Space Weather Modeling and Prediction for Intermediate Time-scales

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1. Overview: "Space Weather" describes the conditions in the terrestrial system, particularly on its outer envelope, that can affect various ground- and space-borne technologies due to the impact of energetic particles and magnetic fields streaming from the Sun. This could occur either due to the continuous flow of solar wind or due to the onset of CMEs or flares in a short interval of time. While the chain of processes involved in transmitting the adverse, hazardous effects of these energetic particles into the Earth's atmosphere is extremely complex, over the past several years considerable effort has been undertaken to understand and predict space weather on time-scales from a few minutes-to-hours up to a few days. A comprehensive road map can be found in Schrijver et al. (2015). Also, studies to understand the effects of adverse solar events occurring on longer time-scales from decades to centuries, on society's space-weather-sensitive instruments, industries, national security systems, etc., have continued for many years. On the verge of a new decadal activity cycle, a solar cycle prediction panel has been formed to assess and accelerate improved physical understanding and eventually to predict upcoming solar cycle features. In particular, progress has been made in recognizing that the most likely "seed" of the next sunspot cycle is the polar field of the previous cycle's minimum.

In addition to very short (hours-to-days) and much longer (decadal to millennial) time scales where solar events could arise, there is an important intermediate time scale, the interval from weeks-to-months (see, e.g. Dikpati & McIntosh 2020 and references there in; see also Simoniello et al. 2012) over which solar activity varies strongly. These events are often called 'quasi-annual' or 'seasonal' variability, during which an enhanced burst of solar activity is followed by a relatively quiet interval. The strongest space weather events happen during the "bursty seasons". Therefore, understanding the origins of and predicting major space weather events on time-scales from weeks to months ahead, has significant scientific and economic value. This 'intermediate' time-scale would also fill-in the gap between the short and longer time-scale forecasts of space weather.

For more than half a century, the Earth's weather has been forecasted by simulating the meanders of the mid-latitude "jet stream" and associated large scale weather systems, such as cyclones and anticyclones (low- and high-pressure patterns with counterclockwise and clockwise flows on weather maps). The jet stream is the product of interactions of global Rossby waves and mean East-West flows in the troposphere and lower stratosphere. Assimilating vast amounts of observational data into complex computational models has led to enormous improvements in forecasting the weather out to more than a week ahead, including cold outbreaks and winter storms as well as floods and dry periods. Recently solar Rossby waves have been observed (McIntosh et al. 2017) and are now being modeled and related to patterns of solar magnetic activity. We are entering a golden era to forecast

Rossby-like waves in the meandering pattern of the Sun's spot-producing toroidal magnetic fields (the solar analog to the Earth's jet stream), leading to an ability to forecast enhanced solar activity bursts weeks to months ahead. In turn, these will allow us to anticipate major space weather events well ahead of time, since they are closely tied to these bursty 'seasons' (McIntosh et al. 2015).

2. Recent progress and current status: In recent years observational evidence for the existence of solar Rossby waves has been accumulating rapidly (McIntosh et al. 2017; Loptien et al. 2018). In addition, surface velocity measurements give further hints of the presence of "giant cell" convection patterns (Hathaway & Upton 2020). Recently, our knowledge about their role in driving dynamics of spot-producing magnetic fields has been substantially advanced. Rossby waves, which arise in thin fluid layers in stars and planetary atmospheres, occur due to variations in Coriolis force with latitude. But unlike planetary waves, solar Rossby waves are most likely magnetically modified. Very much like the Earth's jet stream, solar Rossby waves, particularly the energetically active ones, can create large-scale meandering patterns in the spot-producing magnetic fields (Dziembowski & Kosovichev 1987).

Although signatures of solar Rossby waves have been detected at the photospheric and coronal level, it is most likely that a major part of these waves are generated below the surface, in a much less turbulent zone, such as at or near the base of the convection zone. Theoretical model developments for solar Rossby waves in both hydrodynamic and magnetohydrodynamic regimes, including neutral and unstable waves, nonlinear waves and their interactions with differential rotation and spot-producing toroidal fields are rapidly advancing. The role of recently discovered tachocline nonlinear oscillations (TNOs; see, e.g. Dikpati et al. 2017) in determining the timings and latitude-longitude locations of magnetic flux emergence, and in turn, the 'seasons' of major space weather events has also been demonstrated.

Thus, a key to forecasting space weather on intermediate time-scales requires an accurate estimate of amplitudes and phases of solar Rossby waves and the link between the observations and model-outputs through data assimilation techniques. Such techniques are also being implemented in solar models. So, what needs to be done next?

3. Basic questions and major projects

3.1: Continuous observations of Rossby waves are necessary for the next few sunspot cycles: Observational methods would include helioseismic, as well as surface global velocity and magnetic patterns. Along with space-borne observations (such as from STEREO, SoHO, SDO), ground-based measurements (such as NGGONG -- the Next Generation GONG network) will also be needed. Aligning with our goals of predicting space weather on intermediate time-scales, the observations would be optimized to be most sensitive to changes on time scales of weeks to months.

3.2 Theoretical models of global MHD Rossby waves need to be advanced, with eventual merger into comprehensive MHD models of the convection zone and photosphere: So far, models for meandering pattern-development due to interactions of Rossby waves with mean flows and magnetic fields have been developed in 3D thin-shell shallow-water regimes to conform with the large horizontal scales and much less variation in vertical scale. Models including substantial variations in the vertical are necessary in order to model and predict the attenuation of these waves as they propagate to the solar atmosphere. The Rossby wave models also need to allow for interactions with other waves and instabilities in both the tachocline and the convection zone.

3.3 Connecting model-outputs with observations using advanced data assimilation methods: These prediction models would be initialized using data assimilation of the observations (surface and helioseismic) most closely associated with the physics of each model, to test their ability to predict velocities and magnetic field changes on time scales of weeks to months. Some form of each class of model, or combinations of models, would be tested to determine how model-outputs compare with observed emergence of solar magnetic fields for many magnetic cycles. Advanced data assimilation techniques that produce estimates of forecast uncertainty and error correlation are required.

3.4 Flux emergence models and recipes: In parallel with the above projects, theoretical models for how toroidal flux arises from the base of the convection zone to the photosphere, and its nature in the photosphere, need to be greatly advanced. The relative roles of convection and magnetic buoyancy in this process need to be determined. Furthermore, coupling of flux-emergence, being one of the complex issues, needs to be explored through physical models (see, e.g., Fan 2009) as well as flux-emergence recipes derived from the applications of data assimilation, machine learning, artificial intelligence and information theory.

3.5 Operation of predictive model for the needs of customers and stakeholders: The use of sequential data assimilation that updates the model every few days as new data become available will enable us to predict the enhanced activity bursts up to several weeks ahead. Similar to the way that weather forecast models operate, the accuracy of the prediction is expected to improve as the target time (~four weeks ahead) is approached.

Given recent advancement of Rossby waves observation and theory as described above, and the demonstrated predictive skill through success in 'hindcasts' of timings and locations of major space weather events, in the future, forecasting what to expect in the next few weeks to months will be possible. Close collaborations are necessary among the appropriate Federal agency research and operational programs, involving significant technology transfer to the agency making the forecasts, such as SWPC of NOAA, NASA, NSF and the Air Force, to make decisions on whether (i) equipment is taken off-line now or after waiting for a few days, (ii) a GNSS (Global Navigation Satellite System) related activity can be planned for next week or the week after.

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