Vadose Zone J. Accepted Paper, posted 08/30/2018. doi:10.2136/vzj2018.04.0067

OZCAR: the French network of Critical Zone Observatories

Gaillardet J.[1], Braud I.[2], Hankard F.[1], Anquetin S.[3], Bour O.[4], Dorfliger N.[5], de Dreuzy J.R.[4], Galle S.[3], Galy C.[6], Gogo S.[7], Gourcy L.[5], Habets F[8]., Laggoun F.[7], Longuevergne L.[4], Le Borgne T.[4], Naaim-Bouvet F.[9], Nord G.[3], Simonneaux V.[10], Six D.[3], Tallec T.[10], Valentin C.[11]

Abril G.[12], Allemand P.[13], Arènes A.[14], Arfib B.[15], Arnaud L.[3], Arnaud N.[16,29], Arnaud P.[17], Audry S.[18], Bailly Comte V.[19], Batiot C.[20], Battais A.[4], Bellot H.[9], Bernard E.[21], Bertrand C.[22], Bessière H.[5], Binet S.[7], Bodin J.[23], Bodin X.[24], Boithias L.[18], Bouchez J.[1], Boudevillain B.[3], Bouzou Moussa I.[25], Branger F.[2], Braun J. J.[18], Brunet P.[20], Caceres B.,[26] Calmels D.[27], Cappelaere B.[20], Celle-Jeanton H.[22], Chabaux F.[28], Chalikakis K.[29], Champollion C.[30], Copard Y.[31], Cotel C.[28], Davy P.[4], Deline P.[24], Delrieu, G.[3], Demarty J.[20], Dessert C.[1], Dumont M.[32], Emblanch C.[29], Ezzahar J.[33], Estèves M.[3], Favier V.[3], Faucheux M.[34], Filizola N.[35], Flammarion P.[36], Floury F.[1], Fovet O.[34], Fournier M.[31], Francez A. J.[37], Gandois L.[46], Gascuel C.[34], Gayer E.[1], Genthon C.[3], Gérard M. F.[4], Gilbert D.[22], Gouttevin I.[32], Grippa M.[18], Gruau G.[4], Jardani A.[31], Jeanneau L.[4], Join J. L.[38], Jourde H.[20], Karbou F.[32], Labat D.[18], Lagadeuc Y.[37], Lajeunesse E.[1], Lastennet R.[39], Lavado W.[42], Lawin, E.[47], Lebel T.[3], Le Bouteiller, C.[9], Legout C.[3], Le Meur E.[3], Le Moigne N.[31], Lions J.[5], Lucas A.[1], Malet, J. P.[41], Marais-Sicre C.[11], Maréchal J. C.[19], Marlin C.[27,42], Martin P.[43], Martins J.[3], Martinez J. M.[18], Massei N.[31], Mauclerc A.[5], Mazzilli N.[29], Molénat, J.[44], Moreira-Turcq P.[18], Mougin E.[3], Morin S.[32], Ndam Ngoupayou J.[45], Panthou G.[3], Peugeot C.[18], Picard G.[3], Pierret M. C.[28], Porel G.[23], Probst A.[46], Probst J. L.[46], Rabatel A.[3], Raclot D.[44], Ravanel L.[24], Rejiba F.[31], René P.[48], Ribolzi, O.[18], Riotte J.[18], Rivière A.[49], Robain H.[11], Ruiz L.[34], Sanchez-Perez J. M.[46], Santini W.[18], Sauvage S.[46], Schoeneich P.[50], Seidel J. L.[20], Sekhar M.[51], Sengtaheuanghoung O.[52], Silvera N.[11], Steinmann M.[22], Soruco A.[53], Tallec G.[54], Thibert E.[9], Valdes Lao D.[55], Vincent C.[3], Viville D.[28], Wagnon P.[3], Zitouna R.[56]

Affiliations

1. IPGP, Sorbonne Paris Cité, University Paris Diderot, CNRS, Paris 75231, France
2. IRSTEA, UR RiverLy, centre de Lyon-Villeurbanne, 69625 Villeurbanne, France
3. Université Grenoble Alpes, CNRS, IRD, Grenoble-INP, IGE, 38000 Grenoble, France
4. Géosciences Rennes, UMR 6118, CNRS, Université Rennes 1, Rennes, France
5. BRGM. Water Environment and Ecotechnologies Division. Orléans, France
6. ANDRA Research and development division, 55290 Bure, France.
7. UMR ISTO, CNRS, BRGM, Université d'Orléans, Orléans, France
8. UMR Métis, Sorbonne Université, UPMC, CNRS, Paris 75252, France.
9. Univ. Grenoble Alpes, Irstea, UR ETNA
10. Centre d'Etudes Spatiales de la Biosphère, Toulouse, France
11. iEES-Paris, SU, USPC, UPEC, CNRS, INRA, IRD, F-93140 Bondy, France.
12. UMR BOREA, MNHN, Paris, France.
13. Université de Lyon, UCBL, ENSL, CNRS, LGL-TPE, 69622 Villeurbanne, France
14. SOC - Société d'Objets Cartographiques, Paris, France

15. Aix Marseille Univ, CNRS, IRD, Coll France, CEREGE, Aix-en-Provence, France
16. CNRS INSU, Paris, France.
17. IRSTEA, UR Recover, Aix en Provence, France
18. Géosciences Environnement Toulouse (GET), CNRS, IRD, UPS, Toulouse, France
19. BRGM, D3E, NRE, 1039 rue de Pinville, 34000 Montpellier, France,
20. Hydrosciences Montpellier (HSM), Univ. Montpellier, CNRS, IRD, Montpellier, France
21. Univ. Franche-Comte, Théma, Besançon, France
22. Université Bourgogne/Franche-Comté, CNRS, Chrono-environnement-UMR 6249, Besançon, France
23. IC2MP, CNRS Université de Poitiers, Poitiers France.
24. Univ. Savoie, Edytem, le Bourget de Lac, France
25. Univ. Abdou Moumouni (UAM), Niamey, Niger
26. INAMHI, Quito, Ecuador
27. GEOPS, Univ. Paris-Sud, CNRS, Université Paris-Saclay, Orsay, France
28. UMR LHyGeS, EOST, Université de Strasbourg, Strasbourg, France
29. UAPV, UMR1114 EMMAH, F-84914 Avignon, France
30. Géosciences Montpellier, CNRS, Université Montpellier, UA, F-34095 Montpellier, France.
31. Normandie Univ, UNIROUEN, UNICAEN, CNRS, M2C, 76000 Rouen, France
32. Météo-France - CNRS, CNRM UMR 3589, Centre d'Etudes de la Neige, Grenoble, France
33. Ecole Nationale des Sciences Appliquées (ENSA), Université Cadi Ayyad, Safi, Morocco
34. UMR SAS, INRA, Agrocampus Ouest, Rennes, France
35. Amazonas State University (UFAM), Geography Department, Manaus, Brazil
36. IRSTEA Présidence, Antony, France
37. Univ Rennes, CNRS, Ecobio - UMR 6553, F-35000 Rennes, France.
38. Université de la Réunion, Saint Denis de la Réunion, France.
39. Université de Bordeaux, Laboratoire I2M, UMR 5295, France
40. Peruvian National Service of Meteorology and Hydrology (SENAMHI), Lima, Peru
41. IPGS, EOST, Strasbourg, France.
42. Ministère de l'Enseignement Supérieur, la Recherche et l'Innovation, DGRI/SSRI, Paris, France.
43. Université d'Avignon et des Pays de Vaucluse, UMR ESPACE 7300 du CNRS, 84029 Avignon cedex, France
44. LISAH, Univ Montpellier, INRA, IRD, Montpellier SupAgro, Montpellier, France
45. Department of Earth Sciences, University of Yaoundé 1, Yaoundé, Cameroon
46. EcoLab, Université de Toulouse, CNRS, INPT, UPS, Toulouse, France
47. Université d'Abomey Calavi, Benin
48. Association Moraine, Luchon, France
49. Mines ParisTech, PSL, géosciences. Fontainebleau, France.
50. Univ. Grenoble Alpes, Pacte, Grenoble, France
51. Indian Institute of Science and Indo-French Cell for Water Sciences, Bangalore, India.
52. Department of Agricultural Land Management (DALaM), Vientiane, Lao PDR
53. UMSA, University of La Paz, Bolivia
54. IRSTEA, UR Hycar, 92 761 Antony, France
55. UPMC Univ Paris 06, UMR 7619 METIS, 4 Place Jussieu, F-75005 Paris, France
56. INRGREF, Tunis, Tunisia

Vadose Zone J. Accepted Paper, posted 08/30/2018. doi:10.2136/vzj2018.04.0067

Abstract

This paper presents the French Critical Zone initiative, called OZCAR (Observatoires de la Zone Critique –Application et Recherche – Critical Zone Observatories – Application and Research), a National Research Infrastructure (RI). OZCAR-RI is a network of instrumented sites, organized in 21 pre-existing research observatories, or observation services, and monitoring over the long term, different compartments of the zone situated between "the rock and the sky", the Earth's skin or Critical Zone (CZ). These observatories are regionally-based and all have their individual 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 Critical Zone and of the scientific communities studying it.

Despite this diversity, all OZCAR-RI sites share a main overarching scientific question, which is: how to monitor, understand and predict ("earthcast") the fluxes of water, solutes, gases and sediments of the Earth's near surface and how they will change in response to the "new climatic regime" (climate change, land use and land cover changes).

We describe in this paper a vision for OZCAR strategic development in the next decade, aiming at designing an open infrastructure, building a national CZ community able to share a common and systemic representation of CZ dynamics, and educating a new generation of scientists more apt to tackle the wicked problem of the Anthropocene. We propose to articulate OZCAR around the following main points: i) a set of common scientific questions and cross-cutting scientific activities using the wealth of OZCAR-RI observatories along gradients and the diverse disciplines, ii) an ambitious instrumental development program, iii) a better interaction between data and models as a way of integrating the different time and spatial scales as well as fostering dialogue between communities.

At the international level, OZCAR-RI aimed at strengthening the CZ community by providing

a model of organization for pre-existing observatories and by widening the range of CZ instrumented sites. Embedded into the international CZ initiative, OZCAR is one of the French mirrors of the European eLTER-ESFRI (European Strategy Forum on Research Infrastructure) project.

Keywords: Critical Zone, Observatories, long-term observation, Earthcast, modeling, eLTER

1. Introduction

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 to the last million years since *Homo Sapiens* have lived on the planet. This "great acceleration" (Lewis and Maslin, 2015) has global manifestations, the more evident 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 dangerously be 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, energy (Banwart et al., 2013), and is critical for the sustainability of the economical and recreational services they provide (Easterling, 2007; Millenium Ecosystem Assessment Board, 2005). Achieving the Sustainable Development

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Goals (UN, 2015) requires better understanding and prediction of the functions of this “critical zone”.

The term “Critical Zone” (CZ) was defined by the U.S. National Research Council (NRC), as the zone extending from the top of the canopy down to the base of the groundwater zone. NRC listed the study of this “CZ” as one of the Basic Research Opportunities in the Earth Sciences (U.S. National Research Council Committee on Basic Research Opportunities in the Earth Sciences, 2001). The term “critical” emphasizes two notions. First is that the CZ is one of the main planetary interfaces of 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 Earth’s surface is close to that developed one century ago by Vladimir Vernadsky (1998), re-defining 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 the million year to the second, and by relocalizing environmental questions at the local/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 different scientific disciplines of geosciences and biosciences (climatology, meteorology, glaciology, snow sciences, hydrometeorology, hydrology, hydrogeology, geochemistry, geomorphology, geophysics, land surface interactions, pedology, agronomy, ecology, 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). CZEN aims to create a worldwide community of researchers and educators who study the physical, chemical and biological processes shaping and transforming 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 coveringx Earth's surface. This integrated scientific approach must take into account short and long time scales, the interaction between deep subsurface processes and their coupling with above ground 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 US, 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. This paper presents the French Critical Zone initiative, called OZCAR (Observatoires de la Zone Critique –Application et Recherche – Critical Zone Observatories – Application and Research), a National Research Infrastructure (RI). The aim of this paper is to provide an overview of the OZCAR network, its objectives, components, scientific questions and data management (section 2); the current status of instrumentation (section 3) along with that of databases and metadatabases (section 4), and existing initiatives for linking data and models

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based on OZCAR data (section 5). The discussion (section 6) 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 in this paper were discussed during the kickoff meeting of OZCAR held in Paris, Feb 7, 2017.

2. Presentation of the OZCAR network

2.1. OZCAR, a network of networks

OZCAR is a Research Infrastructure launched in December 2015 with the support from the French Ministry of Education and Research. OZCAR gathers and organizes more than 60 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, more than 50 years ago. The details of OZCAR constitutive observatories and sites are in **Table S1**. All these observatories share however the same characteristic of being highly instrumented areas designed to answer 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 (**Table S1**). They cover different compartments of the CZ (**Fig. 2**).

Over 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 Earth's terrestrial surface.

2.2. 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.

2.2.1. **The RBV network** (Réseau des Bassins Versants) is constituted of catchments ranging from zero order basins to the whole Amazon River system (see **Table S1** in supplementary material for the 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 more than 40 years. They have all been designed to address a specific basic or applied scientific question, span climate gradients ranging from the 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 RBV are monitored karst systems as complex hydro-geol-ogic entities that are characterized by strong surface/subsurface interactions and significant water, mass, energy, and geochemical transport within the CZ. RBV also addresses larger scale (typically continental issues such as the concurrent role of climate and land-use changes on 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

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the Strengbach stream since 1986 (**Fig. 4**; OHGE, Vosges, France). 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 emission by European and North American industries since the 1980's.

2.2.2. 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.

2.2.3. The **CRYOBS-CLIM** observatory focuses on the cryosphere. It aims to answer the following scientific questions: i) How will climate changes impact surface energy and mass budgets of snow / ice-covered surfaces and permafrost ground temperature at different spatial (local to regional) and temporal (seasonal to multidecadal) scales? ii) How will snow/climate feedback mechanisms enhance or attenuate glacier, ice sheet and permafrost changes in the near future? How can observations help to identify climate models weaknesses and to improve the simulations of cryosphere components? iii) What is the future snow and ice-cover retreat and wastage and what will be the impact on water resources and sea level rise? iv) How do 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 **Table S1**.

2.2.4. 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 carbon sink function and the hydrological budget of temperate and sub-boreal peatlands which are ecosystems containing a third of the global surface carbon stock in an area accounting for only 3-5% of the land surface. The French sites were set up in 2008-2010, according to a climatic gradient (lowland to mountain climate), to ensure long-term monitoring of greenhouse gases (GHG: CO_2, CH_4, H_2O, N_2O), dissolved and particulate organic carbon (DOC, POC) fluxes as well as environmental variables that impact GHG, DOC and POC fluxes, and to generate interoperable databases.

2.2.5. The **OSR (Regional Spatial Observatory)** 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 south-west France and in Morocco (Tensift Basin). The specific OSR approach is the extensive use of remote sensing for surface characterization (land use,

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vegetation cover, evapotranspiration, soil moisture, snow cover, etc.) combined with a multi-scale monitoring network of (1) continuous long-term monitoring of experimental plots (crop and snow sites), (2) hundreds of plots annually monitored for surface state, land cover, etc., and (3) experiments conducted at catchment scale with reinforced observations for water and energy budget evaluation.

2.2.6. The **ROSES** (Observatory network for groundwater systems at 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-moniroring 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.

2.2.7. **OPE** (Long-lasting Observatory of the Environment) focuses on a landscape in the eastern part of the Paris Basin (a few hundred km²) around the site pre-selected as the French deep geological repository of high-level and intermediate-level long-lived radioactive wastes. OPE is currently constituted of a monitoring network, covering forest and agricultural areas and measuring atmospheric, meteorological, soil, surface and ground water, 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 over 100 years (if accepted).

2.3. Exploring the CZ with OZCAR observatories

As demonstrated 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. **Table S1** shows that the current situation is quite diverse in terms of monitored CZ compartments and scales, and 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 snow sciences.

As shown in **Fig. 5** and **Table S1**, the OZCAR sites are located all around the world. In France, they include sites in overseas territories like the tropical Caribbeans and Reunion Island. 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, south-east Asia, India, and Amazonia, Andean, Arctic, Antarctica, and Himalayan nations). The sites then cover a large range of climates (oceanic, continental, mountainous, Mediterranean, tropical, polar), lithology (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

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(climate change, land use changes, changes in practices).

3. 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, 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 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, UAV 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 method 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, LS-PIV (Large Scale Particle Image Velocimetry) 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 ADCP surveys are used (e.g. Mangiarotti et al., 2013; Paris et al., 2016).

Ground water 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 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 (TDR sensors) and lysimeters allowing soil solution sampling (i.e. one RBV site (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 for capture of extreme flood events. Only a limited number of chemical variables in OZCAR are measured 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 of 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

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standardization. Different sub-networks inside 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 sizes 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 equipments for the temporal and spatial exploration of the Critical Zone at the catchment scale) was to build a shared and centralized instrumental facility for the long-term monitoring and exploration of the CZ complementing and over-performing the existing site-specific equipments of 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, electric resistivity techniques, flux towers, groundwater well equipements). They are typically used to characterize the OZCAR

CZOs. The "state-of-the-science" instruments are innovative and emergent (scintillometry, hydrogravimetry, hydrogeodesy, optical fiber sensors, UAV exploration, self-potential and spectral-induced polarization electrical methods, isotopic tracing, reactive and inert gas tracer experiments). Examples of such intrumental developments by the CRITEX community are 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 properties of fractured aquifers, Chatton et al. (2017) for the use of CF-MIMS (Continuous Flow Membrane Inlet Mass Spectrometer) to monitor in-situ N_2, O_2, CO_2, CH_4, N_2O, H_2, He, Ne, Ar, Kr, Xe) at high frequency (1 measure every 1.5 seconds) 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 collaborations. 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 determing soil permittivity and bulk soil conductivity based on the soil dielectric properties (Chavanne and Frangi, 2014); integrative sensors based on DGT (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 developped in CRITEX. For example, the hydrosedimentary platform RIPLE is specifically designed for extreme flood monitoring of mountainous rivers measuring every 10 minutes water, fine and coarse sediment fluxes (Michielin et al., 2017). The "River Lab" is a CRITEX prototype set up upon a "lab-in-the-field" concept, measuring

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the chemical composition (major elements) of the river every 30 minutes (Floury et al., 2017). Finally, the "River Truck" is a mobile laboratory containing instruments for continous 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.

Significant instrumentation efforts have also been achieved by the French cryosphere community. POSSSUM (Profile Of Snow Specific Surface Area Measurement Using SWIR reflectance) is an instrument that measures the specific surface area (SSA, a measure for the grain-size) profile in snow boreholes with a vertical resolution of one centimeter and down to 20 m depth (Arnaud et al., 2011). RLS (Rugged Laser Scan) is an automatic laserscan designed to work in Antarctica that scans an area of 150 m^2 every day and allows for monitoring snow accumulation, roughness change, sastrugi dynamics and more (Picard et al., 2016a). Solexs is an optical instrument for the measurent of irradiance profiles in snow which can be related to snow microstructure and ice absorption (Picard et al. 2016b).

4. 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[1] portal that 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:

[1] http://www.ades.eaufrance.fr/ConsultationPEBSSLocalisation.aspx

metadata only vs. possible downloading of the data; raw data vs. corrected data or more elaborated 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. files 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 (**Table S2**).

In terms of metadata provision, the RBV metadata catalog[2] (André et al., 2015) is a common initiative for providing visibility to the data collected within RBV. It follows the INSPIRE[3] (INfrastructure for SPatial InfoRmation in Europe) 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 however limited because currently the definition of the granularity of datasets is heterogeneous; metadata which are not automatically harvested are quickly obsolete; 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 section 6.2).

5. **Linking data and CZ models within OZCAR**

In this section different modeling initiatives developed by the various scientific communities gathered in OZCAR are reviewed. Surprisingly, despite the wide disciplinary spectrum found in OZCAR, common trends can be depicted and observed at the international scale.

[2] http://portailrbv.sedoo.fr/#WelcomePlace:
[3] http://inspire.ec.europa.eu/

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Classically, models in OZCAR can be classified into process understanding, system understanding and management/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/physically-based models deployed usually at small scales (plot to small catchment scale) that intend to represent processes 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 Appendix (**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 catchment) and are generally addressed. Process representations are often simplified (i.e. process-based models with approaches such as reservoir models) as compared to 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 **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 processes 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, geophysical data and gravimetric measurements (**Fig. 7**) showed that water uptake by deep rooted trees is the main driver of groundwater discharge in 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 ecosystemic functions. The models used for management and prediction purposes are usually inspired from 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 observatory). They are implemented into the French operational chain for avalanche hazard forecasting. Other examples are provided in **Table S3**.

Model integration and coupling between compartments of the CZ requires the development of dedicated tools. Modeling platforms allowing for building 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[4] was specifically designed to represent karstic aquifers and provides flexibility to build

[4] http://www.sokarst.org/index.asp?menu=karstmod

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reservoir-based models of various complexity (Mazzili et al., 2017). LIQUID (Branger et al., 2010) was designed to represent the heterogeneity of land surfaces using an object-oriented approach (representing explicitly 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 modelling 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 (Gumières et al., 2011). Other initiatives 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 periurban catchments) or visualization and analysis of the simulation results (Anquetin et al., 2014).

6. 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 biological heterogeneity of the CZ inherited from the geological and climatic histories at the local scale. OZCAR was designed in order to allow the defragmentation of the CZ community at the national scale. In this section, ambitious actions promoted by OZCAR, which should enable the CZ community to progress towards 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.

6.1 Challenging scientific questions that can be addressed in OZCAR

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: 1) the "dynamical architecture" of the CZ; 2) processes and fluxes that shape the CZ; and 3) CZ feedbacks and responses to perturbations (**Fig. 8**).

6.1.1. Dynamical 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, 1) to identify the role of the different interfaces; 2) to quantify the impact of spatial heterogeneity and temporal intermittence on fluxes, connectivity, concentrations and micro-organisms; and 3) to determine residence and exposure times of material in the CZ. Here, the architecture of the CZ is defined in a dynamical rather than in a static view. The dynamical architecture of the CZ can be translated into a series of questions detailed in the following.

(i) What is the upper, lower and lateral extent of the Critical Zone?

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 in determining how to incorporate atmospheric inputs of dust or of Volatile Organic

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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 multi-layered 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).

Since the CZ is not a 1D 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 to fully address CZ functions. Describing the dynamical 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.

(ii) 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, as it is a direct indicator of its dynamical structure. The residence time concept is typically associated with waters, 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 are shown to change significantly with spatial scale and thus these diverse scales must be investigated, taking advantage of the nested structure of observatories (Billings and Sullivan, in press).

(iii) What are the Critical zone interfaces?

To overcome the inherent difficulty of describing a "dynamical architecture" of the CZ, one can describe the CZ 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 topography, the atmosphere/ice-snow 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).

(iv) What is the role of biota in the CZ architecture?

Biota plays 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).

6.1.2. Processes and budgets: biogeochemical cycles, sediment and contaminant propagation through the CZ from highlands to sea.

The CZ, essentially fueled by solar energy, is controlled by a large number of chemical,

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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 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 biochemical 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 over small spatial scales (grain, plot, hillslope) or may be described over very large scale in the case of large watersheds (Billings and Sullivan, in press). 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.

(i) 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).

(ii) 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/hr to 1/min, depending on the process dynamics) are available. At larger scales, as inter-annual 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.

(iii) 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 top soil. Spatially, the dynamics of organic carbon and nutrients through the mountain to sea continuum also deserves more attention.

6.1.3. 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

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of resources exploitation)? Human activities are now considered as one particular and now prominent forcing factor of Earth's surface, and most of the OZCAR sites have been strongly impacted by human practices over time. As the CZ holds resources and offers goods and services to humanity, understanding how this dynamical 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.

(i) How can we use Critical Zone 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 Earth's surface to changes in global or local forcing parameters, or in short, "Earthcast" (Godderis and Brantley, 2013; Sullivan et al., 2018)? 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 variable) 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 et al., 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).

(ii) 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 crop to teak 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 responds 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 (Sullivan et al., 2018).

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 (Billings and Sullivan, in press).

(iii) 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

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evolution of the CZ caused by heterogeneities or sudden changes would result in different evolutionary patterns? Human actions, fires, sudden erosional events, the importance of extreme events on system evolution are factors that could act as tipping events in the evolution of the CZ which clearly need to be better appreciated and incorporated into CZ models. This is why working with socio-ecology is essential.

6.2. 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 over 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.

(i) Addressing the challenges in instrumentation in order to significantly move forward in our understanding of the CZ 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 like those for atmospheric-ground exchanges of matter and energy (using flux tower or accumulation chambers), or for water levels in piezometers and river gauging stations, but significant progress still needs to be accomplished 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 to 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 lab instruments could be beneficially deployed in the field to decrease required manpower and allow for 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 "snow lab" to probe the surface and the snowpack would also provide a major step forward in the observing capabilities of 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 lab 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

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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, down-hole 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 ecological 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.

(ii) How can OZCAR help achieve significant instrumentation advances in the exploration of the CZ?

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., 2017). Ocean and atmospheric scientists have also made significant progress over the last decades on the real-time acquisition of chemical and physical data that should be of high impact for CZ communities. Existing structures exist like ENVRIplus (an inter ESFRI initiative addressing instrumental challenges) or SPICE (Snow Precipitation Intercomparison Experiment) that 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 WMO 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 along 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 instruments and treat data.

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6.3 Challenges in data management

The large amount and variety of data produced in the OZCAR is expected to increase in the near future due to the increase of 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[5] for environmental data. This requires data to be permanently and freely accessible on-line, 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. 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 juridical status of data (Becard et al., 2016) and technical issues about interoperability between systems often developed independently, the availability of the required expertise for web sites design and maintenance, and of course of associated costs.

(i) The challenges in CZ data and metadata access

Identifying, cataloging, and sharing data within OZCAR is a great challenge, starting from a very heterogeneous situation (see section 3), 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 between existing

[5] http://ec.europa.eu/environment/aarhus/

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 lead to initiatives such as the Hydrologic Information System by the CUAHSI[6] consortium (Horsburgh et al., 2009, 2011) for hydrological observatories, 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 between communities. This led to the development of a second generation of Observation Data Model (Horsburgh et al., 2016; Hsu et al., 2017) handling different kinds of data. Concepts such as the O&M (Observation & Measurement[7]) and SOS (Sensor Observation Service[8]) for data harvesting must also be explored and the cost of their deployment evaluated before designing the OZCAR portal.

(ii) How can OZCAR help achieve progress in CZ data management?

OZCAR aims at building a common metadata/data portal gathering metadata first, thus ensuring data discovery, and going very soon to 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

[6] Consortium of Universities for the Advancement of Hydrological Sciences, https://www.cuahsi.org/
[7] http://www.opengeospatial.org/standards/om
[8] http://www.opengeospatial.org/standards/sos

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standards (e.g. INSPIRE) and can be used for other purposes such as 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 towards a commonly shared vocabulary based on the GCMD[9] (Global Change Master Directory) 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; Diaconnu 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 (Digital Object Identifier), data papers (e.g. Nord et al., 2017; Guyomarc'h et al., 2018) and licensing of the datasets (e.g. Creative Common licenses[10]) 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.

6.4 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

[9] https://earthdata.nasa.gov/about/gcmd/global-change-master-directory-gcmd-keywords

[10] https://creativecommons.org/share-your-work/licensing-types-examples/

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 socio-economic scenarios on all the compartments of the CZ (Godderis 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.

(i) Scientific and technical challenges in linking CZ 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 instrumental progresses listed in section 6.2. 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, non-linearity 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 uses, 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 as data reveal behaviors such as "emergent properties" (Sivapalan, 2003; McDonnell et al., 2007) that cannot be represented by 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

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resolved processes (i.e. "parameterization" as defined by the atmospheric science community).

A second challenge is to progress towards 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 sub-surface (e.g. SURFEX (Masson et al., 2013) or ORCHIDEE[11] (Ducoudre 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; name of variables; etc). Another option is to use couplers such as OPEN-MI[12], OpenPALM[13] (Piacentini, 2003) that generally preserve model legacies and provides 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, 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[14] (Peckham et al., 2013), OpenFLUID[15] (Fabre et al., 2013), and JAMS[16] (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

[11] http://forge.ipsl.jussieu.fr/Orchidee

[12] https://sites.google.com/a/openmi.org/home/dashboard2
[13] http://www.cerfacs.fr/globc/PALM_WEB/
[14] http://csdms.colorado.edu/wiki/Main_Page
[15] http://www.openfluid-project.org/
[16] http://jams.uni-jena.de/

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 hydrogeo-eco-logy, 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

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project, Peckham et al. (2013), CUAHSI community model[17] and web services based on the Basic Model Interface (Jiang et al., 2017)) and needs to be extended to a larger scientific community (Kumar, 2015; 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[18]) in the modeling platform will benefit both observational data and modeling data exploration.

In addition, the availability of new data, at unprecedented space and time resolutions, related to the rapid development of new sensors, high resolution satellite data and data obtained by experimentations 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 data scarce 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 for 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).

(ii) 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

[17] https://www.cuahsi.org/data-models/community-models/
[18] https://www.paraview.org/

OZCAR, including sites highly impacted by human activity, offer opportunities for providing data at small scales (grain, macropore and catchment scale) 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 **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 in section 5. OZCAR will also explore complementarity approaches that are often opposed in the literature, like in the use of detailed mechanistic models (Godderis and Brantley, 2013) versus simplified models able to capture the main functions within the critical zone (Savenije and Hrachowitz, 2017). With the development of adapted assimilation techniques 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 reanalyses 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.

6.5 Structural framework of the OZCAR network: possible topologies for OZCAR

OZCAR gathers scientists from different disciplines, both from 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

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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 GHG and energy fluxes along climate gradients then directly connected to climate models. By contrast, OZCAR, and more generally worldwide CZ or LTER (Long Term Ecological Research) 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[19]. 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 Helmoltz Association (Bogena et al., 2006, Zaccharias 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 US. A hub is a highly instrumented CZO (essentially river catchments) 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

[19] https://www.4p1000.org/

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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 RI dedicated to the study of Earth's surface.

6.6 Insertion into international networks

Born under the leadership of the US-NSF, the CZEN 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 on existing observatories (Sullivan et al., 2017; Feder, 2018). The Biological and

Environmental Research Subsurface Biogeochemistry Program of the Department of Energy (DEO) in the USA has developed the "Watershed Function Project", a instrumented watershed-based network taking a "system-of-systems" approach (Hubbard et al., 2018) and utilizes 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 constituted of 4 distributed observatories exploring the long-term ecological, social, and economic impacts of global change at the regional level by measuring above- and below-ground variables and biosphere parameters, and coupling them to remote sensing techniques (Zaccharias et al., 2011). The EU funded between 2009 and 2014 the SoilTrec program gathering 4 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 UK co-funded in 2016, 6 CZOs 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, Critical Zone and Socio-Ecological Research observatories. This led to an ESFRI (European Strategy Forum on Research Infrastructure) 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 of initiating a dialog between geoscience, bioscience and social science communities, restructuring the existing observatories and co-designing Earth Surface models and observation strategies that take into account socio-economical constrains (Richter and Billings, 2015; Mirtl et al., 2018). Together

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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-NSF-funded program, we hope OZCAR offers a model of integration of pre-existing observatories of the CZ at the national scale motivated by ambitious scientific and educational goals shared by the international community (Sullivan et al. 2017).

7. Conclusions

In this paper, we 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 (CZEN). OZCAR is gathering a number of pre-existing instrumented sites grouped in 21 observatories and used for conducting long-term observations or experimentations and encompassing wide gradients of climate, geology, land use and land cover. The OZCAR network is assembling sites initially developed for hydrometeorological, hydrological, hydrogeological, 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 along 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, 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 data base and metadata base 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 sub-surface models, in particular through a better representation of the coupled water, energy and biogeochemical cycles at all times 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.

8. Acknowledgements

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, CEA, IRSN), 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

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Joint Laboratory, Morocco; lNRGREF, 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; UMSAin 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 DEAL 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 rereadings.

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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 strongly influenced by visible and invisible life activities. The integrated study of Critical Zone relies on the collaboration of different scientific communities, listed non-exhaustively in italic.

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 numbers in parentheses correspond to the list of different observatories described in **Table S1**.

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 **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, Yz: Yzeron.

Fig. 4: The 32-years 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 of sulfate concentration due to the decrease of industrial emissions in Western Europe over the period. Superimposed are seasonal variations and abrupt short-term changes.

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 CZ.

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 in the CZ (at the interface with the atmosphere, in the subsurface and at the outlet of catchments) and ii) multi-disciplinary monitoring of “hot spots” and during “hot moments” of the CZ.

Fig. 7: Simulation of the hydrological cycle components in the Nalohou catchment (AMMA-CATCH Benin observatory) using the ParFlow-CLM Critical Zone model. The model 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) (adpated from Hector et al., 2015).

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(Bottom): simulated saturation along profile A shown in part (b). (b) Map of the Nalohou catchment (0.16 km²) with topographic elevation, instrumentation and ERT profile locations (adapted from Hector et al., (2015). (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); saturation, permanent and perched water table in the inland valley (“bas-fond”) (red) at point 3 in (b) (adapted from Hector et al., 2018).

Fig. 8: The main scientific questions defined by the OZCAR community and discussed in the text.

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

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

n°	ATMOSPHERIC	n°	RIVER
1	Rainfall amount	10	Discharge
2	Air temperature	11	Electrical conductivity
3	Wind velocity	12	Water temperature
4	Wind direction	13	Turbidity
5	Air pressure	14	Suspended sediment concentration
6	Humidity	15	Chemical composition of water
7	Radiation	16	Isotopic composition of water O and H
8	Chemical composition of rain		
9	Isotopic composition of rain O and H		

n°	GROUNDWATER	n°	SURFACES
17	Soil moisture content	23	land use/land cover
18	Groundwater level	24	Chemical composition of agricultural inputs
19	Electrical conductivity of groundwater		
20	Temperature of groundwater		
21	Chemical composition of groundwater		
22	Isotopic composition of groundwater O and H		

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Supplementary material of the paper by Gaillardet et al. « OZCAR, the French network of Critical Zone Observatories ».

Appendix 1: Description of OZCAR observatories (Table S1)

A.1.1. **The RBV network** (Réseau des Bassins Versants) is constituted of catchments ranging from zero order basins to the Amazon river system. The different RBV observatories can be grouped into several categories according to their initial scientific questions.

- Group I. The AMMA-CATCH and OHMCV observation systems can be defined as "hydrometerological observatories", aimed to understand the complex interactions between meteorological events and land surfaces. AMMA-CATCH is an observatory located in West Africa studying the concurrent role of climate and land use changes on the water and energy partitioning over terrestrial surfaces, and the impacts on ecosystem dynamics and water resource along a South-North transect (Lebel et al., 2009; Galle et al., 2018). Long-term observations in AMMA-CATCH have in particular allowed for an interpretation of the "Sahel paradox", consisting in a continuous rise of aquifer's level and river runoff (Leduc et al.; 2001; Gal et al. 2017; Descroix et al. 2012) despite the observed decrease of precipitation since the 1970's (Lebel and Ali, 2009). The role of land cover modifications on the increase of superficial runoff, and in particular by the vegetation degradation due to drought and/or land use changes (Favreau et al., 2009; Descroix et al., 2012; Gal et al., 2017) and through rainfall intensification (Panthou et al., 2014) is still under investigation. These processes have been introduced in integrated modelling approaches (Massuel et al., 2011; Boucher et al., 2012; Velluet et al., 2014; Gal et al., 2017) to better explore future changes in the continental water cycle (Leauthaud et al., 2015). Data from AMMA-CATCH have also been used in a study highlighting changes in global circulation and frequency of extreme rainfall in the Sahel

(Taylor et al., 2017). The OHMCV observatory (Delrieu et al., 2005; Boudevillain et al., 2011) and Real Collobrier observatory are working towards an accurate evaluation and prediction of the hydro-meteorological risk associated to extreme precipitation events that characterize the southern border of the Massif Central (Cévennes and Vivarais) and Mediterranean regions. To capture and to document the dispersed risk at the regional scale, the OHMCV observation strategy relies on three main approaches: i) in-situ "classical" monitoring of surface hydrology and hydro-sedimentary variables (precipitation, runoff, infiltration, suspended solids), ii) post-flood socio-hydrometeorological experiments (Ruin et al., 2014) in order to retrieve both hydrometeorological and social observations after a major event, iii) historical archives dating from the XVIth century to better characterize rain and discharge probabilistic distributions. The OHMCV observatory seeks to develop a continuous social observation strategy and collaborates with the co-located socio-ecological sites on issues related to environmental quality and low water levels.

- Group II consists of low-order catchments conducting hydrological and biogeochemical observations, often using nested sites, in particular in order to balance water or geochemical budgets in variable environmental conditions. The ObsErA and part of the M-TROPICS observatories are established in pristine tropical conditions. The Mule Hole Catchment in India is one of the first watersheds in which geophysical techniques coupled with geochemical mass budgets were applied to map the regolith depth and establish weathering mass balances (Braun et al., 2009). It is also the first in which, by coupling observations and modeling in hydrology and ecology, the importance of vertical water niche separation on tree demography was demonstrated for a diverse forest (Chitra-Tarak et al., 2018). The OHGE observatory in the Vosges Mountains was set up in 1985 in order to understand the response of temperate mountain forest ecosystems to acid rain (Probst et al., 1990; Dambrine et al., 1998). The decrease of sulfate concentrations in the Strengbach stream observed since 1986 is

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an iconic case showing the virtue of continuous long term river monitoring (Probst et al., 1995, Pierret et al., submitted; see also **Fig. 3** in the main text). Also in group II, the Auradé, AgrHys, OMERE, Orgeval observatories and the other part of the M-TROPICS observatory are characterized by intense and long-standing agricultural practices and are focus on the impact of agricultural practices on water, nutrient (i.e. nitrate), pesticides, and element cycles in general (Perrin et al., 2008; Ferrant et al., 2013; Molénat et al., 2008; Aubert et al., 2013; Garnier et al. 2016; Buvaneshwari et al., 2017). The OTHU/Yzeron basin is established in urban and perirurban conditions and addresses the impact of urbanization on hydrology (Braud et al., 2013). Group II also includes small catchments of AMMA-CATCH (Galle et al., 2018) and OHMCV observatories (Braud et al., 2014). The HYBAM observatory is thematically related to this group, but as much larger catchments, they are monitored either at ground (Abril et al., 2014) or by satellite (Martinez et al., 2009) for hydrology and hydrogeochemistry. Hybam focus on the Amazon, Orinoco and Congo River systems.

- Group III is constituted of hydrological sites developed for monitoring soil erosion, either in natural conditions (ObsErA, Allemand et al., 2014) or in strongly human-impacted conditions (OMERE sites, OHMCV-Claduègne site, M-TROPICS-Huay Ma Nai site). The Draix-Bléone observatory was set up in 1983 for understanding the influence of reforestation onto erosion fluxes in mountain Mediterranean climate (i.e. Mathys et al., 2003), similar to the Dong Cao catchment (M-TROPICS) since 2002 in Vietnam (Valentin et al., 2008). The OMERE observatories (in Tunisia and Southern France) were designed to study the impact of agricultural practices on water and sediment budgets at the catchment scale (Raclot et al., 2009; Inoubli et al., 2017). For example, research at the Houay Pano catchment (M-TROPICS observatory), aiming at understanding the impact of agricultural or forestry practices on soil erosion has shown that the the conversion of rice-based shifting cultivation to teak plantation-based systems raised sediment yields from 98 to 610 $Mg/km^2/yr$ (Ribolzi et al., 2017).

- Group IV (SNO Karst) is dedicated to the study of karst systems that are complex and heterogeneous hydro(geo)logic entities, characterized by strong surface/subsurface interactions and a high sensitivity to erosion and weathering, making karstic water resource systems highly vulnerable to contamination and climate change. By linking data and models, SNO Karst aims to better understand and model water, mass, energy, and geochemical transport in karstic systems and to enhance the modeling capacity to reproduce variations of water and matter fluxes. Nine sites located in different climatic conditions (see **Table S1**) are instrumented and measure rainfall, discharge, water levels and isotopic and hydro-geo-chemical properties in rainfall, springs, rivers, karstic cavities and drilling.

All the catchment sites from RBV can be placed on a lithology versus climate diagram (see **Fig. 4** in the main text). Their degrees of disturbance are variable and range from "natural" catchments to highly-managed sites.

Although most of the observatories were set up independently, major scientific questions shared by several observatories can be defined: what is the carbon cycle at the catchment scale and how is it perturbed by local and global forcing factors? What are the erosion rates and their controls? What is the influence of extreme events on the cycling of nutrient at the catchment scale? What are the residence time of matters in catchments?

A.1.2. **The H+ network of hydrogeological sites,** created in 2002, provides in-situ observations and experimental data to address current open questions regarding coupled flow, transport and biogeochemical reactions in heterogeneous aquifers, i.e. the deep critical zone. H+ sites are instrumented to quantify the consequences of subsurface heterogeneity on groundwater residence times, flow path structures, solute transport and biogeochemical reactions. This requires the development of specific site instrumentation as well as the

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development of innovative methods for imaging, characterizing and modelling hydrodynamic, transport and processes. Methodological challenge addressed by H+ scientists include i) the development of hydrogeophysical methods to image the dynamics hydrological processes (recharge, flow, transport, reactivity…), ii) the integration of experiments and observations carried out on the H+ sites into models to quantify and predict the dynamics of heterogeneous hydrogeological systems. The latter step is essential to transfer the knowledge obtained on H+ sites to generic modeling tools that can be used in other contexts.

The H+ scientists address three main scientific questions.

- **Understanding the hydrological functioning of heterogeneous reservoirs**, such as karstic aquifers (Larzac, SHE Poitiers, LSBB, Mallorca), fractured systems (Choutuppal, Ploemeur) and alluvial systems (Auverwatch). One of the main objective of H+ sites is to provide field data to understand the role of heterogeneities (permeability distribution, preferential flow paths, fractures, karst conduits, anisotropy, double porosity...) on the recharge of underground reservoirs, their flow dynamics, storage properties and their exchanges and interactions with hydrological systems of surface. This is a particularly critical issue for assessing the resilience of hydrological systems to anthropogenic disturbances and global changes.
- **Characterizing and modelling the transport dynamics of dissolved chemical elements**, such as contaminants and chemical elements that play a key role in critical zone processes (e.g. transport of carbon, nitrogen, and elements originating from rock erosion). The existence of heterogeneity at multiple scales leads to transport phenomena (dispersion, retention, distribution of residence times) that cannot be treated within the framework of conventional models. Modeling of transport phenomena in heterogeneous hydrogeological systems is also an important issue for assessing geothermal and heat storage capabilities of subterranean environments.

- **Elucidating the role of hydrogeological systems as biogeochemical reactors.** During its journey in the soil and the subsurface, the chemical composition of water evolves by interaction with minerals and bacteria. This process plays a major role in the evolution of the quality of water resources, the transport of contaminants, and the geochemical functioning of watersheds. The H + teams thus explore the links between the distribution of flow velocities and residence times, kinetics of reactions and microbial biodiversity in hydrogeological systems.

A.1.3. The **CRYOBS-CLIM observatory** aims is to answer the following scientific questions: i) How will climate changes impact surface energy and mass budgets of snow / ice-covered surfaces and on permafrost ground temperature at different spatial (local to regional) and temporal (seasonal to multidecadal) scales? ii) How will snow/climate feedback mechanisms enhance or attenuate glaciers, ice sheets and permafrost changes in the near future? How can observations help to identify climate models weaknesses and to improve the simulations of cryosphere components? iii) What is the future snow and ice-covered retreat and wastage and what will be the impact on water resources and sea level rise? iv) How do 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?

The overarching goal of CRYOBS-CLIM network is to collect, archive and disseminate a comprehensive and consistent set of observations on the main components of the terrestrial cryosphere (glaciers, snow, permafrost) in a series of well-chosen sites ranging from high altitudes to high latitudes (European Alps, tropical Andes, Himalayas, Antarctica, Svalbard). The monitored variables and research topics are described in **Table S1**. A recent paper by Brun et al. (2017) illustrates the value of the observation strategy. The authors used more than

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50,000 ASTER satellite images to derive digital elevation models and to track glacier thickness changes for the period 2000-2016 over High Mountain Asia. They provided the first estimate of glacier volume change in this under-studied region of the world showing that approximately 90 000 km² of glaciers had melted between 2000 and 2016. These data will help to constrain glacio-hydrological models and to better understand the contribution of glaciers to stream flow and sea level rise in the context of climate change.

A.1.4. **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 carbon sink function and hydrological budget of temperate and sub-boreal peatlands, wetland ecosystems that contain a third of Earth's carbon stock in an area accounting for only 3-5% of the land surface. The French sites were set up in 2008-2010, according to a climatic gradient (lowland to mountain climate, D'Angelo et al., 2016), to ensure long-term monitoring of greenhouse gas (GHG: CO_2, CH_4, H_2O, N_2O), dissolved and particulate organic carbon (DOC, POC) fluxes as well as environmental variables that impact GHG, DOC and POC fluxes, and to generate interoperable databases. The instrumentation of the sites was carried out according to standardized protocols to monitor GHG, DOC and POC concentrations, meteorological parameters, surface and soil temperature and moisture, water table depth and groundwater chemistry at high resolution. Vegetation cover and net primary production are estimated during the growing season. CO_2 (Net Ecosystem Exchange and Respiration) and CH_4 fluxes are monitored at different spatial scales: at ecosystem scale (1000 m^2 high frequency measurements by flux towers) and at plot scale (1 m^2, seasonal resolution by static chambers measurements). So far, instrumented sites are used to deploy experiments on two types of forcing variables: (i) temperature with artificial air warming by using open-top chambers

(OTCs) (Delarue et al., 2011; Delarue et al., 2015); (ii) water table depth with ecohydrological restoration operation (Bernard-Jannin et al., 2017; Gogo et al., 2017)

A.1.5. **The OSR (Regional Spatial Observatory)**. OSR is documenting the long term effects of climate change and increasing anthropogenic pressures on the hydrologic and agro-ecologic evolutions of agricultural regions, at various spatial and temporal scales, in a perspective for sustainable management of water and soil resources. The specificity of the 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 multi-scale monitoring network of (1) continuous long-term monitoring of experimental plots (crop and snow sites), (2) hundreds of plots annually monitored for surface state, land cover, etc., and (3) experiments conducted at catchment scale with reinforced observations for water and energy budget evaluation.

The OSR concept has been yet implemented in two sites located in the South West of France and in Morocco (Tensift basin). In SW France, OSR monitors land use to understand effects of agricultural practices and climate variability on crop functioning from plot to regional scales, in terms of greenhouse/water budgets and production (Battude et al., 2017; Marais Sicre et al., 2016; Tallec et al. 2013). Marti et al. (2016) used high-resolution remote sensing data to monitor snow cover in the Pyrenean Mountain to quantify available water resource. The Tensift OSR is typical of Mediterranean semi-arid watersheds, with an upstream mountainous part receiving most of the precipitations and providing water to a downstream plain occupied by both rain-fed and irrigated agriculture. The measured variables allow the simulation of the impact of climate and anthropogenic changes on water resources in the upstream producing areas (Marchane et al., 2017) and on the downstream aquifer solicited by irrigation and domestic use (Le Page et al., 2012).

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A.1.6. **The ROSES (Observatory network of groundwater systems at national France level)** has been set up to address water management issues reinforced in the framework of the implementation of the European Water Directive. It also answers scientific questions such as (i) the impact of climate change on the behavior of aquifers at national and regional scale, performing assimilation of groundwater level data and modeling (e.g. Vergnes et al., 2012; El Janyani et al., 2012); (ii) the link between the geochemical signature of groundwater and the geological settings in the saturated zone at national scale (e.g. Wendland et al., 2008); (iii) the transfer time and contaminants behavior of agriculture origin as well as emergent contaminants within aquifers of large catchments in France (e.g. Lopez et al., 2015); and (iv) the development of database tools (interoperability) and data treatment (statistical tools). It gathers more than 77 000 stations, with 74 000 groundwater quality 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), a collective work involving several governmental agencies.

A.1.7. **The OPE (Long-lasting Observatory of the Environment)**. OPE focuses on a territory in the eastern part of Paris Basin (up to a few hundred km²) around the project site pre-selected as a French deep geological repository of high level and intermediate level long lived radioactive waste. OPE is currently constituted of a monitoring network, covering forest and agricultural areas and measuring atmospheric, meteorological, soil, surface and ground water, land uses and biodiversity indicators, providing a unique opportunity to document the interactions between human activities and the critical zone around an industrial project scheduled to run over 100 years (if accepted).

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Appendix 2: Diversity of current practices in the OZCAR network for databases and metadatabases (Table S2)

Thematic network	Observatory/sites	Database type	Database portal	Data access	Remarks
RBV	AgrHys[1]	Relational	yes	Public	Basis of the relational data base shared with OMERE
	M-TROPICS[2]	Relational	yes	Public	Basis of the relational data base shared with Auradé
	HYBAM[3]	Relational	yes	Login/password	
	BDOH[4]	Relational	yes	Login/password	Branger et al. (2014). Shared by several observatories (Draix-Bléone, Oracle, Real Collobrier, OTHU/Yzeron. Not conceived to easily provide metadata
	AMMA-CATCH[5]	Relational	yes	Public with login/password	Fully interoperable and fulfills the INSPIRE requirements
	OHMCV[6] OHGE[7] ObseRA[8]	Simple file repository arborescence	yes	Ask contact person or login/password	Part of the OHMCV observatory data available in the BDOH data base
	OMERE[9]	Relational	no	Only metadata	Same initial relational data base as AgrHys
	Auradé	Under construction	no	Only metadata	Same initial relational data base as M-TROPICS
	SNO Karst	Under construction			

1 https://www6.inra.fr/ore_agrhys_eng/Data
2 https://mtropics.obs-mip.fr/data-access/
3 http://www.ore-hybam.org/index.php/eng/Data
4 https://bdoh.irstea.fr/
5 http://bd.amma-catch.org/main.jsf
6 http://ohmcv.osug.fr/spip.php?article30
7 http://bdd-ohge.u-strasbg.fr/index.php/bdd
8 https://morpho.ipgp.fr/Obsera/Home
9 http://www.obs-omere.org/index.php?page=geonetwork&lang=fr

H+[10]	All sites	Relational	yes	Login/password	Normalized variable names based on the GCMD keywords[11]
CRYOBS-CLIM[12]	All sites	Relational	yes	Login/password	Based on the same information system as AMMA-CATCH. Fully interoperable and fulfills the INSPIRE requirements
Tourbières	-	Under construction			
OSR	-	Relational and file repository arborescence	yes	Relational and file repository arborescence	Information system including in-situ data and satellite images
ROSES[13]	ADES	Relational	yes		Operational data base used for the Water Framework Directive reports about groundwater
OPE	-	No	-	Public	

10 http://hplus.ore.fr/base-de-donnees-fr
11 Global Change Master Directory, https://gcmd.nasa.gov/
12 http://data.cryobsclim.fr/main.jsf
13 http://www.ades.eaufrance.fr/LienLocalisation.aspx

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Appendix 3: Examples of scientific papers published within OZCAR community combining data and models (Table S3)

Scientific/operational question	References	Main approach and findings	CZ compartment
Use of data and models for process understanding			
How to represent snow-pack evolution?	Lafaysse et al. (2017)	A 18-year time series of climatological variables and snow characterization from the Col de Porte site (CRYOBS-CLIM observatory) was used to compare various snow-pack evolution models, that were included as a modeling toolbox in the SURFEX land surface model (Masson et al., 2013).	Cryosphere
How does fractured media heterogeneity impact transport processes and biogeochemical reactions in groundwater?	Kang et al. (2015) ; Guihéneuf et al., (2017)	A combination of convergent and push-pull tracer tests can be effectively used to decipher the role of transit time distribution and velocity correlation for modeling transport processes.	Fractured aquifers
	Dorn et al. (2012); Read et al. (2013); Klepikova et al. (2016) Shakas et al. (2017)	Repeated measurements combining electrical, electromagnetic, thermal, hydraulic and geochemical data have provided key in-situ experimental data sets to understand transport processes in fractured media.	Fractured aquifers
	Arfib and Charlier (2016)	Data and models were used to understand salt intrusion in a karstic aquifer.	Karstic aquifers
	Roques et al. (2014) Ben Maamar et al. (2015) Boisson et al. (2013)	Chemical and microbiological sampling, and field hydraulic and tracer tests were used to infer biogeochemical reaction processes in fractured aquifers	Fractured aquifers
What are the main hydrological controls of dissolved organic carbon in a restored peatland?	Binet et al. (2013); Bernard-Jannin et al. (2017)	A hydrological model, calibrated on water table levels, and coupled with a biogeochemical module was shown to correctly reproduced pore water dissolved organic carbon (DOC) concentration time series in a restored peatland. Water table drawdown severity has been identified as the major factor controlling DOC dynamics.	Peatland
What are the water and solute pathways in karst and fractured aquifers?	Maréchal et al. (2004); Le Borgne et al. (2006); Audoin et al. (2008);	Data and models of various complexities helped to identify water and solutes pathways.	Fractured aquifers
	Binet et al. (2017); Cholet et al. (2017); Charlier et al. (2012); Mazzilli et al. (2017) Labat and Mangin	Data and models were used to discriminate between rapid flow via conduits networks and slower flow via matrix or fractured systems	Karstic aquifers

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	(2015) Labat et al. (2016)		
What is the level of complexity required to model erosion at the hillslope scale?	Cea et al. (2014); Cea et al. (2016)	The 2D surface runoff model of Cea et al. (2014) was coupled with an erosion module and plot data from the OHMCV observatory to assess the model complexity required to correctly reproduce the observed sediment yields.	Surface water and sediment transport
	Gumière et al. (2014)	Connectivity of sediment transport was taken into account in the modeling of erosion, with evaluation with data from the OMERE Observatory to properly represent erosion yields.	Surface water and sediment transport
Use of data and models for system understanding			
Can we explain long-term trends in nitrate concentration in rivers in Britanny?	Fovet et al. (2015)	A process-based model, calibrated using a 40-year time series of discharge and nitrogen concentrations, was used to estimate nitrogen transit times and was able to simulate the constant increase of nitrate linked to the increased of fertilization since the 1960s.	Surface water and nitrate
What are the appropriate representations of subsurface water and solute pathways and what are the relevant data and inverse modeling strategies to constrain them?	Leray et al. (2012)	The paper demonstrates the interest of combining hydraulic and age information for the prediction of residence time distributions within hydrogeological models, and showed the possibility of identifying global hydrogeological structures from point-like data.	Fractured aquifer
What are the interactions between hydrological and vegetation cycles in SW Niger?	Velluet et al. (2014); Leauthaud et al, (2017)	A calibrated mechanistic SVAT (Soil Vegetation Atmosphere Transfer) model was first used to retrieve a climatology of water and energy budgets in Niger at the plot scale. Then the model was coupled with the STEP ecological model and the SARAH agronomic model to study interactions between hydrological and vegetation cycles in SW Niger.	Soil – vegetation – atmosphere interface
What are the controlling factors of weathering in the Strengbach catchment and the Mule Hole catchment?	Godderis et al. (2006); Violette et al. (2010)	The WITCH model, coupling kinetics of silicate weathering reactions to the water and carbon cycle in forest ecosystems, initially designed and applied to the granitic Strengbach catchment (OHGE observatory), was coupled with a lumped hydrological model to successfully reproduce the stream chemistry of the Mule Hole catchment.	Catchment hydrology, geochemistry
Can we improve the knowledge of the water balance of the Amazon?	Getirana et al. (2010; 2011)	In large catchments where data are scarce, such as the Amazon, satellite altimetry data were combined with in-situ data from gauging stations to assess and strengthen the water balance computed using a distributed hydrological model. Such datasets were also used for the evaluation of large-scale land surface models.	Continental scale catchment hydrology
Can we predict nitrates and pesticides behavior and transfer in agricultural catchments using agro-hydrological	Ferrant et al. (2011) ; Boithias et al. (2011)	A comparison of a distributed (TNT2) and a semi-distributed model (SWAT) allowed the authors to better understand nitrogen transfer dynamics in a small agricultural catchment. Using the SWAT model,	Soil- Water, Catchment scale

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modelling?		the introduction of the partition coefficient Kd to predict pesticides behavior in stream waters improved pesticide transfer modelling..	
What are the main hydrological controls of bacteria in a tropical mountain watershed?	Kim et al. (2017)	The SWAT model was improved by implementing in-stream resuspension of sediments and transient storage in the hyporheic zone (Houay Pano catchment)	
What is the role played by geology on the hydrological processes during flash-flood events?	Vannier et al. (2016)	A regional distributed hydrological model was used to perform long-term and flash-flood event simulations at the regional scale. Discharge simulation was improved when the weathered bedrock layer was included into the model.	Surface and ground water
Use of model and data for management/prediction purposes			
Can we design a flash flood forecasting system in a karstic environment?	Maréchal et al. (2008)	Hydrological and geochemical data (SNO Karst) were used to design a flash flood warning model for the city of Nîmes (SE France)	Surface water
What is the sustainability of water resources under climate change in the Andes region?	Chevallier et al. (2010) ; Rabatel et al. (2013)	Time series of discharge and glacier mass balance data (CRYOBS-CLIM) were used to provide a synthesis of glacier mass balance evolution for the whole Andean region.	Cryosphere
What are water and irrigation needs in different contexts , and what is the impact of irrigation on water table levels?	Battude et al. (2017); Le Page et al. (2012)	Once calibrated using local information, remote sensing data combined with a water balance model (SAMIR) provided suitable tools for simulating water needs and irrigation. In-situ and remote sensing data were used to model water resources in the area of Marrakech (Morocco), using a coupling between the WEAP (Water Evaluation And Planning System) hydrological model and the MODFLOW groundwater model.	Surface water, aquifers, biosphere
What would be the impact of small ponds rehabilitation on nitrate contamination in the Seine catchment?	Passy et al. (2012)	Observations at small scale (Orgeval observatory) were used to calibrate the Riverstrahler model (Ruelland et al., 2007) that was then applied to the whole Seine river basin.	Catchment hydrology, river geochemistry, nitrate cycle
What is the level of contamination of French aquifers with respect to contaminants from agriculture and emergent pollutants?	Lopez et al. (2015)	The ROSES data base was used to model transfer time and the behavior of agricultural and emergent contaminants within aquifers of large catchments in France.	Groundwater
Can we predict the risk of nitrates and pesticides transfer to surface waters and propose best environmental practices to reduce contaminant fluxes?	Macary et al. (2013 a, b) Ferrant et al. (2013)	A multi-scale method and a multi-criteria modelling coupled with a GIS was applied to assess pesticide contamination risks in agricultural watersheds. The effect of best environmental practices on reducing pesticide and nitrates pollution towards surface water, was assessed. The long term impact of nitrate mitigation scenarios was simulated in a pilot study basin using an agrohydrological modelling.	Soil and Catchment scales
What is motorists' exposure to flash floods and what are their behaviors and mobility	Shabou et al. (2017)	A distributed hydrological model was used to assess exposure of road	Surface water ; Human exposure to

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adaptations with respect to roads flooding?		users to extreme hydrometeorological events. This model requires the combination of social and hydrometeorological data as well as road flooding impact data.	flash flood events

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Table S1.

Observarory (nb reported Fig. 2)	Country	Name	Latitude	Longitude	Catchment/site scales (km2)	Climate	Lithology	Land use	Individual research questions	Measured variables (all the variables are not measured over the whole period)	Oldest measured variables	Web site	Data portal
Network RBV (Réseau de Bassins Versants): catchment hydrology, geochemistry, erosion, soil-plant-atmosphere interactions													
AMMA-CATCH (1)	Mali	Gourma	16°N	1.5°W	1-30000	Semi-arid	Sandstone and schist	Sparse herbaceous vegetation	Ecohydrological monitoring in a pastoral environment	Rainfall, meteo, water level in ponds, groundwater level, soil moisture, surface energy balance, CO2 flux, sapflow, LAI, PAI, vegetation fraction, phenology, herbaceous biomass	1984	http://www.amma-catch.org/	http://www.amma-catch.org/spip.php?rubrique63
	Senegal	Ferlo	15.5°N	15.5°W	idem	idem	Sandstone	idem	idem	Rainfall, soil moisture, soil biogeochemistry	2013	Idem	Idem
	Niger	Niamey square degree	13.5ºN	2.5ºE	0.35-16000	Semi-arid	Gneiss, schist and granite	Fallow savanna, tiger bush and pearl millet	hydrology of endoric basins - rainfall/vegetation interaction	Rainfall, meteo, water level in ponds, gullies and plots, groundwater level in piezometers and wells, soil moisture, surface energy balance, CO2 flux, LAI, vegetation height, herbaceous biomass and species	1990	Idem	Idem
	Benin	Ouémé	9º5N	2ºE	0.16-14000	Soudanian	Migmatite	woodland, shrubland, crops and herbaceous fallow	hydrological cycle - water budget and hydrological processes	Rainfall, meteo, water level in rivers and gullies, groundwater level in piezometers and wells, water chemical analysis, soil moisture, surface energy balance, CO2 flux, sapflow, LAI	1997	Idem	Idem
OHMCV (2)	France	Auzon-Claduègne	44.58°N	4.50E	3.4-116	Mediterranean	Basalt, limestones and marls	Pasture, vineyard and forest	Biogeochemical cycles, climate chang, hydrometeorological extremes in the Mediterranean: intense rain events and subsequent flash-floods, erosion	Rainfall, meteo, water level and discharge in rivers, suspended sediment and physico-chemical properties of surface water, soil moisture,	2005	http://ohmcv.osug.fr/	http://ohmcv.osug.fr/spip.php?article30
		Valescure	44.09N	3.83E	0.3-3.9	Mediterranean	Granite	Decidious forest	Idem	Rainfall, meteo, water level and discharge, physico-chemincal properties of surface water and soil (pH, temperature, conductivity, anions, cations), soil moisture	2003	Idem	Idem
		Tourgueille	44.13N	3.67°E	1-10	Mediterranean	Schist		Idem	Rainfall, water level and discharge in rivers, physico-chemical properties in surface water (temperature, pH, conductivity)	2008	Idem	Idem
		Mont Lozère	44.7°N	3.82°E	0.19-0.81	Sub-Mediterranean	Granite	Mixed forest and grassland	Idem	Rainfall, meteo, water level and discharge, physico-chemincal properties of surface water and soil (pH, temperature, conductivity, anions, cations), soil moisture	1986	Idem	Idem
AgrHys (3)	France	Kervidy-Naizin	47.99°N	-2.83ºW	4,9	Oceanic	Schist	Intensive agriculture	Response time of hydro-geochemical fluxes to climate and anthropogenic forcing	Rainfall, meteo, discharge, groundwater level; physico-chemical and chemical concentration in rainfall, soil, surface water and groundwater; land use and agricultural practices	1990	https://www6.inra.fr/ore_agrhys/	https://www6.inra.fr/ore_agrhys/Donnees/Le-grapheur-VIDAE
		Kerbernez	48.12º N	-4.03ºW	0.095-1.28	Oceanic	Granite	Intensive agriculture	Idem	Idem	1992	Idem	Idem
Auradé (4)	France	Montoussé	43,56 °N	1.06° E	3,2	Temperate oceanic	Marls-limestone	Crops (wheat, sunflower)	Impact of agricultural activities on water, matter (nitrate, carbon) balance and fluxes in watr, soils, ecosystems	Water level in rivers, nitrates, pesticides concentration, physico-chemical properties; 13C, water isotopes in river	1983	http://www.ecolab.omp.eu/bvea/	http://www.ecolab.omp.eu/bvea/donneesdisponibles/donnesdisponibles
ORACLE (5)	France	Orgeval	48.89°N	3.19°E	1 to 1800	Temperate oceanic	Limestones, gypsum and clays	Agriculture	Impact of climate variability on the hydrological cycle (focus on floods and drought) and of agriculture practices on hydro-biogeochemical fluxes and water quality	Rainfall, meteo, water level and discharge in rivers and ditches, groundwater level, soil moisture, suspended sediments, surface and groundwater physico-chemical properties (temperature, pH, conducitvity, DOC, anions), surface energy budget.	1962	https://gisoracle.irstea.fr/	https://bdoh.irstea.fr/ORACLE/
OMERE (6)	France	Roujan	43.50ºN	3.31 ºE	0.0012-0.91	Mediterranean	Limestones and marls	Mediterranean agriculture	Impact of land use change and anthropogeneic practices on the hydrological and sedimentological regime, impact of pesticides on water quality	Rainfall, meteo, water level and discharge in rivers and ditches, suspended sediment, groundwater levels, pesticides concentration, physico-chemical properties of surface water (cations, anions, isotopes, metals), surface energy budget and CO2 fluxes, soil moisture	1992	http://www.obs-omere.org/	http://www.obs-omere.org/index.php?page=geonetwork&lang=fr
	Tunisia	Kamech	36.88ºN	10.88ºE	0.013-2.63	Mediterranean	Sandstone and marls	Idem	Idem	Idem	1994	Idem	Idem

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OTHU (7)	France	Yzeron	47.74°N	4.69°E	2.1-129	Continental with mediterranean influence	Gneiss	Forest, agriculture, urban	Impact of urbanization on hydrology, geomorphology and water quality, ecohydrology	Rainfall, meteo, water level, temperature and discharge in rivers and sewers, physico-chemical properties of water in rivers and sewers	1997	http://www.graie.org/othu/index.htm	https://bdoh.irstea.fr/YZERON/
M-TROPICS (8)	Cameroon	Nyong (Nsimi)	2.9°N	11.4°E	0.6-18500	Tropical	Granite	humid tropical forest	Chemical weathering of silicated rocks	Rainfall, meteo, discharge, groundwater level, tensio-neutronic soil monitoring, hydrochemical parameters (anions, cations, PH, DOC, total suspended sediments	1994	https://mtropics.obs-mip.fr/	https://mtropics.obs-mip.fr/data-access/
	India	Kabini (Mule Hole, Berambadi)	12.2°N	76.9°E	4.3-590	Tropical	Gneiss	Dry forest, agriculture	Impact of agriculture and forest on water and biogeochemical cycles	idem	2003	idem	Idem
	Thailand	Huay Ma Nai	18°13'20"N	100°23'40"E	0,93	Tropical	Sandstone	Intensive agriculture	Land use changes and consequence on soil and water processes in tropical mountains environments	Rainfall, meteo, water level and discharge, suspended sediments, bedload, land-use, water chemistry	2001	idem	Idem
	Laos	Houay Pano	19°51'10"E	102°10'45"E	0,6	Tropical	Schist	Tree plantation	Idem	Rainfall, meteo, water level and discharge, suspended sediments, bedload, land-use	2001	Idem	Idem
	Vietnam	Dong Cao	20°57'40"N	105°29'10"E	0,5	Tropical	Schist	Reforested	Idem	Rainfall, meteo, water level and discharge, suspended sediments, bedload, land-use	2002	Idem	Idem
ObserRA (9)	France	Bras David et Capesterre (Guadeloupe)	16.18ºN	-61.69°E	0.08-16.4	Tropical	Andesite	Tropical forest	Weathering and erosion, sediment and organic carbon	Rainfall, meteo, discharge, suspended sediment, geochemical species, physico-chemistry of rivers and soil	2011	http://www.ipgp.fr/fr/obsera/observatoire-de-leau-de-lerosion-aux-	http://webobsera.ipgp.fr/
EroRun (10)	France	Rivière des pluies, la Réunion	-20.9°N	55.5°E	45	Tropical (with cyclones)	basalt	Tropical forest	Water, sediment and geochemical fluxes	Rainfall, discharge, suspended sediment, geochemical species	2015	http://osur.univ-reunion.fr/observations/soere/rbv/	
OHGE (11)	France	Strengbach	48.21°N	7.20°E	0,8	temperate oceanic mountainous	Granite, gneiss	Forest	Response of ecosystems to climate and anthropogenic perturbations (forest exploitation, atmospheric pollution) - element and water transfert at the atmosphere/soil/plant interface	Rainfall, meteo, water level and discharge in rivers, groundwater levels in piezometers and wells, suspended sediments in rivers, physico-chemical properties (pH, temperature, conductivity, anions, cations, DOC, trace elements) in rivers, springs, soil solutions, rainfall	1986	http://ohge.unistra.fr/	http://bdd-ohge.u-strasbg.fr/index.php/bdd
Real Collobrier (12)	France	Real Collobrier	43.25°N	6.36°E	0.7 to 70	Mediterranean	Gneiss and schist	Mediterranean forest	Flash floods	Rainfall, water level and discharge, suspended matter and bedload transport	1966	https://bdoh.irstea.fr/REAL-COLLOBRIER/	https://bdoh.irstea.fr/REAL-COLLOBRIER/
Draix-Bléone (13)	France	Draix-Bléone	44.1°N	6.3°E	0.0013 to 22	Mediterranean	Marls	badlands or mediterranean forest	Floods and erosion in mountainous catchments, rock weathering and vegetation impact on erosion	Rainfall, meteo, discharge, groundwater level, soil moisture, rainfall stable isotope content; suspended sediment concentration, total solid transport during events, LiDar DTM, vegetation cover, landslides	1983	https://oredraixbleone.irstea.fr/	https://bdoh.irstea.fr/DRAIX/
SNO Karst (14)	France	Baget	42.95 N	1.03 E	13.25	Oceanic	Limestone	Forest and grasslands	Hydro-geo-chemistry of the karst (quantity and quality of the water resource, floods)	Water level and discharge, physico-chemical properties of water (pH, temperature, conductivity, anions, cations, stable isotopes, doc)	1978	http://www.sokarst.org/index.asp?lang=fr	
		Medycyss	47.9ºN	4.6ºE	1200	Mediterranean	Limestone	Mediterranean agriculture	Idem	Rainfall, meteo, water level and discharge in rivers, groundwater levels, soil moisture, physico-chemistry (temperature, conductivity, major and trace elements, stable isotopes, MON, TOC)	2005	http://www.medycyss.org/	
		Fontaine de Vaucluse - LSBB	43.92°N	5.13°E	1130	Mediterranean	Limestone	Forest and grasslands	Idem	Rainfall, meteo, water level, pressure and discharge in springs, physico-chemical properties of water (anions, cations, DOC, stable isotopes), gravimetry, inclinometry	1995	https://www6.paca.inra.fr/emmah/Les-moyens/Sites-experimentaux/Fontaine-de-Vaucluse-LSBB/Fontaine-de-Vaucluse	
		Jurassic Karst	47.1ºN	6.3ºE	1-50	Mountainous	Limestone	Forest	Idem	Rainfall, meteo, water level, physico-chemistry (temperature, pH, conductivity, chlorures, nitrates, COT, COD, turbidity)	2009	https://zaaj.univ-fcomte.fr/spip.php?article13&lang=en	
		Karst-Craie	49.43°N	0.19°E	10-230	Oceanic	Limestone	agricultural lands	Idem	Rainfall, water level, physico-chemistry (temperature, pH, conductivity, chlorures, nitrates, COT, COD, turbidity)	1997	http://www.sokarst.org/index.asp?lang=fr	
		Karst Val d'Orléans	47.85°N	1.937°E	20	Oceanic	Limestone	Forest and grasslands	Idem	Water level, physico-chemistry (temperature, pH, conductivity, chlorures, nitrates, COT, COD, turbidity)	1970	http://www.sokarst.org/index.asp?lang=fr	
HYBAM (15)	Bolivia, Peru, Ecuador, Brazil	Amazon	3,3122° S	60,6303° W	6400000	Humid Tropical	Mixed (sedimentary, volcanic and metamorphic)	Tropical forest	Geodynamical, hydrological and biogeochemical control of erosion/alteration and material transport in the Amazon, Orinoco and Congo basin	Rainfall, water level and discharge in rivers, suspended sediment concentration, physico-chemical properties of rivers (temperature, pH, conductivity), geochemistry (anions, cations, organic carbon)	2003	http://www.ore-hybam.org/index.php/eng	http://www.ore-hybam.org/index.php/eng/Data
Network H+: hydrogeological observatories and sites, the deep CZ.													
H+ (16)	France	Ploemeur	47.74°N	-3.43°W	5 to 20	Oceanic	Micaschists and Granites	grasslands and agriculture	Groundwater flow and transport modeling in a fractured aquifer used for water supply	Groundwater levels and discharge, physico-chemical fluid properties (temperature, conductivity, chemistry), unsaturated zone, geophysical montoring (GPS, sismic, tiltmeter ..)	1991	http://hplus.ore.fr/	http://hplus.ore.fr/base-de-donnees-fr
H+ (16)	France	Poitiers	46.56°N	0.40°E	0,12	Oceanic	Limestones	grasslands	Adapated well nest for groundwater flow and transport experiments and models in a karstic aquifer	Meteo data, groundwater levels, physico-chemical properties (temperature, conductivity, chemistry)	2002	Idem	Idem
H+ + RBV (SNO KARST) (14, 16)	France	Fontaine de Vaucluse - LSBB	43.92°N	5.13°E	1130	Mediterranean	Karst	mediterranean forest + agriculture	Hydrogeological functionning of a large unsaturated zone in karst	Rainfall, meteo, water level, pressure and discharge in springs, physico-chemical properties of water (anions, cations, DOC, stable isotopes), gravimetry, inclinometry	1995	Idem and http://www.sokarst.org/index.asp?lang=fr	Idem

H+ (16)	France	Larzac	43.97°N	3.82°E	100	Mediterranean	Karst	grasslands and forests	Processes that control the spatio-temporal variability of water storage and fluxes in a karstic aquifer	Rainfall, groundwater level, water pressure and discharge, surface energy balance, inclinometry, gravity, GPS, electric resistivity	2006	Idem	Idem
H+ (16)	France	AuverWatch	45.74°N	3.21°E	320	Continental	Alluvial sands	Grassland	Hydro-geo-chemistry of an alluvial system. Focus on river/groundwater interactions, transport of emergent pollutants	Rainfall, water level, river discharge, physico-chemistry (temperature, pH, conductivity,major and traces ions, phytosanitaries, pharmaceuticals, stable isotopes of the water molecule)	2010	Idem + http://wwwobs.univ-bpclermont.fr/SO/auverwatch/index.php	Idem
H+ (16)	India	Hyderabad (Maheswaram and Choutuppal)	17.29°N	78.92°E	04-55	Tropical	Granites	Intensive agriculture	Water and matter fluxes, chemical reactivity,, residence times in a fractured aquifer	Rainfall, meteo, groundwater levels, physico-chemical properties (temperature, conductivity, chemistry, isotopes)	2000	Idem	Idem
H+ (16)	Spain	Majorque	39.41°N	2.95°E	0,12	Mediterranean	Limestones		Water fluxes in a coastal aquifer with saline intrusion	Groundwater levels, ions concentration	2003	Idem	Idem
Network CRYOBS-CLIM: glaciers,snow and permafrost studies													
GlacioClim (17)	France	Alpes-Sarennes	45°07' N	06°07' E	0,5		Mica Schistes, Gneiss	Glacier	Impact of climate change on glaciers and associated water resources	Glacier mass balance, rainfall, meteo, raidation budget, surface energy balance, glacier temperature profile	1949	https://cryobsclim.osug.fr/ and http://devdata.glacioclim.fr/portal/main.jsf	http://devdata.glacioclim.fr/portal/main.jsf
	France	Alpes-Saint Sorlin	45°09' N	06°10' E	3		Mica Schistes, Gneiss	Glacier	Idem	Idem	1957	Idem	Idem
	France	Alpes-Mer de Glace	45°55' N	06°57' E	28		Granite/Gneiss	Glacier	Idem	Idem	1983	Idem	Idem
	France	Alpes-Argentière	45°55' N	06°57' E	19		Granite/Gneiss	Glacier	Idem	Idem	1975	Idem	Idem
	France	Alpes-Gébroulaz	45°19' N	06°07' E	3		Gneiss	Glacier	Idem	Idem	1983	Idem	Idem
	France	Alpes-Col du Dome					Granite/Gneiss	Glacier	Idem	Idem	1997	Idem	Idem
	France	Pyrénées-Ossoue	42°46' N	00°08' W	0,45		Cristaline rocks	Glacier	Idem	Idem	2001	Idem	Idem
	Svalbard	Svalbard-Austre Loven	77.87497	20.97518	5		Cristaline rocks	Glacier	Idem	Idem	2007	Idem	Idem
	Bolivia, Peru, Ecuador, Brazil	Andes-Zongo	16°16' S	68°09' W	1,8		Granites	Glacier	Idem	Idem	1973	Idem	Idem
	Ecuador	Andes-Antizana	00°28' S	78°09' W	1		Basaltes	Glacier	Idem	Idem	1995	Idem	Idem
	Nepal	Himalaya-Mera	27,7°N	86,9°E	5,1		Cristaline rocks	Glacier	Idem	Idem	2007	Idem	Idem
	Antarctic	Antarctique-Cap Prud'homme	-66,69194	139,89667	8000		Gneiss/Migmatites	Polar cap	Idem	Air temperature, humidity, wind speed, snow temperature	2004	Idem	Idem
	Antarctic	Antarctique-Dome C	75°S	123°E			Unknown	Polar cap	Idem	Air temperature, humidity, wind speed, snow temperature	2004	Idem	Idem
Snow (17)	France	Alpes-Col de Porte	45.30° N	5.77° E	0,006253	Mountainous	Limestones	snow field	Interactions snow climate and impact of climate change	Meteo, snow depth, water equivalent, temperature	1959	Idem	Idem
	France	Alpes- Col du Lac Blanc	45° 7'40.38"N	6° 6'41.38"E	0,25	Mountainous	Gneiss	snow field	Idem	Air temperature, humidity, wind, rainfall and snowfall, transported snow, radiation budget, sensible heat flux	1990	Idem	Idem
Permafrost (17)	France	Alpes-Laurichard	45.018°N	6.40°E	0,08	Mountainous	Granite/gneiss	Rocks permafrost	Observation of permafrost in mountains in relation with climate change and modifications of associated risks	Drillings and monitoring of the evolution of the permafrost	1982	Idem	Idem
	France	Alpes-Deux Alpes	45.0°N	6.19°E	6	High mountains	Gneiss	Idem	Idem	Idem	2007	Idem	Idem
	France	Alpes-Aiguille du Midi	45.878°N	6.887°E	0,05	High mountains	Granites	Idem	Idem	Idem	2005	Idem	Idem
	France	Alpes- Dérochoir	45.866°N	6.809°E	0,05	High mountains	Gneiss Schistes	Idem	Idem	Idem		Idem	Idem
Network OSR: Regional spatial observatory													
OSR (18)	France	South-West	43.50°N	1.24°E	0.001-2500	Oceanic mountainous	Marls-limestone	Agriculture and moutains	Understand, model and forecast the continental surface functionning and evolution from the ecosystem to the regional scale using remote sensing data	Rainfall, air temperature, air humidity, soil temperature, soil water content, wind direction and speed, snowfall, surface energy budget, water vapor, N2O and CO2 fluxes, vegetation, land use and practices	2004	http://www.cesbio.ups-tlse.fr/fr/sud_ouest.html	http://www.cesbio.ups-tlse.fr/fr/donnees_sudouest.html#sites
	Morrocco	Tensift	31.5°N	-8°W	20000	Mediterranean	mixed (eruptive and sedimentary)	Mediterranean agriculture and moutains	Idem	Idem	2002	http://www.cesbio.ups-tlse.fr/fr/sud_med.html	http://www.cesbio.ups-tlse.fr/fr/donnees_cesbio_sudmed.html
Network "Tourbières": peatland observatories													
SNO Tourbières (19)	France	Bernadouze	42.80°N	1.42°E	0,08	Oceanic mountainous	mixed (granite and limestone)	Peatland	Impact of global change on the peatland carbon sink, green house gases (H2O, CO2, CH4) cyles, dynamics of organic matter in soils	CO2 fluxes, groundwater level, dissolved organic carbon in the peatland and at the output, physico-chemical properties (pH, conductivity, temperature), meteo	2013	http://www.sno-tourbieres.cnrs.fr/	

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	France	Frasne	46.83°N	6.17°E	3	Mountainous	limestone	Peatland	Idem	Meteo, water level at the outlet, groundwater level, physico-chemical properties (pH, conductivity, temperature), soil temperature, CO2, CH4, H2O and energy fluxes	2008	Idem	
	France	La Guette	47.32°N	2.28°E	0,25	Oceanic	sands	Peatland	Idem	Meteo, water level at the outlet, groundwater level, dissolved organic carbon in the peatland and at the output, physico-chemical properties (pH, conductivity, temperature), soil properties, CO2, CH4, H2O and energy fluxes	2008	Idem	
	France	Landemarais	48.44°N	1.18°O	0,16	Oceanic	granite	Peatland	Idem	Meteo, water level at the outlet, groundwater level, physico-chemical properties (pH, conductivity, temperature), soil properties, CO2, CH4, H2O and energy fluxes	2014	Idem	
Other networks (operational)													
OPE (20)	France	Perennial Observatory of the Environnement	48.56°N	5.34°E	240-900	Continental	Limestones	Agriculture and small forests	Environnemental monitoring of a industrial territory in mutation	Atmospheric parameters, Greenhouse gases and aerosol physico-chemical properties, , surface and groundwater physico-chemical properties, physico-chemistry of soils, biodiversity	2007	http://www.andra.fr/ope/index.php?lang=fr	http://www.andra.fr/ope/index.php?option=com_datarequest&Itemid=331&lang=fr
ROSES (21)	France	All France	na	na	na	na	na	na	Groundwater water level and quality monitoring over whole France and overseas territories	Groundwater level and quality	1892 : groundwater level, strenghen since 2000 1900: groundwater quality	http://www.ades.eaufrance.fr/Spip.aspx?page=spip.php?rubrique141	http://www.ades.eaufrance.fr/LienLocalisation.aspx

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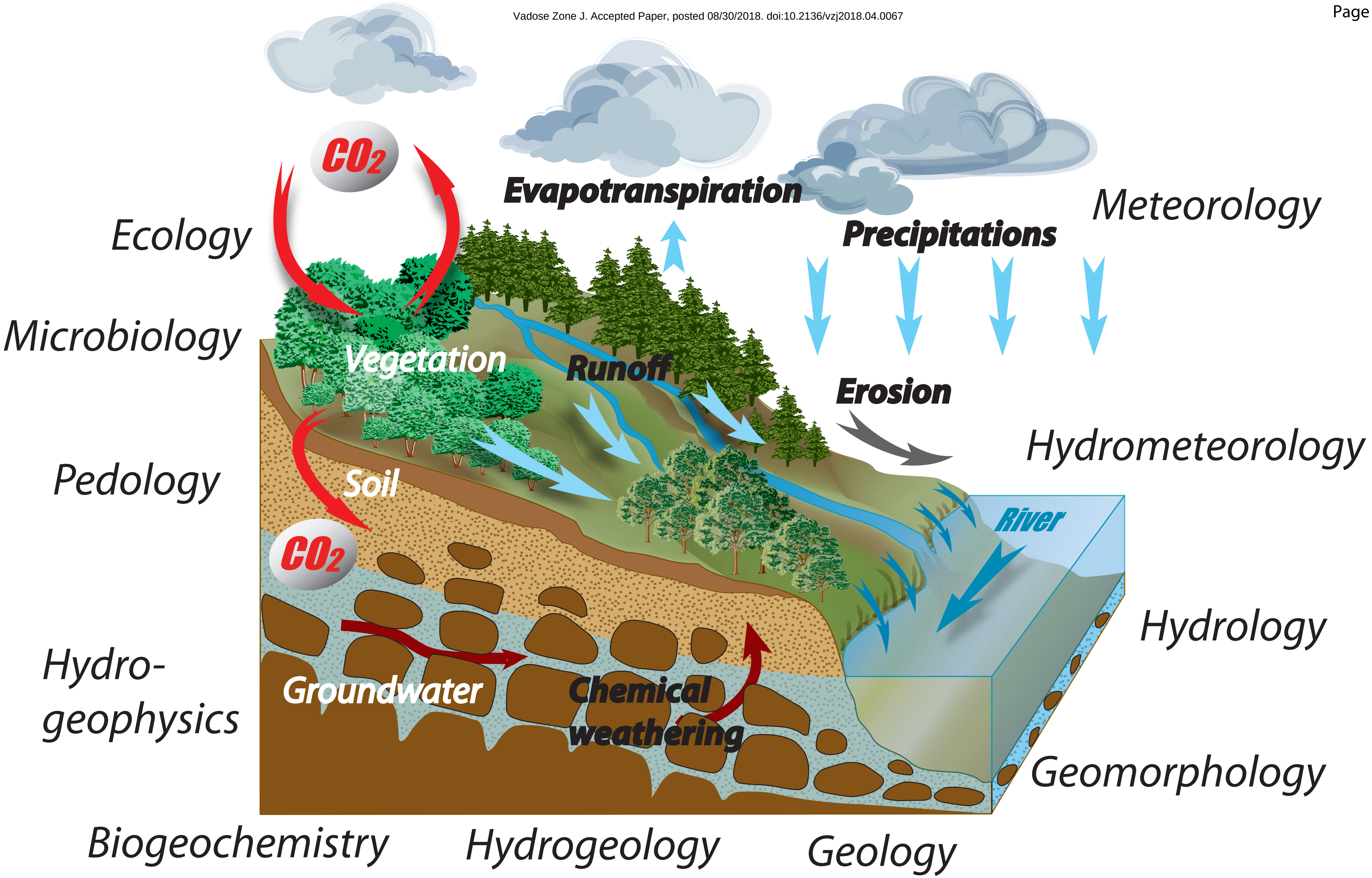

Fig. 1

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Fig. 2

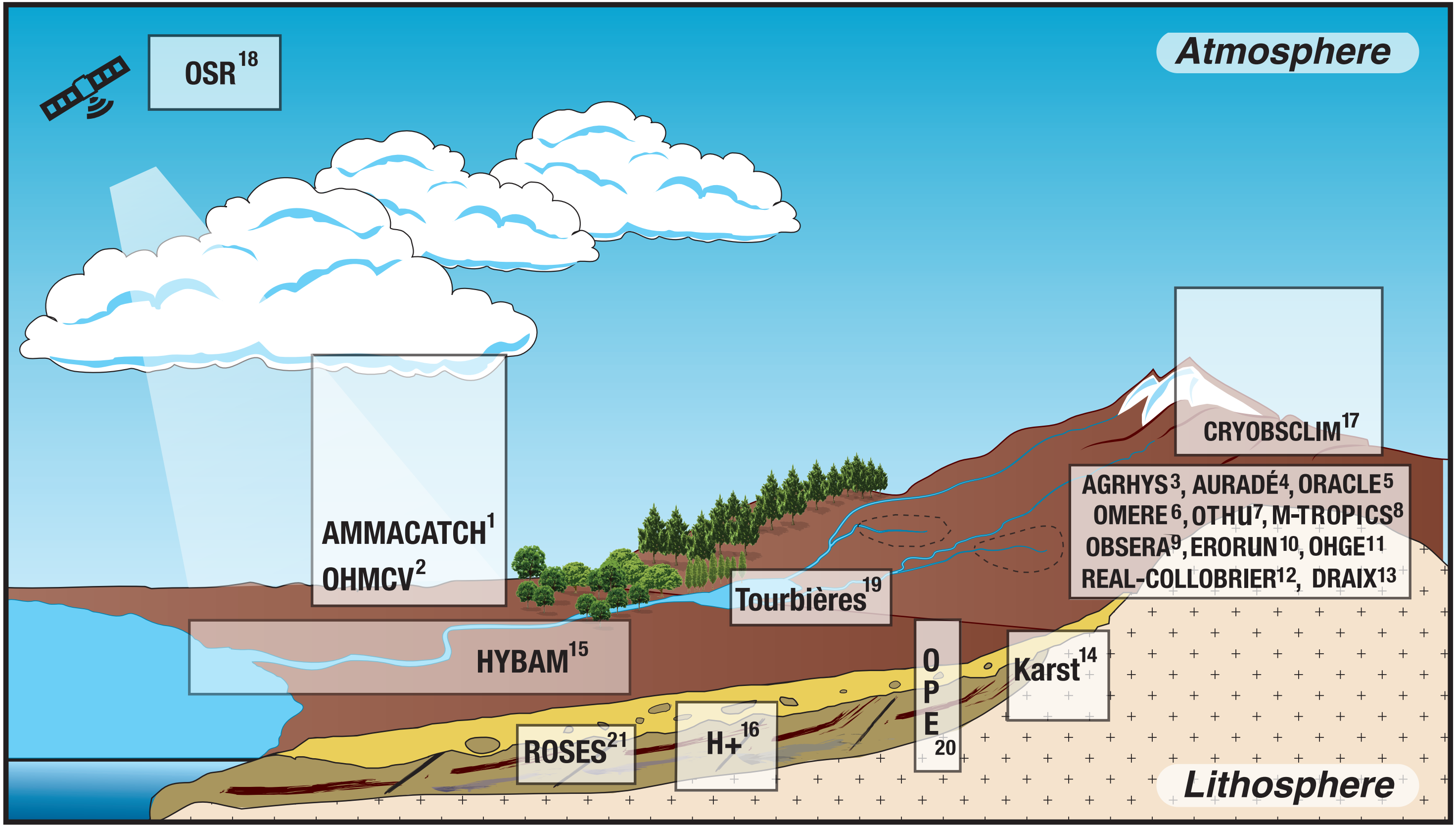

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Fig. 3

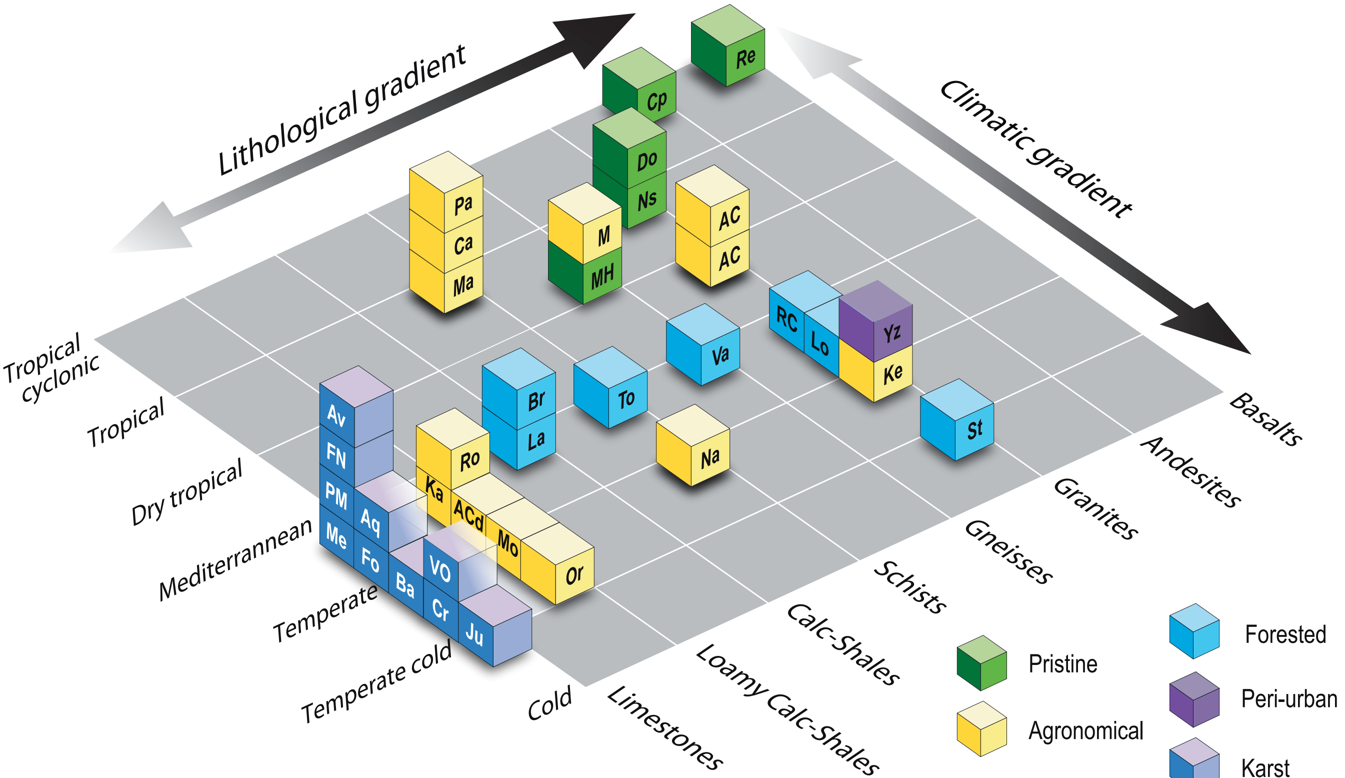

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Fig. 4

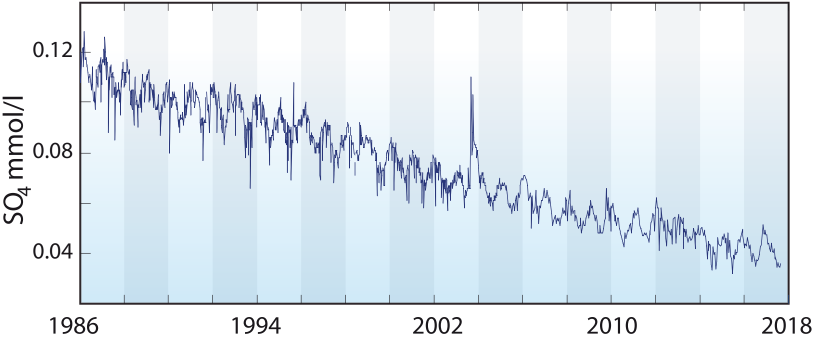

Fig. 5

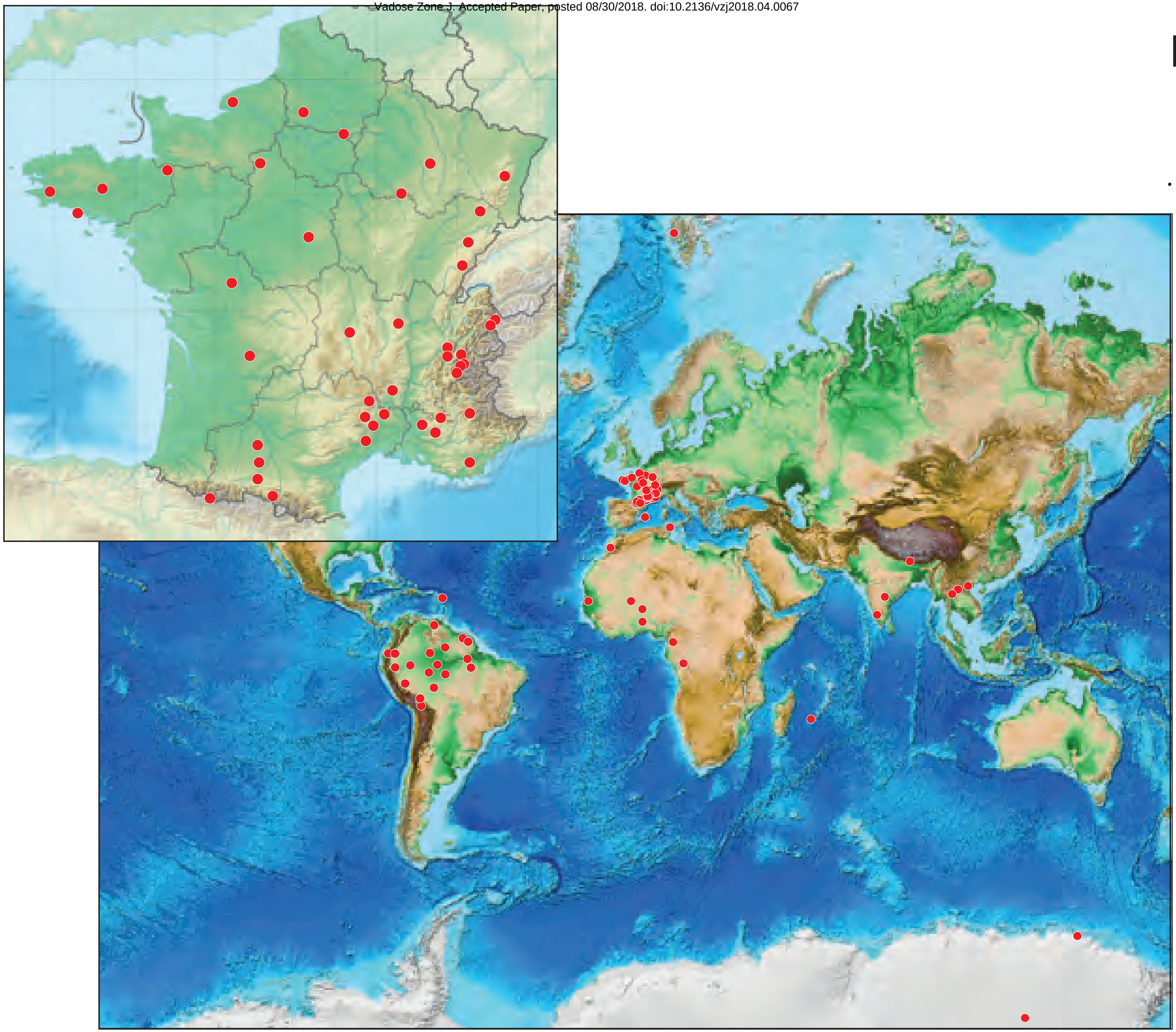

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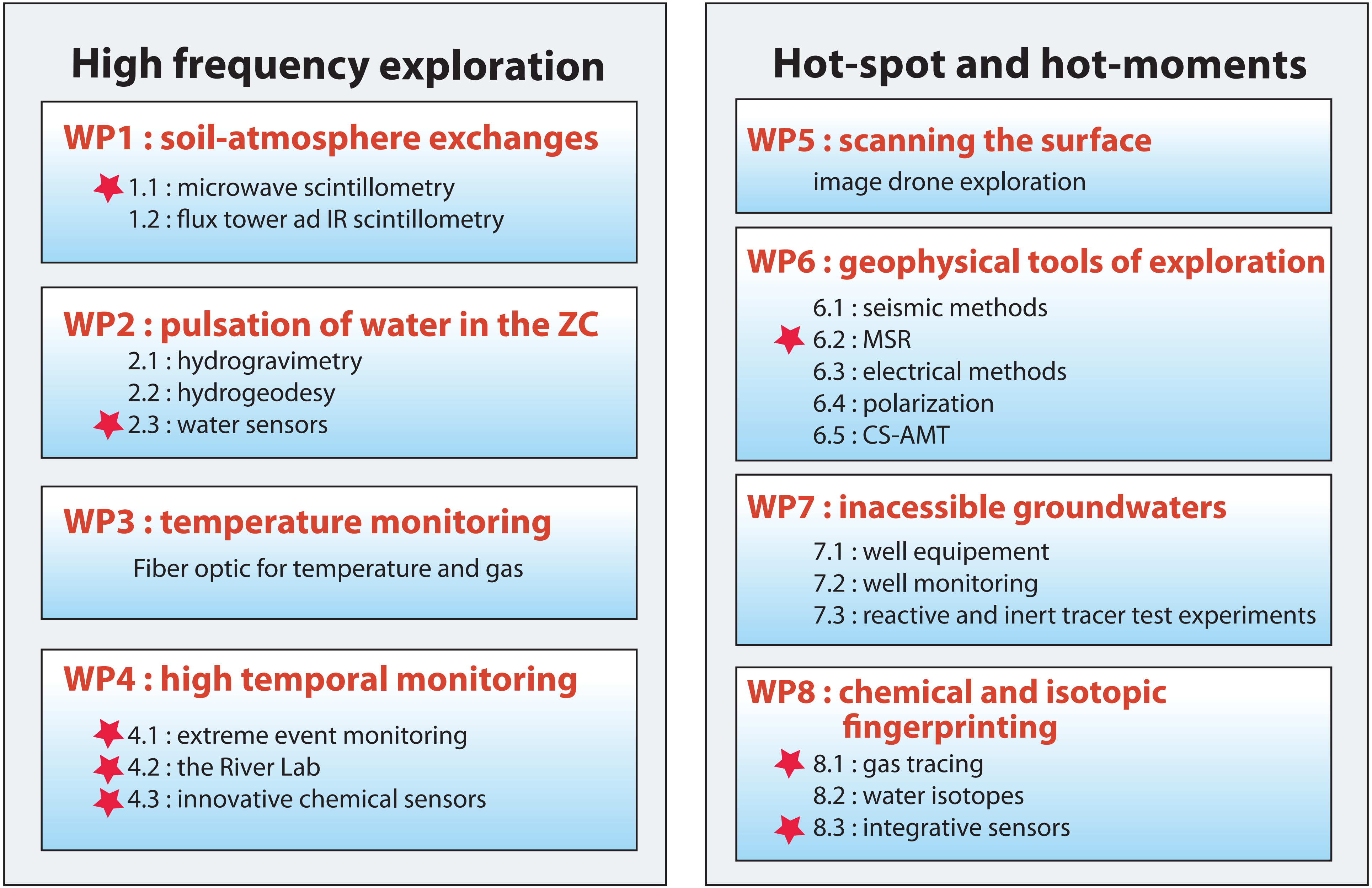
Fig. 6



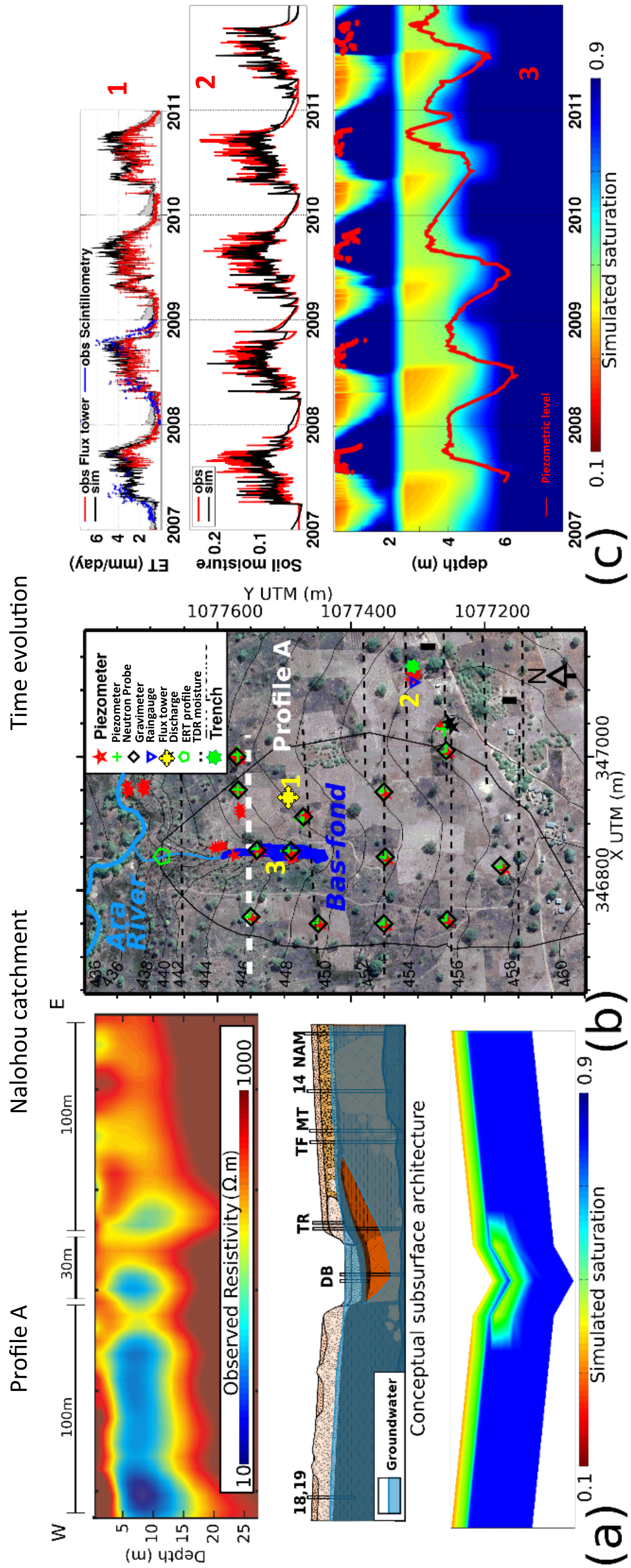

Profile A
Nalohou catchment
Time evolution
Depth (m)
Observed Resistivity (Ω.m)
Groundwater
Conceptual subsurface architecture
Simulated saturation
Ara River
Bas-fond
Profile A
Piezometer
Neutron Probe
Gravimeter
Raingauge
Flux tower
Discharge
ERT profile
TDR moisture
Trench
X UTM (m)
Y UTM (m)
ET (mm/day)
obs Flux tower
obs Scintillometry
sim
Soil moisture
obs
sim
depth (m)
Piezometric level
Simulated saturation
(a)
(b)
(c)

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Fig. 7