Atmospheric Sciences 501. Course Notes. Autumn, 1998

Introduction

Some philosophers of science[1] write about the separation of the natural sciences into two groups. The first group is exemplified by modern physics, where theoretical and experimental approaches are used to search for exact formulations of laws at the most fundamental level, the level of general relativity, Maxwell's and Schrodinger's equations, and "grand unified field theory", should it ever happen. The viewpoint follows the idea initiated by Galileo, Newton, Bacon, and Descartes, that all phenomena can be understood in terms of fundamental laws and boundary conditions. In the second group, the fundamental laws are taken to be given, but the processes are too complex to be addressed directly from the fundamental laws. Since the fundamental laws are already known, the search is for an understanding of the complex phenomena that arise from the fundamental laws and boundary conditions in the form of emergent structures that could be anticipated from the fundamental laws alone. Examples of such emergent structures include turbulent vortices, proteins, trees, people, and thought. This group of sciences also depends on experiment and on theory, but idealized conceptual models that serve as metaphors to aid the understanding of the emergent phenomena are also necessary. Modern biology, including molecular biology, is in this group. So is meteorology.

The complexity of the atmosphere as a physical system can be understood from an estimation of the number of degrees of freedom required to describe it. This would require, at a minimum, a description of the pressure, temperature, velocity components, and composition variables, down to the scale where fluid motions and inhomogeneities are dissipated by viscosity and molecular conductivity. On average, this scale is probably no larger than a few centimeters. Now suppose (conservatively) that the relevant volume of the atmosphere is the area of the Earth multiplied by a depth of 10km, $5\mathrm{x}10^{18}\mathrm{m}^3$. The number of "boxes" of few centimeter size is about 10^{22}, and the number of variables per "box" is about 10, so, on this basis, there are about 10^{23} degrees of freedom that need to be accounted for to fully describe the atmosphere. This calculation does not count the information required to specify the boundary conditions or the microphysical properties of cloud droplets or ice crystals[2]. Neither does it account for the activity at the quantum level that is responsible for absorption and emission of radiation.

Now meteorology is rather unique among the sciences. So far as I know, only meteorologists and medical doctors are expected to make forecasts about the evolution of their particular complex systems that people will actually believe and use[3]. In fact, people expect and often get considerable precision from their meteorological forecasts for as long as a week or so into the future[4]. These forecasts are based on global models with 100km grid boxes, 30 layers, and about 10 variables, that is, about 10^7 degrees of freedom. By the time you finish graduate school (unless you are very speedy), it is likely that some global forecasts will be done at the scale of today's mesoscale forecast models with 100-1000 times the information content of the current global models, i.e., up to about 10^{10} variables. This is still a very far cry from the total number of degrees of freedom of the system. The work of E.N. Lorenz[5] and others suggests that closing much of the remaining gap (a factor of at least 10^{13}) might not improve weather forecasting very much. Despite the complexity of our system, some level of prediction of its behavior is possible because large-scale structures emerge from the possible turbulent chaos of 10^{23} degrees of freedom.

There are many reasons for this. External forcing of the atmosphere by solar radiation and by boundary conditions at the Earth's surface occurs predominantly on large-scales. But, in addition, the atmospheric response tends to organize itself into coherent structures on the mesoscale (10km-100km) and larger. Mid-latitude weather is much more predictable than tropical weather because the dominant mode of organization is at large scales (>100km) that correspond fairly well with simulation model scales. We can imagine that the atmosphere is tracing out a trajectory in an enormous state space. Because it organizes itself into coherent structures, this trajectory avoids most of the volume elements in that state space, passing through only the limited set that are close to the various coherent structures. In mid-latitudes, the coherent structures corresponding to accessible regions of state space evolve rather slowly, on time scales from a large fraction of a day to several days. These structures are the organized weather systems: cyclones, anticyclones, jet streams etc. that appear on weather maps, and the corresponding limited volume of state space has been called the "slow manifold"[6]. The mid-latitude atmosphere evolves along near the slow manifold. The atmosphere (at least at mid-latitudes) tends to remain on the slow manifold because of a key system constraint, air moving across the surface of the Earth must conserve total angular momentum, including the components of angular momentum due to the rotation of the planet and that due to relative motion.

Once one begins to realize that the largest scale coherent structures of the atmosphere exist on a slow manifold because of key physical constraints, it is possible to think of other emergent phenomena in other fields as arising because of constraints that keep those systems near analogous "slow manifolds". At the heart of our field of study may lie insights of far wider applicability. But that is a very philosophical, and very speculative, notion.

For now, let us consider our science, and let us begin at the beginning.

Notes:

1) For example, D. J. Depew and B. H. Weber, "Darwinism Evolving". MIT Press, 1997.
2) The structure of ice crytals in convective clouds has been shown to have a surprising influence on the evolution of mesoscale storms, which can in turn, influence large scales.
3) Planetary orbits have been found to evolve chaotically (unpredictably), so these could also be included among complex systems for which some people expect predictions.
4) People are now beginning to expect seasonal forecasts of statistical properties of the atmosphere on seasonal to interannual time scales: the (El Nino-Southern Oscillation, ENSO phenomena).
5) Lorenz, E. N., 1982: In "Problems and Prospects in Long and Medium Range Forecasting", pp. 1-20. European Center for Medium Range Forecasting, Reading.

6) Lorenz, E. N., 1992: The slow manifold - What is it? **J. Atmos. Sci.**, **4**, 2449-2451. Lorenz discusses discusses the debate about precisely what comprises the "slow manifold".