Climate 2:

Terrestrial Climate changes

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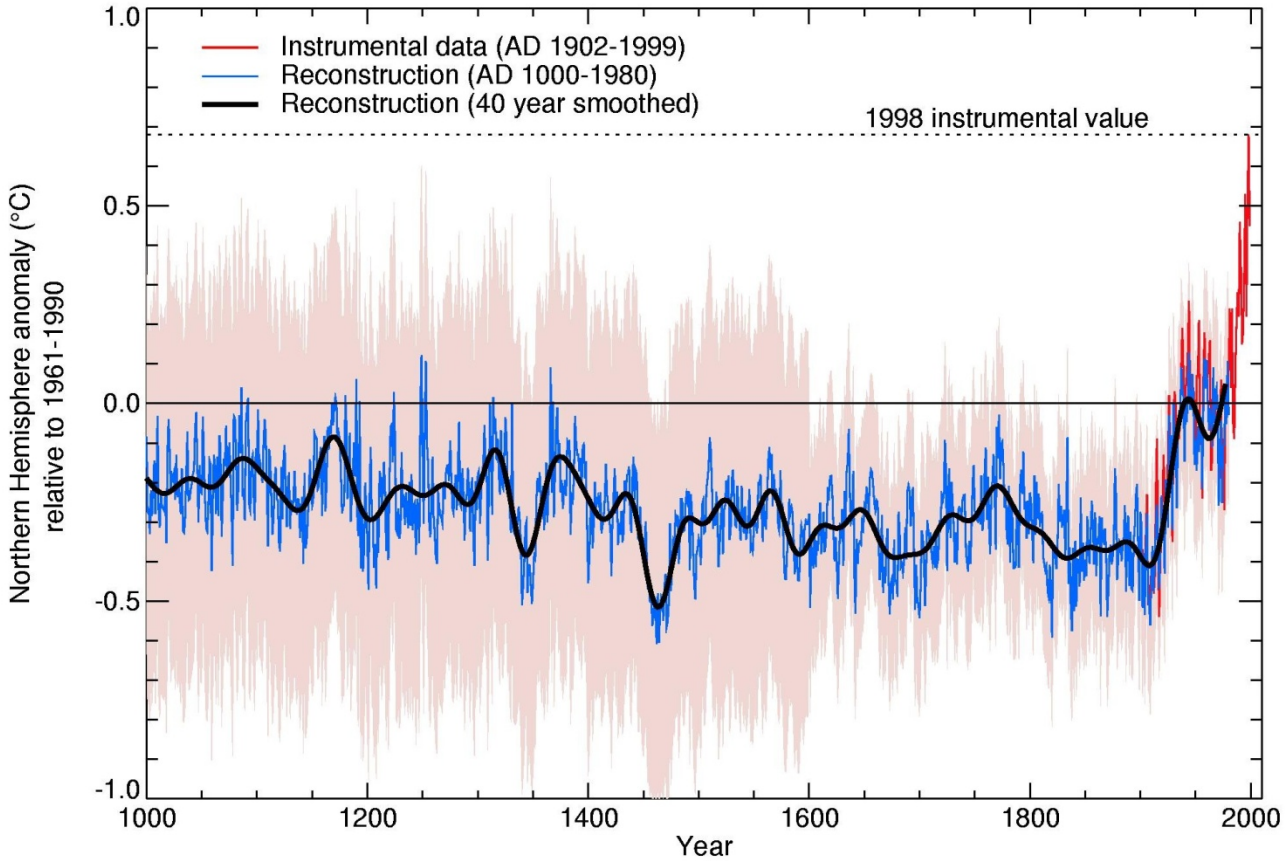
MEAN GLOBAL TEMPERATURE

Analysing **proxy data** showed that the increase in temperature in the **twentieth century** was **the greatest in the last 1,000 years**



MEAN GLOBAL TEMPERATURE

Between 1950 and 1993 **minimum temperatures have grown by a mean** of 0.2°C per decade, roughly **double** the mean growth of the **maximum temperature**. This has led to **decrease** (albeit not present everywhere) **in the daily temperature range.**

PRECIPITATION

- Annual precipitation has **increased**, in the northern hemisphere, at the **middle and high latitudes** (from 0.5 to 1% per decade).

- In the **sub-tropical region** (between 10° N and 30° N), precipitations have, instead, **fallen** on average (circa by 0.3% per decade).

- In the **tropical zone** (between 10° N and 10° S) total rainfalls seem to have **increased** by 0.2-0.3% per decade over the twentieth century, although this increase is not evident in recent decades.

- In the southern hemisphere no comparable systematic changes when adding up precipitations are observed.

- In the regions where total rainfall increased, an even more **significant increase in intense and extreme events** was observed. This pattern was often found also where rain has a negative of absent trend.

SNOW COVERAGE AND EXTENT OF PERENNIAL ICE

- The **reduction in snow cover** and extent of perennial ice is **positively correlated to the increase in mean temperature** of the Earth's surface

- By satellite observation a **reduction of 10% in snow cover** has been estimated since the 60's.

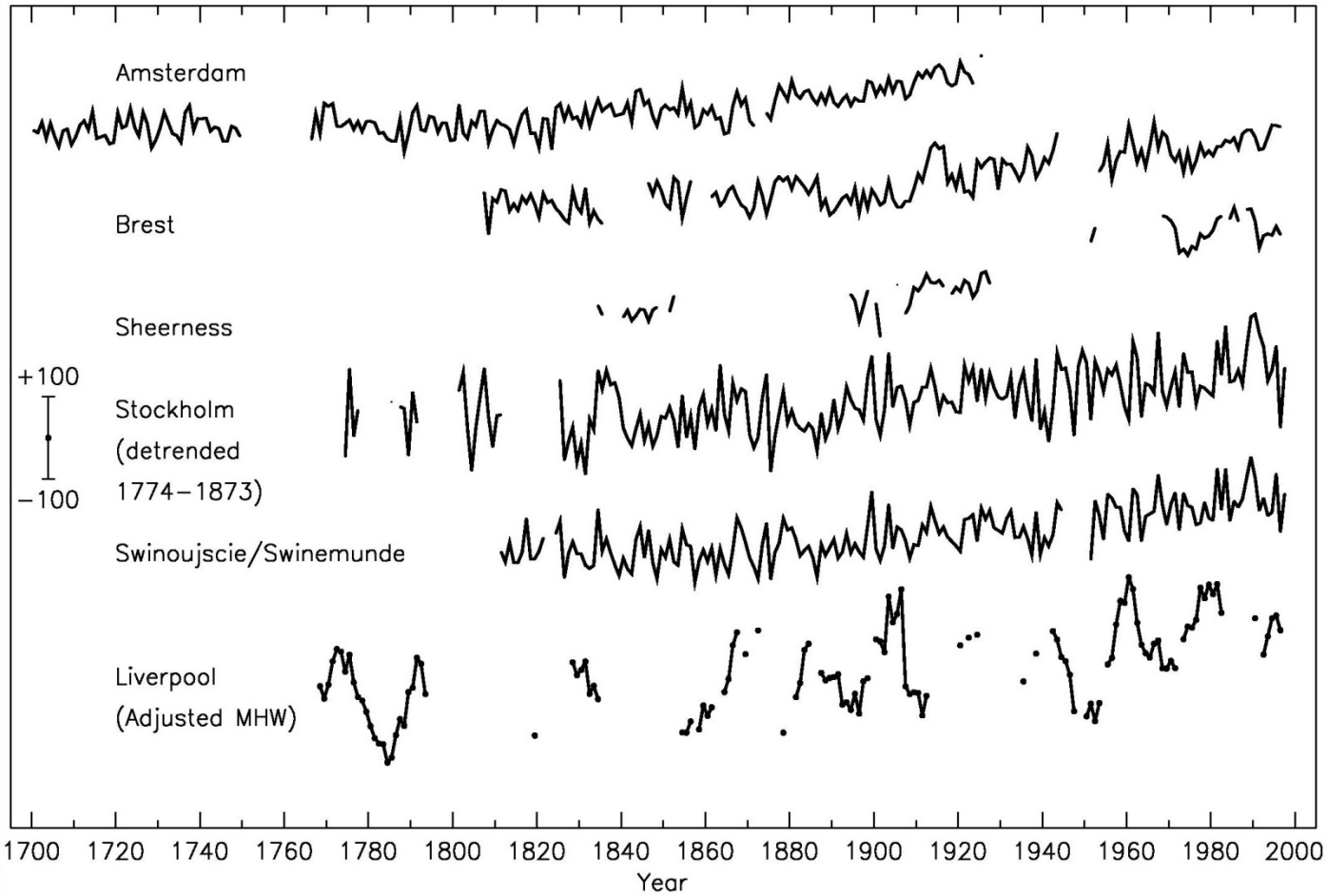
- **Marine ice of the northern hemisphere has diminished**: The extent of Arctic ice in spring and summer has diminished by 10-15% since the 50's.

- **No significant trend in the extent of Antarctic ice has been observed**: after an initial reduction in the mid-seventies, the extent of Antarctic ice has remained stable or slightly increased.

- New data seem to suggest that there has been a **reduction in the thickness of Arctic ice** (by 40% between late summer and early autumn and by a small amount in winter) between 1958-1976 and the mid-nineties. However, measurements are few and incomplete.

SEA LEVEL

The **growth rate of the sea level** in the twentieth century has been estimated, based on tide measurement data, at between **1.0 and 2.0 mm/year**. This growth is greater than that observed in the previous century.



GREENHOUSE GAS CONCENTRATION

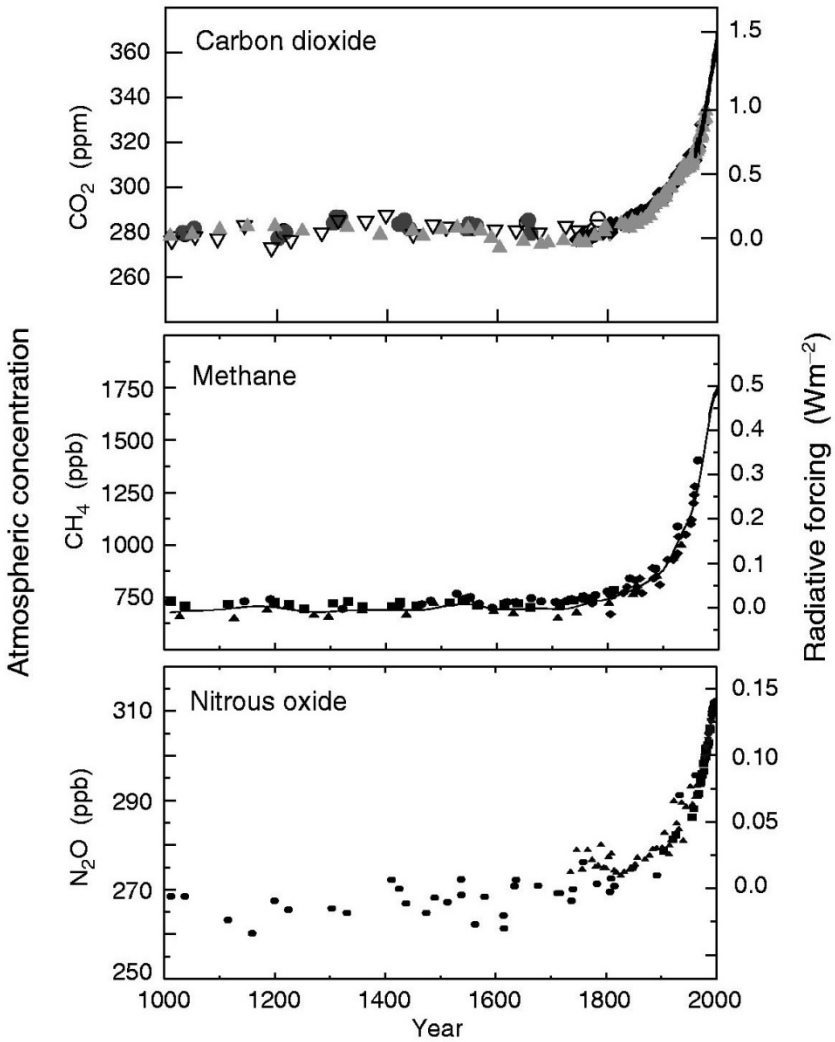
- **Carbon dioxide (CO_2)** has **increased** by **31%** since 1750.

- The **growth rate of CO_2** in the last two decades is **1.5 ppm (0.4%) per year**

- **Methane (CH_4)** has **increased by 1060 ppb (151%) since 1750**; this increase has slowed down in the 90's compared to the 80's.

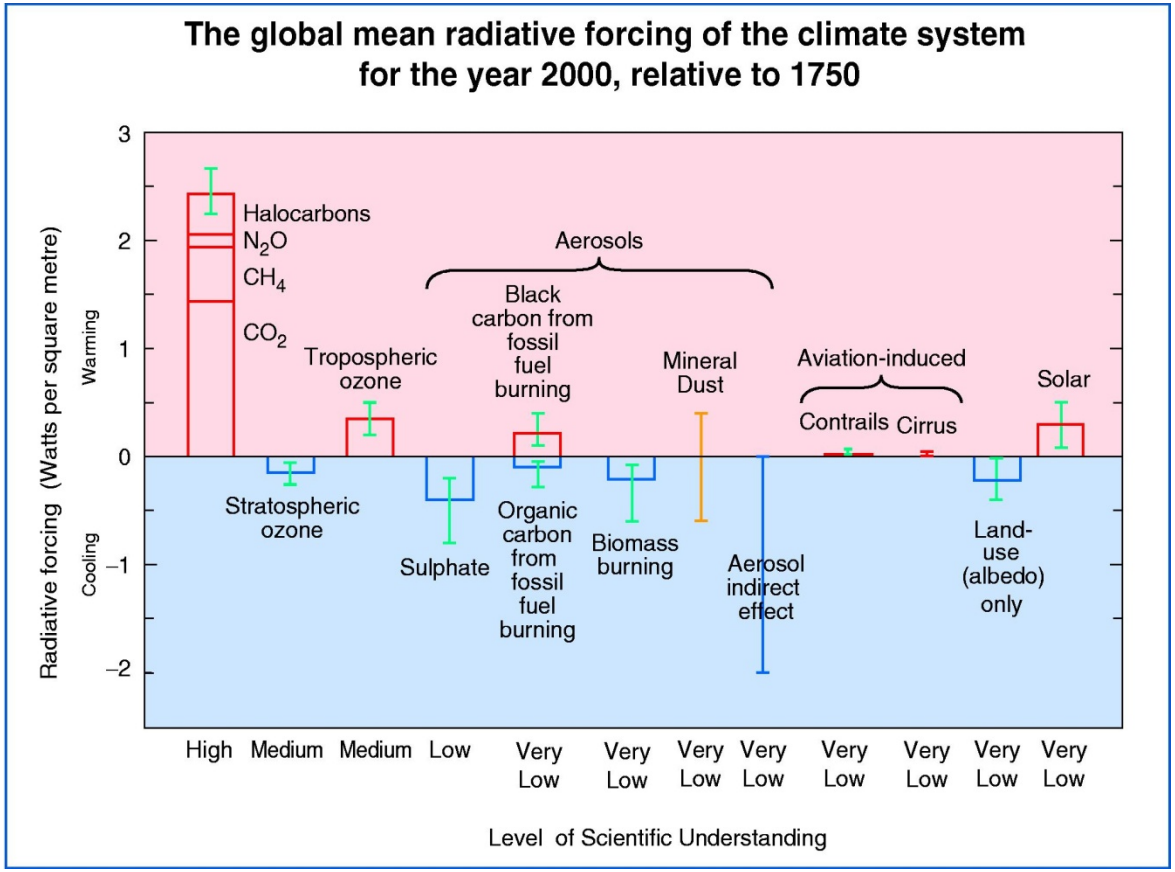
- **Nitrous oxide (N_2O)** has **increased by 46 ppb (17%) since 1750** (1/3 is of anthropogenetic origin).

- **Tropospheric O_3 troposferico** has **increased by 36% since 1750**



RADIATIVE FORCING

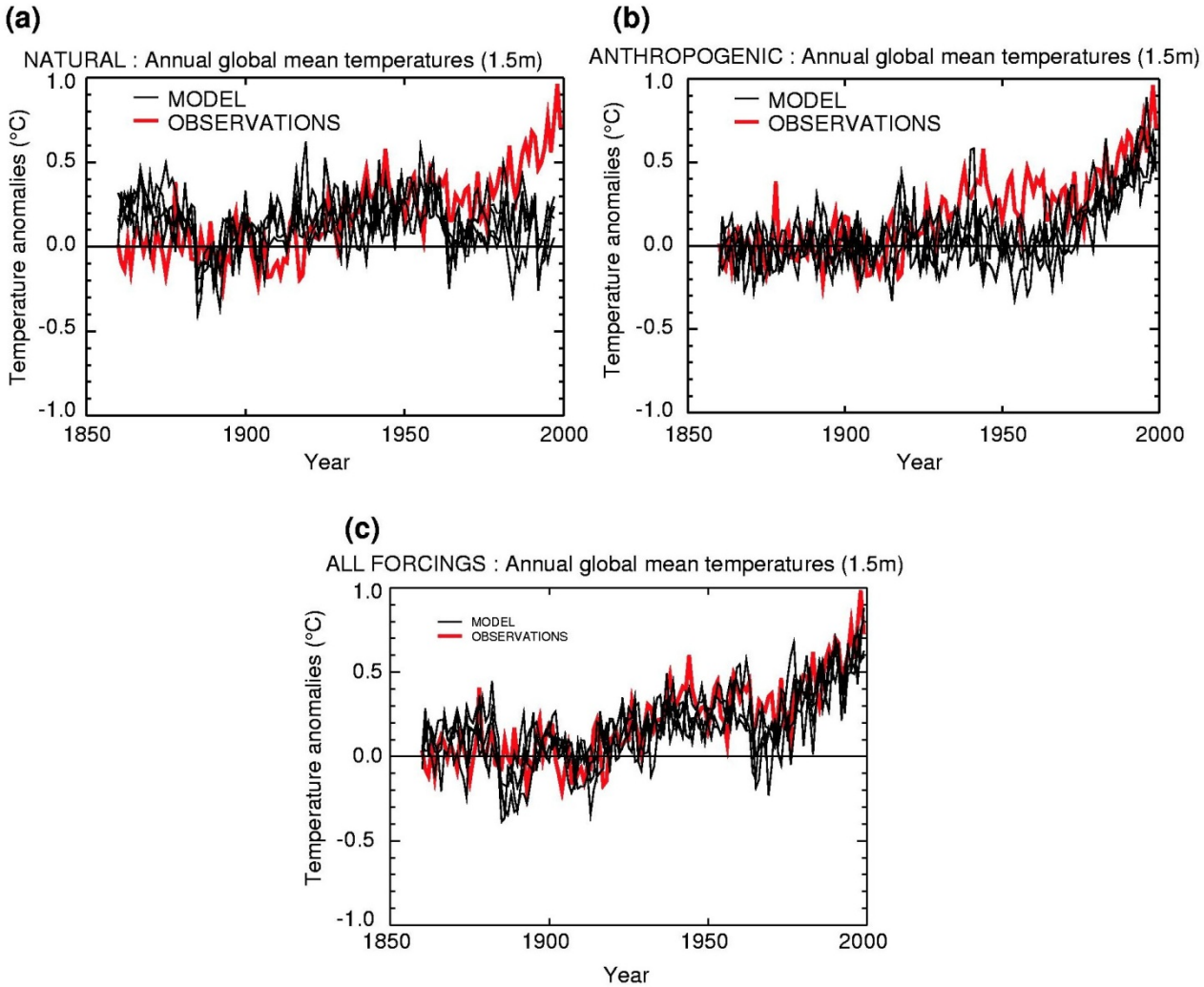
- Radiative forcing due to **greenhouse gas increase** from 1750 to 2000 has been estimated to be **2.43 Wm^{-2}** (1.46 Wm^{-2} from CO_2; 0.48 Wm^{-2} from CH4; 0.34 Wm^{-2} from halocarbon; 0.15 Wm^{-2} from N_2O)
- Radiative forcing due to the **reduction in the O_3** layer from 1979 to 2000 has been estimated to be **– 0.15 Wm^{-2}**
- The **increase in tropospheric O_3** since 1750 has caused a radiative forcing of **0.35 Wm^{-2}**



- With regards to **aerosols** and natural forcing, their contribution to radiative forcing is rather low; **a great uncertainty remains due to the lack of knowledge about the phenomenon**.

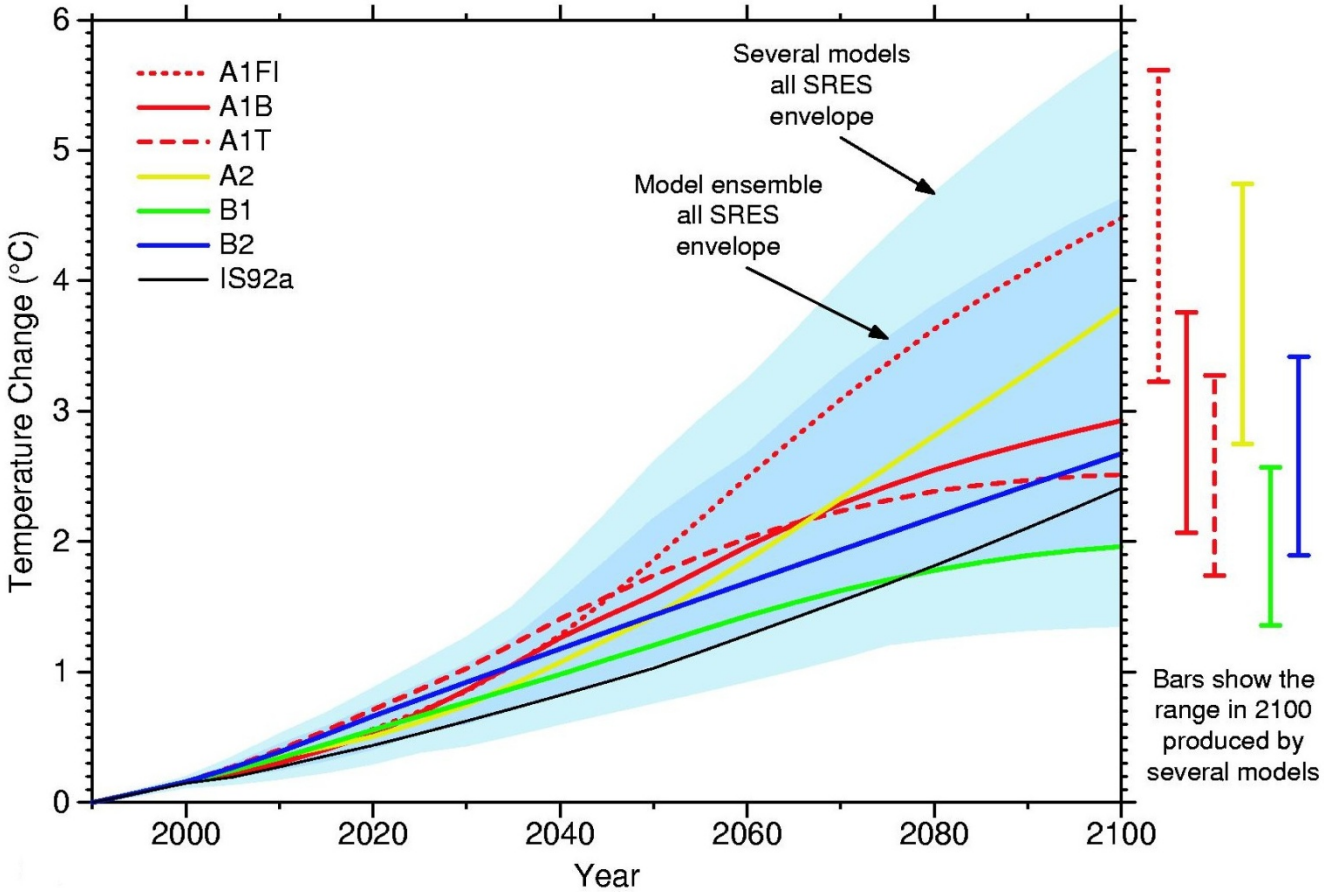
ANTHROPIC CONTRIBUTION TO GLOBAL WARMING?

There is strong evidence, based on model simulations, about the fact that **most global warming observed for the last 50 years is due to human activity.**



FORECAST FOR THE XXI CENTURY

For **global temperature** an **increase** is forecast that may vary from **1.4 to 5.8°C between 1990-2100**



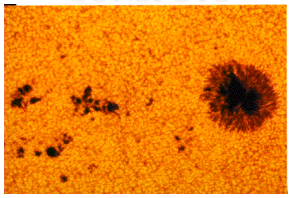
SOLAR IRRADIATION CHANGE

CAUSES

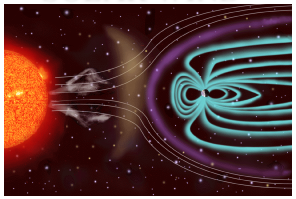
ASTROPHYSICAL PROCESSES

SOLAR ACTIVITY

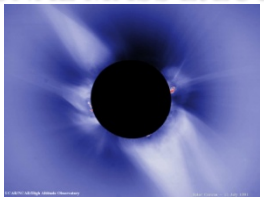
SUNSPOTS



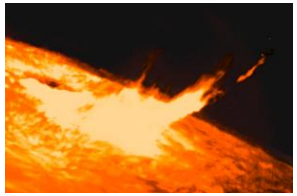
SOLAR WIND



CORONAL MASS EJECTIONS



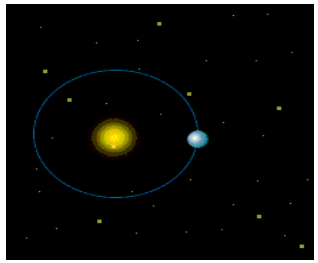
FLARES



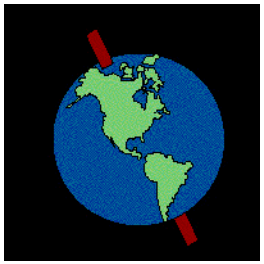
ASTRONOMICAL PROCESSES

MILANKOVITCH THEORY

VARIATIONS IN THE EARTH'S ORBIT



VARIATIONS IN THE EARTH'S AXIS

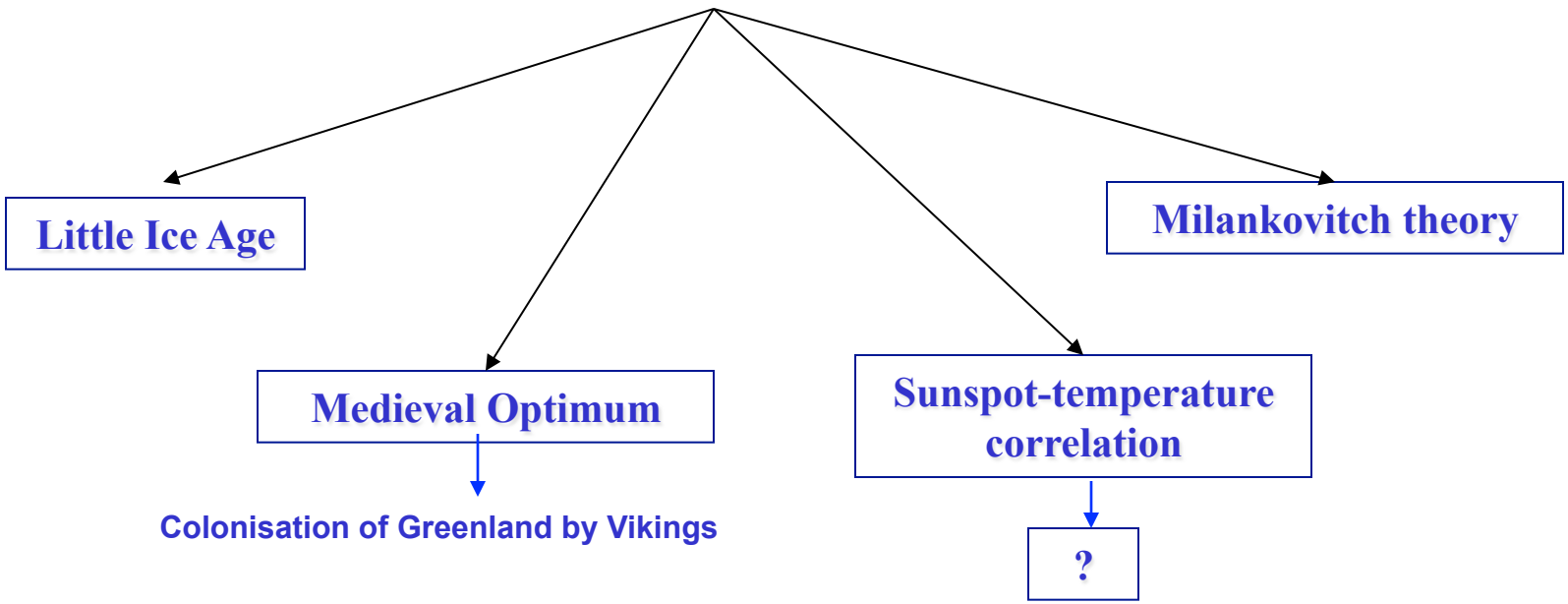


ASTROPHYSICAL PROCESSES

IN FAVOUR OF SOLAR ACTIVITY CAUSES

The sun is the source of energy that warms the Earth, therefore it is reasonable to expect a close relationship between the variation in the flow of that energy and our planet's climate**.**

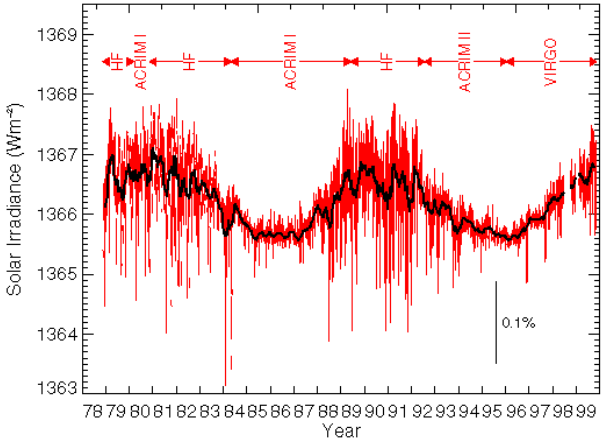
There is **experimental evidence** that relates particular climatic events of the past with different rates of energy received.



SOLAR ACTIVITY RECONSTRUCTION

DIRECT MEASURES

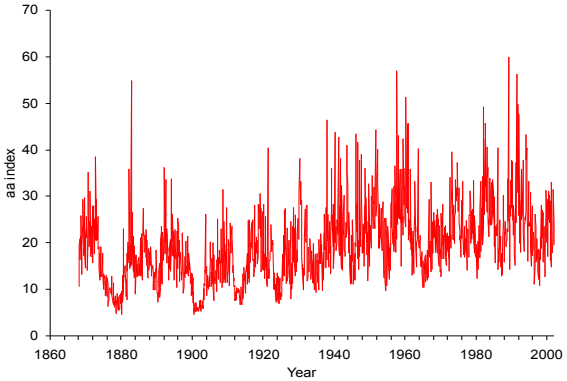
satellite measures



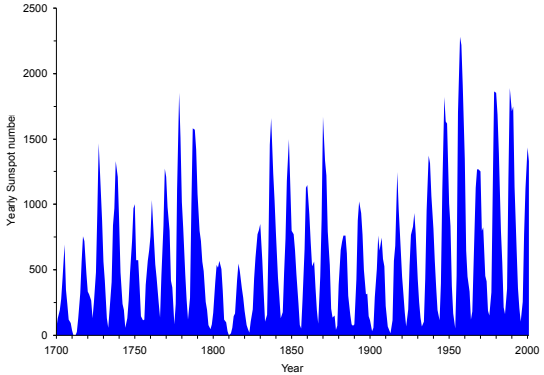
PROXY DATA

Number of Auroras

Geomagnetic indexes



Number of sunspots



REVIEW OF RESULTS

From the mid 1600's to the early 1900's all studies led to the same conclusion: **temperature was inversely correlated to the number of sunspots.**

- 1645 Antonii Mariae de Rheit
- 1651 Riccioli
- 1671 Kircher
- 1676 Robert Hook
- 1729 J. B. Weidenburg di Helmstadt
- 1801 Sir William Herschel
- 1823 Flaugergues
- 1826 Gruithuisen
- 1860 Robert Greg
- 1870 C. Piazzi Smyth
- 1871 E. J. Stone
- 1873-1914 Wladimir Koppen

Discovery of the **11-year solar periodicity on the temperature** → DISPUTE

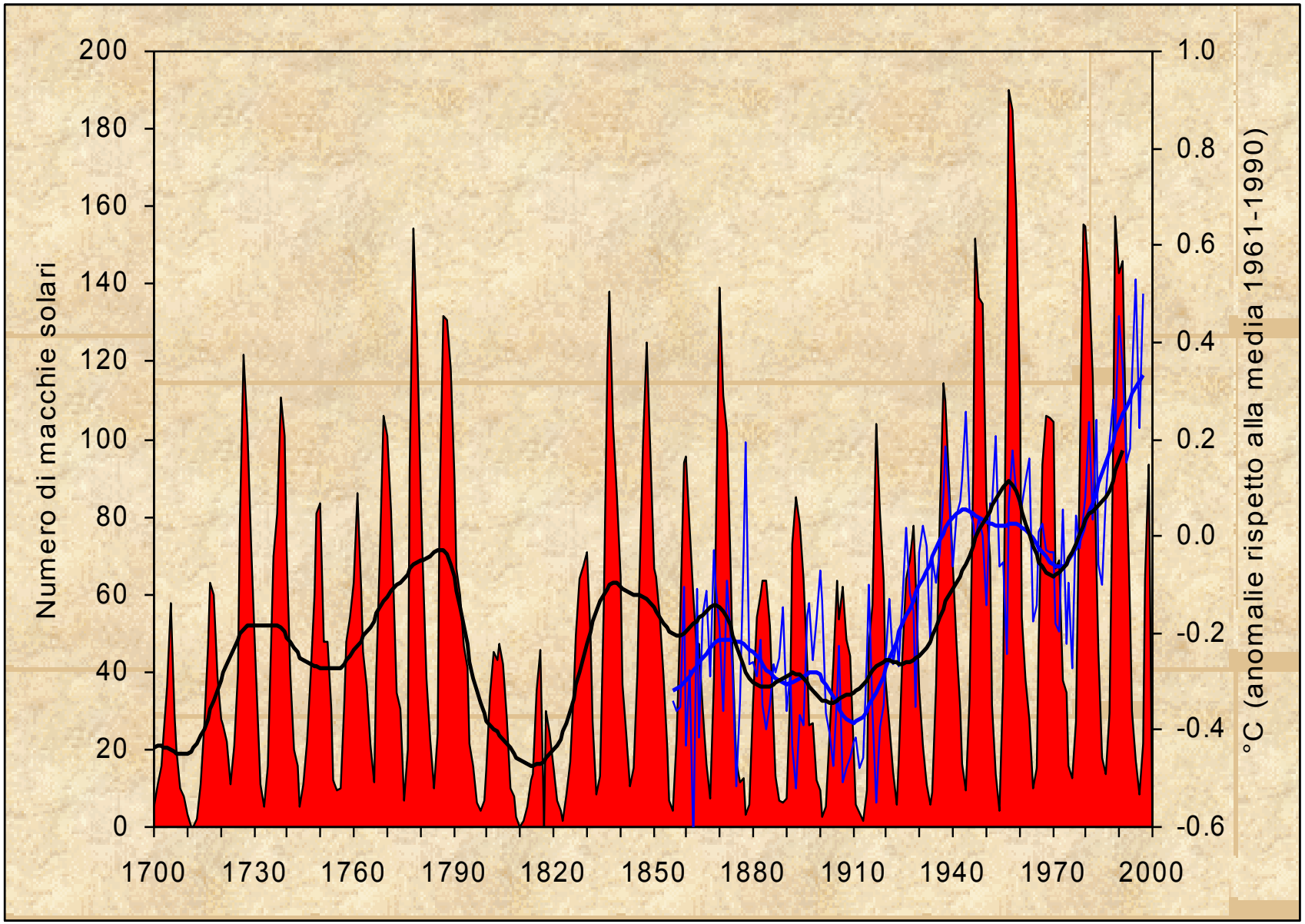
Early decades of the 1900's

Inversion of the **sign of correlation** between temperature and sunspots → Spectral analysis gives different results depending on the time interval considered leading different researchers to **contradictory results**.

Late decades

Besides the Schwabe cycle, the sun presents **variations** also on **longer time scales** that seem parallel to some climate changes → **Gleisberg cycle** 80-90 years.

GLOBAL TEMPERATURE – SUNSPOTS

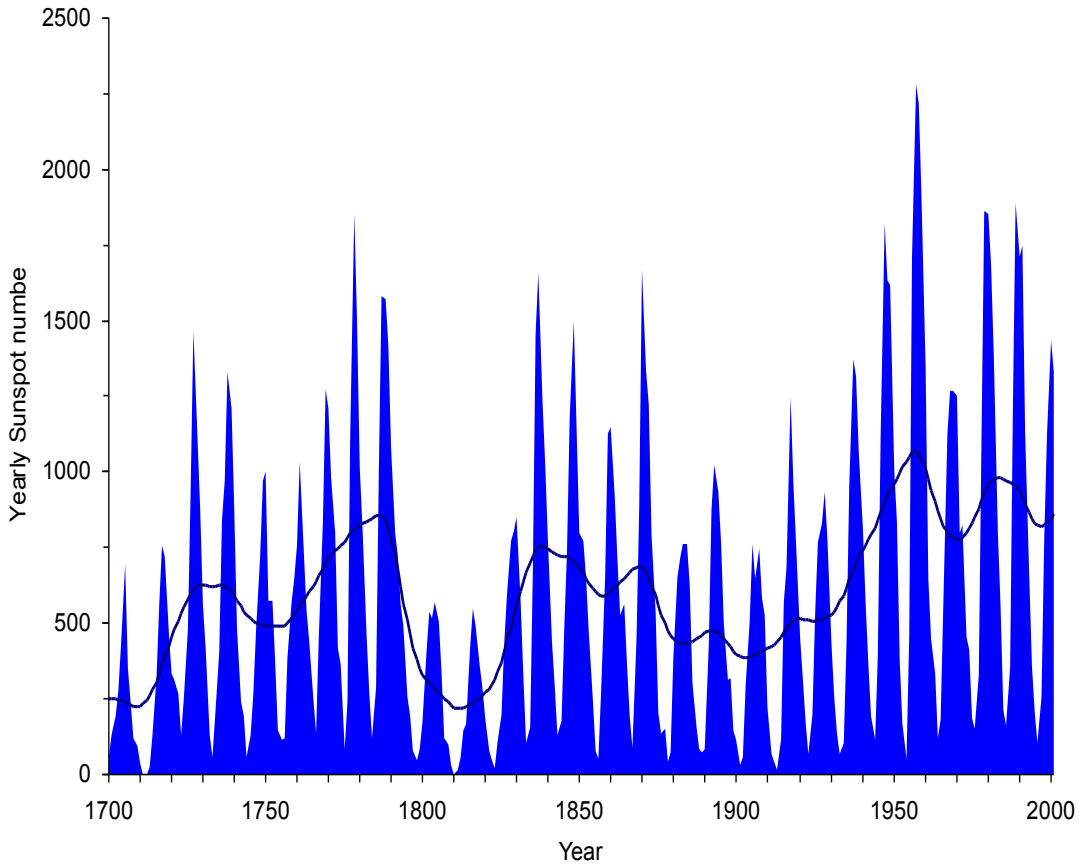


GLEISBERG CYCLE

In the early decades of the 1900's **W. Gleisberg** noticed the presence of a **80-90-year periodicity** and published so many papers about it that since then this cycle has been known as the Gleisberg cycle.

EDDY

ENVELOPE OF SUNSPOTS



By extending the series of sunspots (from 1700 till present) only three Gleisberg cycles can be observed and there are too few to lead to any conclusions.

Recent techniques have enabled the abundance of some **cosmogenetic isotopes** (**^{10}Be** e **^{14}C**) to be used to reconstruct solar activity on much longer scales.

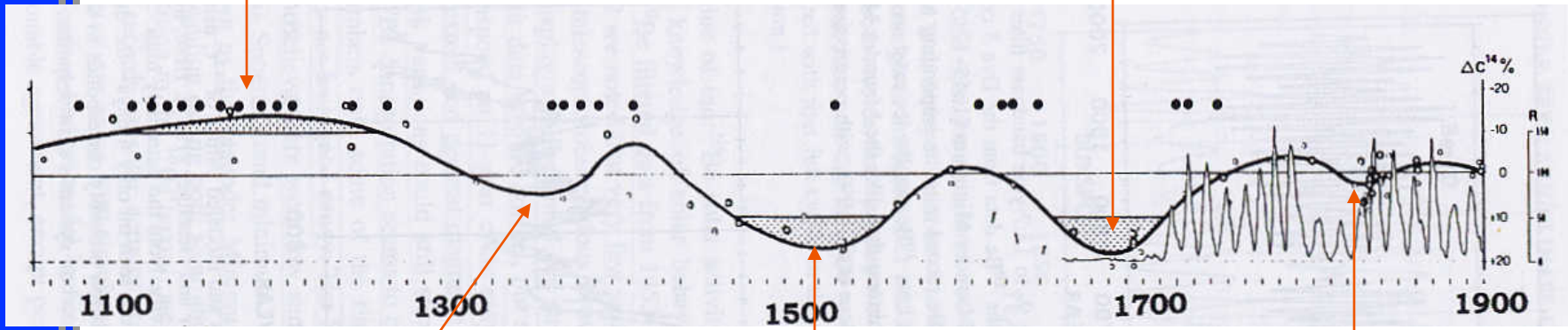
^{14}C

MEDIEVAL MAXIMUM

(1200 circa)

MAUNDER MINIMUM

(1645-1715)



(Eddy, 1976; Eddy and Boornazian, 1979)

DALTON MINIMUM

(1795-1825)

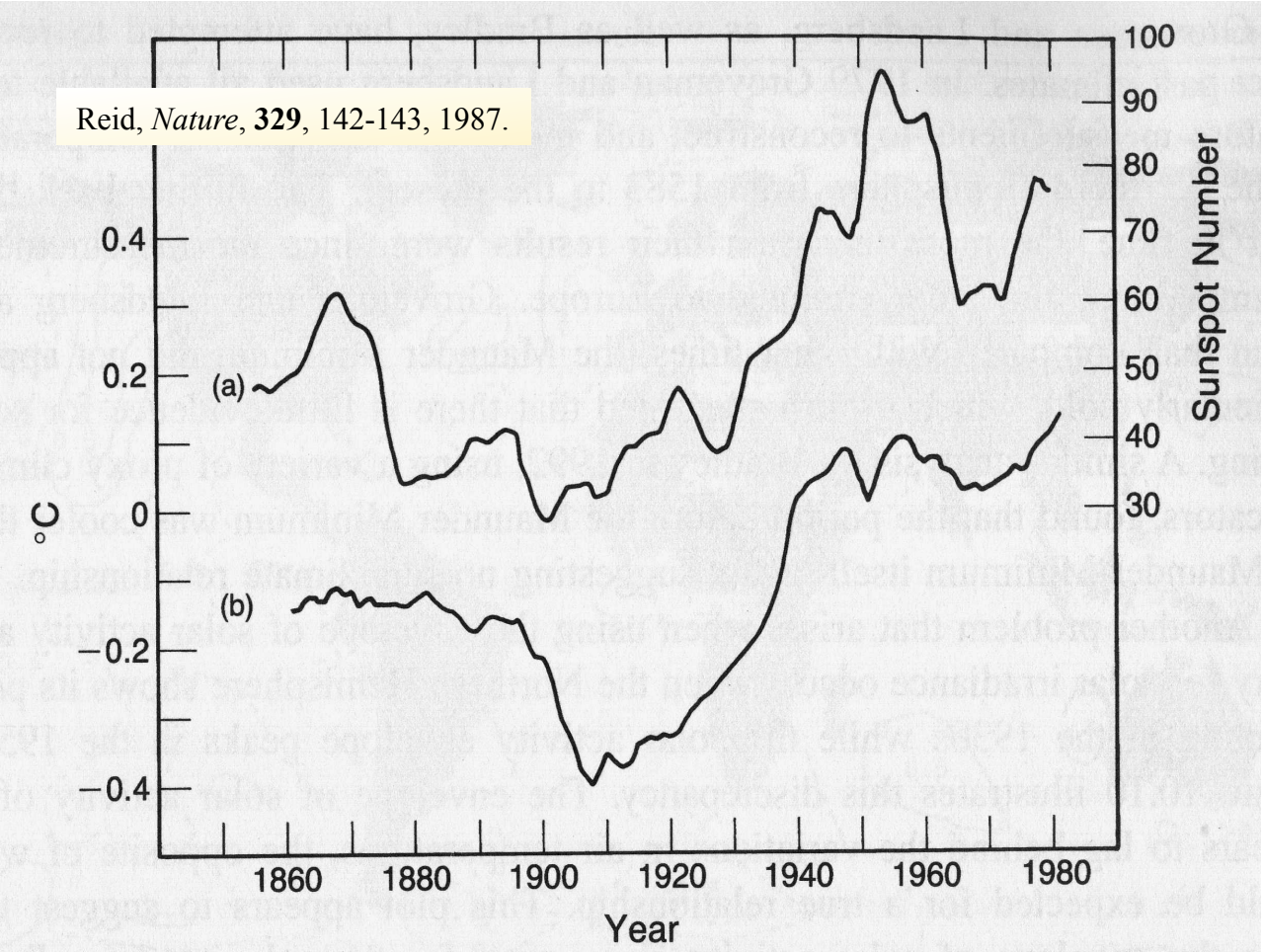
SPOERER MINIMUM

(1500 circa)

NON-SPECIFIED MINIMUM

(1350 circa)

SEA SURFACE TEMPERATURE



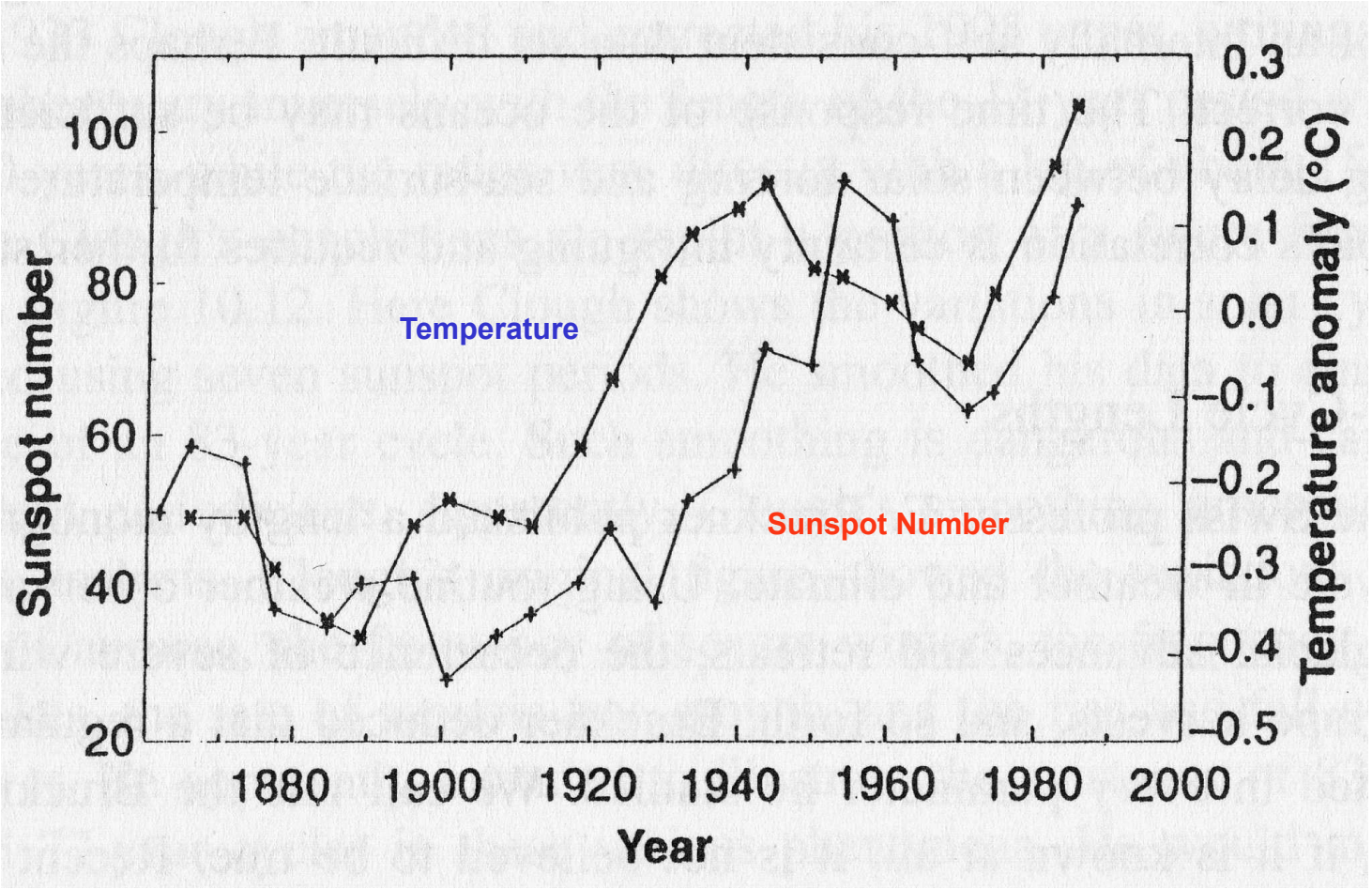
CRITICISM

SST measures are **sporadic** and mainly based on ship observations.

Measuring techniques have **changed** a great deal over time which makes the construction of self-consistent series very difficult.

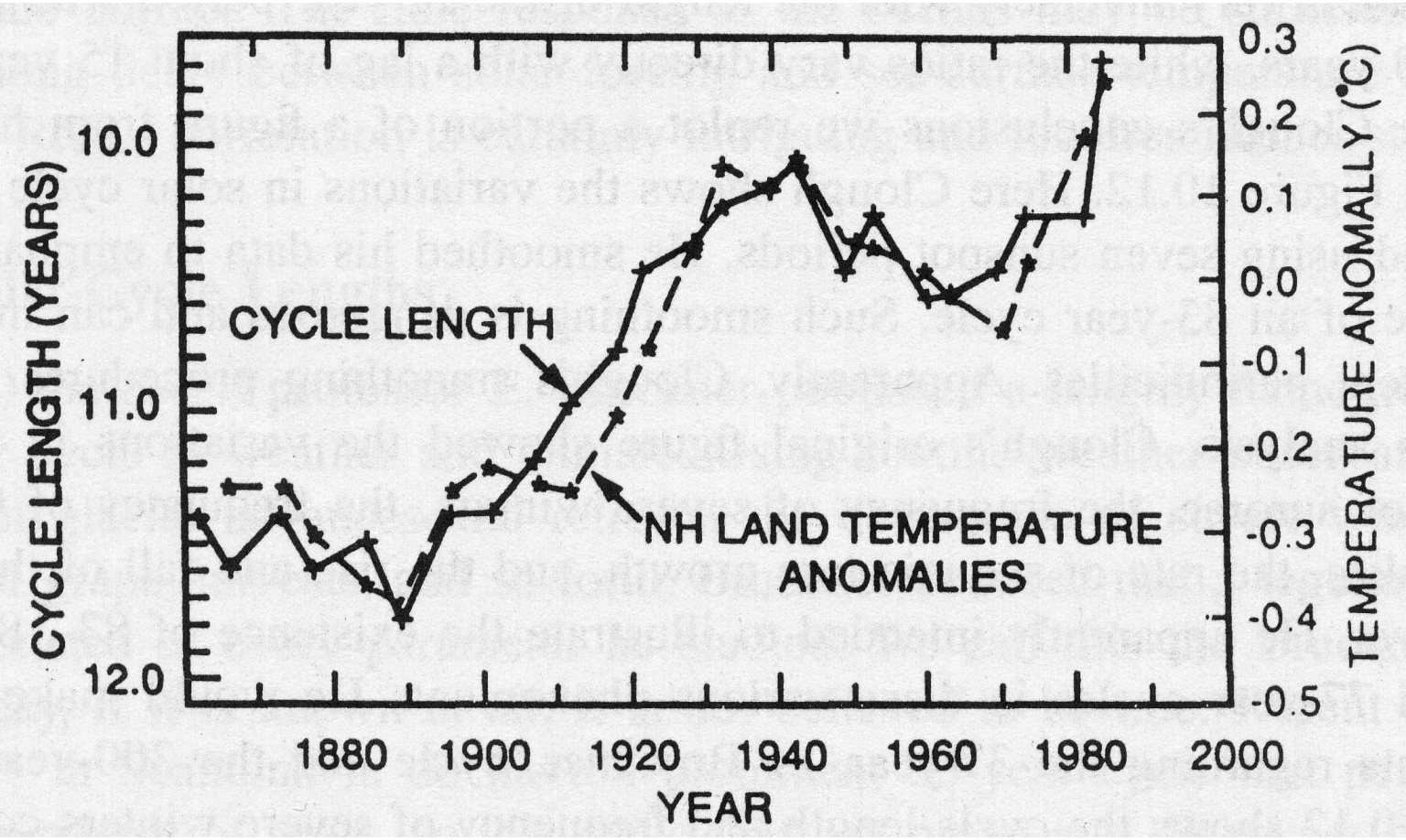
The response of the oceans to solar forcing is so slow that it produces a delayed signal

NORTHERN HEMISPHERE AIR TEMPERATURE



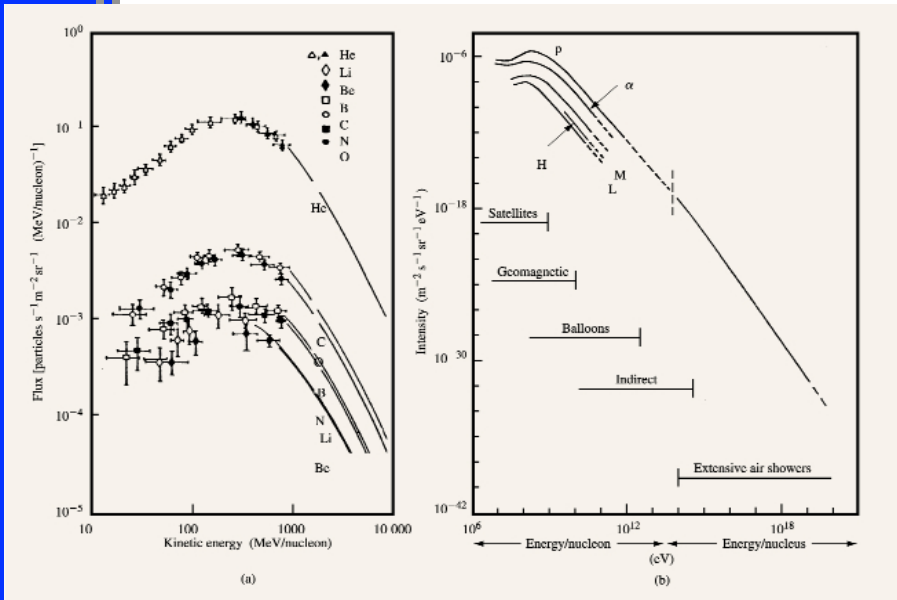
By using the envelope of the sunspot number as a proxy, a **delay in solar activity** can be seen **with respect to the temperature**, **the contrary would be expected** if a relationship existed.

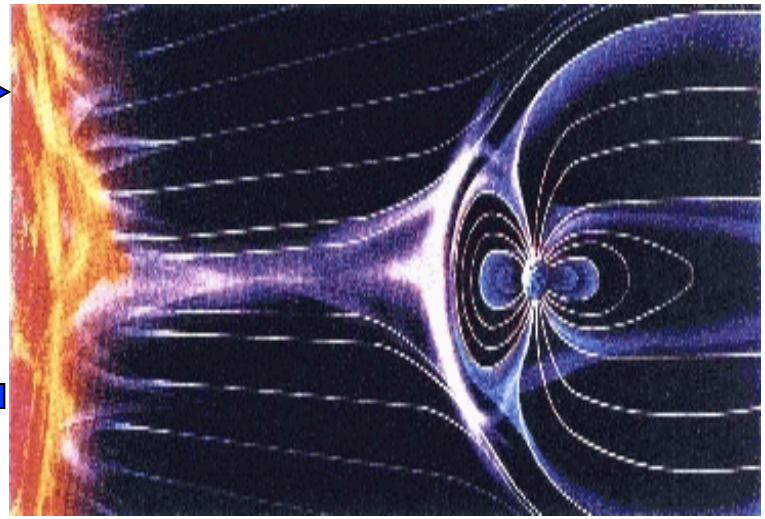
SOLAR CYCLE LENGTH

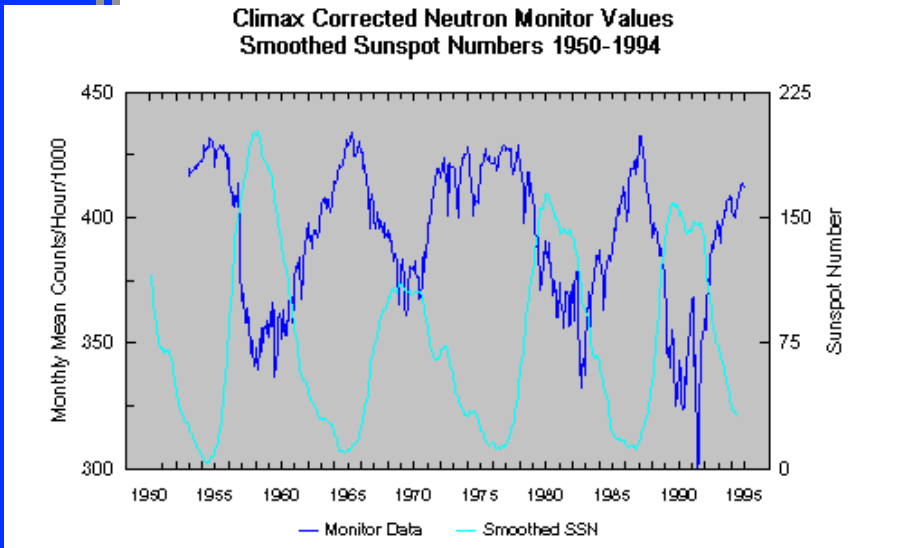


The variation in **sun cycle length** is a good **proxy for solar irradiation**. There is an inverse **correlation with northern hemisphere temperature**. However, this **cannot be indisputable proof** given the low number of data that the series is reduced to.

COSMIC RAYS – THE MISSING LINK?





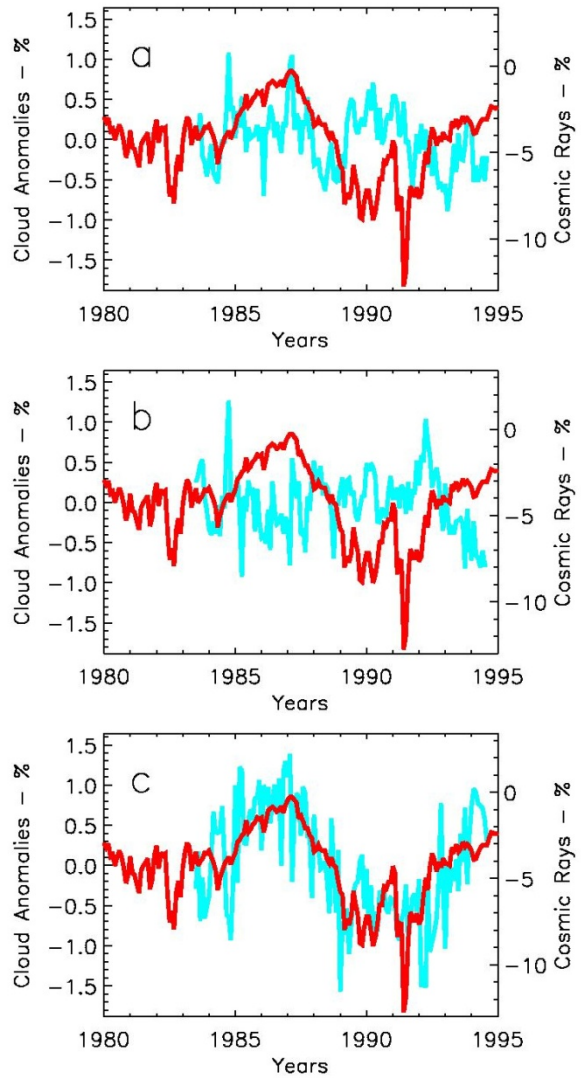


CLOUDINESS AND COSMIC RAYS

High clouds (<440 hPa)

Intermediate clouds (440-680 hPa)

Low clouds (>680 hPa)



Marsh and Svensmark, *Phys. Rev. Lett.*, **88**, 5004-5007, 2000

An increase in high cloud cover prompts global **warming**.

Direct correlation

High clouds - temperature

Inverse correlation

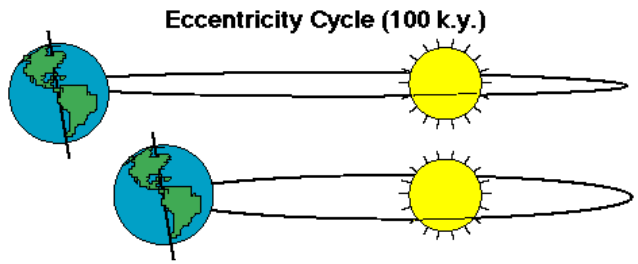
Low clouds - temperature

An increase in low cloud cover prompts global **cooling**.

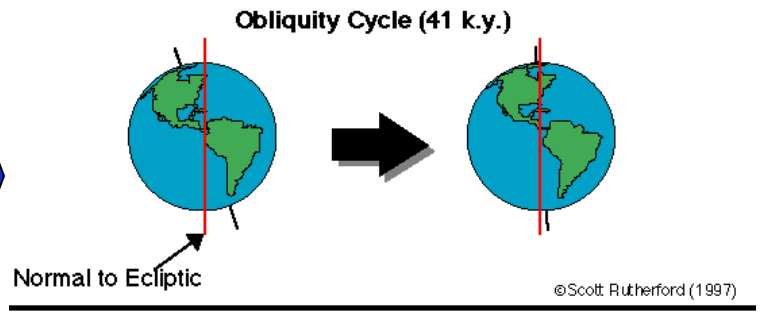
ASTRONOMIC PROCESSES

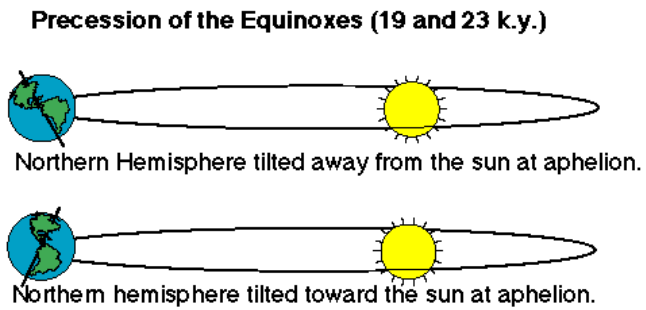
MILANKOVITCH THEORY

The mutual gravitational pull between the Earth and other planets causes changes in the eccentricity of its orbit: it ranges from a maximum of 0.0655 to a minimum of 0.0018 in **100,000 years** (currently being 0.017).



The **tilt of the Earth's axis** with respect to ecliptic is not constant: it ranges between a maximum of 24° 20' and a minimum of 21° 55' with a period of about **41,000 years** (currently tilted at 23° 27' with respect to the orbit plane).

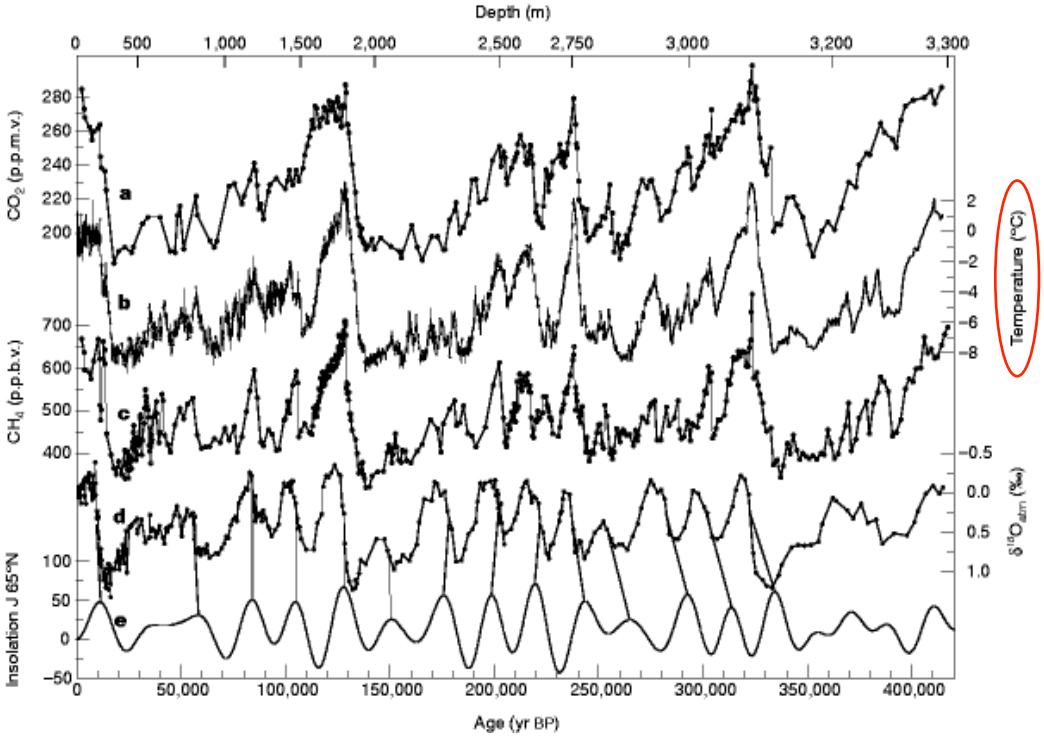




The **Earth's axis** describes a cone with its tip in the center of the Earth over a period of about **26,000 years** and in an opposite direction to that of the planet's rotation (*lunisolar precession*).

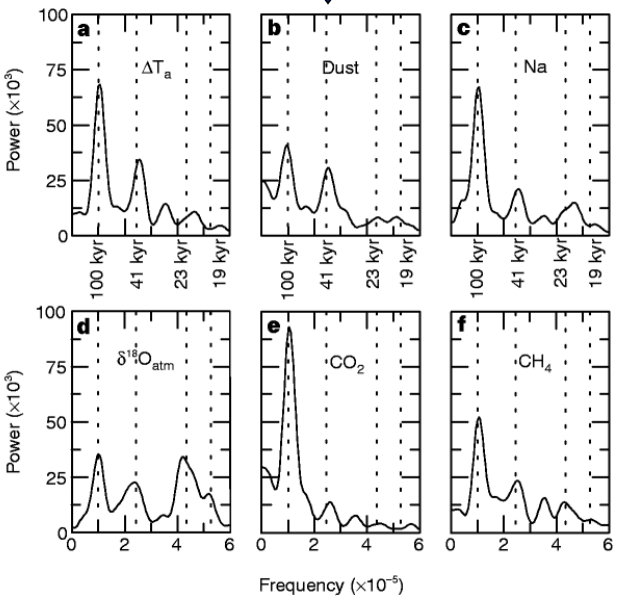
The change in the Earth's tilt implies an identical **change in the line of the equinoxes**: it moves in a clockwise direction as the lunisolar precession and over the same period (50" of arc per year). Another millennial motion contributes to complicating matters: that of the greater axis of the Earth's orbit (**line of apsides**) which is in the same direction as that of the line of the equinoxes (11" of arc per year) thus reducing the period. In conclusion there is a precession of the equinoxes (61" of arc per year) with periodicity around **19,000 years** and **23,000 years**.

EXPERIMENTAL EVIDENCE OF THE MILANKOVITCH THEORY (VOSTOK ICE CORE)



Reconstruction of the last 420,000 years of climate

Spectral analysis



VARIATIONS IN ATMOSPHERIC COMPOSITION

CAUSES

NATURAL

INTERACTIONS BETWEEN THE DIFFERENT CLIMATE SYSTEM COMPONENTS

- Atmosphere-ocean interactions → El Niño
- Atmosphere-biosphere interactions → Exchange of aqueous vapor and CO_2 between atmosphere and ocean; Exchange of aqueous vapor and CO_2 between biosphere and atmosphere

VOLCANIC ERUPTIONS

- Introduction of aerosols into the atmosphere → SO_2 CO_2

OCEAN AND ATMOSPHERE CIRCULATION

- Hydrologic cycle → Aqueous vapor precipitations and cloud cover

ANTHROPIC

INTRODUCTION OF GREENHOUSE GASES INTO THE ATMOSPHERE

- Fossil fuels → SO_2 CO_2 O_3
- Fires → CO_2 CH_4
- Breeding → CH_4

INTRODUCTION OF AEROSOLS INTO THE ATMOSPHERE

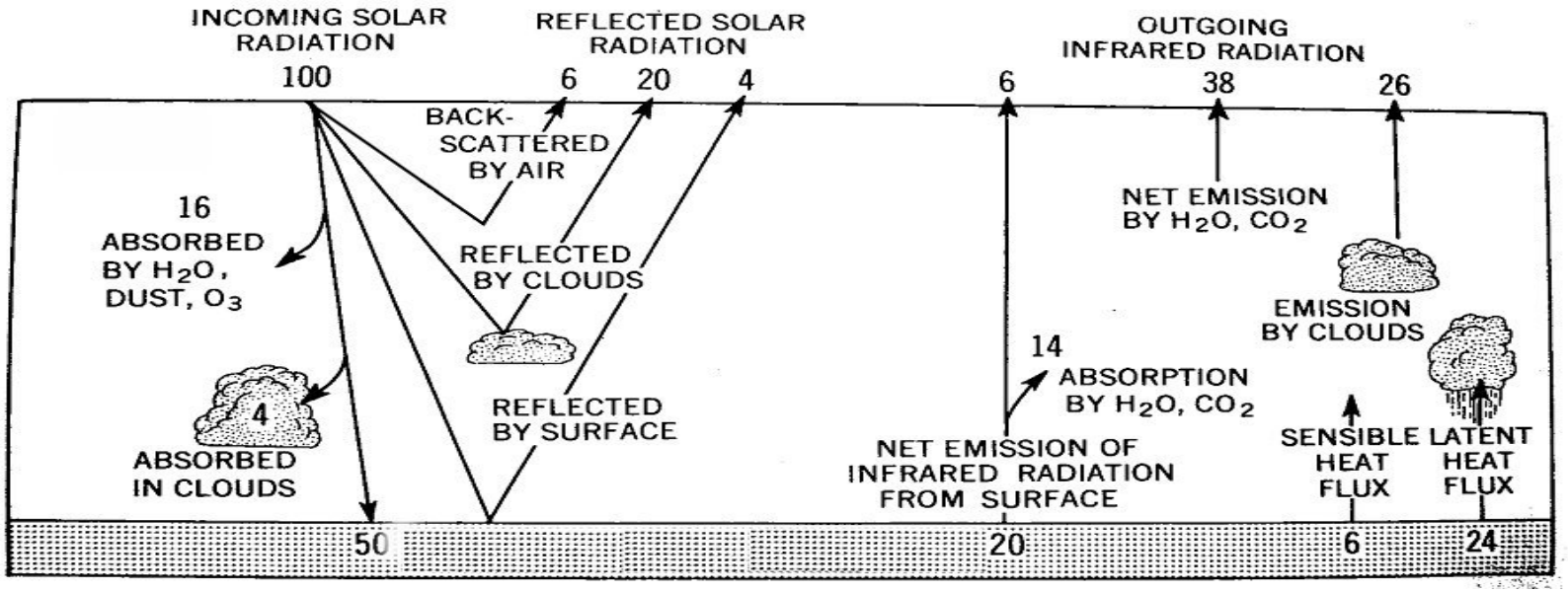
- Fossil fuels → Black Carbon, Organic Carbon
- Fires → Black Carbon

EXPLOITATION OF THE EARTH

- Reduction of the forests → Variations in the albedo

Clouds, aerosols and climate forcing

Radiation budget



•**T**he imbalance of the net radiation (solar + terrestrial) received and emitted by the Earth is the ultimate driving force of the terrestrial climate system.

•**T**he global energy budget of our planet changes in response to variations in both concentrations of the atmospheric radiatively-active constituents and surface reflectance characteristics.

•**C**hanges in atmospheric gaseous composition and particle content (including aerosols and clouds) are expected to produce radiative forcing processes leading to regional warming or cooling effects.

Cloud impact on climate

Radiation fluxes are driven by:

The environment below and above the cloud (T-wv profile, aerosol distribution, surface properties)

Macro-physical structure of the cloud the cloud type (optical thickness, T, vertical and horizontal disomogeneities)
Microphysical structure (particle size, shape, phase,)

In GCM cloud parameterization scheme are sometime incomplete and simplicistic

The change in the net CRF, associated with a forcing, is the quantity governing cloud feedback

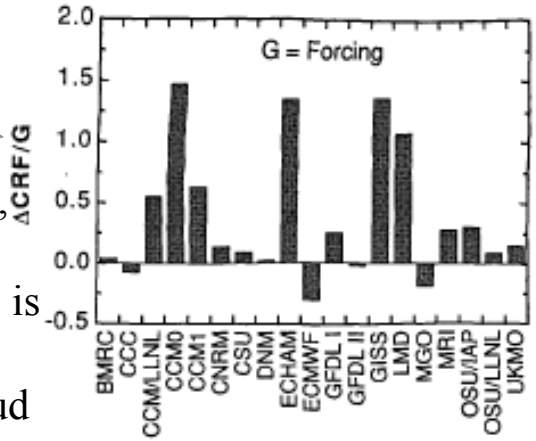


Fig. 3. The cloud feedback parameter CRF/G, as produced by 19 atmospheric GCMs (Cess et al. 1990).

Feedback by clouds is still not well understood!!

Comparison of ΔCRF with measurements show worse results for SW component

Cloud impact on climate

Radiation fluxes ar

The environment below an

aerosol distributi

Macro-physical structur

(optical thickness, T, vertical

Microphysical structure

Ir

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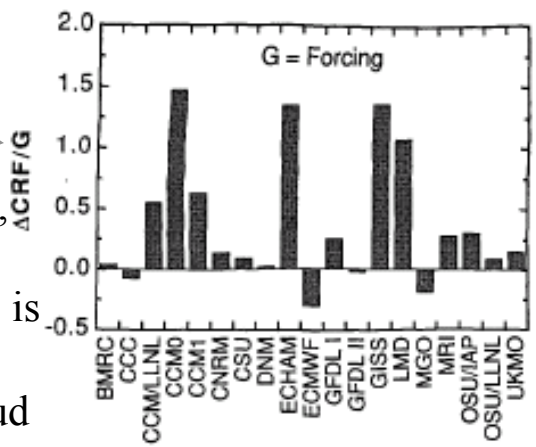

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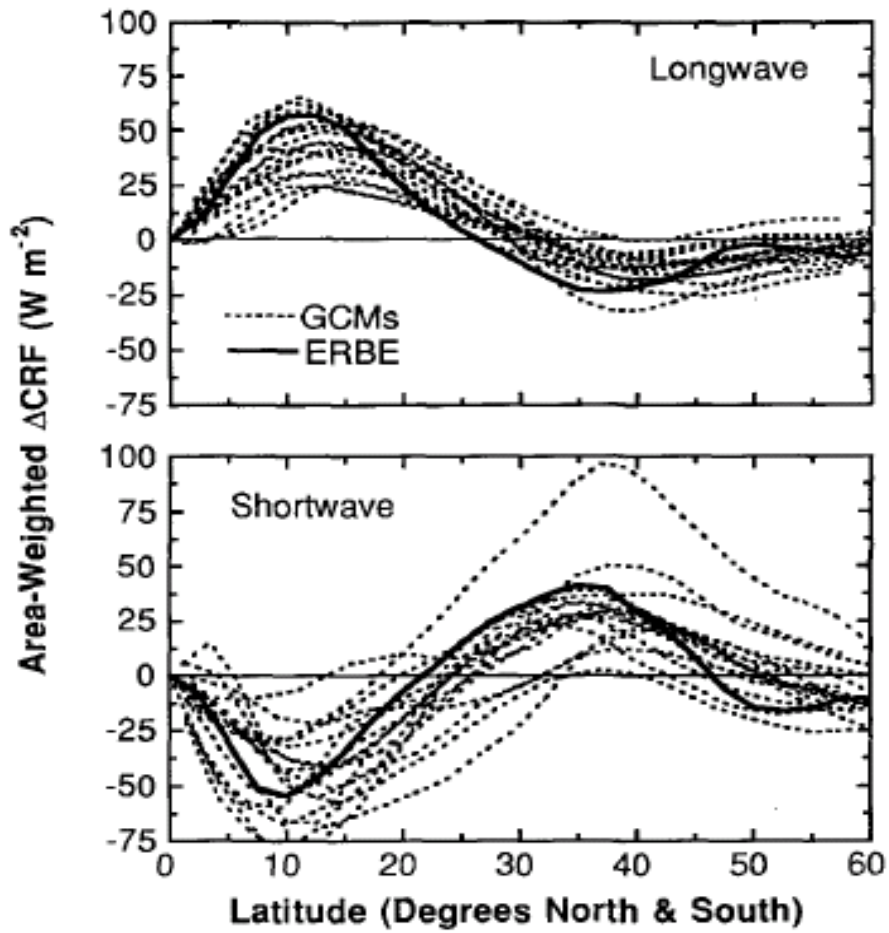


Fig. 4. Comparison of zonal-mean DCRF for 17 GCMs to the ERBE data. These represent 4-yr means.

show worse results for SW component

Cloud forcing

F=outgoing IR flux

Q=solar flux absorbed

$$C_{LW} = F_0 - F$$

clear sky

$$C_{SW} = Q - Q_0,$$

$$C = C_{SW} + C_{LW}.$$

TABLE 1. Estimates of the mean annual, global (except where indicated otherwise) effect of clouds on the net downward flux of total radiation energy at the top of the atmosphere (C), longwave (C_{LW}), and shortwave (C_{SW}) components in W/m². These estimates of cloud forcing are based on climatology with simple models (CLIM), satellite-based observations (SAT), and general circulation models (MOD).

Basis	Investigation	Source	C_{LW}	C_{SW}	$\lvert C_{SW}/C_{LW}\rvert$	C
CLIM	Schneider (1972)*	Simple Model	37.5	-65	1.7	-27.5
	Cess (1976)*	Empirical	45.5	-44.5	1.0	+1
	Ohring et al. (1981)*	NOAA AVHRR 0°-60° N	17.5	-53	3.0	-35.5
SAT	Ellis (1978)	*Nimbus 3* MRIR 65°S-65° N	22	-42	1.9	-20
	Ramanathan et al. (1989)	ERBE	31	-48	1.5	-17
	Ardanuy et al. (1991)	*Nimbus 7* ERB	24	-51	2.1	-27
MOD	Cess and Potter (1987)	Range of 6 GCMs January conditions	23 to 55	-45 to -74	1.0 to 2.0	-2 to -34

*To convert the published cloud *sensitivity* coefficients to the *effect* of clouds Eqs. (2.9–2.11) were used, with $A_c = 0.5$.

Different data sources as well as analysis period

Importance of cloud type (H_c,t) on radiation budget

Overcast sky Chen et al., 2000

TABLE 1. Global annual (4-day averaged) mean overcast sky cloud-induced radiative flux changes in W m^{-2} at the surface, at TOA, and in-atmosphere. SW—shortwave, LW—longwave, and TL—total.

	Surface			TOA			Atmosphere		
Cloud type	SW	LW	TL	SW	LW	TL	SW	LW	TL
Cirrus	−22.2	8.0	−14.2	−25.3	30.7	5.4	−3.1	22.7	19.6
Cirrostratus	−79.5	20.0	−59.5	−87.4	59.7	−27.7	−7.9	39.7	31.8
Deep convective	−118.6	16.3	−102.3	−126.2	60.7	−65.5	−7.6	44.4	36.8
Altocumulus	−28.7	20.3	−8.4	−29.3	13.0	−16.3	−0.6	−7.3	−7.9
Altostratus	−79.6	35.4	−44.2	−80.9	22.1	−58.8	−1.3	−13.3	−14.6
Nimbostratus	−98.2	32.4	−65.8	−98.8	20.6	−78.2	−0.6	−11.8	−12.4
Cumulus	−35.4	33.4	−2.0	−33.8	4.0	−29.8	1.6	−29.4	−27.8
Stratocumulus	−77.7	46.8	−30.9	−74.7	7.7	−67.0	3.0	−39.1	−36.1
Stratus	−88.1	39.2	−48.9	−84.6	7.8	−76.8	3.5	−31.4	−27.9

- SW fluxes: maximum impact from deep convective, nimbostratus, cirrostratus, stratus thickest cloud types
- TOA LW effects: maximum for the 3 high level clouds deep convective cirrostratus and cirrus
- Surface LW effects: maximum for low level clouds

Full sky (importance of cloud cover)

TABLE 2. Global annual mean full sky cloud-induced radiative flux changes in W m^{-2} at the surface, at TOA, and in-atmosphere. The names of three most abundant cloud types are shown in bold.

	Surface			TOA			Atmosphere		
Cloud type	SW	LW	TL	SW	LW	TL	SW	LW	TL
Cirrus	−3.6	1.1	−2.5	−4.2	5.5	1.3	−0.6	4.4	3.8
Cirrostratus	−7.2	1.7	−5.5	−7.9	5.5	−2.4	−0.7	3.8	3.1
Deep convective	−5.8	0.7	−5.1	−6.2	2.9	−3.3	−0.4	2.2	1.8
Altocumulus	−3.1	2.2	−0.9	−3.2	1.5	−1.7	−0.1	−0.7	−0.8
Altostratus	−8.2	3.6	−4.6	−8.3	2.0	−6.3	−0.1	−1.6	−1.7
Nimbostratus	−3.4	1.3	−2.1	−3.4	0.7	−2.7	0.0	−0.6	−0.6
Cumulus	−5.5	5.3	−0.2	−5.2	0.6	−4.6	0.3	−4.7	−4.4
Stratocumulus	−13.2	7.3	−5.9	−12.7	1.2	−11.5	0.5	−6.1	−5.6
Stratus	−2.6	1.2	−1.4	−2.4	0.2	−2.2	0.2	−1.0	−0.8
Sum (true)	−52.6	24.4	−28.2	−53.5	20.1	−33.4	−0.9	−4.3	−5.2

- SW fluxes: maximum modification from stratocumulus, altostratus, cirrostratus (clouds with moderate optical thickness)
- TOA LW effects: maximum for the 3 high level clouds: cirrus, cirrostratus and deep convective
- Different cloud types are most effective in altering the fluxes depending on SW/LW at TOA or at surface

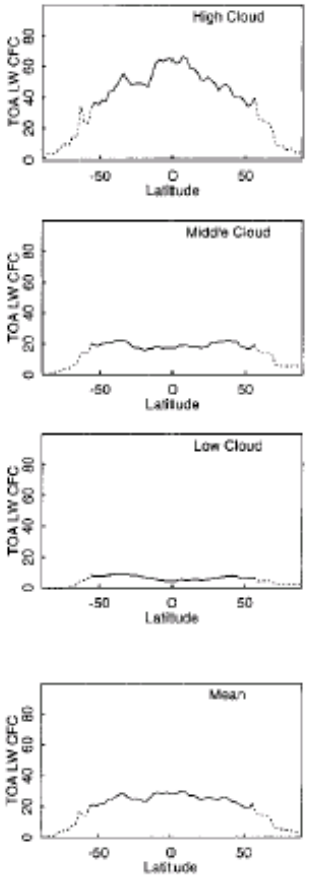
Influence of background condition

Latitudinal/seasonal variation for overcast sky

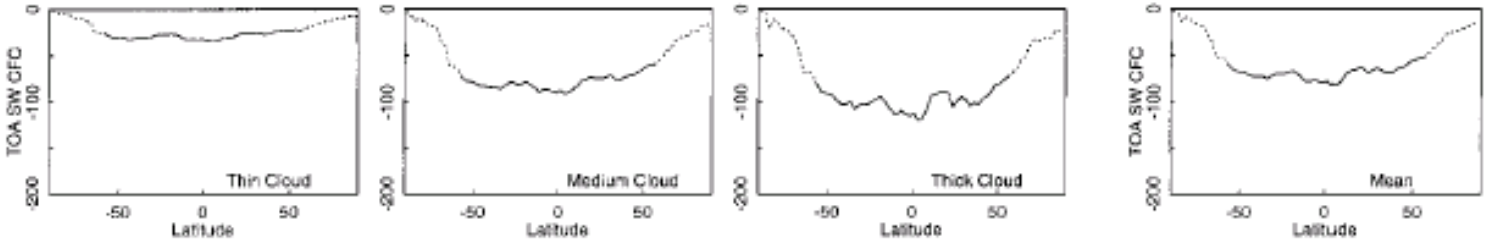
↓

The same cloud does not produce the same flux changes because of the interplay among cloud, surface and atmospheric properties

TOA longwave



TOA shortwave



Sensitivity study

Table 2. Global Mean Changes in Regional, Daily Mean Fluxes (W/m²) Produced by Changing Input Variables by the Indicated Amounts

Changed Parameter	$\Delta S\uparrow_t$	$\Delta S\uparrow_s$	$\Delta S\downarrow_s$	$\Delta L\uparrow_t$	$\Delta L\uparrow_s$	$\Delta L\downarrow_s$
			Atmospheric Properties			
PW ± 25%	-0.9 (0.7)	-0.5 (0.6)	-2.5 (1.5)	-4.9 (3.2)	—	14.9 (7.2)
Change to new aerosol	-0.8 (1.1)	0.2 (0.4)	1.5 (2.2)	0.2 (0.3)	—	-0.6 (0.6)
T_a ± 2K	0.8 (0.8)	0.0 (0.1)	-0.3 (0.4)	7.3 (2.5)	—	17.4 (3.2)
T_a (first level) ± 2K	0.1 (0.2)	0.0 (0.0)	-0.1 (0.2)	1.6 (1.0)	—	23.0 (6.4)
			Surface Properties			
T_s ± 2K	—	—	—	1.8 (1.4)	22.2 (3.5)	—
Change to new surface albedo (land only)	-9.1 (11.3)	-12.6 (15.2)	-2.6 (4.3)	—	—	—
			Cloud Properties			
Cf ± 11.4%	10.3 (9.0)	-1.9 (3.6)	-12.1 (11.5)	-4.7 (3.9)	0.0 (0.0)	8.3
τ ± 10%	4.9 (4.2)	-0.7 (0.9)	-5.5 (4.7)	-0.8 (0.9)	—	0.7 (0.6)
Night τ ± 20%	—	—	—	-0.6 (0.8)	—	0.5 (0.6)
Interpolated τ ± 20%	1.7 (3.4)	-0.3 (0.8)	-1.9 (4.0)	-1.0 (1.2)	—	0.9 (0.9)
Cold τ – 50%	-0.6 (2.3)	0.1 (0.3)	0.6 (2.2)	0.7 (2.2)	—	-0.2 (0.6)
Change to new μ_0-dependence	0.7 (1.8)	-0.1 (0.4)	-0.7 (1.9)	—	—	—
T_c ± 3K	-1.2 (1.0)	0.0 (0.1)	0.2 (0.3)	5.5 (3.3)	—	2.8 (2.4)
Cold (< 250K) T_c ± 4K	-0.2 (0.4)	0.0 (0.0)	0.0 (0.1)	2.2 (3.6)	—	0.7 (1.6)
Change from fixed to variable cloud layer thickness	-0.2 (0.4)	0.0 (0.0)	0.0 (0.1)	0.5 (1.2)	—	1.7 (3.3)
Increase cloud layer thickness	0.1 (1.1)	0.1 (0.1)	0.6 (1.0)	1.8 (2.3)	—	2.1 (2.2)
Cloud detection test*	-1.4 (9.0)	5.4 (13.4)	6.1 (7.9)	-2.1 (3.2)	-35.0 (41.9)	-3.7 (9.5)

The standard deviations of the flux changes for individual map grid cells are given in parentheses. All input quantities are specified by ISCCP data sets for July 15, 1985.

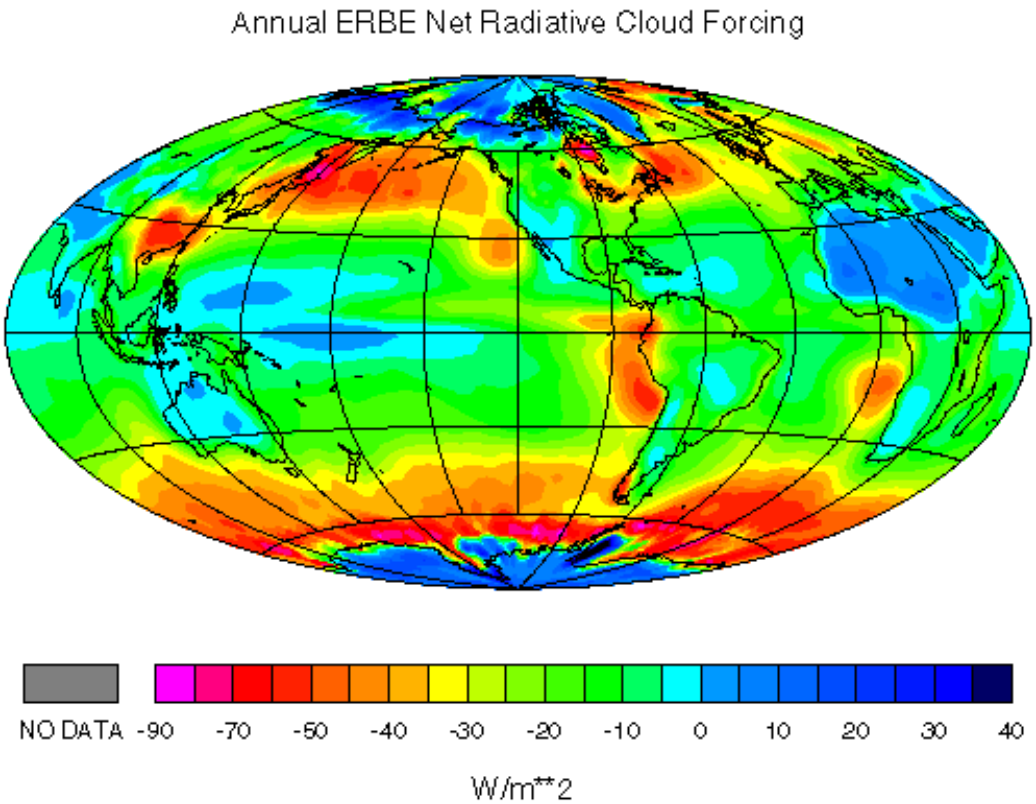
*For the cloud detection test, the global mean cloud and surface properties change by the following amounts: mean (standard deviation)= -11.4% (8.4%) for Cf; -0.98K (6.8K) for T_c; 0.66 (4.68) for τ; -6.4K (7.7K) for T_s; and -0.010 (0.070) for R_s, including ocean; and -0.024 (0.105) for R_s for land only.

Uncertainties in land surface albedo impact
SW fluxes more than cloud cover ones

Uncertainties in land surface temperature and emissivities strongly impact $LW_s\uparrow$

Uncertainties in calculated radiative fluxes are no longer dominated by uncertainties in the cloud properties, but in equal parts by the properties of the atmosphere, the surface and the clouds

Results from ERBE III



Clouds warm the winter hemisphere and cool the summer hemisphere. The SW components dominates the total net flux: the final result is a cooling effect on the planet.

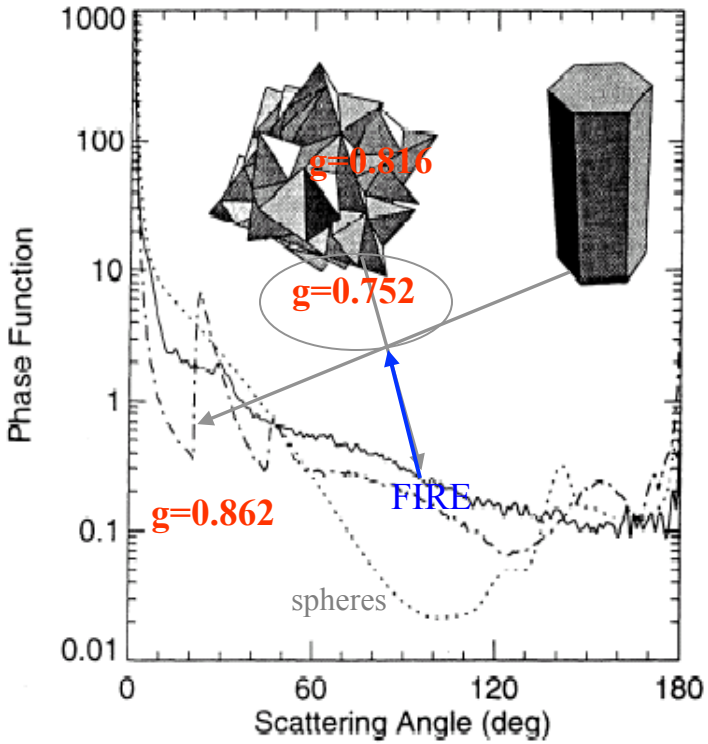
The most significant cooling takes place in the west part of the continents where the sea layering can persist for long time and along the cyclonic systems trajectories over the ocean at the medium and high latitudes.

Deficiencies in radiative transfer processes and parameterizations for climate models

- Microphysical properties (phase, size distribution) are often fixed parameters in GCM
- Complexity of non plane parallel clouds with highly inhomogeneous structures (3-D effects) are taken in account neither in cloud microphysical retrievals (Varnai, 2002) nor in GCM (Gu, 2001)
- Optical properties of non-spherically shaped ice particles (problems in τ and r_{eff} retrievals)
- No multiple layered clouds (uncertainty in cloud base height) very important for surface LW fluxes and difficulties in the parameterization of horizontal inhomogeneities

Importance of shape in RT

λ=0.63μm

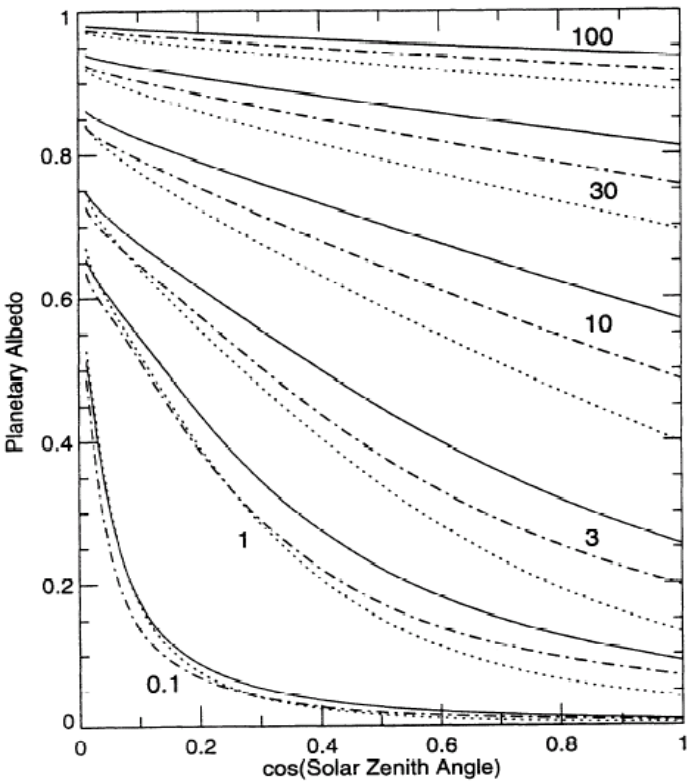


Large differences in phase function at side incidence

R_{eff}=30 μm

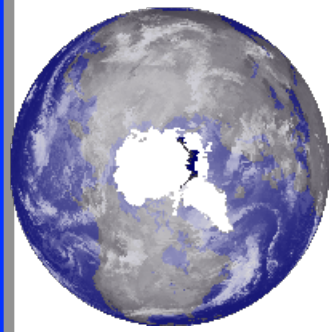
Possible shape for cirrus particles

1. ***random fractal ice***
2. ***regular hexagonal crystals (but halos not so common!)***
3. ***water spheres (ISCCP)***



Planetary albedos for a random fractal ice are Systematically larger than the other ones

Clouds exert their influence on climate also through feedback mechanisms



For instance:

(1) Global warming due to greenhouse effect should cause an increase in the amount of low clouds: a consequent increase in the reflected solar radiation should occur, generating cooling effects (negative feedback).

(2) Thin tropical cirrus clouds are much colder than the underlying surface and tend to enhance the greenhouse effect: an increase in the amount of this cloud type is a positive feedback.

(3) Global warming can cause an increase in the amount of high clouds in the tropical regions, enhancing the greenhouse effect (positive feedback).

However, large uncertainties still exist on the cloud feedback processes

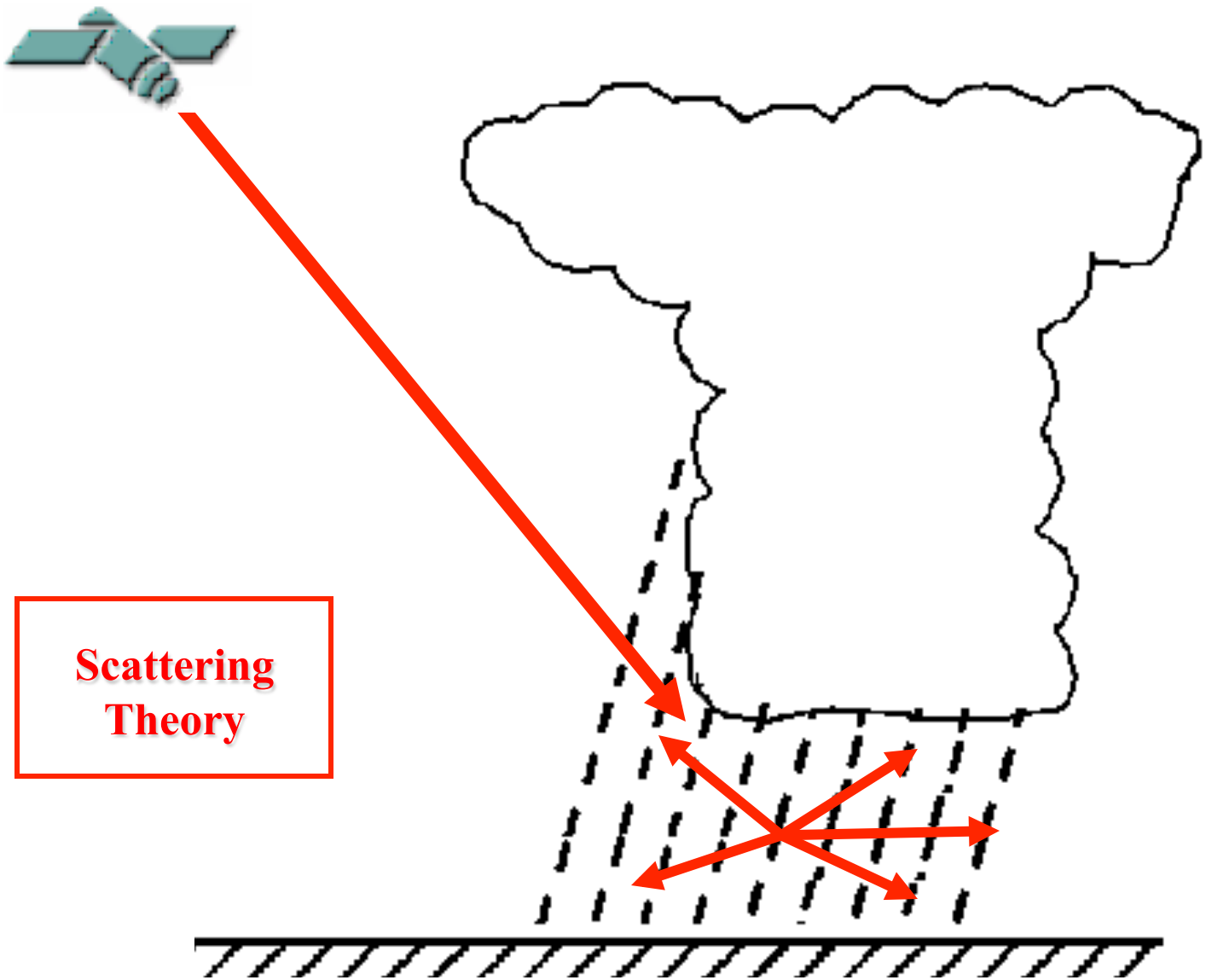
Cloud effects on climate

Clouds exert a strong impact on climate through radiative energy redistribution via the scattering and absorption of radiation, playing also an important role in the hydrological cycle. They constitute the main source of uncertainty in global climate models, arising principally from two types of problems related to cloud-climate interactions:

- **(i) definition of the cloud radiative properties in climate models, through a good knowledge of cloud morphology and microphysical properties;**
- **(ii) simulation of the behaviour of clouds in a changing climate along with their related feedback mechanisms.**

Therefore, accurate in-situ measurements of the radiative, microphysical and chemical properties of different clouds are required in order to obtain **climate change predictions**, quantitative evaluations of **radiative interactions** in the atmosphere and a better understanding of the **feedback mechanisms** that influence the Earth climate, many of which are closely related to cloud parameters (temperature, top height, water content, equivalent radius of the cloud-droplet size distribution).

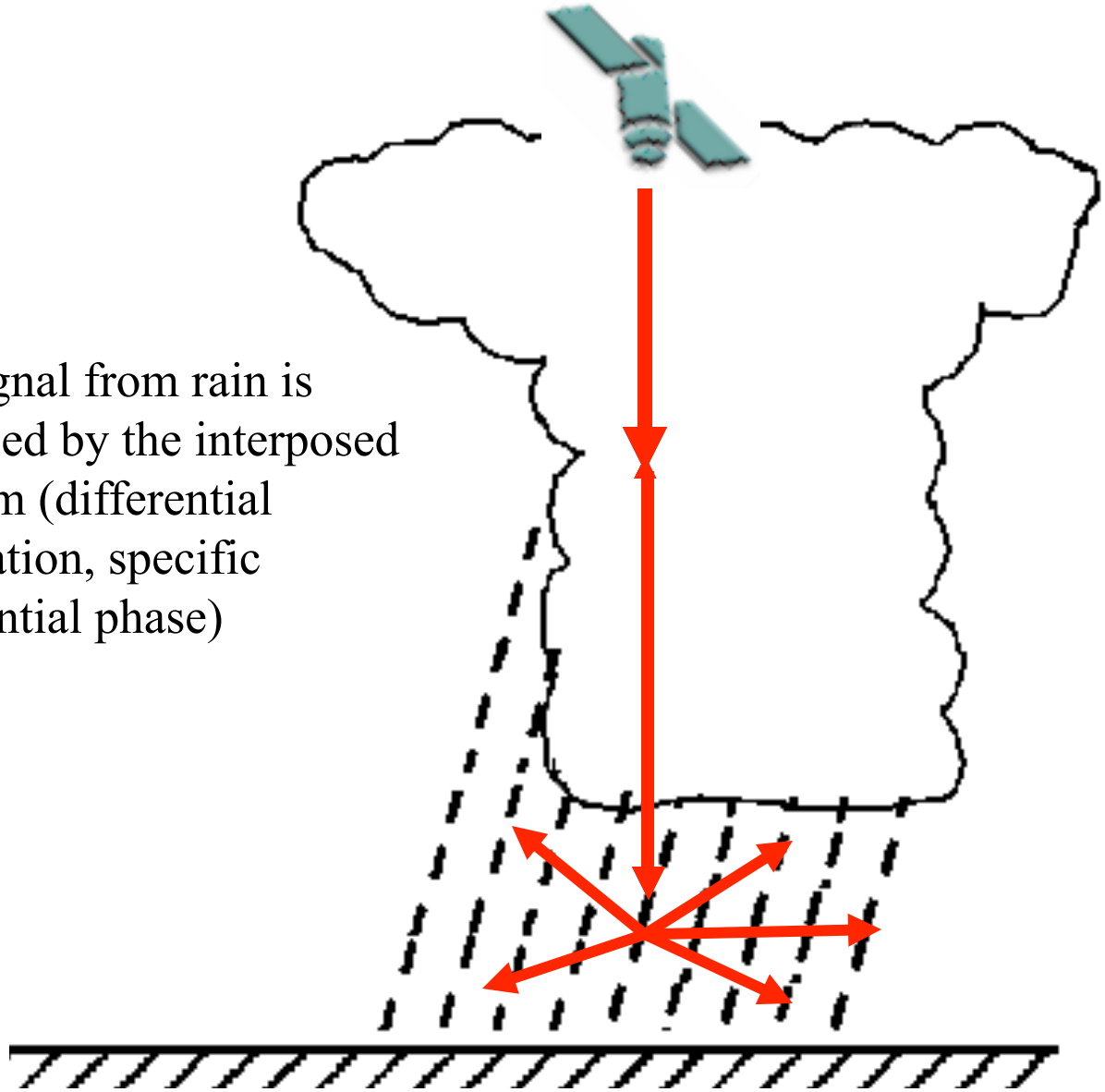
Active Microwave



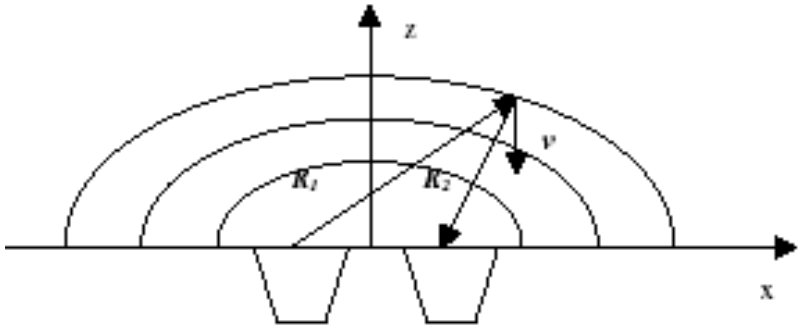
Scattering Theory

Pulsed Active Microwave

The signal from rain is disturbed by the interposed medium (differential attenuation, specific differential phase)



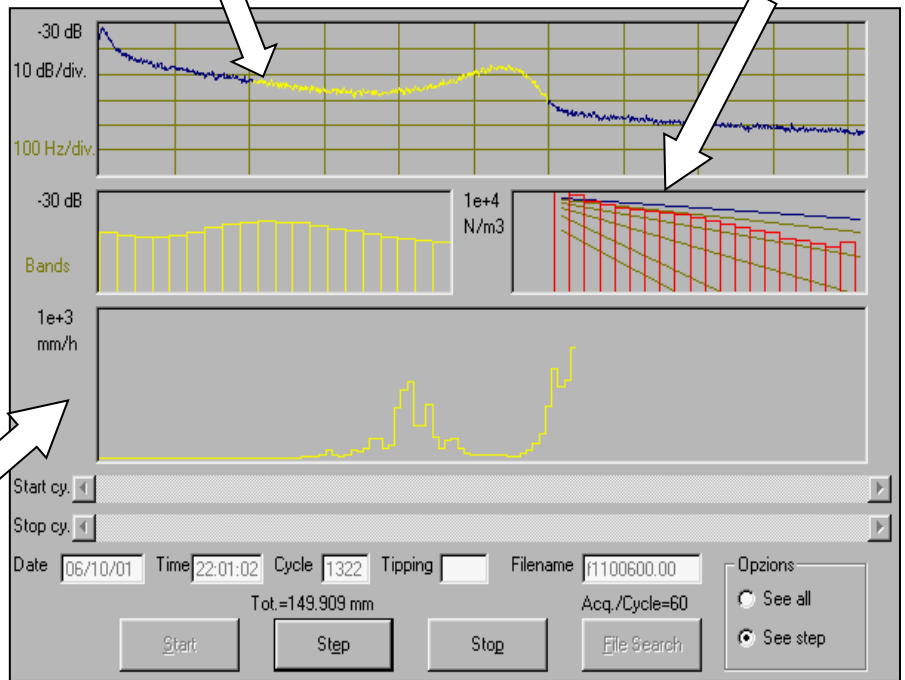
Continuous Active Microwave



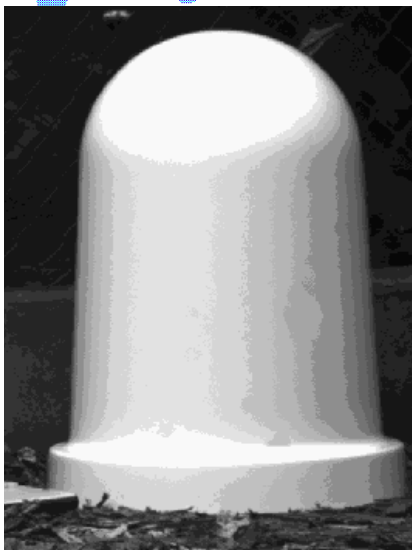
Power spectrum in the running interval (1 min)

Logarithmic presentation of drop concentration vs size.

Power spectrum in the size ranges



rain

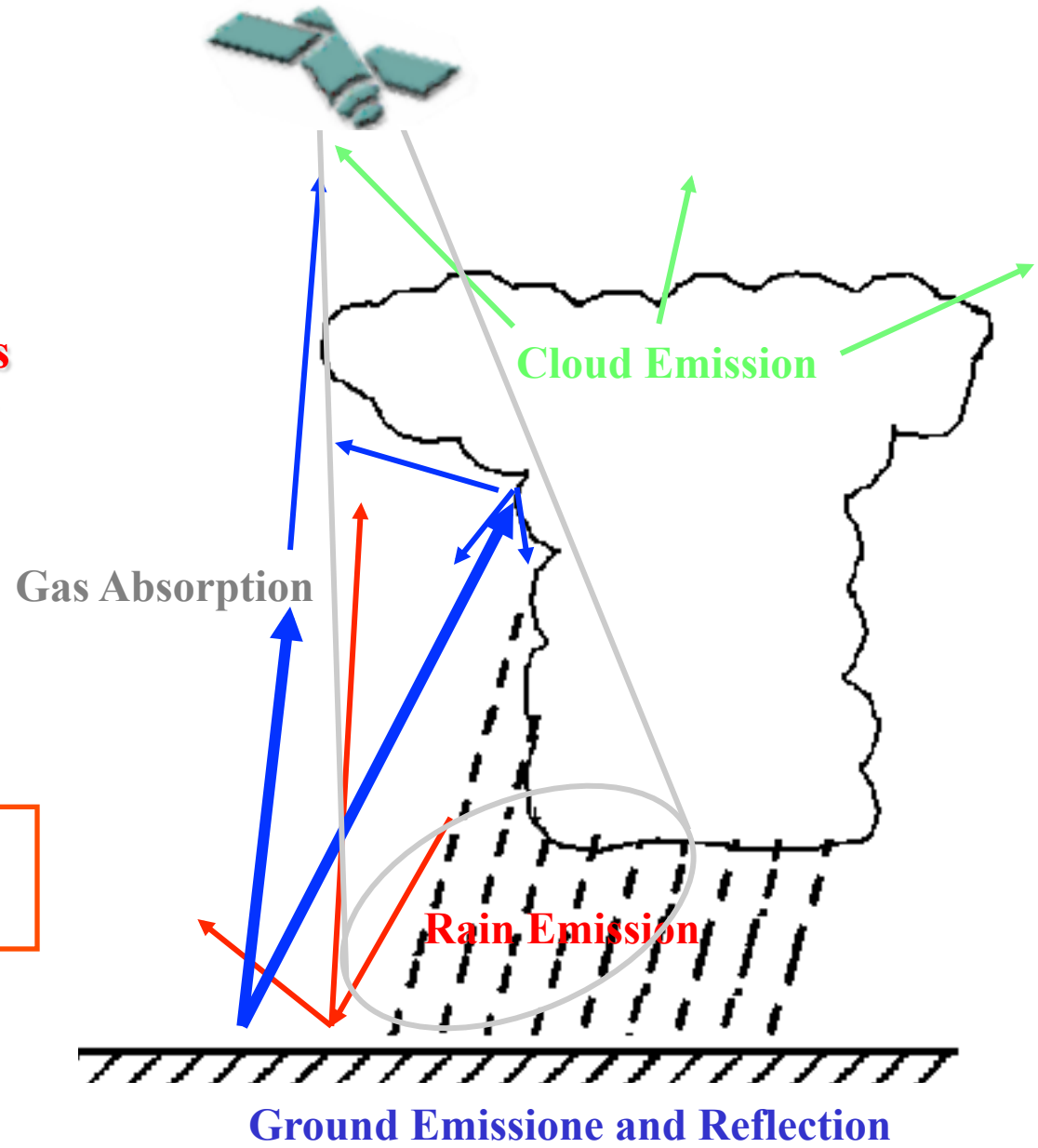


Pludix

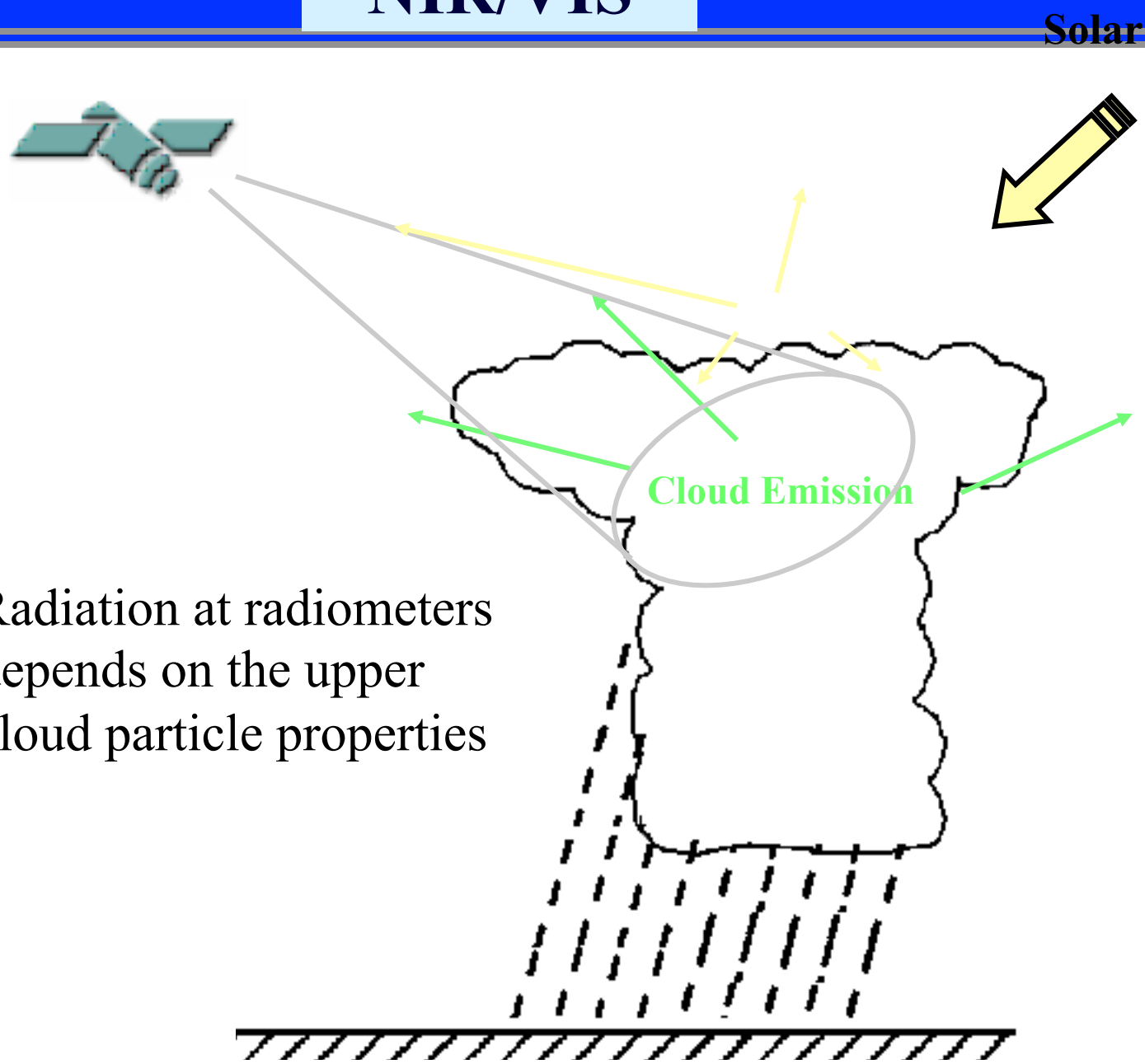
Passive Microwave

Signals depend on scattering and absorption properties of the column under observation

Radiative Transfer Theory



NIR/VIS



Radiation at radiometers depends on the upper cloud particle properties

Scattering

Hypothesis

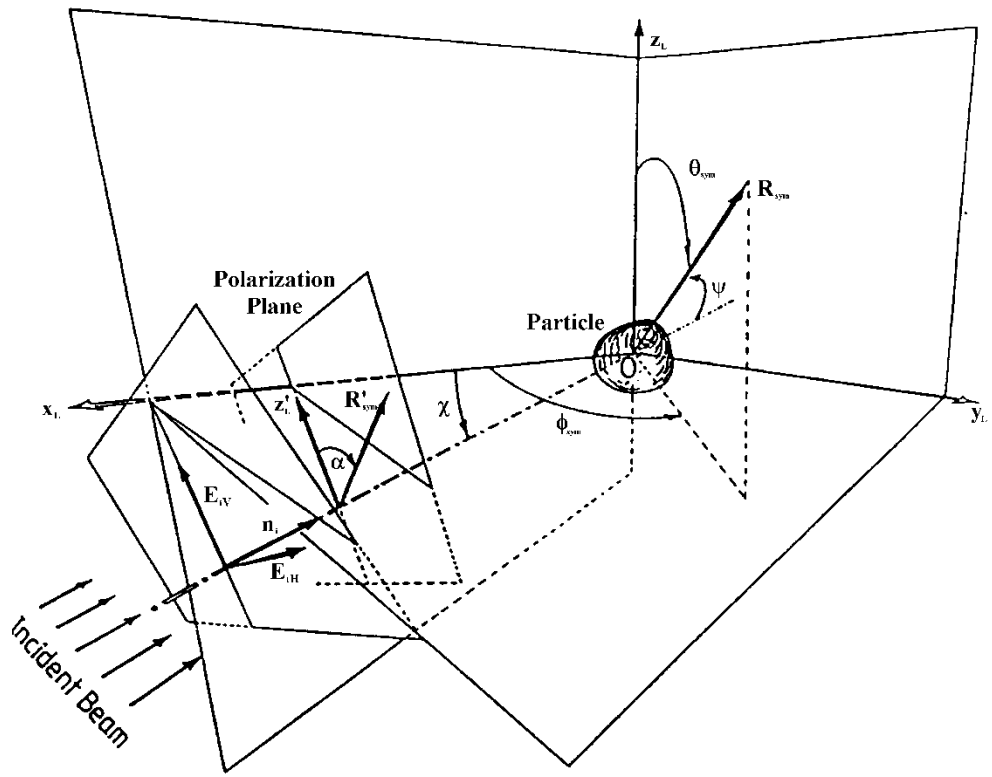
- Electric dipole approximation;
- monochromatic incident wave;
- incoherent scattering;
- absence of electric charges;
- measures are detected in the far field region.

$$\bar{I}_s = \frac{1}{r^2}\bar{\bar{Z}}(\vartheta_s,\varphi_s,\vartheta_i,\varphi_i)\cdot\bar{I}_i$$

Stokes Matrix

depending on

- size, composition, orientation and shape of the scatterer
- frequency and polarization of incident wave



OPEN QUESTIONS

In atmospheric physics hydrometeors can be non-spherical with very complex shape (especially ice crystals and aggregate), often anisotropic and inhomogeneous (like mixed phase particles)

Numerical solutions are needed

Differential methods: scattered fields are computed by solving the vectorial wave equation

- Finite elements method (Volakis et al. 1998)
- Finite difference time domain method (Tang e Aydin 1997)

Integral methods: Maxwell are written in terms of volume integrals over the scatterer volume or surface

- Integral equation method (Van Bladel 1961)
- Discrete dipole approximation (Draine e Flatau 1997)
- Fredholm integral method (Holt 1978)
- T-matrix (Waterman 1971, Mishchenko 1996)

T-MATRIX

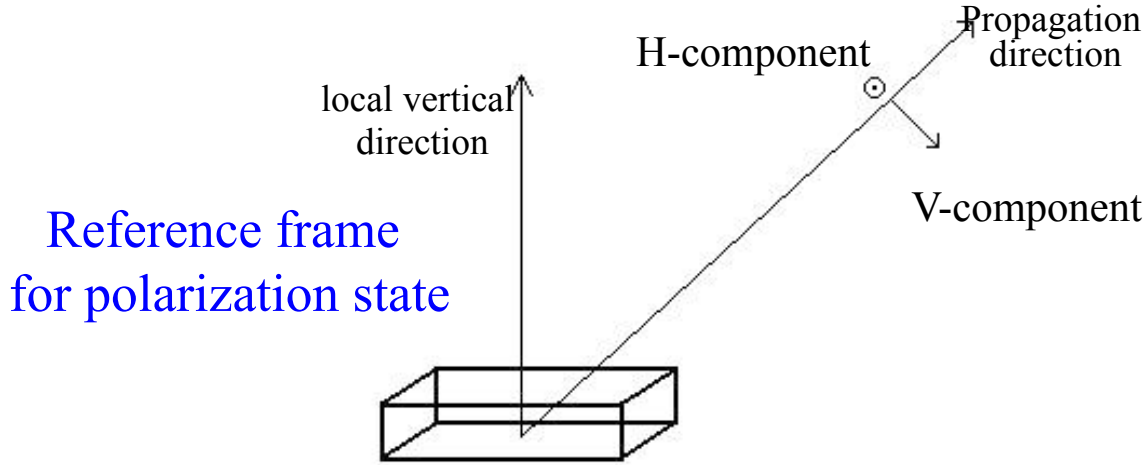
T-matrix connects the scattered and the incident field expansions coefficients in vector spherical wave functions

T-matrix for a 'star-shaped' [$r=r(\theta,\phi)$] particle with fixed orientation can be computed but for high size parameter/high aspect ratio particles. Raindrops can be described by oblate spheroids/Chebychev particles

Averages over orientation distribution can be performed either analitically (randomly oriented/ perfectly oriented) or numerically

Vector radiative transfer equation

The polarization state of the em wave is described by the Stokes parameters

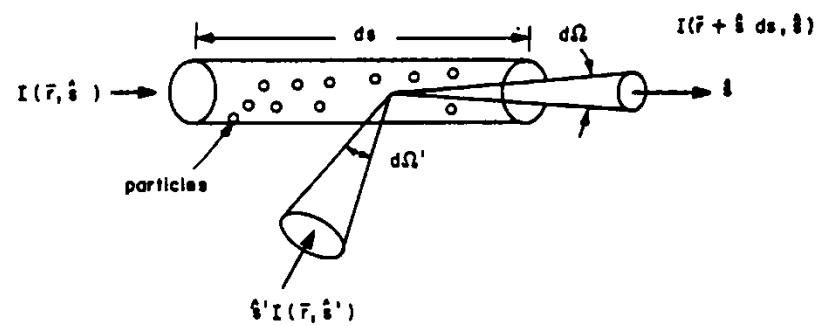


$$\frac{d\bar{I}(\vec{r},\hat{s})}{ds} = -\bar{\bar{k}}_e \cdot \bar{I}(\vec{r},\hat{s}) + C\bar{k}_a(\vec{r},-\hat{s})T(\vec{r}) + \int d\Omega' \bar{\bar{P}}(\hat{s},-\hat{s}') \cdot \bar{I}(\vec{r},\hat{s})$$

Extinction matrix

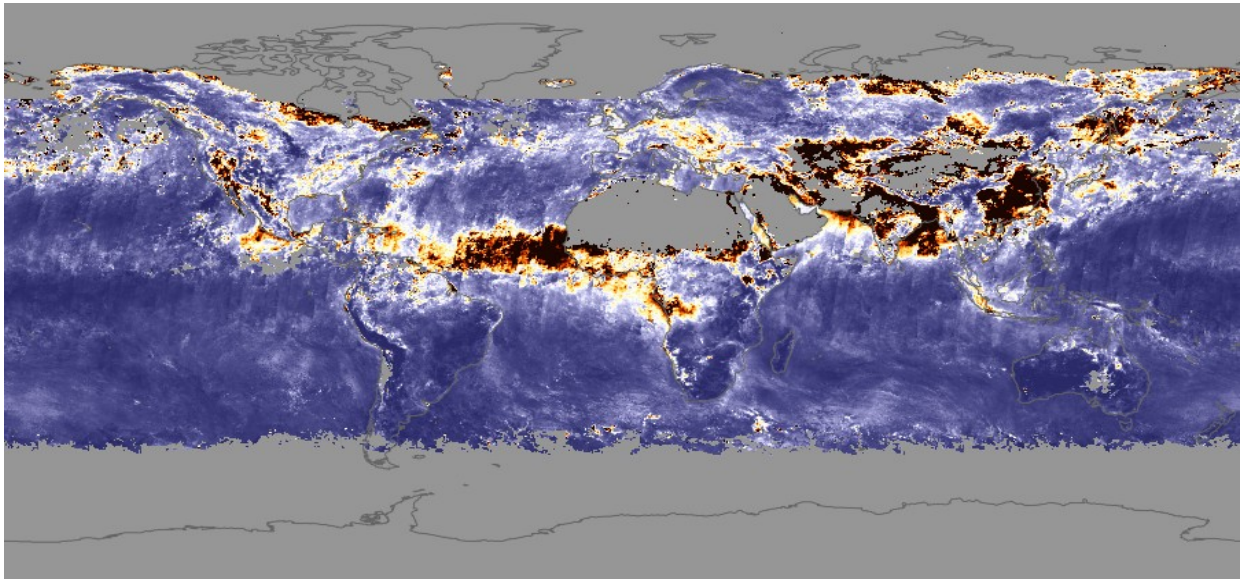
Phase matrix

Absorption vector



Generally the 4 Stokes parameters are coupled

Aerosol impact on climate



1. Aerosols are liquid or solid particles suspended in the air.
2. They influence the climate through:
   a) Direct effects, due to scattering and absorption of solar and terrestrial radiation.
   b) Indirect effects by modifying the microphysics, the radiative properties and the lifetime of clouds.
3. They are subject to vary with space and time.
4. There is limited information on their global distribution.

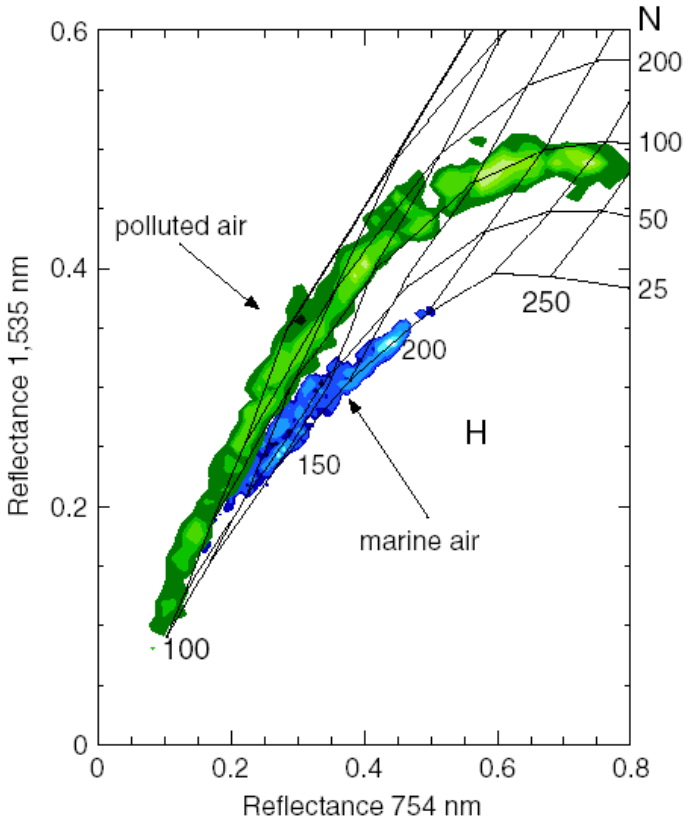
Observational support for aerosol indirect forcing

Satellite studies of clouds near regions of high SO_2 emissions have shown that polluted clouds have high reflectivity on average that backgroud clouds (Kuang and Yung, 2000).

There is a statistically significant correlation of aerosol optical depth (AOD) with cloud optical depth (COD), when COD < 15 (Wetzel and Stowe, 1999).

In-situ measurements have found linkages between CCN concentrations and both drizzle and cloud droplet r_{eff} in marine stratocumulus (Yum and Hudson, 1998).

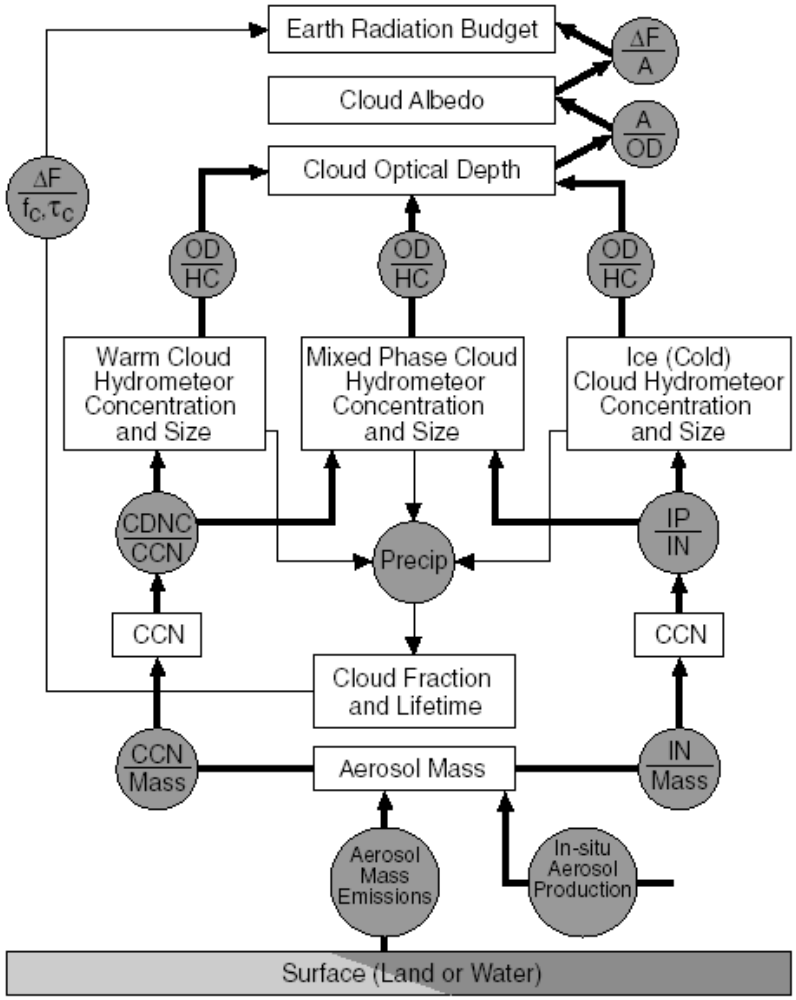
Changes in cloud microstructure due to aerosols are associated with increases in cloud albedo (Brenguier et al., 2000).



(Brenguier et al., 2000)

Aerosol indirect radiative forcing (1)

Indirect forcing by aerosols can be viewed as a series of processes linking various intermediate variables such as aerosol mass, cloud condensation nuclei (CCN) concentration, ice nuclei (IN) concentration, water phase partitioning, cloud optical depth, etc., which connect emissions of aerosols (or their precursors) to the top of the atmosphere radiative forcing due to clouds.



: Symbols: CCN (Cloud condensation nuclei); CDNC (Cloud droplet number concentration); IN (Ice nuclei); IP (Ice particles); OD (Optical depth); HC (Hydrometeor concentration); A (Albedo); f_c (Cloud fraction); τ_c (Cloud optical depth); ΔF (Radiative forcing).

Aerosol indirect radiative forcing (2)

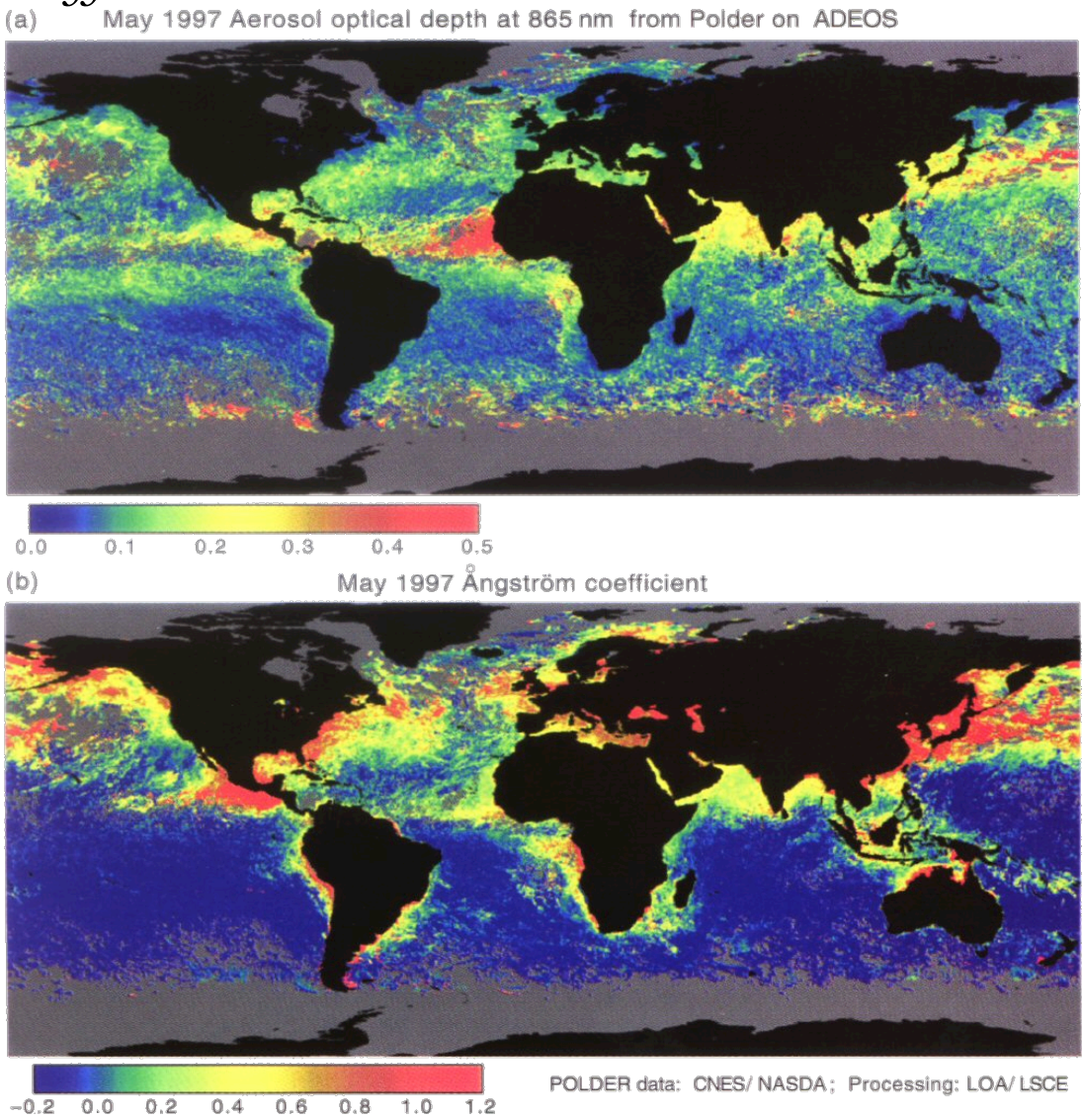
Among all these processes, the linkages vitally important and/or for which significant progress towards quantification has been made in the last five years are:

1) **Factors controlling cloud condensation nuclei**
2) **Factors determining cloud droplet number concentration**
3) **Aerosol impact on Liquid-Water content and Cloud Amount**
4) **Ice formation**

Aerosol direct effects on the radiation balance

✓ **Airborne aerosol particles** can produce important scattering and absorption effects on the incoming solar radiation causing **marked changes in Earth's radiation budget** through their direct extinction effects.

✓ In **Europe** and **North America**, where anthropic sources of aerosols are intense, the columnar particulate matter content mainly consists of sulphates and some soot substances, presenting rather **high values of AOD** at VIS and NIR wavelengths



(Deuzé et al., G.R.L.,1999)

Aerosol direct radiative forcing (1)

→ **Large aerosol loadings** can cause marked changes in the radiation budget of the surface-atmosphere system over wide areas, frequently leading to an increase in the solar radiation fraction reflected toward space, which results in **cooling effects comparable to the warming effects** produced by the increase in greenhouse gases concentration.
(Charlson et al.,Science,1992)

→ When suspended over land regions covered by vegetation and, hence, presenting relatively **high values of the surface albedo**, aerosol particles containing fractions of absorbing substances can assume single-scattering albedo values lower than 0.9 and consequently cause **pronounced warming effects**.
(Hänel et al., J.Aerosol Sci.,1999)

Aerosol direct radiative forcing (2)

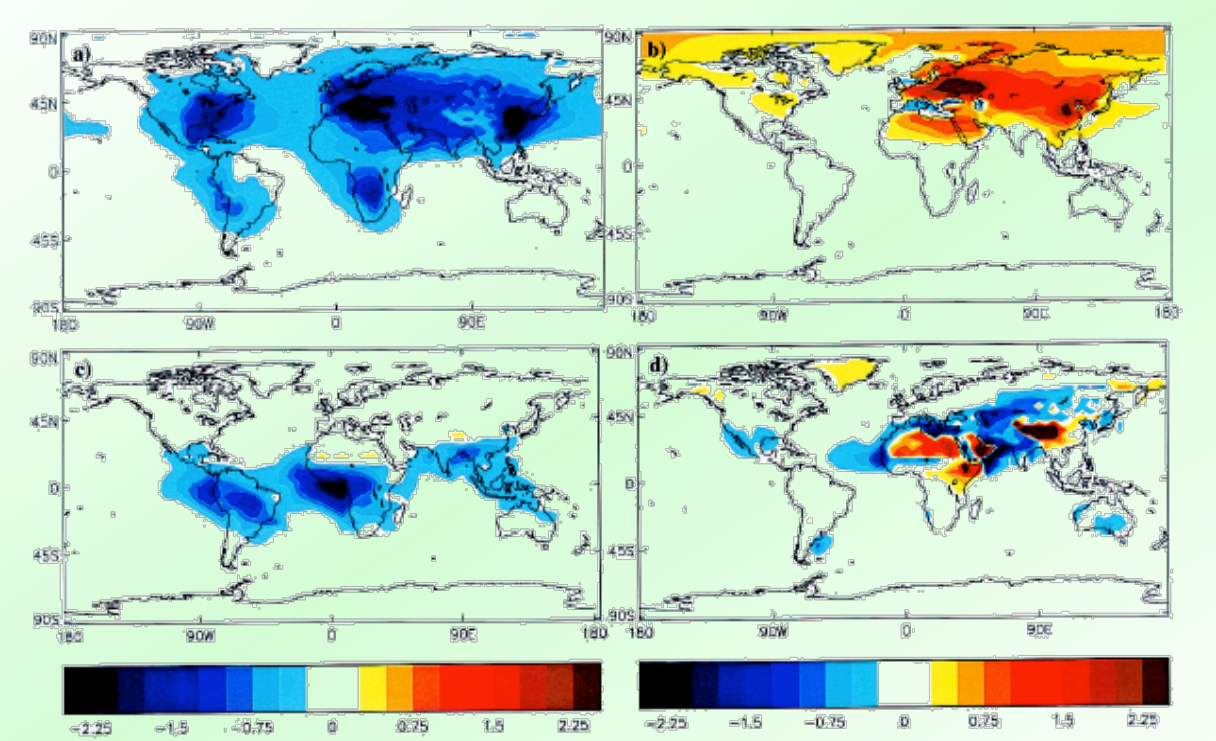
Large uncertainties still exist on the aerosol radiative properties that prevent evaluation of the **direct radiative forcing** caused by tropospheric aerosols on the global scale, due also to the great **spatial variability in aerosol concentration and composition**.

Sulphate aerosols

Organic carbon and black carbon from fossil fuel burning

Organic carbon and black carbon from biomass burning

Mineral dust

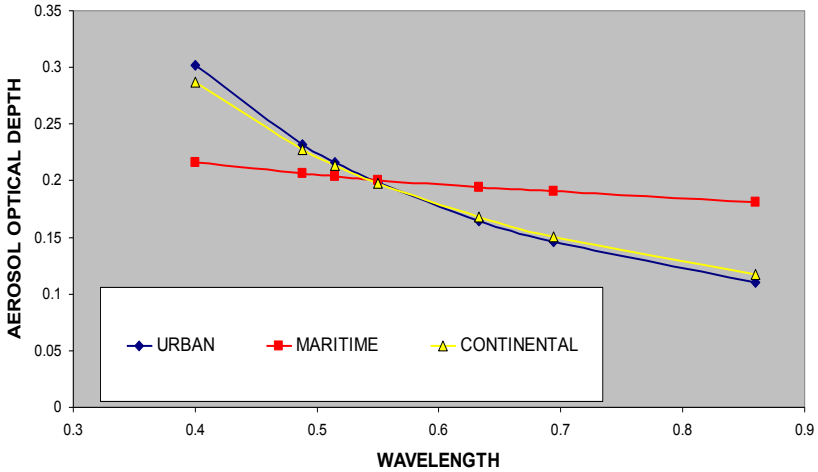


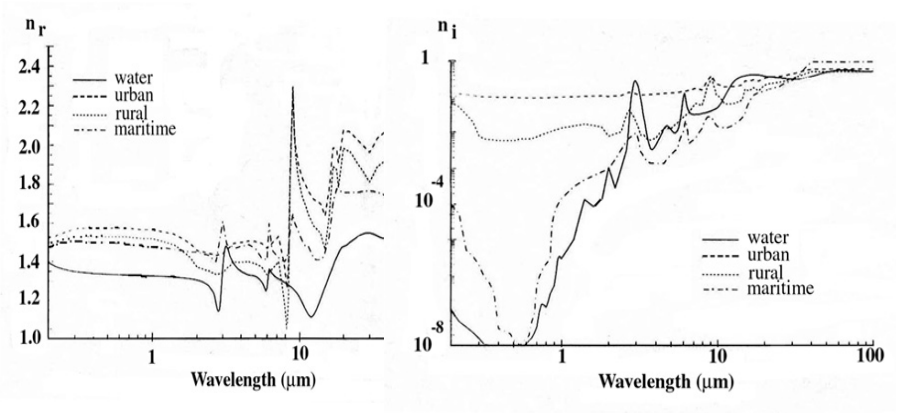
direct aerosol induced radiative forcing (Wm^{-2})

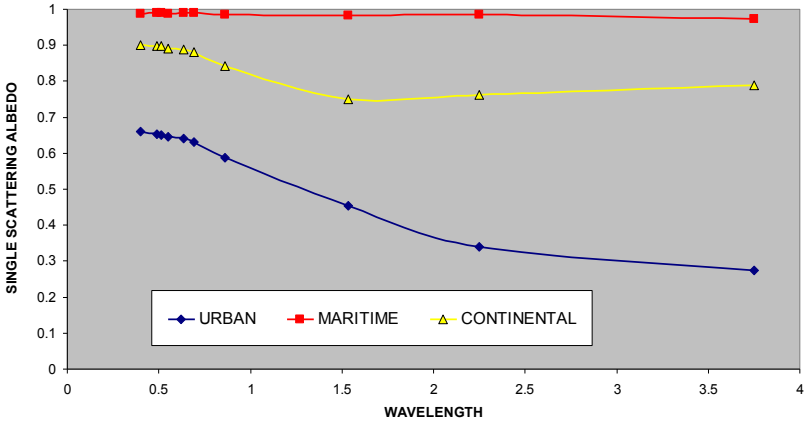
(Haywood & Boucher, Rev. Geophys. 2000)

The key parameters in evaluating direct aerosol radiative effects are:

i) **Radiation wavelength,**
ii) **Particle size-distribution,**
iii) **Particle chemical composition,**
iv) **Particulate refractive index,**
v) **Single scattering albedo ω.**

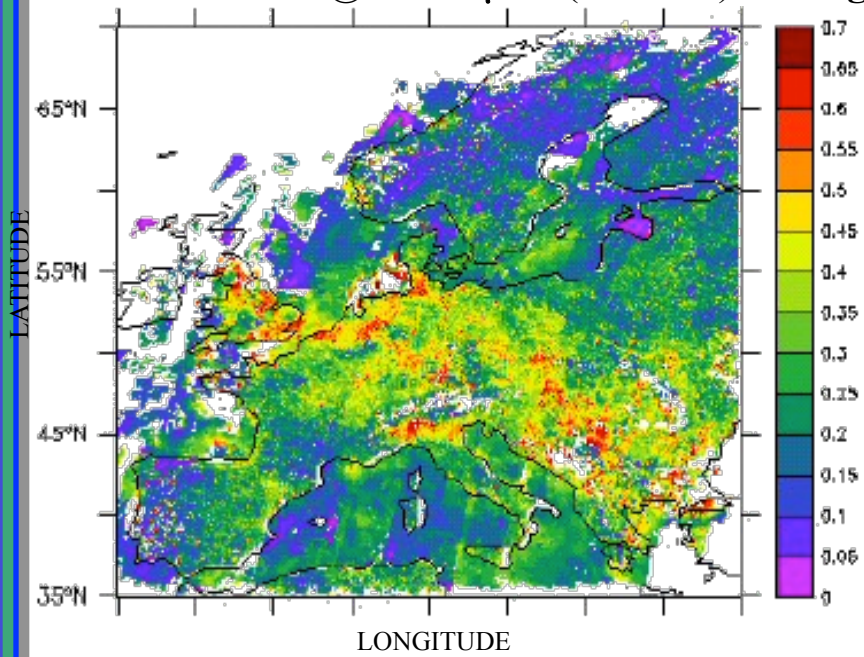




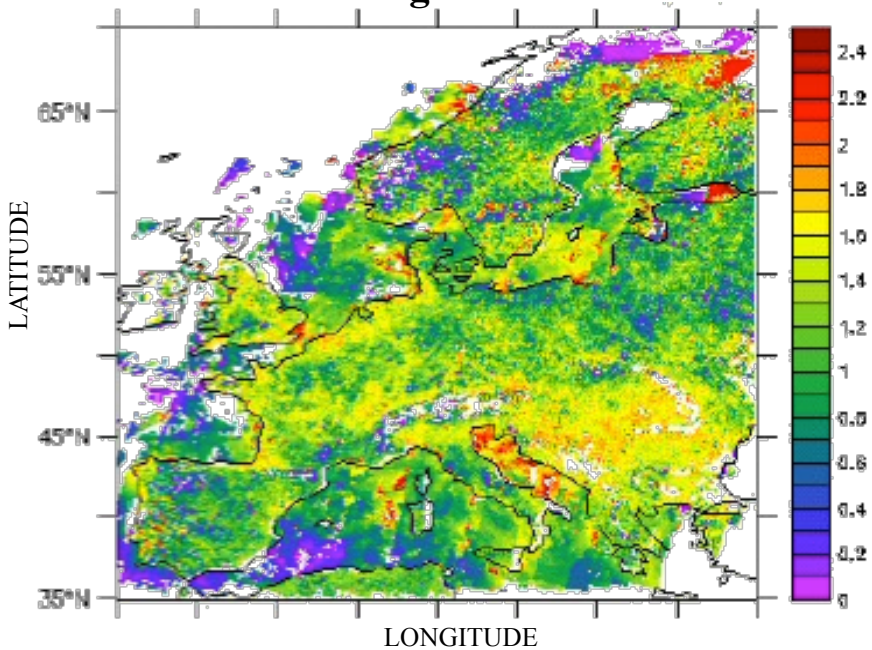


Large **spatial and temporal variability of aerosol parameters** in the European area

mean AOD @ 0.555 µm (ATSR-2) **August 1997**



mean Ångström coefficient α

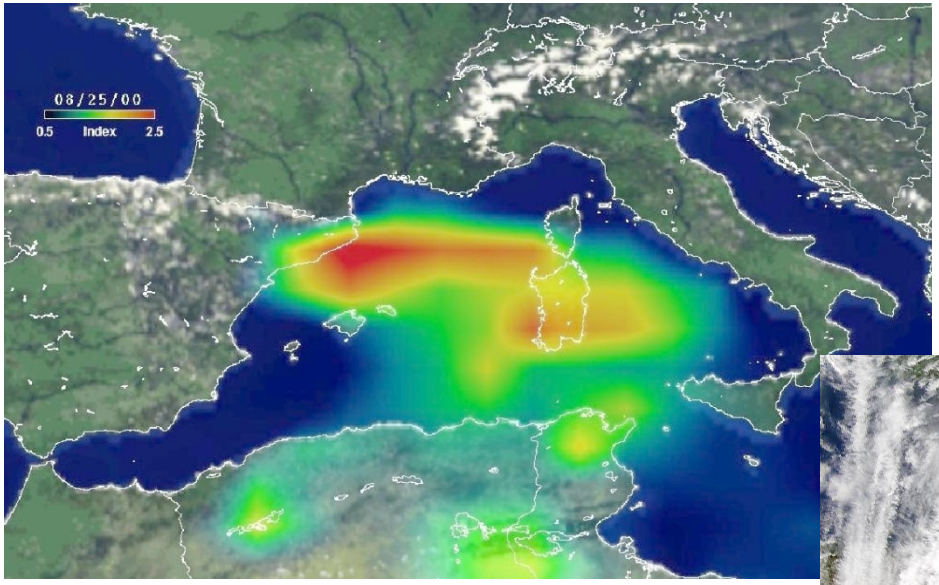


(Robles Gonzalez et al., Atmos.Chem.Phys., 2003)

In the **Mediterranean** aerosol is produced by various **sources**

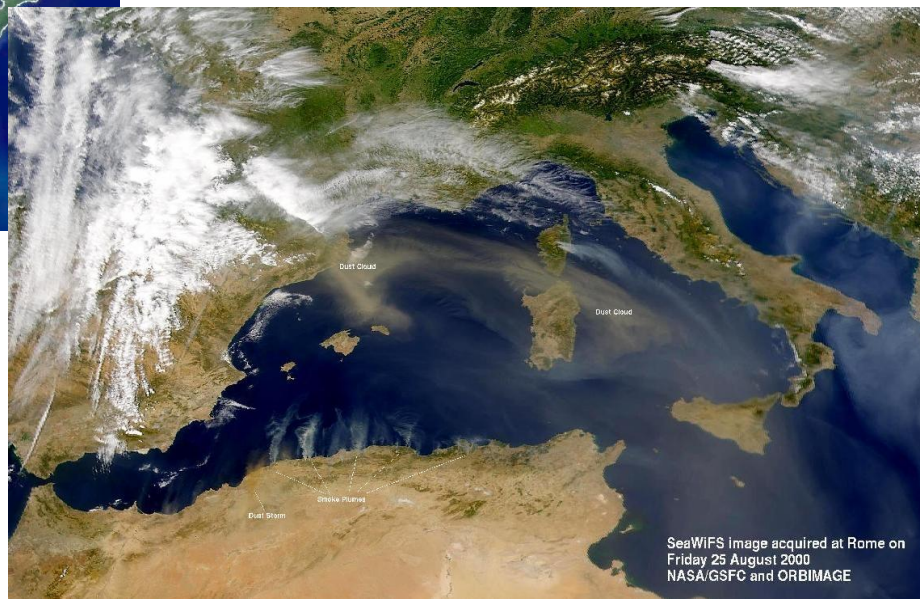
- **desert dust** from Sahara
- **anthropogenic pollution** from highly industrialized regions and large urban areas
- **fire plumes** from forest fires
- **volcanic ash** as well as normal **continental and maritime** particles

Aerosol from different sources is **transported** through the Mediterranean region following the prevailing circulation



TOMS image of August 25, 2000
Aerosol Index from 0.5 (blue) to 2.5 (red)

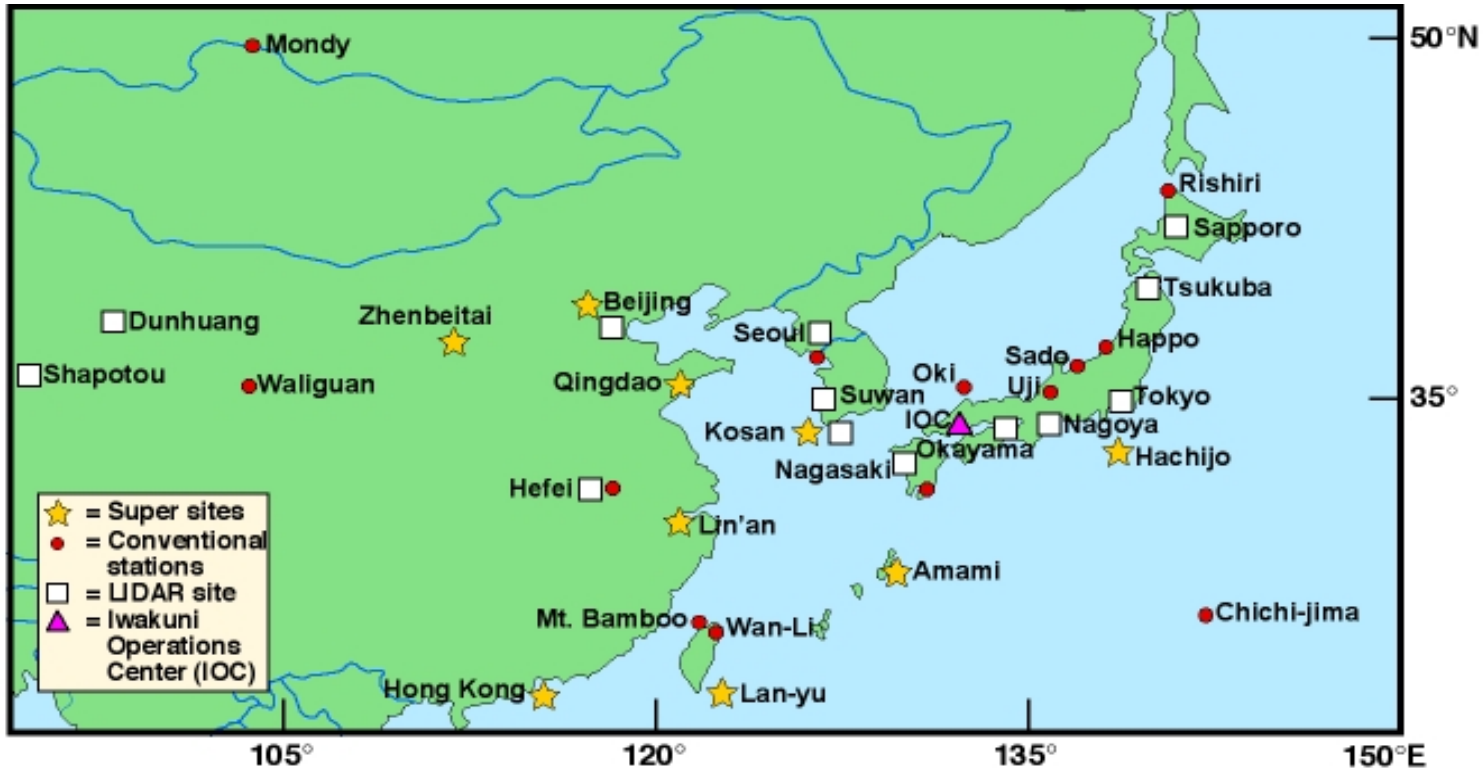
SeaWiFS image of August 25, 2000
(NASA/GSFC and ORBIMAGE)



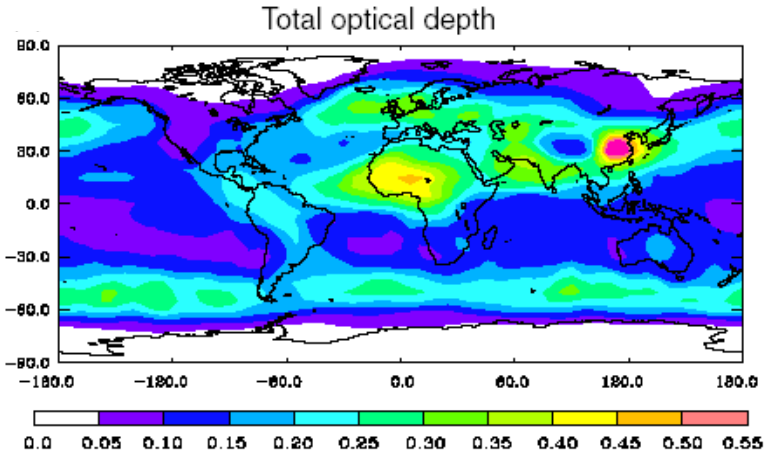
ACE-Asia took place during the spring of 2001 off the coast of China, Japan and Korea.

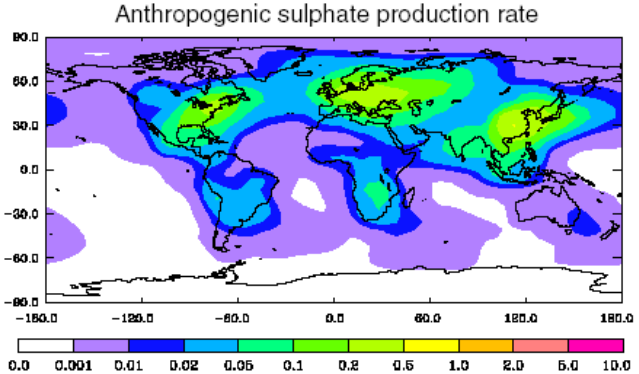
The ACE-Asia region includes many types of aerosol particles of widely varying composition and size derived from one of the largest aerosol source regions on Earth.

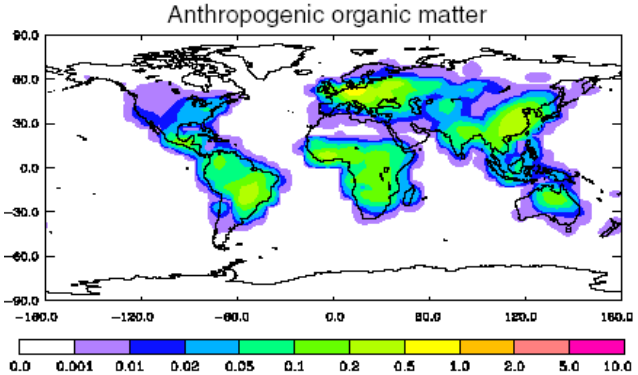
These particles include those emitted by human activities and industrial sources, as well as wind-blown dust.

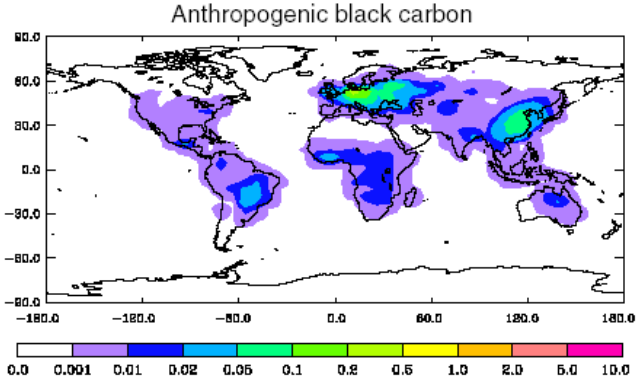


Anthropogenic pollution: the "Asian Brown Cloud"



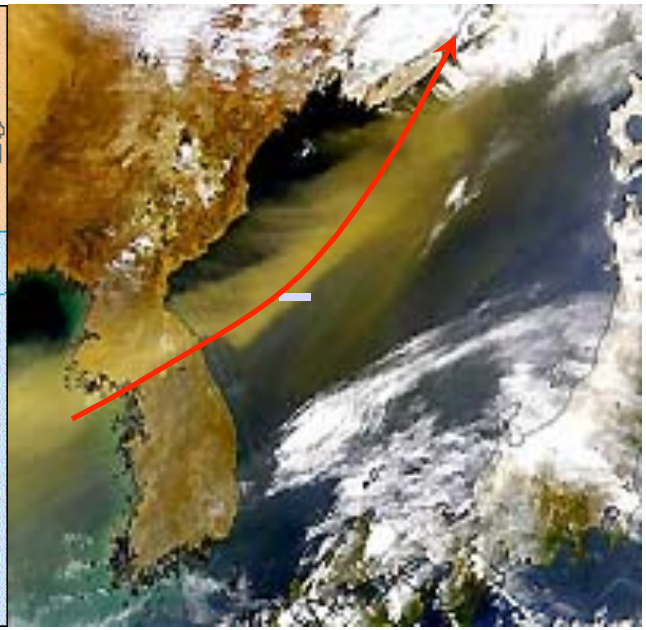






"China's Growing Deserts are Suffocating Korea"

(Sunday NYTimes 14 April 2002)



SeaWiFs - Sea-viewing Wide Field of view Sensor

ISAC