Stochastic Multi-Scale Reconstruction of Turbulent Rotating Flows with Generative Diffusion Models

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Turbulence reconstruction poses significant challenges in a wide range of fields, including geophysics, astronomy, and even the natural and social sciences. The complexity of these challenges is largely due to the non-trivial geometrical and statistical properties observed over decades of time and spatial scales. Recent advances in machine learning, such as generative adversarial networks (GANs), have shown notable advantages over classical methods in addressing these challenges[1 2]. In addition, the success of generative diffusion models (DMs), particularly in computer vision, has opened up new avenues for tackling turbulence problems. These models use Markovian processes that progressively add and remove noise scale by scale, which naturally aligns with the multiscale nature of turbulence. In this study, we introduce Palette, a conditional DM tailored for turbulence reconstruction tasks. The inherent stochasticity of DM provides a probabilistic set of predictions based on known measurements[3]. We validate Palette on a rotating turbulence setup, a representative challenge in geophysical applications where spatial gaps are present in 2D observed snapshots (Figure 1). The effectiveness of Palette is compared with both a GAN and an equation-based data assimilation method, nudging. Through systematic comparison, Palette DM demonstrates superior performance in both pointwise reconstruction and statistical metrics. Our approach could be instrumental in a range of physical applications, from astrophysics to particle tracking. It provides a robust tool for uncertainty quantification and risk assessment, and has the potential to address complex turbulent systems across different spatial and temporal scales. This research was supported from the European Research Council (ERC) grant 882340 and from the MUR - FARE grant R2045J8XAW.

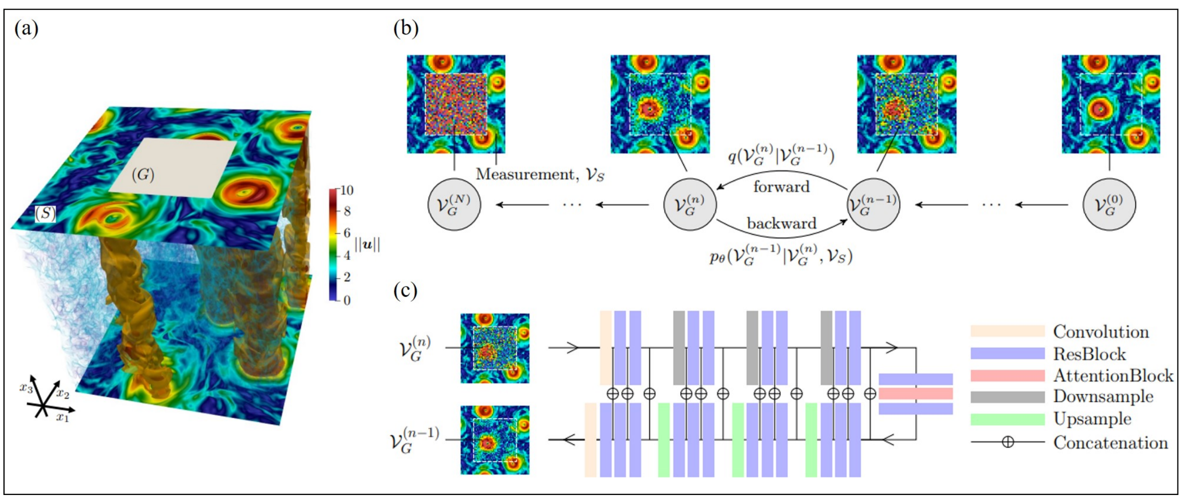

Figure 1: Visualization of velocity magnitude from a 3D snapshot in our numerical simulations, showing both large-scale coherent structures and small-scale velocity filaments. The damaged gap area (G) is marked by a gray square on the top plane, which is surrounded by the measurement support area (S). Schematic overview of the DM Palette protocol: (b) The backward process (from left to right) starts with the combination of pure noise in the gap, $\mathcal{V}_G^{(N)}$, and the frame measurements, $\mathcal{V}_S$. This combination is then progressively denoised using the U-Net architecture shown in panel (c).

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[2] Buzzicotti et al., *Phys. Rev. Fluids* **6(5)** (2021)
[3] Li et al., *Atmosphere* **15(1)** (2024)