Future Directions for Critical Zone Observatory (CZO) Science

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Contributors

Robert S. Anderson, *University of Colorado, Boulder Creek CZO*
Suzanne Anderson, *University of Colorado, Boulder Creek CZO*
Anthony K. Aufdenkampe, *Stroud Water Research Center, Christina River Basin CZO*
Roger Bales, *UC Merced, Southern Sierra CZO*
Susan Brantley, *Penn State University, Shale Hills CZO*
Jon Chorover, *University of Arizona, Jemez – Santa Catalina CZO*
Christopher J. Duffy, *Penn State University, Shale Hills CZO*
F.N. Scatena, *University of Pennsylvania, Luquillo CZO*
Don L. Sparks, *University of Delaware, Christina River Basin CZO*
Peter A. Troch, *University of Arizona, Jemez – Santa Catalina CZO*
Kyungsoo Yoo, *University of Minnesota, Christina River Basin CZO*

Introduction

As we enter the second decade of what E.O Wilson (2002) dubbed the “century of the environment”, there has never been a more important time to accelerate our understanding processes in the Earth’s critical zone (CZ), which extends from bedrock to the atmosphere boundary layer and has been defined as “*… the heterogeneous, near-surface environment in which complex interactions involving rock, soil, water, air, and living organisms regulate the natural habitat and determine the availability of life-sustaining resources*” (NRC, 2001).

Life on Earth depends on the uninterrupted provision of “Critical-Zone services”, ranging from the provision of water of a quality and in a quantity that will support both human activities and ecosystems to the production of food and fiber for a growing global population. This concept of Critical-Zone services expands on that of “ecosystem services” that was introduced in part as a framework for considering the many benefits or services provided by both near-natural and highly-managed ecosystems (Carpenter et al., 2009) by explicitly including the coupled hydrologic, geochemical, and geomorphic processes that underpin ecosystem processes.

The structure and functioning of the CZ have evolved in response to climatic and tectonic perturbations throughout the Earth’s history, with the processes driving change more recently accelerated by human activities (Steffen et al., 2007). The immediate challenge is to develop a robust predictive ability for how CZ attributes, processes, and outputs will respond to projected climate and land-use changes. This predictive ability must be founded on sufficiently broad knowledge of critical-zone processes to describe how the varied climatic and geologic factors that distinguish different regions interact, and require advances in measurement, theory and modeling.

Critical Zone Observatories (CZOs), funded by the U.S. National Science Foundation and the European Commission, offer a unique instrument to address this challenge. CZOs provide essential data sets and a coordinated community of researchers that integrate hydrologic, ecological, geochemical and geomorphic processes from grain to watershed scales. CZOs are the lenses through which we will bring into focus the rich complexity of interactions between the lithosphere, the pedosphere, the hydrosphere, the biosphere and the atmosphere. CZOs are poised to reveal both how mass and energy fluxes interact with life and lithology over geological timescales that see the transformation of bedrock into soils, and how the same coupled processes enact feedbacks between the CZ, changing climate and changing land use over timescales of human decision making.

Over the next decade, the CZO program will produce a fundamental understanding and four-dimensional data sets that will stimulate, inspire, and test the resulting predictive models. The CZOs will:

1. Develop a unifying theoretical framework of CZ evolution;
2. Develop coupled systems models to explore how CZ services respond to anthropogenic, climatic, and tectonic forcings;
3. Develop data sets that document differing CZ geologic and climatic settings, inform our theoretical framework, constrain our conceptual and coupled systems models, and test model-generated hypotheses.

As such, CZOs have the potential to catalyze transformative science of the surface Earth.

Goal 1: Develop a unifying theoretical framework of critical-zone evolution

Landscape change over geological time results from the dance between tectonic processes moving crust and climate-driven geomorphic and geochemical processes rearranging material on the dance floor. In the short term, the steps in this dance are mass transport in hillslope and fluvial systems coupled to water-rock interactions that contribute solutes to hydrological fluxes. While these processes are tied to the hydrologic cycle, they are further modulated by the co-evolution of soils and vegetation. Indeed, in most landscapes the soil cloak itself is a legacy of past environments. While soil components like A horizons record agricultural activities in the past century, processes that break down rock to soil proceed far slower than the periods of climate change that have paced the recent ice ages. Such understanding, however, is too coarse to predict the trajectory of the critical zone over a wide range of time scales and to decouple geological, climatic, and biological forcings that often operate at different rhythms. For example, plant growth is known to affect surficial weathering and hillslope form by bioturbation, fracture formation, alteration of hydrologic fluxes, soil CO_2 generation, and profusion of organic weathering reagents. However, we are not yet able to weave these individual processes into a holistic and predictive conceptual model of landscape evolution. This limitation is primarily due to incomplete knowledge of couplings between hydrological, geochemical, geomorphic, and biological processes that include both positive and negative feedbacks and their distribution in time and space.

In the next decade a well-linked CZO network and its sets of multidisciplinary researchers will develop the theoretical framework in which these processes interact to generate the architecture of CZs in the present landscape. We will employ the data sets collected under a common instrumentation protocol and data structure to triangulate toward the roles of climate and geologic setting that have heretofore been only loosely and at best anecdotally constrained.

Goal 2: Develop coupled systems models to explore how critical-zone services respond to anthropogenic, climatic and tectonic forcings

Landscape and ecosystem response to perturbations associated with climate change and land use pressures depend on a complex suite of coupled processes associated with water, energy and weathering cycles. For example, temperature and precipitation changes may drive a non-linear and irreversible response in ecosystem structure and function (e.g., forest dieback, Breshears et al., 2005). Better prediction of threshold ecosystem response requires a clearer understanding of the physical and chemical landscapes that buffer climatic forcing and shape the environment in which biota respond. Similarly, changes in ecosystem structure will influence ongoing CZ structure formation and, therefore, its capacity for provision of CZ services. Couplings between ecosystem function and water, energy and weathering cycles will be measured at CZOs and form the basis for the development of coupled systems models that allow study of interactions and feedbacks between biological and physical processes in the CZ.

The assimilation of hydrologic, meteorological and (bio)geochemical measurements within and across CZOs into such coupled systems models is key to providing the multi-scale/multi-process understanding that is currently lacking, but necessary to advance CZ predictions.

Goal 3: Develop an integrated data/measurement framework sufficient to document critical-zone geologic and climatic settings, inform our theoretical framework, constrain our conceptual and coupled systems models, and test model-generated hypotheses across a CZO Network

The next generation of Earth surface coupled process models and hypotheses will require exceptionally rich data sets that are continuous in time, intensive in space and comprehensive in process. Diverse data types (e.g., sap flow, sediment transport, groundwater, bedrock weathering) will reveal characteristic rates that span many orders of magnitude. Acquisition of such datasets requires substantial investment in *in-situ* environmental sensors, field instruments, remote sensing, and surface and subsurface imaging, including the development of new technologies. The payoffs of such investments are potentially enormous if we can resolve the fluxes of energy, water and materials within and through the CZ, and provide fundamental insight to ecosystem and landscape evolution and resilience. Clearly, new advances in our ability to quantitatively understand and simulate landscape energy and water cycling will depend on a new approach to measurements and instrumentation that captures spatial and temporal variability in atmospheric inputs superimposed on complex vegetation patterns, overlying heterogeneous, anisotropic subsurface geomedia.

Critical Zone Contribution to Resolving Earth System Processes: *An Example*

Quantitative estimation of watershed carbon balance provides a compelling example. Findings from the late 1980s to mid 1990s that only ~30% of the carbon dioxide released by fossil fuel burning stayed in the atmosphere, with ocean uptake accounting for an additional ~30%, launched a stampede of terrestrial ecosystem and surface-Earth scientists to every biome on Earth to look for the missing sink for the remaining 40%. However, after 15 years of effort, a consensus has yet to emerge regarding the spatial distribution of, or the processes responsible for the 2-4 Pg C y^{-1} *continental sink of the 1990s (IPCC: Solomon et al. 2007), or the observation that continents were likely a net source in the 2000s. One roadblock is that net ecosystem production (NEP) measured at local scales does not often extrapolate well to larger scales (Ometto et al. 2005, Stephens et al. 2007), very possibly due to lack of consideration of lateral export (Chapin et al. 2006, Lovett et al. 2006) and/or the details of spatial and temporal variability. The importance of full watershed-scale carbon balances is illustrated by the one published study that accounted for both vertical carbon fluxes (via eddy covariance tower) and lateral carbon exports via streams, demonstrating that Net Ecosystem Exchange (NEE) went from a net sink of 0.278 Mg C* ha^{-1} yr^{-1} *to a net source of 0.083 Mg C* ha^{-1} yr^{-1} *when lateral stream fluxes were accounted for.*

Critical Zone Observatories for Earth Science Integration and Networking

A deliberate integration of typically segregated surface Earth science disciplines (ecology, hydrology, soil science, geochemistry, geomorphology) across both observations and modeling is the CZO strategy to develop better understanding of the process couplings that lead to long-term landscape evolution and response to short-term environmental change. The development of multiple CZO sites will enable comparison and sensitivity studies that might then serve with reasonable confidence in a predictive mode for non-observatory sites. Such deliberate disciplinary integration across defined watersheds with cross-site linkages spanning geologic and physiographic provinces is a distinctive feature of the CZO framework. For the last 1-3 years, CZOs have been building increasingly integrated multi-disciplinary science teams that are tackling these problems. CZOs have begun to put in place infrastructure for the intensive data gathering effort required to feed these science teams and the conceptual and mathematical models they develop (http://www.criticalzone.org). CZOs have built a national and international network, particularly through collaboration with a parallel effort in the European Union (http://www.soiltrec.eu/), making these data and infrastructure open to all and welcoming outside collaborations.

Of all the environmental observatories, the CZO network is the only type to integrate biological and geological sciences so tightly. As such, in the next decade, CZOs represent a unique opportunity to transform our understanding of coupled surface Earth processes and begin to address quantitatively the impacts of climate and land use change and the value of critical zone services.

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Appendix: A Common CZO Infrastructure

The infrastructure required to measure watershed-scale energy, water, carbon and other mass balances across a CZO network can feasibly be built through incremental additions to existing CZO infrastructure, thereby permitting measurement of:

1. *Fluxes across the watershed boundary.*
   a. *Energy: Measurements of incoming and outgoing visible and infrared radiation, plus latent and sensible heat exchange; and supported by sufficient characterization to distribute these quantities across a watershed.*
   b. *Water: Measurements of precipitation amount and type and stream discharge. Evapotranspiration (ET) is measured using sap flow and eddy-covariance.*
   c. *Carbon: Stream and precipitation gauging stations can be augmented with sensors for carbon species. Quantification of stream* CO_2 *export also requires measurements of gas-exchange coefficients and upstream gradients in free* CO_2*. Eddy-covariance measures both water vapor and carbon dioxide fluxes.*
   d. *Other materials: Sediments, nutrients, and lithogenic solutes can receive similar treatment to carbon by quantifying all depositional inputs and gaseous and water-borne exports. Continuous sensors for turbidity, bed transport and electrical conductivity can readily be deployed, with sample collection and laboratory analysis for solutes.*
2. *Changes to storage in major reservoirs and fluxes between them*
   a. *Energy: Changes in the thermal state of the near-surface.*
   b. *Water: Amounts of and changes in soil-water, snowpack and groundwater storage*
   c. *Carbon and other materials: Once water fluxes are known, measuring concentrations in the water provides other mass fluxes*

The resources required to deploy and manage such an integrated sensor and data system are substantial, with the consequence that very few watersheds have a complete data suite to close the mass and energy balances.

Identifying research watersheds in major climate and physiographic regions, and upgrading their sensor infrastructure to meet the data requirements to close energy, water, carbon and other mass balances should be a high priority. A major goal should be to create an adequate number of CZOs – leveraging proposed NEON and selected LTER sites and data records – to cover major climate and physiographic regions. Leveraging with ARS and USGS watersheds should also be included, to form a broader network of observatories.

As community resources, on the 5-year time frame CZOs and other similarly instrumented watershed observatories could provide scalable, multi-disciplinary evaluations of whole-watershed energy and mass balances for a variety of climatic and geologic settings. Within a decade, CZO scientists could help the surface Earth community answer questions such as of the missing continental carbon sink.