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Sparsity: a ubiquitous but unexplored property of geophysical signals for multi-scale modeling and reconstruction

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Many geophysical processes exhibit variability over a wide range of scales. Yet, in numerical modeling or remote sensing observations not all of this variability is explicitly resolved due to limitations in computational resources or sensor configurations. As a result, sub-grid scale parameterizations and downscaling/upscaling representations are essential. Such representations take advantage of scale invariance which has been theoretically or empirically documented in a wide range of geophysical processes, including precipitation, soil moisture, and topography.
Here we present a new direction in the field of multi-scale analysis and reconstruction. It capitalizes on the fact that most geophysical signals are naturally redundant, due to spatial dependence and coherence over a range of scales, and thus when projected onto an appropriate space (e.g, Fourier or wavelet) only a few representation coefficients are non-zero – this property is called sparsity. The sparsity can serve as a priori knowledge to properly regularize the otherwise ill-posed inverse problem of creating information at scales smaller than resolved, which is at the heart of sub-grid scale and downscaling parameterizations. The same property of sparsity is also shown to play a revolutionary role in revisiting the problem of optimal estimation of non-Gaussian processes. Theoretical concepts are borrowed from the new field of compressive sampling and super-resolution and the merits of the methodology are demonstrated using examples from precipitation downscaling, multi-scale data fusion and data assimilation.