GEOPHYSICAL RESEARCH LETTERS, VOL. 33, L05102, doi:10.1029/2005GL025221, 2006

Predicting the strength of solar cycle 24 using a flux-transport dynamo-based tool

Mausumi Dikpati,[1] Giuliana de Toma,[1] and Peter A. Gilman[1]

Received 13 November 2005; revised 28 December 2005; accepted 11 January 2006; published 3 March 2006.

[1] We construct a solar cycle strength prediction tool by modifying a calibrated flux-transport dynamo model, and make predictions of the amplitude of upcoming solar cycle 24. We predict that cycle 24 will have a 30–50% higher peak than cycle 23, in contrast to recent predictions by Svalgaard et al. and Schatten, who used a precursor method to forecast that cycle 24 will be considerably smaller than 23. The skill of our approach is supported by the flux transport dynamo model's ability to correctly 'forecast' the relative peaks of cycles 16–23 using sunspot area data from previous cycles. **Citation:** Dikpati, M., G. de Toma, and P. A. Gilman (2006), Predicting the strength of solar cycle 24 using a flux-transport dynamo-based tool, *Geophys. Res. Lett.*, *33*, L05102, doi:10.1029/2005GL025221.

1. Introduction

[2] Predicting the properties of an upcoming solar cycle by using old cycle data has been attempted by various methods (see a detailed review by *Hathaway et al.* [1999, and references therein], A particularly popular current method [*Svalgaard et al.*, 2005; *Schatten*, 2005] involves the use of polar fields from previous cycles as "precursors", of the next cycle. Here we propose and test a new method, based on a flux transport dynamo model that has already been demonstrated to reproduce many solar cycle features [*Dikpati et al.*, 2004].

[3] The dynamo-based scheme of *Schatten et al.* [1978] first attempted to make a physical connection between the strength of an upcoming sunspot cycle and the previous cycle's polar fields, assuming that there is a "magnetic persistence" between these two. Schatten et al.'s "magnetic persistence" was based upon a relation between the surface polar fields and the spot-producing toroidal fields, generated by differential rotation shearing (the Ω-effect). Implicit in this "dynamo based" approach is that the polar fields of the previous cycle can be sheared by the solar differential rotation in time to produce toroidal fields of the new cycle. But how are those 5.5 year old polar fields carried down to the shear layer, the tachocline, at or below the base of the convection zone, in time to do that?

[4] Flux-transport type solar dynamos successfully reproduce many large-scale solar cycle features [*Wang and Sheeley*, 1991; *Dikpati and Charbonneau*, 1999; *Küker et al.*, 2001]. Recently *Dikpati et al.* [2004] (hereinafter referred to as DDGAW) developed a calibrated flux-transport dynamo model in order to understand the physical cause of various features observed in cycle 23. DDGAW also demonstrated (their Figure 1) that the polar fields get advected down to the shear layer at sunspot latitudes after 17–21 years, depending on the assumed meridional flow strength, instead of in just 5.5 years. Therefore the polar fields from the past few cycles (*n*-1, *n*-2, *n*-3) rather than just from the previous cycle (*n*-1) should influence the spot-producing toroidal field strength of cycle *n*. Previously *Charbonneau and Dikpati* [2000] showed through the numerical simulation of their flux-transport dynamo that the shear-layer toroidal fields of the cycle *n* have the strongest positive correlation with the polar fields of the cycle *n*-2 compared to that of the cycles *n*, *n*-1 and *n*-3. This correlation is the consequence of the 17–21 years duration of the Sun's memory about its past magnetic fields. Here polar fields of cycle *n* refers to the polar fields present after polar field reversal in cycle *n*.

[5] Therefore, the magnetic persistence of *Schatten et al.* [1978], which was based primarily on the Ω-effect, has now been shown by DDGAW to have a stronger physical foundation in the meridional circulation than in the Ω-effect and the diffusivity, and to be influenced more by fields older than that of the previous cycle's polar fields. Our aim here is to further exploit the DDGAW model to predict the peak of cycle 24. To demonstrate that our model should have the skill necessary to do that, we first "forecast" the relative peaks of the previous 8 solar cycles, 16–23.

2. Predictive Tool Description

[6] The starting point of our calculation is DDGAW's calibrated flux-transport dynamo model (DDGAW equations (1), (2)). The model sustains toroidal or axisymmetric azimuthal fields, as well as poloidal fields that are in meridional planes. DDGAW's model operates with five dynamo ingredients: the solar differential rotation taken from helioseismic measurements; observed surface meridional flow toward the poles, coupled by mass conservation to a much slower equatorward return flow near the bottom of the convection zone; a surface poloidal field source derived from observations of decay and diffusion of previously emerged active regions (the so-called Babcock-Leighton source term), and a smaller poloidal source in the solar tachocline derived from tachocline dynamical theory; a depth-dependent magnetic diffusivity constructed by applying mixing-length and solar interior theories; and an imposed limit (called 'quenching') to the production of poloidal field from toroidal field that is a function of toroidal field amplitude. DDGAW calibrated their model by adjusting the least-known ingredient, the diffusivity profile, and compared the time-latitude diagram of the longitude-averaged magnetic fields derived from model

---

[1] High Altitude Observatory, National Center for Atmospheric Research, Boulder, Colorado, USA.

0094-8276/06/2005GL025221$05.00

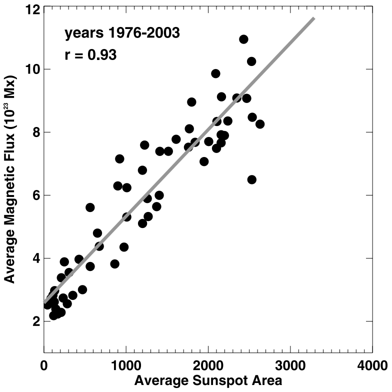

Figure 1. Sunspot area (from SOON and NOAA) in units of 10^{-6} of visible hemisphere and NSO/Kitt Peak photospheric magnetic flux (in 10^{23} Maxwell), both averaged over 6 rotations, for the period 1976–present.

output with that obtained from observations (see Figures 8 and 9 of DDGAW).

[7] DDGAW dynamo operates in the following way: Differential rotation induces toroidal field by shearing the pre-existing poloidal fields. Then the new poloidal fields are regenerated through the lifting and twisting, by various means, of the toroidal fields, followed by decay and diffusion of the emerged flux at the surface [see *Babcock*, 1961, Figure 5]. These surface poloidal fields are then transported toward the poles by the meridional circulation, where they cancel the poloidal fields already there from the previous cycle, to cause polar reversal. A part of poloidal fields in high latitudes is also being 'recycled' into the interior by the meridional circulation. That which reaches the bottom is then carried by meridional flow back toward the equator, and sheared again by the strong differential rotation there, to generate new toroidal field, of the opposite sign to the toroidal field of the previous cycle.

[8] This version of the dynamo is completely self contained and excited, with no external sources of flux. The peak amplitude of the dynamo fields will usually be the same for all cycles unless some time variation is introduced into one of the dynamo ingredients. In order to construct a predictive model that can distinguish one solar cycle amplitude from another, we must add observations of surface magnetic flux that vary from one cycle to the next. Here we construct the solar cycle prediction scheme by modifying DDGAW's self-excited dynamo into a magnetically forced system that induces new toroidal fields from an externally imposed source of poloidal fields, derived from surface observations, at the radius of the solar photosphere. The primary changes are the following.

[9] (i) We replace the DDGAW model formulation of the Babcock-Leighton surface poloidal source by actual surface observations. But toroidal flux is still generated from poloidal flux of previous cycles that has been transported down to the bottom by the meridional circulation.

[10] (ii) The externally imposed surface poloidal source is derived from a long-term observable, namely the observed spot area. Ideally a Babcock-Leighton type surface poloidal source should be more closely related to the average photospheric magnetic flux coming from active regions' decay, but this observable is available only since 1976. The sum of the unsigned magnetic flux for a solar rotation is highly correlated to the average sunspot area for that rotation (r = 0.86). Such correlation increases (r = 0.93) when these observables are smoothed by averaging over 6 rotations (Figure 1). Thus we can derive the surface poloidal source from the long-term spot area data for cycles 12 through 23, taken from the NASA website of David Hathaway (www.ssl.msfc.nasa.gov/ssl/pad/solar/greenwch.htm). Observations [*Wang et al.*, 2000] show that only 10–20% of the flux that emerges survives while transported beyond its original neighborhood. We use a constant value of 14.3% for these calculations.

[11] (iii) In flux transport dynamos the cycle period is determined mainly by the meridional circulation amplitude [*Dikpati and Charbonneau*, 1999], which is observed to vary significantly with time since 1996. But the details are not known prior to 1996. If we run the dynamo with an average meridional circulation the dynamo selects a computed cycle period. Incorporating surface magnetic flux observations in the dynamo also imposes the observed solar cycle period. So artificial phase differences between the imposed and computed cycles occur, which will seriously degrade our ability to simulate the sequence of cycle amplitudes in the induced toroidal field. Therefore we set the meridional flow speed according to the average of all cycles between 12 and 23 (14.5 m/sec peak for a mean cycle period of 10.75 years, period set by much slower return flow at the bottom) and take the bold step of stretching or compressing the surface poloidal source of each cycle to fit with this period. In this way, we keep both the peak flux and the average flux of the cycle the same as before the stretching or compression. We then are able to maintain the phase coherence between the externally imposed cyclic surface source and the cyclic induction of the toroidal field at the tachocline, take prediction of the period out of the problem, and focus on simulation and prediction of the cycle amplitudes.

[12] We initialize our predictive model at the beginning of cycle 12 and, applying the external forcing of the surface poloidal source, we "predict" the cycle peaks of successive cycles through cycle 23, and make a true forecast of the peak for cycle 24, ending the simulation in the year 2020. During cycles 12–15 we are in effect loading the conveyor belt that is the meridional circulation, so we focus our tests of predictive skill on cycles 16–23. Our forecasted quantity is the toroidal magnetic flux generated in the overshoot layer, integrated between mid-latitudes and the equator. This flux corresponds to peak toroidal fields in the range 40–100 kG for different cycles. For the diffusivity profile we selected, and the poloidal source we derived for these simulations, 5–10% of the dynamo-generated magnetic flux should appear at the photosphere.

3. Results

[13] Figures 2a and 2b respectively show the observed cycle peaks and simulated cycle peaks since cycle 12. Comparing the observed cycle peaks in Figure 2a with the simulated peaks in Figure 2b, we find that our model correctly predicts the relative sequence of cycle peaks for cycles 16 through 23. We continue to run the model into the

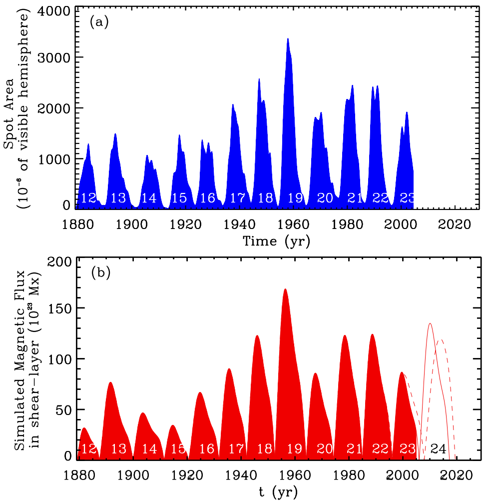

Figure 2. (a) Observed spot area (smoothed by Gaussian running average over 13 rotations) plotted as function of time. (b) Simulated toroidal magnetic flux in the overshoot tachocline within mid-latitudes for the case with a steady meridional flow (solid red area and curve) and with the time-varying flow incorporated since 1996 (dashed red curve).

future, up to 2020 (solid and dashed curves in Figure 2b). Incorporating the constant meridional circulation of 14.5m/sec up to 2020, we predict that the upcoming cycle 24 (solid curve) will be about 50% stronger than the current cycle 23. This prediction is in marked contrast to those of *Svalgaard et al.* [2005] and *Schatten* [2005]. Both predict the cycle 24 peak will be ~40% below that of 23, as measured by Zurich sunspot number. The difference between our prediction and theirs has obvious practical implications in terms of, for example what atmospheric drag to expect on low-orbit satellites.

[14] The dashed curve in Figure 2b is obtained by repeating the above simulation with a steady meridional flow from cycle 12 through 22 and then continuing the simulation through the present to 2020 using observations [*Basu and Antia*, 2003, Figures 10 and 11] that the meridional flow slowed down by 40% during 1996–2002, and assuming it stays low until 2020. This assumption results in a lower peak for cycle 24, but one that is still 30% above cycle 23. Thus depending on the meridional circulation we use, we predict that the peak amplitude of cycle 24 will be 30–50% above that of cycle 23.

[15] In order to measure the skill of our predictive tool, we plot in Figure 3 the correlation between the simulated and observed cycle peaks for cycles 12 through 23. The correlation coefficient is $r = 0.958$ in this case, if we include cycles 12–23, and $r = 0.987$ if we include only cycles 16–23, after the conveyer belt is fully loaded. The straight line fit in Figure 2a clearly reveals that the flux-transport dynamo driven by the observed surface poloidal source (derived from spot area) shows definite skill in reproducing the correct sequence of peaks of the past cycles.

[16] We have done two comparison runs to test the validity of our model. In one we ran our model for 450 years with an artificially constructed cyclic surface poloidal source which is random in peak amplitudes. This randomized surface source lead to predictions that are uncorrelated with the input, showing no skill in the model. We also conducted a sequence of simulations for which to predict cycle n we set the surface poloidal source to zero at the end of cycle *n*-1. For all of cycles 16–23 the cycle peaks obtained in this way were virtually identical to those in Figure 2b, showing that the observational input during cycle *n* had no influence of the prediction for cycle *n*. This confirms that our predicted toroidal flux for cycle *n* depends entirely on poloidal flux from earlier cycles.

4. Conclusions and Discussion

[17] We all must wait for several years to see whether the various forecasts for cycle 24 verify or not. We have confidence in our particular forecast because of the success of our model in 'forecasting' the previous 8 cycles from surface sunspot area data for preceding cycles. Forecasting one cycle ahead may not be the limit of this model's capability. We are trying forecasts for two and even more cycles ahead, to search for the limit of its skill. We expect the skill to decline for each added forecast cycle. It may also be possible to extend the simulation of past cycles all the way back to cycle 1, which began around 1750. Although we do not have spot area data prior to about 1880, there is a good correlation between sunspot area and the classical Wolf sunspot number, which is available back to about 1700 from *Waldmeier* [1961]. A forthcoming paper will report on this simulation in the near future.

[18] An obvious generalization of our model would be to include departures from axisymmetry. We are currently engaged in developing such a model, which would have the capability of producing patterns resembling 'active longitudes', another feature of solar activity of great interest for solar-terrestrial research and prediction. It remains to be determined, however, whether such a model would show skill in predicting the occurrence and evolution of active longitudes. Two of us [*Dikpati and Gilman*, 2005] have recently proposed a new theory for active longitude in which they arise from bulges produced in the solar tachocline by global MHD instabilities there.

[19] A limitation to our model is the assumption of a constant meridional flow prior to 1996; this assumption was required because there are no direct frequent meridional

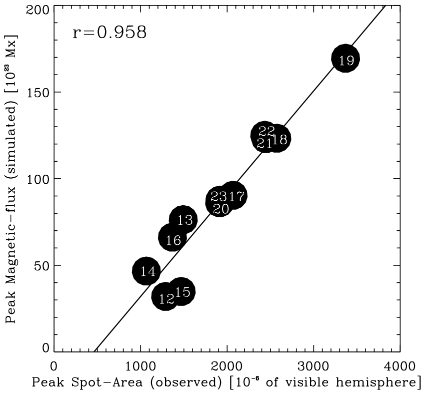

Figure 3. Correlation plots of simulated cycle peaks vs. observed cycle peaks from spot area for cycles 12 through 23.

flow measurements available before that year, though there are efforts underway to estimate meridional flow from Mt. Wilson helioseismic data back to the late 1980's. For still earlier times, only the method described by *Hathaway et al.* [2003] is available, and we (M. Dikpati et al., manuscript in preparation, 2006) are exploring that, but it uses magnetic information from each cycle to estimate the meridional flow for that cycle, so it is not truly independent of the predictions we make for that cycle.

[20] Our overall approach to solar cycle prediction is philosophically similar to that employed in global atmospheric dynamics over the past 50 years or so. We focus on predicting changes in certain global characteristics of a cycle, without attempting to reproduce details that occur on smaller spatial scales and shorter time scales. But some effects of smaller scales are included in parametric form, guided in formulation by observations as well as detailed theory of smaller scale processes.

[21] In conclusion, we argue that the model we have presented shows sufficient skill and future potential that it should be added to the current set of forecast tools for future solar cycles.

[22] **Acknowledgments.** We thank Keith MacGregor for helpful comments on the manuscript, and Eric McDonald for technical help in preparing it. We thank Günther Rüdiger for helpful discussions during our presentation of this work at ISSI meeting in Bern in October 2005, Janet Luhmann, Peter McNiece and many other participants of CCMC workshop, and Ernie Hildner for comments that have helped improve the clarity of this paper. We also thank two anonymous referees for a thorough and critical review of an earlier version of this paper. This work is partially supported by NASA grant NNH05AB521. The National Center for Atmospheric Research is sponsored by the National Science Foundation.

References

Babcock, H. W. (1961), The topology of the Sun's magnetic field and the 22-year cycle, *Astrophys. J.*, *133*, 572–588.

Basu, S., and H. M. Antia (2003), Changes in solar dynamics from 1995 to 2002, *Astrophys. J.*, *585*, 553–565.

Charbonneau, P., and M. Dikpati (2000), Stochastic fluctuations in a Babcock-Leighton mdel of the solar cycle, *Astrophys. J.*, *543*, 1027–1043.

Dikpati, M., and P. Charbonneau (1999), A Babcock-Leighton flux transport dynamo with solar-like differential rotation, *Astrophys. J.*, *518*, 508–520.

Dikpati, M., and P. A. Gilman (2005), A shallow-water theory for the Sun's active longitudes, *Astrophys. J.*, *635*, L193–L196.

Dikpati, M., G. de Toma, P. A. Gilman, C. N. Arge, and O. R. White (2004), Diagnostics of polar field reversal in solar cycle 23 using a flux-transport dynamo model, *Astrophys. J.*, *601*, 1136–1151.

Hathaway, D. H., R. M. Wilson, and E. J. Reichmann (1999), A synthesis of solar cycle prediction techniques, *J. Geophys. Res.*, *104*, 22,375–22,388.

Hathaway, D. H., D. Nandy, R. M. Wilson, and E. J. Reichmann (2003), Evidence that a deep meridional flow sets the sunspot cycle period, *Astrophys. J.*, *589*, 665–670.

Küker, M., G. Rüdiger, and M. Schültz (2001), Circulation-dominated solar shell dynamo models with positive α-effect, *Astron. Astrophys.*, *374*, 301–308.

Schatten, K. H. (2005), Fair space weather for solar cycle 24, *Geophys. Res. Lett.*, *32*, L21106, doi:10.1029/2005GL024363.

Schatten, K. H., P. H. Scherrer, L. Svalgaard, and J. M. Wilcox (1978), Using dynamo theory to predict the sunspot number during solar cycle 21, *Geophys. Res. Lett.*, *5*, 411–414.

Svalgaard, L., E. W. Cliver, and Y. Kamide (2005), Sunspot cycle 24: Smallest cycle in 100 years, *Geophys. Res. Lett.*, *32*, L01104, doi:10.1029/2004GL021664.

Waldmeier, M. (1961), *The Sunspot Activity in Years 1610–1960*, 171 pp., Schulthess, Zurich, Switzerland.

Wang, Y.-M., and N. R. Sheeley Jr. (1991), Magnetic flux transport and the Sun's dipole moment: New twists to the Babcock-Leighton model, *Astrophys. J.*, *375*, 761–770.

Wang, Y.-M., N. R. Sheeley Jr., and J. L. Lean (2000), Understanding the evolution of the Sun's open magnetic field, *Geophys. Res. Lett.*, *27*, 621–624.

G. de Toma, M. Dikpati, and Peter A. Gilman, High Altitude Observatory, National Center for Atmospheric Research, 3080 Center Green, Boulder, CO 80301, USA. (detoma@ucar.edu; dikpati@ucar.edu; gilman@ucar.edu)