Critical Zone

Justin B. Richardson
Dept. of Earth and Atmospheric Sciences, Cornell University, Ithaca, NY, USA

Synonyms

Earth's critical zone

Definition

The critical zone, the near-surface terrestrial environment from the bottom of circulating groundwater to the top of vegetation, hosts the complex interactions involving rock, soil, water, air, and living organisms that regulate life-sustaining resources.

Introduction

The term "critical zone" was first applied to the surface terrestrial environment by Dr. Gail Ashley (1998) in a presentation at the Geological Society of America. In her work, Dr. Ashley introduced the concept of the critical zone when she wrote that a "holistic approach is needed to understand the three-dimensional complex linkages involving physical, chemical, and biological processes" and a study of geologic and surface processes that are "crucial for life" (Ashley 1998). In 2001, the United States National Research Council's Committee on Basic Research Opportunities in the Earth Sciences noted the future importance of the critical zone concept as integrative of disciplines and required to address interconnected problems (NRC 2001). The National Research Council defined the critical zone as "*the heterogeneous, near surface environment in which complex interactions involving rock, soil, water, air and living organisms regulate the natural habitat and determine availability of life sustaining resources*." Brantley et al. (2007) provided an alternative definition of the critical zone as "*the fragile skin of the planet defined from the outer extent of vegetation down to the lower limits of groundwater*," and many others have followed. In all definitions, the critical zone is recognized as a location of complex biogeochemical and physical processes that supports the terrestrial biosphere (Fig. 1) (White and Sharkey 2016). Study of the structure and function of the critical zone explicitly includes study of processes evolving at all timescales from that of the geologist to that of the meteorologist, and explicitly includes atmospheric (i.e., climate), geologic (e.g., volcanic, tectonic), and biologic (e.g., microbes, plants, organisms, humans) changes throughout Earth's deep and recent history (NRC 2001). Critical zone science can provide information for sustainable adaptation to human perturbations (e.g., intensive land use and climate change).

Essential Concepts

The critical zone paradigm is a new integration of existing fields of natural sciences (Fig. 1). One of the essential aspects of this paradigm is that the term "critical" reflects that nearly all terrestrial life, including humans, depends on the critical zone (Giardino and Houser 2015; NRC 2001), establishing a clear link between Earth's surface processes and geosystems with humans (Brantley et al. 2007; Richter and Billings 2015). Land use and climatic impacts are affecting processes that govern biomass productivity, soil formation, geochemical cycling of elements, and water resources (Hooke et al. 2012). For this reason, it is essential for developing predictive abilities of how attributes, processes, and outputs of the critical zone will respond to projected climate and land-use changes. Some of the central scientific concepts that have been investigated through critical zone science are: (1) formation and distribution of weathered bedrock, (2) sustainability

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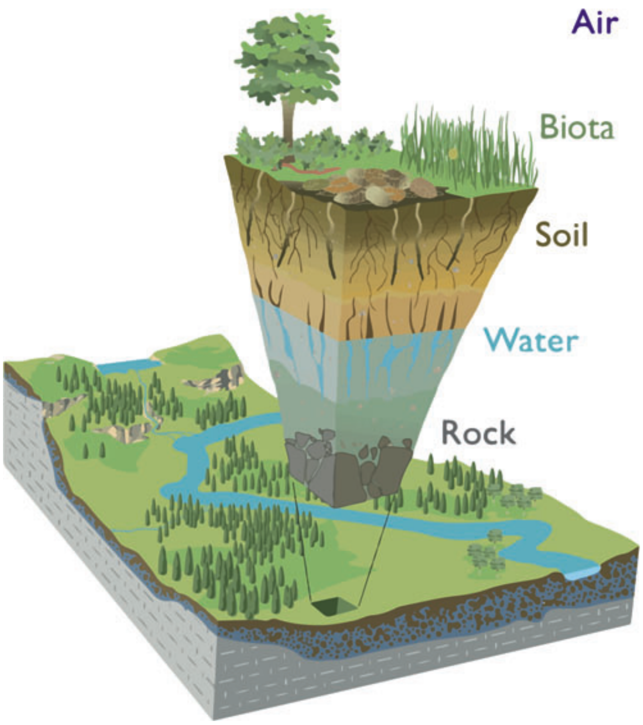

Critical Zone, Fig. 1 An illustration of the Critical zone conceptual model modified from Chorover et al. (2007) (Artwork by R. Kindlimann)

of water and soil resources, (3) tracing the movement of energy and reactive material, and (4) integration of processes across spatial and time scales and with respect to anthropogenic uses and perturbations.

Understanding the biological, chemical, and physical properties controlling bedrock and surficial deposit weathering is a central topic for critical zone science and for parallel efforts in geobiology and geochemistry (Pope 2015). The formation of weathered bedrock has been investigated by Earth scientists for more than 170 years (see Ebelmen 1845; Gilbert 1909). Critical zone science has generated renewed interest in the distribution, structure, and residence of weathered rock, features whose spatial distribution are generally considered to be difficult to measure (Holbrook et al. 2014). The architecture of the weathered bedrock of the critical zone has been shown to be a combination of tectonic, topographic, and weathering processes combined (e.g., Brantley and Lebedeva 2011; St. Clair et al. 2015). Weathering of bedrock may influence sustainability issues, in particular, the feedback between weathering rates and atmospheric CO_2 concentrations (Raymo 1989). Bedrock composition can also directly control the aboveground ecosystem. Hahm et al. (2014) found differences in forest productivity were directly linked to major and minor element composition of the underlying bedrock. The architecture and distribution of fractures is not only important for element cycling, but is also key for reservoirs of materials and energy in the critical zone. For example, the thickness and structure of the weathered bedrock in the critical zone controls many hydrologic properties such as water table elevation, plant-available water, and discharge rates to streams and rivers (Brooks et al. 2015).

Soil and water sustainability is a fundamental component of critical zone science. Much of the framework of critical zone science is built upon principal themes of soil science (e.g., state factor model of Hans Jenny 1941) and hydrology (e.g., subsurface and surface flow by Freeze 1972). Critical zone science focuses on soil sustainability through estimating soil formation rates (e.g., soil formation on a hillslope by Riggins et al. 2011), modeling nutrient cycling (e.g., soil-vegetation cycling rates in a temperate forest by Kraepiel et al. 2015), and quantifying erosion and denudation rates (e.g., sediment transport from following a storm by Foster and Anderson 2016). In addition, water sustainability is considered through snowpack (e.g., snow accumulation in the southern Sierra Nevada by Kirchner et al. 2014), belowground water storage (e.g., water table recharge along a hillslope by Dralle et al. 2014), surface and subsurface flow (e.g., depth of preferential flow rates through soils by Thomas et al. 2013), plant-availability (e.g., plant ecohydrological strategies in seasonally dry ecosystems by Vico et al. 2015), and evapotranspiration losses (e.g., evapotranspiration along an elevation gradient in southern Sierra Nevada mountains by Goulden et al. 2012). While many of these efforts run parallel with traditional soil and hydrological sciences, their integration with other disciplines for broader theoretical understanding and quantitative modeling is pivotal for critical zone science. For an example of greater integration, Bales et al. (2011) observed that during severe droughts in the Sierra Nevada Mountains, California, the majority of water lost from soils and trees can be sourced from water stored in weathered bedrock. In addition, Wilson et al. (2016) linked tillage practices in agroecosystems with soil erosion, which influences crop productivity, carbon storage, and net income from a parcel of land. Critical zone science has built upon existing soil and water sustainability concepts with greater integration as a holistic system (Richter and Billings 2015).

Tracing the movement of material and energy is important for quantifying and modeling local and global critical zone processes, particularly those that are reactive. The movement of materials through soil and unconsolidated material has been a topic of concern for many disciplines. Materials of interest include nutrients (e.g., Davis et al. 2014), inorganic colloids (e.g., Trostle et al. 2016), organic carbon (e.g., Stielstra et al. 2015), trace metals and metalloids (e.g., Ma et al. 2011), and pollutants (e.g., Ma et al. 2014). The movement of these materials through the critical zone controls natural phenomena such as chemical weathering, erosion, nutrient cycling, and anthropogenic issues, such as acid-mine drainage, eutrophication of surface waters, atmospheric CO_2 concentrations, and contamination of drinking water

(Li et al. 2017). Studies of material movement range from empirical studies and process-based models to quantify their movement. Li et al. (2017) described four areas in which reactive transport models may substantially contribute to critical zone science as testable hypotheses: (1) evapotranspiration-chemical weathering controlled by reactive gases, (2) water availability-chemical weathering-atmospheric CO_2-temperature linkages at the global scale, (3) soil moisture influences on carbon stabilization in soil, and (4) plant root controls on soil formation and function. Understanding the movement of energy in the critical zone is important for investigating thermodynamic controls from climate on physical, biological, and chemical processes. Rasmussen et al. (2011) proposed the structure and evolution of the critical zone can be described using climatic and biotic forcings as a single environmental energy and mass transfer (EEMT) parameter with energy flux units (e.g., J m−2 s−1). This concept has many potential applications and may be applied across any chosen spatial and temporal scales. Further coupling the movement of materials and energy are current areas of study with many future implications for understanding the critical zone.

Linking critical zone processes across time and spatial scales is a principal goal of critical zone science. Many chemical reactions occur at molecular microsystems (mineral surfaces, root surfaces, macropores, rock fractures), and critical zone scientists are working to measure their effect on larger scale processes (soil formation, hillslopes development, watersheds ecosystem services). For example, Brantley et al. (2011) notes that as rocks and minerals weather, their size decreases and surface area increases, exerting a control on the rate of chemical weathering in the soil profile with potential influences at the watershed scale in Puerto Rico and Pennsylvania. Moreover, mechanisms occurring in a soil profile or at an acre scale can be coupled with regional and global scale estimates. In addition to size and spatial scales, the other most arduous endeavors for Earth Scientists has been linking short-term processes (hours, days, years) with longer-term changes (decades, centuries, and millennia). Monitoring efforts have been fundamental for quantifying short- and long-term biogeochemical and physical processes of the critical zone. For example, a short-term observation may be daily monitoring for peak streamflow during melt season in a snow-dominated watershed (Chen et al. 2016). As a long-term example, Richter et al. (2000) observed that the impact of atmospheric nitrogen was dominant in biological nitrogen fixation over 40 years, by comparing soils collected and archived from 1962 through 1997 at the Calhoun Experimental Forest. Coupled numerical models, such as Flux-Penn State Integrated Hydrologic Model (Flux-PIHM) (Shi et al. 2013) and Terrestrial Integrated Modeling System (TIMS) (Niu et al. 2014), are the leading edge on combining processes over multiple time scales to evaluate the relative influences of different critical zone parameters, and hold out the capacity to support predictions of critical zone processes in the past and future. Furthermore, coupled numerical models are capable of using contemporary processes to investigate changes over geologic time scales (thousands to millions of years).

Current Investigations

The critical zone is studied at a number of Critical Zone Observatories (CZOs), where multiple scientific communities work in tandem to understand coupled processes, through both field and theoretical approaches. Teams of researchers monitor surface and subsurface water, meteorological conditions, soil properties, and vegetation. In addition, researchers undertake sampling campaigns of vegetation, soils, sediments, regolith, and bedrock. Information generated through monitoring and from sampling campaigns is synthesized to investigate complex systems at CZOs.

While individual CZOs each develop novel approaches to quantify critical zone processes, observatories aim to complete comparable measurements as a network. A key aspect is to use common measurements in which sampling is guided by overarching hypotheses and further developed to reflect site conditions, but materials and methods are implemented in a similar manner across the CZO network (White et al. 2015). Although cross-CZO data comparisons are a substantial goal, many lines of inquiry are site-specific and utilize approaches based on the principal of “best technique and sampling design” at each individual CZO. Thus, even though CZOs are individual entities, data is collected to be comparable with local, regional, and global monitoring efforts. Cross-CZO comparisons that are generalizable across space and time may be modeled using common measurement data and are paramount for creating integrated processes theories needed to expand predictive modeling (i.e., Earth-casting) (White et al. 2015; Richter and Billings 2015).

The United States National Science Foundation (NSF) has funded 10 CZOs across the United States and nine of these still receive funding (White et al. 2015). The NSF CZO program began in 2007 with support of three CZOs: Susquehanna-Shale Hills CZO in Pennsylvania, the Southern Sierra CZO in California, and the Boulder Creek CZO in Colorado. In 2009, three additional observatories were added: Luquillo Mountains CZO in Puerto Rico, Christina River Basin CZO in Delaware and Pennsylvania, and the Jemez River Basin/Santa Catalina Mountains CZO in Arizona and New Mexico. In 2013, four new observatories were selected for funding: Eel River CZO in northern California; Reynolds Creek CZO in Idaho; the Intensively Managed Landscape CZO in Illinois, Iowa, and Minnesota, and the Calhoun CZO in northern South Carolina. Measurements at the NSF-funded CZOs include a common set of variables that quantify Critical zone architecture and evolution, fluxes across the Critical zone boundaries, and changes in storage of the major critical zone reservoirs. The CZOs have recognized that many of the details of overarching science questions can best be addressed if a core set of variables is measured across the CZOs, and if those core measurements are made using the same or readily comparable methods. In 2014, the CZO National Office was created to spur network level research and outreach activities.

There have been many international projects to conduct critical zone research globally. Although some observatories worldwide are not called CZOs, scientists across the international research communities have adopted the framework and nomenclature of "critical zone science," because the paradigm is compelling for addressing environmental sustainability and accelerating interest in Earth surface sciences (White et al. 2015; Richter and Billings 2015). International CZOs and similar projects have identified objectives of determining changes to the critical zone in response to human pressures, and each program has its own approach and strategy. The European Commission funded SoilTrEC in 2009. The SoilTrEC network consisted of four CZOs: Koilaris River Basin in Crete, Damma Glacier in Switzerland, Slavka Forest in the Czech Republic, and in Fuchsenbigl, Austria. Germany has also established the TERENO network, a set of four observatories: Eifel/Lower Rhine Valley, Harz/Central German Lowland, Northeastern German Lowland, and Bavarian Alps/pre-Alps Observatories. Additional CZOs in France and through a United Kingdom-China partnership are in development. Through internationally funded meeting and workshops, there are 60 countries conducting research at 21 funded CZOs as of 2015 (White et al. 2015).

Conclusions

Critical zone science is a new paradigm focusing on integration of existing fields of natural sciences: a systems approach needed to understand the three-dimensional complex linkages involving physical, chemical, and biological processes at the Earth's surface. The term "critical" reflects that nearly all terrestrial life depends on the critical zone. Critical zone science aims to develop predictive abilities, which are essential to understand the past and future effects of climate and land-use. The central scientific concepts investigated through critical zone science are the formation of weathered bedrock, water and soil resources, the movement of energy and reactive material, and integration of natural processes across spatial and time scales. The critical zone is studied at Critical Zone Observatories (CZOs), where multiple scientific communities monitor and conduct sampling campaigns to synthesize the complex interactions systems. Critical zone research is conducted globally as international research communities have adopted the framework and nomenclature to renew interest in Earth surface processes and their sustainability.

Cross-References

- ▶ Anthropogenic CO_2
- ▶ Biogeochemistry
- ▶ Carbon Cycle
- ▶ Earth's Atmosphere
- ▶ Earth's Continental Crust
- ▶ Geochemical Kinetics Nitrogen Cycle
- ▶ Geochemical Thermodynamics, Soil
- ▶ Geochemistry
- ▶ Geochemistry: Low-Temperature
- ▶ Hydrologic Cycle
- ▶ Nutrients
- ▶ Water
- ▶ Weathering: Chemical

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