

## 50-MHz F-Layer Propagation and Solar Cycle 24

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***Six Meters, a Propagation Laboratory*** – The six-meter band is an interesting place to explore ionospheric propagation. When HF conditions are good, as they often are, signals frequently simultaneously propagate by more than one mechanism, and often by more than one path. Untangling these overlapping phenomena can be difficult.

By contrast, while these same propagation processes can occur at six meters, they are relatively rare. As a result, when they occur, often the propagation modes occur in relative isolation, making it easier to understand how they really behave. While the primary discussion here is about F-layer propagation, this principle applies to the E layer as well.

***F Layer and the Sun*** – The F layer is ionized primarily by extreme ultraviolet (EUV) radiation from the Sun. The intensity of solar EUV is strongly dependent on the phase of the solar activity cycle. "Average" levels of solar EUV are not sufficient to raise the MUF above 50 MHz. Consequently, six-meter F-layer propagation is confined almost entirely to the *peak* years of the solar activity cycle<sup>1</sup>. There are actually *two*, intimately related, "solar cycles": the *activity* or "sunspot" cycle, and the solar *magnetic* cycle<sup>1</sup>.

***Solar Activity Cycle*** – The sunspot cycle peaks roughly every 11 years. Sunspots are always found in bipolar pairs or bipolar groups, and they occur in two latitude bands, one north and the other south of the solar equator (Fig. 1 – Left). They come and go within those latitude bands with lifetimes of a few days to several weeks. As a result, some large, persistent spots and groups may live long enough to rotate out of view and then come back into view again 14 days later.

***Solar Magnetic Cycle*** – The *activity* cycle, with its sunspots, solar flares, and coronal mass ejections (CMEs) is the result of an *underlying* cycle of *magnetic* activity *within* the Sun. The period of the solar *magnetic* cycle averages about 22-years.

At *solar minimum*, the global average solar magnetic field is about 1 gauss. At this point, it is basically a dipole with its axis passing through the solar north and south poles. However, the outer layers of the Sun rotate *differentially*. The equatorial plasma rotates fastest ( $\approx 27$  days). The remaining regions rotate progressively slower as one goes further from the equator toward the poles. As the solar cycle progresses, this has the effect of wrapping up the magnetic field in two regions, one north of the equator and the other south of the solar equator – much like ropes wrapping around an axle.

The result is that the initial dipole field is converted into two toroidal-shaped fields, one north and the other south of the equator. One torus has an east-west field direction and the other has a west-east

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<sup>1</sup> *50 MHz F2 Propagation Mechanisms*, Kennedy, J.R., 2000, in Proc. 34<sup>th</sup> Conf. Central States VHF Soc, (ARRL Pub. **257**), 87-105

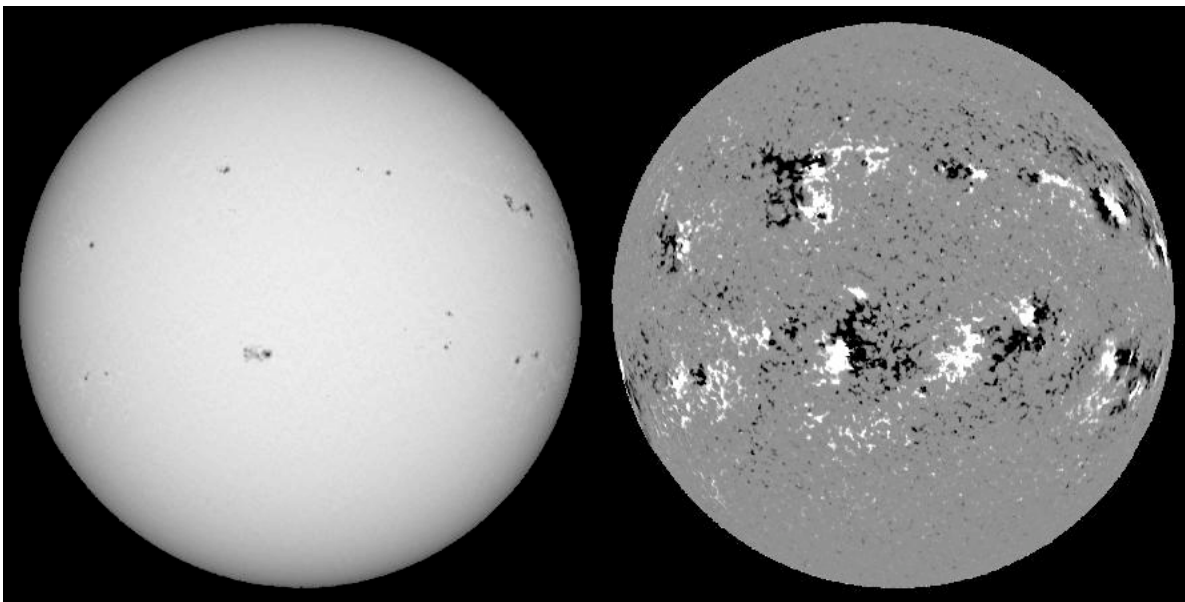
<sup>1</sup> *Solar Cycles and Cycle 24 Predictions*, Kennedy, J., 2007, in Proc. 41<sup>st</sup> Conf. Central States VHF Soc, (ARRL Pub. **329**), 1-13

direction. These two toroids concentrate the initially weak polar field into *much* stronger *localized* fields that can have strengths as high as 6000 gauss during solar maximum.

*These strong local fields lead to solar activity including sunspots, flares, CMEs, and other particle and radiant emissions.*

During solar maximum, so much of the original dipole field is wrapped around the axle that the polar field disappears altogether. Then the field starts to unwind again in the opposite direction. As a result the polar field not only goes through zero, but also *changes sign* and slowly begins to build up again, but pointing the other way.

Thus, the solar magnetic field goes through a complete cycle, with the field direction pointing from north to south, and then back to north again, about every 22 years. Each *magnetic half-cycle* produces a peak in solar activity, producing the 11-year *activity* or sunspot cycle.



**Figure 1:** Two views of the Sun from the National Solar Observatory (NSO) at Kitt Peak near Cycle 23 maximum on 3 April 2000. *Left:* A white-light image shows the two (north and south) sunspot bands. *Right:* This magnetogram shows the magnetic regions giving rise to the spots. White is field pointing out of the Sun, and black pointing into the Sun. Note that the northern and southern leading-trailing polarity patterns are *reversed*, and the magnetic regions are *much bigger* than the spots. (Credit: NSO/AURA/NSF)

**Sunspot Pair and Group Polarity** – Sunspot pairs and groups of sunspot pairs arise from loops of magnetic flux rooted in either the north or south toroids, which then float upward and bulging up through the surface. The field lines loop high above the surface and then return back through the surface to the underlying magnetic toroid.

Since one of the north and south toroids has an east-west polarity and the other has west-east polarity, the *sunspot pairs* and *groups* of pairs have *east-west polarity in one hemisphere and the west-east polarity in the other* (Fig. 1 - Right).

**The New Cycle** – Each “new” activity cycle begins at the *minimum* following the preceding solar maximum. On the almost spotless Sun, new cycle spots begin to appear in two latitude bands about  $30^\circ$

north and south – with opposite polarities from the old-cycle spots. However, new-cycle spots don't necessarily appear at the same time in both the northern and southern hemispheres (more later).

As the cycle progresses, the spots appear in increasing numbers, with their latitude bands slowly moving closer and closer to the equator. By solar maximum, the two bands are centered on about 15° north and south latitude respectively. As the cycle wanes, the cycle spot count decreases and the two bands move to within about 5° of the equator. From there the cycle repeats itself again.

**Cycle Strength** – The amplitude of a cycle is measured by various indices. The international sunspot index<sup>2</sup>,  $R_i$ , is a very common one, as is the 10.7 cm radio flux, F10.7. Both are valid, but in order to simplify the presentation, only  $R_i$  will be discussed here.

$R_i$  values at solar maximum can vary widely from one cycle to the next. In the last 110 years, they have ranged from maximums of about 60 to over 200 (Fig. 2). While there can be some exceptions, as a rule of thumb it takes a persistent period of  $R_i$  of about 100 or more to ensure predictable ongoing east-west F<sub>2</sub> propagation (during the local fall-winter F<sub>2</sub> season, of course).

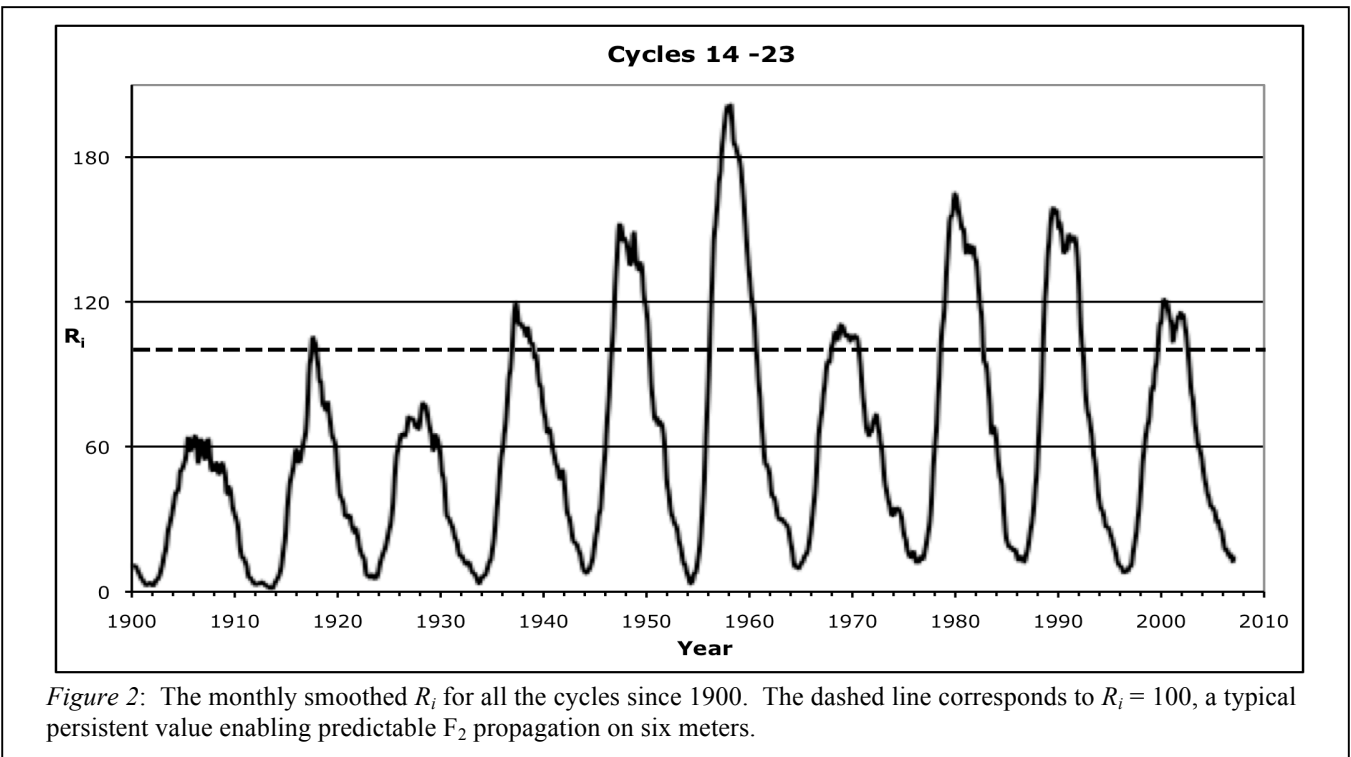


Figure 2: The monthly smoothed  $R_i$  for all the cycles since 1900. The dashed line corresponds to  $R_i = 100$ , a typical persistent value enabling predictable F<sub>2</sub> propagation on six meters.

**Cycle Length** – The duration of each cycle also varies quite a bit. Though the average is 11 years, they have ranged from 9 to 14 years. In fact, an actual 11-year cycle is fairly rare. Most cycle lengths tend to group around either 10 years or 12 years.

**North Cycle, South Cycle** – Curiously, the northern and southern solar hemispheres each have their own timetable. Their periods are the same, but the phases often are somewhat different.

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<sup>2</sup> The value of  $R_i$  is essentially the same as the historical  $R_z$  (Zurich) sunspot number index. It is the sunspot count plus ten times the number of groups, all multiplied by a scaling factor for each reporting station.

This is related to the fact that there is an internal circulation pattern inside the Sun that moves near-surface material from equatorial regions toward the pole in each hemisphere. Near the poles this *meridional flow* drops down into deeper regions and then flows back toward the equator. This circulation pattern is thought to be a “conveyor belt” that collects and recycles old magnetic flux from earlier cycles to seed new magnetic activity of the current and future cycles.

However, measurements of the meridional circulation show that the speed of the flow isn't necessarily the same in both hemispheres. Since the flows are thought to feed earlier-cycle flux into current-cycle activity, if the northern and southern flows have noticeably different speeds, the activity in the slower hemisphere will tend to lag behind the activity in the other hemisphere.

In recent cycles, meridional flow measurements show that the southern flow has been running much slower than the northern one. Correspondingly, the trend since Cycle 19 also has been for southern *activity to lag behind* that of the north.

Studies of Cycles 22, 23, and now the beginning of 24, which plotted the  $R$  index separately for the northern and southern hemispheres, suggest that while the *leading edges* of the two hemispheres' cycles seem to *resynchronize*, the solar maxima and trailing edges of the cycles are phase shifted in time, and the lag has been becoming progressively greater with each recent new cycle.

The apparent resynchronization of the leading edges was seen at the beginning of Cycle 23 and even more dramatically at the beginning of Cycle 24, where the northern activity seemed to just come to a halt for about two years and wait for the south to catch up (see Fig. 3).

This combination of resynchronization and then the southern hemisphere phase lag seems to have led to a number of effects. As the phase lag increases, the north and south solar maxima occur at different times. In Cycle 23, the south reached its peak a year later than the north, leading to a pronounced double maximum. In fact, there have been multimodal peaks in all the cycles since Cycle 19 and also many cycles before 19 (as seen in Fig. 2).

Since the two Cycle 23 peaks occurred at quite different times, the value of the total peak was *diminished*, although the overall length of the period of high activity was *longer*. When the north and south are *in phase*, a single peak occurs. When they are *in phase* and both north and south peaks are *strong*, one gets a powerful cycle, such as Cycle 19 in 1958 ( $R_i = 201$ ).

Another consequence of the resynchronization and phase lag was that Cycle 23 was a quite *long* cycle; it lasted 12½ years. The time one hemisphere spends waiting for the other may explain why it is common for the minimum value of  $R_i$  for cycles that last more than 11.5 years, to be much lower than those of the shorter cycles. Cycle 23 had a very low value.

In recent cycles, meridional flow measurements show that the southern flow has been and still is running much slower than the north. This suggests that Cycle 24 may well have a:

Double-maximum pattern, and be a

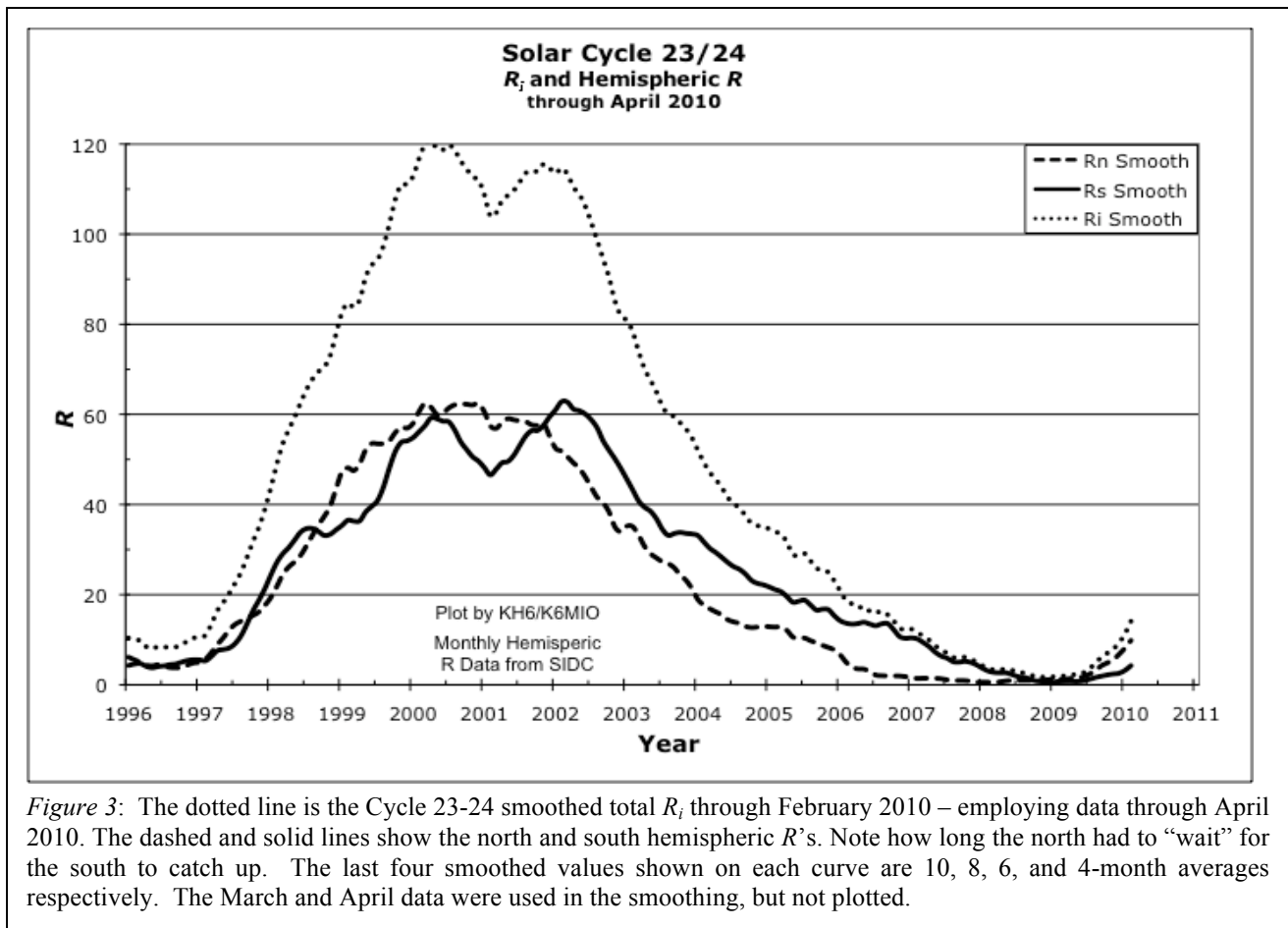
Long cycle.

**Plotting the Cycle** – It is worthwhile to talk a little about how the solar activity plots are produced and how the values of solar minimum and maximum are determined. The daily value of the  $R$  index can

vary radically during a month. The published  $R_i$  is actually the average value over the entire month. Even so, the month-to-month variation of the monthly  $R_i$  is also often large. The good news is that the longer-term trends are quite important and very useful. Consequently, the values are *smoothed* by plotting the 12-month running average of the monthly  $R_i$ . (In detail, it uses data from the month in question, plus those from the six months before and after. But the first and thirteenth months only count at half value and the sum divided by 12.)

The date of solar minimum and the beginning of a new cycle is the date that the twelve-month smoothed  $R_i$  value reaches a minimum. Of course, to observe a minimum one must have already seen the smoothed value begin to rise after that date. However, since the values are based on twelve months of data, including time both before and after the month in question, the *smoothed value* of  $R_i$  cannot be computed until six months later.

**Where Are We Now** – The unusual nature of the long delay in the southern solar hemisphere initially left some uncertainty whether or not there would be a Cycle 24 at all! The specter of another Maunder Minimum was on many minds in the six-meter community (although it was not very visible in the solar physics community).



Under normal circumstances, a clearly positive indication of an upswing in the running average should be seen about one year after the actual solar minimum date. Thus, the December 2008 minimum should lead to a clear upswing in  $R_i$  by about December 2009. The good news is that this appears to have been the case (Fig. 3, lower far-right corner). ***Cycle 24 seems to have really started.***

Figure 3 shows the 12-month smoothed total sunspot index,  $R_i$ , superposed upon the northern and southern hemispheric indices,  $R_n$  and  $R_s$ <sup>4</sup> with an important exception. The *exception* is that this procedure means there is no way to show the last six months of available data (yet).

So, the plot departs from the norm by doing a running average of whatever data were available for the first four of those last six months. Thus, for example, the data point six months before the end of available data is smoothed over ten months, the next over eight months, and so forth. The final two months of data are not plotted because smoothing over that short length of time makes little sense. The overall intention is to extract whatever information shorter smoothing might reveal, while recognizing that the closer one gets to the current month, *the more uncertain that value becomes* due to the vagaries of the normal month-to-month variations.

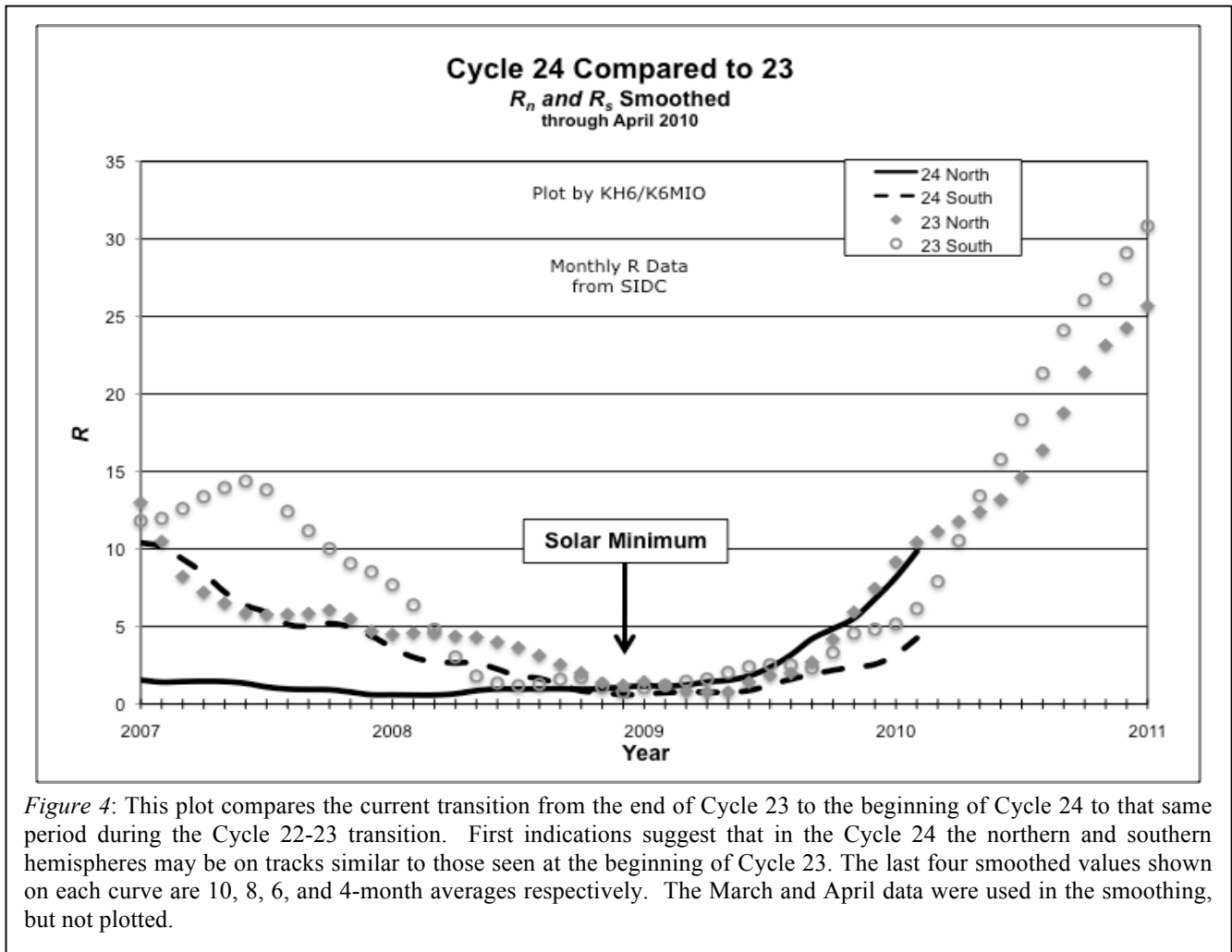


Figure 4: This plot compares the current transition from the end of Cycle 23 to the beginning of Cycle 24 to that same period during the Cycle 22-23 transition. First indications suggest that in the Cycle 24 the northern and southern hemispheres may be on tracks similar to those seen at the beginning of Cycle 23. The last four smoothed values shown on each curve are 10, 8, 6, and 4-month averages respectively. The March and April data were used in the smoothing, but not plotted.

At this writing (May 2010), the monthly  $R_i$  for March and April were lower than the previous months. So, in the short term, there may be a hesitation in the climbing upturn. This may be “real” or just a bump in the road – on a road well known to be bumpy. Most likely it is bump and the longer-term average will continue to climb, *but only time will tell*.

<sup>4</sup> Note that  $R_i = R_n + R_s$

One can make a comparison of the current upswing in  $R_i$  to what the upswing looked like at the beginning of Cycle 23. It is especially interesting to compare them with a close up look at the hemispheric- $R$  values (see Fig. 4). This comparison seems to suggest that, so far, the Cycle 24 northern hemisphere values are tracking pretty close to the Cycle 23 values. In the south, it appears that Cycle 24 is running a little behind Cycle 23 at this point.

It is probably too early to read much into these values at this point, but it is reassuring that even at that level of detail, it seems like Cycle 24 may be starting off on a familiar footing compared to recent history.

***When Will Solar Maximum Occur?*** – So far, Cycle 23 and the start of Cycle 24 have outsmarted virtually all of the professional prognosticators. The author does not profess being any smarter than they.

That being said up front, it is well known that once the  $R_i$  starts to climb after solar minimum, it gets progressively easier to predict what will happen next. *If* Cycle 24 behaves more like “most” cycles, solar maximum would probably occur around the Earth’s northern-hemisphere winter of 2012-13, some four years after solar minimum, but given the level of strangeness in the cycle, it is too early to be sure.

Even more so, it is too early to make *any* kind of data-based inferences about the  $R_i$  value at solar maximum. There are arguments for it being a poor cycle, and there is at least one physics-based model that suggests it will be a fairly good cycle, but occurring later than usual.

***When Might the 6-M DX Start?*** – This is the real question for the six-meter faithful. We are really talking about predicting the timing and quality of *F-layer propagation*. Unfortunately, this depends on not only the *date* of maximum, but also the *value* of  $R_i$  maximum.

Moreover, it turns out that the date that the propagation *first* shows up depends on *three* different parameters. They are the:

1. Date of solar maximum,
2.  $R_i$  at maximum, and the
3. Local terrestrial season.

Taking these factors one at a time, let’s look first at the question of  $R_i$  maximum. Experience shows that, in order to get regular occurrences of  $F_2$  propagation, the ongoing average  $R_i$  needs to be about:

- 60 or more for north-south transequatorial paths, and
- 100 or more for east-west same-side-of-the-equator  $F_2$ .

The key point to recall is that generally these levels will occur *before* solar maximum. However, how *long before* maximum will depend on *how* high  $R_i$  maximum will turn out to be. So to predict the point in time when the propagation will begin, one needs to predict both the date of the maximum and the maximum value of  $R_i$ .

Then there is the fact that F-layer propagation is *seasonal* because of seasonal variations in the Earth’s ionosphere. And these variations depend on the *type* of propagation of interest. For example, east-west

$F_2$  propagation peaks *once* a year in the local fall into early winter. Of course, the Earth’s *local* winters occur six months apart on the calendar, and depending on whether one is in the Earth’s northern or southern hemisphere.

On the other hand, long north-south propagation across the equator requires that both sides of the equatorial F layer be illuminated more or less equally by the Sun, in order to make the transequatorial hop. These conditions occur *twice* a year around the equinoxes in the spring and fall, no matter which hemisphere one is in.

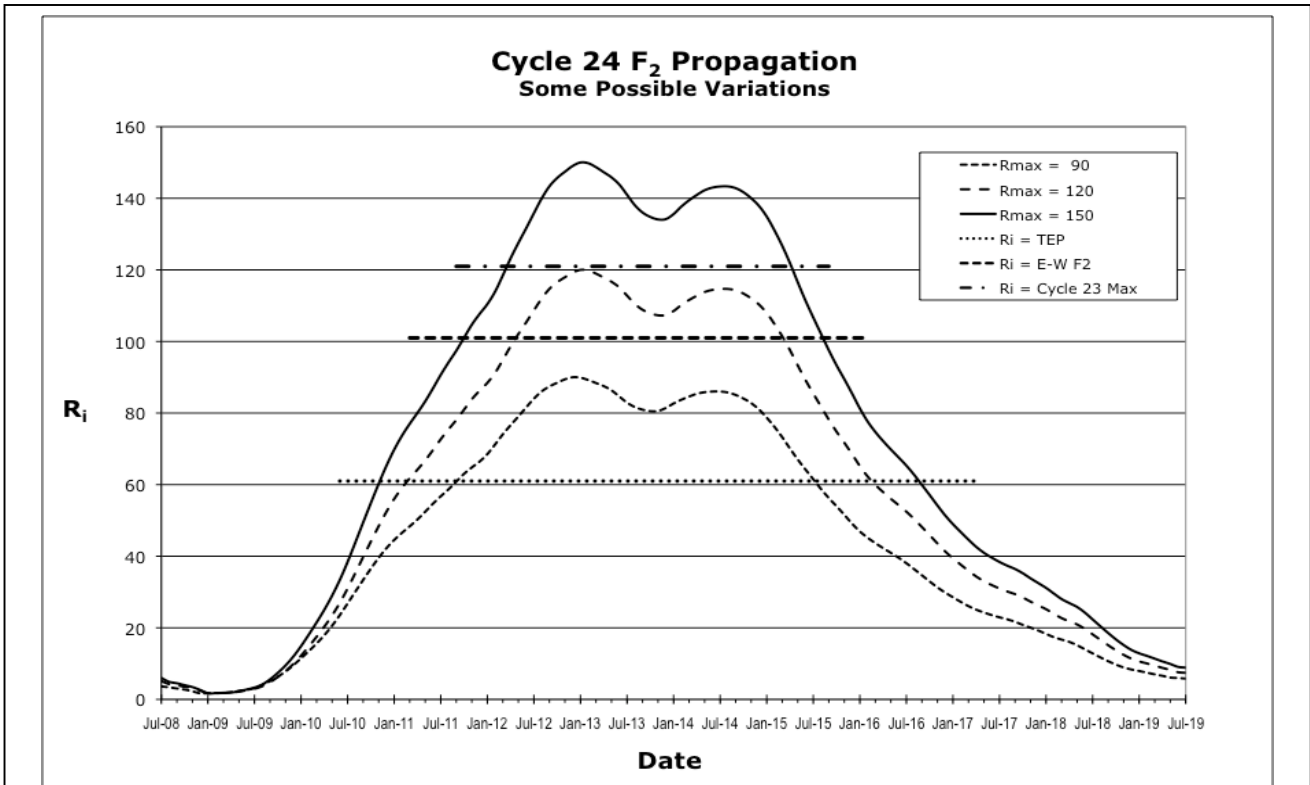


Figure 5: These are three realizations of an  $R_i$  model scaled to maximums of 90, 120, and 150 respectively. It assumes that the slow southern-hemisphere meridional flow “conveyer belt” will lead to another doubled-peaked maximum, like Cycle 23. It shows the time relationship between the beginning of Cycle 24 and the onset and duration of TEP for  $R_i$  of about 60, east-west  $F_2$  of about 100, and the period of time above Cycle 23 at  $R_i = 121$ .

**Making Your Own Predictions** – There is a fairly simple approach that may provide some reasonably useful information about the progress of the cycle toward good propagation conditions. This procedure is based on three suppositions above, and the assumption that the *shape* of the Cycle 23  $R_i$  curve is a suitable proxy for the shape of Cycle 24.

The notion is quite simple. The plots shown in Figure 5 depict Cycle-23-shaped curves rescaled for three different model values of  $R_i$  maximum. One can start plotting the *real* values of the smoothed  $R_i$  month-by-month, as they become available, on the same graph. If nothing too bizarre happens with the cycle, after a couple of years it should become apparent which path the cycle is on, with respect to the model curves. This in turn should allow inferences to be made about the likely value of  $R_i$  maximum.

It will also allow one to estimate the date of the beginning of persistent  $F_2$  propagation. When there is enough data to estimate the path between the three model curves, one can extrapolate the real data

forward in time to estimate of *when* the  $R_i = 60$  and  $R_i = 100$  points will be reached by simply noting the date corresponding to the point where the extrapolation crosses the 60 or 100 lines.

The last step will be to look at what season that date corresponds to in order to see whether it is favorable for east-west or north-south propagation. Then, of course, one can make plans as to where to go for a DXpedition.

**What's It Look Like Now?** – It's far too early (by a year or more) to expect any concrete results from the Figure 5 modeling approach. Nevertheless, there some real data that can be poured in to start the process.

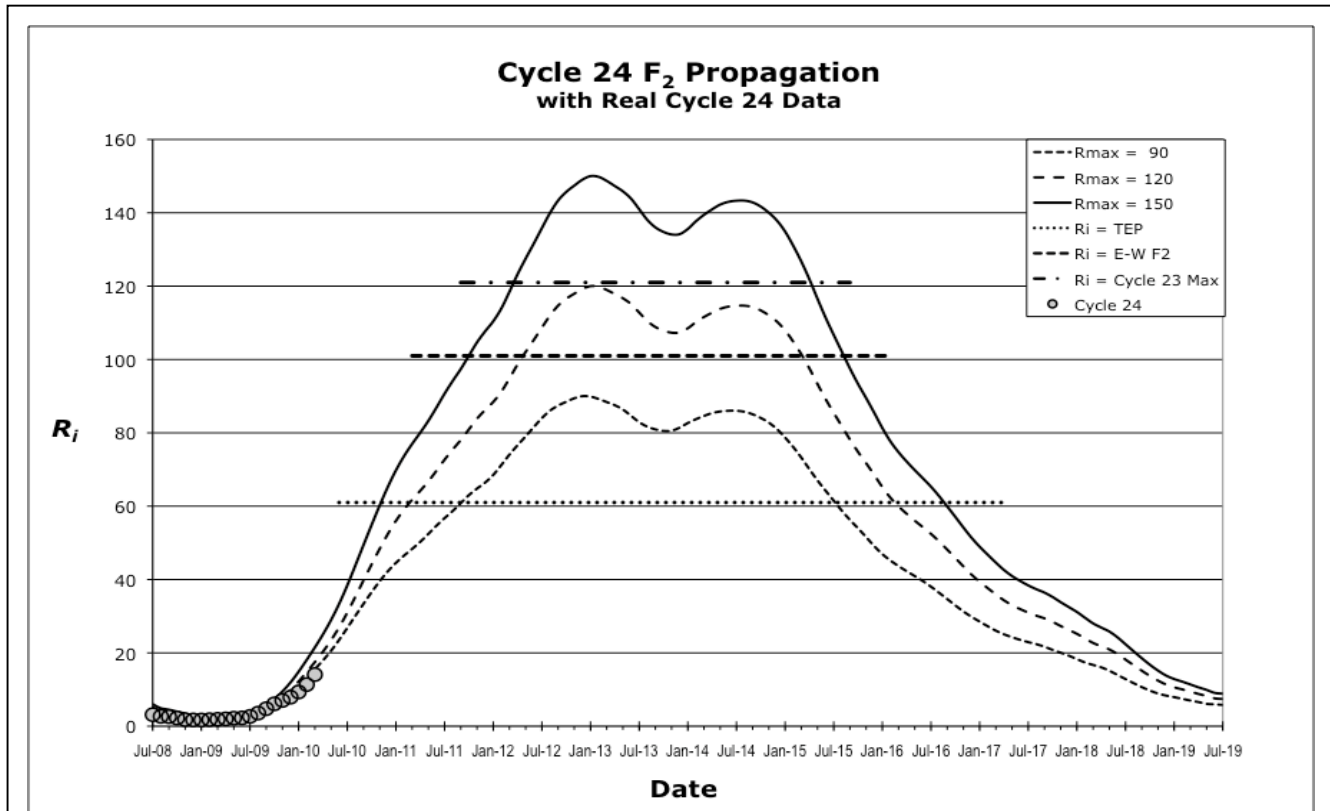


Figure 6: This shows Figure 5 models, with the *addition* of the *real* Cycle 24 smoothed total  $R_i$  data in the gray circles. At the moment, it appears that Cycle 24 is trying to climb up within the range of the models. It is too early to draw any major conclusions, but there are some speculations discussed in the text below.

Figure 6 shows what it currently looks like. It will be noted that so far Cycle 24 seems to be running behind Cycle 23. This was already known from Figure 4 that showed that the southern hemisphere is a little behind the Cycle 23 values at the moment. In the longer term though, it is important to recall that the model assumed that the time from minimum to maximum would be exactly four years. On average, that's a good figure, but in the real world it could be a few months either way. At this point, the data cannot distinguish between heading to a lower  $R_i$  maximum, or a cycle that takes a little longer than four years to reach maximum.

**Cycle 25 and Beyond** – Some people are beginning to think about Cycle 25. There is weak evidence of a 240-year pattern in cycle lengths. If this effect is real, it suggests that Cycle 24 may be the first of

several cycles to get systematically longer. In either case, it would suggest that *Cycle 25 will be longer*, and some say weaker.

Similarly, since the meridional conveyor belt is slowing down, especially in the south, this should lead to a longer cycle. Statistically, slow conveyor belts tend to lead to poor cycles and some expect that effect to be very noticeable in Cycle 25.

**Closing Speculations** – From Figure 6 one could imagine that the likelihood of *not* seeing a wide spread return of persistent TEP before the northern spring of 2011 and perhaps as late at the northern fall of 2011. Likewise, the beginning of widespread persistent F<sub>2</sub> may have to wait until the fall-winter of 2012 or later. If Cycle 24 adopts the path to  $R_i$  maximum = 90, it may never happen at all. We'll know more in another year.

#### *Acknowledgements*

The sunspot data used here are from the compilations by the Solar Influences Data Analysis Center (SIDC) at the Royal Observatory of Belgium ([www.sidc.be](http://www.sidc.be)).

### **Postscript**

The following material was developed after the conference proceedings publication deadline. It was included in the public presentation at the conference.

The National Oceanic and Atmospheric Administration (NOAA) convened an international panel of solar-cycle experts in March 2007 and asked that they come up with a consensus prediction for the Cycle 23 minimum date, and the Cycle 24 maximum date and maximum  $R_i$ . The panel reached a consensus that the minimum would occur around March 2008  $\pm$  six months. The panel was split 50-50 on the maximum prediction. One half said the maximum would occur around October 2011 with an  $R_i$  of about 140. The other half said August 2012, with an  $R_i$  of 90.

It turned out, of course, that the *actual minimum occurred in December 2008*. NOAA and NASA then reconvened the panel in May 2009 and this time there was a consensus prediction for the maximum occurring around May 2013 with an  $R_i$  of 90.

If the model used in Figure 6 is *readjusted* to have a maximum date of May 2013 there is somewhat better agreement between the actual monthly average  $R_i$  and the  $R_i(\text{max}) = 90$  curve. Figure P7 shows an expanded view of the leading edge of the curve for the December 2012 date used in Figure 6. Figure P8 shows the same plot for the revised NOAA predicted maximum date of May 2013.

Making this date adjustment also suggests that Cycle 24 may be even longer than Cycle 23, perhaps reaching 13.8 years.

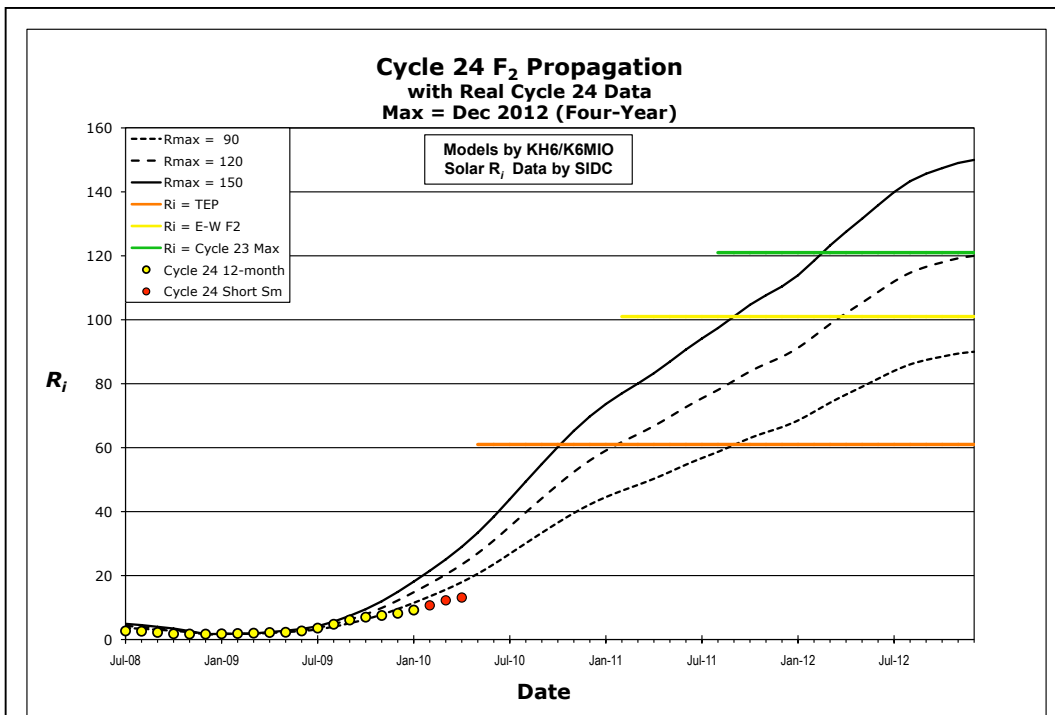


Figure P7: A comparison of recent real data to the model with the December 2012 maximum date. The lower dashed line represents the  $R_f(\text{max}) = 90$  curve. The last three data points (in red) have been smoothed for less than 12 months.

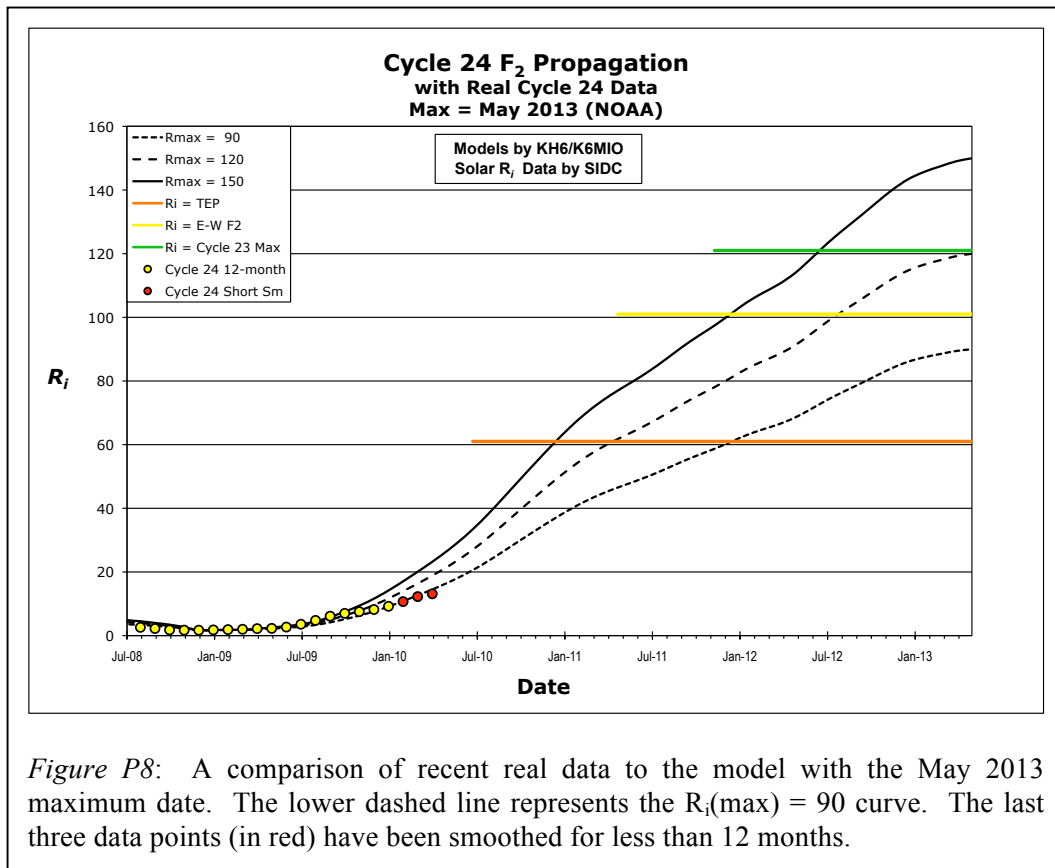


Figure P8: A comparison of recent real data to the model with the May 2013 maximum date. The lower dashed line represents the  $R_f(\text{max}) = 90$  curve. The last three data points (in red) have been smoothed for less than 12 months.