Unravelling long-term behaviour in historic geophysical data sets

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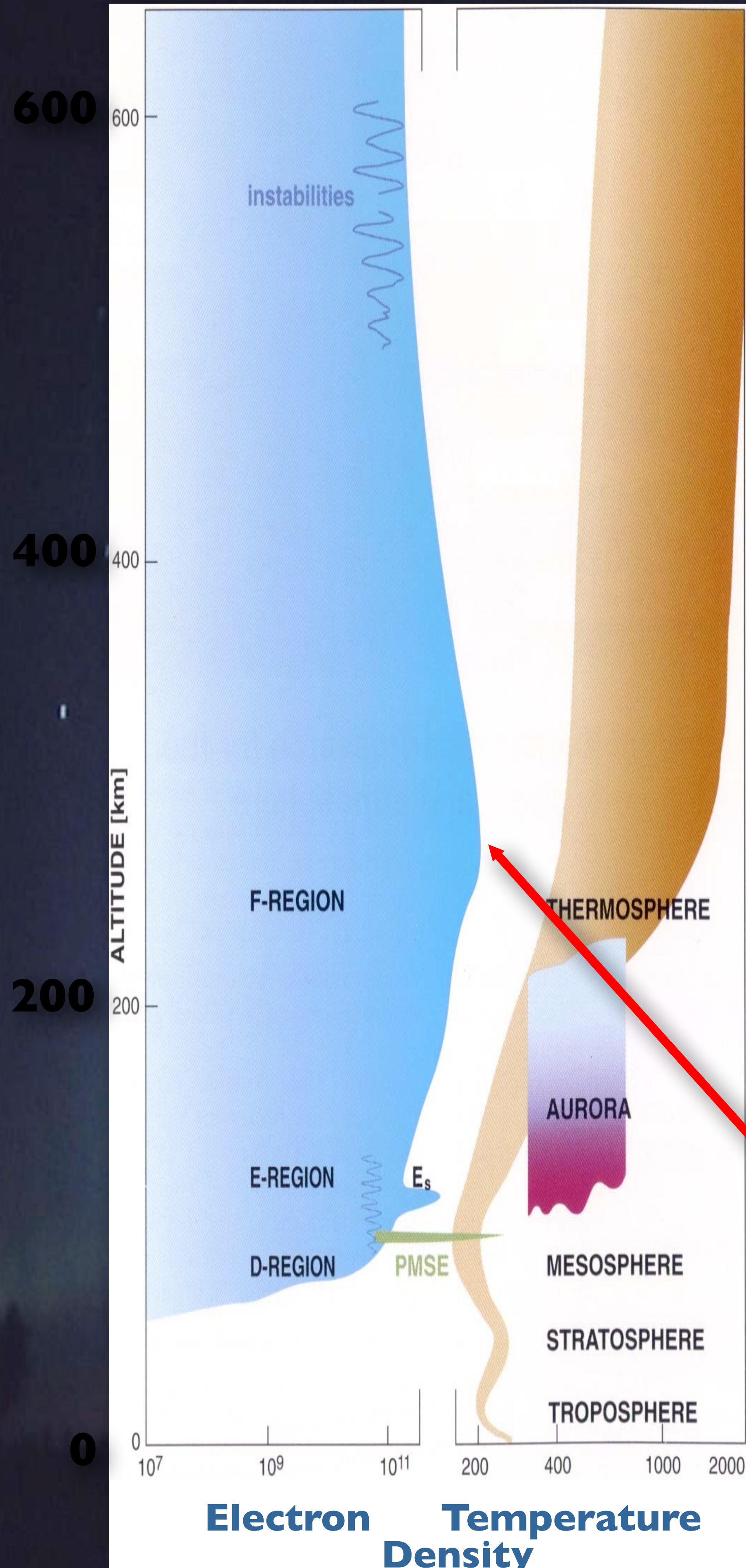
Greenhouse high up?

- 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)



Greenhouse Cooling

Doubling of [CO_2] and [CH_4]

cools

Mesosphere by **10 K** and
Thermosphere by **50 K**.

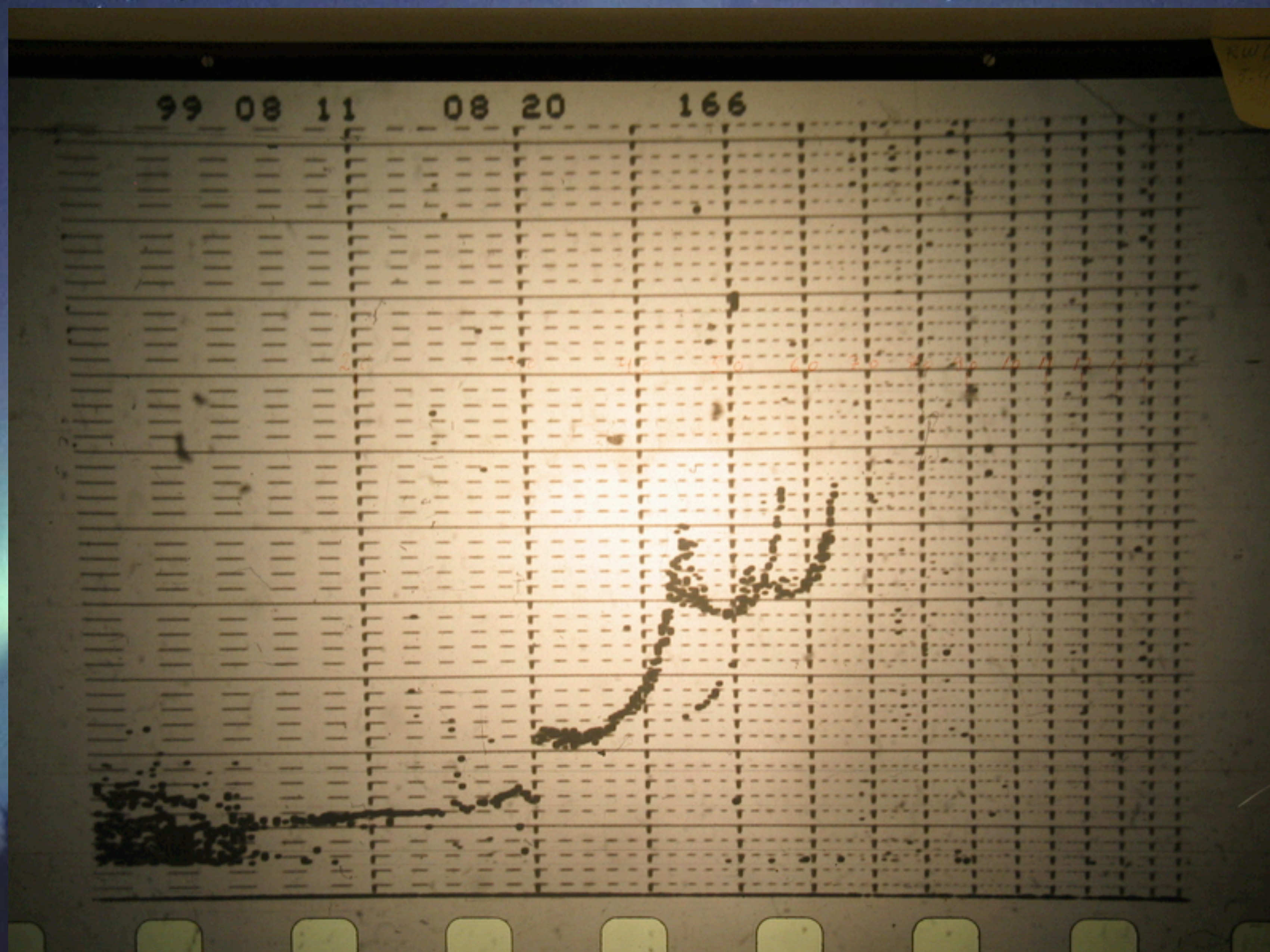
Atmosphere shrinks.

Layer of maximum electron density lowers by 15-20 km.

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.
- Tody: close to 5 million ionograms.
- High data quality:
  first 800.000+ ionograms were analysed by the very same person!

Sodankylä Ionosonde



Empirical hmF2 Formulae

Shimazaki [1955]

$$hpF2 = \frac{1490}{M} - 176$$

Bilitza, Sheikh, Eyfrig [1979]

$$hmF2 = \frac{1490}{M - \Delta M} - 176$$

$$\Delta M = \frac{F1 \times F4}{x - F2} + F3$$

$$F1 = 0.00232 \times R + 0.222$$

$$F2 = 1.2 - 0.016 \exp(0.0239 \times R)$$

$$F3 = 0.00064 \times (R - 25)$$

$$F4 = 1 - \frac{R}{150} \exp\left(\frac{-\Phi^2}{1600}\right)$$

Bradley, Dudeney [1973], eq. (3)

$$hmF2 = a \times M^b$$

$$a = 1890 - \frac{355}{x - 1.4}$$

$$b = (2.5x - 3)^{-2.35} - 1.6$$

Dudeney [1974], eq. (56)

$$hmF2 = \frac{1490(M \times F)}{M - \Delta M} - 176$$

$$\Delta M = \frac{0.253}{x - 1.215} - 0.012$$

$$(M \times F) = M \sqrt{\frac{0.0196 M^2 + 1}{1.2967 M^2 - 1}}$$

$M = M(3000)F2$

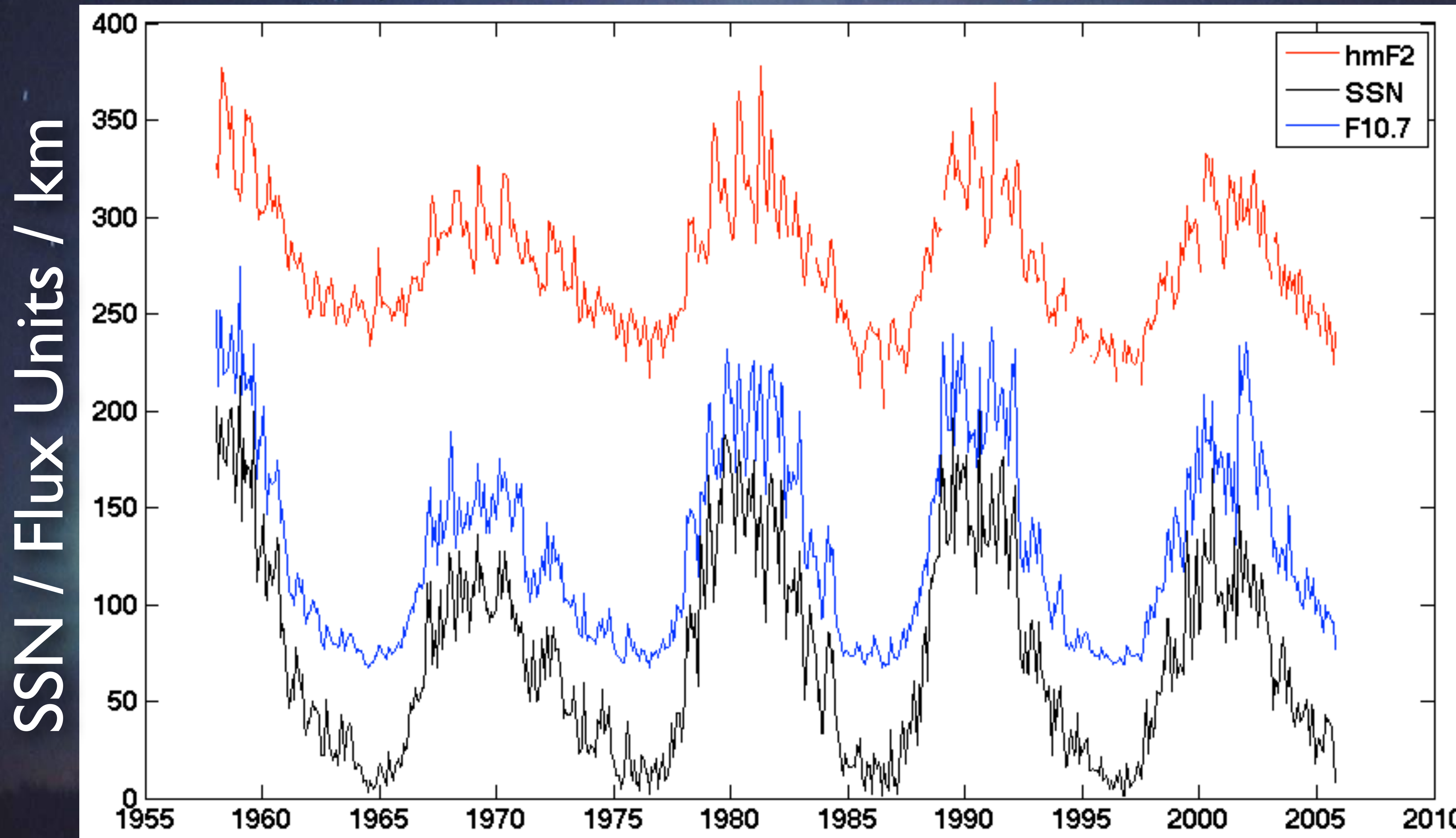
$x = foF2 / foE$

ΔM = Correction Term

Φ = Geomagnetic Latitude

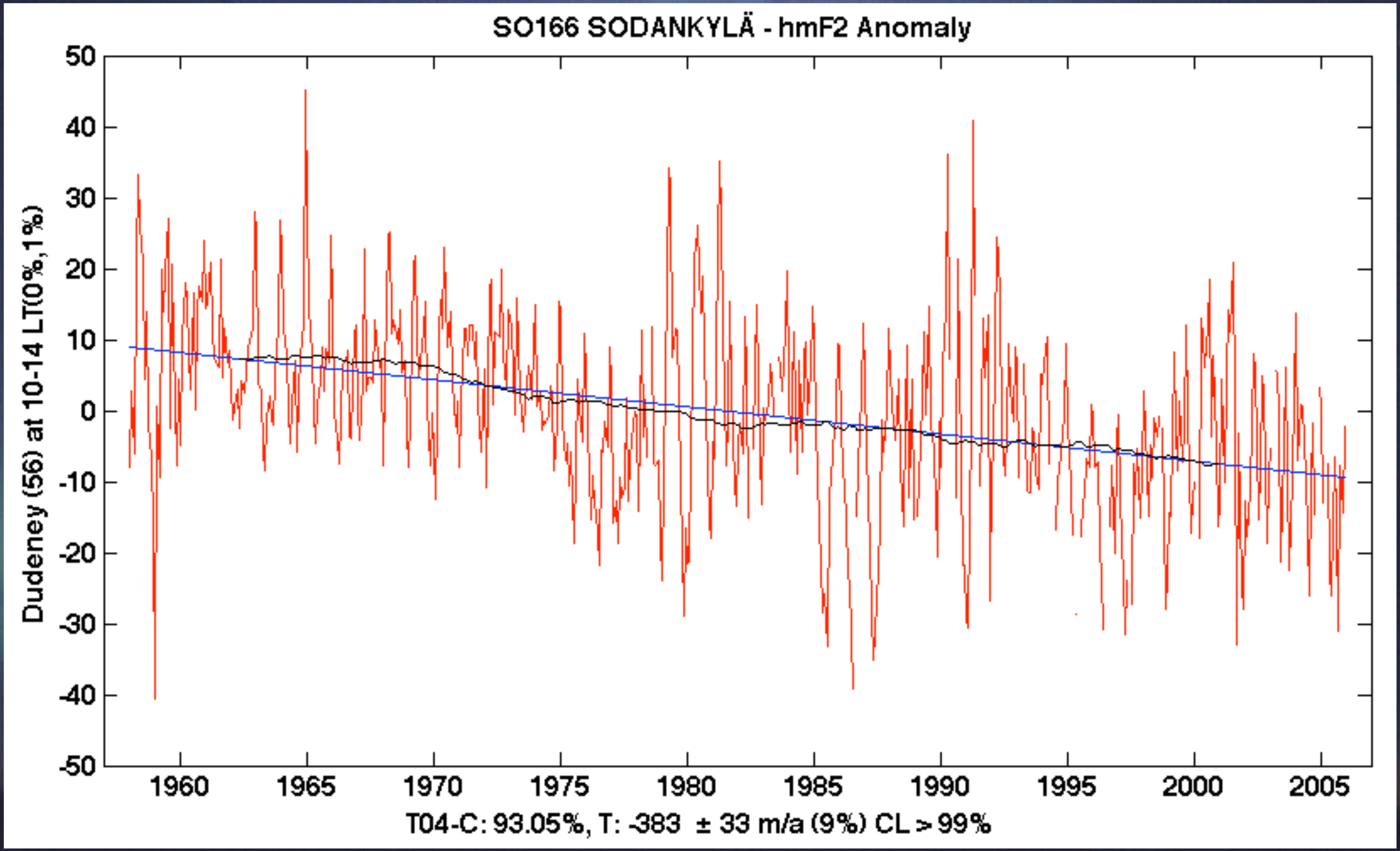
R = Sunspot Number

hmF2 & Solar Activity

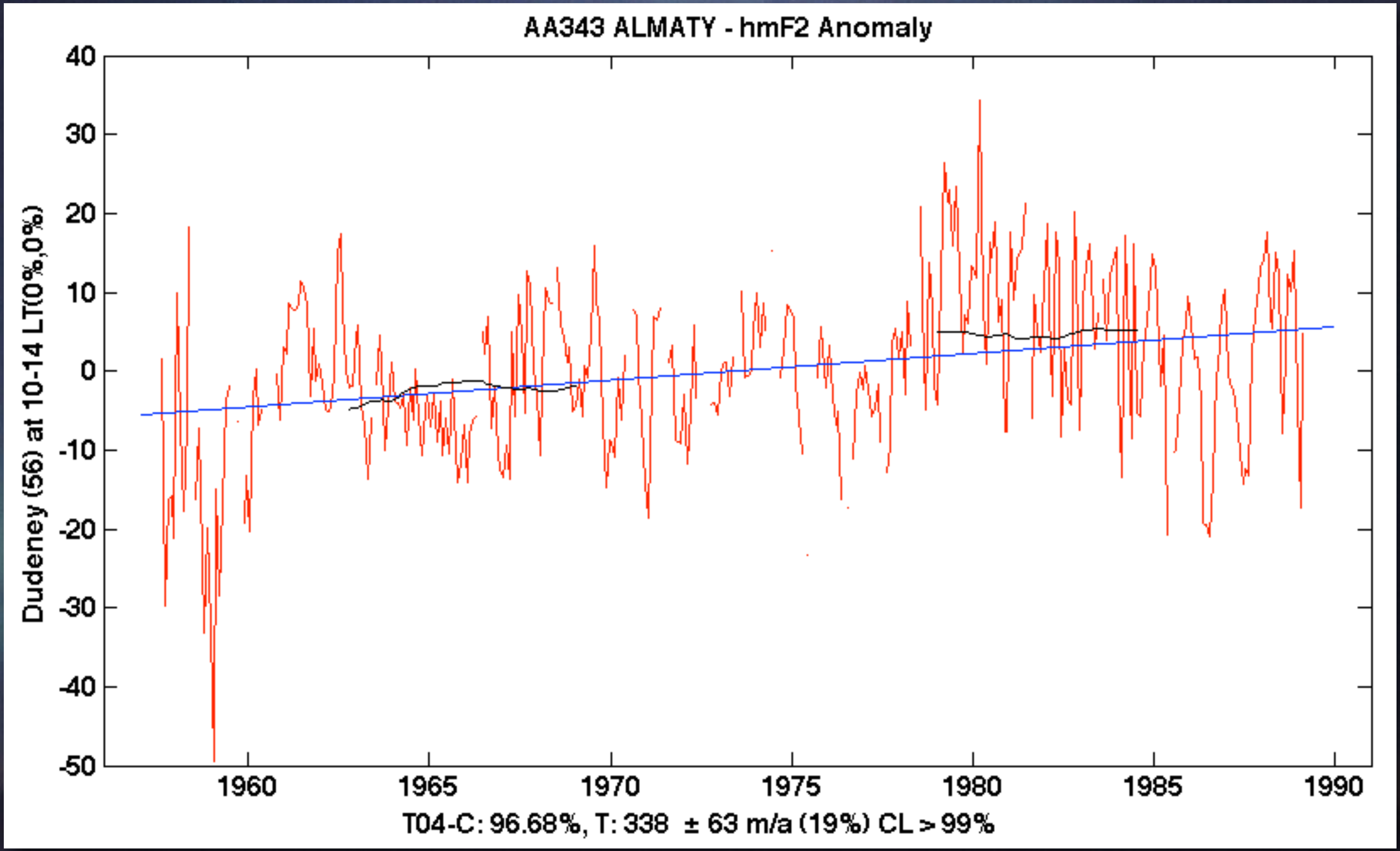


Note: hmF2 computed using the empirical formula of Dudeney (eq. 56; 1974), which has been tested against true height at Sodankylä estimated during different periods of the time series using Titheridge's (1969) single-polynomial method.

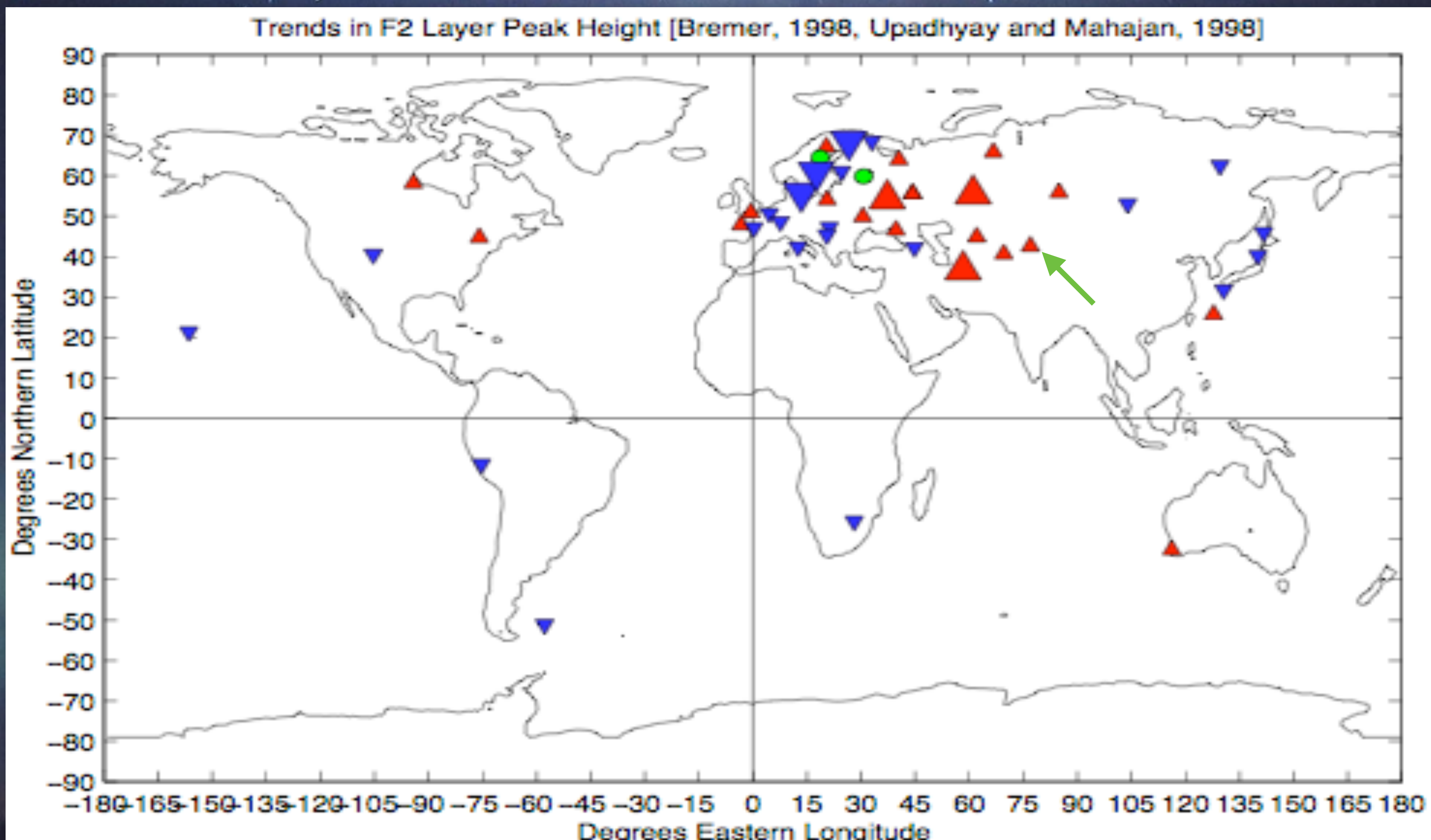
Sodankylä hmF2 Trend



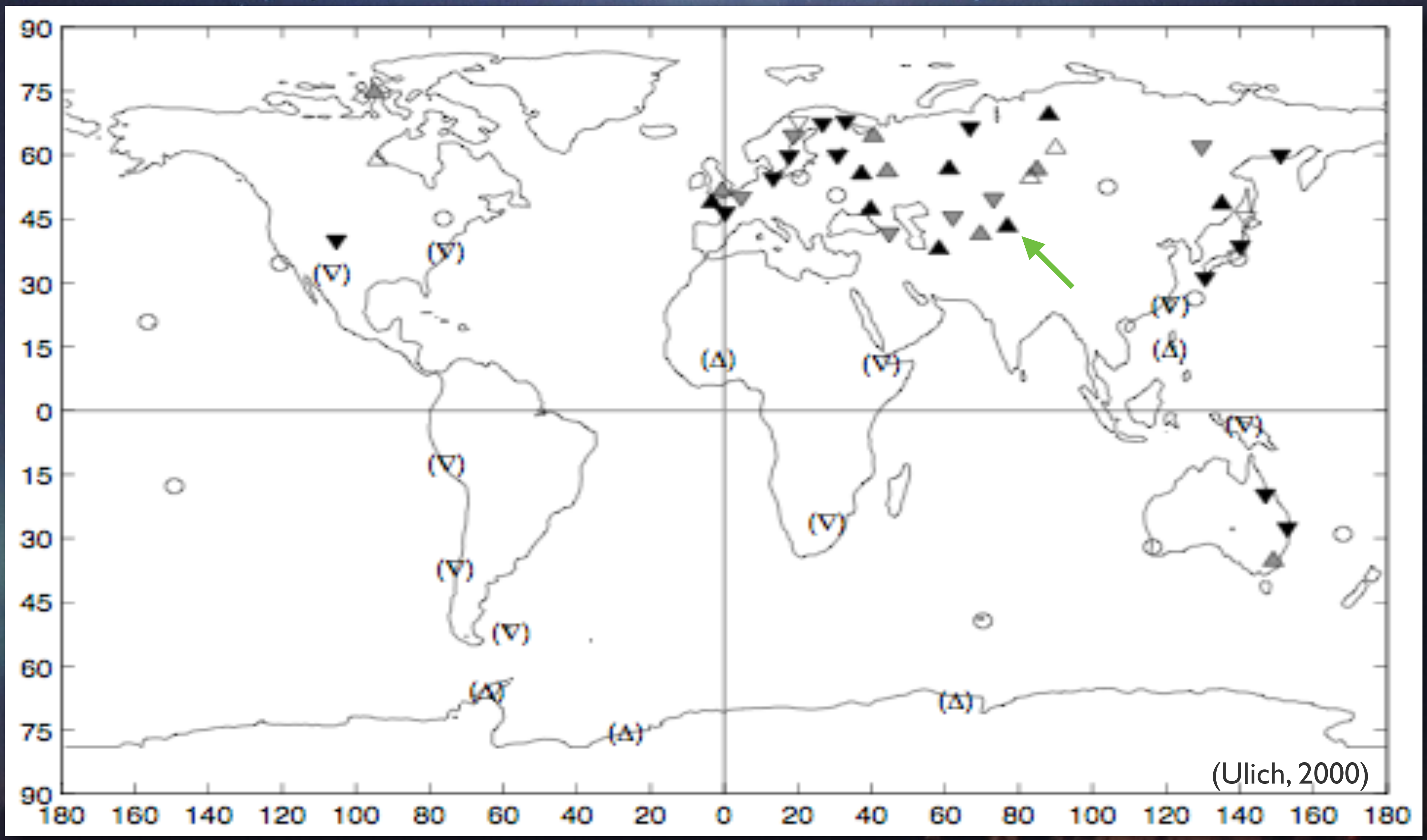
Almaty hmF2


AA343 ALMATY - hmF2 Anomaly
Dudeney (56) at 10-14 LT(0%,0%)
40
30
20
10
0
-10
-20
-30
-40
-50
1960
1965
1970
1975
1980
1985
1990
T04-C: 96.68%, T: 338 ± 63 m/a (19%) CL > 99%

hmF2 Trends


Trends in F2 Layer Peak Height [Bremer, 1998, Upadhyay and Mahajan, 1998]
Degrees Northern Latitude
Degrees Eastern Longitude
90
80
70
60
50
40
30
20
10
0
−10
−20
−30
−40
−50
−60
−70
−80
−90
−180 −165 −150 −135 −120 −105 −90 −75 −60 −45 −30 −15 0 15 30 45 60 75 90 105 120 135 150 165 180

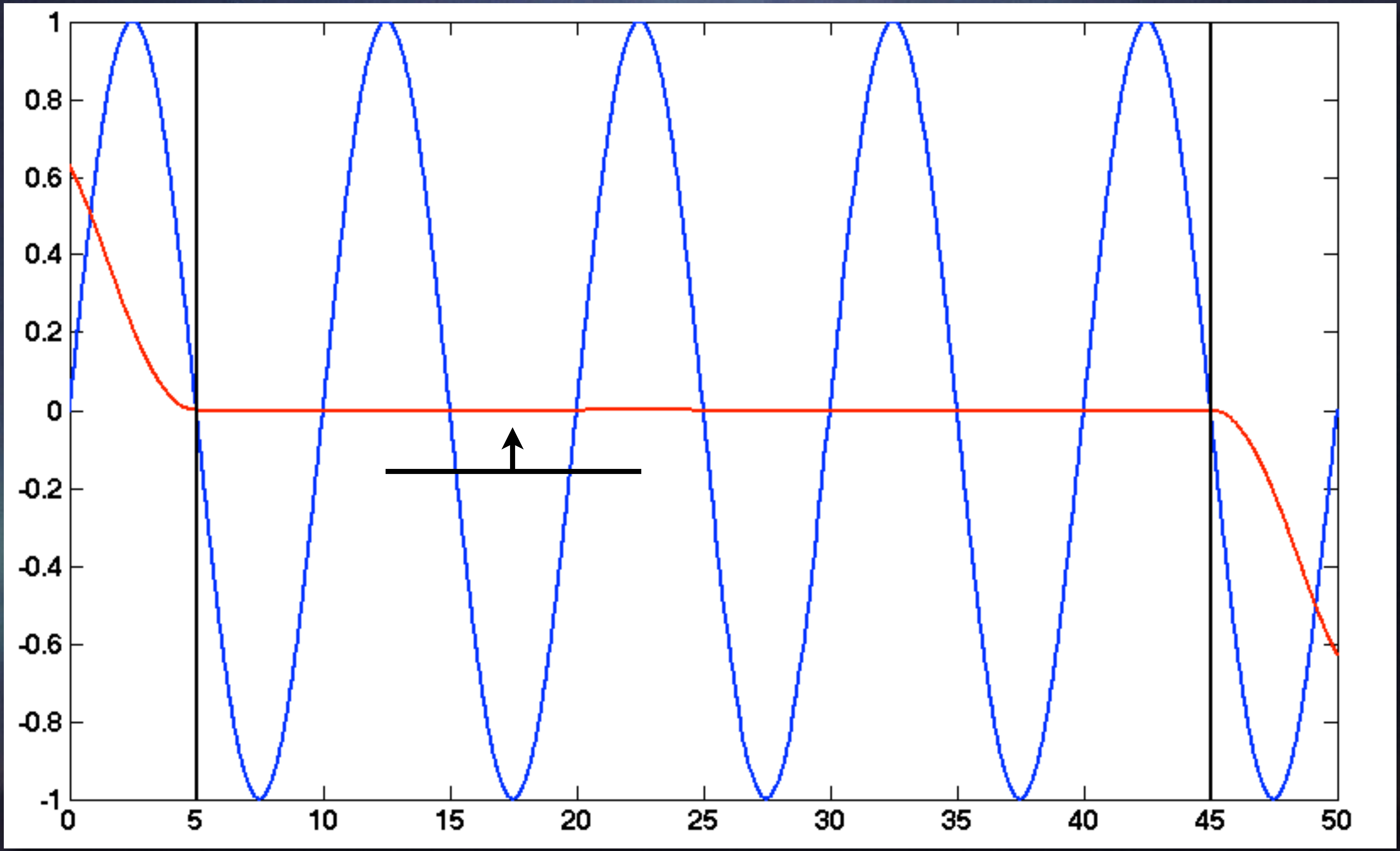
Global hmF2 Trends



Problems

- Data resolution (h, 3-h, day, month(?), ...)
- Low-pass filtering or polynomial fitting...

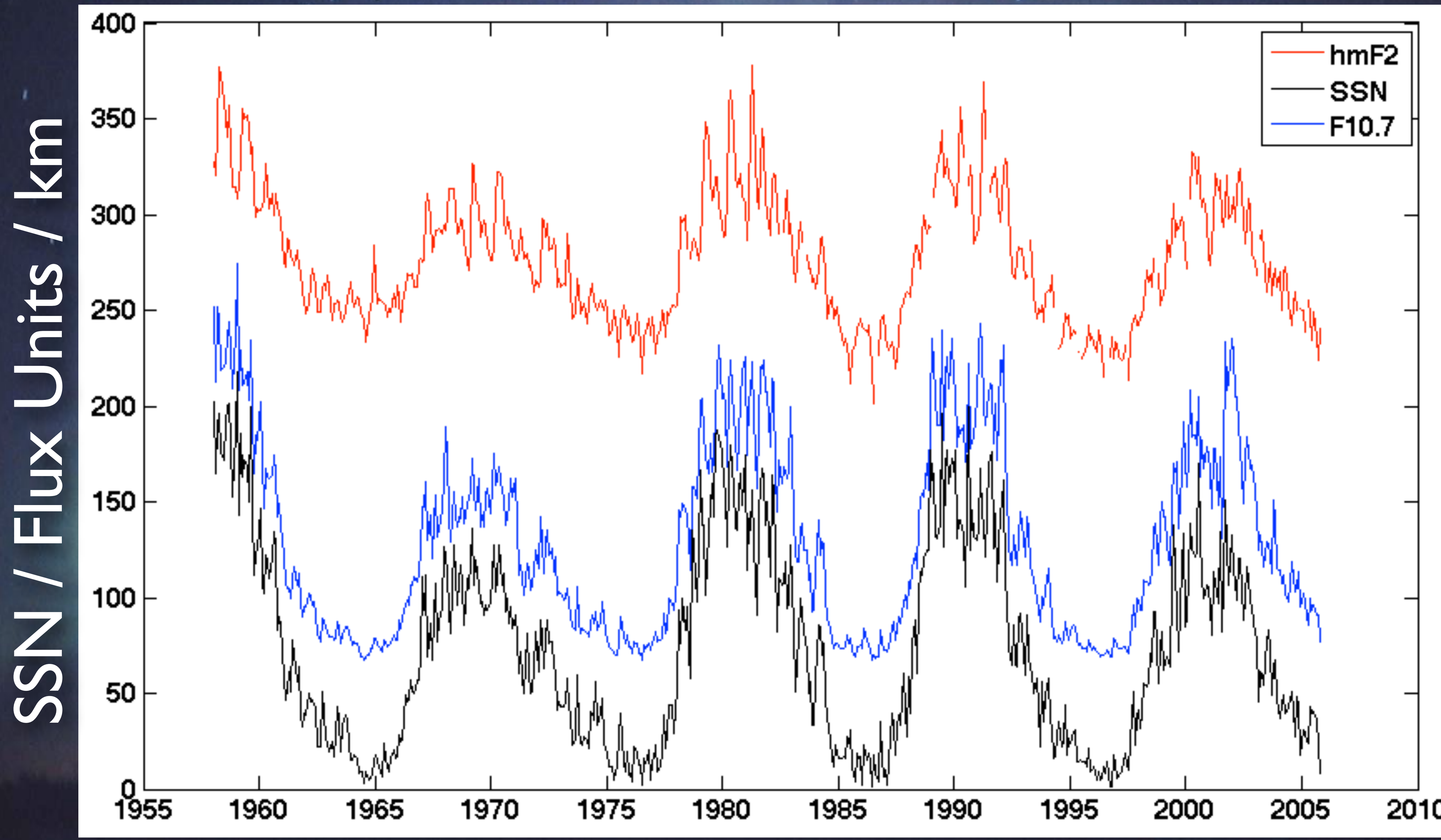
Running Mean Filter



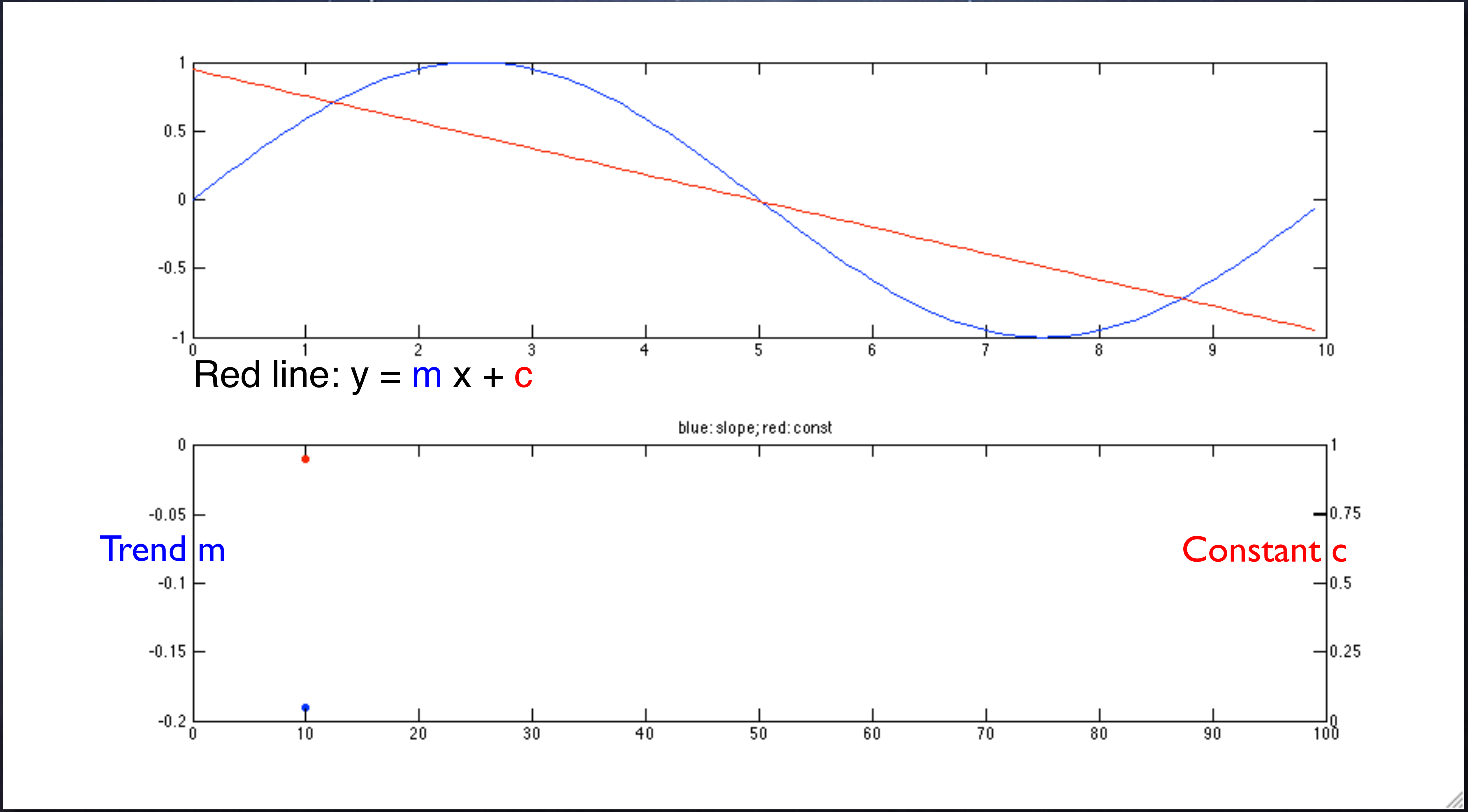
Problems

- 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

hmF2 & Solar Activity

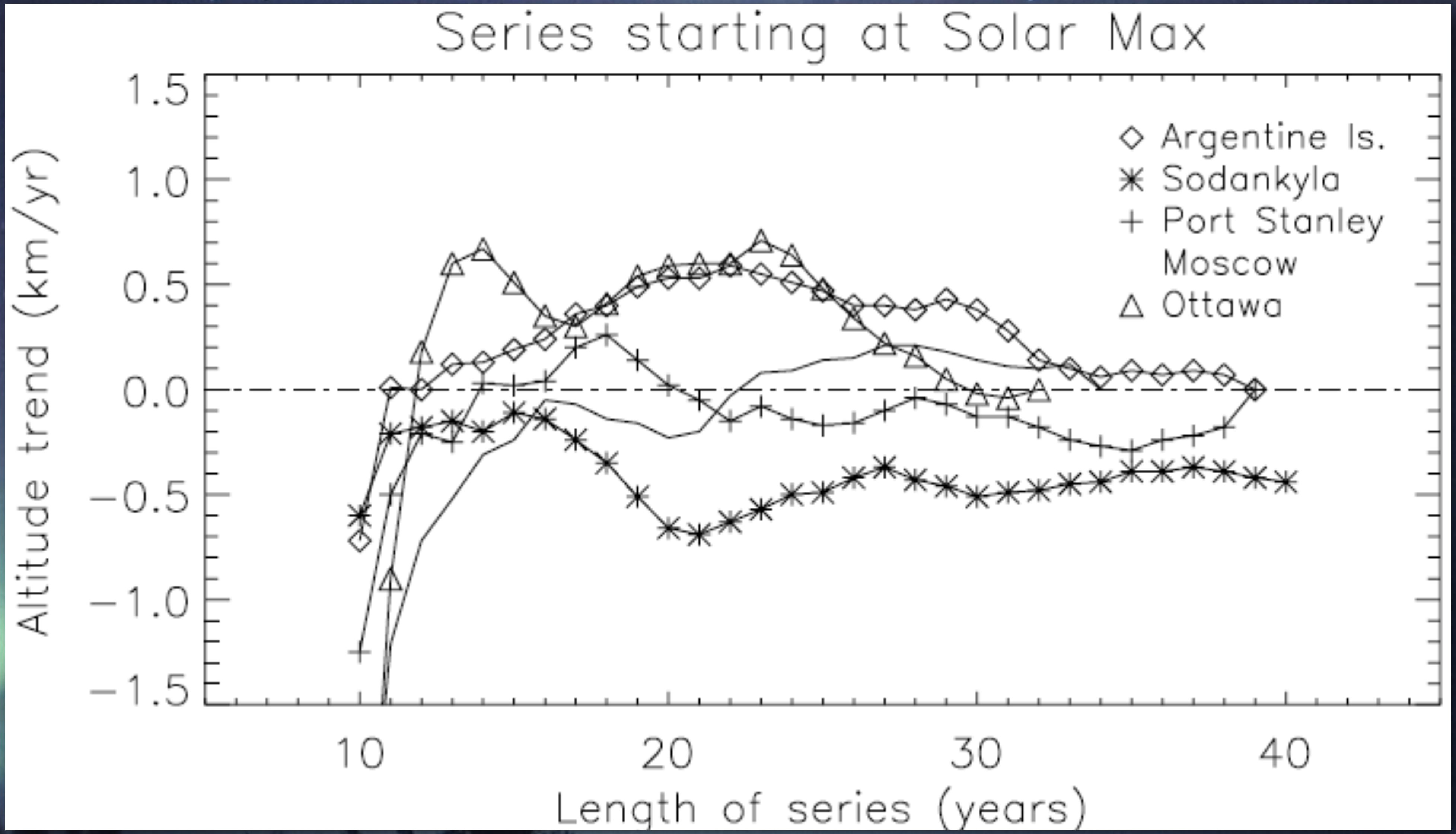


Ringing



1
0.5
0
-0.5
-1
0
1
2
3
4
5
6
7
8
9
10
Red line: y = m x + c
blue: slope; red: const
0
-0.05
-0.1
-0.15
-0.2
Trend m
Constant c
1
0.75
0.5
0.25
0
0
10
20
30
40
50
60
70
80
90
100

Ringing



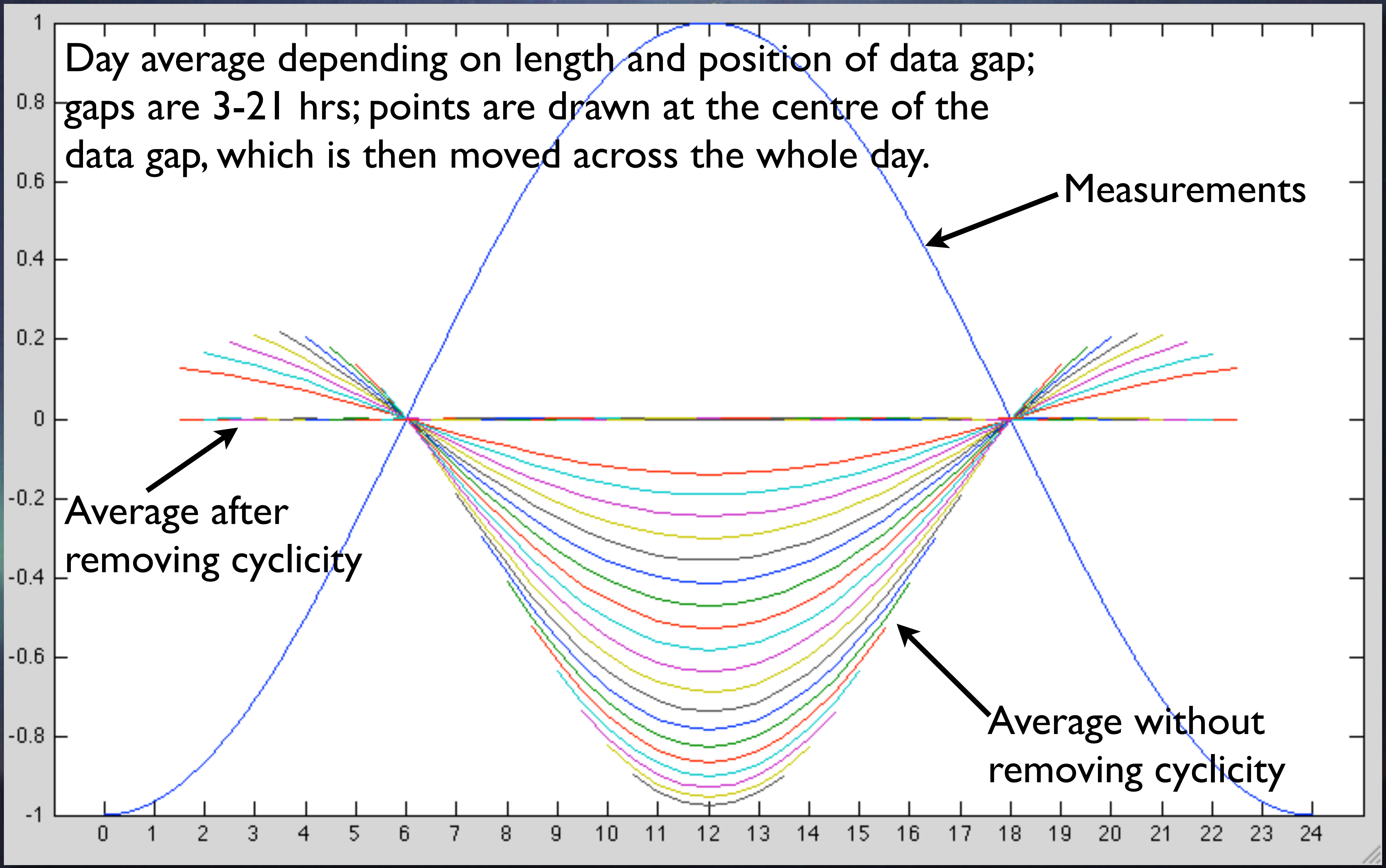
The ringing idea was first introduced by Jarvis et al., 2002. The plots shown here are from a follow-up paper by Clilverd et al., 2003.

Problems

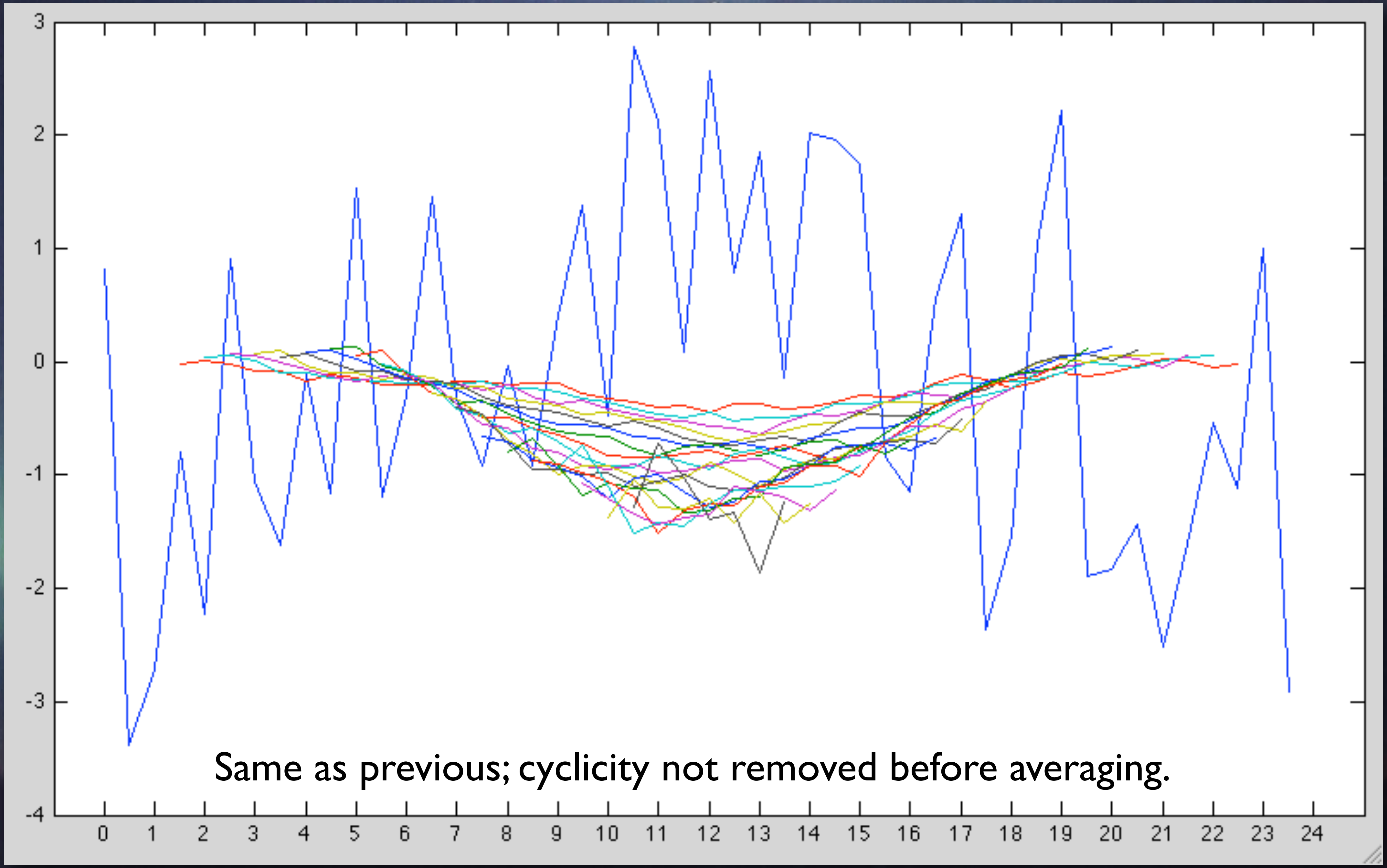
- Data resolution (h, 3-h, day, month(?), ...)
- Low-pass filtering or polynomial fitting...
- Removal of underlying (cyclic) variability: ...
- Data gaps

Example: Data Gaps

Data Gaps

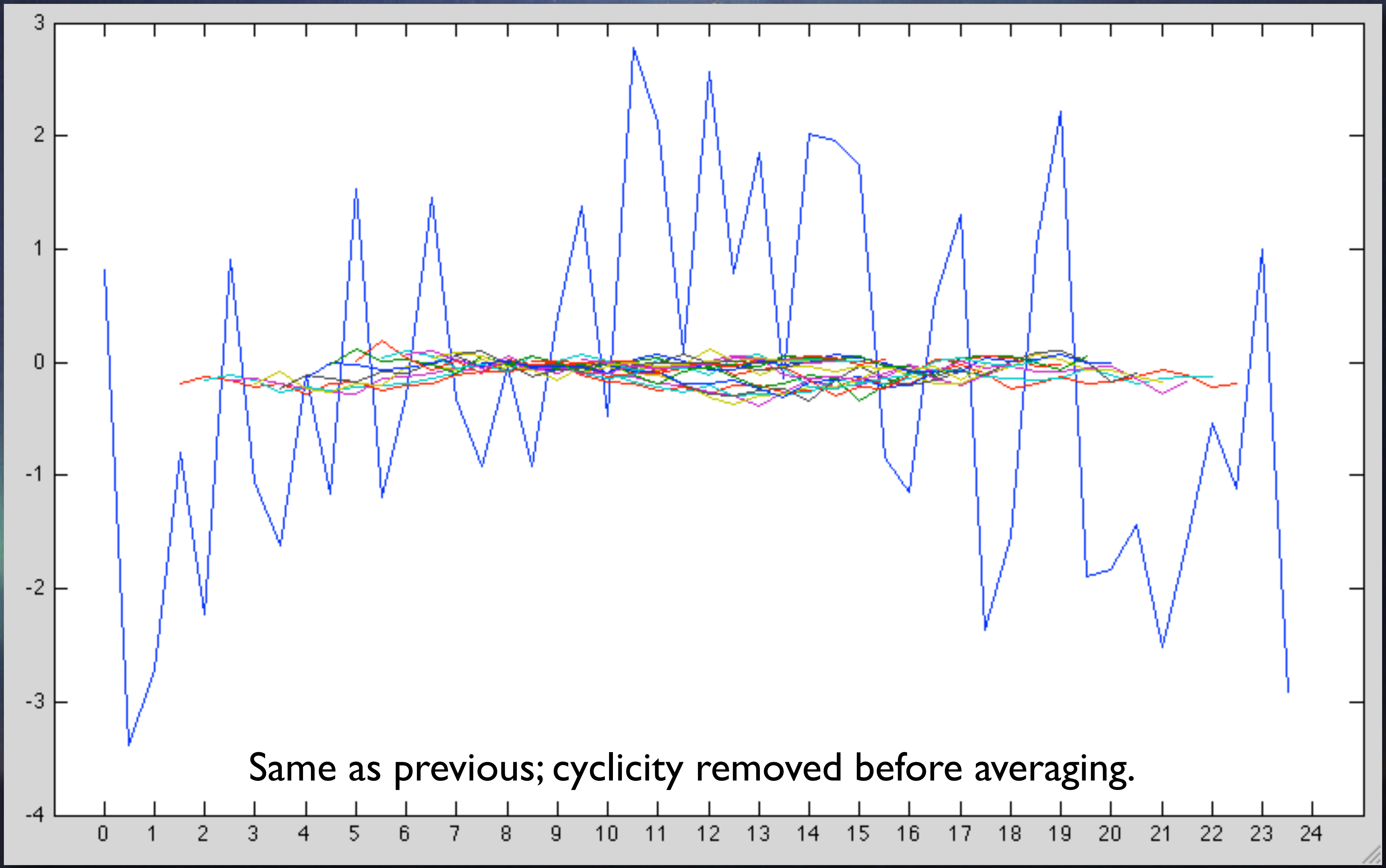

Day average depending on length and position of data gap;
gaps are 3-21 hrs; points are drawn at the centre of the
data gap, which is then moved across the whole day.
Measurements
Average after
removing cyclicity
Average without
removing cyclicity
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24

Data Gaps



Same as previous; cyclicity not removed before averaging.

Data Gaps


3
2
1
0
-1
-2
-3
-4
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
Same as previous; cyclicity removed before averaging.

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

Making models

- Base functions of the model(s) are, e.g.:

$m_i = \varepsilon_i$ -> measurement errors

$+ x_1$ -> constant

$+ x_2 t_i$ -> sampling times

$+ x_3 F_{10.7}(t_i)$ -> solar activity

$+ x_4 Ap(t_i)$ -> geomagnetic activity

$+ x_5 \sin(2\pi t_i)$

$+ x_6 \cos(2\pi t_i)$ -> annual variation

$+ x_7 \sin(4\pi t_i)$

$+ x_8 \cos(4\pi t_i)$ -> semi-annual variation

$+ \ldots$

Modelling the data

The ionospheric property of interest is 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 ε_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:

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

Inverse problem II

Measurements and theory are weighted by the measurement errors:

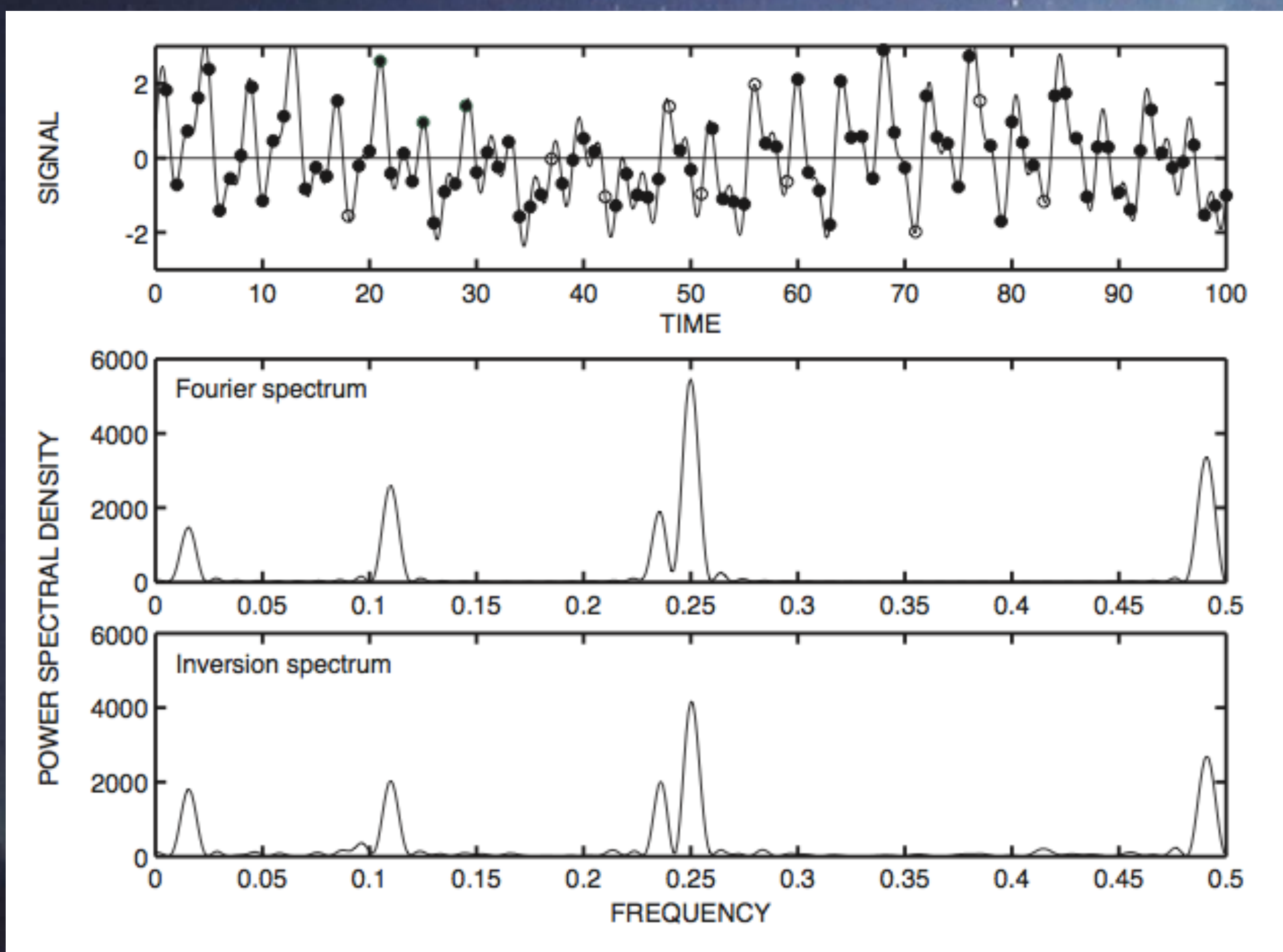
$$B_{ij} := \frac{A_{ij}}{\varepsilon_i} \quad \text{and} \quad b_i := \frac{m_i}{\varepsilon_i}$$

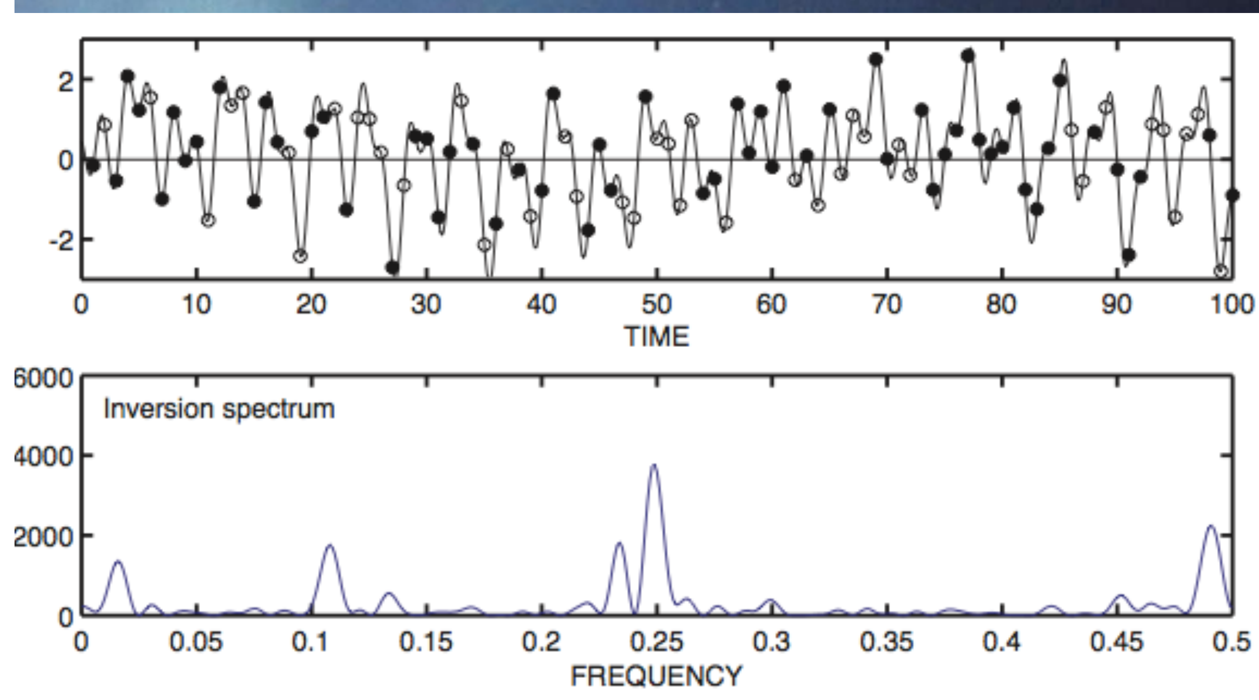
The solution is the vector **x**, which minimises the following expression:

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

We are left with a general least squares problem.
Solving this results in the most probable solution for **x**.

Signal Spectrum by Stochastic Inversion



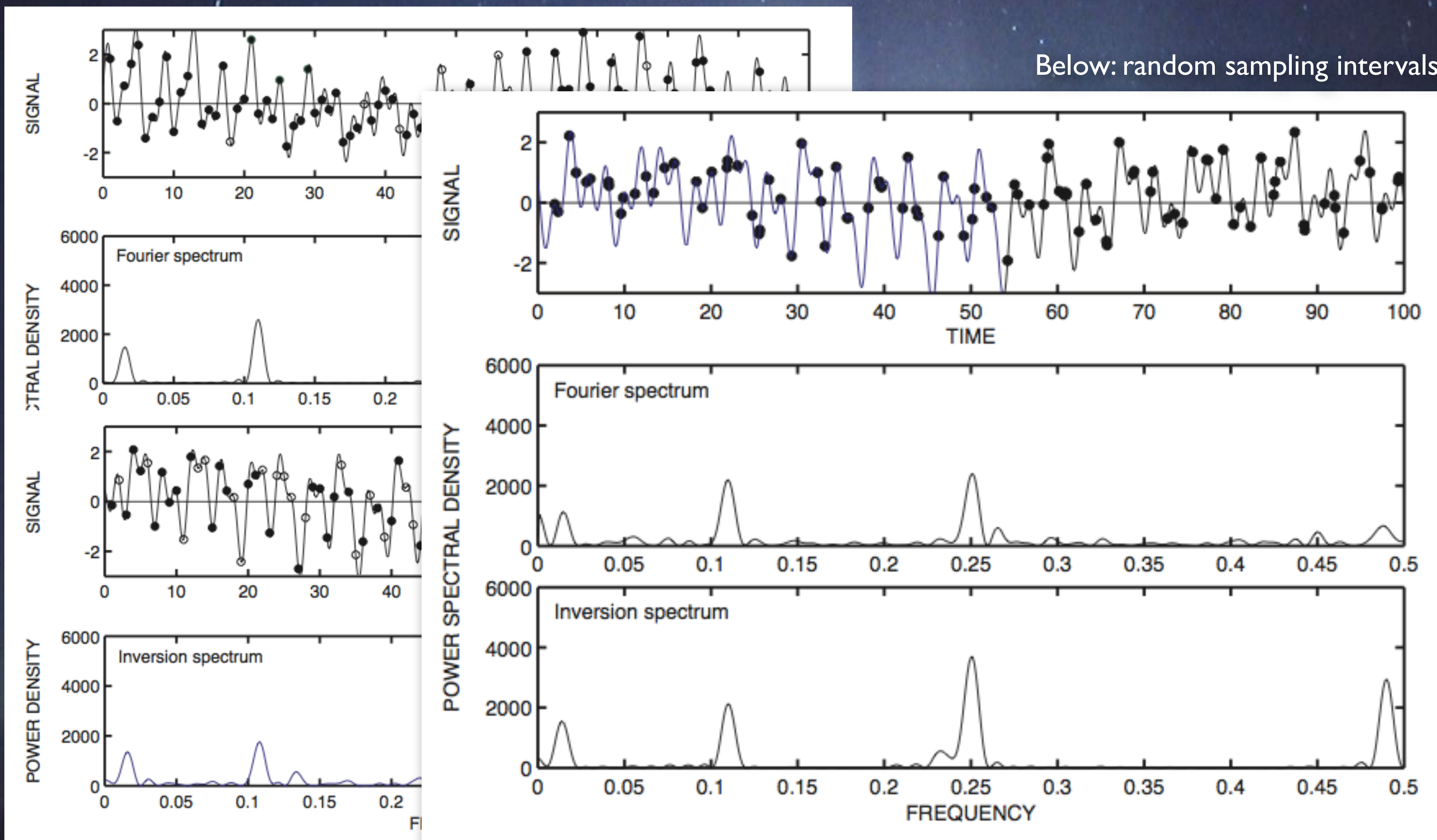


Left: 100 pts for Fourier, 90 for inversion.
Above: 59 pts.

T. Nygrén and Th.Ulich, Calculation of signal spectrum by means of stochastic inversion, Ann. Geophys., 28, 1409-1418, 2010.

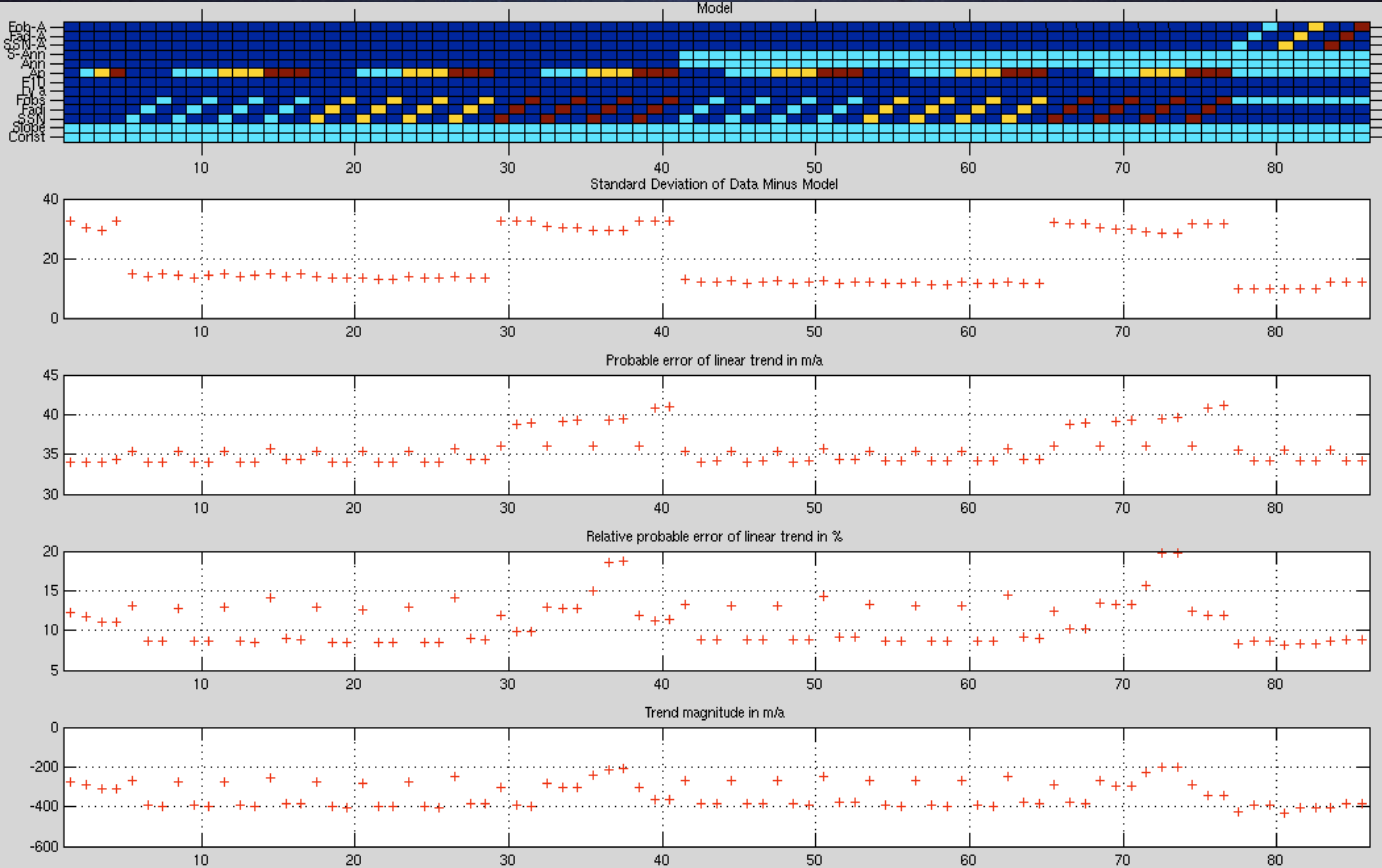
Signal Spectrum by Stochastic Inversion

Below: random sampling intervals.

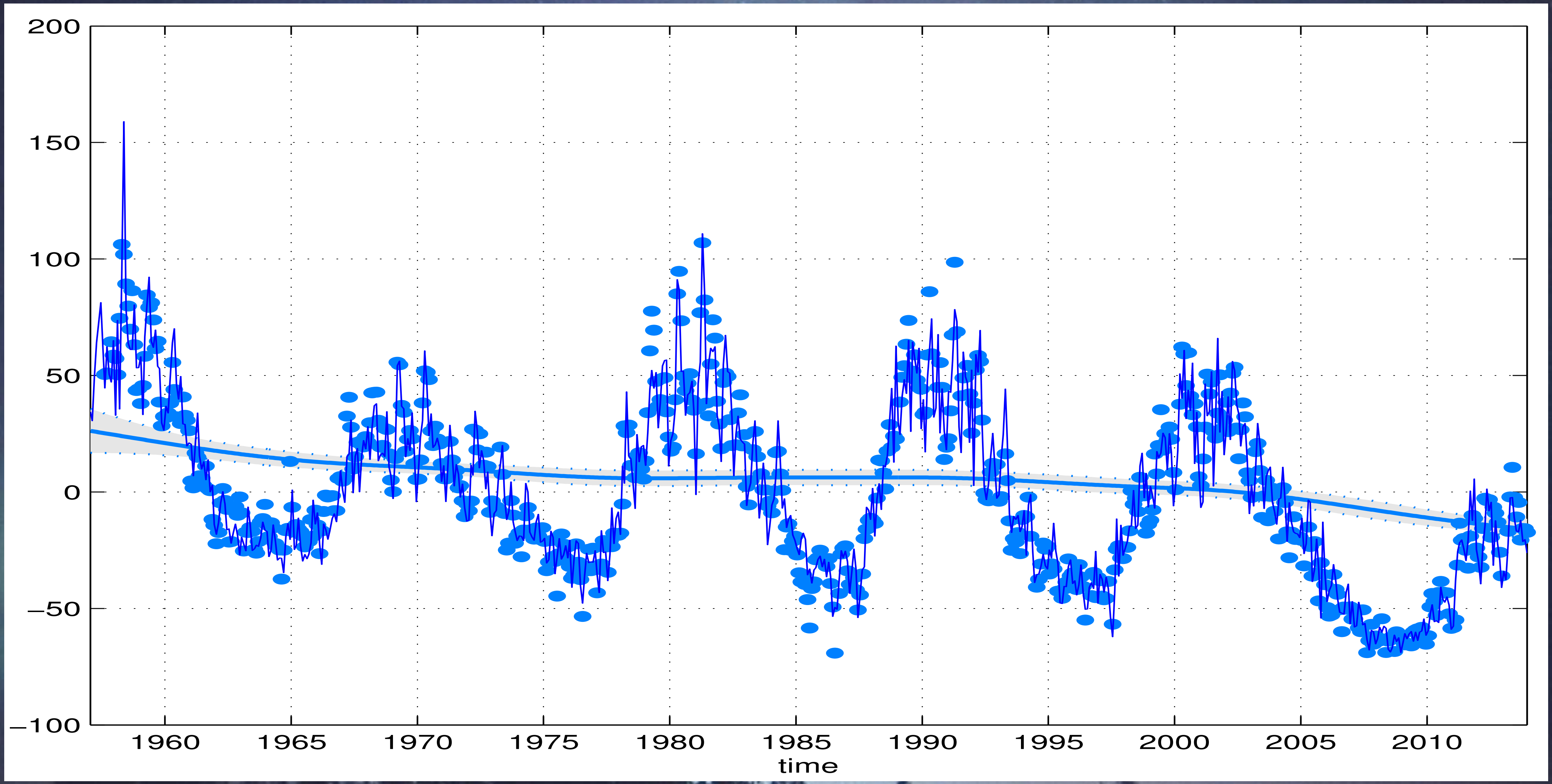


T. Nygrén and Th.Ulich, Calculation of signal spectrum by means of stochastic inversion, Ann. Geophys., 28, 1409-1418, 2010.

Sodankylä F2-layer peak height hmF2



Dynamic Linear Model

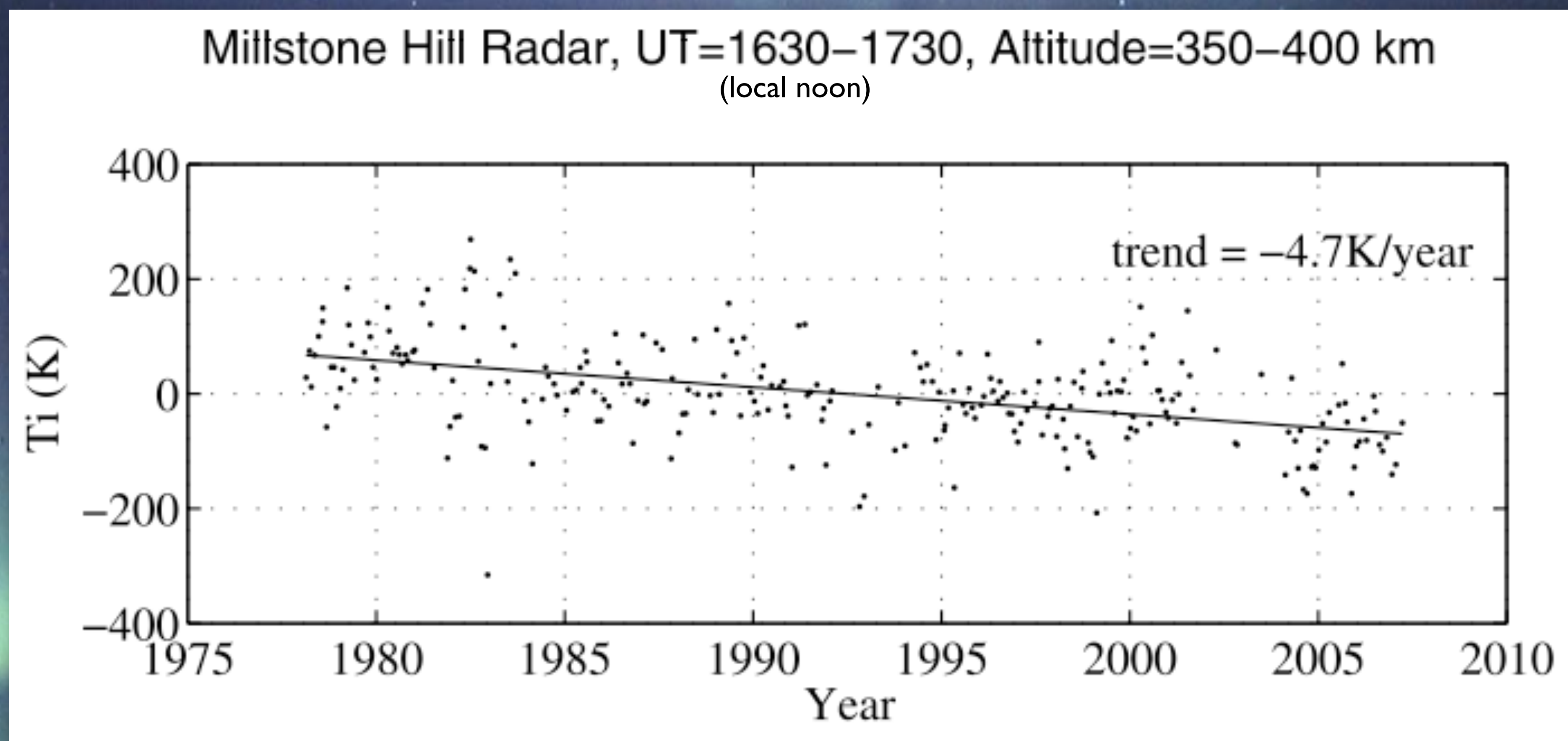


New approach using a dynamic linear model based on constant, trend, annual & semi-annual wave, as well as F10.7cm radio fluxes. Here, hmF2 is based on the same Dudeney (1974) computation as earlier plots.
(Roininen, Ulich, and Laine, Cambridge (UK) Trend Workshop 2014)

Trends in other Observations

Height in km	Method	Parameter	Trend per Year	Reference
75	Sounding rocket	Temperature	-0.6 K	Kokin and Lysenko, 1994
70	Sounding rocket	Temperature	-0.7 K	Golitsyn et al., 1996
60-70	Lidar	Temperature	-0.4 K	Hauchecorne et al., 1991
60	Sounding rocket	Temperature	-0.4 K	Golitsyn et al., 1996
60	Sounding rocket	Temperature	-0.33 K	Keckhut et al., 1999
50-60	Lidar	Temperature	-0.25 K	Aikin et al., 1991
50	Sounding rocket	Temperature	-0.25 K	Golitsyn et al., 1996
40	Sounding rocket	Temperature	-0.1 K	Golitsyn et al., 1996
30-60	Sounding rocket	Temperature	-0.17 K	Dunkerton et al., 1998
30-50	Sounding rocket	Temperature	-0.17 K	Keckhut et al., 1999
30	Sounding rocket	Temperature	-0.1 K	Golitsyn et al., 1996
25	Sounding rocket	Temperature	-0.1 K	Golitsyn et al., 1996
25	Sounding rocket	Temperature	-0.11 K	Keckhut et al., 1999

Direct F-Region Temperature



Long-term temperature trends in the ionosphere above Millstone Hill

J. M. Holt[1] and S. R. Zhang[1]

GEOPHYSICAL RESEARCH LETTERS, VOL. 35, L05813, doi:10.1029/2007GL031148, 2008

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.
- Solution in modelling?
- We don't understand what's going on.
- Student exercise: Find out!

Conclusion

(I lied to you!)

Ionsondes, originally deployed for monitoring ionospheric conditions for HF radio communication and for studying short-term events, are becoming useful in an <u>environmental context</u>.

They provide long-term measurements of our environment!

Do not discontinue atmospheric observations at a time of climate change!


Kiitos!