**7th Workshop**
**Solar Influences on the Magnetosphere, Ionosphere and Atmosphere**
**Sunny Beach, Bulgaria, 1-5 June 2015**

# A comparative study of ionospheric conductivity variations due to solar activity and Earth' magnetic field

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Ionospheric trends

↓

Trends in Sq?

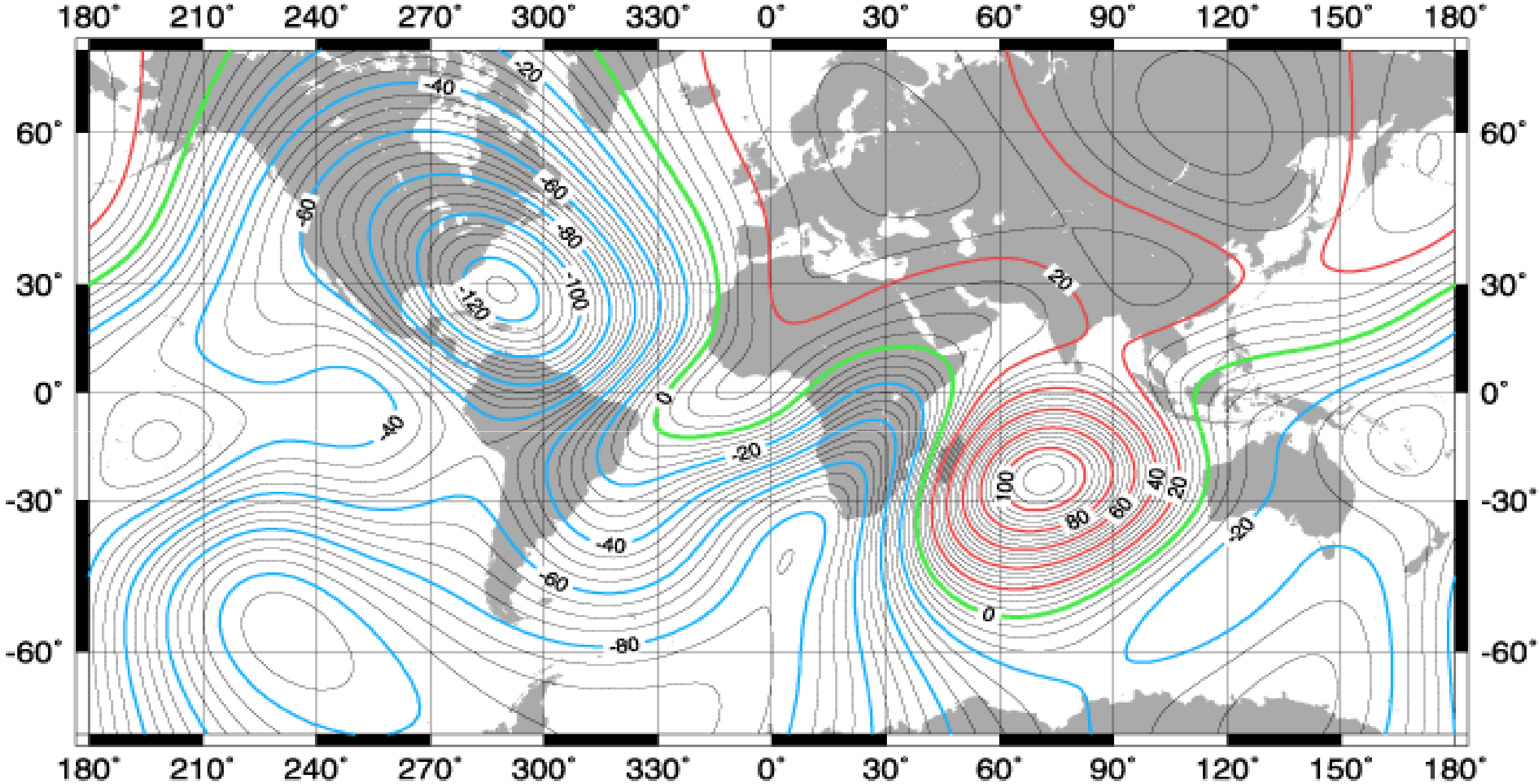
increase in $CO_2$ concentration
(Rishbeth, 1990, 1992; Roble and Dickinson, 1989)

long-term changes in geomagnetic activity and F2-layer storm mechanisms
(Danilov and Mikhailov, 1999; Mikhailov and Marin, 2000)

long-term changes in the Earth's magnetic field (Foppiano et al., 1999)

# US/UK World Magnetic Chart -- Epoch 2000

## Total Intensity - Annual Change (F)

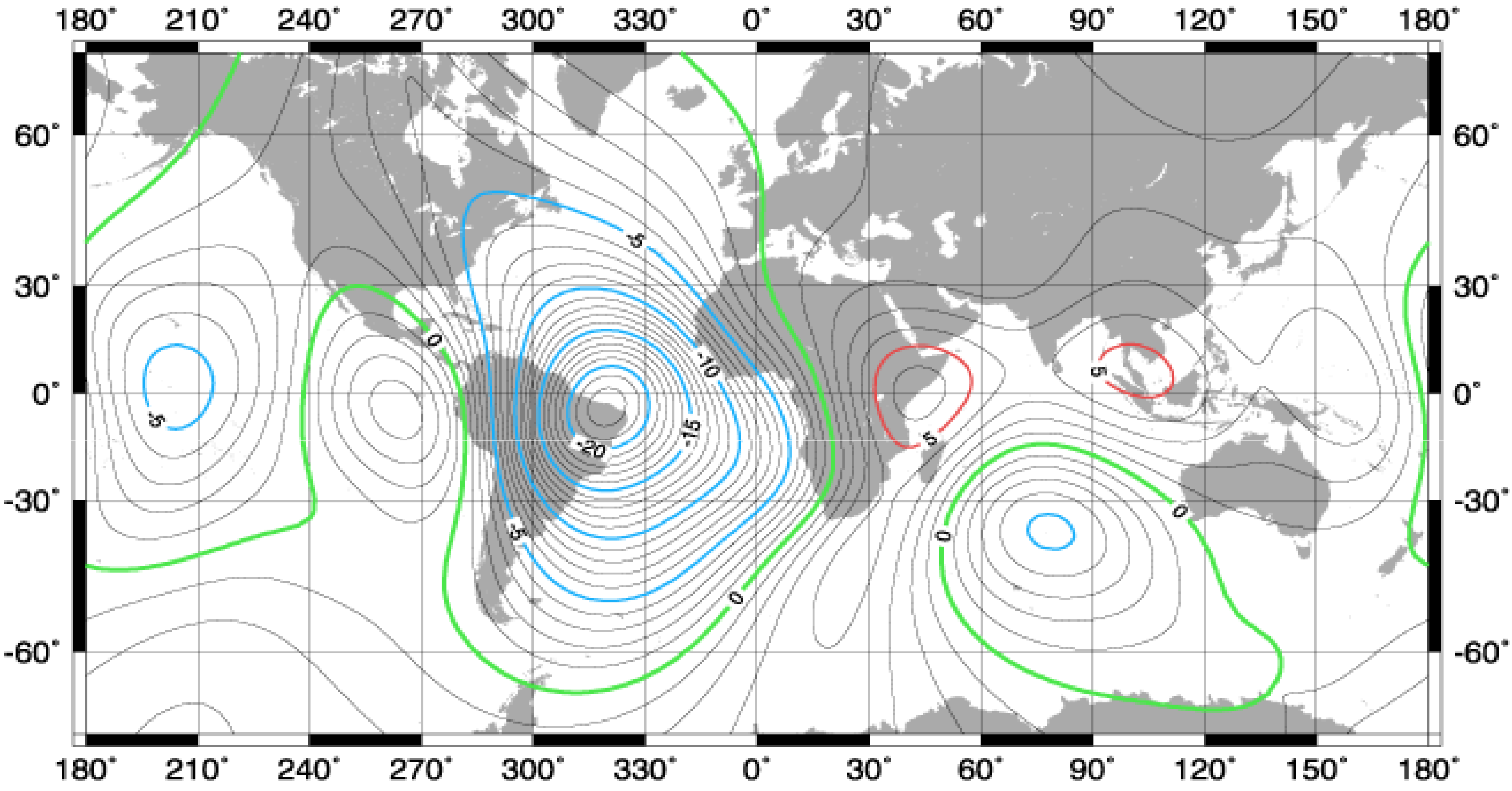



Units : nanoTeslas/yr
Contour Interval : 5 nanoTeslas/yr
Map Projection : Mercator

http://www.ngdc.noaa.gov/seg/WMM/image.shtml

# US/UK World Magnetic Chart -- Epoch 2000

## Inclination - Annual Change (I)




Units: minutes/yr
Contour Interval : 1 minute/yr
Map Projection : Mercator

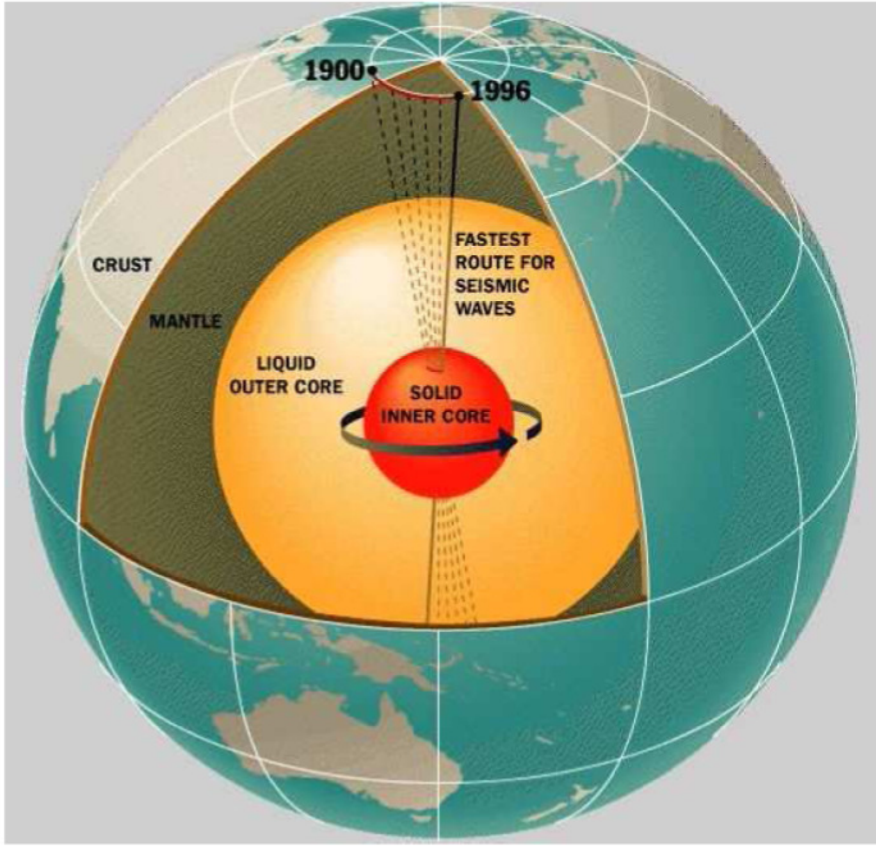
http://www.ngdc.noaa.gov/seg/WMM/image.shtml

➢ The Earth has a solid metallic core, mainly iron, surrounded by liquid iron, followed by the mantle.

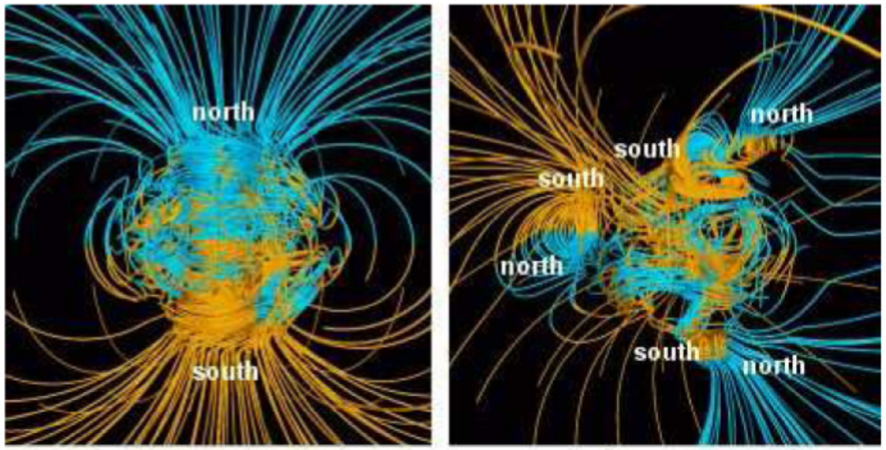
➢Convective motions in the core produces the magnetic field of the Earth.

➢To a first approximation, the field is a N-S dipole (30000nT at the Equator, 60000nT at the poles)

➢The magnetic field varies with time, and polarity has changed in the past through a highly complex process.




Orders of magnitude:
Earth's magnetic field ~ 0.5 G ($5 \times 10^{-5}$ T)
Fridge magnet ~ 100 G ($1 \times 10^{-2}$ T)




between reversals during a reversal

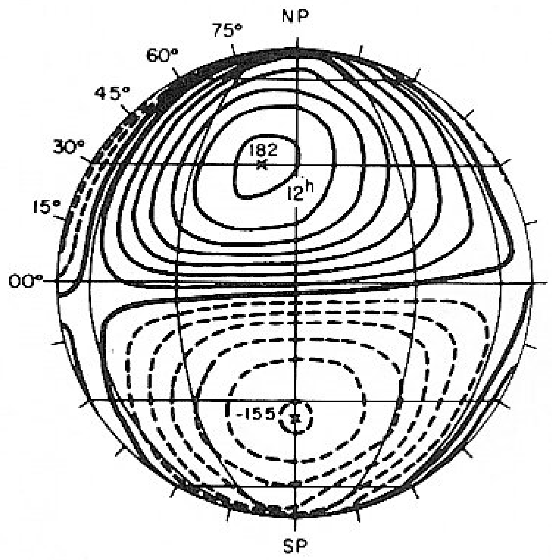
# Previous studies:

## Trends in Sq?

The solar quiet (Sq) magnetic field variation

↓

Manifestation of ionospheric current system




Main variables:

- ionospheric conductivities
- dynamo electric field
- solar diurnal tide
- E-region electron concentration

Yearly averaged Sq current system during the IGY viewed from the magnetic equatorial plane at 12-h meridian. (Matsuchita, S. and Campbell, W. H., *Physics of Geomagnetic Phenomena*, Academic Press, 1967.)

Assuming a uniform current sheet J of infinite extent

Sq variation of H ($\Delta H$) $\propto$ J $\Rightarrow$ **$J = \Sigma (V \times B + Ep)$**

$\Sigma$: integrated layer conductivity ($\Sigma = \int \sigma \, dh$)

V: tidal wind

B: main magnetic field

Ep the polarization electric field.

## Greenhouse effect:

$$\Sigma = \int \sigma \, dh \Rightarrow NmE \Rightarrow foE$$

**increasing trend in $CO_2$ $\Rightarrow$ foE increase $\Rightarrow$ $\Sigma$ increase $\Rightarrow$ positive trend in Sq**

## Earth's magnetic field secular variation effect:

$$J = \Sigma (V \times B + Ep) \quad \text{but } \Sigma \propto 1/B$$

**Rishbeth (1985), Takeda (1996)**

**for a decrease in B by a factor of 10 $\Rightarrow$ $\Sigma$ should increase by a factor of 35**

increasing factor of $\Sigma$ is greater than decreasing factor in B

$\Downarrow$

a net increasing effect in J, so in Sq

in the E layer Ep is comparable to the induced field $V \times B$ [*Rishbeth*, 1997]

$\Downarrow$

Ep changes in a similar way

**Then:**

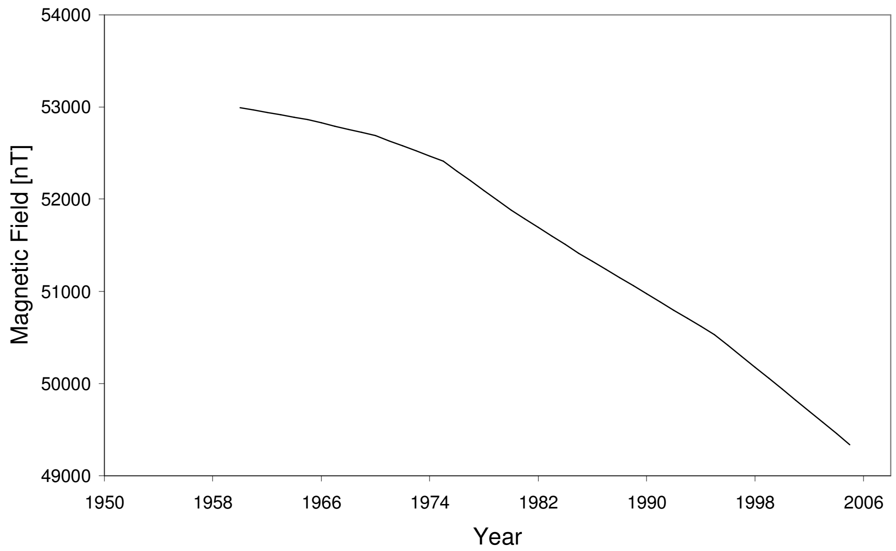
if B decreases to a value $B/\alpha$ and $\Sigma$ increases to a value $\beta\Sigma$, where $\beta > \alpha$

$\Downarrow$

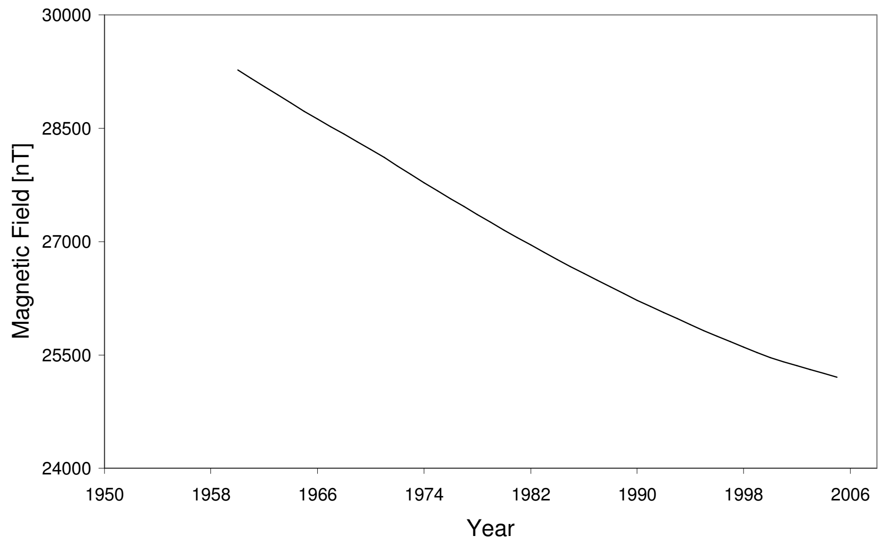
**percentage increase in Sq $\approx (\beta/\alpha - 1) \times 100$**

***So we assessed the expected Sq trend in terms of the observed trends in B and $\Sigma$***

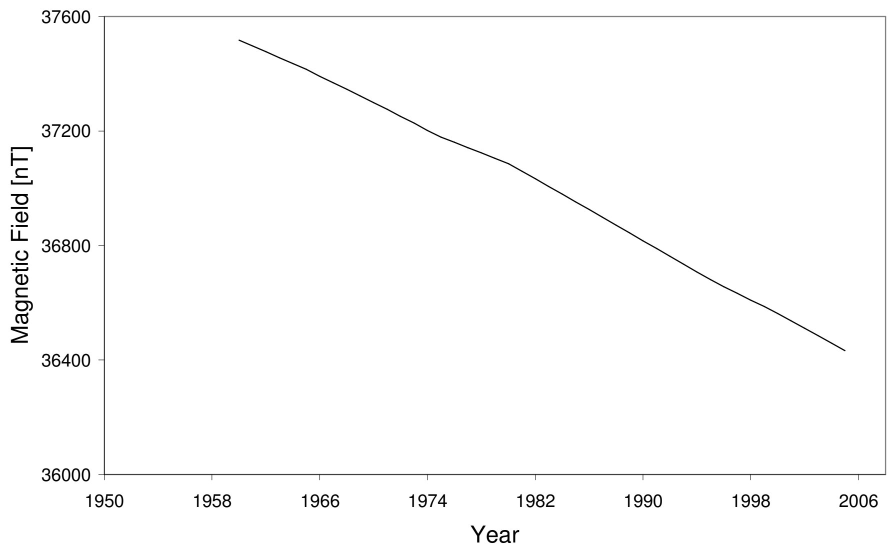
Fredericksburg (38.2ºN, 282.6ºE)




Hermanus (34.4ºS, 19.2ºE)




Apia (13.8ºS, 188.2ºE)




**DGRF - IGRF Geomagnetic Field Model 1945-2010**

Sq and Earth's magnetic field (B) trend values during the period 1960-2001, and percentage change during the period considered

(trend errors correspond to the standard deviation)

| **Station** | **Sq trend $\times 10^{-2}$ [nT/year]** | **% of Sq increase for period 1960-2001** | **B trend [nT/year]** | **% of B decrease for period 1960-2001** |
|---|---|---|---|---|
| Apia | $8 \pm 1$ | **6.6** | $-24.1 \pm 0.2$ | **2.7** |
| Fredericksburg | $4.8 \pm 0.8$ | **5.4** | $-80 \pm 2$ | **6.3** |
| Hermanus | $7.6 \pm 0.6$ | **9.9** | $-96.9 \pm 0.9$ | **13.9** |

Trend values of Pedersen and Hall conductivities, $\Sigma_1$ and $\Sigma_2$, for the period 1960-2001, assessed from the Ionospheric Conductivity Model, provided by World Data Center for Geomagnetism, Kyoto, and expected Sq induced trend due to the average increase between $\Sigma_1$ and $\Sigma_2$

| **Station** | **$\Sigma_1$ trend** | | **$\Sigma_2$ trend** | | **% of Sq increase due to average $\Sigma$ trend** | **% of Sq increase for period 1960-2001** |
|---|---|---|---|---|---|---|
| | **x $10^{-2}$ [S/year]** | **%** | **x $10^{-2}$ [S/year]** | **%** | | |
| Apia | 2.8 ± 0.3 | 5.9 | 2.2 ± 0.1 | 4.2 | **2.3** | **6.6** |
| Fredericksburg | 2.8 ± 0.2 | 10.8 | 2.45 ± 0.07 | 8.4 | **3.5** | **5.4** |
| Hermanus | 16.6 ± 0.9 | 25.6 | 12.6 ± 0.2 | 18.5 | **7.0** | **9.9** |

| | B secular variation + modeled foE trend due to increasing $CO_2$ | **Experimental trend** | B secular variation + experimental foE trend due to increasing $CO_2$ |
|---|---|---|---|
| Apia (13.8°S, 188.2°E) | 2.8% | **6.6%** | 5.8% |
| Fredericksburg (38.2°N, 282.6°E) | 4.0% | **5.4%** | 6.7% |
| Hermanus (34.4°S, 19.2°E) | 7.5% | **9.9%** | 10.2% |

The increase in greenhouse gases concentration also produces long-term variation in the E region temperature [*Aikin et al.*, 1991; *Akmaev and Fomichev*, 1998; *Beig et al.*, 2003; *Lastovicka et al.*, 2006] and diurnal tidal amplitude [*Bremer et al.*, 1997; *Baumgaertner et al.*, 2005]:

- Role of neutral winds? $\Rightarrow$ $J = \Sigma\,(V \times B + E)$
- Effect of temperature decrease on collision frequencies? $\Rightarrow$ $\sigma = f(\nu, n, B)$
- The experimental global pattern of individual foE trends is not uniform being at some places null or negative
- Trend in the dip equator location?

## Present work: Undergraduate thesis of Bruno S. Zossi

Current results from different velocities of ions and electrons

$$j = n\, e\, (v_i - v_e)$$

Velocity difference strongest in the E region:
- electrons ExB drifting
- ion motion governed by collisions with neutrals

$$j = \sigma_P\, \mathbf{E}_\perp - \sigma_H\, \mathbf{E} \times \mathbf{B}/B + \sigma_\parallel\, \mathbf{E}_\parallel$$

- $\sigma_P$: Pedersen conductivity
- $\sigma_H$: Hall conductivity
- $\sigma_\parallel$: Field-aligned (parallel) conductivity

$$\sigma_H = \frac{ne}{B}\left( -\frac{\omega_i^2}{\nu_i^2 + \omega_i^2} + \frac{\omega_e^2}{\nu_e^2 + \omega_e^2} \right)$$ perpendicular to E and B

$$\sigma_P = \frac{ne}{B}\left( \frac{\omega_i \nu_i}{\nu_i^2 + \omega_i^2} + \frac{\omega_e \nu_e}{\nu_e^2 + \omega_e^2} \right)$$ perpendicular to B, parallel to E

$$\omega_i = \frac{eB}{m_i}$$ and $$\omega_e = \frac{eB}{m_e}$$ gyrofrequencies

$\nu_i$ and $\nu_e$ collision frequencies $\Rightarrow$ assumption only $\nu_{in}$ and $\nu_{en}$

$$\nu_{in} = C_{in} n \qquad \nu_{en} = 5.4 \mathrm{x} 10^{-10} n \sqrt{T}$$

$$\sigma_H = f(n, N_e, T, B)$$

$$\sigma_P = f(n, N_e, T, B)$$

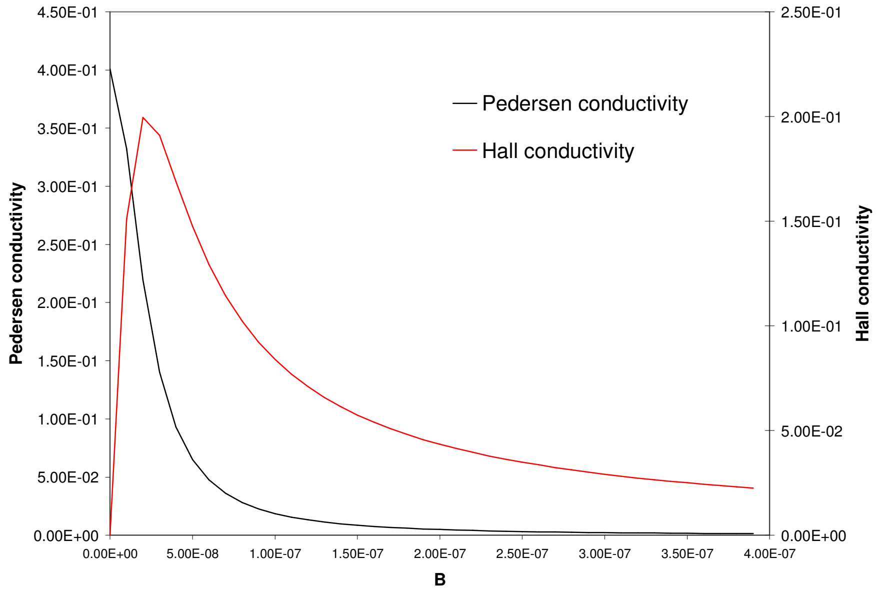
$B = B(t, \text{latitude}, \text{longitude})$ → IGRF

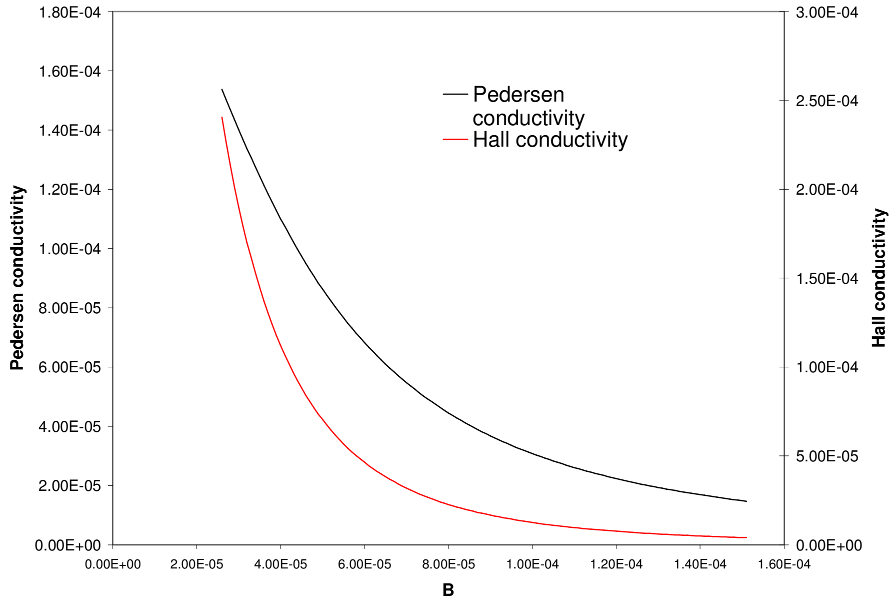
$N_e = f(\text{LT}, \text{season}, \text{latitude}, \text{longitude}, Rz)$ → IRI2012

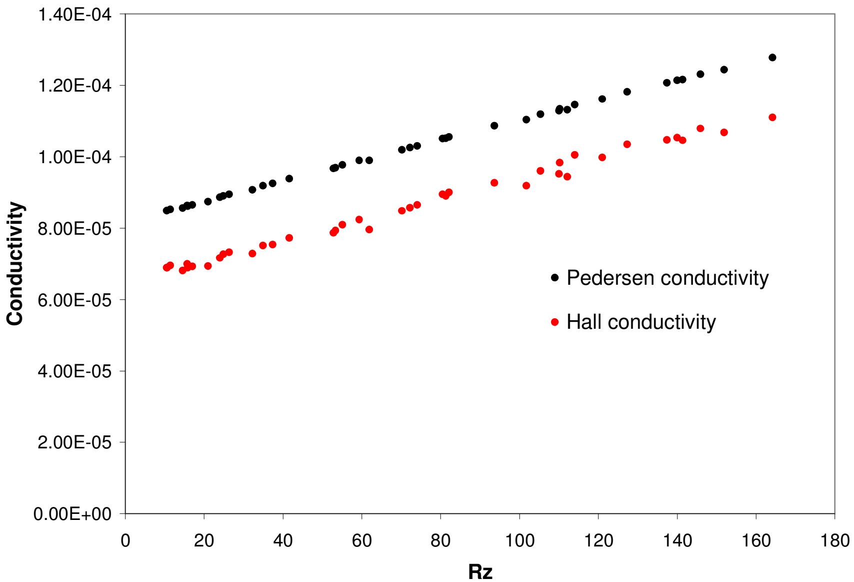
$T = f(\text{LT}, \text{season}, \text{latitude}, \text{longitude}, Rz)$

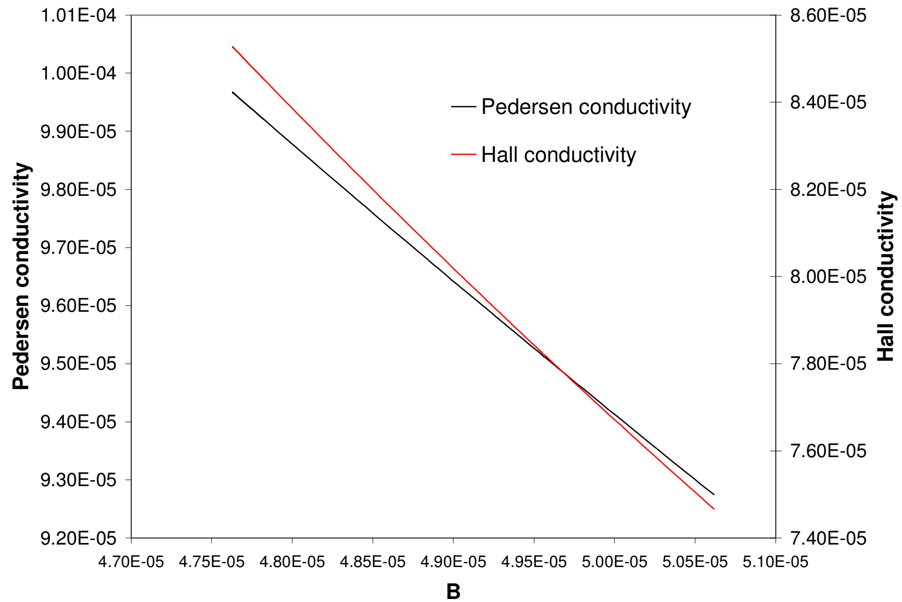
$n = f(\text{LT}, \text{season}, \text{latitude}, \text{longitude}, Rz)$

} NRLMSISE-00


Pedersen conductivity
Hall conductivity
Pedersen conductivity
Hall conductivity
B
4.50E-01
4.00E-01
3.50E-01
3.00E-01
2.50E-01
2.00E-01
1.50E-01
1.00E-01
5.00E-02
0.00E+00
2.50E-01
2.00E-01
1.50E-01
1.00E-01
5.00E-02
0.00E+00
0.00E+00
5.00E-08
1.00E-07
1.50E-07
2.00E-07
2.50E-07
3.00E-07
3.50E-07
4.00E-07


Pedersen conductivity
Hall conductivity
Pedersen conductivity
Hall conductivity
B
1.80E-04
1.60E-04
1.40E-04
1.20E-04
1.00E-04
8.00E-05
6.00E-05
4.00E-05
2.00E-05
0.00E+00
3.00E-04
2.50E-04
2.00E-04
1.50E-04
1.00E-04
5.00E-05
0.00E+00
0.00E+00
2.00E-05
4.00E-05
6.00E-05
8.00E-05
1.00E-04
1.20E-04
1.40E-04
1.60E-04


Pedersen conductivity
Hall conductivity
Conductivity
Rz
1.40E-04
1.20E-04
1.00E-04
8.00E-05
6.00E-05
4.00E-05
2.00E-05
0.00E+00
0
20
40
60
80
100
120
140
160
180


Pedersen conductivity
Hall conductivity
Pedersen conductivity
Hall conductivity
B
1.01E-04
1.00E-04
9.90E-05
9.80E-05
9.70E-05
9.60E-05
9.50E-05
9.40E-05
9.30E-05
9.20E-05
8.60E-05
8.40E-05
8.20E-05
8.00E-05
7.80E-05
7.60E-05
7.40E-05
4.70E-05
4.75E-05
4.80E-05
4.85E-05
4.90E-05
4.95E-05
5.00E-05
5.05E-05
5.10E-05

Mean $\sigma_P$ variation for a half cycle (min-max): ~ 45%

Mean $\sigma_H$ variation for a half cycle (min-max): ~ 55%

| Solar cycle | | | B | Pedersen Conductivity | Hall Conductivity |
|---|---|---|---|---|---|
| 20 | min-max | 1964 - 69 | 0.10 | -0.12 | -0.23 |
| 20 | max-min | 1969 - 76 | 0.17 | -0.20 | -0.37 |
| 21 | min-max | 1976 - 80 | 0.23 | -0.27 | -0.50 |
| 21 | max-min | 1980 - 86 | 0.09 | -0.11 | -0.20 |
| 22 | min-max | 1986 - 90 | 0.05 | -0.06 | -0.11 |
| 22 | max-min | 1990 -97 | 0.28 | -0.33 | -0.60 |
| | | | | | |
| 20 | min-min | 1964 - 76 | 0.28 | -0.33 | -0.60 |
| 21 | min-min | 1976 - 86 | 0.32 | -0.38 | -0.70 |
| 22 | min-min | 1986 - 97 | 0.32 | -0.39 | -0.71 |

| B 10 % variation | Pedersen Conductivity | Hall Conductivity |
|---|---|---|
| 5 - 5.5 x $10^{-5}$ | -11.2 | -19.3 |
| 6 - 6.6 x $10^{-5}$ | -12.6 | -20.5 |
| 2 - 2.2 x $10^{-7}$ | -16.4 | -8.9 |

# Another factor: greenhouse cooling effect

*Roble and Dickinson* [1989], *Rishbeth* [1990], *Rishbeth and Roble* [1992]
assuming a doubling of the atmospheric greenhouse gases
$\Downarrow$
increase of the peak electron density in the E layer, corresponding
to a **foE increase of 0.05-0.08 MHz**
$\Downarrow$
Sq and **conductivity** should also present a positive trend.

Assuming a linear change in foE with increasing $CO_2$ concentration
$\Rightarrow$ period 1960-2001 $\Rightarrow$ $CO_2$ increased by ~20% [*Keeling and Whorf*, 2005]
$\Rightarrow$ foE should increase by 0.005-0.008 MHz ($1.2\times10^{-4}$-$1.9\times10^{-4}$ MHz/year).

Assuming a mean foE value of 3.5 MHz, and since NmE $\propto$ $foE^2$
$\Downarrow$
~0.5% increase in NmE during the 42 years considered
$\Downarrow$
**~0.5% increase in conductivity??**
(since the major part of the conductivity is in the E region then
$\Sigma \propto$ NmE [*Rishbeth and Garriot*, 1969])

**Observation (experimental data analysis):**

*Bremer* [2004, 2008], uses the same method as in the present paper to extract trends and obtains experimental global mean foE trend positive but stronger than the model results:

**0.0013 MHz/year (~6 times larger than the model result)**

⇓

foE should increase ~0.05 MHz, that is a ~1.5 % increase

**~3.0% change in NmE**

JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 101, NO. A4, PAGES 7875–7880, APRIL 1, 1996

# Effects of the strength of the geomagnetic main field strength on the dynamo action in the ionosphere

Masahiko Takeda

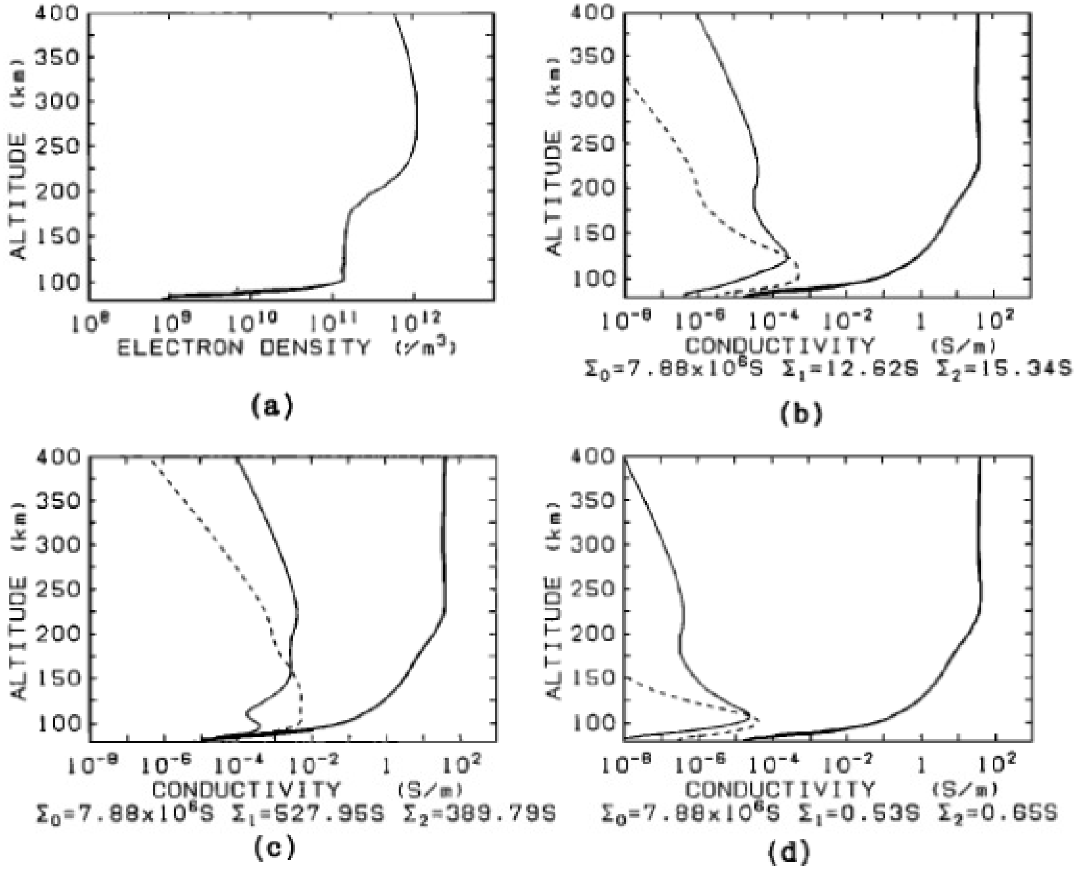



**Figure 1.** Height profiles of (a) electron density (upper left), of conductivity when (b) geomagnetic main field strength is normal, (c) 0.1 times and (d) 3 times (lower right) at 35°N and 135°E in geographic coordinates for R = 35 under the equinoctial conditions at 1200 LT. Thick and thin solid lines and dashed lines represent parallel, Pedersen conductivities, and Hall conductivities, respectively.

JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 116, A12304, doi:10.1029/2011JA017063, 2011

# The response of the coupled magnetosphere-ionosphere-thermosphere system to a 25% reduction in the dipole moment of the Earth's magnetic field

Ingrid Cnossen,[1] Arthur D. Richmond,[1] Michael Wiltberger,[1] Wenbin Wang,[1] and Peter Schmitt[1]

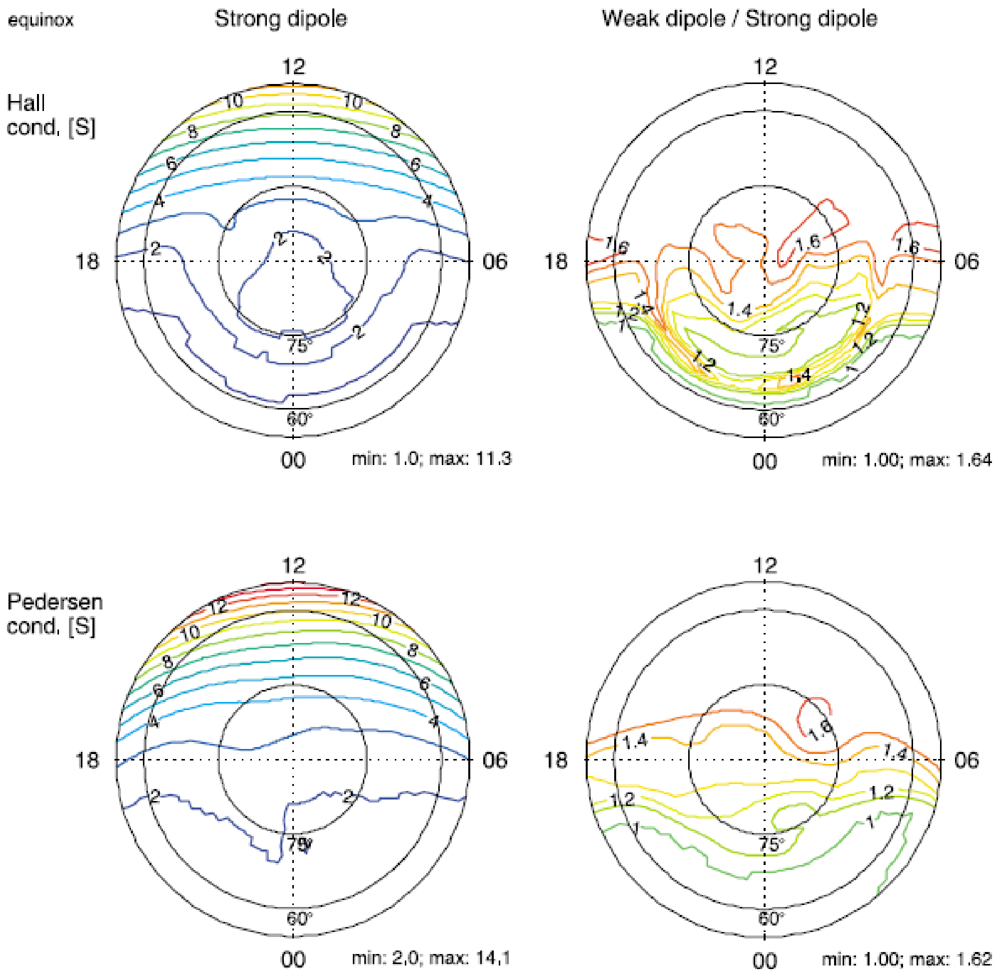



**Figure 2.** The averaged NH and SH (top) Hall and (bottom) Pedersen conductance for (left) the strong dipole and (right) the weak-strong dipole for equinox at 13–15 UT. The view is centered on the dipole, with local noon to the top.

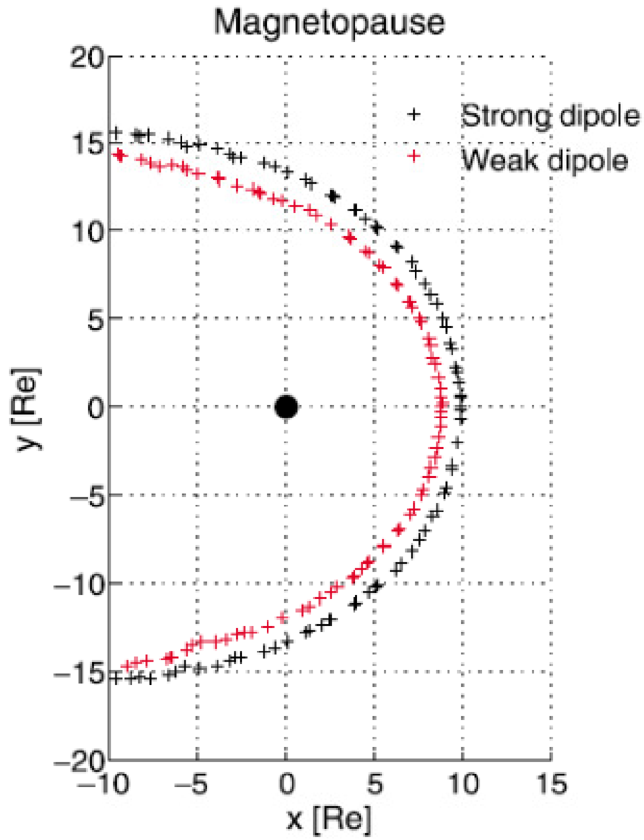



**Figure 1.** Size and shape of the magnetosphere viewed in the solar-magnetic *x-y* plane ($z = 0$) for the strong dipole (black) and the weak dipole (red) for equinox at 14 UT. The boundary is defined as $B_z = 0$, which marks the crossing from the Earth's magnetic field, for which $B_z > 0$, to the IMF, for which $B_z < 0$ at 14 UT.

## Discussion and Conclusions

**Regarding Earth's magnetic field secular variation:**

**positive trend in B $\Rightarrow$ negative trend in $\Sigma$**

**negative trend in B $\Rightarrow$ positive trend in $\Sigma$**

**Regarding solar activity variation:**

**positive trend in solar activity $\Rightarrow$ positive trend in $\Sigma$**

**negative trend in solar activity $\Rightarrow$ negative trend in $\Sigma$**

Now:

- Only solar activity effects are significant
- During Earth magnetic field inversion when dB/dt accelerates and B becomes small and quadrupolar??

The increase in greenhouse gases concentration produces long-term variation in the E region temperature and diurnal tidal amplitude

- Role of neutral winds? $\Rightarrow$ $J = \Sigma ( V \times B + E)$
- Effect of temperature decrease on collision frequencies?

# Thank you very much