Small-Scale Processes and Large-Scale Simulations of the Climate System

BJORN STEVENS
Department of Atmospheric and Oceanic Sciences
University of California, Los Angeles
Los Angeles, California

Simulations of weather and climate have long posed challenges for computational science. Atmospheric and oceanic circulations embody spatial scales that range from micrometers or smaller, to planetary scales and temporal scales from micro-seconds to millennia and beyond. The explicit representation of this range of scales is far beyond the capacity of any envisioned computational platform. For now and the foreseeable future, simulations of atmospheric and oceanic circulations require a massive truncation of scale and hence a loss of information. Because the circulations of interest are turbulent such a truncation is not trivial. If the truncation of information at some scale is not to be accompanied by a loss of predictability at the remaining scales, procedures must be developed for representing the effects of the truncated, or unresolved, scales on those that remain.

When choosing which scales to keep and which to discard, the spectrum of energy in the system often serves as a guide. As common experience can attest, variability is most pronounced on the largest scales (i.e., seasonal differences in weather are larger than day-to-day variations, and the weather varies more across continents than it does across town). Consequently, simulations of the climate system invariably begin by explicitly representing the largest spatial scales and then work their way down the spectrum as computational resources permit. The high-degree of spatio-temporal correlation among atmospheric processes—small scales tend to be fast, and large-scales tend to be slow—means that such a truncation also has a temporal projection.

Currently available computational platforms models of the global atmosphere and ocean are typically restricted to a representation of their respective fluids by numerical meshes capable of sampling spatial scales on the order of 100-200 km in the horizontal, and perhaps 100 - 1000 m in the vertical. Using the very largest computers in existence, calculations on horizontal and vertical meshes whose linear dimensions are a factor of ten more refined are possible, but even these leave an enormous range of scales unresolved. This state of affairs raises one of the central questions of our field, and the focus of my talk: Can the net effect of the smaller-faster scales on the larger-slower scales be represented as a function of those larger-slower scales that are explicitly tracked within a simulation? Although this question is posed in purely practical terms, it has an esthetic quality in that any such representation can be thought of as a formalism of our understanding.

Atmospheric and oceanic scientists often use the word "parameterization" to describe this formalism. In our jargon, the goal is to *parameterize* the collective effects of small-scale processes on large-scale processes. Because small-scale processes are sundry, the parameterization problem is multi-faceted. Typically small scale processes are broken down into distinct classes of problems: clouds, radiative transfer, hydrometeor interactions, surface interactions, small-scale turbulence, chemistry, etc.—processes that can be thought of as the atoms. Although one is interested in only the net effect of all these processes, this atomization facilitates idealization and subsequent study. An artifact of such a decomposition is that it raises the additional question of how, and on what scale, individual processes (atoms), (e.g., clouds, radiation, chemistry,) interact, and hence the extent to which parameterizations must be coupled to one another, and not just the larger-scales. In some sense thermodynamic analogies are useful, for instance in the sense that diffusion parameterizes molecular transport in fluids; however, any attempt to develop a kinetic theory capable of aggregating over many small-scale processes is impeded by a lack of a clear understanding of what exactly constitutes the atoms, and the rules which then govern their behavior.

A conspicuous example of a parameterization in the atmosphere is that for fluxes of heat, momentum, and matter from an interface (Garratt, 1992). Here the question, simply stated, is: Given the state of the large-scale flow above an interface, and some gross characterization of an interface, for instance a measure of its roughness, its temperature, etc., what are the fluxes of momentum, matter, and enthalpy from the interface? Physically these fluxes are carried by correlated fluctuations in the velocity and temperature fields—eddies—whose size scale with the distance to the interface. At the interface, small roughness elements (capillary waves on the ocean; rocks, sand, bushes, cars over land) disturb the flow, leading to small-scale pressure gradients around obstacles, which accelerates the flow and generates eddies that in turn transport enthalpy and matter, which has diffused from the surface roughness elements into the fluid, into the interior of the fluid. In almost any practical application the net effect of these eddies must be represented in some fashion so as to provide meaningful boundary conditions to the larger-scale flow. Attempting to aggregate the fundamental solutions of equations for flow around an ensemble of obstacles has proven fruitless. Instead, what is often called a similarity approach (Barenblatt, 1996) has developed. A key aspect of the similarity approach is to simplify the problem to a point where it becomes empirically tractable and then hope that the answers so derived remain relevant to the less idealized situations.

For the surface flux problem the similarity approach usually consists of first considering flow over a uniformly rough wall in the absence of temperature differences; the essence of which can conceivably be retained by only considering things in terms of two variables, namely the distance z from the surface and a velocity scale that measures the momentum flux, e.g.,

$$u_*^2 \equiv -\overline{w'u'}. \tag{1}$$

Here $\{u, w\}$ denotes the horizontal and vertical components of the velocity field and primes indicate deviations from a large-scale average denoted by an over-bar. To the extent that u_* and z are the only relevant parameters, it is possible to argue on purely dimensional grounds that

$$\frac{d\overline{u}}{dz} = \frac{u_*}{z}\alpha \tag{2}$$

where α is a dimensionless constant. The scaling law in Eq. (2) derives its simplicity, and hence empirical tractability, through the neglect of a variety of other, potentially important, parameters. For instance, the above formulation implicitly says that the structure of the near surface flow is independent of things like viscosity ν, the rotational frequency of the Earth f, the depth of the turbulent boundary layer h, etc. These arguments are asymptotic rather than absolute statements. They effectively state that the Reynolds number (in this case the inverse of the non-dimensional viscosity) $Re = u_* z / \nu$ is so large that the flow ceases to depend on it. Likewise for the Rossby number $Ro \equiv u_*/fz$. In these cases we speak of the flow obeying Reynolds, or Rossby number similarity. The lack of an outer scale measuring the depth of the boundary layer, or the atmosphere as a whole, suggests that to the extent our idealization is valid it depends on z being much less than h. Similarly the application of this formalism assumes that z is much greater than the height of the surface roughness elements. To the extent to which all these statements are true then α should be universal, i.e., once it is empirically determined it can be universally applied. Given α the problem of relating the small-scale flux of momentum (which is responsible for accelerating the mean flow) to a function of the mean flow itself is reduced to integration:

$$-\overline{w'u'} = u_*^2 = C_d U^2. \quad \text{where} \quad C_d \equiv \alpha \ln(z/z_0), \tag{3}$$

where z_0 is an effective height (called the roughness height and defined by the character of the surface) where the extrapolated velocity profile vanishes. Equation (3) forms the basis for the parameterization of surface fluxes in all models of atmospheric circulations. This approach can be generalized to account for heat fluxes that are accompanied by buoyant acceleration of fluid elements. In this case α must be replaced by a function $\psi(\zeta)$ where ζ is a non-dimensional parameter that measures the relative contributions of buoyancy and mechanically induced effects on fluid accelerations. Further extensions to account for a variety of other effects (most notably surface heterogeneity) neglected in the formulation above are invariably also based on elaborations of (3), and remain an active area of research (Fairall et al., 2003).

The details of the formalism above should not, however, detract from an understanding of the basic ideas of the similarity approach, wherein: (i) insight is used to reduce a problem to some essential and idealized formulation; (ii) dimensional analysis is used to identify non-dimensional dependencies; (iii) empiricism is used to determine the form of the functions of the relevant dimensionless numbers. Unfortunately, for most processes we wish to parameterize this three-step recipe is not easy to follow. More often than not our insights are not sufficiently developed to allow compelling simplifications. Even when they are, the empirical step often involves measuring functions that are generally a function of more than one variable, and often not readily accessible to measurement. Toward this end a boot-strapping approach has developed, wherein idealized fluid simulations designed to isolate particular processes, or collections of processes, are used to develop our intuition. Slowly these simulations are refined to their essence, from which pseudo-empirical statements are extracted, and the parameter space is explored.

An example of such an approach is embodied in attempts to parameterize the effects of clouds in large-scale models. Most of the processes directly responsible for cloud formation are related to circulations much smaller than the smallest scale represented by large-scale models. However clouds, and cloud regimes, do exhibit large-scale patterns and thus seem to be under control of the large-scale state. This raises the possibility of using a fine-scale model with a given large-scale forcing to examine which large-scale parameters are essential to cloud formation and how cloud fields respond to changes in these parameters (e.g., Xu and Randall, 1996). Based on this approach, simple statistical rules can be derived, both for use in larger-scale models and for comparison to data. The latter provides a means for evaluating the fidelity of the fine-scale models, which themselves are often dependent on a parameterization of some yet finer scale process (Stevens and Lenschow, 2000; Randall et al., 2003b). In reference to the intial example, this approach would involve solving directly for the flow over a variety of surfaces. Based on the simulation results, essential parameters would be isolated, leading to a formulation of the problem similar to that given in Eq. 2. At this stage, simulations for a variety of roughness types could be conducted to evaluate the constancy of α as u_* and z vary. Given the variety of processes in the atmosphere that go unresolved in large-scale models and our propensity for making problems more complicated rather than simpler, this approach takes enormous effort. Though rewarding when approached creatively, it can often be quite tedious, particularly when nature resists simplification.

In light of the above, another approach has recently been developed. Here fine-scale simulations are embedded in larger-scale simulations, in a sense doing the above outlined procedure “on the fly.” For some processes, such an approach has great promise—particularly those begrudging of simplification and where myriad interactions between unresolved processes occur on a narrow range of scales that are clearly separated from the smallest of the resolved "large-scales." Although these qualifications appear onerous, they are satisfied by some elements of one of the more vexing parameterization problems in the atmospheric sciences, that of relating the statistics of deep convective clouds to the state of the large-scale circulations. Recent applications of this approach, called super-parameterization, or cloud-resolving-convective parameterization (Grabowski and Smolarkiewicz, 1999), have led to remarkable increases in the fidelity of some important aspects of simulations of large-scale atmospheric phenomena (Khairoutdinov and Randall, 2003). This approach is, however, very new and strategies for implementing it are only just now being explored (Randall et al., 2003a). Computationally it is very intensive, and thus can only be done by a very few with access to great resources. Nonetheless it has the potential to enrich our phenomenology and guide attempts to use the more traditional strategies outlined above. For this reason, and because of its immediate practical benefits, it is being explored with great vigor.

REFERENCES

Barenblatt, G. 1996. Scaling, Self-Similarity, and Intermediate Asymptotics. Cambridge, U.K.: Cambridge University Press.

Fairall, C.W., E.F. Bradley, J.E. Hare, A. Grachev, and J. Edson. 2003. Bulk parameterization of air-sea fluxes: updates and verification for the COARE algorithm. Journal of Climate 16(4): 571–591.

Garratt, J.R. 1992. The Atmospheric Boundary Layer. Cambridge, U.K.: Cambridge University Press.

Grabowski, W.W., and P.K. Smolarkiewicz. 1999. CRCP: a cloud resolving convective parameterization for modeling the tropical convective atmosphere. Physica D: Nonlinear Phenomena 133(1-4): 171–178.

Khairoutdinov, M.F., and D.A. Randall. 2003. A cloud resolving model as a cloud parameterization in the NCAR community climate system model: preliminary results. Geophysical Research Letters 28(18): 3617–3620.

Randall, D.A., M. Khairoutdinov, A. Arakawa, and W. Grabowski. 2003a. Breaking the cloud parameterization deadlock. Bulletin of the American Meteorological Society 84(11): 1547–1564.

Randall, D.A., S. Krueger, C. Bretherton, J. Currey, P. Duynkerke, M. Moncrieff, B. Ryan, D. Starr, M. Miller, W. Rossow, G. Tselioudis, and B. Wielicki. 2003b. Confronting models with data: the GEWEX cloud systems study. Bulletin of the American Meteorological Society 84(4): 455–469.

Stevens, B., and D.H. Lenschow. 2001. Observations, experiments and large-eddy simulation. Bulletin of the American Meteorological Society 82(2): 283–294.

Xu, K.-M., and D.A. Randall. 1996. A semi-empirical cloudiness parameterization for use in climate models. Journal of Atmospheric Science 53(21): 3084–3102.