



The Emerging Science of Environmental Applications

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THE SCIENCE OF EARTH AND ENVIRONMENT has matured through two major phases and is entering a third. In the first phase, which ended two decades ago, Earth and environmental science was largely discipline oriented and focused on developing knowledge in geology, atmospheric chemistry, ecosystems, and other aspects of the Earth system. In the 1980s, the scientific community recognized the close coupling of these disciplines and began to study them as interacting elements of a single system. During this second phase, the paradigm of Earth system science emerged. With it came the ability to understand complex, system-oriented phenomena such as climate change, which links concepts from atmospheric sciences, biology, and human behavior. Essential to the study of Earth's interacting systems was the ability to acquire, manage, and make available data from satellite observations; in parallel, new models were developed to express our growing understanding of the complex processes in the dynamic Earth system [1].

In the emerging third phase, knowledge developed primarily for the purpose of scientific understanding is being complemented by knowledge created to target practical decisions and action. This new knowledge endeavor can be referred to as the *science of environmental applications*. Climate change provides the most prominent example of the importance of this shift. Until now, the

climate science community has focused on critical questions involving basic knowledge, from measuring the amount of change to determining the causes. With the basic understanding now well established, the demand for climate applications knowledge is emerging. How do we quantify and monitor total forest biomass so that carbon markets can characterize supply? What are the implications of regional shifts in water resources for demographic trends, agricultural output, and energy production? To what extent will seawalls and other adaptations to rising sea level impact coasts?

These questions are informed by basic science, but they raise additional issues that can be addressed only by a new science discipline focused specifically on applications—a discipline that integrates physical, biogeochemical, engineering, and human processes. Its principal questions reflect a fundamental curiosity about the nature of the world we live in, tempered by the awareness that a question’s importance scales with its relevance to a societal imperative. As Nobel laureate and U.S. Secretary of Energy Steven Chu has remarked, “We seek solutions. We don’t seek—dare I say this?—just scientific papers anymore” [2].

To illustrate the relationships between basic science and applications, consider the role of snowmelt runoff in water supplies. Worldwide, 1 billion people depend on snow or glacier melt for their water resources [3]. Design and operations of water systems have traditionally relied on historical measurements in a stationary climate, along with empirical relationships and models. As climates and land use change, populations grow and relocate, and our built systems age and decay, these empirical methods of managing our water become inaccurate—a conundrum characterized as “stationarity is dead” [4]. Snowmelt commonly provides water for competing uses: urban and agricultural supply, hydropower, recreation, and ecosystems. In many areas, both rainfall and snowfall occur, raising the concern that a future warmer climate will lead to a greater fraction of precipitation as rain, with the water arriving months before agricultural demand peaks and with more rapid runoff leading to more floods. In these mixed rain and snow systems, the societal need is: How do we sustain flood control and the benefits that water provides to humans and ecosystems when changes in the timing and magnitude of runoff are likely to render existing infrastructure inadequate?

The solution to the societal need requires a more fundamental, process-based understanding of the water cycle. Currently, historical data drive practices and decisions for flood control and water supply systems. Flood operations and reservoir flood capacity are predetermined by regulatory orders that are static, regardless

of the type of water year, current state of the snowpack, or risk of flood. In many years, early snowmelt is not stored because statistically based projections anticipate floods that better information might suggest cannot materialize because of the absence of snow. The more we experience warming, the more frequently this occurrence will impact the water supply [5]. The related science challenges are: (1) The statistical methods in use do not try to estimate the basin's water balance, and with the current measurement networks even in the U.S., we lack adequate knowledge of the amount of snow in the basins; (2) We are unable to partition the input between rain and snow, or to partition that rain or snow between evapotranspiration and runoff; (3) We lack the knowledge to manage the relationship between snow cover, forests, and carbon stocks; (4) Runoff forecasts that are not based on physical principles relating to snowmelt are often inaccurate; and (5) We do not know what incentives and institutional arrangements would lead to better management of the watershed for ecosystem services.

Generally, models do not consider these kinds of interactions; hence the need for a *science of environmental applications*. Its core characteristics differentiate it from the basic science of Earth and environment:

- **Need driven versus curiosity driven.** Basic science is question driven; in contrast, the new applications science is guided more by societal needs than scientific curiosity. Rather than seeking answers to questions, it focuses on creating the ability to seek courses of action and determine their consequences.
- **Externally constrained.** External circumstances often dictate when and how applications knowledge is needed. The creation of carbon trading markets will not wait until we fully quantify forest carbon content. It will happen on a schedule dictated by policy and economics. Construction and repair of the urban water infrastructure will not wait for an understanding of evolving rainfall patterns. Applications science must be prepared to inform actions subject to these external drivers, not according to academic schedules based on when and how the best knowledge can be obtained.
- **Consequential and recursive.** Actions arising from our knowledge of the Earth often change the Earth, creating the need for new knowledge about what we have changed. For example, the more we knew in the past about locations of fish populations, the more the populations were overfished; our original knowledge about them became rapidly outdated through our own actions. Applications sci-

ence seeks to understand not just those aspects of the Earth addressed by a particular use scenario, but also the consequences and externalities that result from that use scenario. A recent example is the shift of agricultural land to corn-for-ethanol production—an effort to reduce climate change that we now recognize as significantly stressing scarce water resources.

- **Useful even when incomplete.** As the snowpack example illustrates, actions are often needed despite incomplete data or partial knowledge. The difficulty of establishing confidence in the quality of our knowledge is particularly disconcerting given the loss of stationarity associated with climate change. New means of making effective use of partial knowledge must be developed, including robust inference engines and statistical interpretation.
- **Scalable.** Basic science knowledge does not always scale to support applications needs. The example of carbon trading presents an excellent illustration. Basic science tells us how to relate carbon content to measurements of vegetation type and density, but it does not give us the tools that scale this to a global inventory. New knowledge tools must be built to accurately create and update this inventory through cost-effective remote sensing or other means.
- **Robust.** The decision makers who apply applications knowledge typically have limited comprehension of how the knowledge was developed and in what situations it is applicable. To avoid misuse, the knowledge must be characterized in highly robust terms. It must be stable over time and insensitive to individual interpretations, changing context, and special conditions.
- **Data intensive.** Basic science is data intensive in its own right, but data sources that support basic science are often insufficient to support applications. Localized impacts with global extent, such as intrusion of invasive species, are often difficult for centralized projects with small numbers of researchers to ascertain. New applications-appropriate sources must be identified, and new ways of observing (including the use of communities as data gatherers) must be developed.

Each of these characteristics implies development of *new knowledge types* and *new tools for acquiring that knowledge*. The snowpack example illustrates what this requirement means for a specific application area. Four elements have recently come together that make deployment of a measurement and information system

that can support decisions at a scale of a large river basin feasible: (1) accurate, sustained satellite estimates of snow-covered area across an entire mountain range; (2) reliable, low-cost sensors and telemetry systems for snow and soil moisture; (3) social science data that complement natural and engineered systems data to enable analysis of human decision making; and (4) cyberinfrastructure advances to integrate data and deliver them in near real time.

For snow-dominated drainage basins, the highest-priority scientific challenge is to estimate the spatial distribution and heterogeneity of the *snow water equivalent*—i.e., the amount of water that would result if the snow were to melt. Because of wind redistribution of snow after it falls, snow on the ground is far more heterogeneous than rainfall, with several meters of differences within a 10 to 100 m distance. Heterogeneity in snow depth smoothes the daily runoff because of the variability of the duration of meltwater in the snowpack [6]; seasonally, it produces quasi-riparian zones of increased soil moisture well into the summer. The approach to estimating the snow water equivalent involves several tasks using improved data: (1) extensive validation of the satellite estimates of snow cover and its reflectivity, as Figure 1 on the next page shows; (2) using results from an energy balance reconstruction of snow cover to improve interpolation from more extensive ground measurements and satellite data [7]; (3) development of innovative ways to characterize heterogeneity [8]; and (4) testing the interpolated estimates with a spatially distributed runoff model [9]. The measurements would also help clarify the accuracy in precipitation estimates from regional climate models.

This third phase of Earth and environmental science will evolve over the next decade as the scientific community begins to pursue it. Weather science has already built substantial capability in applications science; the larger field of Earth science will need to learn from and extend those efforts. The need for basic science and further discovery will not diminish, but instead will be augmented and extended by this new phase. The questions to address are both practically important and intellectually captivating. Will our hydrologic forecasting skill decline as changes in precipitation diminish the value of statistics obtained from historic patterns? Where will the next big climate change issue arise, and what policy actions taken today could allow us to anticipate it?

Equally important is improving how we apply this knowledge in our daily lives. The Internet and mobile telephones, with their global reach, provide new ways to disseminate information rapidly and widely. Information was available to avoid much of the devastation from the Asian tsunami and Hurricane Katrina, but we

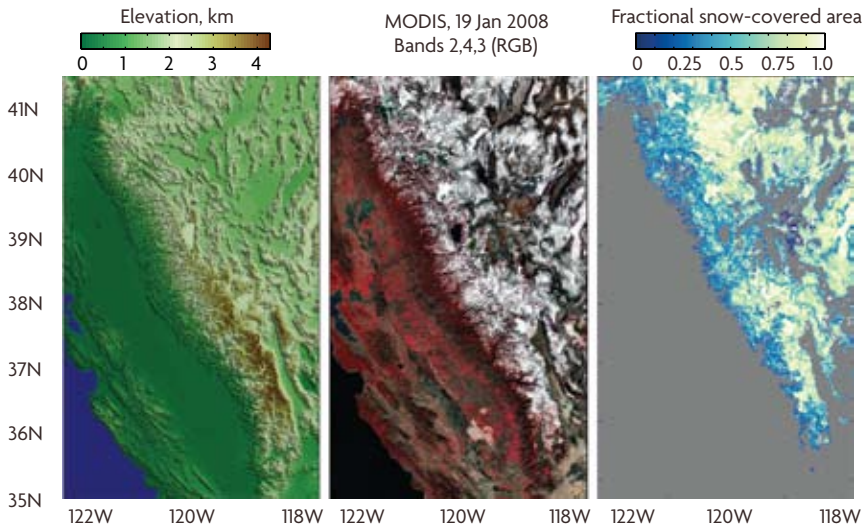


FIGURE 1.

An illustration of the type of data that are useful in analyzing the snow cover. The left panel shows elevations of the Sierra Nevada and Central Valley of California, along with a portion of northwestern Nevada. The middle panel shows the raw satellite data in three spectral bands (0.841–0.876, 0.545–0.565, and 0.459–0.479 μ m) from NASA’s Moderate Resolution Imaging Spectroradiometer (MODIS), which provides daily global data at 250 to 1000 m resolution in 36 spectral bands. From seven “land” bands at 500 m resolution, we derive the fractional snow-covered area—i.e., the fraction of each 500 m grid cell covered by snow, shown in the right panel [10].

lacked the tools for rapid decision making and communication of needed actions. Applications science is therefore integrative; it couples understanding of physical phenomena and research into the ways that people and organizations can use better knowledge to make decisions. The public as a whole can also become an important contributor to localized Earth observation, augmenting our limited satellite and sensor networks through devices as simple as mobile phone cameras. The ability to leverage this emerging data-gathering capability will be an important challenge for the new phase of environmental science.

The security and prosperity of nearly 7 billion people depend increasingly on our ability to gather and apply information about the world around us. Basic environ-

mental science has established an excellent starting point. We must now develop this into a robust science of environmental applications.

REFERENCES

- [1] National Research Council, *Earth Observations from Space: The First 50 Years of Scientific Achievement*. Washington, D.C.: National Academies Press, 2007.
- [2] R. DelVecchio, "UC Berkeley: Panel looks at control of emissions," *S.F. Chronicle*, March 22, 2007.
- [3] T. P. Barnett, J. C. Adam, and D. P. Lettenmaier, "Potential impacts of a warming climate on water availability in snow-dominated regions," *Nature*, vol. 438, pp. 303–309, 2005, doi: 10.1038/nature04141.
- [4] P. C. D. Milly, J. Betancourt, M. Falkenmark, R. M. Hirsch, Z. W. Kundzewicz, D. P. Lettenmaier, and R. J. Stouffer, "Stationarity is dead: whither water management?" *Science*, vol. 319, pp. 573–574, 2008, doi: 10.1126/science.1151915.
- [5] R. C. Bales, N. P. Molotch, T. H. Painter, M. D. Dettinger, R. Rice, and J. Dozier, "Mountain hydrology of the western United States," *Water Resour. Res.*, vol. 42, W08432, 2006, doi: 10.1029/2005WR004387.
- [6] J. D. Lundquist and M. D. Dettinger, "How snowpack heterogeneity affects diurnal streamflow timing," *Water Resour. Res.*, vol. 41, W05007, 2005, doi: 10.1029/2004WR003649.
- [7] D. W. Cline, R. C. Bales, and J. Dozier, "Estimating the spatial distribution of snow in mountain basins using remote sensing and energy balance modeling," *Water Resour. Res.*, vol. 34, pp. 1275–1285, 1998, doi: 10.1029/97WR03755.
- [8] N. P. Molotch and R. C. Bales, "Scaling snow observations from the point to the grid element: implications for observation network design," *Water Resour. Res.*, vol. 41, W11421, 2005, doi: 10.1029/2005WR004229.
- [9] C. L. Tague and L. E. Band, "RHESys: regional hydro-ecologic simulation system—an object-oriented approach to spatially distributed modeling of carbon, water, and nutrient cycling," *Earth Int.*, vol. 19, pp. 1–42, 2004.
- [10] T. H. Painter, K. Rittger, C. McKenzie, R. E. Davis, and J. Dozier, "Retrieval of subpixel snow-covered area, grain size, and albedo from MODIS," *Remote Sens. Environ.*, vol. 113, pp. 868–879, 2009, doi: 10.1016/j.rse.2009.01.001.