Climate over landscapes: The emerging links between geomorphology and the atmospheric sciences

Joseph Galewsky

Department of Earth and Planetary Sciences, University of New Mexico, Albuqueruqe, NM

Gerard Roe

Department of Earth and Space Sciences, University of Washington, Seattle, WA

1. Introduction

During October 1-3, 2007, a workshop on the links between atmospheric sciences and geomorphology was held at the National Center for Atmospheric Research in Boulder, Colorado. The motivation for this workshop was the growing awareness within the geomorphology research community of a pressing need for geomorphologists to become better acquainted with the theories, tools, and datasets used by atmospheric scientists. The Earths surface is intimately linked to the atmosphere, but research into geomorphology has been hampered by a lack of understanding of the atmospheric processes that drive erosion and sedimentation. Thus the aim of the workshop was to bring together atmospheric scientists and geomorphologists to discuss the potential contributions of modern atmospheric science research to geomorphology research and to inform some members of the atmospheric science community about the rates and magnitudes of tectono-geomorphic change that might drive atmospheric processes and about the potential for collaborative research opportunities with geomorphologists. Much of the current interest in the links between atmospheric sciences and geomorphology among workshop participants arises from research over the last 20 years that has shown the ways that climate shapes the evolution of mountain belts and the nature of long-term links between topography and climate change [Chiang et al., 2003; Seager et al., 2002; Held et al., 2002; Broccoli and Manabe, 1992; Cook and Held, 1988]. Of course, atmospheric processes influence almost all geomorphic processes: weathering, soil development, hillslope processes, mass wasting, glacial and periglacial processes, fluvial processes, sediment transport, and ecosystem-land surface interactions. Research into these interactions extend to other geoscience disciplines including ecology, geochemistry, sedimentology, hydrology, tectonics, and ocean science. Given the vast scope of the interactions between the Earths atmosphere and land surface, this workshop and associated white paper were necessarily limited in scope, and only represent a snapshot of the ideas and viewpoints of a small subsection of the two communities and certainly do not represent a comprehensive review of the fields. The workshop consisted of three keynote lectures that included a broad overview of geomorphology, mesoscale meteorology, focusing especially on orographic precipitation, and on global climate dynamics. Following the keynote lectures, a series of more specialized talks focused on regional climate modeling, landscape evolution modeling, atmospheric moist convection, landscape-ecosystem interactions, glaciology, and orogenesis. Extended discussions accompanied each lecture, and the workshop concluded with a wide-ranging group discussion on the potential for future research and training opportunities between atmospheric science and geomorphology research communities. The following white paper summarizes the workshop discussion and concludes with a suggested list of concrete ways to foster and enhance research at the interface of these two exciting disciplines.

1.1. State-of-the-art: Atmospheric sciences

In this section, we provide an overview of the state-of -the-art in the atmospheric sciences, focusing in particular on those atmospheric processes and research techniques most relevant to geomorphology.

One of the most useful perspectives for thinking about the links between geomorphology and atmospheric sciences emerging from the workshop was that of global environmental change. Much geomorphology research involves assessing the potential impact of global climate change, both past and future, on the land surface. In particular, the problem of land surface response to anticipated future climate change is an issue of pressing societal relevance. In addition, determining the response of the atmosphere to global change, including to changes in the land surface across a wide range of time scales, is a primary focus of much of atmospheric science research. While atmospheric scientists certainly do not lack for interesting research questions, workshop participants felt that geomorphologically-motivated questions may stimulate additional and novel research challenges in atmospheric sciences, particularly with regard to extreme events recorded in geological, but not historical records.

The atmospheric sciences are characterized by a very well developed body of theory based on the general principles of geophysical fluid dynamics. These theories provides good explanations for the basic patterns of the large-scale atmospheric circulation, including such features as the ITCZ, the Hadley Circulation, the mid-latitude storm tracks, and topographically-modulated large-scale waves in the jet stream. Each of these features, more or less directly, impact geomorphic processes, by controlling the delivery of precipitation to the land surface, and by setting the basic climate regimes around the Earth.

In addition to these persistent features of the Earths atmosphere, geomorphologists are also concerned with the effects of preferred patterns of climate variability such as El Nino-Southern Oscillation (ENSO), the Madden-Julian Oscillation (MJO), and the Arctic Oscillation (AO). Recognition of these patterns is important for geomorphologists because they are likely to have been active in the past and thus provide an additional framework for interpreting the ancient record of surface processes. Additionally, it is the infrequent perturbations in the climate system that can have the greatest impact on the landscape.

Geomorphologists and atmospheric scientists share a particular interest in the Earths hydrologic cycle. Atmospheric scientists have made excellent progress in understanding many aspects of the large-scale transport of water vapor [e.g. Pierrehumbert et al., 2007], and there is emerging recognition of the importance of land/atmosphere interactions such as evapotranspiration in influencing regional climate [e.g. Pielke, 2001; Pielke et al., 1991]. Indeed, this latter topic represents an especially important area where atmospheric scientists and geomorphologists may be able to fruitfully collaborate on an issue of joint importance.

The great success of numerical weather prediction rightly stands as one of the great scientific and technological triumphs of the 20th century. Forecasts derived from computer simulations now meet or exceed the skill of human forecasters. This skill is achieved through the application of well-understood dynamical equations and frequent, global assimilation of new observations. More recently, advances have come not so much from deterministic forecasts of the evolution of a single atmospheric state, but rather through the development of probabilistic ensemble forecasting techniques, based upon optimal perturbations of initial conditions [Molteni et al., 1996; Toth and Kalnay, 1993]. The workshop participants felt that geomorphic modelers may have much to learn from the lessons of numerical weather prediction, particularly in regards to the development of probabilistic techniques and through exploration of model sensitivities through adjoint modeling techniques [Errico, 1997] . In modeling the atmosphere, one can provisionally make a distinction between simulation and the understanding of a phenomenon [Held, 2005]. In the atmospheric sciences, simulation typically entails the use of global or regional climate models that incorporate the full range of physics thought to play a role. Process-based studies isolate the mechanism of interest, under tightly constrained conditions. Global climate models show skill in simulating the large-scale features of the atmospheric circulation. At present, most global climate models do less well at regional scales and extreme events, particularly precipitation, although this limitation appears to stem at least in part from the relatively low resolutions at which global climate models are typically employed [Sun et al., 2006]. Process models do not have a predictive capability, but have produced valuable insight into processes directly relevant to geomorphology, for example, precipitation in mountainous regions [Rotunno and Ferretti, 2001; Miglietta and Rotunno, 2005], the development of midlatitude and tropical cyclones [Thorncroft et al., 1993; Hill and Lackmann, in press], and organized moist convection [Robe and Emanuel, 2001]. It was recognized by the participants that these two modes of numerical modeling are already in use in the geomorphic community, and that there are likely to be joint research opportunities arising from coupling both kinds of atmospheric models to geomorphic models.

There is much excitement in the atmospheric sciences community about the development of petascale computing that will offer the use of many thousands of processors operating in parallel. This computing power will increase the ability of atmospheric scientists to address the scales of relevance for geomorphologists, both at the very small scale of individual events over catchments, and in long time integrations of past and future climate states.

The development of new ground- and satellite-based radar technologies has offered an unprecedented view into cloud systems globally. The TRMM satellite in particular has provided remarkable coverage of precipitation data over mountainous regions with few, if any, rain gauges [e.g. Barros et al., 2000]. Ground based radars deployed during field campaigns have significantly improved our knowledge of cloud and precipitation processes [e.g. Rotunno and Ferretti, 2003]. The proposed Global Precipitation Mission (GPM) promises great advances in this area and will thus be of interest to geomorphologists.

The atmospheric sciences community has made great progress through the use of community-organized intensive field observation campaigns (e.g., IMPROVE, MAP, IPEX, etc.). These field campaigns have been especially successful at obtaining data sets necessary for calibration and improvement of numerical models, and it was felt by the workshop participants that the geomorphology community could benefit from similar campaigns, possibly jointly organized with atmospheric scientists to explore, for example, the storms that produce land slides and debris flows.

Of all meteorological factors relevant to geomorphology, perhaps the most important is precipitation, which is delivered to the landscape in the form of storms. Understanding the probability distribution of storms as a function of climate state is a key challenge for atmospheric sciences. The basic physics of storms is reasonably well understood, although our understanding of extreme events and our ability to accurately and quantitatively predict precipitation amounts are still limited. In addition, the impact of global climate change on storm processes is not well understood [Sun et al., 2007].

In principal then, understanding the impact of atmospheric processes on landscape dynamics involves knowing the dynamics of individual events, the climatology of those events, and, on long timescales, how storm statistics change as a function of climate. The study of landscape dynamics, therefore, involves the details of individual events as well as their climatology. One of the exciting challenges that geomorphology research offers to atmospheric sciences is the need to understand precipitating weather systems across an astonishingly wide range of time scales from seconds to hundreds of thousands of years and beyond.

To summarize, the atmospheric sciences are a relatively mature field with a well-developed body of theory, tools, and data sets of direct relevance for geomorphologists. The development of probabilistic weather and climate models is well developed compared to similar efforts in the geomorphology community, and it was felt that geomorphologists may be able to profitably exploit those advances made by the atmospheric sciences community. The main barrier to such progress is simply communication and education between these two traditionally disparate communities.

2. Intellectual Challenges

The following ideas are representative of those put forth by meeting participants and of course is not exclusive. We made a start at the workshop, and NSF should foster and cultivate and nurture such opportunities. In the general conversation the group characterized the field and the opportunities from two perspectives: general statements of where the field stands; broad needs for facilitating more effective research; and examples (not comprehensive) of promising research directions involving the two communities, which is included below.

2.1. Statements

1. We currently are unable to predict how landscapes respond to anticipated or projected climate change.

2. The discovery of the coupling of climate, tectonics, and landscape is revolutionizing our field and leading to a new coupling of disciplines.

3. There is currently no quantitative set of metrics linking climate to topography.

4. Real time monitoring technology and high-resolution atmospheric modeling now enables collaborative, mechanistic studies of processes controlling both topographic driven climate and geomorphic processes.

2.2. Key Scientific Goals

1. We need development of geomorphic transport laws spanning the full range from rock to sediment. We need to know where climate shows up in these laws.

2. We need theories for linking the probability distribution of the relevant climate forcings to channel and hillslope morphodynamics. No single theory will apply for all settings.

3. We need to understand the response time of different parts of the landscape. In general this is poorly known at present, but was identified as critical for knowing on what timescales the landscape responds to climate.

4. Geomorphologists need global maps of the probability distributions of the meteorological variables that are most relevant for geomorphology- and theories for how they will change with climate state.

5. We need a global survey of geomorphic processes and morphology (landscape metrics) that examines its dependency on the probability distributions of climate.

6. Scientists need to explore natural experiments that provide signatures of the effects of climate on geomorphology and influence of geomorphology on climate.

7. We need better description of past landscape conditions in order to understand how climate and landscapes have interacted through time

8. In systems of irreducible complexity we need to understand the level of detail at which it is practically feasible to address questions. Under what conditions are we limited more by physics that we dont know or cant parameterize, than by computational resources? Scale, heterogeneity, data resolution, and research objectives directly bear on tractability and style of scientific approach.

9. The surface energy balance (the exchange of heat fluxes) between the land and the atmosphere is a key linkage, and of particular relevance for glaciology, arid climates, and hurricanes. There is an opportunity here for focused cooperation.

2.3. Needs

The main need identified by workshop participants was for better education of geomorphologists in the theory, models, and data sets available from the atmospheric sciences. Participants noted that there is a significant asymmetry between the disciplines. There is a wealth of knowledge in atmospheric science that remains largely untapped by the geomorphology community, particularly in regard to the limitations of models and data sets; thus, greater communication of this knowledge is essential. For atmospheric scientists, on the other hand, geomorphology research can motivate some truly challenging atmospheric science problems that have remained largely unappreciated save for a small number of atmospheric scientists. It was noted that the interactions between climate and landscapes are dauntingly complicated, and that simple answers may prove elusive. However it was also strongly emphasized by participants that it was not necessary to know what was right in all aspects of a problem. In many areas better communication of relatively basic information from one community to the other would yield substantial progress.

In order to address the need for greater education of geomorphologists in the atmospheric sciences, workshop participants identified several specific opportunities:

1. Develop a short course or summer school at NCAR on atmospheric science for geomorphologists, especially graduate students in geomorphology. Such a program should take advantage of NCARs outstanding COMET program.

2. Support IGERT programs for interdisciplinary training of geomorphologists and atmospheric scientists.

3. Support REU programs for Earth sciences undergraduates to receive research experience in the atmospheric sciences - Develop visitor and exchange programs; atmospheric

science departments are not always near geomorphology programs, so there should be support for geomorphologists to conduct research in atmospheric science departments.

4. Support graduate and postdoctoral fellowships on geomorphology/atmospheric sciences links.

It was also recognized that there is a need to increase the visibility of geomorphology within the atmospheric sciences community. Very few atmospheric scientists are aware of the research challenges posed by geomorphic research, so it was suggested that a speaker program be developed to support the travel of geomorphology researchers to give seminars in atmospheric science departments, and that there be joint sessions at national meetings of the AMS and AGU. It was also suggested that the community has a responsibility to write popular and review articles to generate more general interest in the ideas and concepts.

The improvement of natural hazard forecasting is an area of potential interactions between the two fields, but there is little knowledge about the use and requirements for such improved forecasts. Thus, it was suggested that the atmospheric sciences and geomorphology communities jointly engage policy analysts and other stakeholders to better determine the requirements for forecasting landslides, debris flows, and other meteorologically triggered geomorphic hazards.

It was recommended that the communities take advantage of resources within NSFs International programs to develop, for example, graduate student summer schools in geomorphology and atmospheric sciences at National Taiwan University or the University of Reading in the UK. Related programs could be developed with colleagues in Australia, India, and China. The atmospheric sciences community has benefited enormously from the development of community-wide field campaigns, and it was suggested that similar programs, jointly consisting of atmospheric scientists and geomorphologists, could provide valuable datasets for improving the simulation and forecasting of geomorphic processes. It was also suggested that joint funding opportunities be developed to take better advantage of resources at the NSF. The development of such opportunities hinges on reducing the perceived internal barriers in ATM for funding research across the range of time scales relevant to geomorphology.

Finally, on a more technical level, there need to be opportunities for geomorphologists to communicate their data needs to the appropriate atmospheric science entities. A prominent example frequently mentioned by participants is the need for daily or sub-daily output of selected fields from GCM experiments. There are also significant opportunities for collaboration between complimentary numerical modeling efforts. In particular the CSDMS modeling effort must engage the atmospheric community in moving forward.

3. Examples of research problems identified at the workshop

Some specific research problems that were identified during the course of the workshop are given below. They are not intended to be exhaustive and more are indicative of the gamut of possibilities that exist.

1. The stochastic and threshold nature of geomorphic processes. What causes the crossing of a threshold and how do interactions between storms and landscapes create different levels of thresholds?

2. Soil production, and the development of dust storms. The circumstances that lead to dust storms are a function of the land-surface, the climate regime, and extreme wind storms that loft dust into the air.

3. Why is the monsoon different in Asia and North America? It has to do with the large scale circulation response to the land geometry and topography, but has big consequences in turn for the climate experience by each region.

4. How do landscapes affect the probability distributions of extreme events? Several lines of evidence suggest arid landscapes are flashier than humid landscapes: to what extent can this be regarded as driven by the landscape, and in turn what is the consequence for the landscape? More generally what is the relative importance of mean vs. extreme events, and how well can atmospheric science characterize the probability distribution of those extreme events?

5. Hurricanes and coastal/tropical geomorphology. In the tropics, landscape can be wrecked by a single storm. Mesoscale numerical modeling affords a new window on the details of storm dynamics. Opportunities exist for validation from fieldwork.

6. Large scale topography and paleoaltimetry: as reconstructions of paleoelevations are refined by the advent of new techniques, there is an opportunity for climate modeling to address the environmental consequences of the resulting changes in the atmospheric circulation.

7. Also noted was the potential to study the climatic consequences of anthropogenic effects on the landscape, particularly large-scale land use changes. Both regional climate and sediment yields are strongly affected.

8. The connections between global change and permafrost was noted as an important research area. Other changes in periglacial environments, including the response of the landscape to glacial retreat, the response of ecosystems to a change from glacial to nival streams, and changing risks of glacial outburst floods.

9. New perspectives on orographic precipitation such as the development of linear models, isotopic signatures of drying ratios hold promise for understanding paleoclimate histories of a landscape.

10. The range of timescales involved in landscape atmosphere interactions is huge. As a function of the geomorphological question, are there breaks in scale for which processes and mechanisms are identifiably different, and that can be exploited? Or are there principles of self-similarity that can be identified that can extrapolate across scales? Geomorphologists are used to such principles in drainage networks, for example.

11. The need for hydrologists to be involved was noted as crucial, but not well represented at the workshop. It is a crucial step involved between precipitation falling on the landscape, and getting routed into rivers. Also important for numerical modeling.

12. Microclimates (10 to 1000m scale). Small scale landscape features can be important for create for small-scale climate variations. Important for creating ecological niches, in soil development, and in glacier mass balance. Possible opportunities for joint fieldwork.

13. How can paleo data (climatic, biologic, hydrologic, geomorphic) best provide insights on long-term climatic control of landscape evolution and on what timescales, aided by dating techniques such as optically-stimulated luminescence, mass spectrometry, carbon dating, and cosmogenic radionuclides

14. Fire, desert ecology, and climate are intricately linked and strongly affected by episodic droughts. Drought as an agent of geomorphic change has received relatively little attention. On the largest scales the feedbacks between landscape and regional climate (e.g. southwest Australia) were discussed as important questions.

15. Antecendent conditions are important in many natural hazards, for floods, landslides and wildfires. The seasonal history of weather events is not commonly studied in climate, but could be. Also an opportunity to interface with policy and management, evaluate the consequences of climate change.

16. How to tackle the tail? (or the tail that wags the dog). Of great service to geomorphologists and an intellectual challenge to atmospheric scientists, is how to characterize the long tail of small possibilities of extreme events. These are of primary importance in landscape dynamics, but atmospheric science lacks an understanding of what controls the tails of these distributions.

17. Connections between climate and landscape dynamics: areas of joint interest on human timescales center on hydrology and soil moisture; dynamic vegetation; and the response of ice sheets and mountain glaciers.

18. Use of satellite data to foster joint research efforts: remote sensing of such factors orographic precipitation, soil moisture, vegetation provide effective foci for joint collaborations.

19. In highly complicated terrain, downscaling of climate information is a practical inevitability. Determining the relative value of statistical vs. dynamical (either ensemble or deterministic) methods for the questions of interest, would be of great value.

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