OZCAR: The French Network of Critical Zone Observatories

J. Gaillardet, Isabelle Braud, F. Hankard, S. Anquetin, Olivier Bour, Nathalie Dorfliger, Jean-Raynald de Dreuzy, Sylvie Galle, C. Galy, Sébastien Gogo, et al.

▶ To cite this version:

J. Gaillardet, Isabelle Braud, F. Hankard, S. Anquetin, Olivier Bour, et al.. OZCAR: The French Network of Critical Zone Observatories. Vadose Zone Journal, 2018, 17 (1), pp.1-24. 10.2136/vzj2018.04.0067 . insu-01944414

HAL Id: insu-01944414
https://insu.hal.science/insu-01944414
Submitted on 4 Dec 2018

Special Section: Hydrological Observatories

OZCAR: The French Network of Critical Zone Observatories

J. Gaillardet,* I. Braud, F. Hankard, S. Anquetin, O. Bour, N. Dorfliger, J.R. de Dreuzy, S. Galle, C. Galy, S. Gogo, L. Gourcy, F. Habets, F. Laggoun, L. Longuevergne, T. Le Borgne, F. Naaim-Bouvet, G. Nord, V. Simonneaux, D. Six, T. Tallec, C. Valentin, G. Abril, P. Allemand, A. Arènes, B. Arfib, L. Arnaud, N. Arnaud, P. Arnaud, S. Audry, V. Bailly Comte, C. Batiot, A. Battais, H. Bellot, E. Bernard, C. Bertrand, H. Bessière, S. Binet, J. Bodin, X. Bodin, L. Boithias, J. Bouchez, B. Boudevillain, I. Bouzou Moussa, F. Branger, J. J. Braun, P. Brunet, B. Caceres, D. Calmels, B. Cappelaere, H. Celle-Jeanton, F. Chabaux, K. Chalikakis, C. Champollion, Y. Copard, C. Cotel, P. Davy, P. Deline, G. Delrieu, J. Demarty, C. Dessert, M. Dumont, C. Emblanch, J. Ezzahar, M. Estèves, V. Favier, M. Faucheux, N. Filizola, P. Flammarion, P. Floury, O. Fovet, M. Fournier, A. J. Francez, L. Gandois, C. Gascuel, E. Gayer, C. Genthon, M. F. Gérard, D. Gilbert, I. Gouttevin, M. Grippa, G. Gruau, A. Jardani, L. Jeanneau, J. L. Join, H. Jourde, F. Karbou, D. Labat, Y. Lagadeuc, E. Lajeunesse, R. Lastennet, W. Lavado, E. Lawin, T. Lebel, C. Le Bouteiller, C. Legout, Y. Lejeune, E. Le Meur, N. Le Moigne, J. Lions, A. Lucas, J. P. Malet, C. Marais-Sicre, J. C. Maréchal, C. Marlin, P. Martin, J. Martins, J. M. Martinez, N. Massei, A. Mauclerc, N. Mazzilli, J. Molénat, P. Moreira-Turcq, E. Mougin, S. Morin, J. Ndam Ngoupayou, G. Panthou, C. Peugeot, G. Picard, M. C. Pierret, G. Porel, A. Probst, J. L. Probst, A. Rabatel, D. Raclot, L. Ravanel, F. Rejiba, P. René, O. Ribolzi, J. Riotte, A. Rivière, H. Robain, L. Ruiz, J. M. Sanchez-Perez, W. Santini, S. Sauvage, P. Schoeneich, J. L. Seidel, M. Sekhar, O. Sengtaheuanghoung, N. Silvera, M. Steinmann, A. Soruco, G. Tallec, E. Thibert, D. Valdes Lao, C. Vincent, D. Viville, P. Wagnon, and R. Zitouna

The French critical zone initiative, called OZCAR (Observatoires de la Zone Critique–Application et Recherche or Critical Zone Observatories–Application and Research) is a National Research Infrastructure (RI). OZCAR-RI is a network of instrumented sites, bringing together 21 pre-existing research observatories monitoring different compartments of the zone situated between “the rock and the sky,” the Earth’s skin or critical zone (CZ), over the long term. These observatories are regionally based and have specific initial scientific questions, monitoring strategies, databases, and modeling activities. The diversity of OZCAR-RI observatories and sites is well representative of the heterogeneity of the CZ and of the scientific communities studying it. Despite this diversity, all OZCAR-RI sites share a main overarching mandate, which is to monitor, understand, and predict (“earthcast”) the fluxes of water and matter of the Earth’s near surface and how they will change in response to the “new climatic regime.” The vision for OZCAR strategic development aims at designing an open infrastructure, building a national CZ community able to share a systemic representation of the CZ , and educating a new generation of scientists more apt to tackle the wicked problem of the Anthropocene. OZCAR articulates around: (i) a set of common scientific questions and cross-cutting scientific activities using the wealth of OZCAR-RI observatories, (ii) an ambitious instrumental development program, and (iii) a better interaction between data and models to integrate the different time and spatial scales. Internationally, OZCAR-RI aims at strengthening the CZ community by providing a model of organization for pre-existing observatories and by offering CZ instrumented sites. OZCAR is one of two French mirrors of the European Strategy Forum on Research Infrastructure (eLTER-ESFRI) project.

Abbreviations: CZ, critical zone; CZO, critical zone observatory; LTER, long-term ecological research; RBV, Réseau des Bassins Versants; RI, Research Infrastructure.

Core Ideas

- OZCAR is a network of sites studying the critical zone.
- OZCAR covers various disciplines.
- OZCAR will help disciplines to work together for a better representation and modeling of the critical zone.

Received 2 Apr. 2018.
Accepted 2 Aug. 2018.
Supplemental material online.
*Corresponding author (gaillard@ipgp.fr).

Citation: Gaillardet, J., I. Braud, F. Hankard, S. Anquetin, O. Bour, N. Dorfliger, et al. 2018. OZCAR: The French network of critical zone observatories. Vadose Zone J. 17:180067. doi:10.2136/vzj2018.04.0067

Affiliations: J. Gaillardet, F. Hankard, J. Bouchez, C. Dessert, P. Floury, E. Gayer, E. Lajeunesse, and A. Lucas, IPGP, Sorbonne Paris Cité, Univ. Paris Diderot, CNRS, Paris 75231; I. Braud and F. Branger, IRSTEA, UR RiverLy, centre de Lyon-Villeurbanne, 69625 Villeurbanne, France; S. Anquetin, S. Galle, G. Nord, D. Six, L. Arnaud, B. Boudevillain, G. Delrieu, M. Estèves, V. Favier, C. Genthon, T. Lebel, C. Legout, E. Le Meur, J. Martins, G. Panthou, G. Picard, A. Rabatel, C. Vincent, and P. Wagnon, Univ. Grenoble Alpes, CNRS, IRD, Grenoble-INP, IGE, 38000 Grenoble, France; O. Bour, J.R. de Dreuzy, L. Longuevergne, T. Le Borgne, A. Battais, P. Davy, M.F. Gérard, G. Gruau, and L. Jeanneau, Géosciences Rennes, UMR 6118, CNRS, Univ. Rennes, 1 Rennes, France; N. Dorfliger, L. Gourcy, H. Bessière, J. Lions, and A. Mauclerc, BRGM, Water Environment and Ecotechnologies Division, Orléans, France; C. Galy, ANDRA Research and development division, 55290 Bure, France; S. Gogo, F. Laggoun, and S. Binet, UMR ISTO, CNRS, BRGM, Univ. d’Orléans, Orléans, France; D. Valdes Lao and F. Habets, UMR Métis, Sorbonne Univ., UPMC, CNRS, Paris 75252; F. Naaim-Bouvet, H. Bellot, C. Le Bouteiller and E. Thibert, Univ. Grenoble Alpes, Irstea, UR ETNA; C. Marais-Sicre, V. Simonneaux, and T. Tallec, Centre d’Etudes Spatiales de la Biosphère, Toulouse, France; C. Valentin, H. Robain, and N. Silvera, iEES-Paris, SU, USPC, UPEC, CNRS, INRA, IRD, F-93140 Bondy, France; G. Abril, UMR BOREA, MNHN, Paris; P. Allemand, Univ. de Lyon, UCBL, ENSL, CNRS, LGL-TPE, 69622 Villeurbanne, France; A. Arènes, Société d’Objets Cartographiques, Paris, France; B. Arfib, Aix Marseille Univ., CNRS, IRD, Coll France, CEREGE, Aix-en-Provence, France; N. Arnaud, CNRS INSU, Paris; P. Arnaud, IRSTEA, UR Recover, Aix en Provence, France;
(continued on next page)

S. Audry, L. Boithias, J.J. Braun, M. Grippa, D. Labat, J.M. Martinez, P. Moreira-Turcq, Y. Mougin, O. Ribolzi, J. Riotte, and W. Santini, Géosciences Environnement Toulouse (GET), CNRS, IRD, UPS, Toulouse, France; V. Bailly Comte and J.C. Maréchal, BRGM, D3E, NRE, 1039 rue de Pinville, 34000 Montpellier, France; C. Batiot, P. Brunet, B. Cappelaere, J. Demarty, H. Jourde, C. Peugot, and J.L. Seidel, Hydrosciences Montpellier (HSM), Univ. Montpellier, CNRS, IRD, Montpellier, France; E. Bernard, Univ. Franche-Comte, Théma, Besançon, France; C. Bertrand, H. Celle-Jeanton, D. Gilbert, and M. Steinmann, Univ. Bourgogne/Franche-Comté, CNRS, Chrono-environnement-UMR 6249, Besançon, France; J. Bodin and G. Porel, IC2MP, CNRS Univ. de Poitiers, Poitiers, France; X. Bodin, P. Deline, and L. Ravanel, Univ. Savoie, Edytem, le Bourget de Lac, France; I. Bouzou Moussa, Univ. Abdou Moumouni (UAM), Niamey, Niger; B. Caceres, INAMHI, Quito, Ecuador; D. Calmels and C. Marlin, GEOPS, Univ. Paris-Sud, CNRS, Univ. Paris-Saclay, Orsay, France; F. Chabaux, C. Cotel, M.C. Pierret, and D. Viville, UMR LHyGeS, EOST, Univ. de Strasbourg, Strasbourg, France; K. Chalikakis, C. Emblanch, and N. Mazzilli, UAPV, UMR1114 EMMAH, F-84914 Avignon, France; C. Champollion, Géosciences Montpellier, CNRS, Univ. Montpellier, UA, F-34095 Montpellier, France; Y. Copard, M. Fournier, A. Jardani, N. Le Moigne, N. Massei, and F. Rejiba, Normandie Univ, UNIROUEN, UNICAEN, CNRS, M2C, 76000 Rouen, France; M. Dumont, I. Gouttevin, F. Karbou, Y. Lejeune, and S. Morin, Météo-France–CNRS, CNRM UMR 3589, Centre d'Etudes de la Neige, Grenoble, France; J. Ezzahar, Ecole Nationale des Sciences Appliquées (ENSA), Univ. Cadi Ayyad, Safi, Morocco; M. Faucheux, O. Fovet, C. Gascuel, and L. Ruiz, UMR SAS, INRA, Agrocampus Ouest, Rennes, France; N. Filizola, Geography Dep., Amazonas State Univ. (UFAM), Manaus, Brazil; P. Flammarion, IRSTEA Présidence, Antony, France; A.J. Francez and Y. Lagadeuc, Univ. Rennes, CNRS, Ecobio–UMR 6553, F-35000 Rennes, France; J.L. Join, Univ. de la Réunion, Saint Denis de la Réunion, France; R. Lastennet, Univ. de Bordeaux, Laboratoire I2M, UMR 5295, France; W. Lavado, Peruvian National Service of Meteorology and Hydrology (SENAMHI), Lima, Peru; J.P. Malet, IPGS, EOST, Strasbourg, France; C. Marlin, Ministère de l'Enseignement Supérieur, la Recherche et l'Innovation, DGRI/SSRI, Paris; P. Martin, Univ. d'Avignon et des Pays de Vaucluse, UMR ESPACE 7300 du CNRS, 84029 Avignon, France; J. Molénat and D. Raclot, LISAH, Univ. Montpellier, INRA, IRD, Montpellier SupAgro, Montpellier, France; J. Ndam Ngoupayou, Dep. of Earth Sciences, Univ. of Yaoundé, Yaoundé, Cameroon; L. Gandois, A. Probst, J.L. Probst, J.M. Sanchez-Perez, and S. Sauvage, EcoLab, Univ. de Toulouse, CNRS, INPT, UPS, Toulouse, France; E. Lawin, Univ. d'Abomey Calavi, Benin; P. René, Association Moraine, Luchon, France; A. Rivière, Mines ParisTech, PSL, géosciences, Fontainebleau, France; P. Schoeneich, Univ. Grenoble Alpes, Pacte, Grenoble, France; M. Sekhar, Indian Institute of Science and Indo-French Cell for Water Sciences, Bangalore, India; O. Sengtaheuanghoung, Dep. of Agricultural Land Management (DALaM), Vientiane, Lao PDR; A. Soruco, UMSA, Univ. of La Paz, Bolivia; G. Tallec, IRSTEA, UR Hycar, 92 761 Antony, France; R. Zitouna, INRGREF, Tunis, Tunisia.

We have entered the Anthropocene (Crutzen, 2002), a new period in which human activities have become a geological force. Anthropogenic forcing affects many components of the Earth system (Steffen et al., 2015) at a particularly high rate compared with the last million years since *Homo sapiens* has lived on the planet. This "great acceleration" (Lewis and Maslin, 2015) has global manifestations, the great evidence of which is the shifts in atmospheric greenhouse gas concentrations and associated climate change, as well as accelerated land uses and land cover changes due to urbanization and increased human pressure on the environment. This "new climatic regime" is anticipated to have important implications at the regional scale, in the "territories," as defined by Latour (2018), where resources such as water, soil, and biodiversity may be dangerously impacted, potentially leading to an unprecedented degradation of human habitats, dramatic migrations, or economic disasters. The terrestrial surface, i.e. the zone located between the bedrock and the lower atmosphere, sustains basic human needs such as water, food, and energy (Banwart et al., 2013) and is critical for the sustainability of the ecosystem services they provide (Easterling, 2007; Millennium Ecosystem Assessment Board, 2005). Achieving the UN's Sustainable Development Goals (United Nations, 2015) requires better understanding and prediction of the functions of this "critical zone."

The term *critical zone* was defined by the US National Research Council as the zone extending from the top of the canopy down to the base of the groundwater zone. The National Research Council listed the study of the CZ as one of the basic research opportunities in the Earth sciences (National Research Council, 2001). The term *critical* emphasizes two notions. First is that the CZ is one of the main planetary interfaces of the Earth, i.e., the lithosphere–atmosphere boundary layer. It is the layer where life has developed, where nutrients are released from rocks, and on which ecosystems and food production rely. Almost by definition, the CZ is a planetary boundary, shaped by both solar energy and internally driven plate tectonics (mantle convection). This geological vision of the Earth's surface is close to that developed almost century ago in 1926 by Vladimir Vernadsky (Vernadsky, 1998), redefining the term *biosphere* to denote the part of our planet that is transformed by biogeochemical cycles triggered by the input of solar energy and by life processes. The second notion implied by the term *critical* is that we need to take care of it. The CZ is the human habitat in which we build our cities, from which we extract our food and our water, and where we release most of our wastes (Guo and Lin, 2016). As quoted by Latour (2014), "under stress, it may break down entirely or shift to another state."

The concept of the CZ offers a geological perspective on environmental questions by considering all transformation time scales from a million years to a second and by relocalizing environmental questions at the local or regional level, thus taking into account not only global forcing but also local geological, ecosystemic, economic, and societal constraints (Arènes et al., 2018). The CZ initiative aims at fostering the different scientific disciplines in the geosciences and biosciences (climatology, meteorology, glaciology, sciences of the cryosphere, snow and permafrost sciences, hydrometeorology, hydrology, hydrogeology, geochemistry, geomorphology, geophysics, land surface interactions, pedology, agronomy, ecology, and microbiology; Fig. 1) to work on the same questions and at developing an integrated system-oriented understanding of the habitable part of the planet (Brantley et al., 2017).

The Critical Zone Exploration Network (CZEN) initiative (http://www.czen.org/) was proposed in 2003 under the leadership of the US National Science Foundation (Anderson et al., 2004). The CZEN aims to create a worldwide community of researchers and educators who study the physical, chemical, and biological processes shaping and transforming the Earth's CZ through the development of critical zone observatories (CZOs), i.e. well-instrumented and well-characterized field sites in which the different scientific communities can collaborate to better understand the transformations affecting this thin veneer covering the Earth's surface. This integrated scientific approach must take into account

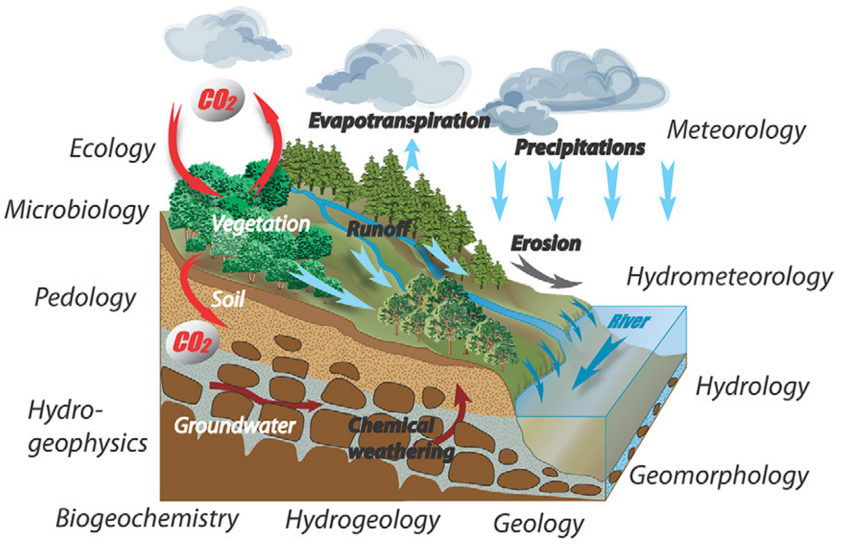


Fig. 1. The critical zone, shown here in particular at the catchment scale, is the thin porous layer at the surface of the Earth formed by the actions of water and acids on rocks. It is located between the lower atmosphere and unweathered bedrock and is strongly influenced by visible and invisible life activities. The integrated study of the critical zone relies on the collaboration of different scientific communities, listed non-exhaustively in italics.

short and long time scales and the interaction between deep subsurface processes and their coupling with aboveground dynamics.

So far there is no “official” definition for how a CZO should be designed. Multidisciplinary and systemic approaches (“the CZ as an entity”, Brantley et al., 2017) seem to be common denominators of all the so-called CZOs. In the United States, CZOs were first established in 2007 (Anderson et al., 2008; White et al., 2015) and presently feature nine instrumented sites, generally river catchments or a whole landscape of limited size (Brantley et al., 2017).

Following the US CZO initiative, several countries successfully launched CZO programs. Here we present the French critical zone initiative, called OZCAR (Observatoires de la Zone Critique—Application et Recherche, or Critical Zone Observatories—Application and Research), a National Research Infrastructure (RI). Our aim is to provide an overview of the OZCAR network, its objectives, components, scientific questions, and data management; the current status of instrumentation along with that of databases and metadatabases; and existing initiatives for linking data and models based on OZCAR data. The discussion builds on the current achievements to take a step forward and describe the ambitions of OZCAR and how this initiative can be related to others worldwide. Most of the ideas put forward here were discussed during the kickoff meeting of OZCAR held in Paris, 7 Feb. 2017.

Presentation of the OZCAR network

OZCAR, a Network of Networks

OZCAR is a RI launched in December 2015 with the support from the French Ministry of Higher Education, Research and Innovation. OZCAR gathers and organizes more than 100 research observation sites in 21 pre-existing observatories that are operated by diverse research institutions and initially created for a specific environmental question of societal relevance, some of them >40 yr ago. The details of OZCAR constitutive observatories and sites are provided in Supplemental Table S1. All these observatories share the same characteristic of being highly instrumented areas, however, designed to address a particular scientific and societal question of local importance, generating continuous standardized series of observations on water quality, discharge, ice and snow, soil erosion, piezometric levels, soil moisture, gas and energy exchange between ground and atmosphere, and ecosystem parameters (Supplemental Table S1). They cover different compartments of the CZ (Fig. 2).

During the last decade, considerable efforts have been made in France to encourage the various research institutions to join together to monitor Earth’s surface. This was enabled through the creation of the Alliance for Environmental studies AllEnvi (www.allenvi.fr) in 2010, formally gathering all the research institutions in charge of studying the Earth’s terrestrial surface.

The “Building Blocks” of OZCAR

Below, we present a short description of the architecture, aims, and significant results of the different blocks composing the OZCAR infrastructure that is organized according to seven thematic networks. A detailed description of the existing observatories and their most significant scientific achievements are given in Appendix 1 in the Supplemental Material.

The Réseau des Bassins Versants Network

The Réseau des Bassins Versants network (RBV) comprises catchments ranging from zero-order basins to the whole Amazon River system (see Supplemental Table S1 for details about site location, climate, geology, land use, main scientific questions, and measured variables). A number of them are shared with research institutions from Southern Hemisphere countries. The common denominator is the use of catchments as integrators of hydrological, biogeochemical, or solid transport processes at different scales. They constitute sentinels of land use–land cover and climate change at the regional level, some of them for >40 yr. They have all been designed to address a specific basic or applied scientific question, span climate gradients ranging from the

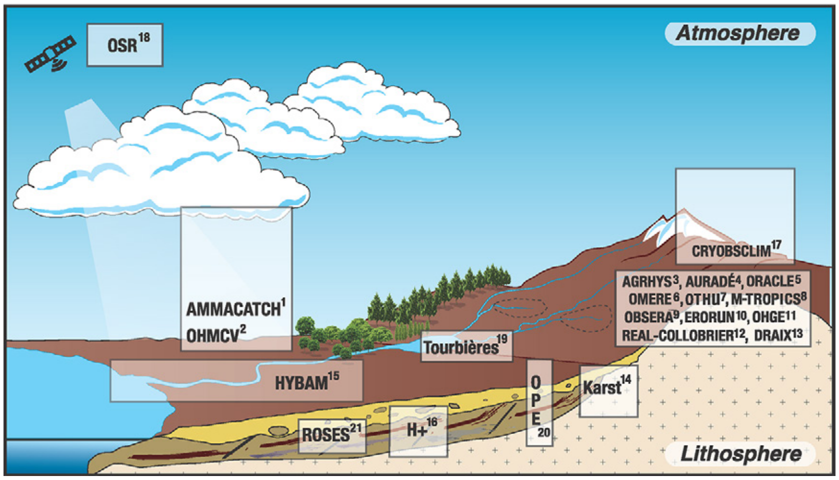


Fig. 2. Location of the different OZCAR-RI observatories on a land-to-sea continuum. Each acronym corresponds to a long-term observatory (primarily defined by a scientific question) and may be constituted of several instrumented sites. The superscript numbers correspond to the list of different observatories in Supplemental Table S1.

tropics to the temperate zone, and cover a range of bedrock types (Fig. 3). While some of them can be considered as "pristine," most of the RBV catchments are intensively cultivated or managed for forestry, the extreme case being a peri-urban catchment draining into the Rhône River in Lyon. Well represented in the RBV are monitored karst systems as complex hydrogeologic entities that are characterized by strong surface–subsurface interactions and significant water, mass, energy, and geochemical transport within the CZ (see Jourde et al. [2018] on that network). The RBV also addresses larger scale (typically continental issues such as the concurrent role of climate and land-use changes in the water and energy budgets on the terrestrial surface in western Africa, continental hydrology and the biogeochemistry of the Amazon, Orinoco, and Congo basins, or the genesis of extreme precipitation events and flash floods in southern France). The long-term monitoring reveals fast-changing environments, as illustrated for instance by the decrease of sulfate recorded in the Strengbach stream since 1986 (Réseau des Bassins Versants,

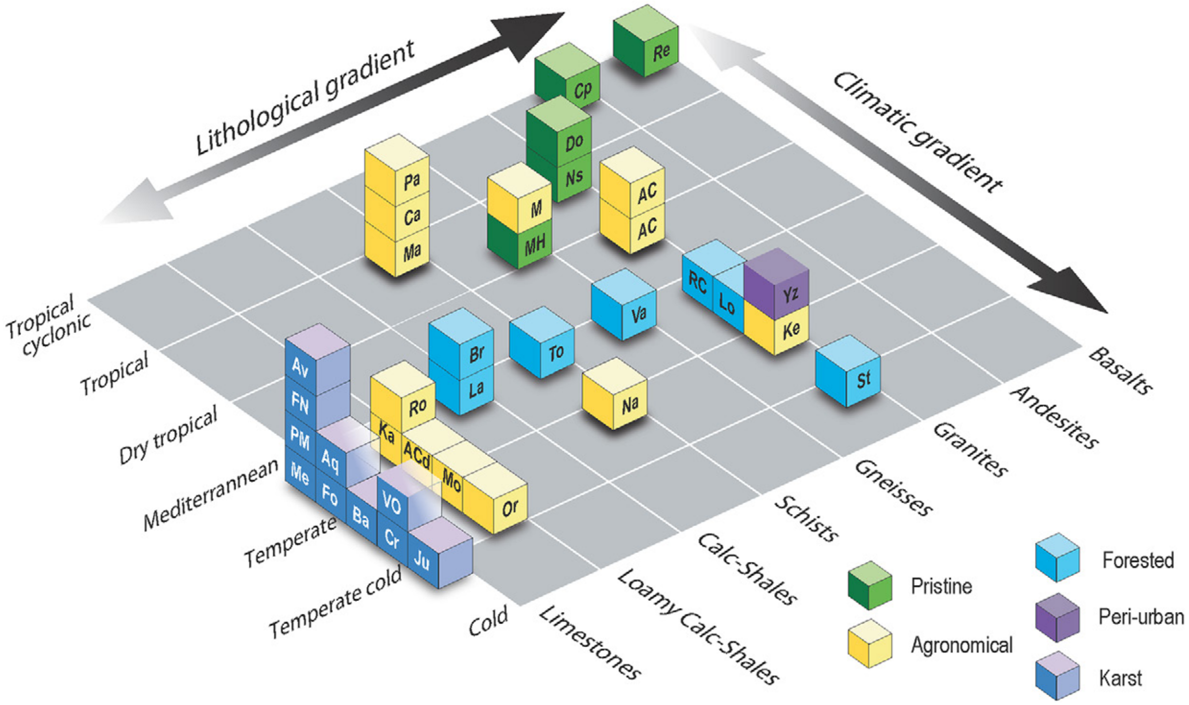


Fig. 3. River catchment sites (the cubes) from OZCAR plotted according to the climatic and lithological gradients, noted with land use types. This diagram shows the range of environmental conditions covered by OZCAR and illustrates the theoretical idea that spatial gradients can be used to predict the temporal evolution of the critical zone (e.g. predicting the effect of climate change at constant rock type). Heterogeneity and sensitivity to initial conditions are limitations to this approach. Site names refer to Supplemental Table S1: AC, AmmaCatch; ACd, Auzon-Claduène; Aq, karst from Aquitaine; Av, Avène; Ba, Baget; Br, Brusquet; Ca, Dong Cao; Cp, Capesterre; Cr, Craie; Do, Donga; FN, Fontaine de Nîmes; Fo, Fontaine de Vaucluse; Ju, Jurassic karst; Ka, Kamech; Ke, Kerien; La, Laval; Lo, Lozère; M, Madiri; Ma, Huay Ma Nai; Me, Medycyss; Mo, Montoussé; MH, Mule Hole; Na, Naizin; NS, Nsimi; Or, Orgeval; Pa, Houay Pano; PM, Port Miou; RC, Real-Collobrier; Re, Réunion Island; Ro, Roujan; St, Strengbach; To, Tourgueille; Va, Valescure; VO, Val d'Orléans; and Yz, Yzeron.

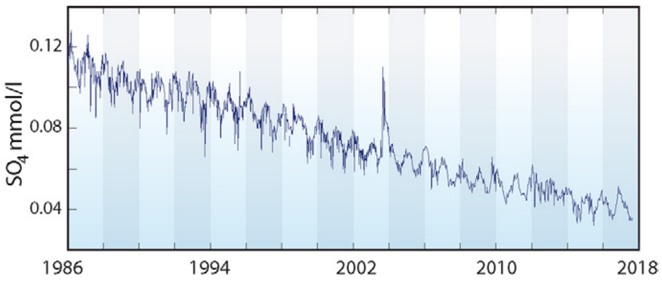


Fig. 4. The 32-yr evolution of the sulfate ion concentration in the stream of the Strengbach catchment (OHGE observatory) showing the wealth of information provided by long-term data series. The overall trend shows a decrease in sulfate concentration due to the decrease in industrial emissions in Western Europe during the period. Superimposed are seasonal variations and abrupt short-term changes.

OHGE site, Vosges, France; Fig. 4). This decrease of sulfate in the stream is an iconic case showing the virtue of continuous long-term river monitoring and the reduction of anthropogenic acidic emissions by European and North American industries since the 1980s.

The H+ Observation Service

The H+ observation service (hplus.ore.fr), created in 2002, is a network of hydrogeological sites located in France and India, aimed at characterizing and modeling flows, transport and reactivity in heterogeneous aquifers. The aim of H+ is the development of characterization and modeling methods adapted to describe the strong heterogeneity (i.e., in terms of permeability and thus residence times) that characterizes the deep CZ. Within this framework, H+ scientists investigate the hydrological functioning and the reactive transport aspects in heterogeneous reservoirs, including karstic aquifers (Larzac, HES Poitiers, LSBB, Mallorca), altered fractured systems (Choutuppal, India, Ploemeur), and alluvial systems (Auverwatch). H+ observatories have particularly developed a specific hydrogeophysical and hydrochemical instrumentation approach for imaging and characterizing the hydrodynamics and transport processes, for measuring residence time distributions, but also for taking into account heterogeneity within appropriate predictive models.

The CRYOBS-CLIM Observatory

The CRYOBS-CLIM (The CRYopshere: a CLIMate OBServatory) observatory focuses on the cryosphere. It addresses the following scientific questions:

1. How is climate change impacting surface energy and mass balance of snow- and ice-covered surfaces and permafrost ground temperature at different spatial (local to regional) and temporal (seasonal to multidecadal) scales?
2. How will snow and climate feedback mechanisms enhance or attenuate glacier, ice sheet, and permafrost changes in the near future? How can observations help to identify climate model weaknesses and to improve the simulations of cryosphere components?
3. What is the future snow and ice-cover retreat and wastage and what will be the impact on water resources and sea level rise?
4. How do seasonal snow, glaciers, rock glaciers, and ice sheet dynamics respond to changes in temperature, surface mass balance, and hydrological processes and what are the impacts in terms of natural hazards?

In order to address these questions, the CRYOBS-CLIM network collects, archives, and disseminates a comprehensive and consistent set of observations on the main components of the terrestrial cryosphere (glaciers, snow, permafrost) in a series of instrumented sites located at high altitudes and high latitudes (European Alps, tropical Andes, Himalayas, Antarctica, Svalbard). The monitored variables and research topics are described in Supplemental Table S1.

The Tourbières Observatory

The Tourbières (Peatland) Observatory is a network of four French instrumented sites and one Siberian mire aimed at studying the effect of global change on the C sink function and the hydrological budget of temperate and subboreal peatlands, which are ecosystems containing a third of the global surface C stock in an area accounting for only 3 to 5% of the land surface. The French sites were set up in 2008 to 2010 according to a climatic gradient (lowland to mountain climate) to ensure long-term monitoring of greenhouse gases (CO_2, CH_4, H_2O, and N_2O), dissolved and particulate organic C (DOC and POC) fluxes as well as environmental variables that impact greenhouse gases and DOC and POC fluxes, and to generate interoperable databases.

The Regional Spatial Observatory

The Regional Spatial Observatory (OSR) is documenting the long-term effects of climate change and increasing anthropogenic pressures on the hydrologic and agro-ecologic evolution of agricultural regions, at various spatial and temporal scales, in a perspective for sustainable management of water and soil resources. The OSR concept is implemented in two sites located in southwestern France and in Morocco (Tensift Basin). The specific OSR approach is the extensive use of remote sensing for surface characterization (land use, vegetation cover, evapotranspiration, soil moisture, snow cover, etc.) combined with a multiscale monitoring network of (i) continuous long-term monitoring of experimental plots (crop and snow sites), (ii) hundreds of plots annually monitored for surface state, land cover, etc., and (iii) experiments conducted at the catchment scale with reinforced observations for water and energy budget evaluation.

The ROSES Observatory Network

The ROSES (observatory network for groundwater systems at the French national level) was initially set up to answer water management issues and was strengthened in the framework of the implementation of the European Water Directive. It gathers more than 77,000 stations, with 74,000 groundwater quality monitoring stations and 4400 monitoring wells. All types of aquifers are monitored in metropolitan territories as well as French overseas territories. All data are stored within the ADES database (http://www.ades.eaufrance.fr) managed by several governmental agencies.

The Long-Lasting Observatory of the Environment

The Long-lasting Observatory of the Environment (OPE) focuses on a landscape in the eastern part of the Paris Basin (a few hundred square kilometers) around the preselected site as the French deep geological repository of high-level and intermediate-level long-lived radioactive wastes. The OPE currently comprises a monitoring network covering forest and agricultural areas and measuring atmospheric, meteorological, soil, surface and groundwater, land use, and biodiversity indicators, providing a unique opportunity to document the interactions between human activities and the CZ around an industrial project scheduled to run >100 yr (if accepted).

Exploring the Critical Zone with OZCAR Observatories

As shown in the above brief overview, OZCAR is a network of networks consisting of highly instrumented sites: individual, nested or paired catchments, hydrogeological sites, plots, glaciers, and lakes that are each monitored for a given set of parameters according to the specific disciplinary question under which they have been designed. Supplemental Table S1 shows that the current situation is quite diverse in terms of monitored CZ compartments and scales and of measured variables. This diversity not only reflects the heterogeneity of the CZ but also the span of scientific questions and communities and, in turn, the diversity of institutional environmental research. The disciplines represented in the OZCAR are hydrology, hydrogeology, biogeochemistry, agronomy, pedology, glaciology, meteorology, climatology, and cryospheric sciences (glaciology, snow and permafrost sciences).

As shown in Fig. 5 and Supplemental Table S1, the OZCAR sites are located all around the world. In France, they include sites in overseas territories like the tropical Caribbean, Reunion Island, and Antarctica. OZCAR sites also exist in 18 other countries through partnerships between the French Research Institute for Sustainable Development (IRD) and national research institutions from other countries (North Africa, West Africa, Southeast Asia, India, Antarctica, and Amazonian, Andean, Arctic, and Himalayan nations). The sites then cover a large range of climates (oceanic, continental, mountainous, Mediterranean, tropical, polar), lithologies (granites, schists, volcanic rocks, limestone, and sedimentary basins) and land use–land cover (tropical, Mediterranean, mountainous forest, more or less intensive agriculture, peatland, urbanized areas, snow- and ice-covered areas). All sites have experienced several centuries, if not millennia, of land management for agricultural practices, especially in the continental part of France and in North Africa. Although focused on diverse scientific questions and variables, all OZCAR observatories and sites can be considered as sharing the main overarching goal, which is how to monitor, describe, and simulate the CZ evolution of a changing planet (climate change, land use changes, changes in practices).

Instrumentation in OZCAR

All observatories integrated into OZCAR are highly instrumented. They have in common standard field meteorological stations recording precipitation (liquid or solid), radiation, air temperature and humidity, wind velocity and direction, and atmospheric pressure. Hydrometeorological observatories use radars, rain gauge networks, and disdrometers to provide accurate estimates of rainfall fields (e.g., Boudevillain et al., 2016). In the case of glaciers and snow observatories, conventional meteorological observations are complemented by field and remote monitoring of snow- and ice-related variables such as the snow water equivalent (SWE), surface specific area, runoff and albedo, or ground temperature, etc. The height and extent of the snow surface are measured by various means (ultrasonic snow depth sensors, photogrammetry, lidar, radar, unmanned areal vehicle, and satellite) for all sites. Specific measurements of the cryosphere also include cosmic ray counts for SWE measurements (Morin et al., 2012), snow particle counter for drifting snow flux measurements (Trouvilliez et al., 2014), high spatial and temporal resolution spectroradiometer for monitoring surface albedo, or radar and seismic methods for mapping bedrock. Observatories focusing on the exchange of energy and matter between the ground and the lower atmosphere (including those on glaciers) are equipped with eddy covariance towers or manual and automatic accumulation chambers producing high-resolution measurements.

Water discharge is measured at standardized gauging stations with high-resolution recording by water level sensors of different types (floats, pressure sensors, radar sensors or ultrasound, Nilometer digital scales). For gauging flood discharge, non-contact methods have been developed and evaluated: surface radar, large-scale particle image velocimetry (LS-PIV) based on images from fixed cameras or videos on YouTube (Dramais et al., 2014; Welber et al., 2016; Le Boursicaud et al., 2016). For large rivers, satellite data or acoustic Doppler current profiler surveys are used (e.g., Mangiarotti et al., 2013; Paris et al., 2016).

Groundwater levels are monitored using pressure transducers. Depending on the process of interest (hydrological cycle, tides, barometric effect, earthquakes), the frequency of measurements varies from one per day to 1 Hz or even greater. These conventional measurements are complemented using multiparameter probes and sampling to analyze major chemical elements and isotopic ratios using a wide range of natural and anthropogenic tracers for water residence time (Leray et al., 2012; Celle-Jeanton et al., 2014). The use of heat as a groundwater tracer is currently being tested on several H+ sites (Chatelier et al., 2011; Klepikova et al., 2014). Precise borehole sampling and monitoring is achieved through multipacker systems, well nests, or well clusters.

The unsaturated zone is less frequently instrumented, usually by soil moisture probes (time-domain reflectometry sensors) and

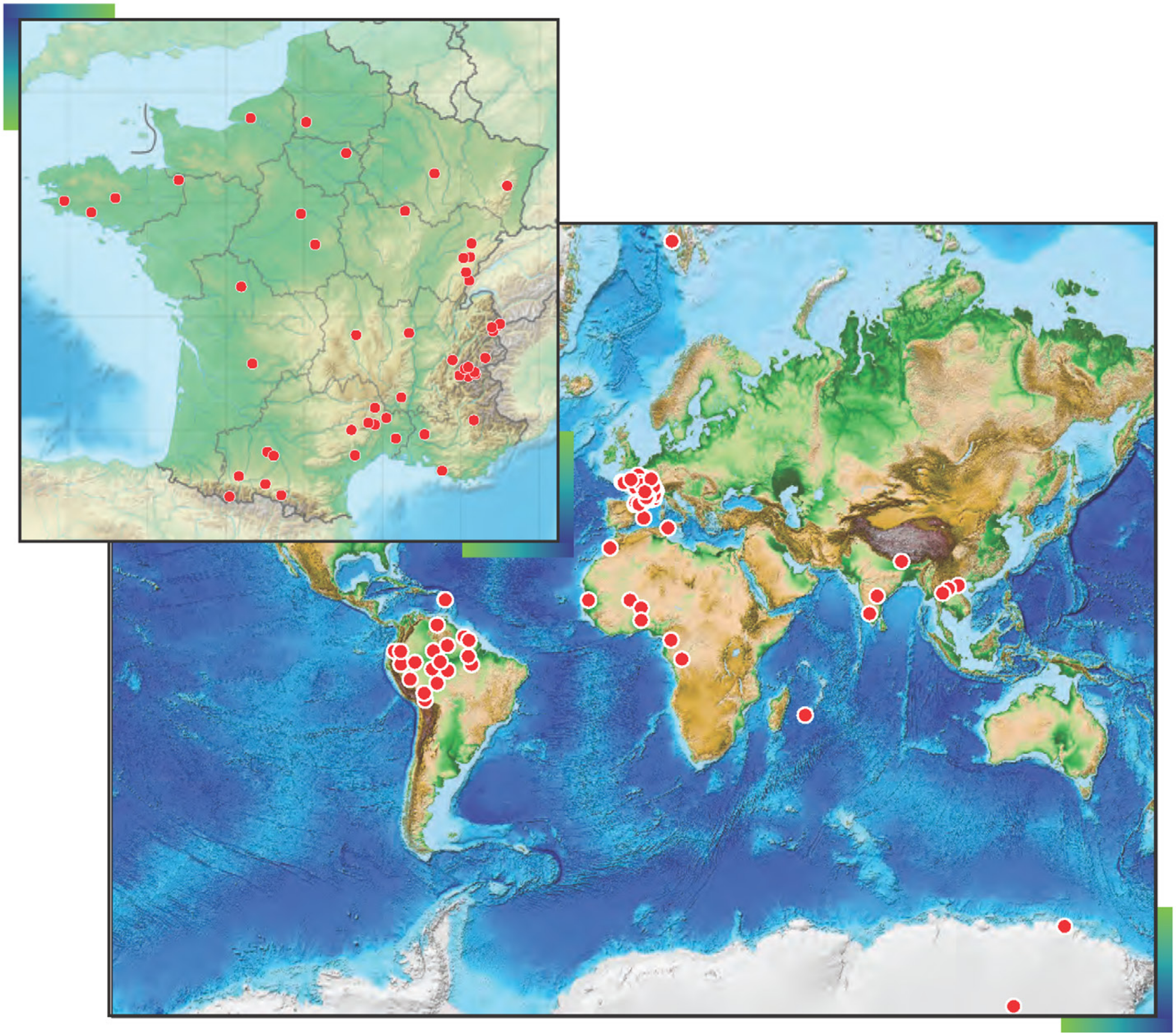


Fig. 5. World map of OZCAR instrumented sites. More than 60 instrumented sites (with scales ranging from the plot to the whole river catchment) are included in 21 observatories or observation services (not represented) funded and evaluated by diverse research agencies. All are monitoring parts of the critical zone.

lysimeters allowing soil solution sampling (i.e., OHGE or OPE). Chemical analyses of river water and suspended matter are usually performed on discrete samples collected in the field manually or by automatic remotely controlled samplers or triggered to water level or turbidity thresholds, therefore allowing the capture of extreme flood events. Only a limited number of chemical variables are measured in OZCAR at a high frequency using commercial probes (conductivity, water temperature, dissolved organic matter with fluorimeter, and nutrients). Suspended matter concentration is also indirectly recorded continuously at a number of sites using turbidimeters. At the OPE, significant efforts have been made to develop in situ chemical probes to expand our present ability for high-frequency chemical monitoring.

This brief overview of the in situ instrumentation in OZCAR shows a large variety of measurements, sensor types, and frequencies of analysis, as well as the absence of standardization. Different sub-networks within OZCAR have, however, established common measurement protocols. This is possible when relatively similar (homogeneous) environmental settings are studied (like peatlands, hydrogeological sites, glaciers, permafrost sites) but remains challenging for catchments of very different size or at sites studied from the perspective of different disciplines, each having different scientific conceptual views. As a community effort, the RBV network (catchment approach) agreed upon a set of common variables that should be measured in all observatories, meant to describe the CZ at the catchment scale. The main difficulty of this exercise lies in the fact that all the required disciplinary skills rarely exist in individual observatories. However, the advantage of networking is that these disciplinary skills can be shared at the network level. Table 1 shows the list of the 24 common parameters agreed upon and measured in small-order catchments of OZCAR. The variables cover all the measurable compartments of the CZ and are thought to be the best compromise among the cost of measurements, the ease of implementation, and their scientific relevance.

In 2011, the two networks RBV and H+ launched CRITEX, a program funded (2012–2020) by the French Government (Equipex program) for developing innovative instruments to monitor the CZ. The overall goal of CRITEX (challenging equipment for the temporal and spatial exploration of the critical zone at the catchment scale) was to build a shared and centralized instrument facility for the long-term monitoring and exploration of the CZ complementing and outperforming the existing site-specific equipment of the RBV and H+ networks. The instruments proposed in CRITEX (Fig. 6) can be grouped into three categories: "state-of-the-practice," "state-of-the-research," and "state-of-the-science" (Robinson et al. (2008). The "state-of-the-practice" instruments in CRITEX are well-established techniques that are classically used to characterize the CZ (seismic and electric resistivity techniques, flux towers, groundwater well equipment). They are typically used to characterize the OZCAR CZOs. The "state-of-the-science" instruments are innovative and emerging (scintillometry, hydrogravimetry, hydrogeodesy, optical fiber sensors, unmanned aerial vehicle exploration, self-potential and spectral-induced polarization electrical methods, isotopic tracing, reactive and inert gas tracer experiments). Examples of such instrument development by the CRITEX community were given by Read et al. (2014) on the use of fiber optic distributed temperature-sensing down boreholes, Pasquet et al. (2015) for the coupling between P and S wave velocities, Schuite et al. (2015) for the use of ground surface deformation for deducing the properties of fractured aquifers, Chatton et al. (2017) for the use of continuous flow membrane inlet mass spectrometry (CF-MIMS) to monitor in situ N_2, O_2, CO_2, CH_4, N_2O, H_2, He, Ne, Ar, Kr, and Xe at high frequency (one measure every 1.5 s) for exploring the CZ, and Mazzilli et al. (2016) for the use of magnetic resonance sounding (MRS) in karst aquifers to identify the presence of water and to reconstruct seasonal variations of water within the unsaturated zone. Finally, the "state-of-the-research" instruments are not commercially available yet and have been developed as prototypes or instrumental platforms (marked by a star in Fig. 6) through academic and industrial collaboration. Such instruments include a μ-wave scintillometer for determining latent heat fluxes in catchments over 1-km distances; the development of a soil moisture sensor determining soil permittivity and bulk soil conductivity based on the soil dielectric properties (Chavanne and Frangi, 2014); integrative sensors based on Diffusive Gradient in Thin Film properties to measure U, Sr, Nd, and Ni isotopes; the passive DIAPASON system deployed in groundwater for isotope tracing (Gal et al., 2017), and the development of a new MRS system for the unsaturated zone (Legchenko et al., 2016). Different platforms were also developed in CRITEX. For example, the hydrosedimentary platform RIPLE is specifically designed for extreme flood monitoring of mountainous rivers measuring water, fine and coarse sediment fluxes every 10 min (Michielin et al., 2017). The River Lab is a CRITEX prototype set up on a "lab-in-the-field" concept, measuring the chemical composition (major elements) of the river every 30 min (Floury et al., 2017). Finally, the River Truck is a mobile laboratory equipped with instruments for continuous measurement of the concentration of dissolved gas (CF-MIMS) and major elements, to be deployed during hot moments in the field. More information on CRITEX is available at http://www.critex.fr.

Table 1. The 24 variables measured in common in the catchments of the Réseau des Bassins Versants network grouped by the different considered compartments. The frequency of the measurement is not fixed but depends on the characteristic timescales.

No.	Variable
	Atmosphere
1	Rainfall amount
2	Air temperature
3	Wind velocity
4	Wind direction
5	Air pressure
6	Air humidity
7	Radiation
8	Chemical composition of rain
9	O and H isotopic composition of rainwater
	River
10	Discharge
11	Electrical conductivity
12	Water temperature
13	Turbidity
14	Suspended sediment concentration
15	Chemical composition of water
16	O and H isotopic composition of river water
	Groundwater
17	Soil moisture content
18	Groundwater level
19	Electrical conductivity of groundwater
20	Temperature of groundwater
21	Chemical composition of groundwater
22	O and H isotopic composition of groundwater
	Surfaces
23	Land use/land cover
24	Chemical composition of agricultural inputs

Significant instrumentation efforts have also been achieved by the French cryosphere community. POSSSUM (Profile of Snow Specific Surface Area Measurement Using Shortwave Infrared Reflectance) is an instrument that measures the specific surface area (a measure of the grain size) profile in snow boreholes with a

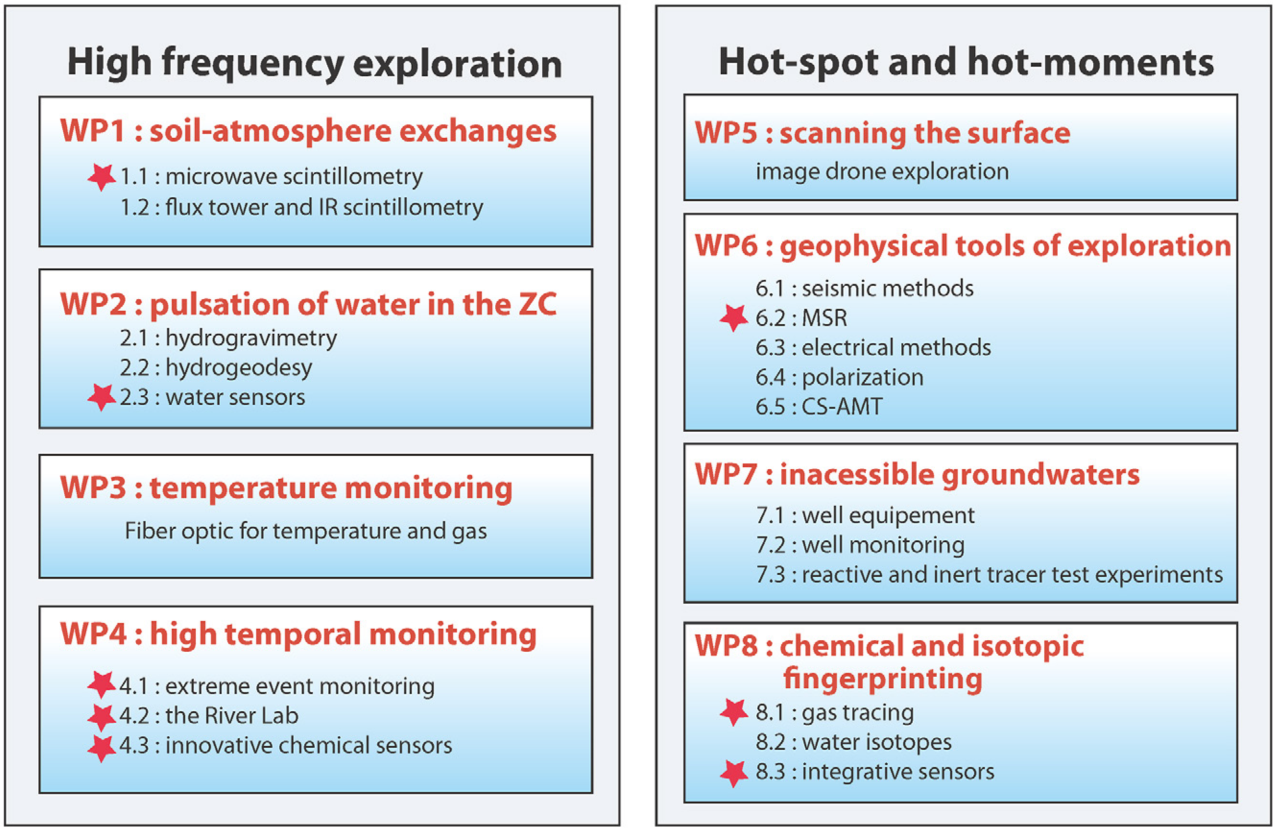


Fig. 6. Overview of the CRITEX program (2012–2020) with the list of the work packages and associated instrumentation. The red stars correspond to "state-of-the-science" instruments developed as prototypes in CRITEX. CRITEX instruments are organized for tackling two scientific objectives: (i) high-frequency monitoring in the critical zone (at the interface with the atmosphere, in the subsurface, and at the outlet of catchments) and (ii) multidisciplinary monitoring of "hotspots" and during "hot moments" of the critical zone.

vertical resolution of 1 cm and down to the 20-m depth (Arnaud et al., 2011). RLS (Rugged Laser Scan) is an automatic laser scan designed to work in Antarctica that scans an area of 150 m^2 every day and allows monitoring of the snow accumulation, roughness change, sastrugi dynamics, and more (Picard et al., 2016a). Solexs is an optical instrument for the measurement of irradiance profiles in snow, which can be related to snow microstructure and ice absorption (Picard et al. 2016b).

Databases and Metadatabases in OZCAR

In order to comply with the public data policy, a mandatory condition for recurrent funding, most of the OZCAR observatories developed data and/or metadata portals where data can be accessed and sometimes downloaded. All portals in OZCAR provide research data with the exception of the ADES portal (http://www.ades.eaufrance.fr/), which provides monitoring information about groundwater level and quality for the whole French territory and was primarily designed for operational use.

A critical analysis of the portals reveals a large heterogeneity in practices in OZCAR: (i) free access vs. access through login/password or no access; (ii) type of data that are provided: metadata only vs. possible downloading of the data; raw data vs. corrected data or more elaborate products including simulation results; (iii) access through information system and GIS interfaces, including sometimes visualization tools, vs. access to files or to ftp files; (iv) data formats and storage: relational databases vs. file repositories; (v) granularity of a dataset (e.g., one rain gauge or all the data collected within one catchment); (vi) level of information provided in the metadata. More specific information on the diversity of current practices in OZCAR is given in Appendix 2 of the Supplemental Material (Supplemental Table S2).

In terms of metadata provision, the RBV metadata catalog (http://portailrbv.sedoo.fr/#WelcomePlace; André et al., 2015) is a common initiative for providing visibility to the data collected within the RBV. It follows the INSPIRE (INfrastructure for SPatial InfoRmation in Europe, http://inspire.ec.europa.eu/) norms and can harvest existing sites when the latter are compliant. For the other portals, a manual system was proposed to feed the metadata. The usefulness of the data portal remains limited, however, because currently the definition of the granularity of datasets is heterogeneous; metadata that are not automatically harvested are quickly obsolete; and metadata documentation is incomplete, implying that access to the data portals is not granted. One particular ambition of OZCAR is to improve data accessibility and interoperability, building on the experience of the scientific teams involved in the network (see below).

Linking Data and Critical Zone Models within OZCAR

Here we review the different modeling initiatives developed by the various scientific communities gathered in OZCAR. Surprisingly, despite the wide disciplinary spectrum found in OZCAR, common trends can be depicted and observed at the international scale. Classically, models in OZCAR can be classified into process understanding, system understanding, and management and/or prediction purposes (Baatz et al., 2018).

All scientific communities in OZCAR have developed or used simple models for identifying and understanding CZ processes at different scales in their observatories. Models are built in order to interpret the collected data, but data can also question existing representations, in particular when new sensors or increased resolution are available. Process identification is performed by each discipline using mechanistic or physically based models deployed usually at small scales (plot to small catchment scale) that intend to represent process complexity using (partial) differential equations and describing the medium heterogeneity. Examples of studies linking data and models conducted in the different OZCAR observatories are shown in Supplemental Table S3. In situ, long-term data as well as experimentation or laboratory experiments are used to test these mechanistic models. For instance in H+, Klepikova et al. (2016) showed how a series of thermal push–pull tests efficiently complement solute tracers to infer fracture aperture and geometry by inverse modeling and better describe aquifer heterogeneity.

Once elementary processes are identified, they can be combined in more or less integrated models to provide a representation of system functioning. Several disciplines and/or compartments of the CZ are involved at larger spatial scales (e.g., small to medium catchments) and are generally addressed. Process representations are often simplified (i.e., process-based models with approaches such as reservoir models) compared with models deployed for process understanding, because they must cope with a larger degree of heterogeneity. A model calibrated with in situ data is thus a powerful tool to extend the knowledge acquired at local sites both in space and time (see examples in Supplemental Table S3). Sensitivity analysis can also help to identify functioning hypotheses that are the most consistent with observations by varying model parameters or comparing different process representations. The AMMA-CATCH observatory, in collaboration with African researchers, gives a good example of this effort. In the Ara catchment (10 km^2), observations of surface fluxes, soil moisture, and groundwater monitoring as well as geochemical and geophysical data and gravimetric measurements (Fig. 7) showed that water uptake by deep-rooted trees is the main driver of groundwater discharge in the dry season (Richard et al., 2013; Hector et al., 2015). The mechanistic ParFlow-CLM model (Maxwell and Miller, 2005), incorporating the identified processes, was chosen to reproduce the observed functioning (Hector et al., 2018).

Finally, a significant number of approaches developed in the OZCAR observatories are motivated by societal challenges such as a better estimation of sea level rise, the prediction of natural risks (floods, droughts, erosion, snow and ice avalanches, contamination, etc.), water resources management, carbon storage, and other ecosystem functions. The models used for management and prediction purposes are usually inspired by those developed for system understanding and are generally simplified to represent the main active processes and to be used operationally and/or in real time due to computational time constraints and to lower data availability. For instance, Crocus (Brun et al., 1992), a numerical model used to simulate snow cover stratigraphy, and the blowing snow scheme SYTRON (Vionnet et al., 2018) were initially tested using field experiments (Col de Porte and Col du Lac Blanc, CRYOBS-CLIM [The CRYospere: a CLIMate OBServatory]). They are incorporated into the French operational chain for avalanche hazard forecasting. Other examples are provided in Supplemental Table S3.

Model integration and coupling between compartments of the CZ requires the development of dedicated tools. Modeling platforms allowing the building of models from available components and for managing exchanges of variables and fluxes between components have been successfully developed in OZCAR, mainly by the hydrological community. KARSTMOD (http://www.sokarst.org/index.asp?menu=karstmod) was specifically designed to represent karstic aquifers and provides flexibility to build reservoir-based models of various complexity (Mazzilli et al., 2017). LIQUID (Branger et al., 2010) was designed to represent the heterogeneity of land surfaces using an object-oriented approach (explicitly representing landscape objects). It was used to address different scientific questions related to the impact of urbanization on water flow (Jankowfsky et al., 2014; OTHU/Yzeron observatory) or flash flood understanding (Vannier et al., 2016; OHM-CV observatory). OpenFLUID (Fabre et al., 2013) was developed in OZCAR to improve the spatial modeling of landscapes dynamics and was successfully used to combine the MHYDAS (Moussa et al., 2002) distributed hydrological model, along with an extension to couple runoff and erosion (Gumiere et al., 2011). Other initiatives have addressed the automation of time-consuming activities such as pre- and post-processing (Lagacherie et al. [2010] for agricultural catchments or Sanzana et al. [2017] for peri-urban catchments) or visualization and analysis of the simulation results (Anquetin et al., 2014).

Discussion

OZCAR organizes pre-existing observatories and well-established communities, supported by diverse funding institutions that have their own vocabularies and representations of the CZ and are working at different timescales. This diversity mimics the physical and ecological heterogeneity of the CZ inherited from the geological and climatic histories at the local scale.

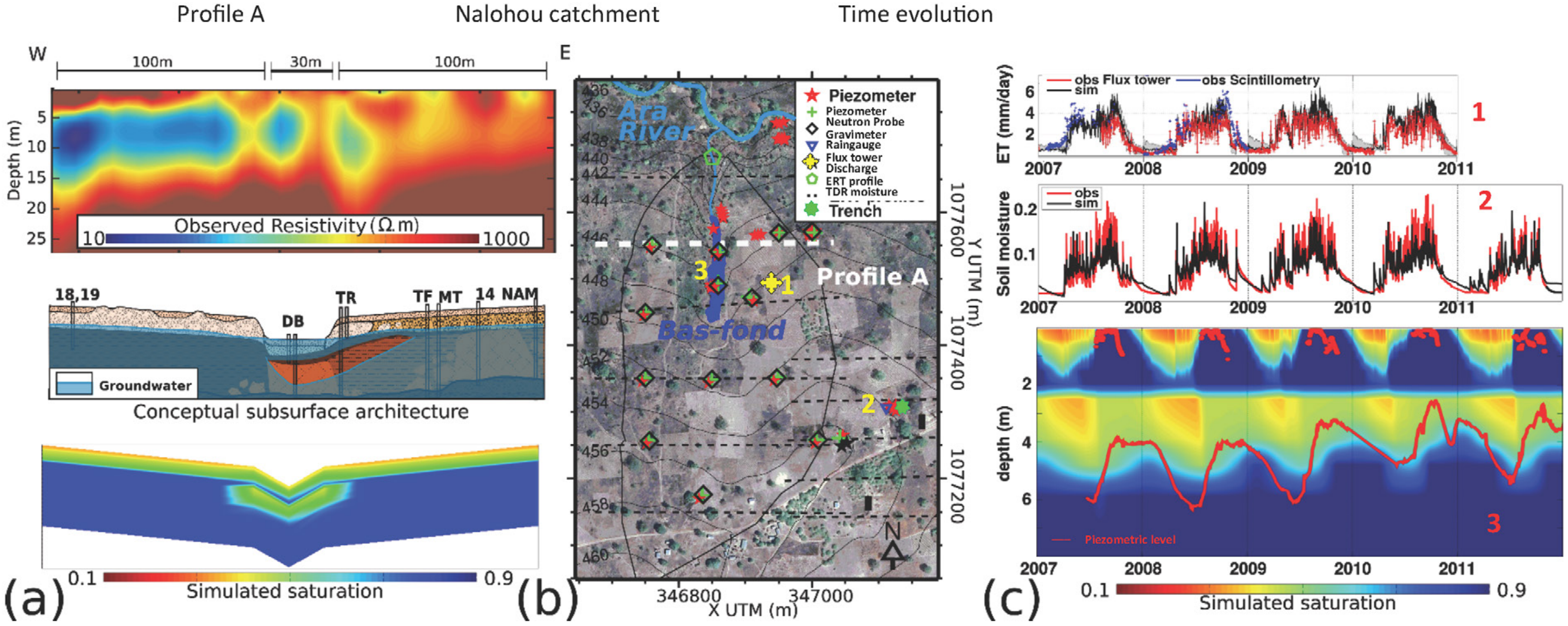


Fig. 7. Simulation of the hydrological cycle components in the Nalohou catchment (AMMA-CATCH Benin observatory) using the ParFlow-CLM critical zone model, which was set up based on observations and previous understanding of the processes and is run without any calibration: (a) constructing the model from observations: geophysical exploration using electrical resistivity tomography (ERT, top) contributes to define the conceptual subsurface architecture, which is implemented in ParFlow (middle) (adapted from Hector et al., 2015), with simulated saturation along Profile A in (b) (bottom); (b) map of the Nalohou catchment (0.16 km^2) with topographic elevation, instrumentation, ERT profile locations (adapted from Hector et al., (2015), and Profile A (dashed white line); (c) simulated and observed critical zone variables: evapotranspiration (ET) at Point 1 in (b), surface soil moisture at 5 cm at Point 2 in (b), and saturation, permanent and perched water tables in the inland valley (bas-fond) (red) at Point 3 in (b) (adapted from Hector et al., 2018).

OZCAR was designed in order to allow the defragmentation of the CZ community at the national scale. Ambitious actions are promoted by OZCAR that should enable the CZ community to progress toward a better integration of scientific questions, data, instruments, and models are presented. Visions of the internal organization of the network and its involvements in international initiatives are also discussed here.

OZCAR Challenging Scientific Questions

Underlying the broad diversity of the disciplines, measured parameters and models encountered throughout OZCAR sites are common, overarching scientific questions that serve to provide fundamental insight into the inner dynamics of the CZ. These grand scientific questions can be separated into three principal topics: (i) the "dynamic architecture" of the CZ; (ii) processes and fluxes that shape the CZ; and (iii) CZ feedbacks and responses to perturbations (Fig. 8).

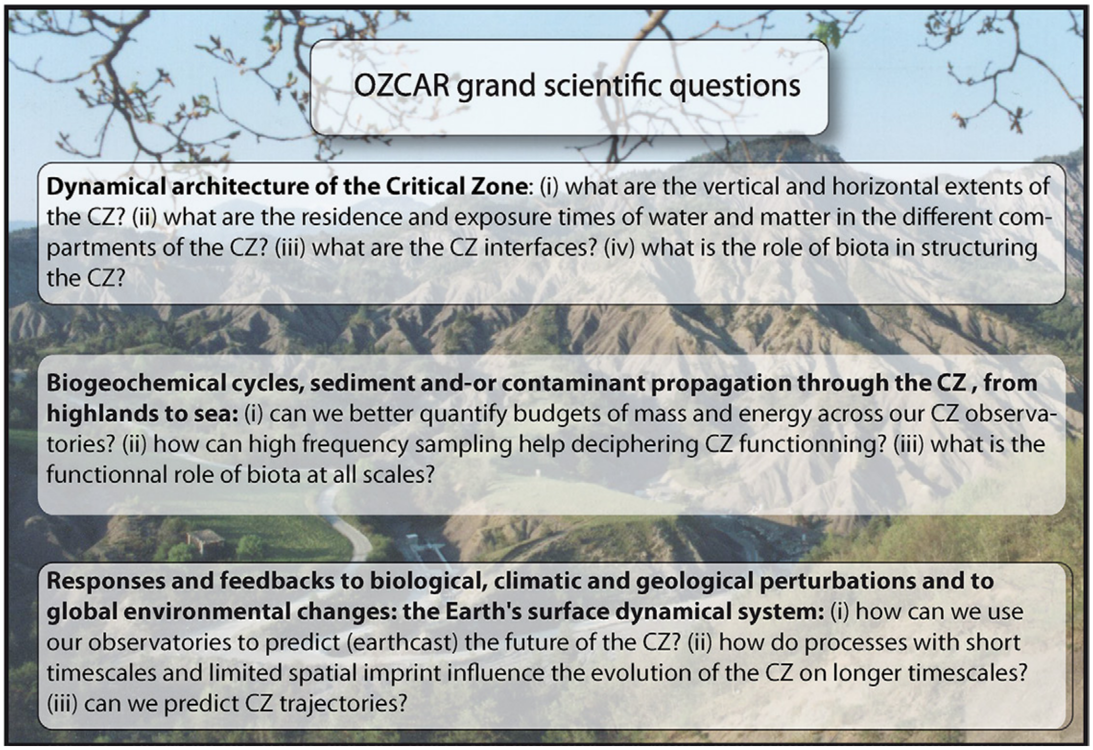
Dynamic Architecture of the Critical Zone

The architecture of the CZ refers to its structural, physical, chemical, and biological organization. The spatial extent of the CZ is still poorly defined, which emphasizes the need to better investigate its lateral and vertical organization (i) to identify the role of the different interfaces; (ii) to quantify the impact of spatial heterogeneity and temporal intermittence on fluxes, connectivity, concentrations and microorganisms; and (iii) to determine residence and exposure times of material in the CZ. Here, the architecture of the CZ is defined in a dynamic rather than in a static view. The dynamic architecture of the CZ can be translated into a series of questions detailed in the following.

What are the upper, lower, and lateral extents of the CZ? The upper limit of the CZ is classically defined as the top of the atmospheric boundary layer. The portion of the atmosphere involved in the CZ as characterized by the location of this upper limit is variable and site specific, depending on local topography and wind patterns. On the catchment scale, only the lower portion of the atmosphere is relevant, but when continental-scale energy couplings are considered, the whole atmosphere plays a role. As an example, a critical question in the assessment of geochemical mass budget studies in CZOs is how to incorporate atmospheric inputs of dust or of volatile organic compounds. These compounds can be produced locally (in which case they are part of the "soil" system) or can be produced at great distance (like Saharan dust in the Lesser Antilles or the Amazon) in the form of marine aerosols that can serve as significant external input sources to a given CZ site of interest.

The lower limit of the CZ is also often poorly defined, and this question is complicated by the fact that in many cases the CZ can be composed of multilayered aquifers in which water infiltrating from the surface can percolate very deeply with very long residence times (Goderniaux et al., 2013; Flipo et al., 2014; Aquilina et al., 2015).

Because the CZ is not a one-dimensional system, its lateral extent is equally as important as its vertical extent. Lateral compartments such as floodplains, peatlands, glaciers, or colluvium are important biogeochemical reactors on the continents that should be considered in order to fully address CZ functions. Describing



OZCAR grand scientific questions

Dynamical architecture of the Critical Zone: (i) what are the vertical and horizontal extents of the CZ? (ii) what are the residence and exposure times of water and matter in the different compartments of the CZ? (iii) what are the CZ interfaces? (iv) what is the role of biota in structuring the CZ?

Biogeochemical cycles, sediment and-or contaminant propagation through the CZ , from highlands to sea: (i) can we better quantify budgets of mass and energy across our CZ observatories? (ii) how can high frequency sampling help deciphering CZ functionning? (iii) what is the functionnal role of biota at all scales?

Responses and feedbacks to biological, climatic and geological perturbations and to global environmental changes: the Earth's surface dynamical system: (i) how can we use our observatories to predict (earthcast) the future of the CZ? (ii) how do processes with short timescales and limited spatial imprint influence the evolution of the CZ on longer timescales? (iii) can we predict CZ trajectories?

Fig. 8. The main scientific questions defined by the OZCAR community.

the dynamic architecture of the CZ is thus a composition exercise that requires not only the spatial, geomorphologic heterogeneity to be taken into account but also the connectivity, i.e., the way hydrological patches are connected in space and time.

What are the residence and exposure times of water and matter in the different CZ compartments? Determining the duration of time that matter spends in the CZ (residence time), as well as the time that the matter is in favorable biogeochemical conditions to react (exposure time), is a primary step in defining CZ architecture because it is a direct indicator of its dynamic structure. The residence time concept is typically associated with water, but it can also be applied to surface (glaciers) or ground (permafrost) ice, sediments, and soils. For example, the residence time of soil material results from a subtle balance between weathering and erosion and, therefore, can provide insightful information into the rates at which soil material is formed or transported out of the catchment as part of the CZ architecture characterization. Ecosystem characteristic times have been shown to change significantly with spatial scale, and thus these diverse scales must be investigated, taking advantage of the nested structure of observatories.

What are the CZ interfaces? To overcome the inherent difficulty of describing a "dynamic architecture" of the CZ, the CZ can be described as a series of critical interfaces. At these interfaces between reservoirs or compartments, energy, water, and matter are transformed because of biological, physical, and chemical gradients (such as redox gradients). These interfaces may be permanent or transient, depending on the hydrological cycle or on the succession of dry and wet seasons. Examples of CZ interfaces are the soil (or ice or snow)–atmosphere interface, the unsaturated–saturated zone interface, hyporheic zones, riparian zones, or more generally the groundwater–river interface, or the topography of the bedrock–saprolite interface (weathering front).

What is the role of biota in the CZ architecture? Biota play a crucial role in most of the chemical and physical reactions in the CZ by regulating hydrological and matter budgets through the control of evapotranspiration, the production of physical stresses on the CZ, and through facilitating chemical reactions. Life is not an explicit variable in all OZCAR sites, but a number of biological variables are measured (particularly, through remote sensing). A challenge of CZ science and observatories is to incorporate measurements that assess more explicitly the role of living organisms (and humans) in the CZ. For example, the role of the "microbiome" is particularly unknown in the world and is thought to be a significant contributor to the major geochemical and hydrological processes governing the CZ (Sullivan et al., 2017).

Processes and Budgets: Biogeochemical Cycles, Sediment and Contaminant Propagation through the Critical Zone from Highlands to Sea

The CZ, essentially fueled by solar energy, is controlled by a large number of chemical, physical, and biological processes that are tightly coupled at the plot, watershed, and continental scales. The concept of terrestrial biogeochemical cycles is probably the best adapted to describe the loops in which water, matter, elements, and contaminants occur at the Earth's surface. These loops act at different spatial and temporal scales and are not necessarily closed at the size of a CZO. An overarching question is therefore how to identify and quantify the hierarchy of CZ processes that govern terrestrial biogeochemical cycles across space and time. The search for these coupled processes shaping the CZ and their quantification in terms of kinetics (i.e., of fluxes involved) is therefore central to the OZCAR network. The different processes may be identified and quantified across small spatial scales (grain, plot, hillslope) or may be described at a very large scale in the case of large watersheds. Typical associated timescales may range from seconds to millions of years (Anderson et al., 2004; Robinson et al., 2008; Sullivan et al., 2016). Moving up through scales, new processes emerge that are not necessarily the sum of the processes described at a smaller scale. Through a suite of observatories and nested catchments, covering a mountain-to-sea continuum, combined with modeling, OZCAR aims to address the following major questions related to the processes and fluxes through the CZ.

Can we better quantify budgets of mass and energy across CZ observatories? This includes constraining the different processes at play in the hydrological budget and their spatial and temporal variabilities: precipitation, evapotranspiration or more generally atmosphere–surface exchanges, wind erosion, infiltration or groundwater recharge, and groundwater–river exchanges. These budgets, first applied to water, must also be applied to other components (sediments, nutrients, contaminants, or total mass) and thus to any particular element regardless of its phase (gas, solute, particulate), including trace elements and micronutrients, and should be established on timescales relevant to the systems considered. OZCAR aims to combine different techniques, models, and tracers to achieve such a goal (e.g., Sullivan et al., 2016).

How can high-frequency sampling help decipher CZ functioning? Solving this question requires time series with sampling frequencies adapted to the different processes and to the scale of investigation. The couplings between processes at the plot or catchment scale can only be disentangled if high-frequency measurements (from 1/h to 1/min, depending on the process dynamics) are available. At larger scales, because interannual variability is large in the CZ, typically decadal observation series are necessary. Such long time series have rarely been collected at the global scale so far and require a focused effort by the international CZ community.

What are the functions of biota in the CZ? The role of biological processes and their quantification remains difficult in the CZ, partly because measurable proxies of life-related processes are lacking. So-called "abiotic" and "biotic" processes are so intertwined that deciphering the causalities is a "chicken and egg" problem. An important question, beyond species diversity, is to identify the functions of macro- and microorganisms in the CZ. "Biolifting" is a particularly interesting mechanism that consists of nutrient withdrawal at depth by roots and release by organic matter decomposition or throughfall inputs in the topsoil. Spatially, the dynamics of organic carbon and nutrients through the mountain-to-sea continuum also deserves more attention.

Responses and Feedbacks to Biological, Climatic, and Geological Perturbations and Global Change: Earth's Dynamic Surface System

The ultimate scientific question that OZCAR wants to tackle is: What is the response of the CZ to perturbations and forcings that can be either "natural" (such as geologic or meteorological forcing) or anthropogenic (such as climate change, shifts in land use, increase in resource exploitation)? Human activities are now considered as one particular and now prominent forcing factor on the Earth's surface, and most of the OZCAR sites have been strongly impacted by human practices over time. Because the CZ holds resources and offers goods and services to humanity, understanding how this dynamic system as a whole responds to events that can be exceptional, periodic, or continuous is important in terms of better informing society and stakeholders (predicting flood events and associated risks, chemical or radioactive dispersion) and propose a scientific basis for an alternative management of these resources.

How can we use CZ observatories to earthcast? Humanity faces unprecedented changes in climate, water and food security issues, and population growth, so the main question is: How can we use different CZOs and their design along gradients to quantitatively predict the response of the Earth's surface to changes in global or local forcing parameters, or in short, "earthcast" (Goddéris and Brantley, 2013)? This question is associated with that of the representativeness of observatories. Is heterogeneity the overriding controlling factor or can we, beyond the local diversity in geology, rock texture, climate, soil and vegetation, land use and human practices define general properties (such as state variables) characterizing the systems? Through their large diversity of location, climatic, and geological contexts, OZCAR observatories offer an unprecedented opportunity to test the relevance of this hypothesis. Monitoring Earth's surface through a series of observatories (Banwart et al., 2013; Kulmala, 2018) poses the question of how these observatories should be chosen, designed, and monitored and also highlights the necessity of defining common metrics for CZOs (Brantley et al., 2016; Sullivan et al., 2017).

How do processes with small characteristic times and limited spatial imprint influence the longer timescales and larger spatial scales? The perturbations induced by human activities on the CZ are a typical case of coupling between timescales, where human actions may be short lived but could have lasting consequences over long timescales. A typical example is that of Laos where a change of land use from rice (*Oryza sativa* L.) crop to teak (*Tectona grandis* L. f.) forest resulted in spectacular and irreversible acceleration of erosion rates (Valentin et al., 2008; Ribolzi et al., 2017). The idea that biota in the CZ respond quickly to climate change and that the structure, function, and dynamics of the CZ can change on timescales much faster than currently considered is particularly important.

The knowledge acquired from observatories can be incorporated into integrated models, able to model and couple the various components of the CZ at different space and time scales in order to better quantify fluxes and storages in the CZ and simulate its response to global change. These models should also have a predictive power to address questions raised by societies and stakeholders, such as risk assessment related to floods, droughts, landslides, contamination, or water resources shortage. By increasing the common use of models and data, well-instrumented CZOs offer a unique opportunity to understand small-scale processes and to hierarchize their importance according to different environmental and climatic conditions. The development of nested instrumentation, as already done in some OZCAR observatories, provides tools to assess the validity of simplifying assumptions and to address the change-of-scale problem and how dominant processes may change when moving from small to larger scales. Another challenge, also highlighted in the first scientific question, is the proper integration of the biotic components as well as representations of human infrastructures and activities in CZ integrated models.

Can we predict CZ trajectories? All parameters being constant, is the evolution of the CZ at a CZO reproducible? In other words, if the same initial conditions are met, would two similar CZOs follow the same evolutionary trend under the same forcing? Could it also be possible that bifurcations in the evolution of the CZ caused by heterogeneities or sudden changes would result in different evolutionary patterns? Human actions, fires, sudden erosional events—these extreme events are factors that could act as tipping points in the evolution of the CZ and clearly need to be better appreciated and incorporated into CZ models.

Challenges in Instrumental Development

A main challenge of future CZ instrumentation is to define tools and methods to image how water flows and how the heterogeneous structure of the geological, soil, and biospheric media generates reactivity hotspots at moving interfaces. Adapted spatial and temporal resolution across a wide range of scales is therefore required to capture emerging patterns driven by water flow in the subsurface, with the main challenge being how to define the right scale of heterogeneity and adapt the instrumentation accordingly. A number of techniques currently available for exploring and probing the CZ may not be adapted to the necessary scale of investigation. This is particularly true at the smallest spatial scales (such as the catchment or plot scale) where geophysical imaging is usually at insufficient resolution, where geochemical signals are not recorded at a sufficiently high temporal frequency, and where spatial techniques are still irrelevant.

Addressing Challenges in Instrumentation to Move Forward in Our Understanding of Critical Zone Functioning

First, high time and space frequency of measurements is clearly a frontier in CZ instrumentation. High-frequency acquisition already exists for parts of the CZ, such as for atmosphere–ground exchanges of matter and energy (using flux towers or accumulation chambers), or for water levels in piezometers and river gauging stations, but significant progress still needs to be made, particularly for spatialization. Better spatial resolution of ground sensors will improve the link with remote sensing data. Cosmic ray investigation or scintillometry are promising techniques that link local to larger scale observations but still require important technological and theoretical development to be adapted to observatories with marked topography. Compared with water and gas, chemical parameters and solids (in suspension or as bedload) are rarely measured at a high temporal frequency in rivers and aquifers, which should be considered as a priority at the catchment or watershed scale. Commercially available laboratory instruments could be beneficially deployed in the field to decrease required manpower and allow cost-effective sample manipulation, provided that the issue of water filtration can be solved. This concept has been developed in oceanography ("lab on ship") but is still in its infancy in terms of CZ research. The River Lab concept described above (Floury et al. 2017) is an example of such a promising approach. A deployable "snow lab" to automatically probe the surface and the snowpack would also provide a major step forward in the observing capabilities for snow. Industrial solutions exist including in situ sampling, pumping, filtration, and on-line analysis, which should be adapted to field requirements to be sufficiently resistant to extreme field conditions (cyclones, extreme cold events). If, in principle, all laboratory instruments can be deployed in the field, the "lab-in-the-field" concept would strongly benefit from the development of low-cost sensors, which have the advantage of being miniaturized, less sensitive to fouling than most commercial probes, deployable at a high spatial resolution, and eventually able to provide real-time data. The development of low-cost chemical sensors for major solutes, for water in the unsaturated zone, and for monitoring solid fluxes in rivers and glaciers is an instrumental challenge that needs a significant investment. Biological data (smart tracers, DNA) acquired at high frequency is also an area of instrumentation requiring considerable development.

The second promising direction of instrumental development, requiring a significant experimental and theoretical effort, is the improvement of the time resolution of geophysical imaging of the CZ ("time-lapse" geophysics) in order to move from snapshot views of the inaccessible CZ to the imaging of preferential water pathways. In addition, downhole exploration and associated experimentation for time-lapse imaging need to be developed as a complement to the ground-based time-lapse exploration. The sensitivity of some geophysical properties to biogeochemical reactions is transforming hydrogeophysics into "biogeophysics" (Binley et al., 2015), a promising field at the frontier of Life and Earth sciences.

Finally, data transmission and synchronization are prerequisites for developing high-frequency observation strategies. Autonomy is also particularly important for reducing the costs of human resources as well as for studying inaccessible CZ components (anoxic groundwaters, caves) or moments (extreme events). It is necessary to develop low-cost, low-energy tele-transmission strategies and systems for harsh and remote environments in order to minimize time-series discontinuity and obtain a large spatial coverage. It is also essential to explore new energy sources and to consolidate existing solutions, in particular within cold environments.

How Can OZCAR Help Achieve Significant Instrumentation Advances in Exploration of the Critical Zone?

Given the instrumental challenges listed above, a significant effort in the upstream development of sensors is required, necessitating the collaboration of users (CZ scientists) with sensor developers. Regardless of the need for higher space and time frequency, many variables of interest in CZ science are still challenging to measure (e.g., most snow internal properties, precipitation amount, and phase; Grazioli et al., 2017) and require innovative developments. Overall, there is a real challenge in encouraging the CZ community to meet with fundamental chemists, physicists, computer scientists, or biologists to develop new sensors. A good example is the extraordinary development of microfluidic techniques supporting unprecedented miniaturization of sensors as exemplified by numerous medical applications. The role of OZCAR will therefore be to develop a network-level technology survey on emerging technologies and technological forums associating sensor developers and CZ scientists on network-level questions like sensor autonomy, data transmission, and assessment of the ability and reliability of automatic sensors to accurately measure CZ parameters (Trouvilliez et al., 2015; Cucchi et al., 2018). Ocean and atmospheric scientists have also made significant progress in the last decades on the real-time acquisition of chemical and physical data that should be of high impact for CZ communities. Existing structures like ENVRIplus (an inter-ESFRI initiative addressing instrumental challenges) or international comparison projects such as SPICE (Snow Precipitation Intercomparison Experiment) led by WMO should also help create favorable conditions for sensor development. An assessment of the ability and reliability of automatic sensors to accurately measure CZ parameters is still required. This is even more true when low-cost sensors are considered (Trouvilliez et al., 2015). This can be done through specific campaigns organized in the framework of OZCAR, similar to what has been done globally by the World Meteorological Organization during the SPICE project in which CRYOBSCLIM participated.

OZCAR finally aims to be a community space for dissemination of sensors and skills and for sharing instruments among the field sites under varying environmental conditions. Sharing instruments within the OZCAR network will follow the model of the CRITEX instrumental facility. Instruments are purchased and managed by individual teams but are accessible to any OZCAR community member. This organization requires training workshops for field-based teams to learn how to use the instruments and how to treat data.

Challenges in Data Management

The amount of data produced in OZCAR is expected to increase in the near future due to the improvement in high-frequency acquisition systems and the development of new sensors. Simultaneously Open Data is pushed in Europe by the INSPIRE directive for spatial data and the Aarhus agreement (http://ec.europa.eu/environment/aarhus/) for environmental data. This requires data to be permanently and freely accessible online, allowing data discovery, visualization, and downloading. Open data is expected to enhance new connections between datasets, data mining, and easier use in models. Scientists are aware of these possibilities but may remain reluctant to openly provide their datasets. The reasons put forward are: lack of technical skills or human resources, legal constraints, data quality and validation, priority for their personal use through embargo on their datasets, lack of traceability of open data, and lack of acknowledgement of their work. Open data also raises practical questions about the definition of a dataset, its granularity, its documentation, the legal status of data (Becard et al., 2016), technical issues about interoperability between systems often developed independently, the availability of the required expertise for website design and maintenance, and of course the associated costs.

The Challenges in Critical Zone Data and Metadata Access

Identifying, cataloging, and sharing data within OZCAR is a great challenge, starting from a very heterogeneous situation (see above), that is common in environmental observation (Horsburgh et al., 2009). Visibility within the scientific community is also a great challenge, pleading for a common metadata/data portal. Given the investment of observatories in data portals and the preference that data remain as close as possible to their producer (Zaslavsky et al., 2011), it seems unrealistic to begin anew and propose the same technical solution for all observatories. The most efficient approach is to work on interoperability among existing sites so that metadata first, and data soon after, can be harvested and accessed transparently by users (e.g., Ames et al., 2012). This challenge of data sharing and interoperability is common to the environmental science community and has led to initiatives such as the Hydrologic Information System by the Consortium of Universities for the Advancement of Hydrological Sciences (CUAHSI) (https://www.cuahsi.org/; Horsburgh et al., 2009, 2011) for hydrological observatories, the EarthChem system (Lehnert et al., 2010) for geochemical data, or CZOData (Zaslavsky et al., 2011) for the CZO Data Management System. All these initiatives had to address semantic and syntactic heterogeneity and proposed shared controlled vocabulary for data and variable indexation (e.g., Horsburgh et al., 2014) and common standards for a data model (e.g., Horsburgh et al., 2008; Zaslavsky et al., 2011). Although individually successful, these initiatives showed limitations in incorporating new data types or sharing data among communities. This led to the development of a second generation of observation data models (Horsburgh et al., 2016; Hsu et al., 2017) handling different kinds of data. Concepts such as the Observation & Measurement (O&M; http://www.opengeospatial.org/standards/om) and Sensor Observation Service (SOS; http://www.opengeospatial.org/standards/sos) for data harvesting must also be explored and the cost of their deployment evaluated before designing the OZCAR portal.

How can OZCAR Help Achieve Progress in Critical Zone Data Management?

OZCAR aims at building a common metadata/data portal, gathering metadata, ensuring data access, taking advantage of the expertise present in the various observatories and of existing international initiatives. First exchanges with the OZCAR community showed that, to be useful, the data portal must provide information down to the level of available variables with their associated location and detailed time windows. This task will require working on the following points: (i) agreement on the fields and file format for providing the metadata so that they can be exposed following standards (e.g., INSPIRE) and can be used for other purposes such as Digital Object Identifier (DOI) declaration; (ii) agreement on the various entries to find data in the portal (location, dates, variables, climate, geology, observatory, programs, funding institutions [Ames et al., 2012]); and (iii) definition of a common ontology and controlled vocabulary for naming the variables—mapping of existing variables toward a commonly shared vocabulary based on the Global Change Master Directory (GCMD; https://earthdata.nasa.gov/about/gcmd/global-change-master-directory-gcmd-keywords) keywords is in progress; (iv) define fluxes of information between the OZCAR portal and existing portals so that the information is always up to date; and (v) document the data lifecycle and propose archiving solutions for long-term preservation (Massol and Rouchon, 2010; Diaconu et al., 2014).

The metadata portal should enable users to download data even if the latter are located in distributed data centers. The downloaded data will be supplied to the users in an identical format. The portal will be considered as a success if researchers use it to retrieve the latest versions of their own data.

The recognition of scientists acquiring data is also a major point to which attention must be paid. Initiatives such as DOI, data papers (e.g., Morin et al., 2012; Nord et al., 2017; Guyomarc'h et al., 2018), and licensing of the datasets (e.g., Creative Commons licenses; https://creativecommons.org/share-your-work/licensing-types-examples/) will be encouraged within OZCAR by providing guidelines on the definition of the corresponding datasets, their granularity, and on filling the associated metadata. It is also planned to propose a minimum Information System kit for observatories that lack the required expertise.

Linking Data and Models, Ambitions and Objectives

OZCAR aims to provide a seamless holistic understanding of the terrestrial compartments of the Earth system and an integrated representation of the coupled water, energy, and matter cycles, including biogeochemical cycles (e.g., Filser et al., 2016), covering various spatial and temporal scales and incorporating the heterogeneity of the critical zone. Such integrated approaches are required to "earthcast," i.e., assess the effect of future global change or socioeconomic scenarios on all the compartments of the CZ (Goddéris and Brantley, 2013). To address these scientific challenges, stronger interactions between data science and modeling approaches are necessary (e.g., Kirchner, 2006; Braud et al., 2014; Brantley et al., 2016), raising key cognitive and technical challenges.

Scientific and Technical Challenges in Linking Critical Zone Data and Models?

A first challenge is related to the process representation at different scales. At small scale, the identification of elementary processes can benefit from the instrumental progress discussed above. One example is the development of geochemical reactive transport models (i.e., Steefel et al., 2015) at the catchment scale exploiting in particular high-frequency datasets of stream chemistry, constraints from new isotopic systems (Sullivan et al. 2016), and the new representation of heterogeneities at the grain size (Le Borgne et al., 2013). Another challenge is the proper representation of vegetation and biological activity on chemical and physical reactions that determine hydrological and matter budgets. When moving to larger scales, unstructured heterogeneity, nonlinearity, and thresholds at all scales (Blöschl and Zehe, 2005), and the scarcity of integrated data at the scale of interest (Cook, 2015), preclude the use of the same approach. It also becomes necessary to include human interactions within the system (water use, infrastructures, agricultural and forested land management, etc.), to create socio-hydrological models (Sivapalan et al., 2012). Equations and representations derived at small scales are often used for larger scales, but this approach is questioned because the data reveal behaviors such as "emergent properties" (Sivapalan, 2003; McDonnell et al., 2007) that cannot be represented by the aggregation of small-scale processes to larger scales, calling for new theories (e.g., Kirchner, 2009; Braun et al., 2016) as well as new concepts for non-explicitly resolved processes (i.e., "parameterization" as defined by the atmospheric science community).

A second challenge is to progress toward integrated modeling of the CZ, requiring the deployment of coupling strategies. Direct coupling is relevant for exchanges such as water and energy fluxes across the surface that are represented in land–surface models and now incorporate many processes of the continental surface and subsurface (e.g., SURFEX [Masson et al., 2013] or ORCHIDEE [http://forge.ipsl.jussieu.fr/Orchidee; Ducoudré et al.,1993; Krinner et al., 2005]). Other examples such as PARFLOW-CLM (Kollet and Maxwell, 2006), DHSVM (Wigmosta et al., 2002), PIHM suite (Duffy et al., 2014), as well as the Dhara modeling framework (Le and Kumar, 2017) are built around an initial model that can be enriched with different coupled modules. They all require specific data transfer and the integration of new modules to fit the model requirements (language, mesh and grid resolution, names of variables, etc.). Another option is to use couplers such as OPEN-MI (https://sites.google.com/a/openmi.org/home/dashboard2) or OpenPALM (http://www.cerfacs.fr/globc/PALM_WEB/; Piacentini, 2003) that generally preserve model legacies and provide interfaces for their coupling, but also robust coupling methods and complementary tools such as data interpolation. A third option is to design platforms that allow coupling various modules and model representations, keeping the specificity of each component in terms of model mesh and time steps, and that provide interfaces to couple models but also a framework for the runtime environment such as LIQUID (Branger et al., 2010), CSDMS (http://csdms.colorado.edu/wiki/Main_Page; Peckham et al., 2013), OpenFLUID (http://www.openfluid-project.org/; Fabre et al., 2013), and JAMS (http://jams.uni-jena.de/; Kralisch and Krause, 2006). Process coupling may also call for the definition of more adapted variables and/or standardized interfaces to favor the coupling between modules describing various processes. Choosing or designing technical solutions adapted to the complexity and heterogeneity of the CZ remains challenging and is an active area of research. In some cases, the dynamics of interfaces should be considered in itself as a research issue requiring adapted characterization and modeling methods. Interactions between vegetation and sediment transport in rivers benefit from the development of accurate topographical devices like lidar and require new models for sediment transport and river evolution (Brodu and Lague, 2012; Jourdain et al., 2017). New data can also reveal the spatiotemporal dynamics of exchange variables and fluxes (McDonnell, 2017), questioning current representations. For example, aquifer–river fluxes revealed by fiber-optic temperature data potentially modify the status of the exchange fluxes from boundary conditions to forcing terms (Anderson, 2005; Klepikova et al., 2014). In hydro-geo-ecology, coupled nutrient transfer and characterization of microorganisms requires recasting classical residence time concepts in the framework of exposure time concepts where hotspot organization can be integrated (Pinay et al., 2015).

Common issues shared at each step of modeling, either when identifying processes or when coupling them, are related to the ability to manage uncertainties coming from observations, process understanding, and model parameterizations. This requires the design of calibration and model evaluation criteria and data assimilation systems that are able to account for this uncertainty. Numerical uncertainty must also be quantified when models are used for predictive purposes.

From a more technical point of view, important challenges are related to our ability to perform coupling between process modules running at different space and time scales and to link databases, GIS layers, and models (Bhatt et al., 2014). Facilitating data–model interactions to build integrated modeling requires novel technical developments allowing both data interoperability and model sharing (e.g., OLES project [Anquetin et al., 2014]; CSMDS project [Peckham et al., 2013]; CUAHSI community model [https://www.cuahsi.org/data-models/community-models/] and web services based on the Basic Model Interface [Jiang et al., 2017]) and needs to be extended to a larger scientific community (Le and Kumar, 2017;

Yu et al., 2016). Such platforms may also benefit from distributed computing facilities that help to keep model development closer to the developers. Moreover, improved visualization capacities are also necessary to represent modeling results and provide more accessible pathways to environmental processes for the broader scientific community (Leonard and Duffy, 2014). Implementing such tools (e.g., Paraview; https://www.paraview.org/) in the modeling platform will benefit both observational data and modeling data exploration.

Finally, new data are available at unprecedented space and time resolutions, related to the rapid development of new sensors, high-resolution satellite data, and data obtained by experimentation that provide information on more diverse variables, sometimes indirectly related to the variables of interest. Big data challenge current modeling practices that were developed in a scarce-data context. This will transform relations between data and models, with critical improvements needed in computation, calibration, and assimilation capacities (Liu et al., 2012). The availability of a large amount of data also opens new perspectives for the derivation of data-driven models (e.g., Kirchner, 2009) that can benefit from data mining and big data analysis (e.g., Bui, 2016) and allow reduction in uncertainties. Data mining can also be used to infer the geometry and model parameters for large systems (Bodin et al., 2012) and provide complementary calibration strategies for high-dimensional models (Bui, 2016; Hsu et al., 1995; Shortridge et al., 2016).

How Can the OZCAR Community Contribute to These Challenges?

Linking data and models will be one of the pillars of OZCAR. In terms of process representations, the large climatic–ecological–pedological–biological gradients covered by OZCAR, including sites highly impacted by human activity, offer opportunities for providing data at small scales (grain, macropore, and catchment scales) and identifying the elementary processes to be implemented into models. Nested instrumented catchments provide data to tackle the change-of-scale problem and identify and model "emergent" behaviors.

To cope with the diversity of models used within the OZCAR community (see Supplemental Table S3), not a single CZ model will be considered (Duffy et al., 2014), and coupling between existing models or modular modeling platforms will be used in order to build dedicated models, adapted to the scientific questions and data availability. Such platforms have already started to be used for integrated land surface–aquifer modeling (e.g., the AquiFR project in France; Habets et al., 2015) and other examples were listed above. OZCAR will also explore complementary approaches that are often opposed in the literature, such as the use of detailed mechanistic models (Goddéris and Brantley, 2013) vs. simplified models able to capture the main functions within the critical zone (Savenije and Hrachowitz, 2017). With the development of adapted assimilation technique approaches, the combination of data and models will ultimately lead to CZ reanalysis, providing valuable and novel information about the CZ, as already widely used by the atmospheric science community to produce re-analyses of the state of the atmosphere and of the components of the water cycle at the global scale (e.g., ERA-Interim; Berrisford et al., 2011). Implementing all the tools will require that the OZCAR community expand to applied mathematicians and computing engineers and train a new generation of CZ modelers.

Structural Framework of the OZCAR Network: Possible Topologies for OZCAR

OZCAR gathers scientists from different disciplines, from both academic and applied research, and a large number of monitored sites that share a common set of instruments used for probing the near surface of our planet. Organizing the topology of such a network is important not only for helping this heterogeneous community to identify network-level ideas and scientific hypotheses to be tested but also to help promote CZ science and maintain recurrent funding by institutions, to improve the visibility of CZ science to society, and to improve collaborations with other Earth surface and environmental science networks.

Several topologic models that optimize the goals pursued by OZCAR are proposed. In all cases, site-based observatories are the permanent and pivotal structures, recurrently funded by different environmental research institutions.

A number of existing research infrastructures, developed in particular by climate and atmospheric science communities, measure one parameter or a limited set of parameters in a series of instrumented sites along gradients. One successful example of such variable-centered RI is provided by ICOS (Integrated Carbon Observation System), a network of flux towers measuring CO_2, as well as other greenhouse gas and energy fluxes along climate gradients then directly connected to climate models. By contrast, OZCAR, and more generally worldwide CZ or long-term ecological research (LTER) observatories assemble a more complex and diverse set of instruments measuring parameters determined by local or regional processes (geology, climatology) that are used to target a systemic approach.

A first possible topology is to define a set of common scientific questions within the network and to organize OZCAR in sub-networks targeting these questions. Several common questions or scientific themes can be proposed that supersede the heterogeneity of existing site-based observatories and foster scientists and disciplines to collaborate. One theme could be reactive transport in porous media. It would associate research teams focusing on hydrogeological, hydrological, and biogeochemical processes to understand and model the interaction between water, minerals, life, and solids in aquifers using the diversity of OZCAR observatories. Another group could be organized on CZ science in headwater catchments, targeting the identification of elementary mechanisms or closing mass and energy budgets locally. Another transverse theme common to numerous observatories could be a "CZ-carbon" theme on the topic of carbon storage in the CZ and its relation to functional biodiversity and the 4‰ initiative (https://www.4p1000.org/). A last thematic cross-site program could address the upscaling issue by targeting the large spatial scales, including the remote sensing resources from OZCAR and taking advantage of the regional-to-continental scale observatories (e.g., Amazon basin).

A second topology model would be a network organization in clusters of sites. In such a model, the different site-based observatories of OZCAR, targeting variable compartments of the CZ (glaciers, peatlands, catchments) would ideally be co-located within a territorial entity that can be a large river basin or a "geo-climatic" entity. This organizational scheme is not far from that of the TERENO (Terrestrial Environmental Observatories) terrestrial infrastructure developed by the German Helmholtz Association (Bogena et al., 2006; Zacharias et al., 2011). Each TERENO consists of a series of instrumented atmospheric, hydrological, ecological co-located sites representing the dominant terrestrial processes, land use, climate, and demographic gradients. The entities could also be socio-ecological systems in which the long-term observatories of OZCAR are co-located. Socio-ecosystems are typically the setting of the Long Term Socio-Ecological Research (LTSER) observatories (Haase et al., 2018). This organization in clusters is also close to the "hub-and-spoke" topology proposed by Brantley et al. (2017) in the United States. A hub is a highly instrumented CZO (essentially a river catchment) in which the broader common metrics of measurements have been defined and which is connected to "satellite" sites focused on a particular compartment of the CZ and in which fewer parameters are monitored.

Finally, a last topologic model for OZCAR could be based on instrumentation. OZCAR could be seen as a network of instruments, some of them mobile (e.g., seismology), some others permanent and site based (i.e., gauging stations, piezometers). The infrastructure could then be organized according to the different sub-networks of instruments allowing for exchange of good practice, data, and models between scientists and centralization of data at the national scale. The instruments and instrumented sites would then be considered as a resource community to test hypotheses along gradients or by combining different exploration techniques. For example, one could imagine a network of mobile hydro-geochemical stations acquiring high-temporal resolution (Floury et al., 2017) data and covering climate, geological, and land use gradients. On-site experimentation could also be an added value of such an infrastructure. This vision of OZCAR as a national equipment facility for the study of the CZ does not preclude a site-based systemic approach, which is important for the societal relevance of CZ studies at the local scale (at the scale of "territories"), but it offers structure for the RI and is fostering collaboration within disciplines. Such a model of organization has been chosen by other RIs in physics and deep Earth science. A good benchmark is the EPOS RI monitoring earthquakes, volcanic eruptions, tsunamis, and plate tectonics in general with a common set of integrated data, models, and facilities (https://www.epos-ip.org/).

Whatever the structure of OZCAR will be in the future, it is essential that the elementary components, the long-term observatories, be maintained and funded. Any topology should be flexible enough to incorporate new sites or instruments and be interoperable with the other RIs dedicated to the study of the Earth's surface.

Insertion into International Networks

Born under the leadership of the US National Science Foundation, the Critical Zone Exploration Network initiative has fostered the development of CZ networks in various countries either by restructuring existing geoscience-centric observatories or by launching competitive calls for encouraging multidisciplinary approaches for existing observatories (Sullivan et al., 2017; Feder, 2018). The Biological and Environmental Research Subsurface Biogeochemistry Program of the Department of Energy (USDOE) in the United States has developed the Watershed Function Project, an instrumented watershed-based network taking a "system-of-systems" approach (Hubbard et al., 2018) and utilizing a scale-adaptive simulation approach to quantify how fine-scale processes occurring in different watershed subsystems contribute to the integrated, time-dependent export of water, nitrogen, carbon, and metals. In Germany, the TERENO network created in 2008 is comprised of four distributed observatories exploring the long-term ecological, social, and economic impacts of global change at the regional level by measuring above- and belowground variables and biosphere parameters and coupling them to remote sensing techniques (Zacharias et al., 2011). The EU funded between 2009 and 2014 the SoilTrec program gathering four European CZOs located along a conceptual life cycle of soil. SoilTrec developed an integrated model quantifying soil processes that support food and fiber production; filtering, buffering and transformation of water, nutrients and contaminants; storage of carbon; and biological habitat and gene pool (Banwart et al., 2013). China and the UK co-funded six CZOs in 2016 representing different geology, soil, and land use types in China. In Australia, CZOs have been established in synergy with existing LTER and the Terrestrial Ecosystem Research Network (TERN) (Karan et al., 2016).

In 2014, the EU started to fund different projects aimed at building a pan-European infrastructure, integrating European LTER, CZ, and socio-ecological research observatories. This led to the European Strategy Forum on Research Infrastructure (ESFRI) project (eLTER-RI) that has been included on the ESFRI road map in 2018 (http://www.lter-europe.net/elter-esfri). This initiative echoes the need for initiating a dialog among geoscience, bioscience, and social science communities, restructuring the existing observatories, and co-designing Earth surface models and observation strategies that take into account socioeconomic constraints (Richter and Billings, 2015; Mirtl et al., 2018). Together with the French LTSER network of the Zones Ateliers (RZA), OZCAR constitutes the French mirror of eLTER ESFRI.

Though the scientific approach and the monitoring strategies are different from the US National Science Foundation funded program, we hope OZCAR offers a model of integration of preexisting observatories of the CZ at the national scale motivated by ambitious scientific and educational goals shared by the international community (Sullivan et al. 2017).

Conclusions

We have described the ambitions and goals of the newly created national research infrastructure OZCAR. OZCAR-RI aims to be the French initiative for the global Critical Zone Exploration Network. OZCAR is gathering a number of preexisting instrumented sites grouped into 21 observatories and used for conducting long-term observations or experimentation and encompassing wide gradients of climate, geology, land use, and land cover. The OZCAR network is assembling sites initially developed for hydrometeorological, hydrological, hydrogeological, as well as cryospheric and biogeochemical questions as well as sites focused on the cryosphere or using remotely sensed observations. The wealth of OZCAR observatories is inherited not only from the geologic, pedologic, and climatic heterogeneity of the CZ along the mountain-to-sea continuum and throughout depth but also from the range of timescales that characterize its functioning. OZCAR sites and observatories have their own initial scientific questions, monitoring strategies, databases, and modeling activities, but all share the main overarching goal: to monitor, understand, and simulate CZ adaptation to a changing planet in the “new climatic regime” (Latour, 2018).

The challenge of OZCAR is thus to build upon the heterogeneity of sites, scientific cultures, and data management practices, to define a strategy at the network level enabling scientists to share models and data in order to significantly improve our integrated understanding of the CZ as a system and form a new generation of scientists.

The OZCAR community aims to achieve this goal by defining cross-site activities, through the construction of a common database and metadatabase environment, by developing and sharing new instruments for exploring the CZ, by defining a set of parameters in some representative sites that should be measured at all sites, and through facilitating the interaction between data and Earth subsurface models, in particular through a better representation of the coupled water, energy, and biogeochemical cycles at all time scales.

To face the unique environmental change that our planet is experiencing in the Anthropocene and to achieve the sustainable development goals as defined by the UN, a significant community effort is needed to better model and predict the response of the Earth system. Beyond the need to better structure the existing French observatories, OZCAR hopes to serve as a benchmark for better organizing the environmental research observatories in other countries and to be part of the European and international CZ network, in particular thanks to its contribution to the pan-European research infrastructure eLTER.

Acknowledgments

OZCAR-RI is supported by the French Ministry of Education and Research, through the Allenvi Alliance. OZCAR observatories have benefited from numerous sources of funding coming from the different research institutions supporting the infrastructure (ANDRA, BRGM, CEA, CNES, CNRS, Ifsttar, INRA, IPEV, IPGP, IRD, IRSN, Irstea, Météo-France, LNE), universities (Avignon Pays de Vaucluse, Bourgogne Franche-Comté, Bretagne Occidentale, Grenoble-Alpes, La Réunion, Lyon, Montpellier, Orléans, Paris Diderot, Pierre et Marie Curie, Rennes, Rouen-Normandie, Savoie-Mont Blanc, Strasbourg, Toulouse, Clermont-Auvergne), and institutes (INP-Toulouse, Mines Telecom, VetAgroSup, IPGP). In the southern countries, the following universities—UCAM, TREMA International Joint Laboratory, Morocco; INRGREF, INAT, Tunisia; Univ. Abdou Moumouni, Niger; Univ. Abomey-Calavi, Bénin; Univ. des Sciences des Techniques et des Technologies de Bamako, Mali; UFAM in Manaus, Brazil; UFF in Rio de Janeiro, Brazil; UNALM in Lima, Peru; UMSA in La Paz, Bolivia; UCV in Caracas, Venezuela; UMNG in Brazaville, Republic of the Congo—as well as the following national hydrological services—ANA, CPRM in Brazil, SENAMHI in Peru and Bolivia, INAMHI in Ecuador, and DREAL in France—are thanked for making international collaboration possible. The French Ministry of Ecological and Inclusive Transition (AFB/ONEMA) is supporting the piezometer network (ROSES). A number of sites were supported by the ANR and PIA (Programme Investissement d’Avenir): Equipex CRITEX (ANR-11-EQPX-0011), LabexOSUG@2020, Labex DRIIHM–OHM du Haut Vicdessos. We also thank the administrative and scientific staff of all institutions contributing to the collection, analysis, and diffusion of the data collected within OZCAR. Tim White and two anonymous reviewers are thanked for their suggestions that improved the manuscript. Lin Ma and Nicole Fernadez are thanked in particular for their careful proofreadings.

References

Ames, D.P., J.S. Horsburgh, Y. Cao, J. Kadlec, T. Whiteaker, and D. Valentine. 2012. HydroDesktop: Web services-based software for hydrologic data discovery, download, visualization, and analysis. Environ. Modell. Softw. 37:146–156. doi:10.1016/j.envsoft.2012.03.013

Anderson, M.P. 2005. Heat as a ground water tracer. Groundwater 43:951–968. doi:10.1111/j.1745-6584.2005.00052.x

Anderson, S.P., R.C. Bales, and C.J. Duffy. 2008. Critical zone observatories: Building a network to advance interdisciplinary study of Earth surface processes. Mineral. Mag. 72:7–10. doi:10.1180/minmag.2008.072.1.7

Anderson, S.P., J. Blum, S.L. Brantley, O. Chadwick, J. Chorover, L.A. Derry, et al. 2004. Proposed initiative would study Earth’s weathering engine. Eos Trans. AGU 85:265–269. doi:10.1029/2004EO280001

André, F., G. Brissebat, L. Fleury, J. Gaillardet, and G. Nord. 2015. The RBV metadata catalog. In: EGU General Assembly 2015, 12–17 Apr. 2015. Vienna. Vol. 17. EGU2015-5960.

Anquetin, S., X. Beaufis, V. Chaffard, and P. Juen. 2014. OLES: Online Laboratory for Environmental Sciences. In: D.P. Ames et al., editors, 7th International Congress on Environmental Modelling and Software, San Diego. 15–19 June 2014. Vol. 1. Int. Environ. Softw. Soc., Manno, Switzerland. p. 630–638.

Aquilina, L., V. Vergnaud-Ayraud, A.A. Les Landes, H. Pauwels, P. Davy, E. Pételet-Giraud, et al. 2015. Impact of climate changes during the last 5 million years on groundwater in basement aquifers. Sci. Rep. 5:14132. doi:10.1038/srep14132

Arènes, A., B. Latour, and J. Gaillardet. 2018. Giving depth to the surface: An exercise in the Gaia-graphy of critical zones. Anthropocene Rev. 5:120–135. doi:10.1177/2053019618782257

Arnaud, L., G. Picard, N. Champollion, F. Domine, J.C. Gallet, E. Lefebvre, et al. 2011. Measurement of vertical profiles of snow specific surface area with a 1 cm resolution using infrared reflectance: Instrument description and validation. J. Glaciol. 57:17–29. doi:10.3189/002214311795306664

Baatz, R., P.L. Sullivan, L. Li, S.R. Weintraub, H.W. Loescher, M. Mirtl, et al. 2018. Steering operational synergies in terrestrial observation networks: Opportunity for advancing Earth system dynamics modelling. Earth Syst. Dyn. 9:593–609. doi:10.5194/esd-9-593-2018

Banwart, S.A.J., J. Chorover, D. Gaillardet, D.T. Sparks, S. White, S. Anderson, et al. 2013. Sustaining Earth’s critical zone: Basic science and interdisciplinary solutions for global challenges. Univ. of Sheffield, Sheffield, UK.

Becard, N., C. Castets-Renard, G. Chassang, M.-A. Courtois, M.

Dantant, N. Gandon, et al. 2016. Ouverture des données de la recherche. Guide d'analyse du cadre juridique en France. doi:10.15454/1.481273124091092E12

Berrisford, P., D.P. Dee, P. Poli, R. Brugge, K. Fielding, M. Fuentes, et al. 2011. The ERA-Interim archive, Version 2.0. Eur. Ctr. Medium-Range Weather Forecasts, Reading, UK.

Bhatt, G., M. Kumar, and C.J. Duffy. 2014. A tightly coupled GIS and distributed hydrologic modeling framework. Environ. Model. Softw. 62:70–84. doi:10.1016/j.envsoft.2014.08.003

Binley, A., S.S. Hubbard, J.A. Huisman, A. Revil, D.A. Robinson, K. Singha, and L.D. Slater. 2015. The emergence of hydrogeophysics for improved understanding of subsurface processes over multiple scales. Water Resour. Res. 51:3837–3866. doi:10.1002/2015WR017016

Blöschl, G., and E. Zehe. 2005. On hydrological predictability. Hydrol. Processes 19:3923–3929. doi:10.1002/hyp.6075

Bodin, J., P. Ackerer, A. Boisson, B. Bourbiaux, D. Bruel, J.-R. de Dreuzy, et al. 2012. Predictive modelling of hydraulic head responses to dipole flow experiments in a fractured/karstified limestone aquifer: Insights from a comparison of five modelling approaches to real-field experiments. J. Hydrol. 454–455:82–100. doi:10.1016/j.jhydrol.2012.05.069

Bogena, H., K. Schulz, and H. Vereecken. 2006. Towards a network of observatories in terrestrial environmental research. Adv. Geosci. 9:109–114. doi:10.5194/adgeo-9-109-2006

Boudevillain, B., G. Delrieu, A. Wijbrans and A. Confoland. 2016. A high-resolution rainfall re-analysis based on radar–raingauge merging in the Cévennes-Vivarais region, France. J. Hydrol. 541:14–23. doi:10.1016/j.jhydrol.2016.03.058

Branger, F., I. Braud, S. Debionne, P. Viallet, J. Dehotin, H. Henine, et al. 2010. Towards multi-scale integrated hydrological models using the LIQUID® framework: Overview of the concepts and first application examples. Environ. Modell. Softw. 25:1672–1681. doi:10.1016/j.envsoft.2010.06.005

Brantley, S.L., R.A. DiBiase, T.A. Russo, Y. Shi, H. Lin, K.J. Davis, et al. 2016. Designing a suite of measurements to understand the critical zone. Earth Surf. Dyn. 4:211–235. doi:10.5194/esurf-4-211-2016

Brantley, S.L., W.H. McDowell, W.E. Dietrich, T.S. White, P. Kumar, S. Anderson, et al. 2017. Designing a network of critical zone observatories to explore the living skin of the terrestrial Earth. Earth Surf. Dyn. 5:841–860. doi:10.5194/esurf-5-841-2017017-36

Braud, I., P.-A. Ayral, C. Bouvier, F. Branger, G. Delrieu, J. Le Coz, et al. 2014. Multi-scale hydrometeorological observation and modelling for flash-flood understanding. Hydrol. Earth Syst. Sci. 18:3733–3761. doi:10.5194/hess-18-3733-2014

Braun, J., J. Mercier, F. Guillocheau, and C. Robin. 2016. A simple model for regolith formation by chemical weathering. J. Geophys. Res. Earth Surf. 121:2140–2171. doi:10.1002/2016JF003914

Brodu, N., and D. Lague. 2012. 3D terrestrial lidar data classification of complex natural scenes using a multi-scale dimensionality criterion: Applications in geomorphology. ISPRS J. Photogramm. Remote Sens. 68:121–134. doi:10.1016/j.isprsjprs.2012.01.006

Brun, E., P. David, M. Sudul, and G. Brunot. 1992. A numerical model to simulate snow-cover stratigraphy for operational avalanche forecasting. J. Glaciol. 38:13–22. doi:10.1017/S0022143000009552

Bui, E.N. 2016. Data-driven critical zone science: A new paradigm. Sci. Total Environ. 568:587–593. doi:10.1016/j.scitotenv.2016.01.202

Celle-Jeanton, H., D. Schemberg, N. Mohammed, F. Huneau, G. Bertrand, V. Lavastre, and P. Le Coustumer. 2014. Evaluation of pharmaceuticals in surface water: Reliability of PECs compared to MECs. Environ. Int. 73:10–21. doi:10.1016/j.envint.2014.06.015

Chatelier, M., S. Ruelleu, O. Bour, G. Porel, and F. Delay. 2011. Combined fluid temperature and flow logging for the characterization of hydraulic structure in a fractured karst aquifer. J. Hydrol. 400:377–386. doi:10.1016/j.jhydrol.2011.01.051

Chatton, E., T. Labasque, J. de La Bernardie, N. Guihéneuf, O. Bour, and L. Aquilina. 2017. Field continuous measurement of dissolved gases with a CF-MIMS: Applications to the physics and biogeochemistry of groundwater flow. Environ. Sci. Technol. 51:846–854. doi:10.1021/acs.est.6b03706

Chavanne, X., and J.-P. Frangi. 2014. Presentation of a complex permittivity-meter with applications for sensing the moisture and salinity of a porous media. Sensors 14:15815–15835. doi:10.3390/s140915815

Cook, P.G. 2015. Quantifying river gain and loss at regional scales. J. Hydrol. 531:749–758. doi:10.1016/j.jhydrol.2015.10.052

Crutzen, P.J. 2002. The "anthropocene". J. Phys. IV 12:1–5. doi:10.1051/jp4:20020447

Cucchi, K., A. Rivière, A. Baudin, A. Berrhouma, V. Durand, F. Rejiba, et al. 2018. LOMOS-mini: A coupled system quantifying transient water and heat exchanges in streambeds. J. Hydrol. 561:1037–1047. doi:10.1016/j.jhydrol.2017.10.074

Diaconu, S., S. Kraml, S. Surace, D. Chateigner, T. Libourel Rouge, A. Laurent, et al. 2014. Scientific data preservation. PREDON Project White Book. HAL-IN2P3 Repository, CNRS, Paris. http://hal.in2p3.fr/in2p3-00959072v1

Dramais, G., B. Blanquart, J. Le Coz, G. Pierrefeu, A. Hauet, D. Atmane, et al. 2014. Hydrometric inter-laboratory tests, procedure and applications. Houille Blanche 5:17–23. doi:10.1051/lhb/2014045

Ducoudré, N.I., K. Laval, and A. Perrier. 1993. SECHIBA, a new set of parameterizations of the hydrologic exchanges at the land–atmosphere interface within the LMD atmospheric general circulation model. J. Clim. 6:248–273. doi:10.1175/1520-0442(1993)006<0248:SANSOP>2.0.CO;2

Duffy, C., Y. Shi, K. Davis, R. Slingerland, L. Li, P.L. Sullivan, et al. 2014. Designing a suite of models to explore critical zone function. Procedia Earth Planet. Sci. 10:7–15. doi:10.1016/j.proeps.2014.08.003

Easterling, W.E. 2007. Climate change and the adequacy of food and timber in the 21st century. Proc. Natl. Acad. Sci. 104:19679. doi:10.1073/pnas.0710388104

Fabre, J.-C., M. Rabotin, D. Crevoisier, A. Libres, C. Dagès, R. Moussa, et al. 2013. OpenFLUID: An open-source software environment for modelling fluxes in landscapes. In: EGU General Assembly 2013, Vienna. 7–12 Apr. 2013. Vol. 15. EGU2013-8821-1.

Feder, T. 2018. Earth's skin is an interdisciplinary laboratory. Phys. Today 71(1):22–27 doi:10.1063/PT.3.3813

Filser, J., J.H. Faber, A.V. Tiunov, L. Brussaard, J. Frouz, G. De Deyn, et al. 2016. Soil fauna: key to new carbon models. Soil 2:565–582. doi:10.5194/soil-2-565-2016

Flipo, N., A. Mouhri, B. Labarthe, S. Biancamaria, A. Rivière, and P. Weill. 2014. Continental hydrosystem modelling: The concept of nested stream–aquifer interfaces. Hydrol. Earth Syst. Sci. 18:3121–3149. doi:10.5194/hess-18-3121-2014

Floury, P., J. Gaillardet, E. Gayer, J. Bouchez, G. Tallec, P. Ansart, et al. 2017. The potamochemical symphony: New progress in the high-frequency acquisition of stream chemical data. Hydrol. Earth Syst. Sci. 21:6153–6165. doi:10.5194/hess-21-6153-2017

Gal, F., P. Négrel, and B. Chagué. 2017. Development and deployment of a passive sampling system in groundwater to characterize the critical zone through isotope tracing. In: 19th EGU General Assembly, EGU2017, Proceedings of the Conference, Vienna. 23–28 Apr. 2017. p. 18562.

Goddéris, Y., and S.L. Brantley. 2013. Earthcasting the future critical zone. Elementa Sci. Anthropocene 1:000019. doi:10.12952/journal.elementa.000019

Goderniaux, P., P. Davy, E. Bresciani, J.R. Dreuzy, and T. Borgne. 2013. Partitioning a regional groundwater flow system into shallow local and deep regional flow compartments. Water Resour. Res. 49:2274–2286. doi:10.1002/wrcr.20186

Grazioli, J., J.-B. Madeleine, H. Gallée, R.M. Forbes, C. Genthon, G. Krinner, et al. 2017. Katabatic winds diminish precipitation contribution to the Antarctic ice mass balance. Proc. Natl. Acad. Sci. 114:10858–10863. doi:10.1073/pnas.1707633114

Gumiere, S.J., D. Raclot, B. Cheviron, G. Davy, X. Louchart, J.C. Fabre, et al. 2011. MHYDAS-Erosion: A distributed single-storm water erosion model for agricultural catchments. Hydrol. Processes 25:1717–1728. doi:10.1002/hyp.7931

Guo, L., and H. Lin. 2016. Critical zone research and observatories: Current status and future perspectives. Vadose Zone J. 15(9). doi:10.2136/vzj2016.06.0050

Guyomarc'h, G., H. Bellot, V. Vionnet, F. Naaim Bouvet, Y. Déliot, F. Fontaine, et al. 2018. A meteorological and blowing snow dataset (2000–2016) from a high-altitude alpine site (Col du Lac Blanc, France, 2720 m a.s.l.). Earth Syst. Sci. Data Discuss. doi:10.5194/essd-2018-74

Haase, P., J.D. Tonkin, S. Stoll, B. Burkhard, M. Frenzel, I.R. Geijzendorffer, et al. 2018. The next generation of site-based long-term ecological monitoring: Linking essential biodiversity variables and ecosystem integrity. Sci. Total Environ. 613–614:1376–1384. doi:10.1016/j.scitotenv.2017.08.111

Habets, F., P. Ackerer, N. Amraoui, B. Augeard, F. Besson, Y. Caballero, et al. 2015. Aqui-FR, un système multi-modèle hydrogéologique à l'échelle nationale. Geol. Geol. 187:105–109.

Hector, B., J.M. Cohard, L. Séguis, S. Galle, and C. Peugeot. 2018. Hydrological functioning of West-African inland valleys explored with a critical zone model. Hydrol. Earth Syst. Sci. Discuss. doi:10.5194/hess-2018-219

Hector, B., L. Séguis, J. Hinderer, J.M. Cohard, M. Wubda, M. Descloitres, et al. 2015. Water storage changes as a marker for base flow generation processes in a tropical humid basement catchment (Benin): Insights from hybrid gravimetry. Water Resour. Res. 51:8331–8361. doi:10.1002/2014WR015773

Horsburgh, J.S., A.K. Aufdenkampe, E. Mayorga, K.A. Lehnert, L. Hsu, L. Song, et al. 2016. Observations Data Model 2: A community information model for spatially discrete Earth observations. Environ. Modell. Softw. 79:55–74. doi:10.1016/j.envsoft.2016.01.010

Horsburgh, J.S., D.G. Tarboton, R.P. Hooper, and I. Zaslavsky. 2014. Managing a community shared vocabulary for hydrologic observations. Environ. Modell. Softw. 52:62–73. doi:10.1016/j.envsoft.2013.10.012

Horsburgh, J.S., D.G. Tarboton, D.R. Maidment, and I. Zaslavsky. 2008. A relational model for environmental and water resources data. Water Resour. Res. 44:W05406. doi:10.1029/2007WR006392

Horsburgh, J.S., D.G. Tarboton, D.R. Maidment, and I. Zaslavsky. 2011. Components of an environmental observatory information system. Comput. Geosci. 37:207–218. doi:10.1016/j.cageo.2010.07.003

Horsburgh, J.S., D.G. Tarboton, M. Piasecki, D.R. Maidment, I. Zaslavsky, D. Valentine, and T. Whitenack. 2009. An integrated system for publishing environmental observations data. Environ. Modell. Softw. 24:879–888. doi:10.1016/j.envsoft.2009.01.002

Hsu, K., H.V. Gupta, and S. Sorooshian. 1995. Artificial neural network modeling of the rainfall–runoff process. Water Resour. Res. 31:2517–2530. doi:10.1029/95WR01955

Hsu, L., E. Mayorga, J.S. Hornburgh, M.R. Carter, K.A. Lehnert, and S.L. Brantley. 2017. Enhancing interoperability and capabilities of earth science data using the Observations Data Model 2 (ODM2). Data Sci. J. 16:4. doi:10.5334/dsj-2017-004

Hubbard, S.S., K.H. Williams, D. Agarwal, J. Banfield, H. Beller. N. Bouskill, et al. 2018. The East River, Colorado, watershed: A mountainous community testbed for improving predictive understanding of multi-scale hydrological–biogeochemical dynamics. Vadose Zone J. 17:180061. doi:10.2136/vzj2018.03.0061

Jankowfsky, S., F. Branger, I. Braud, F. Rodriguez, S. Debionne, and P. Viallet. 2014. Assessing anthropogenic influence on the hydrology of small peri-urban catchments: Development of the object-oriented PUMMA model by integrating urban and rural hydrological models. J. Hydrol. 517:1056–1071. doi:10.1016/j.jhydrol.2014.06.034

Jiang, P., M. Elag, P. Kumar, S.D. Peckham, L. Marini, and L. Rui. 2017. A service-oriented architecture for coupling web service models using the Basic Model Interface (BMI). Environ. Modell. Softw. 92:107–118. doi:10.1016/j.envsoft.2017.01.021

Jourdain, C., P. Belleudy, M. Tal, and J.-R. Malavoi. 2017. The role of hydrology on vegetation removal in a heavily managed gravel bed river: The Isere, Combe de Savoie, France. Geomorphol. Relief Processus Environ. 23:203–217. doi:10.4000/geomorphologie.11761

Jourde, H., N. Massei, N. Mazzilli, S. Binet, C. Batiot-Guilhe, D. Labat, et al. 2018. SNO KARST: A French network of observatories for the multidisciplinary study of critical zone processes in karst watersheds and aquifers. Vadose Zone J. 17:180094. doi:10.2136/vzj2018.04.0094

Karan, M., M. Liddell, S.M. Prober, S. Arndt, J. Beringer, M. Boer, et al. 2016. The Australian SuperSite Network: A continental, long-term terrestrial ecosystem observatory. Sci. Total Environ. 568:1263–1274. doi:10.1016/j.scitotenv.2016.05.170

Kirchner, J.W. 2006. Getting the right answer for the right reasons: Linking measurements, analyses, and models to advance the science of hydrology. Water Resour. Res. 42:W03S04. doi:10.1029/2005WR004362

Kirchner, J.W. 2009. Catchments as simple dynamical systems: Catchment characterization, rainfall–runoff modeling, and doing hydrology backward. Water Resour. Res. 45:W02429. doi:10.1029/2008WR006912

Klepikova, M.V., T. Le Borgne, O. Bour, M. Dentz, R. Hochreutener, and N. Lavenant. 2016. Heat as a tracer for understanding transport processes in fractured media: Theory and field assessment from multiscale thermal push–pull tracer tests. Water Resour. Res. 52:5442–5457. doi:10.1002/2016WR018789

Klepikova, M.V., T. Le Borgne, O. Bour, K. Gallagher, R. Hochreutener, and N. Lavenant. 2014. Passive temperature tomography experiments to characterize transmissivity and connectivity of preferential flow paths in fractured media. J. Hydrol. 512:549–562. doi:10.1016/j.jhydrol.2014.03.018

Kollet, S.J., and R.M. Maxwell. 2006. Integrated surface–groundwater flow modeling: A free-surface overland flow boundary condition in a parallel groundwater flow model. Adv. Water Resour. 29:945–958. doi:10.1016/j.advwatres.2005.08.006

Kralisch, S., and P. Krause. 2006. JAMS: A framework for natural resource model development and application. In: A. Voinov et al., editors, Summit on Environmental Modelling and Software: Proceedings of the iEMSs 3rd Biannual Meeting, Burlington, VT. 9–13 July 2006. http://www.iemss.org/iemss2006/papers/s5/254_Kralisch_1-4.pdf

Krinner, G., N. Viovy, N. de Noblet-Ducoudré, J. Ogée, J. Polcher, P. Friedlingstein, et al. 2005. A dynamic global vegetation model for studies of the coupled atmosphere–biosphere system. Global Biogeochem. Cycles 19:GB1015. doi:10.1029/2003GB002199

Kulmala, M. 2018. Build a global Earth observatory. Nature 553:21–23. doi:10.1038/d41586-017-08967-y

Lagacherie, P., M. Rabotin, F. Colin, R. Moussa, and M. Voltz. 2010. Geo-MHYDAS: A landscape discretization tool for distributed hydrological modeling of cultivated areas. Comput. Geosci. 36:1021–1032. doi:10.1016/j.cageo.2009.12.005

Latour, B. 2014. Some advantages of the notion of "critical zone" for geopolitics. Procedia Earth Planet Sci. 10:3–6. doi:10.1016/j.proeps.2014.08.002

Latour, B. 2018. Down to Earth: Politics in the new climatic regime. Polity Press, Cambridge, UK.

Le, P.V.V., and P. Kumar. 2017. Interaction between ecohydrologic dynamics and microtopographic variability under climate change. Water Resour. Res. 53:8383–8403. doi:10.1002/2017WR020377

Le Borgne, T., M. Dentz, and E. Villermaux. 2013. Stretching, coalescence, and mixing in porous media. Phys. Rev. Lett. 110:204501. doi:10.1103/PhysRevLett.110.204501

Le Boursicaud, R., L. Pénard, A. Hauet, F. Thollet, and J. Le Coz. 2016. Gauging extreme floods on YouTube: application of LSPIV to home movies for the post-event determination of stream discharges. Hydrol. Processes 30:90–105. doi:10.1002/hyp.10532

Legchenko, A., J. Vouillamoz, F. Lawson, C. Alle, M. Descloitres, and M. Boucher. 2016. Interpretation of magnetic resonance measurements in the varying Earth's magnetic field. Geophysics 81:WB23–WB31. doi:10.1190/geo2015-0474.1

Lehnert, K., D. Walker, C. Chan, and J. Ash. 2010. EarthChem: Next generation of data services in geochemistry. Geochim. Cosmochim. Acta 74:A578.

Leonard, L., and C.J. Duffy. 2014. Automating data-model workflows at a Level 12 HUC scale: Watershed modeling in a distributed computing environment. Environ. Modell. Softw. 61:174–190. doi:10.1016/j.envsoft.2014.07.015

Leray, S., J.R. de Dreuzy, O. Bour, T. Labasque, and L. Aquilina. 2012. Contribution of age data to the characterization of complex aquifers. J. Hydrol. 464-465:54–68. doi:10.1016/j.jhydrol.2012.06.052

Lewis, S.L., and M.A. Maslin. 2015. Defining the Anthropocene. Nature 519:171–180. doi:10.1038/nature14258

Liu, Y., A.H. Weerts, M. Clark, H.J. Hendricks Franssen, S. Kumar, H. Moradkhani, et al. 2012. Advancing data assimilation in operational hydrologic forecasting: Progresses, challenges, and emerging opportunities.

Hydrol. Earth Syst. Sci. 16:3863–3887. doi:10.5194/hess-16-3863-2012

Mangiarotti, S., J.M. Martinez, M.P. Bonnet, D.C. Buarque, N. Filizola, and P.M. Ciamp. 2013. Discharge and suspended sediment flux estimated along the mainstream of the Amazon and the Madeira rivers (from in situ and MODIS satellite data). Int. J. Appl. Earth Obs. Geoinf. 21:341–355. doi:10.1016/j.jag.2012.07.015

Massol, M., and O. Rouchon. 2010. Quality insurance through business process management in a French archive. Paper presented at: 7th International Conference on Preservation of Digital Objects, Vienna. 19–24 Sept. 2010. http://www.ifs.tuwien.ac.at/dp/ipres2010/papers/massol-6.pdf

Masson, V., P. Le Moigne, E. Martin, S. Faroux, A. Alias, R. Alkama, et al. 2013. The SURFEXv7.2 land and ocean surface platform for coupled or offline simulation of Earth surface variables and fluxes. Geosci. Model Dev. 6:929–960. doi:10.5194/gmd-6-929-2013

Maxwell, R.M., and N.L. Miller. 2005. Development of a coupled land surface and groundwater model. J. Hydrometeorol. 6:233–247. doi:10.1175/JHM422.1

Mazzilli, N., M. Boucher, K. Chalikakis, A. Legchenko, H. Jourde, and C. Champollion. 2016. Contribution of magnetic resonance soundings for characterizing water storage in the unsaturated zone of karst aquifers. Geophysics 81:WB49–WB61. doi:10.1190/geo2015-0411.1

Mazzilli, N., V. Guinot, H. Jourde, N. Lecoq, D. Labat, B. Arfib, et al. 2017. KarstMod: A modelling platform for rainfall–discharge analysis and modelling dedicated to karst systems. Environ. Modell. Softw. doi:10.1016/j.envsoft.2017.03.015

McDonnell, J.J. 2017. Beyond the water balance. Nat. Geosci. 10:396. doi:10.1038/ngeo2964

McDonnell, J.J., M. Sivapalan, K. Vaché, S. Dunn, G. Grant, R. Haggerty, et al. 2007. Moving beyond heterogeneity and process complexity: A new vision for watershed hydrology. Water Resour. Res. 43:W07301. doi:10.1029/2006WR005467.

Michielin, Y., G. Nord, M. Esteves, T. Geay and A. Hauet. 2017. River Platform for Monitoring Erosion (RIPLE) in mountainous rivers. In: 19th EGU General Assembly, EGU2017: Proceedings from the conference, Vienna. 23–28 Apr. 2017. p.10300.

Millennium Ecosystem Assessment Board. 2005. Living beyond our means: Natural assets and human well-being. Island Press, Washington, DC.

Mirtl, M., E.T. Borer, I. Djukic, M. Forsius, H. Haubold, W. Hugo, et al. 2018. Genesis, goals and achievements of long-term ecological research at the global scale: A critical review of ILTER and future directions. Sci. Total Environ. 626:1439–1462. doi:10.1016/j.scitotenv.2017.12.001

Morin, S., Y. Lejeune, B. Lesaffre, J.M. Panel, D. Poncet, P. David, and M. Sudul. 2012. An 18-yr long (1993–2011) snow and meteorological dataset from a mid-altitude mountain site (Col de Porte, France, 1325 m alt.) for driving and evaluating snowpack models. Earth Syst. Sci. Data 4:13–21. doi:10.5194/essd-4-13-2012

Moussa, R., M. Voltz, and P. Andrieux. 2002. Effects of the spatial organization of agricultural management on the hydrological behaviour of a farmed catchment during flood events. Hydrol. Processes 16:393–412. doi:10.1002/hyp.333

National Research Council. 2001. Basic research opportunities in Earth science. Natl. Acad. Press, Washington, DC.

Nord, G., B. Boudevillain, A. Berne, F. Branger, I. Braud, G. Dramais, et al. 2017. A high space–time resolution dataset linking meteorological forcing and hydro-sedimentary response in a mesoscale Mediterranean catchment (Auzon) of the Ardèche region, France. Earth Syst. Sci. Data 9:221–249. doi:10.5194/essd-9-221-2017

Paris, A., R. Dias de Paiva, J. Santos da Silva, D. Medeiros Moreira, S. Calmant, P.-A. Garambois, et al. 2016. Stage-discharge rating curves based on satellite altimetry and modeled discharge in the Amazon basin. Water Resour. Res. 52:3787–3814. doi:10.1002/2014WR016618

Pasquet, S., L. Bodet, L. Longuevergne, A. Dhemaied, C. Camerlynck, F. Rejiba, and R. Guérin. 2015. 2D characterization of near-surface VP/VS: Surface-wave dispersion inversion versus refraction tomography. Near Surf. Geophys. 13:315–331. doi:10.3997/1873-0604.2015028

Peckham, S.D., E.W.H. Hutton, and B. Norris. 2013. A component-based approach to integrated modeling in the geosciences: The design of CSDMS. Comput. Geosci. 53:3–12. doi:10.1016/j.cageo.2012.04.002

Piacentini, A. 2003. PALM: A dynamic parallel coupler, in high performance computing for computational science. In: J.M.L.M. Palma et al., editors, VECPAR 2002: 5th International Conference, Selected Papers and Invited Talks, Porto, Portugal. 26–28 June 2002. Springer, Berlin. p. 479–492. doi:10.1007/3-540-36569-9_32

Picard, G., L. Arnaud, J.-M. Panel, and S. Morin. 2016a. Design of a scanning laser meter for monitoring the spatio-temporal evolution of snow depth and its application in the Alps and in Antarctica. Cryosphere 10:1495–1511. doi:10.5194/tc-10-1495-2016

Picard, G., Q. Libois, L. Arnaud, G. Verin, and M. Dumont. 2016b. Development and calibration of an automatic spectral albedometer to estimate near-surface snow SSA time series. Cryosphere 10:1297–1316. doi:10.5194/tc-10-1297-2016

Pinay, G., S. Peiffer, J.-R. De Dreuzy, S. Krause, D.M. Hannah, J.H. Fleckenstein, et al. 2015. Upscaling nitrogen removal capacity from local hotspots to low stream orders' drainage basins. Ecosystems 18:1101–1120. doi:10.1007/s10021-015-9878-5

Read, T., O. Bour, J.S. Selker, V.F. Bense, T.L. Borgne, R. Hochreutener, and N. Lavenant. 2014. Active-distributed temperature sensing to continuously quantify vertical flow in boreholes. Water Resour. Res. 50:3706–3713. doi:10.1002/2014WR015273

Ribolzi, O., O. Evrard, S. Huon, A. De Rouw, N. Silvera, K.O. Latsachack, et al. 2017. From shifting cultivation to teak plantation: Effect on overland flow and sediment yield in a montane tropical catchment. Sci. Rep. 7:3987. doi:10.1038/s41598-017-04385-2

Richard, A., S. Galle, M. Descloitres, J.M. Cohard, J.P. Vandervaere, L. Séguis, and C. Peugeot. 2013. Interplay of riparian forest and groundwater in the hillslope hydrology of Sudanian West Africa (northern Benin). Hydrol. Earth Syst. Sci. 17:5079–5096. doi:10.5194/hess-17-5079-2013

Richter, D.deB., and S.A. Billings. 2015. 'One physical system': Tansley's ecosystem as Earth's critical zone. New Phytol. 206:900–912. doi:10.1111/nph.13338

Robinson, D.A., A. Binley, N. Crook, F.D. Day-Lewis, T.P.A. Ferré, V.J.S. Grauch, et al. 2008. Advancing process-based watershed hydrological research using near-surface geophysics: A vision for, and review of, electrical and magnetic geophysical methods. Hydrol. Processes 22:3604–3635. doi:10.1002/hyp.6963

Sanzana, P., J. Gironás, I. Braud, F. Branger, F. Rodriguez, X. Vargas, et al. 2017. A GIS-based urban and peri-urban landscape representation toolbox for hydrological distributed modeling. Environ. Modell. Softw. 91:168–185. doi:10.1016/j.envsoft.2017.01.022

Savenije, H.H.G., and M. Hrachowitz. 2017. HESS Opinions "Catchments as meta-organisms: A new blueprint for hydrological modelling." Hydrol. Earth Syst. Sci. 21:1107–1116. doi:10.5194/hess-21-1107-2017

Schuite, J., L. Longuevergne, O. Bour, F. Boudin, S. Durand, and N. Lavenant. 2015. Inferring field-scale properties of a fractured aquifer from ground surface deformation during a well test. Geophys. Res. Lett. 42:10696–10703. doi:10.1002/2015GL066387

Shortridge, J.E., S.D. Guikema, and B.F. Zaitchik. 2016. Machine learning methods for empirical streamflow simulation: A comparison of model accuracy, interpretability, and uncertainty in seasonal watersheds. Hydrol. Earth Syst. Sci. 20:2611–2628. doi:10.5194/hess-20-2611-2016

Sivapalan, M. 2003. Process complexity at hillslope scale, process simplicity at the watershed scale: Is there a connection? Hydrol. Processes 17:1037–1041. doi:10.1002/hyp.5109

Sivapalan, M., H.H.G. Savenije, and G. Bloeschl. 2012. Socio-hydrology: A new science of people and water. Hydrol. Processes 26:1270–1276. doi:10.1002/hyp.8426

Steefel, C.I., C.A.J. Appelo, B. Arora, D. Jacques, T. Kalbacher, O. Kolditz, et al. 2015. Reactive transport codes for subsurface environmental simulation. Comput. Geosci. 19:445–478. doi:10.1007/s10596-014-9443-x

Steffen, W., K. Richardson, J. Rockström, S.E. Cornell, I. Fetzer, E.M. Bennett, et al. 2015. Planetary boundaries: Guiding human development on a changing planet. Science 347:1259855. doi:10.1126/science.1259855

Sullivan, P.L., L. Ma, N. West, L. Jin, D.L. Karwan, J. Noireaux, et al. 2016. CZ-tope at Susquehanna Shale Hills CZO: Synthesizing multiple isotope proxies to elucidate critical zone processes across timescales in a temperate forested landscape. Chem. Geol. 445:103–119.

doi:10.1016/j.chemgeo.2016.05.012

Sullivan, P.L., A.S. Wymore, and W.H. McDowell. 2017. New opportunities for critical zone science: 2017 Arlington meeting for CZO science white booklet. Critical Zone Observ., State College, PA.

Trouvilliez, A., F. Naaim-Bouvet, H. Bellot, C. Genthon, and H. Gallee. 2015. Evaluation of the FlowCapt acoustic sensor for the aeolian transport of snow. J. Atmos. Ocean. Technol. 32:1630–1641. doi:10.1175/JTECH-D-14-00104.1

Trouvilliez, A., F. Naaim-Bouvet, C. Genthon, L. Piard, V. Favier, H. Bellot, et al. 2014. A novel experimental study of aeolian snow transport in Adelie Land (Antarctica). Cold Reg. Sci. Technol. 108:125–138. doi:10.1016/j.coldregions.2014.09.005

United Nations. 2015. About the sustainable development goals. UN, New York. http://www.un.org/sustainabledevelopment/sustainable-development-goals/

Valentin, C., F. Agus, R. Alamban, A. Boosaner, J.P. Bricquet, V. Chaplot, et al. 2008. Runoff and sediment losses from 27 upland catchments in Southeast Asia: Impact of rapid land use changes and conservation practices. Agric. Ecosyst. Environ. 128:225–238. doi:10.1016/j.agee.2008.06.004

Vannier, O., S. Anquetin, and I. Braud. 2016. Investigating the role of geology in the hydrological response of Mediterranean catchments prone to flash-floods: Regional modelling study and process understanding. J. Hydrol. 541A:158–172. doi:10.1016/j.jhydrol.2016.04.001

Vernadsky, V.I. 1998. The biosphere. Copernicus, New York.

Vionnet, V., G. Guyomarc'h, M. Lafaysse, F. Naaim-Bouvet, G. Giraud and Y. Deliot. 2018. Operational implementation and evaluation of a blowing snow scheme for avalanche hazard forecasting. Cold Reg. Sci. Technol. 147:1–10. doi:10.1016/j.coldregions.2017.12.006

Welber, M., J. Le Coz, J.B. Laronne, G. Zolezzi, D. Zamler, G. Dramais, et al. 2016. Field assessment of noncontact stream gauging using portable surface velocity radars (SVR). Water Resour. Res. 52:1108–1126. doi:10.1002/2015WR017906

White, T., S. Brantley, S. Banwart, J. Chorover, W. Dietrich, L. Derry, et al. 2015. The role of critical zone observatories in critical zone science. In: J.R. Giardino and C. Hauser, editors, Principles and dynamics of the critical zone. Dev. Earth Surf. Processes 19. Elsevier, Amsterdam. p. 15–78.

Wigmosta, M.S., B. Nijssen, P. Storck, and D.P. Lettenmaier. 2002. The distributed hydrology soil vegetation model. In: V.P. Singh and D.K. Frevert, editors, Mathematical models of small watershed hydrology and applications. Water Resour. Publ., Littleton, CO. p. 7–42.

Yu, X., C. Duffy, Y. Gil, L. Leonard, G. Bhatt, and E. Thomas. 2016. Cyber-innovated watershed research at the Shale Hills Critical Zone Observatory. IEEE Syst. J. 10:1239–1250. doi:10.1109/JSYST.2015.2484219

Zacharias, S., H. Bogena, L. Samaniego, M. Mauder, R. Fuß, T. Pütz, et al. 2011. A network of terrestrial environmental observatories in Germany. Vadose Zone J. 10:955–973. doi:10.2136/vzj2010.0139

Zaslavsky, I., T. Whitenack, M. Williams, D.G. Tarboton, K. Schreuders, and A. Aufdenkampe. 2011. The initial design of data sharing infrastructure for the Critical Zone Observatory. In: M.B. Jones and C. Gries, editors, Proceedings of the Environmental Information Management Conference (EIM2011), Santa Barbara, CA. 28–29 Sept. 2011. Univ. of California, Santa Barbara. p. 145–150. doi:10.5060/D2NC5Z4X