BAMS In Box

MOSES

A Novel Observation System to Monitor Dynamic Events across Earth Compartments

Ute Weber, Sabine Attinger, Burkard Baschek, Julia Boike, Dietrich Borchardt, Holger Brix, Nicolas Brüggemann, Ingeborg Bussmann, Peter Dietrich, Philipp Fischer, Jens Greinert, Irena Hajnsek, Norbert Kamjunke, Dorit Kerschke, Astrid Kiendler-Scharr, Arne Körtzinger, Christoph Kottmeier, Bruno Merz, Ralf Merz, Martin Riese, Michael Schloter, HaPe Schmid, Jörg-Peter Schnitzler, Torsten Sachs, Claudia Schütze, Ralf Tillmann, Harry Vereecken, Andreas Wieser, and Georg Teutsch

ABSTRACT: Modular Observation Solutions of Earth Systems (MOSES) is a novel observation system that is specifically designed to unravel the impact of distinct, dynamic events on the long-term development of environmental systems. Hydrometeorological extremes such as the recent European droughts or the floods of 2013 caused severe and lasting environmental damage. Modeling studies suggest that abrupt permafrost thaw events accelerate Arctic greenhouse gas emissions. Short-lived ocean eddies seem to comprise a significant share of the marine carbon uptake or release. Although there is increasing evidence that such dynamic events bear the potential for major environmental impacts, our knowledge on the processes they trigger is still very limited. MOSES aims at capturing such events, from their formation to their end, with high spatial and temporal resolution. As such, the observation system extends and complements existing national and international observation networks, which are mostly designed for long-term monitoring. Several German Helmholtz Association centers have developed this research facility as a mobile and modular "system of systems" to record energy, water, greenhouse gas, and nutrient cycles on the land surface, in coastal regions, in the ocean, in polar regions, and in the atmosphere—but especially the interactions between the Earth compartments. During the implementation period (2017–21), the measuring systems were put into operation and test campaigns were performed to establish event-driven campaign routines. With MOSES's regular operation starting in 2022, the observation system will then be ready for cross-compartment and cross-discipline research on the environmental impacts of dynamic events.

KEYWORDS: Dynamics; Hydrometeorology; Instrumentation/sensors; Measurements; Ecosystem effects; Extreme events

https://doi.org/10.1175/BAMS-D-20-0158.1
Corresponding author: Ute Weber, ute.weber@ufz.de
In final form 2 September 2021

AFFILIATIONS: Weber, Kamjunke, Schütze, and Teutsch—Helmholtz-Centre for Environmental Research (UFZ), Leipzig, Germany; **Attinger**—Helmholtz-Centre for Environmental Research (UFZ), Leipzig, and Mathematisch-Naturwissenschaftliche Fakultät, University of Potsdam, Potsdam, Germany; **Baschek**—Helmholtz-Center Geesthacht, Centre for Materials and Coastal Research (HZG), Geesthacht, and German Oceanographic Museum, Stralsund, Germany; **Boike**—Alfred-Wegener-Institute, Helmholtz-Centre for Polar and Marine Research, Bremerhaven, and Department of Geography, Humboldt-Universität zu Berlin, Berlin, Germany; **Borchardt**—Helmholtz-Centre for Environmental Research (UFZ), Leipzig, and Institute of Hydrobiology, Technische Universität Dresden, Dresden, Germany; **Brix**—Helmholtz-Center Geesthacht, Centre for Materials and Coastal Research (HZG), Geesthacht, Germany; **Brüggemann and Vereecken**—Forschungszentrum Jülich, Jülich, and Institute of Crop Science and Resource Conservation (INRES), University of Bonn, Bonn, Germany; **Bussmann**—Alfred-Wegener-Institute, Helmholtz-Centre for Polar and Marine Research, Bremerhaven, Germany; **Dietrich**—Helmholtz-Centre for Environmental Research (UFZ), Leipzig, and Center for Applied Geoscience, University of Tübingen, Tübingen, Germany; **Fischer**—Alfred-Wegener-Institute, Helmholtz-Centre for Polar and Marine Research, Bremerhaven, and Department Physics and Earth Sciences, Jacobs University Bremen, Bremen, Germany; **Greinert and Körtzinger**—Helmholtz Centre for Ocean Research (GEOMAR), and Faculty of Mathematics and Natural Sciences, Kiel University, Kiel, Germany; **Hajnsek**—German Aerospace Center (DLR), Oberpfaffenhofen, Germany, and Institute of Environmental Engineering, ETH Zürich, Zürich, Switzerland; **Kerschke**—Helmholtz Centre Potsdam–German Research Centre for Geosciences (GFZ), Potsdam, Germany; **Kiendler-Scharr**—Forschungszentrum Jülich, Jülich, and Institute of Physics I, Universität zu Köln, Cologne, Germany; **Kottmeier and Wieser**—Karlsruhe Institute of Technology, Karlsruhe, Germany; **B. Merz**—Helmholtz Centre Potsdam–German Research Centre for Geosciences (GFZ), and Mathematisch-Naturwissenschaftliche Fakultät, University of Potsdam, Potsdam, Germany; **R. Merz**—Helmholtz-Centre for Environmental Research (UFZ), Leipzig, and Institute of Geosciences and Geography, Martin-Luther-University Halle-Wittenberg, Halle, Germany; **Riese**—Forschungszentrum Jülich, Jülich, and Institute for Atmospheric and Environmental Research, University of Wuppertal, Wuppertal, Germany; **Schloter**—Helmholtz Zentrum München–German Research Center for Environmental Health (HMGU), Munich, and School of Life Sciences, Technical University of Munich, Freising, Germany; **Schmid**—Karlsruhe Institute of Technology, Karlsruhe, and School of Life Sciences, Technical University of Munich, Freising, Germany; **Schnitzler**—Helmholtz Zentrum München–German Research Center for Environmental Health (HMGU), Munich, and Faculty of Environment and Natural Resources, Albert-Ludwigs-Universität Freiburg, Freiburg, Germany; **Sachs**—Helmholtz Centre Potsdam–German Research Centre for Geosciences (GFZ), Potsdam, and Institute of Flight Guidance, Technische Universität Braunschweig, Braunschweig, Germany; **Tillmann**—Forschungszentrum Jülich, Jülich, Germany

Although it is well known that global change affects Earth and the environment at many different temporal and spatial scales, currently only limited knowledge is available on the importance of distinct dynamic events for the long-term development of environmental systems. The new observation system Modular Observation Solutions of Earth Systems (MOSES; Fig. 1) focuses on four types of dynamic events: heatwaves and droughts, hydrological extremes, the abrupt thawing of permafrost, and ocean eddies. These events were selected because of their relevance to climate and environmental changes and their socioeconomic impact:

During the summers of 2003 and 2018–20, *record-breaking air temperatures, extensive droughts, and historically low river flows* were recorded across Europe (Herring et al. 2020). Their devastating impact on the functioning of land ecosystems led to an increased vulnerability well beyond the duration of single events (Bastos et al. 2020; Buras et al. 2020), including a strong decrease in primary productivity (Fu et al. 2020; Graf et al. 2020), an unprecedented tree mortality (Margalef-Marrase et al. 2020), and loss of agricultural production (Beillouin et al. 2020). Photochemically induced air pollution increased due to heatwaves, predominantly seen in ozone threshold exceedances (Monks et al. 2009). In rivers, lakes, and reservoirs, widespread algal blooms appeared, some dominated by toxic cyanobacteria (Wentzky et al. 2019). Such extremes are likely to occur more frequently in the future (Samaniego et al. 2018).

Globally, the frequency of *heavy precipitation events* increased in the past 30 years due to warming (Fischer and Knutti 2015), and global projections of *river floods* mostly indicate increases by the end of the century (Arnell and Gosling 2016). In Central Europe, river floods in 2002 and 2013 have broken records, leading to widespread flood defense failures and disastrous damage (Schröter et al. 2015). In 2016 and 2018 a series of flash floods triggered by convective weather systems caused severe damage to buildings and infrastructure and led to geomorphological consequences such as debris flow (Bronstert et al. 2018).

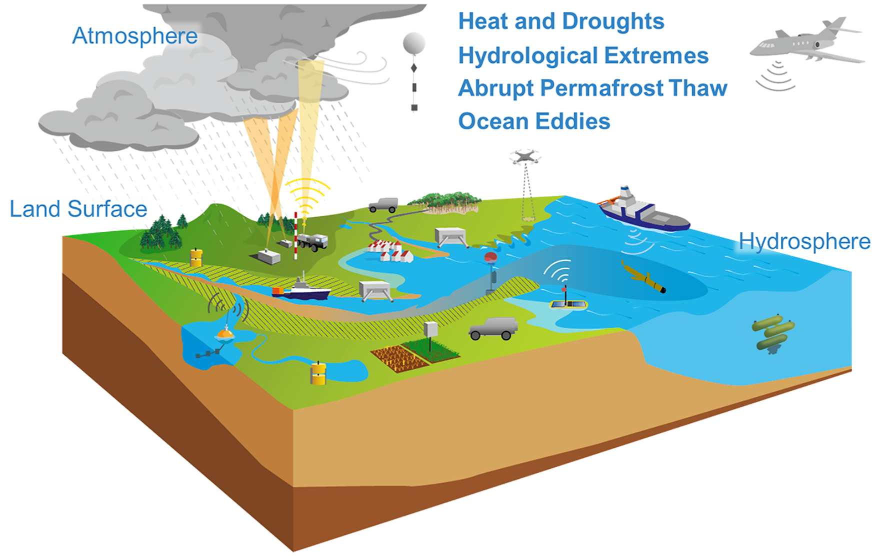

Fig. 1. Schematic presentation of the mobile and modular observation system Modular Observation Solutions of Earth Systems (MOSES). The system is implemented to unravel the impact of distinct dynamic events on the long-term development of the environment. Heatwaves and droughts, hydrological extremes, abrupt permafrost thaw, and ocean eddies are the focus of this event-oriented observation and research initiative. To capture such dynamic events from their formation to their end, MOSES is designed as a "system of systems" with a particular cross-compartment alignment, connecting atmosphere, land surface, and hydrosphere. The block diagram illustrates an event-driven observation campaign for hydrological extremes, capturing the formation of a high precipitation event and the resulting flood wave as it passes through the catchment to the estuary and ocean.

Current modeling studies suggest that *abrupt permafrost thaw* accelerates Arctic greenhouse gas emissions (Turetsky et al. 2020). Such distinct thaw events can potentially release greenhouse gases on short time scales and are triggered, for example, by heatwaves or intense rainfall in the Arctic. While abrupt permafrost thaw actively affects only small areas, it could play a major role in the rapid release of permafrost carbon to the atmosphere and thus contribute to a yet unknown extent to climate warming (Nitzbon et al. 2020).

Ocean eddies have a significant share in the marine carbon uptake or release. Modeling studies indicate that even short-lived eddies a few kilometers in size are important drivers for phytoplankton production with a likely contribution of several tens of percent (Mahadevan 2016; Lévy et al. 2018). Phytoplankton is the base of the marine food chain, produces a large portion of atmospheric oxygen, and is thereby a key player in the uptake or release of carbon.

Despite growing evidence that such dynamic events bear the potential for major and lasting environmental changes, the data required to investigate this potential are still sparse. While long-term trends are typically assessed with stationary observation networks and platforms specifically designed for long-term monitoring, proven event-oriented observation systems and strategies are still missing. Event-oriented observation campaigns require a combination of 1) measuring systems that can be rapidly deployed at "hot spots" and in "hot moments," 2) mobile equipment to monitor spatial dynamics in high resolution, 3) in situ measuring systems to record temporal dynamics in high resolution, and 4) interoperable measuring systems to monitor the interactions between atmosphere, land surface, and hydrosphere (Earth compartments).

The Helmholtz Association of German Research Centres developed MOSES to record dynamic events from their formation to their end, with a particular cross-compartment alignment. Comprehensive datasets on event formation, evolution, and direct impacts are a prerequisite for improved prediction of expected environmental, social, and economic consequences, the feedback on climate as well as for the design of protective measures.

To understand dynamic events and to unravel their long-term impacts, reference datasets are required for the investigated regions. Existing observation networks are integrated into the preparation, course, and subsequent evaluation of the event-driven observation campaigns. Such networks comprise scientific, governmental, and other official monitoring programs. Additionally, valuable reference data are provided by satellite missions such as Sentinel and by international monitoring networks such as Integrated Carbon Observation System (ICOS). The Helmholtz observatories Terrestrial Environmental Observatories (TERENO; Zacharias et al. 2011), Coastal Observation System for Northern and Arctic Seas (COSYNA; Baschek et al. 2017), Cape Verde Ocean Observatory (CVOO; Körtzinger and Zenk 2011), and the Samoylov Permafrost Observation Stations (Boike et al. 2019) serve as anchor points for the implementation activities and for future campaigns.

In the following sections, the observation system and the observing strategy are presented using examples for heat and drought events.

The observation system

MOSES must meet the challenging requirements arising in event-driven campaigns: the system must be mobile and interoperable, cover a broad range of observation scales across Earth compartments, and provide high-resolution data in near–real time. Accomplishing these goals required the development of novel measuring systems as well as the improvement of existing systems. The necessary technical developments focused on the following:

- *Minimization* of sensors for installation on mobile carriers and building of multisensor systems
- *Automation* of measuring systems for intensive field campaigns and for use in areas difficult to access
- *Improvement* and adjustment of existing measuring systems for modular and multipurpose use
- *Near-real-time data transmission* for fast data access and campaign control, fast visualization, and test analysis

Enabled by Helmholtz infrastructure investment of EUR 30 million, MOSES is designed as a modular "system of systems" (Fig. 1). The participating centers developed individual measuring systems that are combined to form specific observation modules (Table 1). These

Table 1. List of MOSES modules and their fields of application: blue = marine, green = terrestrial, and gray = atmospheric operation. The composition of the modules is depicted in Fig. 2 for "land–atmosphere fluxes" and "atmospheric chemistry."

MOSES Modules	Heat and Droughts	Hydrological Extremes	Ocean Eddies	Abrupt Thaw Permafrost
Atmospheric Dynamics	X	X		X
Atmospheric Chemistry	X	X		X
Land-Atmosphere Fluxes	X	X		X
Biota	X	X		
Water Resources	X	X		
Soil and Water Quality	X	X		
Flow and Sediment Dynamics	X	X	X	X
Permafrost Thaw	X	X		X
Coastal Fixed Point Stations	X	X	X	
Marine Mobile Systems		X	X	X
Marine Autonomous Vehicles		X	X	X

modules comprise sensors that are either required to study a certain research topic (e.g., “land–atmosphere fluxes” module) or processes in a certain compartment (e.g., “atmospheric dynamics” module). They are designed to record energy, water, greenhouse gas and nutrient exchanges on the land surface, in coastal regions, in the ocean, in polar regions, and in the atmosphere—with a focus on the interactions between Earth compartments. Each observation module is deployable in various event investigations (Table 1).

MOSES is a distributed infrastructure and its component measuring systems are managed by the participating research centers. A compilation of the observation modules is listed on the home page: www.moses-helmholtz.de/index.php?en=44880. Figure 2 illustrates examples of measuring systems for “land–atmosphere fluxes” and “atmospheric chemistry.” Their cross-compartment interplay is presented in the “Investigating event chains” section.

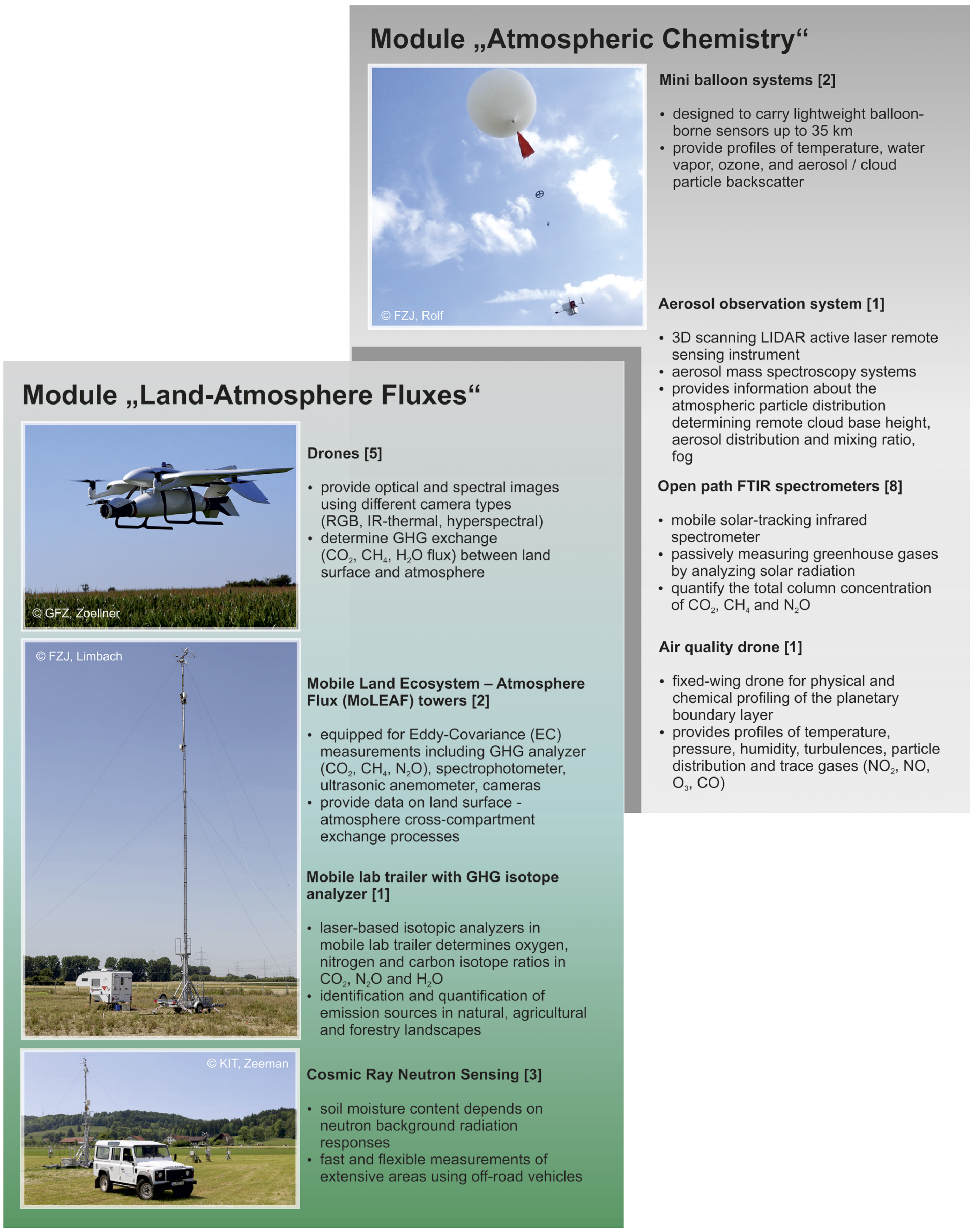

Fig. 2. Measuring systems of the MOSES modules “land–atmosphere fluxes” and “atmospheric chemistry.” Both modules were deployed at the heat and drought test campaigns in 2019 and 2020 as outlined in the “Investigating event chains” section. The numbers in brackets denote the number of measuring systems.

Organization, implementation, and operation

The organization, technical operation, and data management of such a distributed infrastructure requires substantial support from the participating centers, which is provided by core funding. The organizational structure (www.moses-helmholtz.de/index.php?en=44859) builds upon the joint scientific steering committee, technical implementation office and data management team to ensure the operation of the measuring and data management systems.

Event-driven observation campaigns typically demand short reaction times to locate suitable sites, install measuring systems, and provide fast data transmission. To be prepared for this challenge, training is required. As illustrated in Fig. 3, extended device tests began in 2018, including the conception of quality control and assurance measures. To develop and optimize campaign logistics, first test campaigns began in 2018 and will continue, with increasing complexity, until 2022. Subsequently, joint data analysis was organized. Based on the experiences gained during implementation, we developed management procedures for the overall organization and in particular for the deployment of the measuring systems.

The distributed and heterogeneous nature of the observation system poses challenges for the integration of its data. Therefore, a data management infrastructure for a distributed sensor network has been developed (www.moses-helmholtz.de/index.php?en=47151), in which the participating centers act as data providers. The mandatory data policy regulates the sharing of data and data products and facilitates their open access according to the findable, accessible, interoperable, and reusable (FAIR) principles (Wilkinson et al. 2016). For all campaigns and datasets, metadata collection is organized by campaign-specific data management plans (DMPs). These DMPs record responsibilities along with data volumes, characteristics, processing steps, and data flows of the campaigns via a collaborative online tool. Selected metadata are then automatically transferred to the public MOSES Data Discovery Portal (https://moses-data.gfz-potsdam.de/) that provides current information on campaigns, equipment, and collected data. Furthermore, the portal facilitates dataset access after the quality ensured release by the responsible scientists. With the MOSES data management infrastructure, we developed the technical and organizational framework to integrate and advance the scientific data workflows over the next years of operation.

During operation, the Scientific Steering Committee (SSC) will be in charge of the scientific and technical management of the research infrastructure. This committee checks campaign proposals submitted by research consortia with regard to their feasibility and coherence with MOSES aims. Together with the campaign coordinators, the SSC decides on campaign timing, aiming at an efficient allocation of measurement systems and optimal campaign placement. The SSC also acts as a mediator if campaigns compete for equipment and time slots. Approximately two campaigns will be carried out per year, which may last for several weeks to months, depending on the type of event and the scientific scope. The duration of individual campaigns is related to the development of the considered event, characterized by the initial state, drivers, and local feedback processes (Sillmann et al. 2017). For short-lived events such as ocean eddies or high precipitation

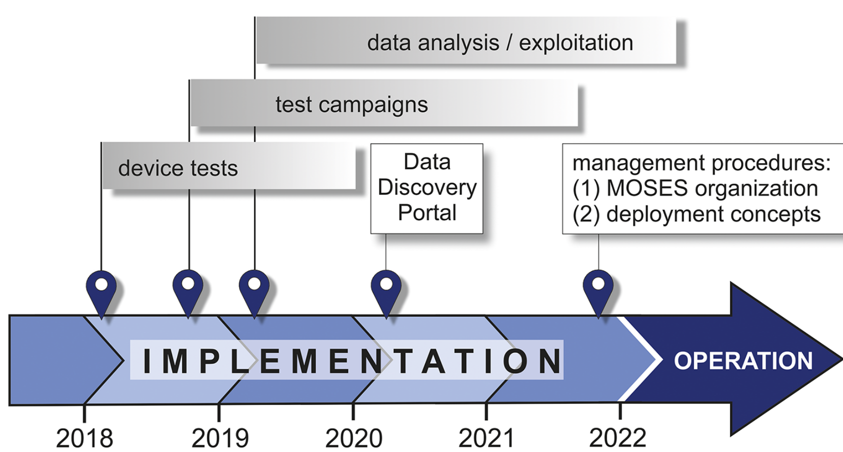

Fig. 3. Timeline of the MOSES implementation period: 2017–21. Device tests, test campaigns, and data analysis started in 2018 and continued to the end of implementation. The public metadata portal (Data Discovery Portal) was released in 2020. Management procedures have been finalized for 2022.

and local floods, campaigns normally take several weeks to months, including embedded intensive operation periods. Longer lasting events such as heatwaves and droughts or abrupt permafrost thaw typically require observation times of about half a year. Furthermore, the investigation of feedback effects may entail subsequent observations in the following year.

For the different event types, deployment concepts have been developed (Fig. 4), which converge according to preparation and response times:

Long-term planning campaigns are mostly required to investigate abrupt permafrost thaw and ocean eddies. To organize the deployment of equipment in conjunction with research vessels and planes or international monitoring facilities, a preparation time of about 2 years must be taken into account. The flexibility of this campaign type is limited because region and time slot of the investigations are fixed.

Medium-term planning campaigns for investigating weather extremes are organized in target regions and time slots exhibiting a high probability of event occurrence. Campaign preparation requires about one year to optimize the instrumental layout and to obtain permissions. During the investigation period, most equipment is installed for stationary, baseline recordings. As soon as events evolve, intensive operation periods are started. With a reaction time ranging from a few days (high precipitation and floods) to a few weeks (heatwaves and droughts), mobile systems are additionally deployed to refine spatial observation, while temporal monitoring rates of the stationary equipment are increased.

The *ad hoc campaign* concept is intended for extreme weather events, such as floods, heatwaves, and droughts that do not occur within the scope of planned campaigns, but within regions suitable for operation. These areas include the TERENO sites or the Elbe River and the German Bight ("Investigating event chains" section). The reaction time to launch such a campaign is short, ranging from only a few days, in the case of an emerging flood, and up to 1 month for heatwaves and droughts. Due to the short preparation time, mainly mobile and autonomous systems are deployed, which reduce the observational comprehensiveness compared to planned campaigns.

Investigating event chains

MOSES is designed to capture and quantify direct impacts of events on affected environmental systems. To meet this aim, we developed an "event chain" approach: An observation campaign starts by recording the initial event with respect to its extent and intensity. The measuring systems will then gather data on the subsequently triggered processes along and across Earth compartments. To investigate long-term environmental impacts, we will analyze the campaign datasets along with datasets available from existing observation facilities for the region of interest (first section), reanalysis data, and modeling approaches.

In this section, the event chain approach is explained for heat and droughts. The respective approaches and schematics for hydrological extremes, abrupt permafrost thaw, and ocean eddies are provided on our home page (www.moses-helmholtz.de).

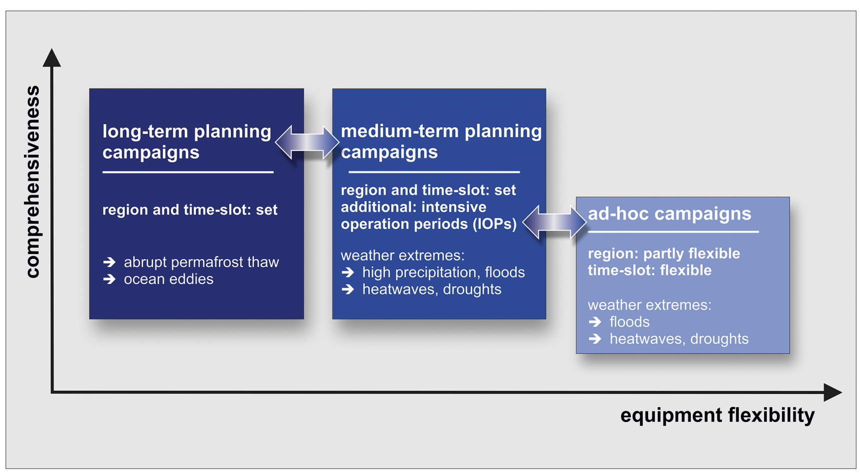

Fig. 4. Deployment concepts for the different event types. Planned campaigns allow for an extensive use of equipment and thus for comprehensive event observation. Ad hoc campaigns require primarily flexible equipment, which reduces the observational range. The two types of campaigns planned well in advance converge with respect to preparation time, while IOPs and ad hoc campaigns converge with respect to response time.

Heatwaves and droughts typically affect the atmosphere, the land surface, and aquatic systems simultaneously, triggering complex interactions of cascading and interconnected processes. Three cross-linked strands of event chains are the focus of MOSES campaigns (Fig. 5):

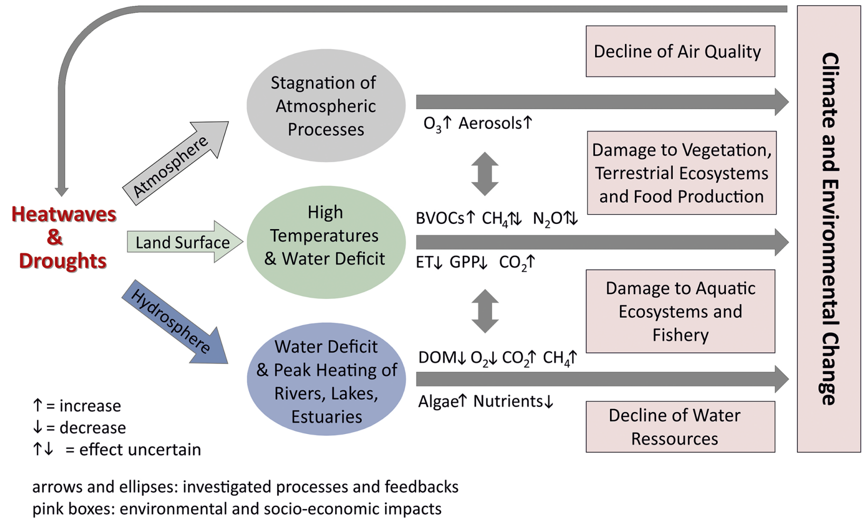

Fig. 5. Schematic diagram of event chains triggered by heat and droughts: 1) in the atmosphere, 2) on the land surface, and 3) in the hydrosphere. Shown here are the main processes and fluxes recorded during MOSES campaigns within and across Earth compartments. The potential environmental and associated socioeconomic impacts range from immediate to long-term effects that might develop within the coming decades (BVOCs = biogenic volatile organic compounds, ET = evapotranspiration, GPP = gross primary productivity, DOM = dissolved organic matter).

1) In the atmosphere, heatwaves increase aerosol and ozone formation due to the temperature and radiation dependence of NO_x and volatile organic compounds (VOCs) reaction kinetics, leading to reduced air quality (Fiore et al. 2012).
2) On the land surface, heat and droughts cause declines in gross primary productivity (Ciais et al. 2005; Fu et al. 2020) and evapotranspiration, leading to increased net CO_2 emissions (Reichstein et al. 2013; Green et al. 2019) and uncertain flux changes of greenhouse gases (GHGs) such as N_2O or CH_4 (Yan et al. 2018). Vegetation stress and insect pests increase biogenic VOC emissions (Joutsensaari et al. 2015; Ferracci et al. 2020), resulting in additional aerosol and ozone formation in the boundary layer by atmospheric oxidation (Penuelas and Staudt 2010).
3) Water resources and aquatic environments are degraded in quantity and quality by heat and droughts, causing increased atmospheric GHG emissions from drying inland waters (Keller et al. 2020). Biogeochemical changes in water bodies (Casas-Ruiz et al. 2020) lead to consequences such as algal blooms in lakes and rivers or changes in coastal ocean productivity (Hosen et al. 2019).

Extensive heat and drought test campaigns started in 2019 at the well-established TERENO sites Pre-Alpine, Eifel, and Harz. These sites also host a number of the German ICOS observatories. The first campaign, Pre-Alpine, served as a device test for deploying the measuring systems shown in Fig. 2 and was embedded in the "ScaleX2019" campaign, which continued earlier international observing activities (Wolf et al. 2017). In this context, the off-road vehicles equipped with cosmic ray neutron sensors (CRNS) participated in a comparison initiative to determine soil moisture dynamics across scales (Jakobi et al. 2020; Fersch et al. 2020) and provided the regional-scale observation component.

With the extreme and consecutive drought years developing in Germany from 2018 to 2020, we continued the test campaigns in some of the most affected regions: The TERENO sites Eifel (coniferous forest) and Harz (mixed forest) were hit by severe drought followed by forest damage and clear-cutting. Comparison campaigns therefore started at both sites in summer 2019 and continued in spring 2020. The studies focused on event chain 2, land surface characteristics and gas exchange with the atmosphere (Fig. 5). Soil moisture dynamics were intensively monitored by mobile CRNS rovers in combination with stationary CRNS and time domain reflectometry (TDR) networks installed at the sites. Airborne (drones and planes) thermal and hyperspectral cameras (Fig. 2) monitored soil temperature and vegetation condition in response to increasing temperatures and progressive drought. Land–atmosphere exchanges of water vapor, O_2, CO_2, CH_4, and energy were studied using mobile towers in combination with the GHG isotope analyzer unit (Fig. 2). At the Eifel site, the cleared areas became a persistent source of CO_2, while the ET flux decreased. The remaining spruce forest was heavily infested by bark beetles, resulting in increased biogenic volatile organic compounds (BVOC) emissions such as terpenes. To quantify such emissions in conjunction with soil moisture and air temperature variations, a BVOC laboratory was set up. Subsequent oxidation and formation of aerosol particles were observed with a mobile aerosol mass spectrometer (Fig. 2), linking the research focus of event chains 1 and 2 as illustrated in Fig. 5.

The summer droughts of 2018 and 2019 also caused historically low water levels in the Elbe River. To assess the effects of low discharge, high irradiation and water temperatures, test campaigns with research vessels were organized in the river and its estuary. Considering event chain 3 (Fig. 5), the campaigns focused on water quality, aquatic ecosystem metabolism and GHG emissions. Using a Lagrangian sampling approach according to travel time, multiparameter probes and water samples recorded temperature, O_2, pH, nutrient loading, dissolved organic matter (DOM), and chlorophyll as a proxy for phytoplankton biomass. Gas analyzers continuously quantified both dissolved and atmospheric CO_2 and CH_4 concentrations. In situ multiparameter probes positioned along the route recorded high-resolution diurnal variations in parameters critical to aquatic ecosystems, such as high water temperatures or O_2 depletion and extreme pH values caused by excessive algal growth. Kamjunke et al. (2021) investigated the key drivers of the significant algal growth observed in 2018 and 2019 and its impact on nutrient dynamics in the river.

With these test campaigns, we collected comprehensive datasets from some regions most affected by the past summer droughts. Such campaigns complement existing observation networks, such as the TERENO and ICOS observatories mentioned earlier, or the Elbe River and the German Bight governmental monitoring programs, by filling event-specific observation gaps: 1) The measuring systems are deployed at "hot spots" and in "hot moments." 2) Mobile monitoring approaches such as CRNS roving or Lagrangian water sampling provide regional high-resolution observations that complement stationary instrumentation. 3) High-resolution time series recorded, for example, by GHG isotope analyzers or aquatic multiparameter stations reveal in situ event dynamics. 4) The interoperable observation modules extend the standard observation ranges of existing facilities, such as for atmospheric variables at the TERENO/ICOS sites or for GHG emissions associated with governmental river and coastal monitoring. In addition, the collected field data are used in combination with remote sensing data, such as on forest damage and clear-cut areas, and with land surface–atmosphere modeling to upscale site observations to the regional scale.

Current state and outlook

During the implementation period 2017–21, the measuring systems have been developed for modular operation while the management procedures to carry out event-driven campaigns have been established. Further prerequisites are event forecasting tools. Several MOSES scientists participate in research projects developing, for example, European/German forecasts for hydrometeorological extremes or marine hydrodynamic models. Information on such complementary research activities is available on our home page: www.moses-helmholtz.de/index.php?en=47303.

From 2022 onward, MOSES will be available for event-oriented research initiatives and collaboration. The observation system provides novel observation opportunities for the scientific community and extends existing observation capacities toward highly mobile and cross-compartmental systems.

Acknowledgments. This work was supported by funding from the Helmholtz Association within the framework of MOSES. We thank all participating centers for their additional personal and financial support, particularly the GFZ coordinating the data management and the UFZ coordinating MOSES as a whole. We also thank A. Srinivasan for proofreading and the three anonymous reviewers for their valuable comments.

References

Arnell, N. W., and S. N. Gosling, 2016: The impacts of climate change on river flood risk at the global scale. *Climatic Change*, **134**, 387–401, https://doi.org/10.1007/s10584-014-1084-5.

Baschek, B., and Coauthors, 2017: The Coastal Observing System for Northern and Arctic Seas (COSYNA). *Ocean Sci.*, **13**, 379–410, https://doi.org/10.5194/os-13-379-2017.

Bastos, A., and Coauthors, 2020: Impacts of extreme summers on European ecosystems: A comparative analysis of 2003, 2010 and 2018. *Philos. Trans. Roy. Soc. London*, **375B**, 20190507, https://doi.org/10.1098/rstb.2019.0507.

Beillouin, D., B. Schauberger, A. Bastos, P. Ciais, and D. Makowski, 2020: Impact of extreme weather conditions on European crop production in 2018. *Philos. Trans. Roy. Soc. London.*, **375B**, 20190510, https://doi.org/10.1098/rstb.2019.0510.

Boike, J., and Coauthors, 2019: A 16-year record (2002–2017) of permafrost, active-layer, and meteorological conditions at the Samoylov Island Arctic permafrost research site, Lena River delta, northern Siberia: An opportunity to validate remote-sensing data and land surface, snow, and permafrost models. *Earth Syst. Sci. Data*, **11**, 261–299, https://doi.org/10.5194/essd-11-261-2019.

Bronstert, A., and Coauthors, 2018: Forensic hydro-meteorological analysis of an extreme flash flood: The 2016-05-29 event in Braunsbach, SW Germany. *Sci. Total Environ.*, **630**, 977–991, https://doi.org/10.1016/j.scitotenv.2018.02.241.

Buras, A., A. Rammig, and C. S. Zang, 2020: Quantifying impacts of the 2018 drought on European ecosystems in comparison to 2003. *Biogeosciences*, **17**, 1655–1672, https://doi.org/10.5194/bg-17-1655-2020.

Casas-Ruiz, J. P., and Coauthors, 2020: Delineating the continuum of dissolved organic matter in temperate river networks. *Global Biogeochem. Cycles*, **34**, e2019GB006495, https://doi.org/10.1029/2019GB006495.

Ciais, P., and Coauthors, 2005: Europe-wide reduction in primary productivity caused by the heat and drought in 2003. *Nature*, **437**, 529–533, https://doi.org/10.1038/nature03972.

Ferracci, V., and Coauthors, 2020: Continuous isoprene measurements in a UK temperate forest for a whole growing season: Effects of drought stress during the 2018 heatwave. *Geophys. Res. Lett.*, **47**, e2020GL088885, https://doi.org/10.1029/2020GL088885.

Fersch, B., and Coauthors, 2020: A dense network of cosmic-ray neutron sensors for soil moisture observation in a pre-Alpine headwater catchment in Germany. *Earth Syst. Sci. Data*, **12**, 2289–2309, https://doi.org/10.5194/essd-12-2289-2020.

Fiore, A. M., and Coauthors, 2012: Global air quality and climate. *Chem. Soc. Rev.*, **41**, 6663–6683, https://doi.org/10.1039/c2cs35095e.

Fischer, E. M., and R. Knutti, 2015: Anthropogenic contribution to global occurrence of heavy-precipitation and high-temperature extremes. *Nat. Climate Change*, **5**, 560–564, https://doi.org/10.1038/nclimate2617.

Fu, Z., and Coauthors, 2020: Sensitivity of gross primary productivity to climatic drivers during the summer drought of 2018 in Europe. *Philos. Trans. Roy. Soc. London*, **375B**, 20190747, https://doi.org/10.1098/rstb.2019.0747.

Graf, A., and Coauthors, 2020: Altered energy partitioning across terrestrial ecosystems in the European drought year 2018. *Philos. Trans. Roy. Soc. London*, **375B**, 20190524, https://doi.org/10.1098/rstb.2019.0524.

Green, J. K., S. I. Seneviratne, A. M. Berg, K. L. Findell, S. Hagemann, D. M. Lawrence, and P. Gentine, 2019: Large influence of soil moisture on long-term terrestrial carbon uptake. *Nature*, **565**, 476–479, https://doi.org/10.1038/s41586-018-0848-x.

Herring, S. C., N. Christidis, A. Hoell, M. P. Hoerling, and P. A. Stott, Eds., 2020: Explaining Extreme Events of 2018 from a Climate Perspective. *Bull. Amer. Meteor. Soc.*, **101** (1), S1–S140, https://doi.org/10.1175/BAMS-ExplainingExtremeEvents2018.1.

Hosen, J. D., and Coauthors, 2019: Enhancement of primary production during drought in a temperate watershed is greater in larger rivers than headwater streams. *Limnol. Oceanogr.*, **64**, 1458–1472, https://doi.org/10.1002/lno.11127.

Jakobi, J., J. A. Huisman, M. Schrön, J. Fiedler, C. Brogi, H. Vereecken, and H. R. Bogena, 2020: Error estimation for soil moisture measurements with cosmic ray neutron sensing and implications for rover surveys. *Front. Water*, **2**, 10, https://doi.org/10.3389/frwa.2020.00010.

Joutsensaari, J., and Coauthors, 2015: Biotic stress accelerates formation of climate-relevant aerosols in boreal forests. *Atmos. Chem. Phys.*, **15**, 12 139–12 157, https://doi.org/10.5194/acp-15-12139-2015.

Kamjunke, N., M. Rode, M. Baborowski, J. V. Kunz, J. Zehner, D. Borchardt, and M. Weitere, 2021: High irradiation and low discharge promote the dominant role of phytoplankton in riverine nutrient dynamics. *Limnol. Oceanogr.*, **66**, 11778, https://doi.org/10.1002/lno.11778.

Keller, P. S., and Coauthors, 2020: Global CO2 emissions from dry inland waters share common drivers across ecosystems. *Nat. Commun.*, **11**, 2126, https://doi.org/10.1038/s41467-020-15929-y.

Körtzinger, A., and C. Zenk, 2011: Research Base Cape Verde: A fascinating laboratory for oceanographers and atmospheric scientists. GEOMAR Doc., 31 pp.

Lévy, M., P. J. S. Franks, and K. S. Smith, 2018: The role of submesoscale currents in structuring marine ecosystems. *Nat. Commun.*, **9**, 4758, https://doi.org/10.1038/s41467-018-07059-3.

Mahadevan, A., 2016: The impact of submesoscale physics on primary productivity of plankton. *Annu. Rev. Mar. Sci.*, **8**, 161–184, https://doi.org/10.1146/annurev-marine-010814-015912.

Margalef-Marrase, J., M. Á. Pérez-Navarro, and F. Lloret, 2020: Relationship between heatwave-induced forest die-off and climatic suitability in multiple tree species. *Global Change Biol.*, **26**, 3134–3146, https://doi.org/10.1111/gcb.15042.

Monks, P. S., and Coauthors, 2009: Atmospheric composition change—Global and regional air quality. *Atmos. Environ.*, **43**, 5268–5350, https://doi.org/10.1016/j.atmosenv.2009.08.021.

Nitzbon, J., S. Westermann, M. Langer, L. C. P. Martin, J. Strauss, S. Laboor, and J. Boike, 2020: Fast response of cold ice-rich permafrost in northeast Siberia to a warming climate. *Nat. Commun.*, **11**, 2201, https://doi.org/10.1038/s41467-020-15725-8.

Penuelas, J., and M. Staudt, 2010: BVOCs and global change. *Trends Plant Sci.*, **15**, 133–144, https://doi.org/10.1016/j.tplants.2009.12.005.

Reichstein, M., and Coauthors, 2013: Climate extremes and the carbon cycle. *Nature*, **500**, 287–295, https://doi.org/10.1038/nature12350.

Samaniego, L., and Coauthors, 2018: Anthropogenic warming exacerbates European soil moisture droughts. *Nat. Climate Change*, **8**, 421–426, https://doi.org/10.1038/s41558-018-0138-5.

Schröter, K., M. Kunz, F. Elmer, B. Mühr, and B. Merz, 2015: What made the June 2013 flood in Germany an exceptional event? A hydro-meteorological evaluation. *Hydrol. Earth Syst. Sci.*, **19**, 309–327, https://doi.org/10.5194/hess-19-309-2015.

Sillmann, J., and Coauthors, 2017: Understanding, modeling and predicting weather and climate extremes: Challenges and opportunities. *Wea. Climate Extremes*, **18**, 65–74, https://doi.org/10.1016/j.wace.2017.10.003.

Turetsky, M. R., and Coauthors, 2020: Carbon release through abrupt permafrost thaw. *Nat. Geosci.*, **13**, 138–143, https://doi.org/10.1038/s41561-019-0526-0.

Wentzky, V. C., M. A. Frassl, K. Rinke, and B. Boehrer, 2019: Metalimnetic oxygen minimum and the presence of Planktothrix rubescens in a low-nutrient drinking water reservoir. *Water Res.*, **148**, 208–218, https://doi.org/10.1016/j.watres.2018.10.047.

Wilkinson, M., and Coauthors, 2016: The FAIR guiding principles for scientific data management and stewardship. *Sci. Data*, **3**, 160018, https://doi.org/10.1038/sdata.2016.18.

Wolf, B., and Coauthors, 2017: The ScaleX campaign: Scale-crossing land-surface and boundary layer processes in the TERENO-preAlpine observatory. *Bull. Amer. Meteor. Soc.*, **98**, 1217–1234, https://doi.org/10.1175/BAMS-D-15-00277.1.

Yan, G., C. Mu, Y. Xing, Q. Wang, and N. Lupwayi, 2018: Responses and mechanisms of soil greenhouse gas fluxes to changes in precipitation intensity and duration: A meta-analysis for a global perspective. *Can. J. Soil Sci.*, **98**, 591–603, https://doi.org/10.1139/cjss-2018-0002.

Zacharias, S., and Coauthors, 2011: A network of terrestrial environmental observatories in Germany. *Vadose Zone J.*, **10**, 955–973, https://doi.org/10.2136/vzj2010.0139.