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Predictions of Solar Cycle 24

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Abstract A summary and analysis of more than 50 predictions of the amplitude of the upcoming Solar Cycle 24 is presented. All of the predictions were published before solar minimum and represent our efforts to anticipate solar maximum at ever-earlier epochs. The consistency of the predictions within their assigned categories is discussed. Estimates of the significance of the predictions, compared to the climatological average, are presented.

1. Introduction

Solar-cycle predictions test our knowledge of the solar dynamo, a term that includes the processes involved in the production, transport, and destruction of solar magnetic field. Models of the dynamo are validated by their ability to predict solar activity over short and long timescales. Predictions of the magnitude and timing of Solar Cycle 24 are also used by a variety of space-weather groups to estimate orbital drag and other consequences of space weather in the upcoming cycle. Solar-activity predictions are used by space-weather operators to plan when to reboost satellites in low-Earth orbit, anticipate radiation exposure for current and upcoming missions, and to plan for outages in radio-based communication and navigation systems. Space-weather operators want to know the significance of each prediction when compared to other predictions.

Sunspot number (R_z) is the most commonly predicted solar activity index. The rate of solar flares and amount of energy they release are well correlated with the sunspot number, as is the rate of coronal mass ejections. Cosmic rays, whose flux is anticorrelated with the solar cycle, are a significant source of radiation hazard in space. Geomagnetic activity has one component that is proportional to R_z and another, which can be a source of significant space weather, that resembles the sunspot number but shifted forward several years (about a quarter cycle). But, in general, the sunspot number (or a proxy index such as F10.7, the spectral irradiance at a radio wavelength of 10.7 cm) is the basic quantity needed for space-weather work. The amplitude of the annual-averaged sunspot number for Solar Cycle n will be called R_n.

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We report here a summary and discussion of the predictions of Solar Cycle 24. The predictions are analyzed within categories to determine trends and consistencies. We also calculate whether each prediction would be considered significantly different from one of the simplest predictions: That Solar Cycle 24 will be a cycle of average amplitude and duration.

2. Predictions of Cycle 24

The Solar Cycle 24 Prediction Panel was convened in October 2006 to develop a consensus prediction of Solar Cycle 24. To ensure that a wide range of predictions were considered, predictions of the amplitude and timing of Solar Cycle 24 were solicited from the community in the categories of Fun, Precursor, Spectral, Climatology, Recent climatology, Neural network, Physics-based, or Other. The call for predictions was published in several newsletters, including the 15 August 2006 "Solar News" (http://solarnews.nso.edu).

The more than 50 predictions in Table 1 are a combination of 15 predictions submitted in response to the call by the Solar Cycle 24 Prediction Panel, four predictions described here, six predictions produced by the Prediction Panel, with the remaining predictions culled from the refereed literature. The table is organized by the predicted sunspot maximum and includes the predicted maximum sunspot number (value and timing), category of prediction, a short summary of method, and the reference. The third column of Table 1 contains a one-letter abbreviation of the category for each prediction. If a prediction was found during the literature search, the category was assigned by the author. No predictions were received or discovered in the categories Fun or Other. Another summary list of predictions was given by Janssens (2005, 2006). The category "Physics-based models" was renamed "Dynamo model" to more accurately reflect the nature of the expected predictions. Four predictions (Thompson (1993), aa_min, aa_4yr, and modified Feynman) were developed during the deliberations of the panel and two consensus predictions were released by the panel (Biesecker, 2007). The consensus predictions were not placed into categories. The references, predicted maxima, and uncertainties are shown in the bottom part of Figure 1. Categories for each prediction are shown by a color coding listed in the upper panel.

Some predictions of Solar Cycle 24 are not included in Table 1. A prediction by Li, Gao, and Su (2005) was omitted as they included multiple predictions, depending on the timing of solar minimum and rise time of Cycle 24. Some of their conditions have already passed; their remaining predictions are that the current solar minimum will be reached in June 2008 (± two months), the next maximum will be in February 2013 (± eight months), and the maximum will be about 137 or 80, depending on whether the cycle is a fast riser or a slow riser. Volobuev and Makarenko (2008) used a combination of the sunspot number and radiocarbon variations to estimate that the upcoming decade will be smaller than the last but did not convert this into a prediction of R_{24}.

It is necessary to have quantitative estimates of the uncertainty of the predictions – in both magnitude and timing. Most of the amplitude predictions included either an error estimate or a range that could be converted into an error estimate. Timing predictions were less precise and usually depend on the timing of solar minimum. As we move into Cycle 24, those timing predictions that depend on the time of minimum and the shape of the rise will become more accurate. Although the timing predictions are listed in Table 1, they will not be discussed further.

Table 1 Predictions of Solar Cycle 24.

Predicted maximum		Category[1] and summary		Author and date
R_{24}	Timing			
185	2010 – 2011	C	Projection of last five cycles (JSC)	Horstman (2005)
180 ± 32	–	P	Disturbed days (panel)	Thompson (1993)[2]
180	2014	S	Modified global minimum analysis	Tsirulnik, Kuznetsova, and Oraevsky (1997)
152–197	–	P	Integral of sunspot number used as precursor	Podladchikova, Lefebvre, and Van der Linden (2006)
155–180	–	D	Modified flux-transport dynamo model calibrated with historical run of sunspot area	Dikpati, de Toma, and Gilman (2006)
160 ± 25	–	P	Analysis of aa index	Hathaway and Wilson (2006)
160 ± 54	2010.6	R	$R_{24} = R_{22}$ (even – odd)	Current work
148		P	aa at minimum (panel)	aa_min (2006)
145	2009.96	N	Neural network forecast	Maris and Oncica (2006)
145 ± 30	2010	D	Fast meridional circulation speed during cycle 22 leads to a strong solar cycle 24	Hathaway and Wilson (2004)
145	2011 – 2012	N	Spectral analysis and neurofuzzy modeling	Gholipour *et al.* (2005)
144	–	P	aa during decline of 23	Jain (2006)
142 ± 24	–	P	aa at solar minimum	Kane (2007)
140 ± 20	2011.80	–	Panel consensus prediction (high)	
140	2012.5	P	Disturbed days analysis	Chopra and Dabas (2006)
135 ± 20		P	aa/R_z precursor (panel)	Modified Feynman (2006)[3]
134 ± 50	2011.7	C	Based on average of the last eight solar cycles	Kennewell and Patterson (2006)
133	2009.5	C	Statistics of $\sqrt{R_z}$	Tritakis, Mavromichalaki, and Giouvanellis (2006)
130 ± 15	–	P	Complexity of Hα synoptic charts	Tlatov (2006)
124 ± 30	–	P	Value of aa at solar minimum	Nevanlinna (2007)
124 ± 23	–	P	Number of disturbed days in Ap	Dabas *et al.* (2008)
124		C	Statistics of equal phase average	Khramova, Krasotkin, and Kononovich (2002)
122 ± 6	2010.88	C	Statistical analysis of cycle parameters	Kim, Wilson, and Cucinotta (2006)
120 ± 60	2011.167	C	Modified McNish–Lincoln model (MSAFE)	Euler and Smith (2006)
120 ± 45	2010.0	R	$R_{24} = R_{23}$ (inertial)	Current work
120 ± 25		P	Behavior of aa (panel)	aa_4yr (2006)
116 ± 13.2	2012 – 1013	S	Spectral analysis of R_z	Echer *et al.* (2004)
115 ± 40	2011.3	C	$R_{24} = R_{z,\mathrm{ave}}$ (average)	Current work

Table 1 (*Continued*)

Predicted maximum		Category[1] and summary		Author and date
R_{24}	Timing			
115 ± 30	–	P	Number of disturbed days	Rabin (2007)
115 ± 28	2010.5	P	Precursor + nonlinear dynamics	Sello (2006)[4]
115 ± 15	–	P	Area of high-latitude unipolar regions	Tlatov (2006)
115 ± 13	–	P	Large-scale magnetic field, presented at October panel meeting	Tlatov (2006)
114.8 ± 17.4	–	C	Cycle $n+1 \propto$ decline of $n-2$	Du and Du (2006)
114 ± 43	–	C	Mean of cycles $1-23$	Prochasta (2006)
112	–	S	Combined empirical mode decomposition and autoregression	Xu *et al.* (2008)
111 ± 18	–	P	Minimum value of Ap	Thompson (2008)
110 ± 65	2/2011	C	Modified McNish–Lincoln model (MSAFE)	Euler and Smith (2006)
110 ± 15	–	S	Transfer function model	de Meyer (2003)
110 ± 11	2012	S	Autoregressive model	Hiremath (2008)
110 ± 10	–	P	Dipole–octupole magnetic moments	Tlatov (2006)
108 ± 38	2011	C	Skewness of previous cycles separated into even/odd cycles	Lantos (2006)
105 ± 9	2010 – 2011	S	Extrapolation of dominant spectral components found by MEM	Kane (1999)
101 ± 20	2012.5	S	Autoregressive, linear prediction	Current work
83.2 – 119.4	2012.21	C	Statistical characteristics of solar cycles	Wang *et al.* (2002)[5]
91.9 ± 27.9	2011.04	S	Autoregressive, moving average	Roth (2006)
90.7 ± 9.2	–	P	Number of spotless days at minimum	Hamid and Galal (2006)
90 ± 10	8/2012	–	Panel consensus prediction (low)	

3. Categorized Predictions

A summary of the predictions in each category is listed in Table 2. The columns show the category of the prediction, the number of predictions of each category in Table 1, the average and standard deviation of the predictions within the category, and the range of the predictions. The definition of the categories and the general characteristics of the predictions in each category are discussed in the following. The first entry in Table 2 is the average of all predictions in Table 1. The precursor category is expanded into subcategories to show the consistency within the subcategories.

3.1. Climatology

A climatological forecast assumes that the future behavior of a system is a function of the averaged behavior from the past. Predictions using statistical analyses of sunspot numbers were placed into this category. An example is that R_{24} will be the climatological average, or

Table 1 (*Continued*)

Predicted maximum		Category[1] and summary		Author and date
R_{24}	Timing			
87.5 ± 23.5	–	S	Coupling between sunspot maxima and aa minima modulations (wavelet analysis)	Duhau (2003)
80 ± 21	2012	S	Mathematical theory of nonlinear dynamics; predicts a long cycle lasting 12 years	Baranovski (2006)
80 ± 30	2012	P	Solar polar field precursor	Schatten (2005)
80	–	D	Flux-transport dynamo model	Choudhuri, Chatterjee, and Jiang (2007)
74 ± 10	–	P	Statistics of low-latitude sunspot groups	Javaraiah (2007)
70 ± 2	–	P	Polar magnetic field strength at solar minima	Svalgaard, Cliver, and Kamide (2005)[6]
70 ± 17.5	2012.96	S	Statistical Gaussian-based extrapolation	Kontor (2006)
<50	2010 – 2011	C	Statistics of the 5303 Å coronal line	Badalyan, Obridko, and Sykora (2001)
42 ± 35	–	S	Periods in R_z and radiocarbon isotopic abundances	Clilverd *et al.* (2006)
low	–	C	Observations of flare energy release during the descending phase of cycle 23 (empirical)	Mariş, Popescu, and Beşliu (2004)[7]

[1] The third column is a one-letter description of the method: C, Climatology; D, Dynamo model; N, Neural network; P, Precursor; R Recent climatology; or S, Spectral.

[2] Thompson (1993) used the method described in Thompson (1993) with data updated through 2006.

[3] This prediction was created during the panel deliberations using the method of Hathaway and Wilson (2006).

[4] This prediction is based on the method of Sello (2003).

[5] The average of the predictions given by Wang *et al.* (2002) is listed in Table 1.

[6] The prediction of Svalgaard, Cliver, and Kamide (2005) was updated at the panel meeting from 75 ± 8 to 70 ± 2.

[7] The predicted maximum of Mariş, Popescu, and Beşliu (2004) was set to 40 in Figure 1.

the average of all previous maxima. Using the information from NOAA (2006), we calculate this to be $R_{z,\mathrm{ave}} = 115 \pm 40$ using all of the numbered solar cycles in the referenced table. This also provides an error estimate for judging the predictions. Timing information can be derived in a similar way. The average time between solar maxima is 11 ± 1.5 years, so Cycle 24 will peak in April 2011, 11 years from the maximum of Cycle 23.

The utility of climatological forecasts can be seen by the large number submitted to the panel and found in the literature. The largest and smallest predictions of R_{24} are in this class. The average of predictions in this category is very close to the actual climatological average.

3.2. Recent Climatology

Recent climatology refers to a forecast where future behavior is related to behavior in the recent past. Two examples are the "inertial" forecast, $R_{24} = R_{23}$, in which it is assumed the

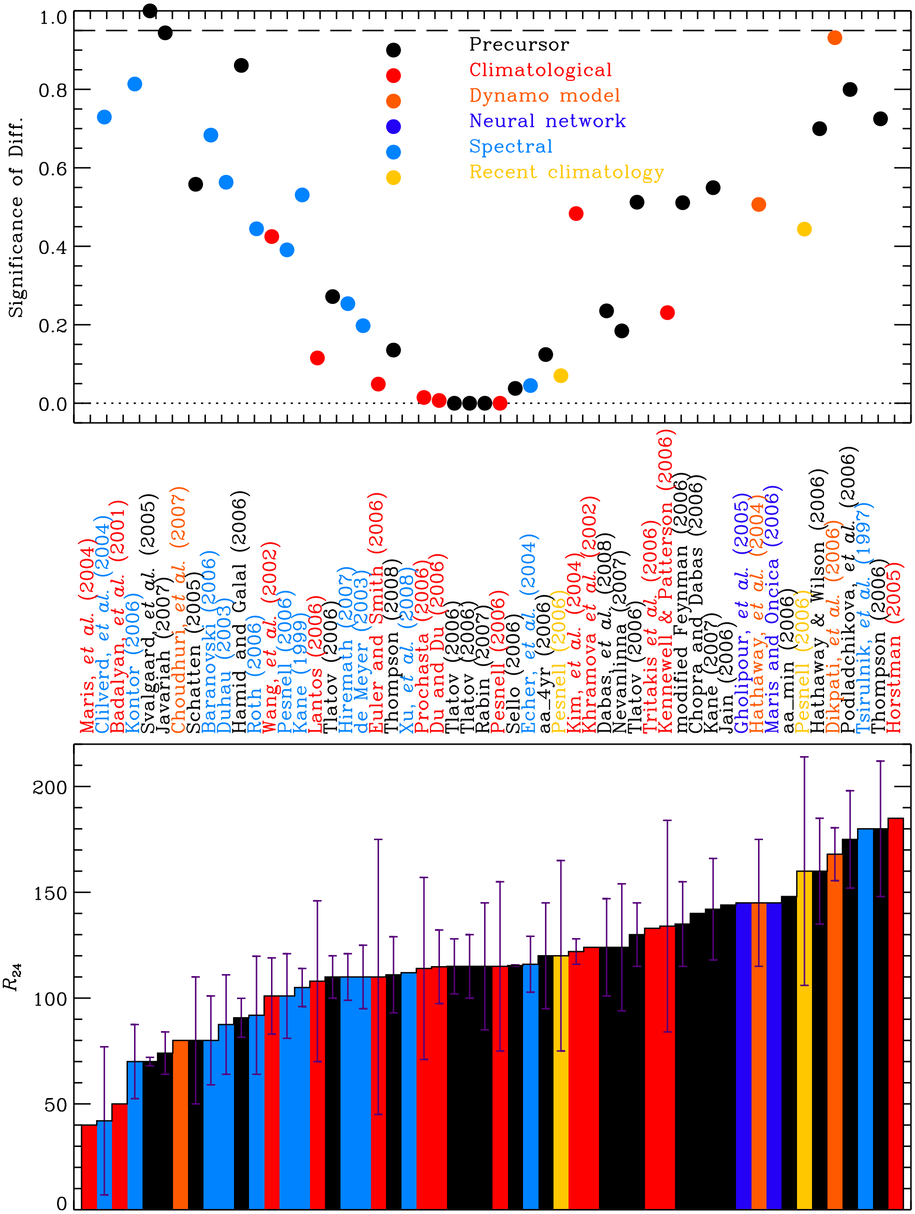

Figure 1 The predictions from Table 1, plotted in order of increasing predicted maximum for Cycle 24. The prediction categories are color coded as in the top panel. The upper plot is the significance of the difference from the climatological average of 115 ± 40 for those predictions that included an error bar. The dashed line shows the estimated "highly significant" level, which one prediction reaches. Two other predictions are statistically significant at the 90% level.

initial conditions of the system will persist throughout the entire period of the forecast, and the "even – odd cycle" forecast, $R_{24} = R_{22}$, which relies on the observation that solar cycles

Table 2 Summary of predictions for Solar Cycle 24.

Category	Number	Average	Range
All	54	117 ± 33	40 – 185
Climatology (C)	13	111 ± 36	40 – 185
Recent climatology (R)	2	140 ± 30	120 – 160
Dynamo models (D)	3	131 ± 45	80 – 168
Spectral (S)	12	100 ± 33	42 – 180
Neural network (N)	2	145	145 – 145
Precursor (P)	22	124 ± 30	70 – 180
Geomagnetic (mostly aa)	12	137 ± 20	111 – 180
aa	7	140 ± 14	120 – 160
Ap	5	134 ± 28	111 – 180
Solar	10	110 ± 30	70 – 175
Polar fields	3	88 ± 24	70 – 115
Other solar	7	116 ± 32	74 – 175

are organized into even and odd cycles with alternating amplitude. The inertial forecast is used in weather forecasting as a base forecast.

Both of these forecasts were derived by using the information in NOAA (2006) and were for above average activity in Cycle 24 and have larger errors than the climatological average. Standard deviations for this prediction category were calculated from the variance of the forecast and actual values (summed over the numbered solar cycles).

3.3. Precursor

Precursor forecasts, which look for leading indicators of solar activity, were the most common category of predictions. Two types of precursors dominate this category:

1. Solar polar magnetic field at minimum ≈ level of activity at next maximum: The three predictions in this category tend to be near or below average for Cycle 24.
2. Geomagnetic activity near minimum ≈ level of activity at next maximum. Seven of the 12 geomagnetic precursor predictions in Table 1 used aa as their indicator of geomagnetic activity, four used Ap, and one used both. All of the predictions were for average to above average levels of activity in Solar Cycle 24.

The remaining precursor predictions used solar properties such as global magnetic field and have a wide divergence in their forecasts.

3.4. Dynamo Model

Dynamo model forecasts are produced by models capable of integrating conservation equations. They can include data-assimilation models. This is the first time that predictions in this category are available. The two most complete models (Dikpati, de Toma, and Gilman, 2006; Choudhuri, Chatterjee, and Jiang, 2007) predict high and low solar activity, respectively. Cameron and Schüssler (2007) discuss the progress and problems in using these models for predictions of solar activity.

3.5. Spectral

A spectral forecast examines a Fourier analysis of the sunspot time series for invariant quantities such as frequencies whose amplitudes are conserved or have a simple time dependence. Wavelet-based and autoregressive forecasts were classified as spectral. The sunspot number was one of the first time series analyzed with autoregressive techniques (Yule, 1927). Three autoregressive forecasts of R_{24} (two submitted and one created during the construction of Table 1) agree in predicting below-average activity for Solar Cycle 24.

Forecasts in the spectral category tended to predict that Solar Cycle 24 will have slightly below average activity. Only one was for a very high amplitude, whereas another provided the lowest quantitative prediction, the possibility that we will see the lowest solar activity since the Dalton minimum in the early 1800s (Clilverd *et al.*, 2006).

3.6. Neural Network

A neural network forecast is derived from a set of nonlinear, statistical, data-modeling algorithms. They are used to determine and model complex relationships between inputs and outputs or to find patterns in data that can be extrapolated. Neural networks can be combined with other techniques, including spectral methods, to increase their accuracy. The two neural network forecasts for Solar Cycle 24 agree in their prediction of an above-average Cycle 24.

Figure 2 shows the categorized predictions with the one-σ error drawn as a colored box and the range within the category drawn as an error bar. The precursor category is also shown split into components to allow comparison of the various methods. The dashed line is drawn at $R_{24} = 115$, showing that almost all of the categories include $R_{z,\mathrm{ave}}$ in their predictions, with the aa precursor class the exception. The disagreement of the solar polar and geomagnetic precursors is large enough to recommend they not be considered equivalent classes.

4. Significance of Predictions

Operational users of solar-activity predictions require predictions with an error estimate that allows the statistical significance of each prediction to be determined. One estimate of the statistical significance is to calculate the significance of the difference of the new forecast from a known forecast. If the significance is high (> 0.95), then the new forecast differs from the old and the effects of the new forecast should be considered. If the significance is low (< 0.90), then the new forecast has a high likelihood that it is drawn from the same probability distribution function as the existing forecast.

One *a priori* prediction is the climatological average of previous maxima ($R_{z,\mathrm{ave}}$). It is based on all previous maxima, has an error estimate, and does not vary wildly from cycle to cycle. Based on the discussion in Press *et al.* (1992), Mandel (1964), and Keeping (1962), we will use Student's t-test to determine whether each prediction differs significantly from $R_{z,\mathrm{ave}}$. Only those predictions that provide an error estimate are included in this analysis.

From Section 3.1 we have $R_{z,\mathrm{ave}} = 115$ from 23 previous maxima and will define σ_0 as 40 and σ_P as the error of the prediction. The variance of the difference is

$$\sigma_T^2 = \sigma_0^2/23 + \sigma_P^2, \tag{1}$$

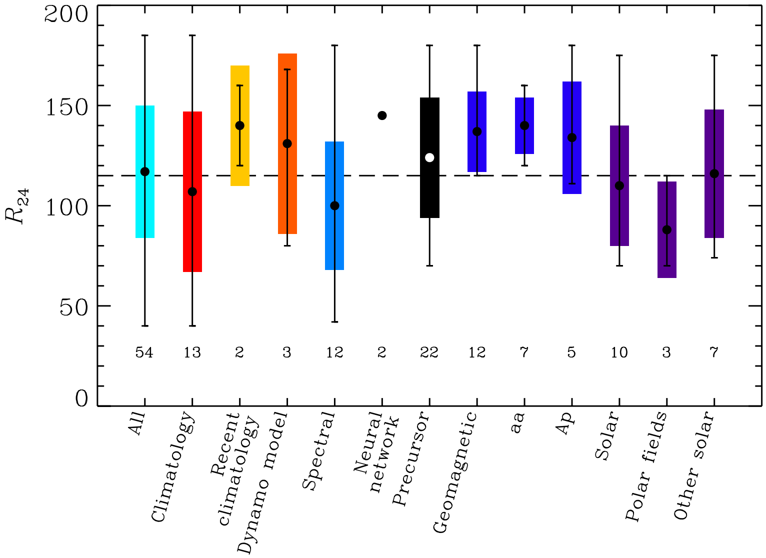

Figure 2 The categorized predictions in Table 2. The dot is the average prediction in each category, the color bar is drawn at the one-σ error limits, and the error bars show the range of each category. Except for the breakouts of the precursor class, the colors correspond to those in Figure 1. The number of predictions in each category is written under the symbols. A dashed horizontal line is drawn at $R_{24} = 115$.

the t variable is

$$t_{\text{test}} = (R_{24,P} - R_{z,\text{ave}})/\sigma_T, \tag{2}$$

and the number of degrees of freedom are given by (Press *et al.*, 1992)

$$n_f = \left(\sigma_0^2/23 + \sigma_P^2\right)^2 / \left[\left(\sigma_0^2/23\right)^2/22 + \sigma_P^4\right]. \tag{3}$$

The significance of the difference is given by Student's probability distribution function (Press *et al.*, 1992; Keeping, 1962; Mandel, 1964):

$$Pr = A(t_{\text{test}} \mid n_f). \tag{4}$$

The probability function is related to the incomplete beta function and is plotted in the upper panel of Figure 1. A level of significance must be selected. For this problem, $Pr > 0.95$ is a valid choice for a highly significant difference, meaning that there is a 1 in 20 chance that the predictions are the same.

The upper panel of Figure 1 shows that over half (24) of the 41 predictions with error estimates differ from $R_{z,\text{ave}}$ with a level of significance below 0.5. Two effects contribute to the statistical significance of the difference. Predicted values that differ from $R_{z,\text{ave}}$ by the sum of their error estimates have $t_{\text{test}} > 1$, increasing their statistical significance. This gives the general behavior of values near one at the high and low limits and small significance in the middle. A smaller effect is how n_f behaves when $\sigma_P^2 \ll \sigma_0^2/23$, which increases n_f and can add about 0.1 to the calculated significance. This is the case for Svalgaard, Cliver, and Kamide (2005), who give $\sigma_P = 2$ and thus gain some significance. The predictions of Javaraiah (2007) and Dikpati, de Toma, and Gilman (2006) benefit to a lesser extent from this effect, both being significant at the 90% level.

5. Summary and Conclusions

The convergence of the climatology predictions to $R_{z,\mathrm{ave}}$ is not surprising, but the large discrepancy in the dynamo models shows that those models do not as yet possess a predictive capability. The precursor category must be further broken out into solar and geomagnetic to produce equivalent classes, illustrating the poor overlap of the two techniques. Precursors were a major contributor to the consensus prediction of Solar Cycle 23 (Joselyn *et al.*, 1997) and their growing discrepancy is worrisome for future work. As a consequence of this divergence, the solar and geomagnetic precursors should be considered as separate categories.

An *a priori* estimate of the upcoming cycle that has a smaller uncertainty than the climatological average should be developed and provided to researchers interested in predicting solar activity. The rather large standard deviation in $R_{z,\mathrm{ave}}$ ($\sigma_0 = 40$ or 30%) means that only extremely large or small predictions would be considered highly statistically significant. Other techniques of ranking solar cycle forecasts, such as the skill scores described by Wilks (1995), could be used to more accurately assess the validity of the various methods. Weather forecasters had to develop similar metrics as numerical weather models became possible (Lynch, 2008).

Even when the level of solar activity can be forecasted with reasonable accuracy, the prediction of exceptional events will always provide new challenges. These include solar radio bursts that overwhelm GPS [such as on 6 December 2006 (NOAA, 2007)], solar-energetic-particle events that reach Earth without warning [often observed as ground level events or GLEs (Shea and Smart, 2000)], and the possibility of solar activity at a location on the disk is determined by conditions far from that location.

Given the wide range of the predictions for Solar Cycle 24, we look forward to this cycle answering important questions about how to predict solar activity.

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