The Solar Radio Microwave Flux

Leif Svalgaard, May 2009

Since 1947 we have routinely measured the flux of microwaves from the Sun at wavelengths between 3 and 30 cm [frequencies between 10 and 1 GHz]. This emission comes from high in the Chromosphere and low in the Corona and has two different sources [although there is debate about their relative importance]: thermal bremsstrahlung [due to electrons radiating when changing direction by being deflected by other charged particles] and 'gyro'-radiation [due to electrons radiating when changing direction by gyrating around magnetic field lines]. These mechanisms give rise to enhanced radiation when the temperature, density, and magnetic field are enhanced, so the microwave radiation is a good 'measure' of 'general' solar activity. As strong magnetic fields are located in specific regions that can live for weeks and often reoccur at or near the same location for months [perhaps even years], there is a strong rotational signal in the emission superposed on a solar cycle variation of a 'background' activity level. At solar minimum, especially a 'deep' one as we now experiencing, the effect of active regions largely disappears and we observe a sort of solar 'ground state'.

As the radio flux measurements [as opposed to the sunspot number] are unaffected by changes of [human] observers and their observing techniques and instrumental and atmospheric differences they may be a 'truer' and more objective measure of solar activity [to the extent that we can reduce this complex concept to a single number per day] and the many decades-long flux record could throw light on the important issue of the long-term variation of solar activity. The solar microwave flux is nominally an *absolute* flux, one solar flux unit defined as [the *very small* amount of] 10^{-22} Watt per square meter per Hertz. Making an absolute measurement is always difficult and considerable uncertainty and debate surrounded these measurements early on, before being settled by international cooperative work in the late 1960s [Tanaka et al., *Solar Phys.* **29** (1973) p. 243-262; http://www.leif.org/research/Tanaka-Calibration-F107.pdf]. By observing the radio flux from supernova remnants [Cassiopeia-A, Cygnus-A, and Virgo-A] one can verify the constancy of the calibration.

The longest running series of observations is that of the 10.7 cm [2800 MHz] flux [often simply referred to as 'F10.7'] started by Covington in Ottawa, Canada in April 1947 and maintained to this day[and hopefully much longer] at Penticton site in British Columbia [http://www.hia-iha.nrc-cnrc.gc.ca/drao/solar_e.html]. The data is available from several sources, e.g. from the NGDC at http://www.ngdc.noaa.gov/stp/SOLAR/FLUX/flux.html, more timely at ftp://ftp.geolab.nrcan.gc.ca/data/solar_flux/daily_flux_values/current.txt. There are three measurements per day with small systematic [and poorly understood] differences. One can either average all three, or as in this work only use the noon value [for Penticton at 20:00 UT, since 1991].

As with all solar indices, there is the issue of the varying distance between the Earth and the Sun. For describing the effect on the Earth's atmosphere and environment the proper values of the indices to use should, of course, be the ones observed at the Earth, but for studying the Sun, those values must be adjusted to the mean distance [at 1 astronomical

unit]. This is not always appreciated and one sees endless discussions about F10.7 changes or flat-lining without the 7% change caused by the varying distance being taken into account. Needless to say, here we use the 'adjusted flux'.

So, what does the record look like? Figure 1 shows the entire record up to date of writing [14 May, 2009], plotting the ~23,000 daily noon values [pink curve] and a running 27-day mean [black curve]:
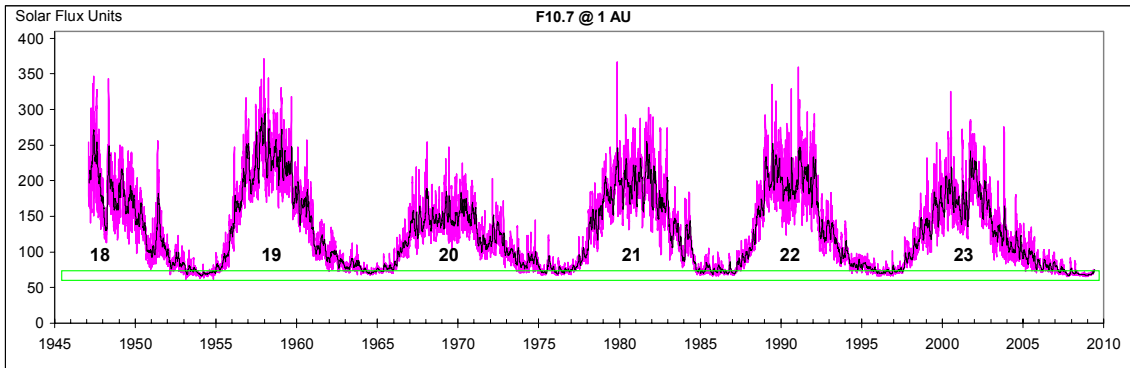

The solar cycle variation is obvious, but so is another fact: [highlighted by the green box] that the flux at every minimum is very nearly the same. There has been no clear systematic variation or trend in the 'ground state'. Figure 2 shows the 1954 minimum overlaid the current minimum, and is a rather dramatic demonstration of the constancy of the ground state (also shows nicely the 27-day recurrence tendency):
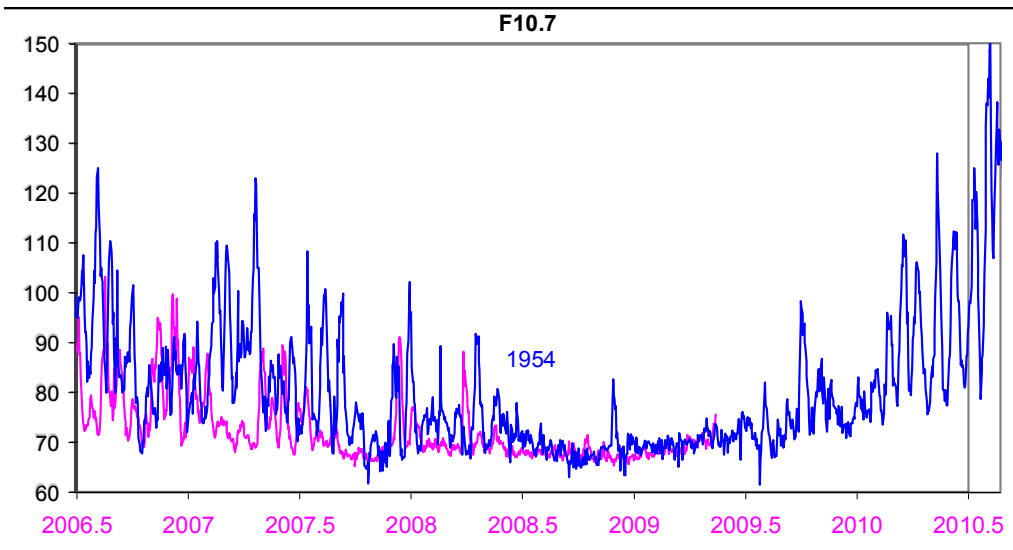

Other observatories have long and continuing series of measurements of the microwave flux. Of note is the long series from Japan (Toyokawa 1951 Nov – 1994 Apr; Nobeyama 1994 May - present) at several wavelengths around the 10.7 cm (e.g. 3.75 GHz = 8 cm; 2 GHz = 15 cm; and 1 GHz = 30 cm). The fluxes at these wavelengths are highly correlated with each other. Figure 3 shows the correlation of 3.75 GHz versus 2 GHz:
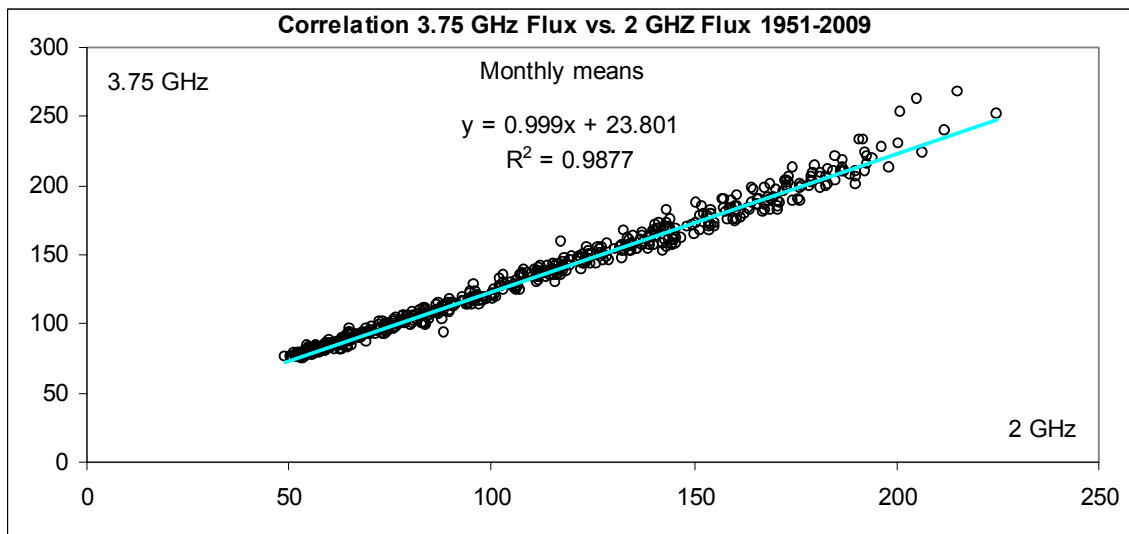
This means that we can use the regression equations to put all the measurements on the same scale, scaling [marked with an asterisk] them to 3.75 GHz (Figure 4):
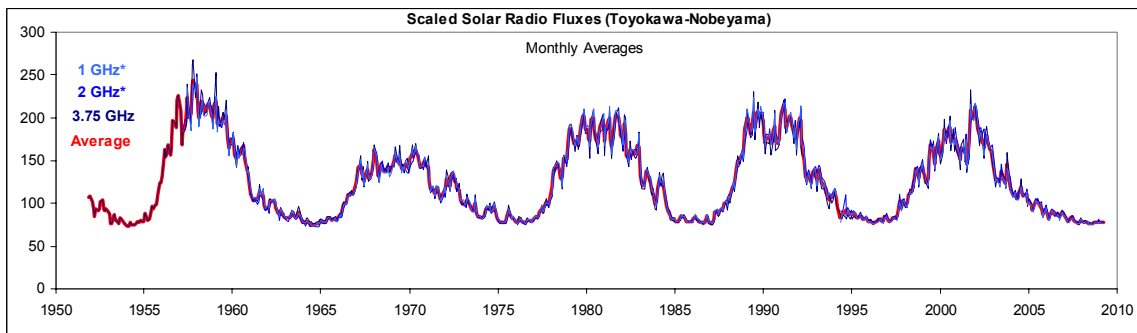
This looks very much like Figure 1 [the coefficient of determination of the correlation with F10.7 is as high as $R^2 = 0.987$, which is a welcome finding as one observatory series then supports the other, at least to the accuracy of the scatter plot]. Scaling the average of the Japanese [scaled] observations to F10.7 we obtain (Figure 5):
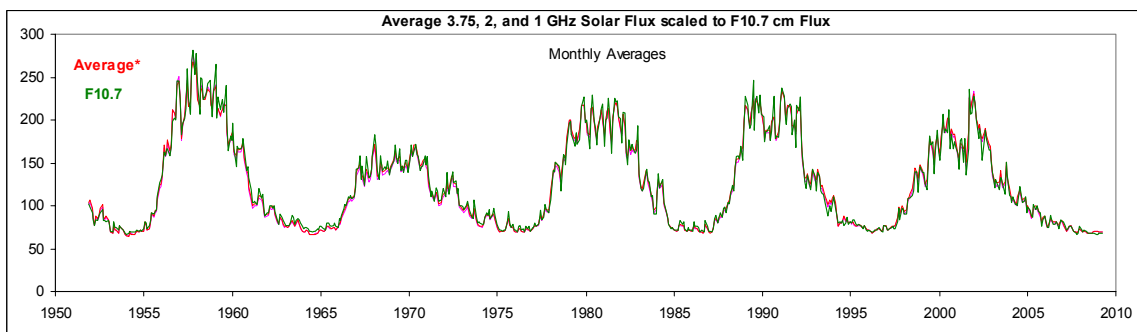
If you look very closely, you might see that the red curve (Japanese stations) lies a little bit below the green curve (Canadian stations) before 1991 and a little bit above the green curve thereafter. Here is a plot of the ratio of the flux values of the two series (Figure 6) with different colored symbol for the Ottawa and Penticton data:
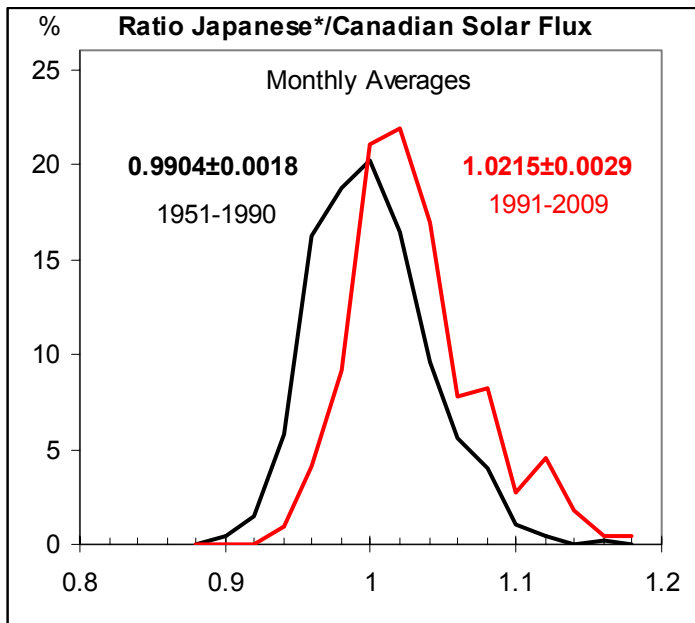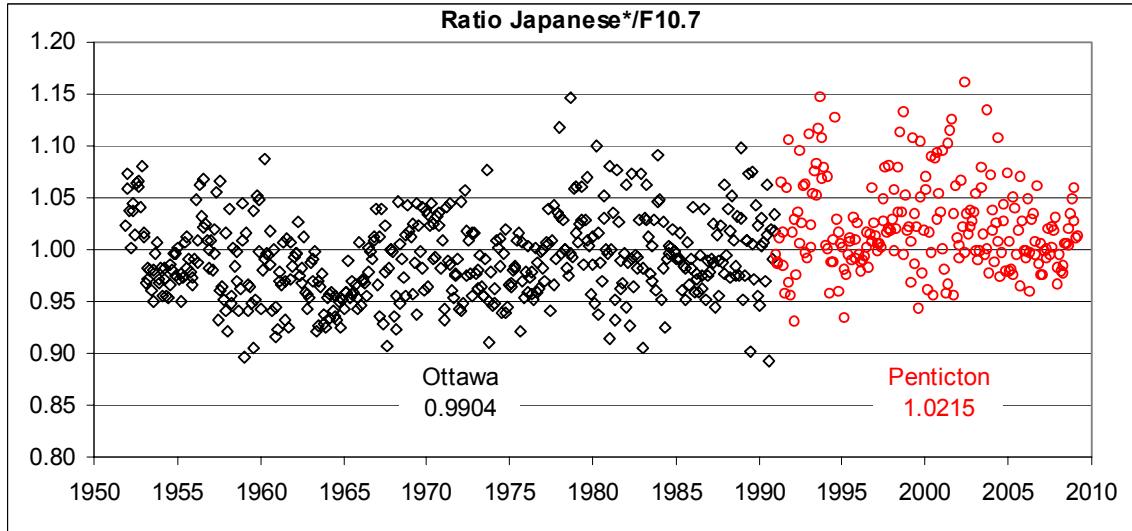

Histograms show clearly the statistical significance (10 σ) of the 3% difference in ratios. We ascribe that to a small systematic difference between the Ottawa and Penticton series rather than to a break in the Japanese series in 1994 [mainly based of the weak argument that none of the several Japanese series at four different frequencies indicate any such break]. Figure 7, left. In any event, the change is but small.

Adding 3% to the Ottawa flux before 1991, rescaling the Japanese measurements to the thus corrected Canadian series, and computing the average flux from the two series gives us the *composite* series shown in Figure 8 below. All of these adjustments are very small, though, and do not substantially alter any conclusions drawn from the measurements. Although the microwave flux measurements are said to be absolute, a further correction [multiplication by the 'URSI'-factor of 0.9] is required to get the 'real flux'. We shall ignore that constant factor as only the relative variation is of interest here.
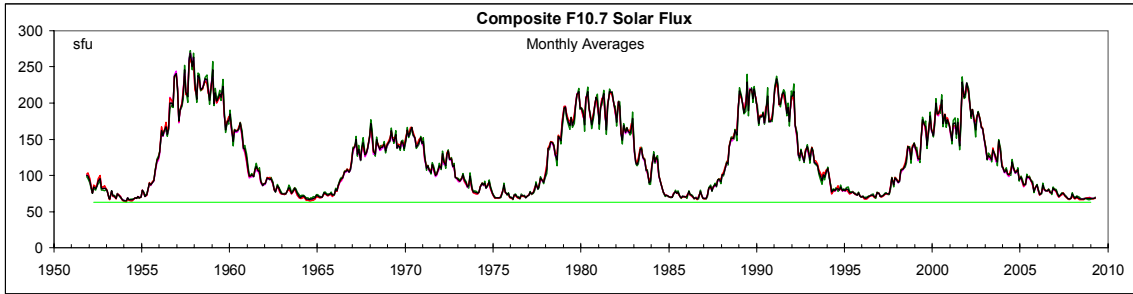
The red and green curves in the composite graph show the Canadian and [scaled] Japanese series going into the composite. On the whole, there is substantial agreement and the microwave flux seems well-determined.

One can now ask how this measure of solar activity compares to other measures, in particular the sunspot number [the Wolf Number]. Anticipating a finding described later, we correlate the sunspot number against the F10.7 flux (Figure 9) for the interval 1951-1988, and obtain a purely formal polynomial fit [as the relationship is not quite linear]:
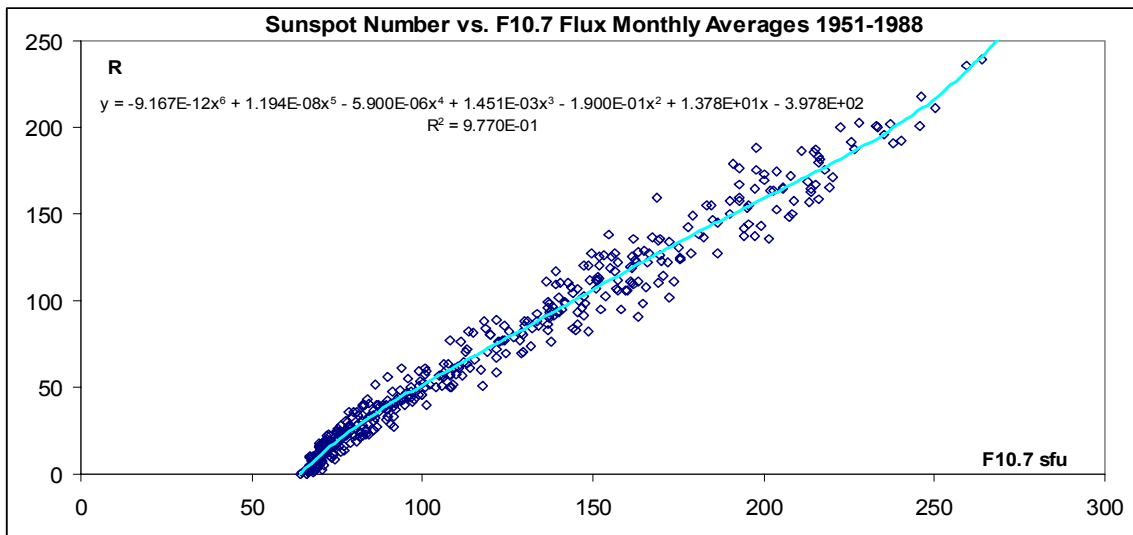

The fit is good ($R^2 = 0.977$) up until ~1989.0 after which time the observed sunspot number falls progressively below the fitted number (Figure 10):
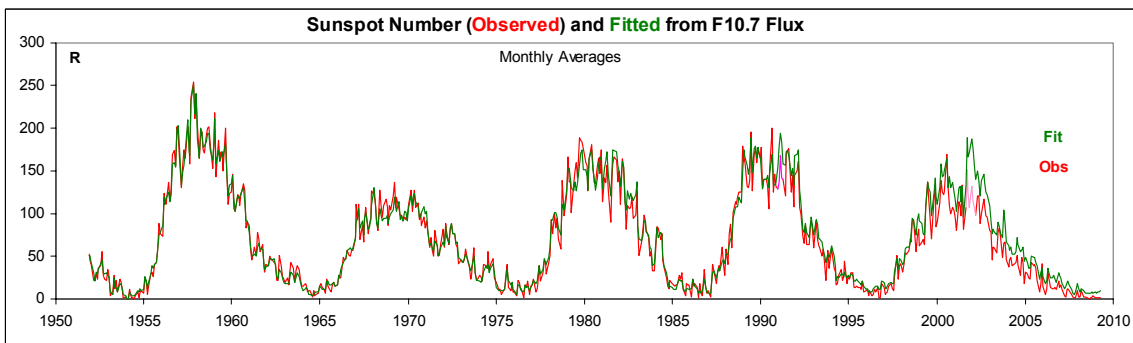
To quantify the drift we divide the observed sunspot number by the fitted one. When the sunspot number is very low [near minimum, marked by *m*; worst case, zero] that quotient becomes very noisy or meaningless, so we plot only cases where the sunspot number was above 5 (Figure 11):
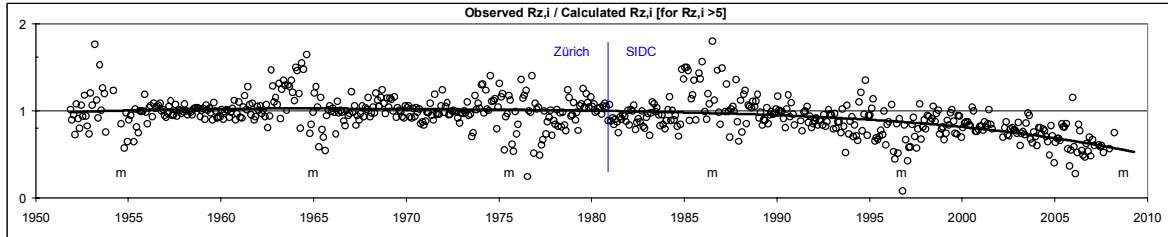
The progressive drift is much larger than the 3% correction and is therefore not due to the correction. It seems inescapable that the relation between the sunspot number and the microwave flux has changed significantly in recent years. Another way of showing this is Figure 12:
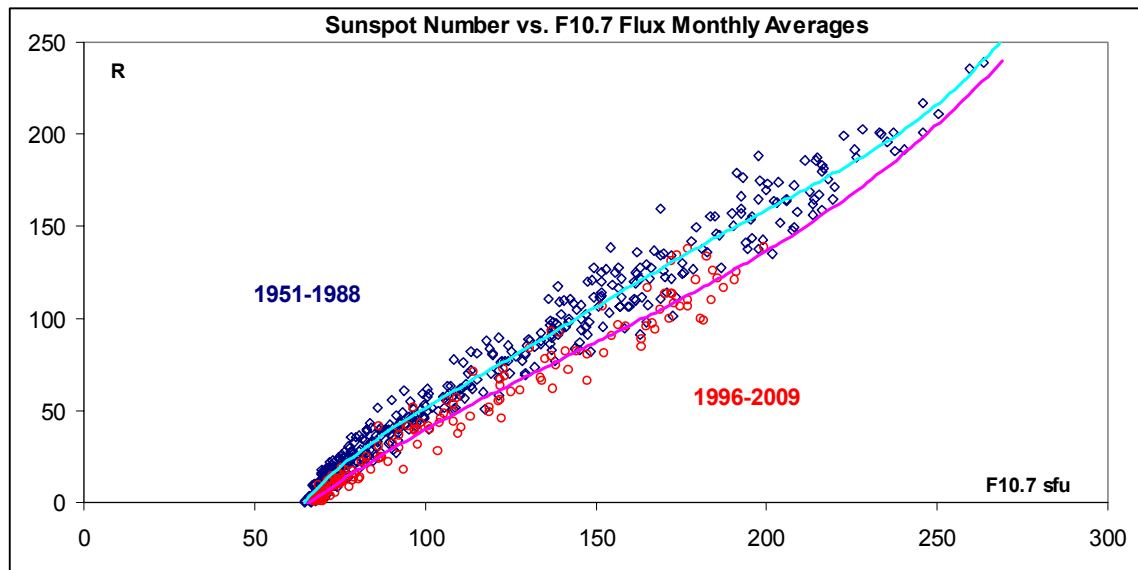
Ken Tapping has come to a similar conclusion (from the 2009 Space Weather Workshop: http://www.fin.ucar.edu/UCARVSP/spaceweather/abstract_view.php?recid=995):
"The Changing Relationship between Sunspot Number and F10.7": Sunspot Number and the 10.7cm solar radio flux are the most widely-used indices of solar activity. Despite their differing nature and origins at different places in the Sun, these two indices are highly-correlated to the point where one can be used as a proxy for the other. However, during Solar Activity Cycle 23 we started to see a small but definite change in this relationship…"

So far we have been on the [relatively] firm ground of data analysis, but when it comes to an explanation of the changed relationship, we enter the realm of pure speculation [for now]. Three obvious hypotheses present themselves:

1) The sunspot counting procedure or observers have changed with resulting artificial changes of the sunspot number as they have in the past.

2) Changes in the Corona or Chromosphere accounting for additional F10.7 emission.

3) Livingston & Penn's observations [http://www.iop.org/EJ/article/1538-4357/649/1/L45/20946.web.pdf?request-id=e22b7626-e93b-4ce3-b6f1-a999655b8888] that the sunspots are getting warmer during the last decade, leading to a decreased contrast with the surrounding photosphere and hence lessened visibility, possibly resulting in an undercount of sunspots.

There has been some criticism of SIDC and SWPC recently related to counting small pores, changing the count inexplicably, and various mistakes, but it seems to this writer that these problems would not be serious enough to account for the continuous and progressive drift shown in Figure 11. The near constancy of the flux at minima since 1954 argues against a change of the physical conditions at the source locations, leaving the exciting possibility that Livingston & Penn may be correct.