PHY2505S
Atmospheric Radiative Transfer and Remote Sounding

Lecture 4

- Applications of Schwarzchild's Equation
- Solar Insolation
- Solar Variability and the Solar Cycle

Schwarzchild's Equation - Summary

- The derivative form of Schwarzchild's Equation:

$$\frac{dI_{\bar{\nu}}}{k_{\bar{\nu}}\,\rho\,dx} = -I_{\bar{\nu}} + J_{\bar{\nu}}$$

- And for local thermodynamic equilibrium: $$\frac{dI_{\bar{\nu}}}{k_{\bar{\nu}}\,\rho\,dx} = -I_{\bar{\nu}} + B_{\bar{\nu}}$$

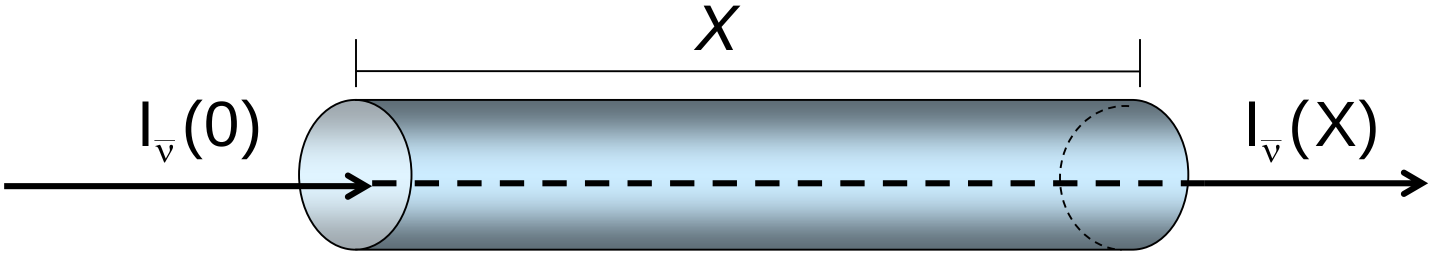
- The integral form of Schwarzchild's Equation, using J = B:

$$I_{\bar{\nu}}(X) = I_{\bar{\nu}}(0)e^{-k_{\bar{\nu}}\,\rho X} + \int_0^X k_{\bar{\nu}}\,\rho B_{\bar{\nu}}\,e^{-k_{\bar{\nu}}\,\rho x'}dx'$$

$$I_{\bar{\nu}}(X) = I_{\bar{\nu}}(0)\tau_{\bar{\nu}}(X) + \int_{\tau_{\bar{\nu}}(X)}^{1} B_{\bar{\nu}}\,d\tau \qquad \tau_{\bar{\nu}}(x) = e^{-k_{\bar{\nu}}\,\rho x}$$

First Example: Lab Gas Cell - 1

- Consider a laboratory cell containing a gas that absorbs radiation, and for which absorption is the only thing that we need to consider, i.e., we can neglect scattering - valid in the infrared.



- In this case, *J* is the blackbody function *B* and Schwarzchild's Equation can be written as:

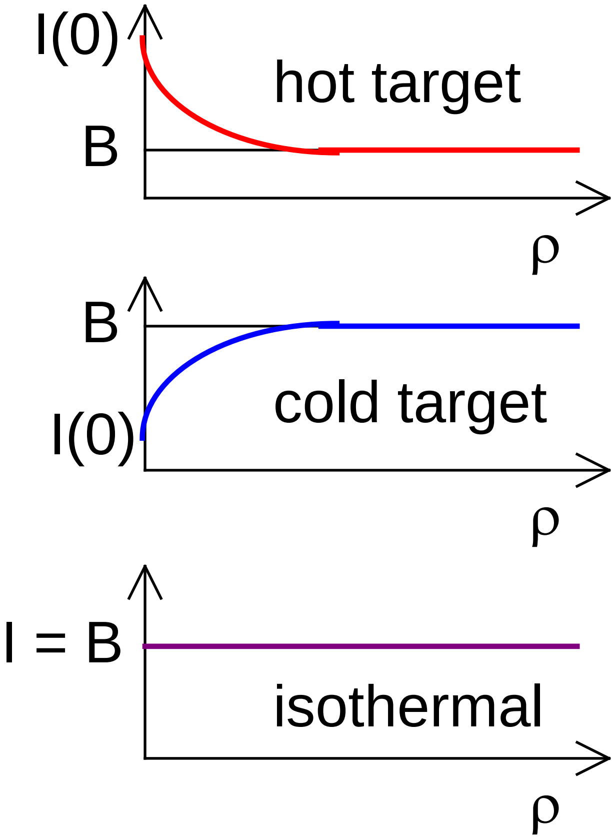
$$I_{\bar{\nu}}(X) = I_{\bar{\nu}}(0)e^{-k_{\bar{\nu}}\rho X} + B_{\bar{\nu}}\left(1 - e^{-k_{\bar{\nu}}\rho X}\right)$$

Measured with no gas in the cell

Measured with gas in the cell

First Example: Lab Gas Cell - 2

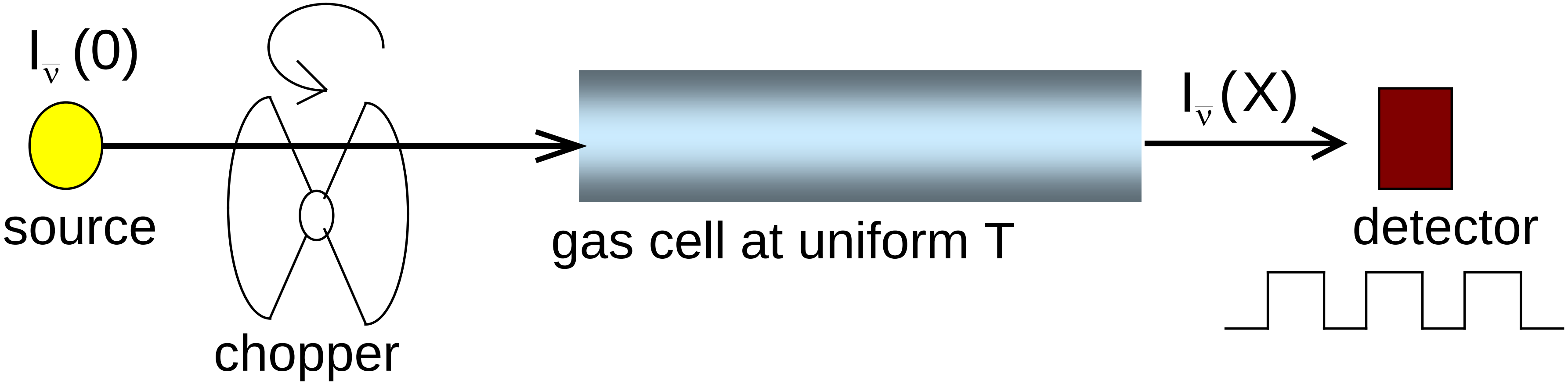
- At “zero” density (vacuum), a detector at the output of the cell will measure *I(0)*
- As the density of the gas (pressure) is increased the measured “exit” intensity will gradually change from *I(0)* to *B*
- In the visible, the emission term is zero (at typical lab temperatures) → Beer’s Law
- In the infrared, the Planck function *B* becomes important. Three possibilities:
  - hot source, cold cell
    - signal decreases from *I(0)* to *B*
  - cold source, hot cell
    - signal increases from *I(0)* to *B*
  - isothermal (source T = cell T)
    - no change



The Use of Choppers

- This gas emission complicates infrared lab experiments.
- One widely used solution is to introduce a chopper that switches rapidly between two values of *I(0)*, and then measure the difference in the output signal.
- The emission signal does not change because the gas temperature is constant.
- Thus, the gas transmission term is isolated by eliminating the gas emission term:

$$\Delta I_{\bar{\nu}}(X) = \Delta I_{\bar{\nu}}(0)e^{-k_{\bar{\nu}}\rho X}$$



$I_{\bar{\nu}}(0)$

source

chopper

gas cell at uniform T

$I_{\bar{\nu}}(X)$

detector

Inhomogeneous Paths

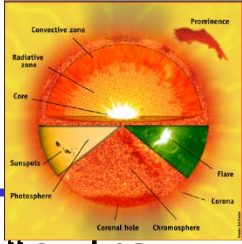
- The real atmosphere is structured in about every physical and chemical manner imaginable in three dimensions, and atmospheric paths are generally <u>inhomogeneous</u> - varying in some parameter(s) such as temperature and pressure.
- To include such inhomogeneous paths, we extend the definition of transmission:

optical path

$$\tau_{\bar{\nu}}(x) = e^{-\chi_{\bar{\nu}}} \quad \text{where} \quad \chi_{\bar{\nu}} = \int_0^x k_{\bar{\nu}}\, \rho dx$$

- This is probably more often called the optical depth. Strictly, for planetary atmospheres, the <u>optical depth</u> means the optical path from the top of the atmosphere to a lower layer. Be careful!
- Note that the transmission from a to b must be the same as that from b to a.
- With this more general expression for τ, Schwarzchild's Equation can be applied to inhomogeneous paths – our second example.

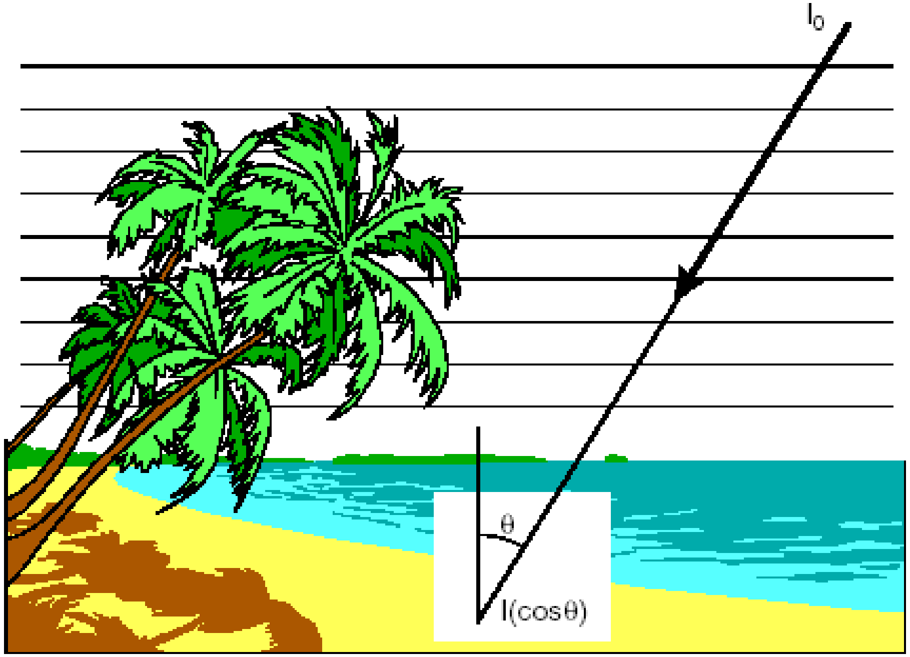
The Sun - A Hot Blackbody



- The solar radiation incident on the Earth’s atmosphere (the “extra-terrestrial” flux density) has the properties of blackbody radiation.
  - → In the UV, visible, and IR regions, seen at low-medium resolution, the solar flux density is almost exactly like that from a blackbody aperture the size and shape of the Sun’s visible disk.
- Temperature of this blackbody = 5780 K.
  - → Can be used to calculate the spectral distribution of the radiation.
- Solar disc subtends an arc of 31.99 minutes at Earth.
  - → This is very small, so the solar radiation is almost exactly a plane wave at the Earth.
- Solar flux density can be described by: $F = I\Delta\Omega \;\; (\text{or} \;\; M_{BB} = B\Delta\Omega)$ where $\Delta\Omega$ is the solid angle subtended by the Sun (6.8×10^{-5} sr).
- Intensity can be found using: $I = (\sigma / \pi)T^4 = 2 \times 10^7 \;\; \text{W m}^{-2} \; \text{sr}^{-1}$
- Thus, the solar flux density at Earth’s orbit is approx. 1370 W m^{-2}.
  - → This is the solar “constant”.

Second Example: Solar Constant - 1

- Now, consider measuring the solar constant from the ground.
- The solar beam is nearly plane-parallel – we can apply the equations for intensity with adequate precision and evaluate the total energy incident upon the radiation detector (the flux density) by multiplying by $\Delta\Omega_s$ – the solar solid angle.
- But the solar radiation passes through the atmosphere, whose transmission properties we do not know
  - → need a way to extract the solar flux density
- This is possible because the Sun moves in solar zenith angle (θ) during the day.



Second Example: Solar Constant - 2

- First split the total spectrum into a large number of bands, each one narrow enough to be described as monochromatic so that Schwarzchild's Equation can be applied to each individual band:

$$I_{total} = \sum_i I(\bar{\nu}_i)\Delta\bar{\nu}_i$$

- Make the plane-parallel atmosphere approximation: the atmosphere is treated by a flat layer of some finite depth.
  - → the total amount of material in the vertical path is M (or U = $\int \rho dx$)
  - → the total in any slant path is M/cosθ
- For a clear sky and the visible spectral region: no emission, so:

$$I(\sec\theta) = I_0 e^{-k_a M \sec\theta}$$

- Making measurements through the day at a range of θ will provide data for a graph...

Second Example: Solar Constant - 3

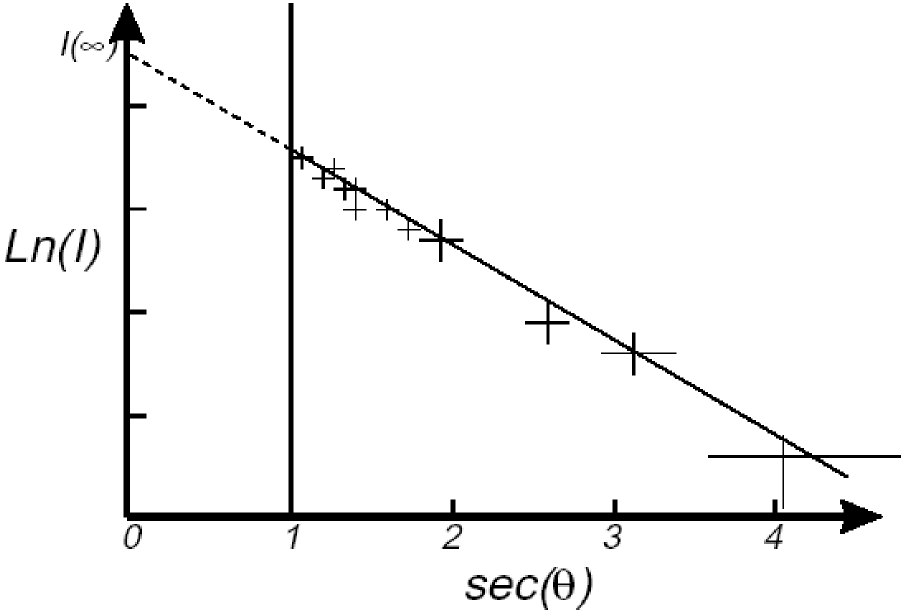
Second Example: Solar Constant - 4

- Rearrange our equation to plot I(sec θ) vs. sec θ:

$$\ln[I(\sec\theta)] = \ln[I_0] - k_a M \sec\theta$$

Equation of a straight line

- The intercept term gives the desired result: *I_0*, the monochromatic extra-terrestrial solar intensity.



- By repeating this at a number of wavelengths, one can obtain the shape of the solar radiation curve and then integrate it to get the **total solar radiation incident upon the Earth's atmosphere**.

Second Example: Solar Constant - 5

What is the weakness of this method?

- The value of *sec* θ is constrained to be > 1 (since *cos* $\theta \leq 1$), therefore we can not construct the full line and the result has to be extrapolated…

Potential errors are thus introduced by:

- The extrapolation
- The assumption of constant conditions over the day
- The measurements in finite wavenumber widths, rather than truly monochromatic
- The non-plane-parallel nature of the atmosphere
- Additional factors as in written notes

However, before the satellite era, this “long method” was the only reliable method for measuring the extra-terrestrial solar flux.

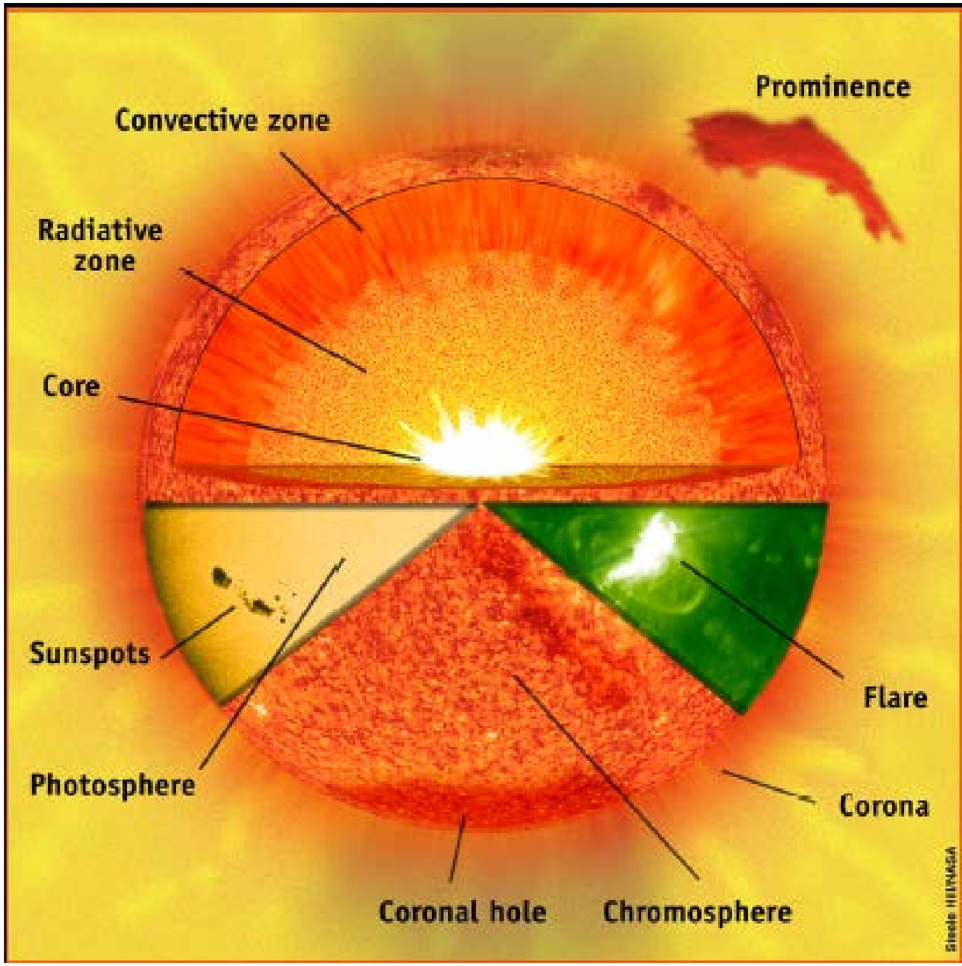
Solar Insolation

The Sun

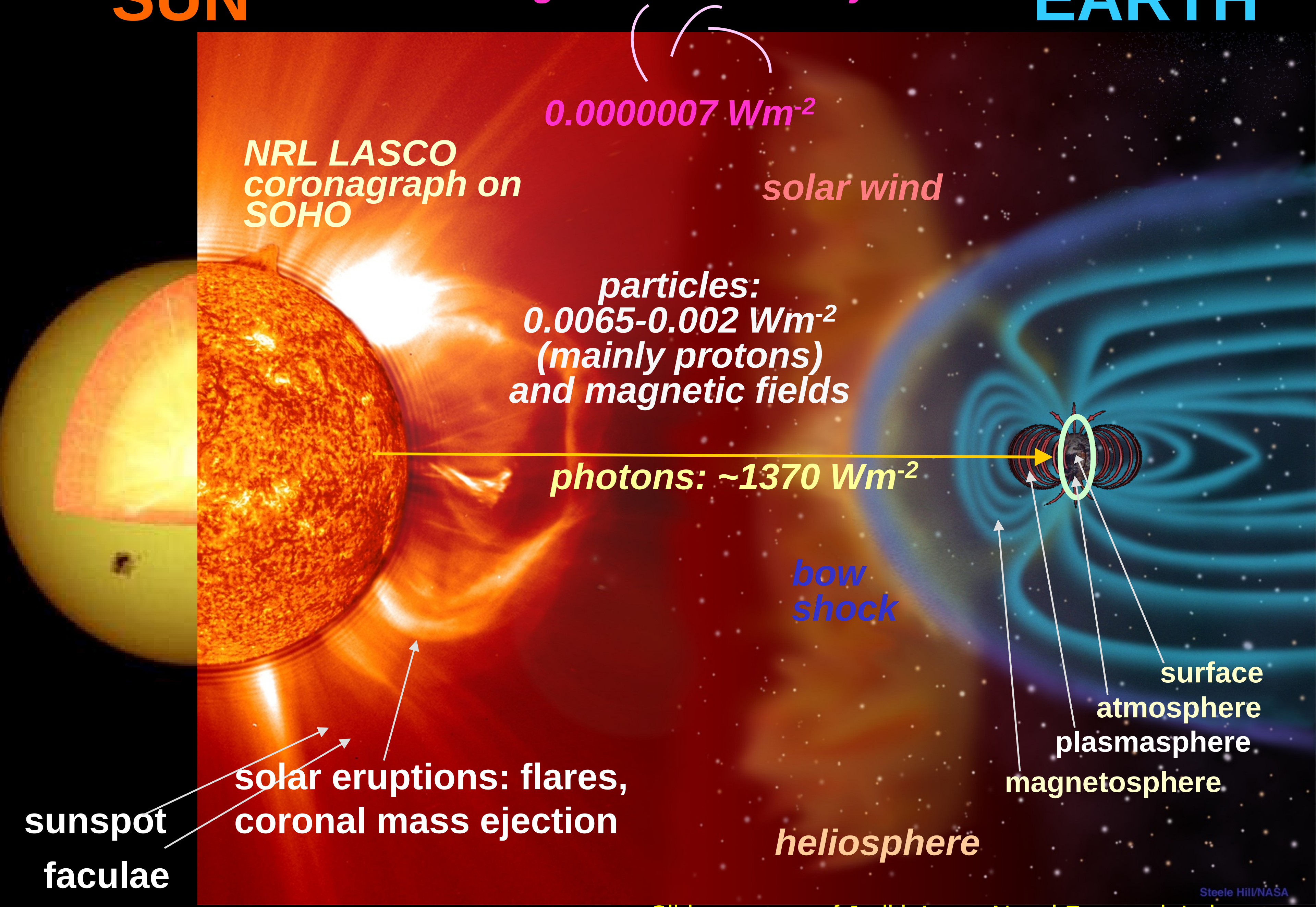
Virtually all the energy that the Earth receives and that sets the Earth's atmosphere and oceans in motion comes from the Sun.

"Once upon a time about 4.6 billion years ago, the sun condensed out of the centre of a thin, hot, spinning disk of interstellar material, according to a theory proposed by Laplace (1796)."   K.N. Liou

- Diameter of about 1.3 million km = 108 Earths
- Visible radius: 6.96×10^5 km
- Mass: 1.99×10^{30} kg
- It accounts for 99% of the mass in our solar system
- Composition: H and He with traces of O, C, N, Ne, Fe, Si, Mg, S, Ca



From: http://sohowww.nascom.nasa.gov/



SUN

galactic cosmic rays

EARTH

0.0000007 Wm^{-2}

NRL LASCO coronagraph on SOHO

solar wind

particles:
0.0065-0.002 Wm^{-2}
(mainly protons)
and magnetic fields

photons: ~1370 Wm^{-2}

bow shock

surface
atmosphere
plasmasphere
magnetosphere

solar eruptions: flares,
coronal mass ejection

sunspot

faculae

heliosphere

Slide courtesy of Judith Lean, Naval Research Laboratory

Properties of Solar Radiation

Source	***Energy (W m^{-2})***	***Solar Cycle change (W m^{-2})***	***Terrestrial deposition altitude (km)***
Solar radiation			
Total irradiance	~1370	1.3	Surface, troposphere
UV 200-300 nm	15.4	0.16	0-50
UV 0 – 200 nm	0.1	0.02	50-500
Particles			
Solar protons	0.002		30-90
Galactic cosmic ray	0.000007		0-90
Solar wind	0.0003		About 500

The Solar Constant (again)

Recall: The solar constant is the solar flux density incident at Earth's orbit (at the top of the Earth's atmosphere) ≈ 1370 W m^{-2}

So, how constant is the solar constant?

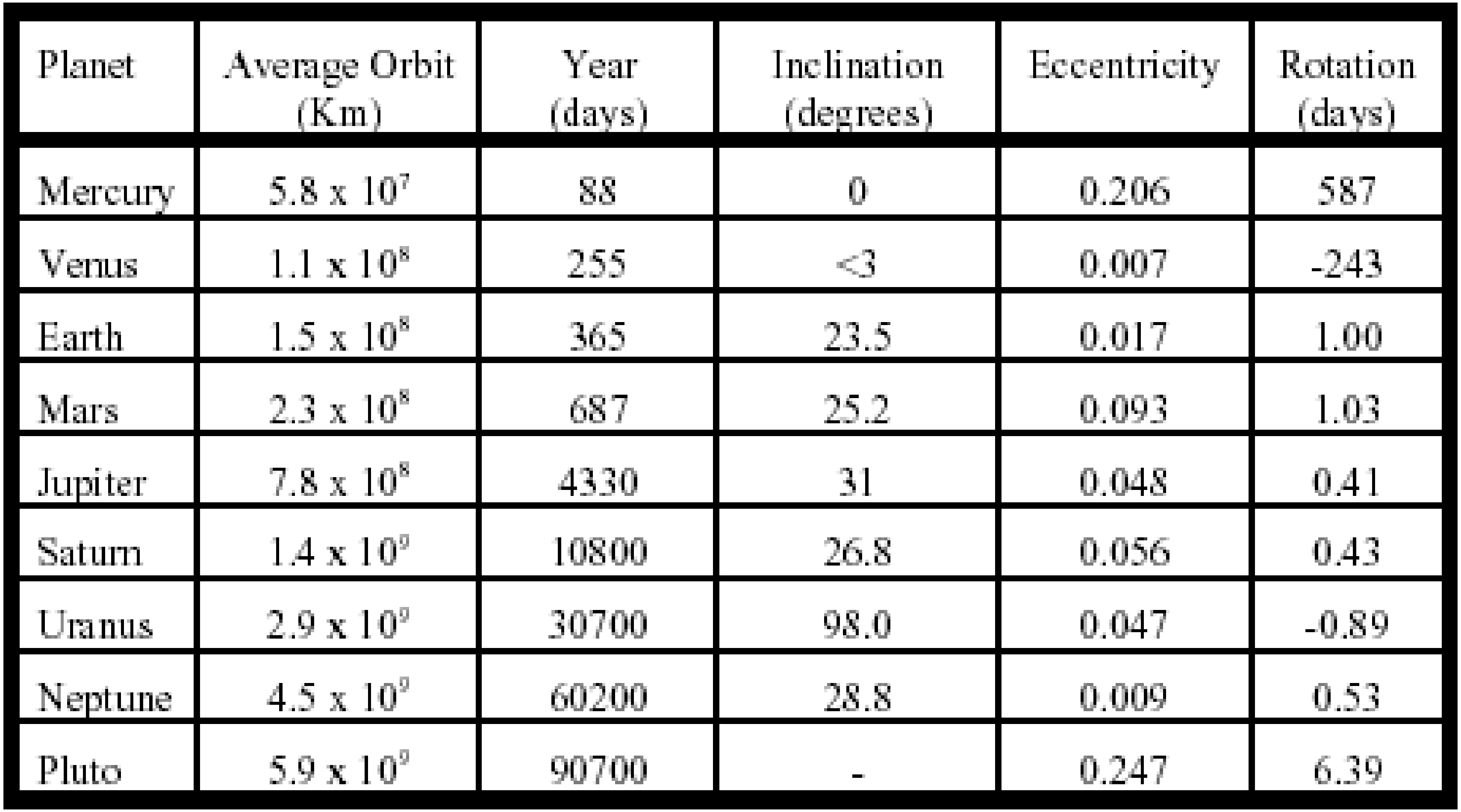
Let's consider the solar input and planetary motion.

- Planets orbit the Sun in elliptical orbits, so the solar radiation incident on the planet must vary with time of year (season).
  - → point of nearest approach (maximum solar input) - perihelion
  - → point of furthest approach (minimum solar input) - aphelion
- The orbit of a planet can also be described using its average distance from the Sun and its eccentricity:

$$e = \sqrt{1 - \left(\frac{\text{minor axis}}{\text{major axis}}\right)^2} = \sqrt{1 - \left(\frac{b}{a}\right)^2} \quad = \text{ zero for a circular orbit}$$

- For Earth, e = 0.017, so the solar radiation varies by about 7%, because the orbital distance varies by 3.5% and the radiation varies with the square of this distance ($1.035^2 = 1.07$).

Planetary Data



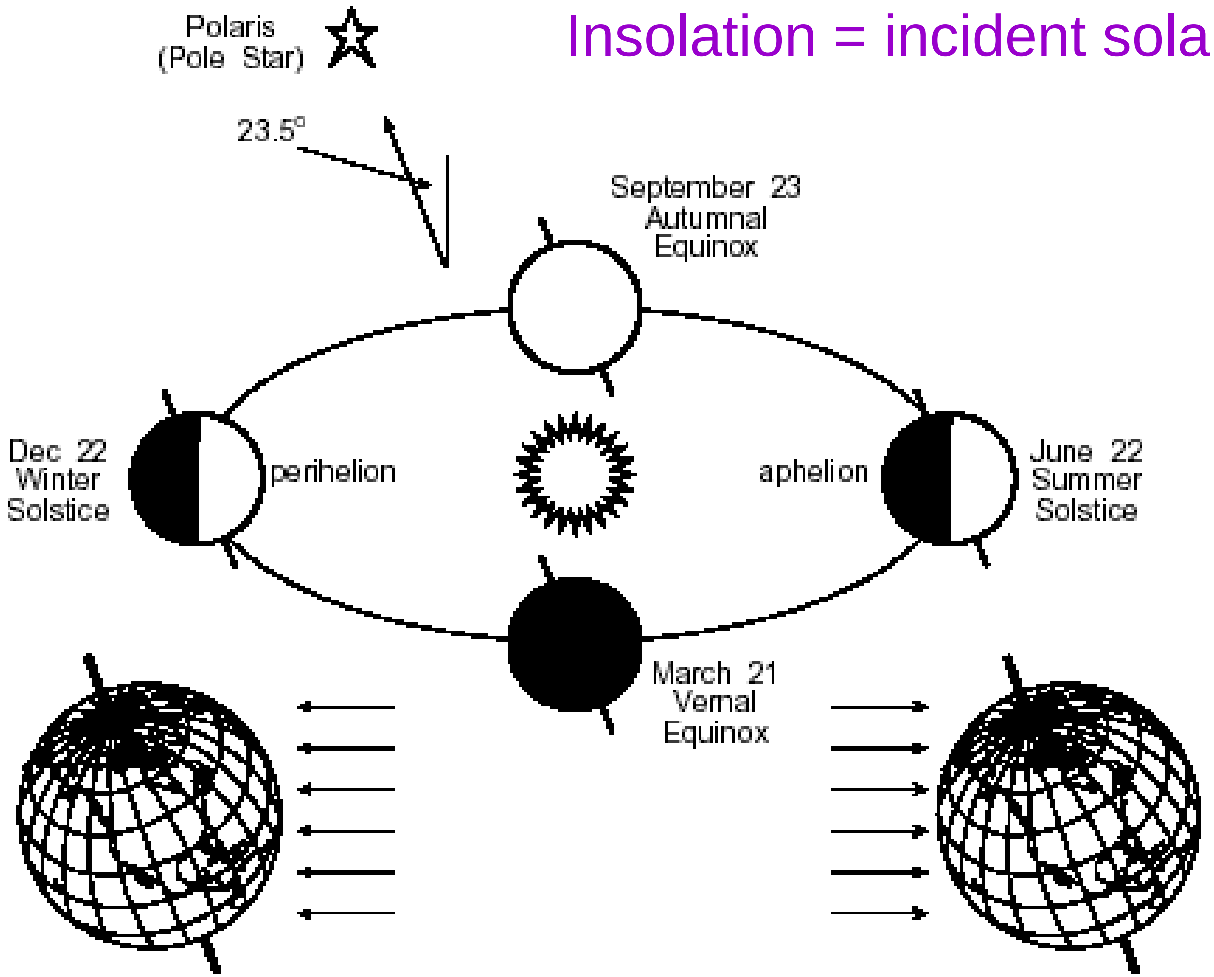
Planet	Average Orbit (Km)	Year (days)	Inclination (degrees)	Eccentricity	Rotation (days)
Mercury	5.8×10^7	88	0	0.206	587
Venus	1.1×10^8	255	<3	0.007	-243
Earth	1.5×10^8	365	23.5	0.017	1.00
Mars	2.3×10^8	687	25.2	0.093	1.03
Jupiter	7.8×10^8	4330	31	0.048	0.41
Saturn	1.4×10^9	10800	26.8	0.056	0.43
Uranus	2.9×10^9	30700	98.0	0.047	-0.89
Neptune	4.5×10^9	60200	28.8	0.009	0.53
Pluto	5.9×10^9	90700	-	0.247	6.39

Seasonal Variations - 1

- In fact, seasonal changes do not correlate with this orbital motion.
  - → different hemispheres have different seasonal phases
  - → perihelion occurs in the Northern hemisphere winter
- The seasonal change is more a function of the <u>planetary inclination</u>, which is the angle that the planetary rotation vector makes with the normal to the orbital plane.
- This inclination causes the average angle which a portion of the planet's surface makes with the solar beam to vary.
- If the "surface" of the atmosphere is not normal to the solar beam then the energy input (ignoring orbital changes) is $F\cos\theta$, where θ is the angle between the solar beam and the vertical - the <u>solar zenith angle</u>.
  - → A planet whose axis of rotation is perpendicular to the plane of the orbit, will see the average solar radiation per unit area decrease uniformly from the equator to the poles.

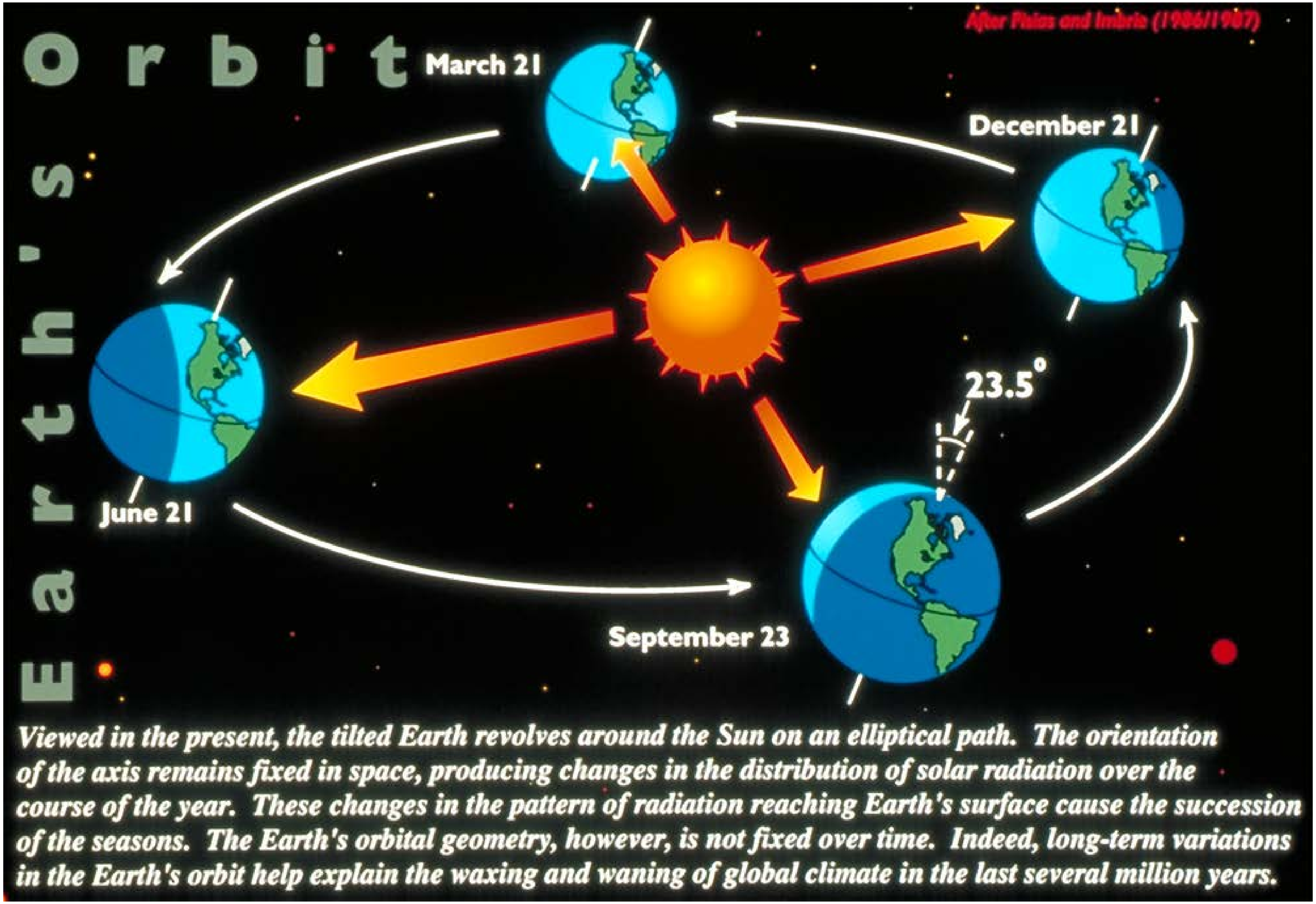
Seasonal Variations - 2

Insolation = incident solar radiation



Variation of solar insolation with orbital position (for Earth)

Seasonal Variations - 3

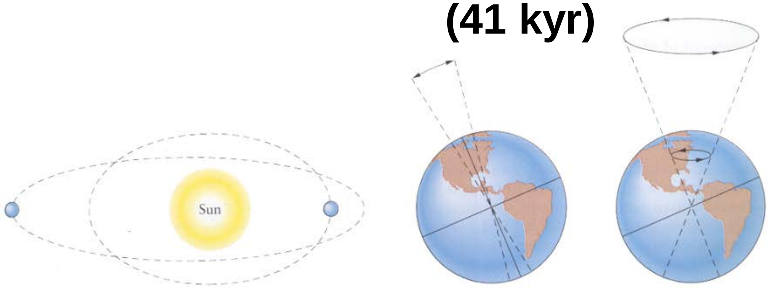


Viewed in the present, the tilted Earth revolves around the Sun on an elliptical path. The orientation of the axis remains fixed in space, producing changes in the distribution of solar radiation over the course of the year. These changes in the pattern of radiation reaching Earth's surface cause the succession of the seasons. The Earth's orbital geometry, however, is not fixed over time. Indeed, long-term variations in the Earth's orbit help explain the waxing and waning of global climate in the last several million years.

Credit: Thomas G. Andrews, NOAA Paleoclimatology Program, http://www.ncdc.noaa.gov/paleo/education.html

Climate Cycles

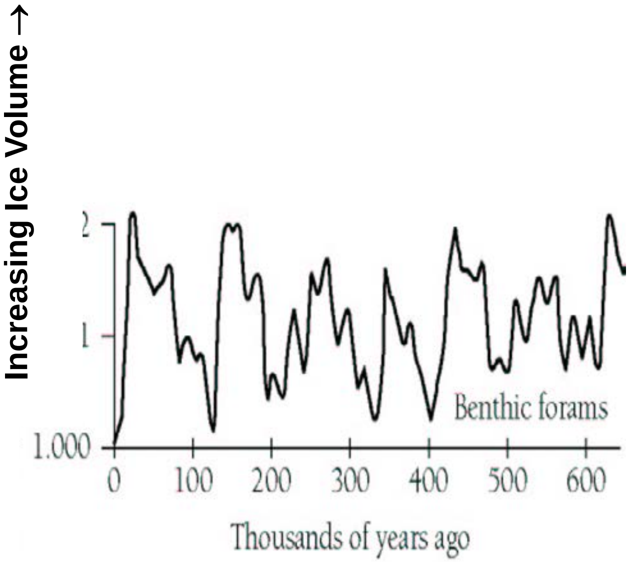
Milankovitch cycles: periodic changes in the flux of solar radiation received by Earth driven by changes in Earth’s orbit

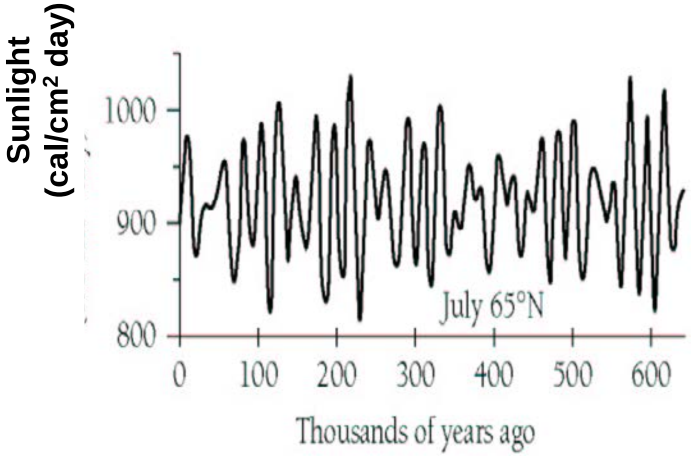


Obliquity (tilt)
(41 kyr)

Eccentricity
(105 kyr)

Precession
(26 kyr)





New: Distribution of Solar Insolation

Daily insolation = flux of solar radiation per unit horizontal area (J/m^2):

$$Q = I\,\Delta\Omega_s \int_{1\ \mathrm{day}} \cos\theta(t)\,dt$$

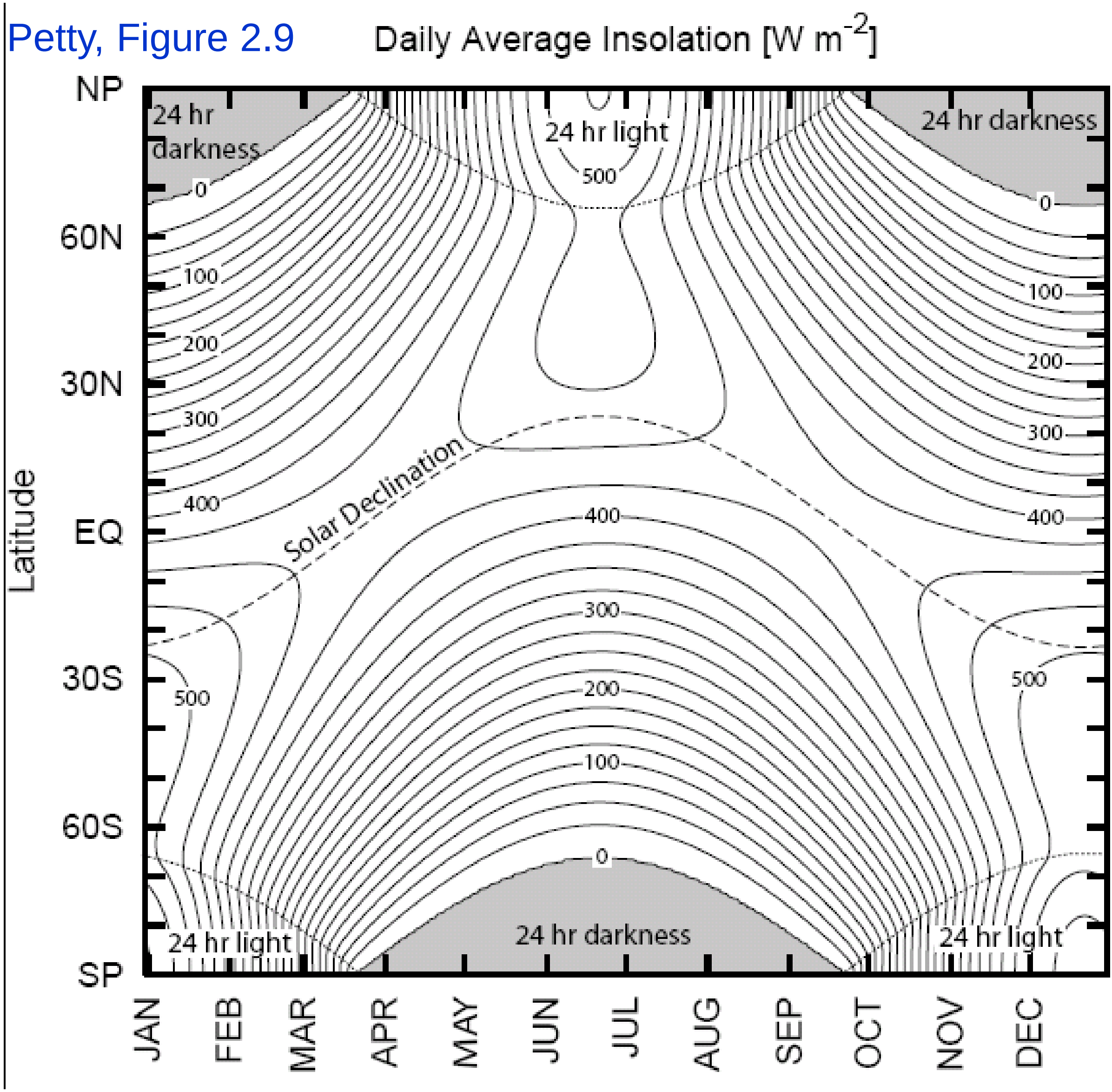
Since Earth rotates about an axis 23.5° to the normal of its orbit around the Sun, $\theta(t)$ varies in a complex way.

The next slide shows the daily solar insolation at the top of the atmosphere as a function of latitude and time of the year

- Maximum daily insolation is at the South Pole in SH summer, followed by the North Pole in NH summer (due to 24 hours of sunlight and Earth being at perihelion December – SH summer)
- Distribution is slightly asymmetric because the Sun is closest to Earth in NH winter, so more radiation is received in the SH
- Night/winter poles receive no solar radiation
- Integration of Q for one year yields the same total solar insolation for corresponding NH and SH latitudes (see slide 25)

Daily Insolation for the Earth

Petty, Figure 2.9



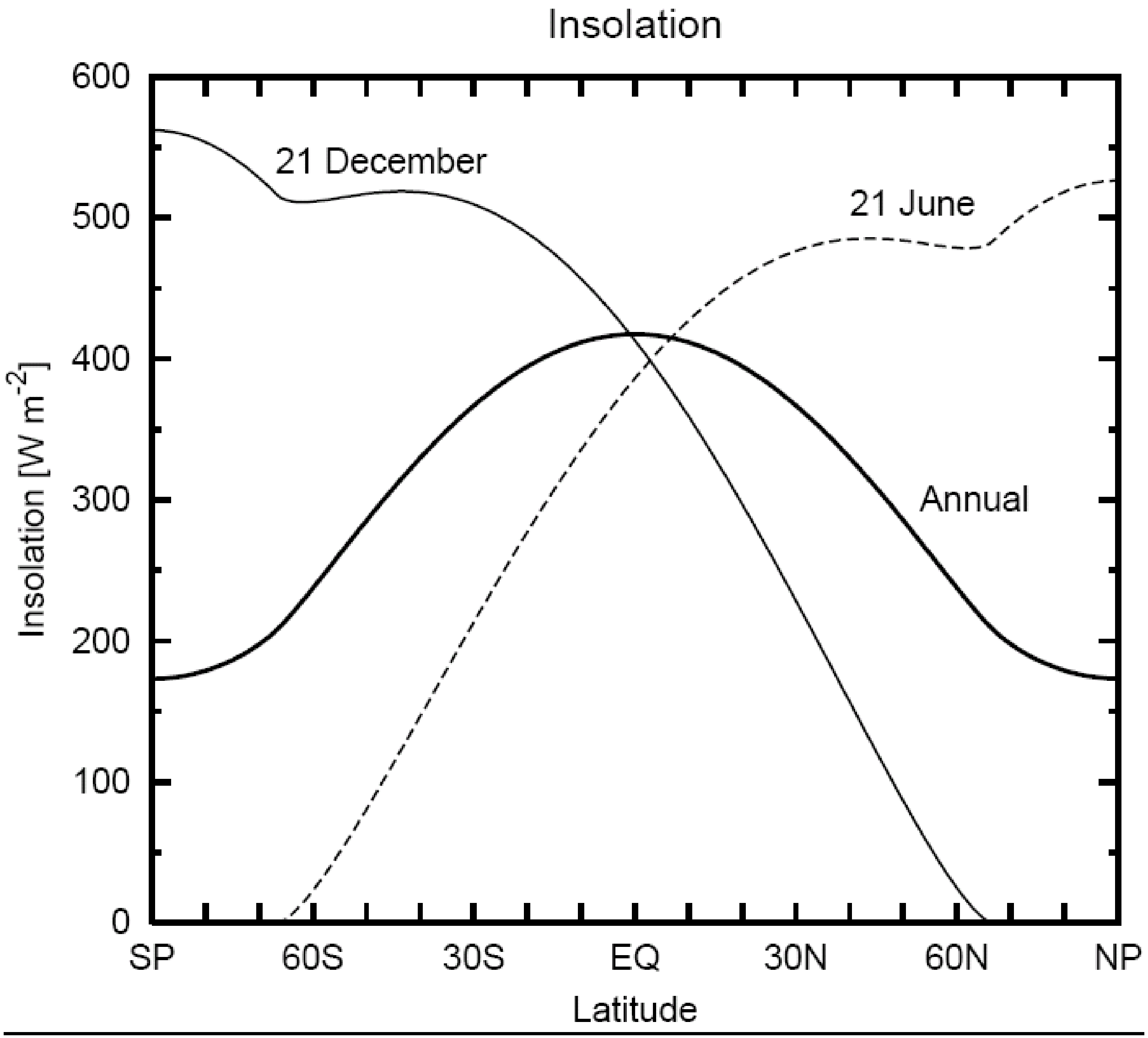
Daily average solar flux density at the top of the atmosphere, as a function of latitude and time of year.

Determined by:

- length of day
- solar zenith angle
- Earth-Sun distance

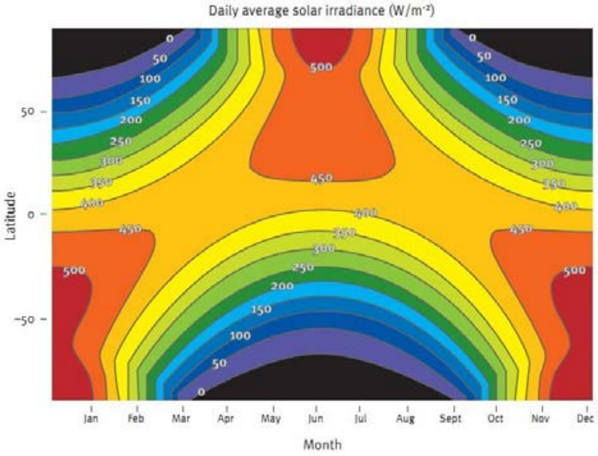
Solar declination indicates where the Sun passes directly overhead.

Daily Insolation for the Earth



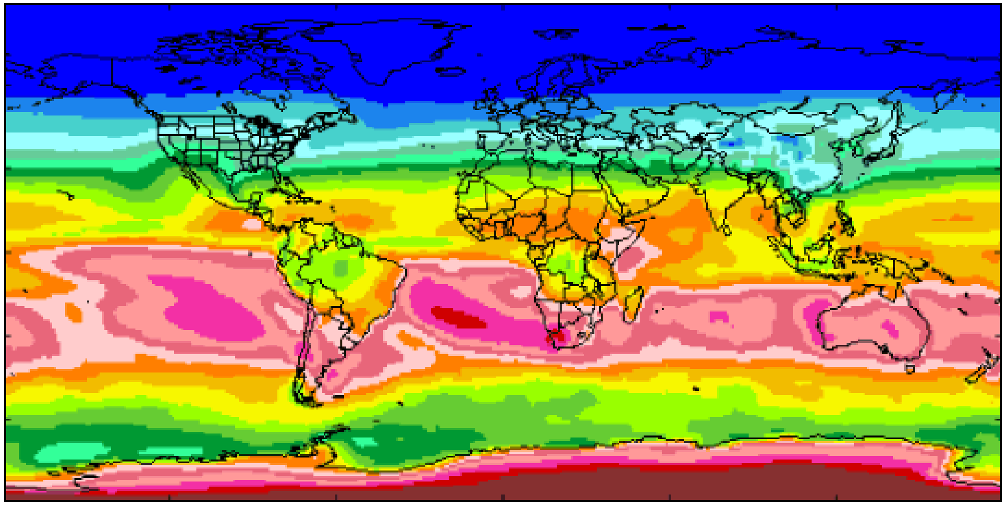
Petty, Figure 2.10

Daily average solar flux density at the top of the atmosphere as a function of latitude, for the two solstice dates and averaged over a year.

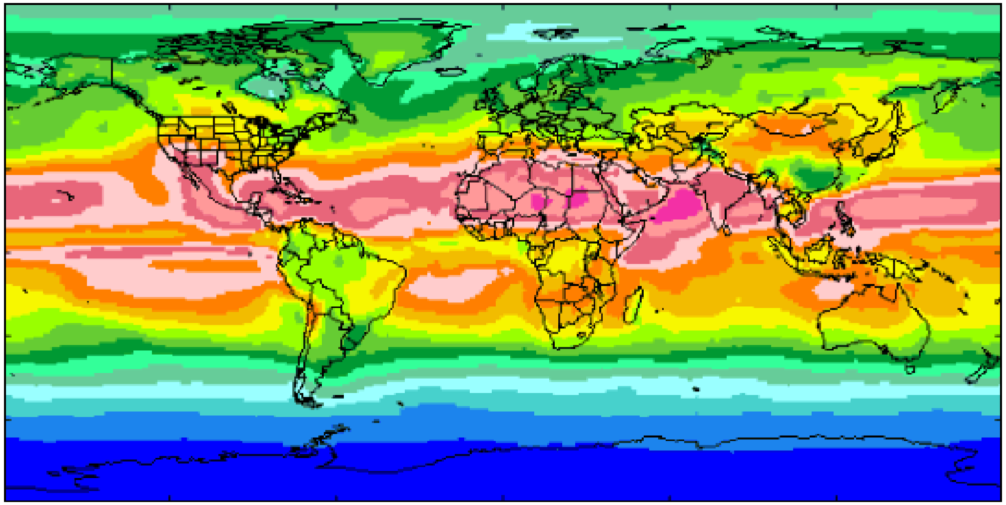


Grantham Institute for Climate Change,
Briefing paper No 5, February 2011

Average Solar Insolation at Surface



January 1984–1993

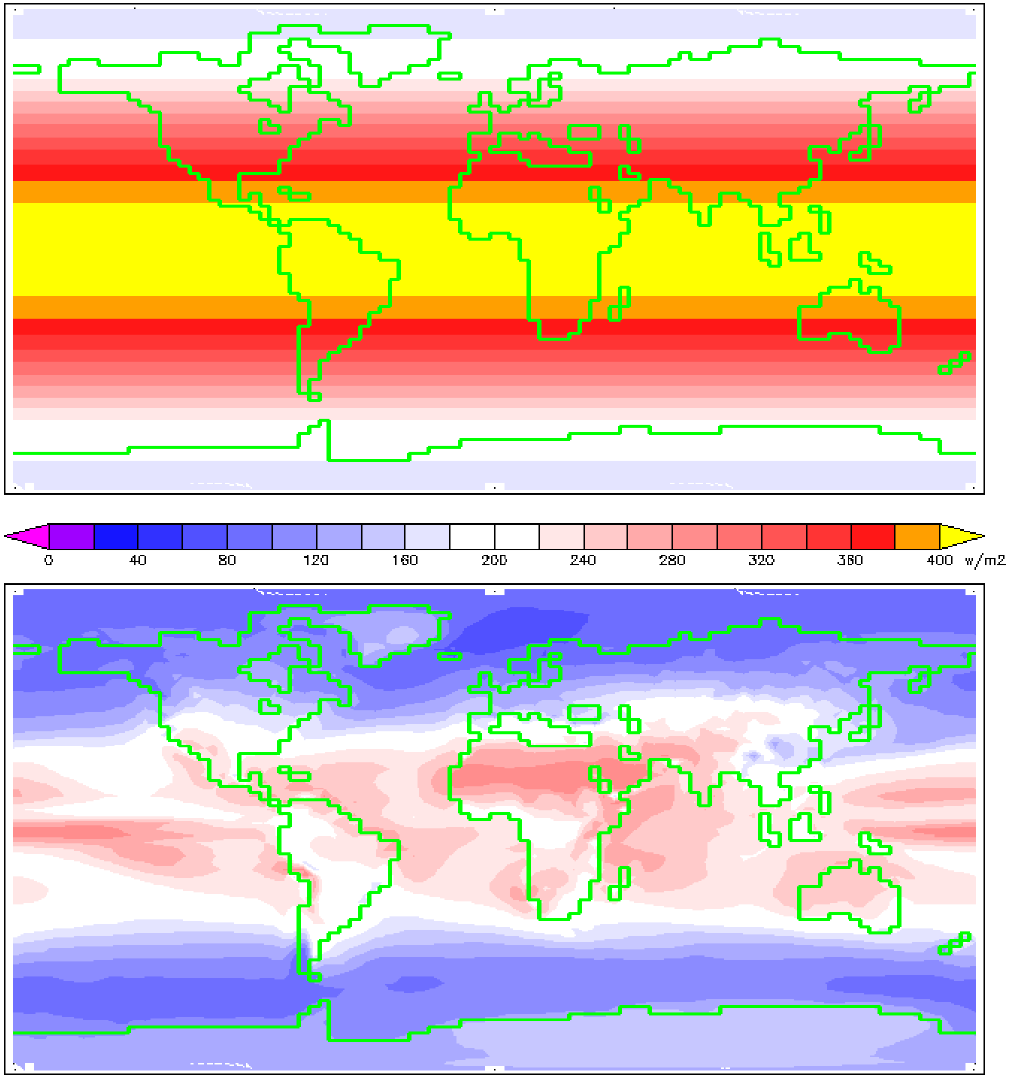


April 1984–1993

False-color images of the average solar insolation over the globe for January and April. The colors correspond to values (kilowatt hours per square meter per day) measured by a variety of Earth-observing satellites and integrated by the International Satellite Cloud Climatology Project (ISCCP). NASA's Surface Meteorology and Solar Energy (SSE) Project compiled these data - collected from July 1983 to June 1993 - into a 10-year average for that period.

http://visibleearth.nasa.gov/view_rec.php?id=1683

Effect of the Atmosphere on Solar Insolation at Surface



William M. Connolley, HadCM3 data

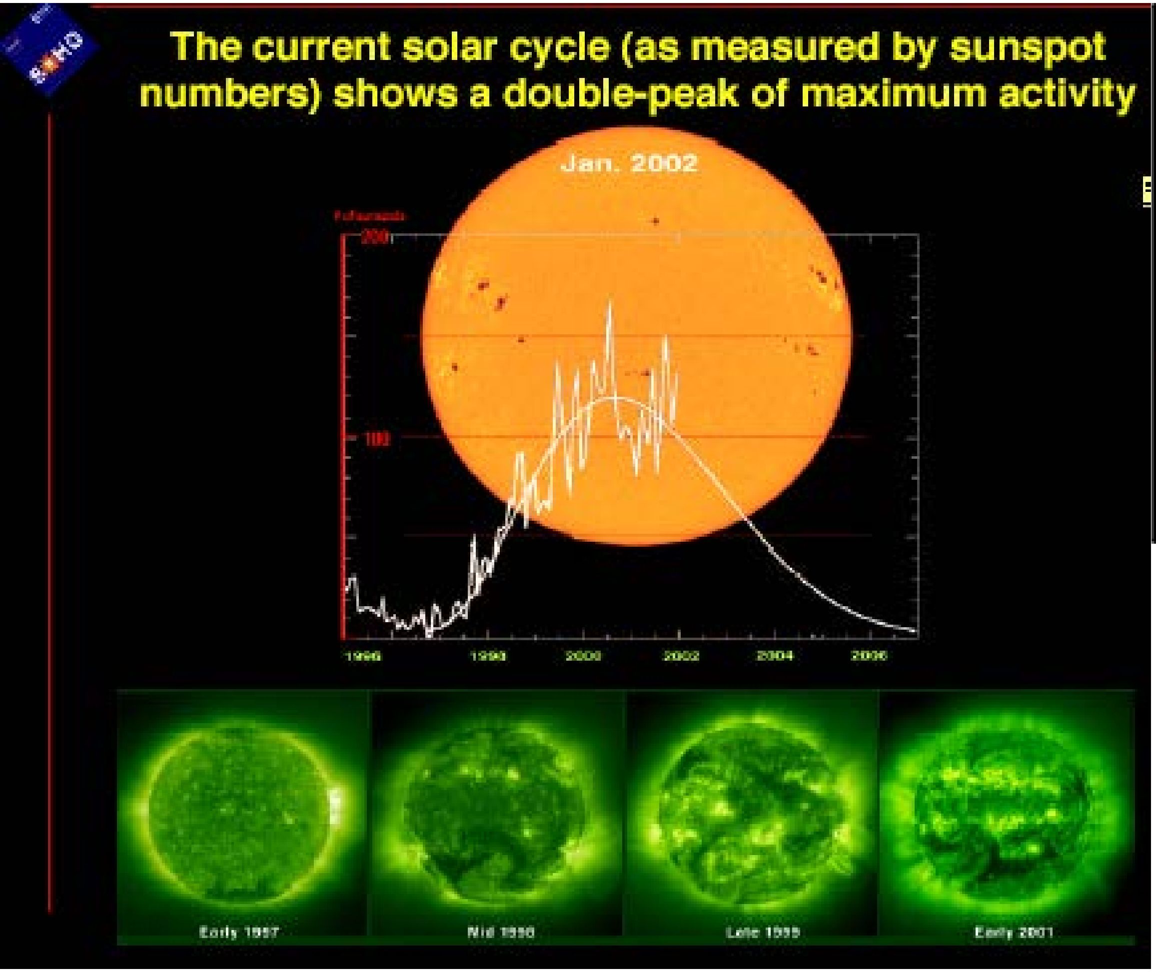
Top panel: the annual mean solar insolation at the top of Earth's atmosphere

Bottom panel: the annual insolation reaching the Earth's surface after passing through the atmosphere

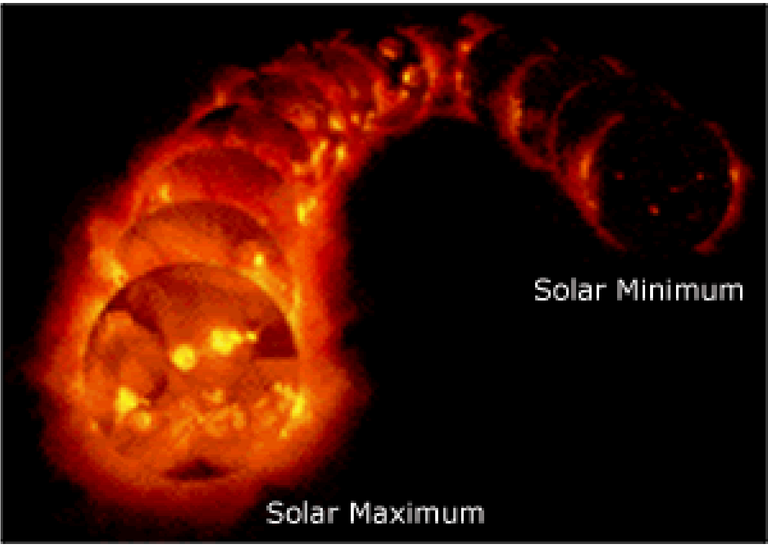
Solar Variability

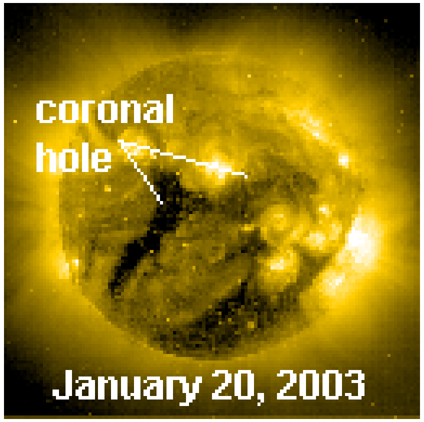
The Solar Cycle

The approximately 11-year quasi-periodic variation in frequency or number of sunspots, coronal mass ejections, solar flares, and other solar activity.



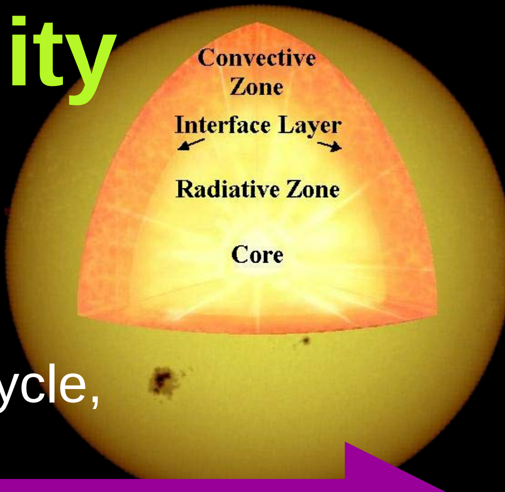
The current solar cycle (as measured by sunspot numbers) shows a double-peak of maximum activity





http://sohowww.nascom.nasa.gov/

Time Scales of Solar Variability



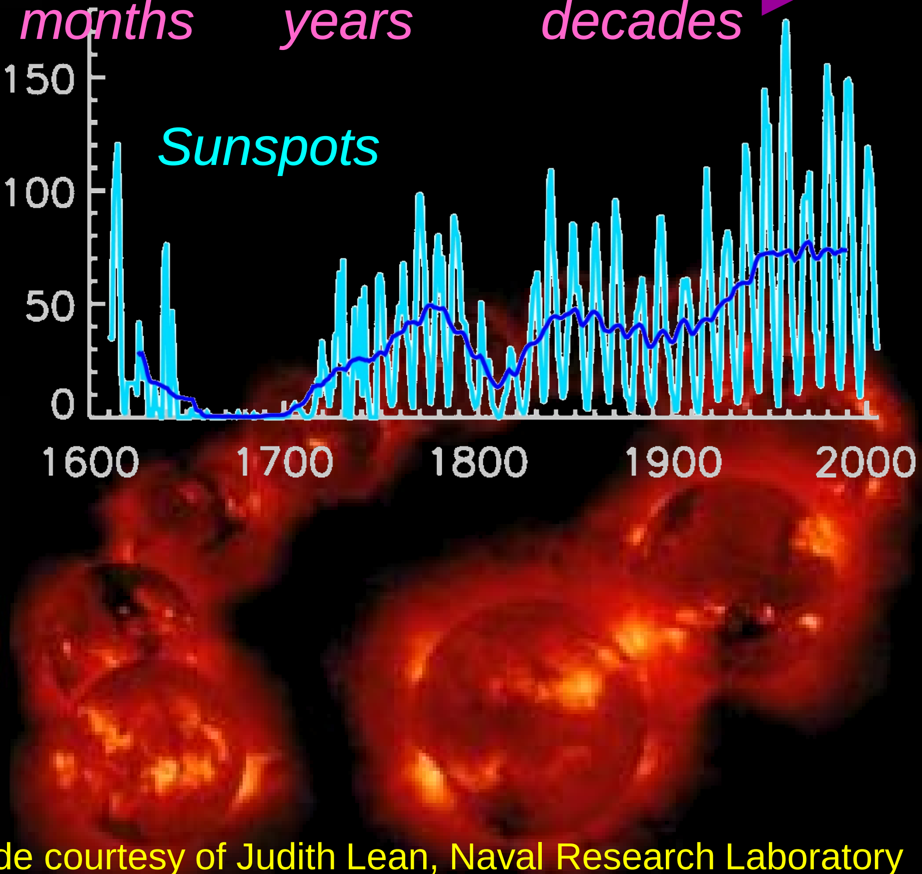
activity cycle,
dynamo

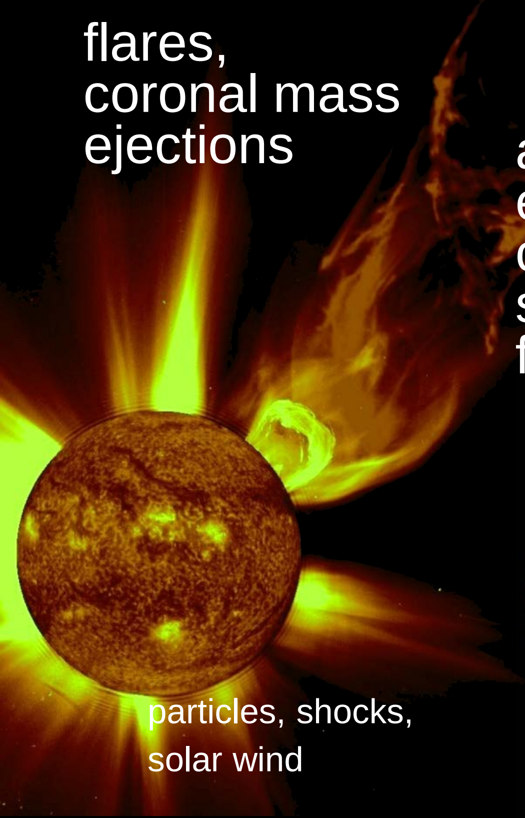
minutes *hours* *days* *weeks* *months* *years* *decades*

flares,
coronal mass
ejections

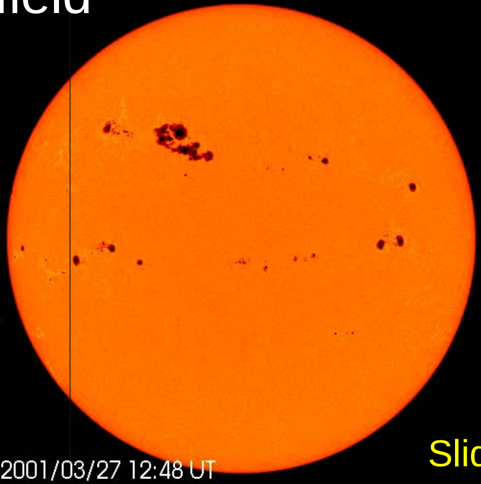
solar rotation

active region
evolution… plage,
coronal holes,
sunspots, magnetic
field



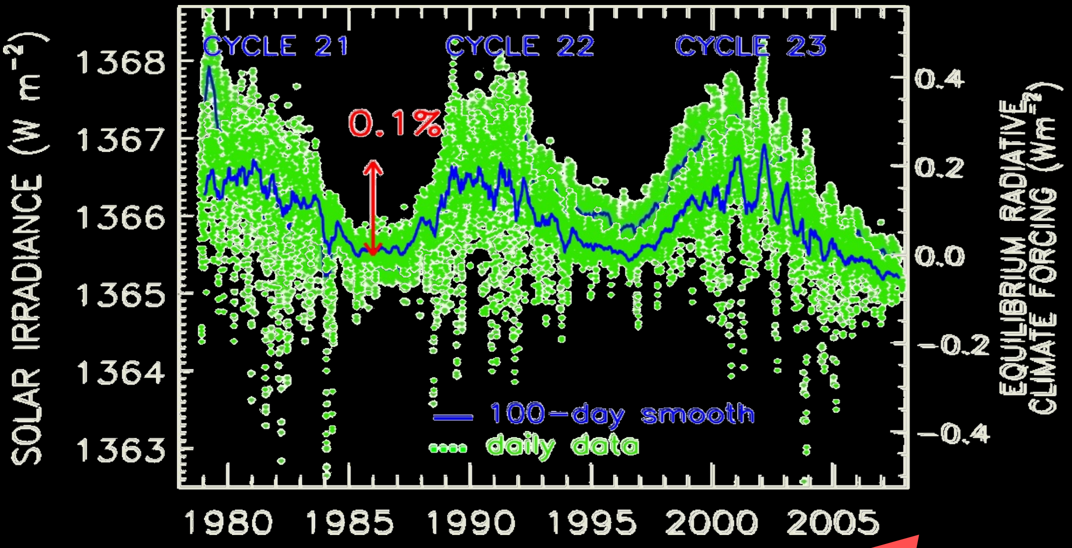


particles, shocks,
solar wind



Slide courtesy of Judith Lean, Naval Research Laboratory

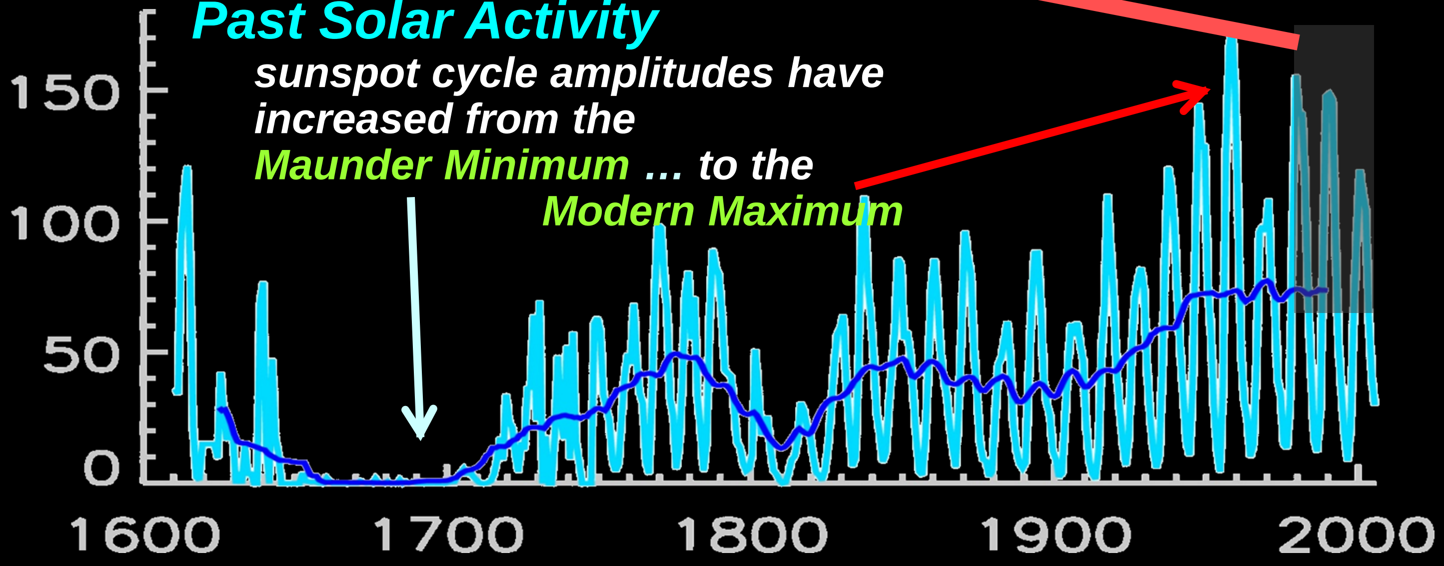
The Sun’s Brightness Varies Continuously



- 5-min oscillation ~ 0.003%
- 27-day solar rotation ~ 0.2%
- 11-year solar cycle ~ 0.1%
- longer-term variations not yet detectable –

  ……do they occur?

data: Fröhlich & Lean,AARev,2004 http://www.pmodwrc.ch

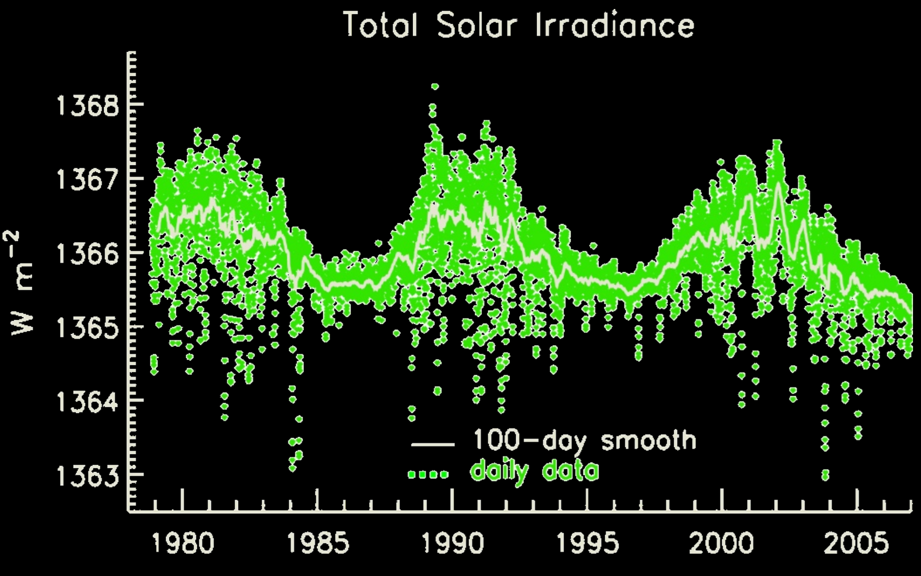


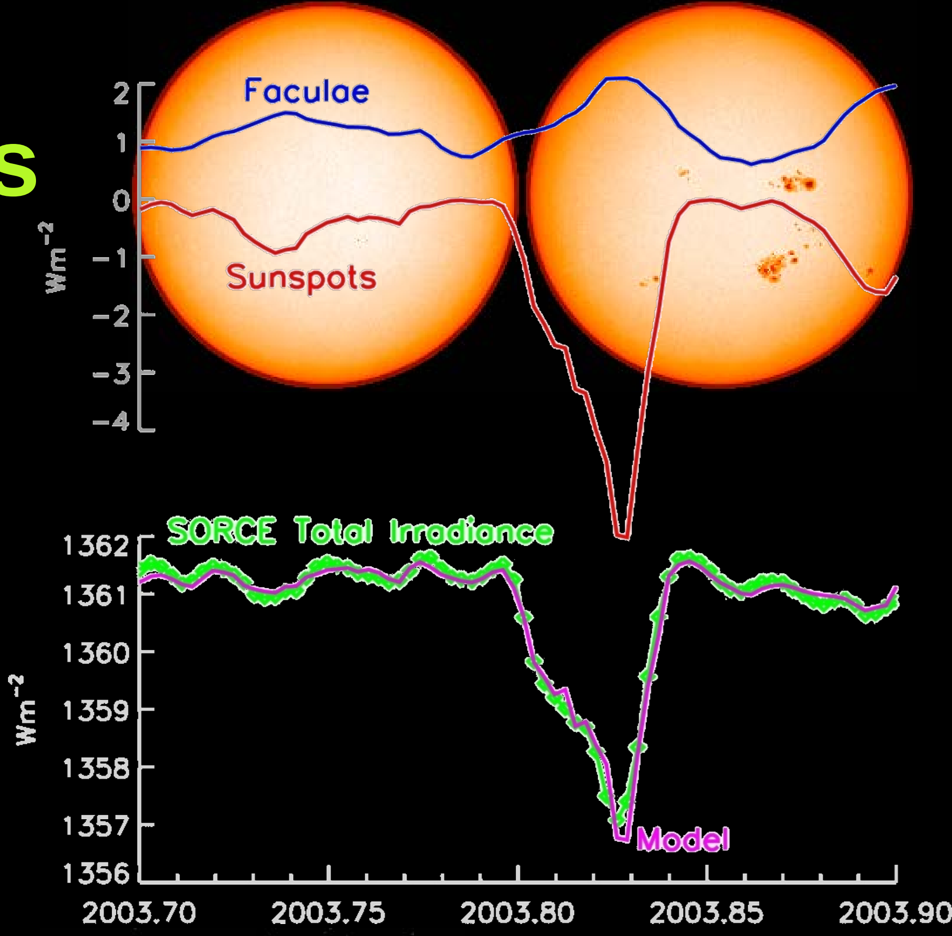
Past Solar Activity

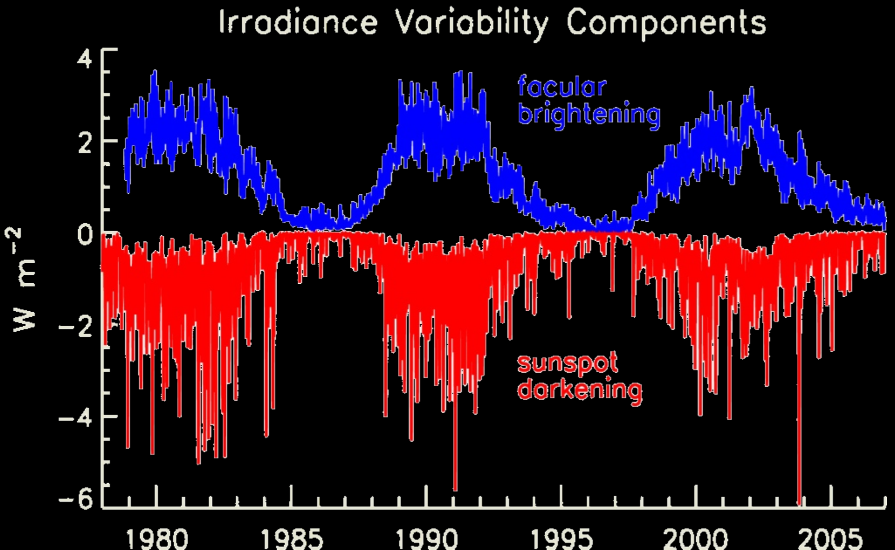
sunspot cycle amplitudes have increased from the Maunder Minimum … to the Modern Maximum

Slide courtesy of Judith Lean, Naval Research Laboratory

Sources of Solar Irradiance Variations







Solar Radiation and Climate Experiment (SORCE)

http://lasp.colorado.edu/sorce

Slide courtesy of Judith Lean, Naval Research Laboratory

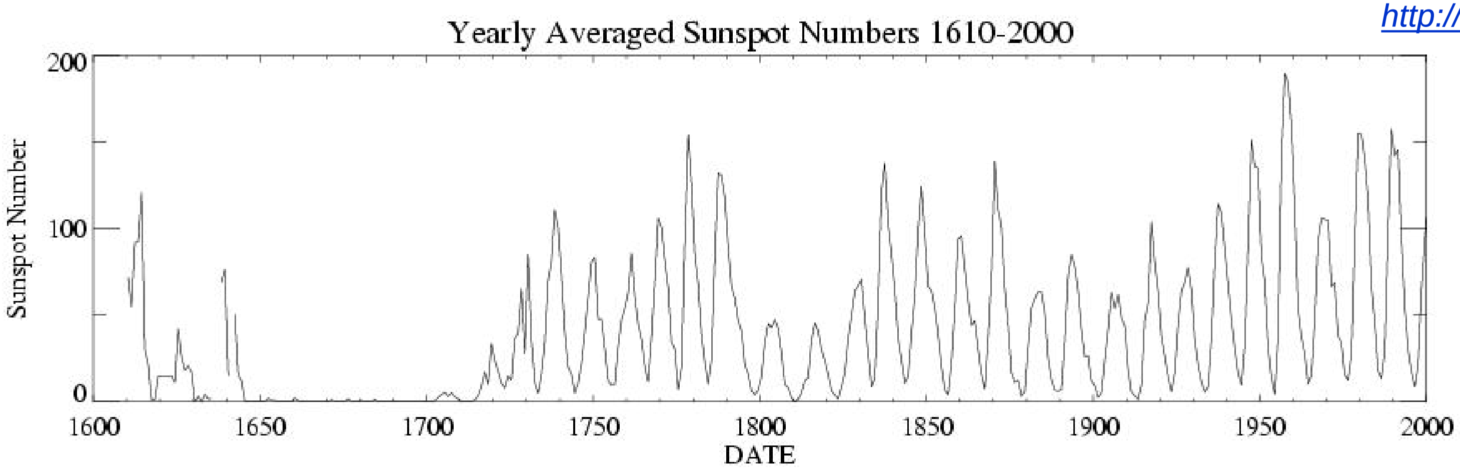
Sunspots

- Temporary disturbed areas in the solar photosphere that appear dark because they are cooler than the surrounding areas.
- Consist of concentrations of strong magnetic flux.
- Usually occur in pairs or groups of opposite polarity that move in unison across the face of the Sun as it rotates.
- High magnetic activity also creates faculae and plages, which are bright hot regions.

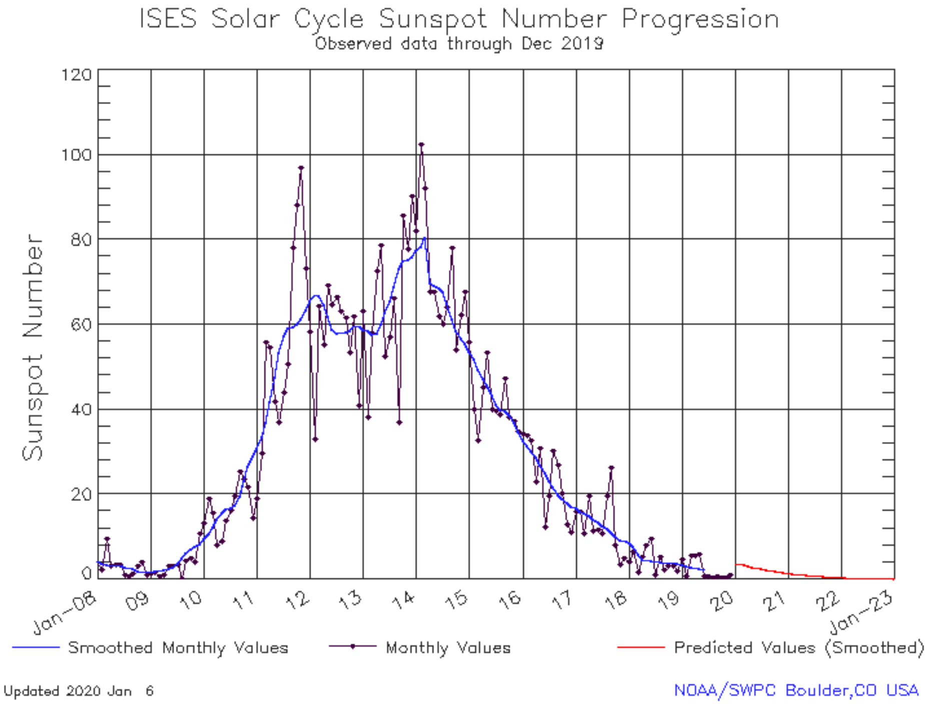

Sunspots changing over a week

Sunspots rotate with the Sun (every 27 days) and can appear, grow, get smaller or disappear over time. They can last from hours to months.

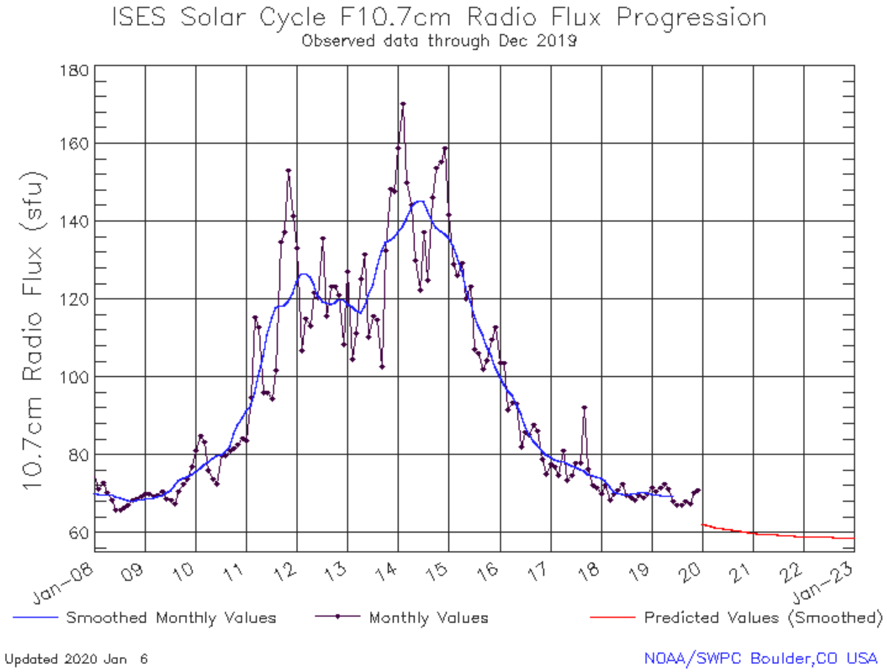
http://sohowww.nascom.nasa.gov/


Yearly Averaged Sunspot Numbers 1610-2000

Current Solar Cycle



ISES = International Space Environment Service
http://www.ises-spaceweather.org/



In both plots, the black line represents the monthly averaged data and the blue line represents a 13-month smoothed version of the monthly averaged data. The forecast for the rest of the solar cycle is given by the red line.

Solar cycle predictions are used by various agencies and many industry groups. The solar cycle is important for determining the lifetime of satellites in low-Earth orbit, as the drag on the satellites correlates with the solar cycle, especially as represented by F10.7cm. A higher solar maximum decreases satellite life and a lower solar maximum extends satellite life.

Plots from NOAA Space Weather Prediction Center
https://www.swpc.noaa.gov/products/solar-cycle-progression

The Effect of the Solar Cycle - 1

The intensity of the Sun varies along with the 11-year sunspot cycle.

- When sunspots are numerous the solar constant is high (~1367 W/m^2). When sunspots are scarce the value is low (~1365 W/m^2). This is due to increased emission from the plages and faculae.
- Eleven years isn't the only cycle. The solar constant can fluctuate by ~0.1% over days and weeks as sunspots grow and dissipate.
- The solar constant also drifts by 0.2% to 0.6% over many centuries.

These small changes can affect Earth in a big way. For example, between 1645 and 1715 (a period astronomers call the "Maunder Minimum") the sunspot cycle stopped; the face of the Sun was nearly blank for 70 years. At the same time Europe was hit by an extraordinary cold spell: the Thames River in London froze, glaciers advanced in the Alps, and northern sea ice increased.

The Effect of the Solar Cycle - 2

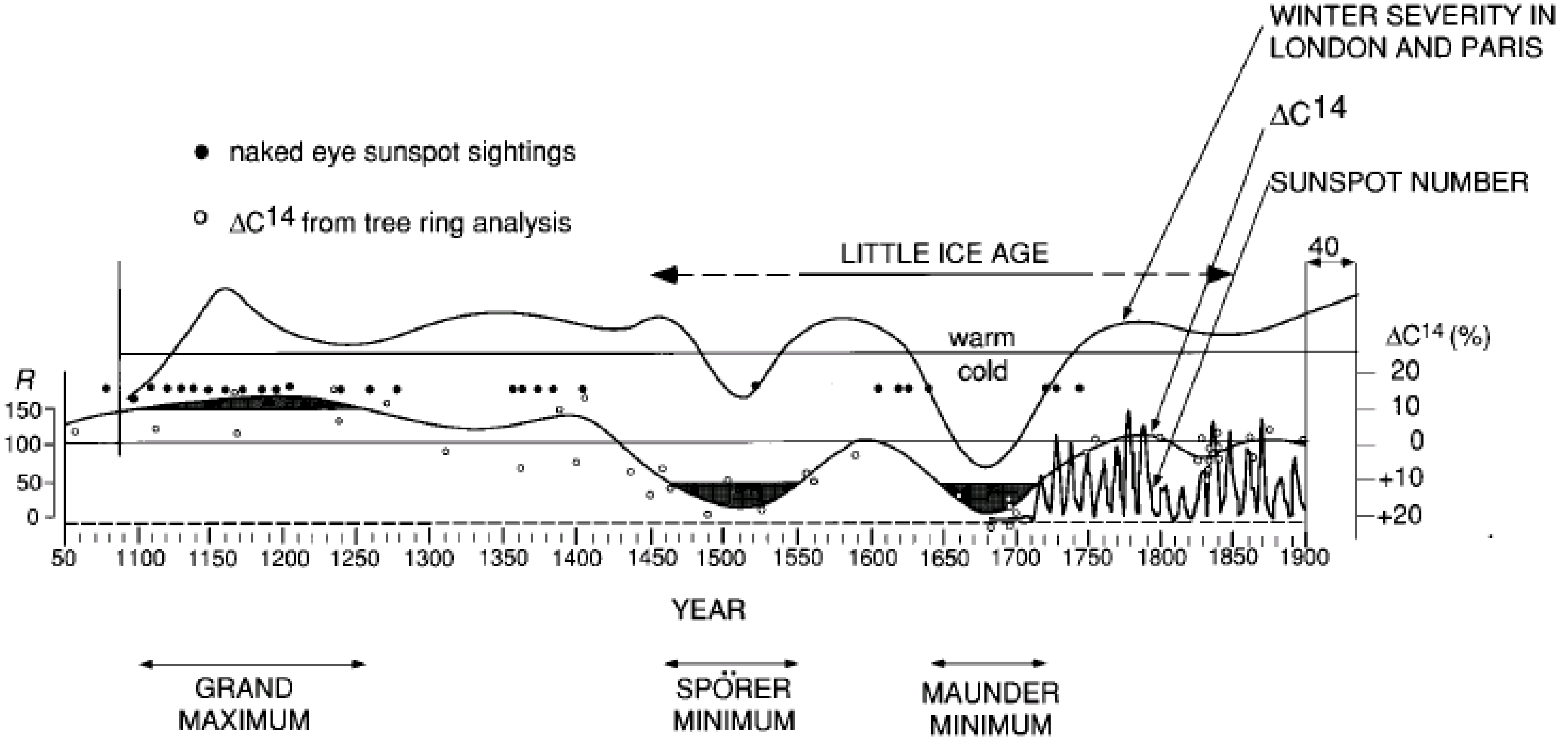


FIG. 15. Shown is the relationship between winter severity in Paris and London (top curve) and long-term solar activity variations (bottom curve). The shaded portions of this curve denote the times of the Spörer and Maunder minima in sunspot activity. The dark circles indicate naked-eye sunspot observations. Details of the solar activity variation since 1700 are indicated in the bottom curve by the sunspot number data. The winter severity index has been shifted 40 yr to the right to allow for cosmic ray-produced ^{14}C assimilation into tree rings. From Eddy (1976, 1977).

From Lean & Rind, J. Climate, 1998.

The Effect of the Solar Cycle - 3

The total energy coming from the Sun only varies by about 0.1% over each 11-year cycle. For a long time scientists didn't notice this, which is why the Sun's intensity is called, ironically, the “solar constant”.

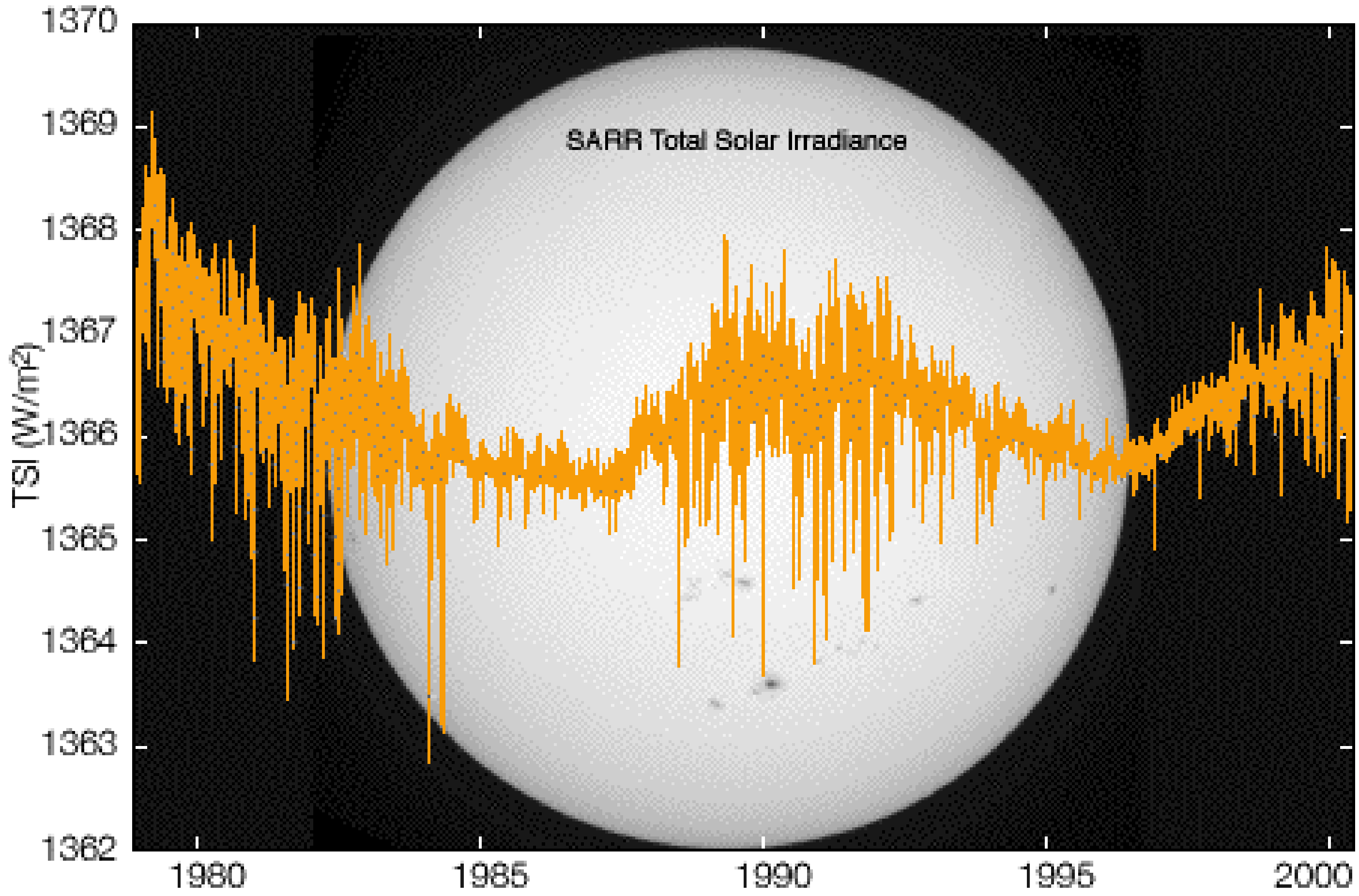


Image credit: Catania Astrophysical Laboratory.

How sensitive is the Earth's climate to changes in solar radiation?

- Sensitivity of climate to solar radiation changes is not well known.
  - → A conservative estimate is that a 0.1% change in solar total radiation will bring about a temperature response of 0.06 to 0.2 °C, providing the change persists long enough for the climate system to adjust. This could take 10 to 100 years.
- The Sun plays a critical role in the Earth's climate system, with both changing continually, over all time scales.
- Physical connections that link the variations seen in one with the variability in the other remain poorly understand.
- We only have continuous monitoring of direct solar radiation since 1979 - a very short period in the life of the Sun.
- Reconstructed data suggests solar radiation changes may
  - → have been the dominant climate forcing in the 1600s &1700s
  - → contribute to about half of the 0.55°C surface warming since 1900
  - → be responsible for <1/3 of surface warming since 1970

Can Solar Changes Affect Earth’s Climate?

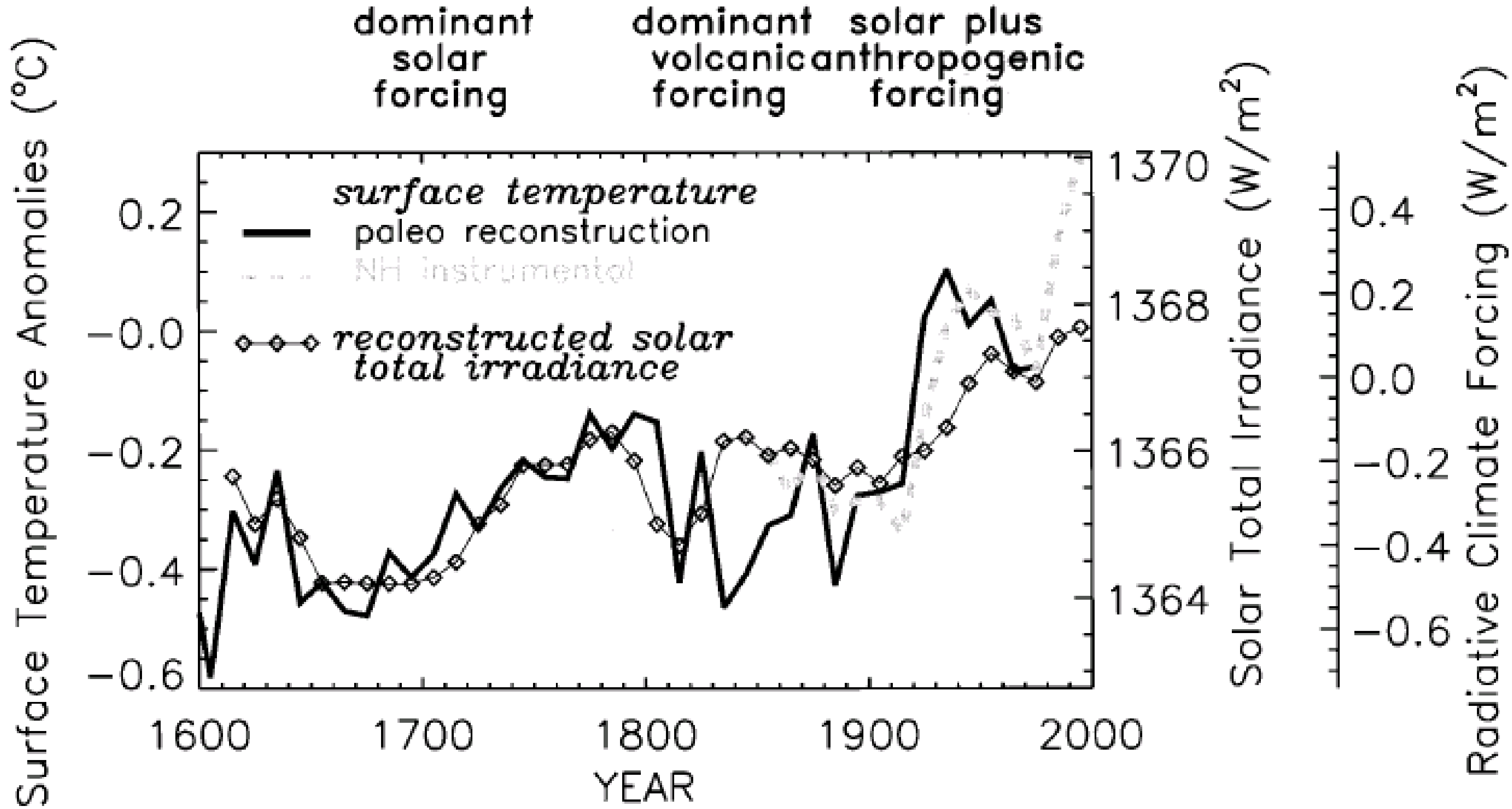
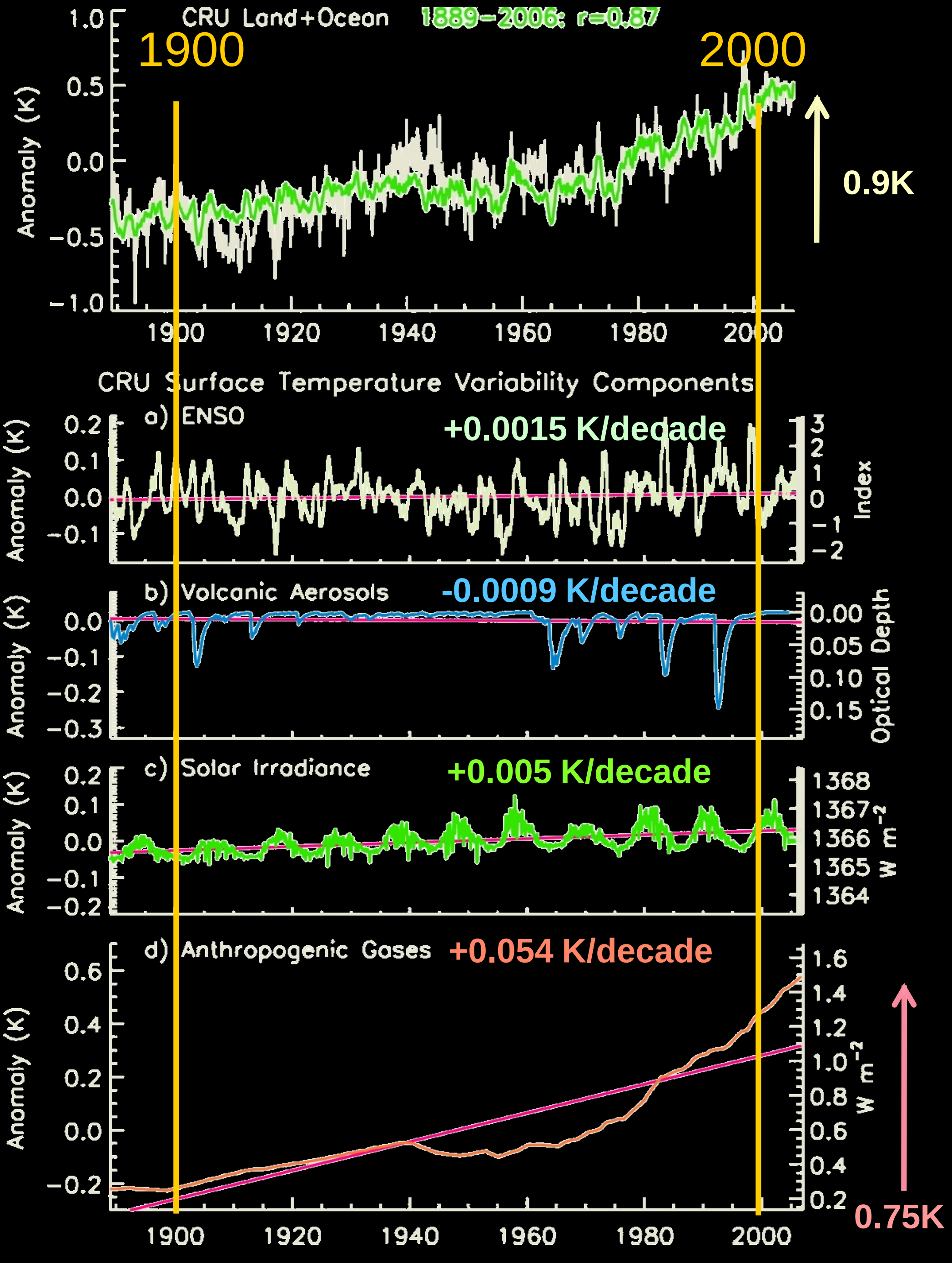


FIG. 16. Compared are decadally average values of the Lean et al. (1995b) reconstructed solar total irradiance (diamonds) from Fig. 13 and NH summer temperature anomalies from 1610 to the present (similar annually averaged data are shown in Fig. 2). The solid line is the Bradley and Jones (1993) NH summer surface temperature reconstruction from paleoclimate data (primarily tree rings), scaled to match the NH instrumental data (Houghton et al. 1992) (dashed line) during the overlap period as given in Fig. 1.

Lean & Rind, J. Climate, 11, 3069-3094, 1998

Solar and Anthropogenic Signals in the Instrumental Era



Slide courtesy of Judith Lean, Naval Research Laboratory

From IPCC 2007 (WG1 Ch. 2 &TS)

- “Continuous monitoring of total solar irradiance now covers the last 28 years. The data show a well-established 11-year cycle in irradiance that varies by 0.08% from solar cycle minima to maxima, with no significant long-term trend.”
  - → The primary known cause of contemporary irradiance variability is the presence on the Sun’s disk of sunspots and faculae.
- “The estimated direct radiative forcing due to changes in the solar output since 1750 is +0.12 [+0.06 to +0.3] W m^{-2}, which is less than half of the estimate given in the TAR, with a low level of scientific understanding.”
  - → Uncertainties remain large because of the lack of direct observations and incomplete understanding of solar variability mechanisms over long time scales.
- “Empirical associations have been reported between solar-modulated cosmic ray ionization of the atmosphere and global average low-level cloud cover but evidence for a systematic indirect solar effect remains ambiguous.”

Updated: From IPCC 2013 (WG1 SPM)

- “The RF *[radiative forcing]* due to changes in solar irradiance is estimated as 0.05 [0.00 to 0.10] W m^{-2} (see Figure SPM.5). Satellite observations of total solar irradiance changes from 1978 to 2011 indicate that the last solar minimum was lower than the previous two. This results in an RF of –0.04 [–0.08 to 0.00] W m^{-2} between the most recent minimum in 2008 and the 1986 minimum.
- “The total natural RF from solar irradiance changes and stratospheric volcanic aerosols made only a small contribution to the net radiative forcing throughout the last century, except for brief periods after large volcanic eruptions.”
- “There is high confidence that changes in total solar irradiance have not contributed to the increase in global mean surface temperature over the period 1986 to 2008, based on direct satellite measurements of total solar irradiance. There is medium confidence that the 11-year cycle of solar variability influences decadal climate fluctuations in some regions. No robust association between changes in cosmic rays and cloudiness has been identified.”

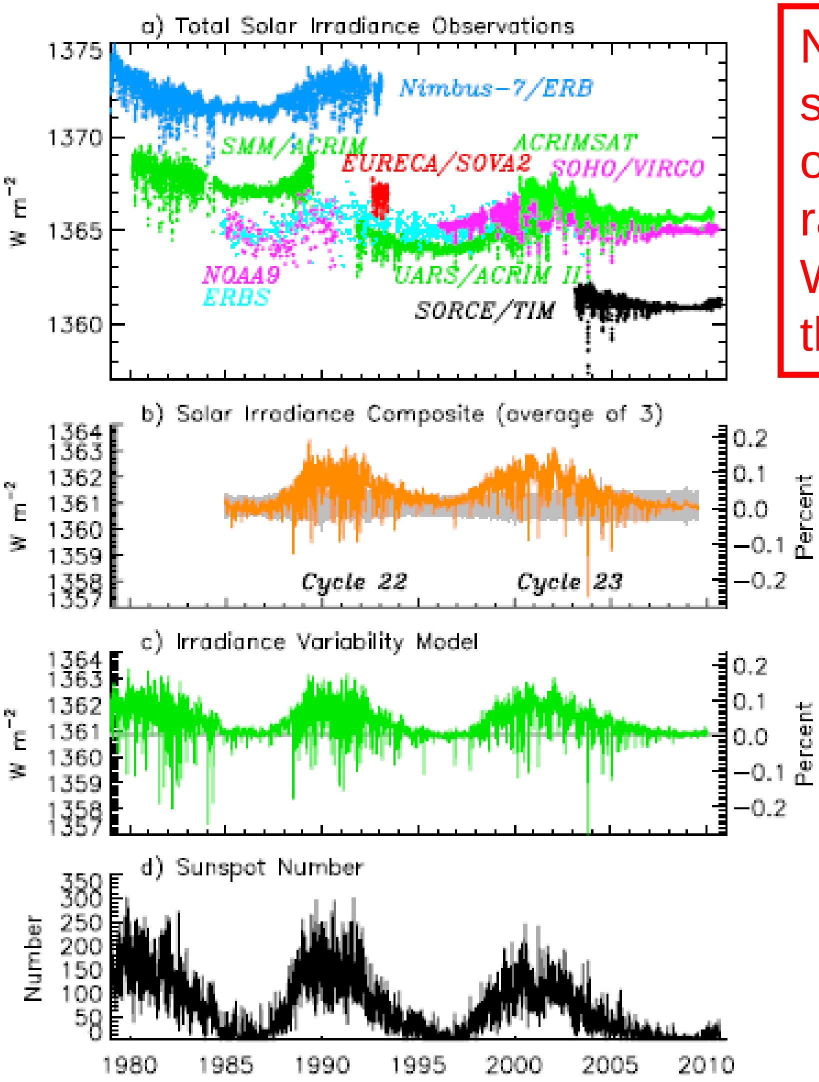
https://www.ipcc.ch/report/ar5/wg1/

GEOPHYSICAL RESEARCH LETTERS, VOL. 38, L01706, doi:10.1029/2010GL045777, 2011

A new, lower value of total solar irradiance: Evidence and climate significance

Greg Kopp[1] and Judith L. Lean[2]

Received 7 October 2010; revised 19 November 2010; accepted 30 November 2010; published 14 January 2011.



Note that the satellite measurements show the same features and are self-consistent, but are offset from each other:
random errors < systematic errors.
We know the solar constant with better precision than accuracy, to approximately ±3 W/m^2.

Figure 1. (a) Space-borne total solar irradiance (TSI) measurements are shown on "native" scales with offsets attributable to calibration errors. Instrument overlap allows corrections for offsets and the creation of a composite TSI record. (b) The average of three different reported composites [ACRIM, PMOD, and RMIB] adjusted to match the SORCE/TIM absolute scale. The grey shading indicates the standard deviation of the three composites. (c) Irradiance variations estimated from an empirical model that combines the two primary influences of facular brightening and sunspot darkening with their relative proportions determined via regression from direct observations made by SORCE/TIM. (d) The daily sunspot numbers indicate fluctuating levels of solar activity for the duration of the database.

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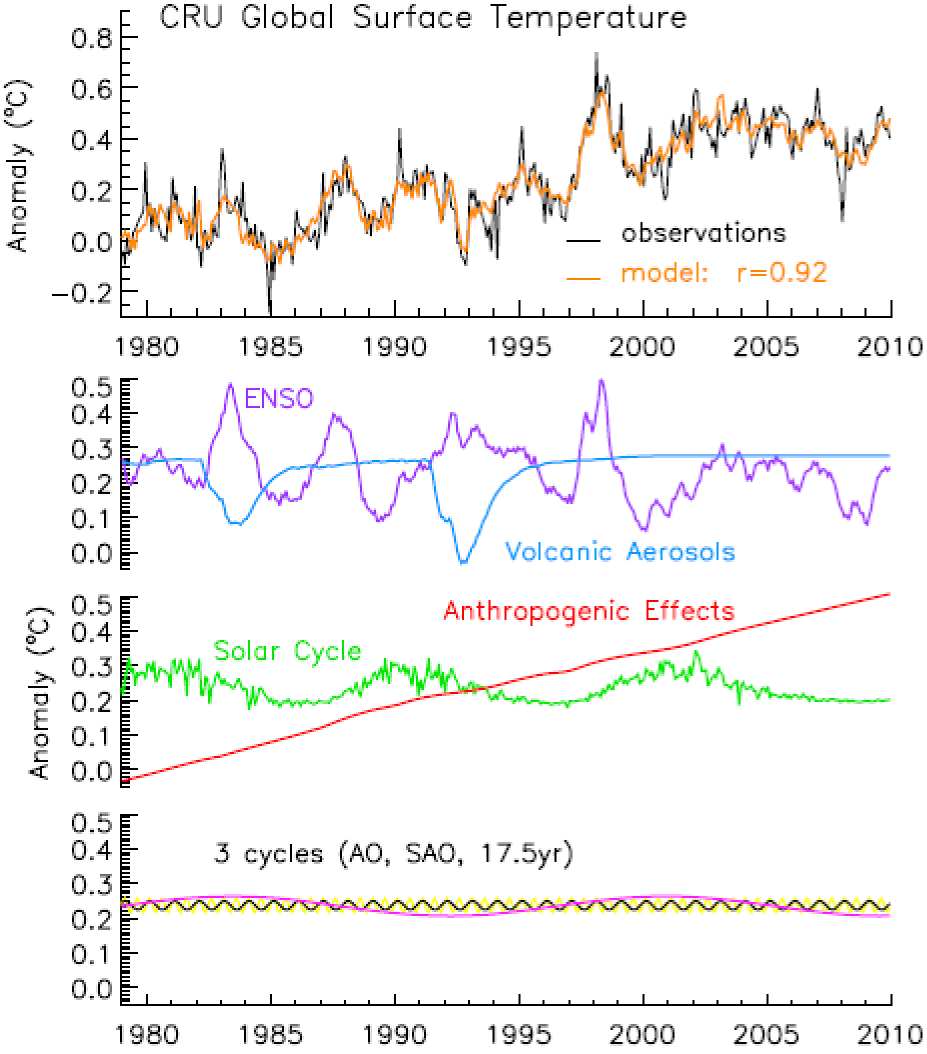
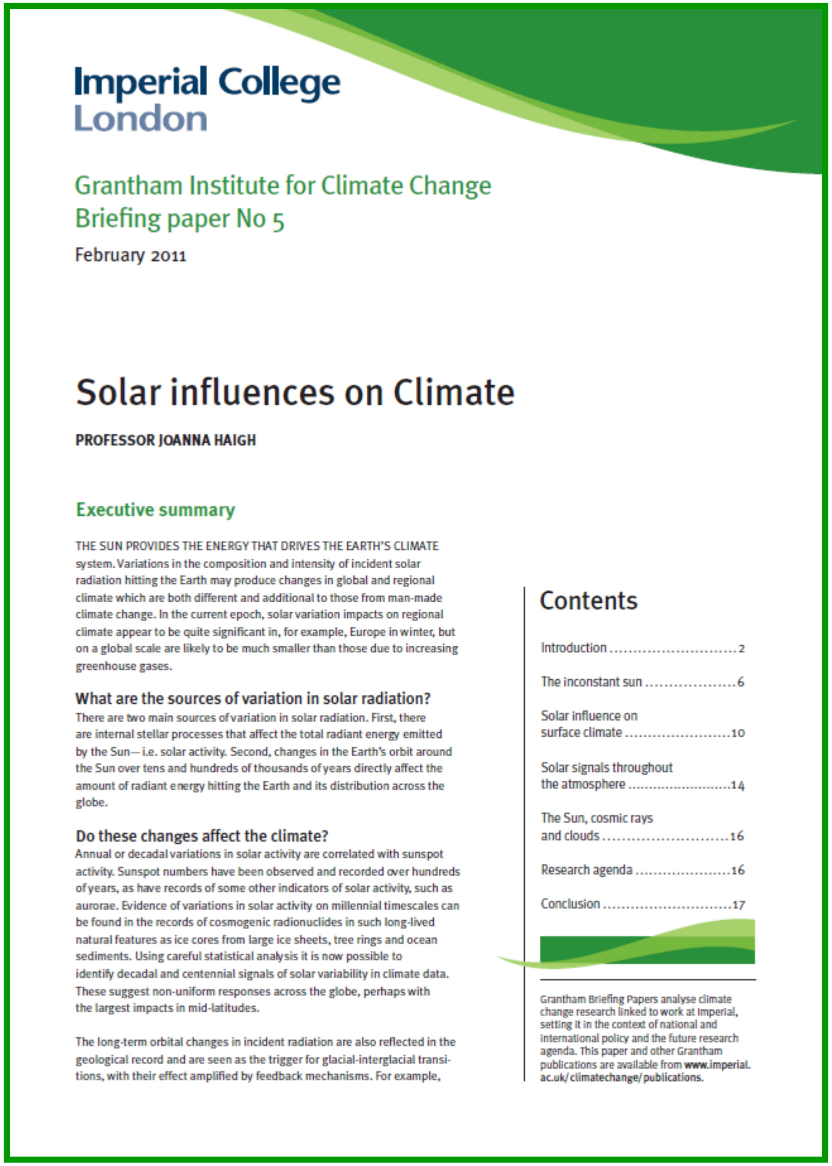


Figure 2. Compared in the top panel are monthly mean variations in the global temperature of the Earth's surface, from the Climatic Research Unit (CRU, black) and an empirical model (orange, following *Lean and Rind* [2009]) that combines four primary influences and three minor cycles, whose variations are shown individually in the lower panels. The temperature record has sufficient fidelity that after removing the four primary effects, namely ENSO (purple) at three different lags, volcanic aerosols (blue) at two different lags, solar irradiance (green), and anthropogenic effects (red), minor cycles identifiable as annual (AO, black), semi-annual (SAO, yellow), and 17.5 year oscillations (pink) are evident in the residuals (bottom panel).

Further Reading

- For a concise overview of solar variability and solar influence on climate, see the Grantham Institute for Climate Change, Briefing paper No 5, February 2011
- https://www.imperial.ac.uk/media/imperial-college/grantham-institute/public/publications/briefing-papers/Solar-Influences-on-Climate---Grantham-BP-5.pdf



Imperial College
London

Grantham Institute for Climate Change
Briefing paper No 5
February 2011

Solar influences on Climate

PROFESSOR JOANNA HAIGH

Executive summary

THE SUN PROVIDES THE ENERGY THAT DRIVES THE EARTH'S CLIMATE system. Variations in the composition and intensity of incident solar radiation hitting the Earth may produce changes in global and regional climate which are both different and additional to those from man-made climate change. In the current epoch, solar variation impacts on regional climate appear to be quite significant in, for example, Europe in winter, but on a global scale are likely to be much smaller than those due to increasing greenhouse gases.

What are the sources of variation in solar radiation?

There are two main sources of variation in solar radiation. First, there are internal stellar processes that affect the total radiant energy emitted by the Sun— i.e. solar activity. Second, changes in the Earth's orbit around the Sun over tens and hundreds of thousands of years directly affect the amount of radiant energy hitting the Earth and its distribution across the globe.

Do these changes affect the climate?

Annual or decadal variations in solar activity are correlated with sunspot activity. Sunspot numbers have been observed and recorded over hundreds of years, as have records of some other indicators of solar activity, such as aurorae. Evidence of variations in solar activity on millennial timescales can be found in the records of cosmogenic radionuclides in such long-lived natural features as ice cores from large ice sheets, tree rings and ocean sediments. Using careful statistical analysis it is now possible to identify decadal and centennial signals of solar variability in climate data. These suggest non-uniform responses across the globe, perhaps with the largest impacts in mid-latitudes.

The long-term orbital changes in incident radiation are also reflected in the geological record and are seen as the trigger for glacial-interglacial transitions, with their effect amplified by feedback mechanisms. For example,

Contents

Grantham Briefing Papers analyse climate change research linked to work at Imperial, setting it in the context of national and international policy and the future research agenda. This paper and other Grantham publications are available from **www.imperial.ac.uk/climatechange/publications.**