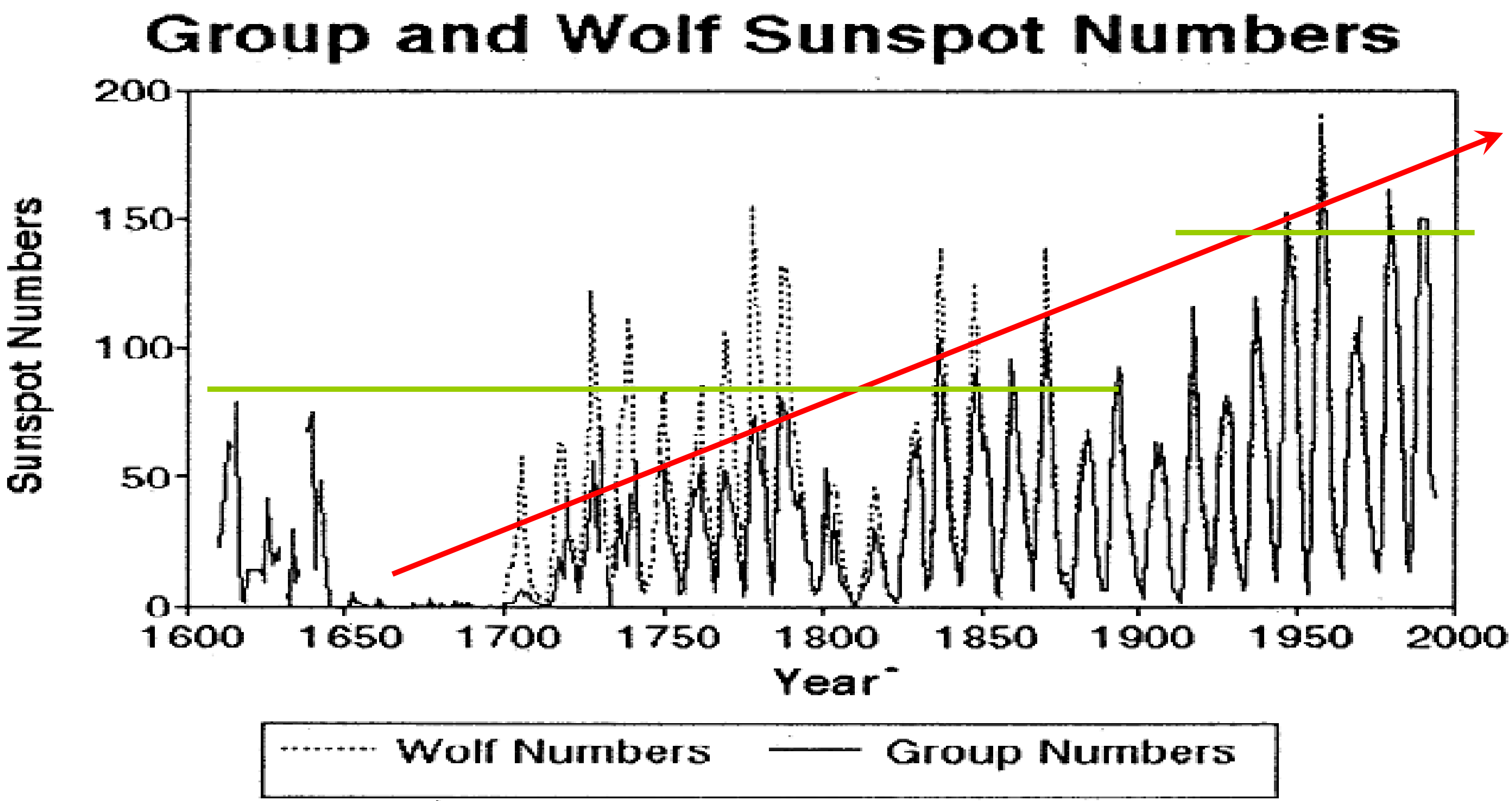
How Well Do We Know the Sunspot Number?

Leif Svalgaard
Stanford University

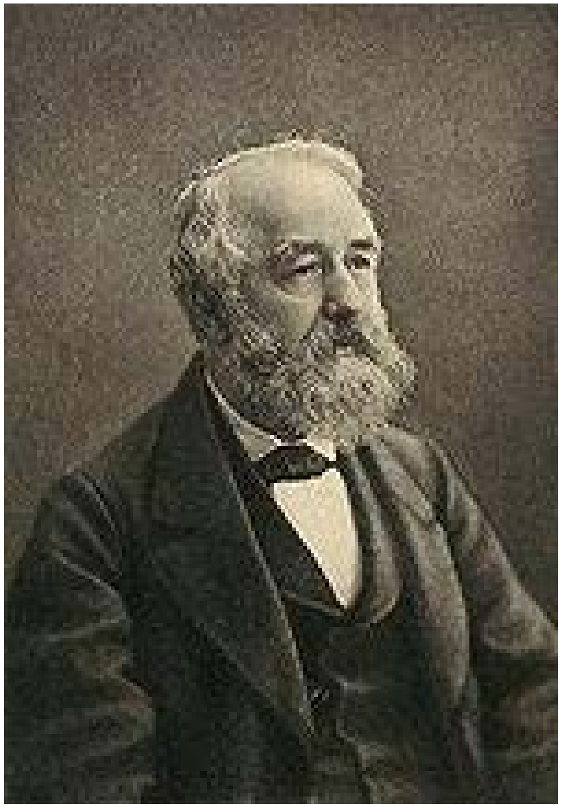
IAU Symposium 286, Mendoza, Argentina, Oct. 2011

The Problem: Discordant Sunspot Numbers



Hoyt & Schatten, GRL *21*, 1994

The Wolf Sunspot Number ~1856



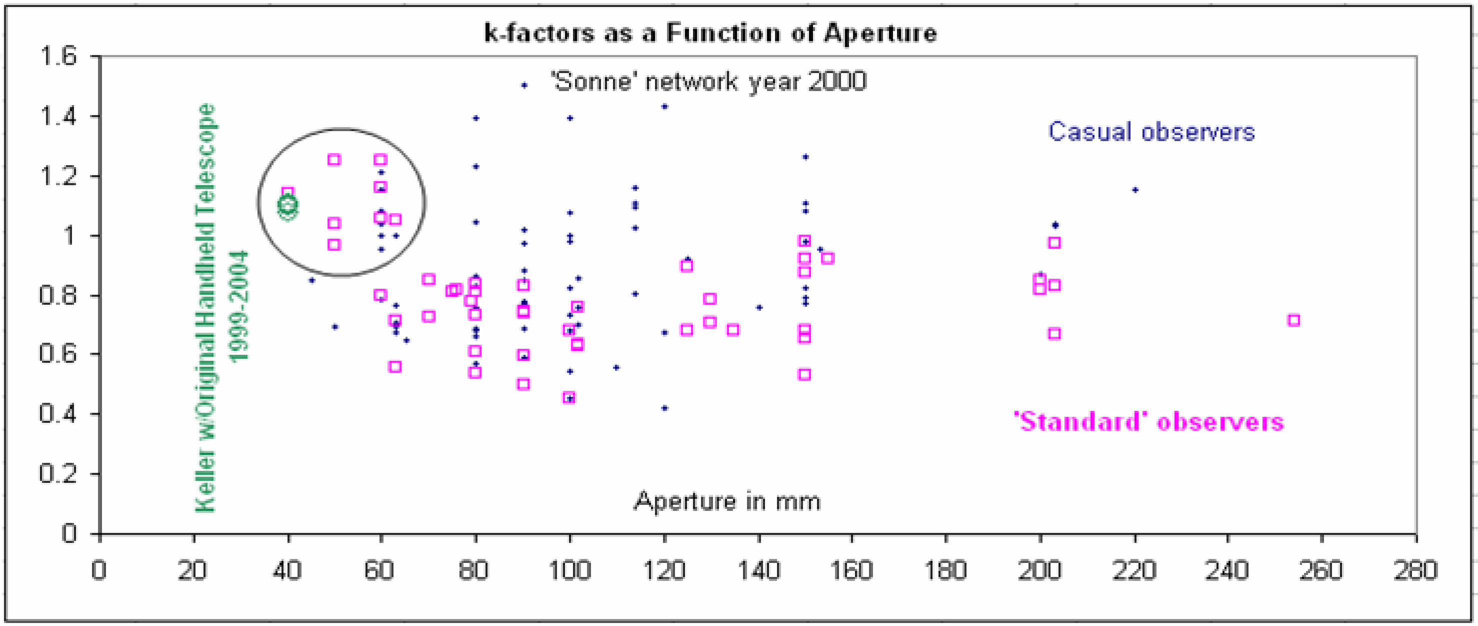
Rudolf Wolf (1816-1893)

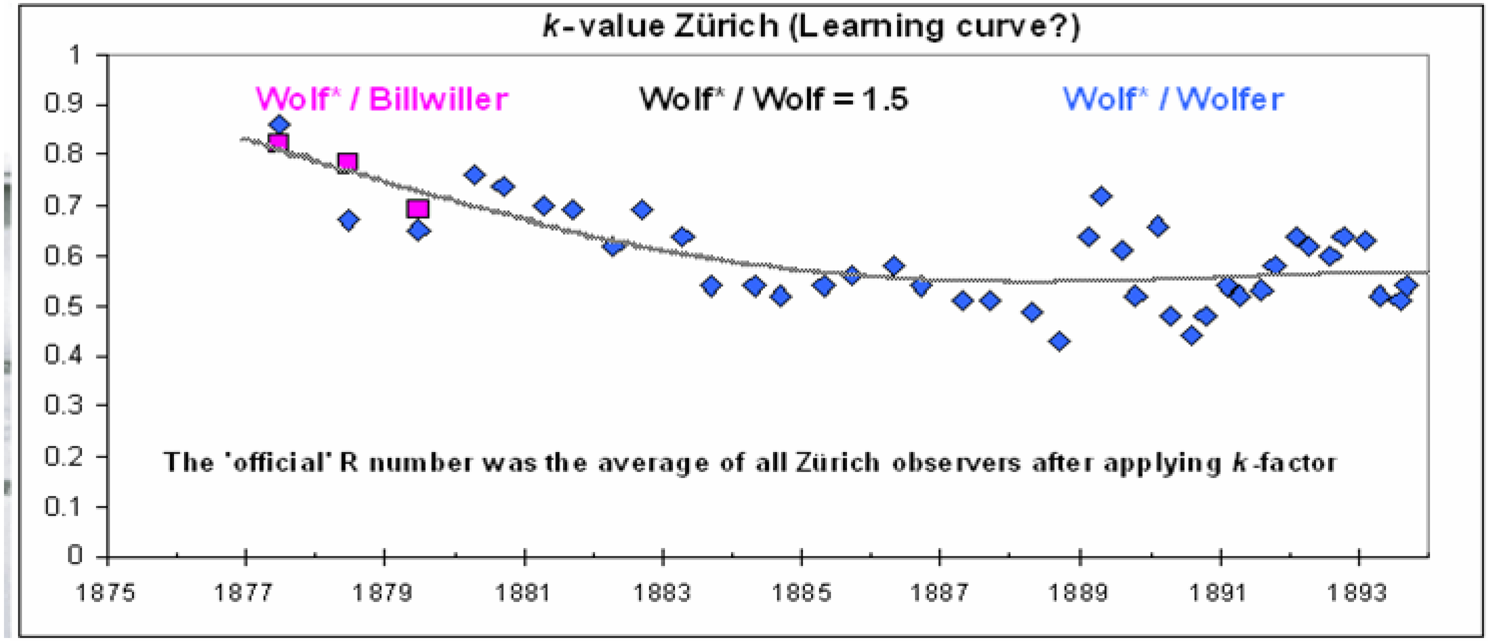
Observed 1849-1893

- Wolf Number = k_W (10*G + S)
- G = number of groups
- S = number of spots
- k_W = scale factor + site + method + personal + …

The *k*-factor was introduced in 1861 to make it possible to incorporate counts from other observers. Wolf himself used k = 1.0 for his main telescope and k = 1.5 for his smaller, portable telescopes

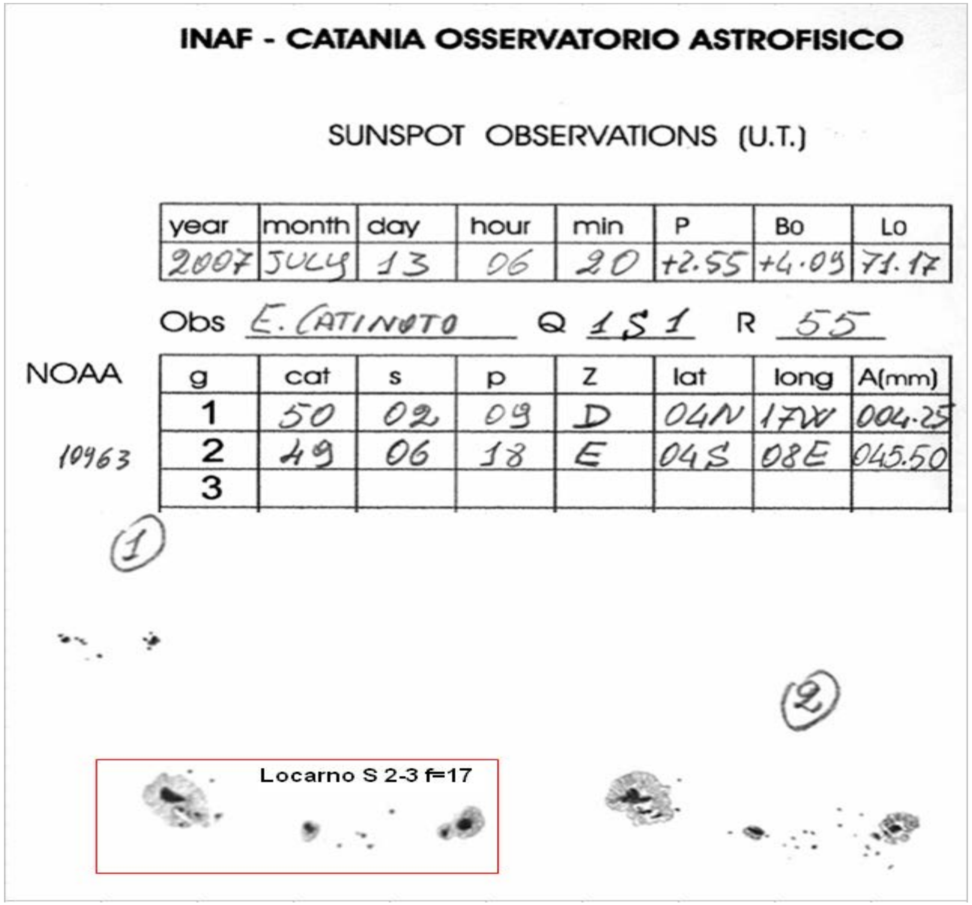
Wolf's Telescopes





***k*-factor** dependence on aperture (best is 80-100 mm)

and experience (it takes years to become good at it)


INAF - CATANIA OSSERVATORIO ASTROFISICO

SUNSPOT OBSERVATIONS (U.T.)

year	month	day	hour	min	P	Bo	Lo
2007	JULY	13	06	20	+2.55	+4.09	71.17

Obs E. CATINOTO Q 151 R 55

NOAA	g	cat	s	p	Z	lat	long	A(mm)
	1	50	02	09	D	04N	17W	004.25
10963	2	49	06	18	E	04S	08E	045.50
	3							

1

2

Locarno S 2-3 f=17

k-factor depends on seeing too.

Seeing can change over time (urban pollution, etc)

Table 2. *k*-factors as a function of seeing for Kandilli Observatory (Atlas *et al.*, 1998)

Seeing	1(worst)	2	3	4	5(best)
Days	244	473	812	682	126
k	0.96	0.95	0.90	0.83	0.74

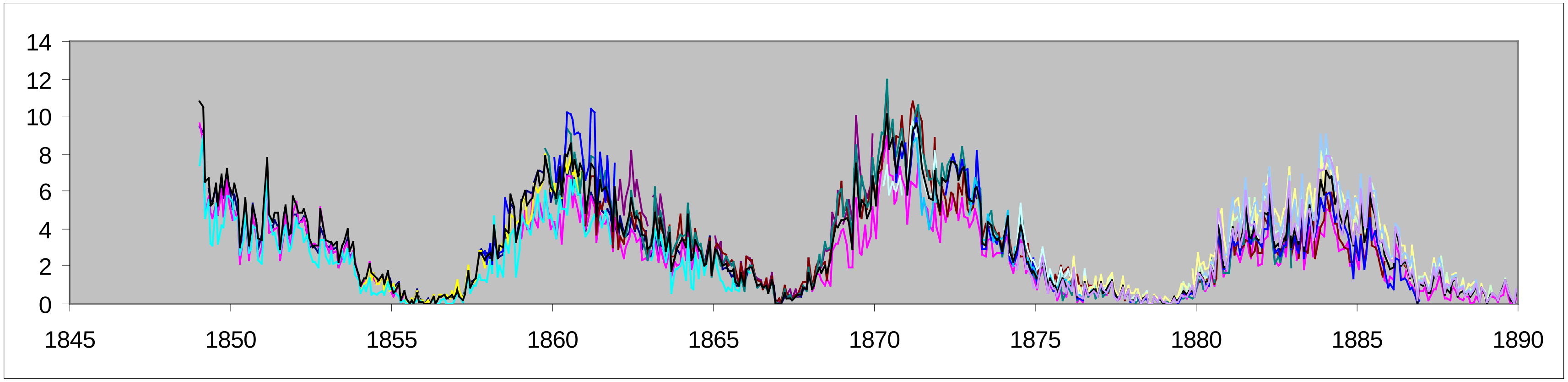
Ken Schatten &
Doug Hoyt, 1994+

New Approach: Group Sunspot Number

Basic Idea: Group SSN = 12*G

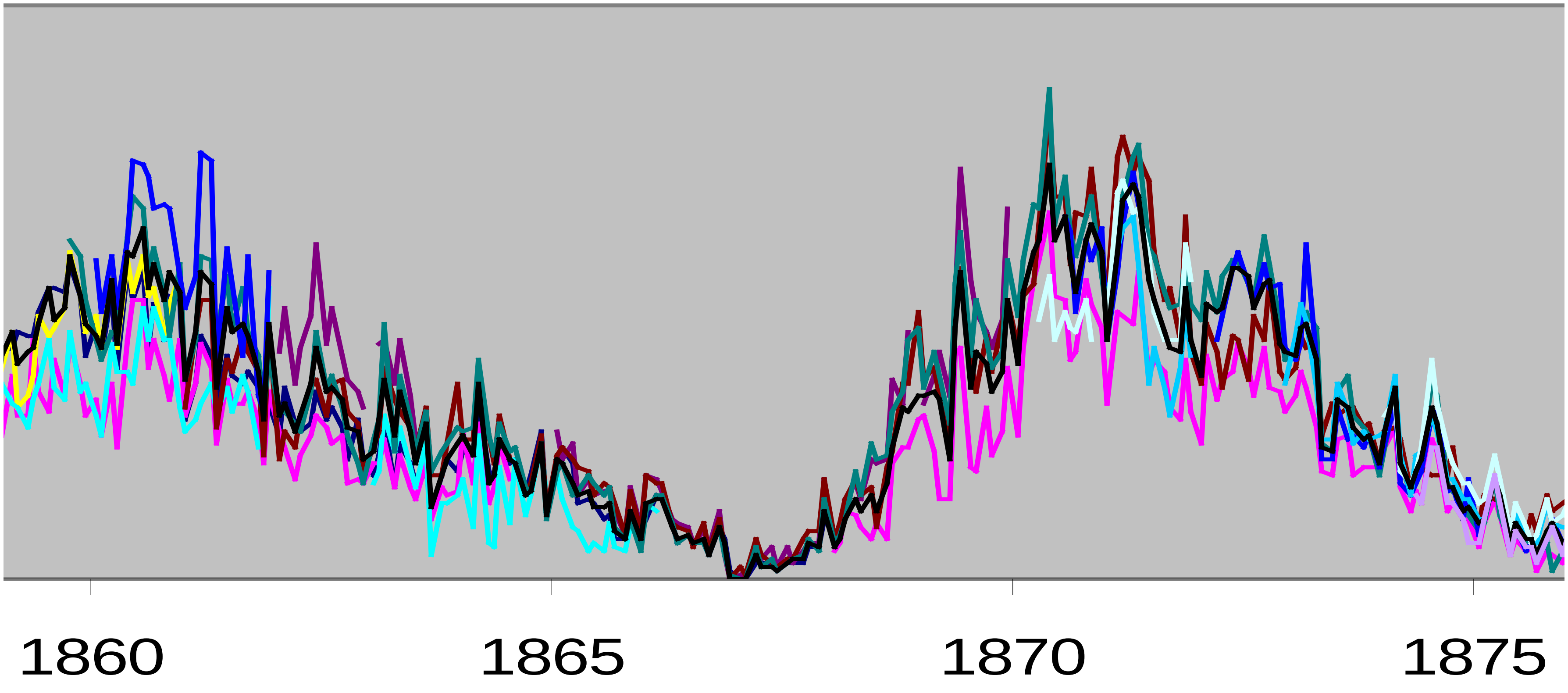
The Number of Sunspot Groups is However also Observer Dependent

Schwabe Wolf Carrington Shea Peters Spoerer Weber Schmidt Secchi
Bernaerts Wolfer Aguilar Ricco RGO



GSN = 12 k_G Groups; So there is also a *k*-factor for GSN

Detail of Previous Plot Showing the Large Variability of the ‘Raw’ GSN



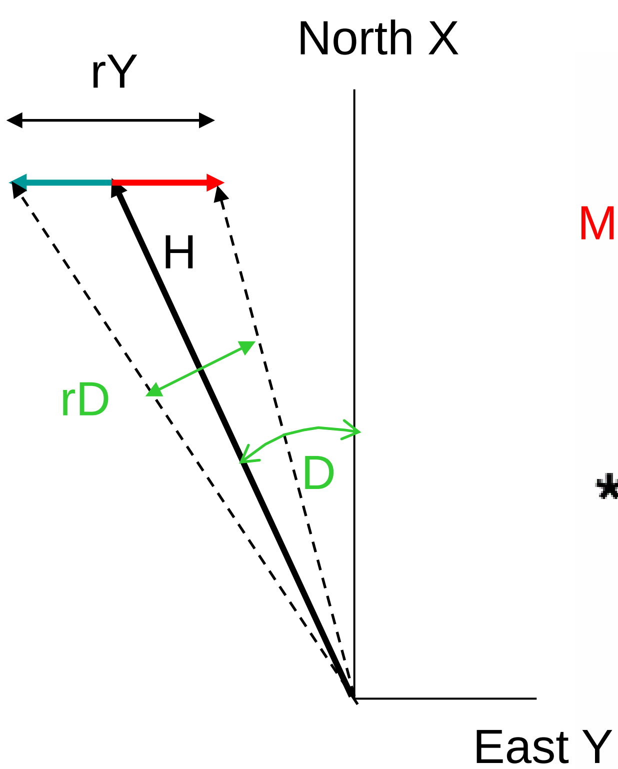
The *k*-factors are the Real Issue in Calibrating the Sunspot Number

The ideal situation would be to have an ‘absolute’ standard to which one can calibrate the ‘relative’ sunspot numbers

Wolf himself discovered [1859] such a standard and remarked: “Who would have thought just a few years ago about the possibility of computing a terrestrial phenomenon from observations of sunspots"

Applied in reverse, this affords an *objective* calibration of the sunspot count by linking it to a physical phenomenon observed independently from sunspot counting

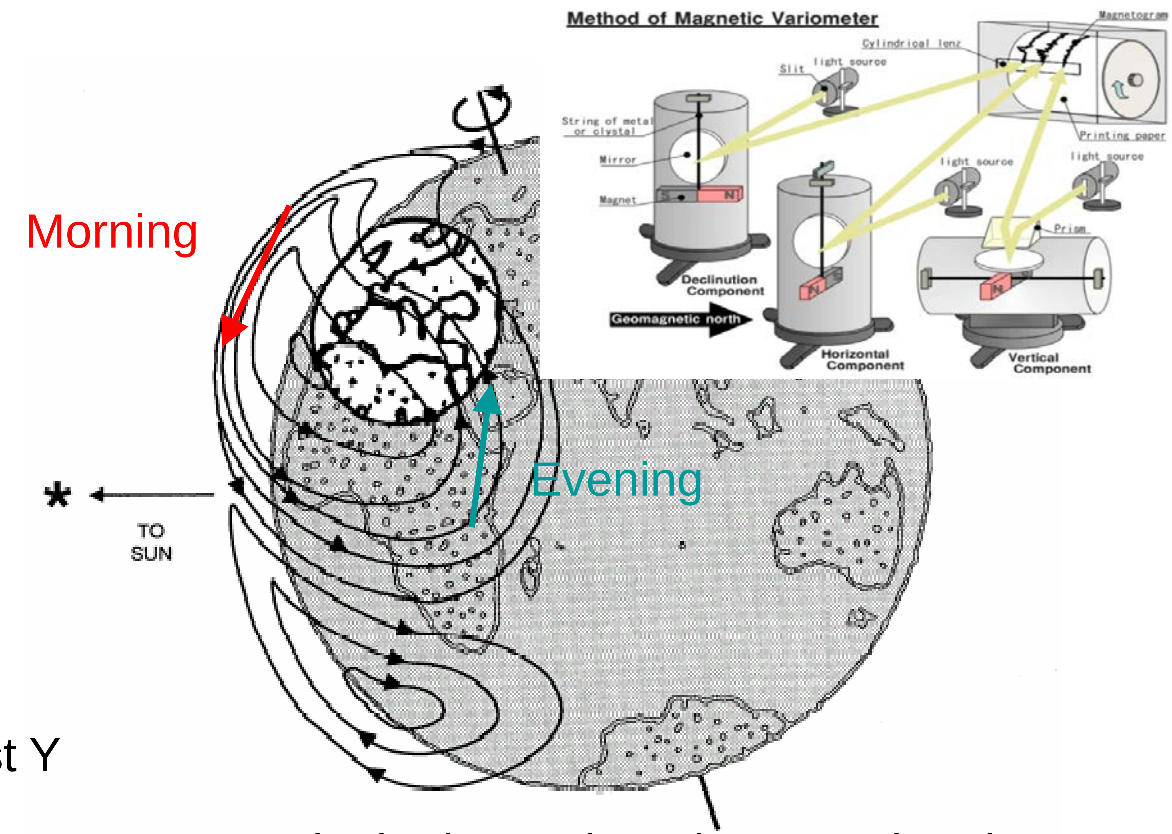
Wolf's Discovery: *rD* = *a* + *b* R_W



$Y = H \sin(D)$

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

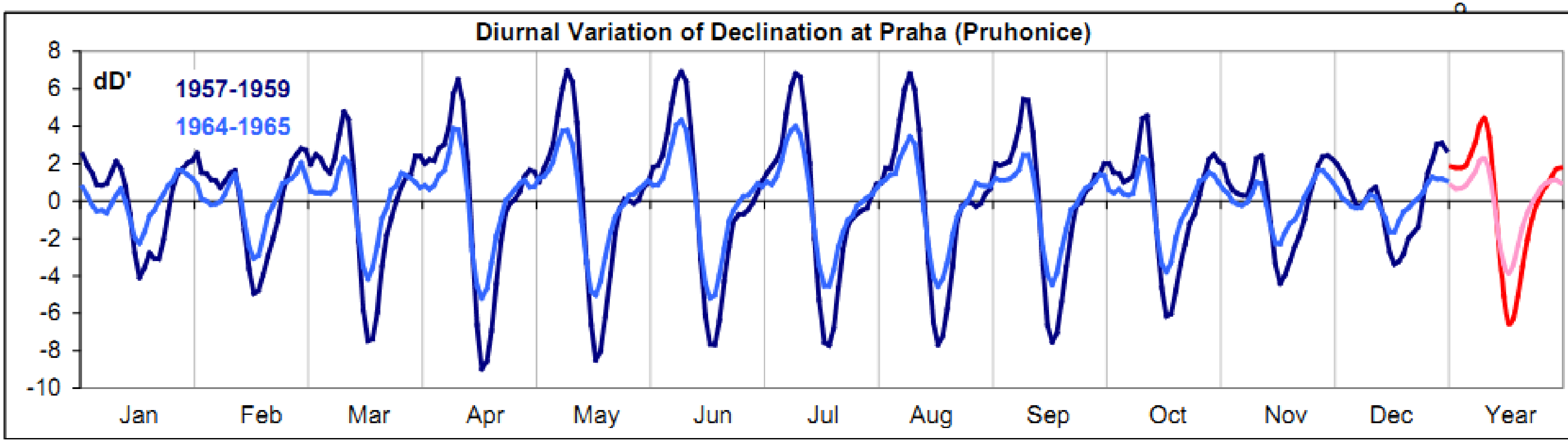
For small dD

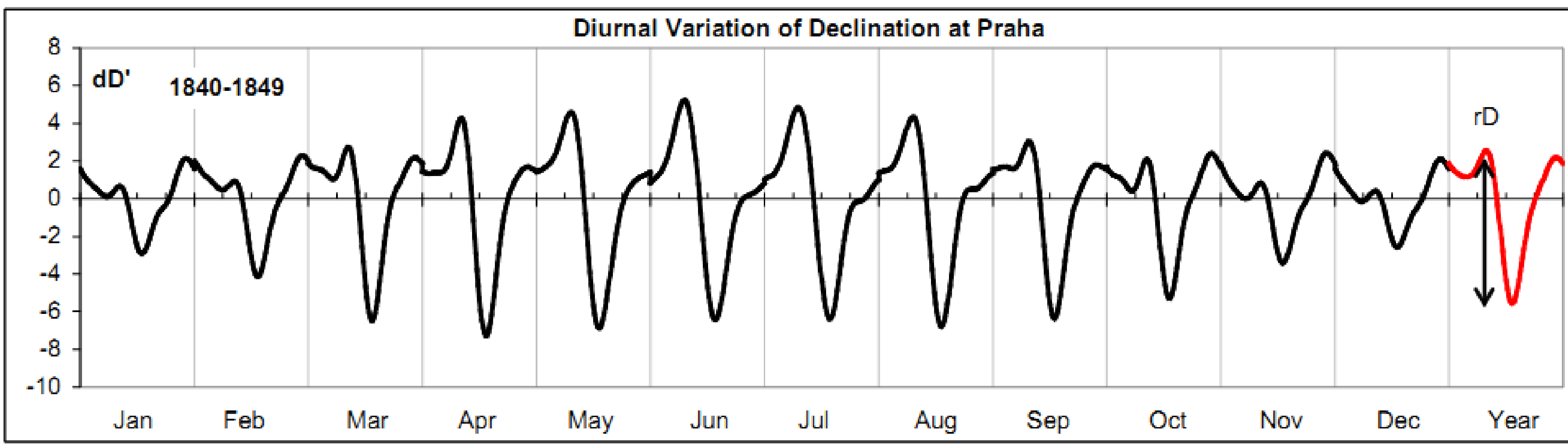


A current system in the ionosphere is created and maintained by solar FUV radiation. The **magnetic** effect of that current can be measured on the ground

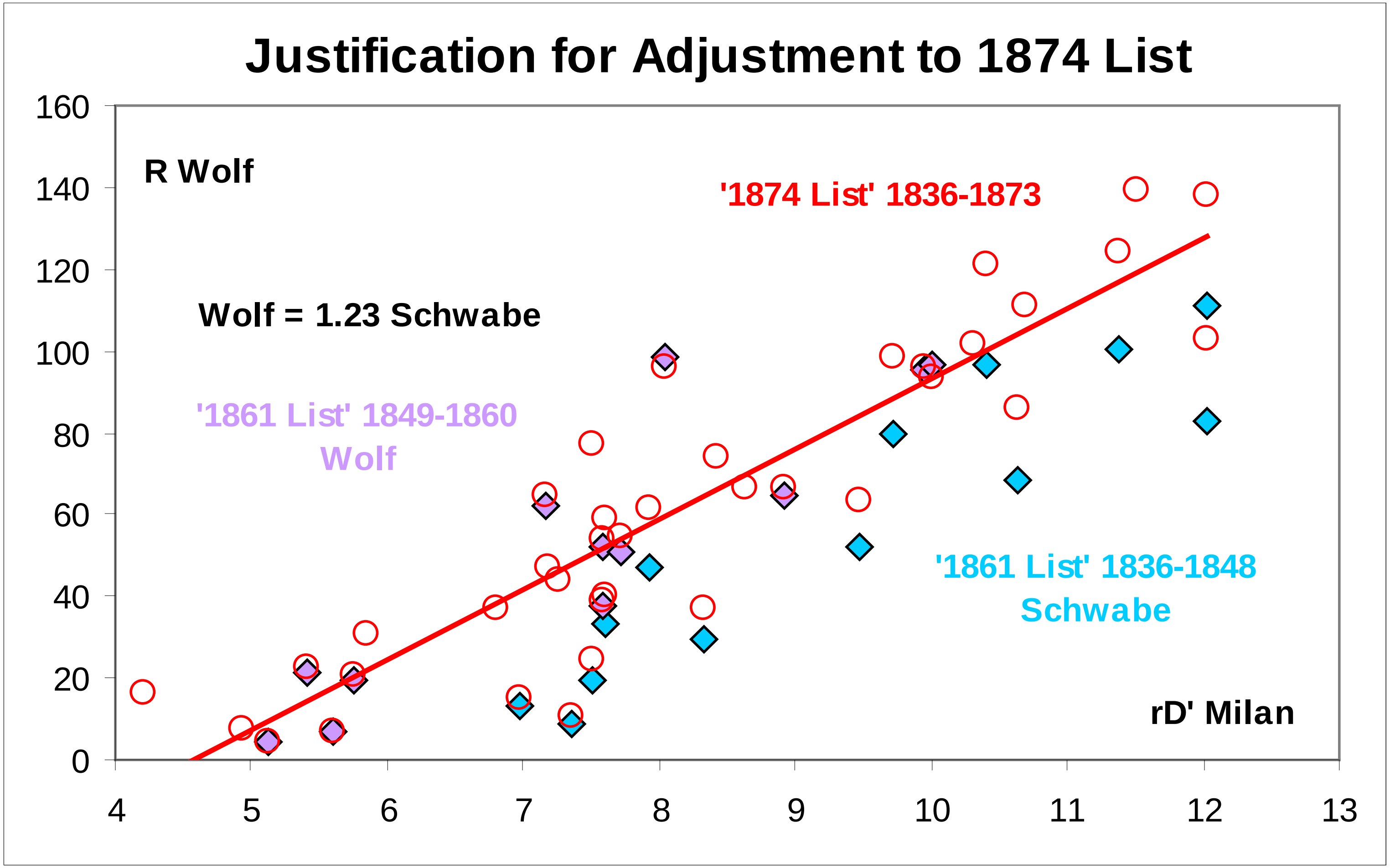
Magnetic Effect of the Current

(easily measured in the 19th and 18th centuries)





Wolf got Declination Ranges for Milan [back to 1836] from Schiaparelli and it became clear that the pre-1849 SSNs were too low



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

Changes to Rudolf Wolf's 1861 List

Abstract of his latest Results. By Prof. Wolf.

(*Translation communicated by Mr. Carrington.*)

Some fine series of observations of Flaugergues, Adams, Arago, and others, have enabled me to fill in previous breaks, and to express in the same unit my Relative numbers (for the abundance of Solar Spots in successive years) for the years from 1749 to 1860. They are as follows:—

1749	63·8	1777	63·0	1805	50·0?	1833	7·5 *m*
1750	68·2 M	78	94·8	06	30·0?	34	11·4
51	40·9	1779	99·2 M	07	10·0?	35	45·5
52	33·2	1780	72·6	08	2·2	36	96·7
53	23·1	81	67·7	1809	0·8	37	111·0 M
54	13·8	82	33·2	1810	0·0 *m*	38	82·6
55	6·0 *m*	83	22·5	11	0·9	1839	68·5
56	8·8	84	4·4 *m*	12	5·4	1840	51·8

1749	80.9	1777	92.5	1805	42.2	1833	8.5 m
1750	83.4 M	78	154.4	06	28.1	34	13.2
51	47.7	1779	125.9 M	07	10.1	35	56.9
52	47.8	1780	84.8	08	8.1	36	121.5
53	30.7	81	68.1	1809	2.5	37	138.3 M
54	12.2	82	38.5	1810	0.0 m	38	103.2
55	9.6 m	83	22.8	11	1.4	1839	85.7
56	10.2	84	10.2 m	12	5.0	1840	64.6

From MNRAS, 1861 and from the current dataset at SIDC in Brussels

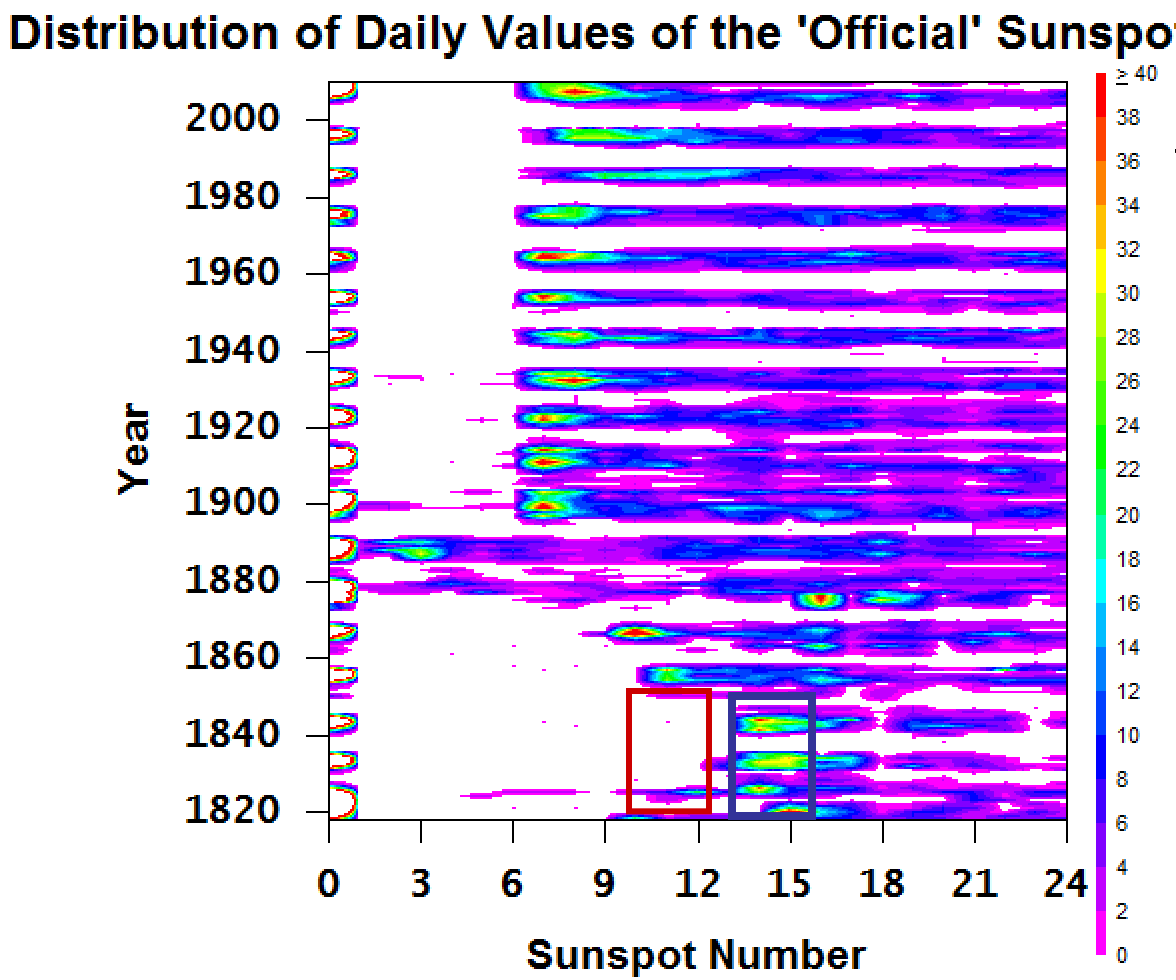
1833	7·5 *m*
34	11·4
35	45·5
36	96·7
37	111·0 M
38	82·6
1839	68·5
1840	51·8

1833	8.5 m
34	13.2
35	56.9
36	121.5
37	138.3 M
38	103.2
1839	85.7
1840	64.6

Most values changed by +25%

lower: SIDC 2009

The Wholesale Update of SSNs before 1849 is Clearly Seen in the Distribution of Daily SSNs



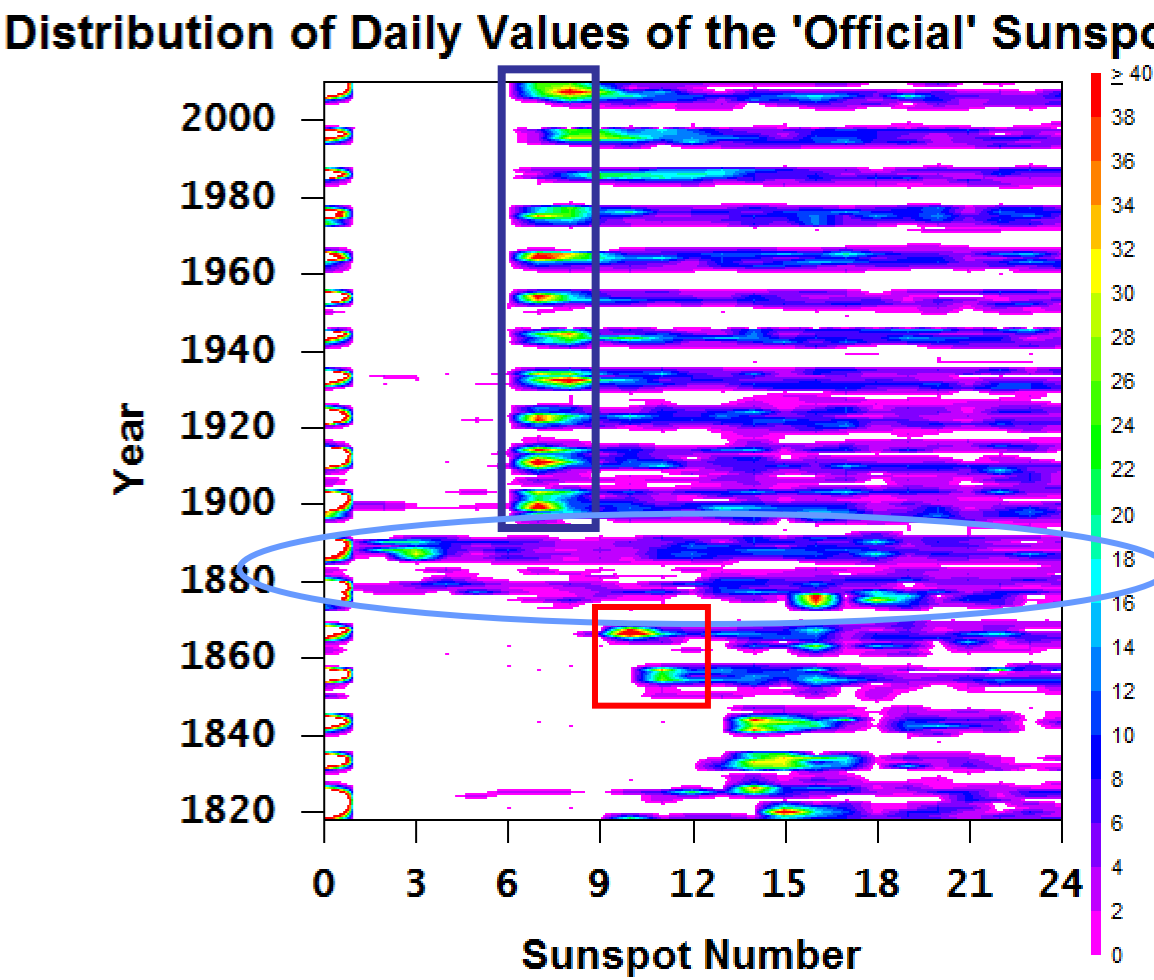
The smallest non-zero SSN is 11, but there are no 11s before 1849

11 * 5/4 = 14

Wolfer’s Change to Wolf’s Counting Method

- Wolf only counted spots that were ‘black’ and would have been clearly visible even with moderate seeing
- His successor Wolfer disagreed, and pointed out that the above criterion was much too vague and advocating counting every spot that could be seen
- This, of course, introduces a discontinuity in the sunspot number, which was corrected by using a much smaller *k* value [~0.6 instead of Wolf’s 1]

The Impact on the SSN after Wolf Died in 1893 is Clearly Seen in the Distribution of Daily SSNs

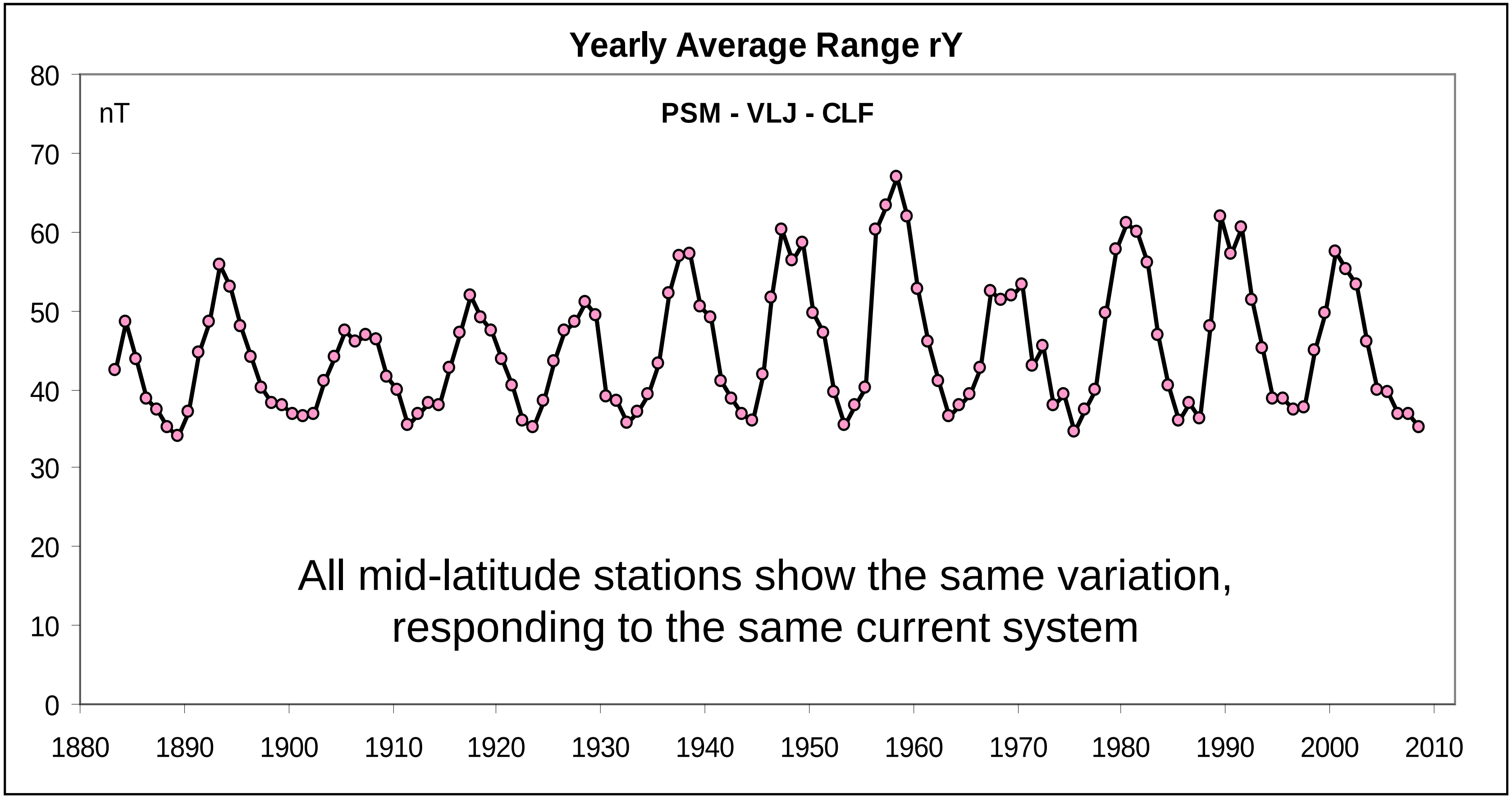


The smallest non-zero SSN is 11, but there are lots of 7s after 1893

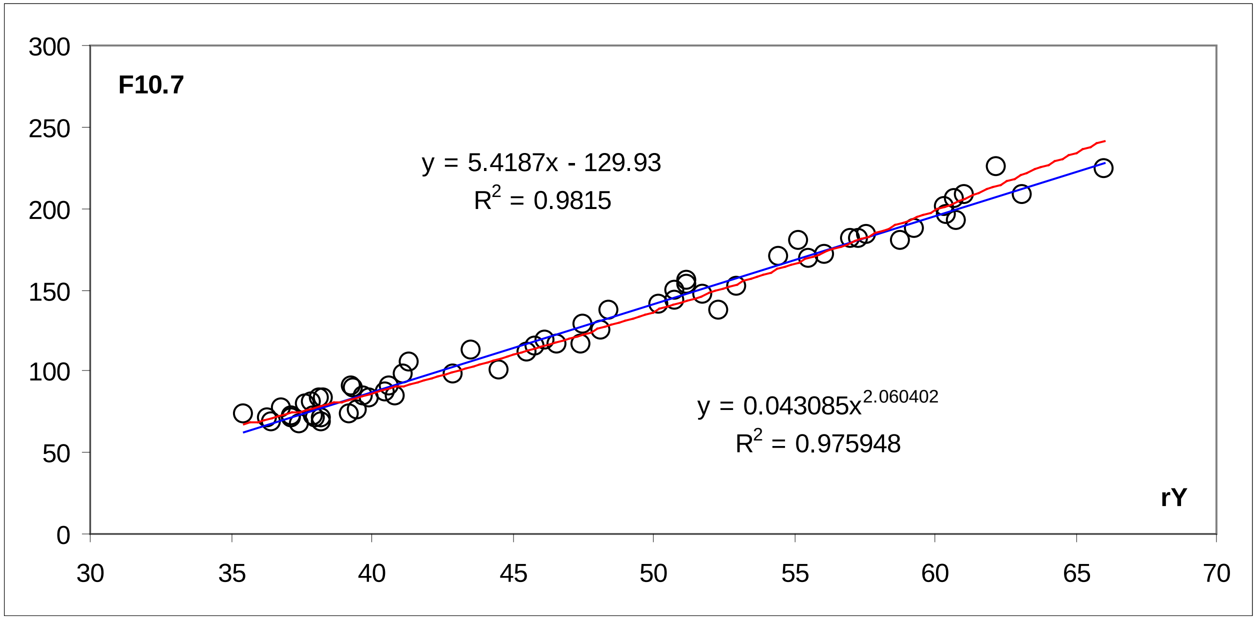
11 * 0.6 = 7

The confused values 1877-1893 are due to the averaging of Wolf and Wolfer's values

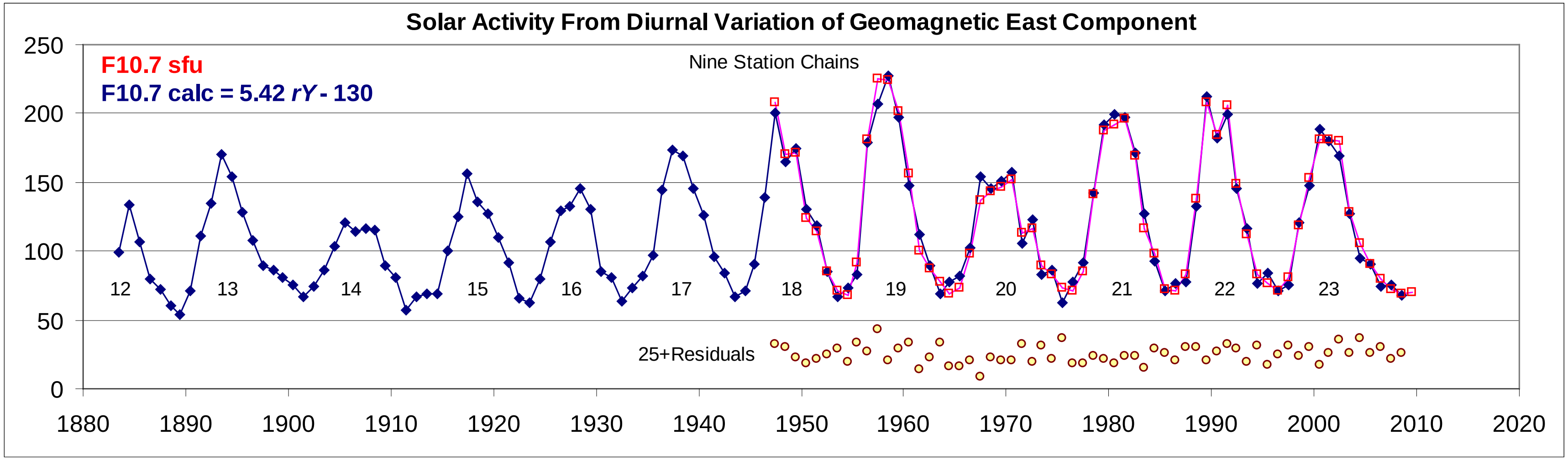
The clear solar cycle variation of *rY*



This extends Wolf's justification for his calibration of the SSN

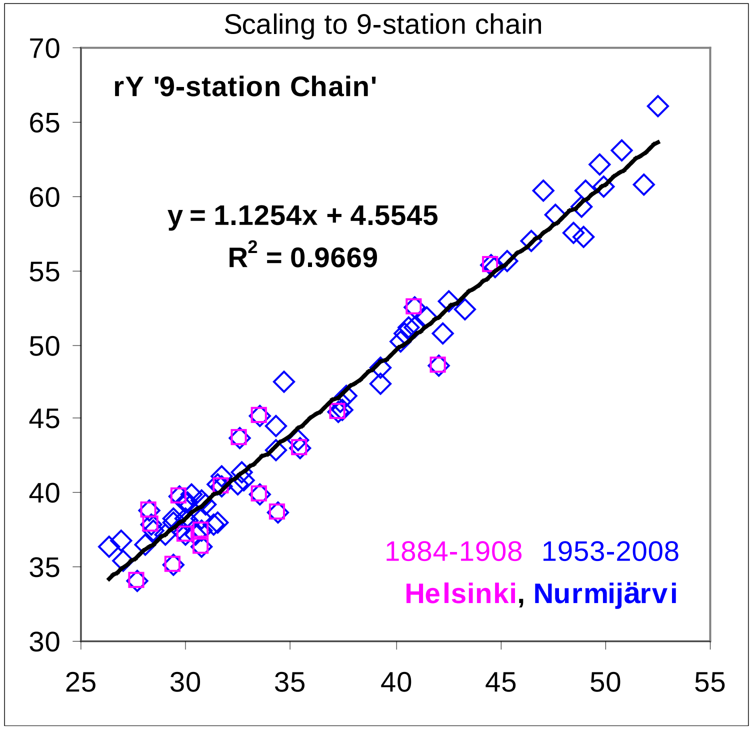


Using *rY* from nine 'chains' of stations we find that the **correlation** between *F10.7* and *rY* is extremely good (more than 98% of the variation is accounted for)

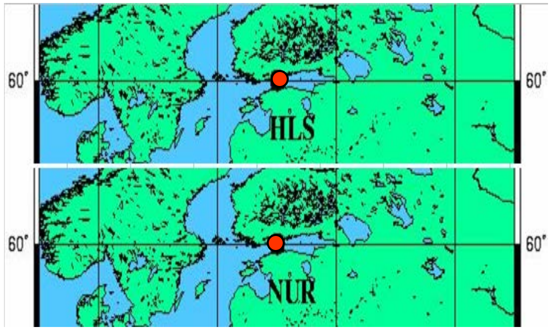


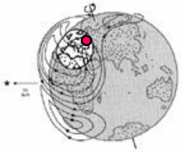
This establishes that Wolf's procedure and calibration are physically sound

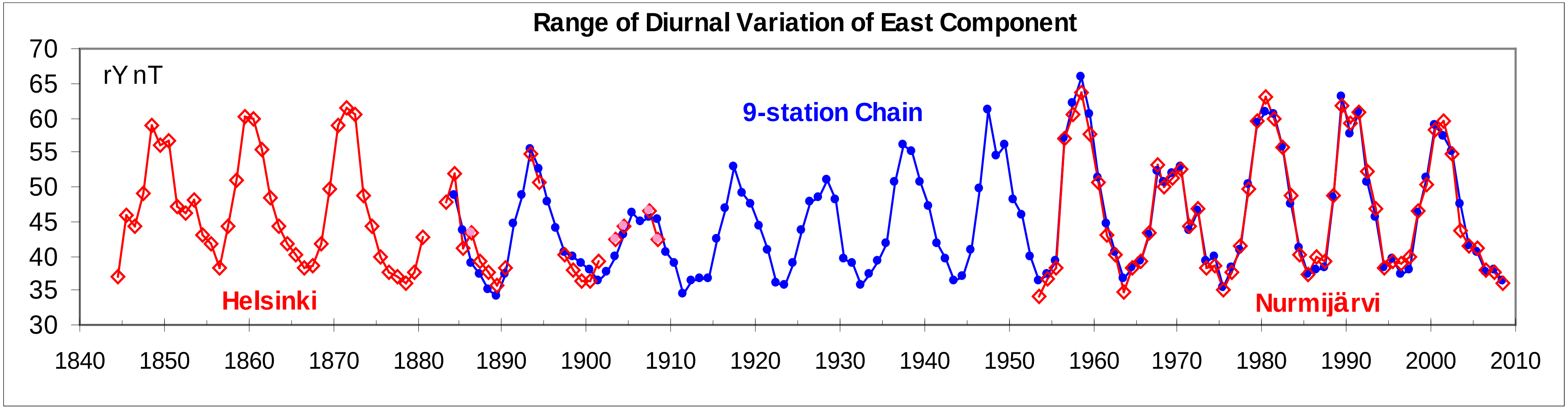
Helsinki-Nurmijärvi Diurnal Variation



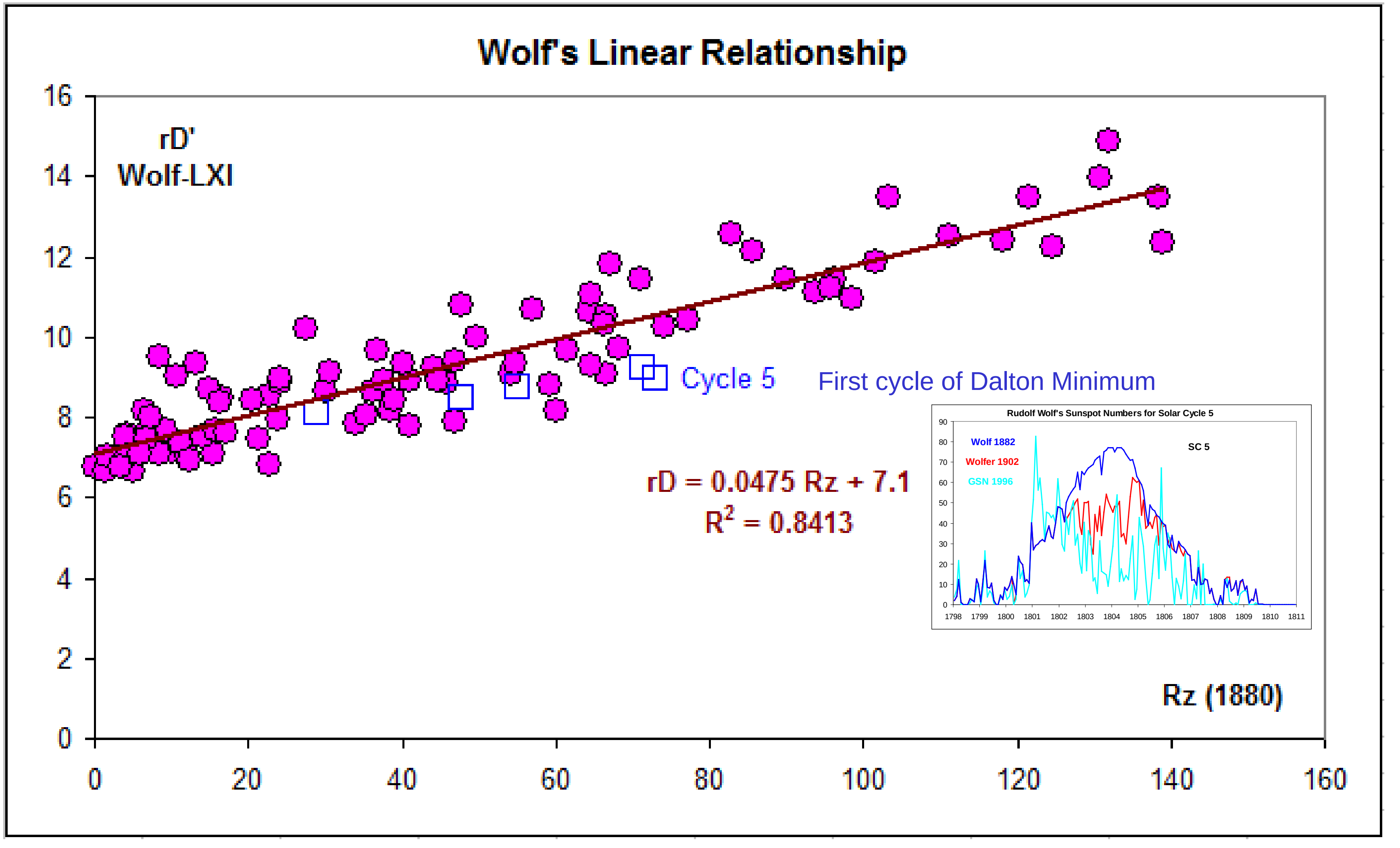
Helsinki and its replacement station Numijärvi scale the same way towards our composite of nine long-running observatories and can therefore be used to check the calibration of the sunspot number (or more correctly to reconstruct the F10.7 radio flux)





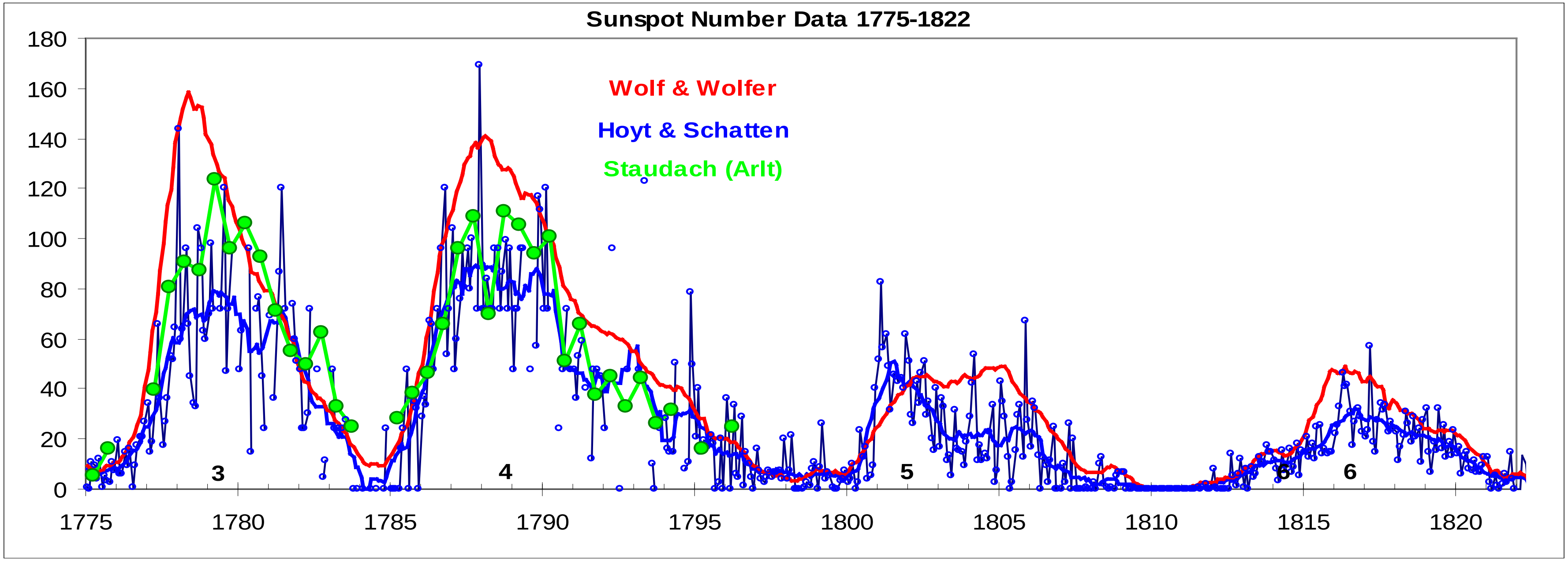


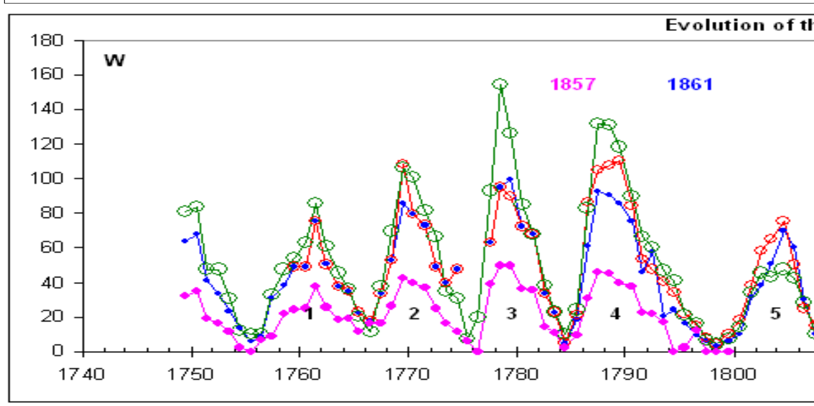
Wolf's SSN was consistent with his many-station compilation of the diurnal variation of Declination 1781-1880

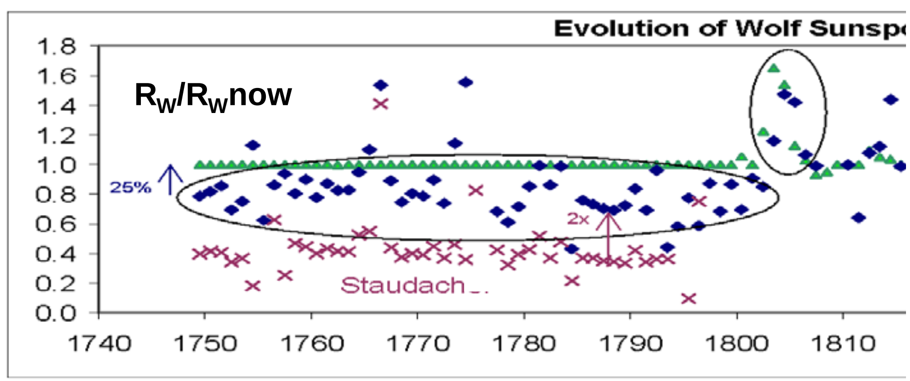


It is important to note that the relationship is *linear* for calculating averages

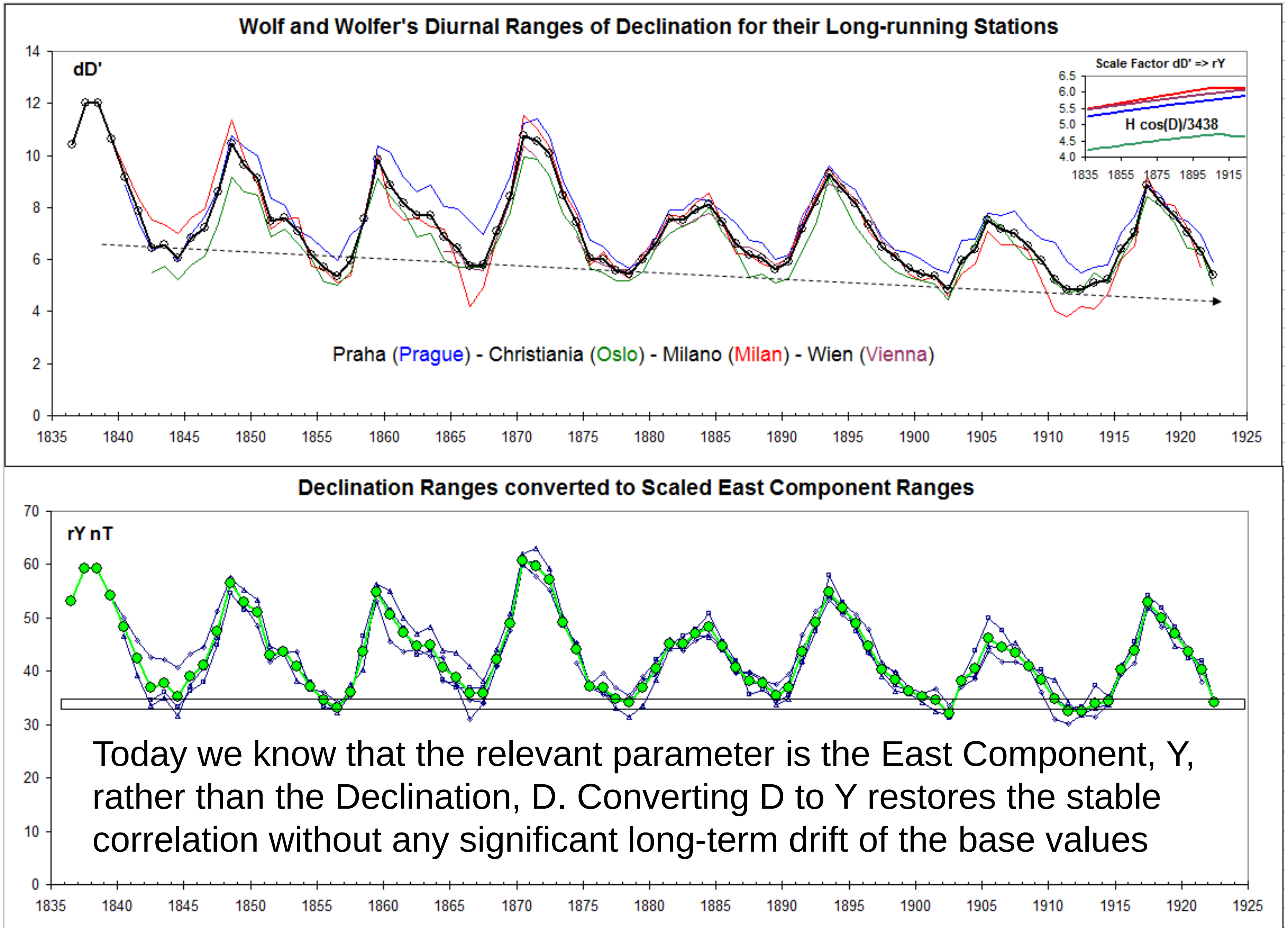
Adjustments to pre-Schwabe SSNs







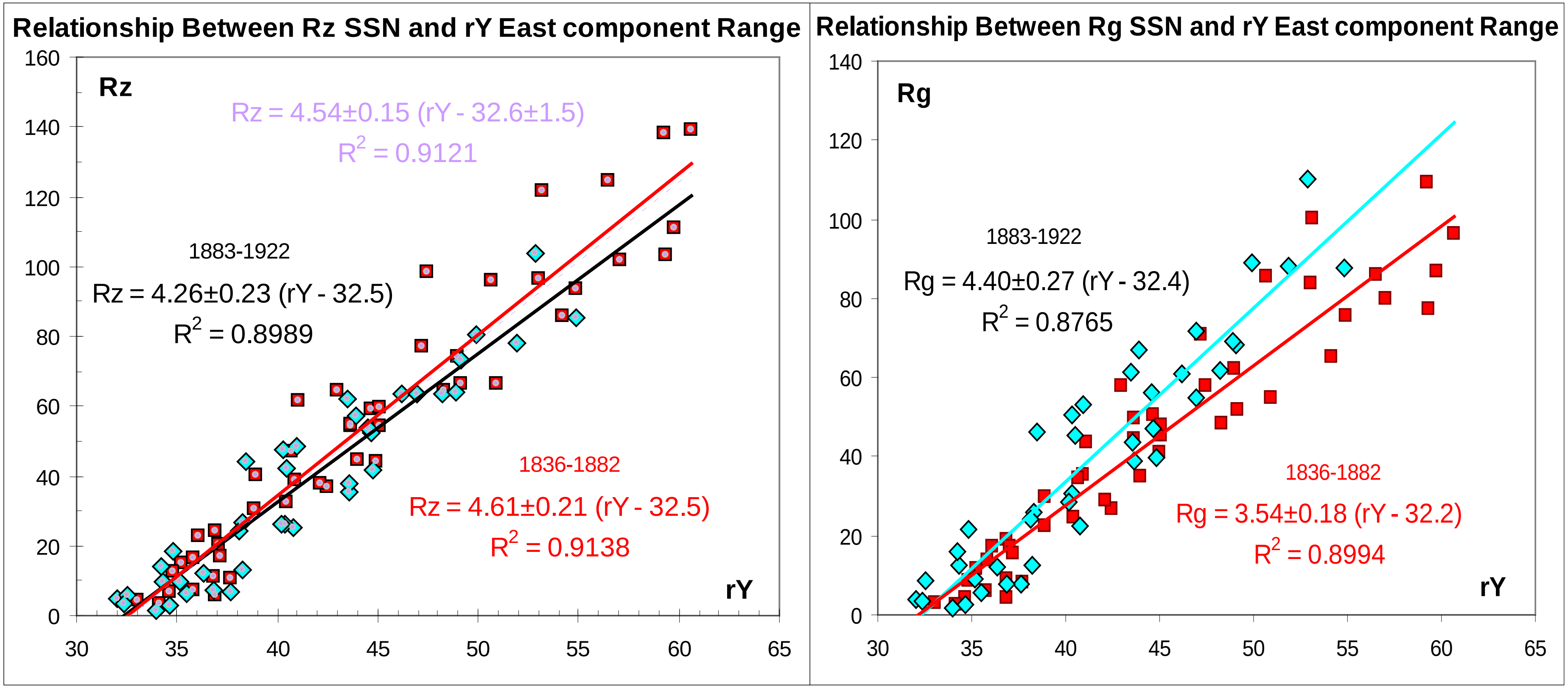
Wolf’s Favorite Geomagnetic Data



Wolf found a very strong correlation between his Wolf number and the daily range of the Declination.

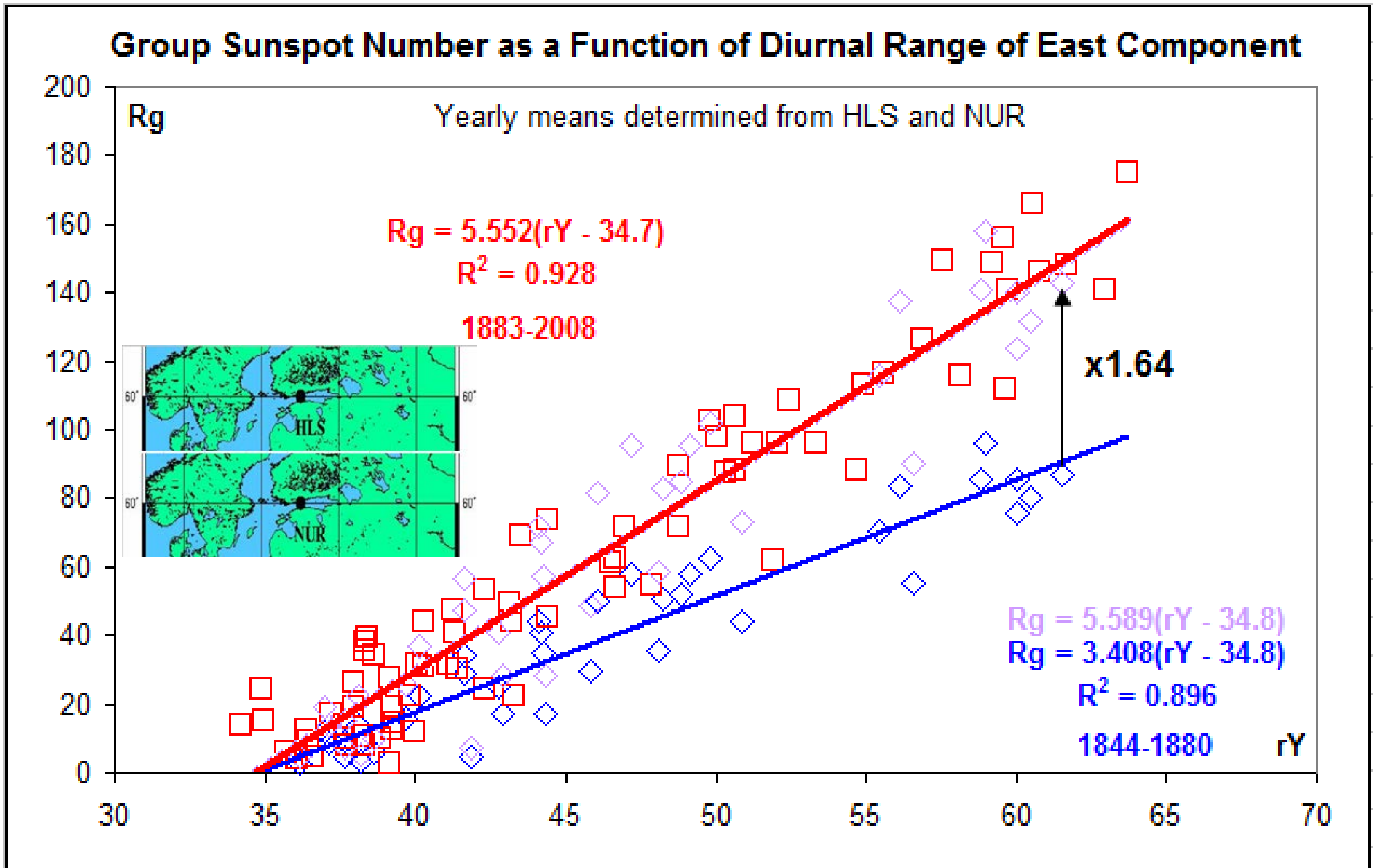
Wolfer found the original correlation was not stable, but was drifting with time and gave up on it in 1923.

Using the East Component We Recover Wolf's Tight Relationship



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

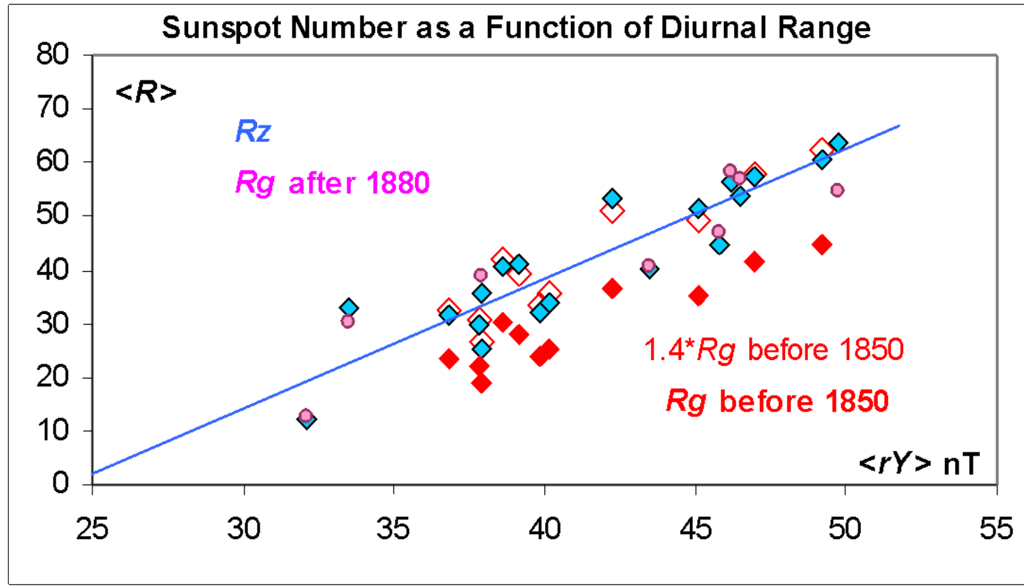
The HLS-NUR data show that the Group Sunspot Number before 1880 must be Increased by a factor 1.64±0.15 to match *rY* (F10.7)

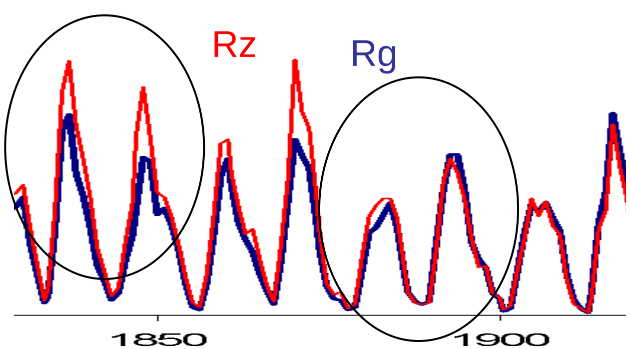


This conclusion is independent of the calibration of the Zürich SSN, Rz

Adolf Schmidt’s Uniform Data

obs	name	lat	long	interval
WDC	Washington D.C.	38.9	283.0	1840-1842
DUB	Dublin	53.4	353.7	1840-1843
MNH	Munchen	48.2	11.6	1841-1842
PGC	Philadelphia	40.0	284.8	1840-1845
SPE	St. Peterburg	60.0	30.3	1841-1845
GRW	Greenwich	51.5	0.0	1841-1847
PRA	Praha	50.1	14.4	1840-1849
HBT	Hobarton	-42.9	147.5	1841-1848
MAK	Makerstoun	55.6	357.5	1843-1846
KRE	Kremsmunster	48.1	14.1	1839-1850
TOR	Toronto	43.7	280.6	1842-1848
WLH	*Wilhelmshaven*	53.7	7.8	*1883-1883*
GRW	*Greenwich*	51.5	0.0	*1883-1889*
WDC	*Washington D.C.*	38.9	283.0	*1891-1891*
PSM	*Parc Saint-Maur*	48.8	0.2	*1883-1899*
POT	*Potsdam*	52.4	13.1	*1890-1899*
COP	*Kobenhavn*	55.7	12.6	*1892-1898*
UTR	*Utrecht*	52.1	5.1	*1893-1898*
IRT	*Irkutsk*	52.3	104.3	*1899-1899*



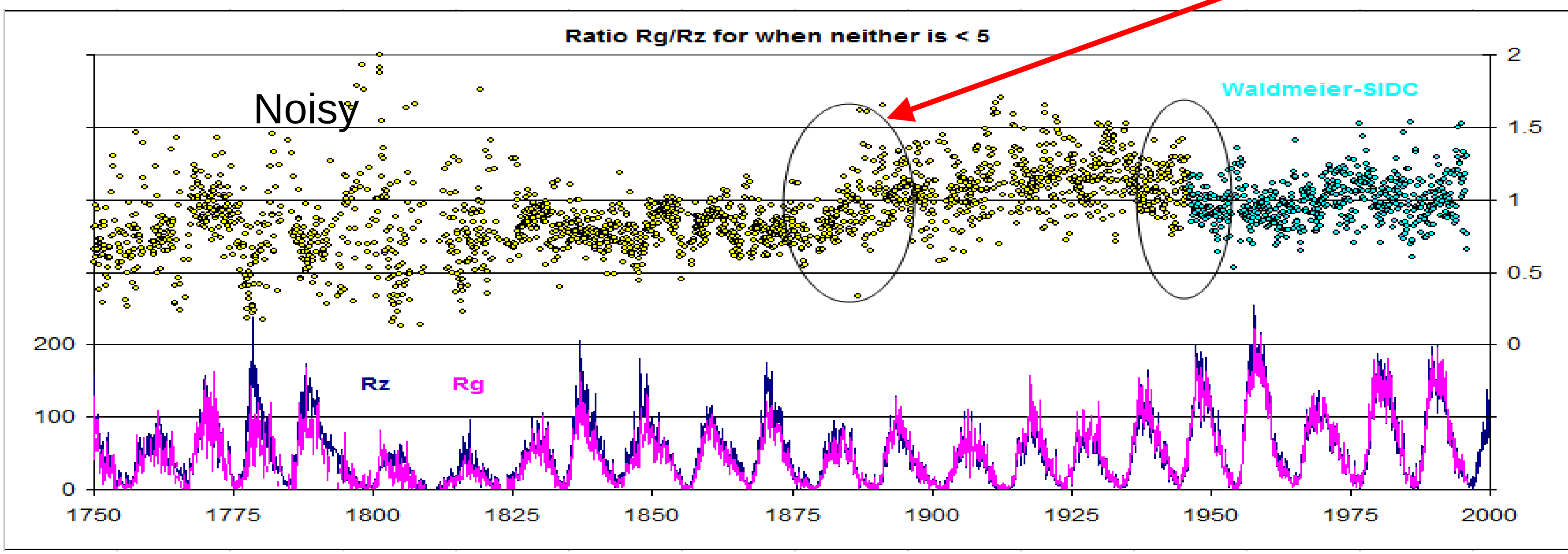


Extensive datasets exist [Schmidt, 1909] from the ‘Magnetic Crusade’ in the 1840s and for times after the First Polar Year 1882. Schmidt has presented that data in a ‘unified format’, processed the same way. From that <rY> can be determined and compared with <Rz> and <Rg> for the same intervals of time, confirming that Rg is ~40% too small before ~1880.

Established so far:

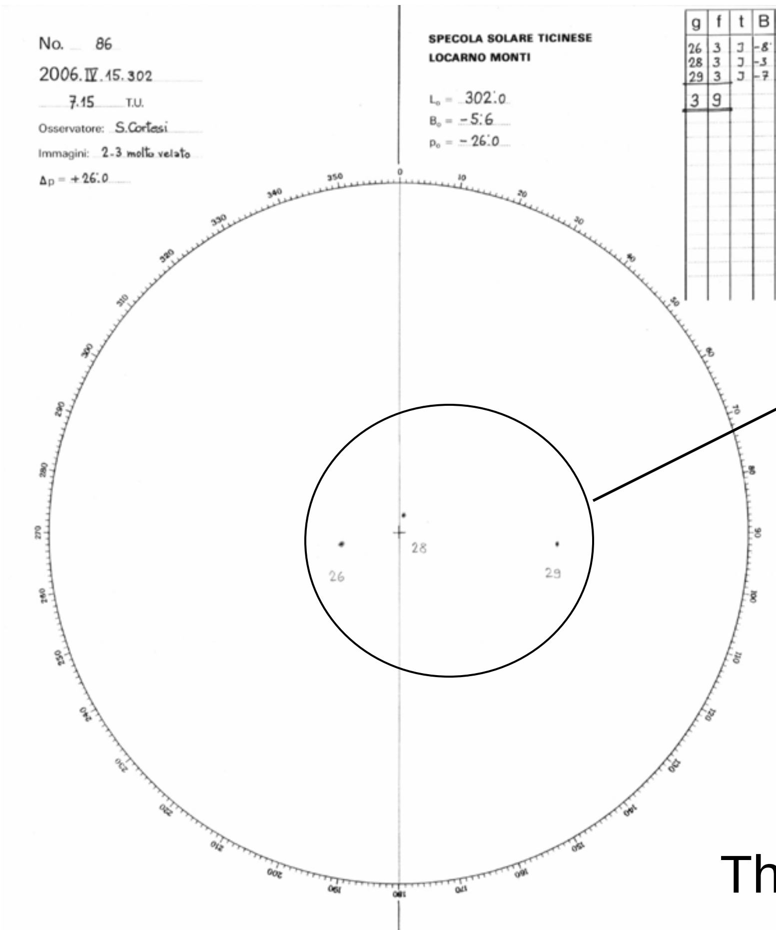
1. The Zürich Sunspot Number has a uniform calibration with respect to the Geomagnetic Response during the 18th and 19th centuries

2. The Group Sunspot Number is seriously too low [~40-60%] before ~1883 [cause under study]

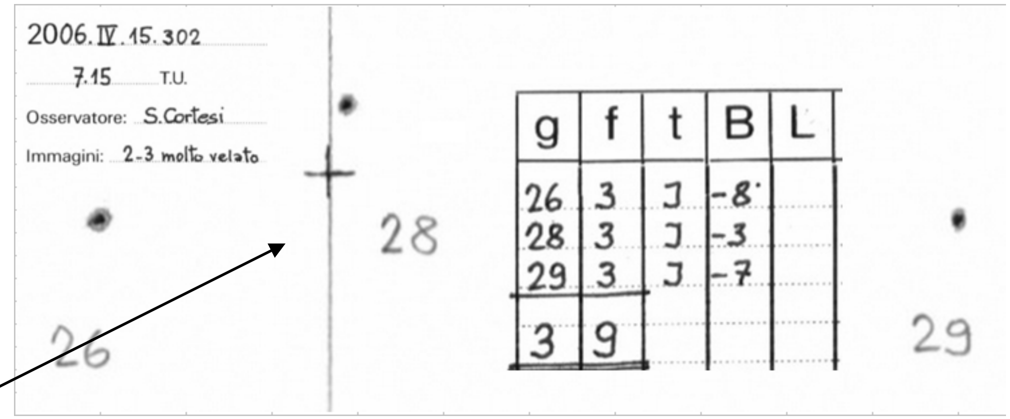


The Second Discontinuity ~1945

At some point during the 1940s the Zürich observers began to weight sunspots in their count



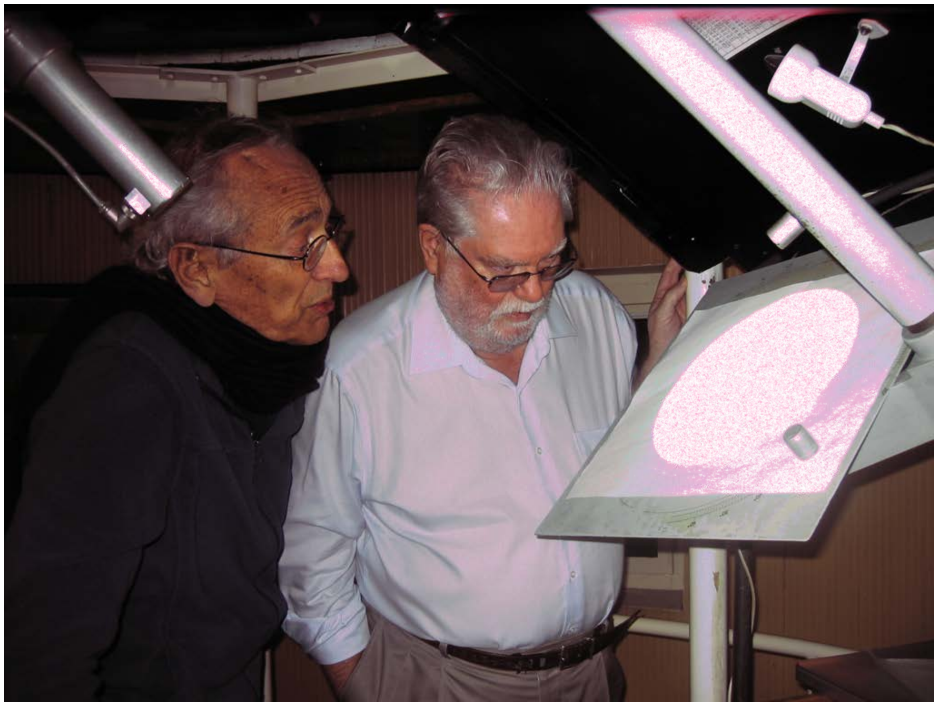
From the Reference Station Locarno by Lago Maggiore



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]

The weighting scheme is not generally known.

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

"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)

Waldmeier *did* have a couple of references to the weighting scheme, although he claimed that the scheme stemmed from 1882. We show elsewhere that it does not.

Waldmeier's Own Description of his [?] Counting Method

Astronomische Mitteilungen der Eidgenössischen Sternwarte Zürich
Nr. 285

1968

Die Beziehung zwischen der Sonnenflecken-relativzahl und der Gruppenzahl

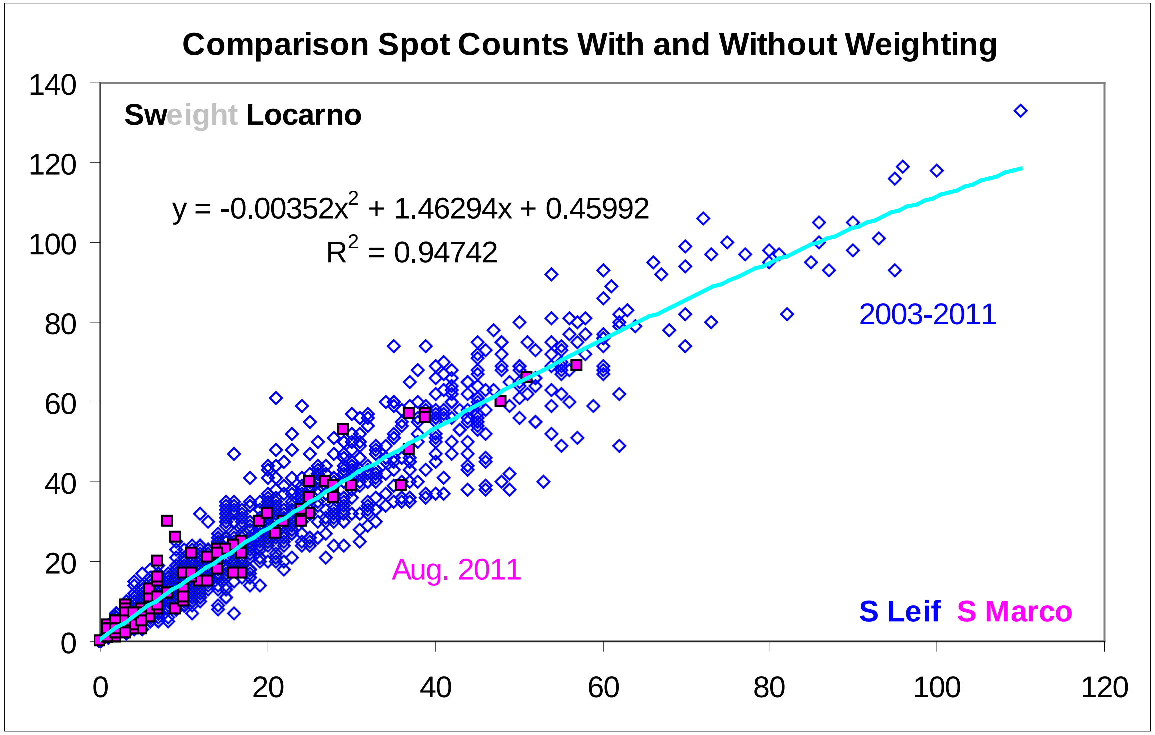
Von

M. Waldmeier

Hofflecken handelte. Später wurden den Flecken entsprechend ihrer Größe Gewichte erteilt: Ein punktförmiger Fleck wird einfach gezählt, ein größerer, jedoch nicht mit Penumbra versehener Fleck erhält das statistische Gewicht 2, ein kleiner Hoffleck 3, ein größerer 5. Die Gruppen- und

"A spot like a fine point is counted as one spot; a larger spot, but still without penumbra, gets the statistical weight 2, a smallish spot with penumbra gets 3, and a larger one gets 5." Presumably there would be spots with weight 4, too.

The Effect of the Weighting

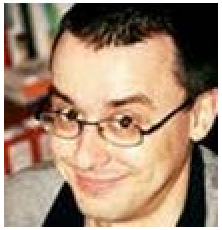


2[nd] degree fit

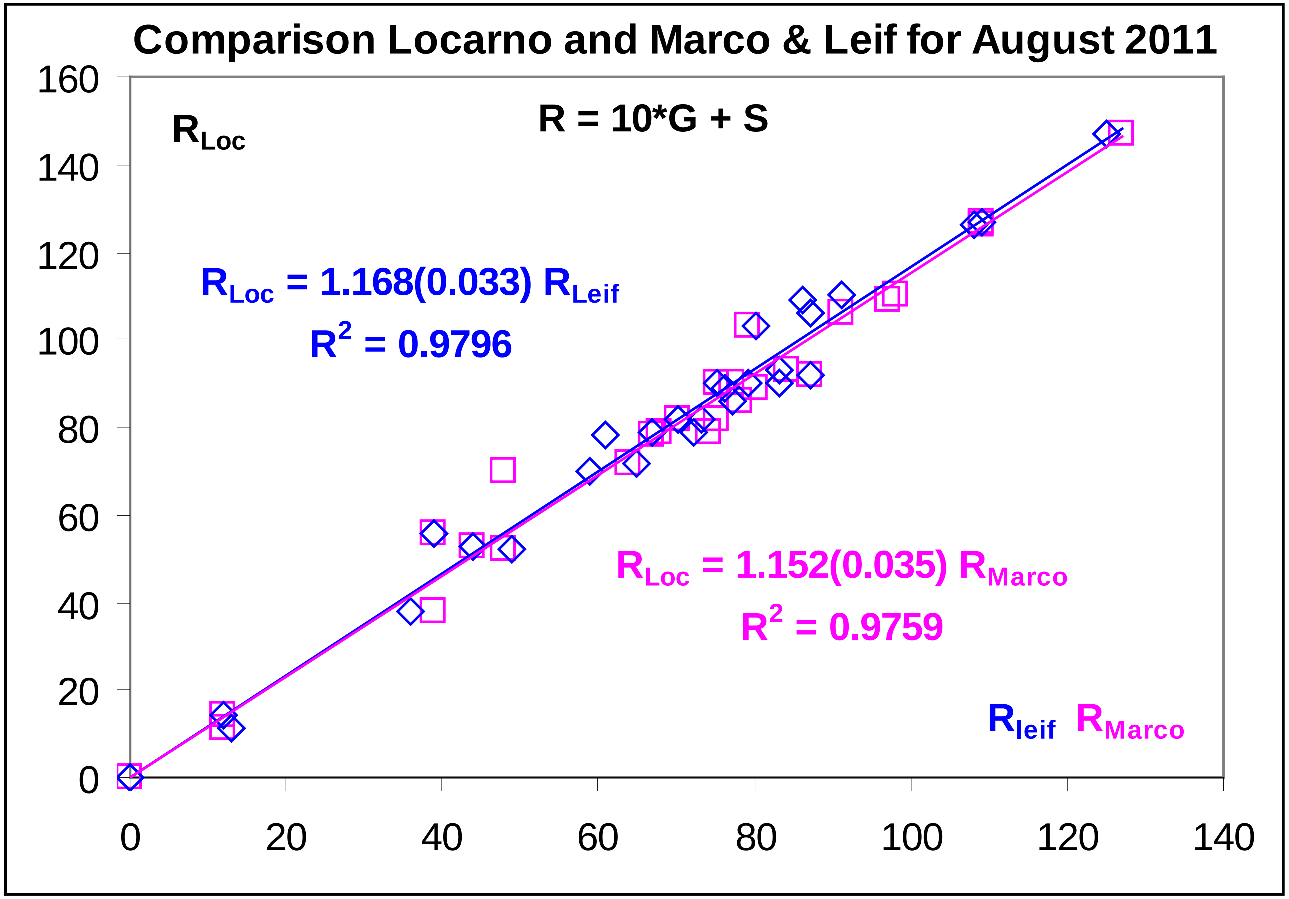
S	Sw	Sw/S
10	14.74	1.4737
25	34.83	1.3933
50	64.81	1.2961
75	90.38	1.2051
100	111.55	1.1155

For typical number of spots the weighting increases the 'count' of the spots by 30-50%

For the limited data for August 2011 Marco Cagnotti and Leif Svalgaard agree quite well with no significant difference. The blind test will continue as activity increases in the coming months.



Comparison of 'Relative Numbers'



But we are interested in the effect on the SSN where the group count will dilute the effect by about a factor of two.

For Aug. 2011 the result is at left. There is no real difference between Marco and Leif.

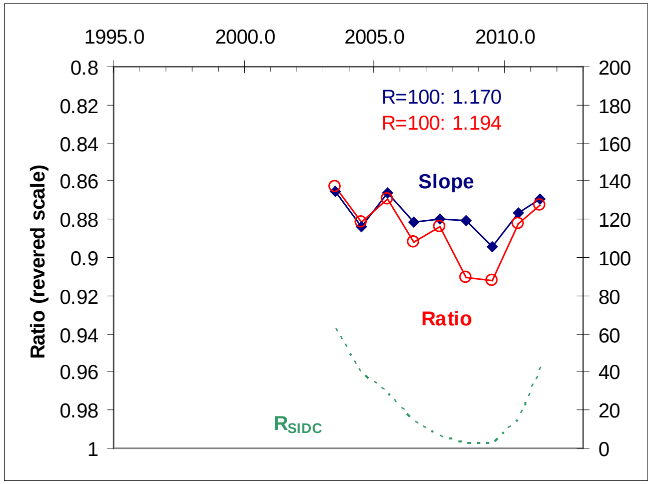
We take this a [preliminary] justification for my determination of the influence of weighting on the Locarno [and by extension on the Zürich and International] sunspot numbers

The Average Weight Factor

1.13+0.00040*R

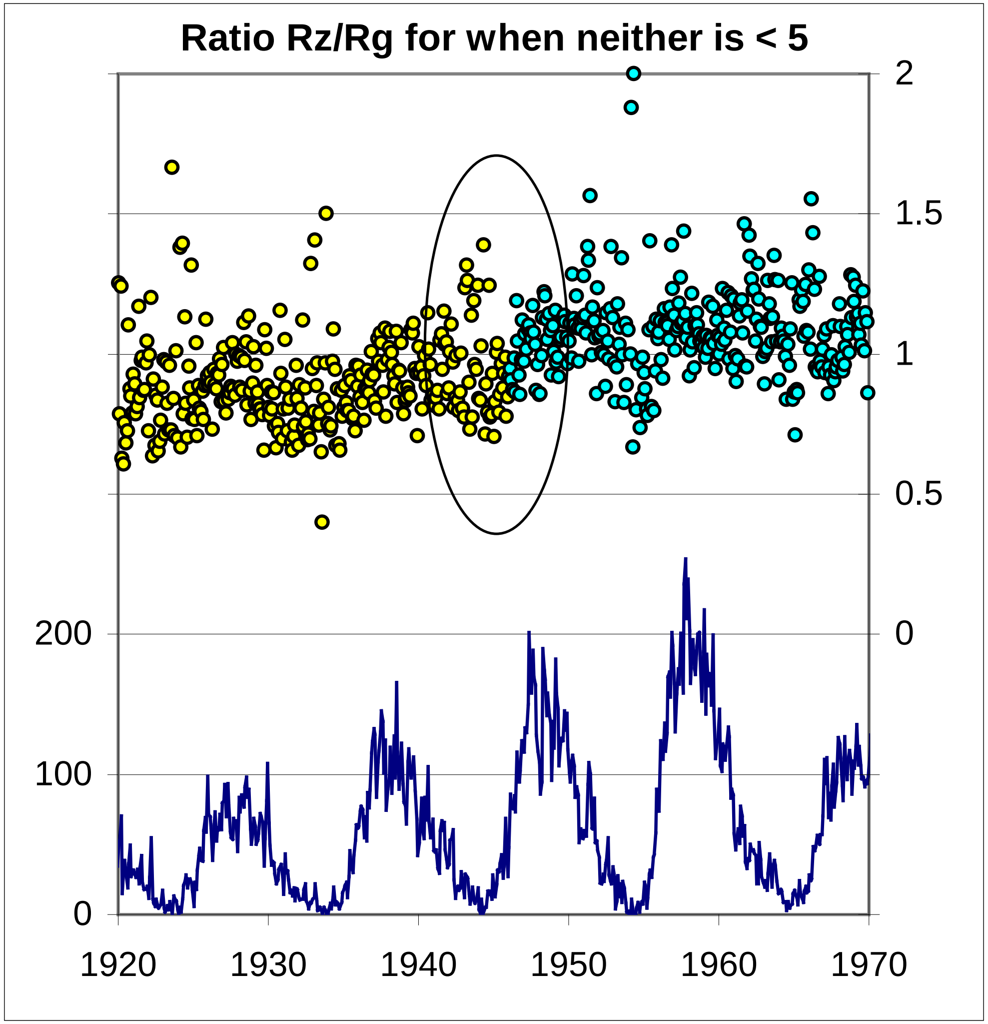
R=100 1.17

	slope	<Rloc>	<Rleif>	ratio	<Rsidc>	inv. Slope	count Loc
all	**0.8722**					**1.1465**	
2011.4	0.8691	70.29	61.36	0.8728	42.84	1.1506	211
2010.5	0.8767	28.30	24.96	0.8822	16.47	1.1406	285
2009.5	0.8945	4.74	4.32	0.9119	3.12	1.1179	309
2008.5	0.8807	4.00	3.64	0.9107	2.85	1.1355	297
2007.5	0.8801	12.33	10.90	0.8842	7.50	1.1362	332
2006.5	0.8814	24.55	21.89	0.8919	15.22	1.1346	312
2005.5	0.8662	50.37	43.80	0.8696	29.83	1.1545	318
2004.5	0.8838	68.63	60.50	0.8816	40.45	1.1315	303
2003.5	0.8654	108.69	93.83	0.8632	63.71	1.1555	190



For yearly values there is an approximately (but weak) linear relation between the weight factor and the sunspot number. For a typical R of 100, the weighting increases the sunspot number by 17%. We estimate that a ‘better’ determination of what makes a Group increases the SSN by another 3% for a total of 20%.

We can see this Effect in the Data

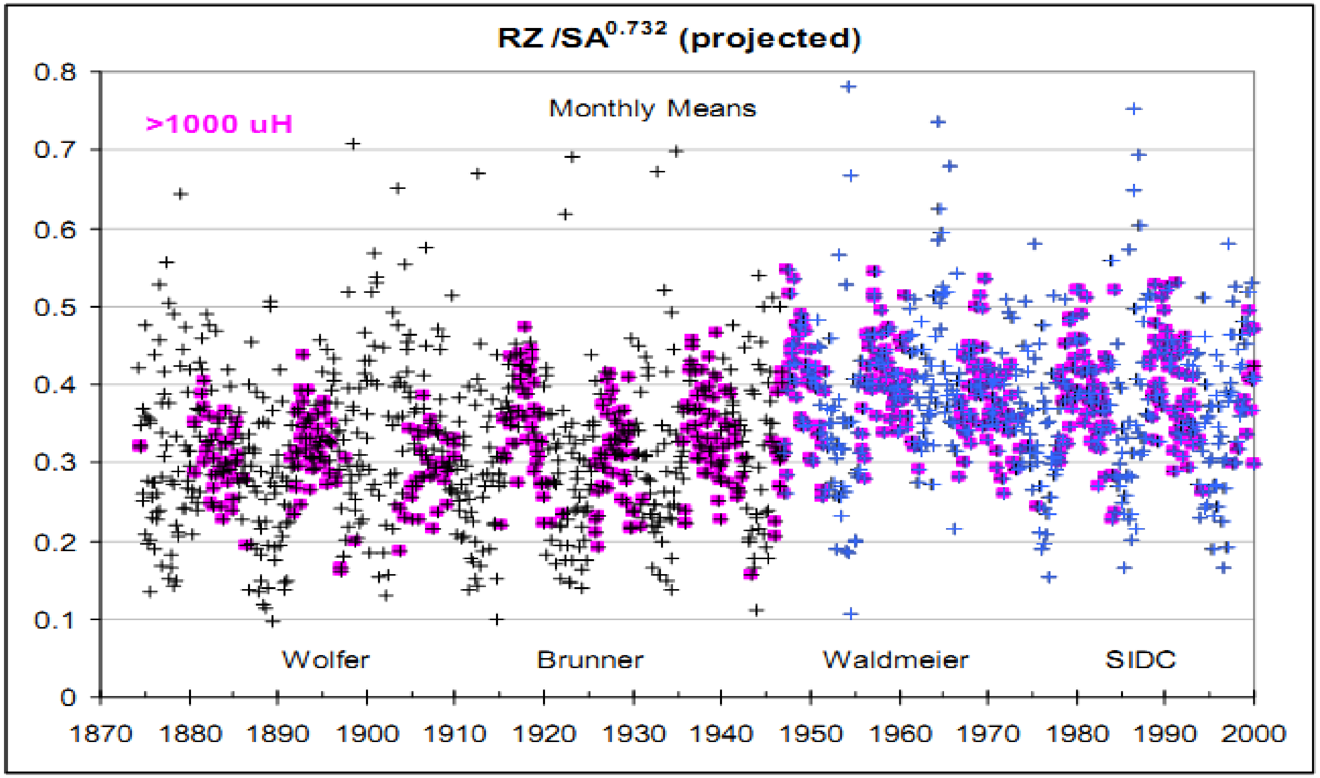


We can compute the ratio Rz/Rg [staying away from small values] for some decades on either side of the start of Waldmeier's tenure, assuming that Rg derived from the RGO data has no trend over that interval.

There is a clear discontinuity corresponding to a jump of a factor of 1.18 between 1945 and 1946. This compares favorably with the estimated size of the increase due to the weighting [with perhaps a very small additional influence from a greater group count]

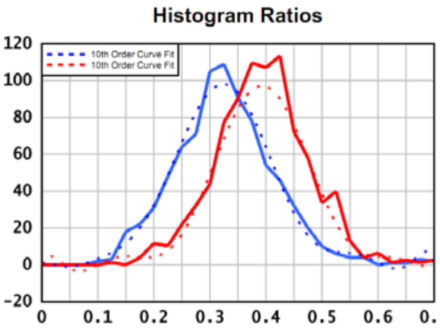
Corroborating Indications of the 'Waldmeier Discontinuity' ~1945

- SSN for Given Sunspot Area increased 21%



Clear change in the relationship around 1945

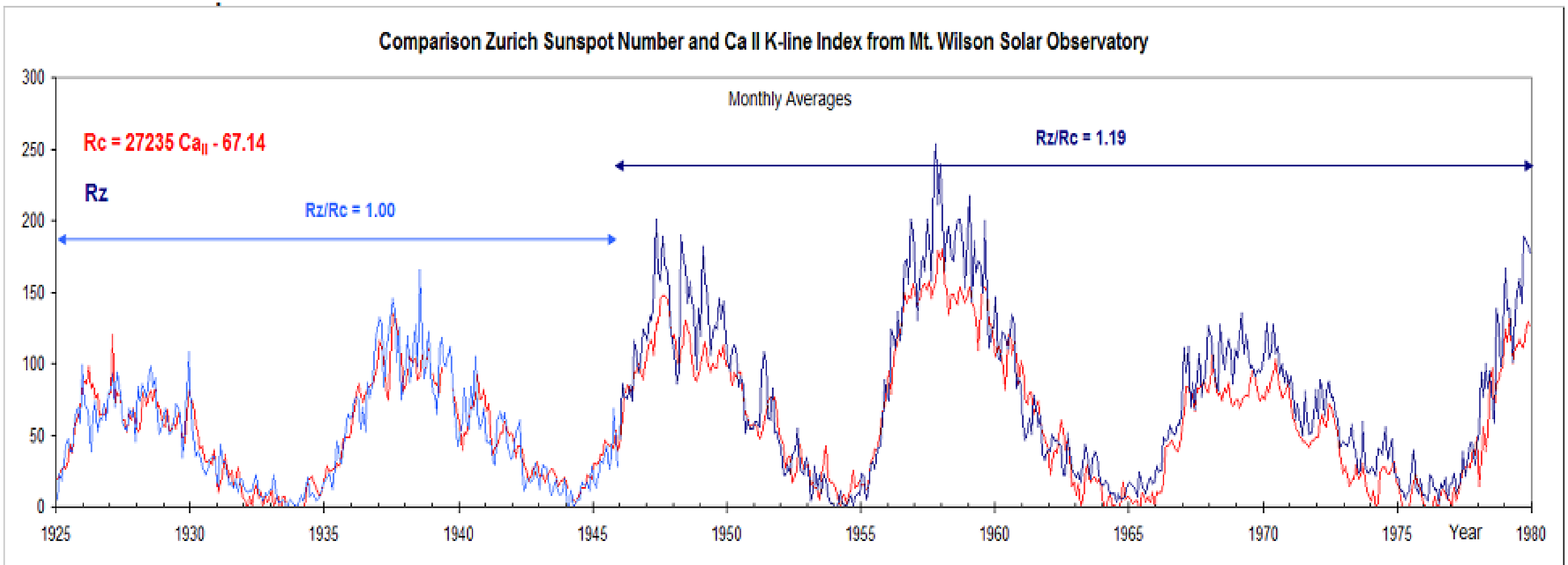
The relationship between sunspot number and sunspot area [SA, Balmaceda] is not linear, but can be made linear raising SA to the power of 0.732. Then taking the ratio makes sense.



Plotting Histograms of the ratio $Rz/SA^{0.732}$

Corroborating Indications of the 'Waldmeier Discontinuity' ~1945

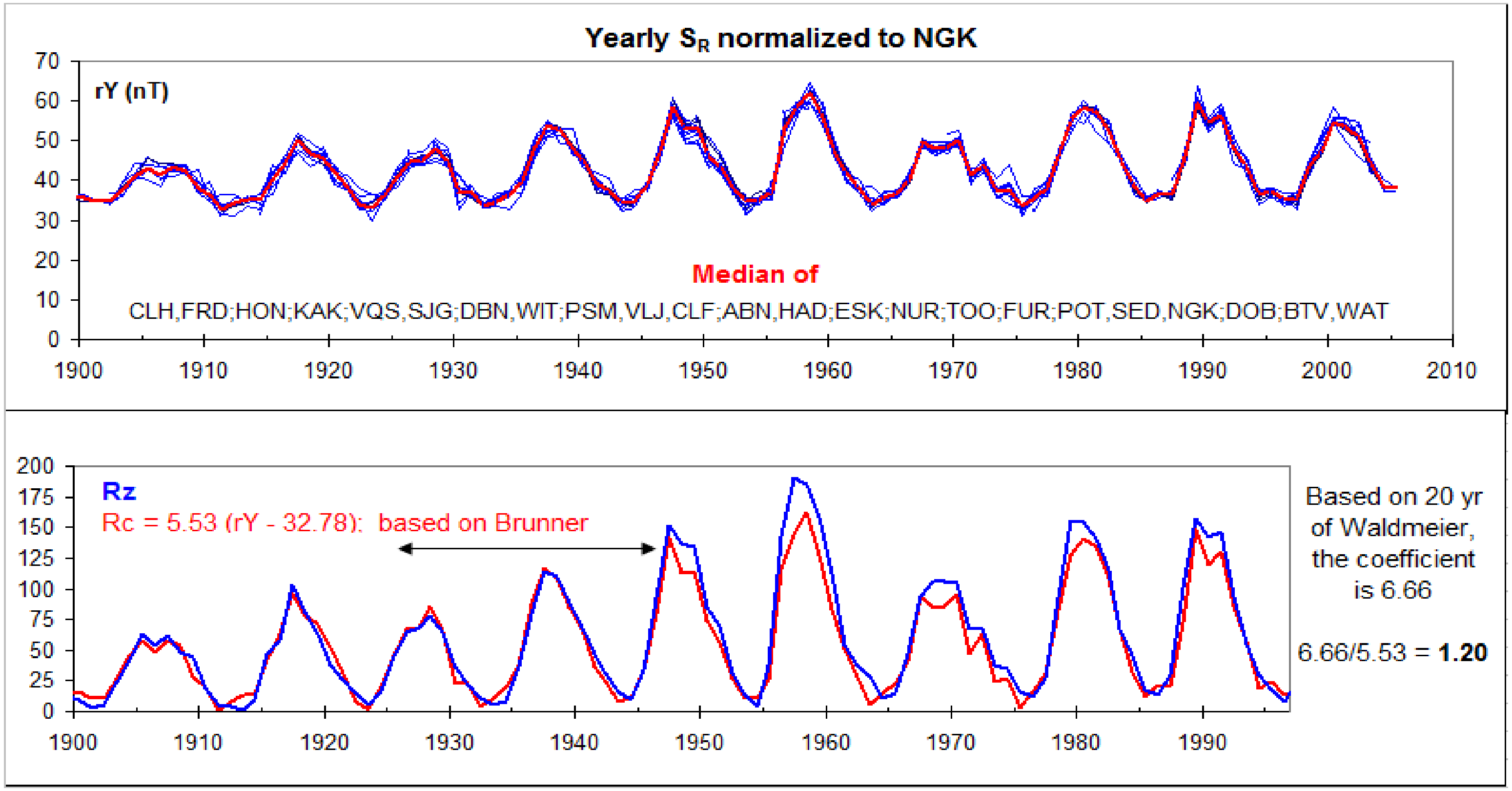
- SSN for Given Ca II K-line index up 19%



Waldmeier's Sunspot Number 19% higher than Brunner's from Ca II K-line

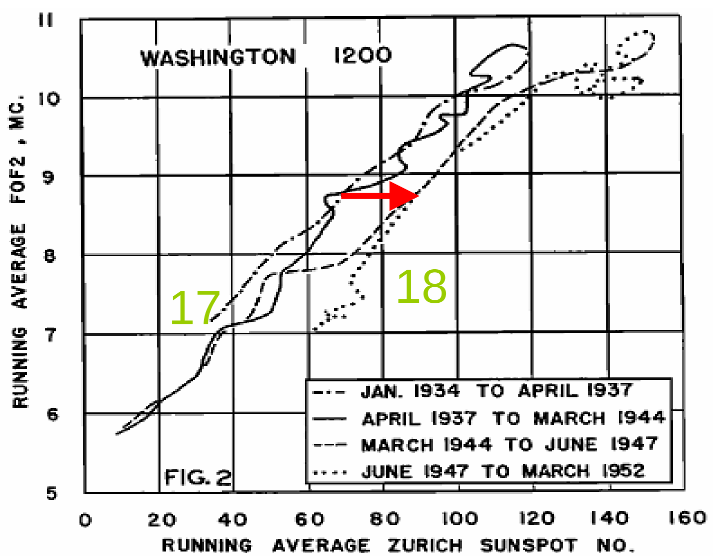
Corroborating Indications of the 'Waldmeier Discontinuity' ~1945

- SSN for Given Diurnal Variation of Day-side Geomagnetic Field increased by 20%



Corroborating Indications of the ‘Waldmeier Discontinuity’ ~1945

- Ionospheric Critical Frequency *foF2* depends strongly on solar activity. The slope of the correlation changed 21% between sunspot cycle 17 and 18



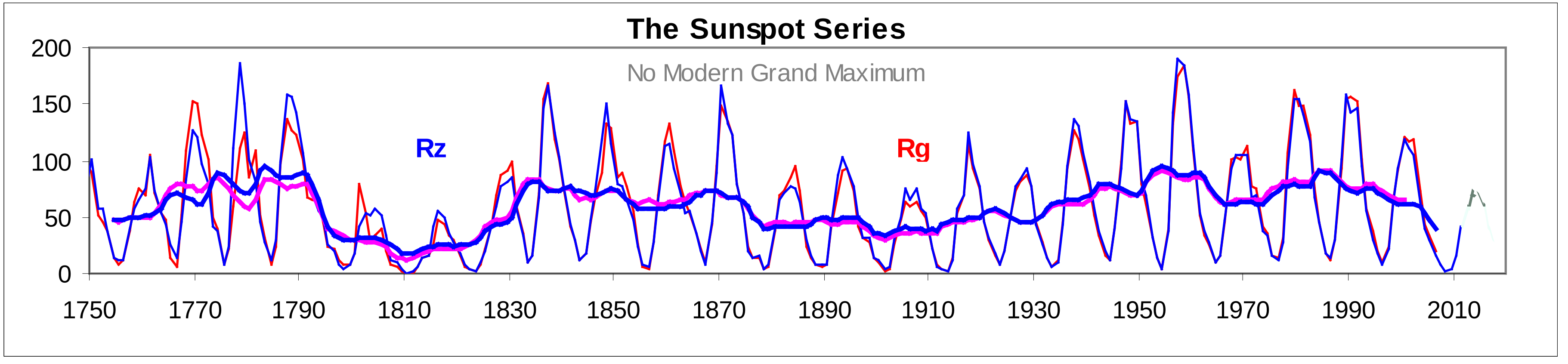
FIGS. 1 AND 2—PLOT OF 12-MONTH RUNNING AVERAGE OF MONTHLY MEDIAN $f^{o}F2$ AGAINST 12-MONTH RUNNING AVERAGE OF MONTHLY ZURICH SUNSPOT NUMBER, LOCAL TIME

F2-layer critical frequency. This is the maximum radio frequency that can be reflected by the F2-region of the ionosphere at vertical incidence (that is, when the signal is transmitted straight up into the ionosphere). And has been found to have a profound solar cycle dependence.

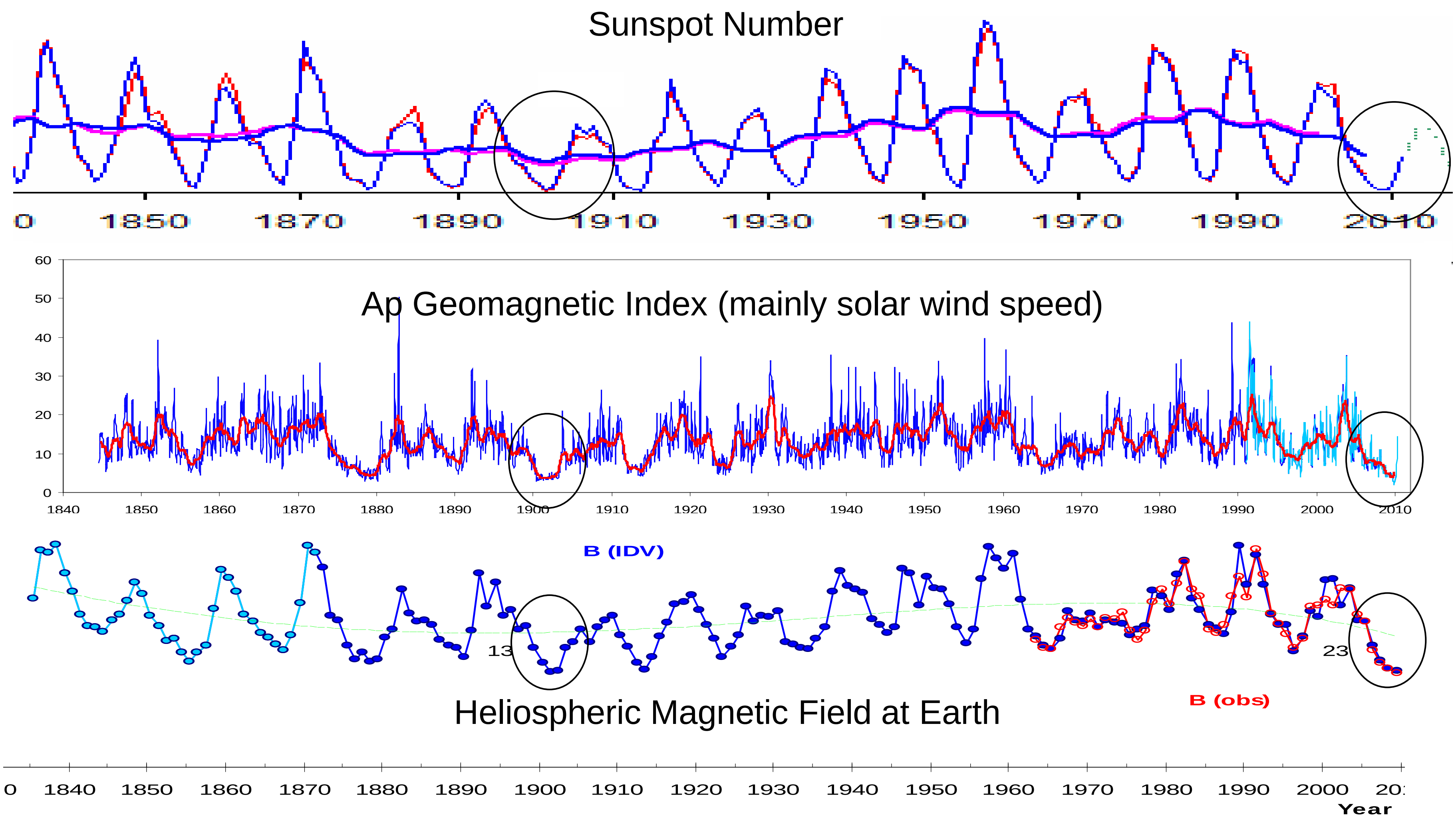
So, many lines of evidence point to an about 20% Waldmeier Weighting Effect

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
  (increase all before 1945 by 20%)
- The second adjustment [~50%] is to Rg ~1883
  (increase all before 1883 by 50%)



Solar Activity 1835-2011 now makes sense



Sunspot Number Workshop I, Sept. 2011

The implications of this conclusion are so important and wide ranging that a Workshop was convened [at Sunspot, New Mexico] to discuss these findings and settle [if possible] the questions and provide the community with an agreed upon and vetted single sunspot series for use in the future.

ve Dooling, NSO/AURA/NSF
URA Inc.

Participants included people from SIDC, NOAA, NSO, and AFRL involved in providing sunspot numbers for operational use.

Especially encouraging was the endorsement by Ken Schatten: "I can only support these efforts"

Next Workshop in Brussels [SIDC] in May, 2012