Comparison of Methodologies to Estimate the Tilt Angle of Solar Active Regions

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INTRODUCTION

Active regions (ARs) are the photospheric manifestations of emerging magnetic **flux ropes** (FRs) formed within the solar interior. A key parameter in their evolution is the inclination of the AR polarity axis with respect to the equatorial direction, commonly referred to as the **tilt angle**. The tilt angle has been, in general, estimated using photospheric line-of-sight (LOS) magnetograms. This estimation relies on the flux-weighted centers of the AR positive and negative polarities, often called **magnetic barycenters**. The tilt is defined as the acute angle between the line connecting the magnetic barycenters and the equatorial plane. We demonstrated[1] that this estimation can be significantly affected during the emergence phase of ARs by projection effects due to the twist of the FRs, also known as **magnetic tongues**.
We review the tilt angle estimation in a selection of 126 bipolar ARs from Solar Cycle 23 using two different methodologies.

METHODOLOGY

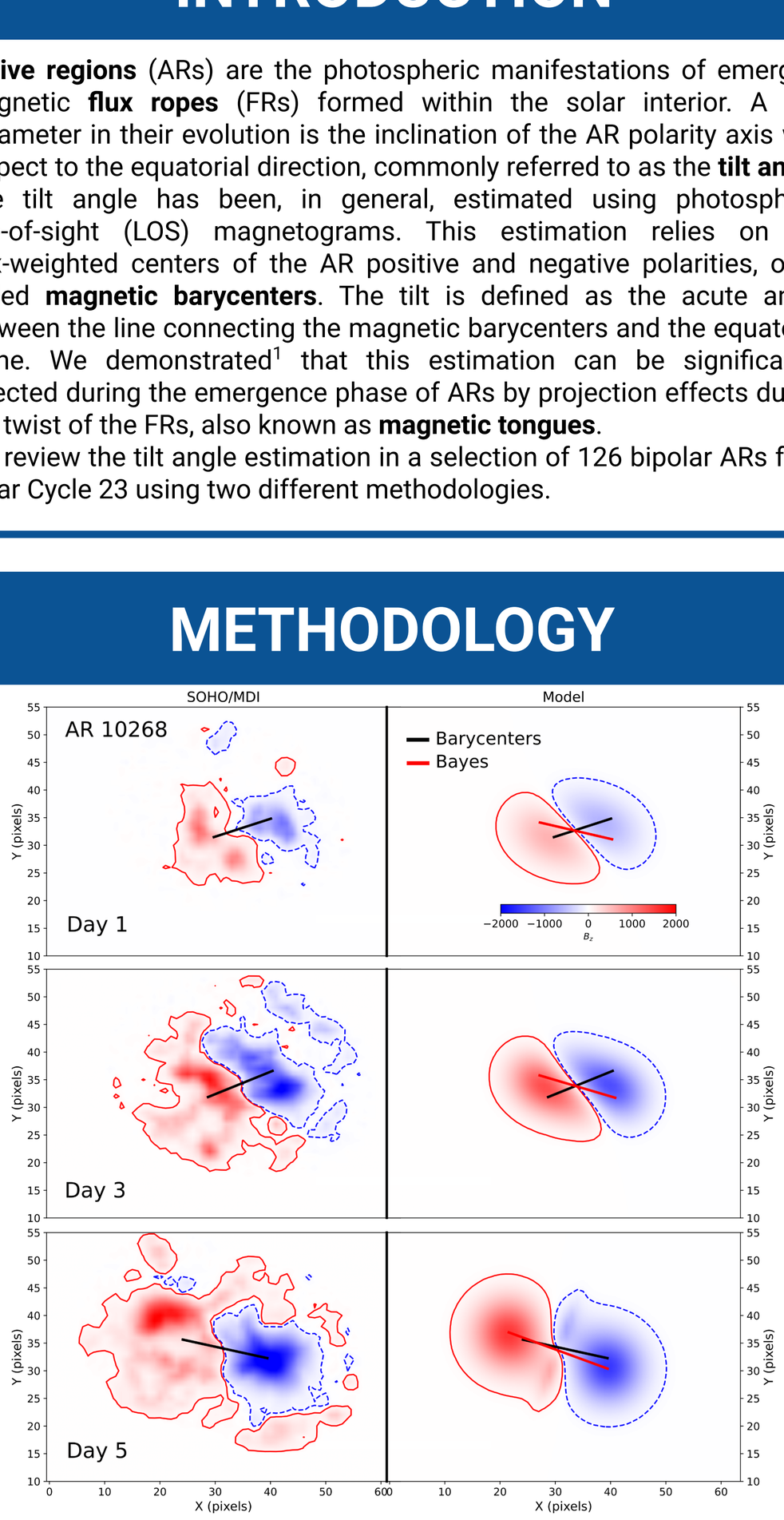

Fig. 1: (*Left*) SOHO/MDI LOS magnetogram of AR 10268. (*Right*) modeled magnetograms.

We introduced[2] a method to model individual LOS magnetograms using a **Bayesian** approach. This method employs a twisted toroidal FR model to generate synthetic line-of-sight (LOS) magnetograms, which are then compared with actual AR observations. We presented[3] temporal models consistent with the observed evolution of the LOS magnetic field of ARs during their emergence phase. These models serve as proxies for the global magnetic parameters of the emerging FRs, such as the tilt angle and the twist (number of turns).

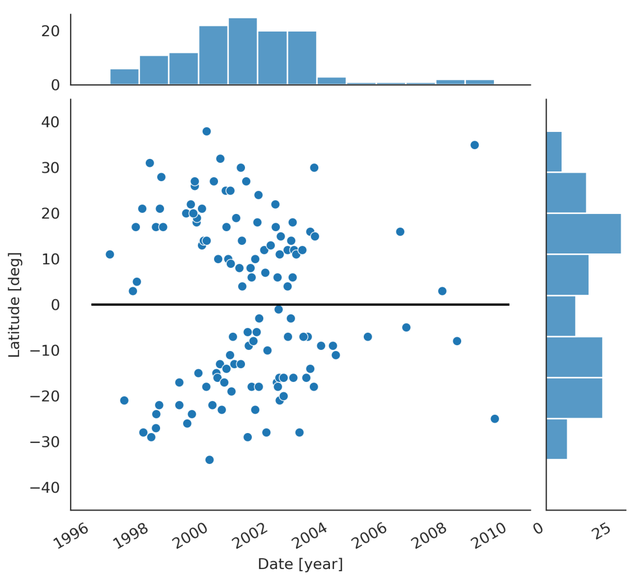

Fig. 2: Sample of AR latitudes of emergence as a function of time.

We track the evolution of ARs located within a longitudinal range of -35° to 35° from the central meridian, using MDI LOS magnetograms.
Our dataset spans a wide range of latitudes and covers most of Solar Cycle 23.

RESULTS AND DISCUSSION

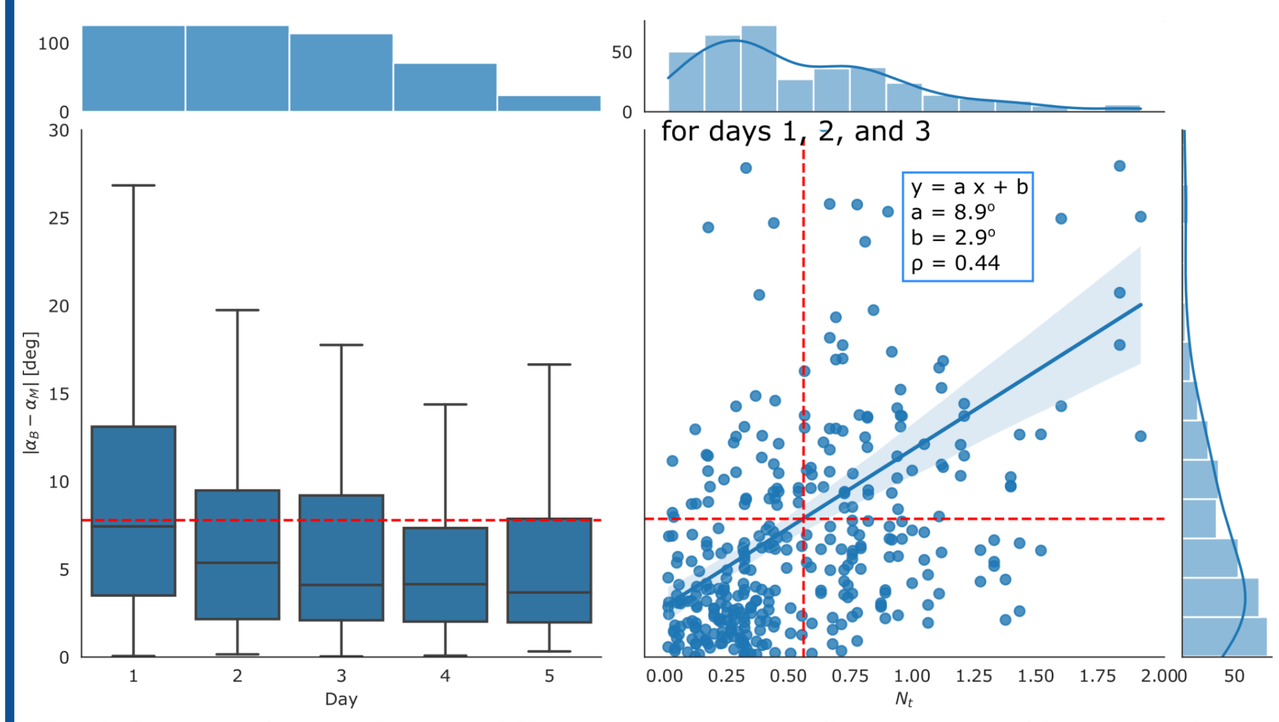

Fig. 3: Boxplot with the absolute difference between the tilt estimated with both methods as function of day of emergence (*left*) and vs the model number of turns (*right*) with a scatter plot. *Red-dashed* lines mark mean values for the respective axes.

We calculate the daily mean tilt obtained using both the barycenter method and the Bayesian model for each AR (**Fig. 3.**). The difference between these estimates (left panel) decreases as the ARs progress toward the end of their emergence phase. If we consider each day as an independent measurement, the average difference between the two estimations is approximately 7.7°. We compare (right panel) this difference with a proxy for the number of turns (twist parameter). We find a correlation between these quantities during the first three days of the AR emergence. This suggests that the primary difference between the two estimations is due to the effect of magnetic tongues. Standard methods to measure tilt angles strongly depend on the stage of the AR evolution, being the presence of magnetic tongues the main problem that affects tilt-angle estimations, during the emerging phase.

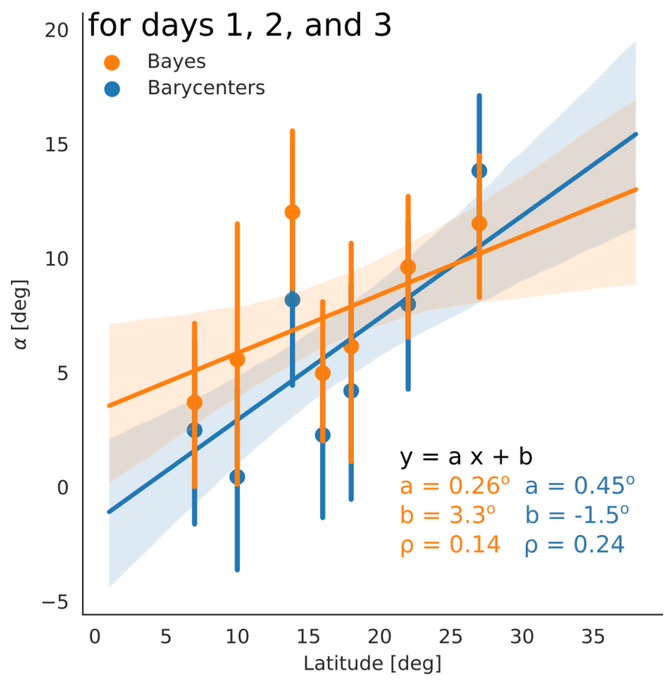

Fig. 4: Daily mean tilt angle as a function of latitude for both estimations. Dots and lines indicate mean tilt and standard deviation within latitudinal bins.

We compare the latitudinal dependence of the tilt obtained using both methods (**Joy's Law**). Positive (negative) tilt corresponds to an inclination where the leading polarity is closer to (farther from) the solar equator than the trailing polarity. The two estimations result in different latitudinal dependencies. In particular, the Bayesian method reduces the range of tilts observed with the barycenter method, as it corrects negative tilts caused by the effect of magnetic tongues. This leads to a smoother latitudinal variation and provides a more robust estimation of the expected inclination of bipoles. Our Bayesian method, which we plan to apply extensively to a large number of ARs, will offer more precise insights into the origin of the tilt angle and its variability throughout the solar cycle.

REFERENCES

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