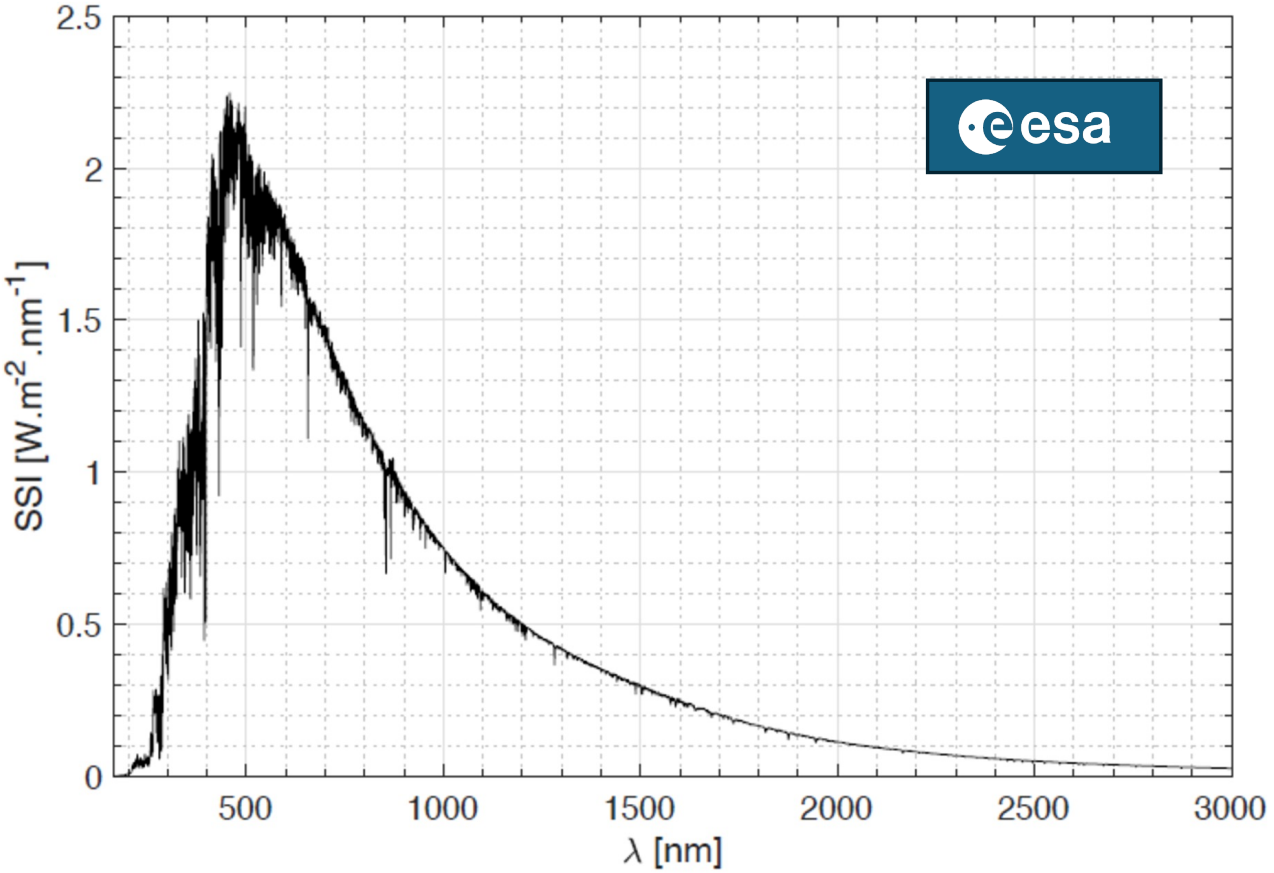


	Mercury	Venus	Earth	Moon	Mars
Day	400°C	464 °C	20°C	110°C	-5°C
Night	-200°C	464 °C	10°C	-150°C	-85°C

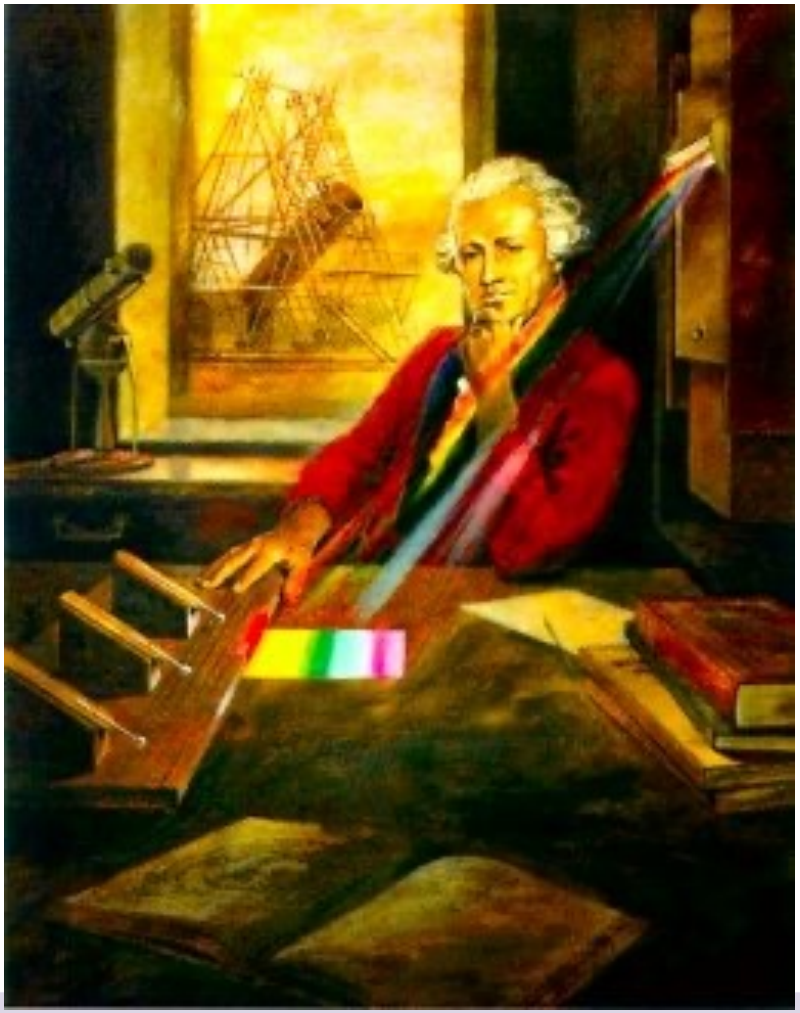


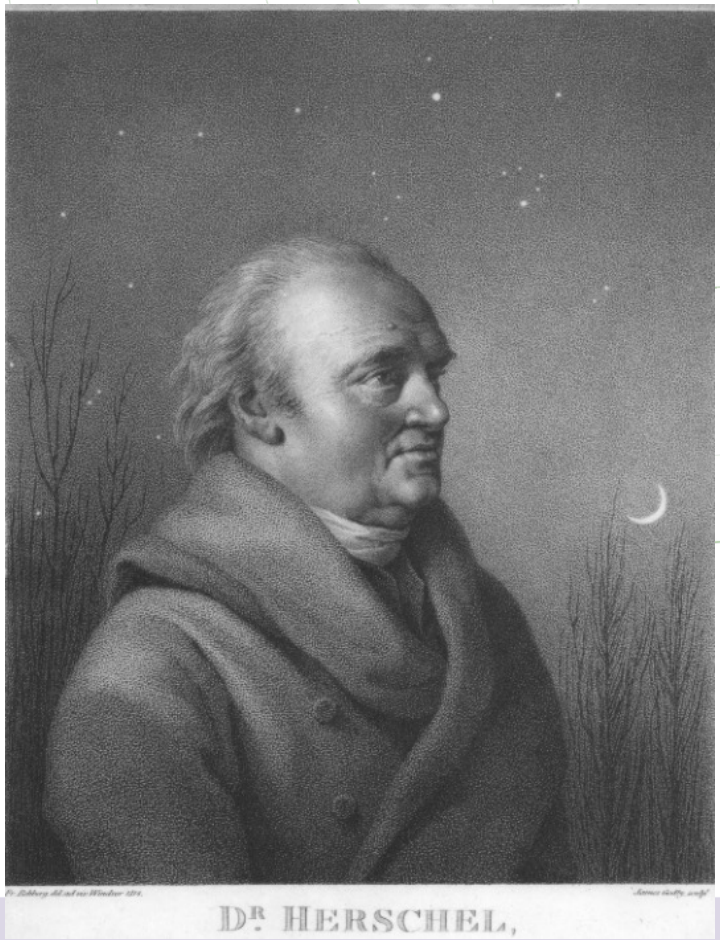
Adapted from
Mann and Jones, 2003

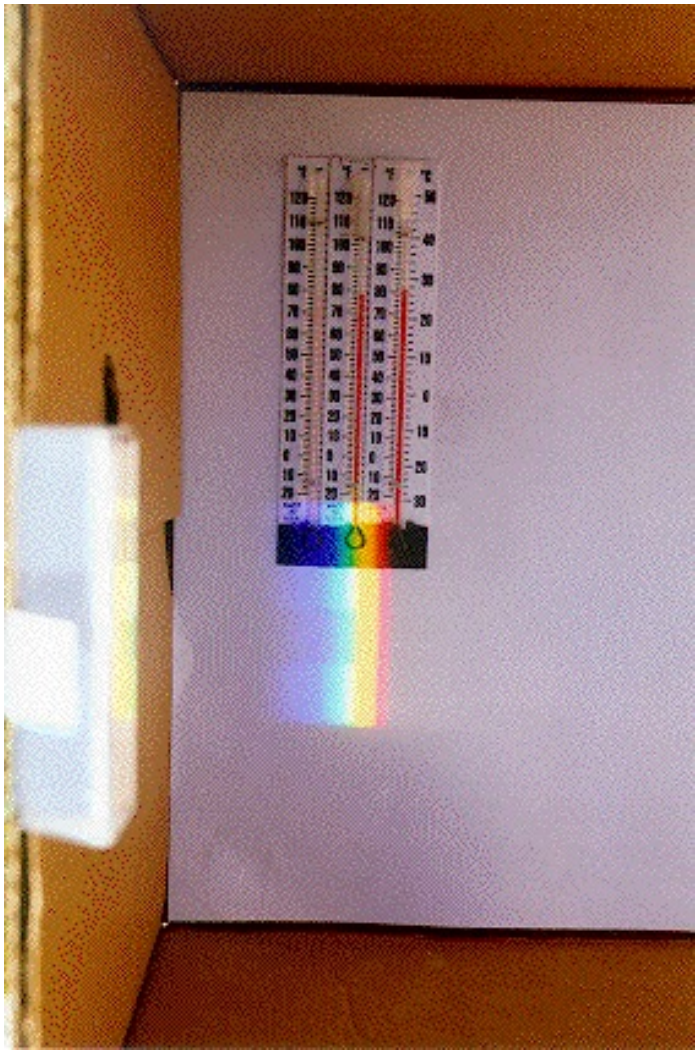

Night
Day
Solar
Radiation
Outgoing Longwave Radiation

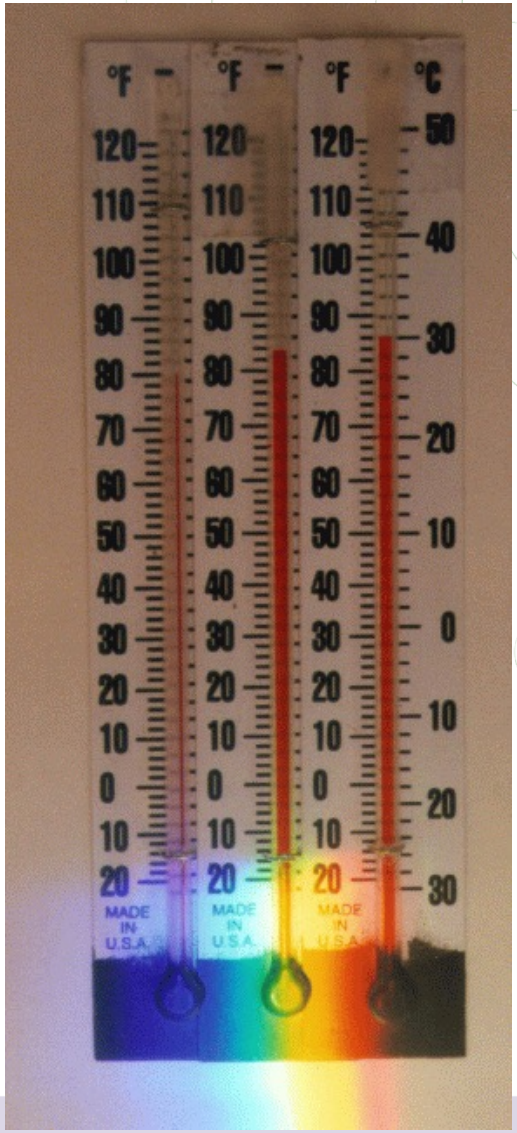

2.5
2
1.5
1
0.5
0
SSI [W.m-2.nm-1]
500
1000
1500
2000
2500
3000
λ [nm]
esa

Frederick William Herschel (1738-1822)

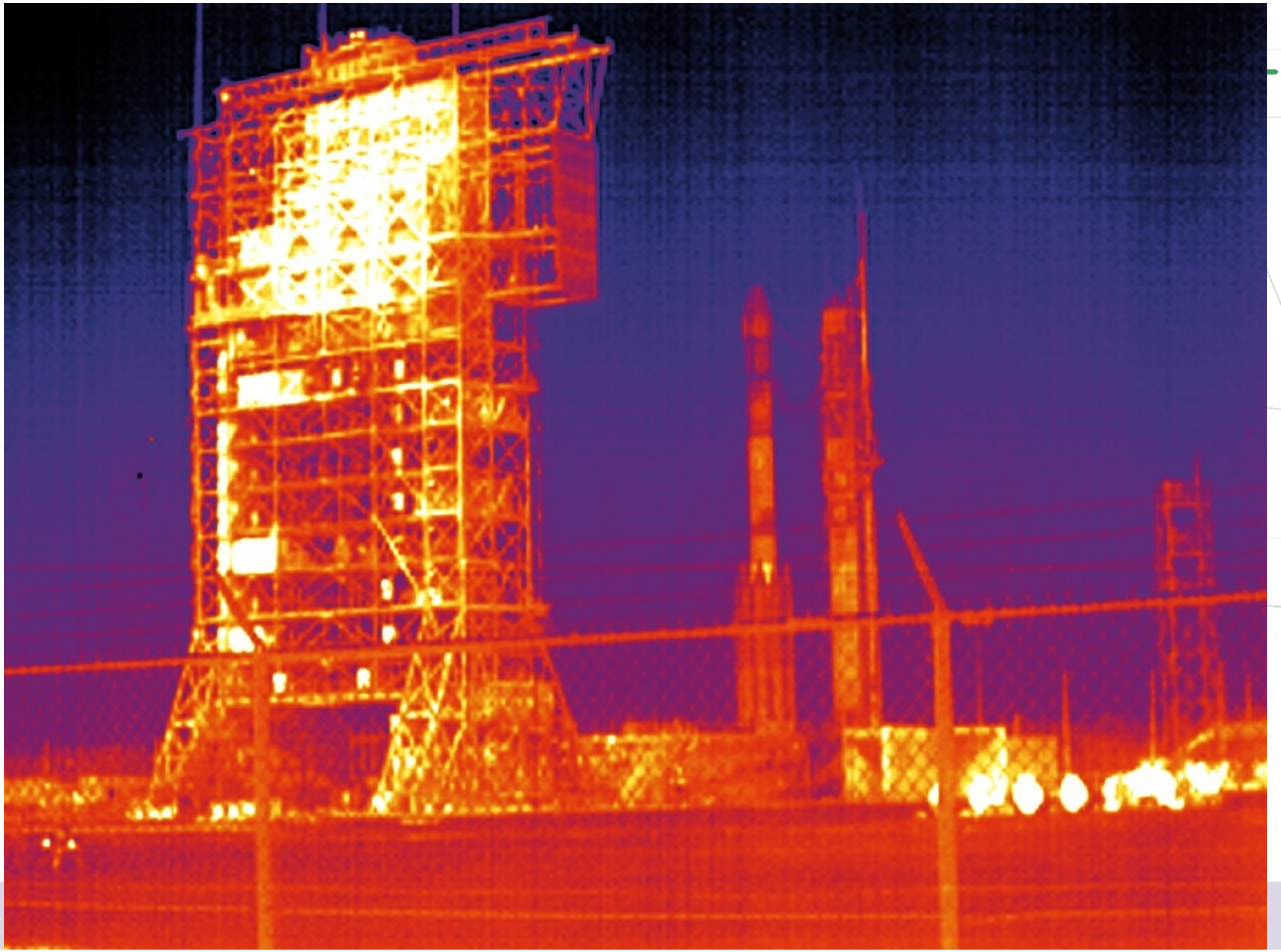


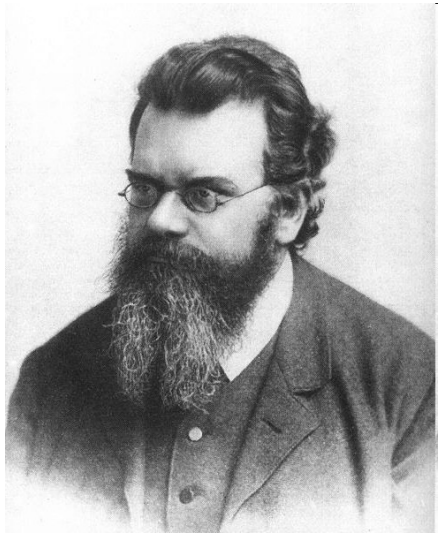


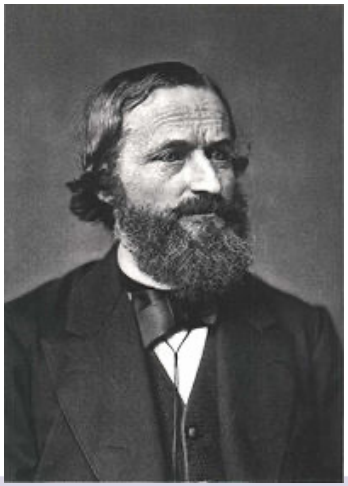


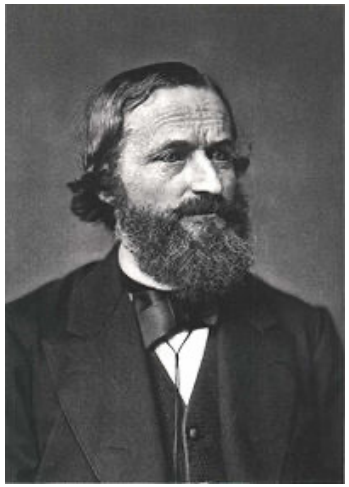

°F
°F
°F
°C
120
110
100
90
80
70
60
50
40
30
20
10
0
10
20
50
40
30
20
10
0
10
20
30
MADE IN U.S.A.

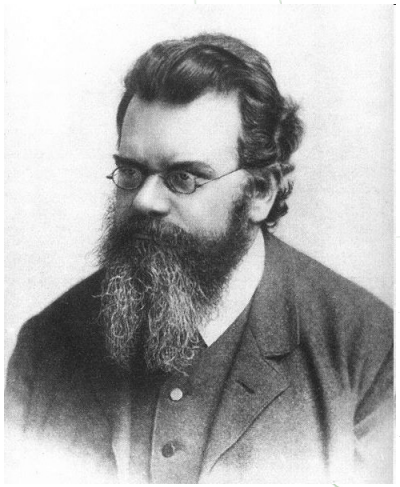

DELTA









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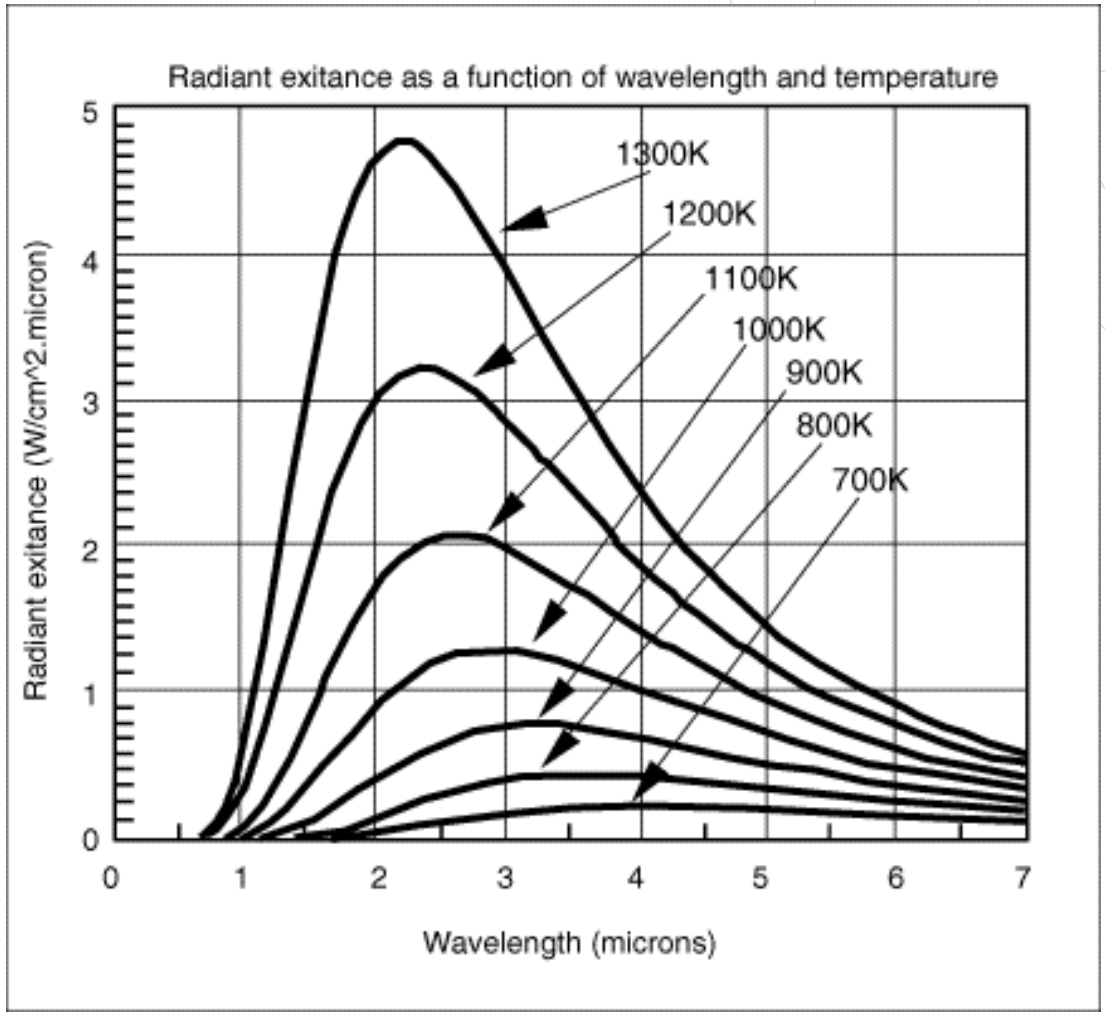
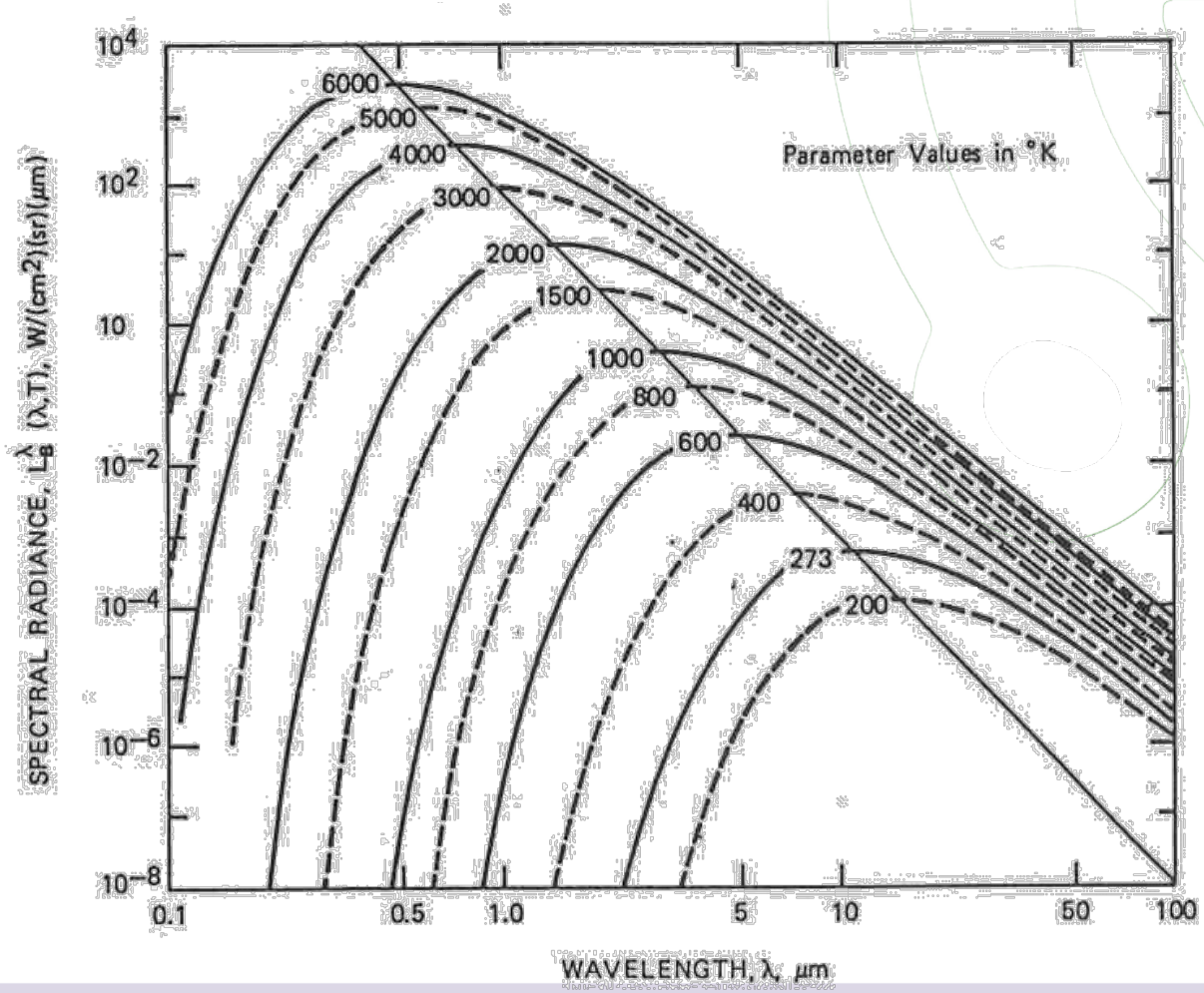
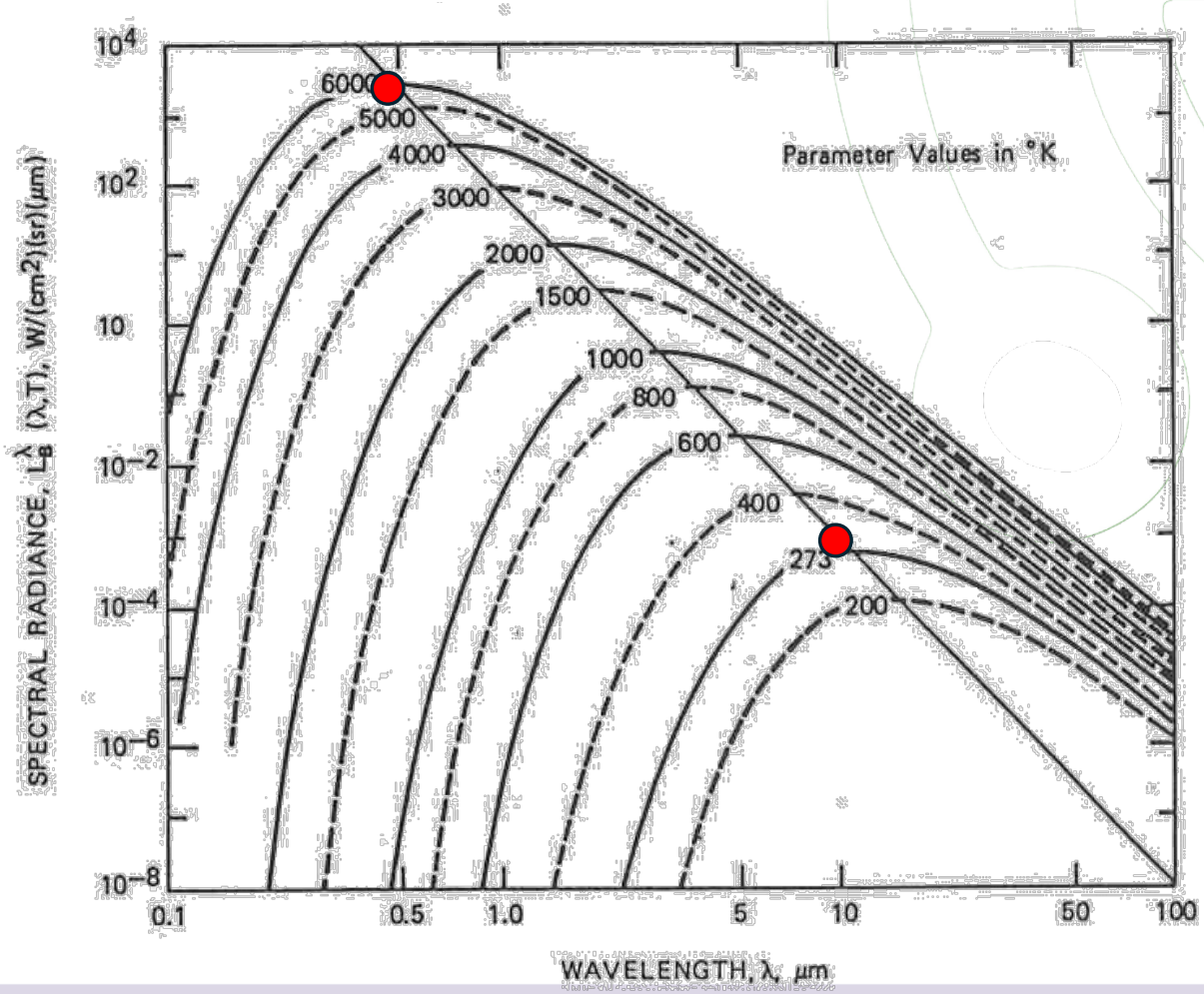
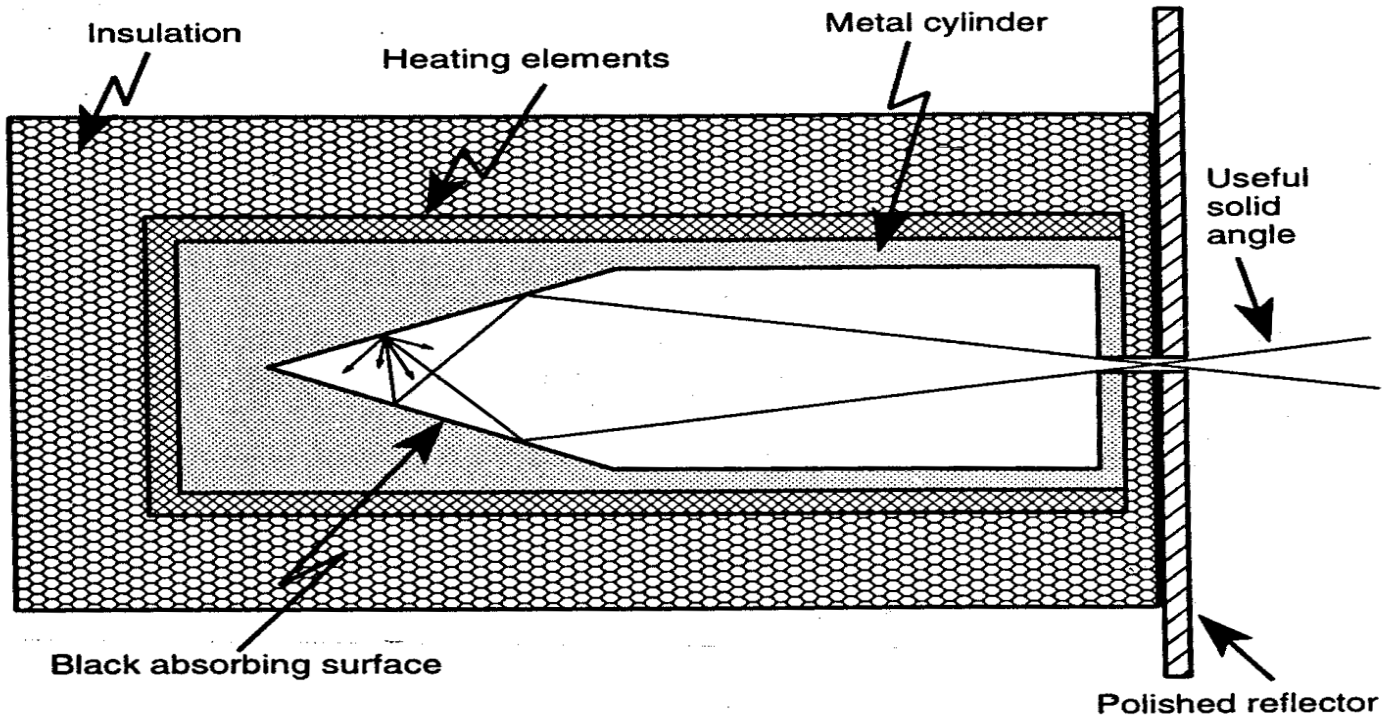

Radiant exitance as a function of wavelength and temperature
Radiant exitance (W/cm^2.micron)
Wavelength (microns)
1300K
1200K
1100K
1000K
900K
800K
700K
0
1
2
3
4
5
6
7

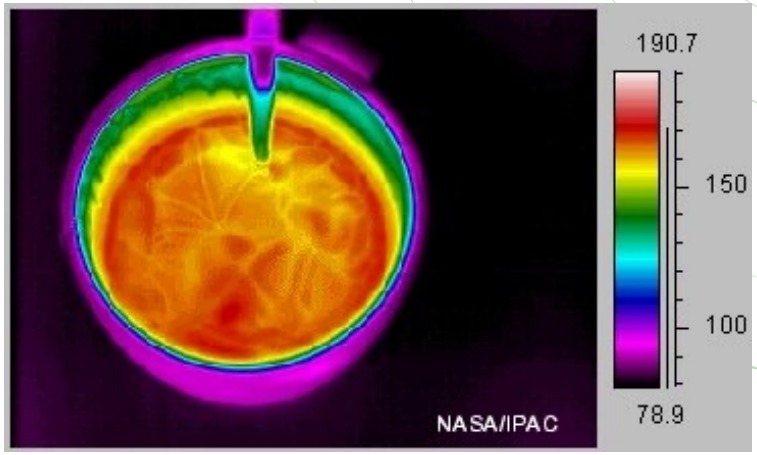
$$\lambda_{max}\, T = 0.28978 \text{ cm K}$$

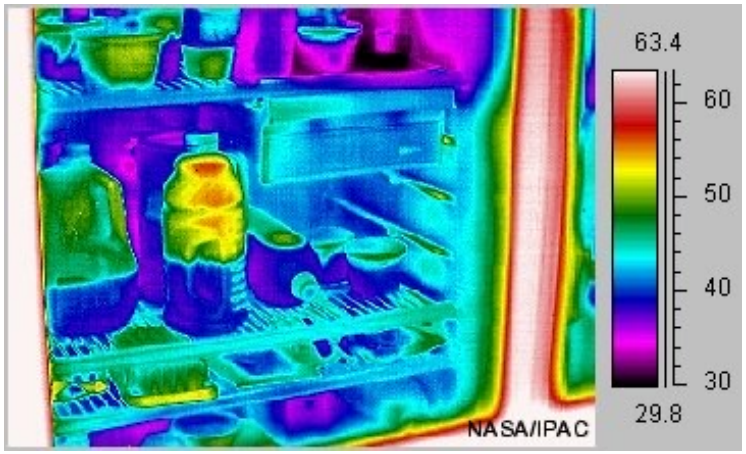


$$\lambda_{max}\, T = 0.28978 \text{ cm K}$$



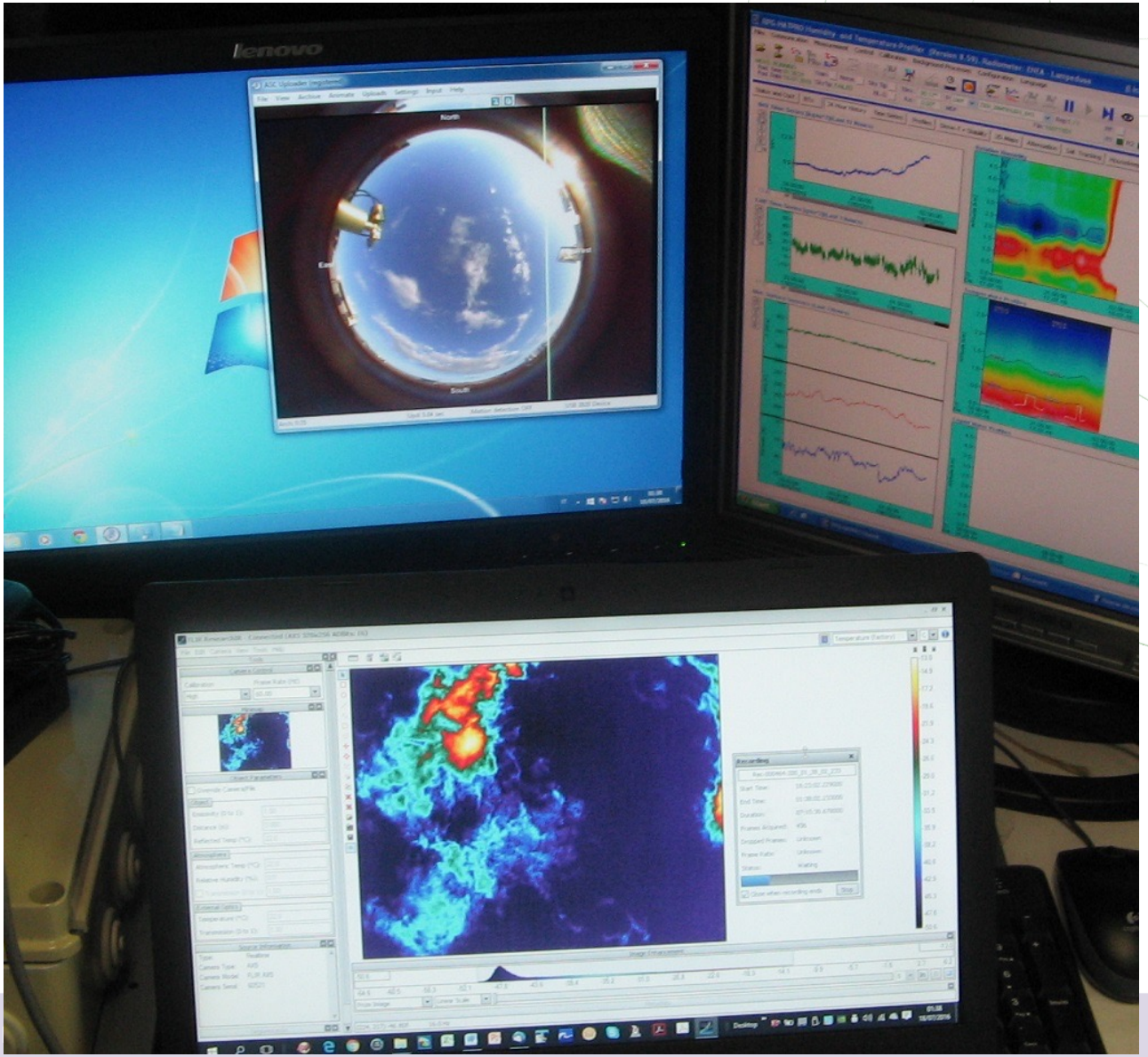

Insulation
Heating elements
Metal cylinder
Useful
solid
angle
Black absorbing surface
Polished reflector

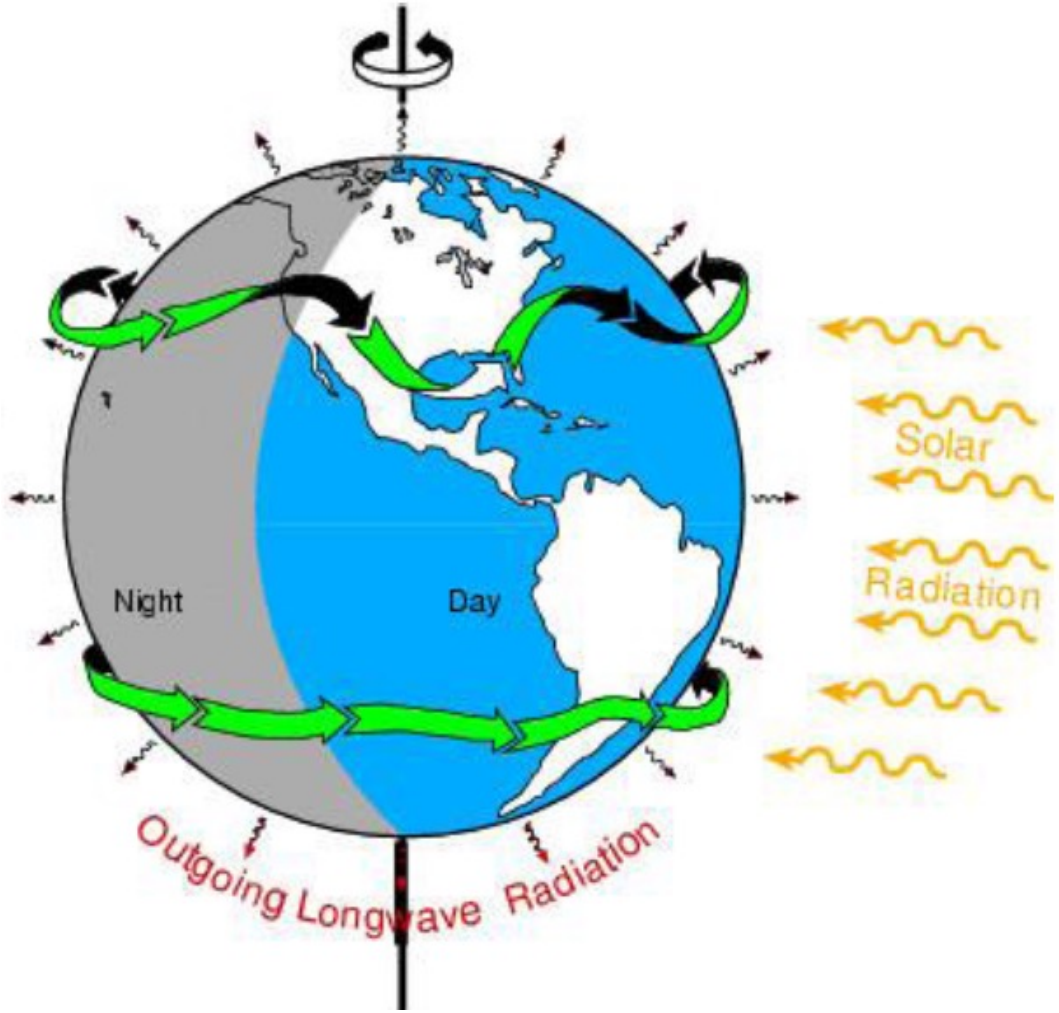

190.7
150
100
78.9
NASA/IPAC

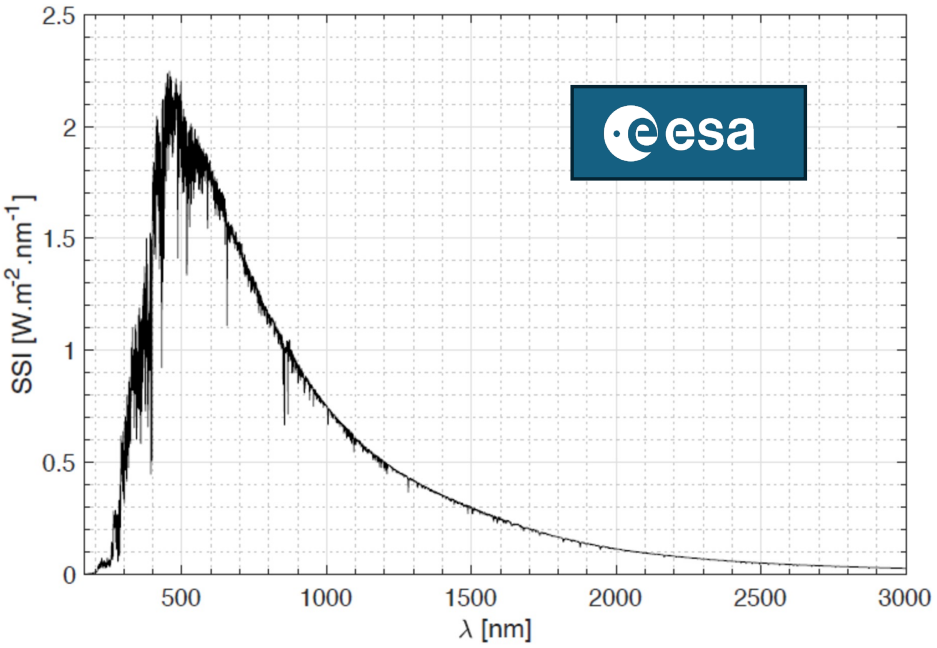

63.4
60
50
40
30
29.8
NASA/IPAC

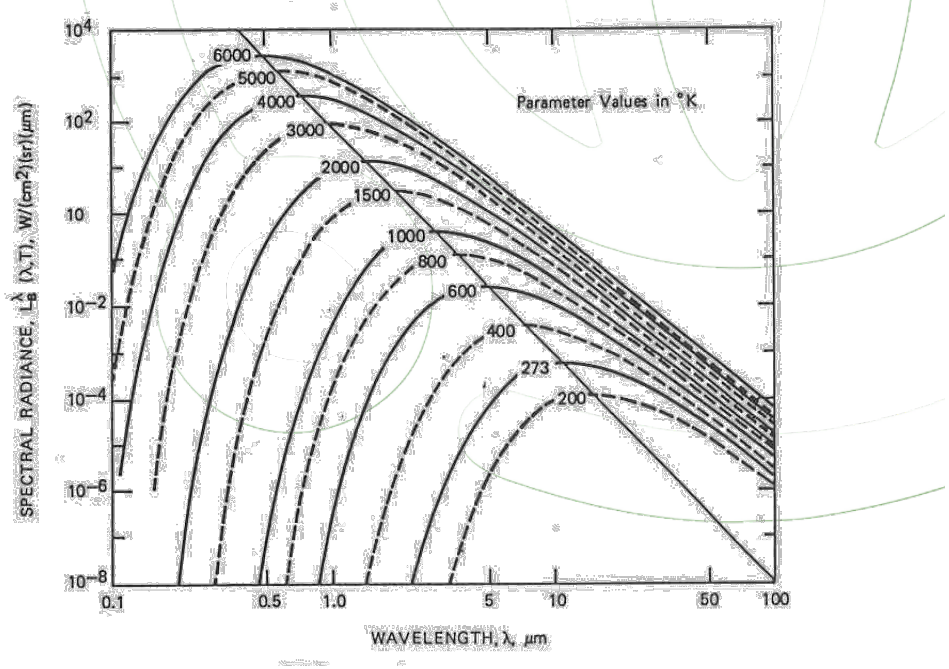

SIATF


NASA/IPAC
91.1
90
85
80
75
72.7

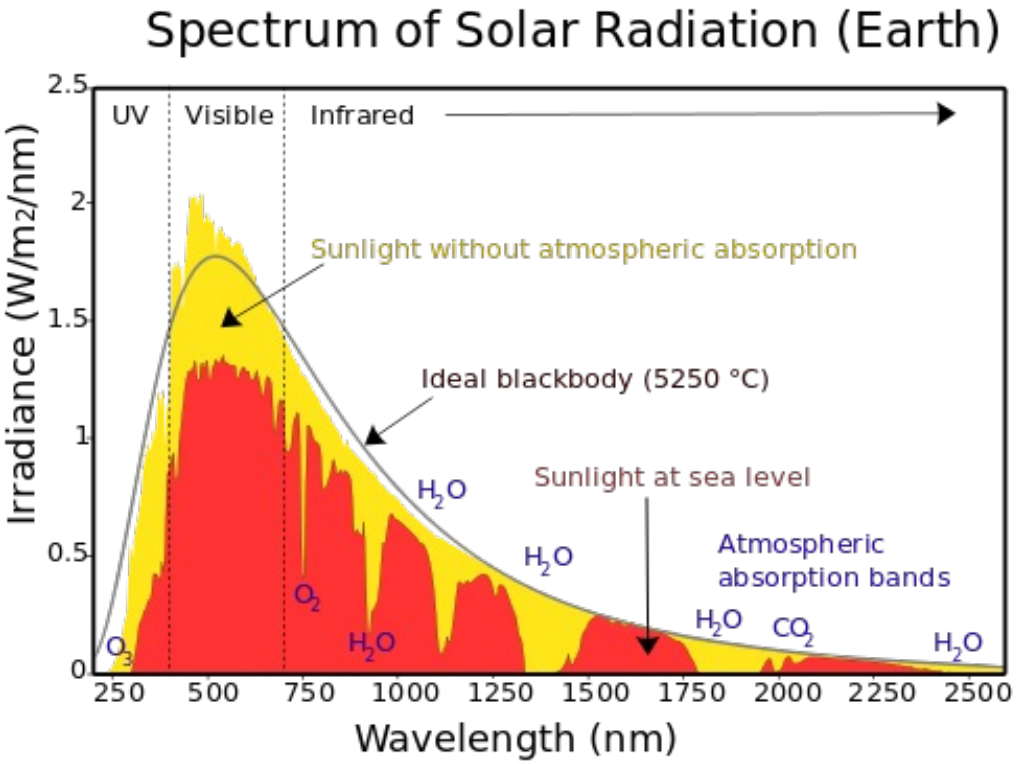

lenovo

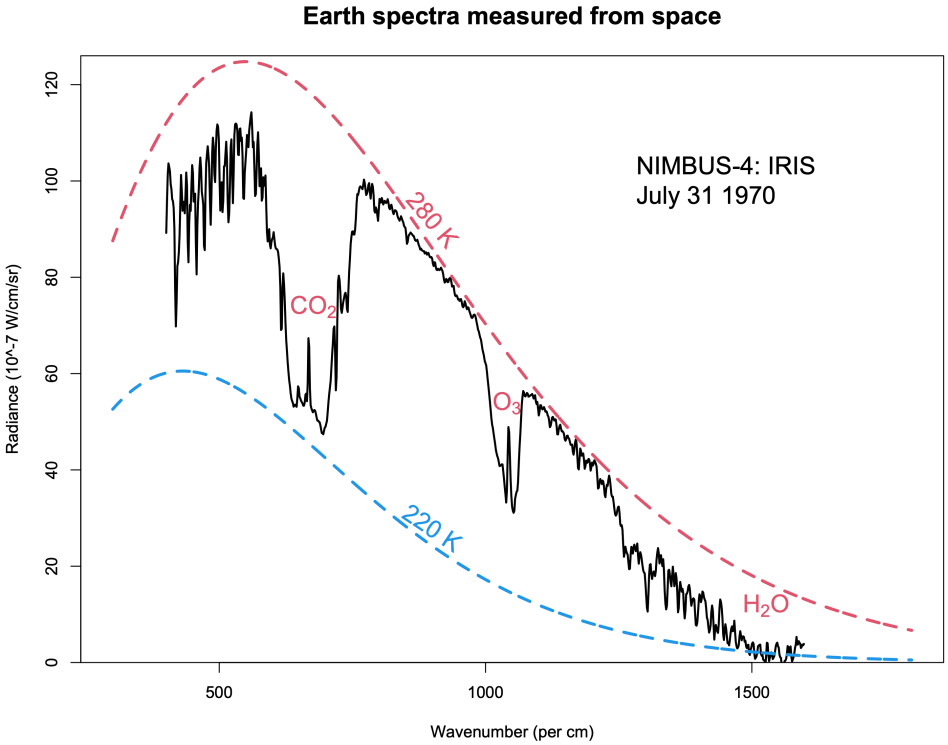

Night
Day
Solar
Radiation
Outgoing Longwave Radiation

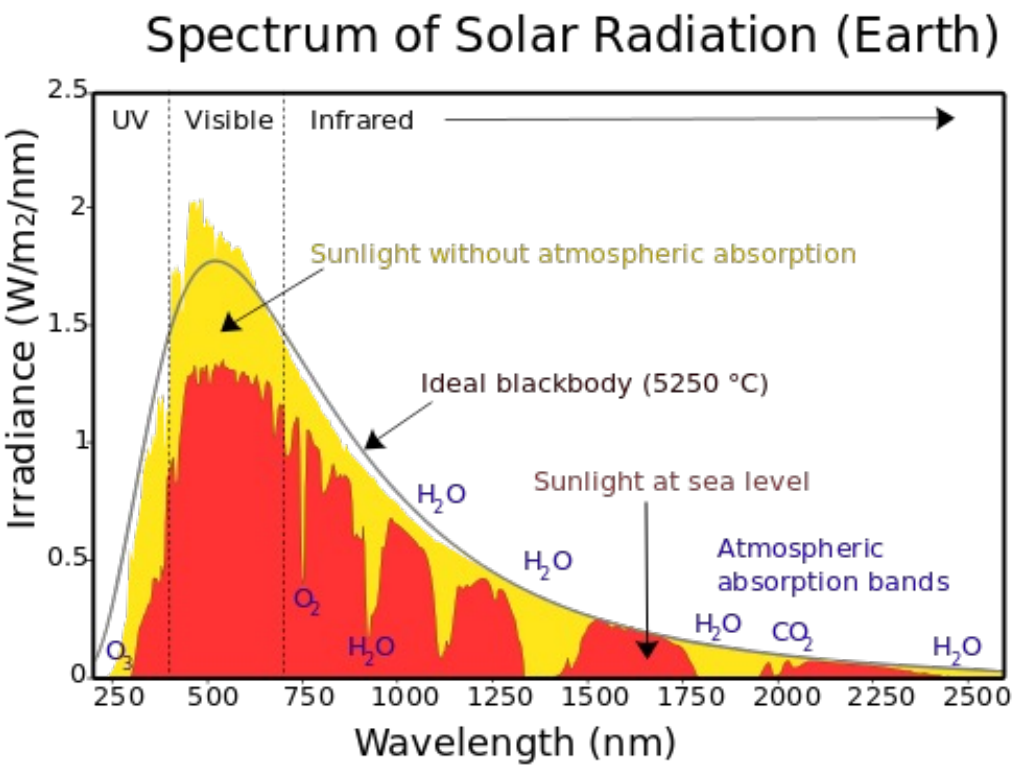

SSI [W.m^{-2}.nm^{-1}]
λ [nm]
0
0.5
1
1.5
2
2.5
500
1000
1500
2000
2500
3000
esa

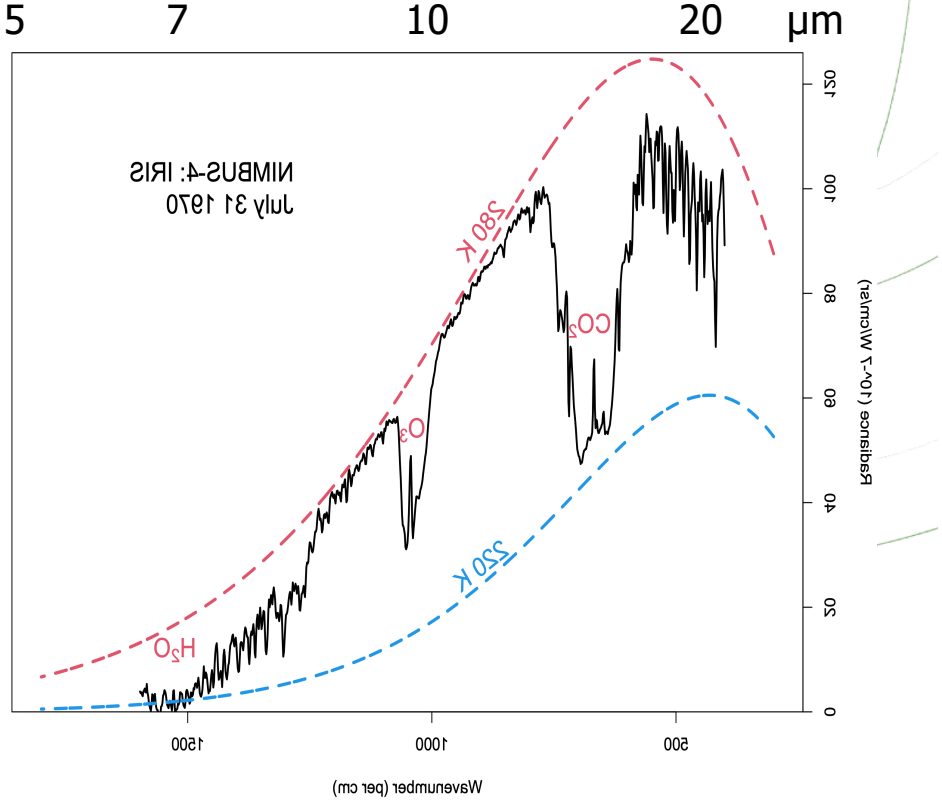

SPECTRAL RADIANCE, L_λ^λ (λ,T), W/(cm^2)(sr)(μm)
WAVELENGTH, λ, μm
Parameter Values in °K
6000
5000
4000
3000
2000
1500
1000
800
600
400
273
200
10^4
10^2
10
10^{-2}
10^{-4}
10^{-6}
10^{-8}
0.1
0.5
1.0
5
10
50
100

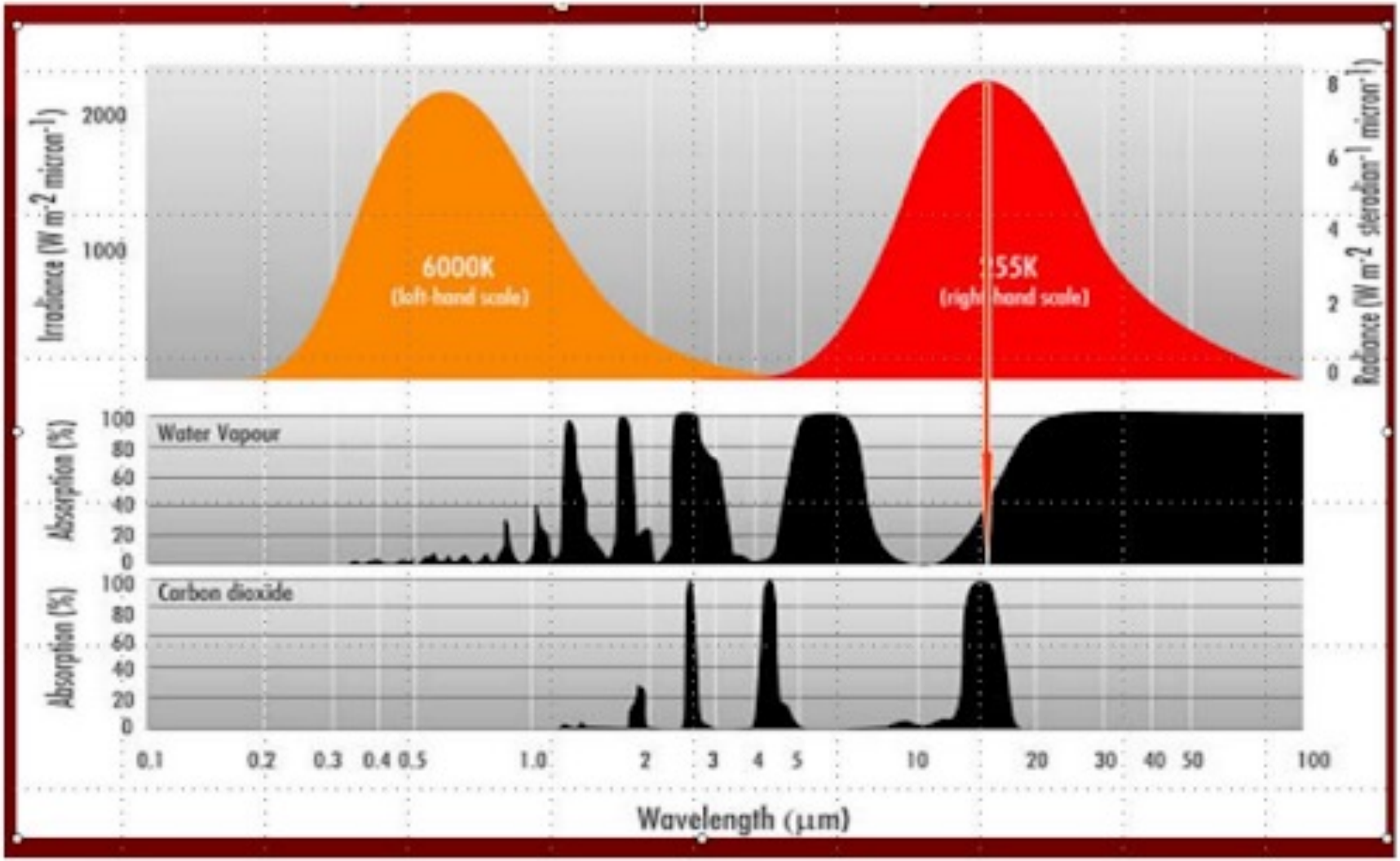
4

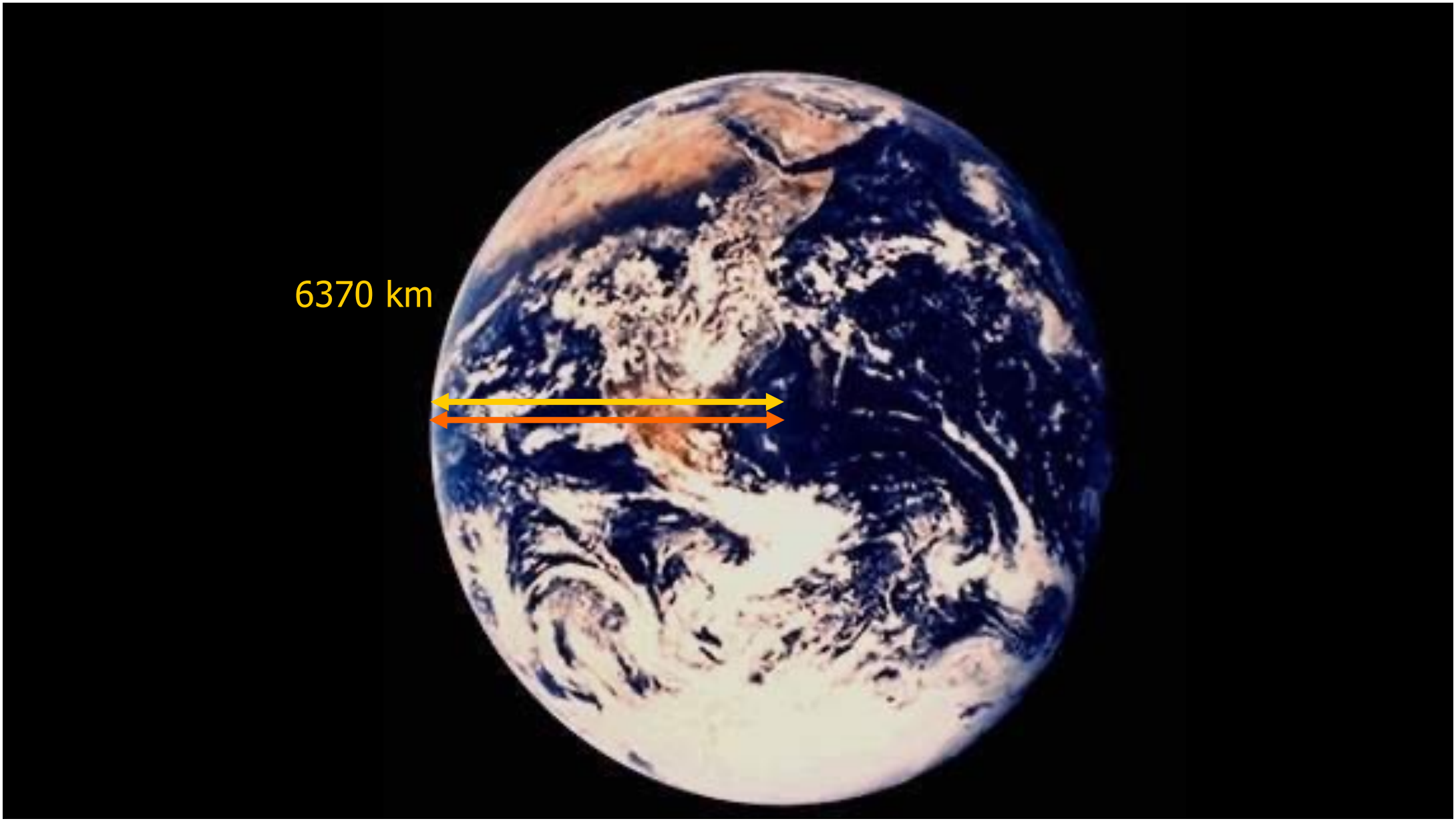

Spectrum of Solar Radiation (Earth)
Irradiance (W/m2/nm)
Wavelength (nm)
UV
Visible
Infrared
Sunlight without atmospheric absorption
Ideal blackbody (5250 °C)
Sunlight at sea level
Atmospheric absorption bands
O3
O2
H2O
CO2

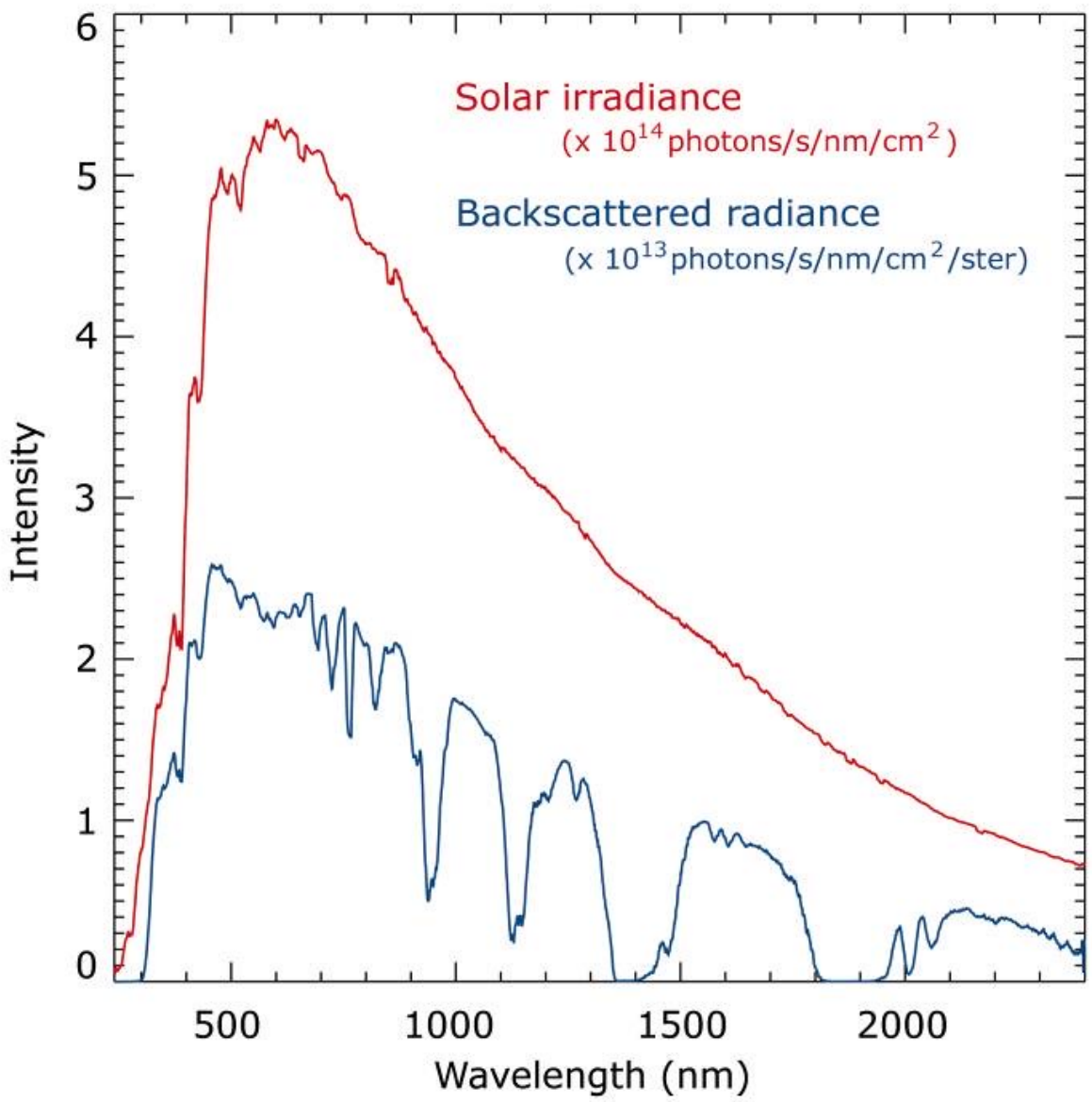

Earth spectra measured from space
NIMBUS-4: IRIS
July 31 1970
280 K
220 K
CO2
O3
H2O
Radiance (10^-7 W/cm/sr)
Wavenumber (per cm)

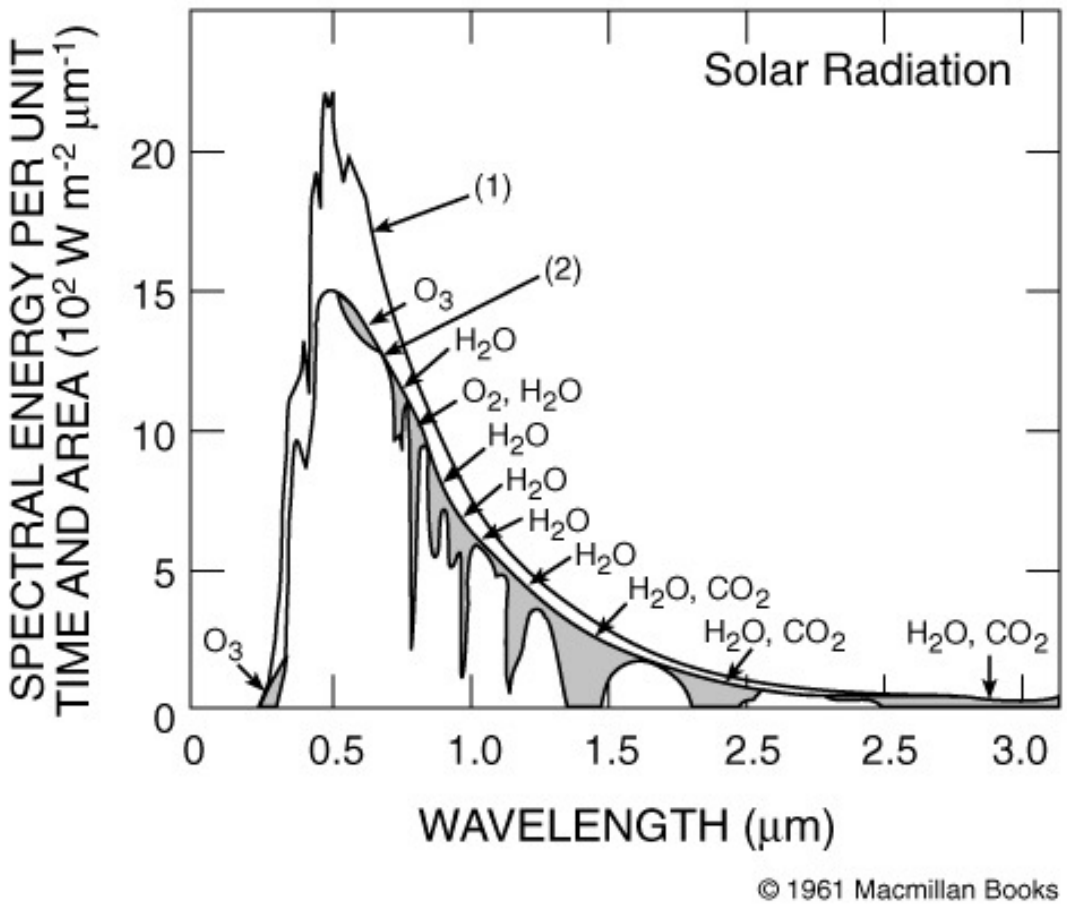

Spectrum of Solar Radiation (Earth)
Irradiance (W/m2/nm)
Wavelength (nm)
UV
Visible
Infrared
Sunlight without atmospheric absorption
Ideal blackbody (5250 °C)
Sunlight at sea level
Atmospheric absorption bands
O_3
O_2
H_2O
CO_2

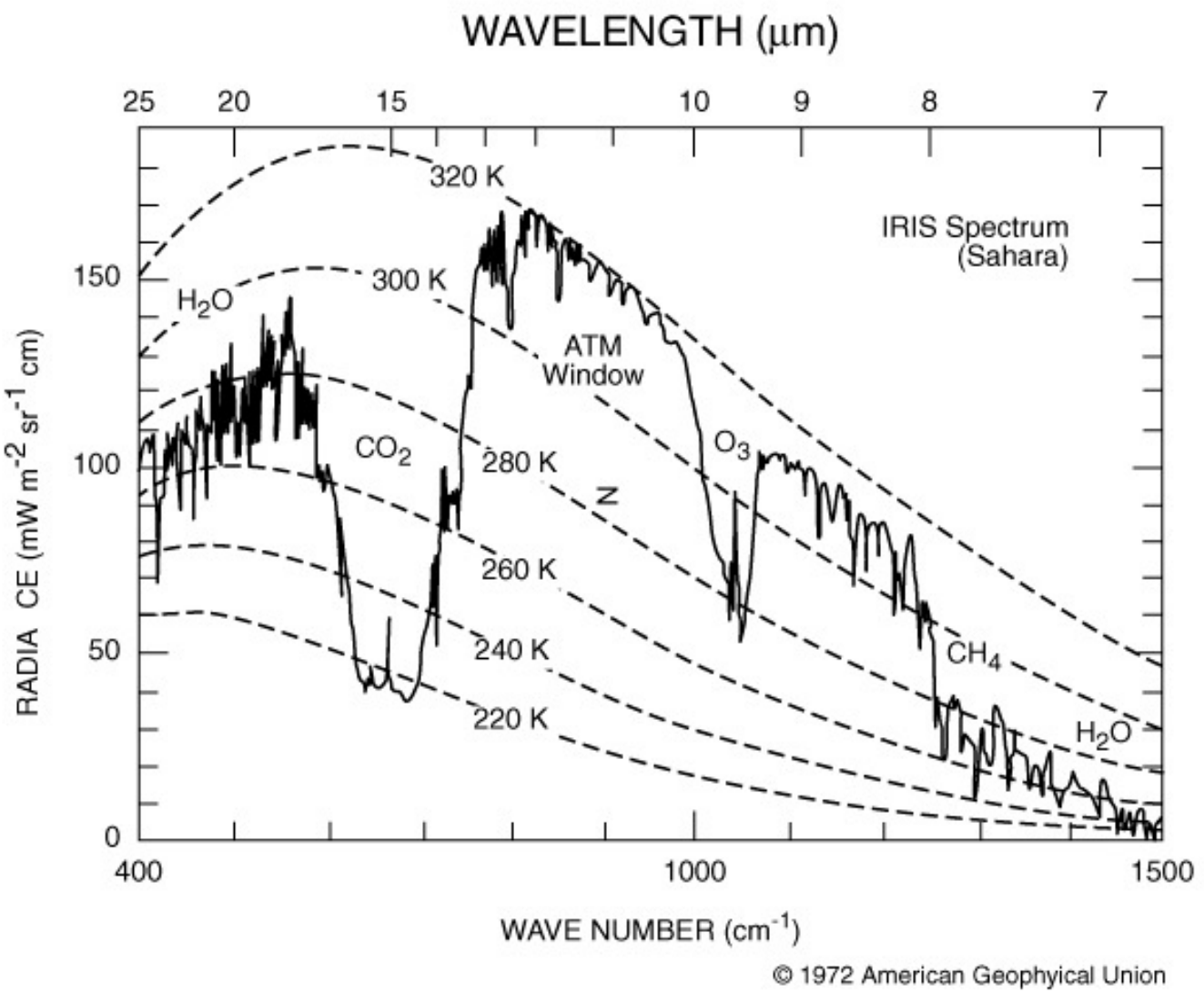

5
7
10
20
μm
NIMBUS-4: IRIS
July 31 1970
280 K
220 K
O_3
CO_2
H_2O
Wavenumber (per cm)
Radiance (mW/m2/sr/cm-1)


Irradiance (W m-2 micron-1)
2000
1000
6000K
(left-hand scale)
255K
(right-hand scale)
Radiance (W m-2 steradian-1 micron-1)
8
6
4
2
0
Absorption (%)
100
80
60
40
20
0
Water Vapour
Absorption (%)
Carbon dioxide
0.1
0.2
0.3
0.4
0.5
1.0
2
3
4
5
10
20
30
40
50
100
Wavelength (µm)


6370 km

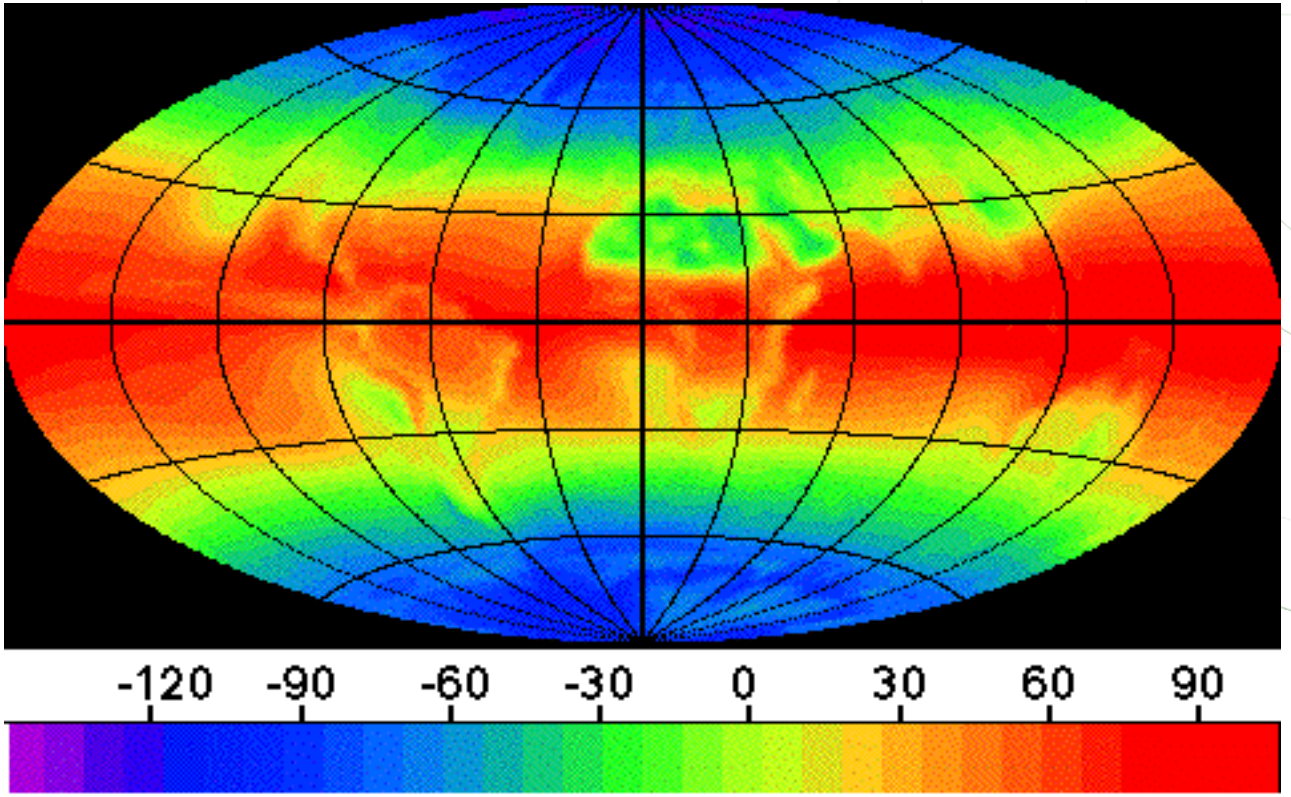

Solar irradiance
(x 10^14 photons/s/nm/cm^2)
Backscattered radiance
(x 10^13 photons/s/nm/cm^2/ster)
Intensity
Wavelength (nm)
0
1
2
3
4
5
6
500
1000
1500
2000


Solar Radiation
SPECTRAL ENERGY PER UNIT TIME AND AREA (10^2 W m^{-2} μm^{-1})
20
15
10
5
0
(1)
(2)
O_3
H_2O
O_2, H_2O
H_2O
H_2O
H_2O
H_2O
H_2O, CO_2
H_2O, CO_2
H_2O, CO_2
O_3
0
0.5
1.0
1.5
2.5
2.5
3.0
WAVELENGTH (μm)
© 1961 Macmillan Books


WAVELENGTH (μm)
25
20
15
10
9
8
7
320 K
300 K
280 K
260 K
240 K
220 K
IRIS Spectrum
(Sahara)
H2O
ATM
Window
CO2
O3
CH4
H2O
150
100
50
0
RADIA CE (mW m-2 sr-1 cm)
400
1000
1500
WAVE NUMBER (cm-1)
© 1972 American Geophyical Union

Overview

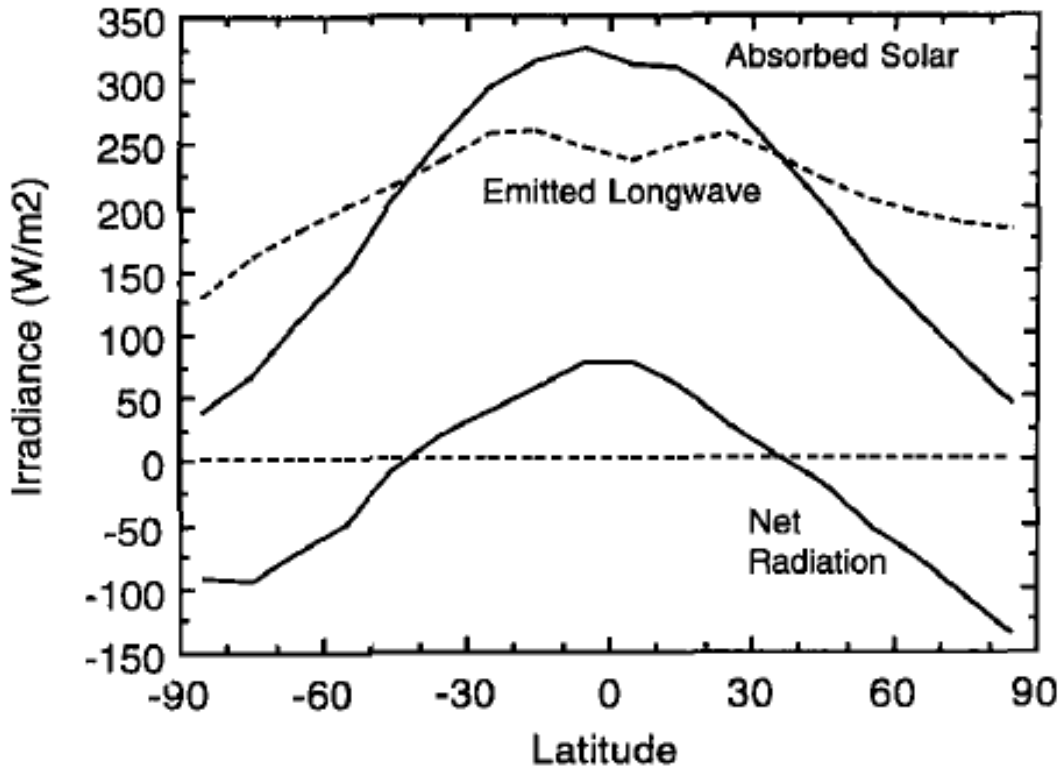
8



Net Radiation Budget [Wm^{-2}]

Mean from Feb. 1985 to Jan. 1989

(Thanks to MI-Hamburg)


Absorbed Solar
Emitted Longwave
Net
Radiation
Irradiance (W/m2)
Latitude
350
300
250
200
150
100
50
0
-50
-100
-150
-90
-60
-30
0
30
60
90

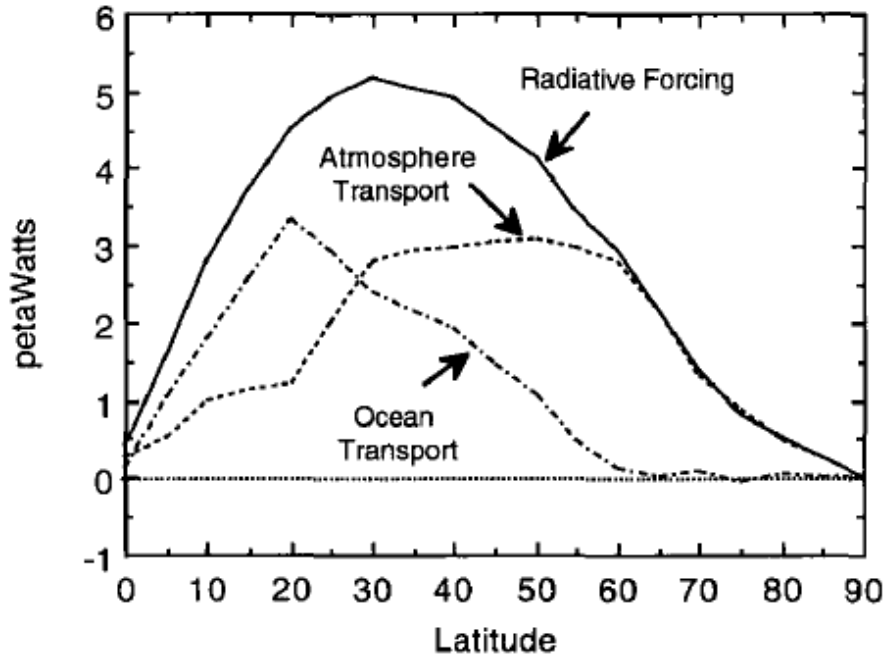
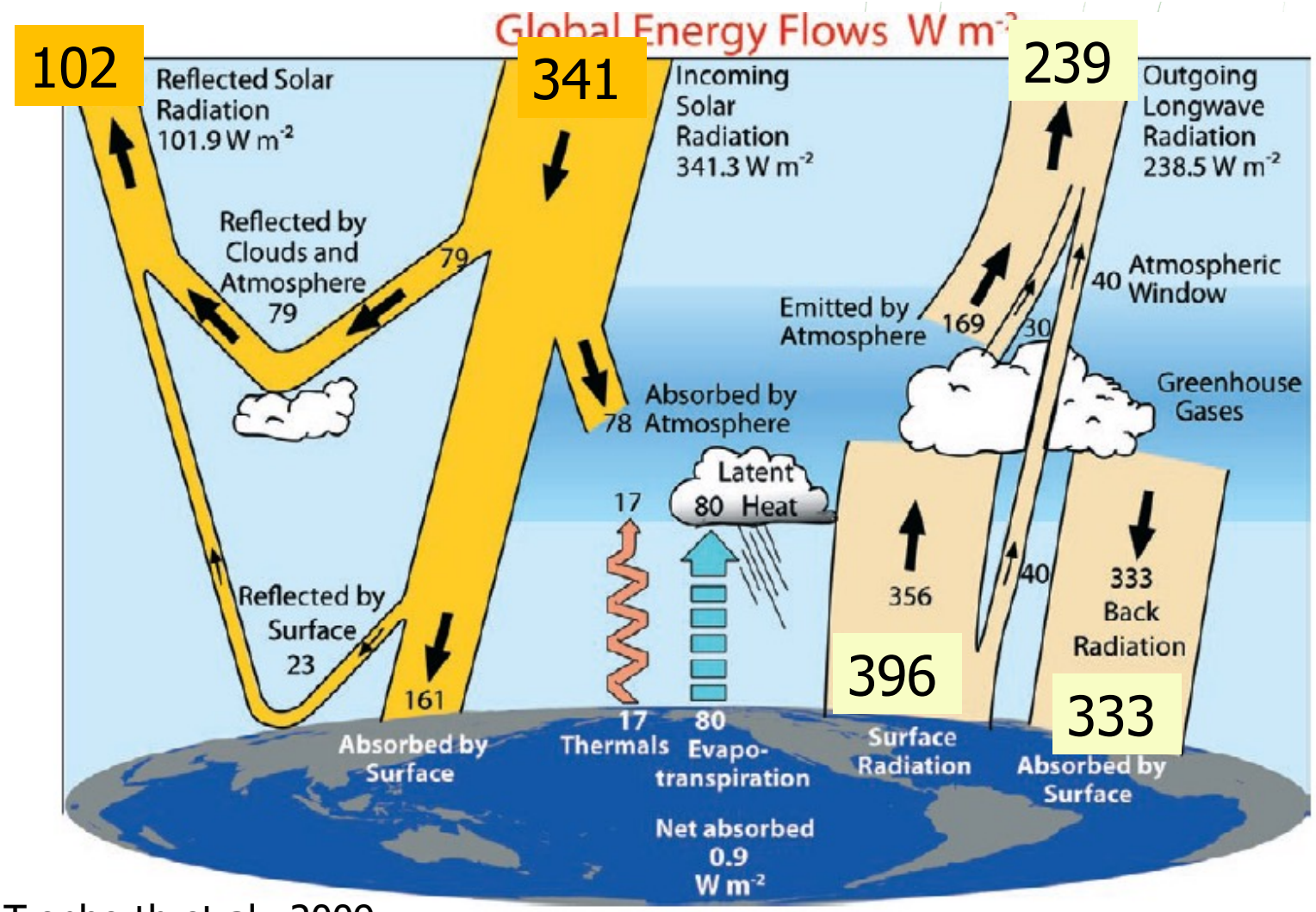


Fig. 2.14 Meridional transport of energy for annual-mean conditions. Net radiation and atmospheric transport are estimated from observations; ocean transport is calculated as a residual in the energy balance. [Adapted from Vonder Haar and Oort (1973). Used with permission from the American Meteorological Society.]



Trenberth et al., 2009

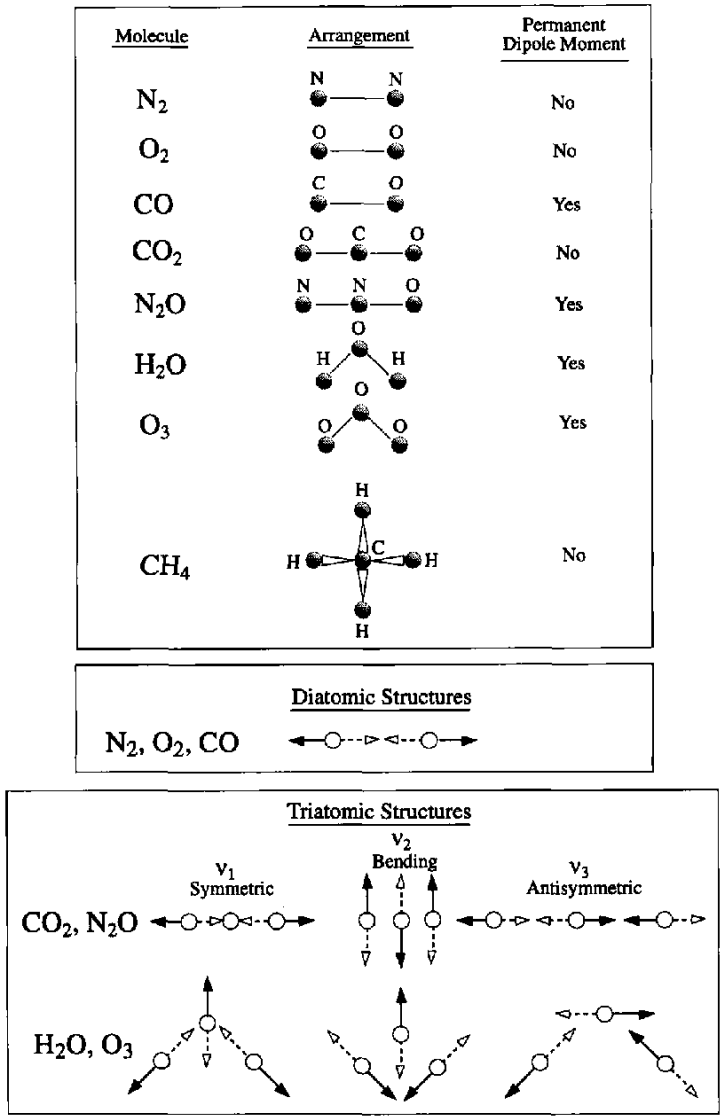
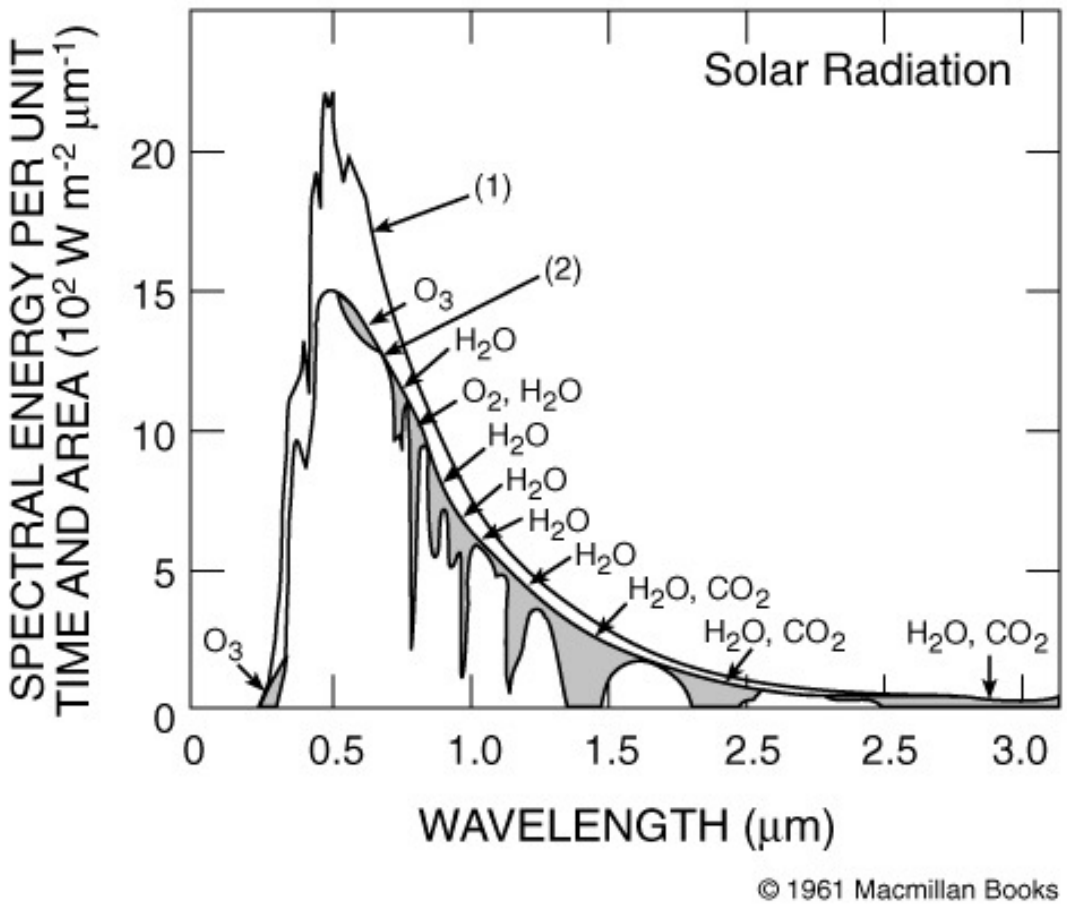
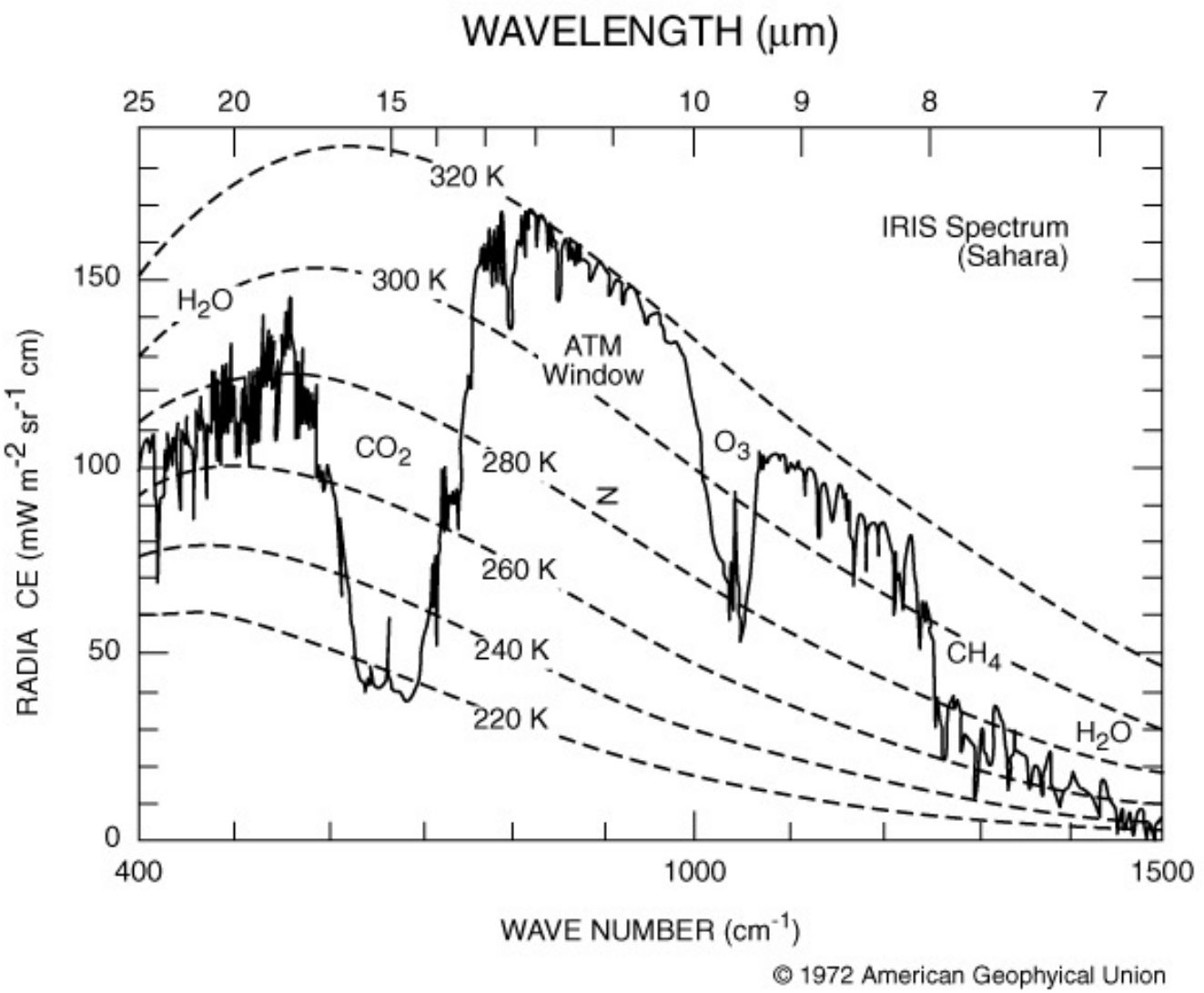
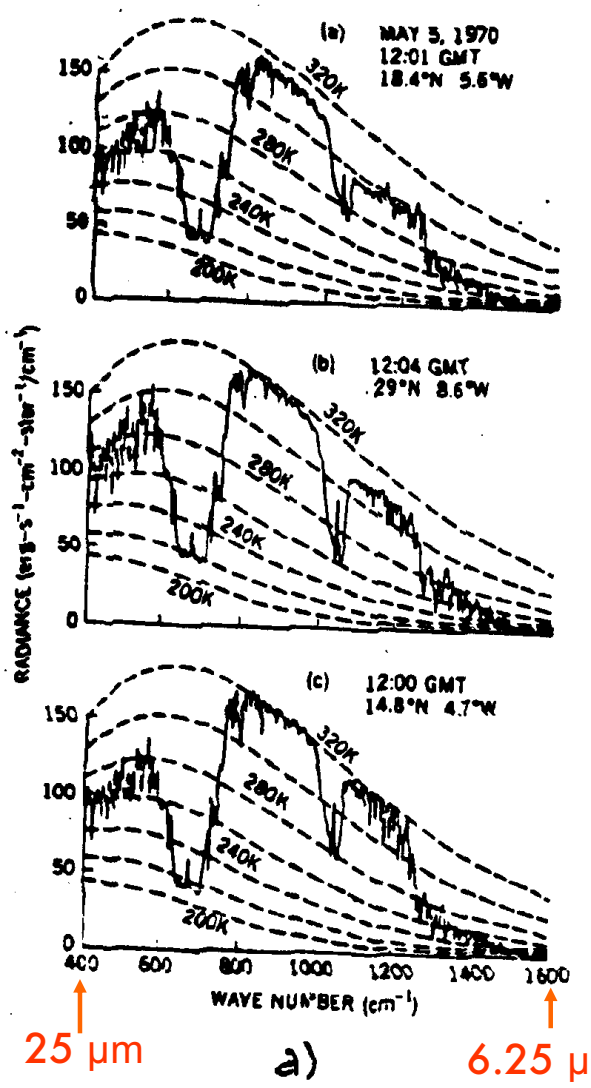
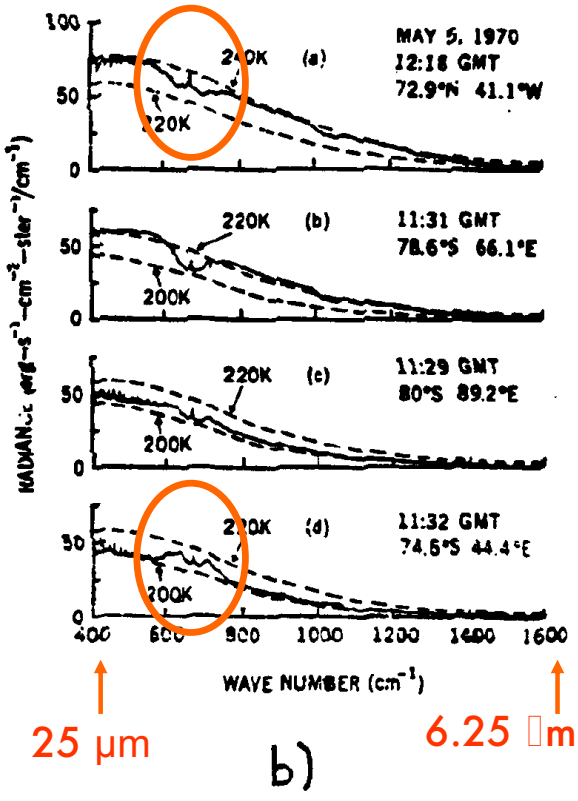


Fig. 3.3 Schematic diagrams showing the vibrational modes of diatomic and triatomic molecules. [From McCartney (1983). Reprinted with permission from Wiley and Sons, Inc.]


Solar Radiation
SPECTRAL ENERGY PER UNIT TIME AND AREA (10^2 W m^{-2} μm^{-1})
20
15
10
5
0
(1)
(2)
O_3
H_2O
O_2, H_2O
H_2O
H_2O
H_2O
H_2O
H_2O, CO_2
H_2O, CO_2
H_2O, CO_2
O_3
0
0.5
1.0
1.5
2.5
2.5
3.0
WAVELENGTH (μm)
© 1961 Macmillan Books

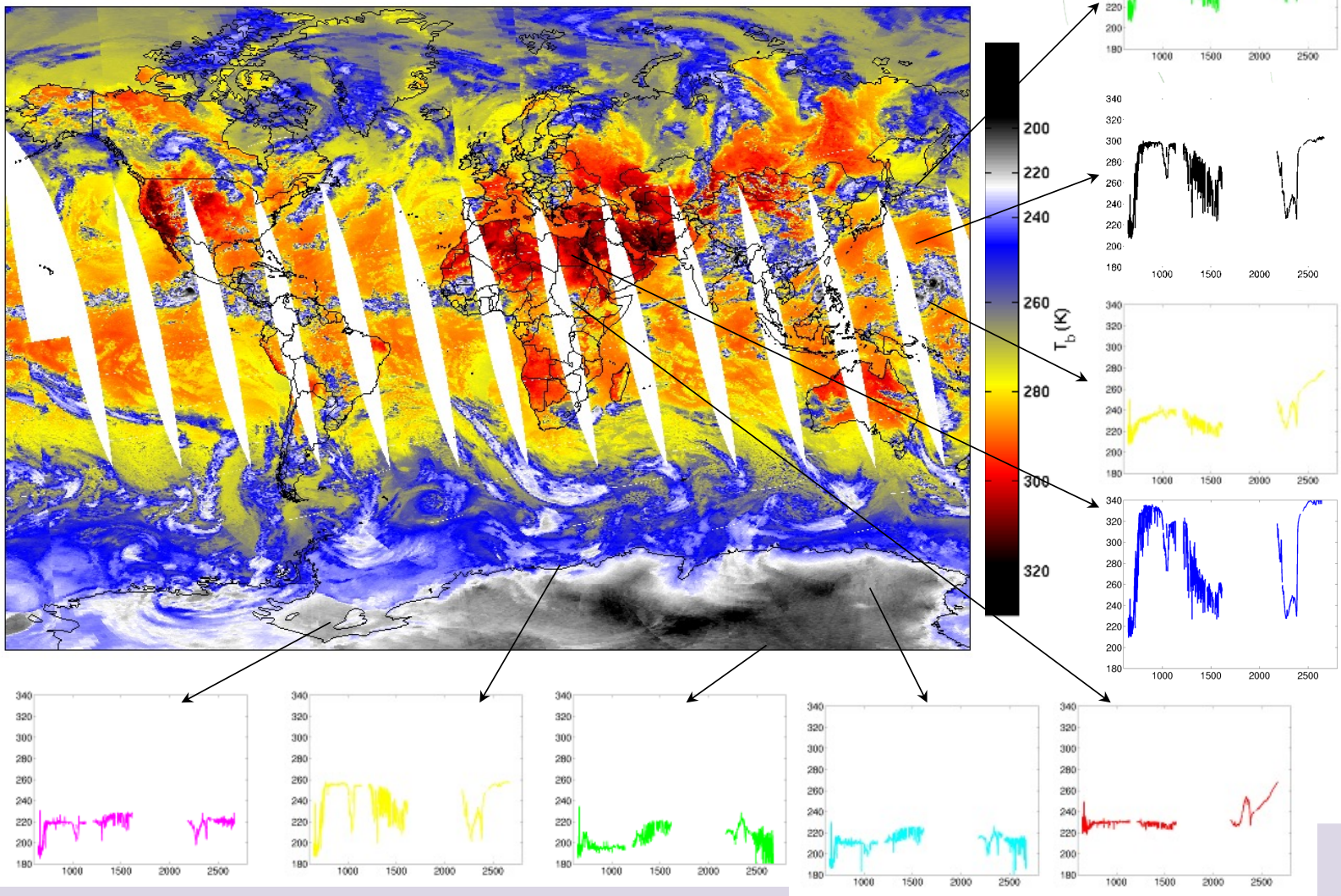

WAVELENGTH (μm)
25
20
15
10
9
8
7
320 K
300 K
280 K
260 K
240 K
220 K
IRIS Spectrum
(Sahara)
H2O
ATM
Window
CO2
O3
CH4
H2O
150
100
50
0
RADIA CE (mW m-2 sr-1 cm)
400
1000
1500
WAVE NUMBER (cm-1)
© 1972 American Geophyical Union

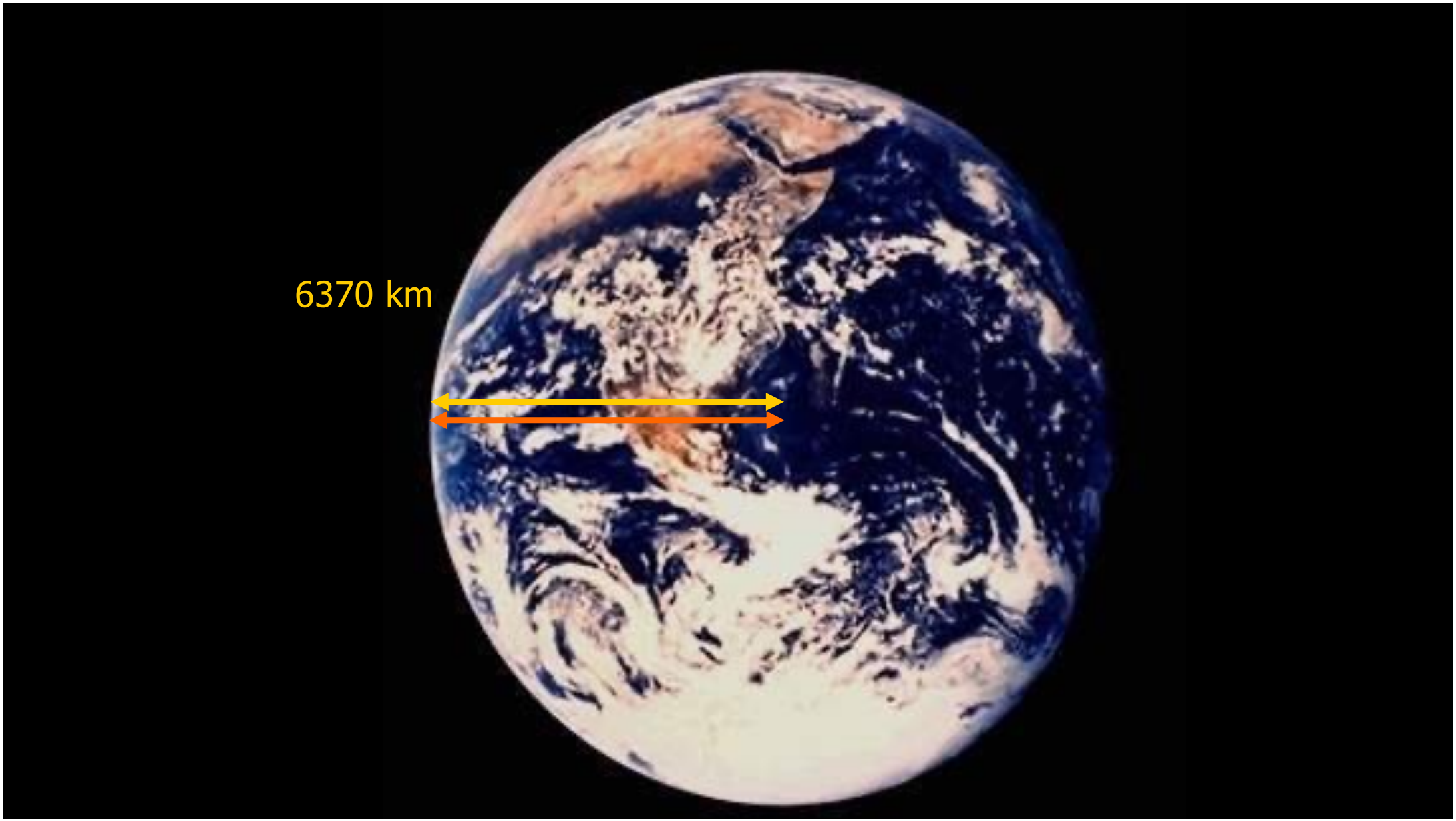

(a) MAY 5, 1970
12:01 GMT
18.4°N 5.6°W
(b) 12:04 GMT
.29°N 8.6°W
(c) 12:00 GMT
14.8°N 4.7°W
320K
280K
240K
200K
RADIANCE (erg-s⁻¹-cm⁻²-ster⁻¹/cm⁻¹)
WAVE NUMBER (cm⁻¹)
25 μm
6.25 μm
a)

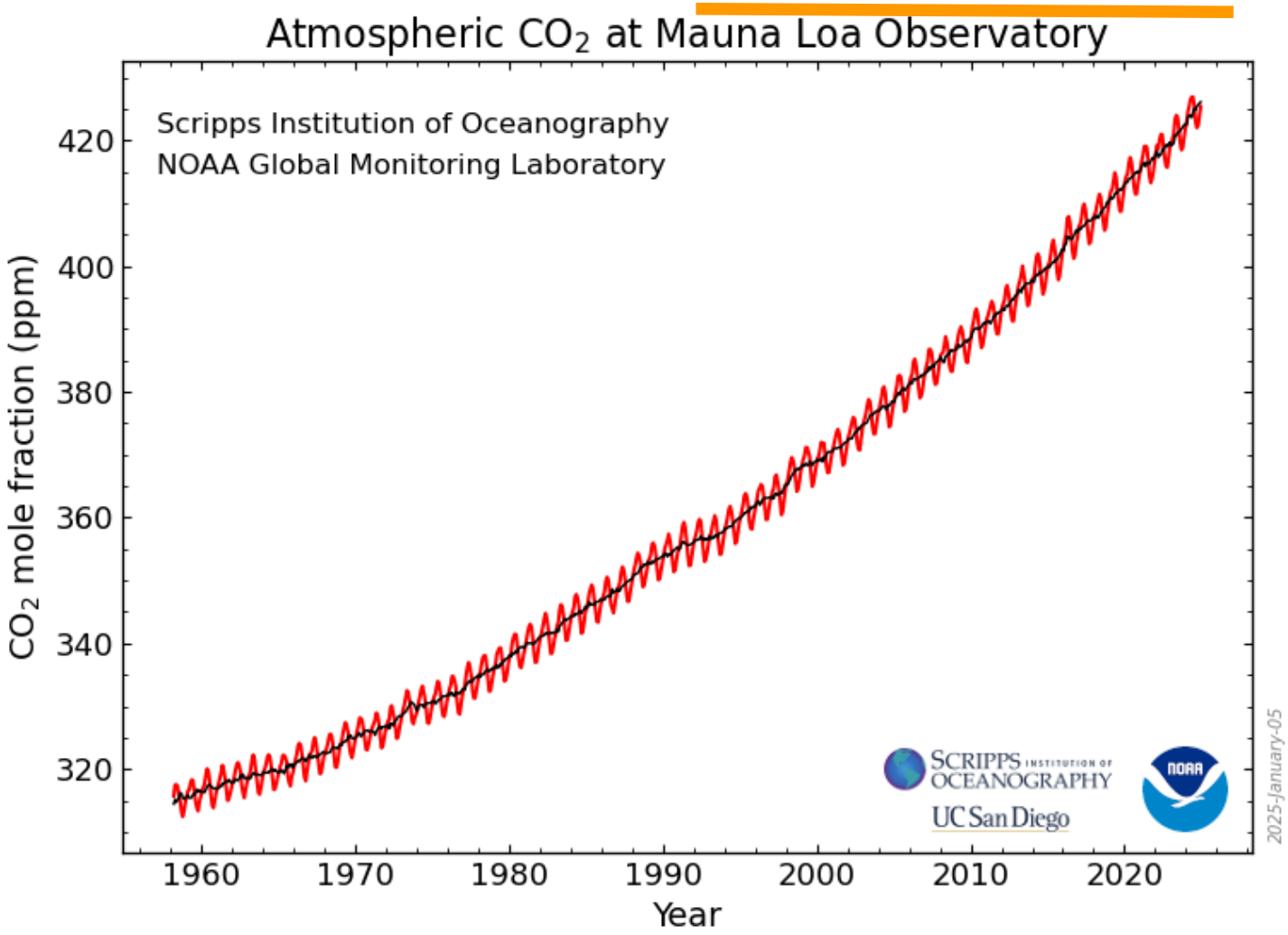

MAY 5, 1970
12:18 GMT
72.9°N 41.1°W
220K (a)
220K (b)
11:31 GMT
78.6°S 66.1°E
220K (c)
11:29 GMT
80°S 89.2°E
220K (d)
11:32 GMT
74.6°S 44.4°E
200K
WAVE NUMBER (cm⁻¹)
25 μm
6.25 μm
b)

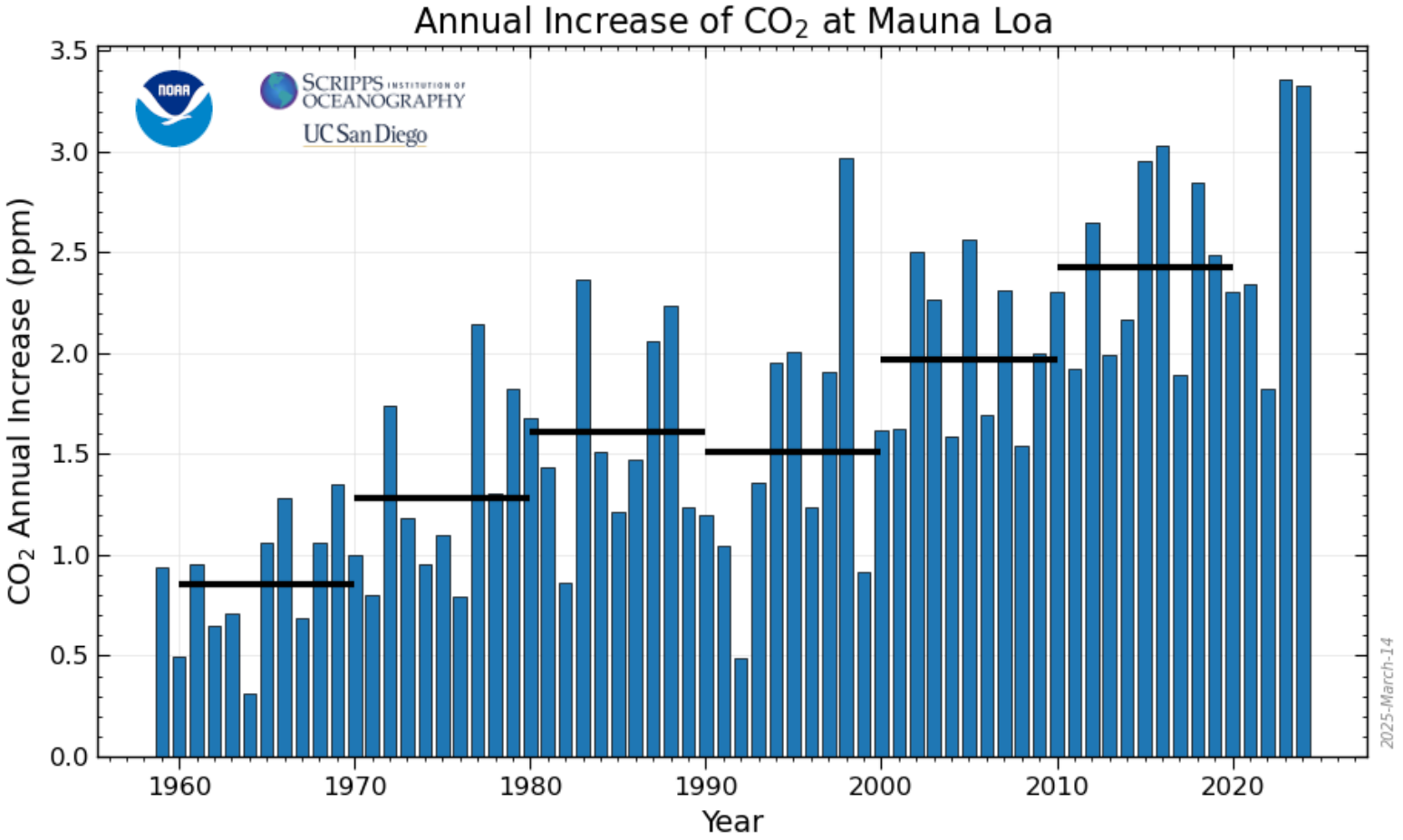
Examples of AIRS Spectra

20-July-2002 Ascending LW_Window

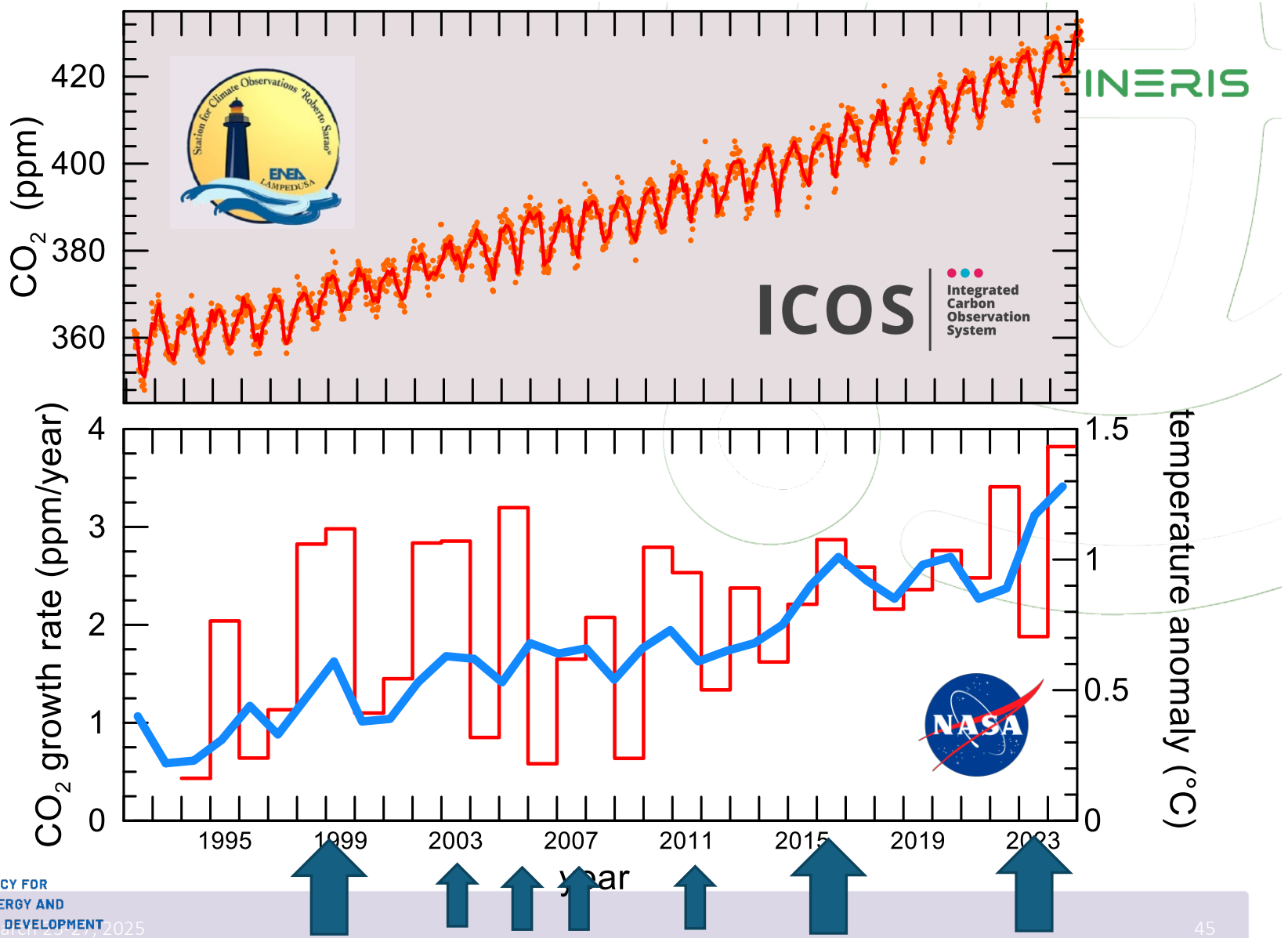


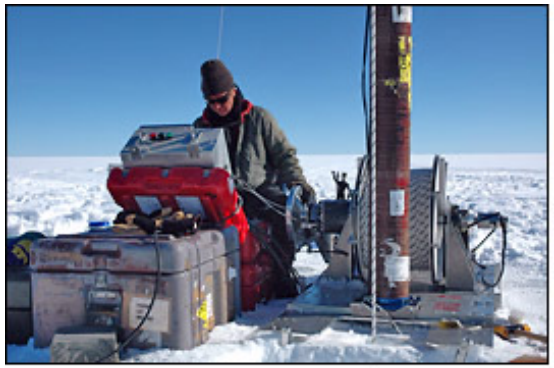
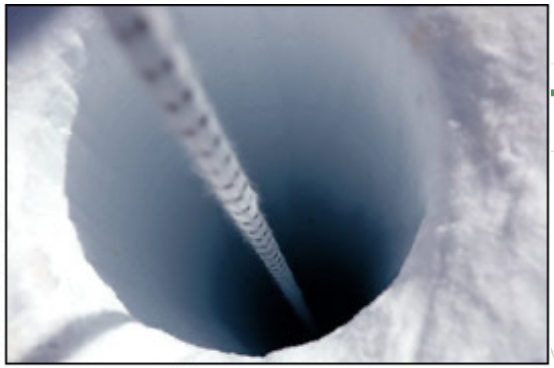

6370 km


Atmospheric CO_2 at Mauna Loa Observatory
Scripps Institution of Oceanography
NOAA Global Monitoring Laboratory
CO_2 mole fraction (ppm)
420
400
380
360
340
320
1960
1970
1980
1990
2000
2010
2020
Year
SCRIPPS INSTITUTION OF OCEANOGRAPHY
UC San Diego
NOAA
2025-January-05

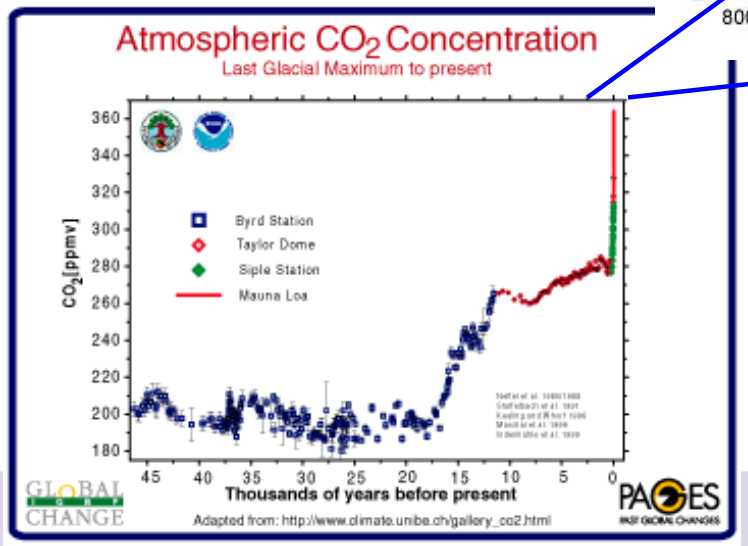

Annual Increase of CO_2 at Mauna Loa
SCRIPPS INSTITUTION OF OCEANOGRAPHY
UC San Diego
CO_2 Annual Increase (ppm)
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
1960
1970
1980
1990
2000
2010
2020
Year
2025-March-14

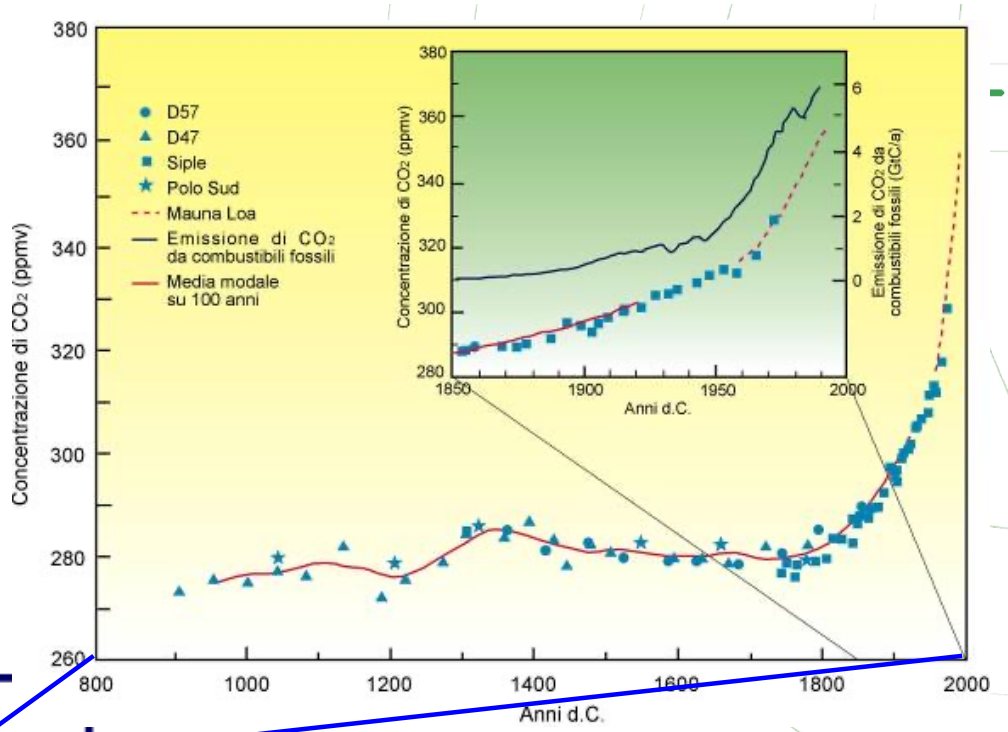

35.5°N, 12.6°E

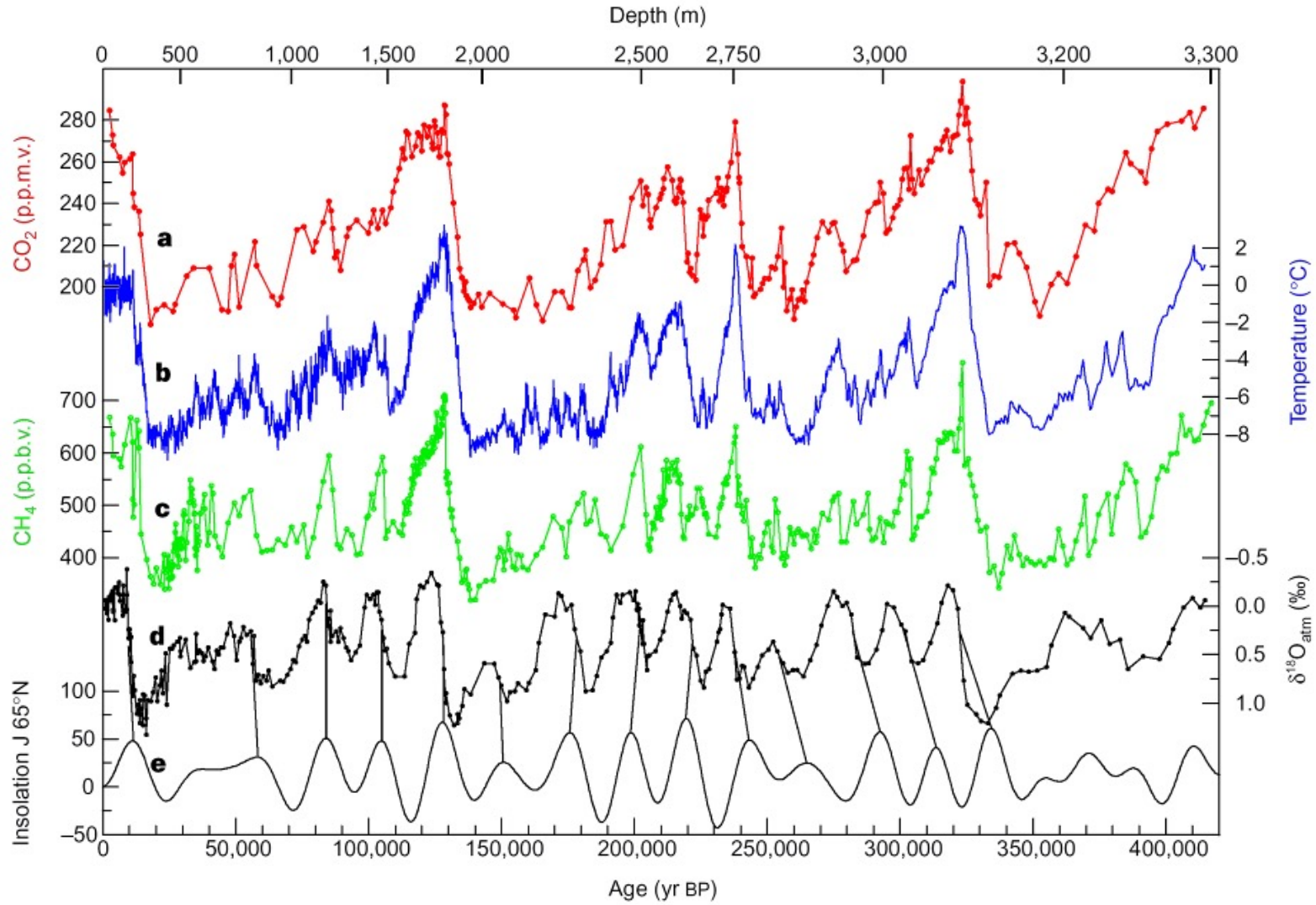

Station for Climate Observations "Roberto Sarao"
ENEA
LAMPEDUSA
ICOS
Integrated Carbon Observation System
INERIS
NASA
CO_2 (ppm)
420
400
380
360
CO_2 growth rate (ppm/year)
4
3
2
1
0
temperature anomaly (°C)
1.5
1
0.5
0
1995
1999
2003
2007
2011
2015
2019
2023
year

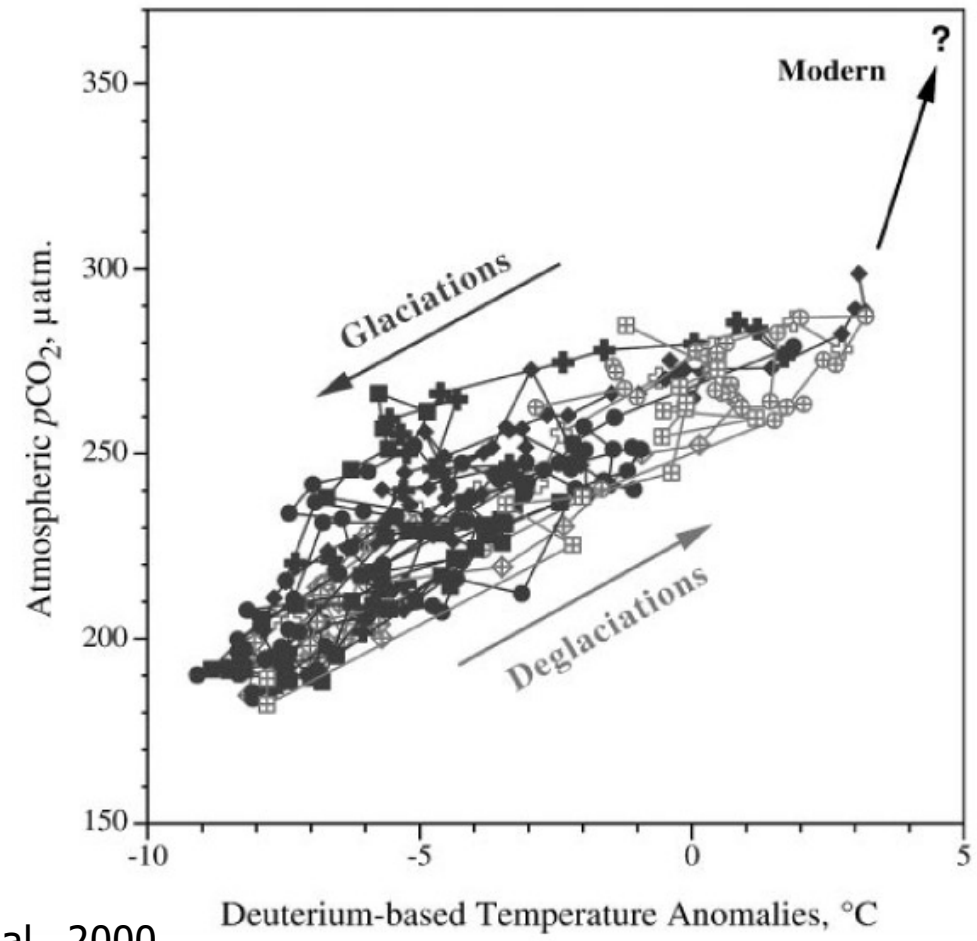



Atmospheric CO_2 Concentration
Last Glacial Maximum to present
CO_2 [ppmv]
Byrd Station
Taylor Dome
Siple Station
Mauna Loa
Thousands of years before present
Adapted from: http://www.climate.unibe.ch/gallery_co2.html
GLOBAL CHANGE
PAGES


D57
D47
Siple
Polo Sud
Mauna Loa
Emissione di CO_2 da combustibili fossili
Media modale su 100 anni
Concentrazione di CO_2 (ppmv)
Anni d.C.
Emissione di CO_2 da combustibili fossili (GtC/a)



Petit et al., 1999



Falkowski et al., 2000

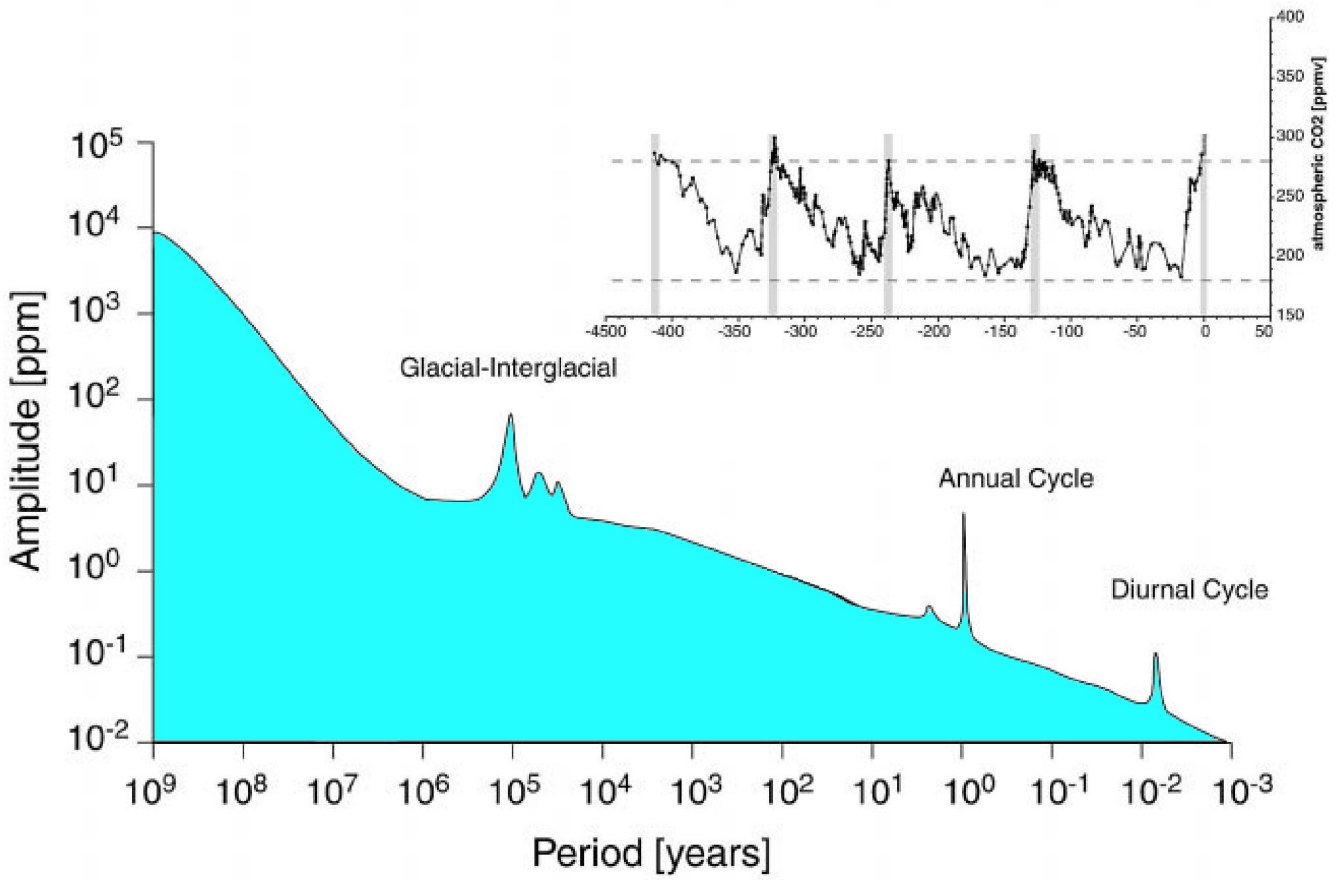
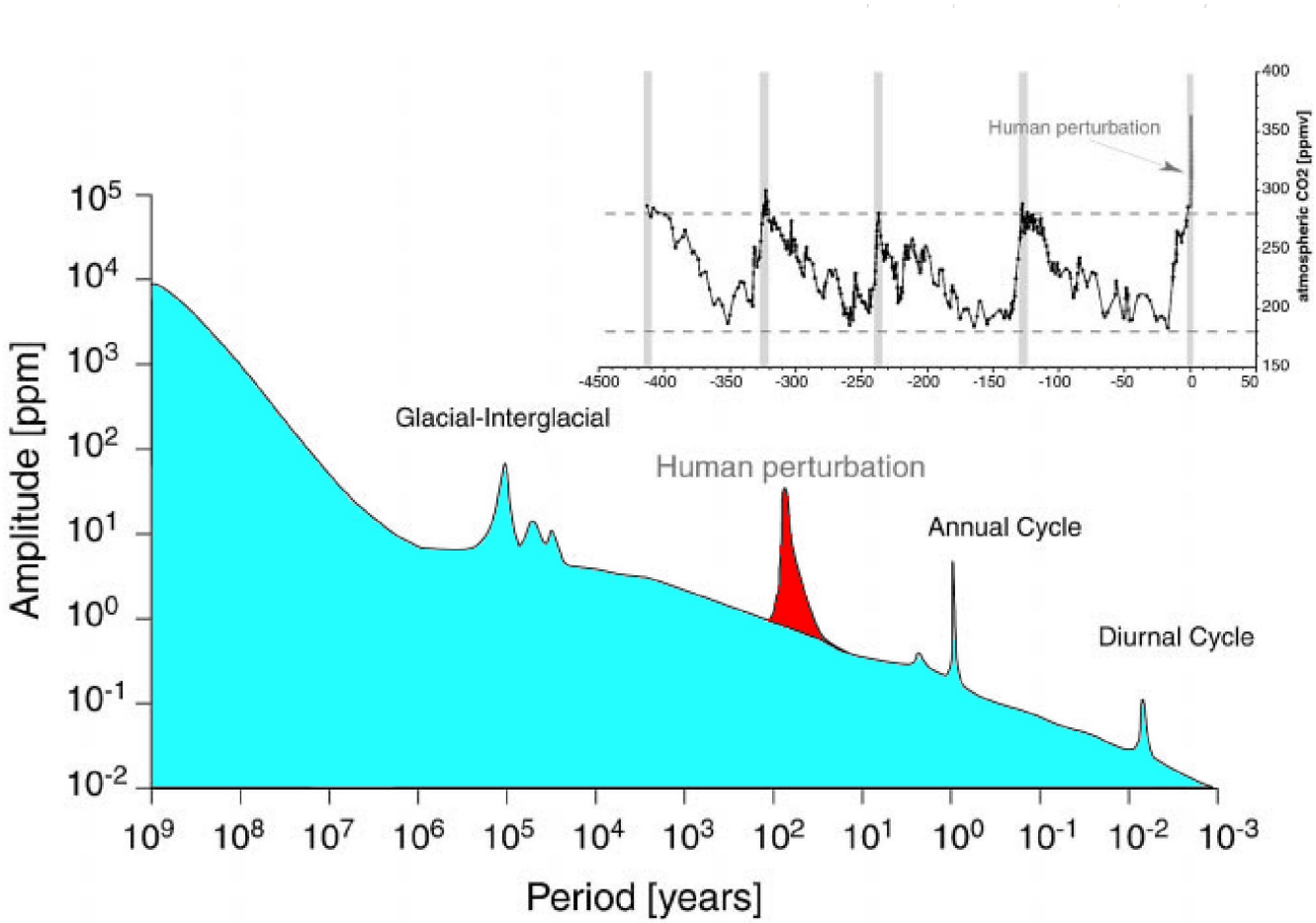


Fig. 2. Schematic variance spectrum for CO_2 over the course of Earth's history. Note the impact of human perturbations on the decade-to-century scale. (**Inset**) Changes in atmospheric CO_2 over the past 420,000 years as recorded in the Vostok ice, showing that both the rapid rate of change and the increase in CO_2 concentration since the Industrial Revolution are unprecedented in recent geological history.

Adapted from Falkowski et al., 2000



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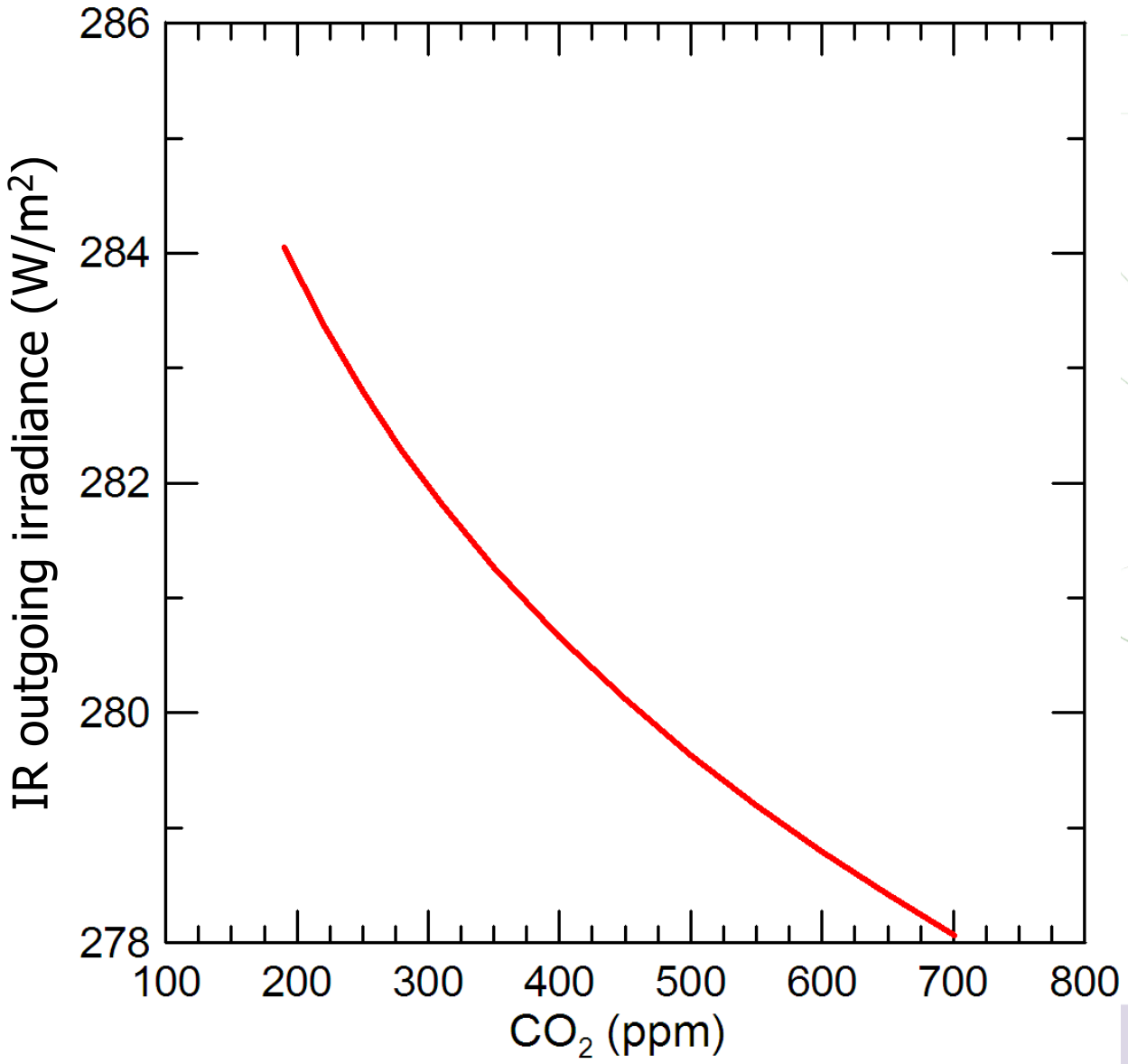
Falkowski et al., 2000

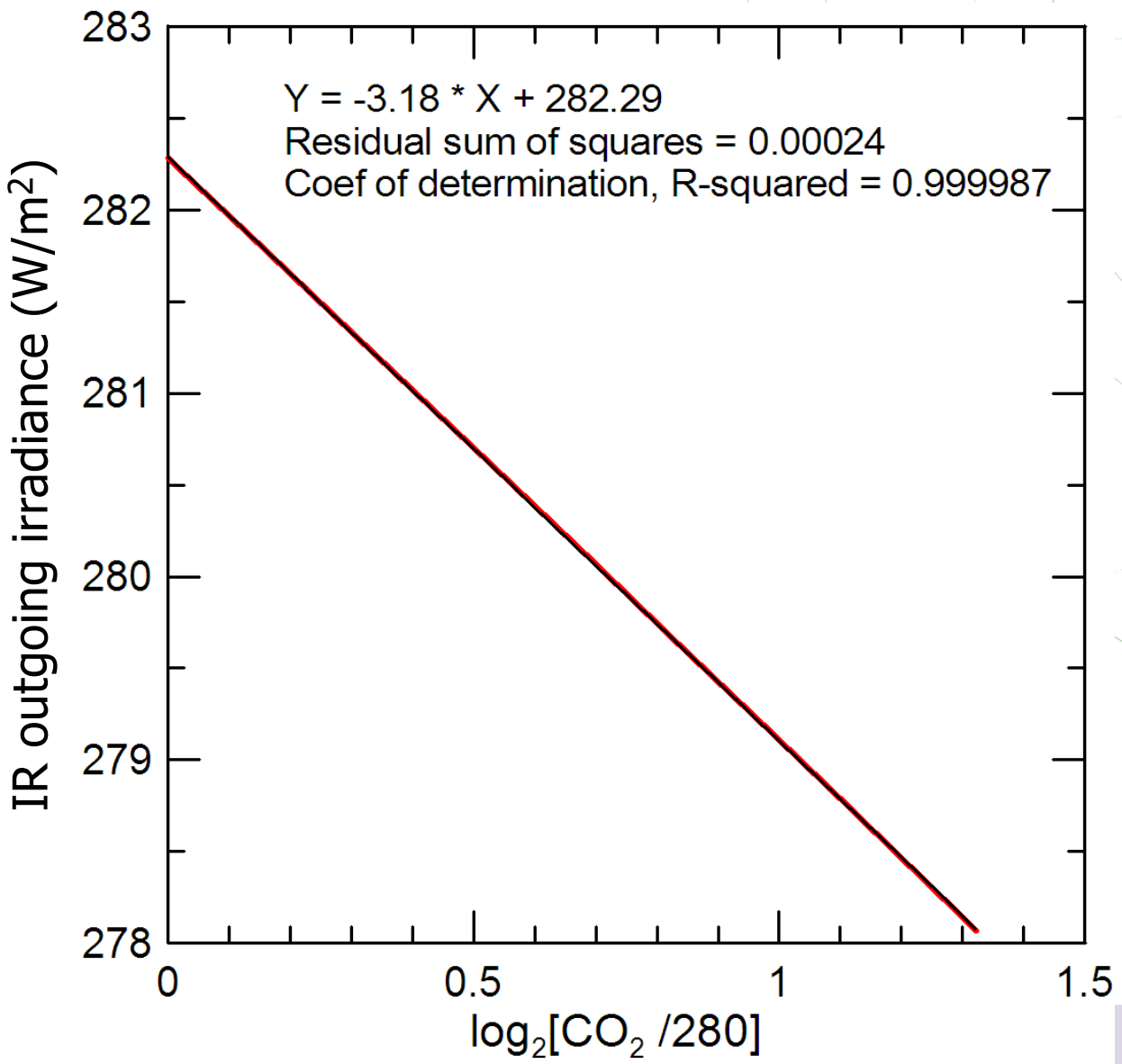
if the quantity of carbonic acid increases in geometric progression, the augmentation of the temperature will increase nearly in arithmetic progression

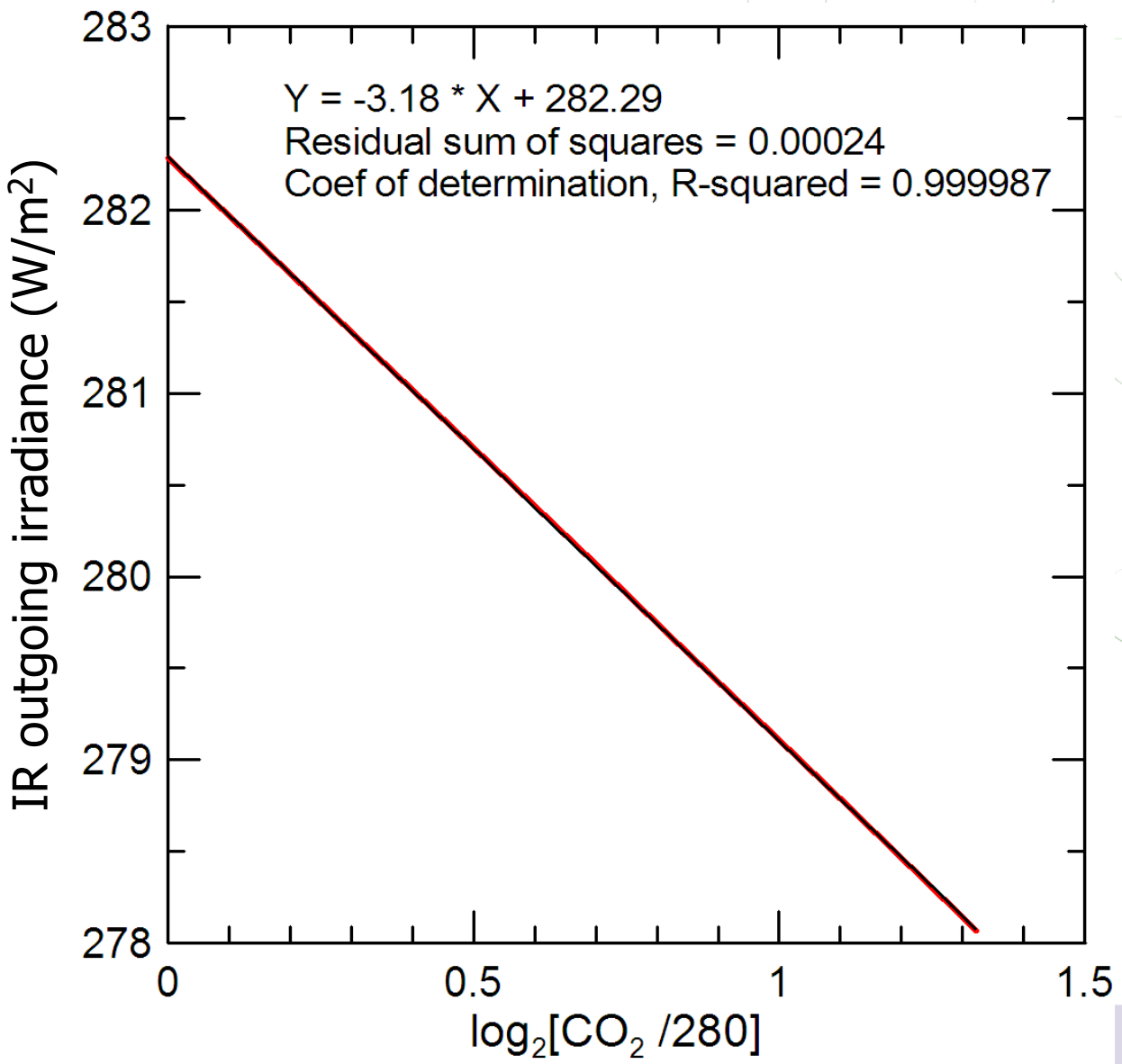
If the quantity of carbonic acid in the air should sink to one-half its present percentage, the temperature would fall by about 4°; a diminution to one-quarter would reduce the temperature by 8°. On the other hand, any doubling of the percentage of carbon dioxide in the air would raise the temperature of the earth's surface by 4°; and if the carbon dioxide were increased fourfold, the temperature would rise by 8°.

1906

1859-1927


286
284
282
280
278
IR outgoing irradiance (W/m²)
100
200
300
400
500
600
700
800
CO2 (ppm)


Y = -3.18 * X + 282.29
Residual sum of squares = 0.00024
Coef of determination, R-squared = 0.999987
IR outgoing irradiance (W/m²)
283
282
281
280
279
278
0
0.5
1
1.5
log₂[CO₂ /280]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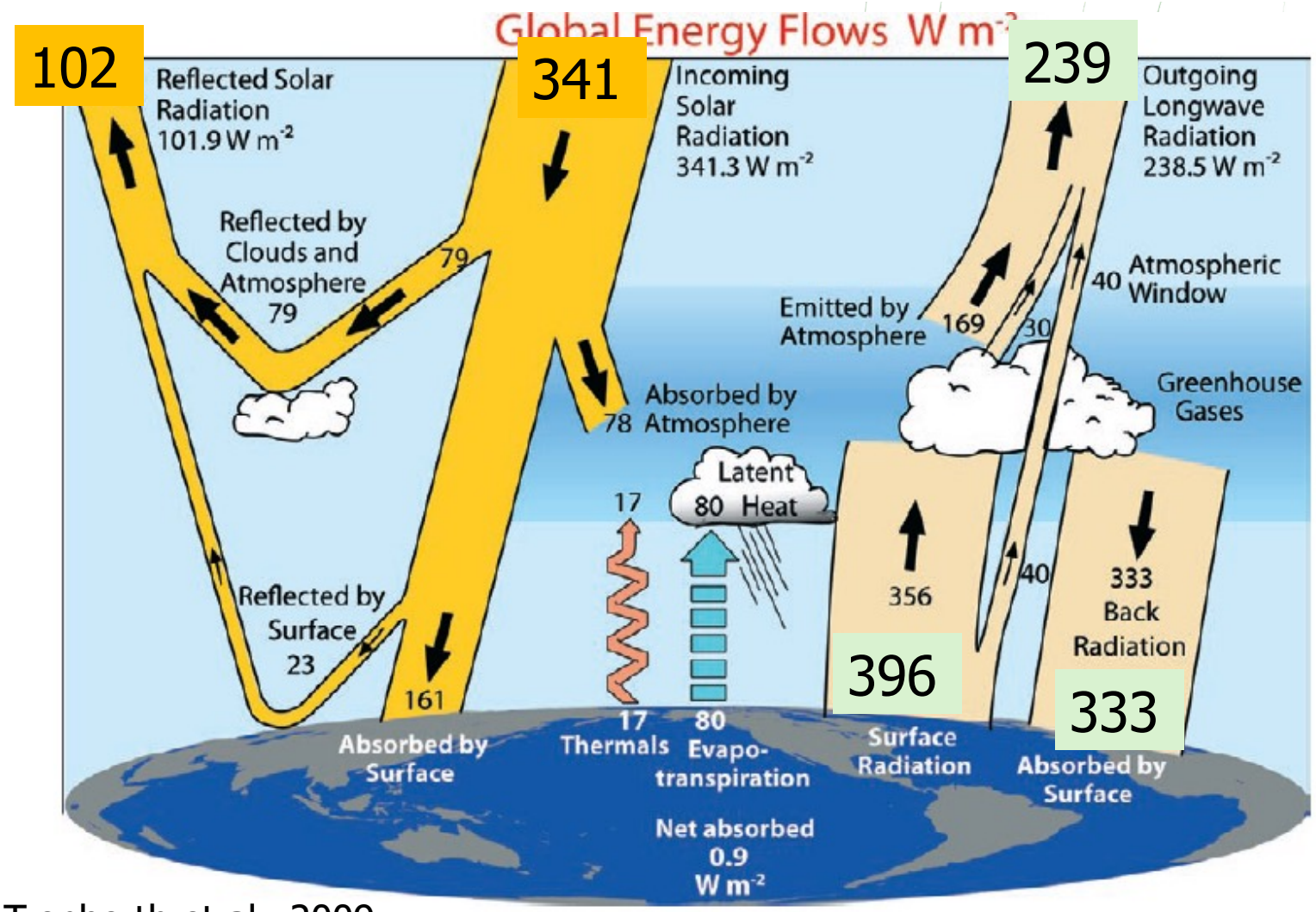
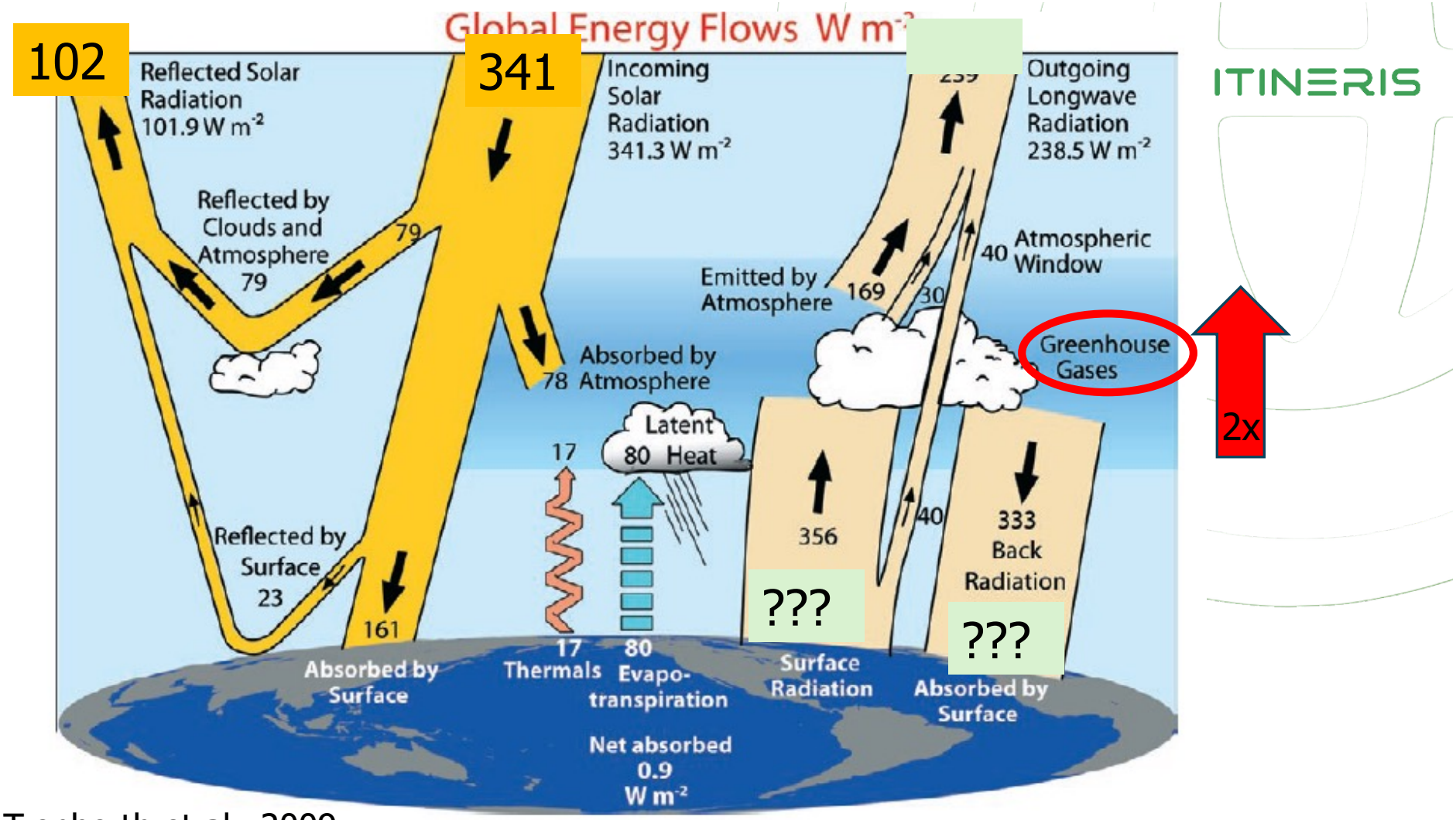
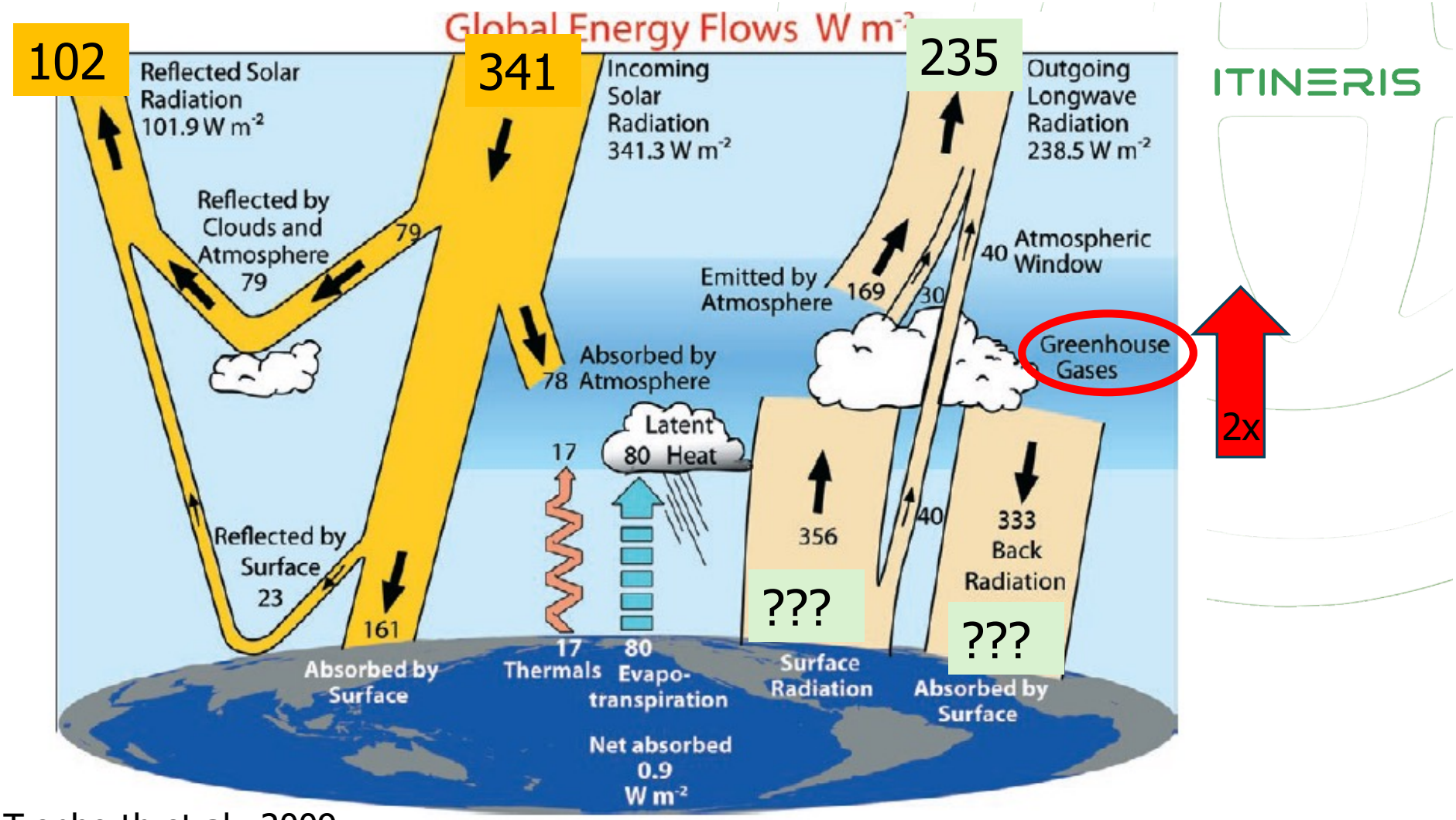
283
282
281
280
279
278
0
0.5
1
1.5
log₂[CO₂ /280]



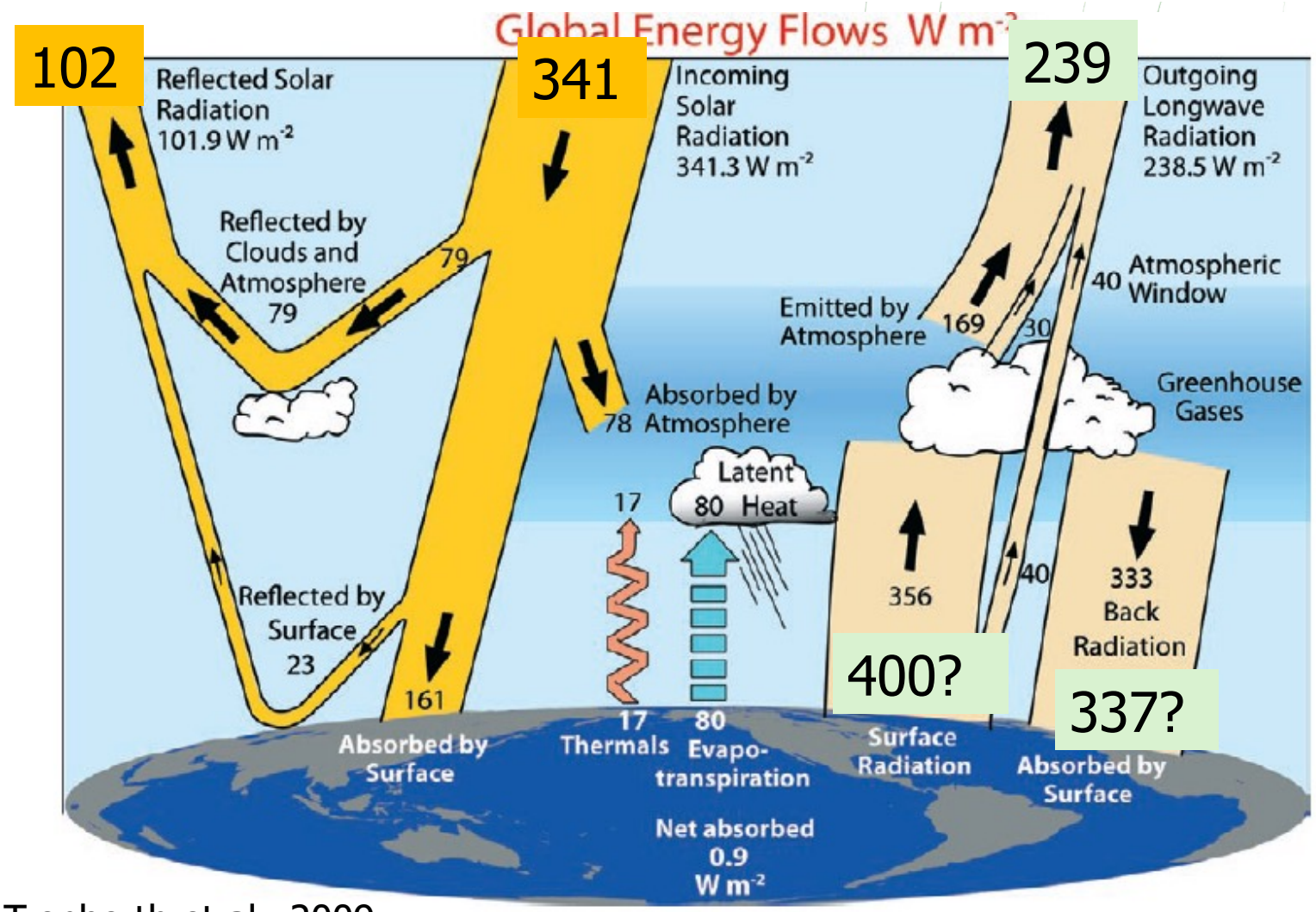
Trenberth et al., 2009



Trenberth et al., 2009



Trenberth et al., 2009



Trenberth et al., 2009

Greenhouse gas emissions → Radiative budget perturbation

Atmospheric CO_2 doubling → top of the atmosphere radiative forcing: +4 W m^{-2}

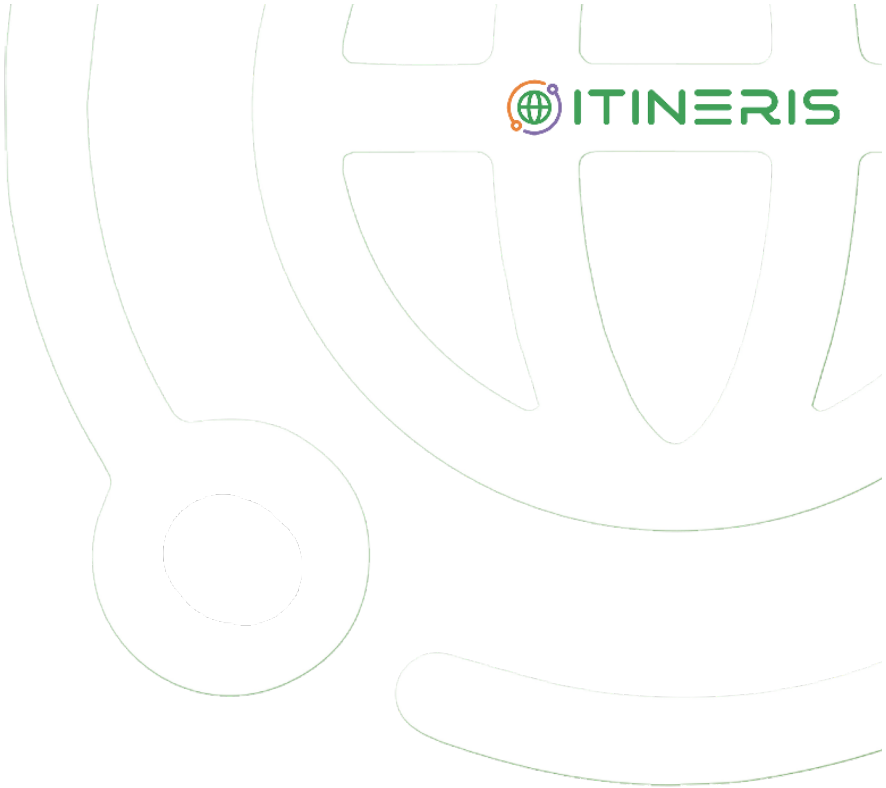
10

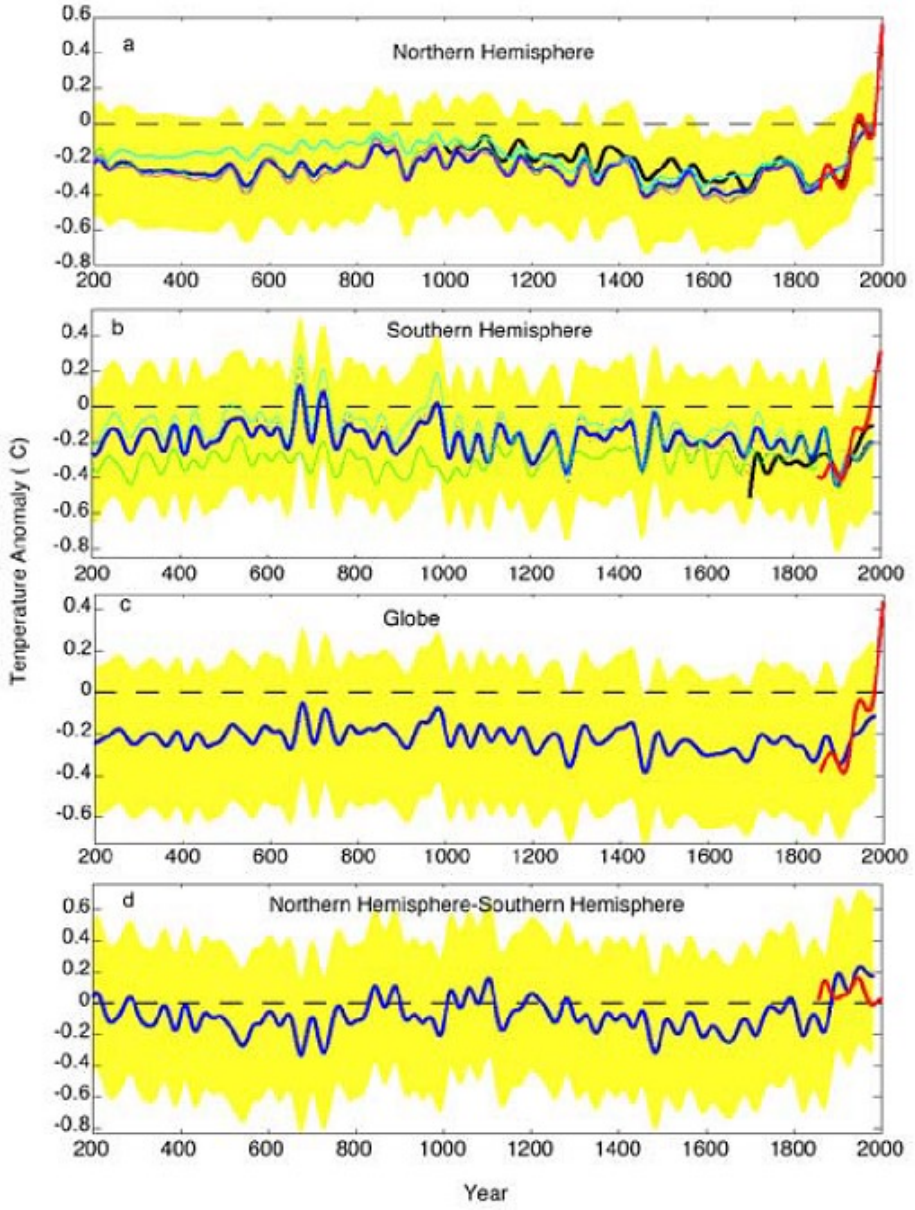
Greenhouse gas emissions

Radiative budget perturbation

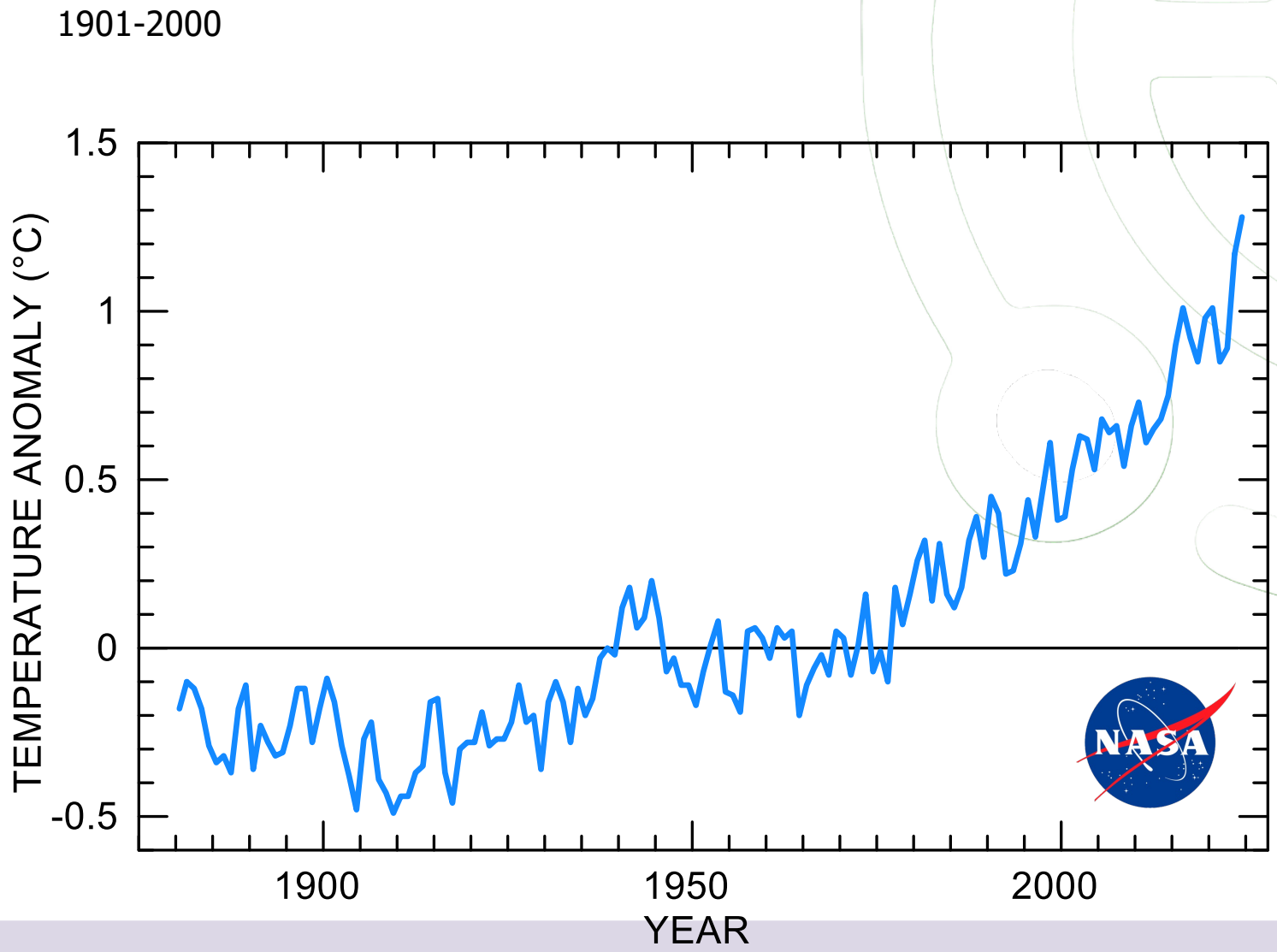
Climate associated changes (temperature, ….)

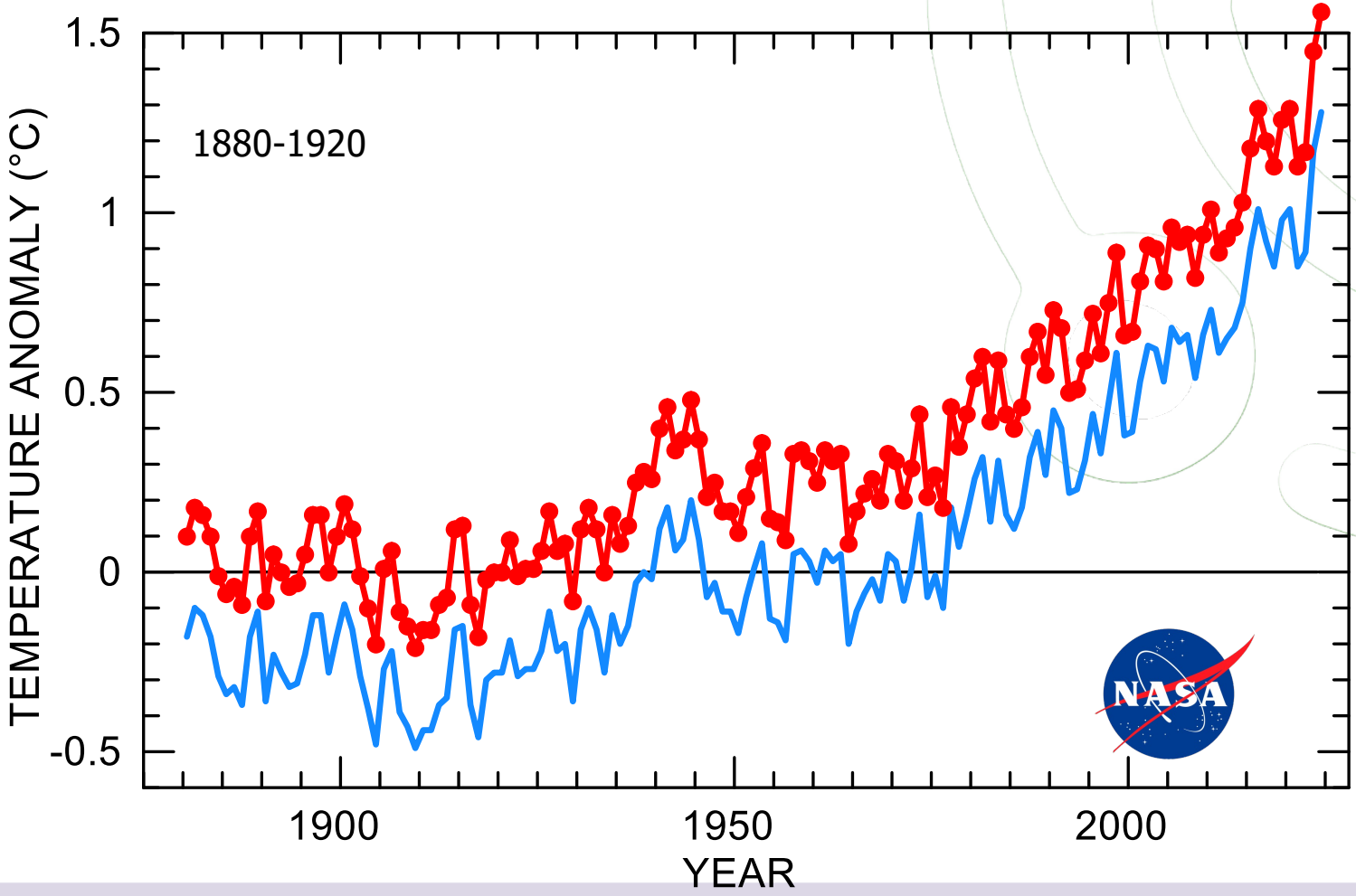
$$\Delta T = \lambda \Delta F$$


ITINERIS

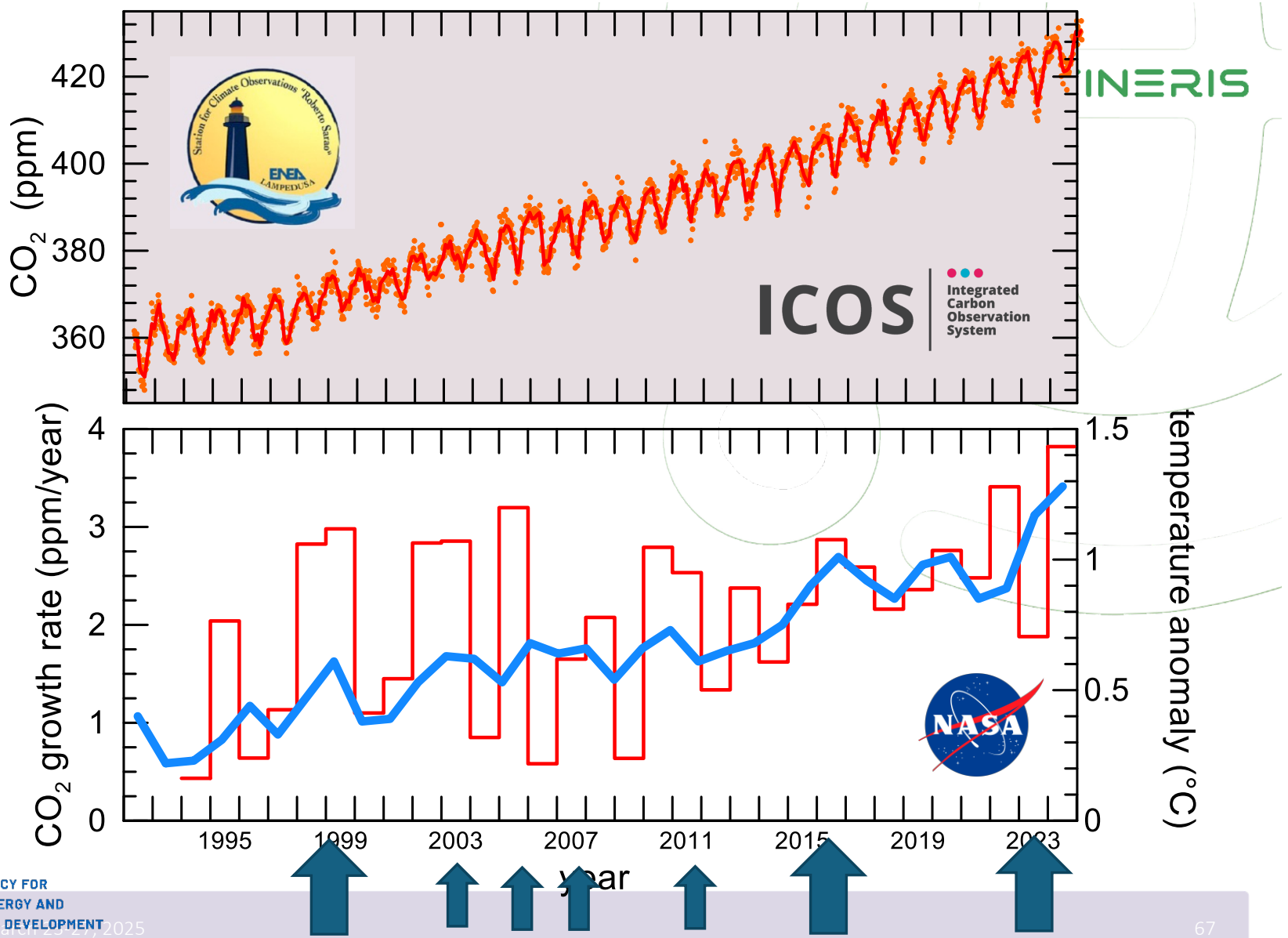


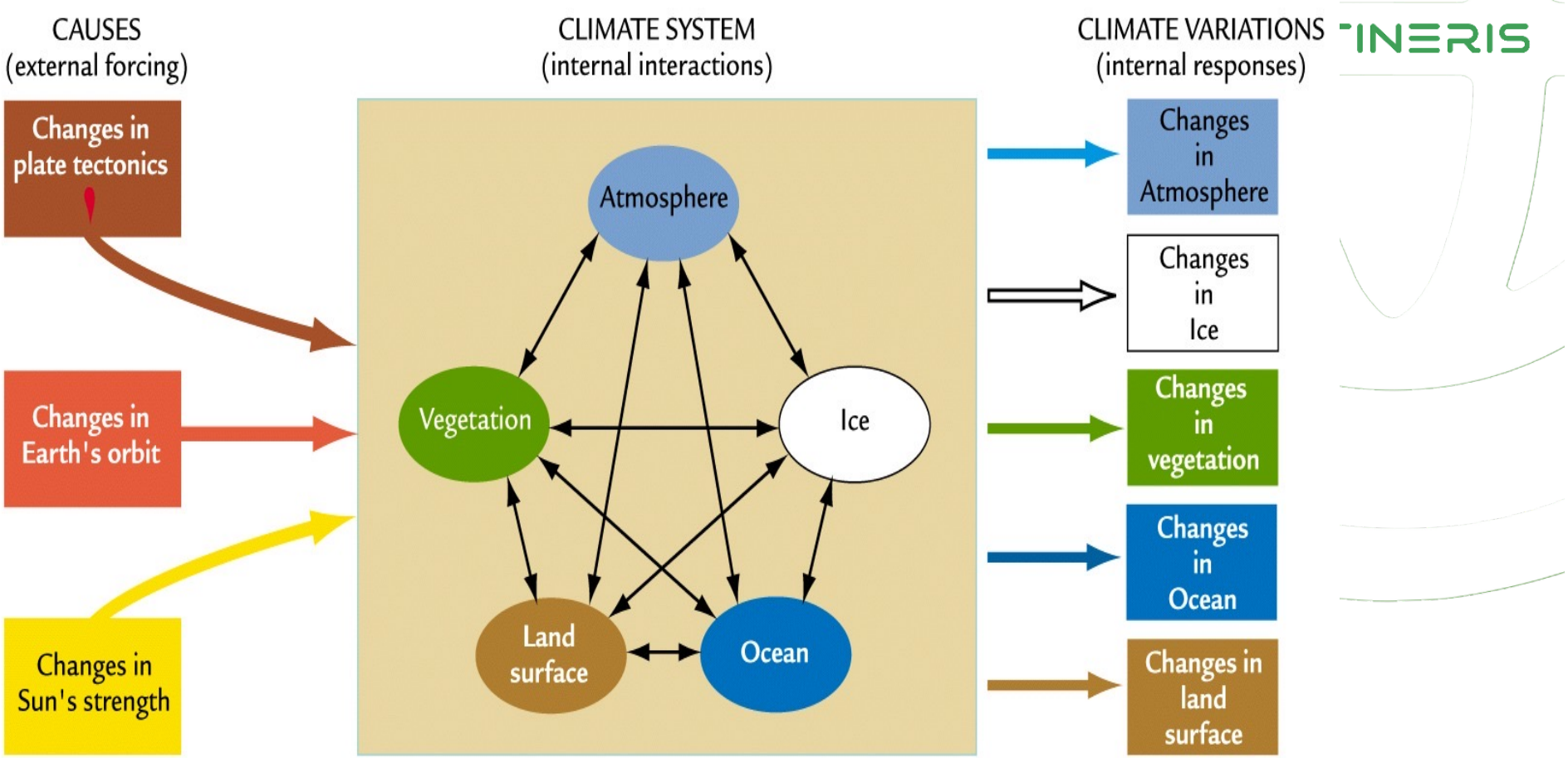
Mann and Jones, 2003


1901-2000
TEMPERATURE ANOMALY (°C)
1.5
1
0.5
0
-0.5
1900
1950
2000
YEAR
NASA


1880-1920
TEMPERATURE ANOMALY (°C)
1.5
1
0.5
0
-0.5
1900
1950
2000
YEAR
NASA


35.5°N, 12.6°E


Station for Climate Observations "Roberto Sarao"
ENEA
LAMPEDUSA
INERIS
ICOS
Integrated Carbon Observation System
CO2 (ppm)
420
400
380
360
CO2 growth rate (ppm/year)
4
3
2
1
0
1995
1999
2003
2007
2011
2015
2019
2023
year
NASA
temperature anomaly (°C)
1.5
1
0.5
0

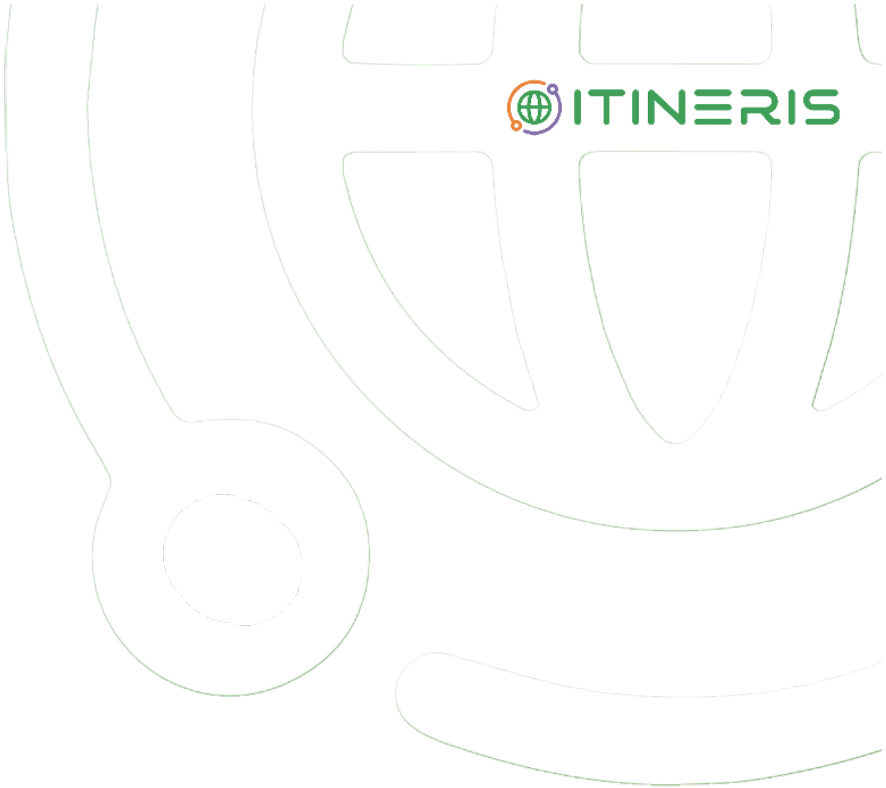

CAUSES
(external forcing)
Changes in plate tectonics
Changes in Earth's orbit
Changes in Sun's strength
CLIMATE SYSTEM
(internal interactions)
Atmosphere
Vegetation
Ice
Land surface
Ocean
CLIMATE VARIATIONS
(internal responses)
Changes in Atmosphere
Changes in Ice
Changes in vegetation
Changes in Ocean
Changes in land surface

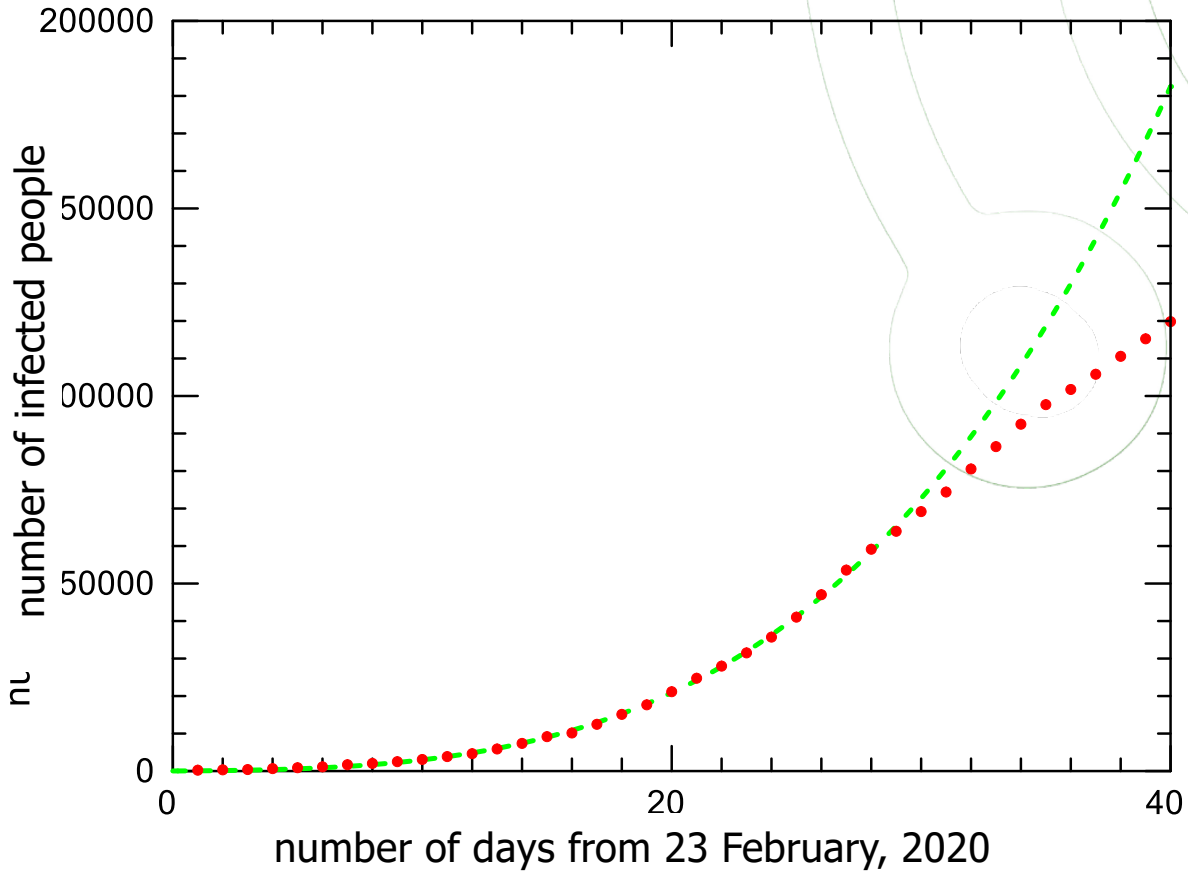
Greenhouse gas emissions

Radiative balance perturbation

Climate (temperature, precipitation, aerosol, clouds, vegetation, land use, temperature profile, biogeochemical cycles, ….)

$$\Delta T = \lambda \Delta F$$


ITINERIS


200000
50000
00000
50000
0
nt number of infected people
0
20
40
number of days from 23 February, 2020

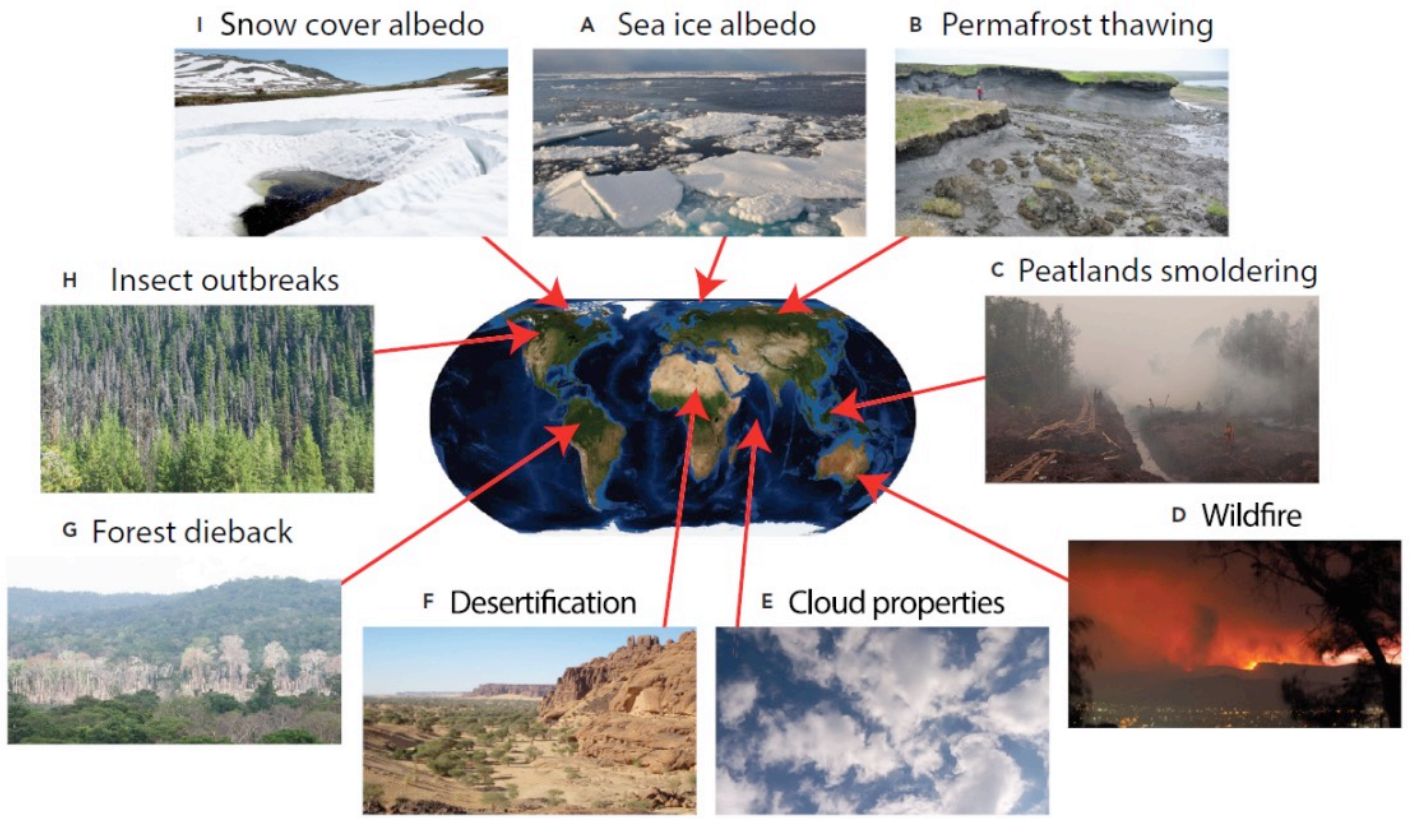


Figure 1. Map of feedback loops

(A–I) The map shows example locations where select positive feedback loops are likely operating. The full extent of the area and locations impacted by each feedback loop are not depicted. Feedback loop summaries: (A) sea ice melting or not forming → decreasing albedo; (B) increasing thawing and decomposition → increasing CO_2 and CH_4 emissions, loss of sequestration; (C) drying and increasing vulnerability to fire/smoldering, decreasing soil organic carbon → increasing release of CO_2 into the atmosphere and decreasing carbon sequestration; (D) increasing fire frequency and/or severity → increasing CO_2 emissions, loss of sequestration, change in albedo; (E) changing cloud distribution and optical properties → altered cloud albedo and greenhouse effect; (F) increasing chronic aridification and hotter drought stress extremes leading to expanding deserts → decreasing CO_2 sequestration, and increasing albedo; (G) dieback of Amazon, boreal, and other forests → loss of sequestration, change in albedo, decreasing evapotranspiration; (H) changing insect distributions and abundances, decreased host tree defense → loss of sequestration, change in albedo; (I) decreasing snow cover → decreasing albedo. See Table S1 for further feedback loop details. Photo credits (also given in Table S3): (A) Patrick Kelley, CC BY 2.0; (B) Boris Radosavljevic, CC BY 2.0; (C) NASA's Earth Observatory, CC BY 2.0; (D) Nick-D, CC BY-SA 4.0; (E) Doggo19292, Public Domain; (F) David Stanley, CC BY 2.0; (G) NASA/JPL-Caltech, (H) Jonhall, CC BY 3.0, (I) Natalia_Kollegova, Pixabay License.

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Table 1. Summary list of feedback loops

Feedback	Effect of climate change	Effect on climate change	+/–
20 physical feedback loops			
1. Planck†	↑ Temperature	↑ Heat loss (radiation)	–
2. Water vapor†	↑ Increasing water vapor content	↑ Greenhouse effect	+
3. Sea ice albedo*†	↑ Sea ice melting or not forming	↓ Albedo	+
4. Ice sheets*†‡	↑ Glacier & ice sheet melting/ instability	↓ Albedo	+
5. Sea level rise‡	↑ Sea levels	↓ Albedo (↑ coastal submergence)	+
6. Snow cover†	↓ Snow cover	↓ Albedo	+
7. Clouds†	Δ Cloud distribution & optical properties	Δ Cloud albedo & greenhouse effect	+
8. Dust†	Δ Dust aerosol abundance	Δ Albedo & greenhouse effect	?
9. Other aerosols†	Δ Atmos. aerosol conc.	Δ Albedo & greenhouse effect	?
10. Ocean stratification	↑ Ocean stratification	↓ Carbon uptake by ocean	+
11. Ocean circ.*	↓ Ocean circ.	Δ Surface temperature	?
12. Solubility pump†	↑ Atmos. CO_2 levels	↓ CO_2 absorption by ocean	+
13. CH_4 hydrates*‡	↑ CH_4 hydrate dissociation rates	↑ Release of CH_4 into atmos.	+
14. Lapse rate†	Δ Temp.-altitude relationships	↓ Global mean temperature	–
15. Ice-elevation‡	↓ Ice sheet/glacier elevation	↑ Glacier & ice sheet melting, ↓ albedo	+

16. Antarctic rainfall‡	↓ Ice sheet extent, ↑ precipitation	↓ Albedo, ↑ deep ocean warming	+
17. Sea ice growth	↓ Sea ice thickness, ↓ insulation	↑ Thin ice growth rate	–
18. Ozone†	Δ Atmos. circ.	↓ Tropical lower stratospheric ozone	?
19. Atmos. reactions†	Δ Atmos. chem. reaction rates	Δ Greenhouse effect	?
20. Chem. weathering‡	↑ Chemical weathering rates	↑ CO_2 taken out of atmosphere	–
21 biological feedback loops			
21. Peatlands†	↑ Drying and fire, ↓ Soil carbon	↑ Release of CO_2 into atmos.	+
22. Wetlands†	↑ Wetlands area (↑ precipitation)	↑ CO_2 seq., ↑ CH_4 emissions	+
23. Freshwater	↑ Aquatic plant growth rates	↑ CH_4 emissions	+
24. Forest dieback*	↑ Amazon and other forest dieback	↓ CO_2 seq., Δ albedo	+
25. Northern greening	↑ Boreal forest area, Arctic vegetation	↑ CO_2 seq., ↓ albedo	+
26. Insects	Δ Insect ranges and abundances	↓ CO_2 seq., Δ albedo	+
27. Wildfire†	↑ Fire activity in some regions	↑ CO_2 emissions, Δ albedo	+
28. BVOCs†	Δ BVOC emission rates	↓ Greenhouse effect, ↑ tropospheric O_3	–
29. Soil carbon (other)	↑ Loss of soil carbon	↑ CO_2 emissions	+
30. Soil nitrous oxide†	Δ Soil microbial activity	↑ Nitrous oxide emissions	+
31. Permafrost*†	↑ Permafrost thawing	↑ CO_2 and CH_4 emissions	+
32. Soil and plant ET	↑ ET from soils and plants	↓ Latent heat flux	+
33. Microbes (other)	↑ Microbial respiration rates	↑ CO_2 and CH_4 emissions	+

33. Microbes (other)	↑ Microbial respiration rates	↑ CO_2 and CH_4 emissions	+
34. Plant stress	↑ Thermal stress, ↑ droughts	↑ Plant mortality, ↓ CO_2 seq.	+
35. Desertification	↑ Desert area	↓ CO_2 seq., Δ albedo	+
36. Sahara/Sahel greening*	↑ Rainfall in Sahara and Sahel	↑ CO_2 seq. by vegetation	–
37. CO_2 fertilization	↑ CO_2 conc., ↑ NPP	↑ Carbon uptake by vegetation	–
38. Coastal productivity	↑ Coastal ecosystem degradation	↓ Coastal ecosystem carbon seq.	+
39. Metabolic rates	↑ Phytoplankton respiration rates	↑ CO_2 released into atmos.	+
40. Ocean bio.	↑ Ocean CO_2, ↑ acidification, ↑ temp.	Δ Ocean carbon sink	?
41. Phytoplankton-DMS†	Δ Plankton DMS emissions	Δ Cloud albedo	?

Loops are divided into two categories: physical (loop numbers 1–20) and biological (loop numbers 21–41). The rightmost column shows the loop direction ("+": reinforcing, "-": balancing, "?": uncertain). Feedback loops that involve potential tipping elements are marked with asterisks (*; see supplemental experimental procedures). As a rough indicator of feedbacks that are more likely to be at least partly included in some climate models, loops that are covered in Figure TS.17 (feedbacks overview) or 5.29 (biogeochemical feedbacks) of IPCC[4] are marked with daggers (†). Many of these feedbacks will have significant effects on Earth's climate, but others are more speculative and possibly negligible. Feedback impacts operate on time scales ranging from short (e.g., months/years) to very long (e.g., millennia); feedbacks we believe to be exceptionally slow are marked with double daggers (‡). Symbols indicate increasing (↑), decreasing (↓), and changing (Δ), and abbreviations correspond to circulation (circ.), concentration (conc.), temperature (temp.), atmospheric (atmos.), chemical (chem.), sequestration (seq.), biogenic volatile organic compounds (BVOCs), ozone (O_3), evapotranspiration (ET), biological pump (bio.), and dimethyl sulfide (DMS). See supplemental experimental procedures and Table S1 for complete loop descriptions, grouping order, limitations (e.g., overlapping loops and uncertain tipping elements), and selected references.

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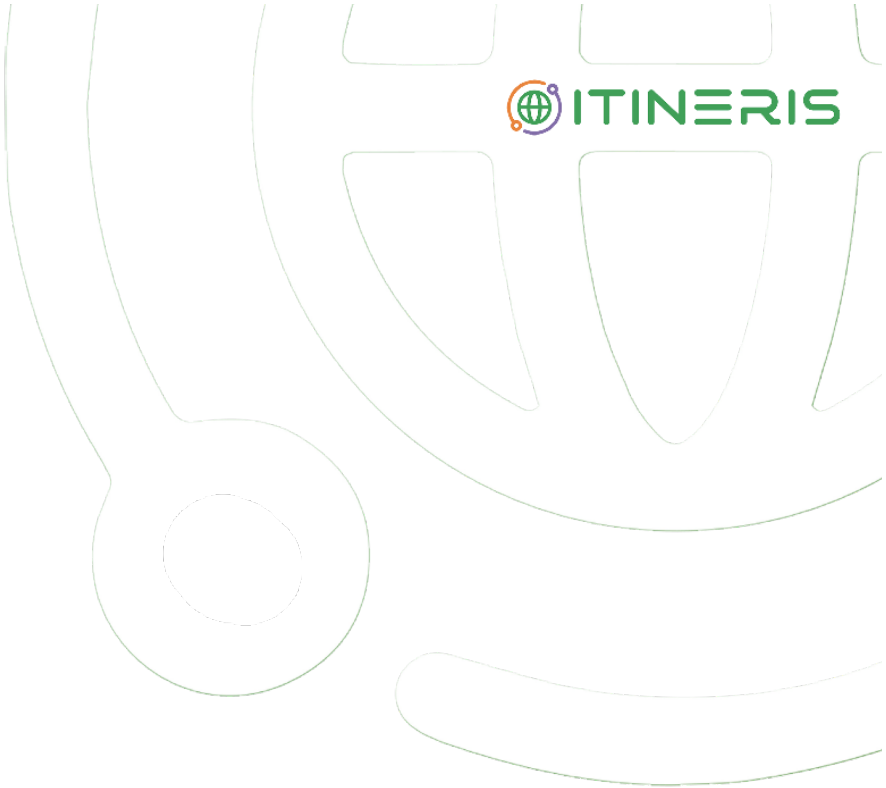
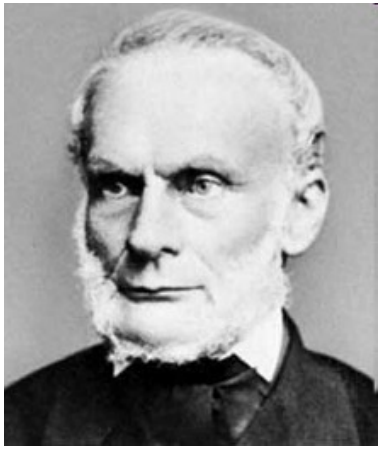
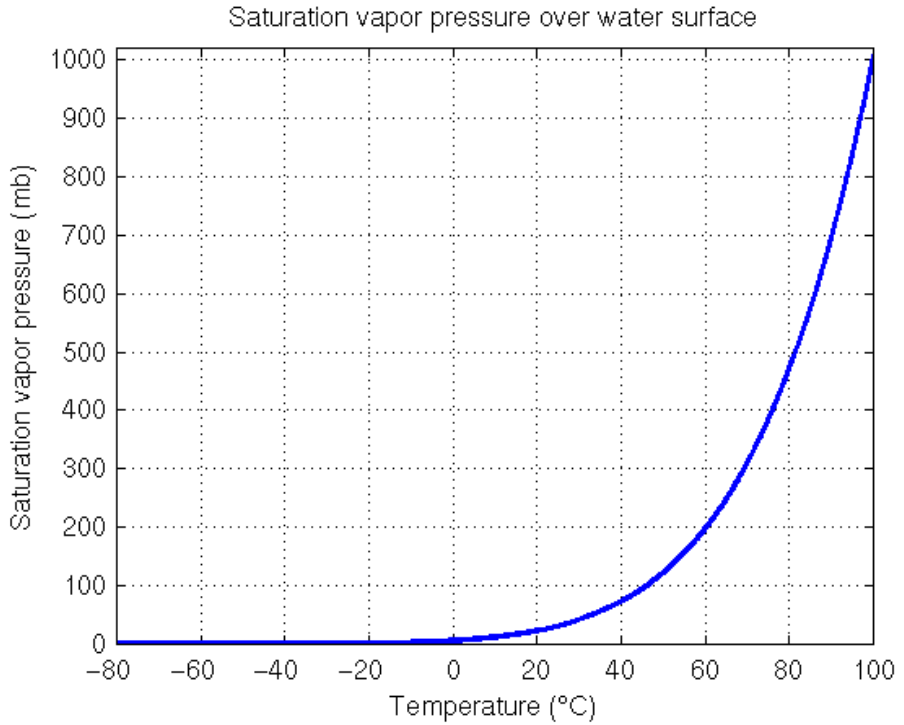
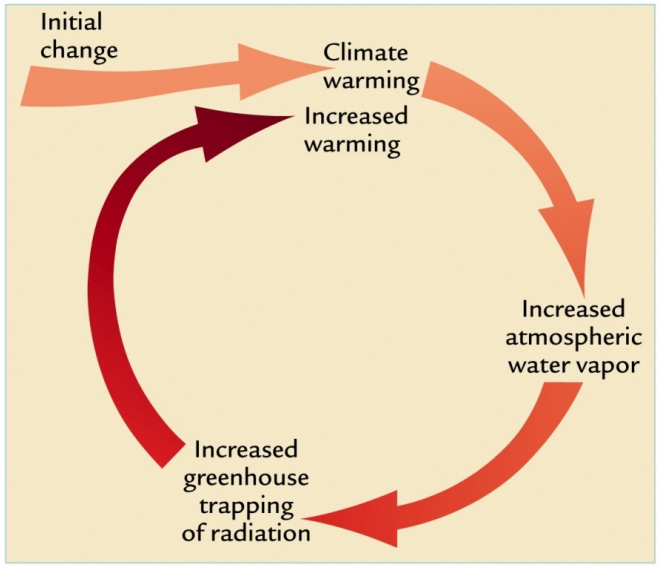
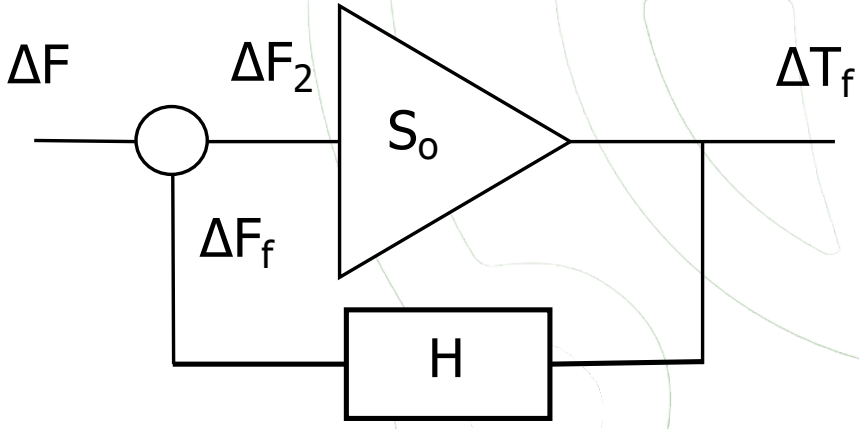

ITINERIS



$$\frac{\mathrm{d}e_s}{\mathrm{d}T} = \frac{L_v e_s}{R_v T^2}$$



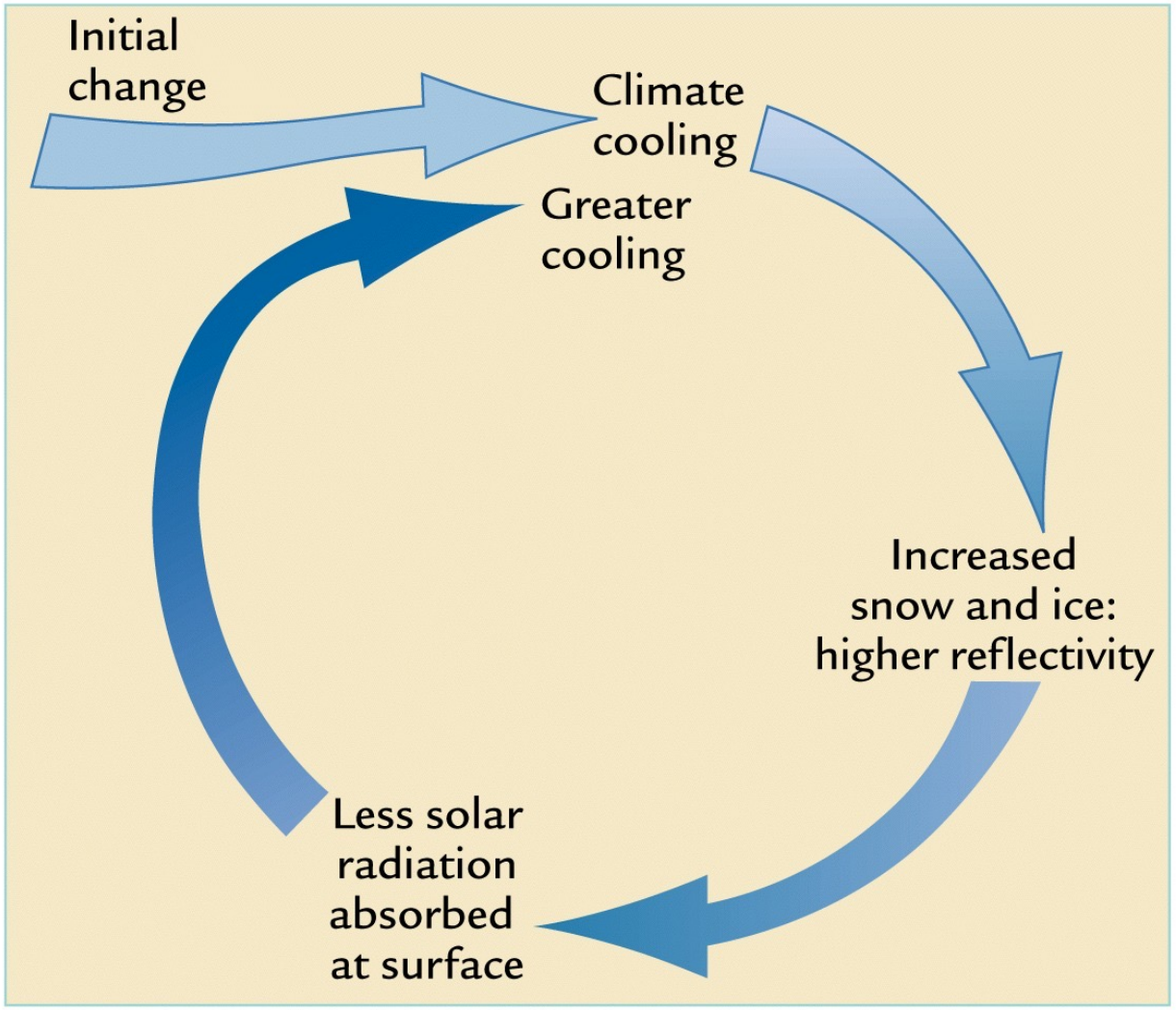


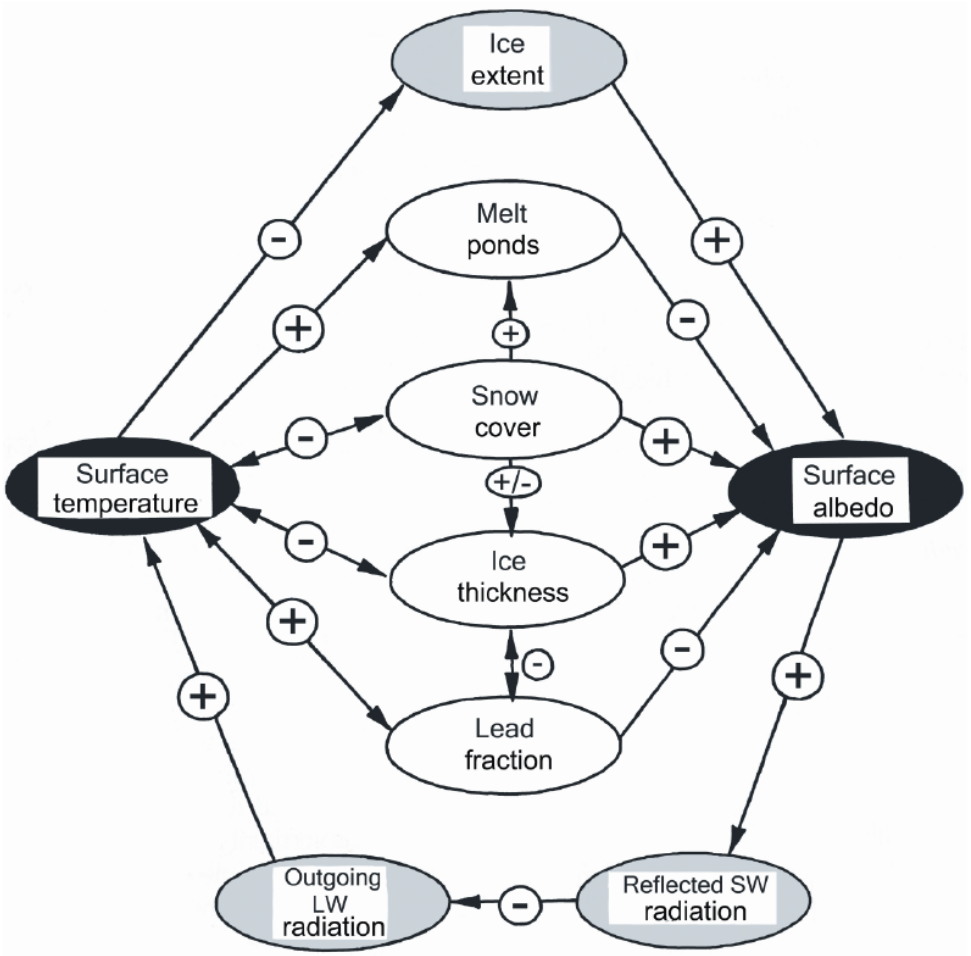


$$S/S_o = 1/(1-S_oH) = 1/(1-f)$$

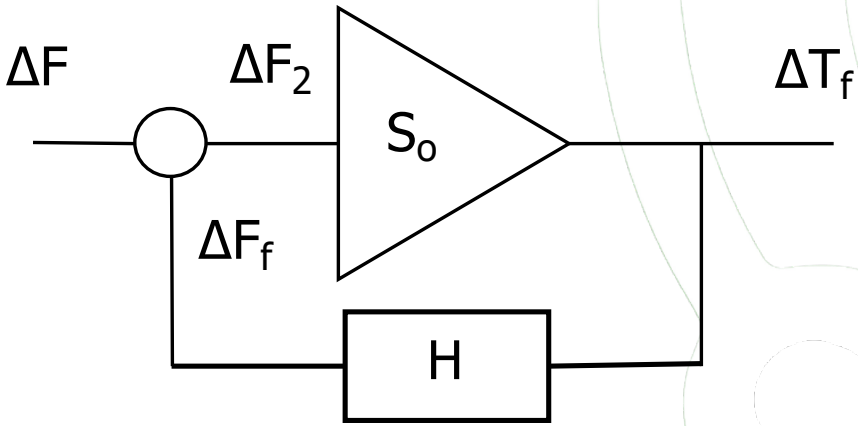
$$\Delta T_f/\Delta T = 1/(1-f)$$

Water vapour feedback
f is about 0.4 $\Delta T_f/\Delta T$ is about 1.7


Initial change
Climate cooling
Greater cooling
Increased snow and ice: higher reflectivity
Less solar radiation absorbed at surface



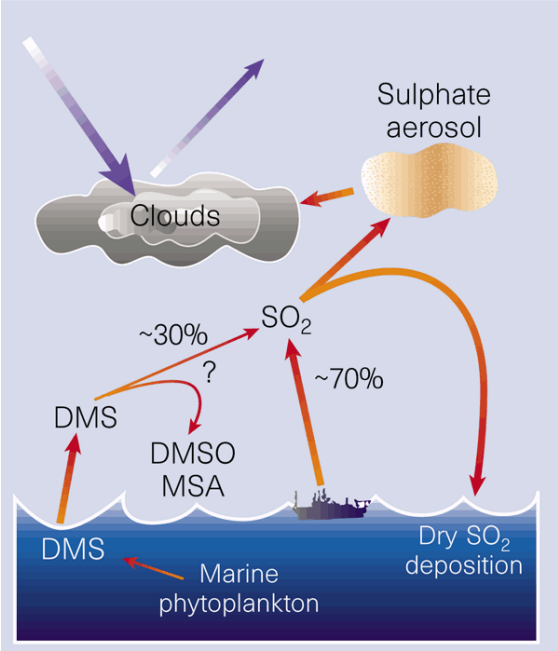
Schematic of the ice- albedo feedback mechanism using the framework of Kellogg [1973]. The direction of the arrow indicates the direction of the interaction. A "+" indicates a positive interaction (an increase in the first quantity leads to an increase in the second). A "-" indicates a negative interaction (an increase in the first quantity leads to a decrease in the second quantity). A "+/-" indicates that the sign of the interaction is uncertain or that the sign changes over the annual cycle [from Curry *et al*., 1996, by permission of AMS].

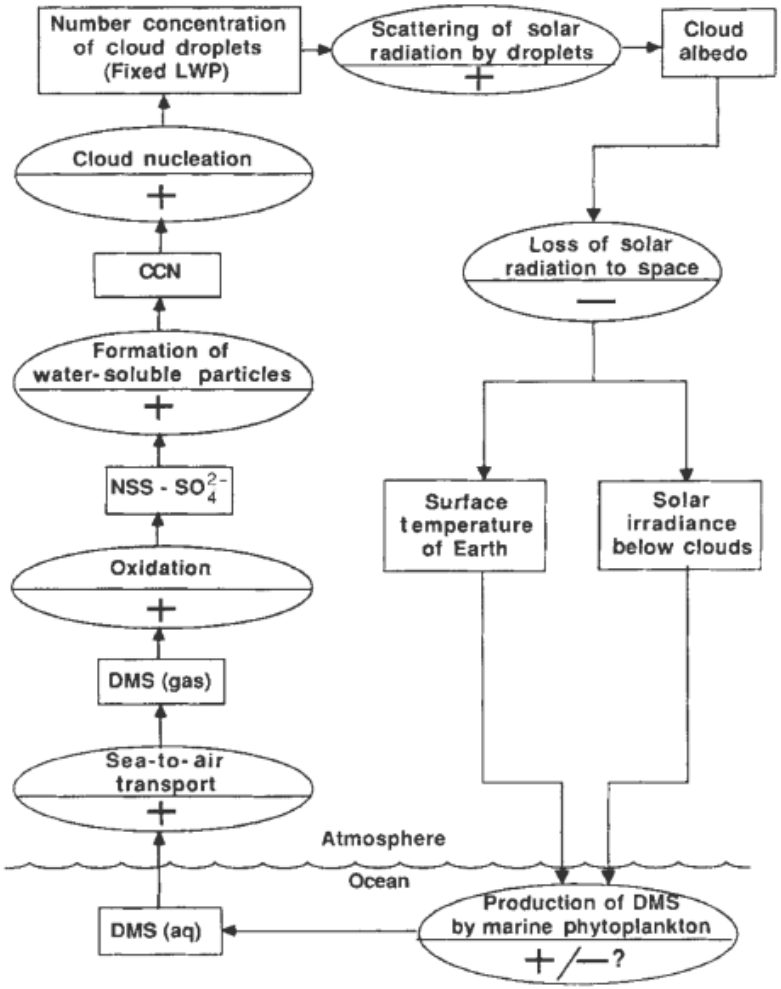


$S/S_o = 1/(1-S_oH) = 1/(1-f)$

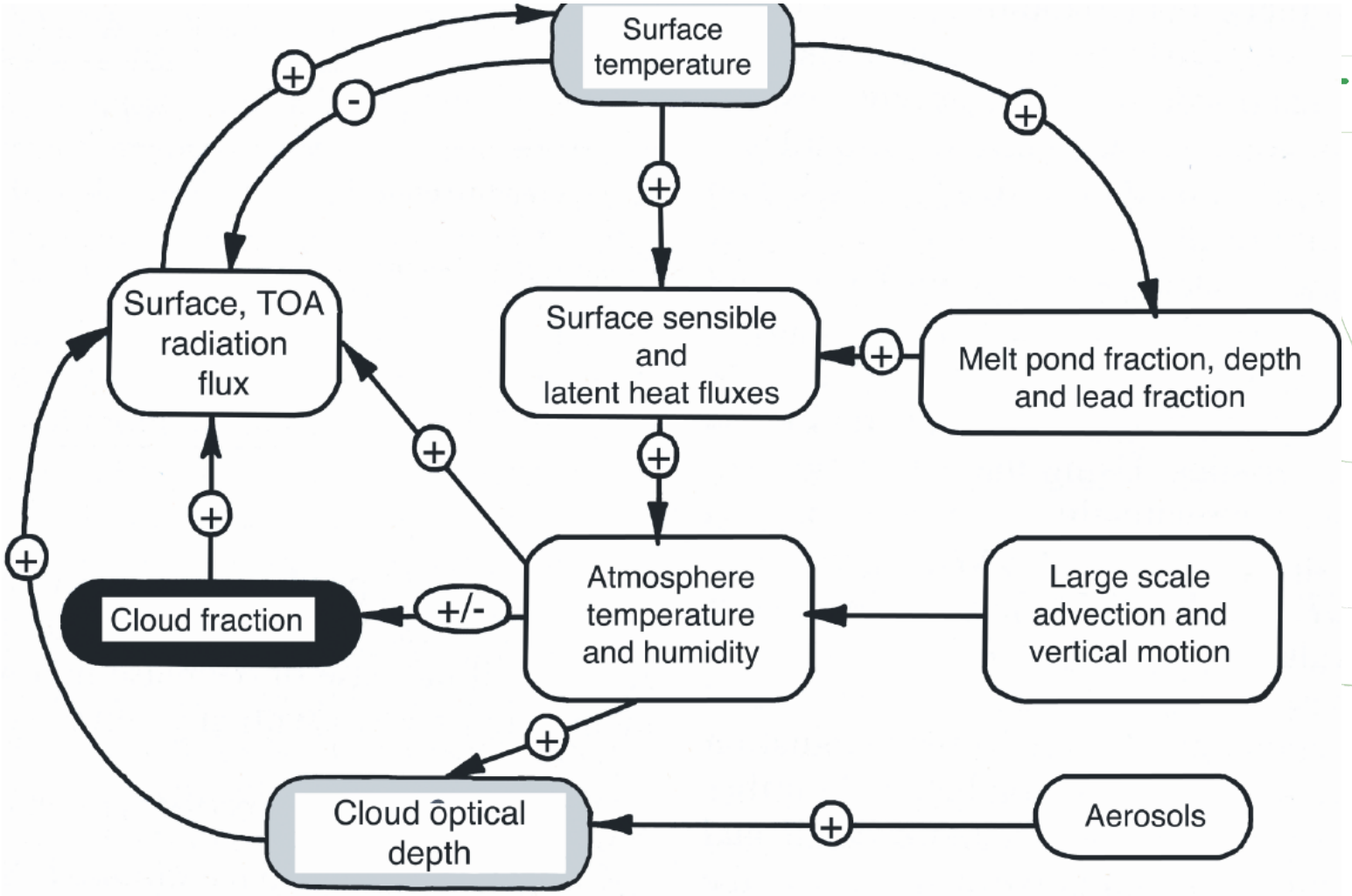
$\Delta T_f/\Delta T = 1/(1-f)$

Ice-albedo feedback
f is about 0.3 $\Delta T_f/\Delta T$ is about 1.45





Charlson et al., 1987



The cloud-radiation feedback mechanism [from Curry *et al*., 1996, by permission of AMS].

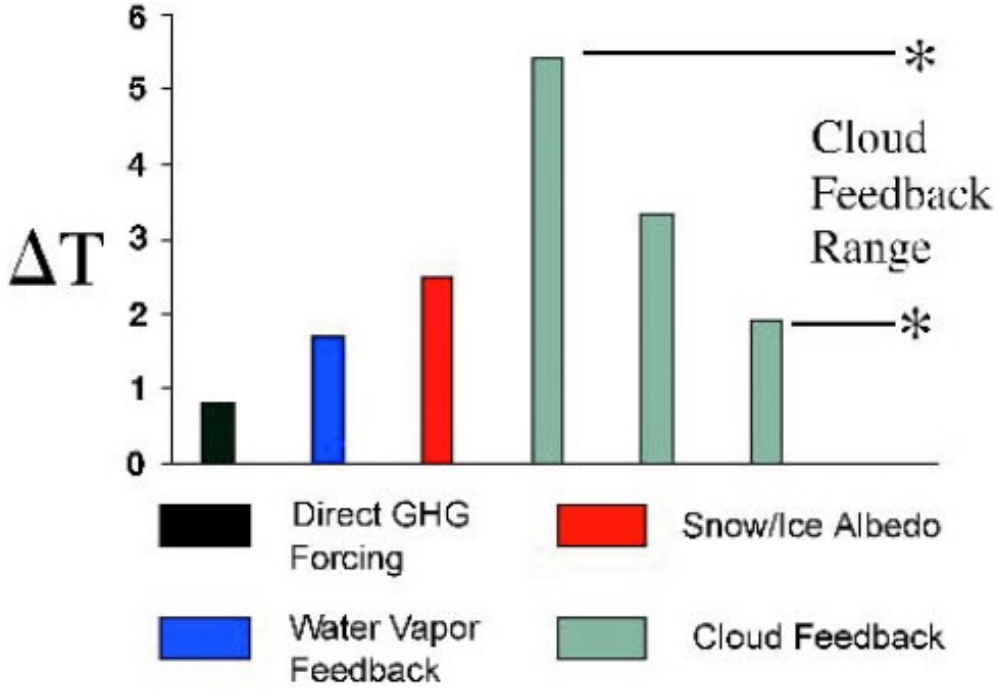
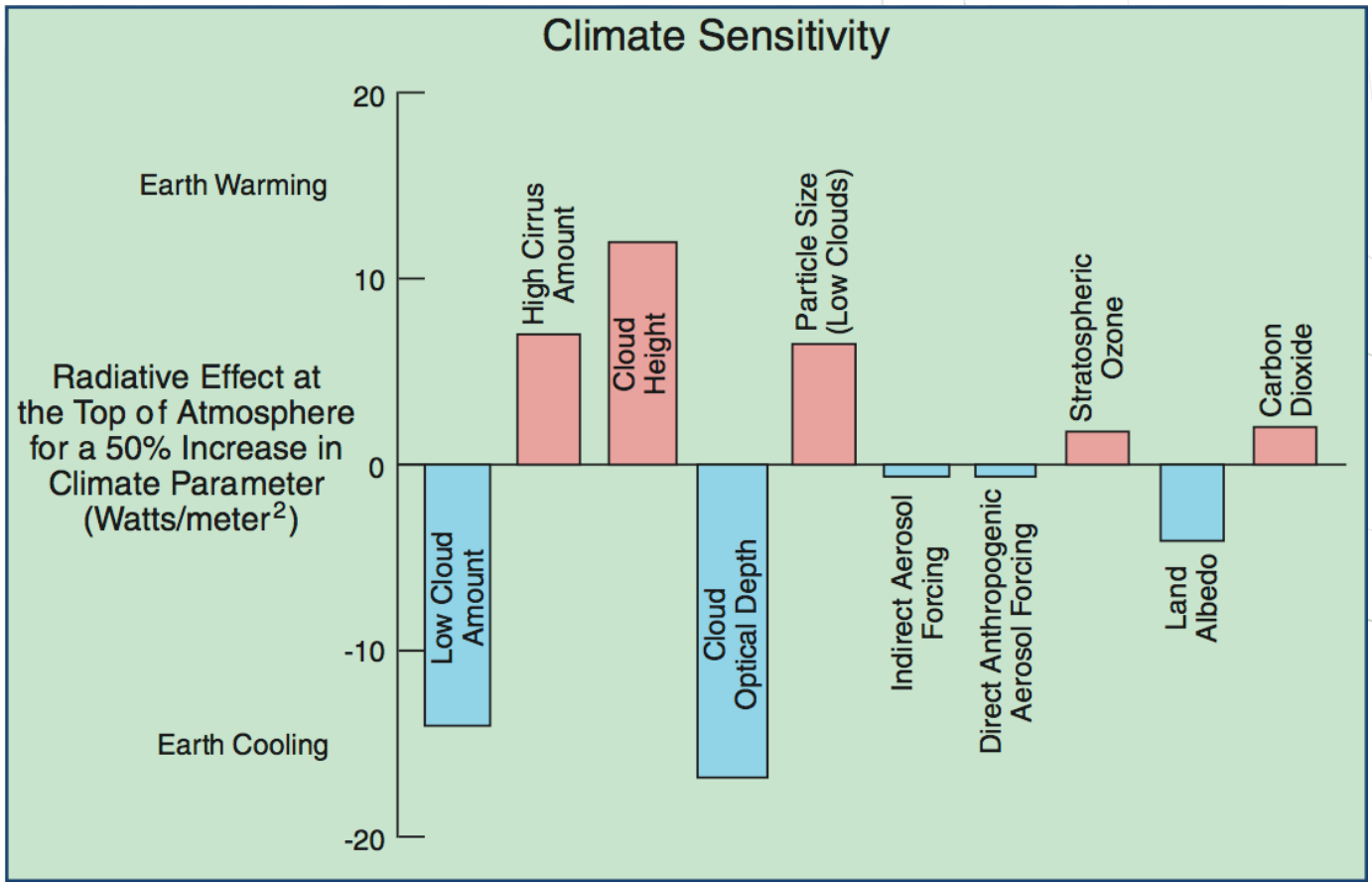
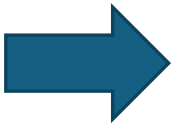


FIG. 13. The response of a single climate model to an imposed doubling of CO_2 as different feedbacks are systematically added in the model (adapted from Senior and Mitchell 1993). Different treatments of cloud processes in the model produce a large spread in predicted surface temperature due to CO_2 doubling.


Climate Sensitivity
Radiative Effect at the Top of Atmosphere for a 50% Increase in Climate Parameter (Watts/meter^2)
20
10
0
-10
-20
Earth Warming
Earth Cooling
Low Cloud Amount
High Cirrus Amount
Cloud Height
Cloud Optical Depth
Particle Size (Low Clouds)
Indirect Aerosol Forcing
Direct Anthropogenic Aerosol Forcing
Stratospheric Ozone
Land Albedo
Carbon Dioxide

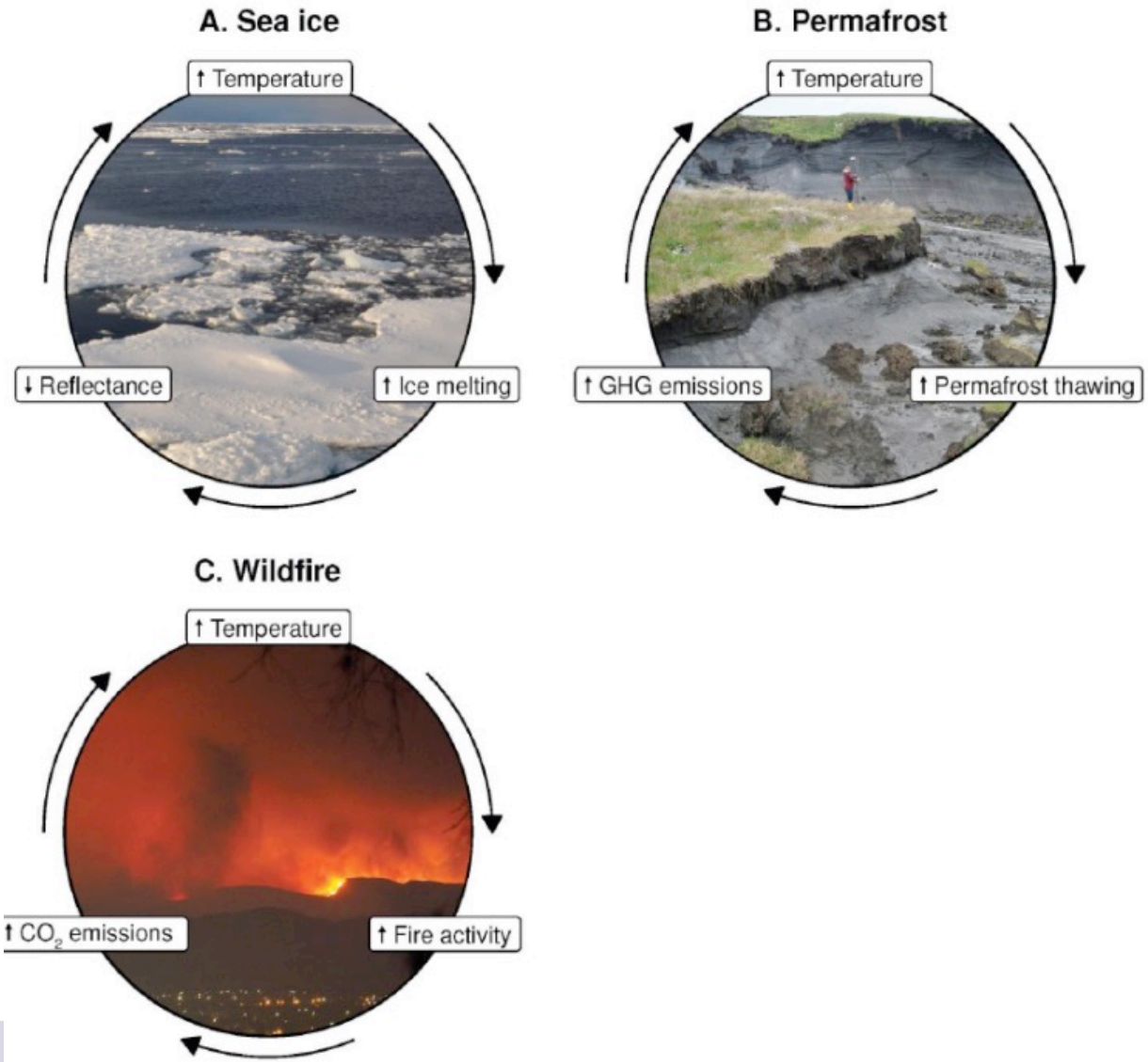
Greenhouse gas emissions



Radiative balance perturbation

Climate (temperature, precipitation, aerosol, clouds, vegetation, land use, temperature profile, biogeochemical cycles, ….)

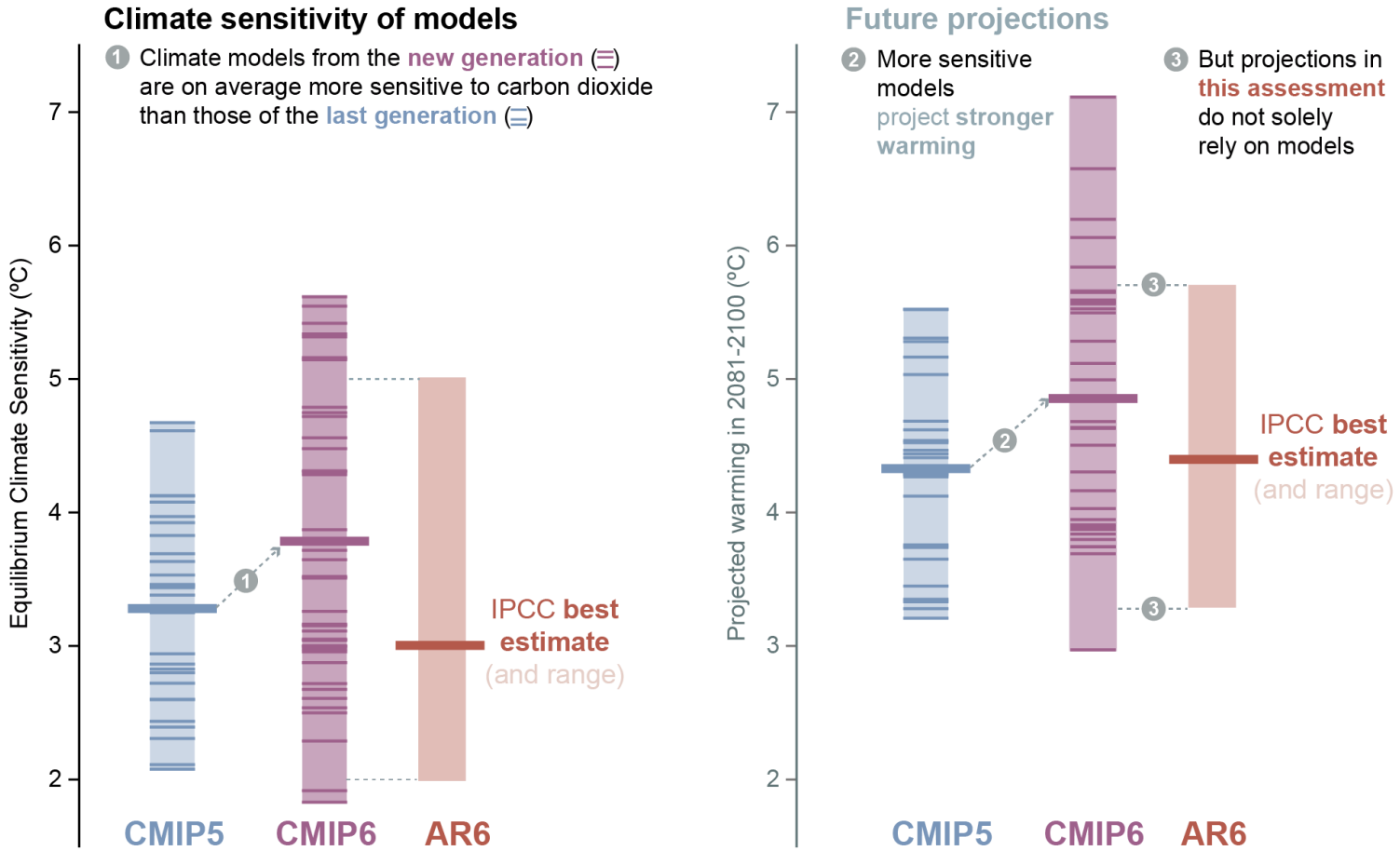
$$\Delta T = \lambda \Delta F$$


A. Sea ice
↑ Temperature
↓ Reflectance
↑ Ice melting
B. Permafrost
↑ Temperature
↑ GHG emissions
↑ Permafrost thawing
C. Wildfire
↑ Temperature
↑ CO_2 emissions
↑ Fire activity

FAQ 7.3: **Equilibrium climate sensitivity** and **future warming**

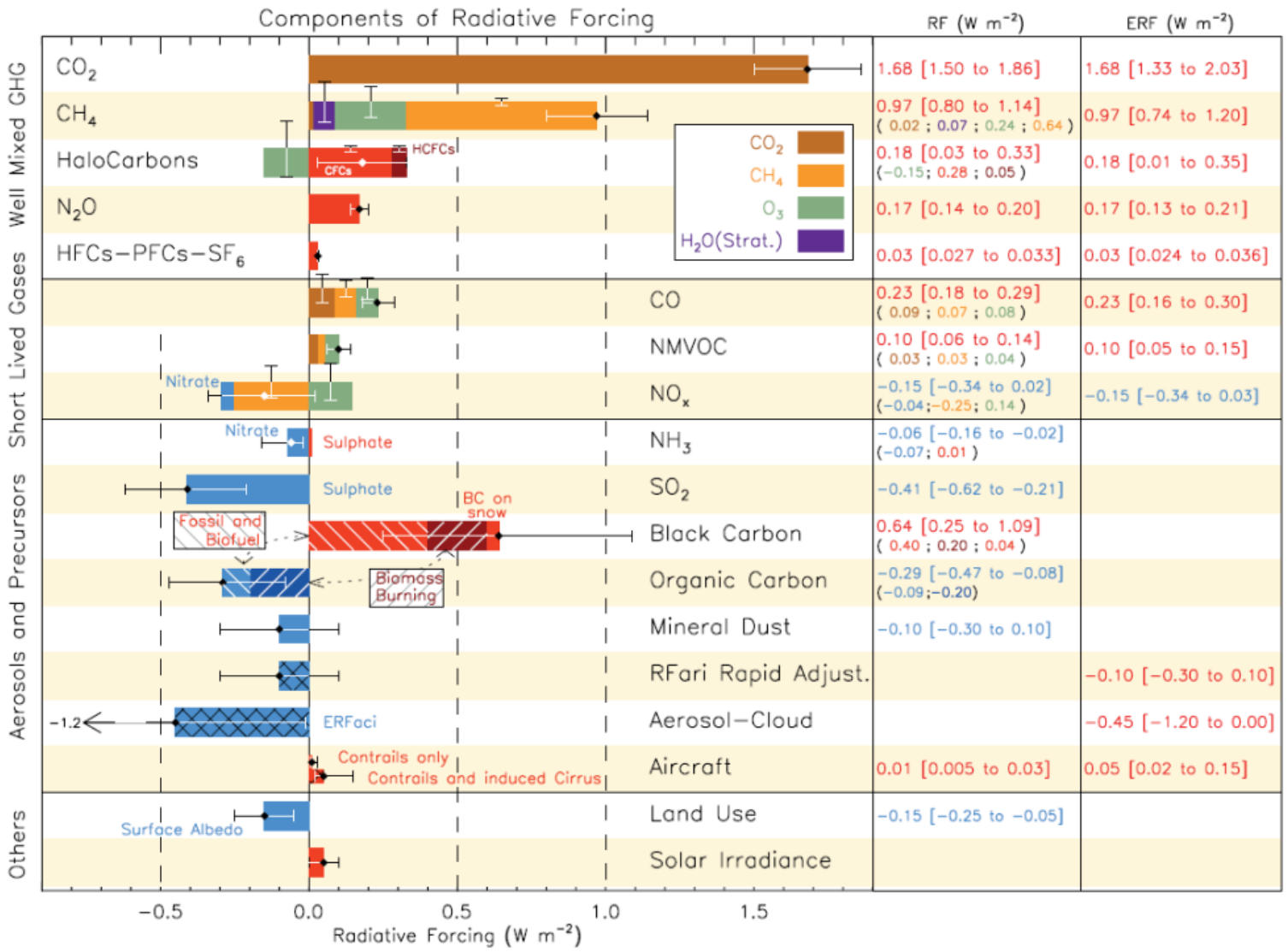
Equilibrium climate sensitivity measures how climate models respond to a doubling of carbon dioxide in the atmosphere.

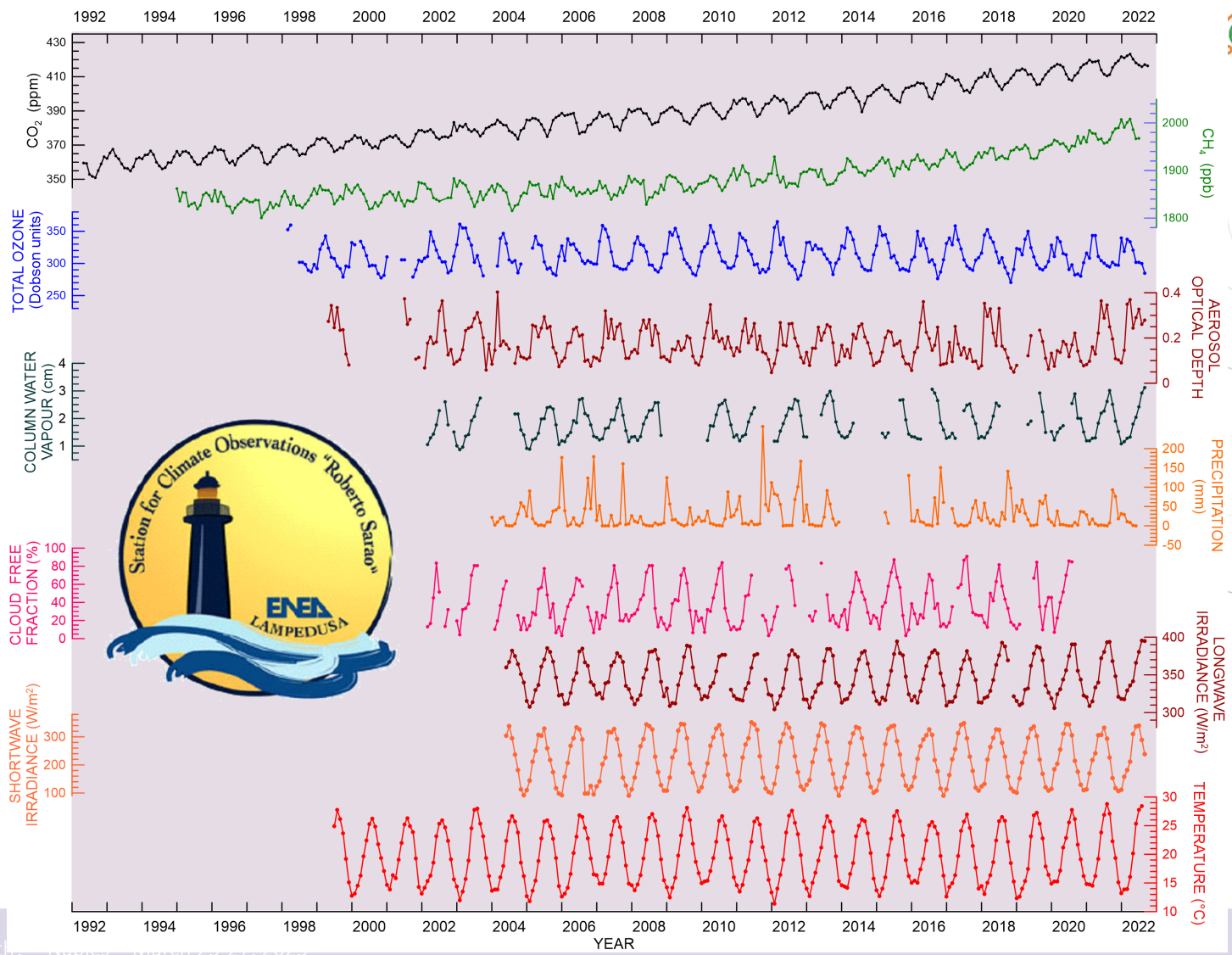
CO_2 at 380 ppm
2°C
temperature
increase



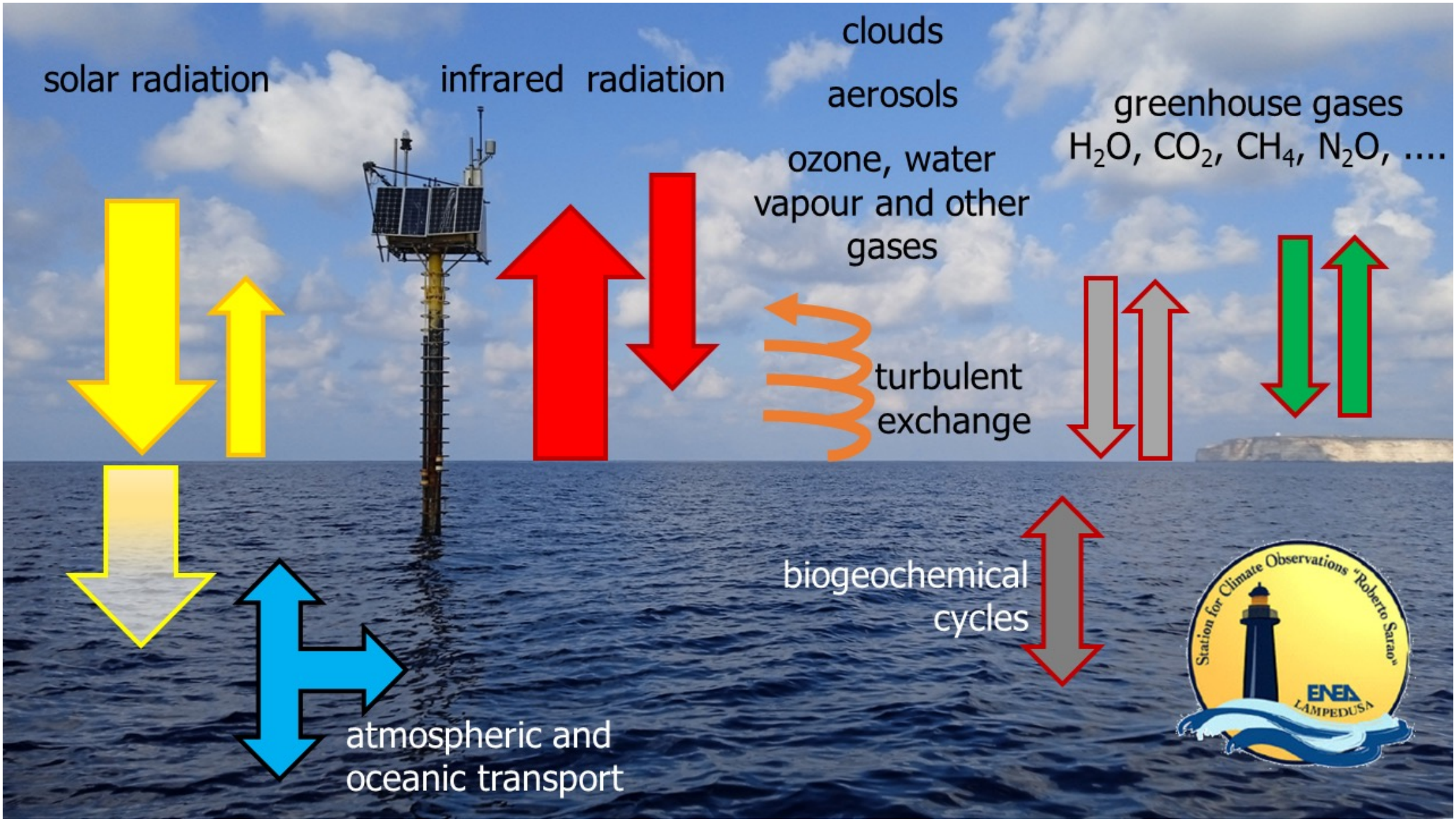
IPCC, 2021

IPCC, 2021


Components of Radiative Forcing
RF (W m⁻²)
ERF (W m⁻²)
Well Mixed GHG
Short Lived Gases
Aerosols and Precursors
Others
CO2
CH4
HaloCarbons
HCFCs
CFCs
N2O
HFCs–PFCs–SF6
CO2
CH4
O3
H2O(Strat.)
CO
NMVOC
NOx
Nitrate
NH3
Nitrate
Sulphate
SO2
Sulphate
BC on snow
Fossil and Biofuel
Black Carbon
Organic Carbon
Biomass Burning
Mineral Dust
RFari Rapid Adjust.
-1.2
ERFaci
Aerosol–Cloud
Contrails only
Contrails and induced Cirrus
Aircraft
Land Use
Surface Albedo
Solar Irradiance
1.68 [1.50 to 1.86]
1.68 [1.33 to 2.03]
0.97 [0.80 to 1.14]
(0.02 ; 0.07 ; 0.24 ; 0.64)
0.97 [0.74 to 1.20]
0.18 [0.03 to 0.33]
(−0.15; 0.28 ; 0.05)
0.18 [0.01 to 0.35]
0.17 [0.14 to 0.20]
0.17 [0.13 to 0.21]
0.03 [0.027 to 0.033]
0.03 [0.024 to 0.036]
0.23 [0.18 to 0.29]
(0.09 ; 0.07 ; 0.08)
0.23 [0.16 to 0.30]
0.10 [0.06 to 0.14]
(0.03 ; 0.03 ; 0.04)
0.10 [0.05 to 0.15]
−0.15 [−0.34 to 0.02]
(−0.04;−0.25; 0.14)
−0.15 [−0.34 to 0.03]
−0.06 [−0.16 to −0.02]
(−0.07; 0.01)
−0.41 [−0.62 to −0.21]
0.64 [0.25 to 1.09]
(0.40 ; 0.20 ; 0.04)
−0.29 [−0.47 to −0.08]
(−0.09;−0.20)
−0.10 [−0.30 to 0.10]
−0.10 [−0.30 to 0.10]
−0.45 [−1.20 to 0.00]
0.01 [0.005 to 0.03]
0.05 [0.02 to 0.15]
−0.15 [−0.25 to −0.05]
−0.5
0.0
0.5
1.0
1.5
Radiative Forcing (W m⁻²)


1992
1994
1996
1998
2000
2002
2004
2006
2008
2010
2012
2014
2016
2018
2020
2022
YEAR
CO2 (ppm)
CH4 (ppb)
TOTAL OZONE (Dobson units)
AEROSOL OPTICAL DEPTH
COLUMN WATER VAPOUR (cm)
PRECIPITATION (mm)
CLOUD FREE FRACTION (%)
LONGWAVE IRRADIANCE (W/m²)
SHORTWAVE IRRADIANCE (W/m²)
TEMPERATURE (°C)
Station for Climate Observations "Roberto Sarao"
ENEA
LAMPEDUSA

ITINERIS


solar radiation
infrared radiation
clouds
aerosols
ozone, water vapour and other gases
greenhouse gases
H_2O, CO_2, CH_4, N_2O, ...
turbulent exchange
biogeochemical cycles
atmospheric and oceanic transport
Station for Climate Observations "Roberto Sarao"
ENEA
LAMPEDUSA

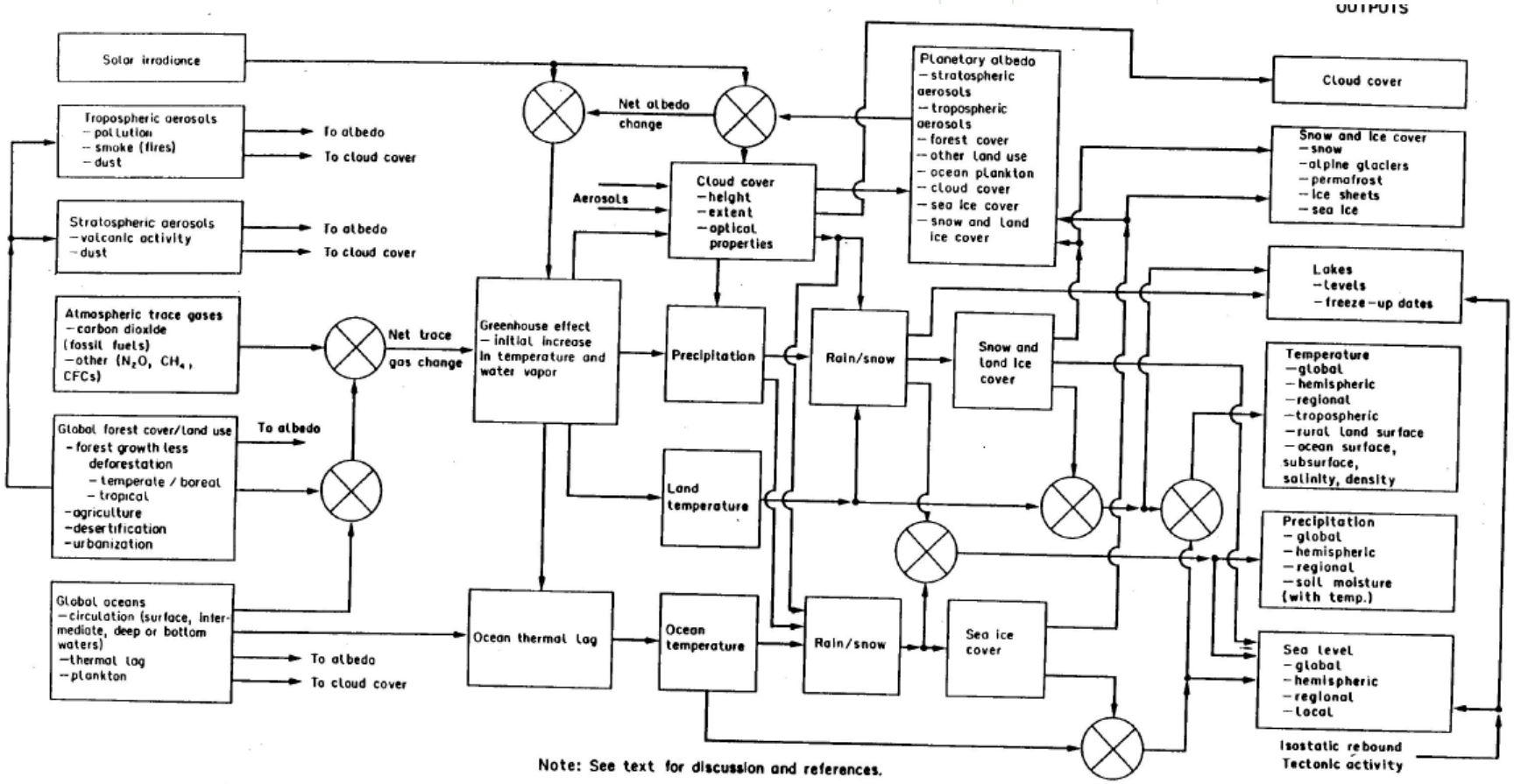
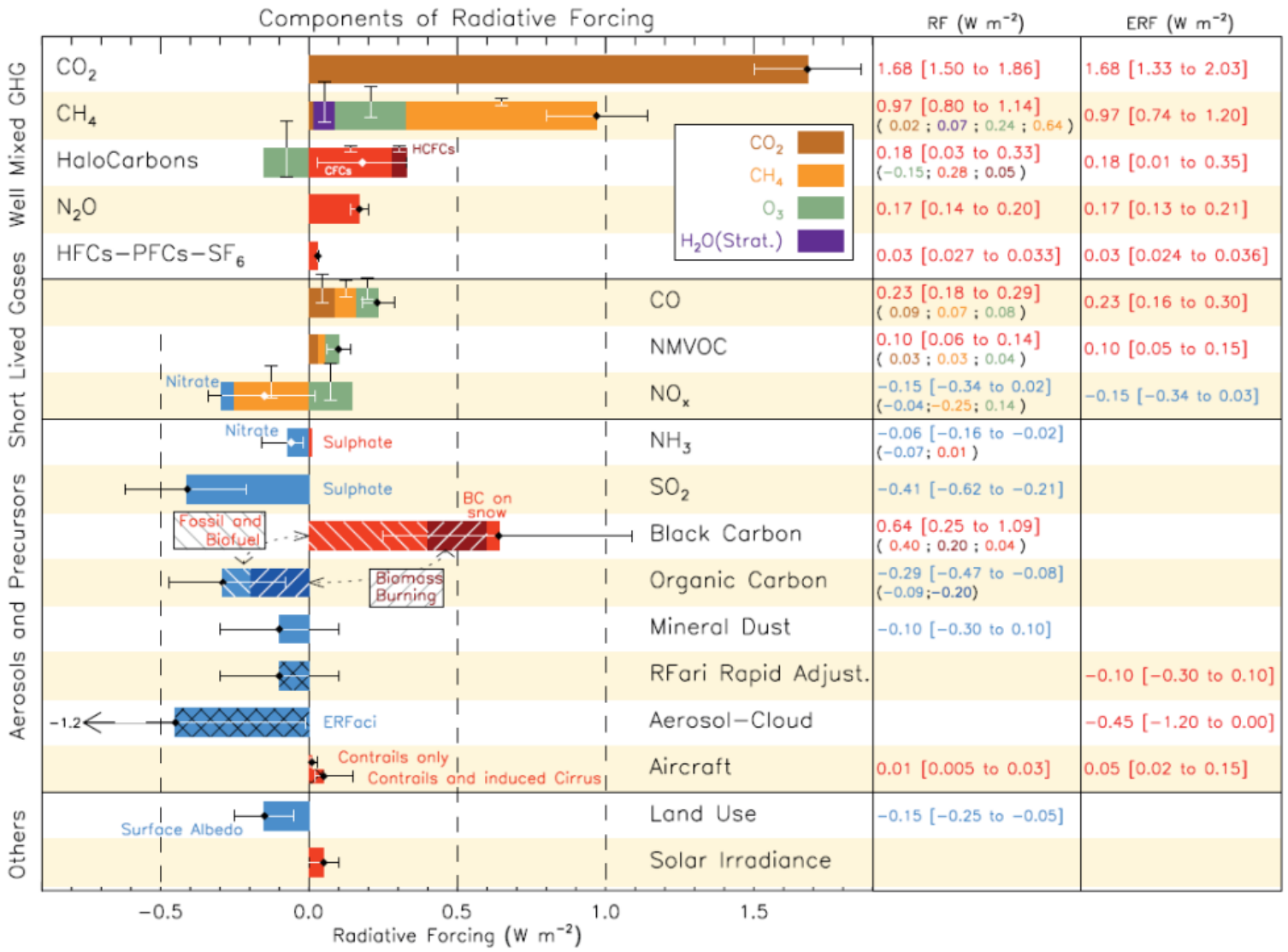


Fig. 1. Illustrative conceptual model of the climate system.

F. WOOD, 1998

The need for systems research on global climate change

IPCC, 2021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ERF (W m⁻²)
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Short Lived Gases
Aerosols and Precursors
Others
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CH4
HaloCarbons
N2O
HFCs–PFCs–SF6
HCFCs
CFCs
CO2
CH4
O3
H2O(Strat.)
CO
NMVOC
NOx
Nitrate
NH3
Nitrate
Sulphate
SO2
Sulphate
BC on snow
Black Carbon
Fossil and Biofuel
Organic Carbon
Biomass Burning
Mineral Dust
RFari Rapid Adjust.
-1.2
ERFaci
Aerosol–Cloud
Contrails only
Contrails and induced Cirrus
Aircraft
Land Use
Surface Albedo
Solar Irradiance
1.68 [1.50 to 1.86]
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(0.09 ; 0.07 ; 0.08)
0.23 [0.16 to 0.30]
0.10 [0.06 to 0.14]
(0.03 ; 0.03 ; 0.04)
0.10 [0.05 to 0.15]
−0.15 [−0.34 to 0.02]
(−0.04;−0.25; 0.14)
−0.15 [−0.34 to 0.03]
−0.06 [−0.16 to −0.02]
(−0.07; 0.01)
−0.41 [−0.62 to −0.21]
0.64 [0.25 to 1.09]
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−0.45 [−1.20 to 0.00]
0.01 [0.005 to 0.03]
0.05 [0.02 to 0.15]
−0.15 [−0.25 to −0.05]
−0.5
0.0
0.5
1.0
1.5
Radiative Forcing (W m⁻²)

IPCC, 2007

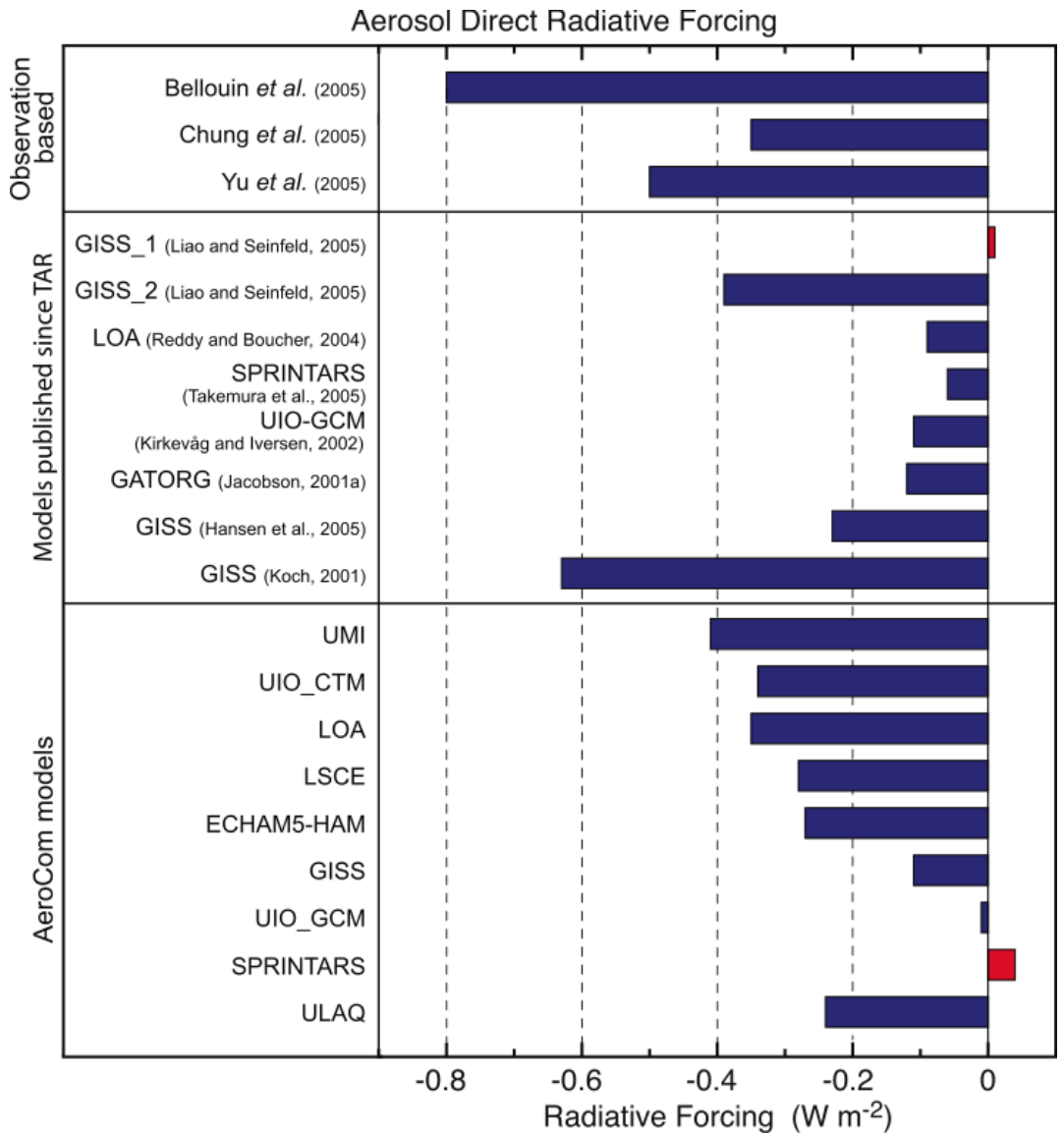
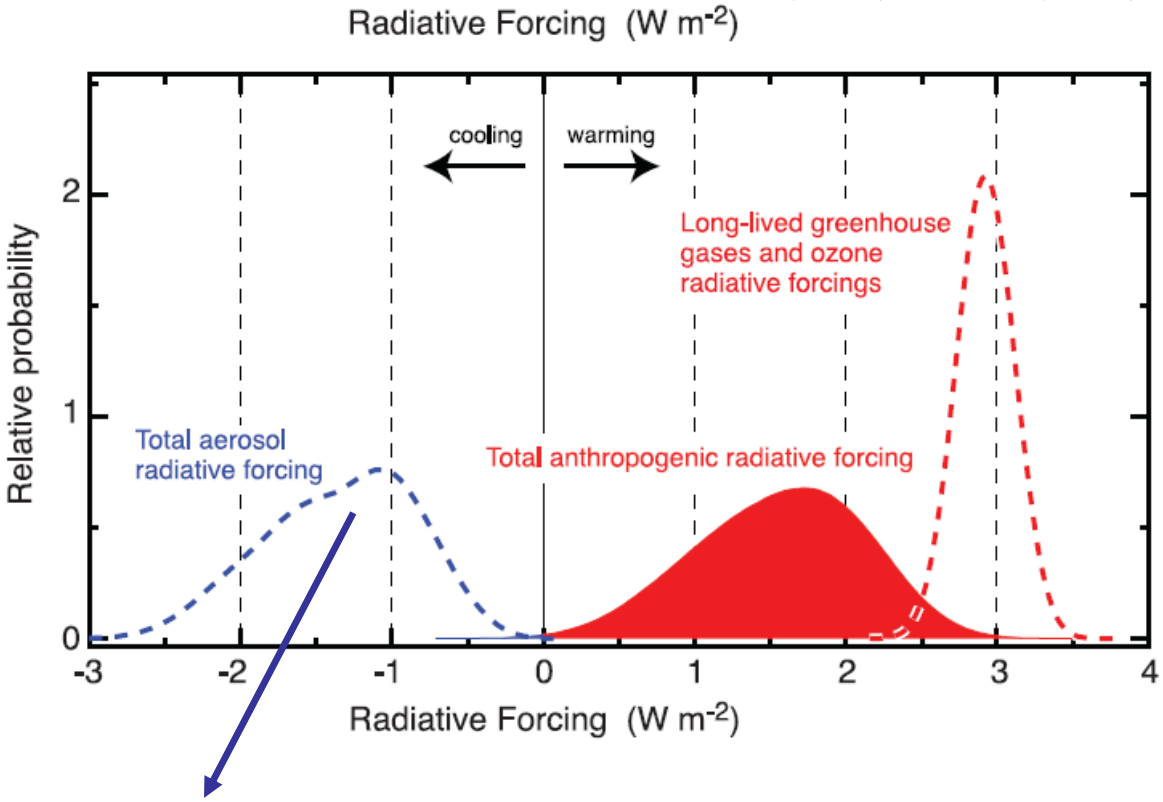


Figure 2.13



DIRECT + INDIRECT

"….although climate forcing by human-made greenhouse gases (GHGs) is known accurately, climate forcing caused by changing human-made aerosols is practically unmeasured."

Hansen et al., 2011

"Aerosol Faustian bargain"

Pierre Bouguer (1698-1758)

Johann Heinrich Lambert
(1728-1777)

August Beer
(1825-1863)

Optical depth

$$k = k_a + k_s$$

$$\tau = \tau_a + \tau_s$$

$$dL_\lambda = -(k_a + k_s)L_\lambda \frac{dz}{cos\theta} = -k\, L_\lambda \frac{dz}{cos\theta}$$

THANKS!

IR0000032 – ITINERIS, Italian Integrated Environmental Research Infrastructures System
(D.D. n. 130/2022 - CUP B53C22002150006) Funded by EU - Next Generation EU PNRR-Mission 4 “Education and Research” - Component 2: “From research to business” - Investment 3.1: “Fund for the realisation of an integrated system of research and innovation infrastructures”

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Ministero dell'Università e della Ricerca
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