Unravelling long-term behaviour in historic geophysical data sets

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First observations during the International Polar Year 1882/83.

SGO established 1913.

Finland independent from Russia in 1917.

SGO part of University of Oulu since 1997.

Oldest scientific research institute in Northern Finland.
Where we are...

✔ European Arctic
✔ High Latitude
✔ Auroral Zone
Doubling of $[\text{CO}_2]$ and $[\text{CH}_4]$ cools
Mesosphere by 10 K and Thermosphere by 50 K.

Atmosphere shrinks.
Layer of maximum electron density lowers by 15-20 km.
Greenhouse high up?

• Model results, assuming doubling of CO$_2$ and CH$_4$:
  • Stratopause cools by 8 K, stratosphere by 15 K.  
    (Brasseur & Hitchman, 1988)
  • Mesosphere and thermosphere cool by 10 K and 50 K, respectively.  
    (Roble & Dickinson, 1989)
  • F2-layer peak (hmF2) lowers by 15-20 km.  
    (Rishbeth, 1990)
  • Riometer absorption decreases.  
    (Serafimov & Serafimova, 1992)
  • Stratopause cools by 14 K, mesosphere by 8 K, thermosphere by 50 K.  
    (Akmaev & Fomichev, 1998)
Sodankylä Ionosonde

- Sodankylä ionosonde measurements began 1st August 1957.
- Until Nov 2005: 1 sounding per 30 min.
- Until Mar 2007: 1 sounding per 10 min.
- IPY (Apr ’07-Mar ’08): 1 sounding per minute.
- April 2008: we forgot to turn off IPY mode.
- High data quality: first 800,000+ ionograms were analysed by the very same person!
Sodankylä Ionosonde
Sodankylä hmF2 & Solar Activity

![Graph of SSN, Flux Units, and km over time from 1955 to 2010]

SSN / Flux Units / km

- Red line: hmF2
- Gray line: SSN
- Blue line: F10.7

Th. Ulich, Kangerlussuaq, Greenland, 2011-07-21

Thomas Ulich, Sodankylä Geophysical Observatory, 2009-03-21
Conclusion

- The enhanced greenhouse effect is clearly visible in the ionosphere.
Almaty hmF2

AA343 ALMATY - hmF2 Anomaly

T04-C: 96.68%, T: 338 ± 63 m/a (19%) CL > 99%

Th. Ulrich, Kangerlussuaq, Greenland, 2011-07-21
Conclusion

• Obviously, my data set is better than yours.
• The enhanced greenhouse effect is clearly visible in the ionosphere.
Global hmF2 Trends

(Ulich, 2000)
Conclusion

• What the ... ???
Problems

• Data resolution (h, 3-h, day, month(?), ...)
• Low-pass filtering or polynomial fitting...
Running Mean Filter
Problems

• Data resolution (h, 3-h, day, month(?), ...)
• Low-pass filtering or polynomial fitting...
• Removal of underlying (cyclic) variability:
  – Choice of proxy (sinusoid, SSN, Group SSN, F10.7 (adj./obs.), Ly-α, Mg II, E10.7, ...)
  – Resolution of proxy: compatibility with data
Sodankylä hmF2 & Solar Activity

The graph shows the variation of SSN, hmF2, and F10.7 from 1955 to 2010. The SSN and hmF2 values are plotted in red and black, respectively, while F10.7 is in blue. The y-axis represents SSN/Flux Units/km, and the x-axis represents the years from 1955 to 2010.
Ringing

Trend

Constant
Ringing

The ringing idea was first introduced by Jarvis et al., 2002. The plots shown here are from a follow-up paper by Clilverd et al., 2003.
Problems

- Data resolution (h, 3-h, day, month(?), ...)
- Low-pass filtering or polynomial fitting...
- Removal of underlying (cyclic) variability: ...
- Data gaps
Example: Data Gaps

Time, e.g. 1 day, resolution 1/min

Something, e.g. Temperature
Data Gaps
Data Gaps
Data Gaps
Problems

• Data resolution (h, 3-h, day, month(?), ...)
• Low-pass filtering or polynomial fitting...
• Removal of underlying (cyclic) variability: ...
• Data gaps
• Measurement errors
• Mathematics of trend detection
  – stepwise or multi-parameter fit
  – error propagation
• Base functions of the model(s) are, e.g.:

\[ m_i = \varepsilon_i \]

\[ + x_1 \]

\[ + x_2 t_i \]

\[ + x_3 F_{10.7}(t_i) \]

\[ + x_4 Ap(t_i) \]

\[ + x_5 \sin(2\pi t_i) \]

\[ + x_6 \cos(2\pi t_i) \]

\[ + x_7 \sin(4\pi t_i) \]

\[ + x_8 \cos(4\pi t_i) \]

\[ + \ldots \]

- \( \varepsilon_i \rightarrow \) measurement errors
- \( t_i \rightarrow \) constant
- \( t_i \rightarrow \) sampling times
- \( F_{10.7}(t_i) \rightarrow \) solar activity
- \( Ap(t_i) \rightarrow \) geomagnetic activity
- \( \sin(2\pi t_i) \rightarrow \) annual variation
- \( \cos(4\pi t_i) \rightarrow \) semi-annual variation
Modelling the data

The ionospheric property of interest is a function of time and a number of other parameters. The model of the data is therefore

\[ m(t) = \mathcal{F}(t, x_1, \ldots, x_M) \]

where

\[ \mathcal{F}(t, x_1, \ldots, x_M) = \sum_{i=1}^{M} x_i f_i(t) \]

The actual measurements \( m_i \) observed at time \( t_i \) are equal to the model plus some measurement error \( \varepsilon_i \)

\[ m_i = \mathcal{F}(t_i, x_1, \ldots, x_M) + \varepsilon_i \]
**Inverse problem I**

This can be expressed as a matrix equation. Usually there are many more data points than unknowns $x_i$ and the problem is over-determined:

$$
\begin{pmatrix}
m_1 \\
m_2 \\
\vdots \\
m_N
\end{pmatrix}
= 
\begin{pmatrix}
f_1(t_1) & f_2(t_1) & \cdots & f_M(t_1) \\
f_1(t_2) & f_2(t_2) & \cdots & f_M(t_2) \\
\vdots & \vdots & \ddots & \vdots \\
f_1(t_N) & f_2(t_N) & \cdots & f_M(t_N)
\end{pmatrix}
\cdot
\begin{pmatrix}
x_1 \\
x_2 \\
\vdots \\
x_M
\end{pmatrix}
+ 
\begin{pmatrix}
\varepsilon_1 \\
\varepsilon_2 \\
\vdots \\
\varepsilon_N
\end{pmatrix}
$$

In other words:

$$
\mathbf{m} = \mathbf{A} \cdot \mathbf{x} + \mathbf{\varepsilon}
$$
Inverse problem II

Measurements and theory are weighted by the measurement errors:

\[ B_{ij} := \frac{A_{ij}}{\varepsilon_i} \quad \text{and} \quad b_i := \frac{m_i}{\varepsilon_i} \]

The solution is the vector \( \mathbf{x} \), which minimises the following expression:

\[ \chi^2 = |B \cdot \mathbf{x} - \mathbf{b}|^2 \]

We are left with a general least squares problem. Solving this results in the most probable solution for \( \mathbf{x} \).
Signal Spectrum by Stochastic Inversion


Left: 100 pts for Fourier, 90 for inversion. Above: 59 pts.
Signal Spectrum by Stochastic Inversion

Sodankylä F2-layer peak height hmF2
Conclusion

• This is pointless?
  I don’t think so...
  ...yet!
## Trends in other Observations

<table>
<thead>
<tr>
<th>Height in km</th>
<th>Method</th>
<th>Parameter</th>
<th>Trend per Year</th>
<th>Reference</th>
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<tbody>
<tr>
<td>75</td>
<td>Sounding rocket</td>
<td>Temperature</td>
<td>-0.6 K</td>
<td>Kokin and Lysenko, 1994</td>
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<td>60-70</td>
<td>Lidar</td>
<td>Temperature</td>
<td>-0.4 K</td>
<td>Hauchecorne et al., 1991</td>
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<td>-0.33 K</td>
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<td>-0.25 K</td>
<td>Aikin et al., 1991</td>
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<td>Golitsyn et al., 1996</td>
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<td>-0.17 K</td>
<td>Dunkerton et al., 1998</td>
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<td>Temperature</td>
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<tr>
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<td>Temperature</td>
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<td>25</td>
<td>Sounding rocket</td>
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<td>Golitsyn et al., 1996</td>
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<tr>
<td>25</td>
<td>Sounding rocket</td>
<td>Temperature</td>
<td>-0.11 K</td>
<td>Keckhut et al., 1999</td>
</tr>
</tbody>
</table>
Direct F-Region Temperature

Millstone Hill Radar, UT=1630–1730, Altitude=350–400 km
(local noon)

Long-term temperature trends in the ionosphere above Millstone Hill
J. M. Holt\(^1\) and S. R. Zhang\(^1\)
Conclusion
(the last one, I promise!)

• Definitely, there’s long-term change in the ionosphere and thermosphere!
• The enhanced greenhouse effect is probably a part of it.
• Other (unknown?) processes are involved.
• Do not discontinue long-term measurements of our (space) environment!
• Solution in modelling?
• We don’t understand what’s going on. Find it out!
Ionosondes, originally deployed for monitoring ionospheric conditions for HF radio communication and for studying short-term events, are becoming useful in an environmental context.

They provide long-term measurements of our environment!