ADVANCING EARTH AND SPACE SCIENCE

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INTRODUCTION

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Special Section:
Advances in scaling and modeling of land-atmosphere interactions

Key Points:

- Scaling in space and time is an essential foundation for understanding land-atmosphere interactions
- A series of papers in this collection demonstrate scale-related advances in a number of areas
- Coordination of research across disciplines is needed

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Scaling Land-Atmosphere Interactions: Special or Fundamental?

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Abstract The highly interactive and variable nature of scales of space and time featured in components of the Earth system imparts enormous complexity to land-atmosphere interactions. Here, we introduce an open special collection on *Advances in Scaling and Modeling of Land-Atmosphere Interactions* that features articles in *JGR*: *Biogeosciences*, *JGR*: *Atmospheres*, *Journal of Advances in the Modeling of Earth Systems*, and *Earth & Space Science*. Collectively, these articles identify interactions across multiple processes, in field experiments, long-term observations, and numerical simulations, which are then used to advance theories of scale interaction to improve predictive models.

Plain Language Summary Scale refers to the patterns in space and oscillations in time of features in our universe. The Earth system features a wide range of scales. Understanding the processes that explain the size, shape, regularity, and changes in those scales looms large in our science. Land-atmosphere interaction refers to the ways that organisms and elements of the land surface influence the structure and evolution of the atmosphere and in turn, how weather and climate processes influence the ground. Numerous studies through coordinated field experiments and computer simulations have helped us advance understanding of how scale influences land-atmosphere interaction. We introduce a special collection that documents many of those.

1. Schooled in Scale

Viewed from billions of kilometers away in space, Earth appears as a single "Pale Blue Dot," in the immortalized phrase of Carl Sagan bestowed upon the image taken by the Voyager 1 space probe. Coming closer, though, a sharper image emerges (Figure 1).

One finds structure to that dot, shades of green and brown continents, a dark ocean, a bright cryosphere, and a hazy, thin blue atmosphere. Zooming further in, those components break into patterns of mountains and rivers, seas and bays, forests and grasslands, layers, and cloud decks. And getting closer, one finds each component has oscillations and variations of branches and rivulets, canyons and plateaus, currents and coastlines. These objects keep revealing more structure in finer, often self-similar form, like Mandelbrot's fractals, down to eddies and organisms, and further into leaves, cells, enzymes, molecules, and atoms.

And then, if you wait seconds, days, decades, or eons, landscape patterns change. Bigger things typically take longer than smaller ones. As a result, the pattern changes—sometimes occurring slowly and subtly, ebbing and flowing in an oscillatory manner, or they can occur quickly and abruptly, morphing into a new state of order.

Each element and its dynamics come with variations in space and time that can be encompassed by the concept of scale. Earth systems science is preoccupied with the interactions of these elements, which cannot be understood without a stipulation of the scales of interest (Ge et al., 2019). The most straightforward of these interactions are ones where common processes at all scales can be defined by a single relationship, often a power-law, leading to the concept of scale invariance (Paleri et al., 2022). The most interesting interactions are the ones that break those rules and lead to "upscale" and "downscale" behavior, whereby processes at one scale determine the shape and function of another scale. These are most common at the intersections of biology, hydrology, geology, and meteorology, often within what is termed the "critical zone." This interlocking also harkens to the origins of

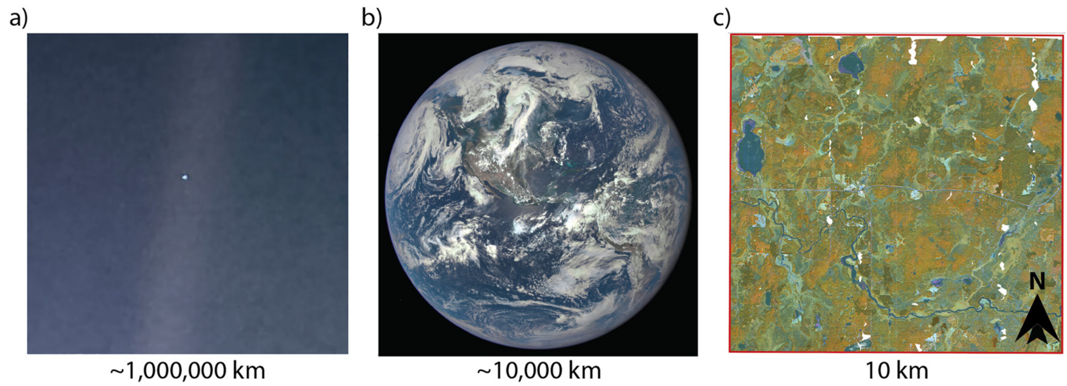

Figure 1. The Earth at three scales, as (a) a pale blue dot seen from Voyager 1 (source: NASA), (b) closer up from EPIC (source: NASA https://epic.gsfc.nasa.gov/), and (c) down to land cover seen over a 10 × 10 km area at 1 m resolution from first three principal components of a hyperspectral visible and near IR image over the CHEESEHEAD19 study area (Butterworth et al., 2021).

our discipline in Alexander von Humboldt's conception in his lithograph "Naturgemälde" which depicted the multi-faceted scales of the "web of life" (Wulf, 2015).

It should be no surprise then that the interactions of the land surface, its organisms and their environment, with the overlying atmosphere would be shaped by scale. Biology tends to scale up from genes and cells to biomes, while the atmosphere derives its scale from large scale energy imbalance down to turbulent dissipation (Desai, 2022). This fundamental clash frustrates our ability to measure and simulate those interactions and forecast how they will change. Not surprisingly, the scale challenge captures the heart of many experiments—in the field as well as in computer-based models.

Thus, while we present here a special collection on *Advances in Scaling and Modeling of Land-Atmosphere Interaction* at https://agupubs.onlinelibrary.wiley.com/doi/toc/10.1002/(ISSN)2169-8961.ADVSCLMDL, the concerns of the papers within are in many respects quite ordinary and ubiquitous.

There is a long history of studies, going back many decades, on how scales of the land surface influence and are influenced by atmospheric scales. Early model simulations found the importance of soil moisture, albedo, roughness, and heating on the atmosphere (Betts et al., 1996; Charney, 1975; Garrat, 1993), while others laid out the role of vegetation and hydrology (Avissar, 1995; Blöschl & Sivapalan, 1995; Pielke et al., 1998), and some tackled the challenge in models (Giorgi & Avissar, 1997; van Heerwaarden et al., 2014).

Dickinson (1995) had already called out specific research needs for advances in coupling and scale representation. From that time onward, large cooperative field experiments have helped build the playing board on which much of our theories rest, including classic studies like BOREAS (Sellers et al., 1995) and LITFASS-2003 (Beyrich et al., 2006) as well as more recent studies such as HiWATER-MUSOEXE (Wang et al., 2015), SCALE-X (Wolf et al., 2017), LAFE (Wulfmeyer et al., 2018), HI-SCALE (Fast et al., 2019), and CHEESEHEAD19 (Butterworth et al., 2021). They have helped to advance observing techniques and analytical tools, fine-tune model parameters, and build long-lasting scientific communities. These studies help inform advances in multi-scale modeling such as seen in HydroBlocks (Chaney et al., 2016) or the Ecosystem Demography model (Longo et al., 2019).

2. A Scale for All Silos

For this collection, we ran an open solicitation for articles in *JGR*: *Biogeosciences*, *JGR*: *Atmospheres*, *Journal of Advances in the Modeling of Earth Systems*, and *Earth & Space Science*, with the specific goal of reaching a broad range of communities, many of whom have been making advances within their own disciplines (Desai, Butterworth, et al., 2021). By building a cross-journal collection, we sought to scale the barriers to our current understanding that are hampered by the "siloing" of our knowledge.

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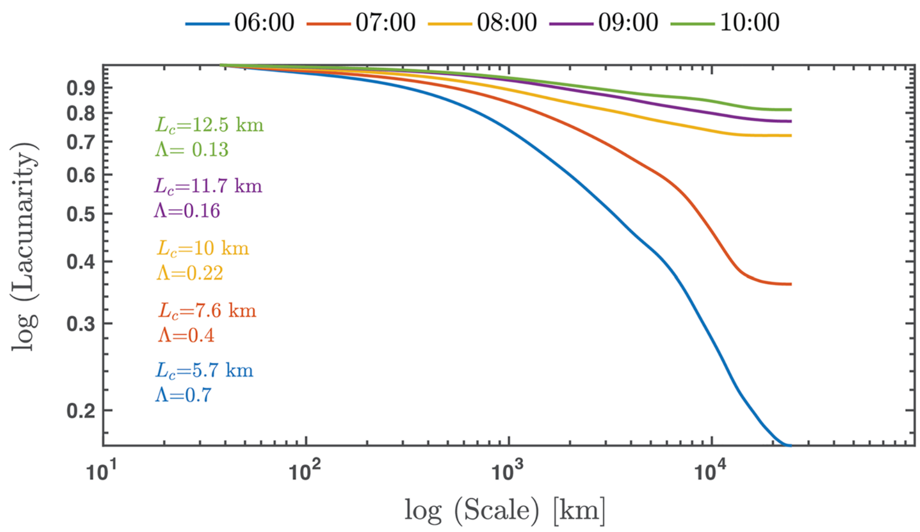

Figure 2. Change in lacunarity of land surface temperature (*y*-axis) over a 5 hr period (color) as a function of spatial aggregation scale (*x*-axis), shows a rapid change in spatial scales over the course of a single morning.

Consider the example of specifying scales of land surface properties for modeling the atmospheric boundary layer, the lowest 1–2 km of the atmosphere, the part of earth's atmosphere most directly influenced by surface processes (Stull, 1988) and heterogeneity (Bou-Zeid et al., 2020). Under increasing surface heterogeneity, large-scale transport by atmospheric circulations becomes increasingly important (Morrison et al., 2021). It turns out fractal geometry has the answer for identifying those scales with lacunarity analysis (Allain & Cloitre, 1991), which has had a history of application in ecology (Plotnick et al., 1993), but not so much in atmospheric sciences.

Lacunarity helps specify the appropriate scale for spatial fields (Scott et al., 2022). Lacunarity profiles reveal the spatial variability of any given quantity at each spatial scale. When the profile asymptotes, it indicates that there are no spatial structures and changes happening at larger scales. A heterogeneity measure can then be obtained representing the integrated characteristic heterogeneity scale of the spatial structures in the domain, from zero being perfectly homogenous to one as perfectly heterogenous. Yet, these measures of scale are dependent on the domain and the resolution used to calculate them, and necessitate tailoring the question of scale to the scientific study. For example, consider thermal heterogeneity scales for five consecutive hours for land surface temperature distribution within a 30 × 30 km domain collected on 5 October 2019 in northern Wisconsin USA during the CHEESEHEAD19 field campaign (Figure 2). A time scale of an hour appears to be large enough for the surface heterogeneity to change notably from a rather heterogeneous distribution to a more homogenous one. This information can be coupled with spatially distributed measurements by multiple eddy covariance towers to test how these spatial scales influence transport processes and their impact on issues like eddy covariance energy imbalance (Wanner et al., 2022).

Land-atmosphere field experiments have continued to provide insight on scaling through advances in observing capability as noted in several papers in this collection. For example, from CHEESEHEAD19, Murphy et al. (2022) find canopy structural metrics do not linearly scale with spatial resolution, which influences how those metrics link to ecosystem functions through water-use and light-use efficiencies. Meanwhile, with a range of atmospheric profilers and surface radiation observations, Sedlar et al. (2022) show how atmospheric boundary layer development is influenced by scales of cloud regimes and its imprint on turbulent fluxes. In the LAFE experiment in the Southern Great Plains, US, Späth et al. (2022) deployed a novel strategy for simultaneous measurements of atmospheric surface layer profiles of temperature, winds, and moisture to successfully infer regional-scale surface-atmosphere fluxes using scale-invariant theories such as Monin-Obukhov similarity relationships. Meanwhile, in the same region, during HI-SCALE, Sakaguchi et al. (2022) demonstrate how scales of land cover heterogeneity differ from those of soil moisture heterogeneity in developing modes and mesoscale patterns in surface energy balance.

Longer-term and distributed observations also allow for investigation of scale. Young et al. (2022) noted how the sensitivity of evapotranspiration across a continent as observed in the Ameriflux network of eddy covariance flux towers (Novick et al., 2018) scales primarily with plant lifecycle phenology in energy-limited regions, while water limitation dominates elsewhere. Yan et al. (2021) look further into spring plant phenology in China across a network of thousands of weather stations and find that large-scale atmospheric teleconnections such as the Atlantic Multidecadal Oscillation imprint themselves on the spring blooming times of individual organisms.

These spatial scaling analyses are complemented by those that focus more on the temporal dimension. Turner et al. (2021) noted substantial temporal lags in wetland methane fluxes in response to wetting changes while Yun et al. (2022) reported a reversing of carbon dioxide uptake to source observed from decadal flux measurements on the Tibetan Plateau arising from a trend of warming soil temperatures promoting high emissions events outside the growing season. A more novel temporal linkage is noted in Li et al. (2022) who found temporal oscillations of atmospheric pressure led to a pumping effect on atmospheric moisture in the vadose zone in soils.

For both space and time, a key effort in Earth systems science has been upscaling and downscaling observations from one scale to compare against another. Bottom-up approaches need to identify key space and time covariates and statistical approaches to fuse multiple measurements across scale. One approach to identify these for CO_2 fluxes used an artificial intelligence approach with pairs of eddy covariance sites at differing distances (Reed et al., 2021). Wu et al. (2022) evaluated bottom-up scaling across multiple products for global soil nitrous acid (HONO) emissions. Levy et al. (2022) reviewed the key challenges for upscaling when it comes to the UK greenhouse gas program and finds an essential role for uncertainty propagation, a factor also evaluated for gross primary productivity upscaling by Xie et al. (2022). For comparing to top-down measurements, such as flux towers to satellites, source areas and (non-)linearities in downscaling need to be taken into account, whether that is for carbon emissions in a salt marsh (Hill & Vargas, 2022), hotspots of methane in eddy covariance flux tower footprints (Rey-Sanchez et al., 2022), or land surface temperature over heterogeneous landscapes (Desai, Khan, et al., 2021).

The importance of how these scale effects then play out on the planet has often been tested with coupled Earth system models. In some cases, like in Clifton and Patton (2021), the scale effect is minimal, as they showed that scale dependency of organized turbulence doesn't have a strong impact on scales of ozone removal by deposition to plants. While in others, like Simon et al. (2021), land surface variation scales promoted an increase in turbulent kinetic energy convection and rainfall. In similar respects, Cheng et al. (2022) simulated the role of topography driving low-level wind convergence, and thereby enhancing heat fluxes and convection. Atmospheric transport and coupling to surface and hydrological processes also played a role in dust transport and emission (Han et al., 2022) and influencing stream outflow (Getirana et al., 2021).

3. Scaling a Mountain

So, how can these findings be put to work for improving our models and forecasts of land-atmosphere processes? Several papers in the collection go into specific modeling advances to improve scale-relevant processes. These include work on improving plant water cycling with hydrodynamic approaches (Bohrer & Missik, 2022) and advancing stomatal conductance formulations (Otu-Larbi et al., 2021). New approaches to move beyond plant functional types to detailed species and land use delineations were found to be important for air quality modeling (Luttkus et al., 2022), biogenic volatile organic compound crop emission models (Havermann et al., 2022), and for site-level data assimilation in ecosystem models (Jung & Hararuk, 2022). A particularly novel advance by Berkelhammer et al. (2022) involved incorporating the multidimensional scale of root foraging for water and nutrients in space and time across the soil continuum, a process whose inclusion improves simulations of plant drought recovery.

With additional manuscripts in review for the collection at the time of submission of this introduction, there are bound to be more intriguing findings and modeling advances. To push the field forward, a recent workshop identified needs for cross-disciplinary training, funding, and observations, particularly of atmosphere boundary-layer dynamics and entire soil profiles (Beamesderfer et al., 2022). Hopefully some of those calls will be heeded. Here, we wish for readers to find a rich array of findings, reviews, and concepts that when placed on the scale, weigh toward the side of knowledge gained to incorporate into your own work. For those that seek to do so, please look far and wide, and near and deep, brushing off the scales of works past, so that our collective wisdom is increased, more interconnected, and increasingly scale-aware.

Data Availability Statement

Land surface temperature data for the example in Figure 2 is found at https://doi.org/10.26023/5J4W-8XPH-250N.

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