History and Calibration of Sunspot Numbers

Edward W. Cliver, AFRL
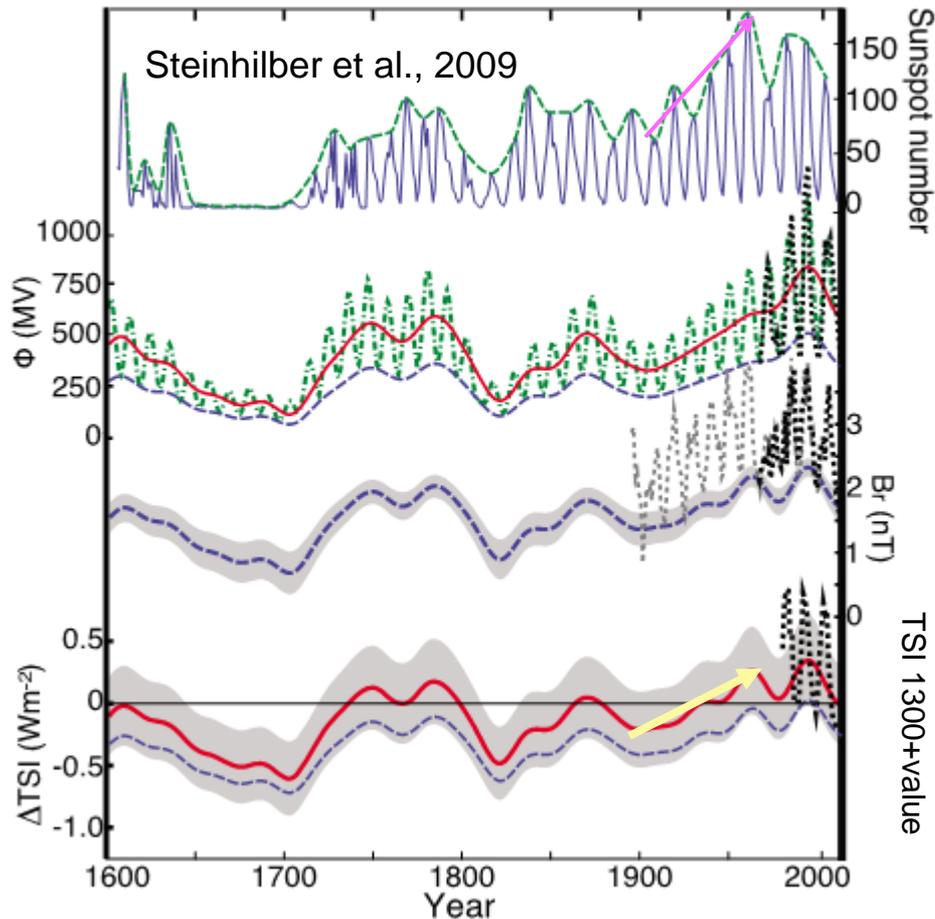
Leif Svalgaard, Stanford Univ.

Kenneth H. Schatten, a.i. Solutions

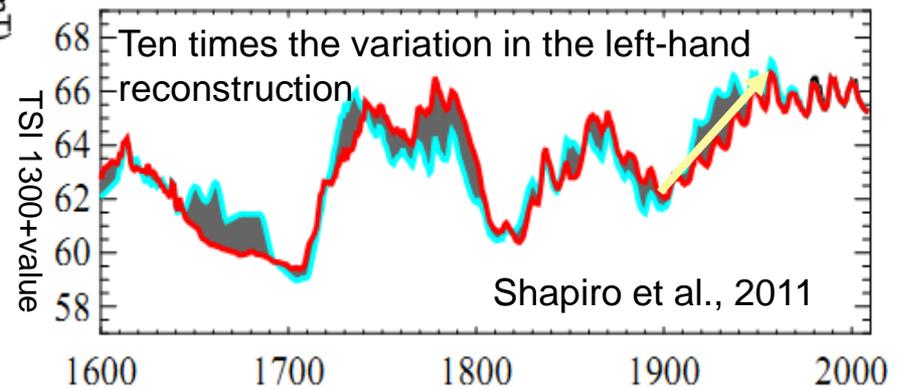IUGG XXV General Assembly, IAGA Symposium A12.2

Melbourne, Australia, 6 July 2011

Why is it Important to Know the Sunspot Number in the Past?
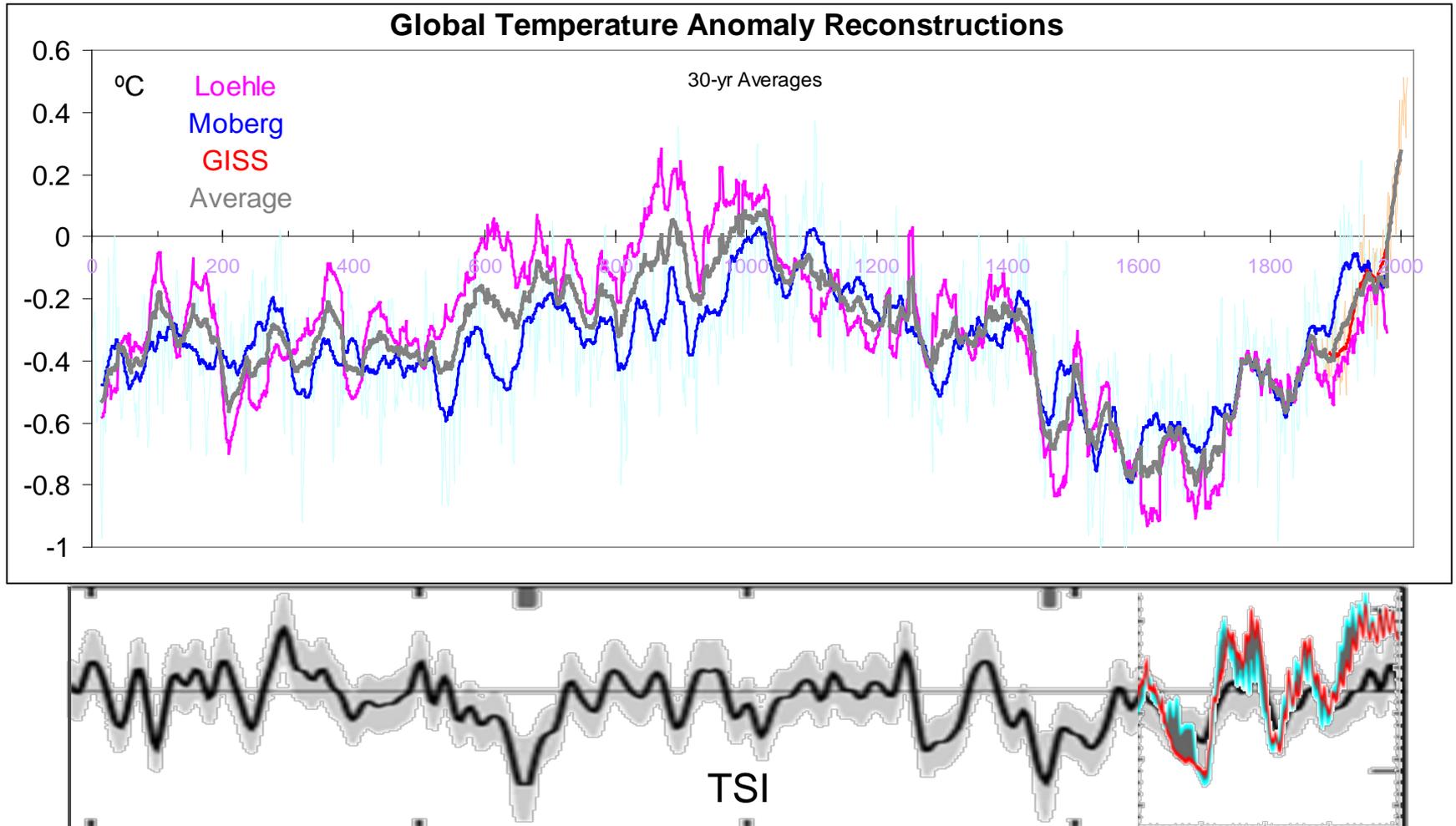

Steinhilber et al., 2009

Apart from the intrinsic interest for solar physicists, records of past solar activity feed into the climate debate and thus reach far outside our own field.
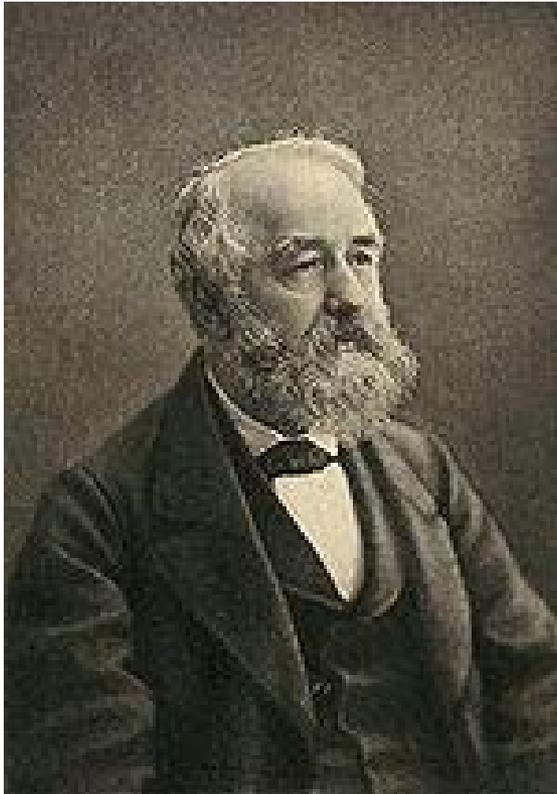
Reconstructions of the solar output (TSI) use the sunspot number to calibrate the cosmic ray record, and become **very** sensitive to perceived trends, if any, of solar activity.

Ten times the variation in the left-hand reconstruction

Shapiro et al., 2011

2

How Much of Climate Variation is Due to Variation of Solar Activity?

Global Temperature Anomaly Reconstructions

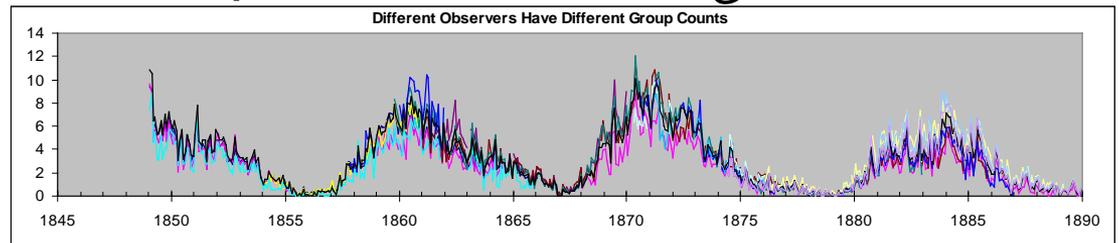ºC — Loehle, Moberg, GISS, Average — 30-yr Averages

TSI

The Sunspot Number(s)

Rudolf Wolf (1816-1893)
Observed 1849-1893

- Wolf Number = $k_W (10*G + S)$
- G = number of groups
- S = number of spots

- Group Number = 12 k_G G

Different Observers Have Different Group Counts

The '12' is to make the mean for the past ~100 years the same as the mean Wolf Number

Ken Schatten

Wolf's Several Lists of SSNs

- During his life Wolf published several lists of his 'Relative Sunspot Number':
- 1857 Using Sunspot Drawings By Staudacher 1749-1799 as early SSNs
- 1861 Doubling Staudacher's Numbers to align with the large variation of the Magnetic 'Needle' in the 1780s
- 1874 Adding newer data and published list
- 1880 Increasing all values before his own series [beginning 1849] by ~25% based on Milan Declination
- 1902 [Wolfer] reassessment of cycle 5 reducing it significantly, obtaining the 'Definitive' List in use today

Major Adjustments to Wolf Number

Evolution of the Wolf Number
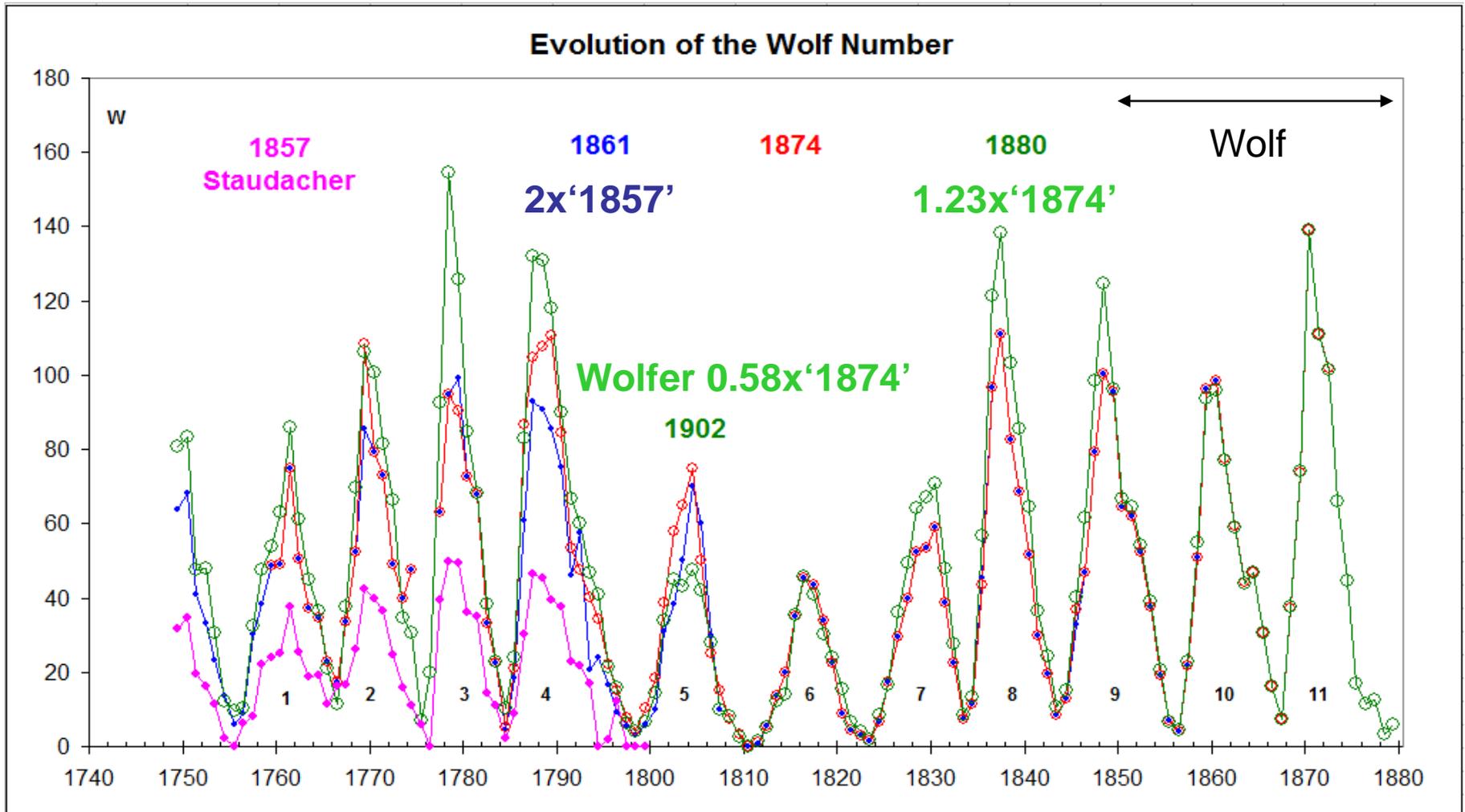
Wolf published several versions of his series over time, but did not modify his own data

The Wholesale Update of SSNs before 1849 is Clearly Seen in the Distribution of Daily SSNs
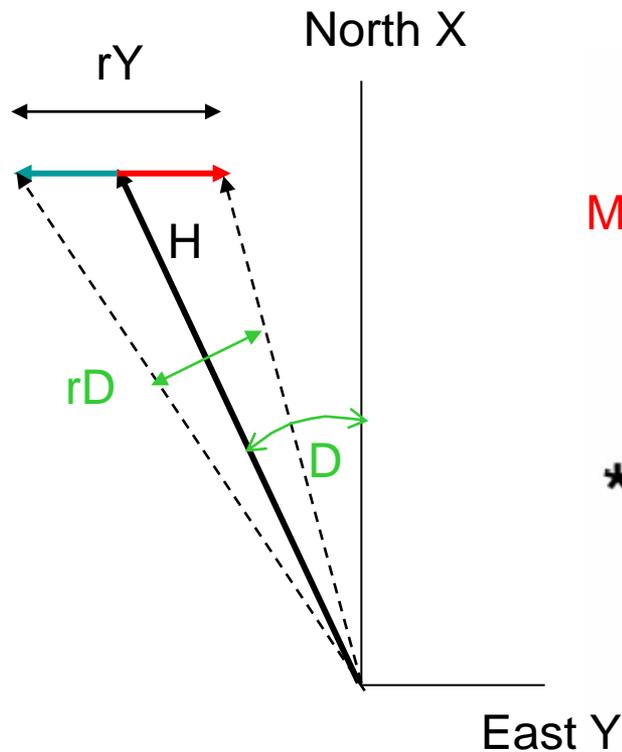
Distribution of Daily Values of the 'Official' Sunspot Number
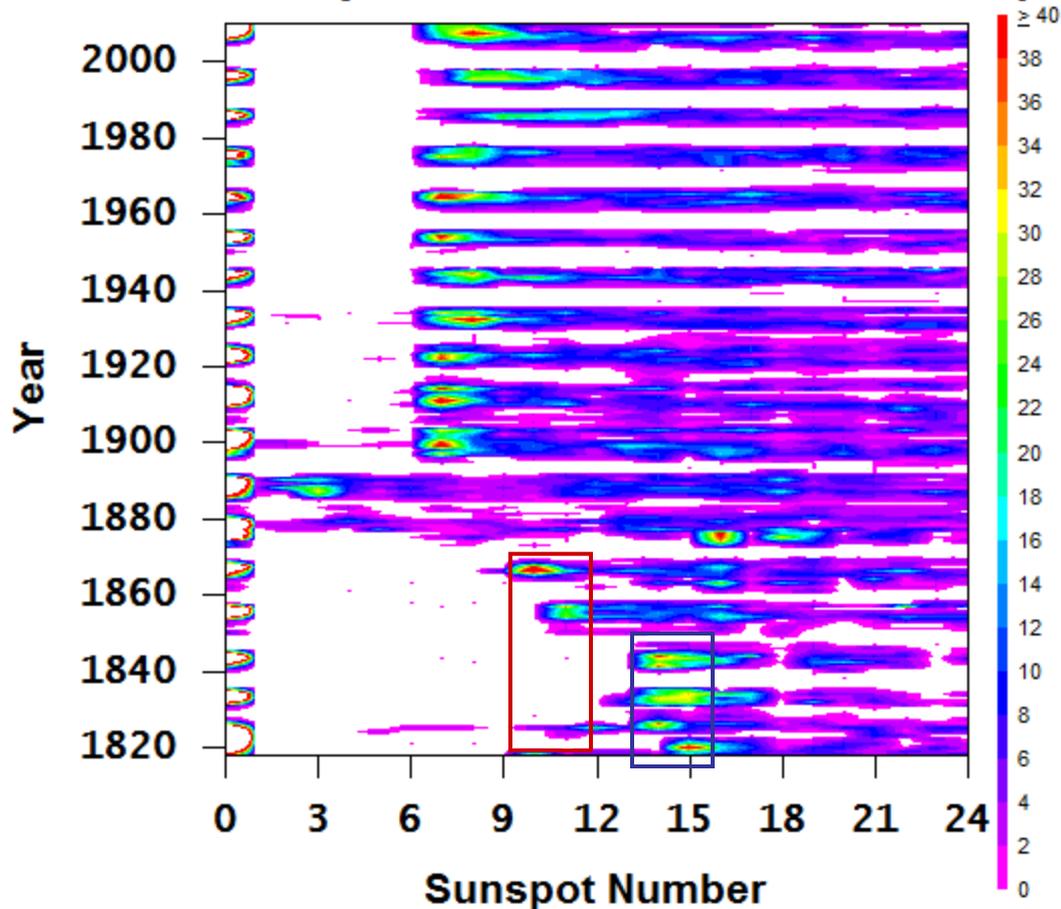
The smallest non-zero SSN is 11, but there are no 11s before 1849

11 * 5/4 = 14

Justification of the Adjustments rests on Wolf's Discovery: $rD = a + b\,R_W$

North X

rY

H

rD

D

East Y

Morning

Evening

TO SUN

Method of Magnetic Variometer

$Y = H\sin(D)$
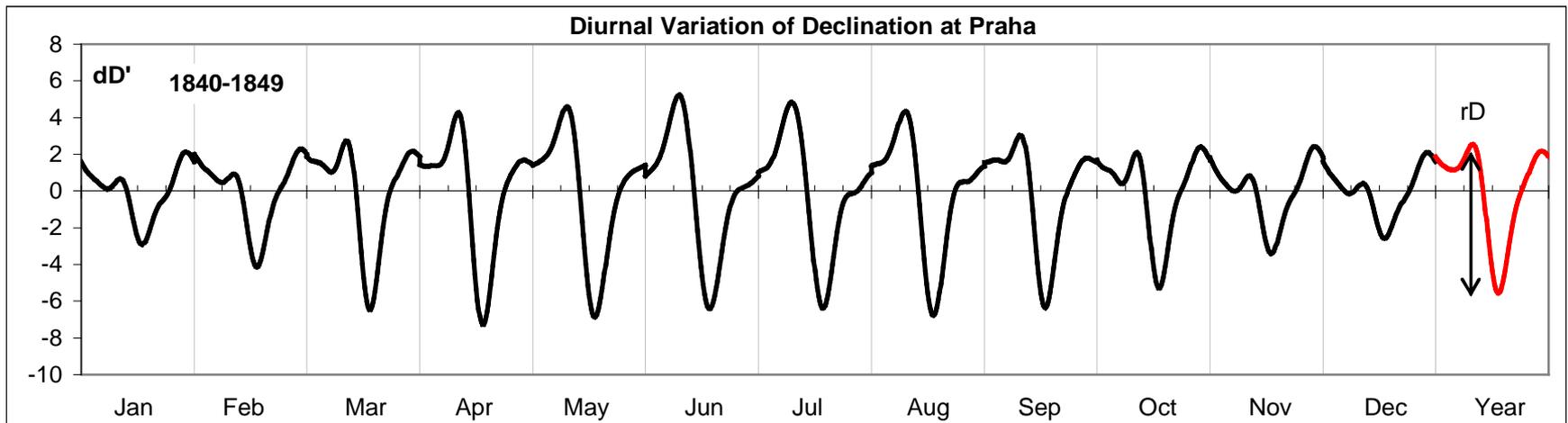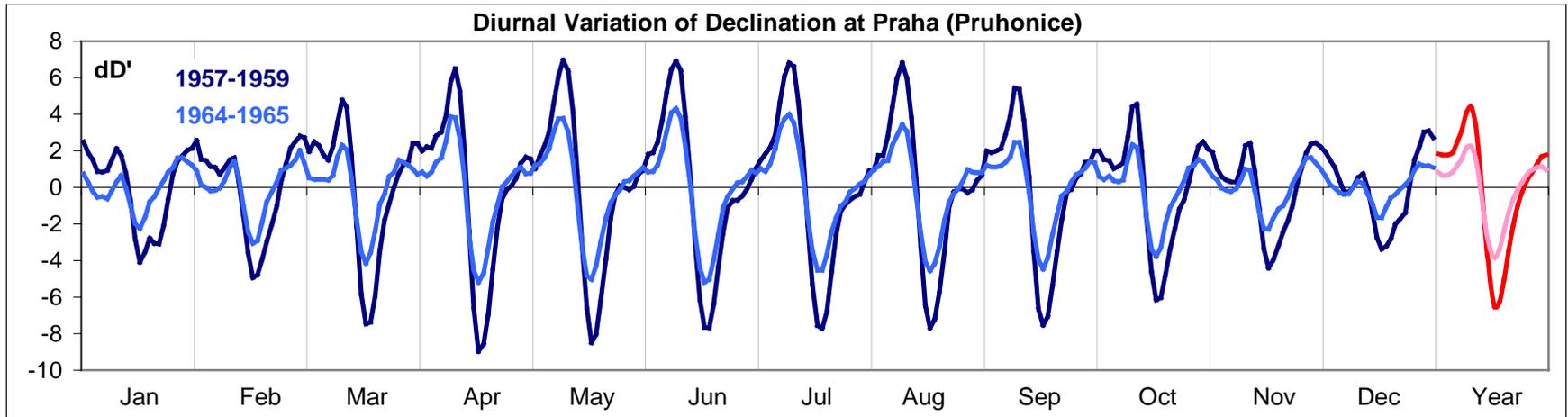
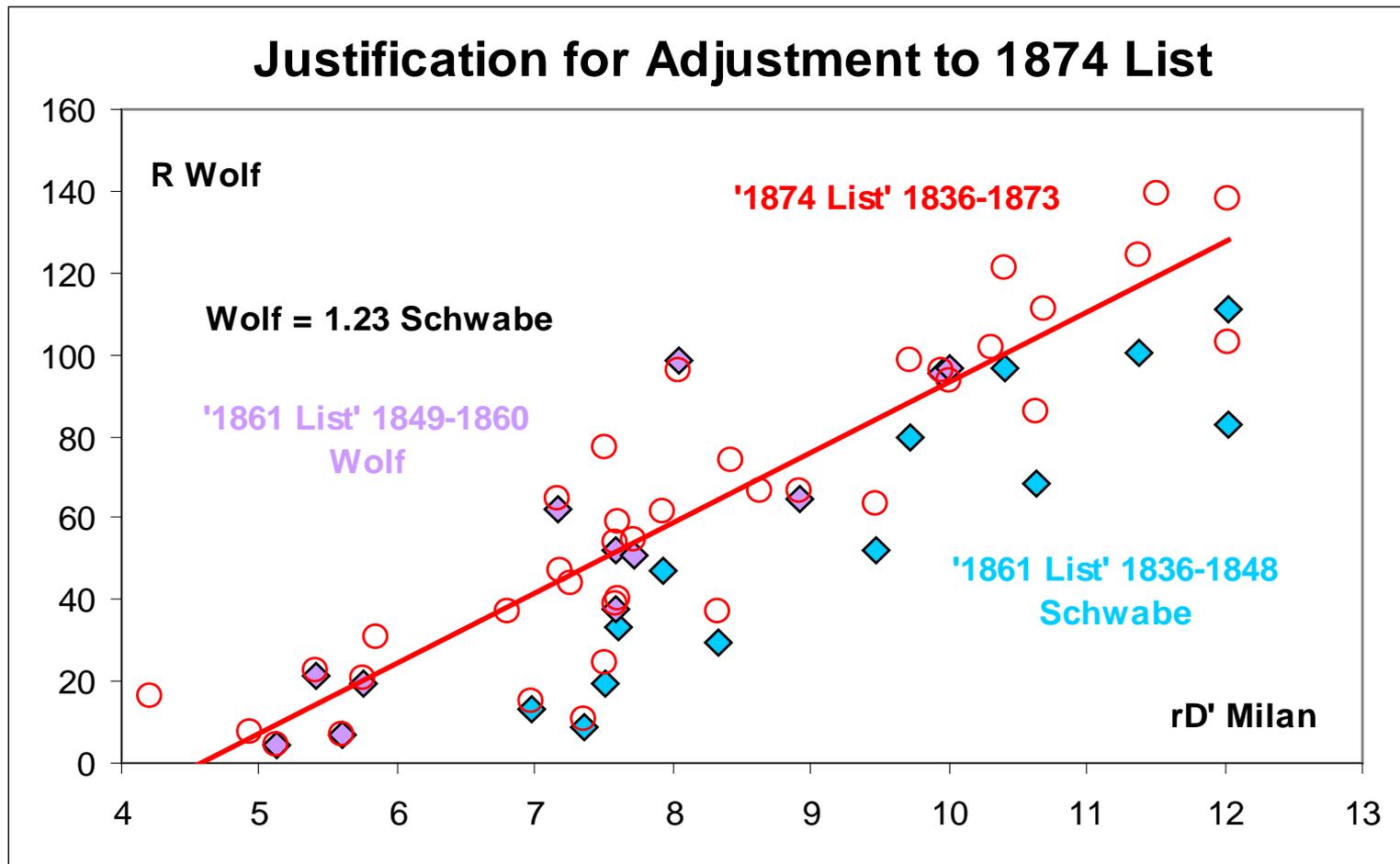$dY = H\cos(D)\,dD$

For small D, dD and dH
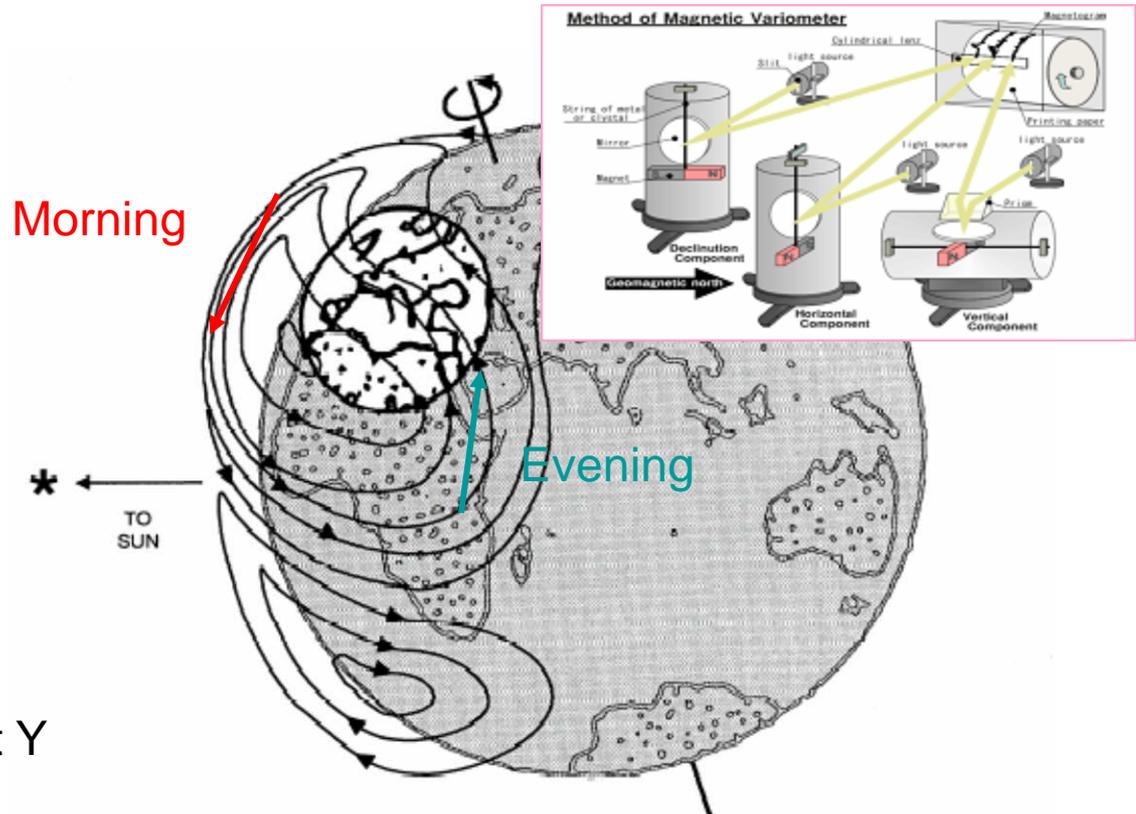
A current system in the ionosphere [E-layer] is created and maintained by solar FUV radiation. Its magnetic effect is measured on the ground.

The Diurnal Variation of the Declination for Low, Medium, and High Solar Activity

Diurnal Variation of Declination at Praha (Pruhonice)

Diurnal Variation of Declination at Praha

9

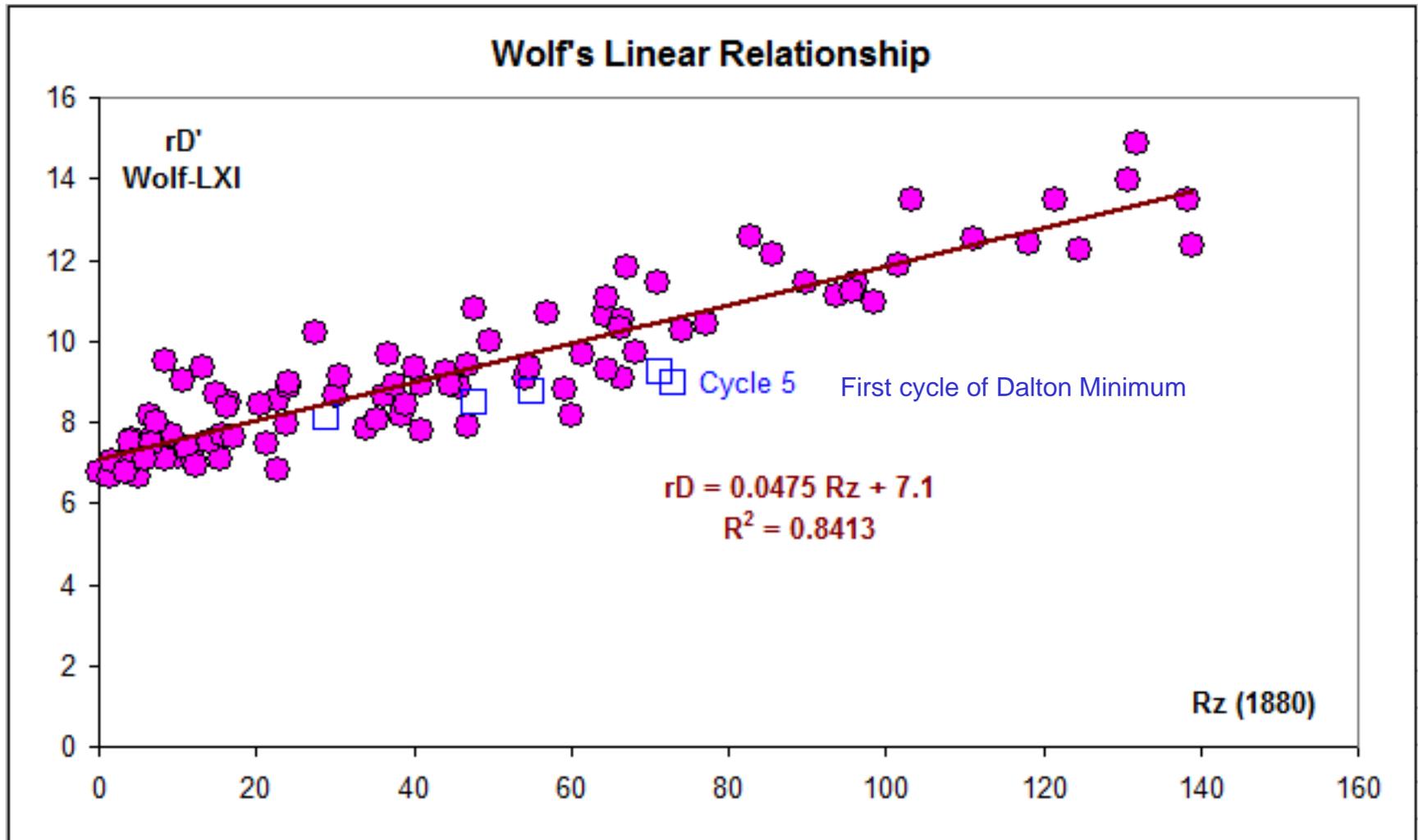# Wolf got Declination Ranges for Milan from Schiaparelli and it became clear that the pre-1849 SSNs were too low

Justification for Adjustment to 1874 List

R Wolf

'1874 List' 1836-1873

Wolf = 1.23 Schwabe

'1861 List' 1849-1860 Wolf

'1861 List' 1836-1848 Schwabe

rD' Milan

The '1874' list included the 25% [Wolf said 1/4] increase of the pre-1849 SSN

Wolf's SSN was thus now consistent with his many-station compilation of the diurnal variation of Declination 1781-1880

Wolf's Linear Relationship

rD'
Wolf-LXI

Cycle 5   First cycle of Dalton Minimum

$$rD = 0.0475\, Rz + 7.1$$
$$R^2 = 0.8413$$

Rz (1880)

It is important to note that the relationship is *linear* for calculating averages

Wolfer's Revision of Solar Cycle 5 Based on Observations at Kremsmunster

Rudolf Wolf's Sunspot Numbers for Solar Cycle 5

Wolf 1882
Wolfer 1902
GSN 1996
SC 5
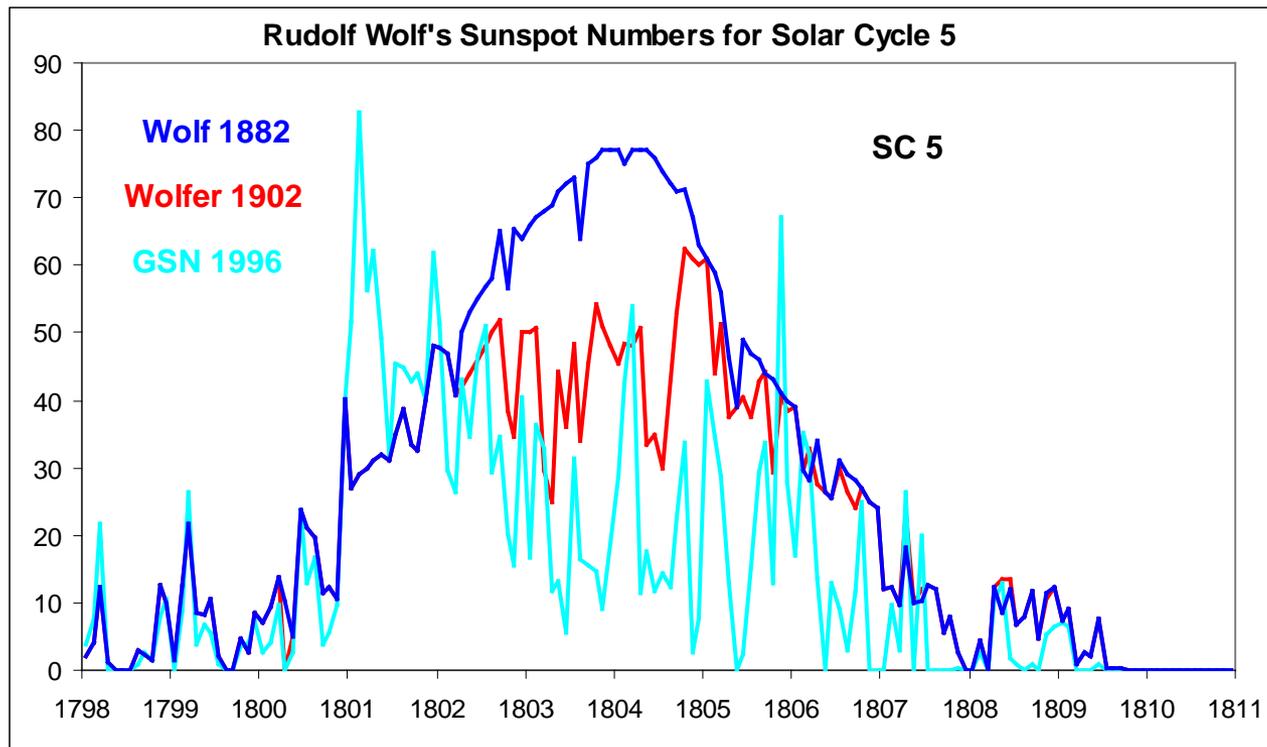
Wolf used 4' Fraunhofer telescopes with aperture 80 mm [Magn. X64]

This one from 1863 on
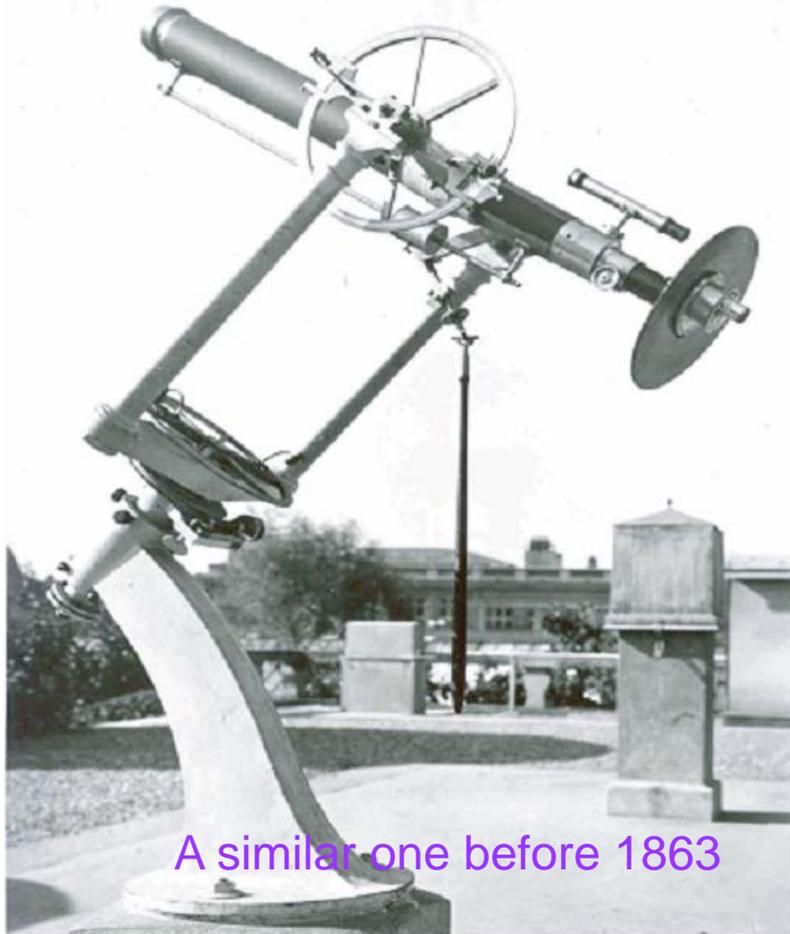
A similar one before 1863

Still in use today [by T. Friedli] continuing the Swiss tradition [under the auspices of the Rudolf Wolf Gesellshaft]

This is the 'Norm' Telescope

13

Wolf occasionally [and eventually – from 1870s on - exclusively] used much smaller handheld, portable telescopes [due to frequent travel], leaving the 80mm for his assistants or when he was home

These telescopes also still exist and are still in use today to safeguard the stability of the series

Wolf estimated that to scale the count using the small telescopes to the 80mm Standard telescope, the count should be multiplied by 1.5

The Use of the Two Telescopes, too, can be Seen in the Distribution of the Daily Values

Distribution of Daily Values of the 'Official' Sunspot Number

11 * 1.5 = 16.5
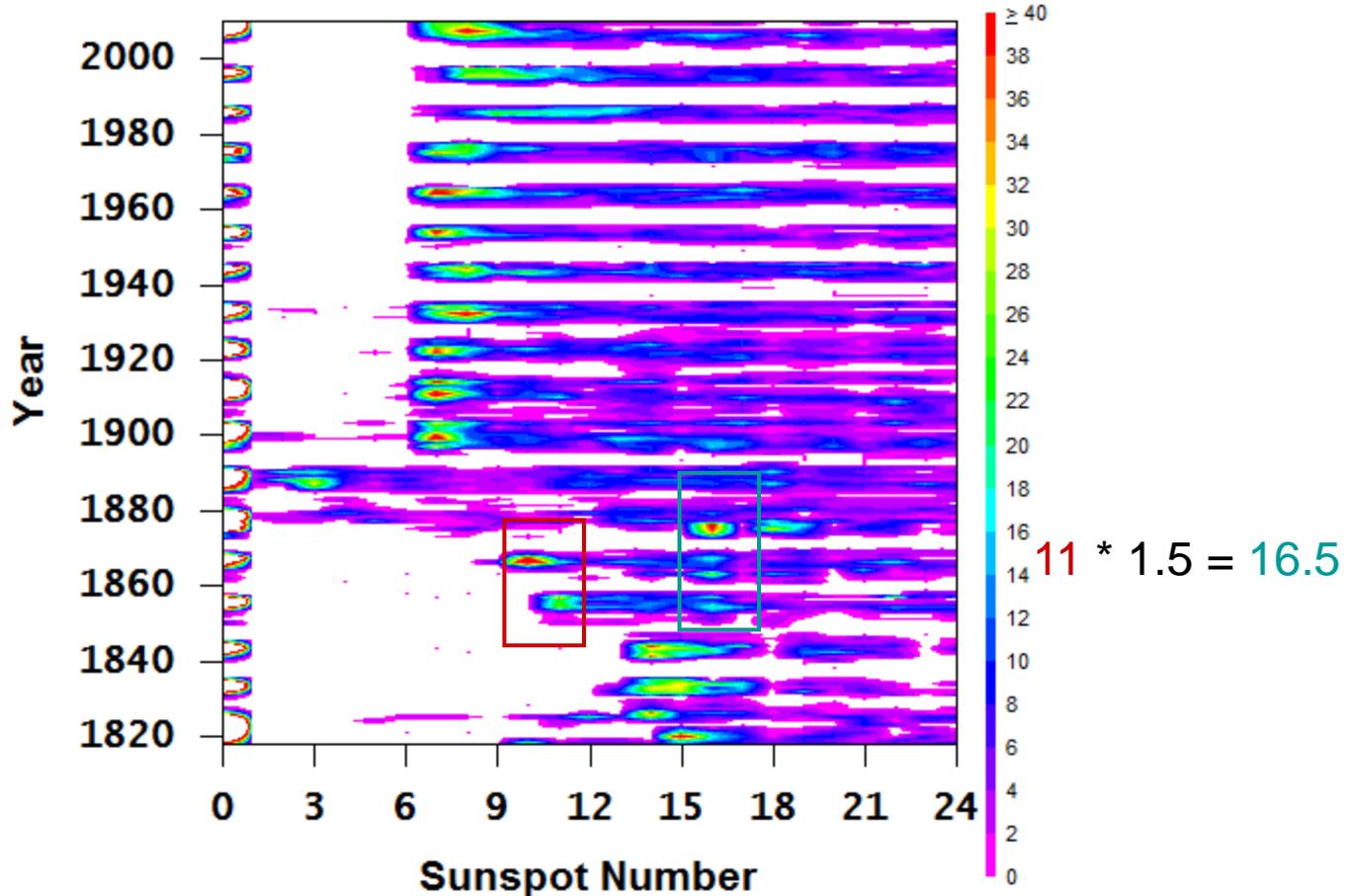
Alfred Wolfer became Wolf's Assistant in 1876 and Used a Different Counting Method

- Wolf did not [with the 80mm] count small spots and pores that could only be observed under good 'seeing'
- With the smaller Handheld Telescope this was really not an issue because those small spots could not been seen anyway
- Wolfer insisted on counting ALL the spots that could be seen as clearly black with the 80mm Standard Telescope [this has been adopted by all later observers]
- During 16 years of simultaneous observations with Wolf, it was determined that a factor of 0.6 could be applied to Wolfer's count to align them with Wolf's [actually to 1.5 times the 'Handheld' values]
- All subsequent observers have adopted that same 0.6 factor to stay on the original Wolf scale for 1849-~1860

This, too, can be seen in the Distribution of Daily Values

Distribution of Daily Values of the 'Official' Sunspot Number
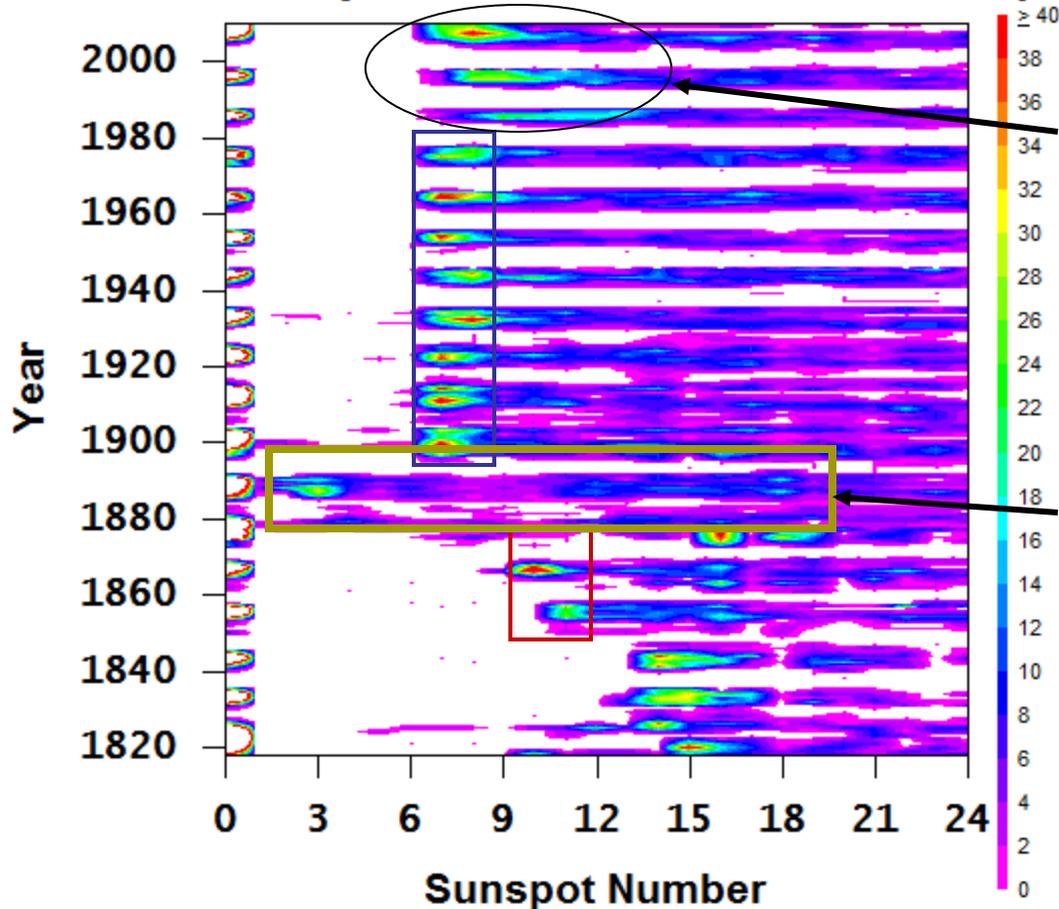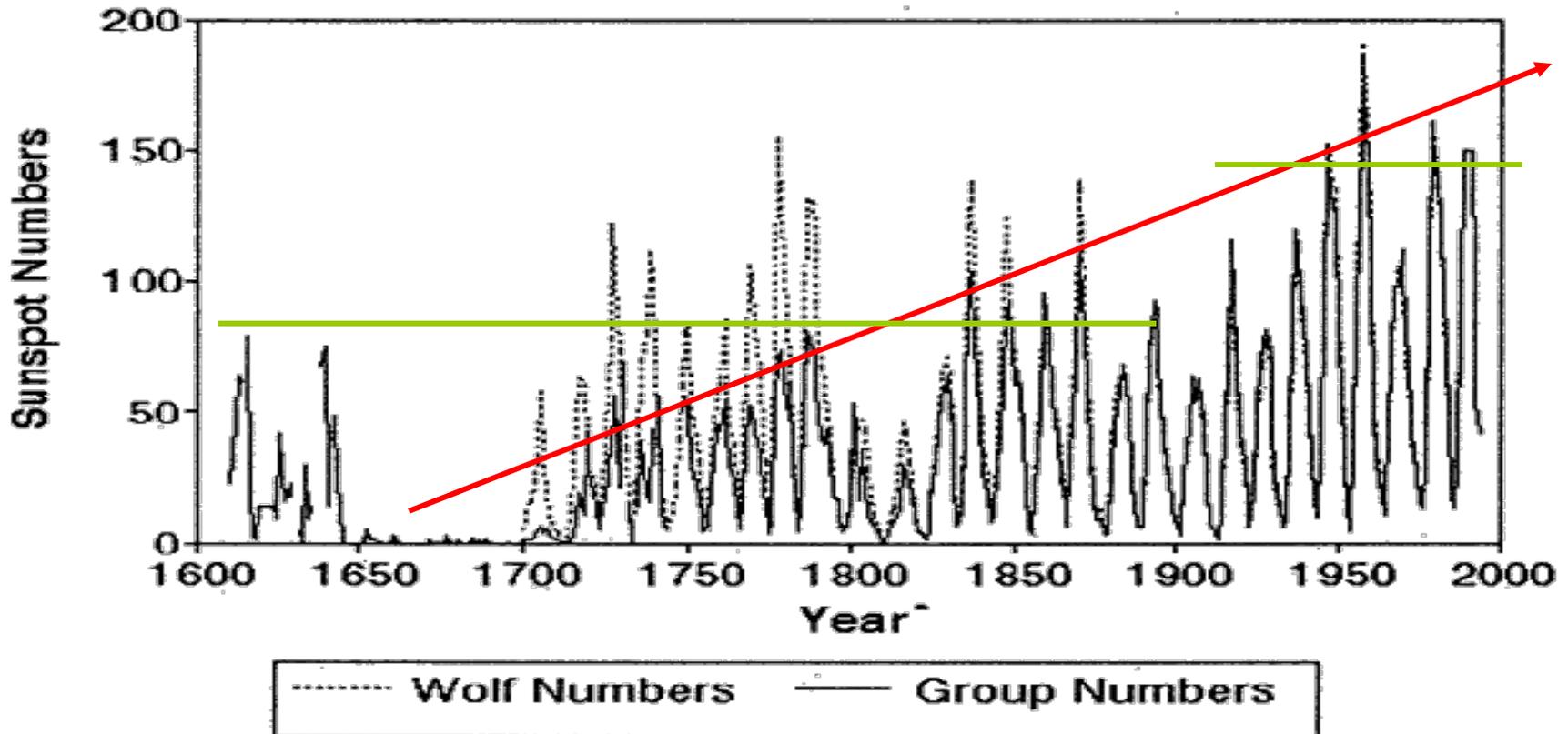

Another problem is with SIDC, but we shall not now discuss that here

11 * 0.60 = 7

This mess is caused by mixing the two counting methods

And Now, The Problem: Discordant Sunspot Numbers

Group and Wolf Sunspot Numbers

Hoyt & Schatten, GRL *21*, 1994

The Ratio Group/Zurich SSN has Two Significant Discontinuities
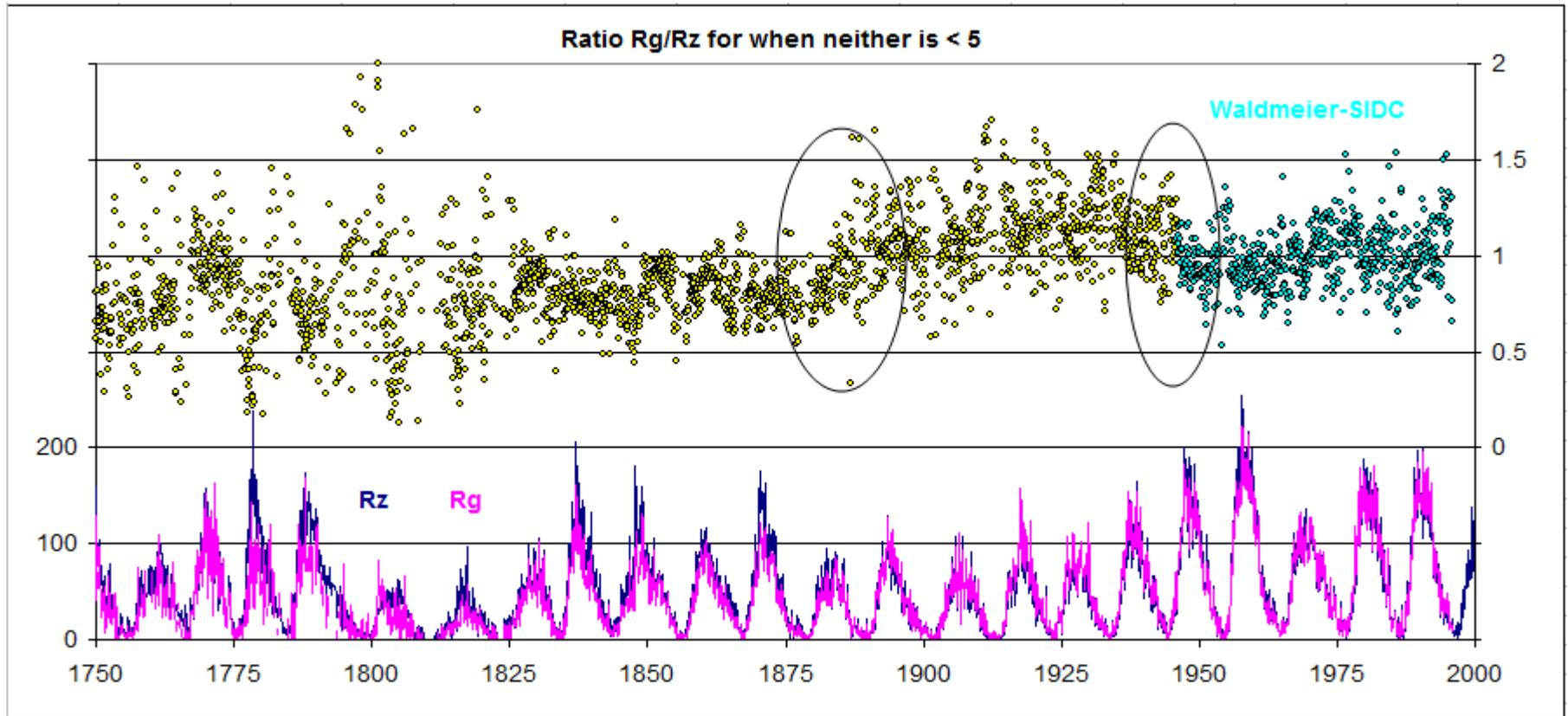
At ~1946 (After Max Waldmeier took over) and at ~1885

Removing the Recent one [+20%] by Multiplying Rz before 1946 by 1.20, Yields
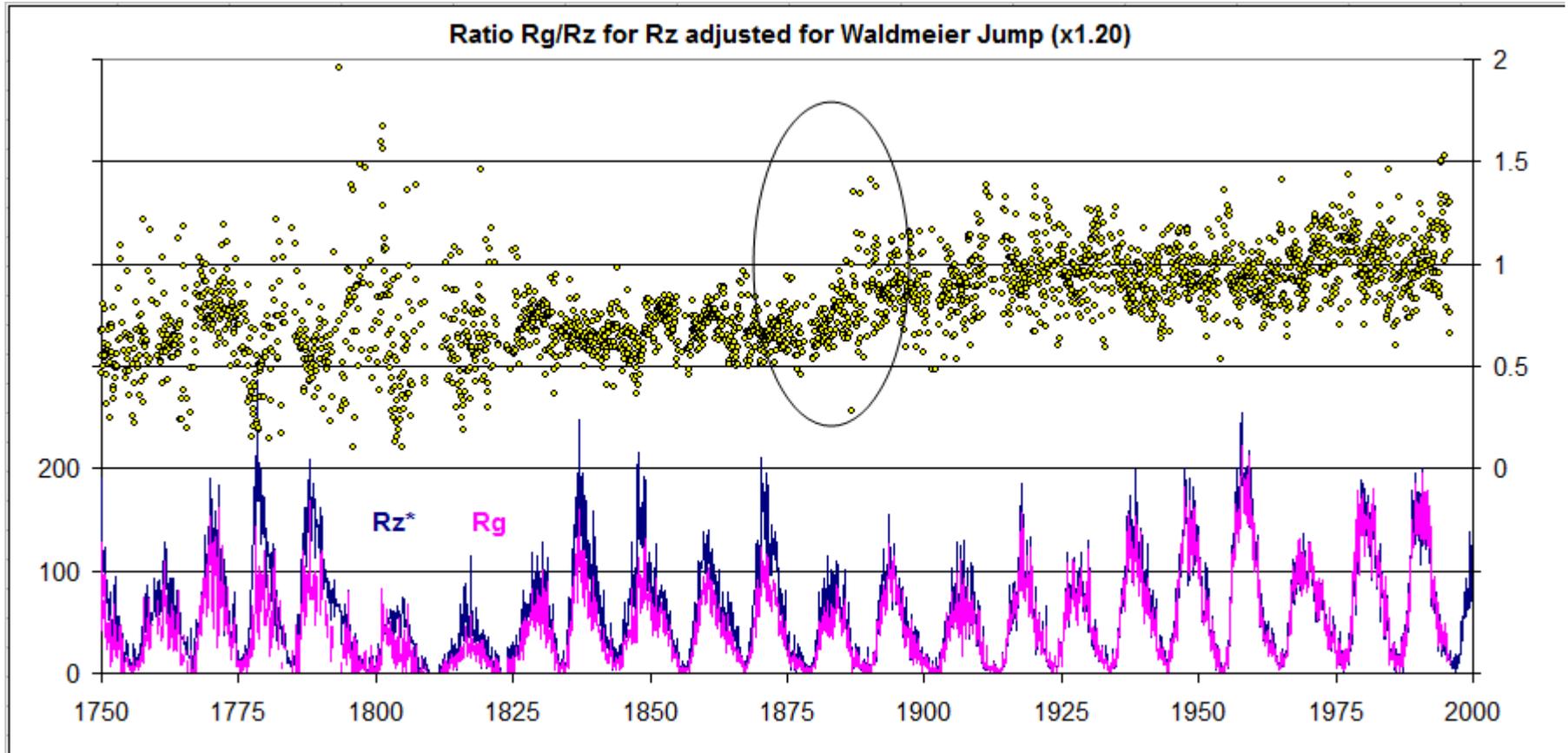
Leaving one significant discrepancy ~1885

Removing the Early one by multiplying Rg by 1.47, Yields
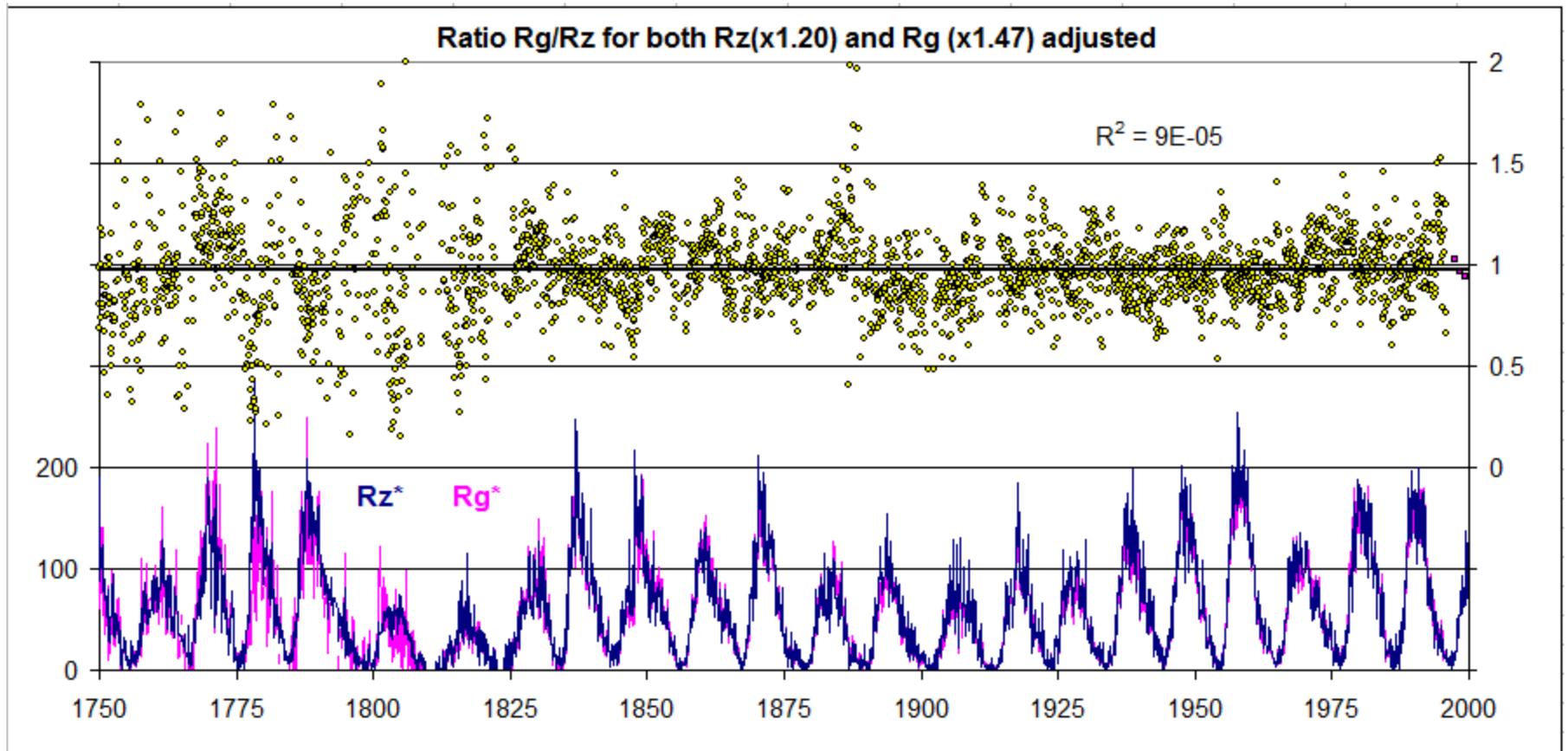
There is still some 'fine structure', but only TWO adjustments remove most of the disagreement

Detailed Comparison
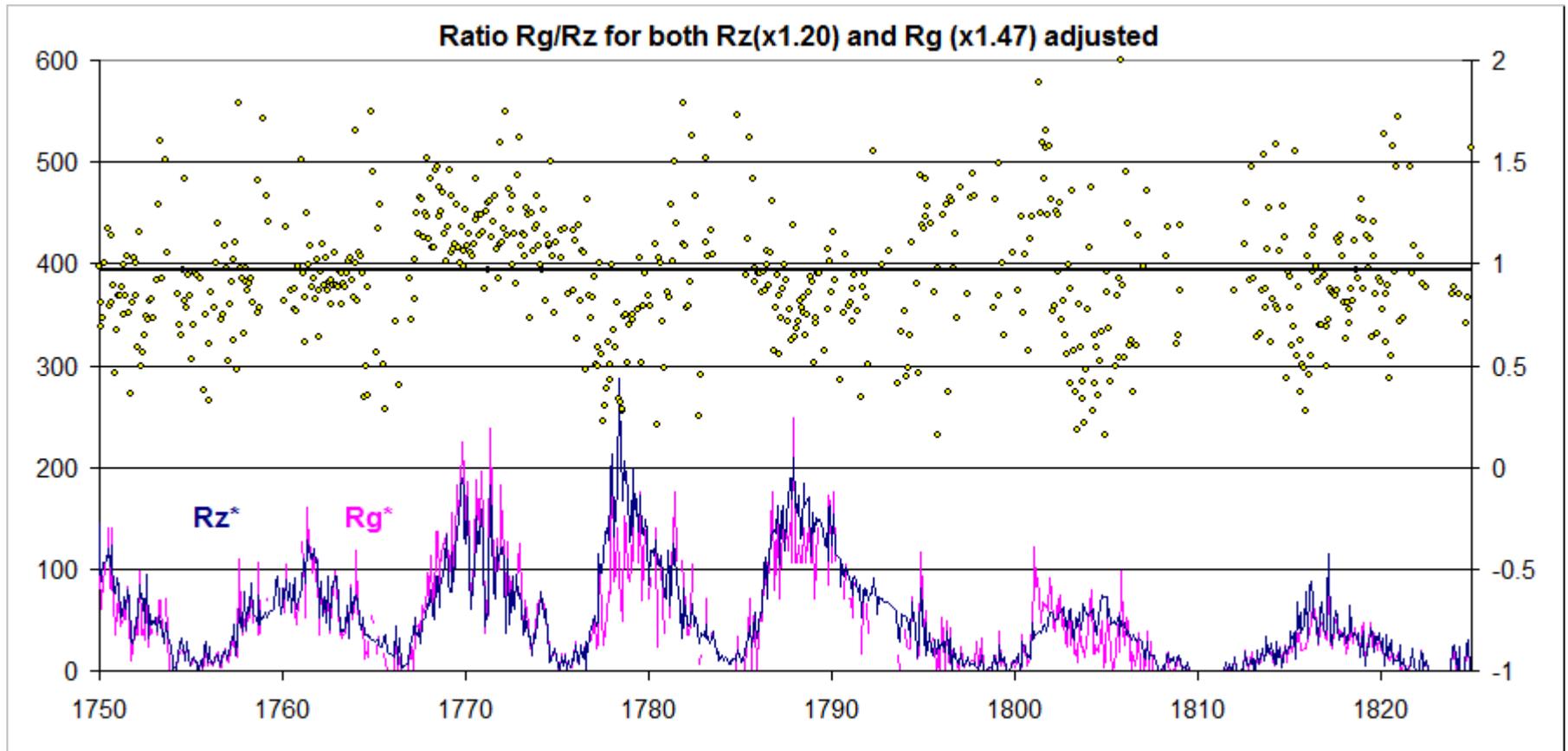
Understandable large scatter in the early data

Comparison Continued

Ratio Rg/Rz for both Rz(x1.20) and Rg (x1.47) adjusted

Comparison Continued
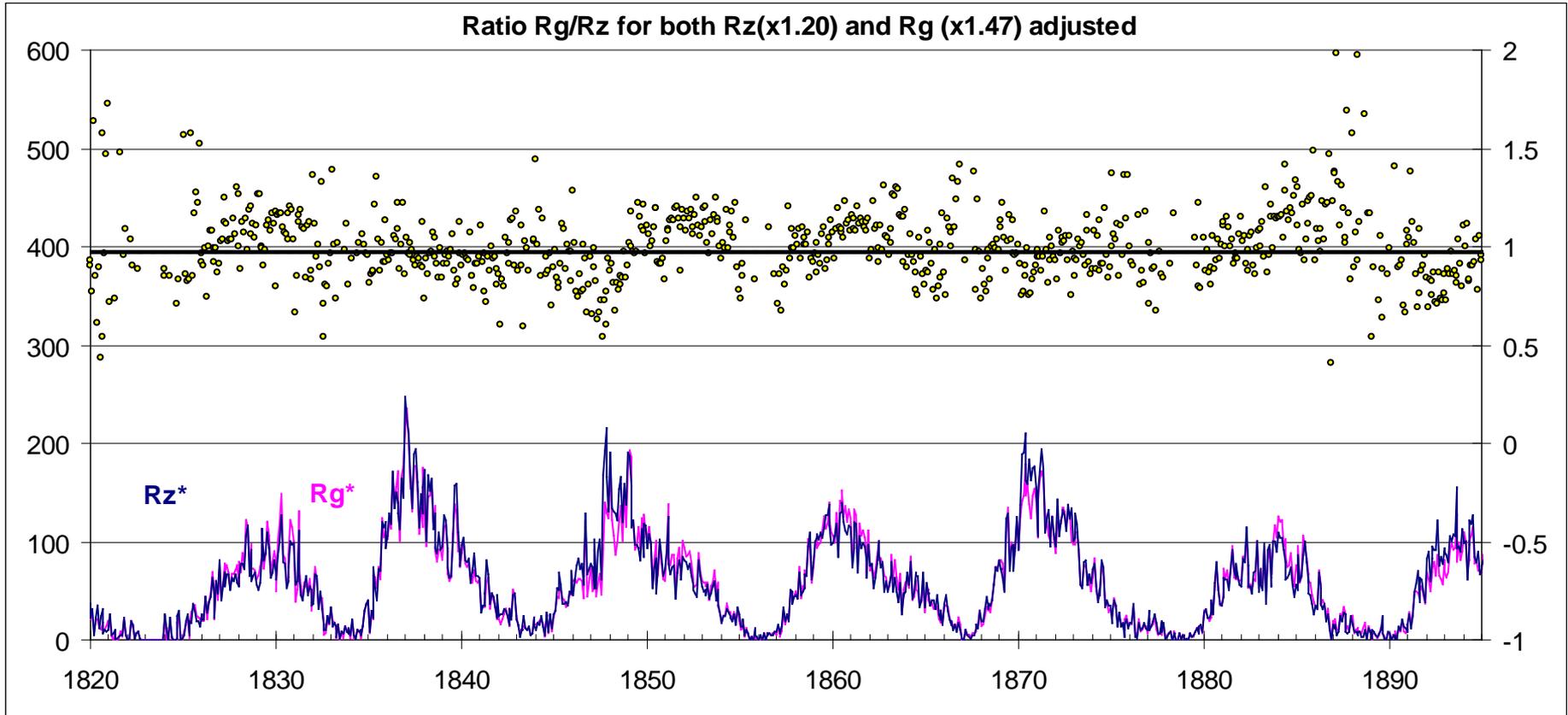
Ratio Rg/Rz for both Rz(x1.20) and Rg (x1.47) adjusted
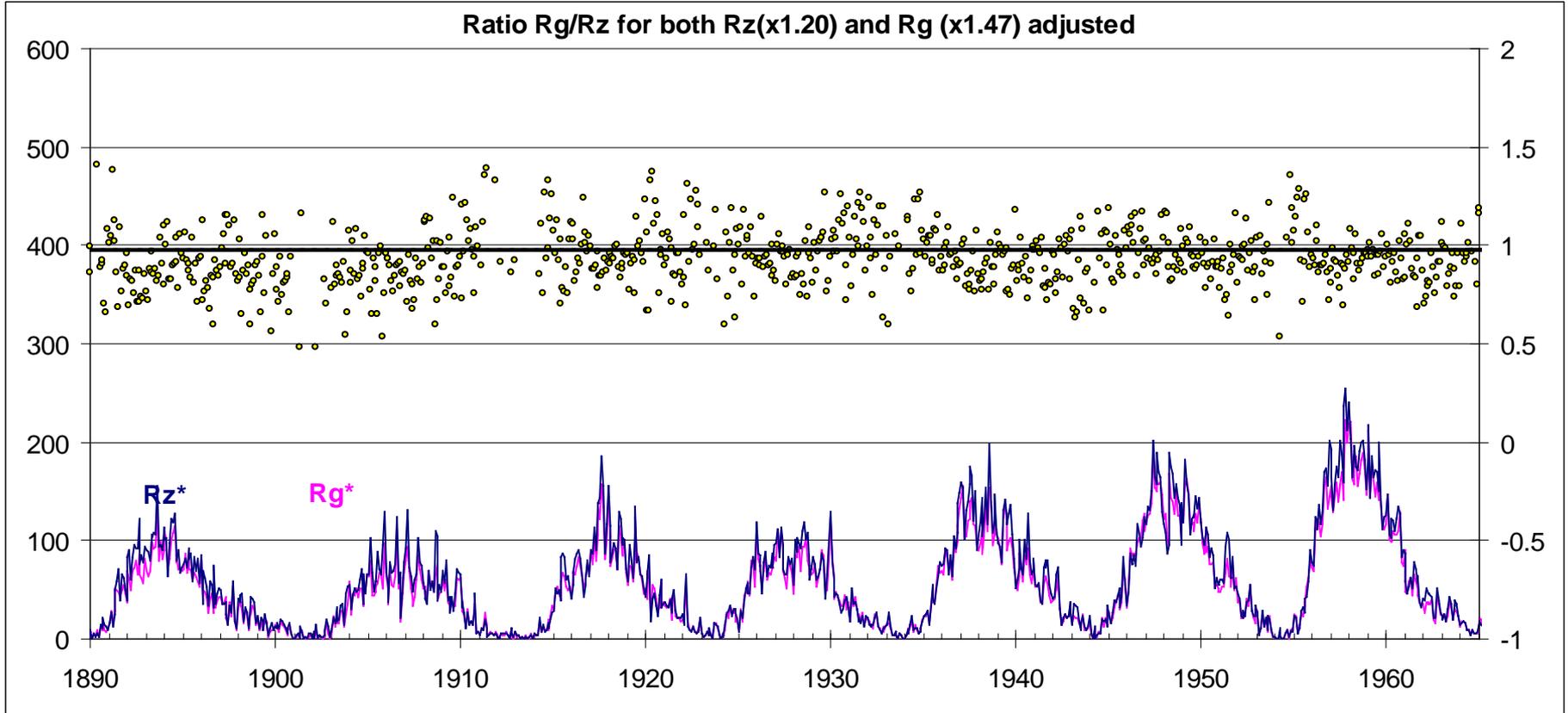
Comparison, Recent Times

Ratio Rg/Rz for both Rz(x1.20) and Rg (x1.47) adjusted
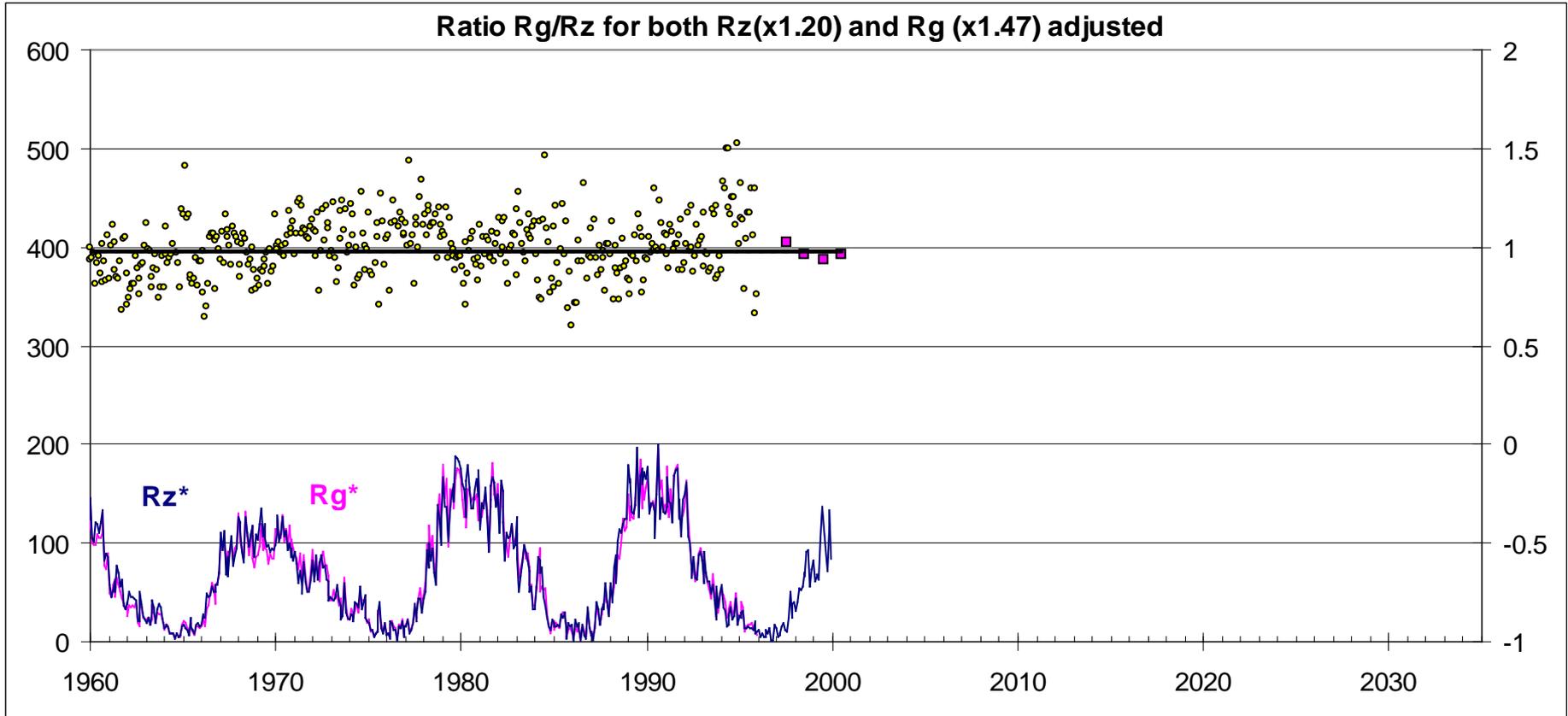
The Group SSN ends with 1996. Yearly values [pink squares] can be constructed from Hathaway's list of Active Regions [Yearly file sizes scale with number of regions]

Corroborating Indications of the 'Waldmeier Discontinuity' ~1946

- SSN for Given Sunspot Area increased 21%
- SSN for Given Ca II K-line index up 19%
- SSN for Given Diurnal Variation of Day-side Geomagnetic Field increased by 20%
- Ionospheric Critical Frequency *foF2* depends strongly on solar activity. The slope of the correlation changed 20% between sunspot cycle 17 and 18

Sunspot Areas vs. Rz

$RZ/SA^{0.732}$ (projected)

>1000 uH

Monthly Means

0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0

Wolfer   Brunner   Waldmeier   SIDC

1870 1880 1890 1900 1910 1920 1930 1940 1950 1960 1970 1980 1990 2000
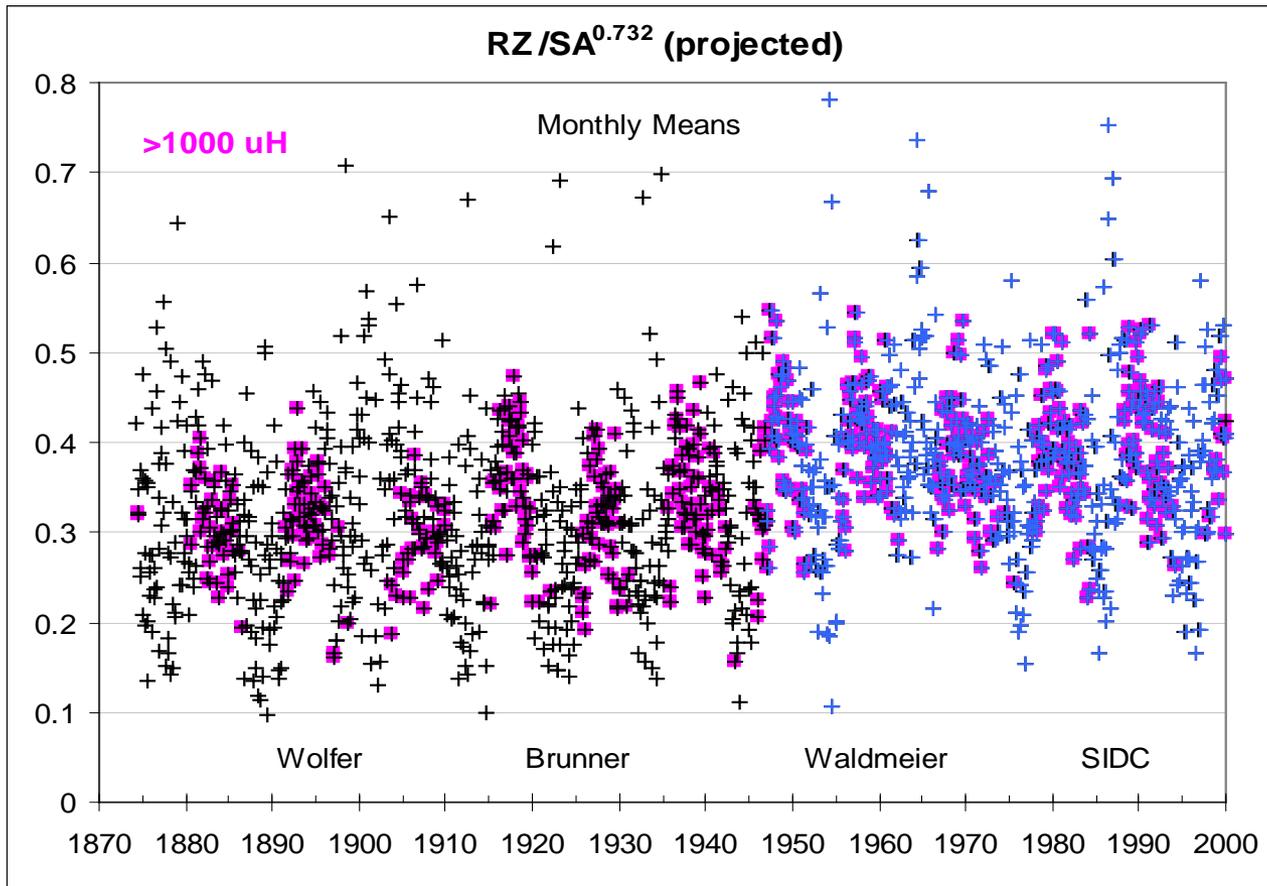
The relationship between sunspot number and sunspot area [SA, Balmaceda] is not linear, but can be made linear raising SA to the power of 0.732. Then taking the ratio makes sense.

Pink squares show the ratios for SA exceeding 1000 micro-hemispheres

Clear change in the relationship around 1945

Quantifying the Waldmeier 'Jump'

Histogram Ratios

1874-1944 **0.3244**

1945-2000 **0.3921**

Waldmeier Jump

0.3921/0.3244 = **1.212**

Plotting Histograms of the ratio $Rz/SA^{0.732}$
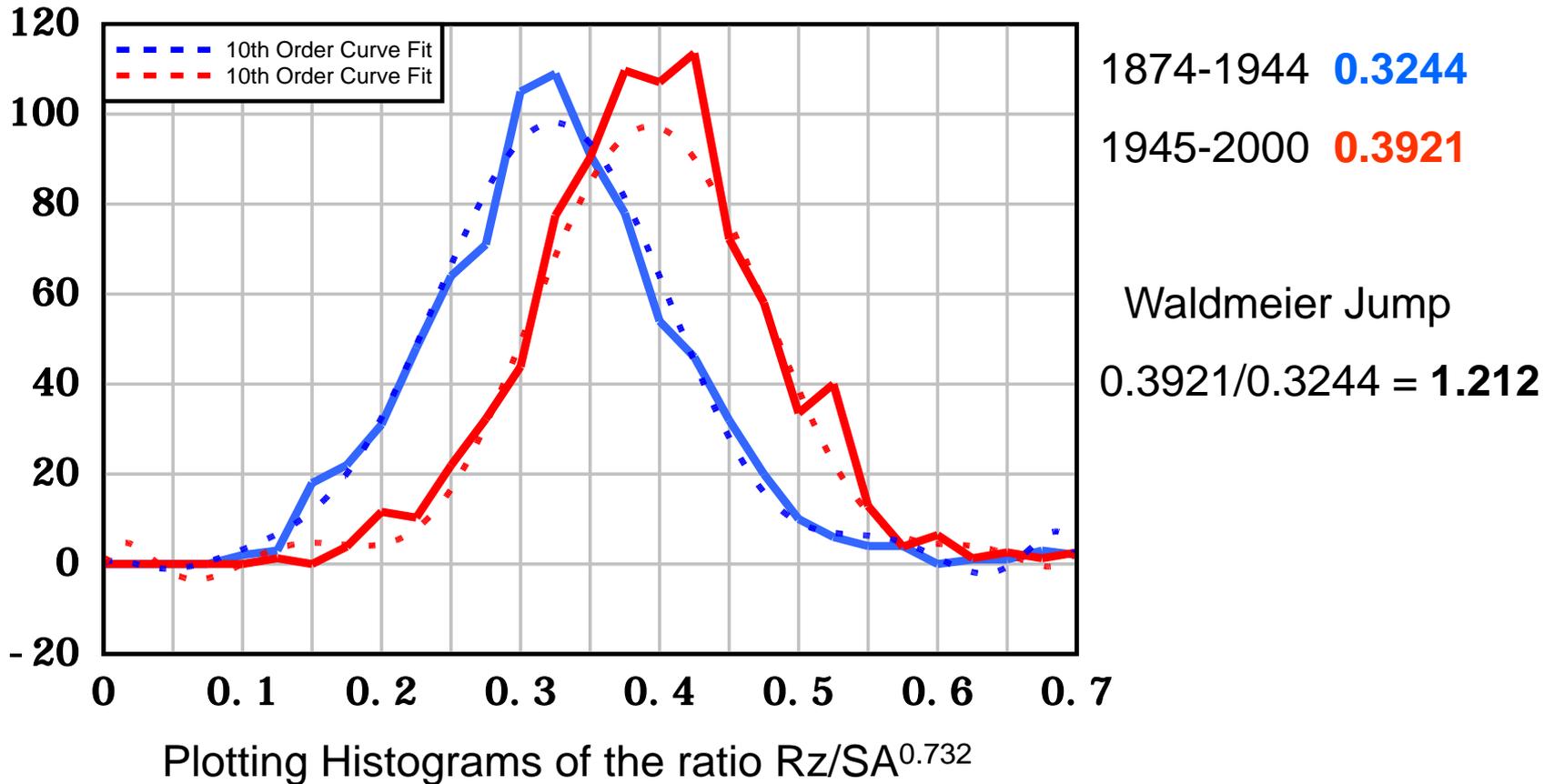
Illustrating that Observed Rz after 1945 is Higher than Deduced from Sunspot Areas

Comparison Zurich Sunspot Number and That Derived from Sunspot Areas

Rz

$Rc = 0.3244 * SA^{0.732}$

Monthly Means

Waldmeier Jump = x**1.21**
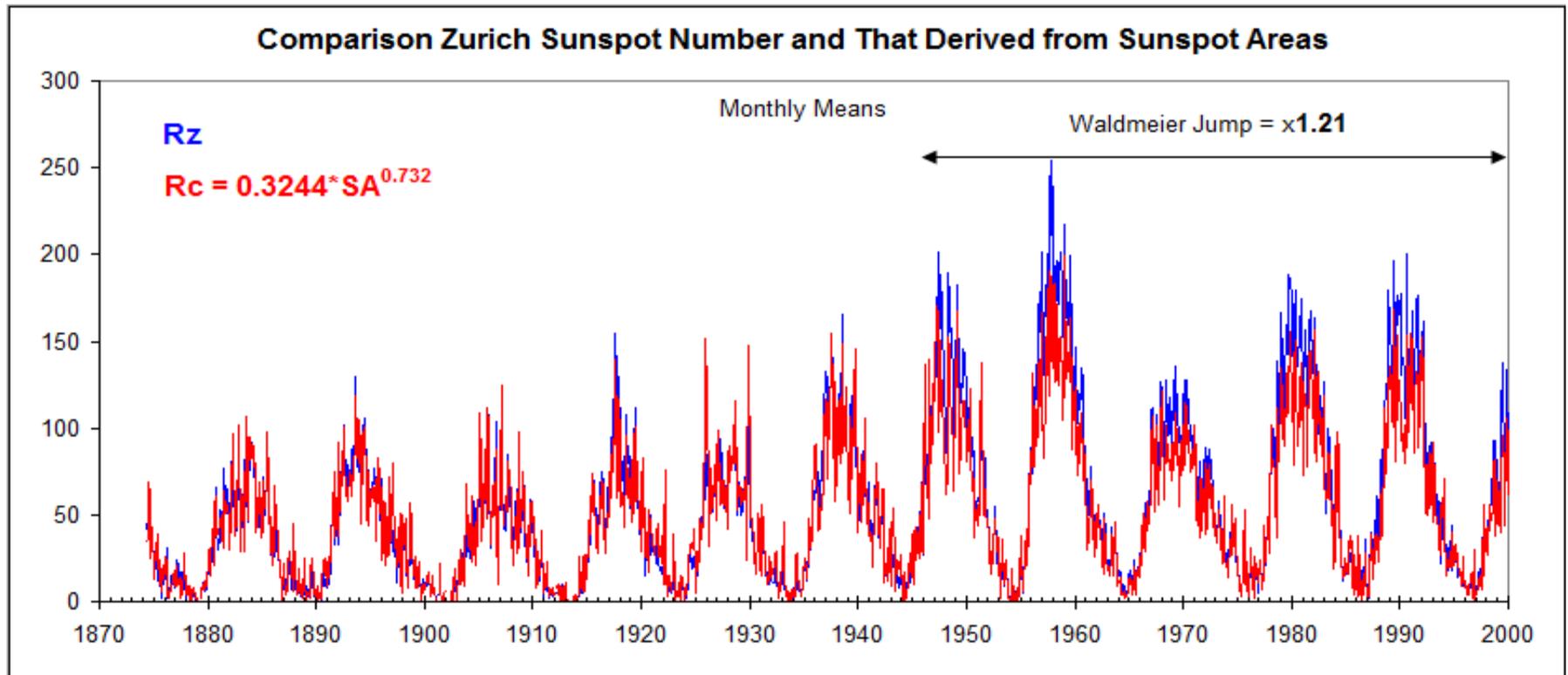
Ca II K-line Data Scaled to Rz shows similar Jump in Rz Sunspot Number after 1945

From ~40,000 CaK spectroheliograms from the 60-foot tower at Mount Wilson between 1915 and 1985, a daily index of the fractional area of the visible solar disk occupied by plages and active network has been constructed [Bertello et al., 2008]. Monthly averages of this index is strongly correlated with the sunspot number SSN = 27235 CaK – 67.14 [before 1946].

Comparison Zurich Sunspot Number and Ca II K-line Index from Mt. Wilson Solar Observatory

Monthly Averages

$Rc = 27235 \, Ca_{II} - 67.14$

Rz

Rz/Rc = 1.00

Rz/Rc = 1.19
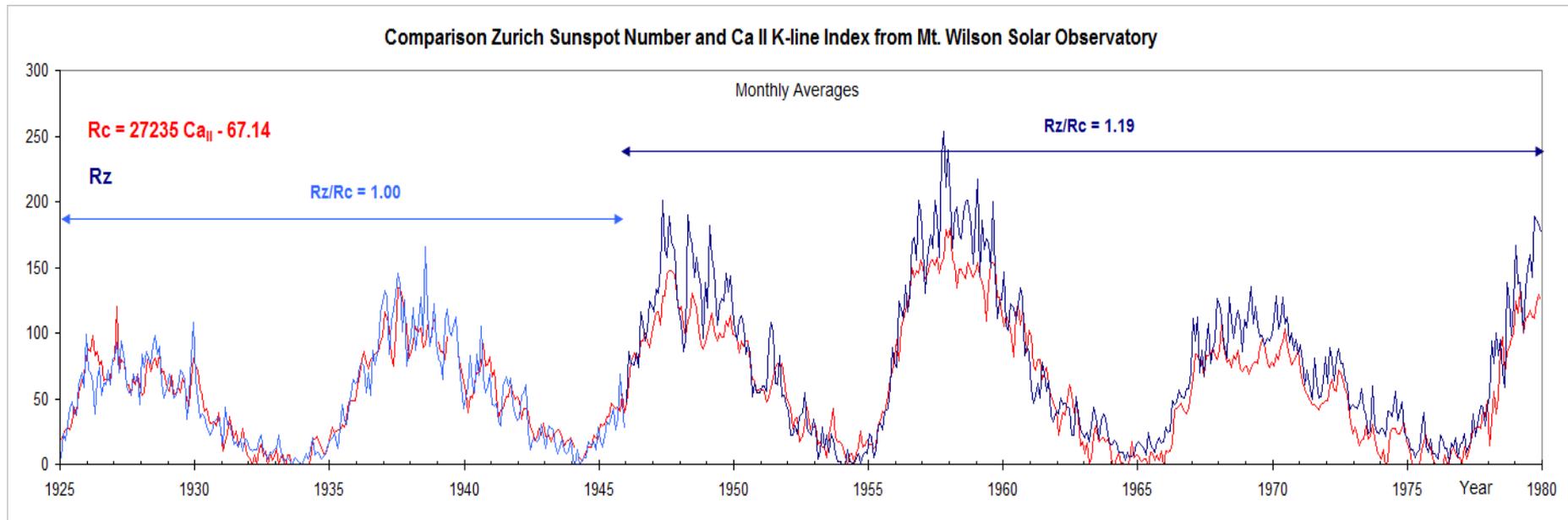
Waldmeier's Sunspot Number 19% higher than Brunner's from Ca II K-line

This is clearly visible in Daily Values without any analysis
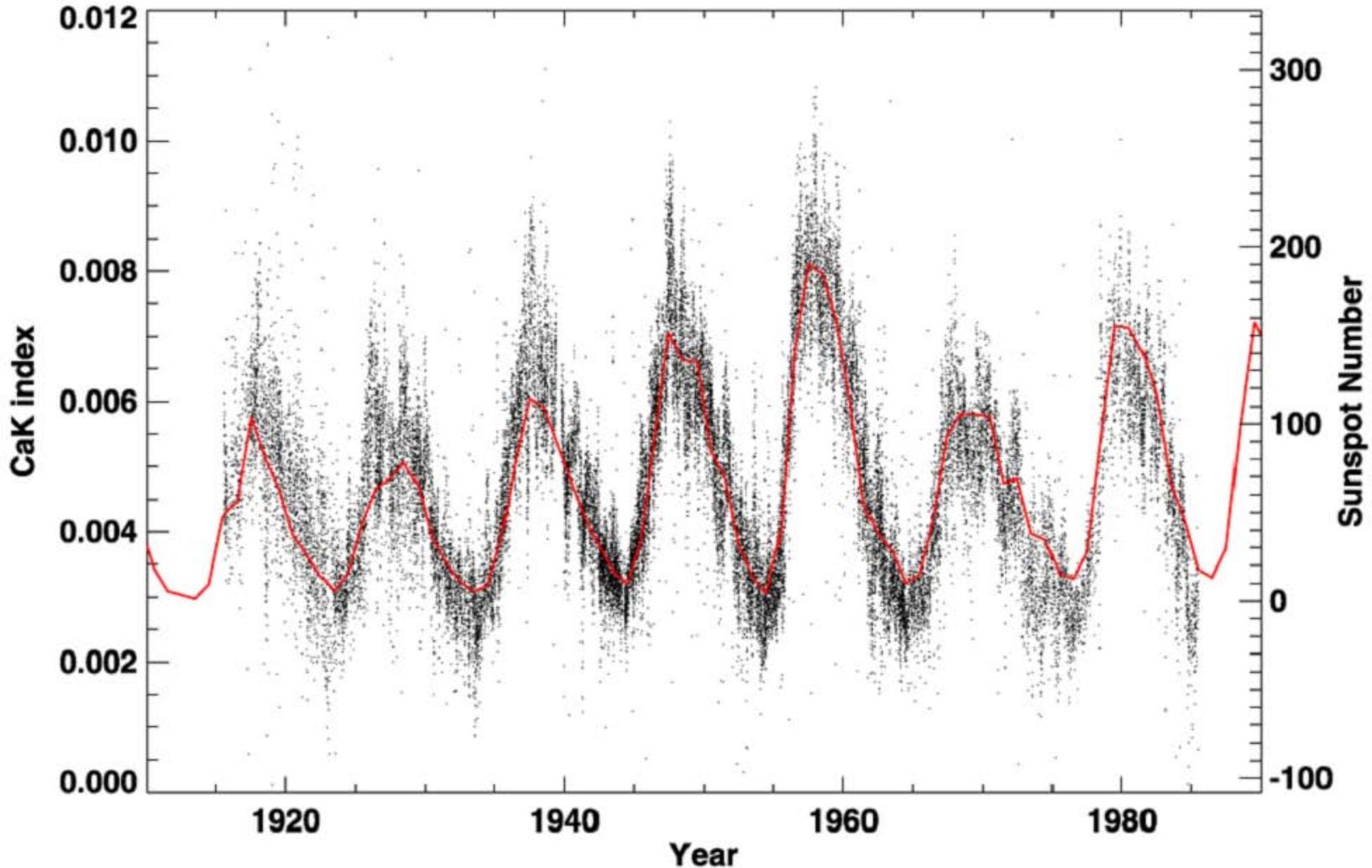
The Amplitude of the Diurnal Variation, *rY*, [from many stations] shows the same Change in Rz ~1945

Yearly S_R normalized to NGK

rY (nT)

Median of
CLH,FRD;HON;KAK;VQS,SJG;DBN,WIT;PSM,VLJ,CLF;ABN,HAD;ESK;NUR;TOO;FUR;POT;SED,NGK;DOB;BTV,WAT

Rz
$Rc = 5.53 (rY - 32.78)$; based on Brunner

Based on 20 yr of Waldmeier, the coefficient is 6.66

$6.66/5.53 = \mathbf{1.20}$
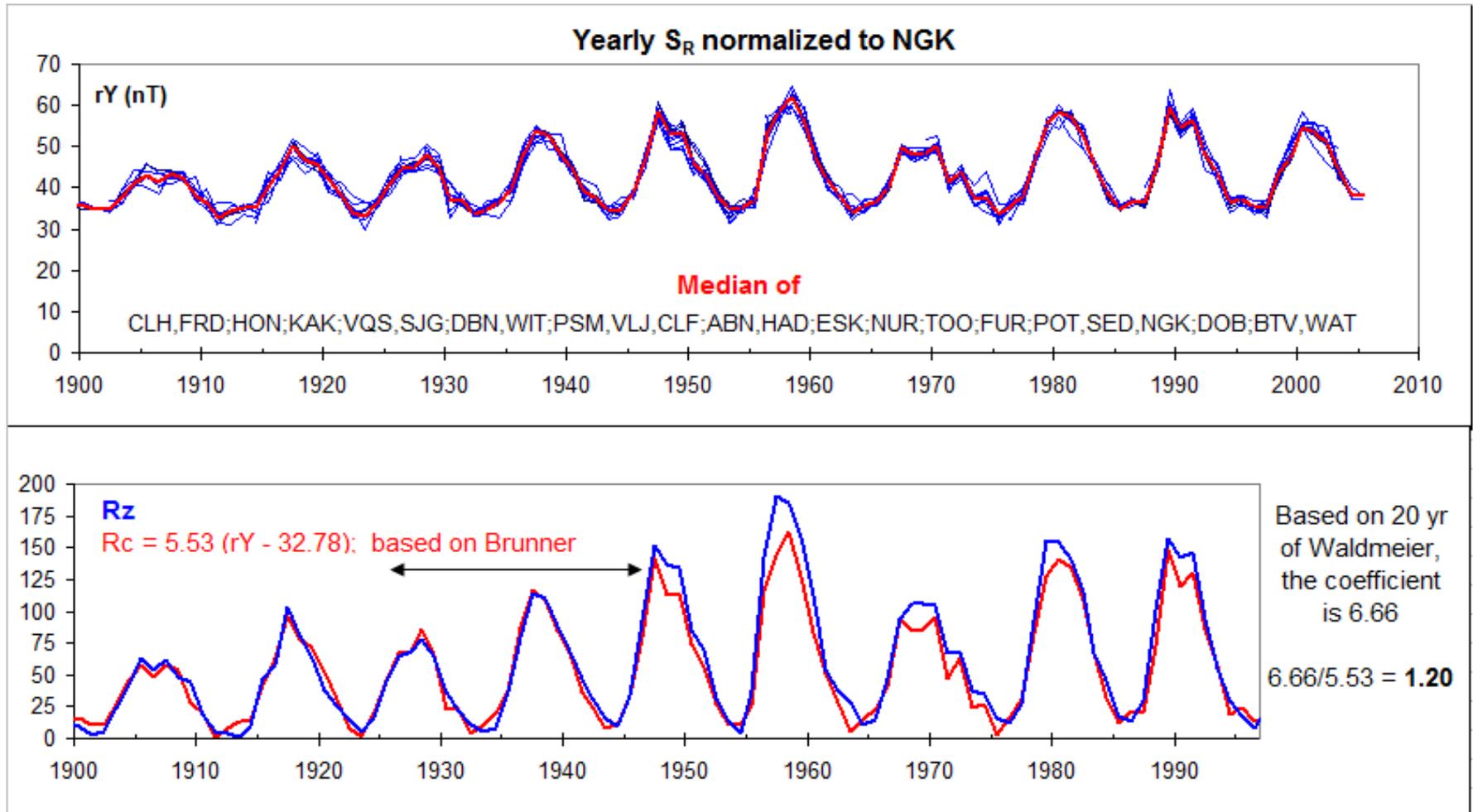
At some point during the 1940s the Zürich observers began to weight sunspots in their count

Weights [from 1 to 5] were assigned according to the size of a spot. Here is an example where the three spots present were counted as 9, inflating the sunspot number by 18% [(3*10+9)/(3*10+3)=1.18]

Waldmeier claimed that the weighting scheme dates from 1882. We can show that Wolfer did not apply it.
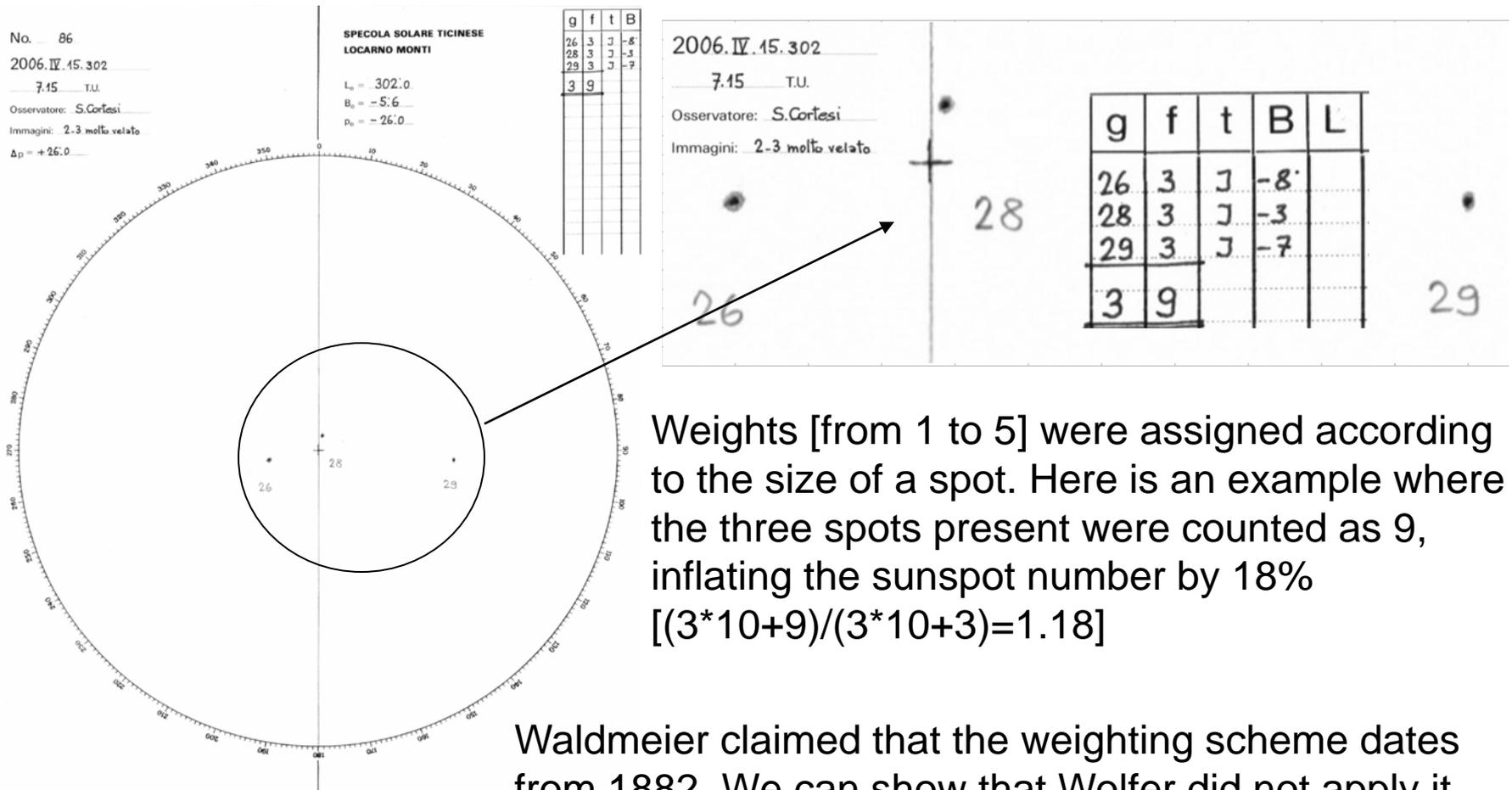
Plausible Explanation of the ~1945 'Waldmeier' Discontinuity:

How many groups?
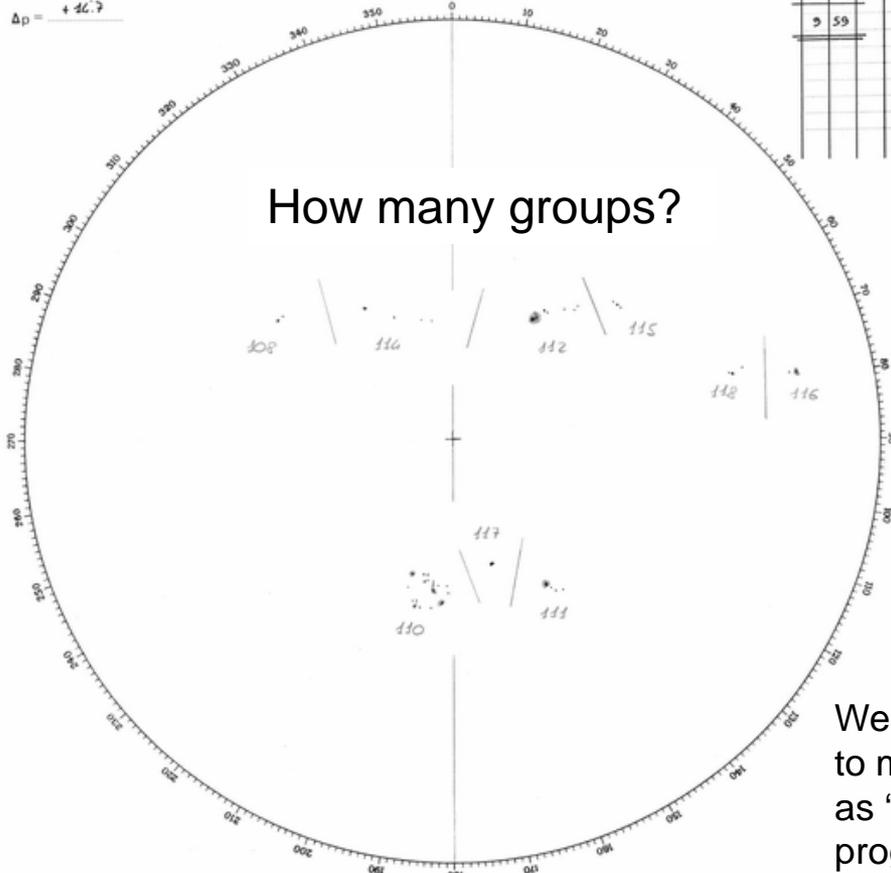
The weighting scheme (14%), possibly combined with a 'better' determination of what makes a 'Group' due to Waldmeier's new Active Region Classification (6%)

We elected to increase the earlier Rz values in order to maintain the modern values to make the adjustment as 'painless' as possible (some operational computer programs use current Rz as input!)

34

What Do the Observers at Locarno Say About the Weighting Scheme:

Sergio Cortesi started in 1957, still at it, and in a sense is the *real* keeper of the SSN, as SIDC normalizes everybody's count to match Sergio's

"What you show in your presentation is convincing! For sure the main goal of the former directors of the observatory in Zurich was to maintain the coherence and stability of the Wolf number, and changes in the method were not done just as fun. I can figure out that they gave a lot of importance to verify their method of counting. Nevertheless the decision to maintain as "secret" the true way to count is for sure source of problems now!"

(email 6-22-2011 from Michele Bianda, IRSOL, Locarno)

Karl Rapp

The Early ~1885 Discrepancy

- Since the sunspot number has an arbitrary scale, it makes no difference for the calibration if we assume Rg to be too 'low' before ~1885 or Rz to be too 'high' after 1885

Ratio Rg/Rz for both Rz(x1.20) and Rg (x1.47) adjusted

$R^2 = 9E-05$
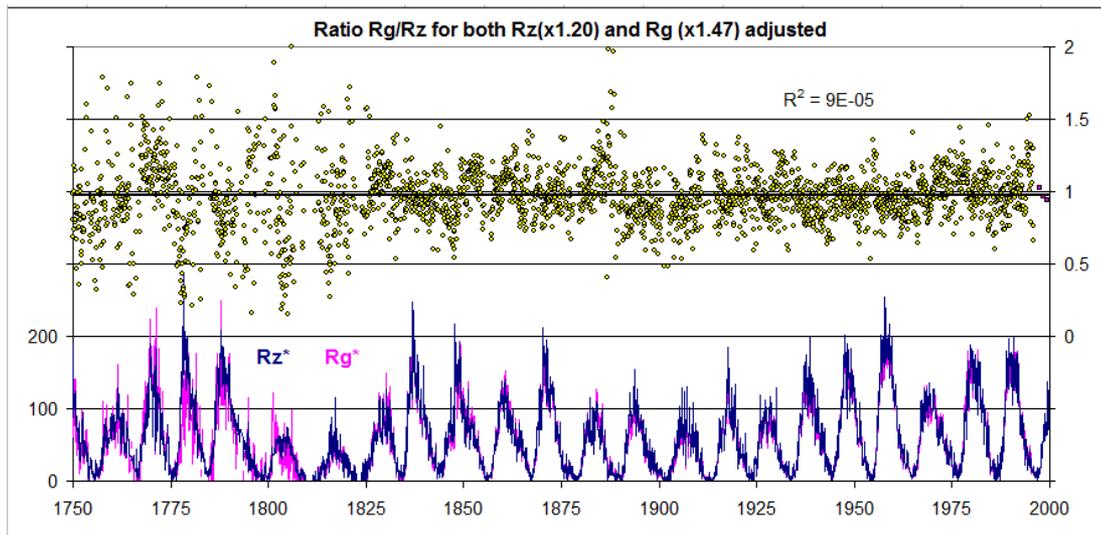
By applying Wolf's relationship between Rz and the diurnal variation of the Declination we can show that it is Rg that is too low

Comparing Diurnal Ranges

- A vast amount of hourly [or fixed-hours] measurements from the mid-19th century exists, but is not yet digitized

- We often have to do with second-hand accounts of the data, e.g. the monthly or yearly averages as given by Wolf, so it is difficult to judge quality and stability

- Just measuring the daily range [e.g. as given by Ellis for Greenwich] is not sufficient as it mixes the regular day-side variation in with night-time solar wind generated disturbances

Adolf Schmidt's (1909) Analysis

Schmidt collected raw hourly observations and computed the first four Fourier components [to 3-hr resolution] of the observed Declination in his ambitious attempt to present what was then known in an 'einheitlicher Darstellung' [uniform description]

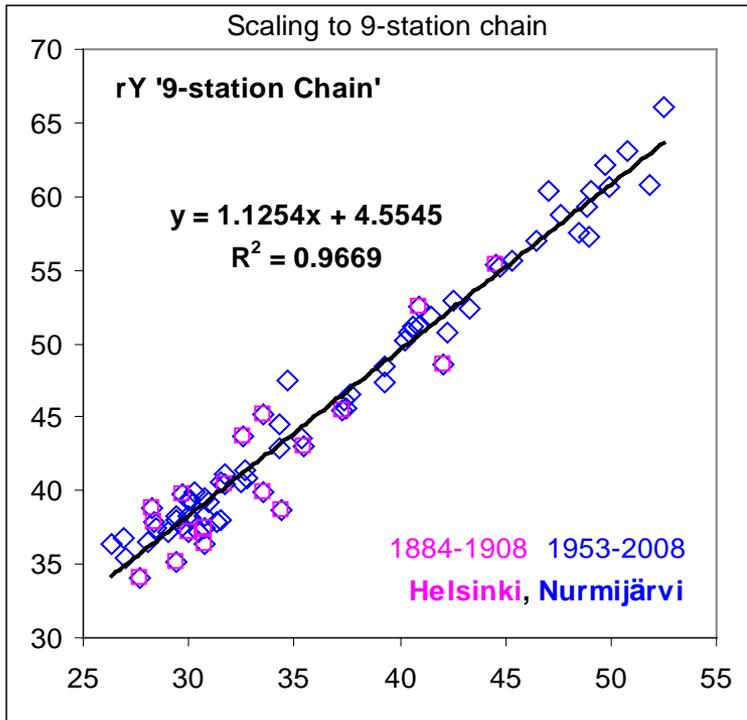| Observatory	Years	Lat	Long
Washington DC	1840-1842	38.9	282.0
Dublin	1840-1843	53.4	353.7
Philadelphia	1840-1845	40.0	284.8
Praha	1840-1849	50.1	14.4
Muenschen	1841-1842	48.2	11.6
St. Petersburg	1841-1845	60.0	30.3
Greenwich	1841-1847	51.5	0.0
Hobarton	1841-1848	-42.9	147.5
Toronto	1842-1848	43.7	280.6
Makerstoun	1843-1846	55.6	357.5
Greenwich	1883-1889	51.4	0.0
P. Saint-Maur	1883-1899	48.8	0.2
Potsdam	1890-1899	52.4	13.1
København	1892-1898	55.7	12.6
Utrecht	1893-1898	52.1	5.1
Odessa	1897-1897	46.4	30.8
Tokyo	1897-1897	35.7	139.8
Bucarest	1899-1899	44.4	26.1
Irkutsk	1899-1899	52.3	194.3
Zi-ka-wei	1899-1899	31.2	121.2

Potsdam 1890-1899
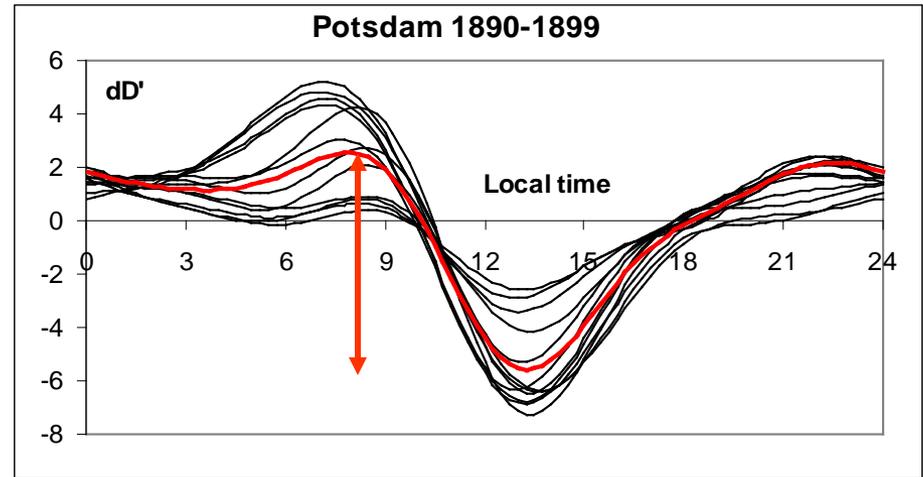
Engelenburg and Schmidt calculated the average variation over the interval for each month and determined the amplitude and phase for each month. From this we can reconstruct the diurnal variation and the yearly average amplitude, dD [red curve].
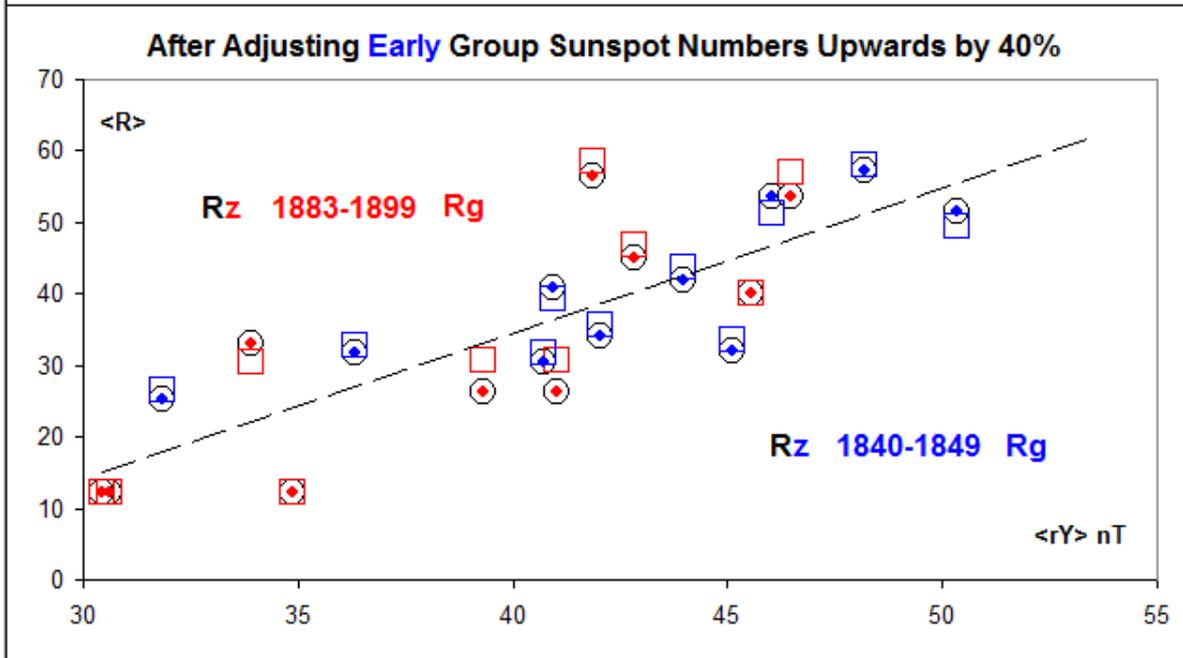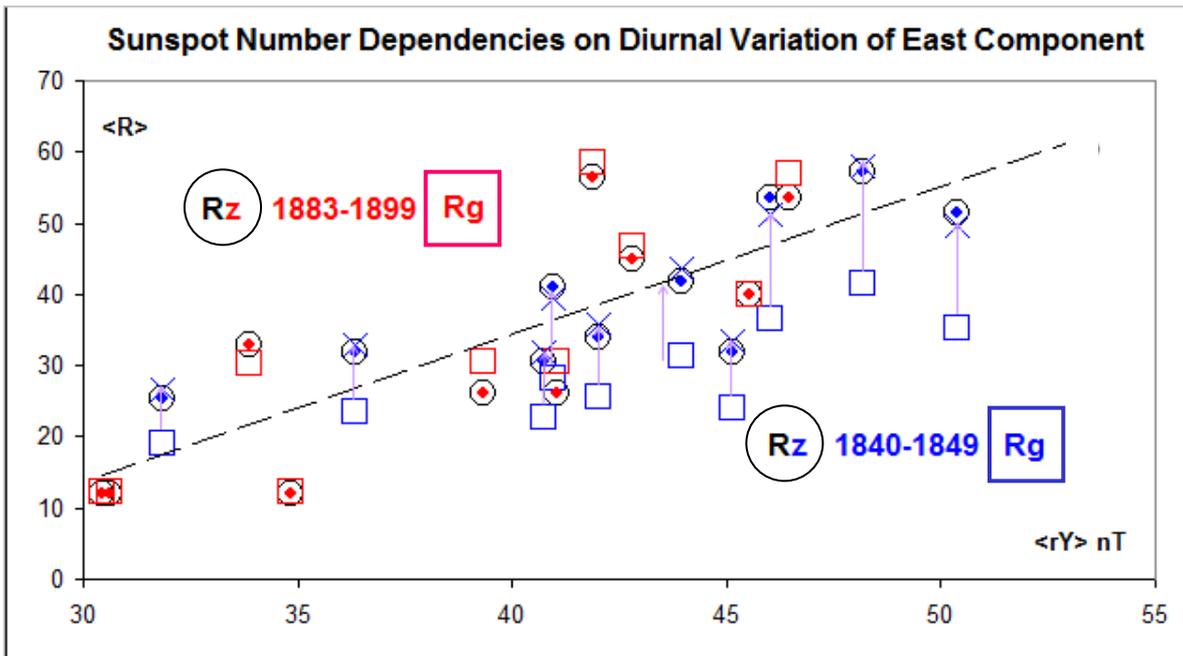
Procedure:
For each station we now compute the averages over the interval of <Rz>, <Rg>, and of the diurnal range [converted to force units, nT, from arc minutes] and plot <Rz> against the range <rY> (calculated from dD) as the black circles with a color dot at the center. The color is blue for the early interval and red for the later interval.

The Group Sunspot Numbers <Rg> is plotted as blue and red squares. It is clear that <Rg>s for the early interval fall significantly and systematically below corresponding <Rz>s. Increasing the early <Rg>s by 40% [the arrows to the blue crosses] brings them into line with <Rz> before Waldmeier.

39

Helsinki-Nurmijärvi Diurnal Variation

Scaling to 9-station chain

rY '9-station Chain'

$y = 1.1254x + 4.5545$

$R^2 = 0.9669$

1884-1908   1953-2008

Helsinki, **Nurmijärvi**

Helsinki and its replacement station Numijärvi scales the same way towards our composite of nine long-running observatories and can therefore be used to check the calibration of the sunspot number (or more correctly to reconstruct the F10.7 radio flux – see next slide)

HLS

NUR
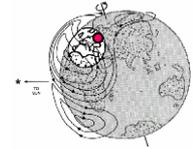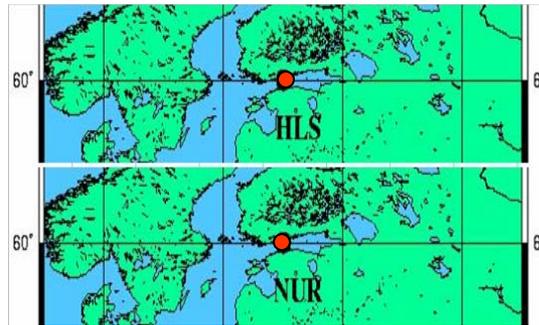
Range of Diurnal Variation of East Component

rY nT

9-station Chain

Helsinki

Nurmijärvi

40
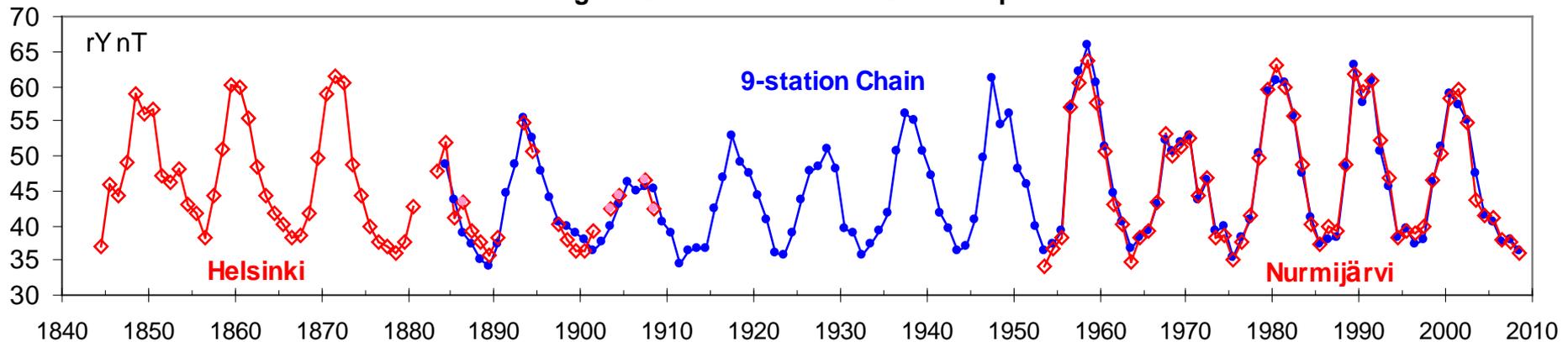
The Diurnal Range *rY* is a very good proxy for the Solar Flux at 10.7 cm

Relationship F10.7 and Diurnal Range rY

1947-2005

$y = 5.9839x - 129.25$
$R^2 = 0.9736$
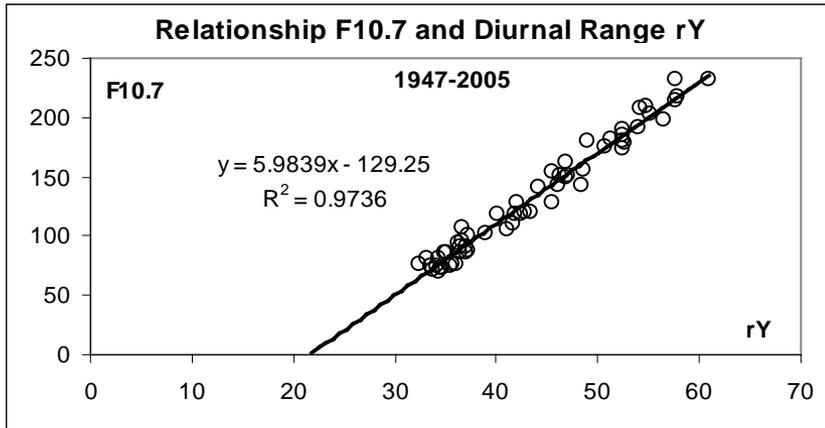
Which itself is a good proxy for solar Ultraviolet radiation and solar activity in general [what the sunspot number is trying to capture].

Comparison Observed and Calculated F10.7

F10.7 obs.

F10.7 calc from rY
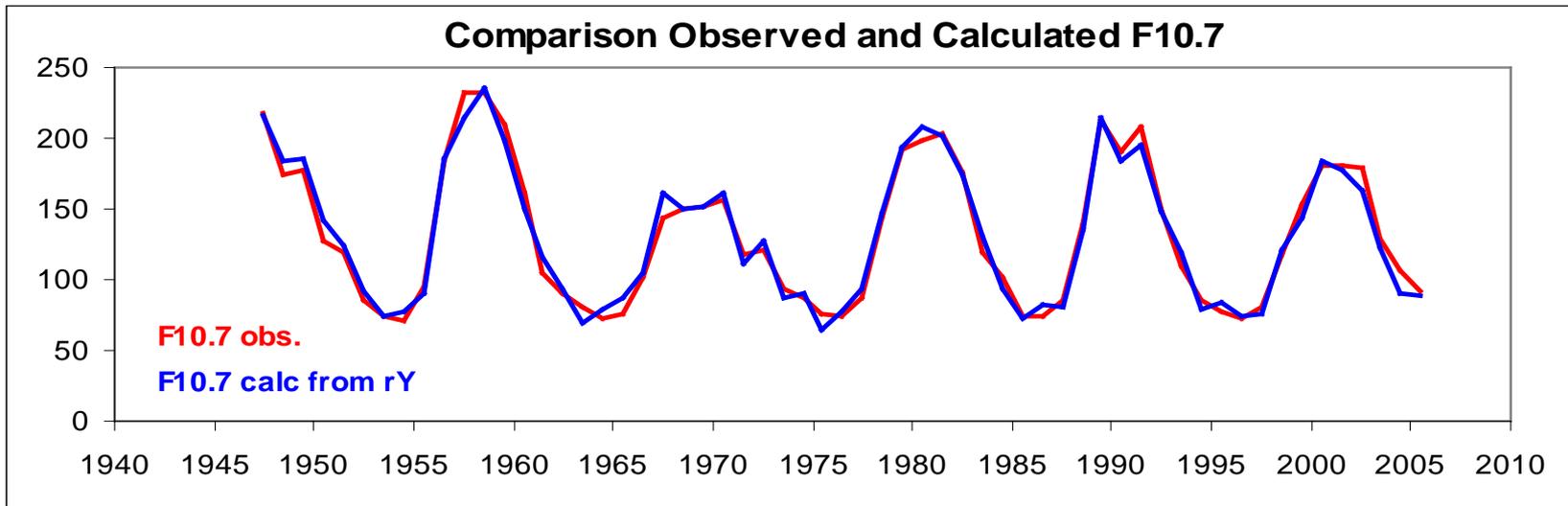
The HLS-NUR data show that the Group Sunspot Number before 1880 must be Increased by a factor 1.64±0.15 to match rY (F10.7)

Group Sunspot Number as a Function of Diurnal Range of East Component

Yearly means determined from HLS and NUR

$Rg = 5.552(rY - 34.7)$
$R^2 = 0.928$
1883-2008

x1.64

$Rg = 5.589(rY - 34.8)$
$Rg = 3.408(rY - 34.8)$
$R^2 = 0.896$
1844-1880
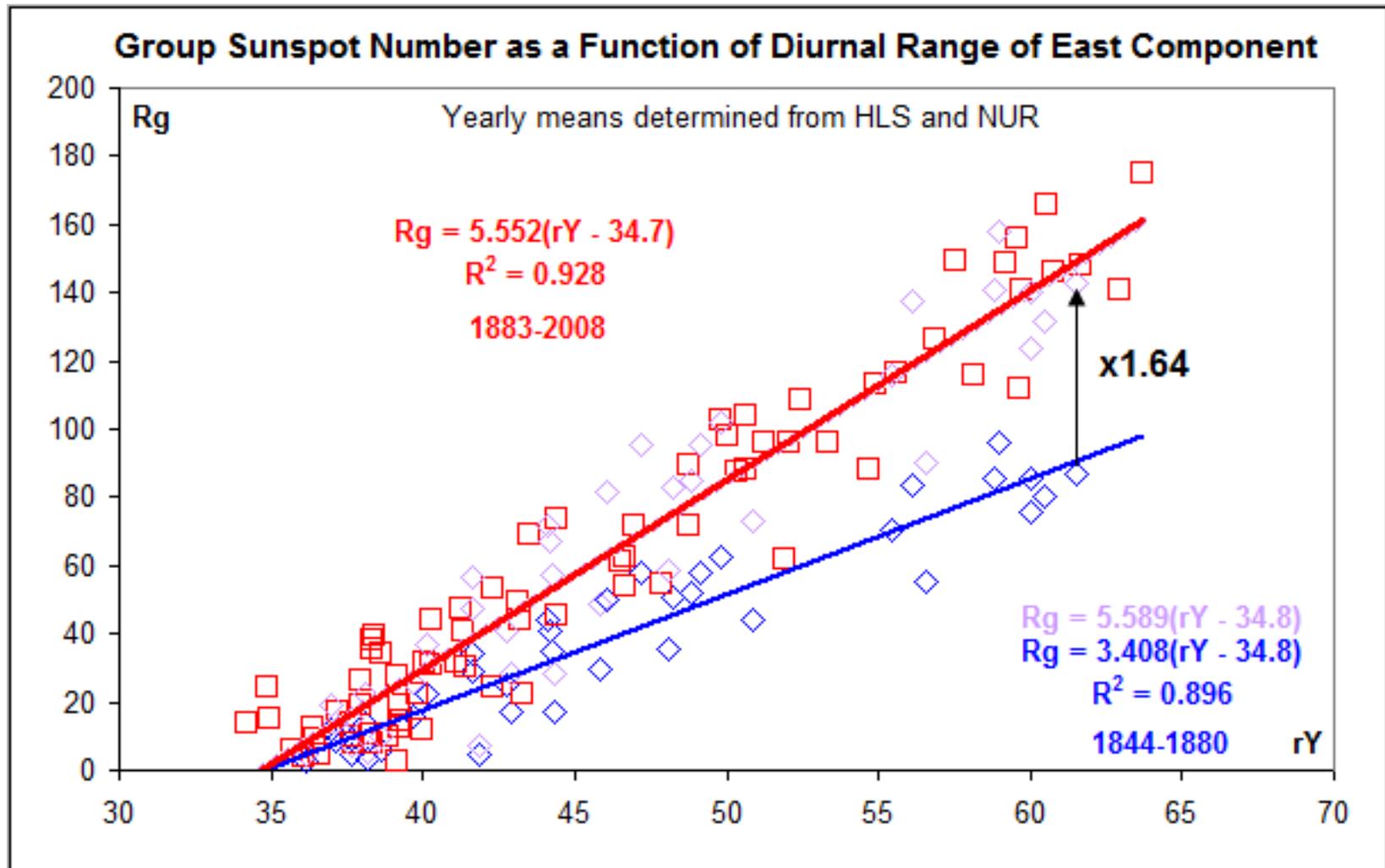
This conclusion is independent of the calibration of the Zürich SSN, Rz

Wolf's Geomagnetic Data

Wolf and Wolfer's Diurnal Ranges of Declination for their Long-running Stations

dD'

Scale Factor dD' => rY

H cos(D)/3438

Praha (Prague) - Christiania (Oslo) - Milano (Milan) - Wien (Vienna)

Declination Ranges converted to Scaled East Component Ranges

rY nT

Today we know that the relevant parameter is the East Component, Y, rather than the Declination, D. Converting D to Y restores the stable correlation without any significant long-term drift of the base values
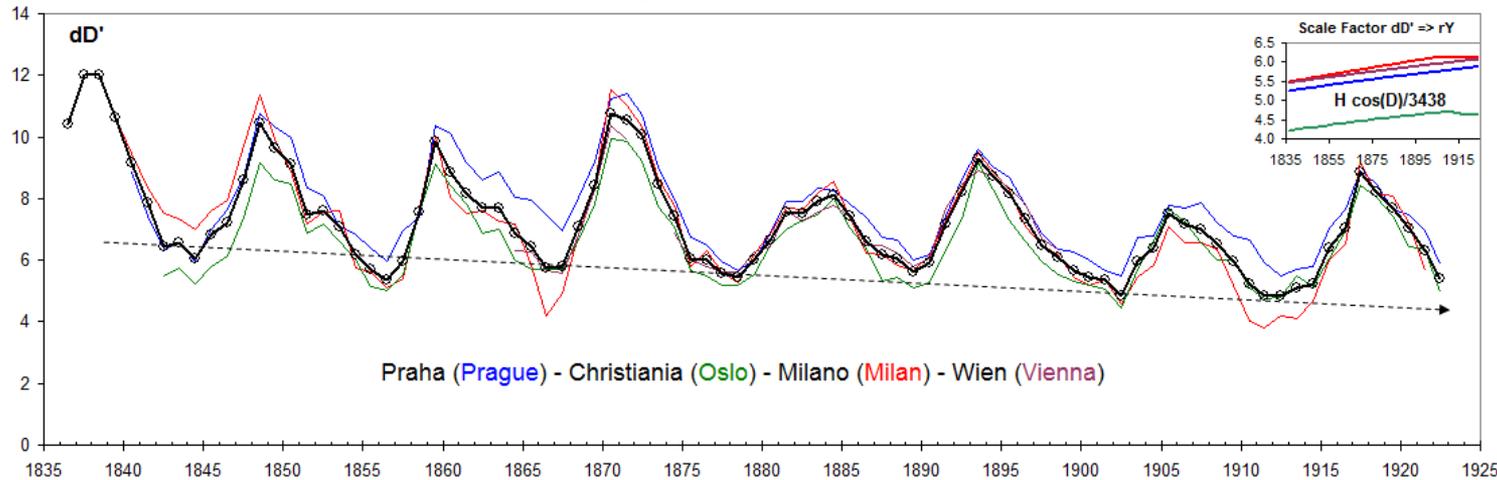
Wolf found a very strong correlation between his Wolf number and the daily range of the Declination.
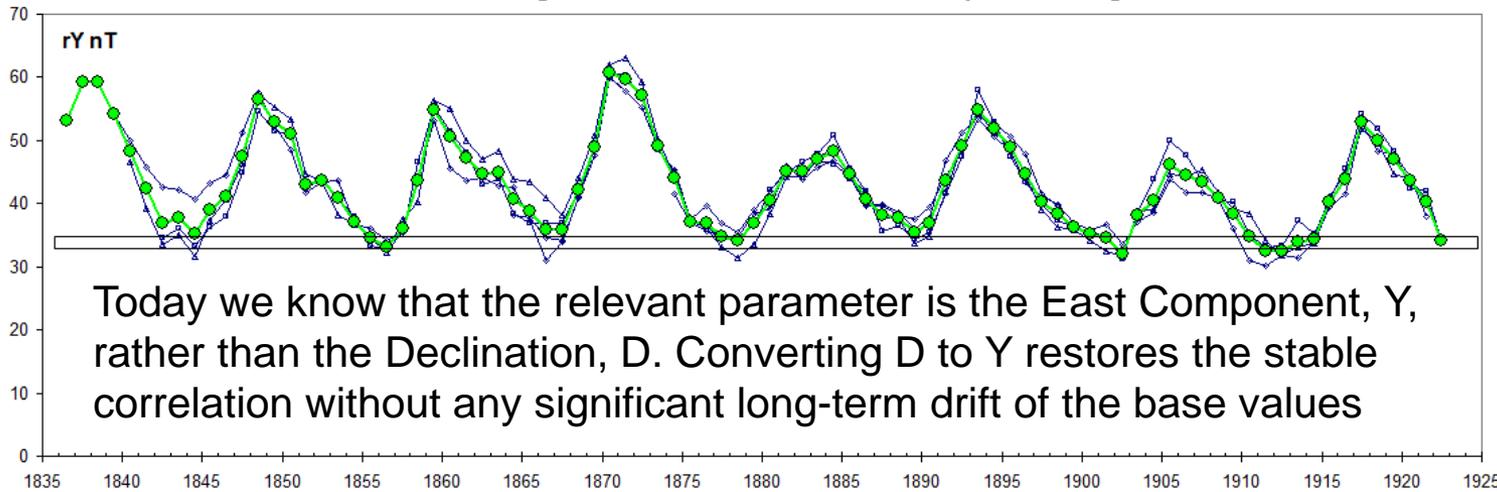
Wolfer found the original correlation was not stable, but was drifting with time and gave up on it in 1923.

43

Using the East Component We Recover Wolf's Tight Relationship

Relationship Between Rz SSN and rY East component Range

Rz

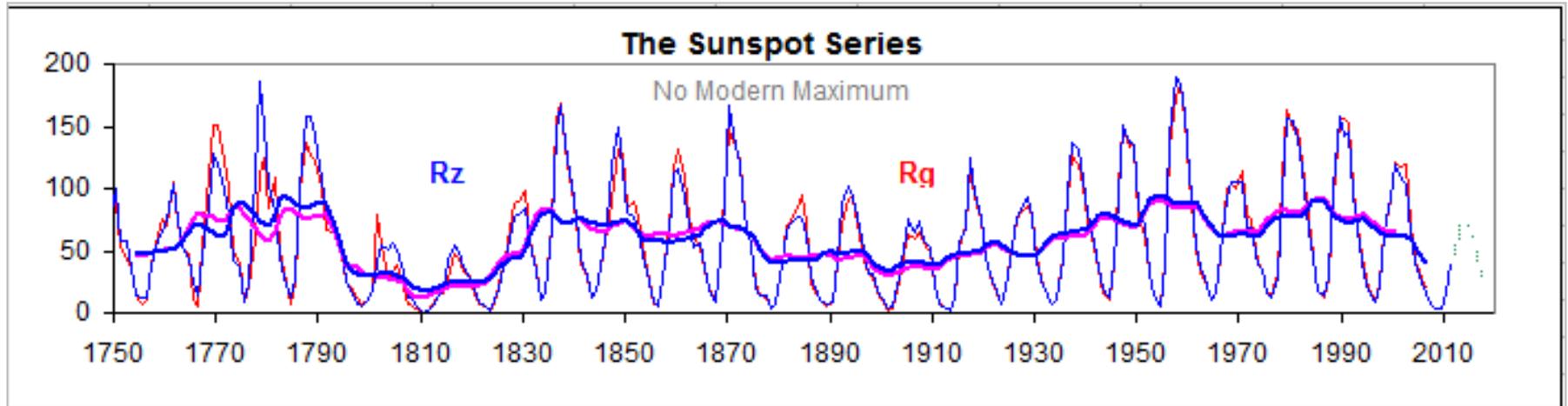$Rz = 4.54\pm0.15\ (rY - 32.6\pm1.5)$
$R^2 = 0.9121$

1883-1922
$Rz = 4.26\pm0.23\ (rY - 32.5)$
$R^2 = 0.8989$

1836-1882
$Rz = 4.61\pm0.21\ (rY - 32.5)$
$R^2 = 0.9138$

rY

Relationship Between Rg SSN and rY East component Range

Rg

1883-1922
$Rg = 4.40\pm0.27\ (rY - 32.4)$
$R^2 = 0.8765$
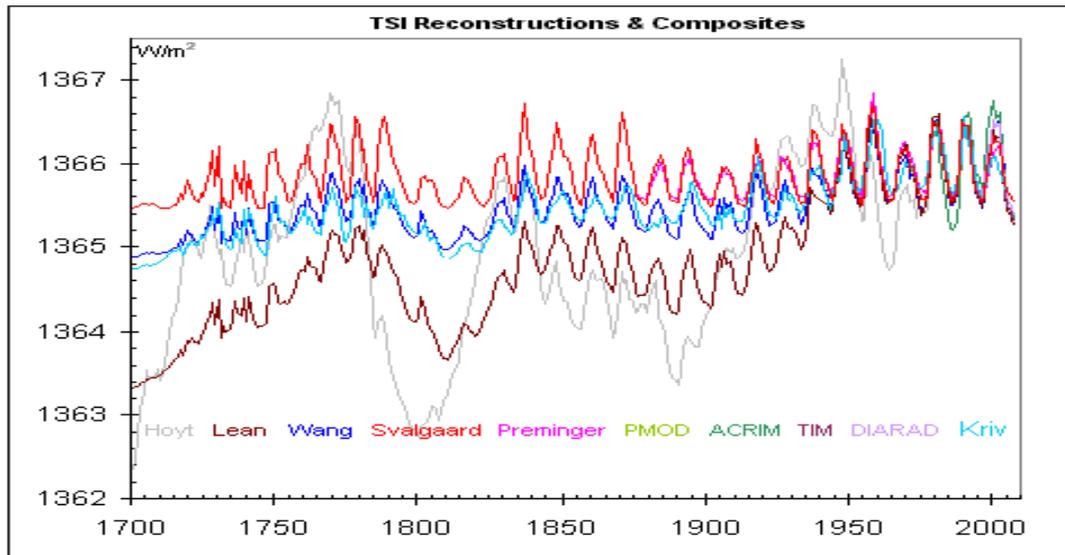
1836-1882
$Rg = 3.54\pm0.18\ (rY - 32.2)$
$R^2 = 0.8994$

rY
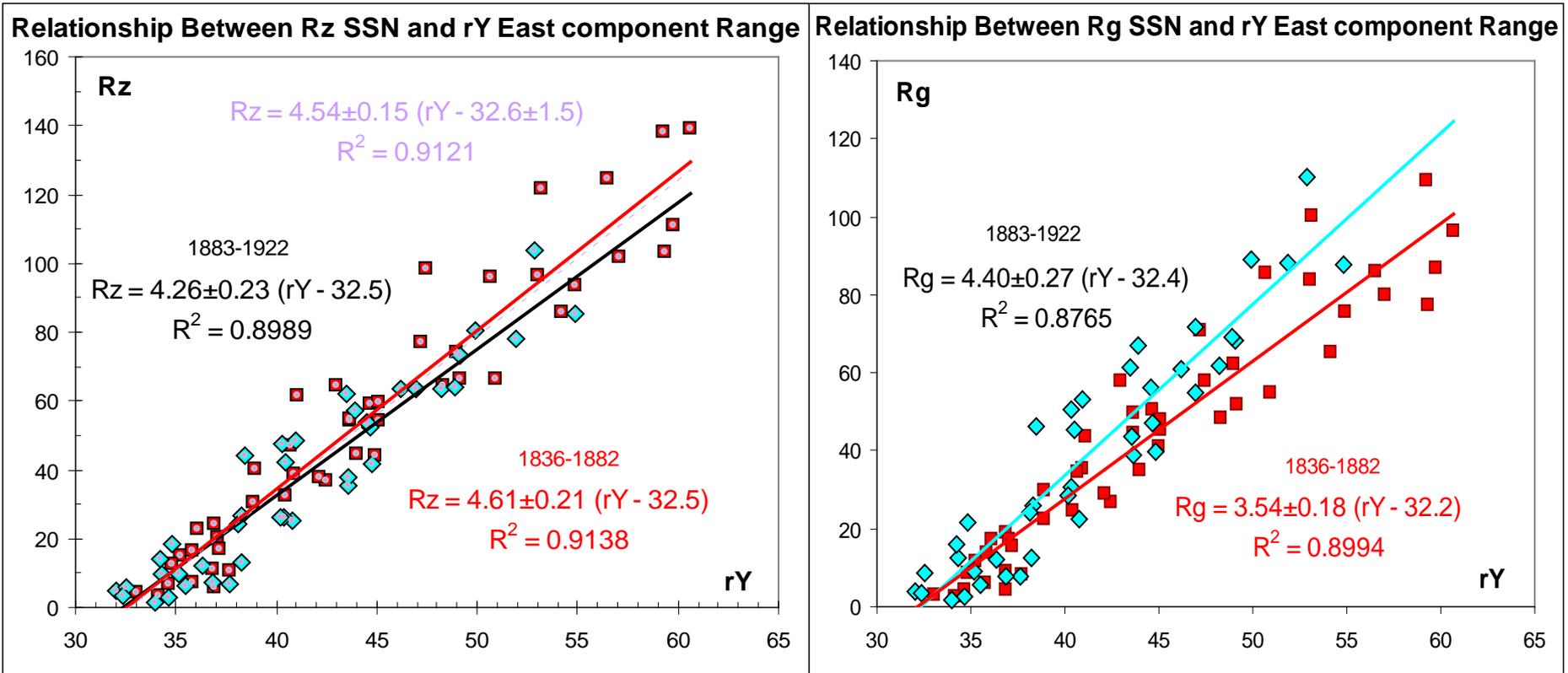
The regression lines are identical within their errors before and after 1883.0. This means that likely most of the discordance with Rg ~1885 is not due to 'change of guard' or method at Zürich. It is also clear that Rg before 1883 is too low.

Conclusions

- The Zürich Sunspot Number, Rz, and the Group Sunspot Number, Rg, can be reconciled by making only TWO adjustments

- The first adjustment [20%] is to Rz ~1945

- The second adjustment [~50%] is to Rg ~1885

The Sunspot Series

What Does the 'No Grand Modern Maximum' Do to TSI?

TSI Reconstructions & Composites

Hoyt   Lean   Wang   Svalgaard   Preminger   PMOD   ACRIM   TIM   DIARAD   Kriv

Shapiro et al., 2011

Historically, the TSI reconstruction by Hoyt & Schatten of 20 years ago had a large variation with significant climate impact. Since then the variation has 'shrunk' to hardly any climate impact (~0.1º).

In a recent paper there has been a reversal of the 'flattening' of TSI. The old (uncorrected) Group Sunspot Number is the basis for this reappraisal, so we see how important the calibration of the SSN is. And how difficult it will be to get acceptance for our adjustments.
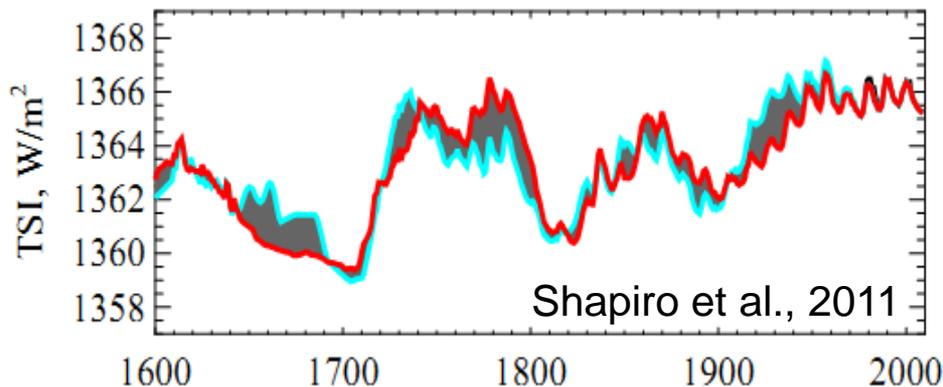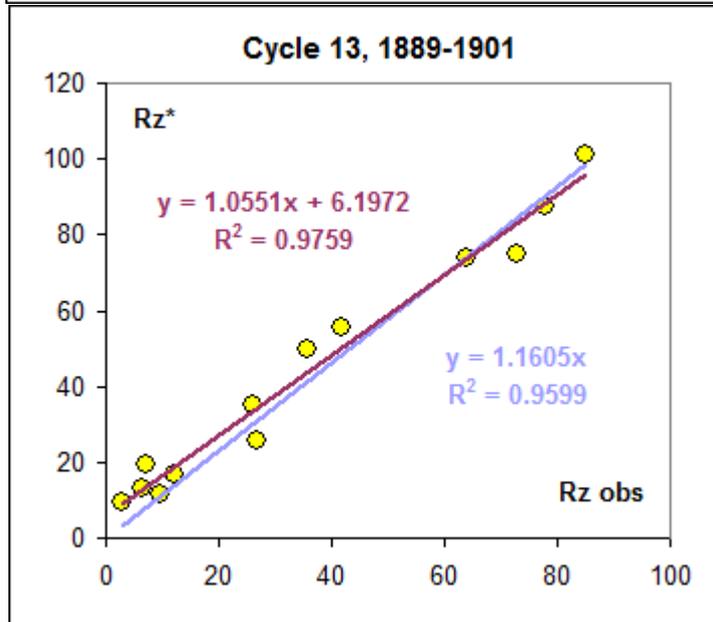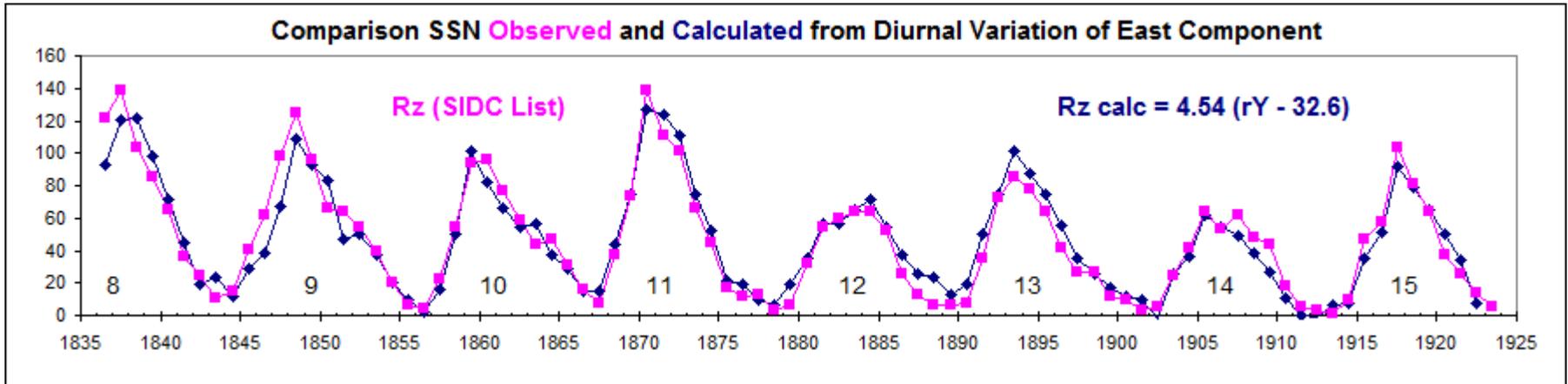
Where do we go from here?

- Find and Digitize as many 19th century geomagnetic hourly values as possible
- Determine improved adjustment factors based on the above and on model of the ionosphere
- Co-operate with agencies producing sunspot numbers to harmonize their efforts in order to produce an adjusted and accepted sunspot record that can form a firm basis for solar-terrestrial relations, e.g. reconstructions of solar activity important for climate and environmental changes
- Workshop in Sunspot, NM, Sept. 2011 with all 'players' as a first step [and one in Brussels, 2012]

Abstract

The sunspot number (SSN) record (1610-present) is the primary time sequence of solar and solar-terrestrial physics, with application to studies of the solar dynamo, space weather, and climate change. Contrary to common perception, and despite its importance, the international sunspot number (as well as the alternative widely-used group SSN) series is inhomogeneous and in need of calibration. We trace the evolution of the sunspot record and show that significant discontinuities arose in ~1885 (resulting in a ~50% step in the group SSN) and again when Waldmeier took over from Brunner in 1945 (~20% step in Zürich SSN). We follow Wolf and show how the daily range of geomagnetic activity can be used to maintain the sunspot calibration and use this technique to obtain a revised, homogeneous, and single sunspot series from 1835-2011.

Comparing Individual Solar Cycles

Comparison SSN Observed and Calculated from Diurnal Variation of East Component

Rz (SIDC List)

Rz calc = 4.54 (rY - 32.6)

Cycle 13, 1889-1901

Rz*

$y = 1.0551x + 6.1972$
$R^2 = 0.9759$

$y = 1.1605x$
$R^2 = 0.9599$

Rz obs

The noise is large enough to leave the comparison inconclusive.

Only remedy is more 19th geomagnetic data.

Slopes of Rz Comparisons

Forced through Zero   With Offset

Solar cycle #