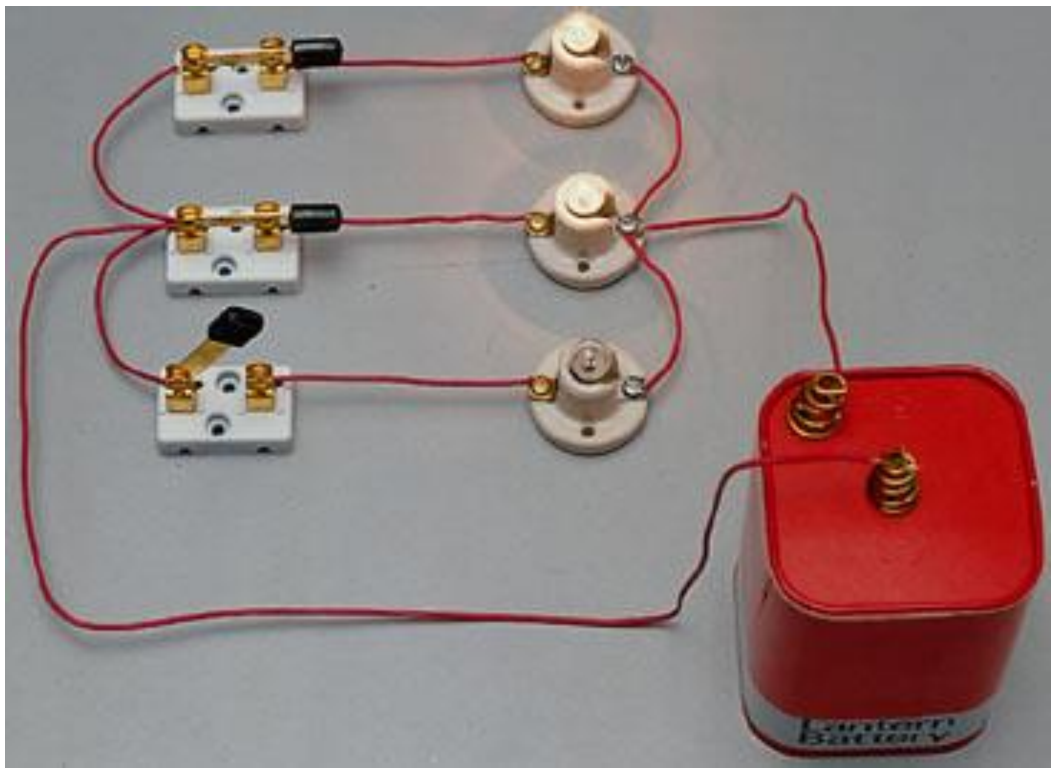
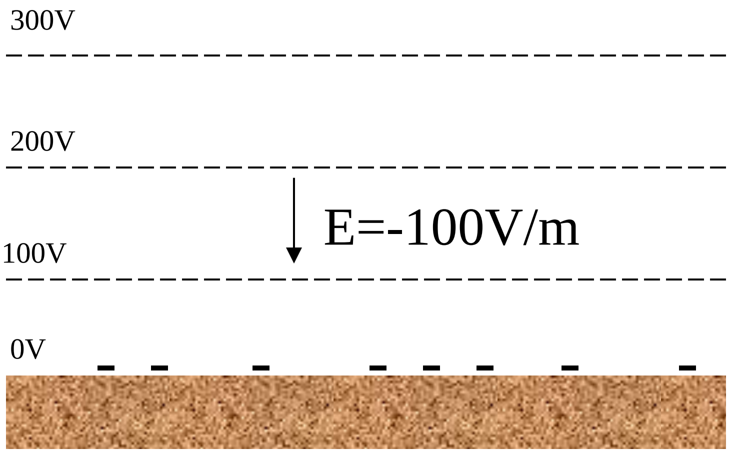
The
Global Atmospheric Electric Circuit

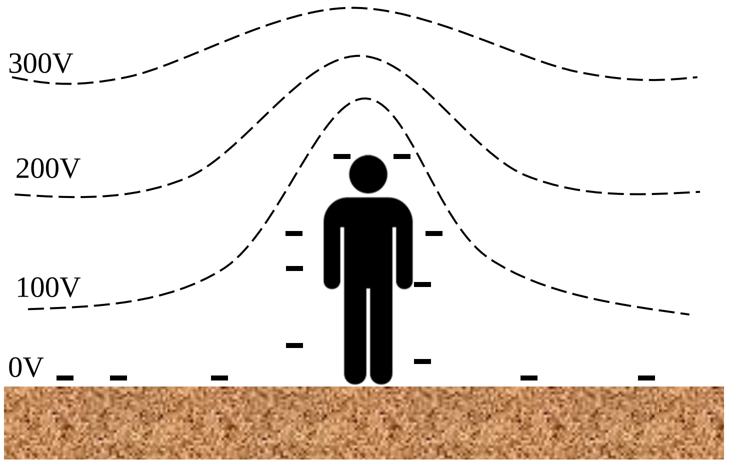


Historical Background

- ✓ 1752 Lemonnier discovered that in fair weather regions there is a persistent E-field of ~100 V/m pointing downward

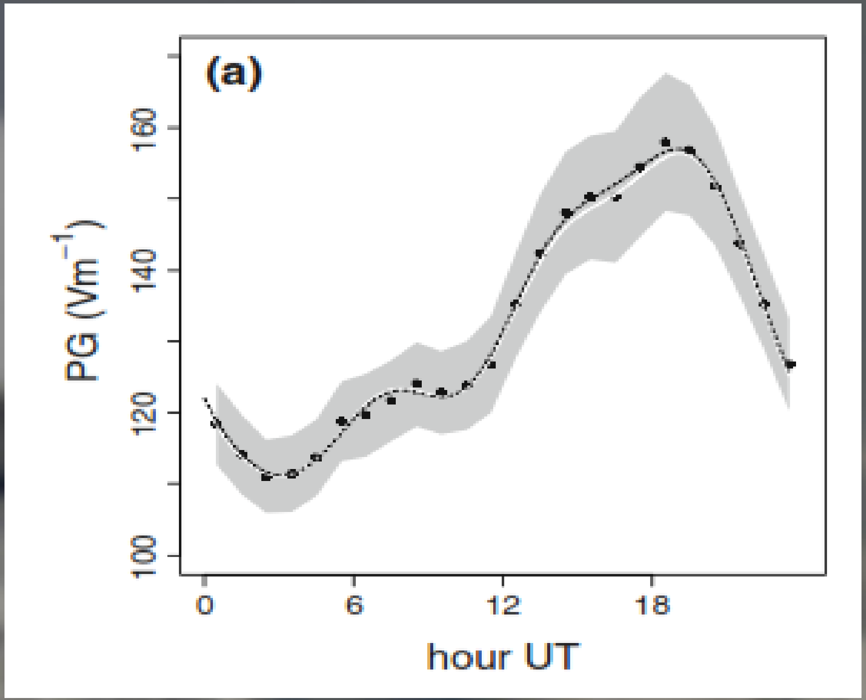


- ✓ Why do we not get electric shock? (200 V between head and ground)



History

Cruise I, II, II (1909-1914)
Cruise IV, V, VI (1915-1921)
Cruise VII (1928-1929)



Carnegie Curve

Harrison (2013)

✓ 1920s: There exists a diurnal variation of the atmospheric electric field, which is independent of location and local time, but dependent only on universal time:

~100V/m

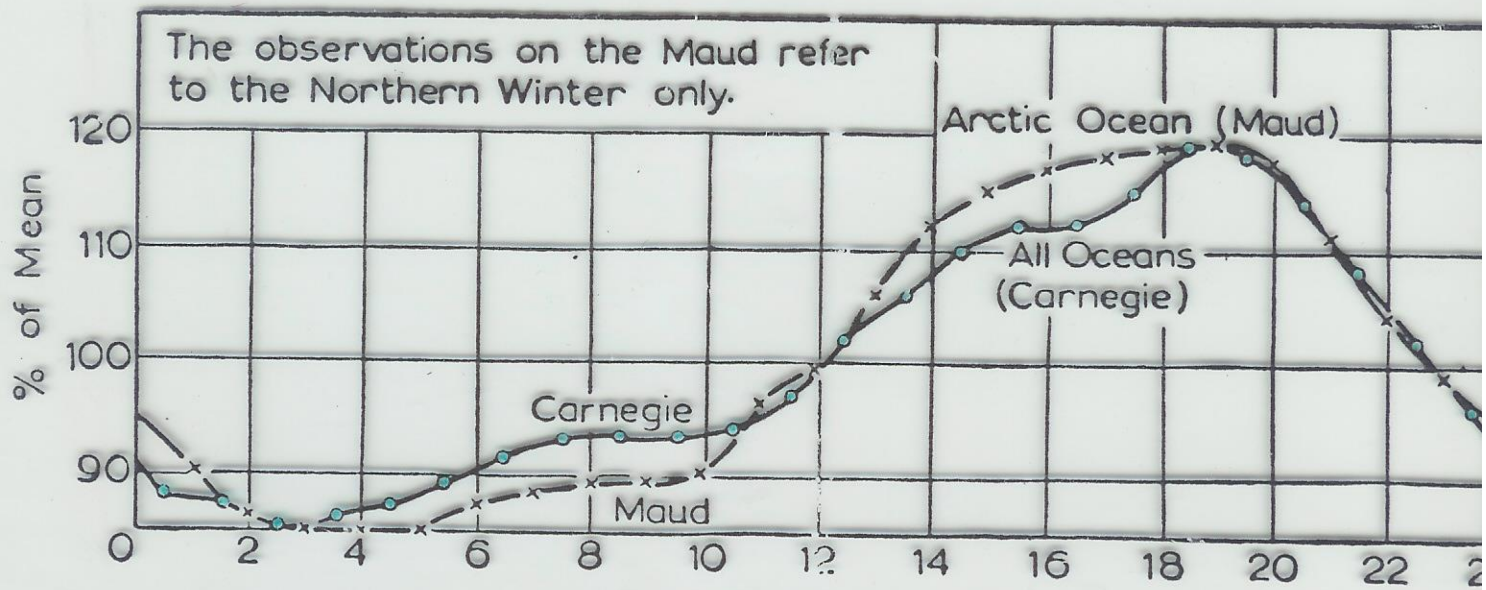


FIG. 26. Diurnal variation of potential gradient over oceans. (From WHIPPLE and SCRASE, 1936, Fig. 9A, p. 19.)

"Carnegie Curve"

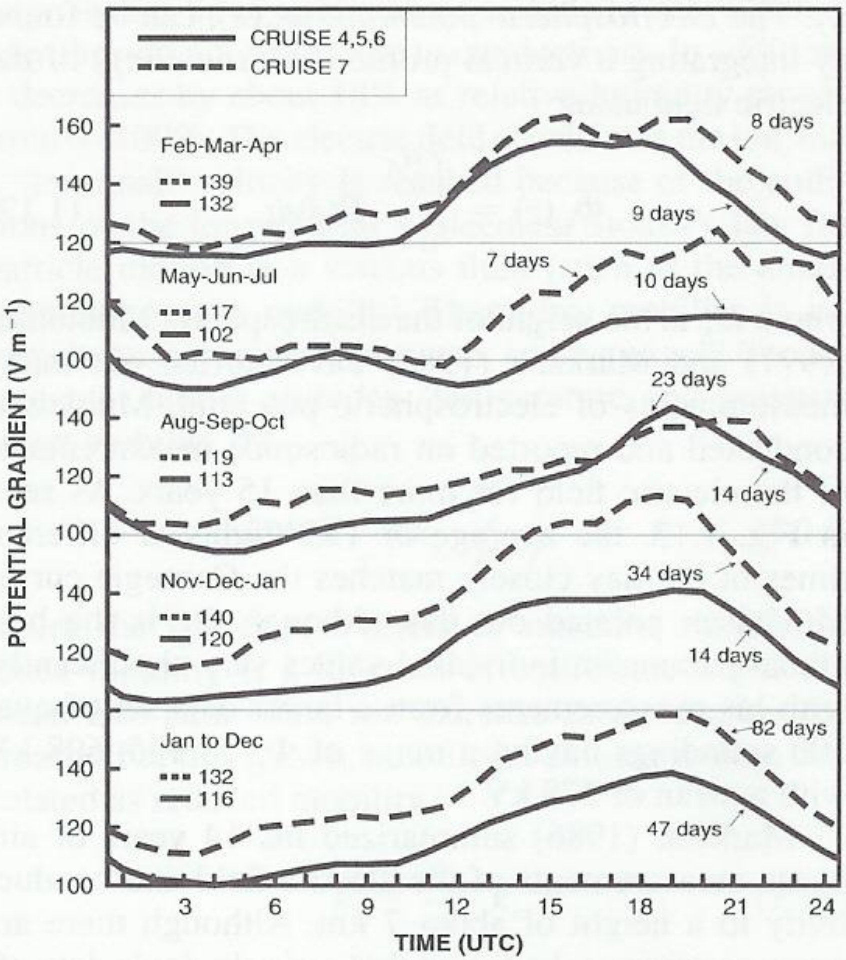


Fig. 1.12. Mean diurnal variations of the potential gradient for 3-month periods measured during fair weather on four cruises of the Carnegie during the years 1915–21 (cruises 4–6) and 1928–29 (cruise 7). The numbers by the line codes in each are the mean potential gradient for the curve. (From Torreson et al. 1946, with permission.)

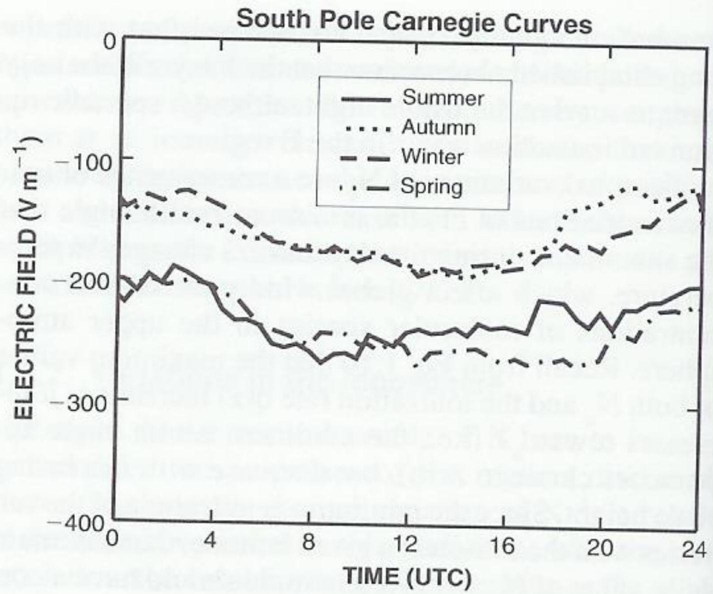


Fig. 1.9. Southern hemisphere seasonal variation in fair weather electric field. (After Cleary et al. 1997, with permission.)

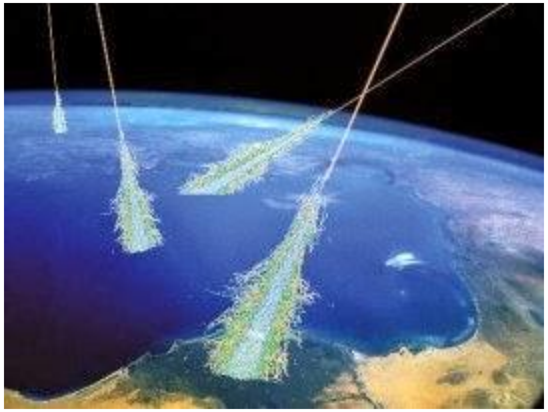
✓ Implication of E-field → Earth has a *negative* charge of ~500,000 C

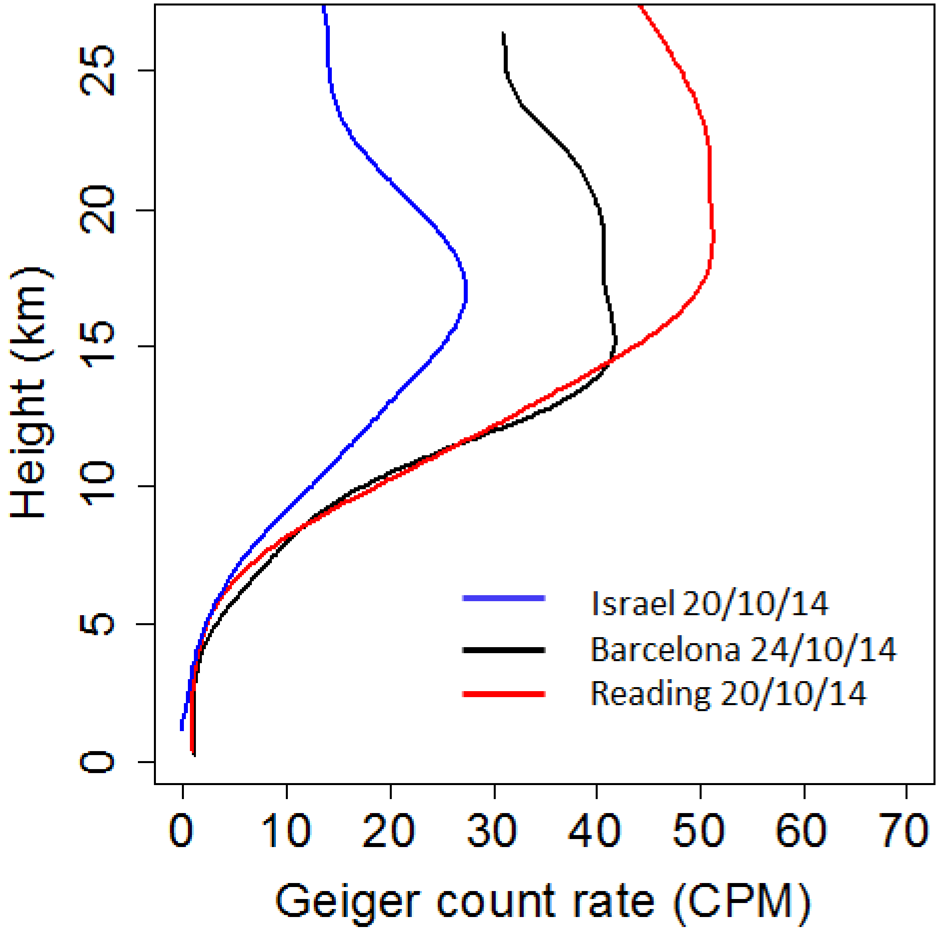
Charge of the Earth

$$Q = 4\pi R^2 \varepsilon_o E = R^2 E_o / k$$
$$= 4.5 \times 10^5 \text{ Coulomb}$$

ε_o = permittivity of free space (electric const.)
= 8.85×10^{-12} F/m

✓ 1887 Linss discovered ions in the atmosphere, implying that air had a finite conductivity





Ionization produced by cosmic rays

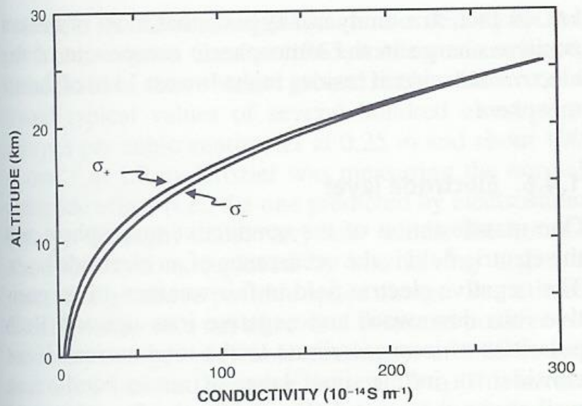


Fig. 1.16. Positive and negative conductivity for fair weather from the relationship derived by Woessner et al. (1958) from their balloon-borne Gerdien cylinders.

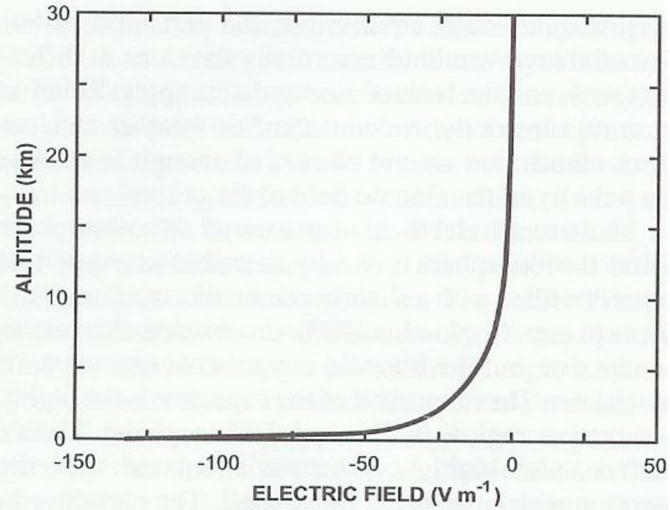
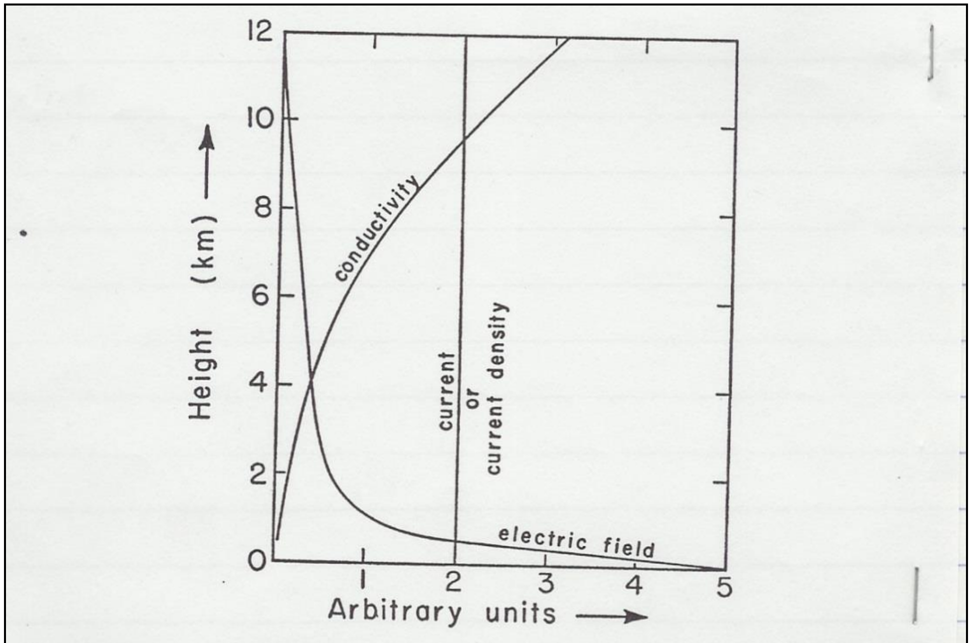


Fig. 1.7. Profile of the electric field in fair weather using a relationship derived by Gish (1944).

σ x E

$j = \sigma E$

Conduction Current



. 9.5 Schematic representation of the trend of the various parameters of the atmosphere's fair weather electrical state as a function of elevation.

Conduction Current

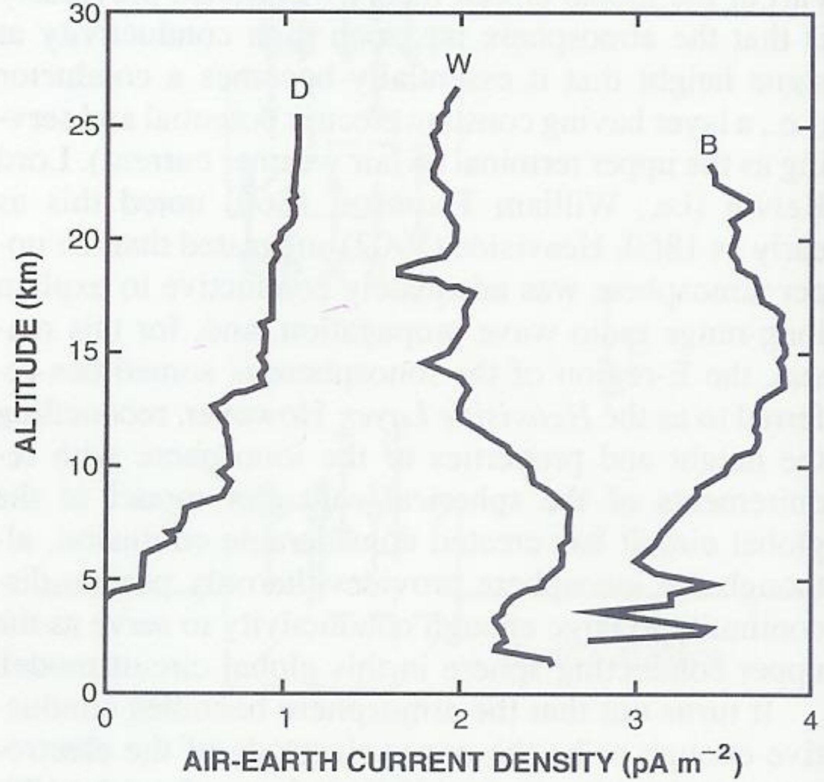
$J(R) = \sigma_o\ E(R) = 2 \times 10^{-12}$ Amp/m^2

$\sigma(R) = \sigma_o = 3\times10^{-14}$ Siemen/m [S/m]

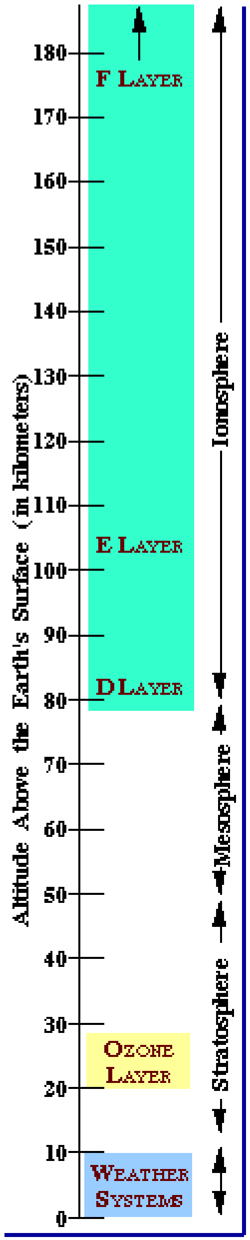
The conduction current varies little with altitude up to z~50 km

Globally, $i = J(R)\ 4\pi R^2$

~ 1000 Amp



✓ 1900 CTR Wilson measured the air-Earth current which has a value $\sim 2\times10^{-12}$ A/m^2



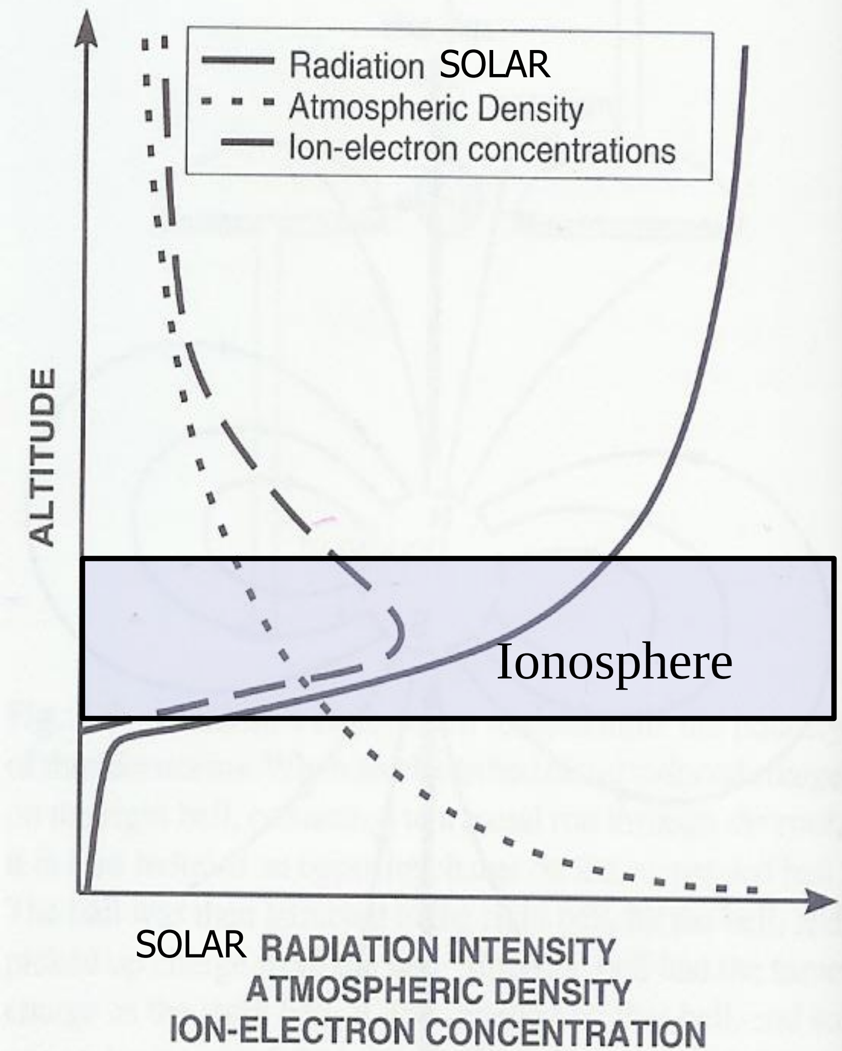
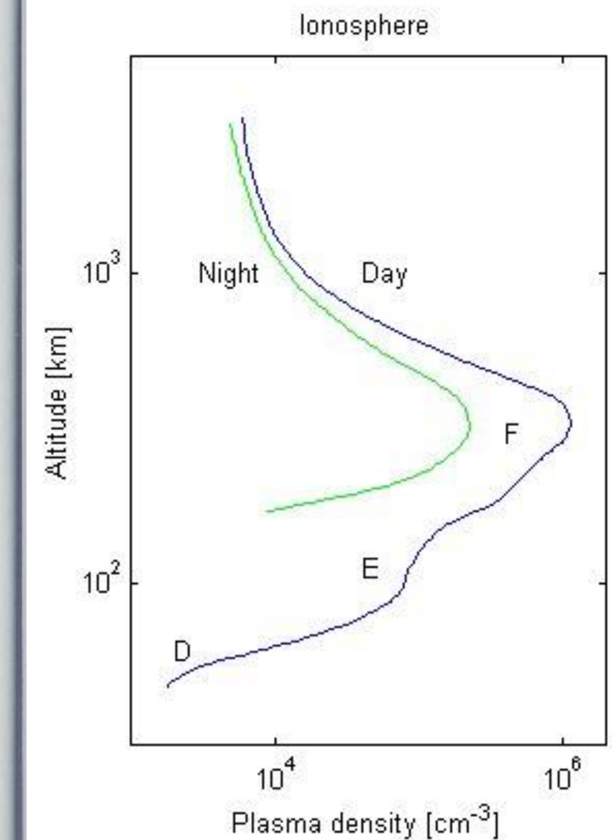
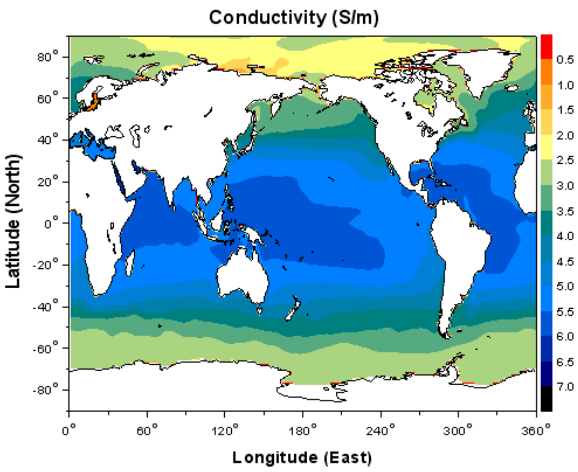


Fig. 1.5. Trends in radiation flux and particle number density that result in a Chapman layer. (From Whitten and Poppoff, 1971, with permission.)



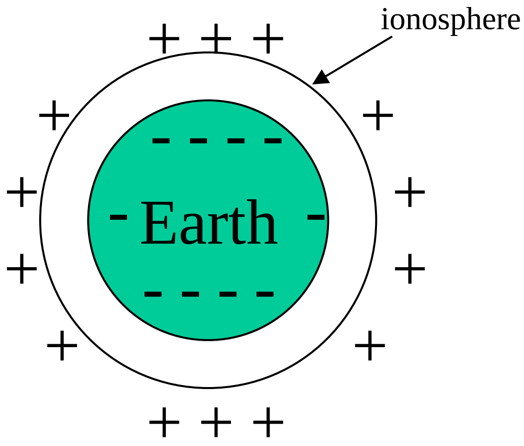
Due to the high conductivity of the Earth, the Earth-ionosphere represent a spherical capacitor



σ(i) ~10^{-5} S/m

σ(o) ~1 S/m

σ(air) ~10^{-14} S/m

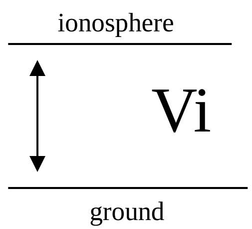


Ionospheric Potential

The potential difference between the ionosphere (height h) and the Earth’s surface, known as the ionospheric potential, is :

$$V = -\int_{R}^{R+h} E(r)dr = -\int_{R}^{\infty} E(r)dr$$

since E=0 for r> R+h (or z>h).



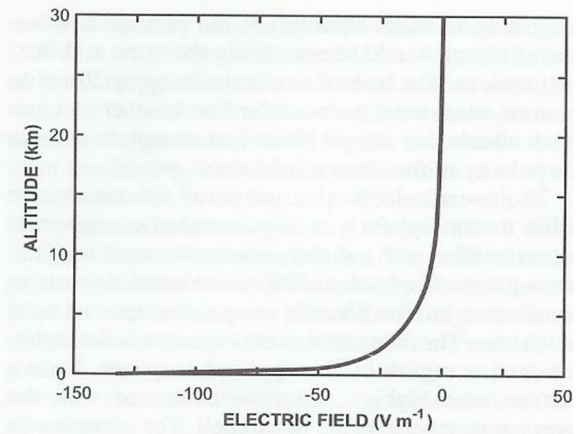
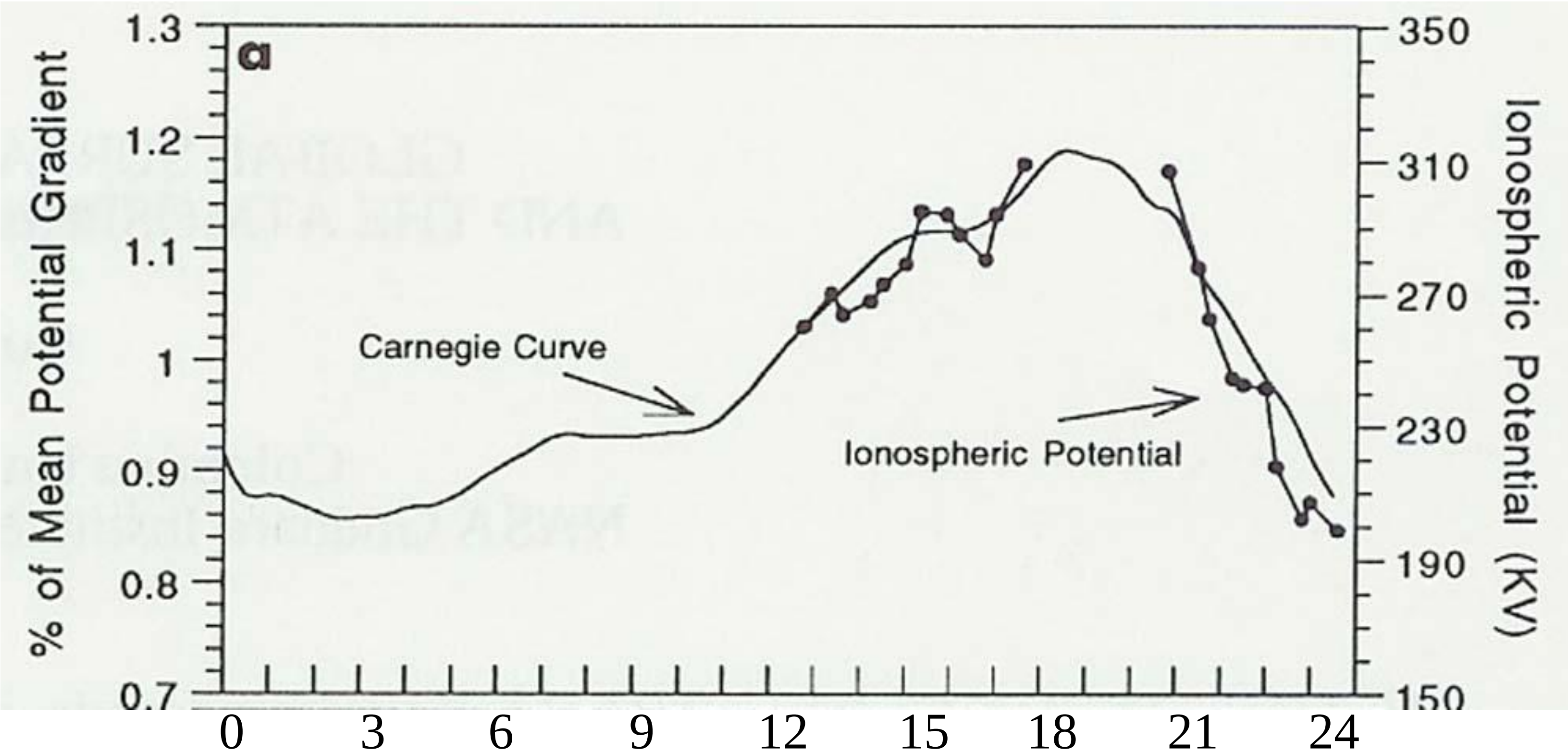
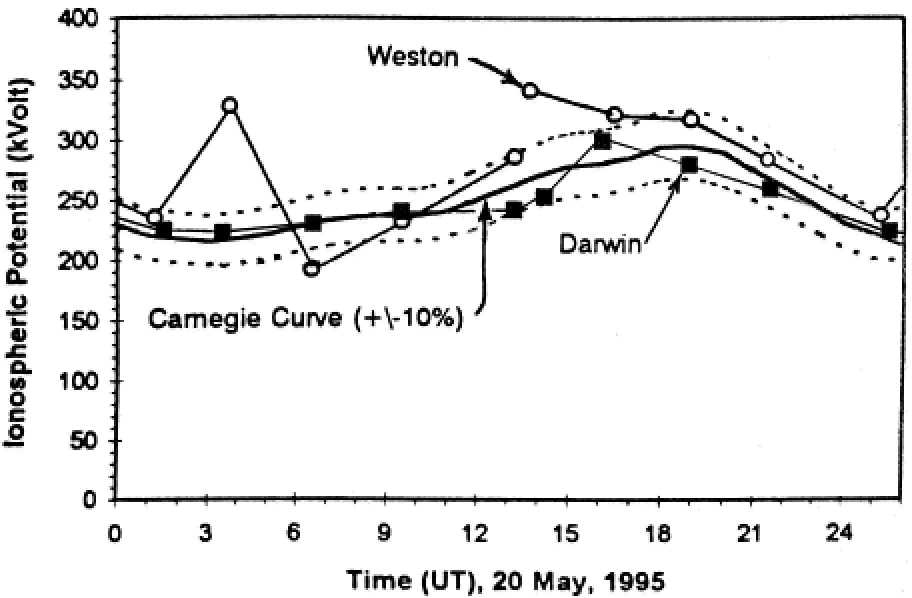
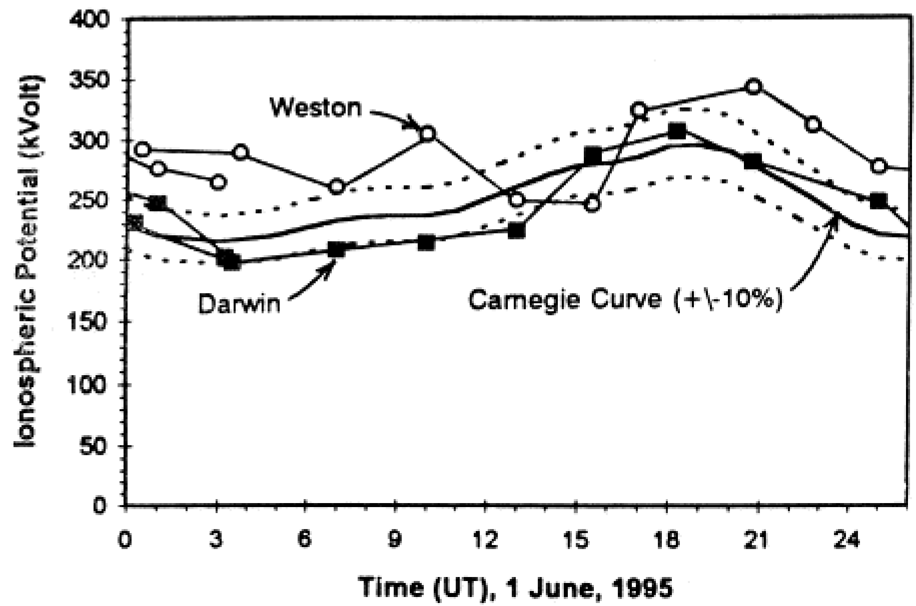


Fig. 1.7. Profile of the electric field in fair weather usin
a relationship derived by Gish (1944).

Most measurements show values of V~ 3×10^5 Volt (300kV)


a
% of Mean Potential Gradient
Ionospheric Potential (KV)
Carnegie Curve
Ionospheric Potential
1.3
1.2
1.1
1
0.9
0.8
0.7
350
310
270
230
190
150
0 3 6 9 12 15 18 21 24


Weston
Darwin
Carnegie Curve (+\-10%)
Ionospheric Potential (kVolt)
Time (UT), 20 May, 1995
0 50 100 150 200 250 300 350 400
0 3 6 9 12 15 18 21 24


Weston
Darwin
Carnegie Curve (+\-10%)
Ionospheric Potential (kVolt)
Time (UT), 1 June, 1995
0 50 100 150 200 250 300 350 400
0 3 6 9 12 15 18 21 24

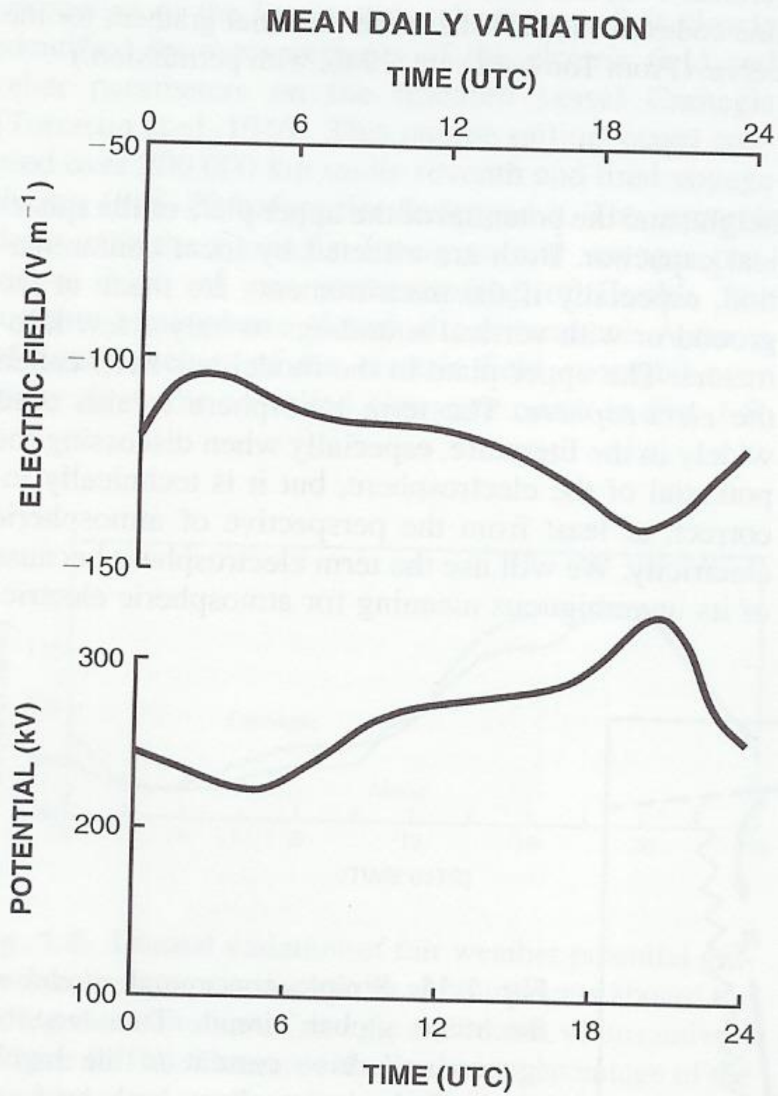


Fig. 1.13. Mean diurnal variations of electric field from the Carnegie (top) compared with the potential of the electrosphere (bottom) from balloon soundings of the potential gradient. (After Mühleisen 1977, with permission.)

Capacitance of the Earth

$C = Q/V \sim 4x10^5 C/3x10^5 V \sim 1$ Farad

The typical time scale for the discharging of the capacitor is

$$\tau = R_{\Omega} C = 300 \text{ sec! } (5\text{-}10 \text{ minutes})$$

- ✓ 1920 Wilson suggested the generator was global thunderstorms

- ✓ 1929 Whipple showed that the diurnal variations of the fair weather field matches the diurnal variations of global thunderstorms

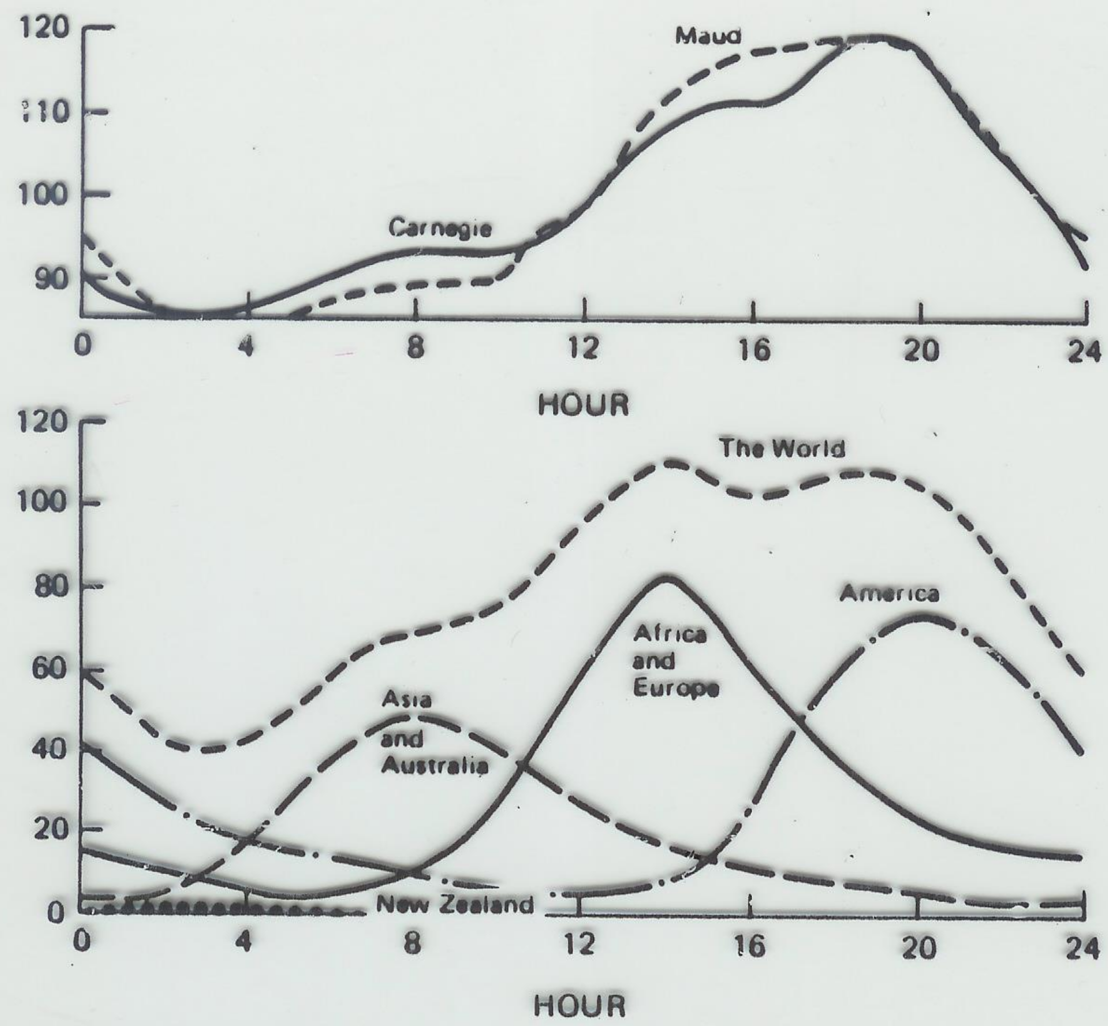


FIGURE 15.3 (a) Annual curve of the diurnal variation of the atmospheric electric field on the oceans (volts per meter) as measured by the *Carnegie* and *Maud* expeditions (Parkinson and Torrenson, 1931) and (b) annual curve of the diurnal variations of global thunderstorm activity according to Whipple and Scrase (1936).

The Global Atmospheric Electric Circuit

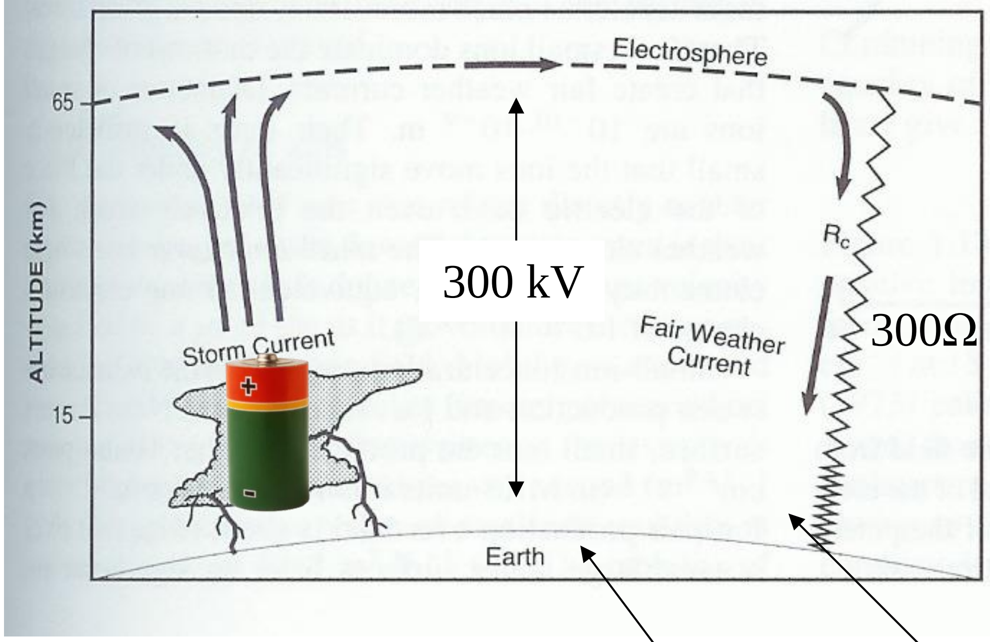
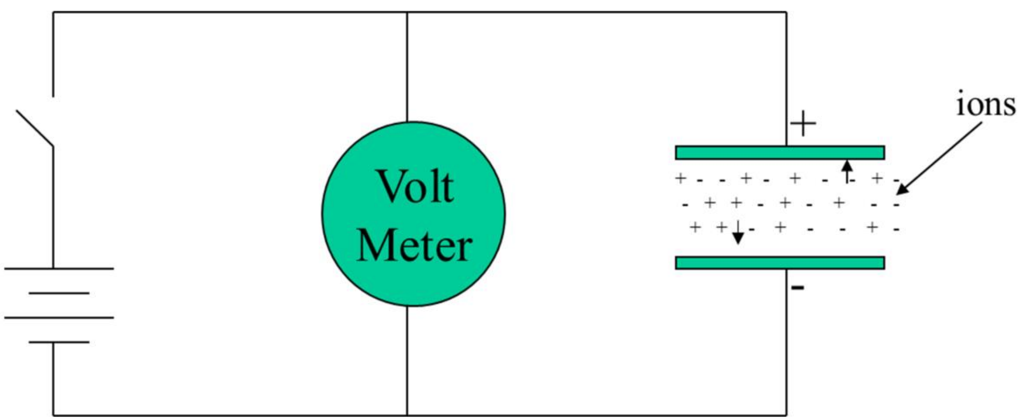
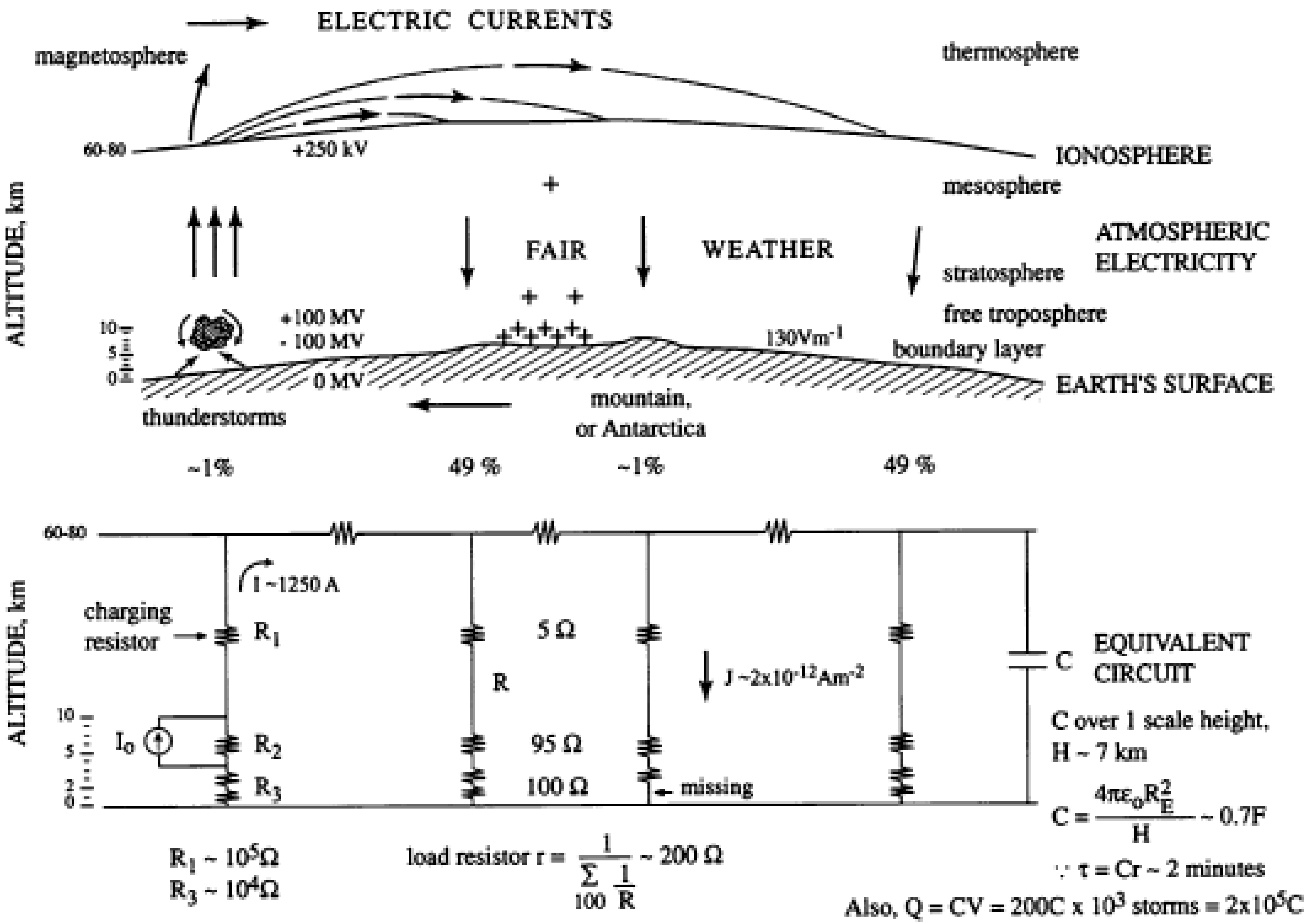


Fig. 1.11. Simple conceptual model of the main global circuit. Thunderstorm 'generators' drive current to the highly conductive electrosphere and back to ground as fair weather current. R_c is the columnar resistance, which is greater in the lower atmosphere. The altitudes are approximate, typical ones; not to scale.

Q ~ -500,000 C

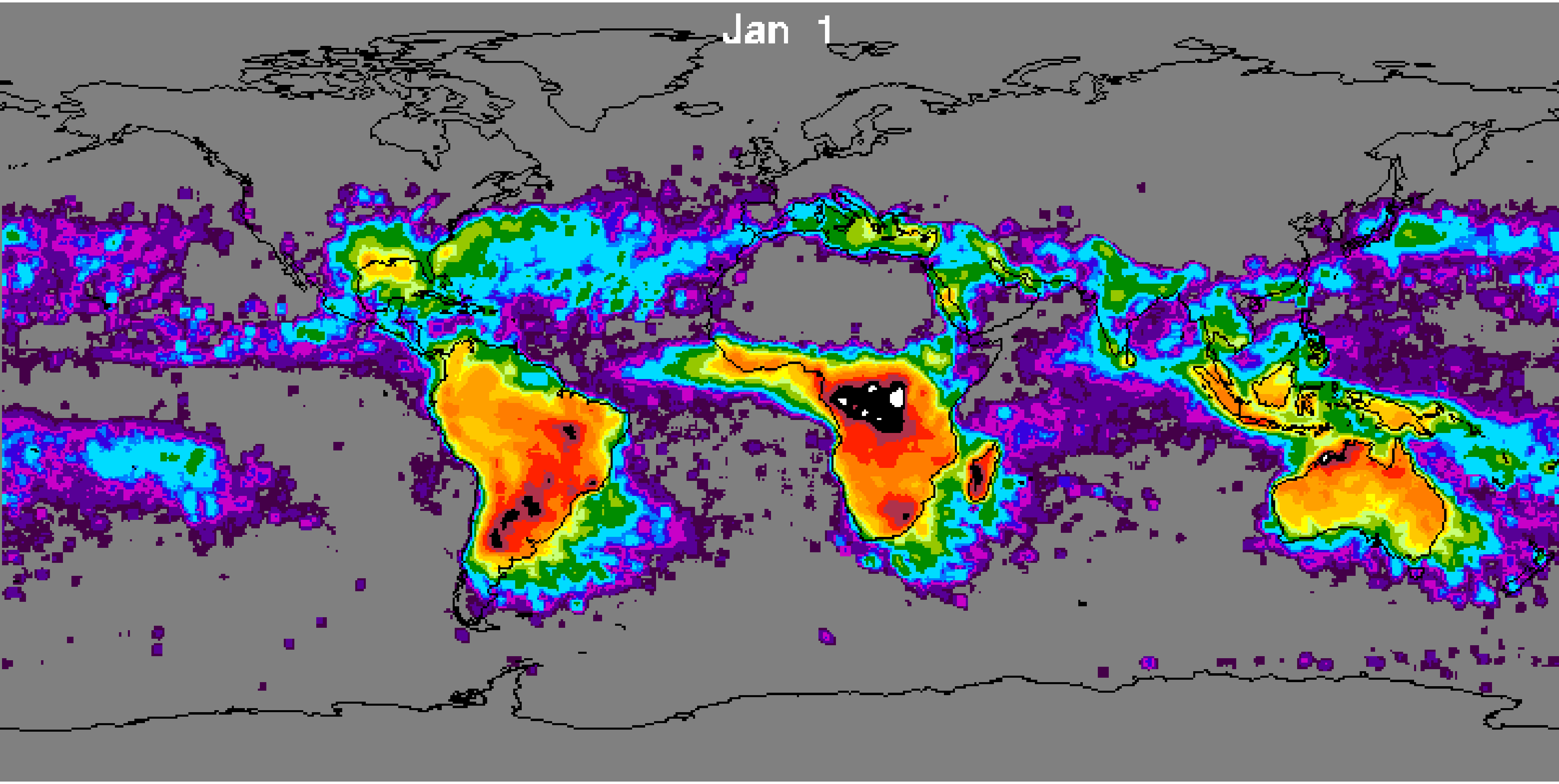
PG ~ -100 V/m
I ~ 2 pA/m^2



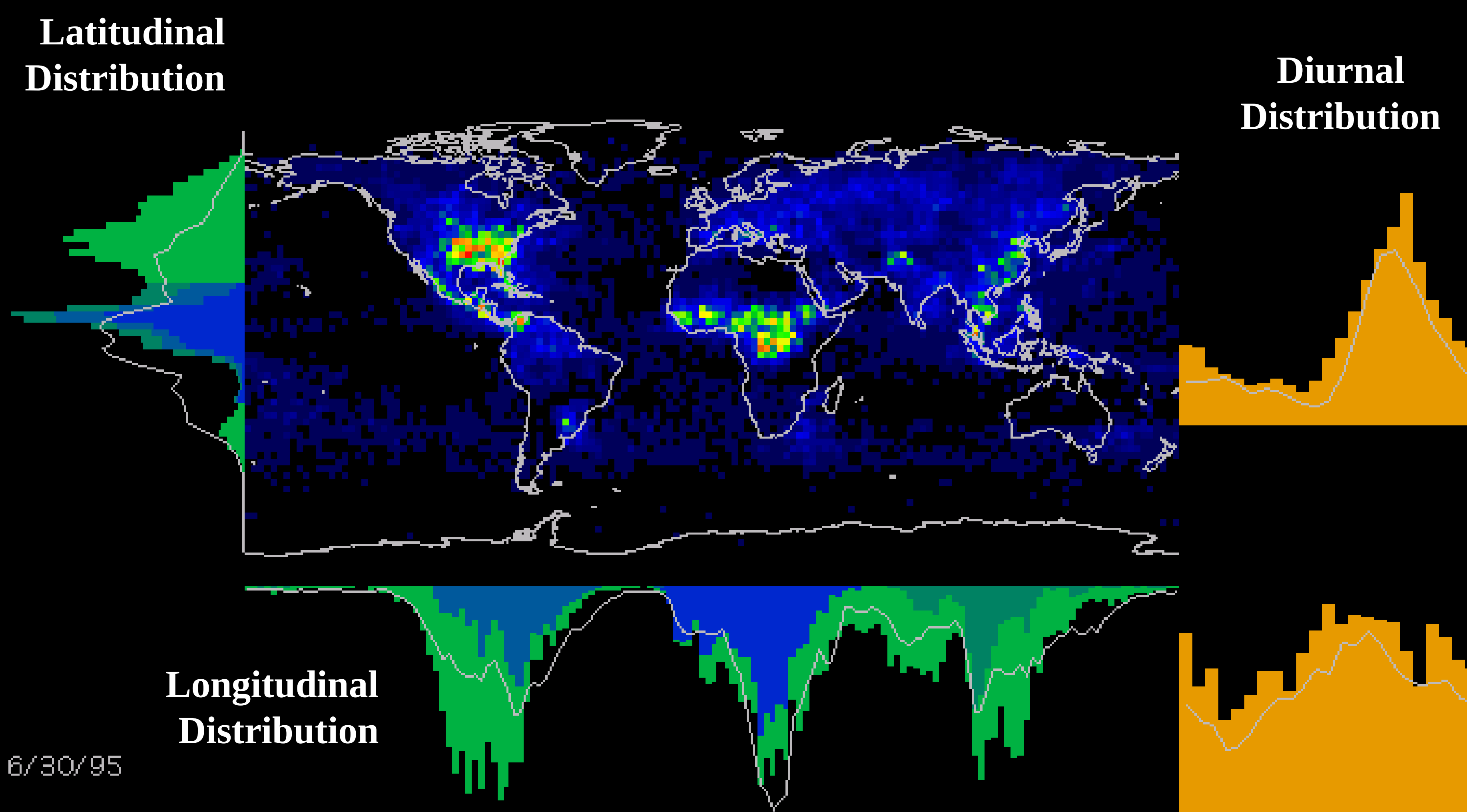


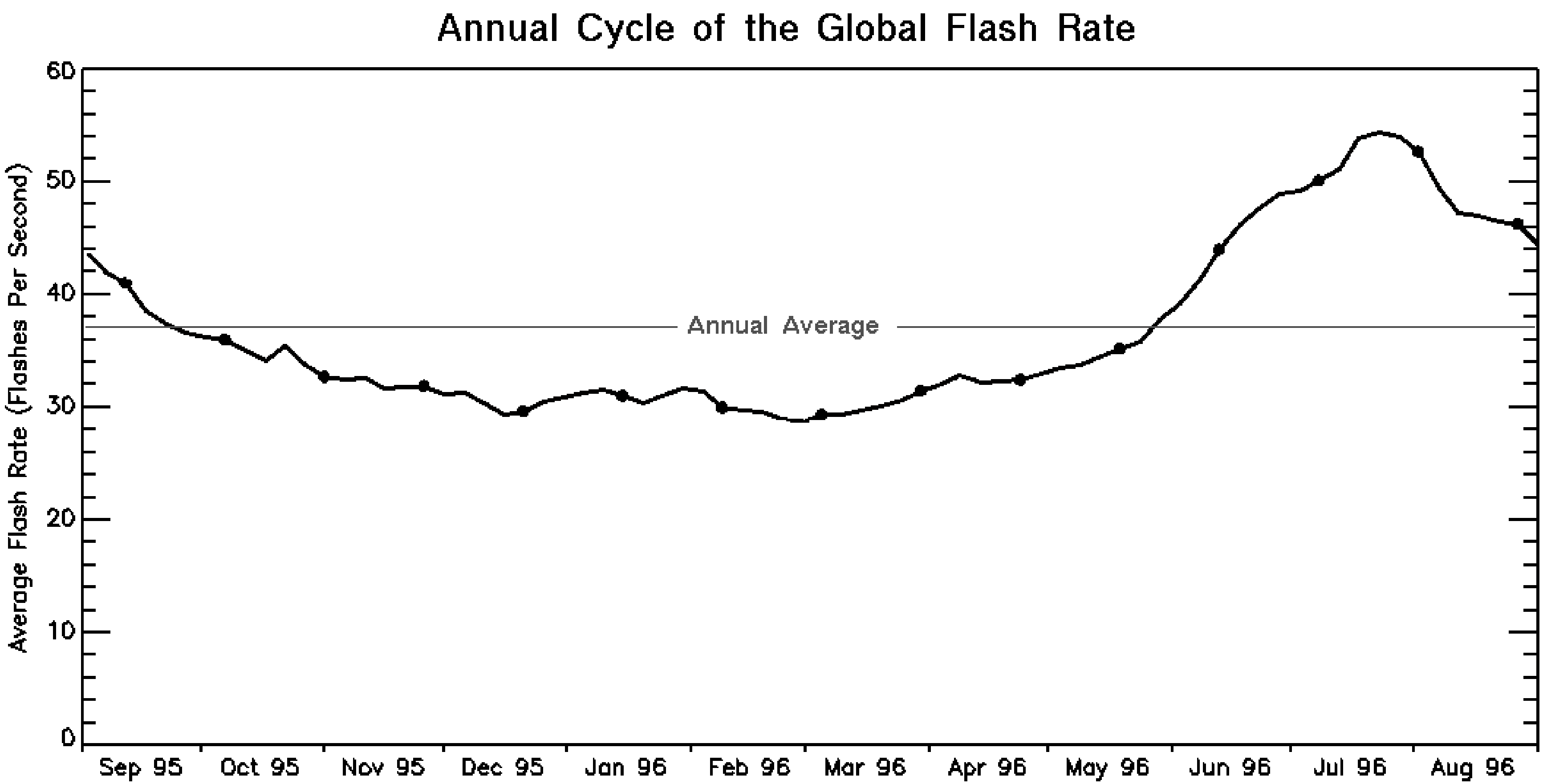
Rycroft et al. (2000)

Where are the batteries?



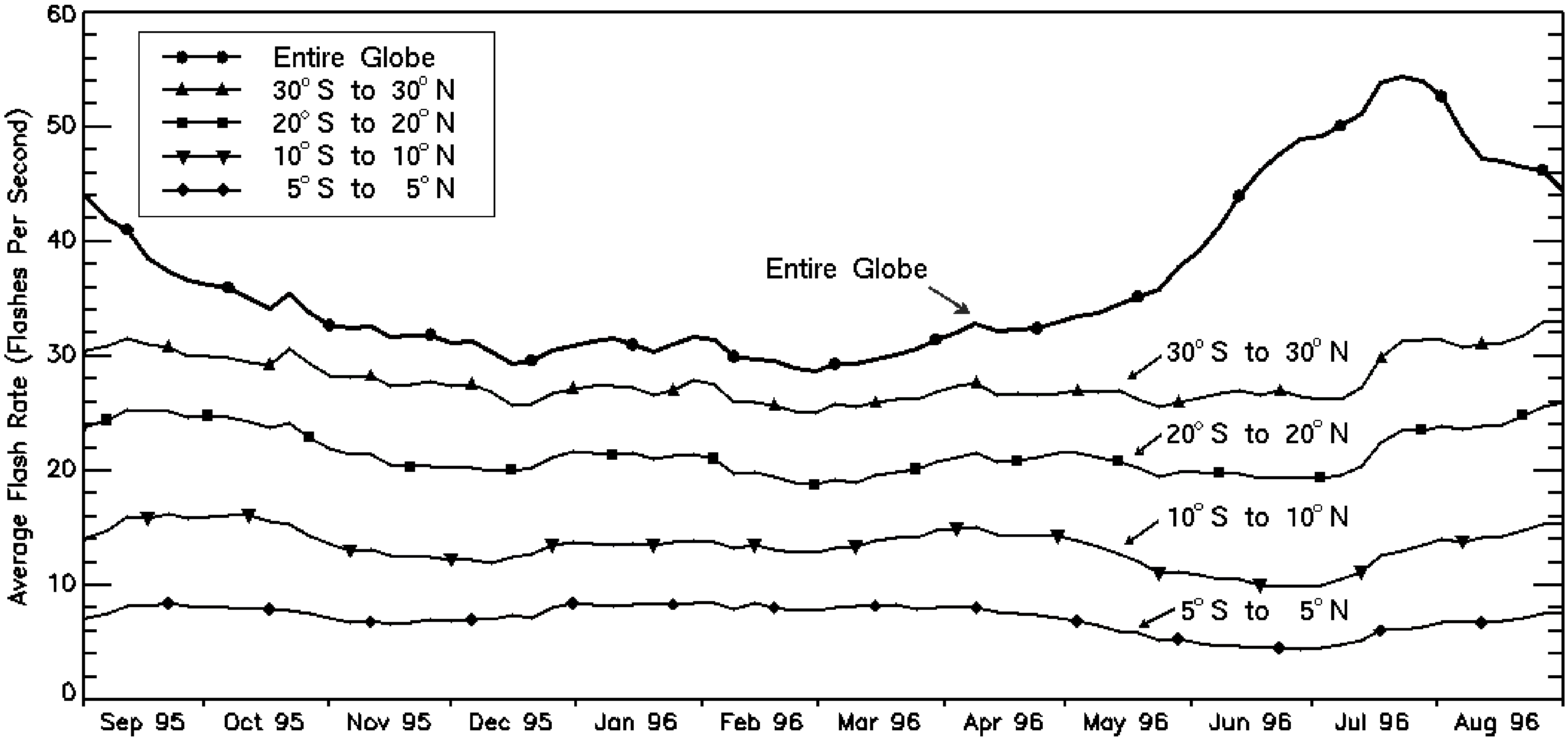
~1000 thunderstorms

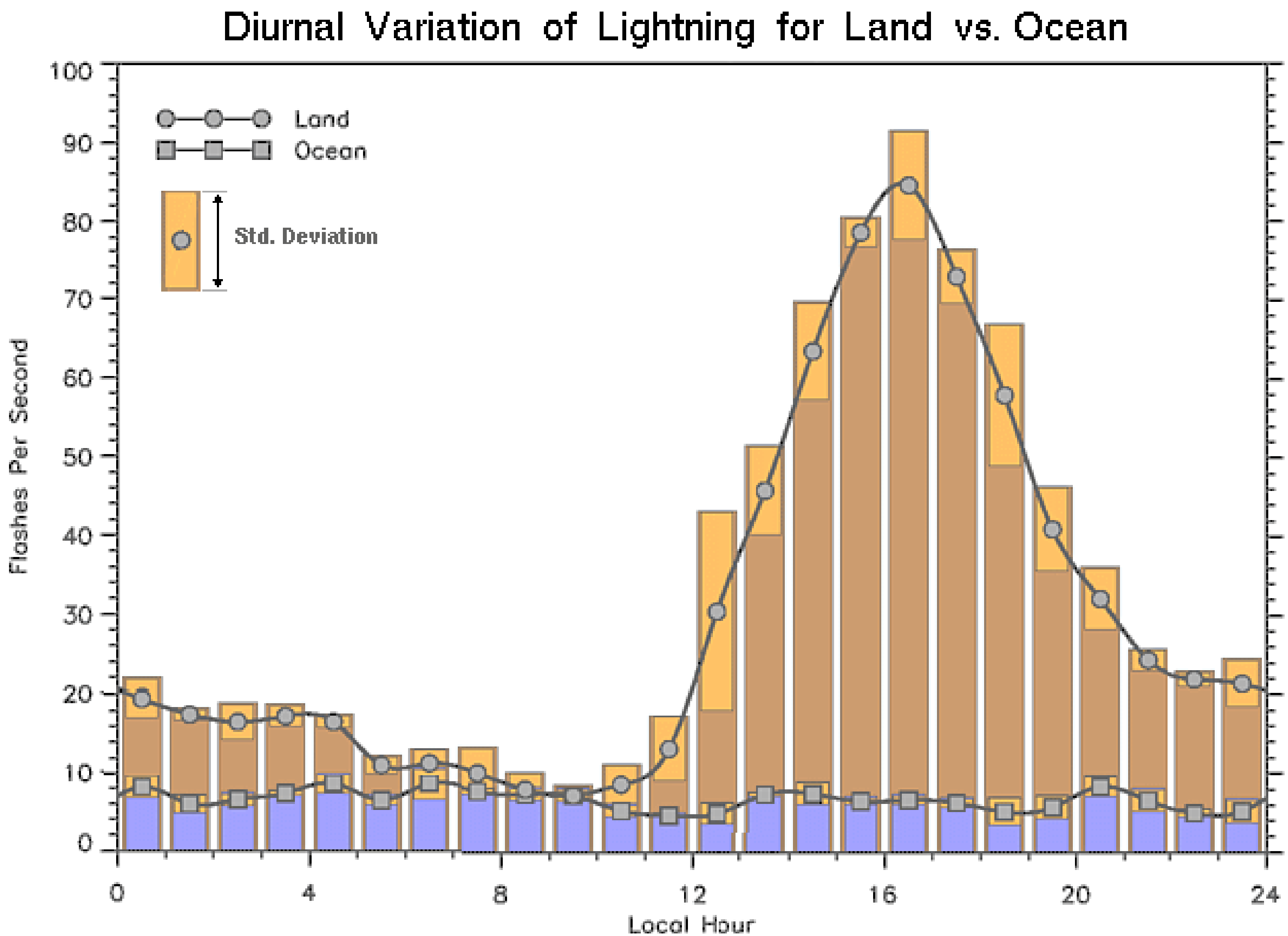

Latitudinal
Distribution
Diurnal
Distribution
Longitudinal
Distribution
6/30/95



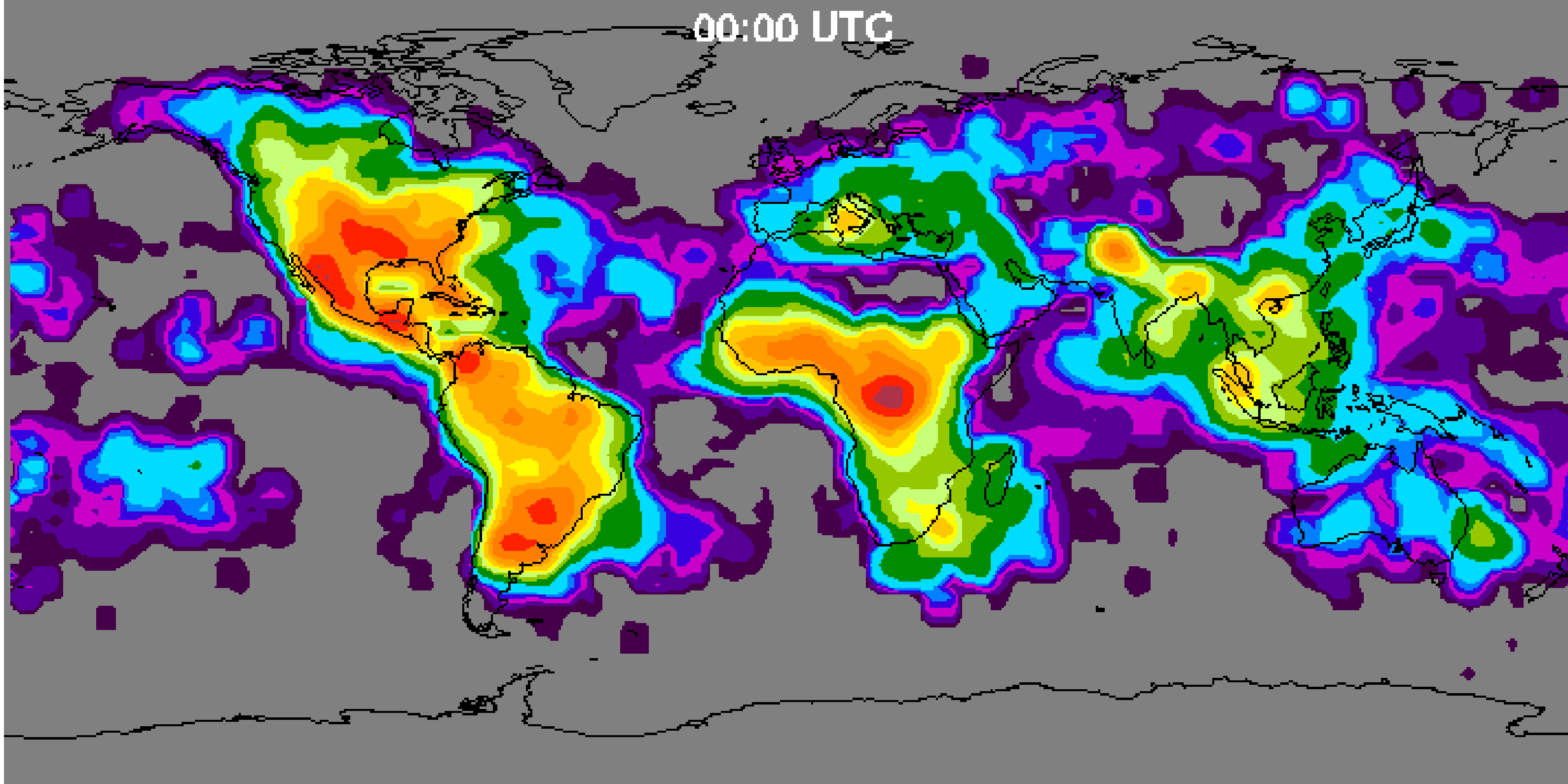
Annual Cycle of the Global Flash Rate
Average Flash Rate (Flashes Per Second)
0
10
20
30
40
50
60
Annual Average
Sep 95
Oct 95
Nov 95
Dec 95
Jan 96
Feb 96
Mar 96
Apr 96
May 96
Jun 96
Jul 96
Aug 96

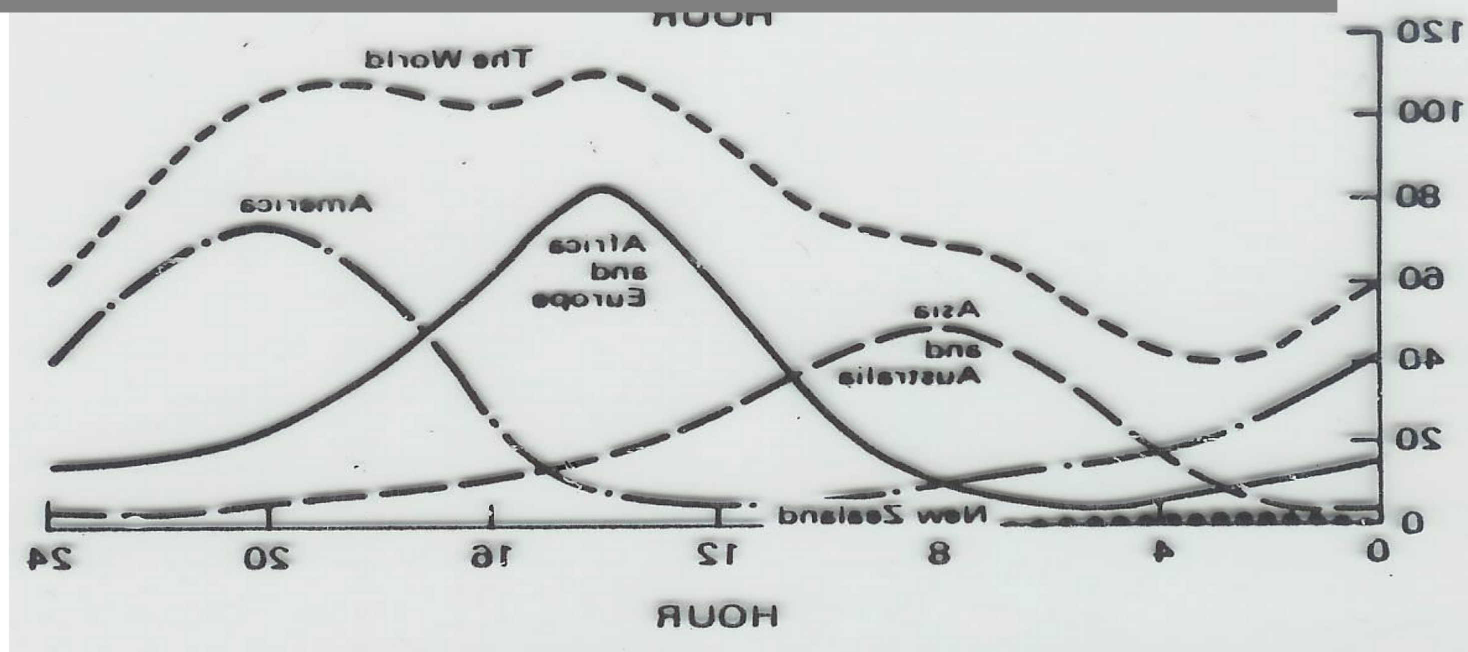
Latitudinal Distribution of the Global Flash Rate

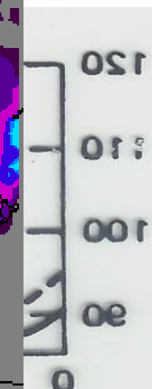




Diurnal Variation of Lightning for Land vs. Ocean
Land
Ocean
Std. Deviation
Flashes Per Second
Local Hour
0
10
20
30
40
50
60
70
80
90
100
0
4
8
12
16
20
24

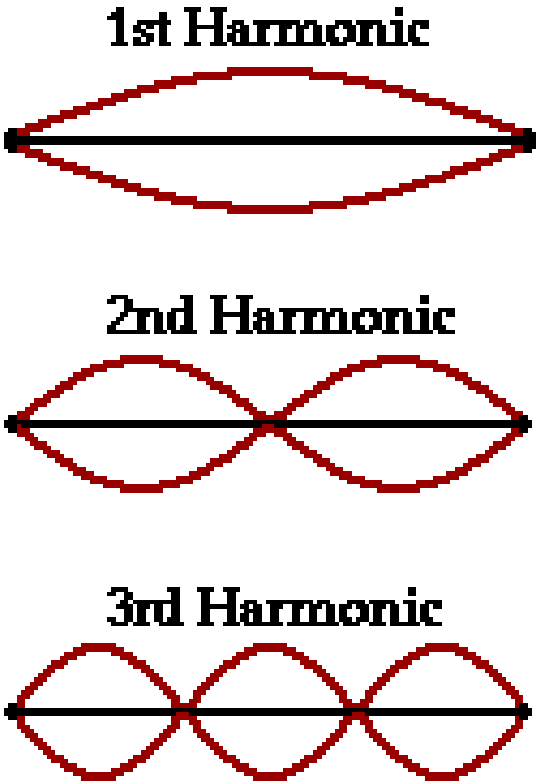

00:00 UTC

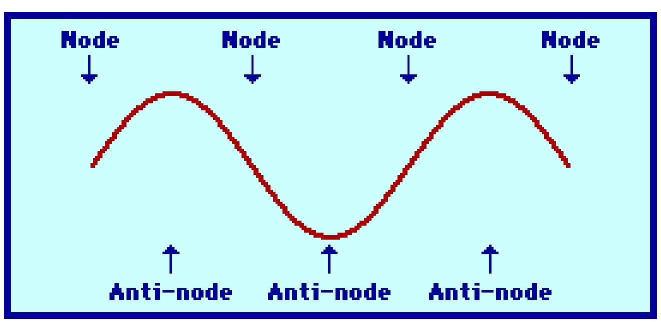

The World
America
Africa and Europe
Asia and Australia
New Zealand
HOUR
24
20
16
12
8
4
0
120
100
80
60
40
20
0


120
110
100
90
0

There is also an AC component to the Global Electric Circuit

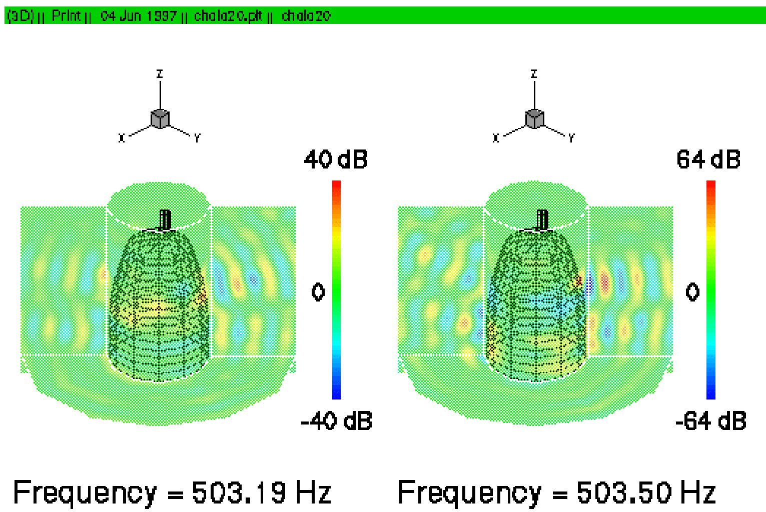
- ✓ 50-100 flashes per second
- ✓ Generation of EM waves
- ✓ Trapped in Earth-ionosphere waveguide





Standing Waves

$$\text{Frequency} = \frac{nV}{L} \quad \text{(Hz)}$$



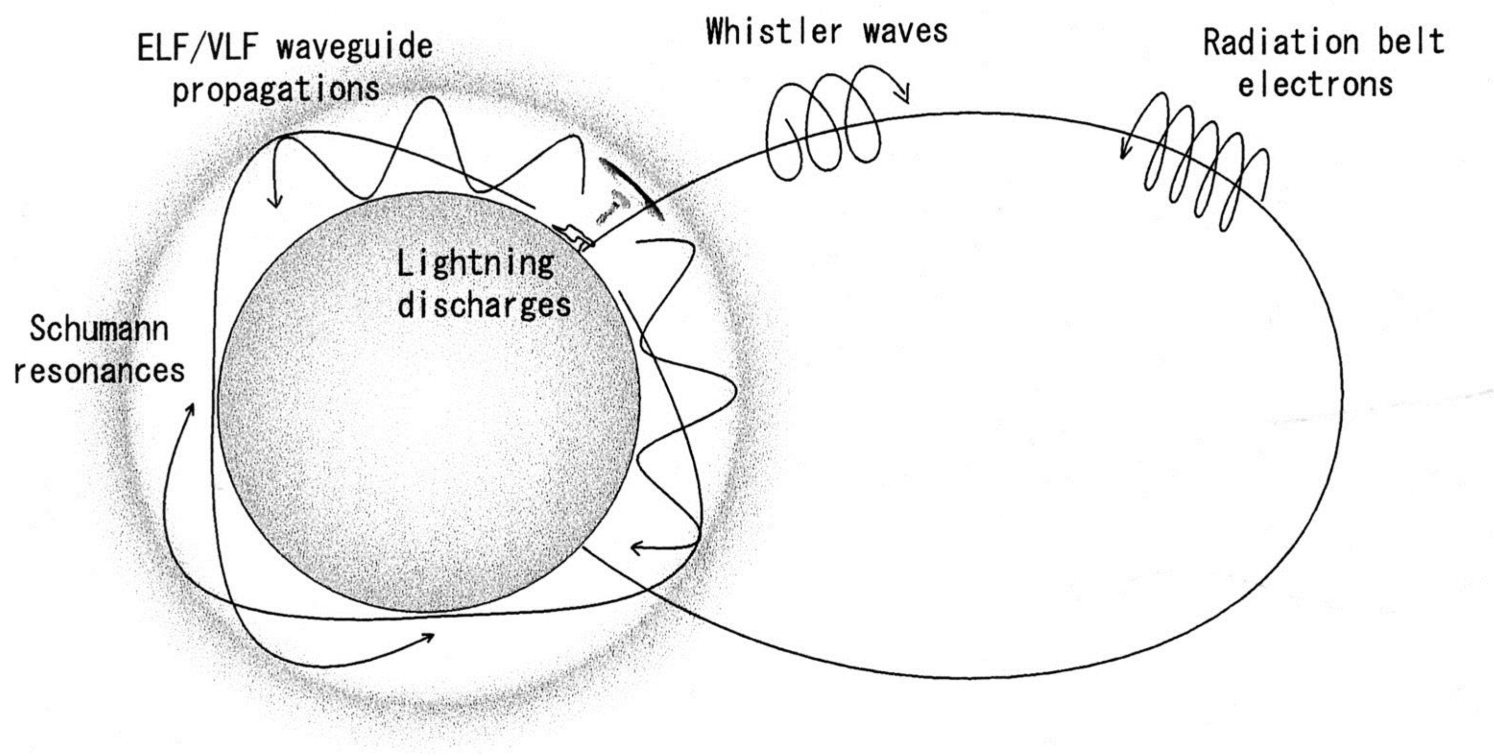
Bell 1

Bell 2

ELF- Schumann Resonances

Extremely Low Frequency (ELF) Range
F < 100 Hz

(Schumann, 1952)



$$f_n \sim \frac{nc}{2\pi a} \sim 8, 14, 20 \ldots \text{Hz}$$

Waveguide Cutoff

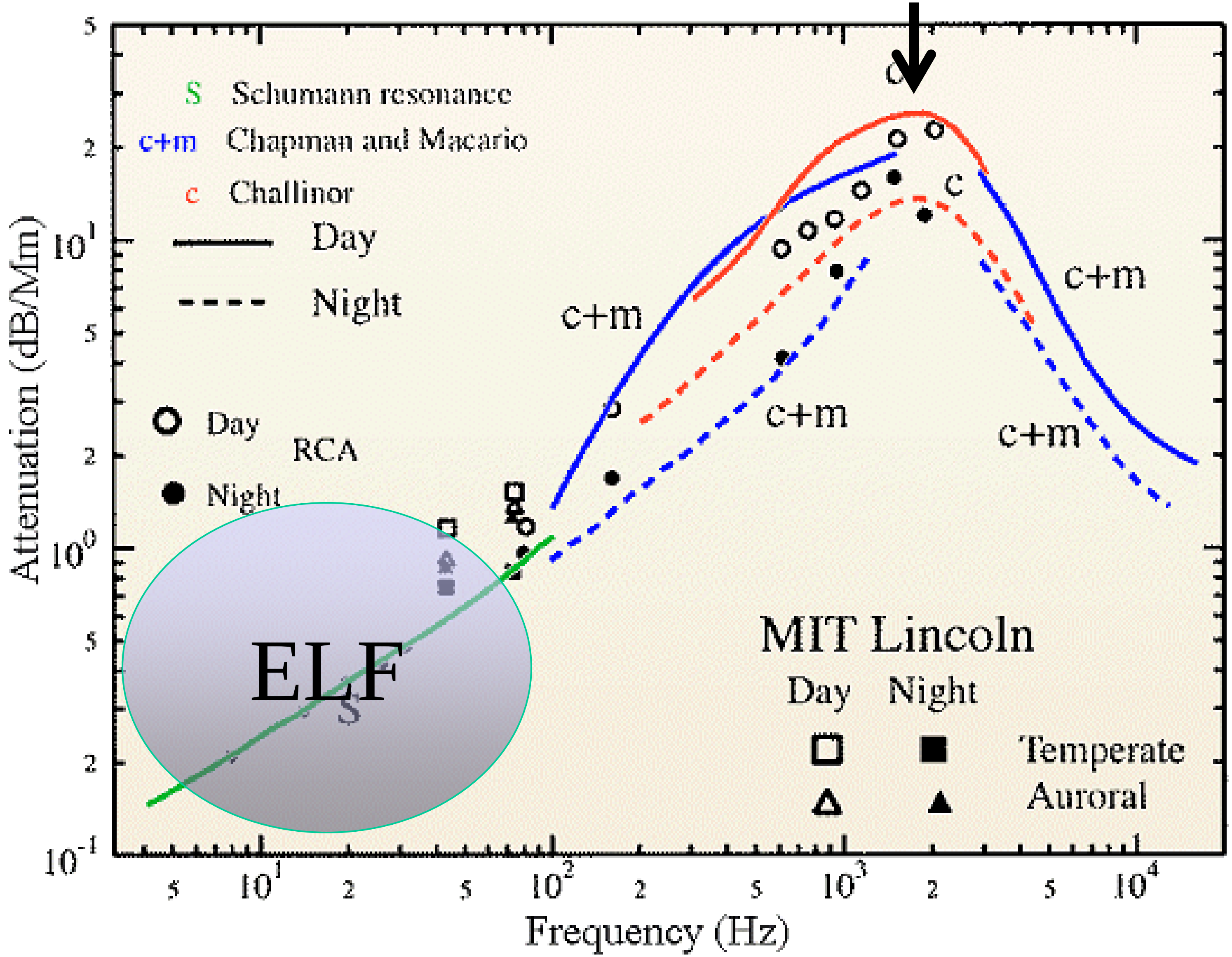
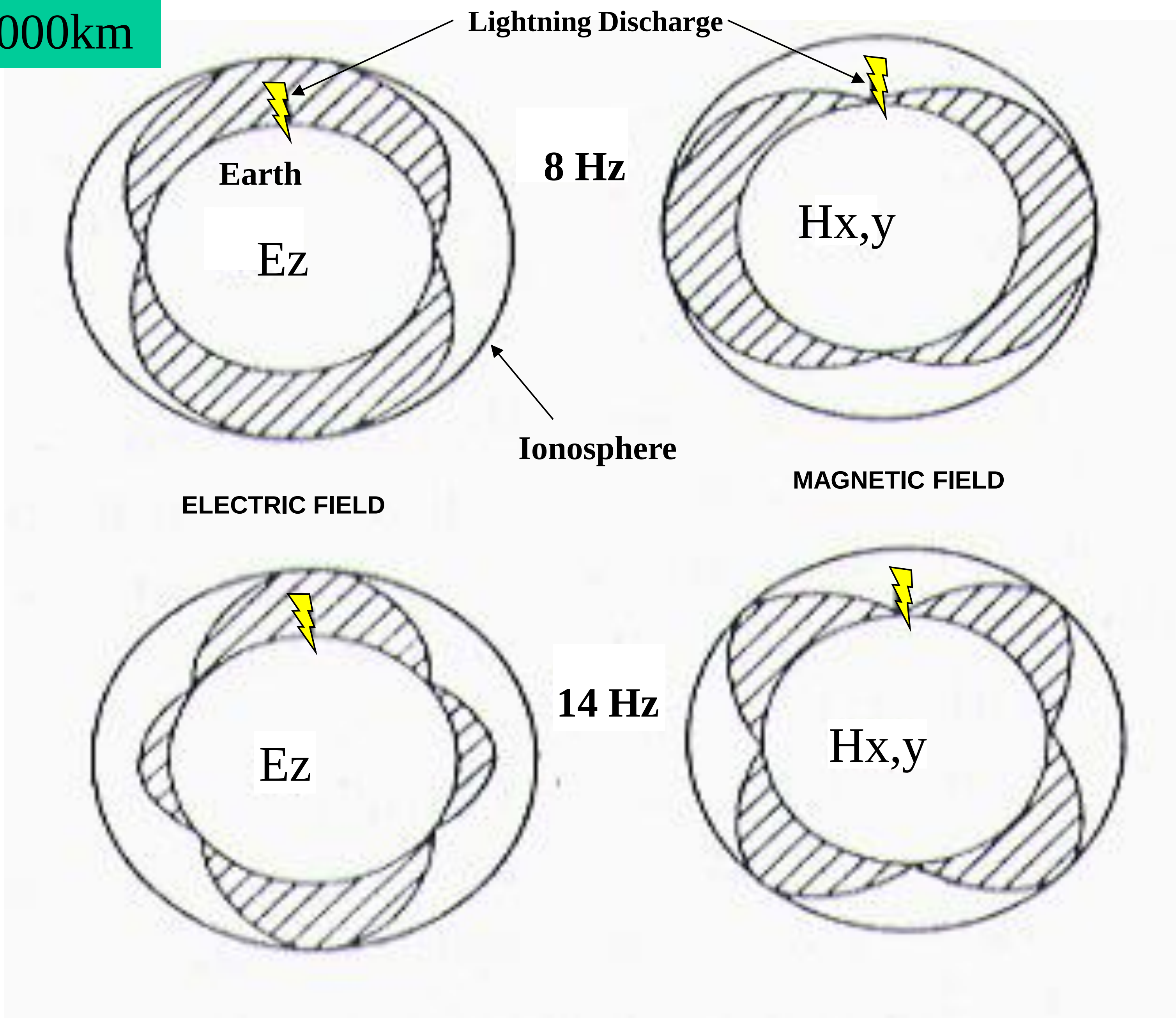


Figure 6 ULF/ELF/VLF path attenuation (dB/Mm) versus frequency

Schumann Resonance Modes 1 and 2

$$F \sim \frac{n\,c}{40{,}000\text{km}}$$



Theory

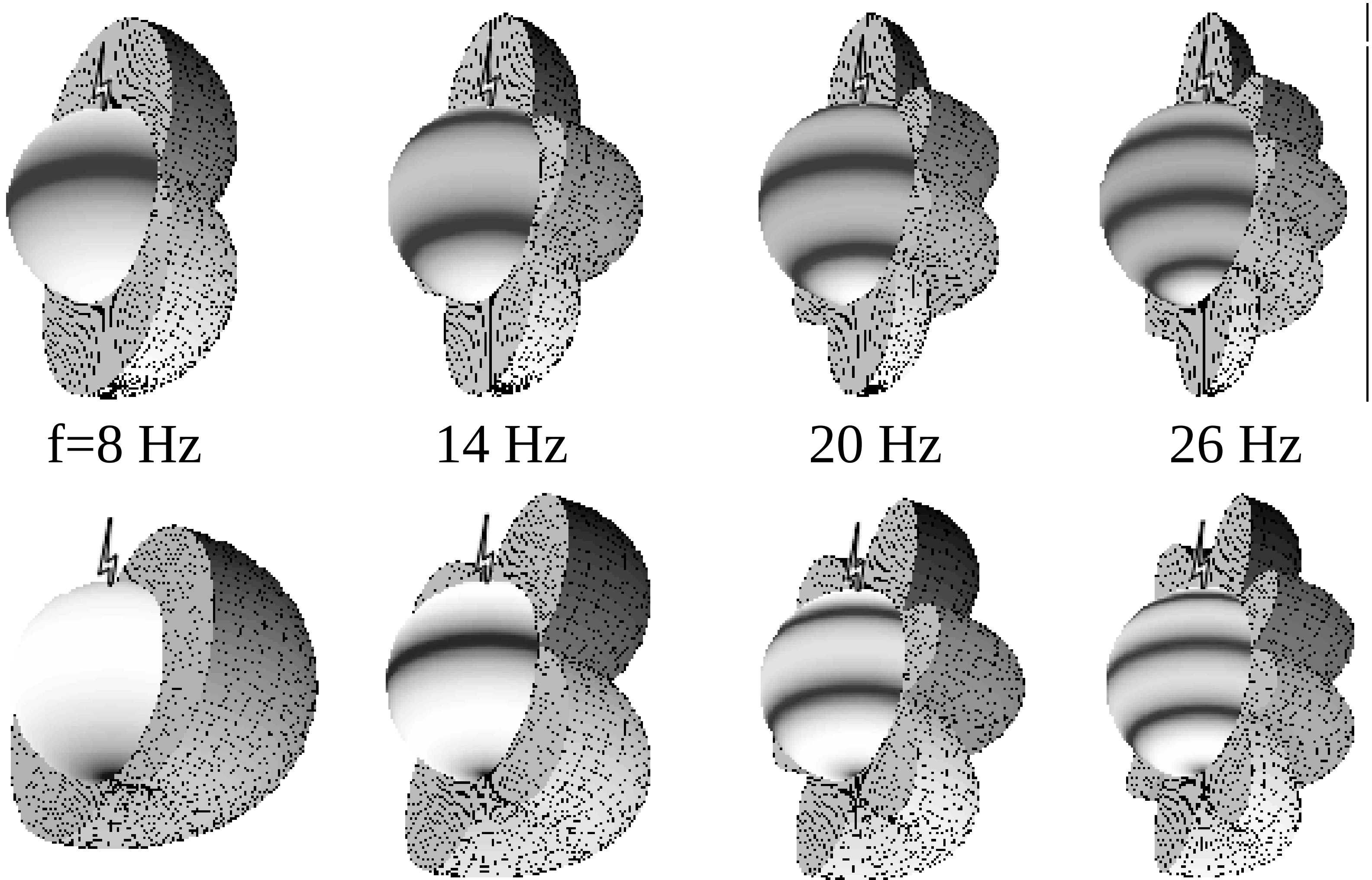
$$E_r(\omega) = -\frac{M_c(\omega)}{4\pi\varepsilon_0 h a^2}\frac{i\nu(\nu+1)}{\omega}\sum_{n=0}^{\infty}\frac{(2n+1)P_n(\cos\theta)}{n(n+1)-\nu(\nu+1)}$$

$$H_\varphi(\omega) = \frac{M_c(\omega)}{4\pi h a}\sum_{n=1}^{\infty}\frac{(2n+1)P_n^1(\cos\theta)}{n(n+1)-\nu(\nu+1)}$$

ω = angular frequency
Θ = great circle angle from lightning to the observer
ε_0 = vacuum permittivity;
a = radius of the Earth;
h = the height of the Ionosphere;
$P_n(\cos\theta)$ and $P_n^1(\cos\theta)$ are Legendre and associated Legendre functions of degree n and order 0,1 respectively
ν, the modal eigenvalue related to the propagation constant of the Earth-Ionosphere spherical-shell cavity
$M_c(\omega)$ is the vertical charge moment of the lightning ground flash.

Angular Distributions of Schumann Resonance Modes

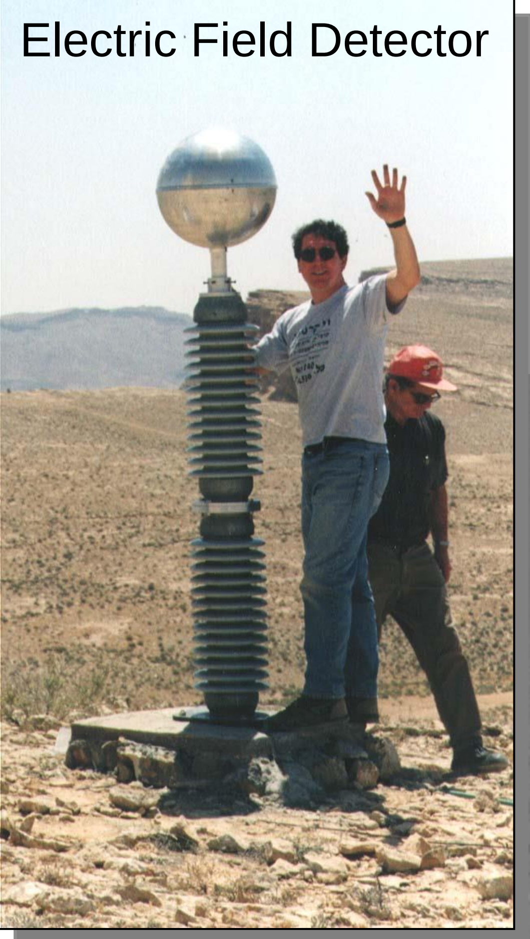
Electric

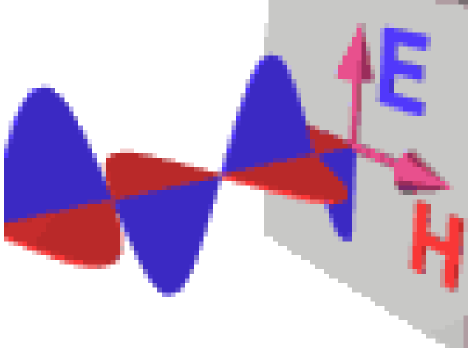


Magnetic

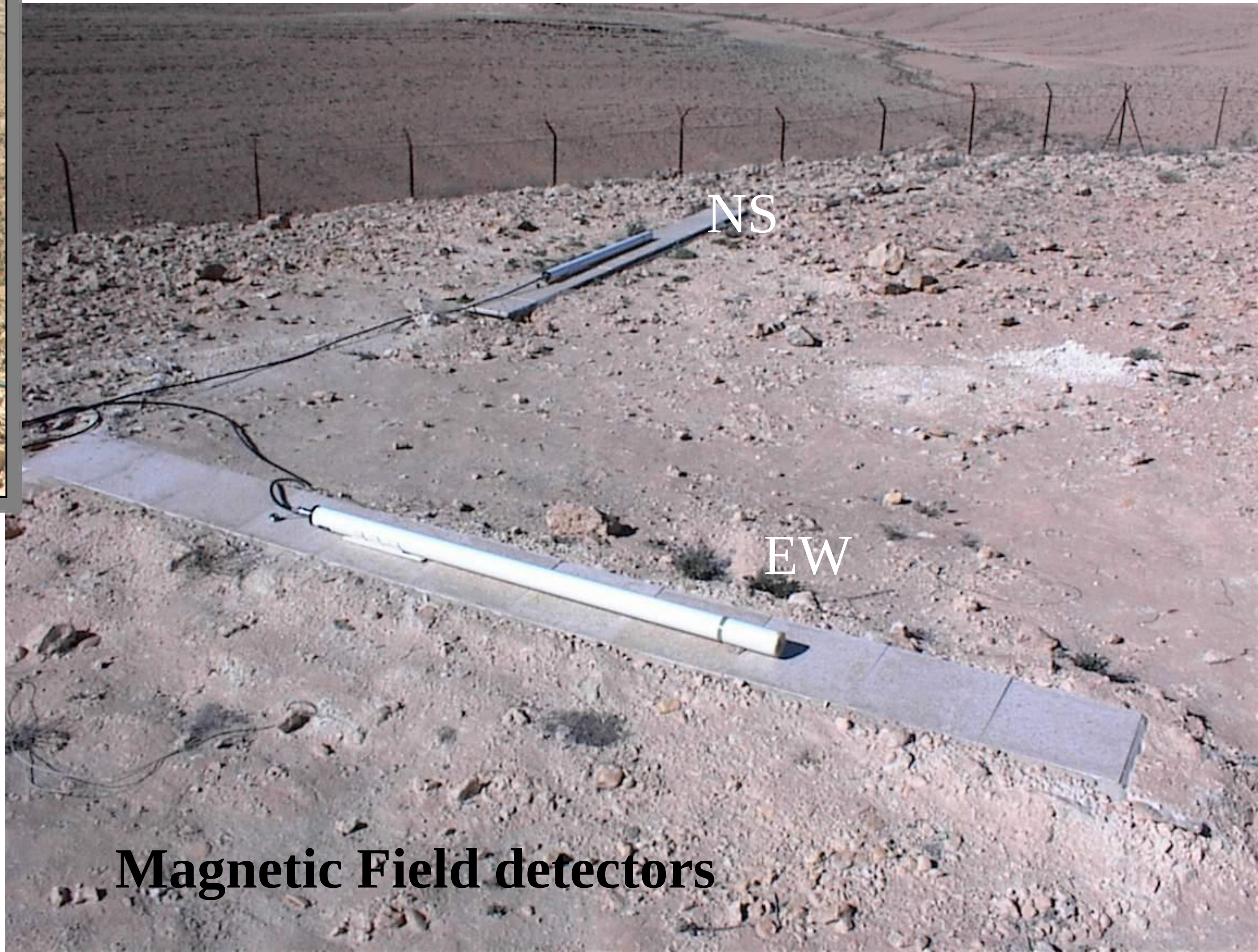
$$F \sim \frac{n\,c}{40{,}000\,\text{km}}$$

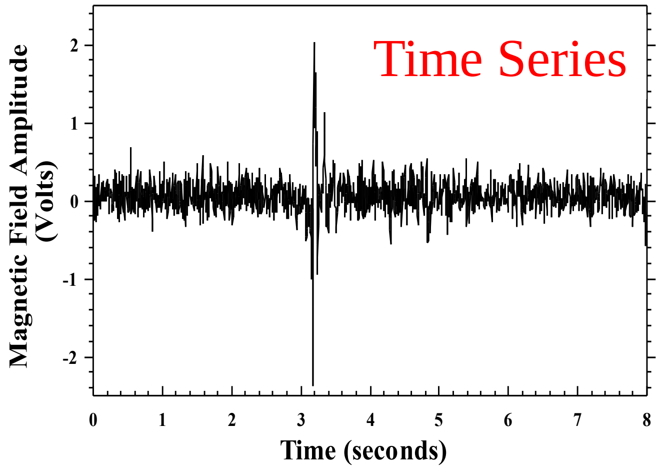
(Schumann, 1952)

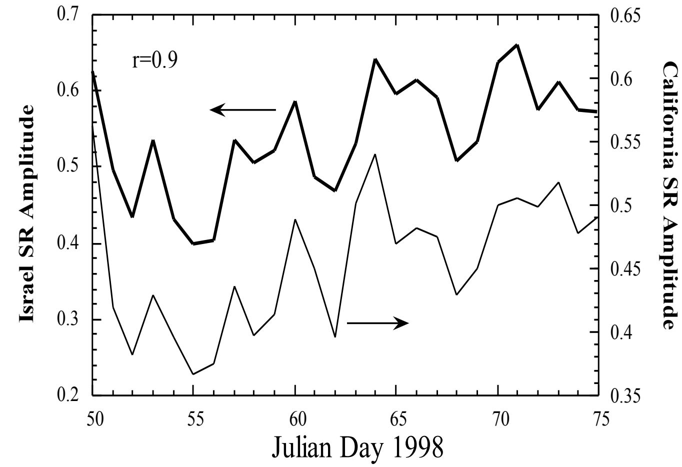




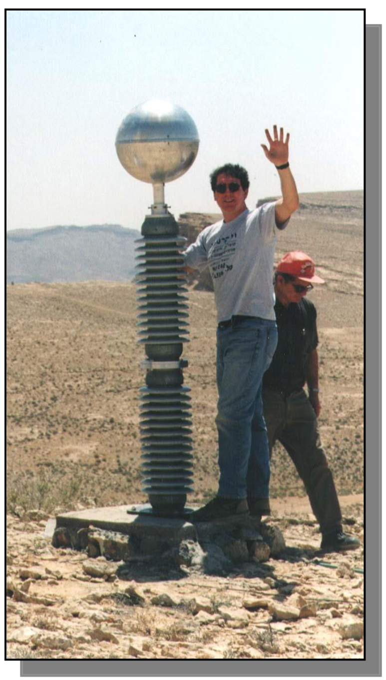
Mitzpe Ramon

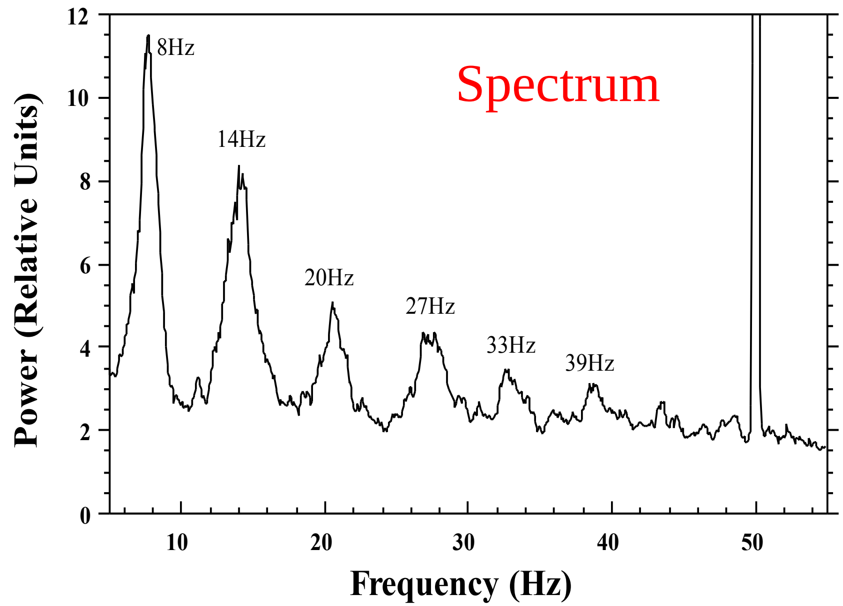






Negev Desert
Israel





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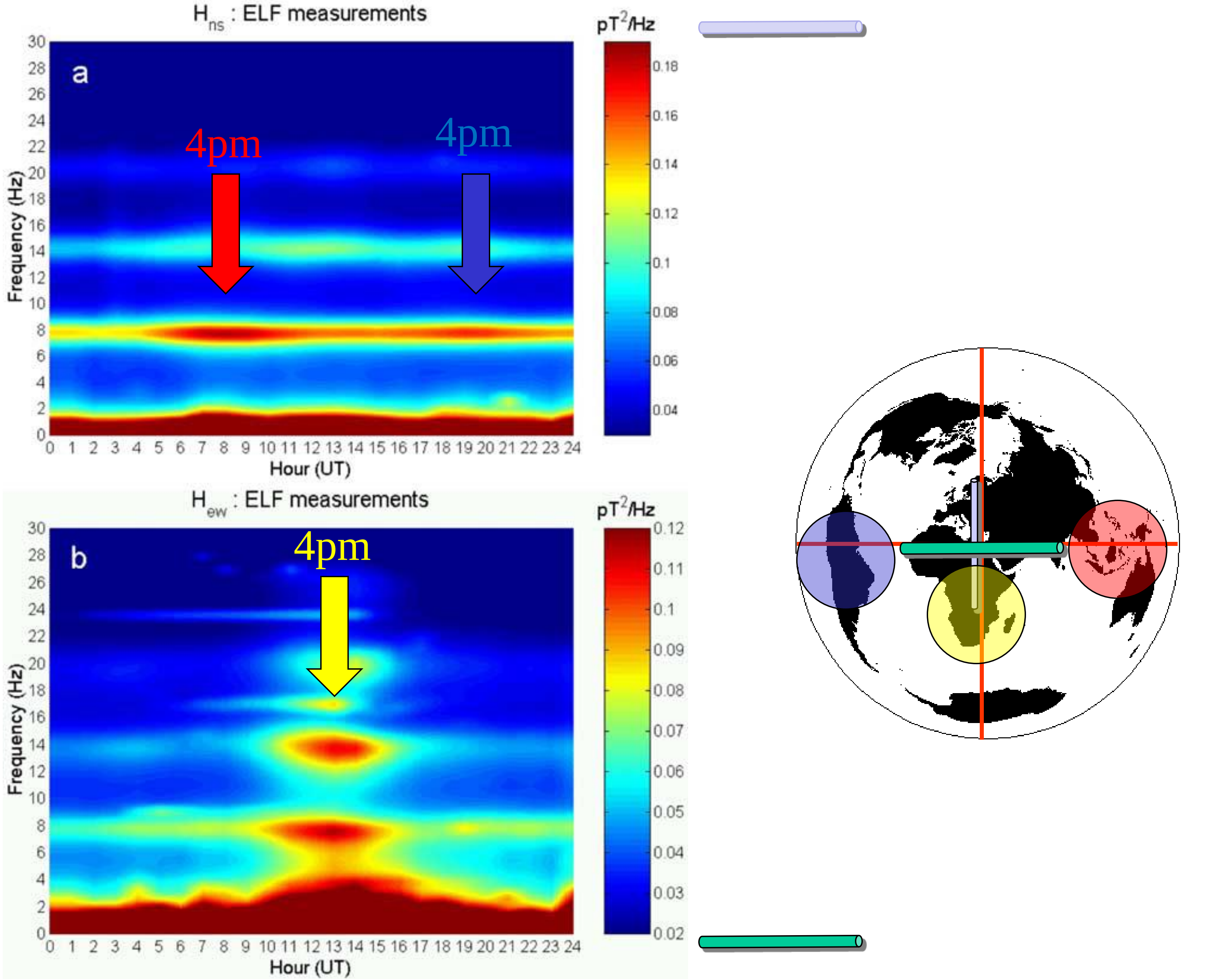


H ns : ELF measurements
pT2/Hz
a
4pm
4pm
Frequency (Hz)
Hour (UT)
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
0.18 0.16 0.14 0.12 0.1 0.08 0.06 0.04
H ew : ELF measurements
pT2/Hz
b
4pm
Frequency (Hz)
Hour (UT)
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
0.12 0.11 0.1 0.09 0.08 0.07 0.06 0.05 0.04 0.03 0.02

Huge Range of Horizontal and Vertical Scales

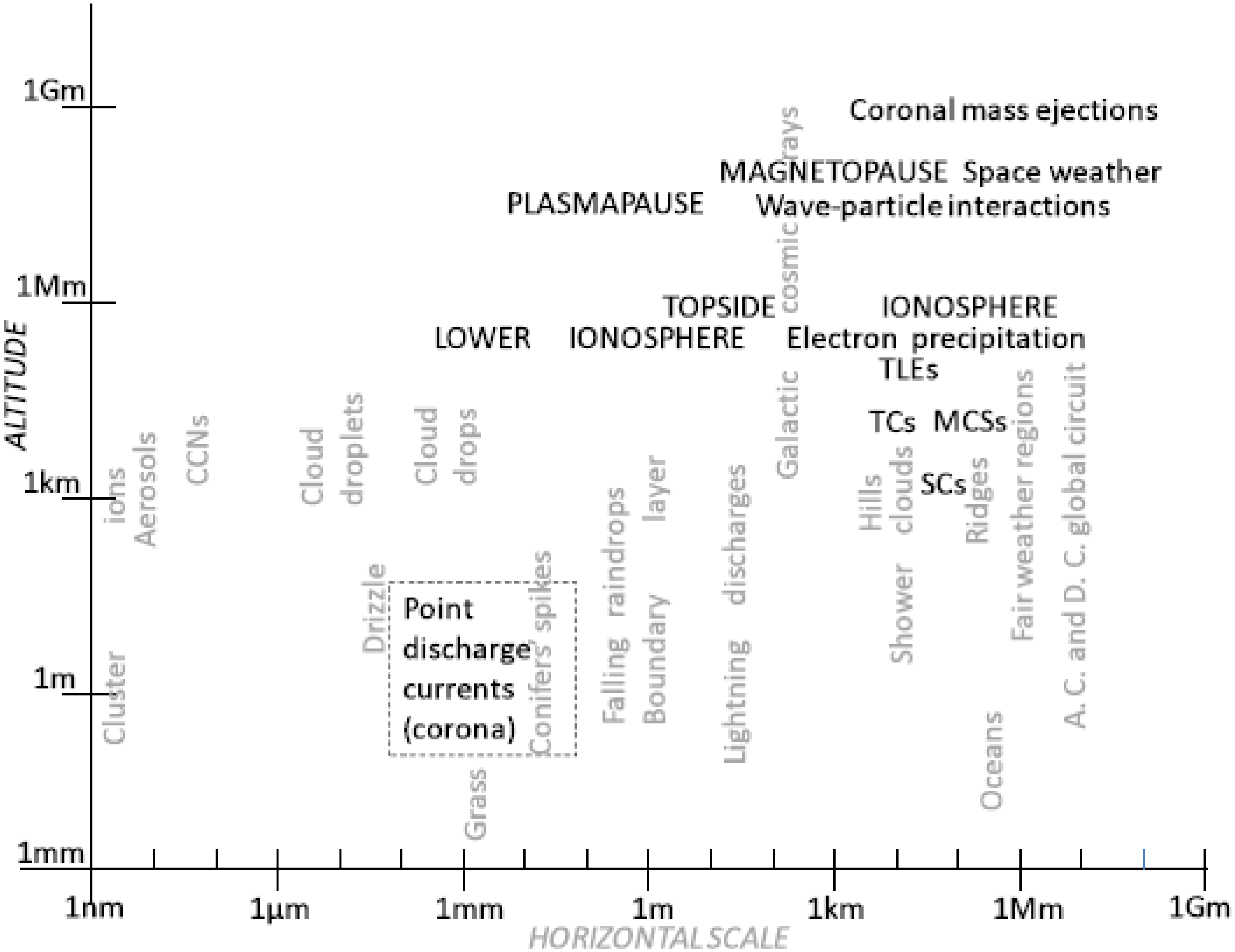


Fig. 1 Diagram indicating the very large range of horizontal and vertical scales involved in various electrical phenomena of interest in the Earth's atmosphere and near-Earth space environment. *Words appearing horizontally* show different regions at different altitudes where different physical processes make their presence felt and *Words appearing vertically* show features with a certain horizontal scale which are important over the altitude range indicated. (Here, TCs is an abbreviation for thunderclouds—other such terms are explained in the text)

Rycroft and Harrison (2011)

Huge range of Temporal Scales

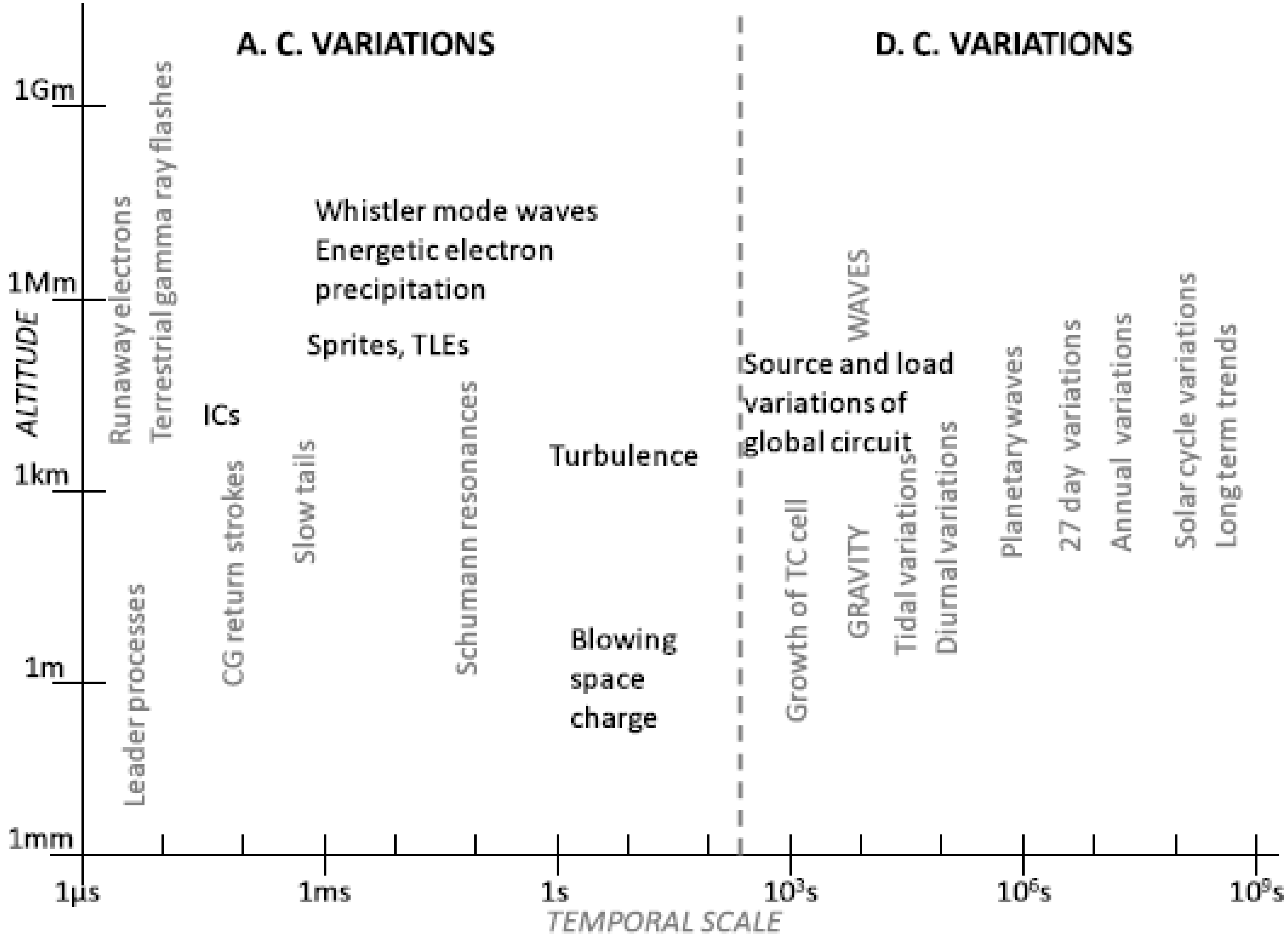
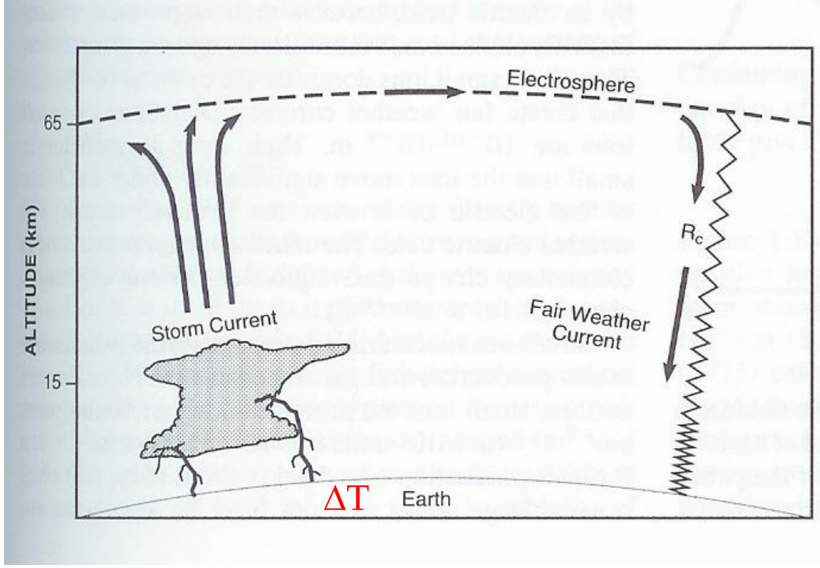
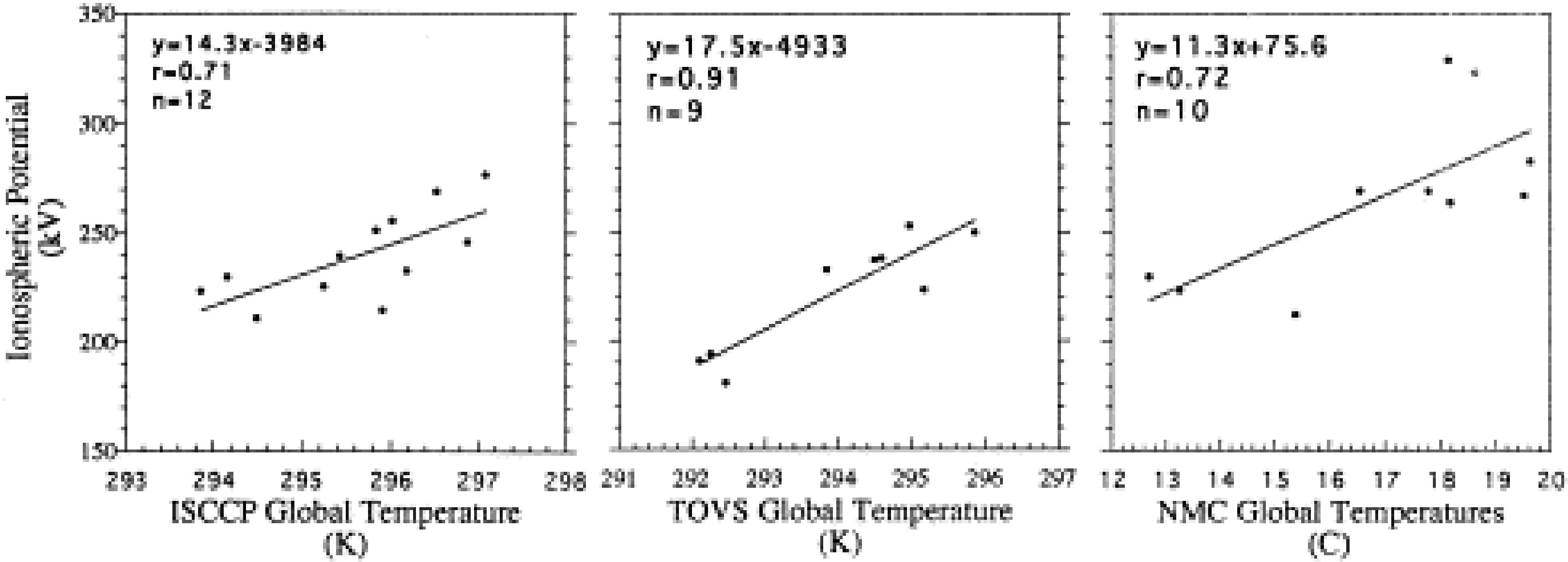


Fig. 2 Diagram showing the enormous range of time scales involved in important processes (*horizontal words*) occurring at different altitudes. *Vertical words* represent different phenomena which occur on different temporal scales over different altitude ranges—see the text for a fuller discussion. The boundary between A.C. and D.C. variations is placed at ~200 s, the *RC* time constant of the poorly conducting atmospheric region between the good conducting Earth and the ionosphere

Rycroft and Harrison (2011)

Global Circuit and Climate Change

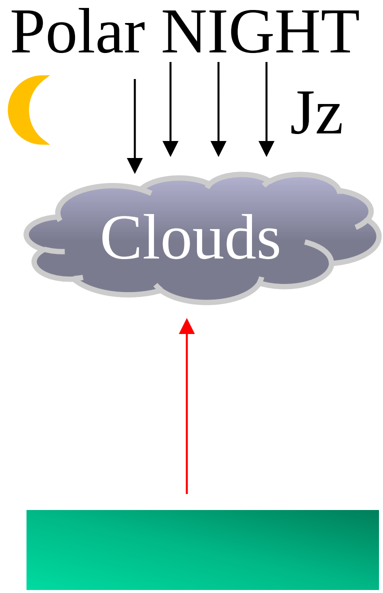


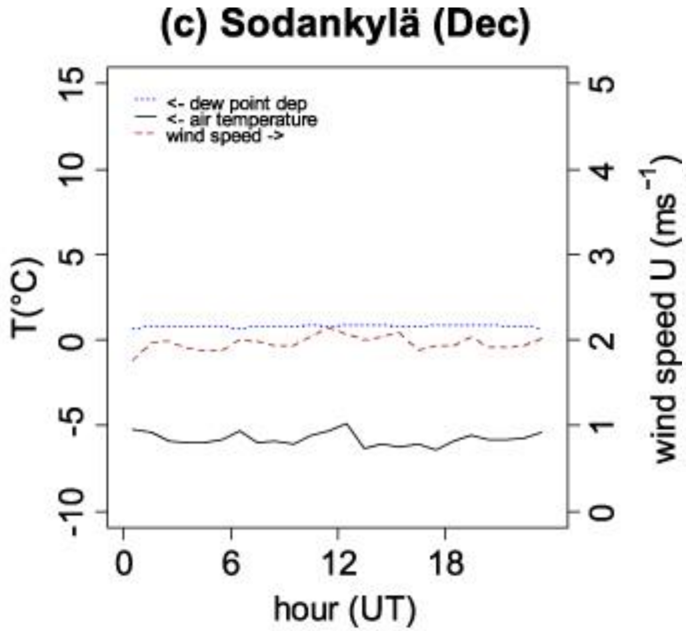


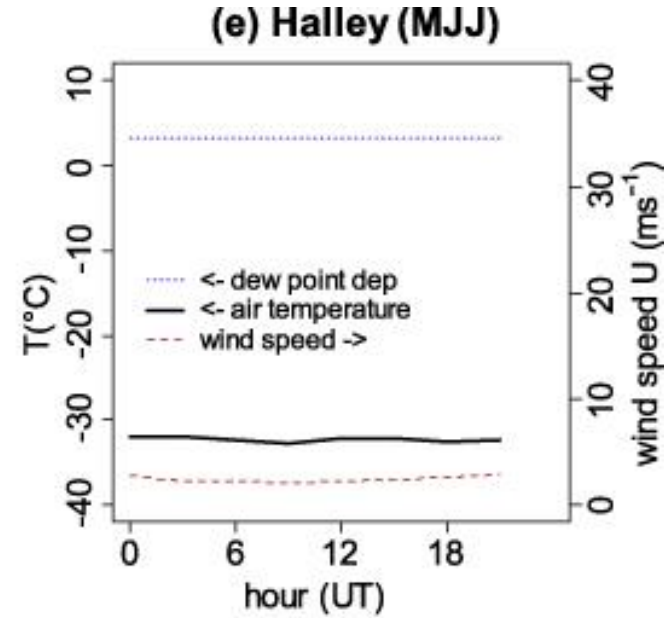
(ISCCP: International Cloud Climatology Project)

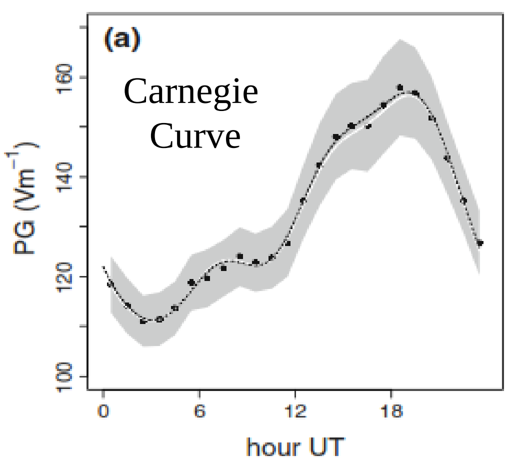
(TOVS: TIROS Operational Vertical Sounder, provides skin temperatures)

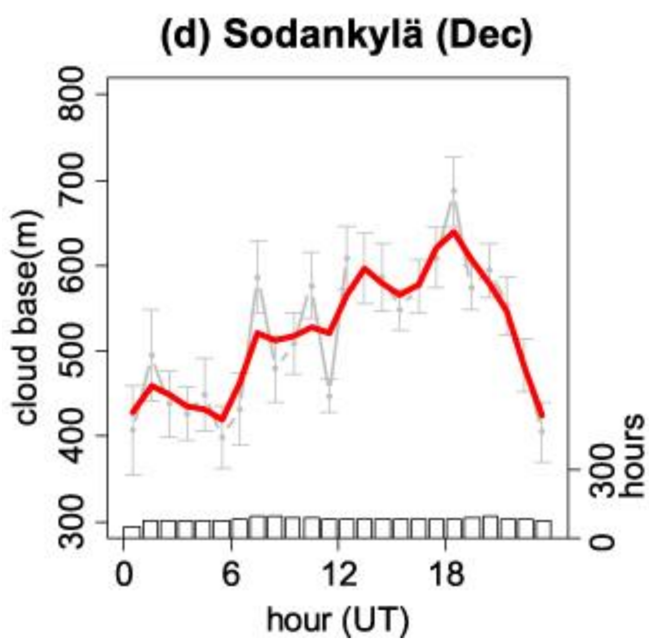
(NMC: National Meteorological Center)

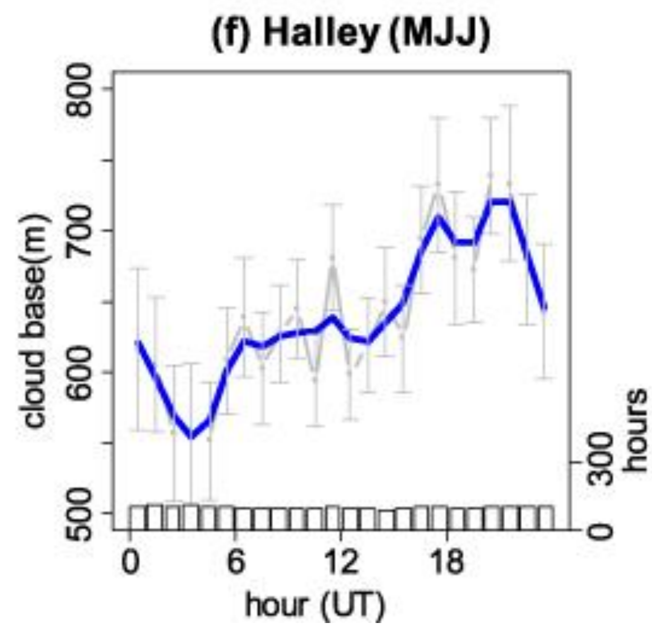








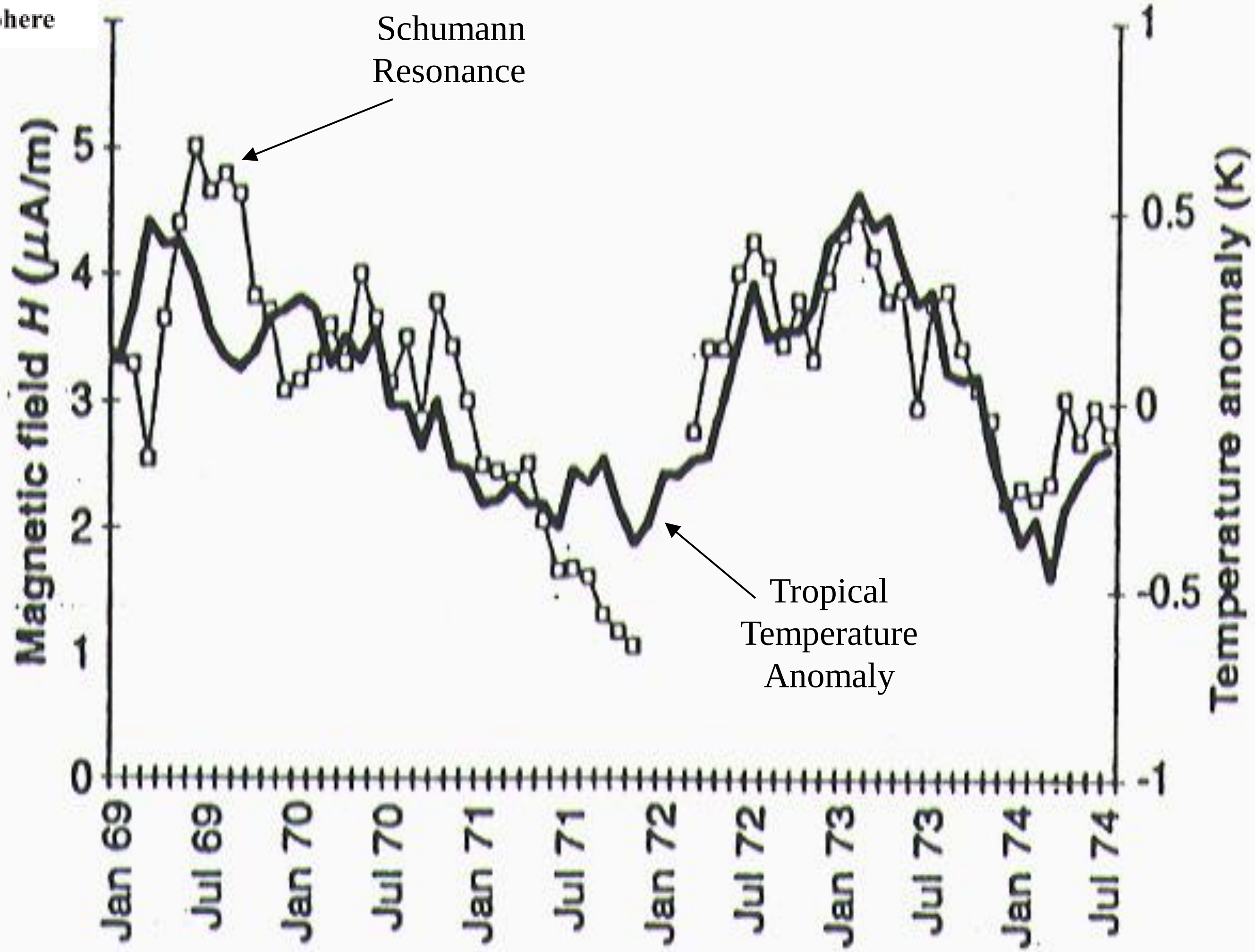


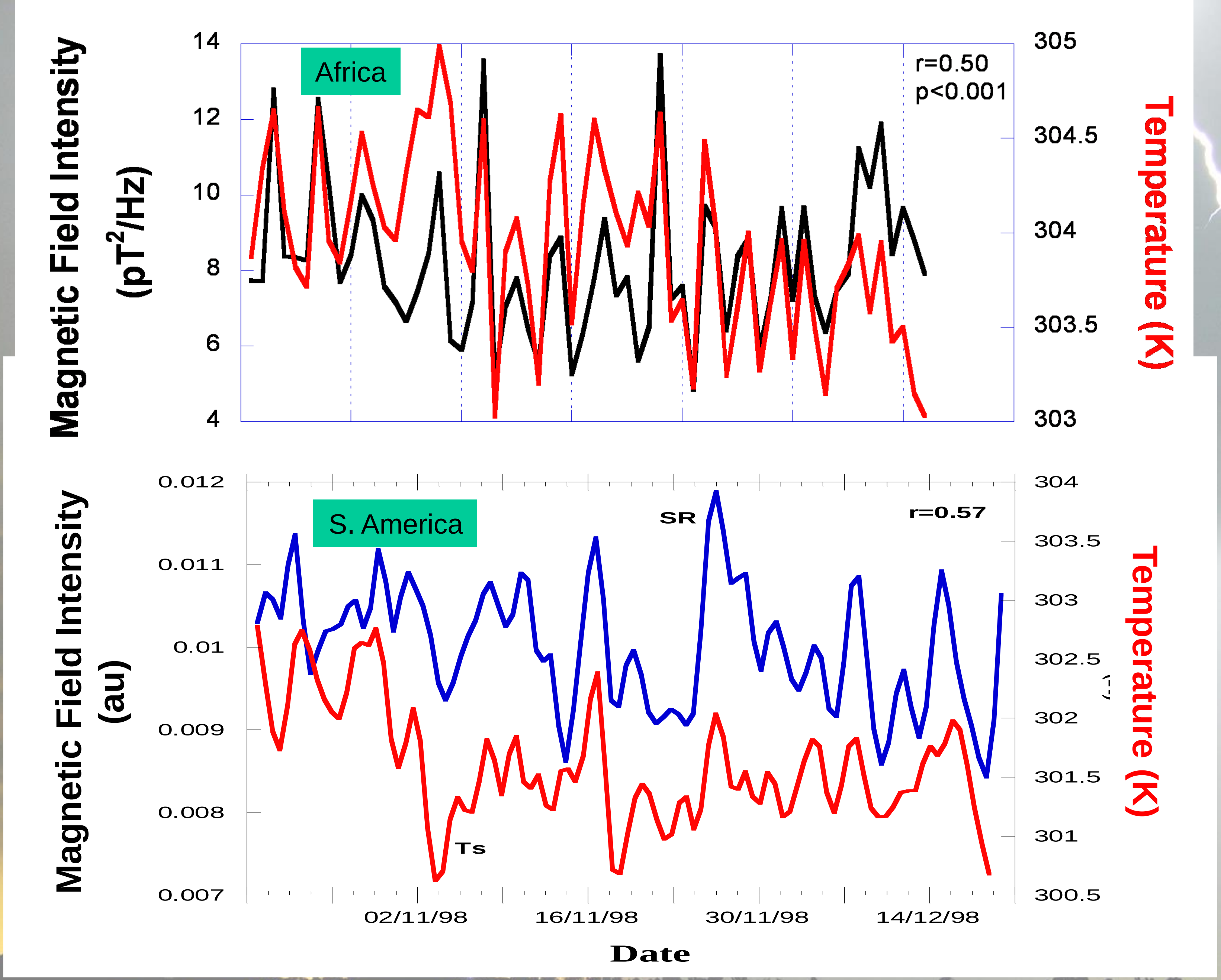


Harrison and Ambaum (2013)

6 years of data

Williams (1992)

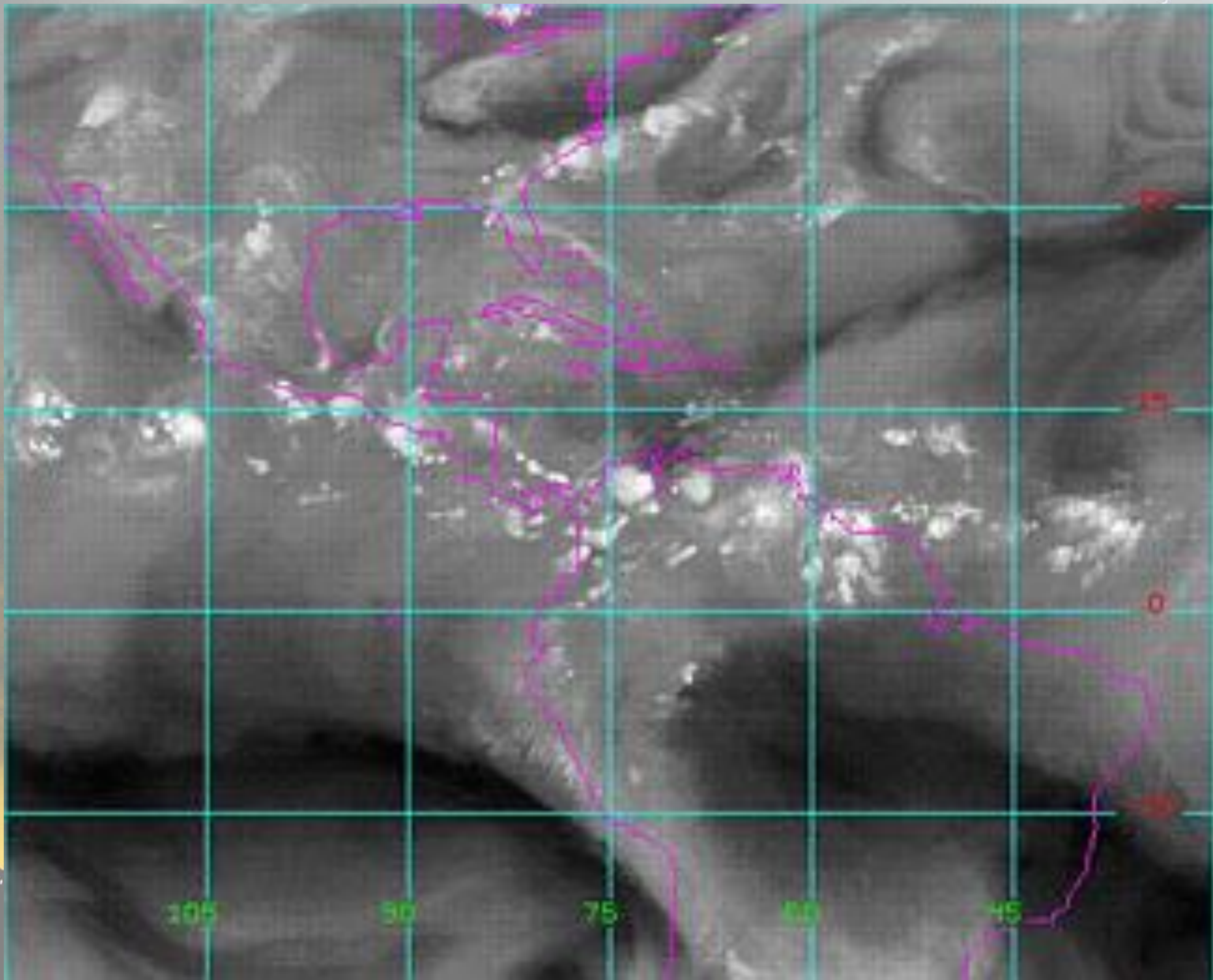




Price and Asfur (2006)

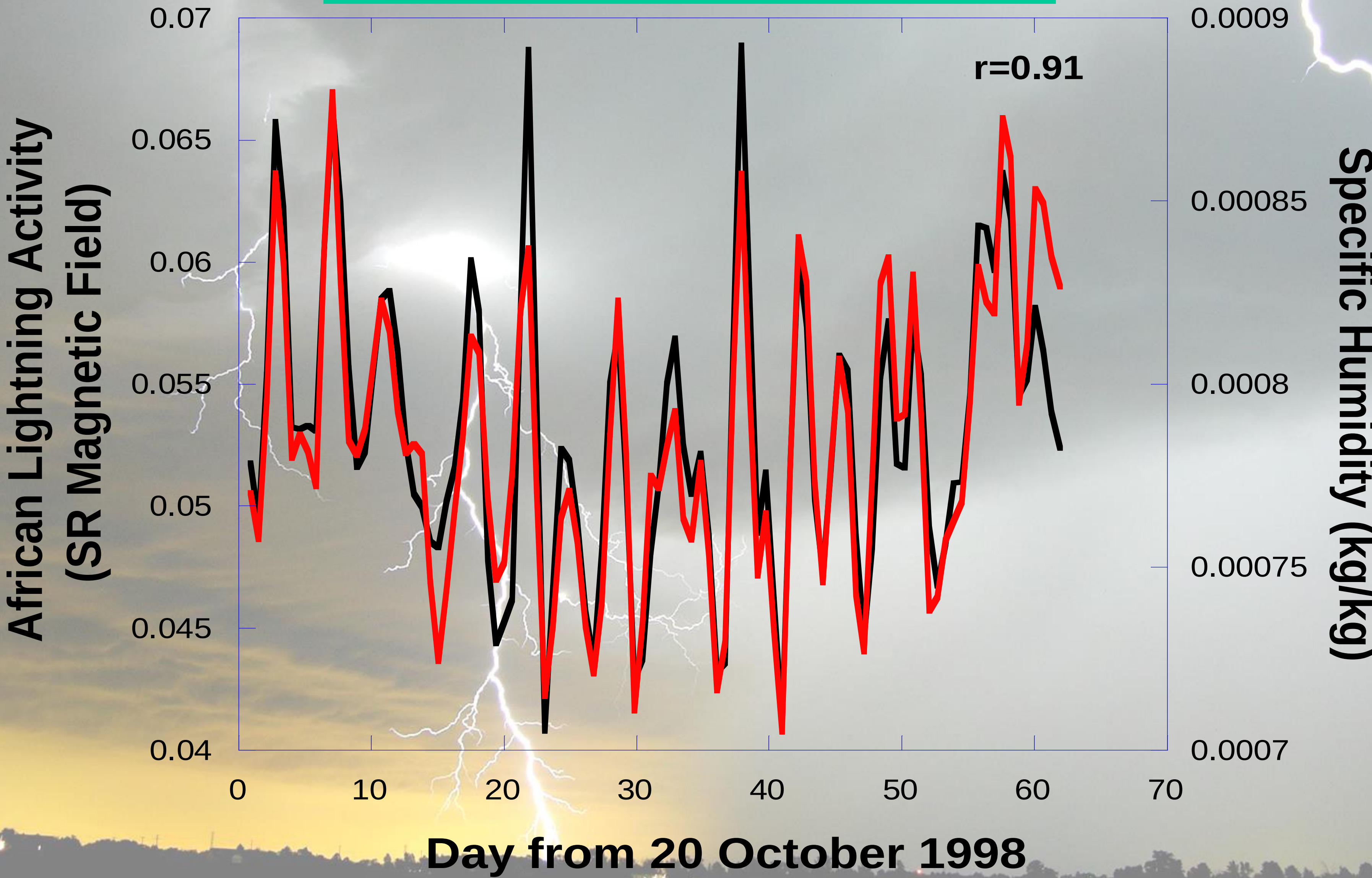
Upper Tropospheric Water Vapour

Upper Tropospheric Water Vapour



Lightning Activity vs. Specific Humidity (300mb) +24hours

26% SR change => 0.1 g/kg change



Price and Asfur (2006)

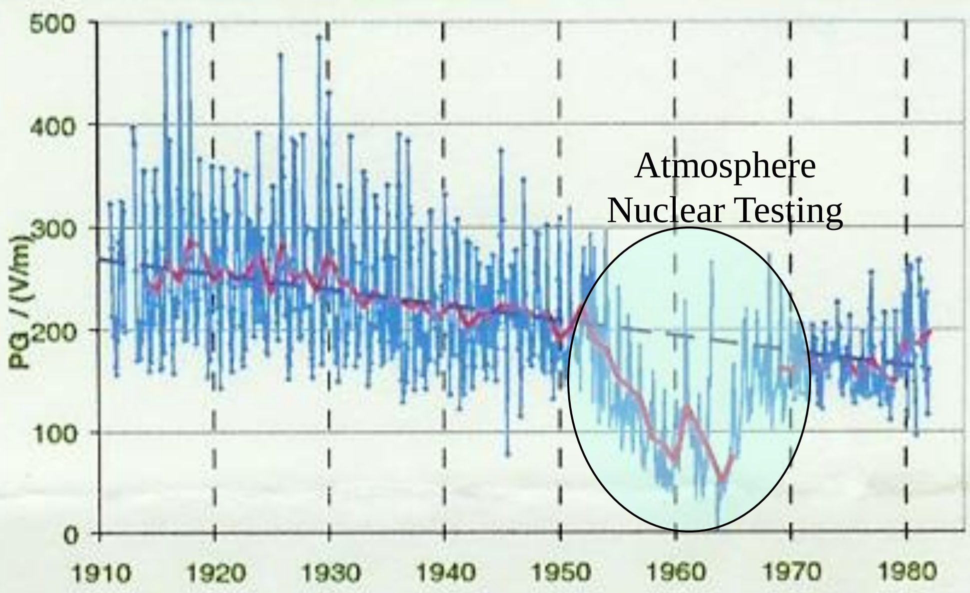
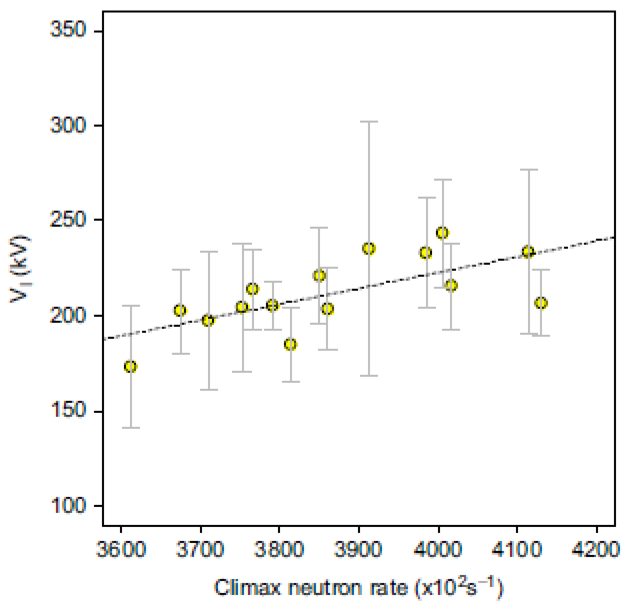


Figure 2. Monthly-average values of the Potential Gradient (PG) observed on 0a days, at Eskdalemuir, with the yearly 0a averages shown (solid red line) where available, from 1914. A linear trend line (dashed blue line) has been fitted to the monthly averages 1911-1981, with the 1951-1969 data excluded.

Harrison (2002)

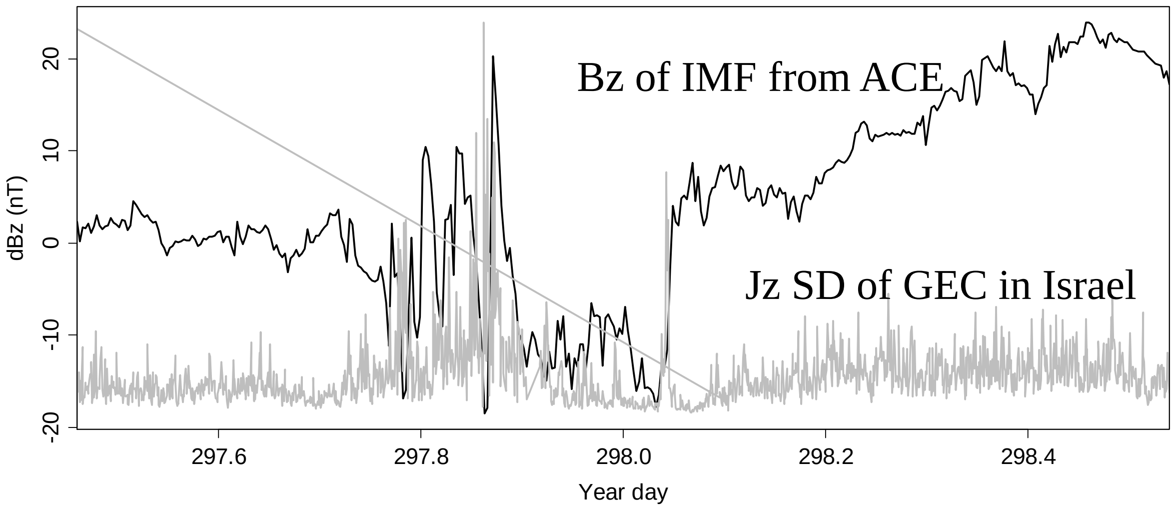
Solar Influences on the Global Circuit

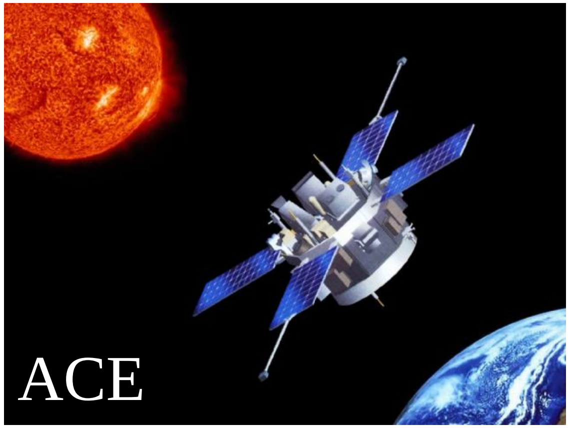


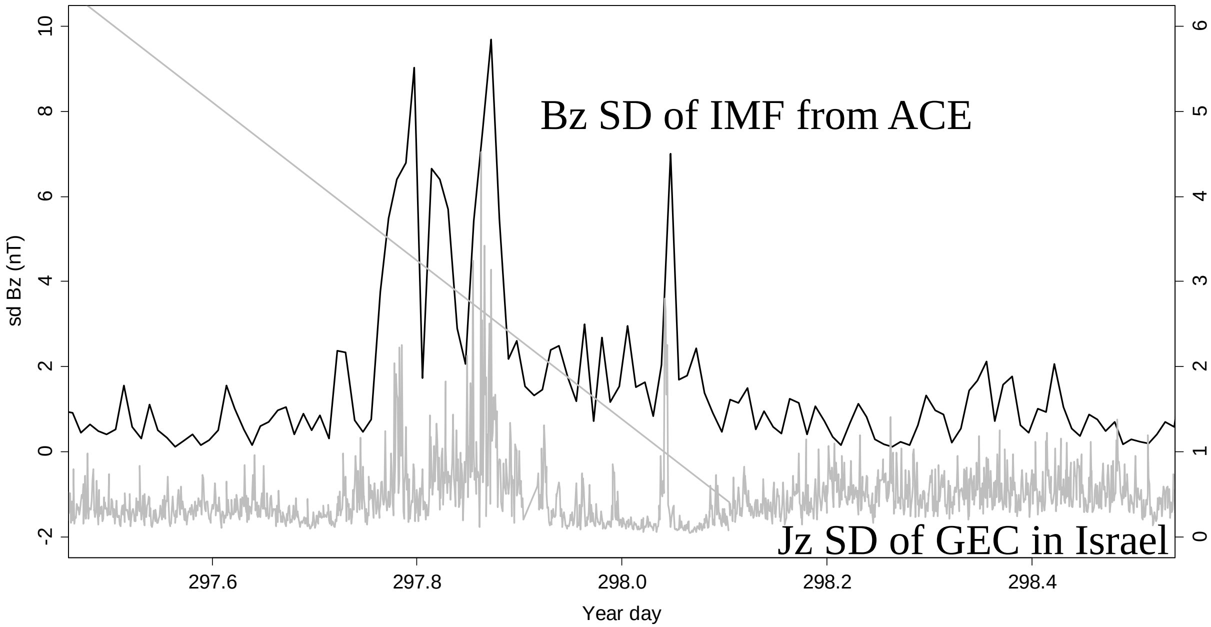
Harrison and Usoskin (2010)

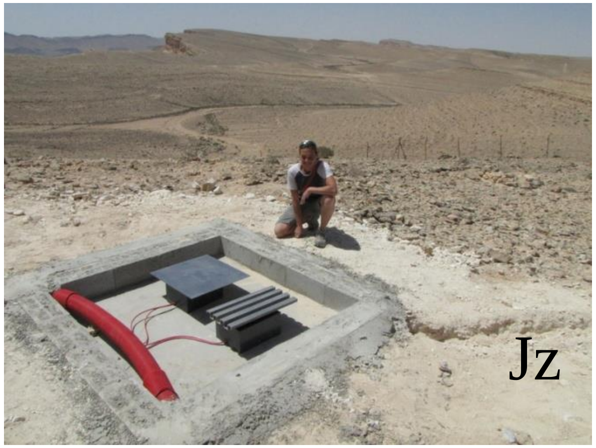
DC Circuit

24 October 2011



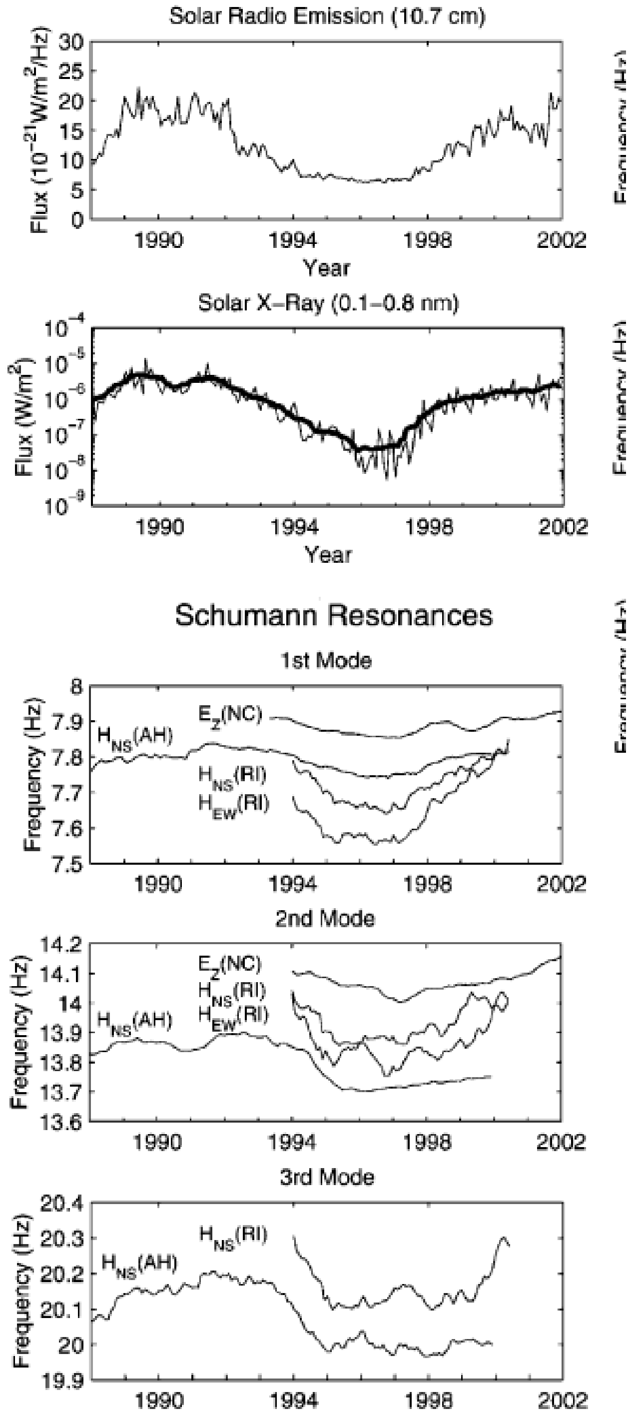


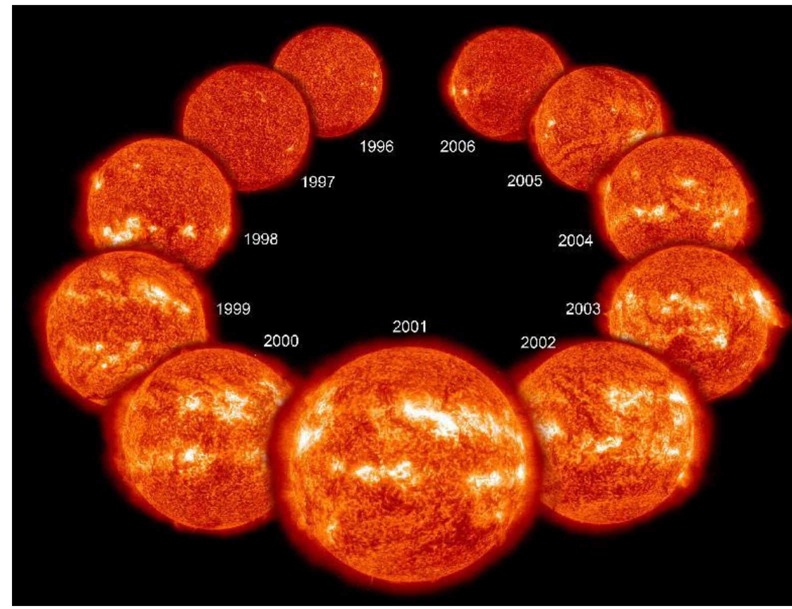




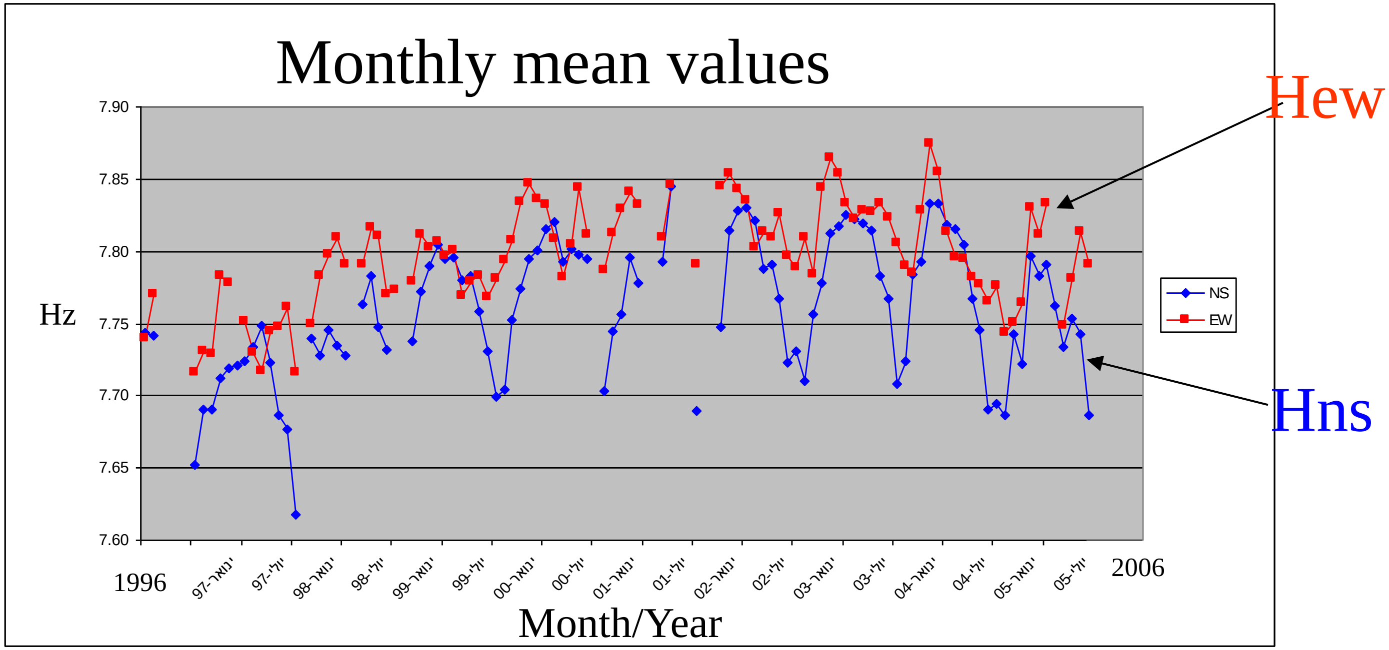
AC Circuit

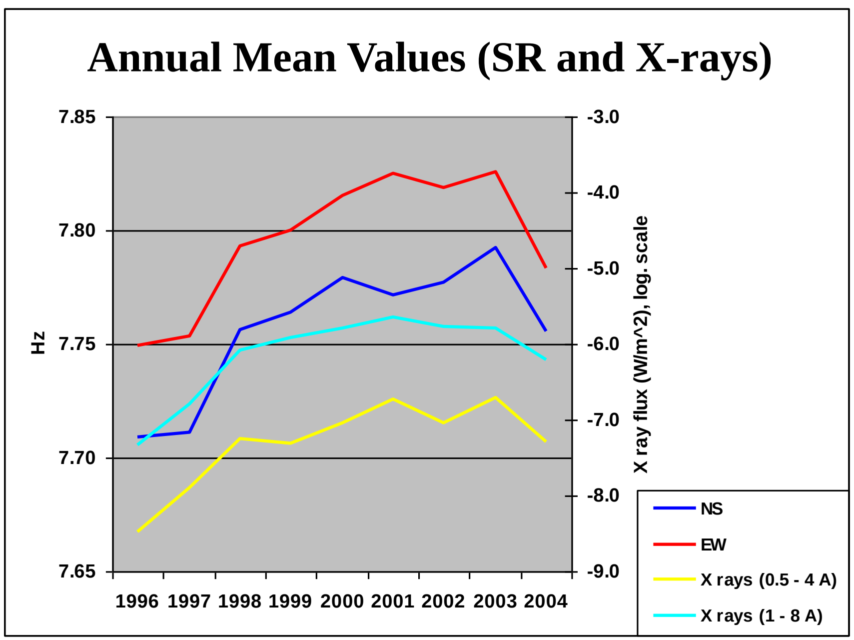
Satori et al. (2005)

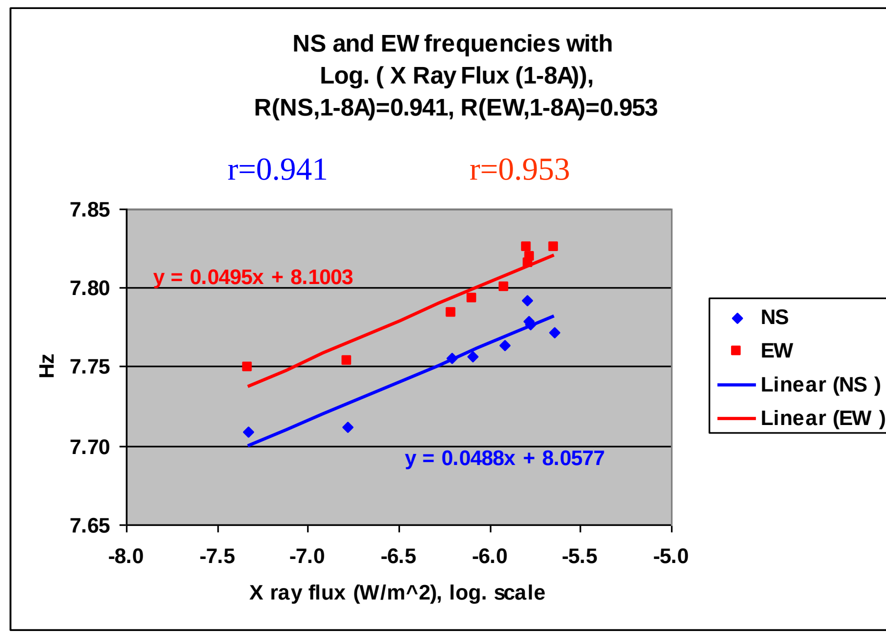




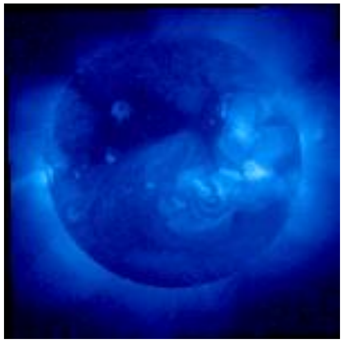
Frequency of first SR mode (~7.8Hz)



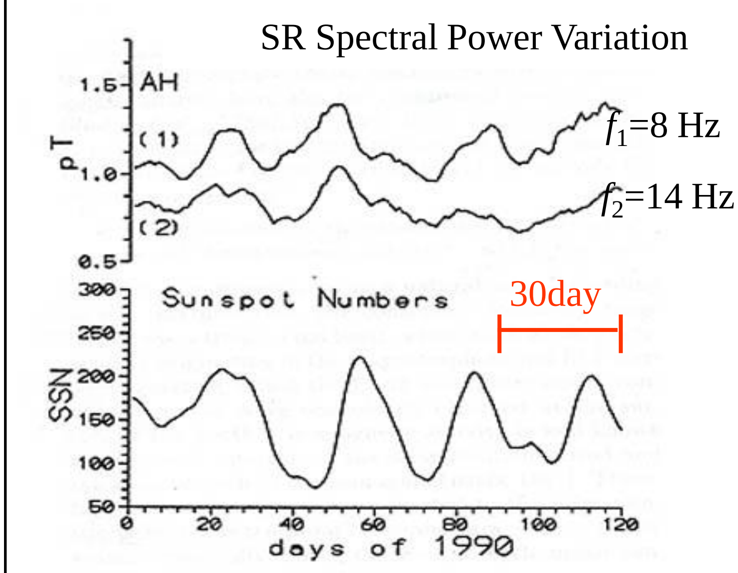




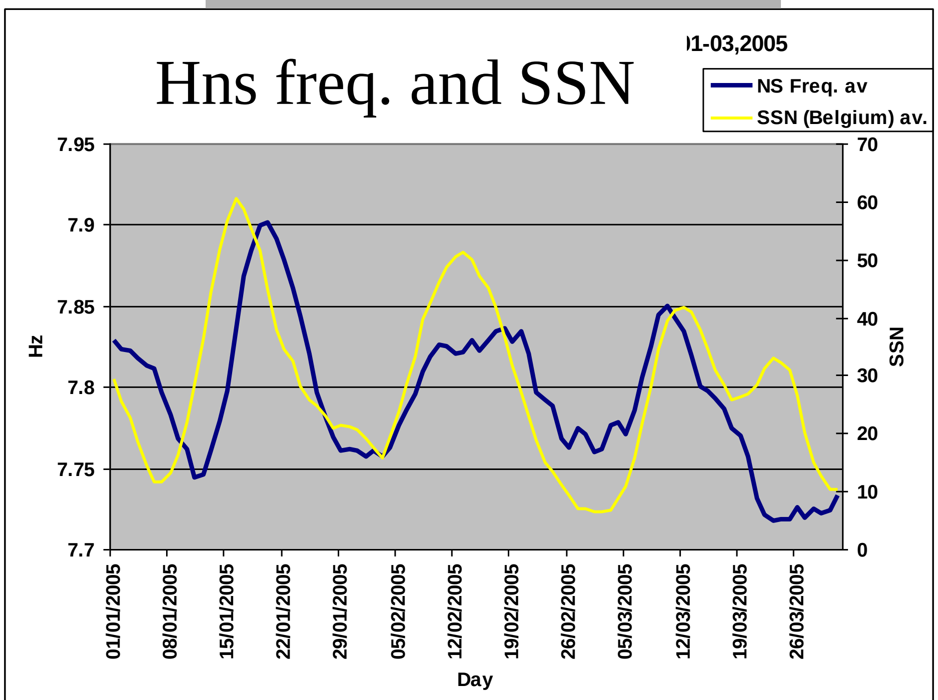
27-day solar rotation effects on SR frequency

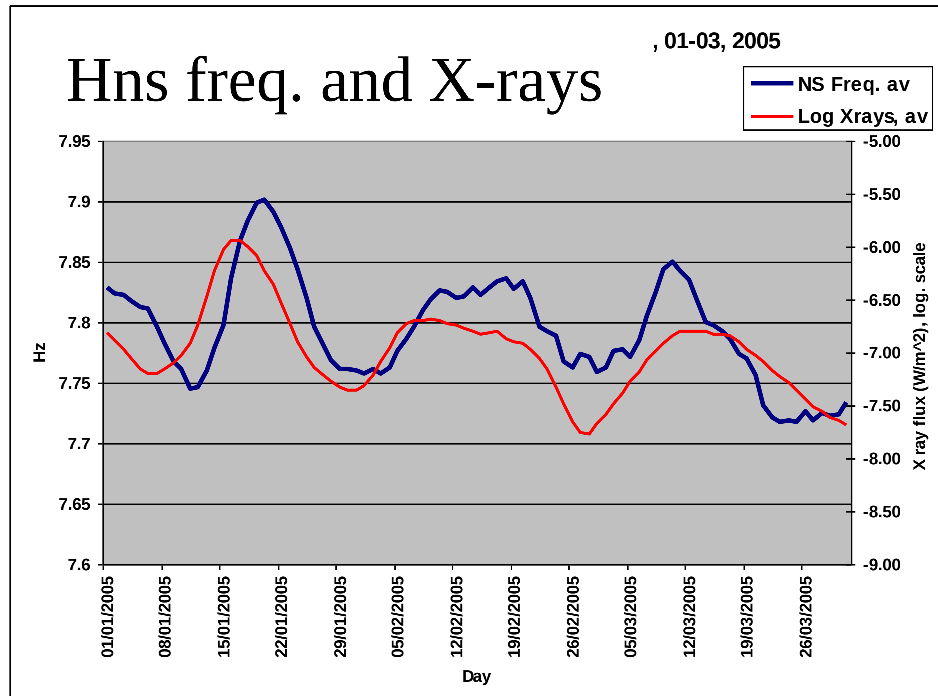


January-March 2005



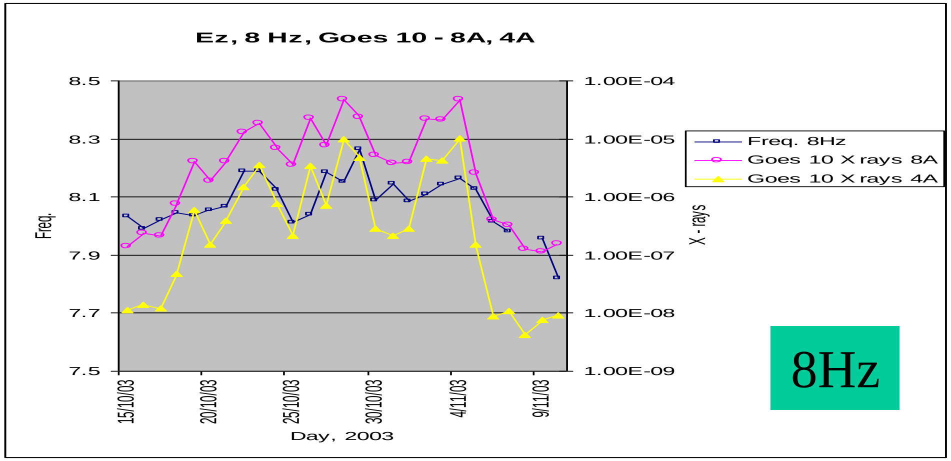
[*Füllekrug and Fraser-Smith*, 1996]

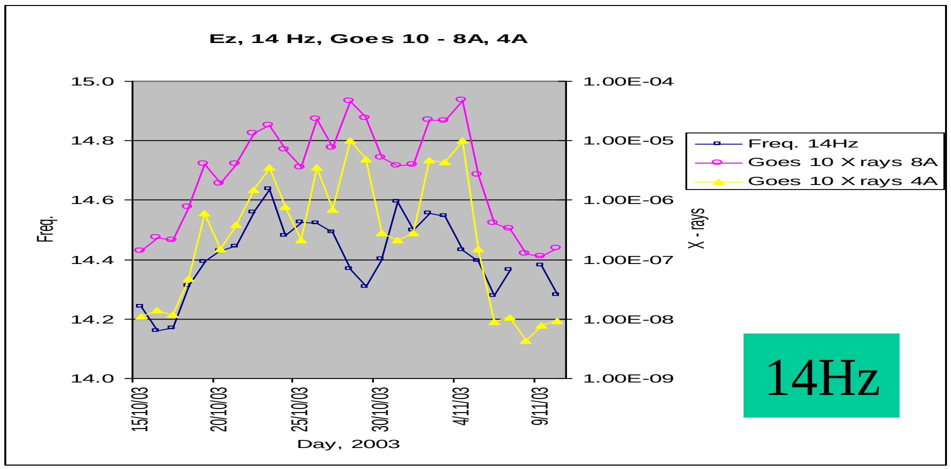


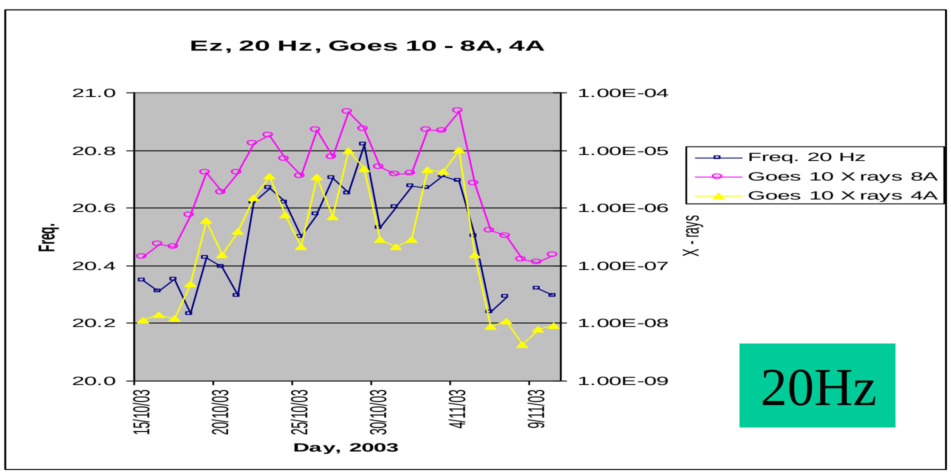


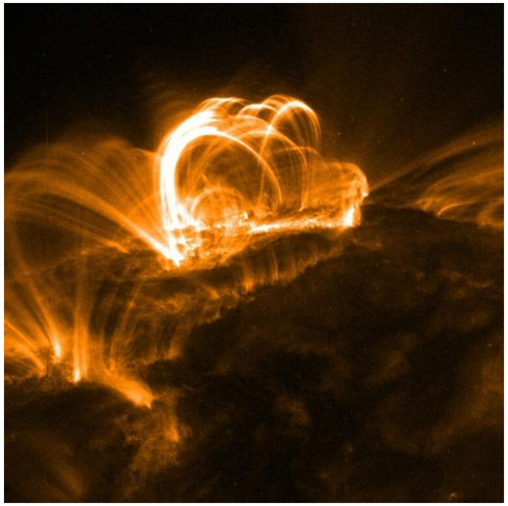
Solar Flares - X rays

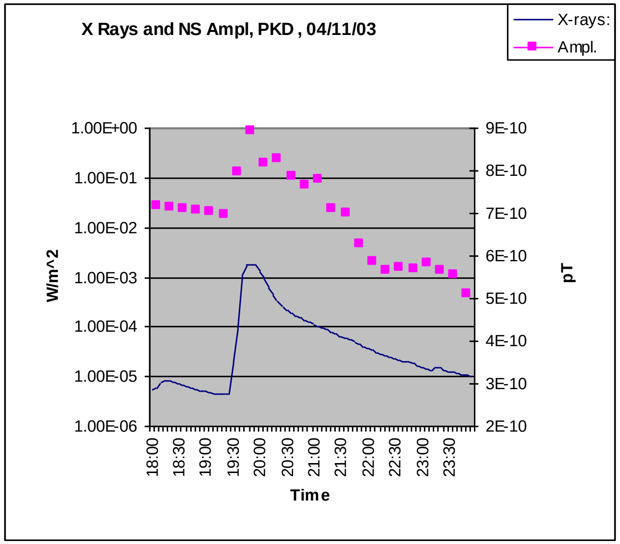
15 Oct-15 Nov 2003





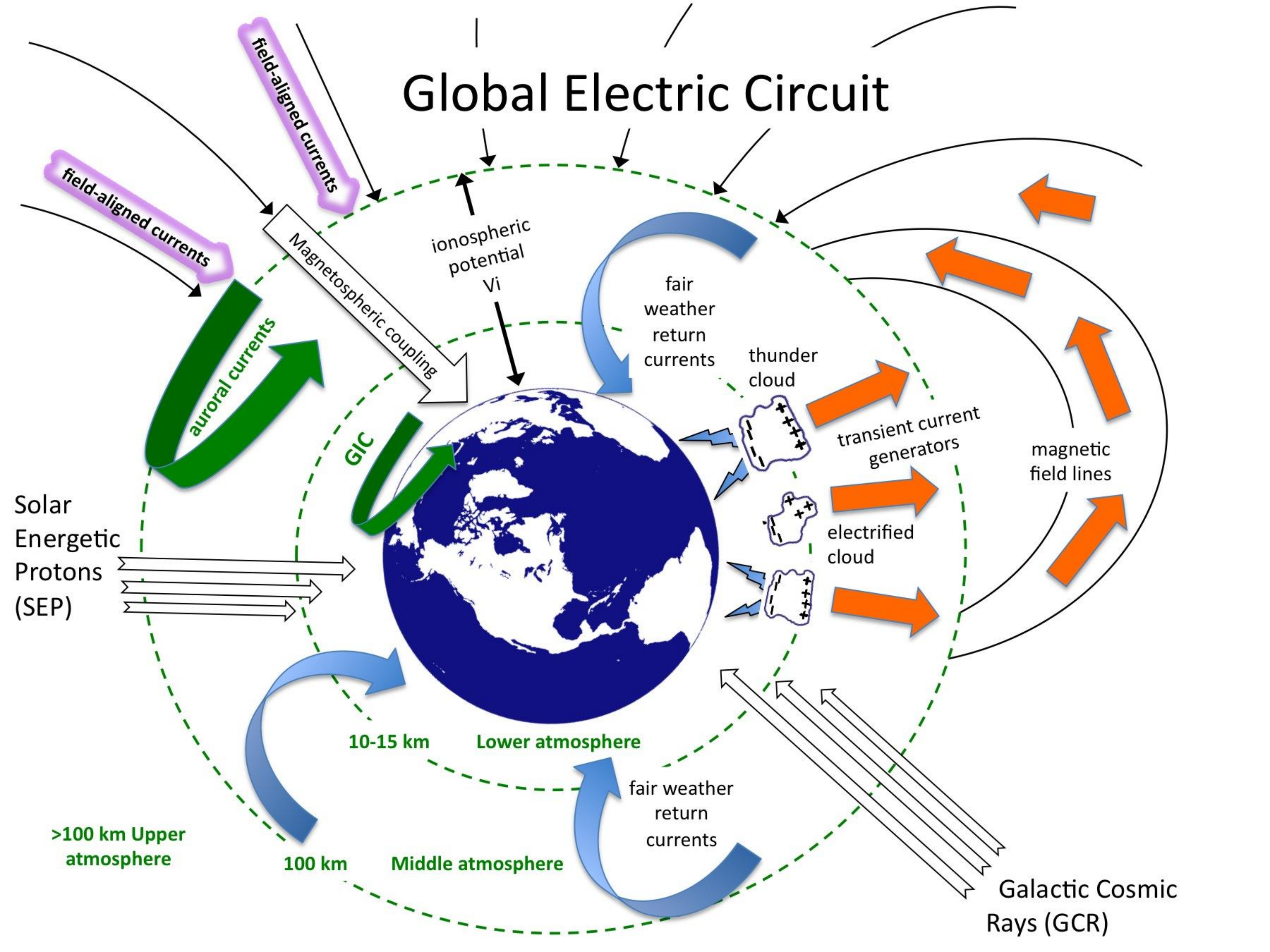






What do all these changes mean?

- ✓ Changes in thunderstorms?
- ✓ Changes in waveguide?
- ✓ Changes in conductivity?



Global Electric Circuit
field-aligned currents
field-aligned currents
Magnetospheric coupling
ionospheric potential Vi
auroral currents
GIC
fair weather return currents
thunder cloud
transient current generators
magnetic field lines
electrified cloud
Solar Energetic Protons (SEP)
10-15 km
Lower atmosphere
fair weather return currents
>100 km Upper atmosphere
100 km
Middle atmosphere
Galactic Cosmic Rays (GCR)

What have we learned?

- ✓ The global atmospheric electric circuit is made up of both a DC component and AC component
- ✓ The DC circuit depends on global thunderstorm activity (area coverage, intensity) and atmospheric conductivity (ions, aerosols)
- ✓ The AC circuit depends on global lightning activity (intensity and number of flashes) and ionospheric parameters (D-layer reflection height, ionospheric conductivity profile)
- ✓ There is evidence that solar variability (solar cycle, solar rotation, solar flares) influence both DC and AC circuit parameters
- ✓ These Solar impacts may result from changes in the Earth-ionosphere cavity, and/or even changes in cloud and thunderstorm activity itself.
- ✓ The GEC may also be a sensitive tool to study climate change.