Creating the basis for climate change adaptation: from observation to modeling

Climate change presents significant threats to terrestrial water security and ecosystem services. To address and adapt to these challenges, it is crucial to generate reliable model predictions at operationally relevant resolutions. Achieving this requires access to appropriate data sources, including **multi-source Earth observation and socio-economic census data**, to parameterize and evaluate next-generation terrestrial models. A unique feature of UFZ's program-oriented research is its robust foundation bolstered by (i) long-term operated, large research infrastructures, (ii) mobile platforms for event-driven monitoring, (iii) large-scale remote sensing observatories. Specifically, UFZ is committed to Helmholtz's long-term operated environmental observatories and platforms like TERENO, MOSES, and eLTER (Zacharias, et al., 2011; Mollenhauer et al., 2018). The data collected through these initiatives, combined with digital workflows adhering to the FAIR principles, serve as an exceptional basis for researching both, long-term trends in environmental conditions and short-term extremes (Weber et al., 2022). The development of data products at regional scales is further supported by remote sensing technologies, monitoring large-scale and long-term changes in essential variables such as soil moisture (Peng et al., 2021a, Dong et al., 2023; Schmidt et al., 2023), evapotranspiration (García-García and Peng 2023), vegetation (see the Forest monitor and Preidl et al., 2020). Joint analysis of different products and scales also enable us to monitor and understand the evolution of climate extremes (e.g. Markonis et al., 2021; Kunz et al., 2022; García-García et al., 2023), as well as their impacts on vegetation and water quality. **Such cross-scale and cross-compartment data sets provide a foundation for gaining new insights into environmental interactions and serve as the basis for developing regionalized data products, models and services** (Figure 1). For example, UFZ has initiated two pivotal knowledge transfer projects "**Drought monitor**" and "**Forest monitor**", capitalizing on these infrastructure resources. Two key features of this strategy are described in more detail below: (i) **multi-scale soil moisture monitoring** and (ii) **linking remote sensing and forest modeling**.

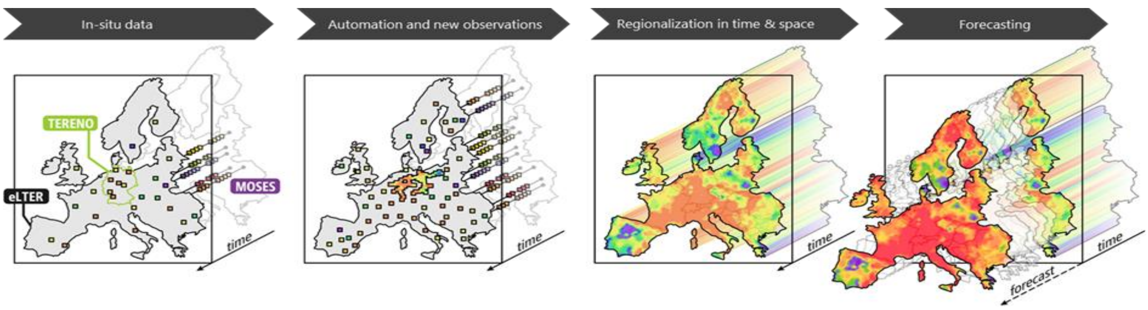

Figure 1: Processing chain from in-situ observation to forecasting

Multi-scale soil moisture monitoring. An example of the successful implementation of this "observation to modeling" strategy is the work on multi-scale prediction of soil moisture. Soil moisture is a key climate variable and controls the land-atmosphere interactions. Representative data on the spatial and temporal variability of soil moisture are therefore an indispensable prerequisite for the development and application of environmental models.

However, reliable monitoring of soil moisture is a big challenge: it varies widely in space, time, and at different scales. The non-invasive and regional-scale monitoring technique “Cosmic-Ray Neutron Sensing” (CRNS) has been in the focus of UFZ research strategies in the past. Today, the UFZ is one of the world's leading centers of excellence for the theory and application of this technology, which has become a nucleus for a wide range of interdisciplinary research on soil moisture regionalization. At the same time, satellite remote sensing has become another pillar of UFZ for monitoring even global-scale soil moisture dynamics (Peng et al., 2021 a, Peng et al., 2021 b). The combined multi-scale soil moisture monitoring activities bring together several departments at the UFZ as well as collaborations across centres (e.g., DLR, FZJ, GFZ). This includes works (i) on the robust methodological foundation for CRNS (Köhli et al., 2015, 2023; Schrön et al., 2017, 2023), (ii) on innovative approaches to real-time acquisition of regional soil moisture using mobile CRNS applications (Schrön et al., 2018, 2021; Heistermann et al., 2022; Altdorff et al., 2023), (iii) on innovative model-based regionalization approaches (Dega et al., 2023), (iv) on the investigation of flood evolution (Kunz et al., 2022; Wieser et al., 2023) including the corresponding data exploration and visualization (Rink et a., 2022), (v) on the near-realtime integration, quality control, provisioning, and visualization of incoming measurement data (Schmidt, L. et al., 2023), (vi) on methods for testing and improving satellite data products using CRNS (Schmidt et al., 2023), (vii) on European and global scale high-resolution soil moisture data and products (Bogena and Schrön et al. 2022; Fan et al., 2023), and (vii) towards the optimization of large-scale hydrologic models through incorporation of CRNS and remote sensing data (Boeing et al., 2022; Fatima et al., 2023; Li et al., 2023).

Linking remote sensing and forest modeling. Forests play an important role in the Earth's carbon cycle, as they store large amounts of carbon. Forests also provide crucial (ecosystem) services to society and to human well-being. Climate extremes such as droughts, heat waves, and environmental disturbances like storms and fires are affecting forest dynamics and their associated socio-ecological impacts. At UFZ, the high-resolution forest model FORMIND has been developed to simulate forests at the continental scale accounting for every single tree (e.g. for the Amazon, Rödig et al. 2019, Bauer et al. 2021). The simulation of individual trees allows capturing not only the forest structure but also tree species diversity. On the other hand, satellite remote sensing has also been applied to provide large-scale, spatially continuous products on forest bio-physical characteristics (Doktor et al., 2009, Lange et al., 2017). Combined, remote sensing and modelling allow for new insights on short and long-term climate change impacts on forests. For example, (i) airborne hyperspectral sensors have been used to provide tree species classifications and forest functional components such as leaf traits (Richter et al., 2016, Dechant et al., 2017), (ii) remote sensing and radiative transfer models have been combined to identify the main ecological drivers which constitute the signal of a temperate forest in Germany (Hase et al., 2022), (iii) Lidar observations and radiative transfer models have been used to derive forests attributes like biomass, basal area, stem number, productivity (GPP,NPP) and carbon sequestration (Rödig et al. 2019, Bauer et al. 2021), (iv) forest modeling and remote sensing have been combined to analyze forest fragmentation at global scale and its impact on the global carbon cycle (Fischer et al. 2021), (v) the GIS web application UFZ Forest Monitor has been developed and is maintained by the Spatial Data Infrastructure (SDI) at UFZ.

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