Emulating Numerical Simulations of the Sun to Infer Synthetic Plasma Motions at the Photosphere

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Introduction

Satellites and ground-based observatories probe the Sun's photosphere and atmosphere and are key in studying solar activity. Meanwhile, numerical models of the Sun have been steadily bridging the gap with observations and reflect our best understanding of the physics that govern the Sun and granulation. However, there are relevant physical quantities that can be modelled but that cannot be directly measured and must be inferred. **Recently, neural network computing has been used in conjunction with numerical models of the Sun to be able to recover the full velocity vector in photospheric plasma of the Quiet Sun (*i.e.* in the absence of significant magnetic activity). We used satellite observations as input in the fully convolutional DeepVel neural network (Asensio Ramos *et al.*, 2017) to generate instantaneous synthetic plasma motions, *i.e.* plasma motions that reflect the physics of a numerical model but are made to look as if they were observed by a specific instrument.**

Metrics

- **C** = Pearson linear correlation coefficient;
- **A** = Normalized dot product between the reference velocity vector field and the inferred velocity vector field.

DeepVel Test Set: Resampled Simulation Data of Granulation

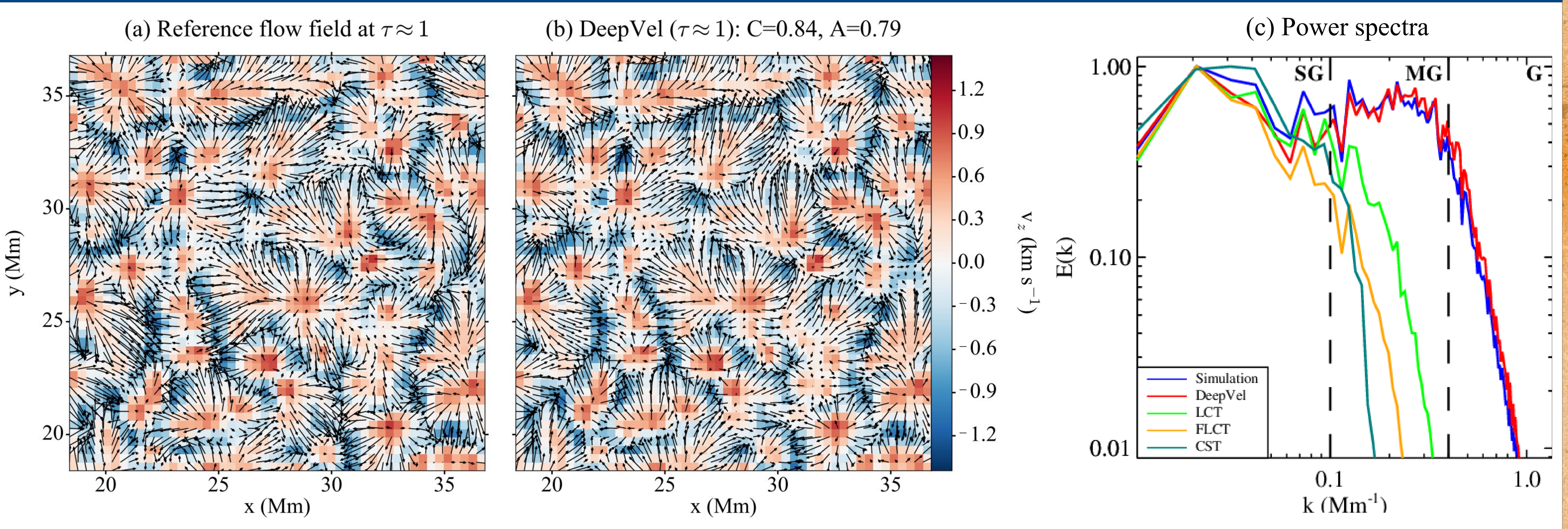

Figure 1: **Transverse velocity vectors** computed by (a) the Stein & Nordlund (2012) magnetoconvection simulation resampled at the SDO/HMI spatial resolution (**reference field**) and (b) the **DeepVel** neural network trained using results from the Stein & Nordlund (2012) numerical simulation. All vector fields were averaged over 30 minutes. The vertical component of the velocity field computed by the Stein & Nordlund (2012) simulation is displayed in the background. Inside a granule, plasma rises (positive vertical velocities) and the transverse velocity vectors **diverge**. In the intergranular network, plasma sinks back into the star's interior (negative vertical velocities) and transverse velocity vectors **converge**. (c) **Kinetic energy spectra** E(k) as a function of the wave number k (which is inversely proportional to the spatial scale). The reference vector field and the velocity field inferred using DeepVel are in agreement at supergranular scales (SG: order of 10 Mm or larger), mesogranular scales (MG: between 1 Mm and 10 Mm) and granular scales (G: 1 Mm or less).

DeepVelU Test Set: Resampled Simulation Data of Granulation

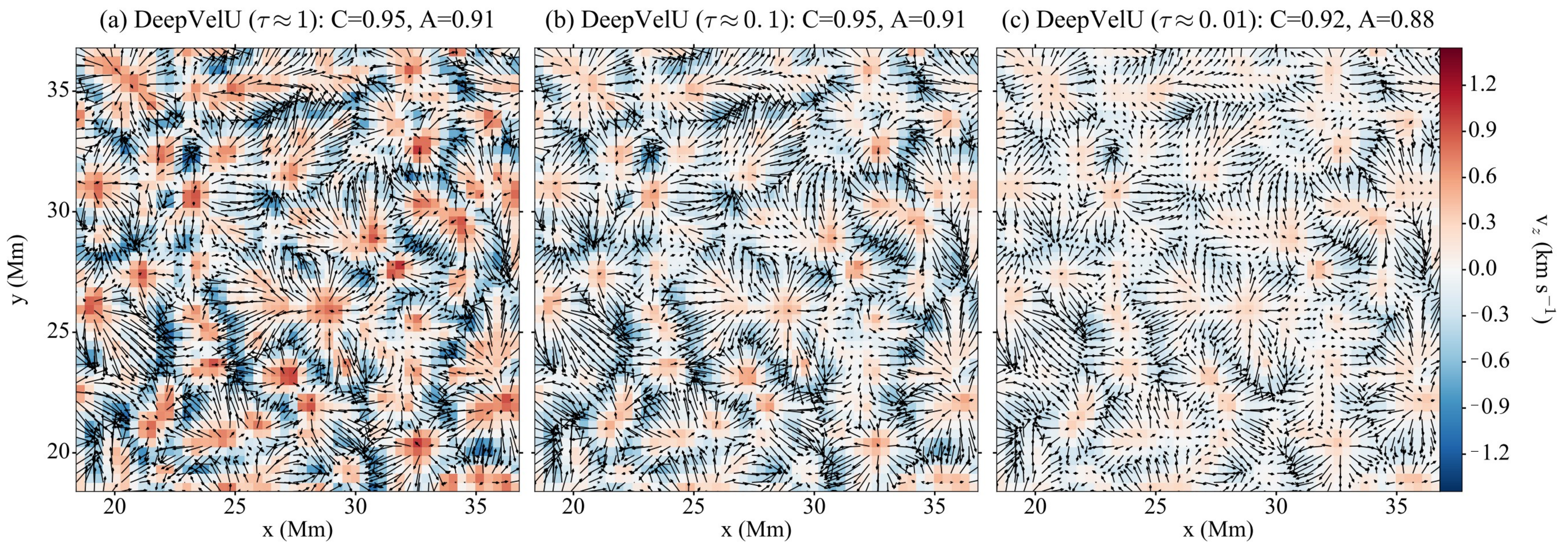

Figure 2: Preliminary results for the **transverse velocity vectors** computed at optical depths (a) $\tau \approx 1$, (b) $\tau \approx 0.1$ and (c) $\tau \approx 0.01$ simultaneously by **DeepVelU** (*name subject to change*), **a new architecture for the DeepVel neural network** which is inspired from the U-Net neural network (Ronneberger *et al.*, 2015). DeepVelU was trained using the same training set as in Figure 1(b). The vertical component of the velocity field computed by the Stein & Nordlund (2012) simulation at each corresponding optical depth is displayed in the background. The metrics suggest an improvement for the spatial distribution and the orientation of the inferred velocity vectors.

Test Set: Resampled Simulation Data of a Sunspot

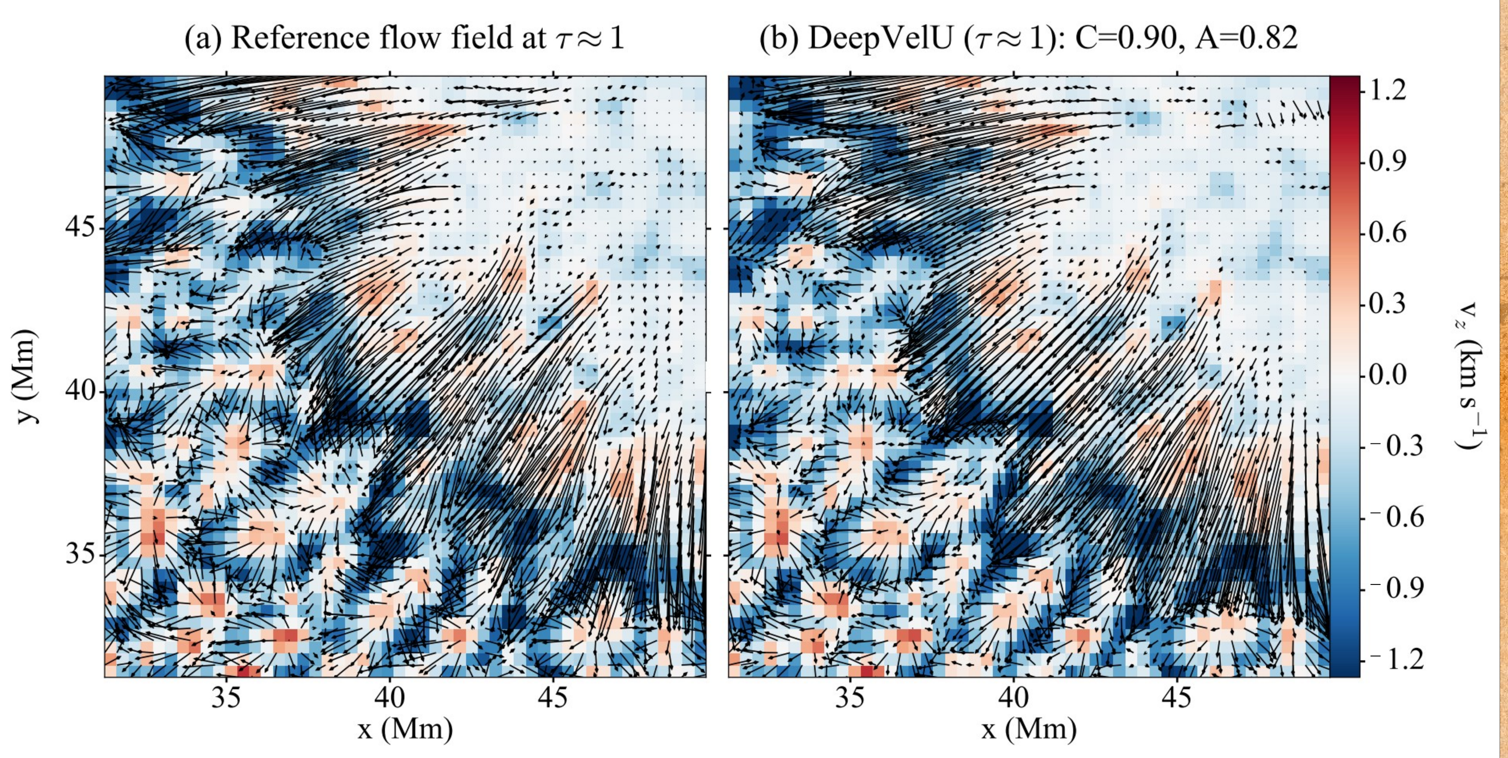

Figure 3: **Transverse velocity vectors** computed by (a) the MURaM simulation of a sunspot (initial spatial resolution of 96 km/pixel; Rempel & Cheung, 2014) resampled at the SDO/HMI spatial resolution (**reference field**) and (b) the **DeepVelU** neural network trained using results from the MURaM numerical simulation. All vector fields were averaged over 30 minutes. The vertical component of the MURaM velocity field is displayed in the background.

Results: SDO/HMI Data as Input

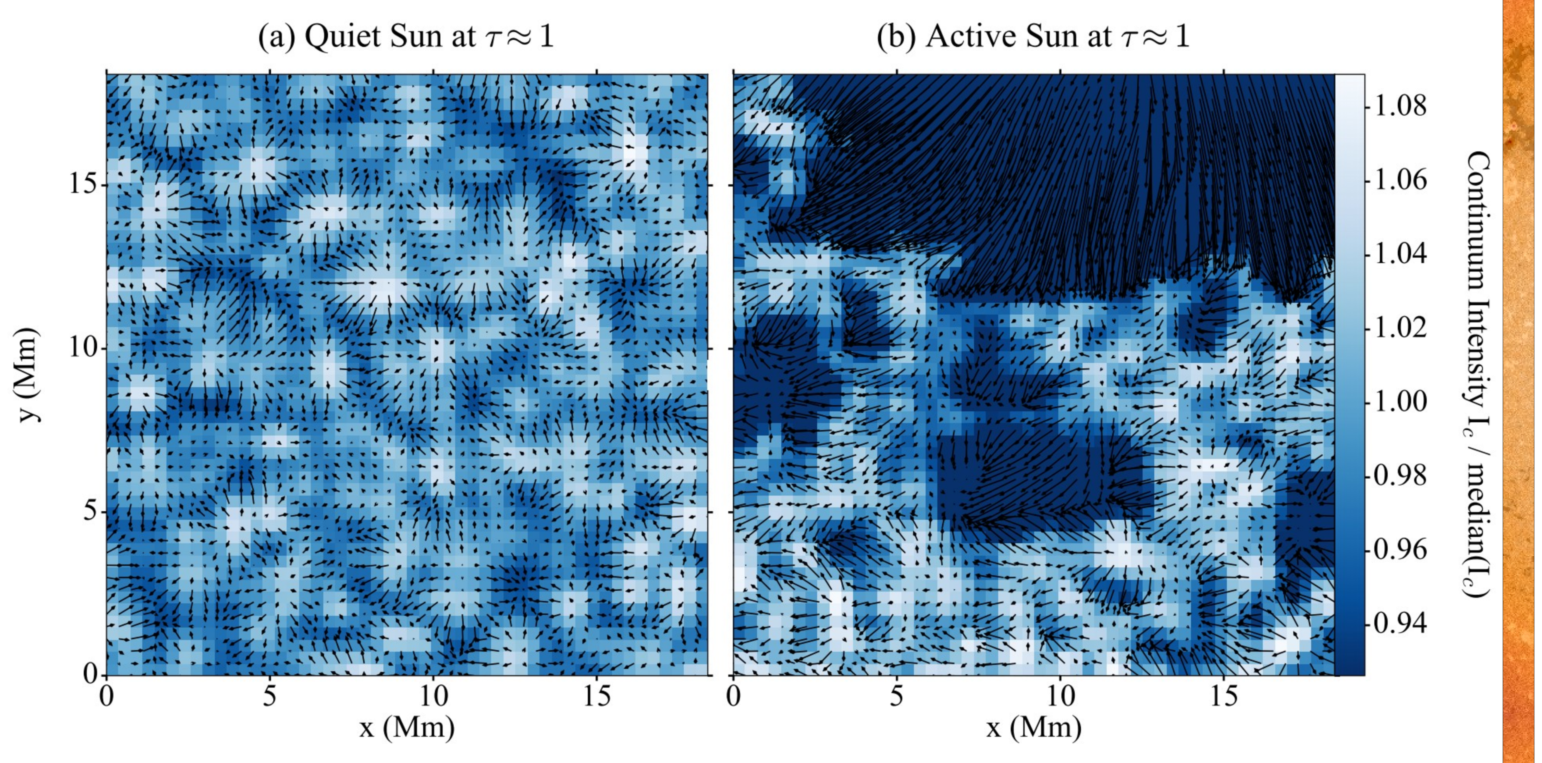

Figure 4: **Transverse velocity vectors** computed by the **DeepVelU** neural network from the **continuum intensity measured by SDO/HMI** for (a) a patch of **Quiet Sun** on 2010-10-08, and (b) a patch of **Active Sun** on 2014-09-10. The continuum intensity, normalized by its median value within the field of view, is displayed as background. Inside a granule, the ascending plasma is hotter (higher intensity) and the transverse velocity vectors **diverge**. In the intergranular network, the sinking plasma is colder (lower intensity) and the transverse velocity vectors **converge**.

Results: High-Resolution Synthetic Data & Subsurface Flows

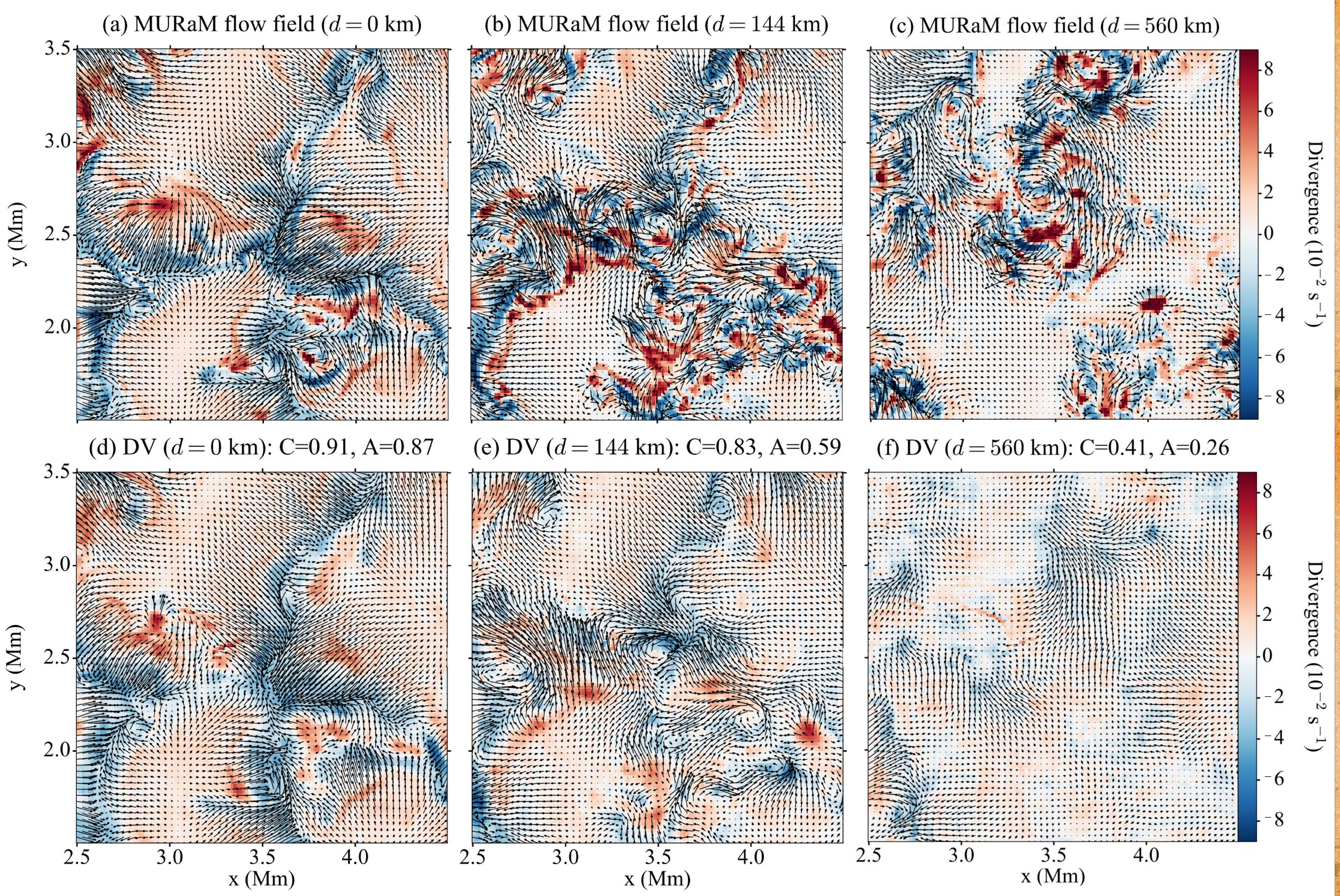

Figure 5: **Transverse velocity vectors** computed at depths d = {0, 144, 560} km below the Sun's surface. The divergence of the vector field is displayed as background (colorscale). (Top row) MURaM model of granulation (spatial resolution of 16 km/pixel; Vögler *et al.*, 2005). (Bottom row) Output of a version of **DeepVel** trained using the MURaM model. As d increases, convective motions of the plasma become more difficult to emulate from surface data.

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Conclusion

- **Results:** Velocity fields inferred by the DeepVel convolutional neural network **capture the behaviour of the Quiet Sun and Active Sun at spatial and temporal scales that are compatible with observations recorded by SDO/HMI**.
- **Future:** Invoke a similar technique to eventually derive **other physical quantities of interest that cannot yet be measured directly at the photosphere or anywhere else in the solar atmosphere**.

References

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