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Designing a network of critical zone observatories to explore the living skin of the terrestrial Earth

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Abstract. The critical zone (CZ), the dynamic living skin of the Earth, extends from the top of the vegetation canopy through the soil and down to fresh bedrock and the bottom of groundwater. All humans live in and depend on the critical zone. This zone has three co-evolving surfaces: the top of the vegetation canopy, the ground surface, and a deep subsurface below which Earth's materials are unweathered. The US National Science Foundation supported network of nine critical zone observatories has made advances in three broad critical zone research areas. First, monitoring has revealed how natural and anthropogenic inputs at the vegetation canopy and ground surface cause subsurface responses in water, regolith structure, minerals, and biotic activity to considerable depths. This response in turn impacts above-ground biota and climate. Second, drilling and geophysical imaging now reveal how the deep subsurface of the CZ varies across landscapes, which in turn influences above-ground ecosystems. Third, several mechanistic models providing quantitative predictions of the spatial structure of the subsurface of the CZ have been proposed.

Many countries now fund networks of critical zone observatories (CZOs) to measure the fluxes of solutes, water, energy, gas, and sediments in the CZ and some relate these observations to the histories of those fluxes recorded in landforms, biota, soils, sediments, and rocks. Each U.S. observatory has succeeded in synthesizing observations across disciplines; providing long-term measurements to compare across sites; testing and developing models; collecting and measuring baseline data for comparison to catastrophic events; stimulating new process-based hypotheses; catalyzing development of new techniques and instrumentation; informing the public about the CZ; mentoring students and teaching about emerging multi-disciplinary CZ science; and discovering new insights about the CZ. Many of these activities can only be accomplished with observatories. Here we review the CZO experiment in the US and identify how such a network could evolve in the future. Specifically, we recognize the need for the network to study network-level questions, expand the environments under investigation, accommodate both hypothesis testing and monitoring, and involve more stakeholders. We propose a "hubs-and-campaigns" model that promotes study of the CZ as one unit. Only with such integrative efforts will we learn to steward the life-sustaining critical zone now and into the future.

1 Introduction

Humans live at Earth's surface – a surface that changes at timescales ranging from milliseconds to millions of years. Understanding how to sustain a growing human population on this changing substrate while simultaneously sustaining diverse ecosystems and the services they provide is a grand challenge for scientists and decision makers (Easterling, 2007; Millenium Ecosystem Assessment Board, 2005). In recognition of the critical nature of Earth's surface, the United States (U.S.) National Research Council defined the zone from the upper vegetative canopy through ground water as the "critical zone" and listed study of this "CZ" as one of the *Basic Research Opportunities in the Earth Sciences* (U.S. National Research Council Committee on Basic Research Opportunities in the Earth Sciences, 2001). Only recently has the critical zone been recognized as a distinct co-evolving entity driven by physical, chemical, and biological processes that sustain life. To tackle the critical zone for the first time as an entity -- rather than to study pieces of it separately -- presents a grand challenge (Fig. 1). Understanding this zone requires researchers drawn from many disciplines including geology, hydrology, climate science, ecology, soil science, geochemistry, geomorphology, and social science to work in collaboration. Critical-zone science uses measurements as the foundation for advances in understanding and prediction. Scientists measure fluxes of solutes, water, energy, gases, and sediments (SWEGS) as they are today and then compare them to the histories and impacts of those fluxes recorded over geological time in landforms, regolith structure, soils, and sediments. Critical zone scientists also relate these fluxes to natural and anthropogenic drivers as well as to the structure of the critical zone, including biota, soil, and regolith properties. In this way, models can scale CZ properties across the landscape and project the CZ changes across time into the future. From this endeavor has emerged the concept of critical zone science, a new paradigm adopted around the world to investigate Earth's surface from canopy to bedrock in its entirety as one integrated unit.

CZ science is defined by these criteria: i) it targets Earth's surface from canopy through groundwater; ii) it encompasses timescales from milliseconds (or less) to millions of years; iii) it incorporates insights from all relevant disciplines. Some have described CZ science as an attempt to put geology into watershed and ecosystem science, or the study of the interaction of rocks and biota. Each of those descriptors falls short of the full complexity of describing the CZ as one entity. After about a decade of critical zone observatories (CZOs) funded by the U.S. National Science Foundation (NSF), we here review the evolution of CZ science as an interdisciplinary experiment. In this review of the CZO enterprise, we take stock of successes

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and weaknesses as a way to map future opportunities. In this paper we address a broad question: what programs and infrastructure are needed by the community to understand the CZ of the future? We explicitly acknowledge that our review is focused on the experiment in the U.S. -- we see this approach as an experiment like any other, and we focus this paper from that perspective. We acknowledge the many other observatory networks around the world (http://www.czen.org/site_seeker) and invite comments or future papers on how those other networks are constituted. We also welcome input as to how the U.S. system might better fit into the global system.

One way to review the U.S. program to date is to summarize performance through quantitative metrics. As manifested today, the program funds nine CZOs situated across a range of landscapes in the U.S. (Fig. 2). In addition, interdisciplinary field observatories that host critical-zone science involve thousands of interdisciplinary investigators in more than 25 nations (Fig. 3) (Giardino and Houser, 2015). Other metrics further highlight how CZ science has energized people and approaches in the U.S. and abroad (Tables 1, 2, 3, 4). Indeed, the term "critical zone" (White and Sharkey, 2016) has been used in 925 papers as of 2017, in title, abstract, or keyword as recorded in Web of Science. The term has even entered the realm of geopolitics (Latour, 2014). This is remarkable given that critical-zone science as an idea only dates from 2001. But less quantifiable is the impact of the idea of the CZ: for example, one country hosting one of the longest observatory networks in the world (France) is now specifically promoting communication among disciplines and sites, a specific example of the power of the CZ idea. Thus, quantitative metrics such as those in Table 1 do not fully illustrate the way CZ science has progressed. In the rest of the paper we discuss the arc of ideas, the strengths and weaknesses, and an approach for the future of CZ science.

2 Non-observatory approaches used to study the CZ

We start by a very brief backward look to summarize approaches to investigate the CZ. Here, we do not seek to exhaustively summarize history but only to place the CZO experiment within a context. For example, the scientific disciplines of today largely did not yet exist until the early 1900s, and the earliest natural scientists therefore tended to be multi-disciplinary (e.g. Berner, 2012; CFIR CSEPP, 2005; Forbes, 1887; Warkentin, 2006). It was not until the 1900s that scientists began to focus on portions of the Earth system that could be understood in a reductionist sense (Riebe et al., 2016). It is instructive to consider the approaches to studying CZ science that have emerged during this latter period.

First, as scientific disciplines developed throughout the 20th century, small-grant funding to single investigators or small teams became the dominant mechanism to fund research to explore questions about the CZ in the U.S. This approach eventually promoted the individual disciplines of geochemistry, geobiology, geomorphology, hydrology, soil science, ecology, meteorology, and others. Such disciplinary growth allowed scientific endeavors to mature, as exemplified in the proliferation of disciplinary journals published worldwide. For example, Web of Science currently indexes 225 journals in the fields of environmental sciences, 184 in multidisciplinary geosciences, and 150 in ecology, with some journals cross-reported in more than one category.

Second, as questions about landforms, soils, water, and biota at Earth's surface sharpened, needs arose to fund multi-investigator campaigns targeting specific questions. Campaigns were concerted, multi-investigator, multi-year projects designed to understand a particular process or set of questions. In 1970, questions about environmental problems and human health grew in the U.S. and drove more funding for both small-investigator and campaign grants (CFIR CSEPP, 2005). Perhaps the largest and most global example of a "campaign" was the International Geosphere-Biosphere Program (IGBP) that engaged 10,000 scientists from more than 20 disciplines and 80 countries around the world (CFIR CSEPP, 2005).

Eventually, a third type of funding paradigm to study the CZ also grew hand in hand with single-investigator and campaign-style science. Specifically, centers of excellence were funded in the U.S. to draw together expertise into institutions to focus on specific problems or approaches. One impetus for this was the inauguration in 1987 by the NSF Science and Technology Center program. This effort eventually supported two centers of especial relevance to critical zone research: SAHRA (Sustainability of semi-Arid Hydrology and Riparian Areas) and NCED (National Center for Earth-surface Dynamics). NCED (2002 to 2012) focused on developing a quantitative, predictive Earth-surface science by integrating geomorphology, ecology, hydrology, sedimentary geology, engineering, social sciences, and geochemistry by combining field, experiment, and computational approaches. NCED and its reincarnation as NCED2 focus on advancing a predictive Earth-surface science but are not focused on understanding the critical zone as one entity. A similarly ambitious institution, the National Center for Ecological Analysis and Synthesis (NCEAS), was established in 1995 as the first national synthesis center for ecology.

Other examples of institutionalized centers of excellence also were important in developing aspects of CZ science. For example, the Community Surface Dynamics Modeling System (CSDMS; http://csdms.colorado.edu/wiki/Main_Page) is building and promoting a library of models for various Earth surface processes and supports a broad community of modelers. The National Center for Airborne Laser Mapping (NCALM, established in 2003) provides research-quality airborne light detection and ranging (LiDAR) observations to the community. Another example is the Consortium of Universities for the Advancement of Hydrologic Science, Inc. (CUAHSI; https://www.cuahsi.org/), which aims to advance hydrologic sciences broadly across the U.S. and its member universities. Other centers of excellence have been established to promote use of instrumentation such as the NSF-funded Purdue Rare Isotope Measurement Laboratory (PRIME Lab), a dedicated research and service facility for accelerator mass spectrometry (AMS) including measurement and interpretation of cosmogenic isotopes.

3 Environmental observatories and networks

In addition to the three types of initiatives summarized in the last section, environmental scientists have long recognized the need for place-based, integrative science. This recognition has led to a "deep" history and a diverse set of place-based, experimental, and long-term observation sites. Early on, many of these were established to investigate impacts of specific land use activities. One of the first was the Rothamsted Experimental Station in Harpenden, England, founded in 1843 to study the effects of fertilizers on crops. Within the U.S., the concept of using paired watersheds to investigate the hydrologic and geomorphic impacts of land use treatments began at Watson Wheel Gap, CO in 1910, where a pair of small instrumented catchments were monitored to evaluate changes in stream flow and sediment yield (Van Haveren, 1988).

As human population and land use increased, researchers began to write about the need to compare long-term measurements at both pristine and human-impacted sites (Leopold, 1962). The U.S. Geological Survey thus developed a hydrologic benchmark network (HBN) of 57 basins (Cobb and Biesecker, 1971) to make long-term hydrologic measurements. The mandate of the HBN was expanded to include observations not only of stream flow and water quality but also soil chemistry and aquatic ecology monitoring in 2011 (McHale et al., 2014). Thirty-seven hydrologic benchmark watersheds are still maintained (Mast, 2013), but the original vision to also characterize vegetation and geology has remained unfulfilled.

The paired-watershed approach pioneered in Watson Wheel Gap, CO, was replicated much later in many other locations in the U.S., including Hubbard Brook (NH), Coweeta Hydrologic Laboratory (NC), and the H.J. Andrews Experimental Forest (OR) among others. These pioneer sites, in turn, led to the establishment of over 70 forest and rangeland sites that focused on fundamental and applied questions spanning hydrology, silviculture, soil science, and climate research (Lugo et al., 2006).

In the early 1980s, as academic scientists pointed out the difficulties of answering questions about long-term natural processes given the realities of short-term funding (Bormann and Likens, 1979; Callahan, 1984), the U.S. National Science Foundation Directorate of Biological Sciences created the Long-Term Ecological Research (LTER) program to carry out observation-based research across a network of sites that spanned the major biotic regions of North America. These efforts were aided by early work of the U.S. Forest Service to understand watershed hydrology (Swank and Crossley, 1988*)*. The LTER effort was initiated predominantly by ecosystem ecologists asking questions about organisms with long life cycles, including how they are maintained by natural water and nutrient fluxes in the face of long-term as well as episodic, acute environmental changes (Dodds and al., 2012). Although not exclusively based on the study of watersheds as pioneered in the late 1960s (Bormann and Likens 1967), many LTERs follow a model that emphasizes the study of energy, water, and material flows through a watershed (Hynes 1975). Going forward, the LTER network contains 28 LTERs and aims to incorporate consideration of social science (LTER Network Office, 2011).

A big step was taken in 1991 toward incorporating geology into these largely water-land use-ecology observatories when the U.S. Geological Survey inaugurated the Water, Energy and Biogeochemical Budgets (WEBB) program. WEBB targetted interactions among water, energy, and biogeochemical fluxes in five sites chosen at least partly by their inherent geological character and pristine nature.

Then, in 2008, another long-term research program was called for by agricultural researchers (Robertson et al. 2008), resulting in the establishment of the Long-Term Agroecosystem Research (LTAR) program in 2011. This network, today including 18 LTARs, promotes long-term agricultural research facilities, experiments, and watershed-based studies focused on sustaining agriculture and increasing crop yields under changing climate conditions while minimizing or reversing any adverse environmental impacts (http://www.tucson.ars.ag.gov/ltar/).

The most recent addition to the development of observatories in the U.S. is the National Ecological Observatory Network (NEON). NEON is a nationwide, distributed observatory that aims to understand and forecast the impacts of climate change, land use, and invasive species on ecology by providing i) consistent, continental, long-term, multi-scaled data, and ii) a research platform for investigator-initiated sensors, observations and experiments (Loescher et al., 2017). NEON has 84 sites across the U.S. Like LTER, NEON is a program funded by the Directorate of Biological Sciences at NSF to study ecological change (Golz et al., 2016).

As in the U.S., international observatory networks have also grown, many for substantially the same reasons that they grew in the U.S.– to study land use, water, and ecology. In at least one country (France), a network (OZCAR: Observatoires de la Zone Critique: applications et recherche) emphasizes individual disciplines at each observatory and provides as much as 50 years' worth of data to enable research in some sites. The long-term, place-based ecological research that was pioneered by the U.S.A. LTER network has also been adopted by the broader international community in the International LTER (ILTER) network (Vanderbilt and Gaiser, 2017). Today, the European Commission is promoting an approach to develop a European Research Infrastructure in the form of a network associating CZOs, LTERs and LTSERs. Here, LTSER stands for Long Term Socio-Ecological Research. Indeed, many of the European countries maintain strong observatory infrastructures that are much more tightly linked with local stakeholders than observatories in the U.S. This may result from the lack of truly "natural" territories in Europe, given the long history of development on the continent but also the willingness to co-construct research questions with stakeholders to build a sustainable environmental future.

4 The CZO Network

Clearly, this history shows how the pantheon of observatories has long targeted land use, water, ecosystems, and agriculture. None of these efforts were intended to incorporate the deep geological underpinnings and long-timescale perspectives that have come to be the hallmarks of CZ science. More specifically, none of these observatories targeted the entire CZ as one entity. As such, this place-based environmental science often was forced to use statistical approaches to explain variability that was caused by underlying geological heterogeneity. Recognizing this in the late 2000s, researchers within the water, soil, geochemistry, and geomorphology communities began articulating a need for integrated science across the entire zone from canopy to bedrock to incorporate the underlying geology (Anderson, 2004; Brantley et al., 2006; Committee on New Research Opportunities in the Earth Sciences at the National Science Foundation, 2012; U.S. Committee on Integrated Observations for

Hydrologic and Related Sciences, 2008; U.S. National Research Council, 2010; U.S. Steering Committee for Frontiers in Soil Science, 2009). These researchers also recognized that advances in studying Earth's surface were fragmented precisely because investigators typically targeted many different sites without coordination among disciplinary approaches. Under the paradigm of small funded projects, different types of measurements were made but they were completed at so many different sites that integration of observations into models was difficult to impossible.

Eventually the need to study the CZ as one integrated entity resulted in the NSF program establishing the Critical Zone Observatory program in 2007 (White et al., 2015). By 2007, three CZOs had been funded (Anderson et al., 2008). Two years later, three more CZOs were funded. By 2013 this number had grown to nine observatories supported through a competitive selection process. In addition to the expansion of sites in 2013, a CZO National Office (NO) was established in 2014 through an NSF competitive process with the intent of establishing the CZO Network to provide administrative network structure and function (White et al., 2015). The number of CZOs has remained stable through 2017.

Inauguration of the CZO program implicitly defined the term "critical zone observatory" to be distinct within the long history of observatories in the US and abroad as an observatory that promotes study of the entire CZ as one entity. As implemented today, CZOs are sites or closely connected sets of sites with no required size or specified range of conditions. In fact, the physical scope of a CZO is set only by the fundamental questions driving the establishment of the observatory. A fundamental characteristic of a CZO is that it is able to operate over a long enough period to quantify thoroughly controlling mechanisms and to capture temporal trends that may reveal further how the critical zone operates. Another characteristic of a CZO is that it is amenable to study by many disciplines. Importantly, a CZO is an adaptive and agile hypothesis-testing machine, not simply a monitoring program.

The physical scope of some U.S. CZOs are defined by watershed boundaries, some by land use, others by the range of climate conditions, and still others by contrasts in lithology or geomorphic history. The common elements are: 1) the focus on the entire above- and below- ground critical zone and its fluxes, 2) documentation of CZ structure, 3) mechanistic process studies, and 4) analysis of history of the landscape that gave rise to the current structure. This last feature is a crucial aspect of CZOs that distinguishes them from previous studies that typically do not consider "deep time" (i.e., geologic time) and often fail to document the critical zone below the soil. Previous papers have described how researchers have grappled at a specific CZO with the establishment of a measurement design (Brantley et al., 2016) and modeling design (Duffy et al., 2014; Niu et al., 2014). In addition to hypothesis-testing, CZOs accomplish nine additional roles to advance CZ science, as described in the next section.

5 The nine roles of CZOs

Here we highlight the nine important roles that can only be accomplished at an observatory and amplify the description of each role with examples of scientific results from the CZO network today.

First, CZOs act as *synthesizers of interdisciplinary research approaches* at one specific site that lead to emergent understanding and ultimately result in more deeply-informed process-based models (e.g.Kumar et al., 2017, in review; Rasmussen et al., 2011). In other words, observatories induce scientists from different disciplines to make measurements using different disciplinary approaches at the same location instead of making them at disparate sites, driving understanding that crosses the boundaries of disciplines in describing CZ function (Hynek et al., 2016; Sullivan et al., 2016). To date, much of the synthesis has crossed only two disciplines at a time: for example, several papers have emphasized how geomorphological concepts related to erosion must be incorporated to understand chemical weathering, and vice versa (Rempe and Dietrich, 2014; Riebe et al., 2016). Likewise, researchers have related tree roots to water cycling (Vrettas and Fung, 2015). But many puzzles remain concerning multi-disciplinary aspects of CZ entities, and much effort is currently focusing on such frontiers. A good example is how human impact alters the hydrologic and biogeochemical dynamics and material transport of the near-surface critical zone (Kumar et al. 2011). In another example, distributed CZO data were used to develop a predictive framework linking regolith structure, root-zone storage and vegetation to dry periods (Klos et al., 2017, in review). CZOs have fostered measurements from all disciplines in centralized places and this is the first step toward addressing broader multi-disciplinary models describing CZ function.

Second, CZOs provide *stable platforms for measurements made over long-term durations* (Table 2). Some of the datasets now available at CZOs are extremely long in duration. For example, the Reynolds Creek CZO recently published 31 years of hourly data that is spatially distributed at 10 m resolution for air temperature, humidity, precipitation amount and phase across the 239 km^2 Reynolds Creek Experimental Watershed (Kormos et al., 2016). Reynolds also published another 10 year data set that spans the rain-snow transition zone (Enslin et al., 2016). Many of the long-term datasets made at CZOs are measurements that are common to all CZOs and have been designed to test the hypothesis that new understanding will emerge about processes and function from such cross-cutting data. For example, characterization of dissolved organic matter (DOM) coordinated with similar methodology across five CZOs revealed a strong role for CZ structure in setting the origin, composition and fate of DOM in streams (Miller et al., 2016). In another example, a coordinated effort emerged to measure and understand the relationships among chemical species' concentrations and water discharge in streams (e.g. Godsey et al., 2009; Kirchner, 2003). This led to papers published by CZ scientists in a special issue of *Water Resources Research* (Chorover et al., 2017, in press). The goal now is to use CZO knowledge of subsurface structure to explain concentration-discharge behavior a priori for other settings.

Third, CZOs act as *a stimulus and test-bed for modelling and prediction*. For example, almost every CZO has proposed models of soil and regolith formation, and several have been described in publications in a special issue of *Earth Surface Processes and Landforms* (Riebe et al., 2016). Many of the standard water or coupled land surface-air models have also been tested and new modules have been developed at CZOs (Table 3). One CZO has contributed a hierarchy of numerical models for understanding processes that occur over microseconds to millennia (Duffy et al., 2014). Another CZO has contributed a model to exploit LiDAR resolution data to understand the role of micro-topographic and vegetation variability in controlling moisture (Le and Kumar, 2017, in review; Le et al., 2015) and biogeochemical changes (Woo and Kumar, 2017, in review) in agricultural landscapes. Researchers at another CZO developed a rigorous energy-balance snowmelt model that is now being used with airborne LiDAR (Painter et al., 2016) and other remotely sensed data for water supply forecasting. Work at the Luquillo CZO in Puerto Rico has allowed testing of models for stream channel self-organization at many other locations (Phillips and Jerolmack, 2016). In other efforts, researchers are investigating and modelling how hydraulic conductivity, root water uptake efficiency, and hydraulic redistribution by plants combine to sustain evapotranspiration through dry seasons (Quijano et al., 2013; Quijano et al., 2012; Vrettas and Fung, 2015).

Fourth, CZOs act as *baselines to understand and teach about the impact of catastrophic events.* For example, the impacts of wildfires were studied on soil microbiota (Weber et al., 2014), sediment yields (Pelletier and Orem, 2014), snow accumulation (Harpold et al., 2014), and water quality (Murphy et al., 2012; Reale et al., 2015) at two CZOs in the western USA. Likewise, effects of the 2013 Colorado Front Range storm (Gochis et al., 2015) on debris flows (Anderson et al., 2015), soil moisture (Ebel et al., 2015), cosmogenic radionuclides (Foster and Anderson, 2016), and concentration-discharge behavior (Rue et al., 2017) were studied at the Boulder Creek CZO. A flash flood within a research catchment of Boulder Creek CZO in 2016 instigated analysis of Horton overland flow in these landscapes (Klein et al., 2017). CZOs that experience catastrophic events use the baseline data captured before the event to place the scope of the impact into perspective. Such natural disasters also engender public interest in research: Boulder Creek CZO research on the 2013 Colorado Front Range storm has been featured in radio, press, and public forums and wildfire research has been featured in outreach from three CZOs.

Fifth, CZOs act as *the organizing design for systematic campaigns to investigate process-based mechanisms* in across various CZ environments. One example of this is the initiative in which every CZO in the U.S. pursued geophysical measurements. Many papers have been published exemplifying this approach to map out the subsurface architecture (Befus et al., 2011; Holbrook et al., 2014; Olyphant et al., 2016; Orlando et al., 2015). Increasingly, geophysicists are travelling among CZOs to image the subsurface with a battery of instruments and evolving approaches that reveal the below-ground landscape (St. Clair et al. 2015). In another example, one CZO began emphasizing slope aspect as a useful natural experiment to examine controls on CZ architecture and function (Anderson et al., 2009). This early abstract led to similar analyses at CZOs and emerging concepts of linkages between aspect, water, biota, regolith structure, and episodic events (Ebel et al., 2015; West et al., 2014). Finally, deep drilling projects were proposed and then pursued at many CZOs, and these data in turn led to a special issue describing regolith formation (Riebe et al., 2016). Successful campaigns have also been mounted to investigate mountain snow and water balance (Harpold et al., 2014), and the distribution of micro-organisms in soils (Griffin et al., 2017, in review).

Sixth, CZOs act as *catalysts for the development of new techniques and instrumentation from all disciplines* which can then be tested globally. For example, at the Eel River CZO, a unique vadose zone monitoring system (VMS) has been installed consisting of 19 m long holes drilled along contour of a hillslope at 55º relative to the horizontal and filled with sleeves with monitors for temperature, pressure, and electrical conductivity. This is giving access to the generally inaccessible deep vadose zone in the weathered bedrock to test reactive transport models incorporating gas and water chemistry (Druhan et al., 2017). At another CZO, rainfall simulation experiments have elucidated controls on the ratio of the concentration of carbon in eroded sediment to that of original soil in order to improve management practices for erosion (Papanicolaou et al., 2015). One CZO is pioneering the use of neutron scattering (NS) to analyze pores as small as nanometers in rocks and how they contribute to weathering reactions (Navarre-Sitchler et al., 2013). Water-balance instrumentation using robust wireless-sensor networks, developed at the Southern Sierra CZO (Kerkez et al., 2012), has been extended to the river-basin scale (Zhang et al., 2017), and is being deployed at other locations across the U.S. An approach developed to scale annual evapotranspiration measured at flux towers across the broader forested landscape of the Sierra Nevada (Goulden et al., 2012) is also being applied to flux-tower sites and forested areas across the western U.S.

Seventh, CZOs serve as *hubs for informing regional resource-management decisions, and for educating the public about societally relevant problems*. For example, measurements of evapotranspiration made at one CZO and scaled across the Sierras provide a basis for estimating sustainable forest densities in both current climate and a warmer, dried climate (Goulden and Bales, 2014). While it is accepted that the overly dense forests that are in part the result of decades of fire suppression are at high risk of wildfire and drought-induced mortality, action to restore forests remains slow. This work has major implications for forest restoration and payment for ecosystem services. Research on water resources is routinely communicated to water managers in California and the intermountain west by the Southern Sierra and Boulder Creek CZOs through briefings, workshops and data products. Research on snowpack and water resources for water managers in Colorado, Utah and Wyoming has similarly been communicated in a series of workshops co-organized by the Boulder Creek CZO in 2015. In other parts of the country, the Eel River CZO team is documenting controls on the summer spread of cyanobacteria in the Eel River, which has led to biannual gatherings of students, agency members, native Americans, and practitioners to learn to recognize algae types. Other CZO investigators routinely write op-eds and produce video that are distributed to media audiences and teach in pre-college classrooms. For example, the Southern Sierra CZO is a contributor to the *Sustainable California* web TV channel that was launched with other collaborators.

Eighth, CZOs act as *incubators that grow innovative teaching and mentor junior scientists* who easily work across multiple disciplines. As shown in Table 1, 39 post-doctoral scholars worked at CZOs in 2015 along with 106 undergraduate and 186 graduate students. As more and more institutions in the United States have advertised positions that mention critical zone science, these CZO students have moved easily into university department faculties where they are changing the research and education environment. Likewise, the recently completed InTeGrate project, Introduction to Critical Zone Science, is a one-semester undergraduate curriculum with lecture slides, online resources, and data drawn from the CZOs. This innovative new course uses the CZ as a unifying approach to teach complex Earth and environmental sciences (White et al., 2017, in press). Many other teaching and training workshops have also been presented by the CZOs. For example, a Modeling Institute was presented in 2016 on the Dhara model and a training workshop was presented on the Role of Runoff and Erosion on Soil Carbon Stocks: From Soilscapes to Landscapes in collaboration with CUAHSI.

Ninth, CZOs act as *impetus for discoveries and emergent hypotheses* that can only result from systematic and multi-disciplinary observations across or within specific CZ environments. Some of these hypotheses are disciplinary while others are cross-disciplinary. A full elucidation of these hypotheses is beyond the scope of this paper: indeed, only a subset of these are shown in Table 4 while many have been published elsewhere (Brantley et al., 2017, in review; Li et al., 2017). Here we summarize three of the most multi-disciplinary of the discoveries. As it happens, all three have large implications for the prediction of flowpaths relevant to the largest supply of accessible and drinkable water available to humans -- water contained in rock and regolith (Banks et al., 2009; Fetter, 2001). These three discoveries have been made both by non-CZO scientists and scientists within a CZO. For example, one geophysics group outside of a specific CZO discovered a distinct geometry at depth that is consistent with the influence of regional tectonic stress fields on patterns of fractures and weathering through hillslopes at CZOs and other locations (St. Clair et al., 2015). The theoretical underpinning proposed for this so-called “bowtie-shaped” geometry has important implications for predicting flowpaths of water in regolith *a priori*. CZOs also discovered significant water storage that is seasonally available in the vadose zone of weathered bedrock and that moves as preferential flow along fractures (Bales et al., 2011; Salve et al., 2012). This rock moisture, missing from land surface models, has very significant implications for understanding and predicting climate. Finally, CZO workers have also identified depth intervals in the subsurface in some sites that document mineralogical reactions and that roughly mimic the land surface topography albeit with lower relief (Brantley et al., 2013). Such “reaction fronts” can inform researchers about sub-surface flow paths (Brantley et al., 2017). All of these ideas are being tested at other settings around the world.

6 Three emergent paradigms

As mentioned above, common measurements are being made at all the CZOs in the U.S. (Table 2). In general, these measurements target the “SWEGS” fluxes – solute, water, energy, gas, and sediments -- as they move through the CZ, as well as such features as the form and age of the landscape. Some of the observations are more extensive than others: for example, hydrometeorological data, soil moisture dynamics, and measurements of concentration and discharge in streams are on-going at every CZO. As the common observational data accumulate, CZOs have been both developing new models and pursuing data comparisons with established models (Table 3). In the last several years, researchers have not only been integrating observations within a CZO but also integrating across multiple CZOs. At the highest level of cross-network synthesis, three general, overarching paradigms have emerged which we describe below.

First, we have observed that differences in natural and anthropogenic inputs at Earth's surface translate into differences in water, regolith structure, minerals, and biotic activity at depth, and we are starting to detect how these deep properties also impact the biota, climate, and CZ services (e.g. Chorover et al., 2011; Richardson and Kumar, 2017, in press; Sullivan et al., 2016) (Richter and Billings, 2015).

Second, we have observed how the deep surface of the Critical Zone varies across landscapes. Under hills, imaging has revealed locally consistent patterns of subsurface critical zone structure of depth, fracture density, porosity, and weathering (e.g. Befus et al., 2011; Orlando et al., 2015; St. Clair et al., 2015).

Third, we now have mechanistic models that provide quantitative predictions of the spatial structure of the deep surface relative to the ground surface topography (e.g. Lebedeva and Brantley, 2013; Rasmussen et al., 2015; Rempe and Dietrich, 2014; Riebe et al., 2016). These three broad generalizations have been informed by up to ten years of work at multiple CZOs as well as work by the greater critical zone science community.

With this ongoing integration of paradigms across CZOs, scientists have also begun to discern an important link between the CZ and the evolving conceptualization of "ecosystem services". This concept emphasizes how biodiversity, ecological processes, and spatial patterns in the near surface environment provide services to society (MEA, 2005). As discussed by CZO network scientists (Field et al., 2015; 2016), CZ science demonstrates the contribution of the deeper CZ to ecosystem "provisioning" and elucidates the longer time scales of CZ evolution, leading to the idea of "critical zone services". Through this lens, services such as water quality regulation, soil development, and carbon stabilization are seen as tightly dependent on CZ function, evolution and architecture. Indeed, the CZ is the ideal context for integrating deep subsurface and long time-scale perspectives from geosciences into the otherwise bio-centric conceptualization of ecosystem services. Doing so remains an emphasis of CZO network activities.

7 Strengths and weaknesses of the current CZO Network

Clearly, this history show The current CZO network as constituted in the U.S. and abroad has many strengths. Students are trained to cross disciplines within their graduate work. Postdoctoral scholars are educated with observatory personnel that derive from many disciplines. Collaborations are constantly developing and allowing scientists to see problems in new ways, and accepting new and different perspectives. Ideas are growing across the network about regolith formation (Riebe et al., 2016), snow hydrology (Harpold et al., 2014), microbial diversity (Fierer et al., 2003), trees (Brantley et al., 2017, in review), critical transitions (Kumar et al., 2017, in review), and many other topics. We have produced an enormous dataset

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(http://criticalzone.org/national/data/datasets/). We no longer treat parts of the CZ as mere components or black boxes: instead, we incorporate more specificity and understanding when we describe the integrated system. We are finding innovative ways to communicate the CZ concept to the public. We have stimulated and promoted development of CZOs worldwide.

Although there have been many successes, we have observed several weaknesses in the approach as it is constituted today. Since each observatory is individually funded based on the merits of its targeted science and management, there is an obvious competition for resources in addressing common measurements versus site-specific measurements. This competition for time and resources leads to a less-than-optimal approach to finding emergent network-scale outcomes as opposed to individual, site-based outcomes. Of course, site-specific outcomes can have implications and impacts that are just as important as network-scale outcomes and we need to find mechanisms to foster all such approaches while acknowledging limitations in resources. Further, given how new CZ science is, we are just beginning to articulate transformative ideas that cut across disciplines and we have difficulty communicating discoveries in a simple fashion on a transparent and inviting website. Perhaps one of our biggest challenges is maintaining the integrity of an inter-disciplinary suite of measurements in a common database and managing site data in ways that invite other researchers to find and use the datasets and use the field sites (Hinckley et al., 2016). The need for better data management is especially important given the many new data-driven approaches that are arising within environmental science (Bui, 2016).

These considerations lead to a basic question: what is the best way to advance CZ science? From review we point to four challenges going forward that loom large in designing the future network. First, what is the best approach for generalizing and scaling place-based studies to principles-based understanding through coordinated team effort? Second, how do we link appropriately with other programs in the U.S. and worldwide to develop a set of representative sites across the large number of possible environmental gradients to advance a broad understanding of CZ science? Third, how should we balance the roles of CZOs in providing infrastructure for monitoring while always supporting hypothesis driven science? Fourth, what funding and management models would enable increased and broader involvement of the broader community of CZ scientists who are not yet part of a core CZO team? These four issues are addressed in the next section where we propose a new model for the future of the network.

8 The future network

Different approaches that have been successful in investigating aspects of the environment were described above. These strategies can be summarized as i) small investigator grants targeting parts of the CZ, ii) campaign-style multi-investigator grants targeting multiple sites, iii) modelling efforts, and iv) observatories. Looking into the future, all are needed.

For example, individual grants (example (i) from above) can support sharply focused hypotheses that may lead to important discoveries about elements of the CZ. This kind of research, typically supported by a core grant from within a specific

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discipline (e.g. hydrology) sustains both the discipline and advances CZ science. The last decades of research has clearly shown that some advances come from single investigator research. Approach (ii), campaign-style research, has the advantage of exploring CZ questions over a range of conditions (Larsen et al., 2015). Such campaigns are more likely to focus on material properties than process dynamics and campaign-style research can focus many different one-time measurements, or measurements across a larger spatial scale, than CZOs can routinely accomplish. Modelling (approach iii) is always important as a means to guide and test field data collection and to probe for deeper understanding. The Critical Zone Observatory approach (iv) is the only approach that tackles fundamental questions and can also provide the nine important roles described above. In particular, only observatories can provide the long-term data and the diverse co-located observations from all disciplines that we need to understand the CZ. By working together with modelling organizations, only place-based observatories can knit together disparate views by acting as Meccas for scientists from all disciplines with all models.

However, to promote the emergence of informative ideas that can supersede the heterogeneity of the CZ, CZOs still need to perform more collaboratively as a network. Given this need, one approach may be for the community to identify a broad common-question for the future and then to design the future network to target this overall question. One proposed example for the next decade of CZO research is the following question of central importance:

> *How can we increase our understanding of surface and subsurface landscapes and fluxes as we face climate and other anthropogenic changes in the future?*

With such a question, the entire CZO network could then test sub-questions and sub–hypotheses together, but with experiments at different sites with different characteristics.

To address this question, some adjustments to the current topology of the CZO network should be evaluated and updated, to continue performing the nine observatory roles listed above, or to perform emerging roles. Indeed, many other topologies can be imagined (Fig. 4). Going back as early as the 1960s (Leopold, 1962), many scientists have similarly considered aspects of what is needed for environmental networks. For example, one topology might be to choose new observatories to fill in gaps among the current nine CZOs, as shown schematically in the diagram. Another model might be to continue the current nine CZOs as the future network. Another model might be to choose nine (or some other optimized number) completely new CZOs, i.e. treating the country as a blank slate. Another model might be to complete a careful analysis of the current CZOs in the context of Long Term Ecological Research (LTER) sites and Long Term Agricultural Research (LTAR) sites and then to extend the network appropriately (see Richter et al., submitted). NEON should also be part of this leveraging, as it becomes operational nationwide. A fifth model might be to establish one hub and then choose smaller sites along environmental gradients extending out from the hub. Finally, many CZOs might be funded for research along with smaller satellite sites that extend from the central CZO.

In thinking about the future network topology, we emphasize the need to find solutions to the four problems, stated as questions at the end of the last section: 1) the need to generalize from place-based to principles-based understanding; 2) the inadequacy of nine observatories in elucidating the highly heterogeneous and variable CZ; 3) the need for balance between measurements for hypothesis-testing and common, core measurements as network infrastructure; and 4) the need to incorporate the broader community of researchers into the CZO program.

The best way to address these issues appears to be to design something like the hub-and-spoke model but with multiple hubs and a high degree of scientific coordination with the other networks noted above. In addition, instead of spokes, i.e., lines of satellite sites that extend geographically out from the hub, we prefer to call these "campaigns", noting that in some cases these satellites might indeed be spokes, but in other cases might be located in vastly disparate locations. This model would promote the need for long-term measurements (at carefully chosen hubs), the need for short-term targeted measurements at specific locations both within the U.S.A. and abroad (carefully chosen campaign sites), and involve many new investigators as well. This long-term hub and short-term campaign emphasis has been promoted in the literature by researchers both inside and outside the current CZO funding framework (Banwart et al., 2012; Larsen et al., 2015). Fundamentally, the argument for the hub and campaign approach is that the two methods benefit from each other: the hub provides the unique opportunity to dig deep into understanding mechanisms and process dynamics. The campaign approach provides an opportunity to test the generality of specific findings, ideas, or theories across some relevant gradient of controls.

Specifically, we propose a "hubs-and-campaign" network that would consist of several CZOs as hubs that would provide the infrastructure for common measurements – and would be stimuli for ephemeral campaigns that would be funded for shorter time periods with more constrained purposes. The hubs would perform all nine of the CZO roles listed above and would receive stable funding. In contrast, the campaigns would be funded in efforts for shorter time periods to test specific hypotheses or ideas. In this way, the network would be able to change appropriately with time and cover more environments, would provide both infrastructure and hypothesis testing, and could be nimble and inviting for more groups to participate. In this regard, it might make sense if the hubs were located in settings of broad interest from a scientific and societal point of view. Alternately (or in addition), the hubs could be located to test specific hypotheses about critical zone structure and control across gradients. Such gradients could include climate or lithology or disturbance. Hubs might be chosen for their strategic and scientific importance. Hubs would presumably also be chosen in recognition of the needs of human resources for education and outreach, and for the need for both applied and curiosity-driven science. The potential use of hubs as attractors for students and scientists and platforms for increasing diversity in the Earth and environmental sciences would need to be stressed.

9 Conclusions

We now recognize the critical zone as an entity composed of very intriguing co-evolving systems that create a remarkable structured dynamic skin of the Earth. We are seeing the first maps of this structure as they emerge and we are discovering how the structure influences water resources and hydrologic processes, vegetation, ecosystems, erosion, biogeochemical processes, and even regional climate. Surface and deep processes are connected. The first set of testable models has been proposed and point to specific measurement programs. But this is only the beginning. While progress has been made, the central questions remain: what controls the critical zone properties and processes, how do critical zones respond to climate and land use change, and how can we use our advancing understanding to benefit societal needs? These fundamental questions will require a sustained research commitment. The critical zone is a frontier area of science where only the first observations have been obtained. New methods, instrumentation, and theory are needed to lay a foundation for understanding.

Here we suggest critical zone science in future research may be best advanced through a combination of distributed long term observatories strongly coupled with campaign style focused investigations. These field campaigns would radiate from the central hub observatory to test specific hypotheses and theories across controlling gradients. The observatories would focus on the necessary long-term monitoring to reveal mechanisms and dynamics. The field campaign would collect data over shorter periods.

The decision by the US National Science Foundation to support a network of Critical Zone Observatories has laid the foundation of a new discipline of critical zone science since 2007. Former graduate students supported at the CZOs are now taking up faculty posts and rapidly introducing new courses that span the many disciplines needed to reveal critical zone workings. Another generation is in the making. Findings from the CZOs are being absorbed by agencies and put to practice. The power of the critical zone concept has spread across the globe and stimulated the building of numerous critical zone observatories. We are seeing just the beginning.

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Table 1. Metrics enumerating the U.S. CZO experiment

CZOs in the United States	9
CZOs worldwide	45*
Countries with interdisciplinary field observatories hosting CZ science**	25
Papers citing critical zone in keyword WOS as of 2017#	926
Papers listing critical zone in title in WOS as of 2017	242
Post-doctoral students educated at CZOs in 2015	39
Graduate students educated at CZOs in 2015	186
Undergraduate students educated at CZOs in 2015	106

*Includes Germany (TERENO), France (RBV/CRITEX), UK, and China

**Giardano and Houser (2015)

#Papers returned through searching Web of Science (WOS) as of 05/28/2017 that include "critical zone" in title or key word or abstract etc. (not including abstracts for meetings)

Table 2. Common measurements made at the CZO network in the U.S.A.

Critical Zone Observatory – Measurement Type	Boulder Creek	Cal-houn	Catalina-Jemez	Eel River	Intensively Managed Landscapes	Luquillo	Reynolds Creek	Susquehanna Shale Hills	S. Sierra
Land-Atmosphere Exchange									
LIDAR	X	X	X	X	X	X	Y,Z	X	X,Y
Eddy flux	Y	Z	X		X,Y,Z		Y	X	X,Y,Z
Wind speed and direction	X	Z	X	X	X,Y	Y	Y	X	X
Precipitation and throughfall	X	X,Z	X	X	X,Y	Y	Y	X	X,Y
Wet deposition and bulk deposition	X	Z	X		Y	Y	Y	x	X,Y
Snowpack distribution and duration	X		X						X
Vegetation and Microbiota									
Structure and function above and below biomass	X	X	X	X	X	Y	Y,Z	X	X,Y
Microbial composition above and below ground	X	X	X	X	X	Y	X		X
ET-species composition and structure relationships	Y	Z	X	Y	Y		Y,Z	X	X
Soil (Vadose Zone)									
Solid - elemental composition and mineralogy	X	X	X	X	X	X	Z	X	X,Y
Solid - texture and physical characterization	X	X	X	X	X	X	Z	X	X,Y
Solid – organic matter content	X	X	X	X	X	X	Z	X	X
Solid – radiogenic isotope composition	X	X	X		X	X		X	X,Z
Fluid – soil moisture (sensors)	X	X	X	X	X	X	Y,Z	X	X
Fluid – soil temperature (sensors)	X	X	X	X	X	X	Y,Z	X	X
Fluid – soil solution chemistry (samplers)	X	Z	X		X	X		X	X,Y
Fluid – soil gas chemistry (samplers/sensors)		X	X	X		X,Y	Z	X	X
Saprolite and Bedrock (Saturated Zone)									
Solid – petrology and mineralogy	X	X	X	X	Y	X	Z	X	X,Z
Solid – elemental composition and OM content	X	X	X	X	X	X	Z	X	X,Z
Solid – texture, physical/architectural constraints	X	X	X	X	X	X	Z	X	X
Fluid – potentiometric head, temperature (sensors)	X	X	X	X	X	X	Y	X	X
Fluid – groundwater chemistry (samplers/sensors)	X	X	X	X	X	X	Y	X	X
Fluid – saprolite/weathered bedrock gas chemistry		X	Z	X					
Geophysical surveys – depth to bedrock	X	X	X		X	X		X	X
Surface Water									
Instantaneous discharge	X	X	X	X	X,Y	X,Y,Z	Y	X	X,Y
Stable isotopes of water	X	X	X		X	X		X	X
Stream water chemistry (samplers/sensors)	X	X	X	X	X	X,Y,Z	Z	X	X,Y
Sediments (samplers/sensors)	X	X	X	X	X	X,Y,Z	Y,Z	X	Y,X
Extent of wetted channel				X					Y,X
Aquatic biota (invertebrates, fish, etc.)				X		Y			Y
Age or rate constraints									
Cosmogenic radionuclides	X	X	X			X			X
**C ages	X	X	X			X			
Optical Stimulated Luminescence ages	X								

x: instrumentation in place or sampling is occurring, owned and operated by the CZO; y indicates instrumentation is currently in place, owned and operated by a partner of the CZO; z indicates that it is planned to be installed or implemented in the future by the CZO

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Table 3: Models used by the U.S. CZOs (abbreviations in Fig. 2)

Model name	Systems modeled	Future X-CZO application	CZOs using model
PIHM	Hydrology	Possible	CR, SH, CL
Flux-PIHM	Hydrology, land/atmosphere	Possible	SH
tRIBS	Hydrology		LQ, CL
hsB-SM	Hydrology		CJ
VS2D	Unsaturated hydrology		BC
Dhara	Near surface critical zone	Possible	IML, SH
Optimal sensing	Soil moisture		CL
HydropedoToolbox (Matlab)	Soil moisture		SH
OTIS	Streambed hydrologic exchange		SH
Alpine glaciers 1&2d	Ice motion		BC
Fluid exchange model	Estuary fluid flux		CR
PHREEQC	Aqueous geochemistry		LQ
WITCH	Weathering	Possible	SH
ROMS	Ocean		EL
WRF	Weather forecasting		EL, RC
ISNOBAL	Snowcover mass		RC, SS
SHAW	Heat and Water fluxes		RC
CHILD	Erosion, sediment transport, surface evolution	Possible	BC, CL
SOrCERO	Erosion and deposition		CL
Digital glacier bed	Elevation of glacier bed		BC
Gully Erosion Profiler	Channel profile evolution		BC
Hillslope Trajectory	Erosion		BC
Range and Basin	Mountain evolution		BC
Landlab	General 2d models		BC
FEMDOC-2D	Hillslope DOC transport		CR
IDOCM_1D	Heat and DOC in soils		CR
CENTURY	Soil carbon		LQ
CN reforest dynamics	Tree/soil C and N		CL
BIOME BGC	Carbon		SH, RC
Plant-soil feedback	Plant-soil, soil production		CL
Root deformation	Soil deformation from roots		BC
GASH	ET and throughfall		LQ
NPZD	Ecosystem		EL
PIHMSed	Hydrology, sediment transport, uplift, weathering	Possible	SH
PIHM-DOC	Hydrology, dissolved organic carbon		CR, SH
TIMS	Hydrology, microbial, geochemical, geomorph, ecology		CJ
RHESSys	Hydrology, ecology	Possible	SS
AWESOM	Atmosphere, Watershed, Ecology, Stream and Ocean Model	Possible	EL
tRIBS-ECO	Hydrology, erosion, soil C		CL

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Table 4. A few emergent hypotheses from the CZO network

1) CZ architecture controls hydrologic and geochemical processes that drive concentration-discharge relationships in rivers.
2) The depth to fresh bedrock across uplands landscapes may be predictable from models that account for regional stress fields, advancing chemical reaction fronts, drainage of the fresh bedrock, and/or fracturing from freeze-thaw.
3) Aspect differences can be used to reveal the mechanisms and effects of climate on the CZ.
4) The deep microbial community is linked to overlying vegetation: microbial community is distinctly different under agriculture fields, brush, grassland, perennial forest and deciduous forest.
5) The deep microbial community is linked to lithology: the microbial community is distinctly different on granite, basalt, shale, and sandstone.
6) The deep architecture of the Critical Zone controls water availability to plants and microbial communities, which in turn influence regional climates.
7) Subsurface reaction fronts may sometimes be used to map flow paths in the subsurface.
8) Human impact in intensively managed landscapes has resulted in a critical transition that has changed the landscape from primarily a transformation-dominated system characterized by long residence times of water, carbon, and nutrients, to a transport-dominated system characterized by fast movement of water, sediment, carbon, and nutrients through the landscape into receiving water bodies.

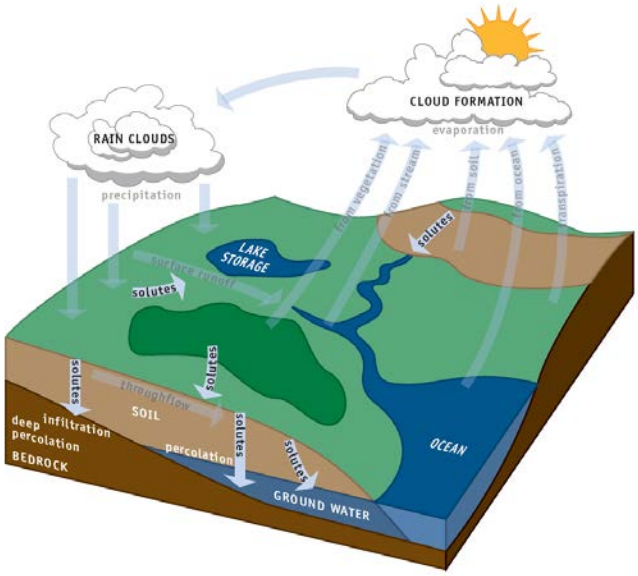

Figure 1. Understanding the critical zone requires harnessing insight from many disciplines on processes and fluxes from the top of the vegetation canopy down into groundwater, across timescales from milliseconds to millennia. Figure reproduced from Anderson et al. (2004).

Figure 2. The current network of 9 Critical Zone Observatories funded in the United States to investigate all aspects of the critical zone. Abbrevations used in Table 2: Eel River (ER), Southern Sierra (SS), Jemez Catalina (JC), Boulder Creek (BC), Reynolds Creek (RC), Intensively Managed Landscapes (IML), Susquehanna Shale Hills (SH), Calhoun (CL), Luquillo (L).

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Figure 3. Location map of the 45 CZO locations in the U.S., Germany (TERENO), France (RBV/CRITEX), UK, and China.

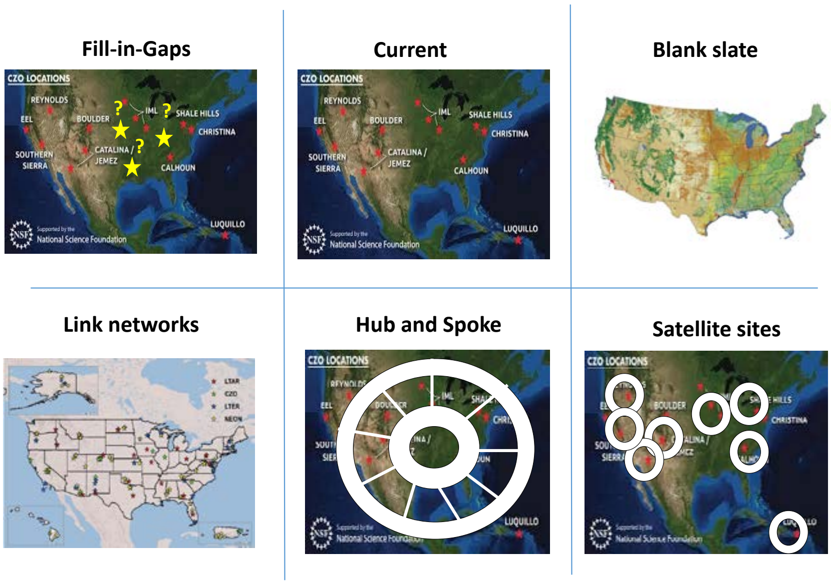

Figure 4. Possible conformations of a future CZO network.