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The composite nature of physical geography: Moving from linkages to integration

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Abstract

This editorial is the product of the *Progress in Physical Geography* lecture at the April 2013 meeting of the Association of American Geographers. The paper was presented by George Malanson, the North American Editor, and the co-authors presented critiques based on a draft. Subsequently, the manuscript was developed and revised based on discussion at the meeting and additional exchange among the co-authors.

Keywords

biogeography, climatology, geomorphology, human-environment, hydrology, interaction, modeling

Introduction

Physical geography is a composite discipline of several interconnected scientific subfields, each of which has standing in its own right. While some disagreement exists on the relative importance of, and even the number of, recognized subfields, most practitioners would agree that four – biogeography, climatology, hydrology, and geomorphology (with foci on the biosphere, atmosphere, hydrosphere, and lithosphere (taken conceptually)) – subsume the bulk of the research

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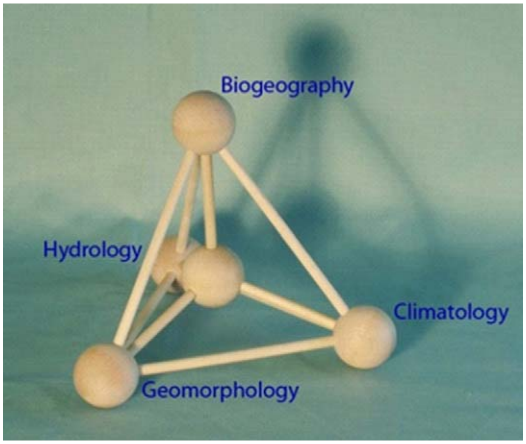

Figure 1. A three-dimensional tetrahedron represents the four primary domains and subdisciplines of physical geography (biogeography/biosphere; climatology/atmosphere; geomorphology/lithosphere; hydrology/hydrosphere) with their integration in the center.

in physical geography (e.g. Clifford, 2009). Practitioners often self-identify predominately with one area by aligning the bulk of their work within conceptual divisions of the environment into biosphere, atmosphere, hydrosphere, and lithosphere. The field of physical geography seems to go through cycles in the amount of attention paid to integration among these subfields (Stoddart, 1965). These cycles may be in the form of a punctuated equilibrium, wherein the equilibrium condition is slight integration, but in a research environment that has placed a premium on interdisciplinary studies in recent years, it has become clear that the separation of these areas is to a large degree artificial (Martin and Johnson, 2012).

Here we aim to encourage more integration by examining where physical geography has been influential and where it might develop a new equilibrium. While Venn diagrams are a traditional way to start such ventures through examining relationships between sets, they tend to emphasize domain overlap rather than integration; Clifford (2009) noted how Fenneman's (1919) Venn diagram left the center of the primary circle unexplained while focusing on its circumference. Integration is better visualized in a tetrahedronal diagram (Figure 1) in which each of the four subdisciplines occupies a vertex of the regular tetrahedron and the center represents their integration. Therefore, the tetrahedron can be thought of as a 3D representation of 4D relationships between the different subdisciplines and/or spheres of physical geography. In the tetrahedron, any three of the domains creates an equilateral triangle and can be imagined similar to a soil texture triangle or a Holdridge life zones triangle. Unlike simple bivariate plots where the relationships between only two variables can be easily visualized, or 2.5D graphics where three variables can be represented in quasi-3D, the tetrahedron is a non-orthogonal representation much like the real world where variables are intercorrelated. The axes internal to the tetrahedron can be thought of as the eigenvectors, while the 'closeness' of the object of interest to the centroid of the tetrahedron can be thought of as the loading on these eigenvectors (Figure 1). As such, the position of a specific study within the tetrahedron feature space is a mapping of the relative strength of each of the subdisciplines for that study. Many studies lie close to a vertex or can be well described in reference to a single triangular face, but we start on the edges.

To begin, we identify historical and recent geographical research for the six binary links that define the edges of the tetrahedron. We then choose two areas for examining triangular links, recognizing that others are as illustrative. Last, we consider areas where all four domains are brought to bear, and we discuss how we can improve such linkages. Physical geography that expands the temporal dimensions for places engages all four vertices, human-environment interaction pulls physical geography toward the center of the tetrahedron, and modeling provides a vehicle.

II Binary links

1 Climatology/biogeography – atmosphere/biosphere

The link in geographical research between the atmosphere and the biosphere is most developed in the area of plant geography, wherein the distributions of biomes, functional types, species, or finer divisions are seen in response to spatiotemporal change in temperature and moisture availability (Daniels and Veblen, 2000). Patterns of different plant structure and leaf type in relation to temperature gradients were described by von Humboldt and Bonpland (1807) and this is a common starting point for chapters on biogeography in current introductory textbooks. Since then, geographers have refined the description for various areas, such as the USA (Kuchler, 1949; Nichols, 1923) and aspects of this association have been at the heart of paleoclimate reconstruction using biological data (discussed below). Studies have also examined atmosphere-biosphere connections over the range from individual species to biomes. One of the most dynamic applications of these principles is in the arena of species distribution (or niche) modeling (Franklin, 2010). Work that uses models to *simulate* the response of vegetation to climate change is a salient current extension of this core connection (Malanson, 2011a; Murray et al., 2013).

Geographers also have been concerned with biogeographic function. Geographic patterns of productivity have been mapped at multiple scales (Luus and Kelley, 2008), but the global-scale work garners the most attention (Justice et al., 1998; Still et al., 2003). While most work emphasizes net primary productivity, significant geographical work on net ecosystem productivity (Grant et al., 2011; Kljun et al., 2006) and net biome productivity (Beringer et al., 2007) advances our understanding of function. In addition to being a response to climate, the pattern of productivity is also an effect of the biosphere on the atmosphere because the biosphere, including soil, is a major sink and a potential source for carbon. The idea of a carbon sink has been explored locally (Scull, 2007) and for extensive regions (Dull et al., 2010; Myneni et al., 1997) as well as globally (Pan et al., 2011; Trumbore et al., 1996) while the release of methane from existing carbon stores is seeing increased attention (e.g. Wadham et al., 2012). In addition to the composition of the atmosphere, vegetation and soil affect albedo, surface roughness, and water content (McPherson, 2007), which are central to modeling and understanding the impacts of climate change (Pitman, 2003; Salmun and Molod, 2006; Zabel et al., 2012).

2 Geomorphology/biogeography – lithosphere/biosphere

The link between the lithosphere and the biosphere is most developed in biogeomorphology. Viles (2011) highlighted early work in biogeomorphology, citing luminaries such as Darwin, Lyell, and Penck. She noted the effects of organisms in creating whole landscapes, ranging in scale from the Great Barrier Reef to microdepressions. In practice, biogeomorphology is primarily about the effects of plants and animals on geomorphic processes and patterns and is a 'sub-field of geomorphology' (Viles, 2011: 246), although interactions go both ways (Butler et al., 2003, 2007; Resler et al., 2005). The organizing theme is that the rates of surficial processes (at least for Earth) are usually changed by organisms. Some of the earlier work is focused on the reverse direction, with topography providing a simple differentiation (Vann, 1959; von Humboldt and Bonpland, 1807), but most of this topographic work is now tied to geospatial applications (e.g. Warner et al., 1991).

Among environments where current research in biogeomorphology is most active, Viles (2011) identified river channels. Therein she focused on riparian vegetation and bank stability. She noted the mechanical and hydrological roles played by the vegetation, with attention to large woody debris (e.g. Bendix and Cowell, 2010; Brierley et al., 2005; Malanson and Kupfer, 1993; Piegay and Gurnell, 1997), but animals are also important (e.g. Butler and Malanson, 1998; Gurnell, 1998; Harvey et al., 2011). Geomorphology plays an equally large role in affecting biogeographic processes, whether in differentiating wetland and/or riparian vegetation (e.g. Tooth and McCarthy, 2007) or influencing differences in plant species at a fine scale within a wetland.

3 Lithosphere/atmosphere – geomorphology/climatology

This area is perhaps the least dynamic, but at a longer timescale is important. The response of landforms to climate – and the very idea of climate change – is rooted in glacial geomorphology (Agassiz, 1840) and is still current (Clark et al., 2012; James, 2003). This response of landforms to climate, however, extends to all climatic regions (e.g. Migon, 2009). The core of these relations must include water, but some research foci are essentially binary.

The effect of geomorphic surfaces on the atmosphere has implications at multiple scales (as illustrated by Willmott and Matsuura, 1995, for near-surface air temperature). Crossing the largest range of scales, at the finest geomorphological scale but the largest atmospheric scale, chemical weathering of rock affects the composition of the atmosphere and thus global climate. While recognized by geographers (Dadson, 2010), this link between climatologists and geomorphologists is not as strong as this functional connection would indicate; more work is on erosion than weathering (e.g. see Brocklehurst, 2010; Finlayson et al., 2002). At the broadest scale, tectonic activity and climate change are linked (Scuderi, 1990, 1992). For ongoing processes, renewed focus on the role of erosion on carbon flux falls into this link if we consider soil carbon to be non-biospheric; much work in this area does focus on the geomorphology (Kuhn et al., 2009; Quine and Van Oost, 2007) at local (Dlugoss et al., 2012; Yadav and Malanson, 2009), regional (Nadeu et al., 2012; Smith et al., 2001, 2005) and global scales (Van Oost et al., 2007).

A more intimate connection is in aeolian geomorphology, wherein the process of aeolian transport of sediment mixes the two spheres. Geographers have worked on landform processes at local (Hesp, 2002; Sherman and Bauer, 1993; Tchakerian, 1991; Yang et al., 2011) and regional scales (Arbogast and Johnson, 1998; Goudie and Middleton, 2001; Lee and Tchakerian, 1995). More specifically, dust in the atmosphere is an important factor in climate dynamics (Dentener et al., 1996).

4 Lithosphere/hydrosphere – geomorphology/hydrology

Water moving on and through the upper layer of the Earth affects weathering and then accounts for most of the erosion, transport, and deposition of Earth materials (i.e. sediment) (Roy and Lamarre, 2011). One of the best-developed research areas in physical geography is fluvial geomorphology and, herein, a distinction between hydrology and geomorphology is difficult to maintain. Clifford (2011) summarizes the concepts in this area by focusing on rivers within drainage basins. The focus is on processes, particularly erosion, in an explicit systems frame and scale context.

Highlights in the area of fluvial geomorphology start with the Strahler school, which had a major influence in Britain (e.g. Chorley, 1978; Gregory, 1973; Richards, 1982), perhaps more than in the USA. Basic research has elucidated process above all else (e.g. Calver and Anderson, 2004; Powell, 1998), but pattern and history are also important (e.g. Lane and Richards, 1997; Macklin et al., 2006). In the USA, following in the footsteps of Strahler and Schumm, highlights include the interaction of flood flows and geomorphology (Constantinescu et al., 2011; Rhoads and Kenworthy, 1995; Woltemade and

Potter, 1994), but the insights of Jim Knox and Stan Trimble on non-equilibrium sediment flux and storage dominate the field, perhaps because this work has been tied to climate and land cover work beyond the geomorphology-hydrology link (e.g. Knox, 1972, 1977, 1993, 2006; Trimble, 1981, 1983, 1999, 2009).

5 Climatology/hydrology – atmosphere/hydrosphere

Because a number of major hydrologic components are located within the atmosphere, these two spheres are the most difficult to distinguish from one another. Fundamental connections are the processes and patterns of water vapor and clouds and the drivers of precipitation. While hydrologists tend to take atmospheric inputs and outputs as boundary conditions, and climatologists are not much concerned with the movement of water on or below the surface, the area of hydroclimatology is thriving (Mather, 1991; Nickl et al., 2010; Willmott et al., 1985). The connection between the processes and patterns of precipitation and those of surface water flux and storage deserves more attention than it gets, but new work on satellite measurement of precipitation may address this (Chappell et al., 2013).

Hydroclimatology has been applied to water resources regionally (Day, 2009; Granger, 1983; Larsen, 2000; Wise, 2012) while flooding problems have been addressed for single rivers (Choi, 2008; Konrad, 1998; Todhunter, 2001; Zume and Tarhule, 2006). The connection to climatology is especially clear where flooding is functionally linked to climate change (Wilby and Keenan, 2012). For water resources, early work examined where water came from (e.g. Hoyt and Langbein, 1944) and the connection to atmospheric circulation continues (Kingston et al., 2006; Rohli et al., 2008). Much of the emphasis is regional (Goodrich and Walker, 2011; Keim et al., 2011; Wise, 2012), but it includes study of fundamental processes as well as regional and global patterns (Ellis and Barton, 2012; Fekete et al., 2004). Again, the link to climate change is obvious (Xu, 1999). Some research on the amount of water is not so much about resources; glacier volume and movement provide important evidence of climate change (Diolaiuti et al., 2011; Hall and Fagre, 2003; McCabe and Fountain, 2013; Ohmura and Reeh, 1991). Some of this work also focuses on processes per se (Fountain and Walder, 1998; Hock, 2005; Post and Motyka, 1995).

6 Hydrology/biogeography – hydrosphere/biosphere

The binary connection here is diffuse because life is inseparable from water. The link between the hydrosphere and the biosphere, and hydrology and biogeography, is most developed where an abundance of water affects plants and patterns of vegetation, as in wetlands and floodplains (Bendix, 1997; Craig and Malanson, 1993), but extending to in-stream biota (Bragg et al., 2005). However, the prior process of runoff generation is affected strongly by infiltration as well as interception (Holder, 2006; Levia and Frost, 2006) and evapotranspiration (Williams et al., 2012).

Much of the work connecting hydrology and biogeography is in the area of flood effects in wetlands, wherein the hydroperiod (in addition to climate) and the dynamics of water levels differentiate biogeography based on anoxia nutrient inputs and the tolerances and adaptations of species to these negative and positive drivers of productivity. Geographers have mostly worked on the details linking processes within wetlands (e.g. Burt and Pinay, 2005; Holden et al., 2004; Thompson, 2004) rather than broad differences. An important area for current research is the role of wetlands as sites for transforming organic matter into methane (Butler and Malanson, 1995; Chen et al., 2013; Moore and Roulet, 1993; Roulet et al., 1992), and while this research is connected to the atmosphere it is not specifically climatology.

III Multiple links

Binary links provide common insights into the importance of scale and other interactions:

- The adaptations (of function) that suit species to the climate of their time and place become complicated by the simultaneous temporal and spatial changes in geomorphology and hydrology (and interactions with other species).
- In biogeomorphology spatial patterns and processes of landforms and organisms are intertwined with the adaptations of the plants to climate and their relation to the force of water in erosion.
- The effects of geomorphic patterns and processes on the atmosphere illustrate that local processes are integrated with global phenomena, but depend on exposure – surfaces not covered by plants and soil.
- Fluvial landforms are the spatial result, and context for, the processes connecting water and Earth surface materials, with vegetation controlling rates.
- The connection between precipitation and surface water flux and storage is through landforms and vegetation.
- At the scales studied by geographers, the connections between water and life are complicated by landforms and flows across time and space.

Much research in physical geography goes beyond binary connections (even in constructing the above list of examples, some Procrustean effort was needed). For example, riparian landscapes, including wetlands on floodplains and deltas, combine fluvial geomorphology, biogeomorphology, and ecohydrology (e.g. 'wetlands science') with a link (albeit weak) to hydroclimatology in the response of floodplain geomorphology to climate change (Knox, 1993). Primarily because of a foundation in fluvial geomorphology, the conceptual links between pattern and process are well developed in riparian geography (e.g. Bendix and Hupp, 2000; Corenblit et al., 2007; Graf, 1978; Hughes, 1997; Malanson, 1993). The example of riparian landscapes illustrates the inevitability of linking conceptual spheres and subdisciplines, when one focuses on particular places, but questions of scale are embedded (Walsh et al., 1997). However, more general linkages for physical geographers are possible.

IV From links to integration

Combining all four domains of biogeography, climatology, geomorphology, and hydrology would seem to be natural for physical geographers. All four are covered as interacting in any introductory text in the subject. At the most advanced levels, we think of the connections in systems as elucidated by Chorley and Kennedy's (1971) *Physical Geography: A Systems Approach*, but an integrative systems approach can be hard to find in geography (Malanson, 2011b). But we can look beyond individual studies to a meta-domain of research. To move toward the center of the tetrahedron (Figure 1), we see two directions to follow. First is the more explicit treatment of time at multiple scales. Much research in physical geography includes time in process studies (e.g. in rates) or as change, but crossing temporal scales leads to integration across subdisciplines. Second, the greater the relevance of physical geography to human activity, and vice versa, is explicit in research, the more the interaction among subdisciplines is necessary. The links among subdisciplines are fostered most strongly in studies of long-term and human-connected climate change.

1 The treatment of time

Considering time across scales necessitates consideration of space across scales. The relationship

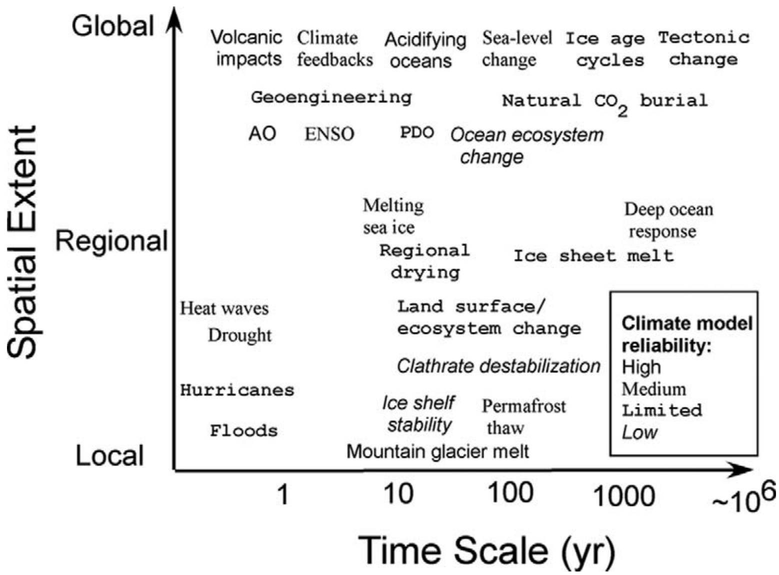

Figure 2. A Stommel diagram, but with many geographic processes occurring off the diagonal (their reliability in climate models are differentiated by font).

is best illustrated in Stommel diagrams (Malanson, 1999; see also Figure 2). Most processes and patterns are arrayed along the diagonal of the graph, linking temporal and spatial scales. Crossing temporal scales in physical geography means addressing paleoenvironments.

One important reason that paleoenvironmental studies have such well-developed linkages among the different environmental spheres is because these studies use proxies for measuring attributes of past physical environments. These proxies integrate different components of the Earth system. Work on past climate uses biogeographical, geomorphological, and hydrological observations together; for example, in paleolimnological research, lake sediments incorporate multiple proxies that integrate signals from all different subfields (Moser, 2004; Moser et al., 1996; see also, for example, Baker et al., 2000; Caffrey and Doerner, 2012; Kiage and Liu, 2006; Reinemann et al., 2009; Tingstad et al., 2011).

Why have paleoenvironmental studies seen more well-rounded linkages among spheres than studies of the present? To engage in such multidimensional study requires a specific spatial focus. A scan of titles of work on paleoenvironments indicates that most include place names, revealing that many, perhaps most, are specific to a locale. This specificity contrasts with the generalizability for which those studying the present strive. It is not that paleogeographical research is idiosyncratic, but that it can contribute to greater generality – a theory of climate change – by doing place-specific studies. Moreover, by locating studies in a particular place in the study of long-term change, paleogeographers deal with scale as a basic innate aspect of their studies. Other physical geographers, with no mega-theory to which to contribute (e.g. evolution and plate tectonics are established theories), must strive for a more limited generality in each and every study. Moreover, in order to emphasize particular, often binary, relations of process and pattern we choose model systems where we can, to the extent possible, hold other factors constant. This approach has been a good model for science, but it may be limiting in practice.

Can work in paleoenvironmental and global climate geography provide the model for pulling more work into the center of the tetrahedron? Agnew (1993), writing for human geographers, identified place as the outcome of processes (the focus of much physical geography), history (a strong component of much physical geography and the raison d'etre for paleogeographers) and location (bringing in the quantification of relative spatial relations and scale). Richards and Clifford (2008) argued for a such a localized approach to physical geography, at least in geomorphology. But a change of scale to places is another level of complication, and a concept of geodiversity (Gray, 2004) for conservation considers the variation in place, long important in biogeography. Bringing process, history, and location (spatial pattern and scale) and geodiversity together could be a way toward making a geography that nears the center of the tetrahedron through work on place, with spatial tools enabling more inclusion of spatiality in physical geography.

2 The human component

Underpinning much of the increased focused on paleoenvironmental studies is an interest in characterizing natural environmental variability and, crucially, how these environmental systems respond to change. Global environmental change, perhaps the defining issue of our time, therefore presents a special opportunity for physical geographers.

Long-recognized in geography (Marsh, 1864), the impact of human activities on the spheres of physical geography has spanned millennia, but its intensification in recent centuries has reversed von Humboldt's (1845) position on 'the reciprocal, although weaker, action which [man] in his turn exercises on these natural forces' in the phenomena summarized as global change. The fingerprint of humans on the physical world modifies and augments relationships within the spheres, and in most cases this impact cannot be separated in our study of the physical world; see commentaries by Harden (forthcoming), Malanson (forthcoming), and Retchless et al. (forthcoming) on the human component in research on geomorphology, biogeography, and climatology, respectively. Given this suffusion, the challenge for physical geographers is to understand the variability in the Earth system, to differentiate anthropogenic from non-anthropogenic processes, and to assess resources and hazards in the system (e.g. Johnston, 1983; Macdonald et al., 2012); Harden (2012) noted that advance in physical geography also reinvigorates human-environment geography.

Ties to human activities exist in the binary links discussed above. Bioclimatology has had a long history of significant practical importance in agriculture, which often is left out of physical geography (but see Goldblum, 2009; Mearns et al., 1996; Thornthwaite, 1953). Fluvial geomorphology is often applied to river management in some way (Csiki and Rhoads, 2010; Fryirs and Brierley, 2000; Graf, 1975, 1985, 2001; Gregory et al., 2008), given that drainage basins are, as Clifford (2011: 503) describes them, 'hybrid human-environmental systems'. Abrahart et al. (2012) have provided direction for new work under the rubric of river forecasting. Anticipating floods (or low flows) is a connection of hydroclimatology that links basins with global-scale processes, but also with organisms and people. In ecohydrology, the effects of vegetation on runoff generation (Abrahams et al., 1995; Gurnell and Gregory, 1987; Maetens et al., 2012; Post and Malanson, 1994) also link to flood flows (Peel, 2009).

Bringing the feedbacks between human action and physical geography into focus also forces us to cross scales because humans break scale boundaries (Figure 2). In geomorphology, local processes are linked to continental-scale erosion. For example, erosion of 1–20 t/ha/yr in c. 4 ha agricultural fields (Yadav and Malanson, 2009) and as much as 8 m/yr for mountaintop mining in an area of c. 160 km^2 (DeWitt, 2013) accumulate to continental-scale erosion of $\sim$5t/km^2/yr for the coterminous USA (Smith et al., 2001) and to global estimates up to $\sim$21 Gt/yr (Wilkinson and McElroy, 2007). Given links to carbon and to atmospheric carbon dioxide, these processes affect the climate system that drives agricultural and energy extraction processes. Thus, as geographers work on global climate models, other aspects of major global change, especially land use change, have become increasingly important components for understanding the processes (e.g. Feddema et al., 2005).

Climate change is the keystone of global change because it has feedbacks through all spheres. Incorporating multiple factors in global climate models (i.e. general circulation models) and then interpreting their implications are now inescapable motivations for linking the subdisciplines of physical geography. A range of feedbacks have been described (e.g. Salmun and Molod, 2006; Sitch et al., 2003; Walko et al., 2000) and we recognize that details of all four subdisciplines must be integrated if climate models are to be accurate and useful. The application of information on climate change to the study of other areas of concern, such as integrated assessment for regions (Chhetri et al., 2010; Mearns et al., 2012), includes the subdisciplines in its definition. Although Clifford and Richards (2005) pointed out the pitfalls therein, Earth system as a mega-theory, encapsulated by Schellnhuber (1999) as: E = (N, H), where N and H are the natural and human (and simply expanding Stoddart's 1965 prescription for geography), is one avenue toward the center of the tetrahedron.

V Moving forward

Full modeling of ongoing climate change and its potential consequences is the logical extension of paleoenvironmental physical geography as a focus for integration of the subdisciplines. Paleoenvironmental studies integrate the subdisciplines through the use of proxies because the interaction of the four spheres means that information is correlated; global climate models require information on interaction in order to represent the relevant processes. Not all physical geography needs to model climate change, but efforts to contribute to an understanding of climate and its impacts, as paleoenvironmental studies do, will better take advantage of geography's unique perspective and ability to link subdisciplines.

Modeling per se is also an important objective, and the concept can be extended beyond general circulation modeling. Where physical geography can effectively integrate its subfields is in the development and use of theory as embodied in models. While models can mean many things to many people, as explicitly described for geomorphology by Odoni and Lane (2011), models of all kinds lead to links. Theoretical models that will advance the research frontier, however, may challenge physical geography. Martin and Johnson (2012) concluded that process-based models could take advantage of new data sources to advance the biogeosciences (their term for the core of the physical geography tetrahedron). Physical geographers need to 'model-up' in the areas of mathematical and computer-programming skills that are essential for explicitly specifying and evaluating meaningful theory where all subdisciplines intersect with human activity. This new call echoes other – now decades old and more full-throated – calls made by Chorley and Kennedy (1971), Terjung (1976) and others. However, the challenges of moving more physical geography closer to the center of the tetrahedron are ever-present.

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