SEP Appendix E3:
Weather Extremes

Summary

The Climate, Water and Society (CWS) cluster investigates and teaches challenging topics related to climate change and their adaptation. *Extreme Weather* case study involves multiple fields represented within CWS, ranging from monodisciplinary studies to research that requires crossing disciplines. Our research aim is to gain detailed understanding of the fundamental coupled processes that lead to extreme weather under climate change conditions. By advancing in this understanding, we are in a position to improve representations of key processes in the hydrological cycle, such as evaporation, clouds and precipitation, and the subsequent reduction of uncertainties in the projections of weather extremes calculated by regional and global climate models.

Potential impacts of extreme weather encompass, among others, fire, floods, air pollution, and impacts of renewable energy. Here, we present three examples of CWS studies to extreme weather that act at different time scales: days (clouds, precipitation, flooding), weeks (heatwaves) and months (droughts) (see infographics). The first example is on cloud spatial organization, and its potential impact on precipitation. The second example is on the role of land-atmosphere interactions occurring at the local scale that appear to be a key factor in enhancing the intensity of heatwaves and droughts. The final example shows how we transfer this knowledge in an interdisciplinary MSc course. In all these examples, active interaction of the various CWS groups has been key. We foresee that the case study "Extreme Weather" will play a role in the cooperation between the different CWS disciplines in the coming years, both in research and in education.

Case Description

Background

Extreme weather poses major challenges for society. These challenges include understanding and predicting its severity, frequency and impacts. Within the cluster for Climate, Water and Society (CWS), fundamental understanding of the link between climate change and extreme weather plays an important role in research and education. The new "Extreme Weather" initiative stimulates multidisciplinary collaboration among CWS groups, by setting up PhD projects involving multiple chair groups and joint MSc courses. The general approach starts with the recognition that there is a need to integrate natural science disciplines and to study various time-scales to understand and represent extreme weather in models. We present here three examples that are currently carried out at CWS. Related to intense precipitation, occurring at time scales of hours and days, the research aims to identify changes of cloud organization that may be triggered by climate change. In researching heatwave extremes, happening on timescales of days to weeks, we focus on analysing how the enhancement of heatwaves is driven by abnormal phenomena occurring in the atmosphere and on the land. This connects to droughts, with typical time scales of weeks to months. By selecting droughts as a central theme in the starting course of the master program Earth and Environment, MSc students learn that hydrological, meteorological and soil processes need to be integrated in order to understand and quantify long and short-term changes in the exchange of energy, water and carbon between the pedosphere, hydrosphere, biosphere and atmosphere.

Concrete Collaborations

Within the CWS cluster, there are active collaborations among groups on poorly understood processes in the global and regional hydrological cycle. A first collaboration is on the largest uncertainty in climate projections: the role of clouds in regulating climate. In a joint PhD project, the Aquatic Ecology and Water Quality Management (AEW) and Meteorology and Air Quality (MAQ) groups investigate how clouds organize in the trade wind (sub-tropics) region, which is highly sensitive to climate change. Here, we combine the expertise of AEW in studding complex system using a dynamic system approach to the expertise of MAQ on physical processes associated to clouds.

The main aims are to analyse whether there are multiple states of cloud organization and whether critical transitions between these states can be expected in a warming climate. A second collaboration between the Hydrology and Quantitative Water Management group (HWM) and MAQ, studies enhancements of heatwaves due to processes acting at a *local scale* and the role of *large-scale* atmospheric circulation in these enhancements. It was shown that accumulation of heat in the lower layer of the atmosphere leads to enhanced land desiccation. In joint publications by the HWM, MAQ, and WSG groups in 2018 and 2020 it is shown that mid-latitude heatwaves in early spring impact summer droughts, while tropical wet season droughts impact consecutive dry season heat. These studies attempt to quantify links between heatwaves and droughts, and place emphasis on the multi-scale and multi-process character of extreme weather. In all these studies, the outcome is a quantification of the main relevant processes and an improvement of their representations in weather, hydrological and climate models.

Joint Research Approach

What links the studies presented above is a combination of comprehensive observations collected at global and regional scales and of a hierarchy of weather and climate models coupled to the land surface, that include hydrological and plant physiological processes. In the project on cloud organization, we make use of a large amount of remote sensing data to design an effective and objective method to quantify cloud organization. This innovative method based on principle analysis could be used in the future to analyse the degree to which weather and climate models manage to reproduce similar states of cloud organization as observed in nature (digital twin approach). Within the project of enhancement of heatwaves by local land-atmosphere couplings, we employ surface and atmospheric observations and conceptual models. The drought studies rely on long remote sensing and operational ecosystem/surface networks that sample fluxes between land and atmosphere. CWS groups actively cooperate within these networks, e.g. with the Loobos temperate forest site managed by MAQ.

Stakeholder involvement

The improved representation of extreme weather in operational weather, climate and hydrological models is of prime importance for short-term predictions of extreme weather (where can damage be expected?) and long-term predictions related to climate change (e.g. relevant for insurance companies). Our research is at the forefront of representing important *coupled processes* in these models. Our main stakeholders are international research institutes that develop and operationalize weather, hydrological, and climate models. Active collaborations exist with the European Centre for Medium-Range Weather Forecast (ECMWF, https://www.ecmwf.int/), the KNMI in the Netherlands, commercial weather and sustainable energy companies like DTM and Whiffle, and applied research institutes working in the field of water cycles and subsurface, i.e. DELTARES (https://www.deltares.nl/en/).

Link to education

At CWS, special emphasis is placed on transferring research methods to students. A representative example is the course *Interdisciplinary Topics in Earth and Environment*. This course, which is taught in the first year of the MSc programme Earth and Environment, devotes a large amount of time to why, when and how droughts are controlled by processes in the pedosphere, hydrosphere, biosphere and atmosphere. Through a combination of theoretical lectures, practical tutorials and discussion sessions, students learn about interactions between these different spheres. The students compile all this information into a portfolio, including critical reviews of peer-published papers. As a final assignment, they are required to draft a research proposal that places emphasis on the multi-scale and multi-disciplinary aspects of the research on droughts.

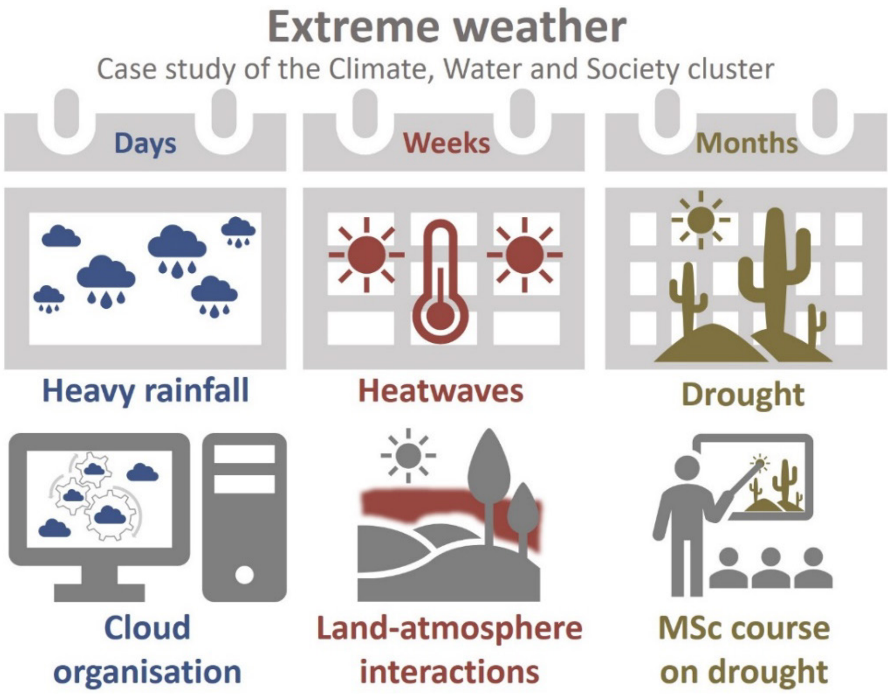
Research Highlights

The most representative papers of our research[1] show the relevance of our approach. We have selected papers in which three groups of the CWS are actively involved: Aquatic Ecology and Water Quality Management (AEW), Hydrology and Quantitative Water Management (HWM) and Meteorology and Air Quality (MAQ). These papers illustrate the richness in methods that emanate from collaboration and the joint use of observations and models. For instance, in the paper of Janssens et al. (2020) system dynamic theory (AEW) is used to extract information on the cloud fields (MAQ). Other papers show the role of hydrology in controlling desiccation and evapotranspiration (HWM). Understanding these hydrological processes appears crucial to study atmospheric feedbacks that enhance heatwaves and droughts.

Impact

Human society is highly impacted by extreme weather with dramatic effects on natural and urban ecosystems. Among the most important impacts, water scarcity and flooding, disruptions in the food chain, enhancing of human stress by worsening of the air quality and fires are in direct relation with the current research and education activities carried out at the CWS cluster. By improving our understanding of the causes of heavy precipitation, heatwaves and droughts we improve the predictability of extreme weather in climate and weather models coupled to hydrological and land conditions. By so doing, decision makers can base their decisions on better data which will subsequently improve planning and reduce the economic costs associated to extreme weather.

Infographic of the case study on extreme weather at the CWS cluster



Main extreme weather studies carry out within the CWS cluster (upper panel) and their characterization as a function of the time scales. The specific investigations focus on specific attributions to extreme weather like cloud organization and land-atmosphere interactions, or the education link to the MSc course are show below.

1

- **Benedict I, van Heerwaarden C.C. van er Linden E., Weerts A. H. Hazeleger W. (2018)** Anomalous moisture sources of the Rhine basin during the extremely dry summers of 2003 and 2018. Weather and Climate extremes
- **Janssens, M., Vilà-Guerau de Arellano J, Scheffer M.,** et al. (2020) Cloud patterns have four interpretable dimensions. *Geophysical Research Letters* (under revision)
- Miralles, D., **Teuling, A. J., van Heerwaarden, C. and Vilà-Guerau de Arellano J**. (2014) Mega-heatwave temperatures due to combined soil desiccation and atmospheric heat accumulation. *Nature Geoscience* **7,** 345–349. https://doi.org/10.1038/ngeo2141 (314 citations).
- Schumacher D.L., Keune J. **van Heerwaarden C. C., Vilà-Guerau de Arellano J, Teuling, A. J.** and Miralles D. (2019) Amplification of mega-heatwaves through heat torrents fuelled by upwind drought. Nature Geoscience 12, 712-717. https://doi.org/10.1038/s41561-019-0431-6 (20 citations)
- **Smith, N., Kooijmans, L., Koren, G., van Schaik, E., van der Woude, A**., Wanders, N., Ramonet, M., Xueref-Remy, I., Siebicke, L., Manca, G., Brümmer, C., Baker, I., Haynes, K., **Luijkx, I., Peters, W.** (2020). Spring enhancement and summer reduction in carbon uptake during the 2018 drought in northwestern Europe Philosophical Transactions of the Royal Society B 375(1810), 20190509. https://dx.doi.org/10.1098/rstb.2019.0509
- **Koren, G., van Schaik**, E., Araújo, A., **Boersma, K., Gärtner, A**., Killaars, L., Kooreman, M., **Kruijt, B., van der Laan-Luijkx, I**., Randow, C., **Smith, N., Peters, W**. (2018). Widespread reduction in sun-induced fluorescence from the Amazon during the 2015/2016 El Niño Philosophical Transactions of The Royal Society of London Series B-Biological Sciences 373(1760), 20170408. https://dx.doi.org/10.1098/rstb.2017.0408
- **Buitink, J., Swank, A. M., van der Ploeg, M., Smith,** N. E., Benninga, H.-J. F., van der Bolt, F., Carranza, C. D. U., **Koren, G**., van der Velde, R., and **Teuling, A. J**.: Anatomy of the 2018 agricultural drought in The Netherlands using in situ soil moisture and satellite vegetation indices, Hydrol. Earth Syst. Sci. Discuss., https://doi.org/10.5194/hess-2020-358, in review, 2020.