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Scale-Dependent Data Assimilation of Solar Photospheric Magnetic Field

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Abstract: Modeling the evolution of the solar photospheric magnetic flux, typically used to drive coronal and solar wind models, is a key challenge to forecasting near earth space weather variability. Accurate estimations of the solar global magnetic field are paramount in predicting space weather events that effect terrestrial communication and guidance systems. The magnetic flux is difficult to model due to the emergence of magnetic *active regions* which arise from unobservable zones below the photosphere. For this reason the model used in our forecast has severe bias at the scale of emerging active regions. We use wavelet based multiresolution analysis to separate scales in model and observations during the application of an ensemble Kalman filter. Our method of assimilation for the photospheric flux demonstrates a unique version of a scale-dependent EnKF. We demonstrate that our assimilation method allows accurate data assimilation of observed active regions despite large, scale-dependent model bias.

Keywords: Kalman filters, sequential control algorithms, wavelets, multiresolution analysis, ensemble Kalman filter, space weather

1. INTRODUCTION

Understanding, monitoring, and forecasting space weather is of utmost importance in predicting and mitigating geoeffective events. The observable origin of much space weather is found in studying the magnetic flux across the photosphere. Here we present a multiscale data-assimilation method and its application to modeling the magnetic flux transported across the solar photosphere.

To model the solar photospheric flux we use the Air Force Data Assimilative Photospheric Transport (ADAPT) model detailed in Arge et al. (2010, 2011, 2013) and Hickmann et al. (2015). ADAPT represents a collaborative modeling effort between Los Alamos National Laboratory in Los Alamos New Mexico and the Air Force Research Laboratory at Kirtland AFB in Albuquerque New Mexico. In ADAPT the magnetic flux is propagated across the sun's surface using the combined effects of differential rotation, meridional flow, and super granular diffusion based on Worden and Harvey (2000). The observations of the solar magnetic flux assimilated into ADAPT maps utilized in this work are from the GONG (Global Oscillation Network Group) instruments. GONG observations are assimilated into ADAPT within a longitudinal observation window ranging over $(-90°, 60°)$ in *central meridian distance* (CMD). The GONG observations can be assimilated at a cadence of 10 minutes, for the examples shown in this paper a cadence of 6 hours was used. The dynamical system underlying ADAPT has scale-dependent bias that is typical of the solar photosphere modeling problem. The underlying stochastic nature of new flux emergence is the primary challenge of modeling the global photospheric field, since we are limited to observing less than half of the solar surface at any given time. Flux emergence occurs in the form of large collections of magnetic flux, known as *active regions*, which are primary drivers of large space weather events.

In Figure 1 we show GONG observations of a solar active region rotating into view on the east limb of the sun and then clearly tracking across the observable disk over a period of 10 days. Figure 1 reveals the observed active region separated into two spatial scales through wavelet based multiresolution analysis (MRA). Much of the active region's flux present at the fine scale dissipates as it traverses the solar surface. At the coarse scale, though the shape of the region changes significantly, the sharpness of the region's borders remains and much of the active region's flux at this scale is not dissipated. Observations used in Figure 1 were made at three different times. The first observation shown was recorded on the 9^{th} of July 2010 at 17:54 UT when the active region was first clearly observed in the GONG image data. The second observation in Figure 1 is taken when the active region is at the central meridian (from GONG July 15, 2010 at 11:54 UT). GONG last fully observes the active region

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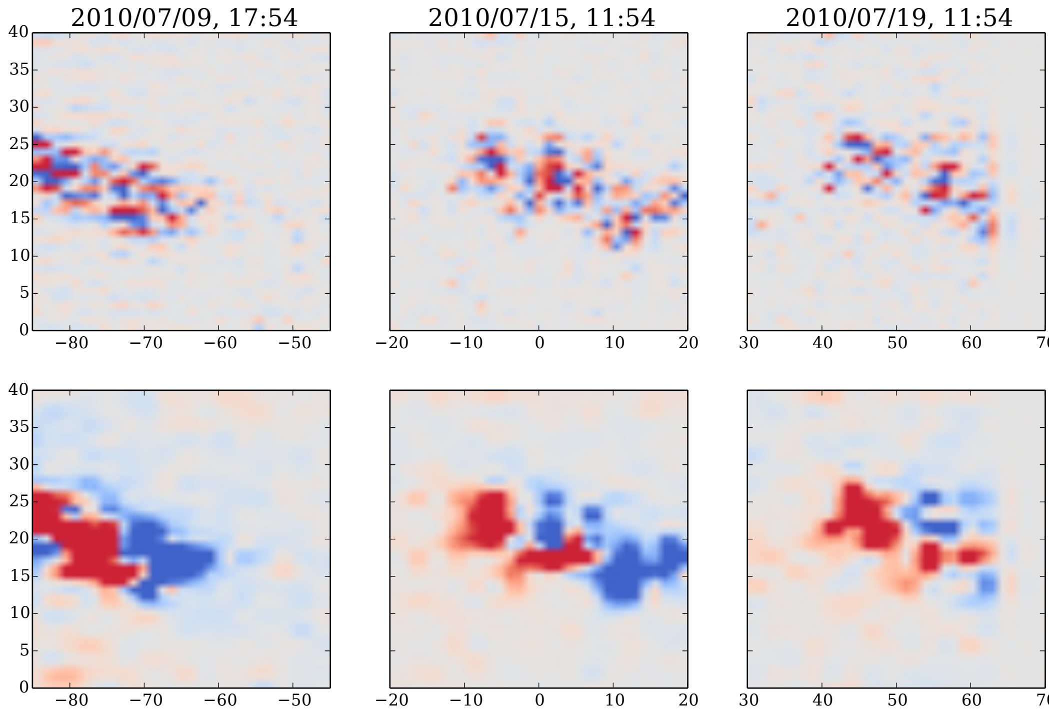

Fig. 1. Here we show GONG observations of a solar active region as it propagates across the observation window. Observations have been separated into two scales using multiresolution analysis. The finer *detail* scale is represented in the top row while the coarse *approximation* scale is shown in the bottom row. The x and y axis of each frame represent the location on the solar surface in latitude-longitude using *Central Meridian Distance* (CMD) for the longitudinal coordinates. Note, in the right sub-figures the boundary of the GONG observation region becomes visible as a sharp cutoff between longitudes $60°-70°$.

on the 19^{th} of July 2010 at 11:54 UT before the active region exits the west limb, pictured in the third column of Figure 1.

ADAPT relies on regular observational updates to account for new flux sources since ADAPT currently only accounts for random weak field emergence, along with the transport and diffusive properties, of the photosphere. This dissipation of active regions at large scales occurs at a faster rate than observed through GONG, see Figure 2. When ADAPT is coupled with a scale-independent assimilation strategy like the standard EnKF this difference in flux evolution of active regions causes an even faster dissipation rate as misaligned flux regions are averaged. Figure 2 shows the same active region depicted in the GONG observations of Figure 1 undergoing pure ADAPT evolution. When the ADAPT active region evolution is split into a fine, *detail*, scale and a coarse, *approximation*, scale, as shown in Figure 2, we observe that the primary effect of ADAPT evolution at the large scale is dissipation. The example in Figure 2 is of a rather large active region so even with dissipation there is still a significant active region pictured after 10 days of evolution. For smaller regions, which are more common, the active region could fully dissipate in this time frame which is much different than observed behavior of active regions.

If data assimilation is carried out in the ADAPT model without accounting for this scale-dependent bias, such as when using a standard EnKF, active regions tend to diffuse after only a few cycles of observation and model evolution. Active regions can be assimilated more accurately if one uses a scale-dependent EnKF, since a scale-dependent filter allows tuning of the observation error and model covariance at each scale separately. We show that a wavelet based EnKF does much better at preserving the structure of coherent active regions. Moreover, once the emergent active region is introduced into the ensemble, successive observations will further refine its structure.

Our multiresolution EnKF directly couples wavelet analysis with the EnKF by partitioning the range of the observation operator. This restricts the range of the observation operator to a scale-dependent subspace and can eliminate some of the ill-posedness of the filtering problem associated with poorly observed scales (Alekseev and Navon (2001) and Liu (1994); Liu et al. (1995)). The coupling of ensemble Kalman filters and multiresolution analysis is not entirely new. However, previous MRA applications to EnKF (Chou et al. (1993), Buehner and Charron (2007); Buehner (2012), Deckmyn and Berre (2005), Kasanickỳ et al. (2014), and Beezley et al. (2011)) have focused on providing a more accurate approximation to the ensemble covariance and did not separate scales within observations explicitly. Though this previous work has been important and, indeed, motivated much of our thinking about scale-dependent assimilation, our approach focuses on analyzing the scale-dependence of the observations and gives a direct way to include scale-dependent information into the EnKF algorithm.

This paper is organized as follows. In section 2 we review the classical wavelet multiresolution analysis and set up notation. Section 3 describes our multiresolution ensem-