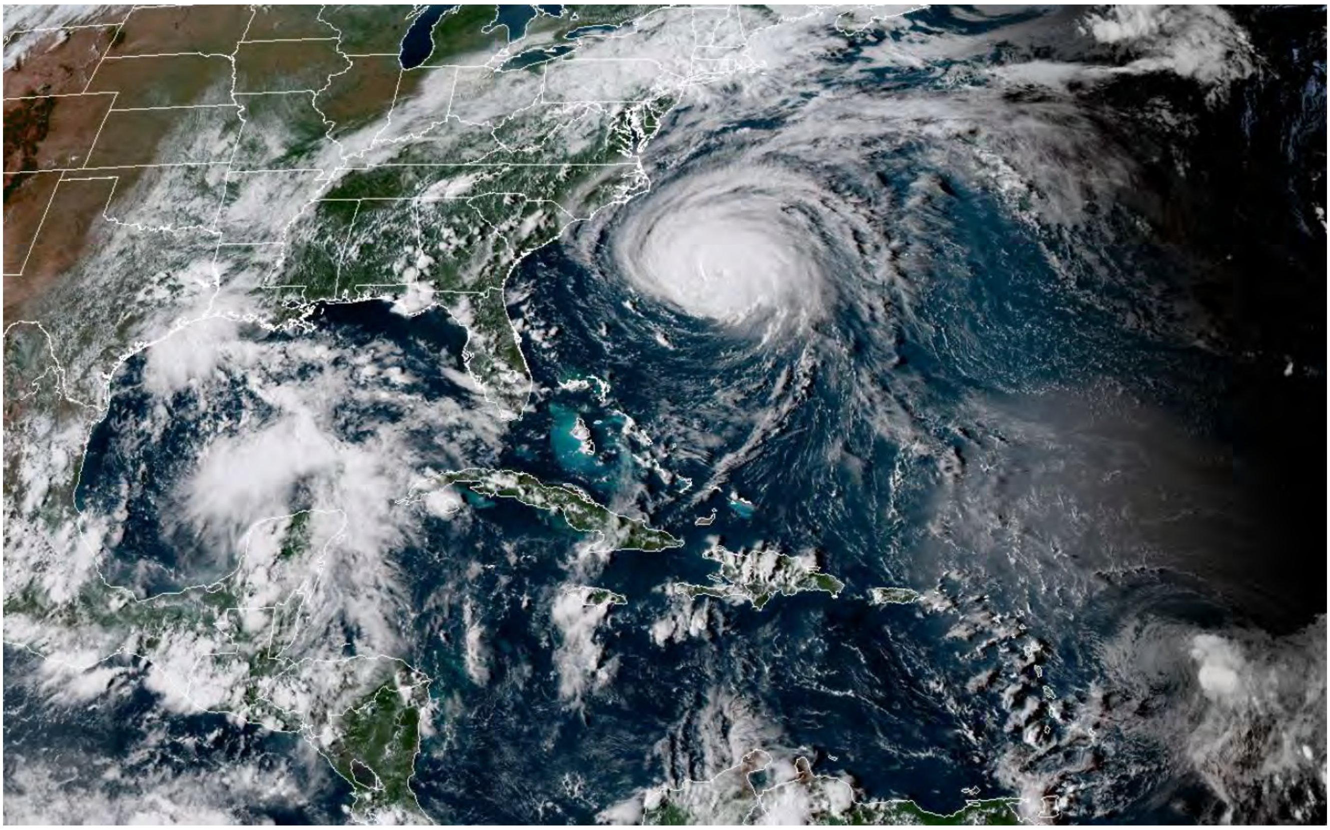
Extreme Weather and Climate

From atmospheric processes to impacts on ecosystems and society



20th International
Swiss Climate Summer School

Grindelwald, Switzerland
28 August – 2 September 2022

C2SM Center for Climate Systems Modeling

Swiss Climate Research

UNIVERSITÄT BERN
OESCHGER CENTRE CLIMATE CHANGE RESEARCH

Abstracts

Extreme Weather and Climate

From atmospheric processes to impacts on ecosystems and society

20th International
Swiss Climate Summer School

Grindelwald, Switzerland
28 August – 2 September 2022

C2SM Center for Climate Systems Modeling

Swiss Climate Research

Universität Bern
Oeschger Centre Climate Change Research

Supporting bodies:

Oeschger Centre
University of Bern
www.oeschger.unibe.ch

Center for Climate Systems Modeling
ETH Zürich
c2sm.ethz.ch

Federal Office of Meteorology and Climatology
MeteoSwiss
www.meteoswiss.ch

Swiss Academy of Sciences
SCNAT
scnat.ch

Past Global Changes
PAGES
pastglobalchanges.org

ThinkSwiss
Swiss Confederation
thinkswiss.org

Table of contents

Evaluating forecasts for high-impact weather events

Sam Allen[1,2,3], Jonas Bhend[3], Olivia Martius [2,4], Johanna Ziegel[1,2]

[1]Institute of Mathematical Statistics and Actuarial Science, University of Bern, Bern, Switzerland
[2]Oeschger Centre for Climate Change Research, University of Bern, Bern, Switzerland
[3]Federal Office of Meteorology and Climatology (MeteoSwiss), Zurich, Switzerland
[4]Institute of Geography, University of Bern, Bern, Switzerland

The impacts associated with adverse weather and climate conditions are well-documented. To mitigate these impacts, operational weather services issue warnings that inform the general public when hazardous conditions are expected, and outline what action should be taken to minimise the associated risks. For these warnings to be useful, weather services require accurate and reliable predictions for high-impact weather events. Methods to evaluate forecasts for these high-impact events can therefore play an integral role when developing warning systems. However, evaluating forecasts for extreme events is known to be a challenging task [1], and this is exacerbated further by the fact that high-impact weather often manifests as a result of several confounding features, a realisation that has motivated considerable recent research on so-called compound weather events. Both univariate and multivariate methods are therefore required to evaluate forecasts for high-impact weather.

Traditionally, the accuracy of weather forecasts is measured using scoring rules. Scoring rules condense all information regarding forecast performance into a single value, providing a convenient framework with which to objectively rank and compare competing forecasts [2]. In this work, we review weighted scoring rules, which allow particular outcomes to be emphasised during forecast evaluation in a theoretically desirable way, and we demonstrate how these can be used to verify forecasts for high-impact weather events. We compare approaches to construct weighted scoring rules, and exploit recent theoretical developments [3] to apply these scores in a multivariate setting. These results are then leveraged to introduce additional approaches that target high-impact events during forecast evaluation; in particular, we introduce graphical diagnostic checks that alert forecasters to systematic errors in their predictions that are associated with the occurrence of high-impact events.

To illustrate the practical benefit afforded by these weighted verification tools, they are employed in a case study to evaluate forecasts for extreme heat events issued by the Swiss Federal Office of Meteorology and Climatology (MeteoSwiss). Extreme heat provides a salient example of a compound weather event: while short and intense periods of extreme heat can have serious implications for human health (among other things), persistent hot periods further strain the human body by inhibiting its ability to recover, and MeteoSwiss regularly issue heat warnings to help mitigate the impacts of these events. Using these novel methods for forecast evaluation, we find that established forecasting methods exhibit deficiencies when interest is on high-impact events. This opens the door for future studies on how these evaluation methods can be utilised in order to improve forecasts for extreme or compound weather.

References

[1] S. Lerch et al., Forecaster's dilemma: Extreme events and forecast evaluation, *Statistical Science* **32**, 106 (2017), 10.1214/16-STS588.

[2] T. Gneiting, A. Raftery, Strictly proper scoring rules, prediction, and estimation, *Journal of the American Statistical Association* **102**, 359 (2007), MR2345548.

[3] S. Allen et al., Evaluating forecasts for high-impact events using transformed kernel scores. Preprint. Available at https://arxiv.org/abs/2202.12732.

Heavy precipitation events in the Atacama, the driest place on Earth

Moshe Armon[1], Heini Wernli[2]

[1]Institute for Atmosphere and Climate Science, ETH Zurich, Zurich, Switzerland

Years can pass by with no significant rainfall in many places across the Atacama Desert [1]. Yet, when rain is precipitating it can have tremendous effects. The desert is situated next to the cold pacific ocean, and in the rain Shadow of the Andes Mountains. Given the low amount of rainfall and the low number of observations, the characteristics of rainfall during heavy precipitation events were seldomly analyzed [2].

In this study, we (a) use a high-resolution satellite remote sensing rainfall data (IMERG), to identify thousands of heavy precipitation events over the past 21 years (Fig. 1), (b) characterize rainfall properties during these events, and (c) identify the governing atmospheric conditions on days of heavy precipitation, using meteorological reanalysis (ERA5) data.

Heavy precipitation events occur throughout the Atacama. Preliminary analyses indicate that the events with the largest volume of rainfall have distinct features, depending on the region: northern Atacama events are the most frequent, and happen mainly in summer from localized convection. These events are characterized by a high pressure anomaly to the south of the Atacama, and surprisingly low surface temperatures. Conversely, winter events occur on the southern part of the desert, and are related to large scale atmospheric circulation patterns. They generally happen in relation to upper tropospheric low pressure anomalies and higher than normal sea surface temperature. The high-resolution datasets we use enable us to characterize small-size events, with substantial implications at the local scale, which can help to cope with natural hazards.

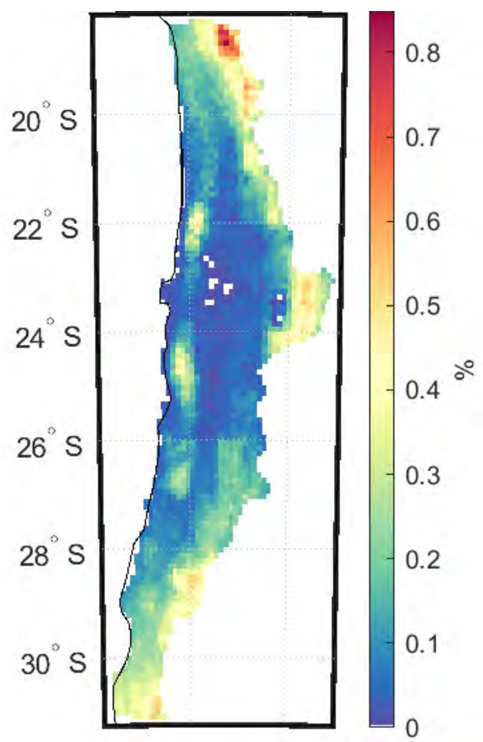


Figure 1: Frequency of identified heavy precipitation events in the Atacama desert; Data from high-resolution satellite remote sensing (IMERG; 2000-2021). Please note the north eastern Atacama hotspot (summer events) and the southern Atacama (winter events).

References

[1] Böhm, C., Reyers, M., Knarr, L., Crewell, S., The Role of Moisture Conveyor Belts for Precipitation in the Atacama Desert, *Geophysical Research Letters* **69**, e2021GL094372 (2021), https://doi.org/10.1029/2021GL094372

[2] Morin, E., Marra, F., Armon, M., Dryland Precipitation Climatology from Satellite Observations, *In: Levizzani, V., Kidd, C., Kirschbaum, D., Kummerow, C., Nakamura, K., Turk, F. (eds) Satellite Precipitation Measurement. Advances in Global Change Research* **48**, (2020), https://doi.org/10.1007/978-3-030-35798-6_19

Countries most exposed to individual and compound extremes at different global warming levels

Fulden Batibeniz[1], Mathias Hauser[1], Sonia I. Seneviratne[1]

[1]Institute for Atmospheric and Climate Science, Department of Environmental Systems Science, ETH Zurich, Zurich, Switzerland

Abstract

It is now certain that human-induced climate change is increasing the incidence of extreme temperature, precipitation and drought events globally. A critical aspect of these extremes is their concurrency that may result in substantial impact on society and environmental systems. Therefore, quantifying compound extremes in current and projected climate is necessary to take measures and adapt to future challenges. Here we investigate pre-industrial and projected changes of individual and concurrent extremes using multi-model simulations of the 6th phase of the Coupled Model Intercomparison Project (CMIP6). We focus on individual and simultaneous occurrence of extreme events: heat wave, drought, maximum 1-day precipitation (Rx1day) and extreme wind (wind) in the pre-industrial period (1850-1900) and at four global warming levels (GWLs of +1°C, +1.5°C, +2°C and +3°C). We find that, on a global scale, most investigated individual extremes become more frequent and affect more land area for higher GWLs. This increase differs depending on the considered months and implies both unprecedented shifts in timing and disproportional increases in frequency of concurrent events for different climate regions. As a result, concurrent occurrences of the investigated extremes become 2.7 to 8.1 times more frequent for a GWL of 3°C. At +3°C the most dramatic increase is identified for concurrent heat wave-drought events with an eight-fold increase in subtropical countries, a seven-fold increase in northern middle and high latitude countries, and a five-fold increase in tropical countries, respectively. Our results also suggest that years without any individual events will decrease six-fold while the number of years with two concurrent events will double. Given the projected disproportional frequency increases across GWLs and decreasing non-event years, our results strongly emphasize the risks of uncurbed greenhouse gas emissions.

Introduction

The socio-economic impacts of individual and concurrent extremes are accelerating as the climate changes [1]. The intervals between extremes are becoming shorter which puts vulnerable communities and ecosystems at risk. In addition, while most countries are affected by climate extremes, some economies such as in south and southeast Asia are more vulnerable than advanced economies in the northern hemisphere [2]. These emerging challenges motivate the need for a comprehensive analysis of potential changes in exposure to individual and concurrent extremes on the population- and country-level. In this study, we investigate the individual occurrences of heat waves, droughts, extreme precipitation and extreme wind as well as compound heat wave-drought, and extreme precipitation and extreme wind events, all of which can have severe impacts on different sectors. The first combination - heat wave-drought - influences wildfire, crops, natural vegetation, power plants and fisheries [4]. The second combination - extreme wind and precipitation - can cause storm surges, floodings, runoff, and result in the destruction of infrastructure and damage to the economy. Building on previous work on projected changes in compound extreme events, we investigate here for the first time the human exposure to these concurrent extremes in addition to individual extremes. We do so in a manner consistent with the 6th Assessment Report of the Intergovernmental Panel on Climate Change (IPCC AR6) framework by analyzing the projections for different global warming levels (GWLs, +1°C, +1.5°C, +2°C and +3°C) on country and regional scales. We analyze simulations from 17 climate models from the CMIP6 archive to investigate the occurrence of individual and compound events under natural climate variability and future global warming. To estimate exposure, we use current population estimates provided by the Gridded

Population of the World version 4 (GPWv4) data set (Center for International Earth Science Information Network - CIESIN - Columbia University, 2018). Together, the use of climate change projections and population distributions enables the investigation of changes in the exposure to climate extremes at the regional and country levels.

Conclusions

Investigating future changes in impactful individual and concurrent extremes is important to be prepared for future climate risks. In this study, we have investigated the current state and future change of individual and concurrent occurrences of heat wave, drought, Rx1day, wind events at global warming levels (GWLs) of +1°C, +1.5°C, +2°C and +3°C relative to the pre-industrial period for three climate regions. Utilizing simulations from 17 CMIP6 global circulation models allowed us to gain a robust understanding of extremes in current and future climate. Our results indicate that all climate regions are under the increasing influence of concurrent heat wave-drought events and Rx1day-wind events with higher GWLs. Even though this change is more substantial for heat wave-drought events, Rx1day-wind events are also on the rise. While the most prominent increase is observed in Subtropical Countries (STC) for heat wave-drought events, it is also observed in Tropical Countries (TRC) for Rx1day-wind events. While heat wave-drought events increased substantially, Rx1day-wind events increased less in Northern Middle and High Latitude Countries (MHC) and STC. However in TRC both heat wave-drought and Rx1day-wind events increased at the same rate, indicating the less variable climate in TRC. Our results also highlight the important timing shifts in the occurrence of individual and concurrent extremes in the future climate. Individual extreme events increase inhomogeneously across months leading to unprecedented frequency increases in some months in the future. Another important highlight of our study is increasing human exposure to multivariate extremes in parallel with the decreasing number of non-event years, even without considering the expected rise in the human population. Quantifying frequency and timing of the individual and concurrent extremes at warming levels provides a perspective to The Paris Agreement's goals that pursue efforts to limit the temperature increase to +2°C [3]. Our results suggest that there is a prevailing increase in frequency, shifts in timing of multivariate extremes from +1.5°C to +2°C, that will likely exacerbate human exposure to these extremes. These unprecedented changes in frequency and timing can lead to an elevated risk for the environment and society across the globe. Therefore, our results suggest an urgent need for concrete actions to mitigate current greenhouse gas emissions.

References

[1] IPCC, 2021: Summary for Policymakers. In: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. In Press.

[2] Guo, J., Kubli, D., Saner, P., Ronke, P., Institute, S.R., 2021. The Economics of Climate Change: No Action Not an Option. Swiss Re Institute.

[3] UNFCCC, U., 2015. Paris Agreement.

[4] Zscheischler, J., Martius, O., Westra, S., Bevacqua, E., Raymond, C., Horton, R.M., van den Hurk, B., AghaKouchak, A., Jézéquel, A., Mahecha, M.D., Maraun, D., Ramos, A.M., Ridder, N.N., Thiery, W., Vignotto, E., 2020. A typology of compound weather and climate events. Nat. Rev. Earth Environ. 1, 333–347. https://doi.org/10.1038/s43017-020-0060-z

Capturing future soil-moisture droughts from irregularly distributed ground observations

Verena Bessenbacher[1], Lukas Gudmundsson[1], Sonia I. Seneviratne[1]

[1]Institute for Atmospheric and Climate Science, ETH Zürich, Zürich, Switzerland

With a rapidly warming climate, future droughts are predicted to increase in frequency, duration, extent and severity for many regions [2, 3, 4, 5], whilst uncertainty of drought predictions in CMIP6 ensembles remains high [6]. Monitoring the occurrence of agricultural and ecological droughts (i.e. soil moisture droughts), in present and future climate is therefore vital. However, available drought monitoring products use information from soil moisture ground observations only sparsely and only for validation [1], with a few exceptions on country level [8, 9, 17]. Since in-situ soil moisture observations are the only observations that extend into the vegetation-relevant root-zone, are therefore often referenced as gold standard of soil moisture observations [7], it is vital that they are more utilised in global efforts for drought monitoring.

A central challenge of these observations included in the international soil moisture network ISMN [1] is that they are not evenly distributed across the globe, favouring Europe and the US. The density of the station net is below necessary densities for interpolation (141 stations per 1 Mio. km^2 [12, 13, 14]) for most regions of the world and never dense enough for data assimilation (30 stations per 1 Mio. km^2, [8]) (see Fig. 1), misrepresenting large areas of the globe. Installing new measurement stations is costly, therefore placing them should focus on alleviating the problem of these underrepresented regions and ecosystems.

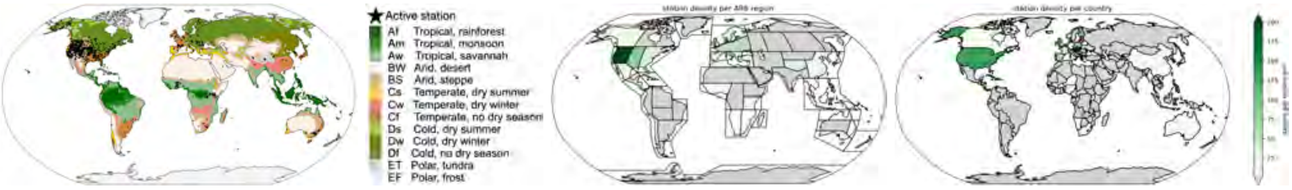


Figure 1: An overview of the ISMN station network. From left to right: (1) currently active ISMN stations (black dots) and their respective Köppen-Geiger class (colored map). (2) ISMN station densities for each AR6 region and (3) country.

We apply a statistical learning method adapted from [15] to identify under-represented ecosystems for informing future station placement. We overlay these with maps of future drought occurrence and drought uncertainty to scan for regions which are especially vulnerable in the future given the current station net. The analysis is build around an up-scaling approach where a random forest model is trained to predict soil moisture as a function of gridded atmospheric precipitation and temperature. It then estimates soil moisture at locations without observations. For doing so we rely on the CMIP6 ensemble as a laboratory.

First results show that strategically placing new soil moisture observation stations leads to an increase in soil moisture estimates and is more efficient than other station placement strategies that rely on geographical distance to existing stations or randomly placing stations. Doubling the stations systematically leads to an 0.3 increase in correlation of observed soil moisture anomalies globally. Tropical and continental-boreal regions are most under-sampled, whilst also predicted to have a high drying trend in the future and/or high uncertainty in future trends (compare [6, 16]). Our framework is therefore showing the importance of expanding the soil moisture measurement net and how currently under-sampled regions correspond to regions with high future drought risk

References

[1] Dorigo, W., Himmelbauer, I, Aberer, D., Schremmer, L. et al, Hydrology and Earth System Sciences. 10.5194/hess-25-5749-2021.

[2] Lu, J, Carbone, G. J., Grego, J. M., Scientific Reports. 10.1038/s41598-019-41196-z.

[3] Prudhomme, C., Giuntoli, I., Robinson, E L., Clark, D. B. et al. Proceedings of the National Academy of Sciences. 10.1073/pnas.1222473110.

[4] Wang, T., Tu, X., Singh, V. P., Chen, X., Lin, K. Journal of Hydrology. 10.1016/j.jhydrol.2021.126091.

[5] Spinoni, J., Barbosa, P., Bucchignani, E. et al. JOURNAL OF CLIMATE. 10.1175/JCLI-D-19-0084.1.

[6] Cook, B. I., Mankin, J. S., Marvel, K. et al. Earth's Future. 10.1029/2019EF001461.

[7] Gruber, A., Dorigo, W.A., Zwieback, S., Xaver, A., Wagner, W. Vadose Zone Journal. 10.2136/vzj2012.0170.

[8] Gruber, A., Crow, W. T., Dorigo, W. A. Water Resources Research. 10.1002/2017WR021277.

[9] Mozny, M, Trnka, M, Zalud, Z., Hlavinka, P., Nekovar, J., Potop, V., Virag, M. Theor Appl Climatol. 10.1007/s00704-011-0460-6.

[10] Vogel, M. M., Zscheischler, J., Wartenburger, R., Dee, D., Seneviratne, S. I. Earth's Future. 10.1029/2019EF001189.

[11] Qi, W., Feng, L., Yang, H., Liu, J. Geophysical Research Letters. 10.1029/2021GL097060.

[12] Oki, T, Teruyuki, N., Dirmeyer, P. Journal of the Meteorological Society of Japan, 77, 1B, 235-255.

[13] Kloster, S., Mahowald, N. M., Randerson, J. T., Lawrence, P. J. Biogeosciences. 10.5194/bg-9-509-2012.

[14] Seneviratne, S. I., Corti, T., Davin, E. L., Hirschi, M., Jaeger, E. B., Lehner, I., Orlowsky, B., Teuling, A. J. Earth-Science Reviews. 10.1016/j.earscirev.2010.02.004.

[15] Gudmundsson, L., Seneviratne, S. I. Hydrology and Earth System Sciences. 10.5194/hess-19-2859-2015.

[16] IPCC, 2021: Summary for Policymakers, In: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. In Press.

[17] Seneviratne, S. I., Hirschi, M., Michel, D. `https://iac.ethz.ch/group/land-climate-dynamics/research/swisssmex/current_status.html`. last access: 08.06.2022.

Predicting Prosumers, Rebounds and (Pro-) Environmental Spillovers: The Case of Residential Photovoltaic Systems

Patrick Bigler[1,2], Benedikt Janzen[1,2]

[1]KPM University of Bern
[2]OCCR - Oeschger Centre for Climate Change Research

Overview

Electricity accounts for roughly 18% of global total energy usage and still, nowadays, almost 2 out of 3 kWh are produced from fossil sources. Switzerland's share of electricity in total energy usage is higher with 25%, while the carbon intensity is much lower at around 5%. With growing demand from other economic sectors such as transport, electricity usage is bound to increase further. Distributed energy is regarded as an important contributor to increasing renewable electricity's production share. Even though photovoltaic instalations (PV) are increasing, the deviance between actual production and potential is still large, as the Swiss federal institute of energy estimates PV potential to be 40 times higher than actual production in 2019.

Private household's PV adoption has been a topic of increasing academic relevance. In the beginning, most empirical papers have mainly focused on the identification of factors driving the adoption (i.e. Kwan, 2012 or Rai et al., 2016). Another central part of the policy discussion concerning renewable, more efficient electricity production is related to so-called rebound effects. Specifically, in the context of solar panels, if solar users' electricity consumption is unaffected by their decision to install residential photovoltaic systems, any PV generated electricity should reduce conventional electricity generation 1:1. However, estimates of solar rebound effects from Australia (e.g. La Nauze, 2019), the United States (e.g., Qiu et al., 2019[4]) as well as European countries (i.e. Frondel et al., 2020[3]) are fairly consistent across studies and range between 15%-21%.

We add to this literature in multiple ways. First, most of the literature has focused on either aggregate data and/or survey data. In this paper, we rely on detailed household-level panel data to investigate solar panel adoption patterns. Second, we apply state-of-the-art machine learning techniques to analyze the adoption patterns, which allows us to prevent overfitting and compare out-of sample predictive power. Third, to our knowledge we are the first to estimate the solar rebound effect for Switzerland.

Furthermore, we also consider the impact of residential solar panel adoption on peers' environmental behavior. In this paper, we draw on a salient piece of information, namely the presence of solar panels on neighboring roofs, to investigate peer effects in environmental contributions. The presence of solar panels on neighboring roofs can enact behavior through multiple channels. It could make climate change more visible thus enacting pro-environmental behavior. However, it could also signal readily availability of electricity and thus enacting higher consumption. The research closest to our work is La Nauze (2021)[2], who investigates how installing solar panels affect neighbors' purchases of green power. This paper provides further evidence on the impact of residential solar panel adoption on peers' environmental behaviour.

Methods

We use a high-resolution panel data set of 165,000 individual households in the canton of Bern, Switzerland spanning from 2008 to 2019. The data set has only been previously employed by Feger et al. (2021) [1] to infer tariff and subsidy designs for policymakers to incentivize solar panel adoption. We combine electricity consumption and price as well as information on PV installation from energy utilities with socio-demographic information from tax fillings. Moreover, we add information on buildings, weather data as well as estimated PV potential. We proceed in three steps: It is likely that a households' decision to adopt a solar panel and its electricity consumption level are related. To overcome this potential source of treatment assignment bias we adopt a matching approach. For each PV household, we match a similar household who has not installed a solar panel. To estimate adoption probabilities we use our extensive micro-data and apply state-of-the-art machine learning techniques such as penalized logistic regression. The estimated propensity scores are used in a radius matching algorithm to match a suitable control for every solar household.

Next we follow Qiu et al. (2019)[4] and examine the causal impact of solar electricity generation on households‘ own electricity consumption by estimating the following equation for our matched sample:

$$ec_{it} = \delta ep_{it} + p_t + HDD_{it} + CDD_{it} + \mu_{it} + \epsilon_{it}, \quad (1)$$

where the dependent variable ec_it measures electricity consumption of household i in year t, ep_it is solar electricity production of household i in year t, and μ_it are household-year fixed effects that control for time-variant unobservables. For PV owners, utilities provide us additionally with feed-in electricity data (ef_t). Since PV owners not only consume grid electricity at time t (eg_t), but also self-consume part of their PV electricity (es_t). The information on ef_t is crucial to estimate rebound effects, as otherwise consumption of solar household's would be underestimated. HDD and CDD control for weather related electricity consumption (heating and cooling). Therefore the coefficient of interest δ measures the potential solar rebound effect.

In a third step, we are interested in potential spillover effects from adopting a solar panel. To do so we estimate fixed effects regression of PV presence in the neighbourhood on electricity consumption, propensity to purchase green electricity and propensity to install a PV.

Results

We present pre-eliminary results of our machine learning application in the following. Our models' predictive performance is evaluated based on sensitivity, specificity, precision, and false positive rate. Comparing the machine learning approaches to a baseline logistic regression shows that all models perform comparably well in terms of specificity. Lasso estimates outperform Ridge and convential logistic regression in terms of false positive rate and precision, while logistic regression is superior in truly predicting adopters. This implies that the Lasso model predicts a positive outcome too seldom, but if it does it is remarkably precise and almost exclusively right. Results for the solar rebound and potential environmental spillover effects will be available by the conference's time.

Conclusions

This paper contributes to the understanding of solar panel diffusion by applying machine learning techniques to a detailed panel data set of 165,000 households in the canton of Bern, Switzerland. Although the improvement in predictive performance using machine learning techniques is marginal, policy makers can still learn something from the results as prediciting solar panel adoption is a difficult task due to its rare occurence. While it does not drastically improve predictive performance, using machine learning does help improving external validity by preventing overfitting.

We provide first evidence on the impact of solar panels on consumer electricity consumption behaviors in Switzerland as well as potential spillover effects to neighboring households. When evaluating the impacts of distributed solar panel adoption, ignoring rebound effects can lead to overestimation of environmental benefits. On the other hand, ignoring potential spillover effects (e.g., positive effect on individual mitigation actions) might lead to underestimation of environmental benefits. Therefore, from the perspective of the policy maker, it is important to have detailed information on behavioral effects of solar panel adoption to inform the discussion on climate change mitigation.

References

[1] F. Feger et al., Welfare and Redistribution in Residential Electricity Markets with Solar Power, *Review of Economic Studies*, forthcoming. (2022)

[2] A. La Nauze, Motivation, signaling and peer effects: Evidence from rooftop solarand household green power purchases, *Review of Economics and Statistics*, forthcoming. (2022)

[3] M. Frondel et al., Photovoltaics and the Solar Rebound: Evidence for Germany. *USAEE Working Paper No. 20-475.* (2020), 10.2139/ssrn.3716945

[4] Y. Qiu et al.,Quantifying the rebound effects of residential solar panel adoption. *Journal of Environmental Economics and Management*, **96**, 310 (2019), 10.1016/j.jeem.2019.06.003

Geographically varying temperature thresholds for societal attention and health impacts of heat waves

Ekaterina Bogdanovich[1], Lars Guenther[2], Markus Reichstein[1], Alexander Brenning[3], Dorothea Frank[1], Mike S. Schäfer[4], Georg Ruhrmann[3], René Orth[1]

[1]Max Planck Institute for Biogeochemistry, Jena, Germany
[2]University of Hamburg, Hamburg, Germany
[3]Friedrich Schiller University, Jena, Germany
[4]University of Zurich, Zurich, Switzerland

Heat waves have severe impacts on economy, ecosystems, and society [1, 2]. In many regions, hot temperature extremes are expected to become more frequent and intense in the future [3]. It is not clear, however, to which extent Europeans perceive heat waves as important and potentially pressing issues, which may for example vary according to a region's climatic conditions. We analyze and compare the response of societal attention and public health to heat waves across twelve European countries for the period 2010-2020. In particular, we consider Google search attention to *heat wave* and *heat stroke* (which summarizes relevant search requests with similar search terms and across languages), as well as related excess mortality and press mentions.

We explore several temperature variables in this context and find that societal attention and excess mortality are most strongly related to maximum and mean temperatures. Further, these relationships exhibit a threshold behavior with a temperature above which the sensitivity of societal attention, press mentions, and excess mortality to temperature is clearly increased. Applying a piecewise regression analysis, we identify these temperature thresholds in the relationships of societal attention and mortality with temperature in each country (Figure 1). In general, we find higher temperature thresholds in countries with warmer climate. These results are consistent across Google search attention, press mentions and excess mortality, even though excess mortality tends to be less strongly related to temperature, as it is potentially affected by other factors.

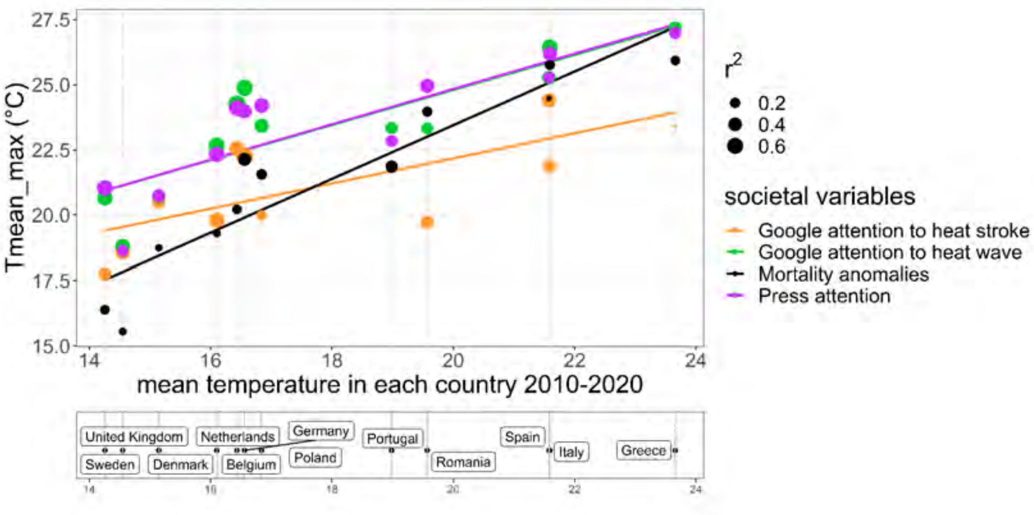


Figure 1: Temperature-related thresholds in societal variables for weekly maximum of daily average temperature Tmean_max (°C). Countries are ordered according the average temperature during 2010-2020.

The country-specific temperature thresholds identified from empirical data will further be used to study the countries' preparedness for future climate conditions. In the next step, applying the thresholds to climate model projections, we will identify the expected annual number of relevant heat wave days and their trends for the next decade. This allows us to identify regions and time periods with a high sensitivity to heat waves where improved management and adaptation is particularly important.

References

[1] An der Heiden, M., Muthers, S., Niemann, H., Buchholz, U., Grabenhenrich, L., Matzarakis, A., Heat-Related Mortality: An Analysis of the Impact of Heatwaves in Germany Between 1992 and 2017, *Deutsches Ärzteblatt International* **117**, 603 (2020)

[2] Hajat, S., O'Connor, M., Kosatsky, T., Health effects of hot weather: from awareness of risk factors to effective health protection, *The Lancet* **375**, 856-863 (2010)

[3] IPCC, Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, *Cambridge University Press* (2021)

A long-term perspective on the drivers of the Indian summer monsoon onset.

Angela-Maria Burgdorf[1,2], Martin Wegmann[3], Stefan Brönnimann[1,2], Yvan Orsolini[4]

[1]Oeschger Centre for Climate Change Research, University of Bern, Bern, Switzerland
[2]Institute of Geography, University of Bern, Bern, Switzerland
[3]EPFL – École polytechnique fédérale de Lausanne, Lausanne, Switzerland
[4]NILU – Norwegian Institute for Air Research, Kjeller, Norway

The Asian Monsoon is considered the largest weather system on the globe, affecting nearly half of the world's population. Its seasonal changes in winds and rain govern the pulse of life of nature and humankind and have so for centuries. While a mature body of research examines Monsoon variability during the instrumental period, very little is known beyond 1870. Moreover, the main focus of previous research has been on monsoon rainfall rather than monsoon onset. However, particularly the onset of the Indian summer monsoon is crucial to hundreds of millions of people since it strongly impacts the growing season and thus food security. In this study, we investigate monsoon onset variability of Mumbai back to 1806 using documentary, instrumental, and reanalysis data. More specifically, documentary and instrumental onset time series are compared to a newly reconstructed monsoon onset time series based on daily precipitation data from the latest version of the Twentieth Century Reanalysis (20CRv3).

Furthermore, we study the potential large-scale drivers of the Indian summer monsoon onset. Besides El Niño-Southern Oscillation (ENSO), we explore relationships between the monsoon onset and other modes of variability like the Indian Ocean Dipole (IOD), and Pacific Decadal Oscillation (PDO), Atlantic Multidecadal Oscillation (AMO). Additionally, we review the Blanford Hypothesis. Henry Francis Blanford (1884) [1] proposed an inverse relationship between the Himalayan winter/spring snow amount and the monsoon onset and rainfall in the subsequent summer. This proposed Eurasian snow cover – monsoon link has been evaluated in numerous studies, but generally with a focus on the overall monsoon precipitation amount rather than the onset. Furthermore, the lack of a long-term perspective has limited previous investigations, as the monsoon onset is shown to be dominated by strong decadal variability.

For the first time, our study evaluates the nature of this link along with other drivers of the Indian summer monsoon onset back to the early 19th century and sheds light on its underlying dynamics.

References

[1] Henry Francis Blanford, On the connexion of Himalayan snowfall and seasons of drought in India, *Proc R Soc Lond* **37**, 3 (1884), 10.1098/rspl.1884.0003.

Where can we cool down? Chasing the urban heat in Bern with different methods

Moritz Burger[1,2], Moritz Gubler[1,2,3], Stefan Brönnimann[1,2]

[1]Oeschger Centre for Climate change Research, University of Bern, Switzerland
[2]Institute of Geography, University of Bern, Switzerland
[3]Institue for Lower Secondary Education, Bern University of Teacher Education, Switzerland

Mean summer air temperatures as well as the likelihood for prolonged and more intense and more frequent heatwave periods are increasing across Europe due to the ongoing anthropogenic warming. Cities are especially prone to the alteration in summer air temperatures and extremes due to the so-called urban heat island (UHI) effect which leads to even higher temperatures in urban environments, especially during calm nights after sunny and radiative intense days. The UHI effect causes various negative impacts for cities and its residents regarding public health (e.g. increased fatigue, cardiovascular problems), environment (e.g. increased vulnerability of urban trees) or economy (e.g. cooling costs, reduced productivity of people).

To plan adequate adaptation measures to counteract these negative effects and cool down the city, detailed knowledge about the intra-urban air temperature variability within a city is crucial. Different methods to estimate the temperature distribution in cities exist, such as measuring with in-situ data, numerical climate modeling or geostatistical modeling. In Bern, a very dense low cost air temperature network has been installed since the summer of 2018 [1] and different models to investigate the urban heat have already been set up. This includes a geostatistical model to estimate nighttime UHI intensity means for heatwave periods [2] and another geostatistical model to estimate absolute temperature fields for every single night during summer [3], both having a spatial resolution of 50 m. Additionally, two numerical urban climate models have been applied: The non-hydrostatic microscale model MUKLIMO 3 with a resolution of 50 to 200 m [4] and the high resolution (10 m) PALM 4-U urban climate model which is able to resolve large eddy simulations within the modeling process. In this project, we want to compare the different methods and evaluate the capability of them to realistically predict the nighttime urban air temperature distribution in a city with complex terrain. To do so, we will investigate one night of a heatwave in summer 2018 (30^{th} of July to 31^{st} of July), with all models and validate their spatial and temporal performance in order to assess their potentials to contribute to urban planning initiatives and adaptation plans to make cities cooler in a warming world.

References

[1] Gubler, M., Christen, A., Remund, J., Brönnimann, S., Evaluation and application of a low-cost measurement network to study intra-urban temperature differences during summer 2018 in Bern, Switzerland., *Urban Climate* **37**, 100817 (2021), https://doi.org/10.1016/j.uclim.2021.100817.

[2] Burger, M., Gubler, M., Heinimann, A., Brönnimann, S., Modelling the spatial pattern of heatwaves in the city of Bern using a land use regression approach., *Urban Climate* **38**, 100885 (2021), https://doi.org/10.1016/j.uclim.2021.100885

[3] Burger, M., Gubler, M., Heinimann, A., Brönnimann, S., Modeling the intra-urban nocturnal summertime air temperature fields at a daily basis in a city with complex topography, *submitted*

[4] Hürzeler A., Hollósi, B., Burger M., Gubler M., Brönnimann, S., Assessment of the urban climate model MUKLIMO 3 for three heatwaves in Bern, *draft version*

Climate mitigation reduces global economic losses from increased extreme heat

Christopher W. Callahan[1,2], Justin S. Mankin[2,3,4]

[1]Program in Ecology, Evolution, Environment, and Society, Dartmouth College
[2]Department of Geography, Dartmouth College
[3]Department of Earth Sciences, Dartmouth College
[4]Ocean and Climate Physics, Lamont-Doherty Earth Observatory of Columbia University

Anthropogenic climate change is likely to substantially increase the frequency and intensity of extreme heat events globally [1]. Tropical regions–which are broadly poorer than mid-latitude regions–will experience the most rapid and severe emergence of human-driven heat extremes [2], posing a challenge to human health and well-being.

Despite the severe impacts of extreme heat in a warming world, the macroeconomic consequences of extreme heat events, and their implications for optimal climate mitigation, are poorly understood. Empirical climate-economy studies have generally focused on average temperatures instead of heat extremes [3, 4]. Extreme heat is difficult to measure and data limitations in the poorest and warmest parts of the world have prevented existing studies from being globally representative. As a result, the implications of climate change for extreme heat events have generally not been integrated into cost-benefit analysis of climate policy and metrics such as the social cost of carbon.

In recent work, we used empirical regression techniques to show that extreme heat intensity–defined as the temperature of the hottest five days in each year–substantially reduces economic growth in subnational regions [5]. These effects are mediated by the underlying average temperature: Warm tropical regions experience large negative effects of increased extreme heat intensity, whereas cooler midlatitude regions experience weak negative effects or even benefits.

Here we quantify the macroeconomic effects of increased extreme heat intensity in the future. We use climate models from the sixth phase of the Coupled Model Intercomparison Project (CMIP6) to project changes in extreme heat intensity over the remaining century. We then apply our empirically derived coefficients to quantify the associated change in economic output.

We find that projected increases in the temperature of the hottest five days in each year have a major economic penalty (Fig. 1). At 2 °C of global mean surface temperature change, the global economy is more than 1.25% smaller than it would have been otherwise, and at 3 °C, it is more than 2.5% smaller. These losses are substantial compared to the "damage functions" that have been previously used in Integrated Assessment Models (IAMs) to compute optimal climate policy: One major IAM assumed a 2.1% global economic loss at 3 °C from all impacts of global warming combined [6]. Our results show that extreme heat alone could account for the entirety of these previous estimates, implying substantial underestimations of optimal climate policy in previous studies.

Strong climate mitigation, by reducing anthropogenic intensification of heat extremes, could reduce these losses. We estimate that holding warming to 1.5 °C instead of 2 °C could avoid a cumulative economic loss of $10 trillion, and holding warming to 2 °C instead of 3 °C could avoid a cumulative economic loss of $35 trillion. The benefits of mitigation are also apparent across emissions scenarios (Fig. 1, inset): Following the SSP3-7.0 scenario (high emissions) yields economic losses in 2100 that exceed 4.5% of global GDP, but following the SSP1-2.6 scenario (strong mitigation) instead holds economic losses in 2100 to $\sim$2% of global GDP.

These results reveal previously unquantified costs of future extreme heat intensification, which strengthens the economic case for stringent climate mitigation. Further, because these losses occur specifically on the five warmest days of each year, our results demonstrate that adaptation investments targeted to those specific days may yield disproportionate benefits.

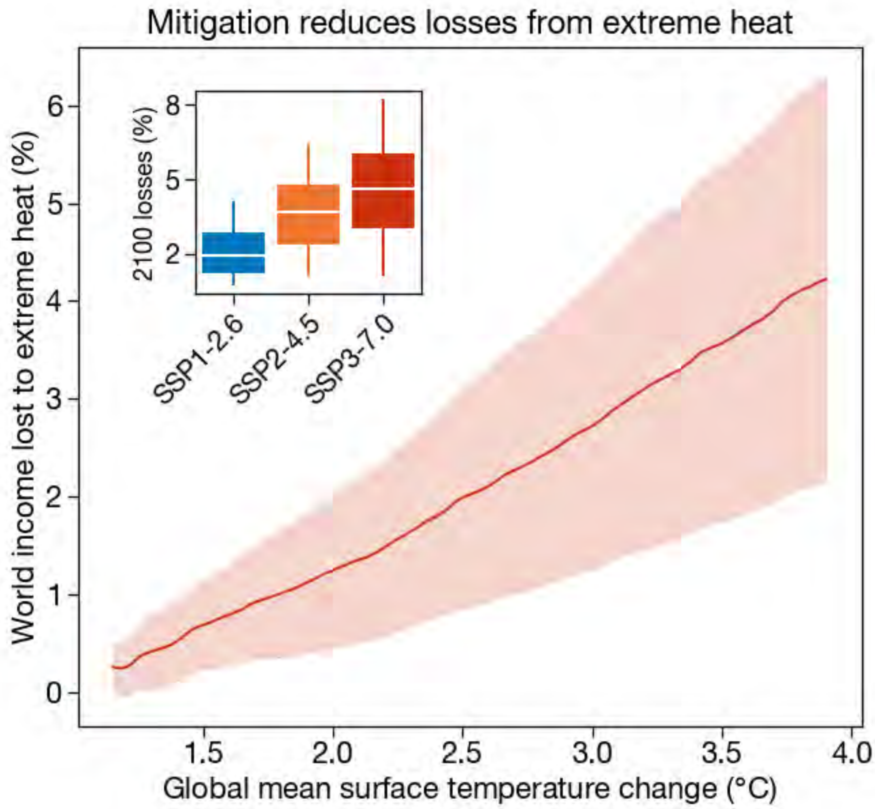


Figure 1: Global economic losses from increased extreme heat intensity. Main plot shows the share of global output lost due to warmer temperatures during the hottest five days of the year from the SSP3-7.0 scenario, referenced to global mean surface temperature change from 1850–1900. Thick line shows the ensemble mean across uncertainty sampling of climate models and empirical regression bootstraps, and shading shows the mean ± the ensemble standard deviation. Inset shows the share of output lost in 2100 under three emissions scenarios. White line shows the median across uncertainty from climate models and regression bootstraps, box spans 1.5 times the interquartile range, and whiskers extend to the 5th and 95th percentiles.

References

[1] G. A. Meehl, C. Tebaldi, More intense, more frequent, and longer lasting heat waves in the 21st century, *Science*, **305**, 994 (2004), 10.1126/science.1098704

[2] L. J. Harrington, D. J. Frame, E. M. Fischer, E. Hawkins, M. Joshi, C. D. Jones, Poorest countries experience earlier anthropogenic emergence of daily temperature extremes, *Environmental Research Letters*, **11**, 055007 (2016), 10.1088/1748-9326/11/5/055007

[3] M. Dell, B. F. Jones, B. A. Olken, Temperature shocks and economic growth: Evidence from the last half century, *AEJ: Macroeconomics*, **4**, 66 (2012), 10.1257/mac.4.3.66

[4] M. Burke, S. M. Hsiang, E. Miguel, Global non-linear effect of temperature on economic production, *Nature*, **527**, 235 (2015), 10.1038/nature15725

[5] C. W. Callahan, J. S. Mankin, Globally unequal effect of extreme heat on economic growth, *under review* (2022)

[6] W. Nordhaus, Projections and uncertainties about climate change in an era of minimal climate policies, *AEJ: Economic Policy*, **10**, 333, 10.1257/pol.20170046

Flash Flood Hazard: an Economic Analysis for Central America and the Caribbean

Dino Collalti[1,2]

[1]Department of Economics, University of Bern, Switzerland
[2]Oeschger Centre for Climate Change Research, University of Bern, Switzerland

What is the dynamic response of the economy on frequent, small scale natural disasters? I examine this question by using a novel, physically based indicator of flash flood incidence. Over the last twenty years, more people have been affected by floods than any other natural disaster.[1] flash floods are floods that follow shortly and causative after heavy rainfall. They are a highly localized phenomenon that occurs in basins of no more than a few hundred square kilometers and a response time of few hours [1].

In the recent decade, economists became increasingly interested in studying economic impacts of natural disasters: tropical storms [2], earthquakes [3], droughts [4] and floods [5]. For many countries, natural disasters are a primary reason for their lower economic development and a major channel through which climate and environmental degradation impact the economy [6]. Despite the growing interest in the economics of natural disaster, the focus has been on large, high impact but low frequency events such as hurricanes. However, it has been recognized that frequency is as important as intensity: for the economic growth of developing countries with limited capacity to fund reconstruction, losses to GDP are bounded only if natural disasters remain under a threshold with respect to their intensity and frequency [7]. If either the intensity or frequency of natural disaster increase beyond that threshold, GDP losses increase sharply.

In this empirical analysis, I study the effect of flash floods that are caused by extreme rainfall events. I use a intensity-duration flash flood classification as a physical measure for floods. This classification is based on intensity-duration-frequency (IDF) curves from conditional copula sampling and information on confirmed flash flood events in Jamaica [8]. It is thus well calibrated for Central America and the Caribbean. Two exercises are conducted. First, I estimate the effect a flash flood has on aggregate economic activity by using satellite images of night lights. I find that after a small contemporaneous increase in a flooded location's night light activity, estimates are significantly negative until 10 months after a flood for a cumulative impact of -10.1%. After a year, flash floods have no additional effect on night light activity, but the level has decreased persistently. Second, the reaction of establishments to flash floods is investigated. Representative establishment-level data from the World Bank Enterprise Surveys is employed. The analysis indicates that establishments significantly reduce investments into machinery, equipment and vehicles by 150'000 USD per flood. They do not, however, see a decrease in sales nor do they lay off their employees. This points towards a resilience of firms to cope with such low impact but frequent natural disasters.

These results are an important stepping stone from climate science to economic impacts. Global warming likely increases the frequency and intensity of flood events in many parts of the world. While accounting type figures of direct damages are collected and used in global warming scenarios, they do not tell us anything about the actual impact on the economy. How direct damages propagate through the system and what the aggregate consequence is depends on the behavior of firms and households, credit constraints as well as the frequency of natural hazards. This propagation has implications for damage function estimation of economic climate models and, more importantly, to inform policymakers adequately about the risk of climate change.

[1]Authors, own calculation using EMDAT database. Since 2000, 1.7 Billion people have been affected by floods, followed by droughts (1.4 Billion), storms (0.8 Billion) and earthquakes (0.12 Billion).

References

[1] Norbiato et al., Flash flood warning based on rainfall thresholds and soil moisture conditions: An assessment for gauged and ungauged basins, *Journal of Hydrology* **362**, 274 (2008).

[2] E. Strobl, The economic growth impact of natural disasters in developing countries: Evidence from hurricane strikes in the Central American and Caribbean regions, *Journal of Development Economics* **97**, 130 (2012).

[3] Barone Guglielmo and Mocetti Sauro, Natural disasters, growth and institutions: a tale of two earthquakes, *Journal of Urban Economics* **84**, 52 (2014).

[4] Barrios et al., Trends in rainfall and economic growth in Africa: A neglected cause of the African growth tragedy, *The Review of Economics and Statistics* **92**, 350 (2010).

[5] Kocornik-Mina et al., Flooded cities, *American Economic Journal: Applied Economics* **12**,35 (2020).

[6] Felbermayr Gabriel and Gröschl Jasmin, Naturally negative: The growth effects of natural disasters, *Journal of Development Economics* **111**, 92 (2014).

[7] Hallegatte et al., Why economic dynamics matter in assessing climate change damages: illustration on extreme events, *Ecological Economics* **62**, 330 (2007).

[8] Collalti Dino et al., Flash-flood detection via copula-based IDF curves, *unpublished* , (2022).

Quantifying impact-relevant heat wave durations

Kelley De Polt[1], Ekaterina Bogdanovich[1], René Orth[1]

[1]Department of Biogeochemical Integration, Max Planck Institute for Biogeochemistry, Jena, Germany

Heat waves are generally defined as periods during which hot temperatures exert stress on natural and human systems. Recently, heat waves have increased in frequency, duration, and intensity, and this trend is projected to continue as a consequence of climate change [1]. This increase has motivated further research regarding the understanding of heat waves and their resulting impacts. Though the study of heat waves is hampered by an unclear definition; different choices can be found in the literature which further limits comparability between impacts diagnosed in different studies. These definitions vary between different research communities as they are developed in relation to impacts in different societal or ecological sectors. One such sector of interest is impacts upon human health. Due to complex interaction between climate conditions and the public health response there is no single heat wave definition based on heat-related illness and mortality [2]. In particular, the temporal scale is unclear. A recent study focused on hot temperatures at a half-monthly time scale to analyse biophysical and societal impacts, but emphasised the need to determine more objective impact-relevant spatial and temporal scales [3].

The goal of this current study is to determine impact-relevant temporal scales using country-scale societal attention and public health data for Germany. Societal attention is represented by two metrics. The first is print and web-based press articles from news sources which mention the term “heat wave”. The second is Google trends data of the search topics “Heat Wave” and “Heat Stroke”. Google trends provides data on the magnitude of online search interest over time for selected regions; it has been shown to be relatively accurate in measuring public interest [4]. Public health data is represented by mortality anomalies and heat-related hospitalizations measured at a weekly scale. As mortality data is related to all-causes this means several drivers are affecting the temporal evolution; to somewhat address these confounding effects, we compute anomalies by removing the mean seasonal cycle to mitigate impacts of drivers affecting mainly this mean seasonal cycle, while then associating excess mortality (i.e., positive anomalies) with temperature extremes.

We consider heat waves defined as the hottest temperatures of n consecutive days in each year, where n varies between 1 and 100 days, and constitutes the range of different temporal scales considered in our analysis. Thereby, for example the hottest week can occur at a different time than the hottest month or season (Fig. 1). For each considered time scale, we calculate the impacts of the respective heat waves from the different years to determine the most impact-relevant heat wave time scale. We distinguish between heat waves as singular events and heat waves as part of multi-hazards to analyse potential differences in their impact-relevant time scales; where multiple hazardous events may occur simultaneously, cascading, or cumulatively over time and space [5]. Further analyses will focus on more countries to finally investigate the differences between impact-relevant heat wave time scales, and to relate them to climatic or socio-economic characteristics of the different countries.

The results of this study will establish and implement a methodology to determine the most impact-relevant time scale for climate extremes. While focusing on heat waves here, the approach is applicable to other types of climate extremes as well. Knowing heat wave time scales (i.e., daily, weekly, monthly) will assist in identification of major events in the historical record as well as in future climate projections, particularly as trends in heat wave frequency and intensity might be different for different time scales.

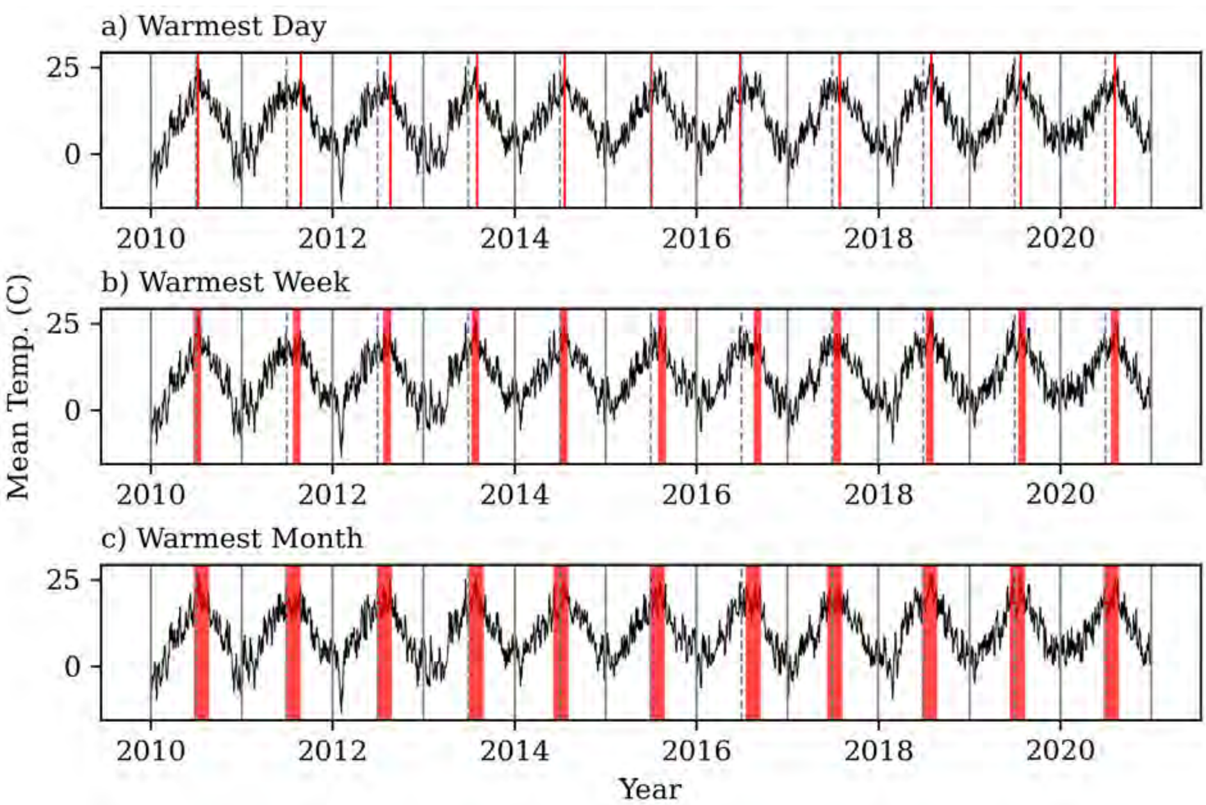


Figure 1: The warmest day (a), week (b), and month (c) for Germany for each year in the time period of 2010 to 2020.

References

[1] IPCC, 2021: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, In press, doi:10.1017/9781009157896.

[2] J. C. Montero et al., Difficulties of defining the term, "heat wave", in public health, *International Journal of Environmental Health Research* **23**, (2013), 10.1080/09603123.2012.733941

[3] R. Orth et al., Contrasting biophysical and societal impacts of hydro-meteorological extremes, *Environmental Research Letters* **17**, (2022), 10.1088/1748-9326/ac4139

[4] M. Scharkow, J. Vogelgesang, Measuring the Public Agenda using Search Engine Queries, *International Journal of Public Opinion Research* **23**, (2011), 10.1093/ijpor/edq048

[5] UNDRR, Terminology for Disaster Risk Reduction (2017), https://www.undrr.org/terminology

Nationwide projections of mortality impacts due to heat and cold under different climate change scenarios in Switzerland

Evan de Schrijver[1,2,3], Sidharth Sivaraj[2], Christophe Raible[2,4], Oscar H. Franco[1], Kai Chen[5,6], Ana M. Vicedo-Cabrera[1,2]

[1]Institute of Social and Preventive Medicine (ISPM), University of Bern, Bern, Switzerland
[2]Oeschger Center for Climate Change Research (OCCR), University of Bern, Bern, Switzerland
[3]Graduate school of Health Sciences (GHS), University of Bern, Bern, Switzerland
[4]Climate and Environmental Physics, Physics Institute, University of Bern, Bern, Switzerland
[5]Yale Center on Climate Change and Health, Yale School of Public Health, New Haven, Connecticut, United States
[2]Department of Environmental Health Sciences, Yale School of Public Health, New Haven, Connecticut, United States

Climate change is expected to substantially increase the heat-related mortality burden in Switzerland, especially amongst the more vulnerable such as the elderly. However, to date, few studies have examined the additive impacts population ageing and adaptation strategies when projecting future health impacts at a high resolution. For public health, high-resolution estimates at district level of future health impacts due to climate change, will help Swiss policy makers design tailored and local adaptation strategies. Therefore, in this study we aim to 1) project heat- and cold related mortality under various climate change scenarios and 2) identify coherent and plausible adaptation strategies under different scenarios of climate and calculate the corresponding impacts under different degrees of adaptation, population ageing and urbanization. We first estimated the district-, age(<75 and over 75years)-specific temperature-mortality association using a two-stage time series design with distributed-lag nonlinear models during the 1990-2010 period in Switzerland. We then applied the temperature-mortality association to the different projections of temperature under different warming scenarios (1.5C, 2.0C and 3.0C, 4.0C) and different population ageing and urbanization scenarios according to Shared Socio-economic pathway(SSP) (SSP3 and SSP5) and projected the corresponding heat and cold-related mortality. Results were expressed as the net-difference in future heat- and cold-related mortality under warming scenarios as well as different climate, ageing and urbanization scenarios compared to the 1990-2010 baseline. Our preliminary findings suggest that under 4.0C warming, the annual heat-related mortality will increase by 676 deaths (95% CI: -329 ; 1,937), while annual cold-related mortality is likely to decrease by 1,282 deaths (95% CI: 672 ; 2006). The heat-related mortality fraction will increase from 0.22% (95%CI: -0.16; 0.54) to 1.30% (95%CI: -0.63; 3.49) mortality fractions and decrease from 5.27% (95%CI: 3.15; 11.33) to 5.23% (95%CI: 1.86; 8.60) for cold. Moreover, including scenarios of future population ageing and low adaptation will further amplify heat- and cold-related mortality(work in progress). In conclusion, our preliminary findings suggest that the heat-related mortality is likely to increase 6-fold under 4.0C by 2071-2091 and this could further be exacerbated by a high degree of population ageing and urbanization. We therefore encourage policy makers to mitigate the impacts of climate change and to design and implement efficient adaptation strategies.

Record shattering precipitation extremes

Iris de Vries[1], Sebastian Sippel[1], Erich Fischer[1], Reto Knutti[1]

[1]Institute for Atmospheric and Climate Science, ETH Zürich, Switzerland

In the very recent past, several world regions have been exposed to extreme weather events that broke observational records by large margins. For example, June and July of last year featured extreme heat in western North-America and Canada, as well as extreme rainfall and floods in southern Germany and Belgium. Both events exceeded the likely range of extremes in historical observations and model simulations, and both events resulted in considerable suffering and losses.

Many studies have shown that climate change leads to an increase in extreme weather events, such as heat waves, droughts, and extreme rainfall [1, 2]. Models show an increasing occurrence of extremes that exceed previous records by large margins under continued climate change, and more and more often we also observe such extremes in the real-world climate [2]. Yet, our infrastructure and emergency strategies are often based on experience of past extreme events, making them insufficient for the extreme events of the present and future. It is important to better understand the probabilities and characteristics of record shattering extremes in the current and future climate to inform adaptation policies and improve risk and impact management.

It is common to quantify the effect of climate change on climate extremes as a change in probability and/or severity of a particular type of extreme in a warmer world relative to the preindustrial world. In this study, however, we take on a more experience-centred focus and assess the probability that existing records are broken by a large margin (shattered). To do so, we analyse initial condition large ensemble simulations under high-emission scenarios (SSP370, SSP585). We assess the probability of record shattering daily and multi-day precipitation events per grid cell in single member realisations by updating the prevailing record based on the maximum encountered value in the past of the model realisation, and scouting for events that exceed the prevailing record by a large margin. This approach yields spatial maps of local susceptibility to record shattering precipitation events, which can be of great relevance for local policymakers.

Furthermore, we assess record shattering probabilities in spatially aggregated regions, allowing for estimation of precipitation record shattering probabilities as a function of time, and thus as a function of global temperature increase. Using this approach for 7-day temperature extremes, it was shown that record shattering probability is strongly associated with warming rate [2]. This finding has important implications for the expected damage associated with the course of future warming, determined by global climate action targets. Improved understanding of the behaviour of precipitation extremes as a function of global warming rates is therefore of high importance as well.

We show preliminary results of the spatial and temporal characteristics of record shattering in simulated precipitation. We aim to extend this study to include an analysis of drivers of record shattering precipitation extremes in current and future climate, as well as a comparison with observed precipitation extremes.

References

[1] G. Myrhe et al., Frequency of extreme precipitation increases extensively with event rareness under global warming, *Scientific reports* **9**, 16063 (2019), https://doi.org/10.1038/s41598-019-52277-4.

[2] E. M. Fischer, S. Sippel, R. Knutti, Increasing probability of record-shattering climate extremes, *Nature Climate Change* **11**, 689–695 (2021). https://doi.org/10.1038/s41558-021-01092-9

Climate change increases the severity of marine acidification extreme events

Flora Desmet[1], Nicolas Gruber[1], Matthias Münnich[1], Meike Vogt[1], Eike E. Köhn[1]

[1]Environmental Physics, Institute of Biogeochemistry and Pollutant Dynamics, ETH Zürich, Zürich, Switzerland

The global ocean rapidly acidifies as it takes up anthropogenic CO_2 from the atmosphere. Ocean acidification (OA) refers to the concurrent long-term decrease of the ocean pH and aragonite saturation state (Ω_A) [1]. On top of this trend, extreme events of unusually low pH and Ω_A occur episodically in the ocean. Superimposed OA and episodic strong excursions in the seawater carbonate chemistry can have potential deleterious effects on marine organisms and ecosystems [2].

Using a high resolution regional ocean model coupled to a biogeochemical-ecosystem model (ROMS-BEC), we characterize ocean acidification extreme events (OAXs) defined as spatiotemporally connected grid cells of extremely low pH and Ω_A, and investigate the mechanisms by which they are being formed in the upper 150 m of the northeast Pacific Ocean. In a second step, we investigate the respective role of atmospheric CO_2 rise and climate modes in the occurrence of OAXs, with an emphasis on the most severe ones. To this end, we use daily output of a hindcast simulation from 1984 to 2019.

We find that OAXs are mainly triggered by the wind-driven upwelling of deep waters at the U.S. West Coast and by ocean mesoscale cyclonic eddies [3]. The former causes shallow and intense OAXs at the coast, while the latter leads to large OAXs that can last several months to years and propagate from the coast to far offshore, occupying a substantial fraction of the upper 150 m depth of the ocean (e.g., Fig. 1). Our results underline the key role of oceanic mesoscale processes in shaping these extreme events.

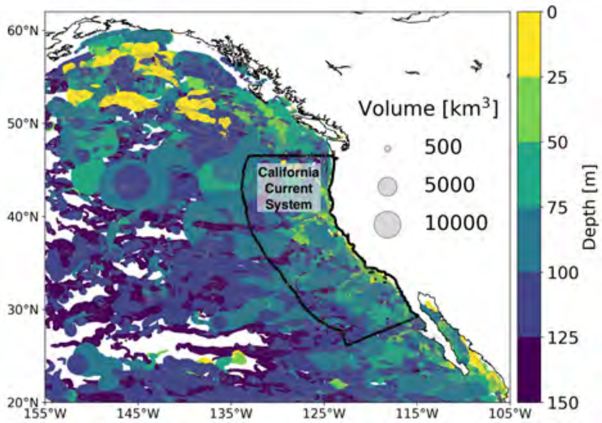


Figure 1: Spatial extent and distribution of low pH-Ω_A extreme events (OAXs) in the upper 150 m depth of the northeast Pacific Ocean. Plotted are the trajectories of the large and long-lasting events associated with mesoscale cyclonic eddies detected between 1984 and 2019. The color indicates the mean depth of the extreme at each given day of the trajectory. The dot size scales with the volume of the extreme at each given day. The black line encompasses the California Current System up to 750 km off the U.S. West Coast. *Modified from [3].*

Furthermore, we find that atmospheric CO_2 rise is the primary driver of the increase in the annual volume hit by pH extremes during the last four decades in the upper 250 m depth of the northeast Pacific (e.g., Fig. 2), with 92% of this volume between 2010 and 2019 being a direct consequence of the increase in CO_2 in the atmospheric forcing. The increase is fastest and strongest near the surface

(0-50 m depth) and slower at the subsurface (50-250 m depth), especially in coastal regions (e.g., Fig. 2). In the subsurface of coastal regions we find strong interannual modulations of OAXs occurrence, volume and intensity by climate modes such as the El-Niño-Southern Oscillation (ENSO). The negative (positive) phase of ENSO, namely La Niña (El Niño), increases (decreases) the occurrence of OAXs in the southern and central part of the California Current System along the U.S. West Coast, compared to normal ENSO years.

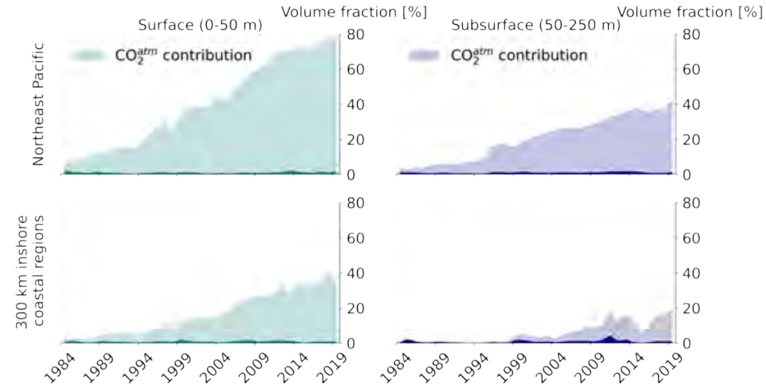


Figure 2: Timeseries of the annual volume fraction hit by pH extremes in the (top) Northeast Pacific and (bottom) 300 km inshore coastal regions only in (left) 0-50 m depth and (right) 50-250 m depth layers. Dark filled areas depict the volume fraction for a control simulation using an atmospheric CO_2 forcing stabilised around atmospheric CO_2 concentrations of year 1979 and light filled hatched areas represent the additional volume fraction hit by pH extremes in the hindcast simulation with increasing atmospheric CO_2.

The combination of the imprint of atmospheric CO_2 rise on OAXs and of periods of enhanced OAXs occurrence by natural variability, namely the upwelling season at a seasonal timescale and La Niña years at an interannual timescale, causes highly severe OAXs, i.e., long, large and intense spatiotemporal coherent events, to develop. Such severe OAXs occur at increased frequency in the last two decades of our hindcast, potentially impacting OA sensitive marine organisms over large volumes and long durations in the Northeast Pacific.

References

[1] Doney et al., Ocean Acidification: The Other CO_2 Problem, *Annual Review of Marine Science* **1**, 169 (2009), 10.1146/annurev.marine.010908.163834.

[2] Doney et al., The Impacts of Ocean Acidification on Marine Ecosystems and Reliant Human Communities, *Annual Review of Environment and Resources* **45**, 11.1 (2020), 10.1146/annurev-environ-012320-083019.

[3] Desmet et al., Tracking the space-time evolution of ocean acidification extremes in the California current system and northeast Pacific, *Journal of Geophysical Research: Oceans* **127**, (2022), 10.1029/2021jc018159.

Influence of Land Surface Temperature on Permafrost Dynamics - a Northern Hemisphere Perspective of the last 40 Years

Sonia Dupuis[1,2], Frank Göttsche[3], Sebastian Westermann [4], Stefan Wunderle [1,2]

[1]Oeschger Centre for Climate Change Research, University of Bern, Bern, Switzerland
[2]Institute of Geography, University of Bern, Bern, Switzerland
[3]Institute of Meteorology and Climatology Research, Karlsruhe Institute of Technology, Karlsruhe, Germany
[4]Department of Geosciences, University of Oslo, Oslo, Norway

Northern high latitudes have experienced pronounced warming throughout the last decades with remarkable temperature peaks especially during winter and springtime [1]. The warming affects the sensible ecosystem, vegetation dynamics and the cryosphere (sea ice, snow and permafrost). Land surface temperature (LST) is an important indicator for ecological and climate change [2]. On a global scale, observation of LST is only available from very few in-situ stations or climate models with coarse spatial resolution. Both data sources are not sufficient to model small-scale effects in ecosystems or dynamics of permafrost layers on large areas. In contrast, LST information can be retrieved from various satellite data (e.g. Landsat 8 or MODIS (Moderate Resolution Imaging Spectroradiometer)). To retrieve statistically significant changes of Essential Climate variables (ECV), a time series of at least 30 years is needed [3]. Only data of the Advanced Very High Resolution Radiometer (AVHRR) on-board the NOAA and MetOp satellite series cover a sufficiently long period of more than four decades. The AVHRR Global Area Coverage (GAC) data set, archived at the Remote Sensing Research Group's facilities, will be spatially enhanced to contribute to the aim of the proposed project: A study of the influence of LST on permafrost utilizing a novel LST data set based on 40 year AVHRR data. In the past, a variety of LST retrieval algorithms have been developed, which usage depends on the specifications of the TIR channels. AVHRR's two thermal channels allow to apply the split-window method to reduce the atmospheric effect [4] and to retrieve LST.

The present project expects to contribute to the analysis of the spatial and temporal variability of LST and its relation to land cover categories and snow cover fraction. The determination of the main impacts of trends and anomalies will be showcased. Additionally, an analysis of the interaction of LST with vegetation, snow and permafrost is expected. Finally, the data set should be ingested into the ESA Permafrost CCI toolchain.

References

[1] AMAP: Arctic Climate Change Update 2021: Key Trends and Impacts. Summary for Policy-makers, *Arctic Monitoring and Assessment Programme (AMAP)*, Tromsø, Norway, 16 pp, (2021)

[2] Yang, J., Zhou, J., Göttsche, F., Long, Z., Ma, J. and Luo, R., Investigation and validation of algorithms for estimating land surface temperature from Sentinel-3 SLSTR data, *International Journal of Applied Earth Observation and Geoinformation*, **91**, 102136, (2020), 10.1016/j.jag.2020.102136

[3] Lieberherr, G., Riffler, M., Wunderle, S., Performance Assessment of Tailored Split-Window Coefficients for the Retreival of Lake Surface Water Temperature from AVHRR Satellite Data, *Remote Sensing*, **1334**, 9(12), (2017), 10.3390/rs9121334

[4] Lieberherr, G., Wunderle, S., Lake Surface Water Temperature Derived from 35 Years of AVHRR Sensor Data for European Lakes, *Remote Sensing*, **990**, 10(7), (2018), 10.3390/rs10070990

A multiproxy reconstruction of Holocene climate and land-use impacts on vegetation dynamics in the Eastern Swiss Alps.

Laura Dziomber[1,2], Maria Leunda[1,2,3], Lisa Gurtner[1], Christoph Schwörer[1,2]

[1]Institute of Plant Sciences, University of Bern, Bern, Switzerland
[2]Oeschger Centre for Climate Change Research, University of Bern, Bern, Switzerland
[3]WSL Swiss Federal Research Institute, Birmensdorf, Switzerland

Mountain vegetation is particularly affected by climate change. With rising temperatures, plant populations are either forced to shift their range upslope to more suitable areas, adapt to changing conditions or suffer decline. Despite the growth of monitoring programs assessing the impacts of current global change on alpine ecosystems, there is still an insufficient use of long-term studies in conservation biology to understand ecosystem responses on long timescales. Paleoecology has made important contributions to the reconstruction of past climate-driven vegetation changes based on the study of biotic proxies such as pollen and macrofossils preserved in lake sediments.

The last climate change of a similar magnitude and rate as projected for this century occurred during the transition between the last Ice Age and the Holocene interglacial (ca. 11,700 years ago), when temperatures rapidly increased by 2-4 °C within less than a century. Studying this time period can provide new insights into vegetation changes resulting from climatic drivers. Understanding the response of vegetation to rapid temperature increase and human impact is a fundamental prerequisite to produce accurate and reliable predictions of future mountain vegetation and mitigate climate change impacts. The overarching goal of this large-scale, multiproxy study is to better understand past vegetation dynamics and the impact of future climate change on plants at multiple scales; from the genetic to the community level.

We present ongoing work on macrofossil and pollen analysis from the Lai da Vons sedimentary record (1991 m a.s.l), an alpine lake situated at the treeline ecotone in Eastern Switzerland. Our results reveal that the first trees could already establish 13,500 years ago, in response to rising temperatures. Closed forests dominated by conifers like Pinus cembra and Larix decidua expanded during the Early Holocene, when summer temperatures were even warmer than today. However, from 6,500 years cal. BP onwards, increasing human impact led to an opening of the landscape, with more shrubs and herbs and a more diverse species composition.

In a next step, we will use novel molecular methods in order to track adaptive and neutral genetic diversity of conifers through the Holocene by analyzing ancient DNA from subfossil conifer needles. The combination of these well-established palaeoecological methods with novel molecular techniques to understand vegetation changes to climate variations can be insightful for future forest management and conservation in the Alps.

Hydrological disruptions due to ENSO in a changing climate

Mandy B. Freund[1]

[1]CSIRO, Melbourne, Australia

The basic science of climate change is well understood, yet climate change remains one of the greatest global challenges. Ongoing changes to our climate system are inevitable; the hydrological impacts remain poorly understood and bear large uncertainties and significant risks, particularly in the case of climate extremes. The naturally occurring El Niño Southern Oscillation has impacts around the world, though only happens every 2-7 years [1] meaning only a handful of events have been directly observed. Of particular concern are the future swings of ENSO that are projected to change with further greenhouse warming. The frequency of extreme El Niño events and their counterpart La Niña events are projected to increase with global mean temperatures [2, 3, 4]. At the same time, El Niño events have already undergone changes leading to more El Niño events occurring in the Central Pacific rather than the Eastern Pacific [5]. This is projected to continue under future emission scenarios [6]. As ENSO's variability is closely linked to rainfall extremes around the globe [7], projected changes to natural variability become a substantial source of uncertainty for hydrological projections. The cascading impacts are poorly understood due to their uncertain response to forcing factors and intrinsic event diversity [8] but bear a high risk for major rainfall disruptions in large parts of the world.

The evaluation of the cumulative risk related to changes of ENSO episodes on hydrological variables at a multi-annual time scale is essential. Swings of ENSO are often related to hydrological extremes of opposing character during ENSO warm and cool phases. For example, during El Niño events Australian rainfall is reduced by 30-60% whereas La Niña conditions can lead to flooding and filling of reservoirs. The cumulative hydrological impact of an ENSO episode depends therefore depends on the occurrence of a "recharging" phase following an extreme dry event. Given the recent shift towards more El Niño events occurring in the Central Pacific [5], this natural recharge mechanism may be limited with continued global warming. Specifically, Central Pacific El Niño events are often followed by a second El Niño event rather than La Niña conditions, as occurred in 2014-2016. These consecutive ENSO events increase the risk of multi-year droughts [9] with dramatic implications for water security. The cumulative impacts of ENSO episodes and the recharging ENSO cycle play a critical role in water resources management but remains largely unknown.

References

[1] Rasmusson, E. M. and Carpenter, T. H.: Variation in tropical sea surface temperature and surface wind fields associated with the Southern Oscillation/El Niño, Mon. Wea. Rev., 110, 354, 1982.

[2] Cai, W., Santoso, A., Wang, G., Yeh, S.-W., An, S.-I., Cobb, K., Collins, M., Guilyardi, E., Jin, F.-F., Kug, J.-S., Lengaigne, M., McPhaden, M. J., Takahashi, K., Timmermann, A., Vecchi, G., Watanabe, M. and Wu, L.: ENSO and greenhouse warming, Nature Climate change, 5(9), 849–859, doi:10.1038/nclimate2743, 2015a.

[3] Cai, W., Wang, G., Santoso, A., McPhaden, M. J., Wu, L., Jin, F.-F., Timmermann, A., Collins, M., Vecchi, G., Lengaigne, M., England, M. H., Dommenget, D., Takahashi, K. and Guilyardi, E.: Increased frequency of extreme La Niña events under greenhouse warming, Nature Climate change, 5(2), 132–137, doi:10.1038/nclimate2492, 2015b.

[4] Cai, W. et al., Increased variability of eastern Pacific El Niño under greenhouse warming, Nature, 1–18, doi:10.1038/s41586-018-0776-9, 2018.

[5] Freund, M. B., Henley, B. J., Karoly, D. J., McGregor, H. V., Abram, N. J. and Dommenget, D.: Higher frequency of Central Pacific El Niño events in recent decades relative to past centuries, Nature Geosci, 6, 450–455, doi:10.1038/s41561-019-0353-3, 2019a.

[6] Yeh, S.-W., Kug, J.-S., Dewitte, B., Kwon, M.-H., Ben P Kirtman and Jin, F.-F.: El Niño in a changing climate, Nature, 461(7263), 511–514, doi:10.1038/nature08316, 2009

[7] Dai, A. and Wigley, T. M. L.: Global patterns of ENSO-induced precipitation, Geophys. Res. Lett., 27(9), 1283–1286, doi:10.1029/1999gl011140, 2000.

[8] Wang, G. and Hendon, H. H.: Sensitivity of Australian Rainfall to Inter–El Niño Variations, J. Climate, 20(16), 4211– 4226, doi:10.1175/JCLI4228.1, 2007.

[9] Freund, M.B., Marshall, A.G., Wheeler, M.C. and Brown, J.N. Central Pacific El Niño as a precursor to summer drought-breaking rainfall over southeastern Australia. Geophysical Research Letters, 48(7),2021

The severe back-to-back winters of 762-764 CE: Linking pan-European weather and climatic extremes to a volcanic source using Greenland ice core records

Imogen Gabriel[1], Gill Plunkett[2], Peter Abbott[1], Bergrún Óladóttir[3], Joe McConnell[4], Will Hutchison[5], Andrea Burke[5], Maria Hörhold[6], Melanie Behrens[6], Eliza Cook[7], and Michael Sigl[1,8]

[1]Climate and Environmental Physics and Oeschger Centre for Climate Change Research, University of Bern, Bern, Switzerland
[2]School of Natural and Built Environment, Queen's University Belfast, Belfast, UK
[3]Icelandic Meteorological Office, Reykjavík, Iceland
[4]Desert Research Institute, Reno, Nevada, USA
[5]School of Earth and Environmental Sciences, University of St Andrews, St Andrews, UK
[6]Alfred-Wegener-Institut Helmholtz-Zentrum für Polar- und Meeresforschung, Bremerhaven, Germany
[7]Physics of Ice, Climate and Earth, Niels Bohr Institute, University of Copenhagen, Copenhagen, Denmark
[8]Department of Geosciences, University of Oslo, Oslo, Norway

The two winters of 762/763 and 763/764 CE were among the harshest and most severe of the last 2000 years. Historical documents and proxy records (i.e. Speleothem records) cite widespread frost, famine, and generally cooler temperatures from Ireland to the Black Sea [1, 2, 3, 4]. Previous analysis of Greenland ice core records identified an acidity peak coinciding with the severe winters of 762-764 CE, suggesting a possible volcanic influence. However, the source and nature of the eruption (tropospheric or stratospheric) remained unknown, which has ultimately hindered robust climate impact assessments.

The polar ice cores offer the opportunity to reliably reconstruct past volcanic eruptions (source, duration, and plume height) due to their high-resolution and preservation of volcanic events (tephra particles and sulphate aerosols) [5]. Therefore, to resolve the uncertainties surrounding the 762 CE acidity peak, we adopted a multi-parameter approach across several Greenland ice cores. We (i) robustly determined the total duration of the event using the annually resolved high-resolution ice core chronologies; (ii) undertook targeted sampling of the ice core records for cryptotephra geochemical analysis and correlation to proximal volcanic material to pinpoint the source volcano; and (iii) conducted high-resolution sulphur isotope analysis to confirm the volcanic origin of this event and constrain the plume height of the eruption (tropospheric or stratospheric).

Preliminary analysis has revealed that the acidity peak in 762 CE is the product of an explosive stratospheric volcanic event, occurring at the end of a period of elevated tropospheric volcanic emissions. Through geochemical analysis of the cryptotephra particles associated with this peak, a correlation has been made to a volcanic system in Iceland. Ultimately, due to the stratospheric nature and latitudinal position of this eruption in 762 CE, it could be considered as a likely cause for the severe winters of 762-764 CE.

References

[1] McCormick, M., Dutton, P. E., and Mayewski, P. A., Volcanoes and the climate forcing of Carolingian Europe, AD 750-950, *Speculum* **82(4)**, 865-895 (2007), 10.1017/S0038713400011325.

[2] Fohlmeister, J., Vollweiler, N., Spötl, C., and Mangini, A., COMNISPA II: Update of a mid-European isotope climate record, 11 ka to present, *The Holocene* **23(5)**, 749-754 (2012), 10.1177/0959683612465446.

[3] Newfield, T.P., The contours, frequency and causation of subsistence crises in Carolingian Europe (750-950 CE), in, *Crisis alimentarias en la edad media: Modelos, explicaciones y representaciones*, 117-172 (2013).

[4] Affolter, S., Häuselmann, A., Fleitmann, D., Edwards, R.L., Cheng, H., and Leuenberger, M., Central European temperature constrained by speleothem fluid inclusion water isotopes over the past 14,000 years, *Science Advances* **5(6)**, (2019), 10.1126/sciadv.aav3809.

[5] Abbott, P.M. and Davies, S.M., Volcanism and the Greenland ice-cores: the tephra record, *Earth-Science Reviews* **115(3)**, 173-191 (2012), 10.1016/j.earscirev.2012.09.001.

Paleoenvironmental changes since 16,000 cal. BP - the diatom record from varved lake sediments of Holzmaar, Germany

M. Luján García[1], Stella Birlo[1], Bernd Zolitschka[1]

[1]GEOPOLAR, Institute of Geography, University of Bremen, Germany

Diatom stratigraphies of well-dated sedimentary records are widely used to characterize past environmental changes of aquatic systems. Holzmaar, a maar lake located in the West-Eifel Volcanic Field (Germany), has continuous deposition since the Pleniglacial with a high potential for detecting climatic and anthropogenic impacts. Until today, only a few time windows have been studied based on diatoms but never the entire record [[1, 2]]. In addition to diatoms, we analysed magnetic susceptibility (MS), biogenic silica (BSi) and the elemental composition (XRF) to assess the main trends of paleoenvironmental changes with a centennial resolution for the 14 m-long composite record.

MS shows relatively stable but low measurements along the record except for increased values for the Pleniglacial (prior to 14,500 cal BP), the Laacher See Tephra (13,000 cal BP) and since the Iron Age (younger than 2000 cal BP). Ca/Ti ratios are very low during the Pleniglacial, highest during the Lateglacial and decrease throughout the Early Holocene. TOC/TN ratios fluctuate on a low-level suggesting dominance of autochthonous lacustrine productivity. The patterns of diatom assemblages allow us to infer the trophic history of Holzmaar. There is a distinct variation at the Pleistocene/Lateglacial transition (during the Bölling/Alleröd interstadial), where *Staurosira construens* is replaced by *Stephanodiscus minutulus*, BSi, Ca/Ti and TOC/TN increase suggesting higher lacustrine productivity and a shift of the trophic level from oligotrophic to mesotrophic. During the Younger Dryas stadial there is a decrease of organic productivity and an increased wind intensity. The Holocene Thermal Maximum (~9000–6000 cal BP) is dominated by *S. minutulus* and *Nitzschia paleacea*. The dominance of these two species and the increases of TOC/TN as well as of TS suggest lake eutrophication with periodic anoxia. During the Late Holocene (after 4200 cal BP), *Lindavia radiosa* and *Pantocsekiella comensis* are dominant suggesting warmer conditions, eutrophication and increased minerogenic influx related to human impact. Moreover, the appearance of *Aulacoseira subarctica* is related to a cold and wet period during the Little Ice Age.

Our multiproxy approach enables us to reconstruct not only environmental conditions for the Pleniglacial/Lateglacial and Lateglacial/Holocene transitions as well as for the Younger Dryas stadial, but also human impact (Late Holocene) and catastrophic events (e.g. the Laacher See eruption). An overview of environmental changes during the last 16,000 years is provided with Fig. 1. Future studies will utilize this multiproxy approach to investigate specific time windows (the Dantean and Homerian anomalies) with high temporal resolution to better understand short-term variabilities of aquatic ecosystems and their catchment areas in response to past climatic changes for an improved assessment of future developments.

References

[1] Baier, J. et al., Diatom and geochemical evidence of mid- to late Holocene climatic changes at Lake Holzmaar, West-Eifel (Germany), *Quaternary International* **113**, 81 (2004), https://doi.org/10.1016/S1040-6182(03)00081-8.

[2] Brüchmann, C., Negendank, J.F.W, Indication of climatically induced natural eutrophication during the early Holocene period, based on annually laminated sediment from Lake Holzmaar, Germany, *Quaternary International* **123-125**, 117 (2004), https://doi.org/10.1016/j.quaint.2004.02.013

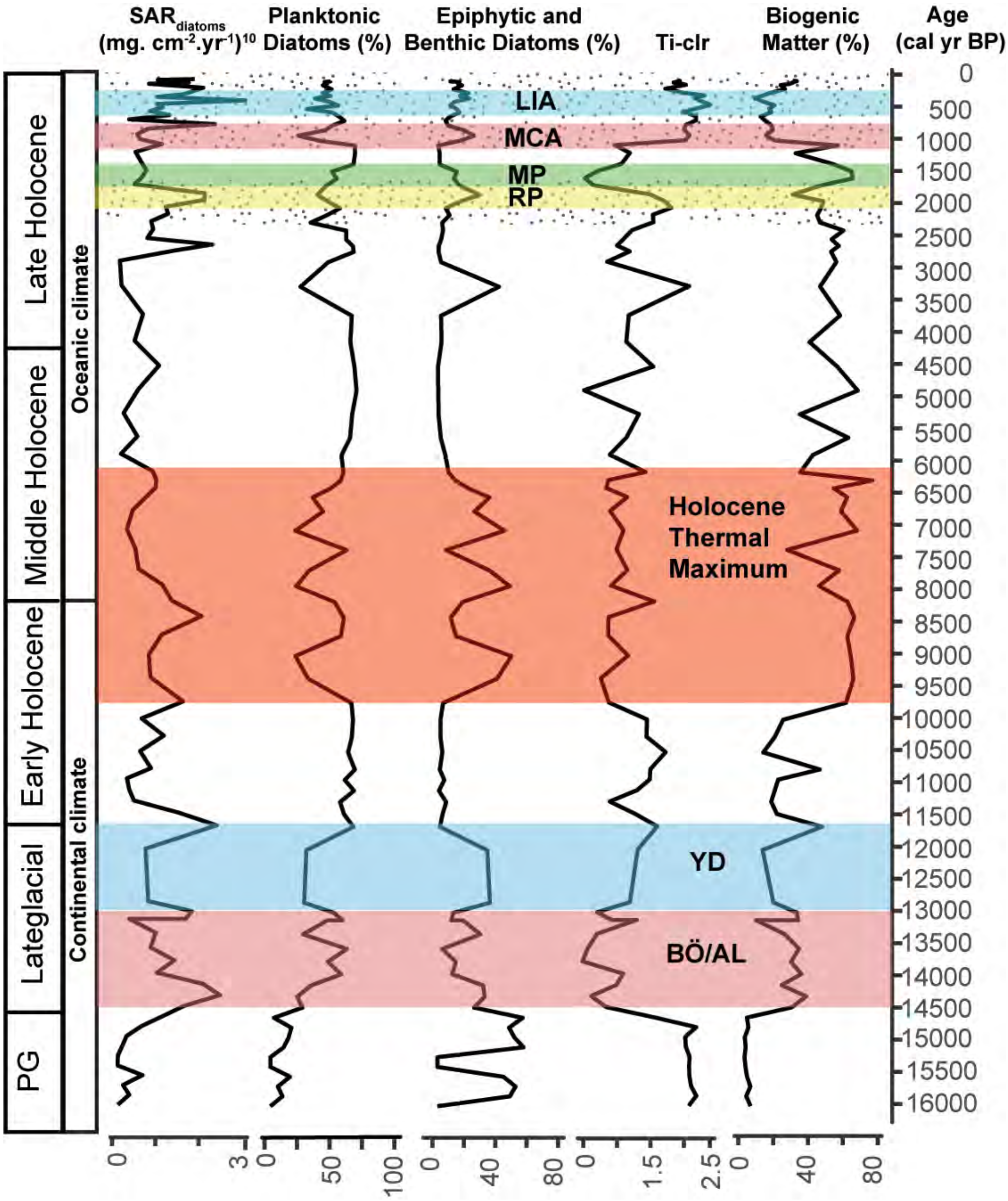


Figure 1: Summary of environmental conditions from the Pleniglacial (PG) until today for Lake Holzmaar. Prominent climatic intervals or events are shaded in colour and labelled: Bölling/Alleröd interstadial (BÖ/AL), Younger Dryas (YD), Holocene Thermal Maximum, Roman Period (RP), Migration Period (MP), Medieval Climate Anomaly (MCA) and Little Ice Age (LIA). The dotted pattern indicates periods with increased soil erosion.

Radiocarbon Inventories of Switzerland (RICH) : Source apportionment of atmospheric CO_2, sampling strategy and first results

Dylan Geissbühler[1, 2], Thomas Laemmel[1, 2], Philip Gautschi[3], Lukas Wacker[3], Sönke Szidat[1, 2]

[1]Department of Chemistry, Biochemistry and Pharmaceutical Sciences, University of Bern, Bern, Switzerland
[2]Oeschger Centre for Climate Change Research, University of Bern, Bern, Switzerland
[3]Laboratory of Ion Beam Physics, Institute for Particle Physics and Astrophysics, Federal Institute of Technology Zurich (ETHZ), Zurich, Switzerland

Anthropogenically-induced climate change is strongly linked with perturbations of the carbon cycle from the excess emission of greenhouse gases into the atmosphere, especially carbon dioxide (CO_2). Radiocarbon (^{14}C) measurements of atmospheric CO_2 are unique in their capabilities to provide information on carbon source apportionment and transport, especially of fossil-fuel derived CO_2 which is ^{14}C-free [1]. This top-down approach acts as a complementary way to assess the distribution and amount of anthropogenic CO_2 emissions, compared to traditional bottom-up inventories of emissions in different sectors of human activity. For natural sources of CO_2, the emitted ^{14}C content can bring insight into their carbon turnover and changing dynamics.

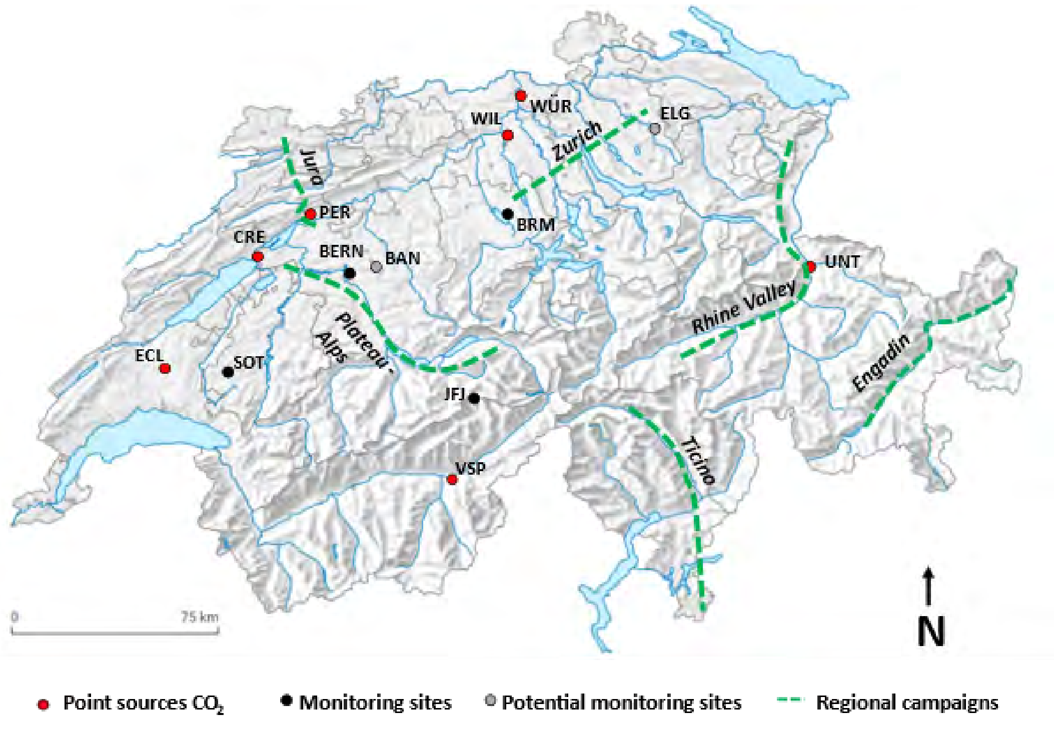


Figure 1: Map of Switzerland indicating the multiple aspects of the sampling strategy in this project. Campaigns will be of three main kinds, investigations of CO_2 hot spots (industrial and urban sites), monitoring sites at tall towers and regional campaigns to explore differences between ecoregions. Jungfraujoch (JFJ) serves as a regional background site.

The Radiocarbon Inventories of Switzerland (RICH) project aims to build a comprehensive database and model of the distribution and cycling of radiocarbon in Switzerland across the atmosphere, soils, rivers and lakes reservoirs. The project presented here will serve to specifically construct an inventory of atmospheric $^{14}CO_2$ in this larger scope. This will be achieved by sampling air in strategic ways (Fig.1), and measuring its $^{14}CO_2$ content, as well as CO_2 concentration. First, air masses passing over Switzerland will be sampled automatically with dedicated sampling devices installed at multiple tall towers located across the territory. In parallel to this, more localized measurements will focus on industrial

CO_2 hot spots as well as natural variations of $^{14}CO_2$ across the multiple ecoregions of Switzerland. This will bring information on the radiocarbon signature of concentrated anthropogenic CO_2 emissions, the spatial representation of diffuse natural CO_2 emissions across multiple ecosystems, as well as their subsequent atmospheric transport. As a complement to the atmospheric samples, ^{14}C measurements from leaf biomass are also planned, which will allow to quantify the integration of $^{14}CO_2$ to the vegetation, and ultimately to soils.

One of the main challenges in this work is to develop a robust air sampling method and strategy allowing us to effectively capture meaningful atmospheric $^{14}CO_2$ signatures. Also, a precise and well-thought sample handling protocol will be needed to ensure a low sample contamination and guarantee the 1.5-2‰ precision allowed by the Accelerator Mass Spectrometer MICADAS used at ETH Zurich [2]. Graphitization of air samples will be done by using the Air Loading Facility also available at ETHZ [3], allowing for a simplified workflow in the preparation of 5L atmospheric samples. A robust $^{14}CO_2$ background value is obtained from biweekly integrated samples taken at the Jungfraujoch (JFJ) high altitude research station, located at 3463m asl.

References

[1] Levin, I., Hesshaimer, V., 2000. Radiocarbon – A Unique Tracer of Global Carbon Cycle Dynamics. *Radiocarbon* **42**, 69–80. https://doi.org/10.1017/S0033822200053066

[2] Wacker, L., Bonani, G., Friedrich, M., Hajdas, I., Kromer, B., Němec, M., Ruff, M., Suter, M., Synal, H.-A., Vockenhuber, C., 2010. MICADAS: Routine and High-Precision Radiocarbon Dating. *Radiocarbon* **52**, 252–262. https://doi.org/10.1017/S0033822200045288

[3] Gautschi, P., 2017. A new method to graphitize CO_2 from atmospheric air for radiocarbon analysis., Master's Thesis., ETHZ.

Developing storylines for very rare precipitation extremes

Claudia Gessner[1], Erich M. Fischer[1], Urs Beyerle[1], Reto Knutti[1]

[1]Institute for Atmospheric and Climate Science, ETH Zurich, Switzerland

Heavy precipitation events are among the costliest natural disasters in central Europe, destroying the local infrastructure and causing multiple fatalities. Due to the lack of long homogenous climate data and methodological framework, it is uncertain how intense precipitation extremes could get. A common approach is to extrapolate into the tails of precipitation distribution, using the GEV distribution [1]. Since these extrapolations are uncertain for events beyond the observational record and they are not based upon physics, this study develops climate storylines of very rare precipitation events during cold months (October - April) in a near future climate model simulation with CESM2.

In an approach referred to as ensemble boosting [2], large samples of re-initialized heavy rainfall events are generated to estimate how extreme they could get. We find that the most extreme precipitation can be substantially exceeded in the boosted ensembles during cold months over central Europe. Repeating the ensemble boosting method can efficiently generate even more extreme precipitation events with a hundredfold increased return periods. The associated atmospheric dynamics show certain patterns during precipitation extremes with characteristic impact on the precipitation over CEU.

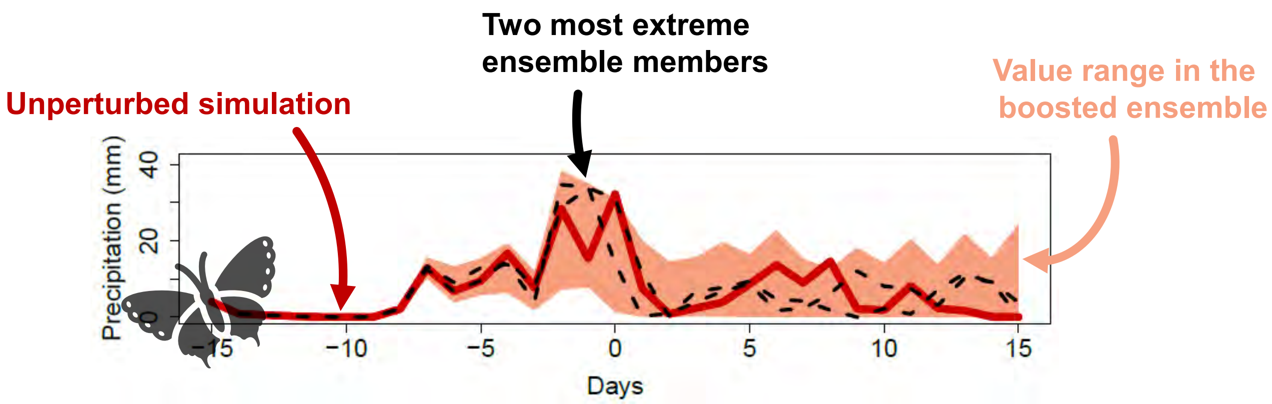


Figure 1: Example of ensemble boosting. Development of the most extreme 3-day precipitation event in the CESM2 near future simulation (thick dark red line), averaged over central Europe. Light red shading indicates the value range in the initial condition ensemble simulation, started with a lead time of 14 days before the peak of precipitation (butterfly). Both dashed black lines display the two most extreme ensemble members, i.e., with highest 3-day accumulated precipitation.

Second, we apply ensemble boosting to an analog of the flood-related precipitation in December 1993 over central Europe. The boosted ensembles reveal that the amount of precipitation could have been largely exceeded, which would have aggravated the flood. As a result, the ensemble boosting method can provide storylines of heavy rainfall development beyond the observational record, which can be used to generate worst-case scenarios and stress test the socioeconomic system.

References

[1] Gilleland & Katz, Analyzing seasonal to interannual extreme weather and climate variability with the extremes toolkit, *18th Conference on Climate Variability and Change, 86th American Meteorological Society (AMS) Annual Meeting* **229**, (2006)

[2] Gessner et al., Very Rare Heat Extremes: Quantifying and Understanding Using Ensemble Reinitialization, *Journal of Climate* **34**, 6619-6634 (2021), doi: 10.1175/JCLI-D-20-0916.1.

The effect of 3DVAR data assimilation on instability indices over the Iberian Peninsula

Santos J. González-Rojí[1,2], Sheila Carreno-Madinabeitia[3], Jon Sáenz[4,5], Gabriel Ibarra-Berastegi[6,5]

[1]Oeschger Centre for Climate Change Research, University of Bern, Bern, Switzerland
[2]Climate and Environmental Physics, University of Bern, Bern, Switzerland
[3]Department of Mathematics, University of the Basque Country (UPV/EHU), Vitoria-Gasteiz, Spain
[4]Department of Physics, University of the Basque Country (UPV/EHU), Leioa, Spain
[5]Plentziako Itsas Estazioa (BEGIK), University of the Basque Country (UPV/EHU), Plentzia, Spain
[6]Department of Energy Engineering, University of the Basque Country (UPV/EHU), Bilbao, Spain

The simulation of extreme precipitation events is rather complicated in the regional climate models as their simulation depends on many factors such as spatial resolution, topography, or physics parameterizations [1]. However, evaluating the thermodynamic conditions that can trigger these events is a must for a proper diagnosis of their effects. The Iberian Peninsula (IP) is an interesting location for the evaluation of such events, as this complex area is influenced by large-scale moisture transports [2] and the atmospheric circulation over that region is affected by teleconnection patterns [3, 4]. Hence, it is important to evaluate the performance of the Weather and Research Forecasting (WRF) model in such a complex area at simulating the thermodynamic conditions that can trigger these events.

Here, we evaluate the performance of two downscaling experiments simulating different parameters used to evaluate the unstable conditions in the atmosphere: convective available potential energy (CAPE), the convective inhibition (CIN) and the total totals index (TT). The first experiment (N) is driven by initial and boundary conditions from ERA-Interim; The second experiment (D) is similar to N, but it includes additionally a 3DVAR data assimilation step every 6 hours. A spatial resolution of 15 km was employed in both simulations, and the indices were calculated using the open-source R package *aiRthermo* [5].

The first evaluation of each parameter was performed against the data collected by each of the eight evenly distributed radiosonde available over the IP. The D experiment outperforms N for all the parameters evaluated in terms of correlation, standard deviation and root mean squared error, and independently of the season evaluated. Additionally, N overestimates or underestimates (depending on the parameter) the variability of the observed parameters in most of the seasons, while D is able to capture the variabilities in most of the seasons. In general, the 3DVAR data assimilation step improves the simulation of the dew point temperature and virtual temperature profiles, and consequently, the simulation of the instability parameters.

The heterogeneous distributions of CAPE, CIN and TT over the IP are highlighted in the seasonal maps over the IP. During winter atmospheric instability is found on the Atlantic coast of the IP, while in summer the Mediterranean coast and the Ebro basin are more prone to develop unstable air masses. Assuming that convection can be triggered orographically or due to the effect of coastal breezes, which is totally feasible in the highlighted areas, the patterns obtained with D would be in agreement with the precipitation patterns observed over the IP by previous studies [6].

References

[1] J. Sillmann, V. V. Kharin, X. Zhang, F. W. Zwiers and D. Bronaugh, Climate extremes indices in the CMIP5 multimodel ensemble: Part 1. Model evaluation in the present climate, *J. Geophys. Res.-Atmos.,* **118**, 1716–1733 (2013), 10.1002/jgrd.50203.

[2] M. Gómez-Hernández, A. Drumond, L. Gimeno and R. Garcia-Herrera, Variability of moisture sources in the Mediterranean region during the period 1980–2000, *Water Resources Research*, **49**, 6781–6794 (2013), 10.1002/wrcr.20538

[3] I. I. Zveryaev, J. Wibig and R. P. Allan, Contrasting interannual variability of atmospheric moisture over Europe during cold and warm seasons, *Tellus A*, **60(1)**, 32–41 (2008), 10.1111/j.1600-0870.2007.00283.x

[4] P. M. Sousa, R. M. Trigo, D. Barriopedro, P. M. M. Soares, A. Ramos and M. L. R. Liberato, Responses of European precipitation distributions and regimes to different blocking locations, *Climate Dynamics*, **48**, 1141–1160 (2017), 10.1007/s00382-016-3132-5

[5] J. Sáenz, S. J. González-Rojí, S. Carreno-Madinabeitia and G. Ibarra-Berastegi, Analysis of atmospheric thermodynamics using the R package aiRthermo, *Computers & Geosciences*, **122**, 113-119 (2019), 10.1016/j.cageo.2018.10.007

[6] C. Viceto, M. Marta-Almeida and A. Rocha, Future climate change of stability indices for the Iberian Peninsula, *Int. J. Climatol.* **37**, 4390–4408 (2017), 10.1002/joc.5094

Mean ocean temperature during Terminations II-IV

Markus Grimmer[1,2], Daniel Baggenstos[1,2], Jochen Schmitt[1,2], Sarah Shackleton[3], Jeffrey Severinghaus[4], Hubertus Fischer[1,2]

[1]Climate and Environmental Physics, Physics Institute, University of Bern, Bern, Switzerland
[2]Oeschger Center for Climate Change Research, University of Bern, Bern, Switzerland
[2]Department of Geosciences, Princeton University, Princeton, USA
[2]Scripps Institution of Oceanography, University of California, San Diego, USA

Deglaciations are the largest natural global warming events across the Quaternary. These transitions of the global climate from its cold glacial into the warmer interglacial state are the consequence of changes in the latitudinal distribution of insolation, amplified by major positive feedbacks such as the ice-albedo feedback and the greenhouse gas feedback. During this large-scale reorganization of the climate system, the planet takes up vast amounts of energy. This energy is largely partitioned between Earth's two dominant energy reservoirs on glacial-interglacial time scale: the ocean and the latent heat stored in glacial ice sheets. Thus, global ocean heat content (OHC), in combination with global sea level, are the two key metrics for the determination of Earth's energy imbalance during glacial-interglacial transitions [1].

Ratios of noble gases and molecular nitrogen trapped in polar ice cores can be used as a proxy for past mean ocean temperature (MOT), which is directly linked to OHC. Since noble gases are inert, the combined atmosphere-ocean system can be considered a closed system for them. Thus, their past atmospheric abundances are solely dependent on their well understood temperature-dependent physical solubilities in ocean water. As the atmosphere is well-mixed, a single ice core sample is sufficient to obtain a snapshot of the global ocean's noble gas content, and, thus, through the temperature-dependent solubilities, its heat content. Thanks to high precision mass spectrometry measurements, the 1σ uncertainty of recent MOT reconstructions is on the order of 0.4°C [2]. As a consequence, MOT has proven to be a novel powerful proxy for the past climate.

Here we present a new MOT dataset for the MIS6-5 period based on noble gas ratios in the EDC ice core. Our MIS6-5 record spans from 163kyr-116kyr, thereby complementing and largely expanding on a recent publication, in which the authors determine MOT variations during the Last Interglacial (LIG) with ice from Taylor Glacier [3]. In accordance with [3], we find an overshoot in MOT at the onset of the LIG, which is believed to be a consequence of the sustained reduction in AMOC during Heinrich Stadial 11. We also find hints of glacial MOT variability, which probably again is connected to the AMOC. Having thus available a complete picture of the MOT evolution throughout Termination II and the following LIG, we can furthermore compare the MOT changes of this time period with those of other glacial-interglacial transitions, namely Termination I, for which MOT datasets already exist [1, 4, 5], as well as Terminations III and IV, which we are currently in the process of measuring. First data for Termination IV suggest a similar, possibly even bigger, overshoot in MOT at the onset of MIS9 as seen at the end of Termination II.

References

[1] Baggenstos et al., The Erath's radiative imbalance from the Last Glacial Maximum to the present, *P. Natl. Acad. Sci. USA* **110**, 14881 (2018), 10.1073/pnas.1905447116.

[2] Haeberli et al., Snapshots of mean ocean temperatur over the last 700 000 years using noble gases in the EPICA Dome C ice core, *Clim. Past* **17**, 843 (2021), 10.5194/cp-17-843-2021.

[3] Shackleton et al., Global ocean heat content in the Last Interglacial, *Nat. Geosci.* **13**, 77 (2020), 10.1038/s41561-019-0498-0.

[4] Bereiter et al., Mean global ocean temperatures during the last glacial transition, *Nature* **553**, 39 (2018), 10.1038/nature25152.

[5] Shackleton et al., Is the noble gas-based rate of ocean warming during the younger dryas overestimated?, *Geophys. Res. Lett.* **46**, 5928 (2019), 10.1029/2019GL082971.

A place-based risk appraisal model for exploring residents' attitudes toward nature-based solutions to flood risks

Sungju Han[1,2], Philip Bubeck[2], Annegret Thieken[2], Christian Kuhlicke[1,2]

[1]Helmholtz Centre for Environmental Research, Department of Urban and Environmental Sociology, Leipzig, Germany
[2]University of Potsdam, Institute of Environmental Science and Geography, Potsdam, Germany

Traditional ways of reducing flood risk have encountered limitations in a climate-changing and rapidly urbanizing world. For instance, there has been a demanding requirement for massive investment in order to maintain a consistent level of security as well as increased flood exposure of people and property due to a false sense of security arising from the flood protection infrastructure. Against this background, nature-based solutions (NBS) have gained popularity as a sustainable and alternative way of dealing with diverse societal challenges such as climate change and biodiversity loss. In particular, their ability to reduce flood risks while also offering ecological benefits has recently received global attention. Diverse co-benefits of NBS that favor both humans and nature are viewed as promising a wide endorsement of NBS. However, people's perceptions of NBS are not always positive. Local resistance to NBS projects as well as decision-makers' and practitioners' unwillingness to adopt NBS have been pointed out as a bottleneck to the successful realization and mainstreaming of NBS [1]. Therefore, unraveling interactive relationships between diverse stakeholders' attitudes and hazard-prone places with NBS intervention is essential. So far, only a few review papers about NBS (e.g. [2]) and a strand of paper that streams from river restoration have identified several key determining factors for public attitude towards NBS. In this study we argue that the place where a hazard exists should be considered as a critical contextual factor alongside flood risk appraisals and perceptions of NBS themselves. We have developed a theoretical framework – the 'Place-based Risk Appraisal Model (PRAM)' – that draws on constructs inspired by theories of place and risk perception. A citizen survey was conducted in five municipalities in Saxony-Anhalt, Germany where dike relocation and floodplain restoration projects have been conducted along the Elbe River. An example of the project in Dessau-Roßlau is illustrated in Fig.1.

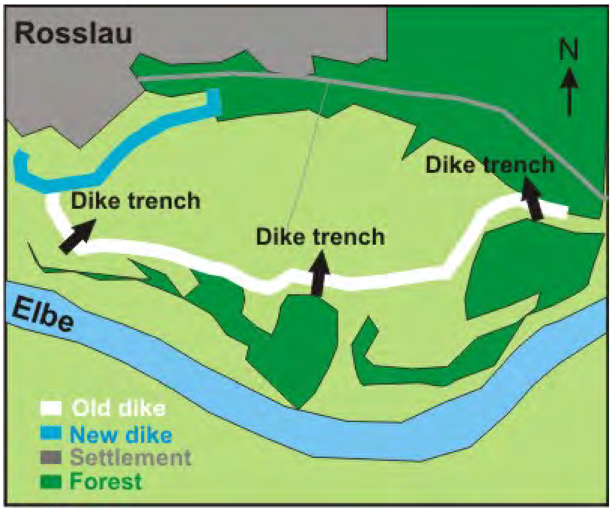


Figure 1: Illustration of Dessau-Roßlau Dike relocation and floodplain restoration project.

Structural equation modeling was adopted to explore the path coefficients and to test the PRAM (Fig.2). Attitudes toward the projects were assessed in terms of 'perceived risk-reduction effectiveness' and 'supportive attitude'. In terms of place-related variables, the construct 'nature bonding' proved to be a positive predictor of perceived risk-reduction effectiveness whereas 'place identity' was a negative predictor of a supportive attitude. With regard to risk-related constructs, well-communicated information, trust, and perceived co-benefits were consistently positive factors for both perceived risk-reduction effectiveness and supportive attitude, while 'threat appraisal' affected both attitudinal factors negatively. The study emphasizes that risk appraisal, pluralities of place contexts to each individual, and their relations are key for determining attitudes toward NBS. Understanding these influencing factors and their interrelationships enables us to provide theory- and evidence-based recommendations for the effective realization of NBS.

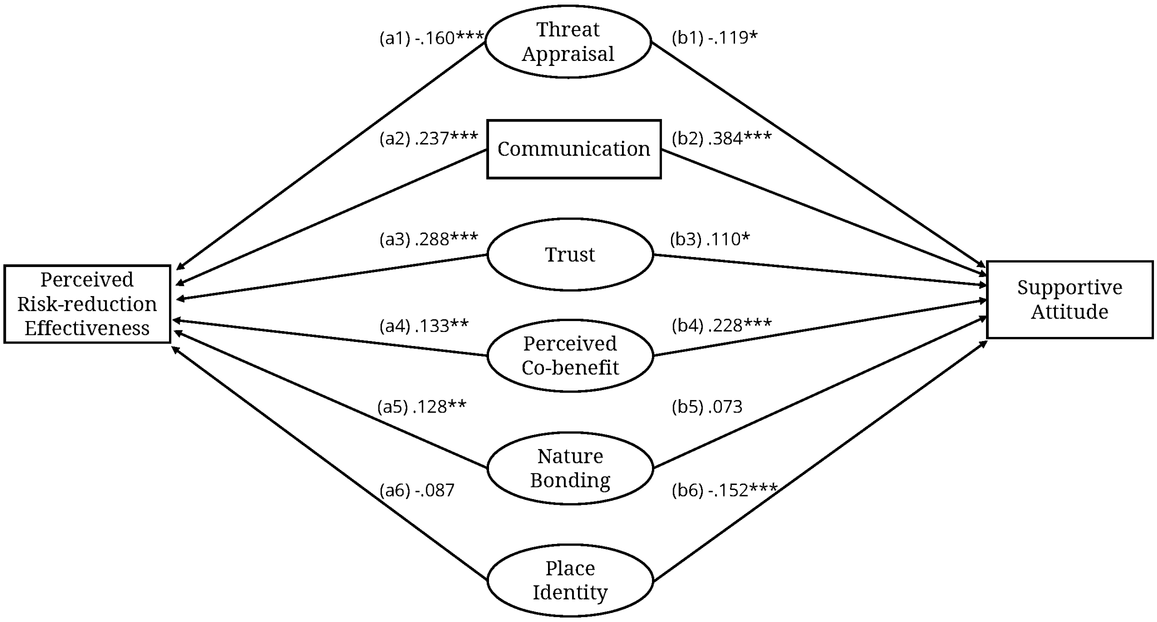


Figure 2: Structural equation model with standardized path coefficient. Ovals denote latent variables, squares denote manifest variables. *** indicate the path with significant relationship with alpha = 0.01, with alpha = 0.05, * with alpha = 0.01. Covariance coefficients are omitted. Goodness of fit: X2 = 273.050 (190 d.f.), p =0.000, CFI = 0.970, TLI = 0.962, RMSEA = 0.052, SRMR = 0.063

References

[1] Bark, R. H., Martin-Ortega, J., & Waylen, K. A., Stakeholders' views on natural flood management: Implications for the nature-based solutions paradigm shift?, *Environmental Science & Policy* **115**, 91-98(2021), https://doi.org/10.1016/j.envsci.2020.10.018.

[2] Han, S., & Kuhlicke, C., Reducing Hydro-Meteorological Risk by Nature-Based Solutions: What Do We Know about People's Perceptions?, *Science* **11**, 12 (2019), https://doi.org/10.3390/w11122599

Identification, characteristics and dynamics of Arctic extreme seasons in ERA5 and CESM climate simulations

Katharina Hartmuth[1], Maxi Boettcher[1], Heini Wernli[1], and Lukas Papritz[1]

[1]ETH Zürich, Institute for Atmospheric and Climate Science, Zürich, Switzerland

The Arctic atmosphere is strongly affected by anthropogenic warming leading to long-term trends in surface temperature and sea ice extent [1, 2]. In addition, it exhibits strong variability on time scales from days to seasons. While recent research elucidated processes causing long-term trends as well as synoptic extreme conditions in the Arctic, we investigate unusual atmospheric conditions on the seasonal time scale. We introduce a method to identify extreme seasons – deviating strongly from a running-mean climatology – based on a principal component analysis in the phase space spanned by the seasonal-mean values of surface temperature, precipitation, and the atmospheric components of the surface energy balance. Given the strongly varying surface conditions in the Arctic, this analysis is done separately in Arctic sub-regions that are climatologically characterized by either sea ice, open ocean, or mixed conditions.

Using ERA5 reanalyses for the years 1979-2018, our approach identifies 2-3 extreme seasons for each of winter, spring, summer, and autumn, with strongly differing characteristics and affecting different Arctic sub-regions. Results will be shown for two contrasting extreme winters affecting the Kara and Barents Seas, including their substructure, the role of synoptic-scale weather systems, and potential preconditioning by anomalous sea ice extent and/or sea surface temperature at the beginning of the season (see Fig. 1).

To statistically quantify and confirm these results, we further apply our method to large ensemble simulations of the CESM climate model [3], using roughly 1000 years of data in present-day climate (1990-2000) and end-of-century simulations (2091-2100), respectively. Results show a strong similarity between the characteristics of extreme seasons in ERA5 and CESM for the present-day period. The identified seasons predominantly show the most extreme seasonal-mean anomalies of the applied surface parameters, confirming that our approach captures seasons with extraordinary conditions. Preliminary results will also be shown about our current investigation of possible changes in the characteristics and driving mechanisms of Arctic extreme seasons in the warmer end-of-century climate.

The framework developed in this study and the insight gained from analyzing both, reanalysis and climate model data, will be insightful for better understanding the effects of global warming on Arctic extreme seasons.

References

[1] M. C. Serreze and R. G. Barry, Processes and impacts of Arctic amplification: A research synthesis, *Glob. Planet. Change* **77**, 85 (2011), https://doi.org/10.1016/j.gloplacha.2011.03.004

[2] J. Cohen et al., Recent Arctic amplification and extreme mid-latitude weather, *Nat. Geosci.* **7**, 627 (2014), https://doi.org/10.1038/ngeo2234

[3] J. W. Hurrell et al., The Community Earth System Model: A framework for collaborative research, *B. Am. Meteorol. Soc.* **94**, 1339 (2013), https://doi.org/10.1175/BAMS-D-12-00121.1

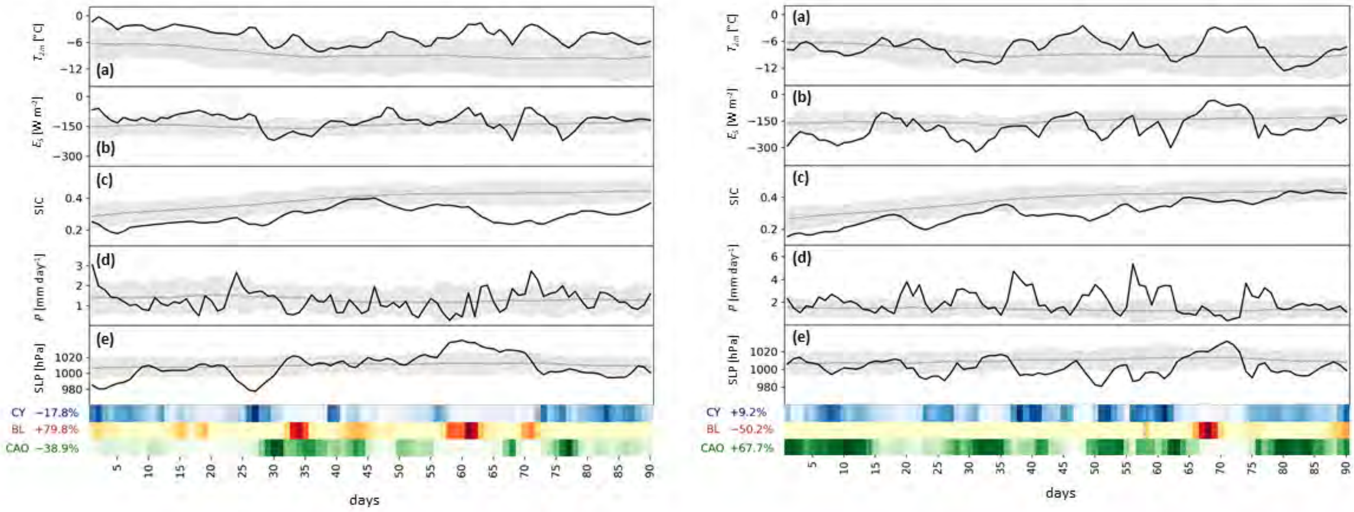


Figure 1: Time series of daily-mean **(a)** 2 m temperature (in °C), **(b)** sum of net surface sensible and latent heat fluxes (in $\mathrm{W\,m^{-2}}$), **(c)** sea ice concentration, **(d)** precipitation (in $\mathrm{mm\,day^{-1}}$) and **(e)** sea-level pressure (in hPa) averaged in the region of the Kara and Barents Seas in DJF 2011/12 (left panel, black lines) and DJF 2016/17 (right panel). A transient climatology is shown by grey lines. Grey shading shows the standard deviation of daily-mean anomalies in all winter seasons relative to the respective transient climatology. Blue, orange, and green heatmaps at the bottom of the figure show the daily-mean coverage of the region by cyclones, blocks, and CAOs, respectively (the darker the color the higher the coverage). Relative frequency anomalies of the three weather systems are given in percentages. The horizontal axis indicates days since the start of the season with day 1 corresponding to 01 December.

Analysis of multi-seasonal meteorological storylines leading to reduced forest greenness in Europe in 2000–2020

Mauro Hermann[1], Matthias Röthlisberger[1], Arthur Gessler[2,3], Andreas Rigling[2,3], Cornelius Senf[4], Thomas Wohlgemuth[2], Heini Wernli[1]

[1]Institute for Atmospheric and Climate Science (IAC), ETH Zürich, Zurich, Switzerland
[2]Swiss Federal Institute for Forest, Snow and Landscape Research (WSL), Zurich, Switzerland
[3]Institute of Terrestrial Ecosystems (ITES), ETH Zürich, Zurich, Switzerland
[4]Ecosystem Dynamics and Forest Management Group, Technical University of Munich, Freising, Germany

Recent forest decline in Europe is strongly influenced by meteorological conditions imposed by seasonal variations of temperature, $T2m$, and precipitation, P, and can be monitored with forest greenness. This work quantitatively investigates anomalous characteristics of the three-year meteorological storyline preceding events of reduced forest greenness in Europe's temperate and Mediterranean biome in the phase space of seasonal-mean anomalies of $(T2m, P)$. A specific focus is on the amplitude, persistence, and co-variability of these anomalies. A pragmatic approach based on remote sensing observations of normalized difference vegetation index $NDVI$ serves to identify low forest $NDVI$ events at the 50 km scale in Europe in June to August 2000—2020. An independent forest disturbance data set is used to qualitatively validate the identified more than 1'500 low $NDVI$ events.

The identified events occur in summers with particularly dry and hot conditions but their meteorological storylines feature significant anomalies during multiple seasons preceding the events, with clear differences between the two biomes. In the Mediterranean biome, the anomalously dry conditions persist over more than 1.5 y prior to the events, whereas $T2m$ is anomalously warm only during the last 0.4 y (Fig. 1b,d). In contrast, in the temperate biome, $T2m$ is anomalously large during most of the 2.5 y prior to the events and, most interestingly, the autumn/winter preceding the events is characterized by anomalously wet and warm conditions (Fig. 1a,c). These anomalies potentially induce a negative legacy on the following summer drought. The seasonal-mean anomalies of P are strongly determined by synoptic-scale weather systems, such that long dry periods are characterized by a deficit of cyclones and an excess of anticyclones (Fig. 1e-h). A final analysis investigates the peculiarities of low $NDVI$ events that occur in two consecutive summers and the potential role of drought legacy effects. In the temperate biome, the second event summer of an event sequence has less hot and less dry anomalies than the first one and than during a single event.

In summary, detailed investigations of the multi-annual meteorological storyline of low forest $NDVI$ events provided clear evidence that anomalies of surface weather and synoptic-scale weather systems over time periods of up to 2.5 y can negatively impact European forest activity, with important differences between the temperate and Mediterranean biomes.

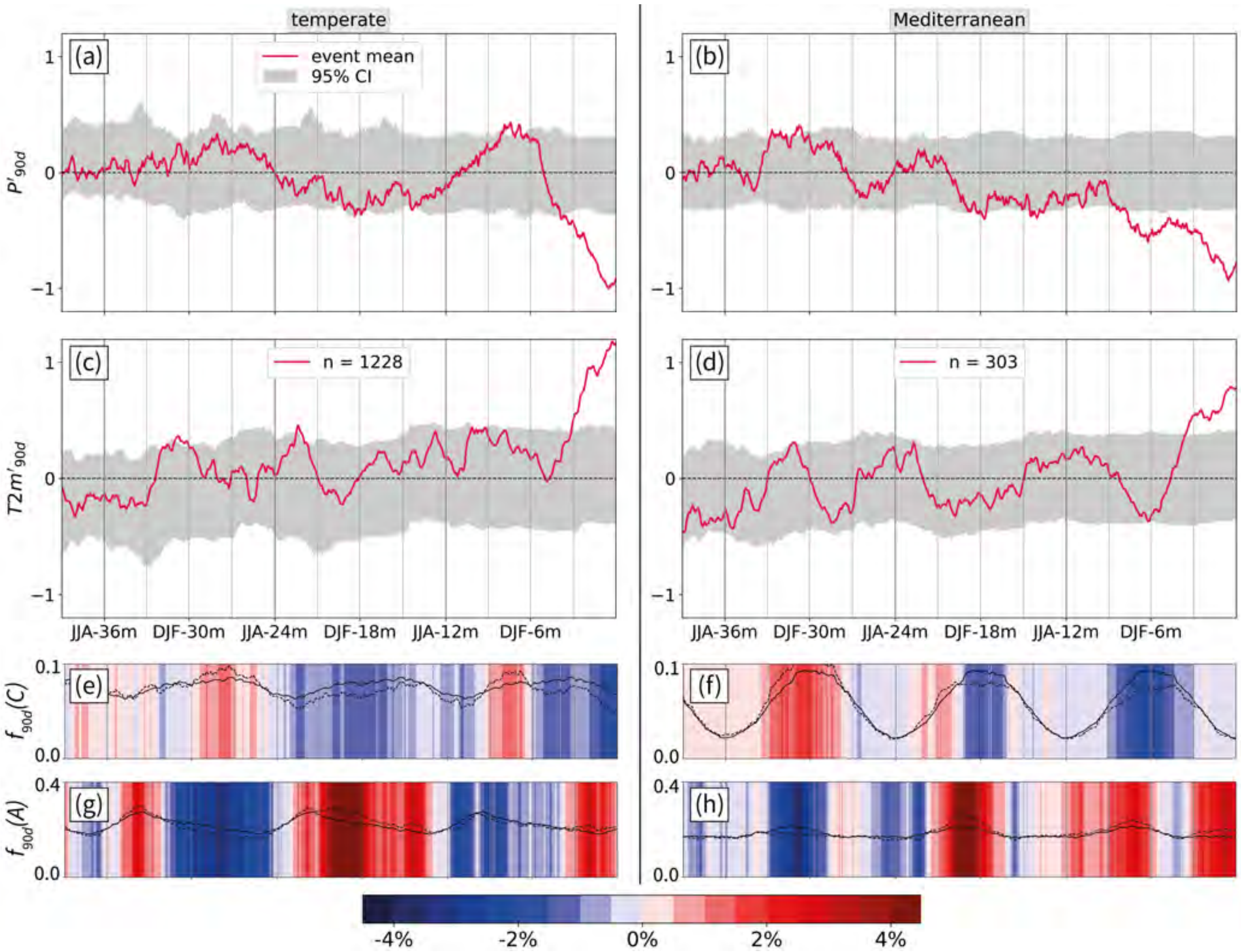


Figure 1: A central figure of the study showing the 3-year meteorological storyline prior to low $NDVI$ events in (a,c,e,g) temperate forests and (b,d,f,h) Mediterranean forests. Red lines show the event-mean evolution of normalized 90-day running mean (a,b) precipitation and (c,d) temperature anomalies. The grey shading indicates 95% confidence interval of the reference climatology. Collocated 90-day mean (e,f) cyclone and (g,h) anticyclone frequency during events (dashed) and climatology (solid) are shown as black lines, anomalies are indicated as heat map.

References

[1] A. Bastos et al., Direct and seasonal legacy effects of the 2018 heat wave and drought on European ecosystem productivity, *Science Advances* **6**, eaba2724 (2020), doi:10.1126/sciadv.aba2724.

[2] A. Buras et al., The European Forest Condition Monitor: Using Remotely Sensed Forest Greenness to Identify Hot Spots of Forest Decline, *Frontiers in Plant Science* **12**, (2021), doi:10.3389/fpls.2021.689220.

[3] G. Messori et al., Atmospheric jet stream variability reflects vegetation activity in Europe, *Agricultural and Forest Meteorology* **322**, 109008 (2022), doi:10.1016/j.agrformet.2022.109008.

[4] B. Schuldt et al., A first assessment of the impact of the extreme 2018 summer drought on Central European forests, *Basic and Applied Ecology* **45**, 86 (2020), doi:10.1016/j.baae.2020.04.003.

A Global Assessment of Heatwaves since 1850 in different Datasets

Laura Hövel[1], Ralf Hand[1], Stefan Brönnimann[1]

[1]Institute of Geography and Oeschger Center for Climate Change Research, University of Bern, Switzerland

Over the past century there was a significant increase in heatwaves in several regions around the globe. This increase is projected to continue with ongoing global warming and forms a serious risk for various ecosystems as well as human health. Changes in the occurrence and the characteristics of heatwaves since the middle of the 20th century are extensively studied in observational datasets and model simulations. However, there is a research gap concerning preindustrial (1850-1900) heatwaves and heatwaves in the early 20th century and their connections to forcings and large-scale variability modes.

In this study we analyse the occurrence of summer heatwaves and the spatial and temporal distribution of different heatwave characteristics using a 36-member ensemble of atmospheric model simulations with prescribed SSTs and observed volcanic forcings over the period 1409 -2009. In addition we use different observational datasets (20CRv3, ERA5, EUSTACE, station data) to compare to the model simulations. For the heatwave calculation we use a new approach, a 31-year running baseline climatology, which allows us to compare heatwave characteristics like heatwave days per season or cumulative intensity across different centuries. We further compare preindustrial heatwaves to recent heatwave events and analyse how global or local heatwave hotspots change over time.

Our analysis shows that the different observational datasets show a comparable distribution of heatwave characteristics. Furthermore, the ensemble spread of the atmospheric model simulations is able to capture the variability of the observational data (20CRv3) and can therefore be used to analyse preindustrial and early 20th century heatwaves. Additionally, the agreement with the observational datasets allows to use the simulations to analyse earlier preindustrial time periods that are not covered by observations. With our on-going analysis of preindustrial heatwaves, we consequently contribute to a better understanding of past climate extremes.

Benchmarking the Performance of Dynamically Downscaled Precipitation

Rachael N. Isphording[1,2], Lisa V. Alexander[1,2], Margot Bador[3]

[1]Climate Change Research Centre, University of New South Wales, Sydney, Australia
[2]ARC Centre of Excellence for Climate Extremes, University of New South Wales, Sydney, Australia
[3]Centre National de la Recherche Scientifiques, Toulouse, France

Although climate change occurs globally, impacts are experienced on a local to regional scale. Because of this, climate change risk assessments and adaptation planning occur at regional and local scales as well. Global Climate Models (GCMs) are pivotal for informing mitigation strategies by showing the magnitude of present and future climate change [1], but the spatial resolution of GCMs is too coarse to resolve the features relevant to climate risk assessments and adaptation planning [2]. For this reason, downscaled Regional Climate Models (RCMs) are needed.

There have been recent calls from national governments to provide downscaled climate projections (from RCMs) to better understand climate risk and inform climate adaptation strategies across industries and regions [3]. However, within the scientific community, there is ongoing debate surrounding the added value that downscaled RCMs provide when compared to GCMs and how best to quantify added value [4, 5, 6]. Precipitation is frequently evaluated in these added value studies, but presently, there is no standardized framework or metrics identified to evaluate RCM precipitation output. Because of this, it can be difficult to make a one-to-one comparison or properly assess what useful information RCMs provide.

Recently, an international group of experts [7] outlined a benchmarking framework to assess simulated precipitation in Earth System Models (ESMs) across generations (e.g., from the Coupled Model Intercomparison Project). They identified a set of performance metrics that can serve as a baseline to gauge model performance in simulating the: spatial distribution, seasonal cycle, temporal variability, observed distributions of intensity and frequency, extremes, and dry periods, as shown in Figure 1. Largely adapted from this framework, a standardized benchmarking framework is introduced to assess simulated precipitation in RCMs. While this framework can be applied to any region or sub-region, we demonstrate its effectiveness over Australia using high-resolution simulations from the CORDEX-Australasia ensemble. We find that individual model performance is quite sensitive to the choice of the performance metric and the choice of benchmark, highlighting again the need for a standardized model evaluation framework. Focusing on one metric, we find substantial inter-model spread that we explore by assessing the role of the driving GCM or the RCM modelling setup.

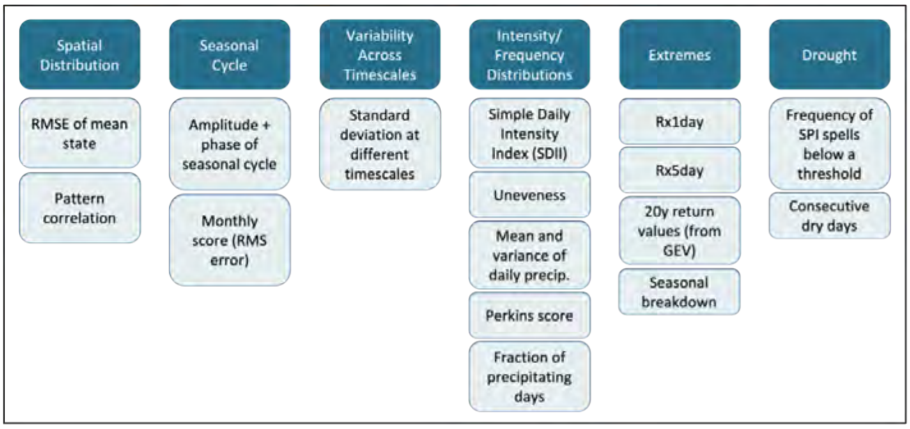


Figure 1: A summary of baseline performance metrics identified to evaluate simulated precipitation in Earth System Models (adapted from U.S. DOE, 2020).

References

[1] IPCC, Summary for Policymakers In: Climate Change 2021: The Physical Science Basis, *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Masson-Delmotte, V., P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T. K. Maycock, T. Waterfield, O. Yelekçi, R. Yu and B. Zhou (eds.)]. Cambridge University Press. pp. 3−32 (2021), 10.1017/9781009157896.001.

[2] Kotamarthi, R., Hayhoe, K., Mearns, L., Wuebbles, D., Jacobs, J., and Jurado, J., Downscaling Techniques for High-Resolution Climate Projections *Cambridge University Press* (2021), 10.1017/9781108601269

[3] Commonwealth of Australia, Royal Commission into National Natural Disaster Arrangements, (2020), https://naturaldisaster.royalcommission.gov.au/publications/royal-commission-national-natural-disaster-arrangements-report

[4] Parker, R. J., Reich, B. J., and Sain, S. R., A multiresolution approach to estimating the value added by regional climate models, *Journal of Climate* **28**, 22 (2015), 10.1175/JCLI-D-14-00557.1

[5] di Virgilio, G., Evans, J. P., di Luca, A., Grose, M. R., Round, V., and Thatcher, M., Realised added value in dynamical downscaling of Australian climate change, *Climate Dynamics* **54**, 1435 (2020), 10.1007/s00382-020-05250-1

[6] Lloyd, E.A., Bukovsky, M. and Mearns, L.O., An analysis of the disagreement about added value by regional climate models, *Synthese* **198**, 11645–11672 (2021), 10.1007/s11229-020-02821-x

[7] U.S. DOE, Benchmarking Simulated Precipitation in Earth System Models Workshop Report, DOE/SC-0203, U.S. Department of Energy Office of Science, Biological and Environmental Research (BER) Program. Germantown, Maryland, USA.

Extreme Humid Heat Variability during the South Asian Summer Monsoon

Catherine Ivanovich[1], Deepti Singh[2], Adam Sobel[1,3,4], and Radley Horton[4]

[1]Earth and Environmental Sciences, Columbia University, New York, NY, United States
[2]School of the Environment, Washington State University Vancouver, Vancouver, WA, United States
[3]Applied Physics and Applied Mathematics, Columbia University, New York, NY, United States
[4]Lamont-Doherty Earth Observatory, Columbia University, Palisades, NY, United States

Extreme humid heat is a multivariate compound extreme with direct societal implications, and understanding when it tends to occur is critical to preparing for its negative effects on human health, energy demand, and economic productivity. Colloquially, the South Asian summer monsoon precipitation is thought to bring cool relief after the taxing extreme heat season in the spring [1], and previous literature studying the occurrence of extreme humid heat in this region has thus focused primarily on the pre-monsoon season [2, 3]. However, recent studies have suggested that extreme humid heat may actually persist past the onset of the summer monsoon [4], and potentially occurring during monsoon breaks [5]. Building on previous research identifying humid heat extremes during the absence of deep convection in otherwise hot and humid environments [6, 7, 8], we characterize the humid heat conditions that occur in South Asia surrounding monsoon onset in comparison to those taking place during monsoon breaks.

We find that in contrast to dry bulb temperatures, wet bulb temperatures are sustained throughout the monsoon season in South Asia. On average, wet bulb temperatures are higher in the week following monsoon onset than the week preceding, driven by increases in specific humidity associated with the ongoing precipitation. Wet bulb temperatures are also anomalously high during monsoon breaks of three or more days and peak on the final day of a break. This increase in humid heat is accompanied by simultaneous increases in dry bulb temperature due to decreased cloud cover and increased surface sensible heating, as well as positive specific humidity anomalies that build throughout the break duration. Overall, moisture modulation is found to be essential to the occurrence of extreme humid heat under both conditions, while the contribution from dry bulb temperature can differ dramatically. These results highlight the active precipitation and breaks of the monsoon as previously overlooked times for potential exposure to extreme humid heat in South Asia.

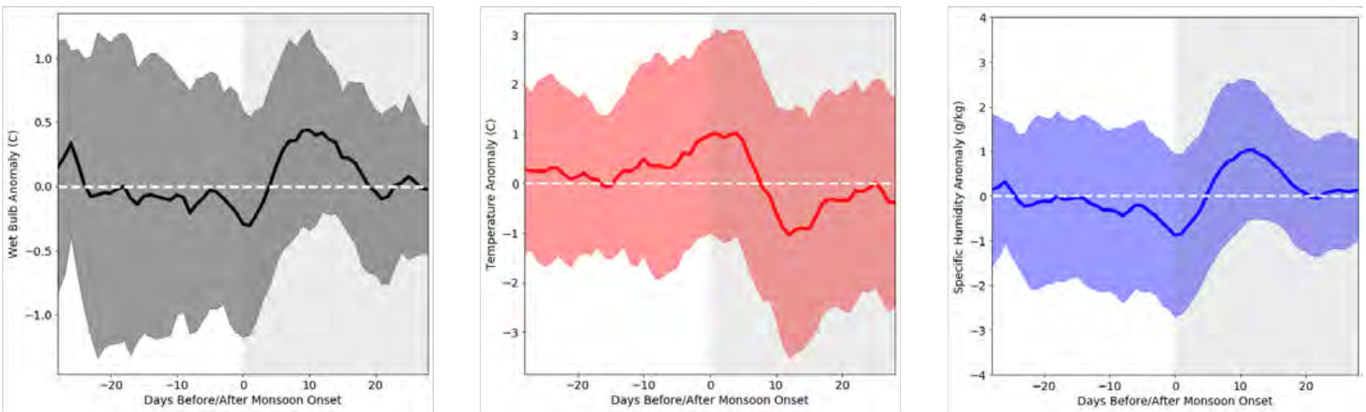


Figure 1: Composites of wet bulb temperature, dry bulb temperature, and specific humidity anomalies four weeks before and after monsoon onset. Colored shading shows +/- 1 standard deviation. Light grey shading shows time after monsoon onset.

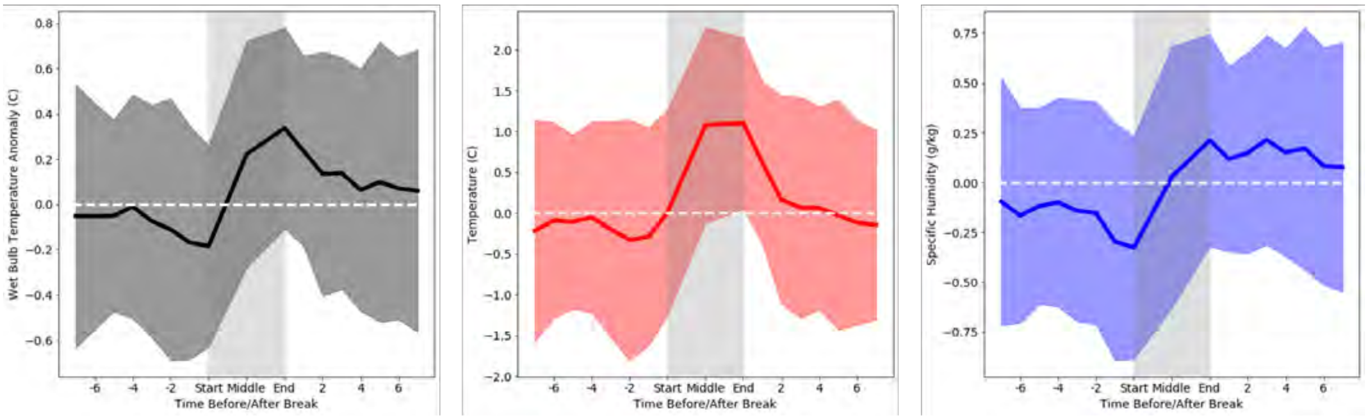


Figure 2: Composites of wet bulb temperature, dry bulb temperature, and specific humidity anomalies one week before and after a monsoon break. Colored shading shows +/- 1 standard deviation. Light grey shading shows normalized break duration.

References

[1] Kothawale, D. R., Revadekar, J. V., Kumar, K. R. Recent trends in pre-monsoon daily temperature extremes over India, *Journal of Earth System Science* **119**, 51 (2010), 10.1007/s12040-010-0008-7

[2] Monteiro, J. M., Caballero, R. Characterization of extreme wet-bulb temperature events in southern Pakistan, *Geophysical Research Letters* **46**, 10659 (2019), 10.1029/2019gl084711

[3] Im, E., J. S. Pal, Eltahir, E. A. B. Deadly heat waves projected in the densely populated agricultural regions of South Asia, *Science Advances* **3(8)**, 1 (2017), 10.1126/sciadv

[4] Raymond, C., T. Matthews, Horton, R. M. The emergence of heat and humidity too severe for human tolerance, *Science Advances* **6(19)**, 1 (2020), 10.1126/sciadv.aaw1838

[5] Ivanovich, C., Anderson, W., Horton, R., Raymond, C., Sobel, A. The influence of intraseasonal oscillations on humid heat in the Persian Gulf and South Asia, *Journal of Climate* **43**, 4309 (2022), 10.1175/JCLI-D-21-0488.1

[6] Raymond, C., T. Matthews, R. M. Horton, E. M. Fischer, C. Ivanovich, L. Suarez-Gutierrez, Zhang, Y. On the controlling factors for globally extreme humid heat, *Geophysical Research Letters* **48**, 1 (2021), 10.1029/2021gl096082

[7] Buzan, J. R. Huber, M. Moist heat stress on a hotter Earth, *Annual Review of Earth and Planetary Sciences* **46**, 623 (2020), 10.1146/annurev-earth-053018-060100

[8] Matthews, T. Humid heat and climate change, *Progress in Physical Geography: Earth and Environment* **42(3)**, 391 (2018), 10.1177/0309133318776490

Quantifying Windstorm damage relations in Norway using damage functions

Ashbin Jaison [1,2], Clio Michel[1,2], Asgeir Sorteberg[1,2], Øyvind Breivik [1,3]

[1]Geophysical Institute, University of Bergen, Norway
[2]Bjerknes centre for climate research
[3]Norwegian Meteorological Institute

Extreme winds account for more than half of Norway's insurance claims related to natural hazards [1]. Quantifying windstorm-damage relations is crucial to prepare for and mitigate the effects of future wind events. However, there has never been an attempt to quantify windstorm-damage relations for Norway. The work in hand employs four different damage functions at the municipality level of Norway, including a newly proposed modified Prahl damage function [2]. We evaluate the damage functions in terms of forecast accuracy. The damage function by Prahl exhibits greater model applicability and has a better forecast accuracy in the majority of the municipalities. The spatial distribution of losses suggests severe damages along the west coast of Norway. Further inland in Norway, there are seldom any losses due to Norway's unique topography and demography. The high values of the exponent parameter of the Prahl damage function in municipalities with relatively fewer losses indicate a lack of storm preparedness. On the other hand, the municipalities which experience severe damage, particularly on the western coast and the Lofoten archipelago, seem less sensitive to windspeed changes. We also observe a great agreement between the observed and fitted losses at both the municipality and national levels justifies the applicability of damage functions to predict damages caused by winds.

References

[1] Finance Norway, Natural Disaster Statistics (NASK), (2019)

[2] B.F. Prahl et al., Applying stochastic small-scale damage functions to German winter storms, *Geophysical Research Letters* **39**, (2012)

Toward Globally Consistent Impact Forecast for Tropical Cyclones-related Population Displacement

Pui Man Kam[1,2], Christopher Fairless[1], David N. Bresch[1,3]

[1]Institute for Environmental Decisions, ETH Zurich, Zurich, Switzerland
[2]Internal Displacement Monitoring Centre, Geneva, Switzerland
[3]Swiss Federal Office of Meteorology and Climatology, MeteoSwiss, Zurich, Switzerland

Every year, there are millions of people being internally displaced by tropical cyclones (TCs)- related hazards [1]. Displacement can be a short-term precautionary evacuation before the onset of natural disasters. However, if people's home and community infrastructures are severely damaged, displacement can be long-term. Often displaced people are subject to heightened risks to their physical and mental well-being. An implementation of an impact-based forecast system for population displacement could aid decision making process for pre-emptive evacuation planning and allocation of humanitarian resources, and such reducing the adverse impacts from TCs.

This project presents the implementation of the impact forecast system for population displacement using a python-based, open-source, globally consistent platform called CLIMADA (CLIMate ADAptation)[3]. The platform integrates probabilistic hazard, exposure, and vulnerability information to compute the potential impacts from TC events. Previous works have shown that CLIMADA is effective in scenario-based narratives for displacement risk and climate change [3], and an implementation of operational impact forecast for building damages from winter storms [4].

The first prototype of the forecast system extracts information from ensemble TC forecast tracks from the European Centre for Medium-Range Weather Forecast (ECMWF), a global population layer at ~1km resolution, and vulnerability functions that relate the exposed people to the intensity of TC wind speed. Uncertainty and sensitivity analysis is also performed using the (quasi-) Monte-Carlo sampling method, which has already been implemented in CLIMADA [5]. This analysis samples not only the meteorological variability that comes from the ensemble forecast, but also the uncertainties from the population layer and the vulnerability of the population.

An example case study of displacement forecast two days prior to the landfall of cyclone Yasa in Fiji during mid-December 2020 is presented, revealing the potential of the displacement forecast system and uncertainties from the forecast results. Fig. 1a presents the probability distribution of the forecasted number of potentially displaced people in Fiji considering the uncertainties from the ensemble members, total population in Fiji, and the vulnerability. The most probable number of displacement concentrated at around 20 thousands people and a long tail of low probability, high impact scenarios. Fig. 1b, on the other hand, shows how much sensitivity of the parameters that contribute to the overall uncertainties in fig. 1a. Although the uncertainties mainly come from the spread of ensemble forecast, the knowledge of the vulnerability of the communities in Fiji should be well-considered in the decision making process as well.

The open-source data and codes of this implementation of displacement forecast are also transferable to other users, hazards, and impact types. The showcase of this project hopefully could encourage the wider use of impact-based of forecasting, and also trigger the conversations on how to include forecasting uncertainties in issuing warnings and decision making.

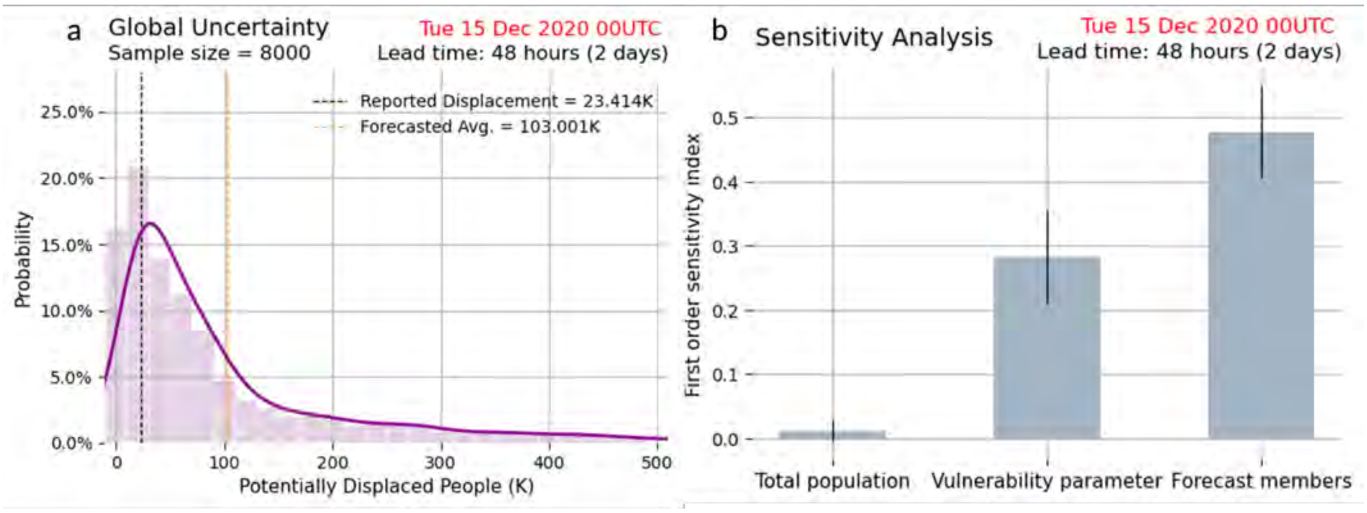


Figure 1: The uncertainty and sensitivity analysis of the forecasted results in terms of the number of potentially displaced people in Fiji two days in advance of the landfall of cyclone Yasa on 17 December 2020. (a) Probability distribution of the global uncertainty (b) The first-order sensitivity of the different model parameters.

References

[1] IDMC (2022), Global Internal Displacement Database (Geneva, Switzerland: Internal Displacement Monitoring Centre) available at `http://www.internaldisplacement.org/database`

[2] Aznar-Siguan, G. and Bresch, D. N. (2019), CLIMADA v1: a global weather and climate risk assessment platform, *Geosci. Model Dev.*, **12**, 2085-97, 10.5194/gmd-12-3085-2019

[3] Kam, P. M. et al. (2021), Global warming and population change both heighten future risk of human displacement due to river floods, *Environ. Res. Lett.*, **16**, 044026, 10.1088/1748-9326/abd26c

[4] Röösli, T. et al. (2021), Towards operational impact forecasting of building damage from winter windstorms in Switzerland, *Meteorol. Appl.*, **26**(6), e2035, 10.1002/met.2035

[5] Kropf, C. M. et al. (2022), Uncertainty and sensitivity analysis for probabilistic weather and climate risk modelling: an implementation in CLIMADA v.3.1.0, *Geosci. Model Dev.*, Preprint, 10.5194/gmd-2021-437

[6] Sobol', I. M. (2001), Global sensitivity indices for nonlinear mathematical models and their Monte Carlo estimates, *Math. Comput. Simul.*, **55**(1-3), 10.1016/s0378-4754(00)00270-6

Understanding the evolution of droughts and their associated global and regional drivers

Woon Mi Kim[1], Isla Simpson[1], Flavio Lehner[2]

[1]National Center for Atmospheric Research, Climate and Global Dynamics Laboratory, Boulder CO, USA
[2]Department of Earth and Atmospheric Sciences, Cornell University, Ithaca NY, USA

Droughts are extreme climate events that are characterized by a prolonged period of negative moisture balance in the atmosphere and soil which can last from several weeks to years [1]. The events are of critical importance as they do not simply affect society's well-being, but threaten water availability, energy, and food security on regional and global scales [2]. In the last few decades, modern observational records have clearly indicated increases in severity and frequency of droughts mainly on the mid latitude lands [3]. These increases are primarily caused by the ongoing global warming and are expected to intensify in the future warming scenarios [3, 4, 5].

Despite its importance, our understanding of the entire life cycle of droughts is still not complete. Many studies on droughts and associated drivers are focused on the mature phase of the events when severe dryness is already evident in a region. This fact indicates that some important questions are still missing in drought studies:

i How persistent dry periods (droughts) begin and how they are connected to daily precipitation and temperature events,

ii Which global and regional drivers determine the longevity of droughts enlarging their mature phase,

iii Which mechanisms terminate long-lasting droughts, and lastly

iv How global and regional drivers of droughts evolve over time from the initiation to the termination phases of droughts.

Our project aims to answer the proposed questions by investigating the complete life cycles of droughts. To this end, we use observational-based data and the CESM2 large ensemble [6, 7]. In the first part, we characterize spatial and temporal extension of daily precipitation and temperature events and droughts across the globe during the modern observational era (1979-2021). Through this analysis, we explore possible links between daily hydrological events and droughts, and detect drought hot-spot regions. Then, we identify global and regional drivers of droughts in the hot-spots and how these drivers evolve with the progression of droughts. We also attempt to statistically quantify the contribution of each driver at different phases of droughts. In the second part, we perform observation and model comparison to evaluate the model's ability to represent drought-related processes and also to disentangle global and regional drivers at each phase of droughts. In the last part, we focus on how the drought drivers will change under different future climate scenarios.

A comprehensive investigation of the entire life cycles of droughts is clearly necessary as the initiation and termination stages of droughts are still under-explored topics. Our research will provide more understanding of the nature of droughts and their changes in the future, which can potentially lead to a development of an early warning system for these extreme events, and prepare and plan with improved mitigation policies and adaptation strategies in the future.

References

[1] A. Dai, Increasing drought under global warming in observations and models., *Nature climate change* **3(1)**, 52-58 (2013), doi:10.1038/nclimate1633.

[2] D. A. Wilhite, M. H. Glantz, nderstanding: the drought phenomenon: the role of definitions., *Water international* **10(3)**, 111-120 (1985), doi:10.1080/02508068508686328.

[3] V. Masson-Delmotte et al., IPCC, 2021: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change., *Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA*, In press, doi:10.1017/9781009157896.

[4] F. Lehner, S. Coats, T. F. Stocker, A. G. Pendergrass, B. M. Sanderson, C. C. Raible, J. E. Smerdon, rojected drought risk in 1.5 C and 2 C warmer climates., *Geophysical Research Letters* **44(14)**, 7419-7428 (2017), doi:10.1002/2017GL074117.

[5] G. Naumann, L. Alfieri, K. Wyser, L. Mentaschi, R. H. Betts, H. Carrao, J. Spinoni, J. Vogt, L. Feyen, Global changes in drought conditions under different levels of warming, *Geophysical Research Letters* **45(7)**, 3285-3296 (2018), doi:10.1002/2017GL076521.

[6] G. Danabasoglu et al., The community earth system model version 2 (CESM2), *Journal of Advances in Modeling Earth Systems* **12(2)**, e2019MS001916 (2020), doi:10.1029/2019MS001916.

[7] K. B. Rodgers et al., Ubiquity of human-induced changes in climate variability, *Earth System Dynamics* **12(4)**, 1393-1411 (2021), doi:10.5194/esd-12-1393-2021.

Predicting risks of temperature extremes using large-scale circulation patterns with r–Pareto processes

Jonathan Koh[1], Daniel Steinfeld[2], Olivia Martius[2], Johanna Ziegel[1]

[1]Institute of Mathematical Statistics and Actuarial Science, Oeschger Centre for Climate Change Research, University of Bern, Switzerland
[2]Institute of Geography, Oeschger Centre for Climate Change Research, University of Bern, Switzerland

Temperature extremes with large impacts are spatially compounding in nature [1]. These hazards occur when multiple locations are affected by the same event within a given time period. Modeling these compound weather events is particularly challenging, and the growing field of spatial extremes [2] seeks to address this difficulty. If prediction of these extremes is the primary focus, then machine learning approaches offer attractive tools that can be combined with spatial extremes to help select the most relevant covariates in a model.

Many surface temperature extremes are associated to a particular weather pattern known as atmospheric blocking [3]. Blocks disrupt the large-scale westerly flow and eastward progression of synoptic weather systems, leading to persistent and quasi-stationary weather conditions at the surface. In this study, we introduce a data-driven methodology that predicts the occurrence, intensity and spatial dependence of surface temperature extremes using 500hPa geopotential (Z500) anomalies and blocking indices over the North Atlantic and European region as covariates. We use data from the ERA5 reanalysis and combine methods from the spatial extremes and machine learning literature. In particular, we fit Generalized r-Pareto processes [4] with an appropriate risk functional to daily positive 2m temperature anomalies in central Europe from 1979–2021 using loss functions motivated by extreme-value theory in a popular boosting algorithm.

Our final model has three sub-components: The first predicts the probability that the mean temperature anomaly in our chosen risk region exceeds a high threshold; the second predicts the intensity of these exceedances at each grid cell in the study region; the last predicts the spatial extent of these extremes in the study region. We find which circulation patterns in the Euro-Atlantic sector are most important in each sub-component. Figure 1 shows the average of Z500 patterns during the 25% most intense and 25% least intense temperature extremes, and also highlights which are the most important covariates in each sub-components of the model.

References

[1] Zscheischler, J. et al. (2020) A typology of compound weather and climate events, *Nature Reviews Earth & Environment* **1**:7, 333–347, doi: https://doi.org/10.1038/s43017-020-0060-z.

[2] Davison, A. C. et al. (2012), Statistical modeling of spatial extremes, *Statistical Science* **2** 161–186, doi: http://dx.doi.org/10.1214/11-STS376.

[3] Pfahl, S. and Wernli, H. (2012) Quantifying the relevance of atmospheric blocking for co-located temperature extremes in the Northern Hemisphere on (sub-)daily time scales, *Geophysical Research Letters* **39**, L12807, doi: https://doi.org/10.1029/2012GL052261.

[4] de Fondeville, R. and Davison, A. C. (2022), Functional peaks-over-threshold analysis, *Journal of the Royal Statistical Society: Series B (Statistical Methodology)* **In press**, doi: https://doi.org/10.1111/rssb.12498.

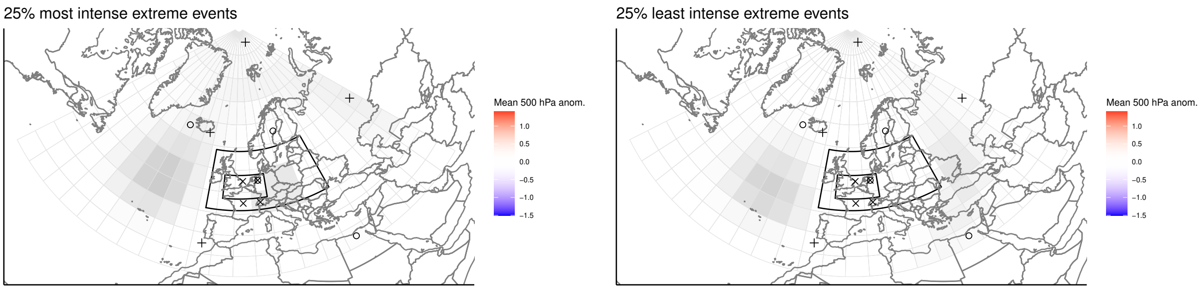


Figure 1: Average of Z500 patterns (standardized anomalies) during the 25% most intense (left) and 25% least intense (right) temperature extremes in central Europe. Indicated in both plots are the four most important covariates (Z500 grid cells) in the occurrence (X), intensity (cross), and spatial dependence (circle) sub-components of the model. Big rectangle indicates the study region, small rectangle the risk region.

On the vertical structure and propagation of marine heatwaves in the Eastern Pacific

Eike E. Köhn[1], Nicolas Gruber[1,2], Matthias Münnich[1], Meike Vogt[1]

[1]Environmental Physics, Institute for Biogeochemistry and Pollutant Dynamics, ETH Zurich, 8092 Zurich, Switzerland
[2]Center for Climate Systems Modeling (C2SM), ETH Zurich, 8092 Zurich, Switzerland

Anthropogenically driven ocean warming increases the frequency and intensity of marine heatwaves (MHWs) with potentially far-reaching consequences for marine life, such as the disruption and reorganisation of food-webs [2, 2, 3, 4, 5]. As MHWs are typically detected using satellite observations at the ocean surface, only little is known about their vertical extent [6]. This is a significant knowledge gap, since the subsurface MHW structure can reveal information about the underlying MHW drivers and can determine the MHW's effect on marine organisms.

In this study, we investigate the vertical structure of Eastern Pacific (EP) MHWs in a hindcast simulation (1979-2019) performed with a regional ocean model (ROMS) (Fig. 1). We identify and track vertically propagating MHWs by connecting adjacent grid cells in the vertical and temporal dimension, in which temperature exceeds a seasonally varying 90th percentile threshold. We restrict our analysis to the upper 500m of the ocean and to MHWs that affect the ocean surface at least once, thus to MHWs that are potentially detectable with satellites.

We find that allowing for the vertical propagation of surface MHWs leads to longer event durations compared to the surface-only perspective (55 vs. 27 days on average). This implies that MHWs affect upper ocean ecosystems for substantially longer time periods than diagnosed from the surface-only perspective. We further find that the mean depth reached by MHWs generally increases with the MHW duration. About 80% of MHWs in the EP are restricted to the surface mixed layer. Extreme surface temperatures are most likely to be associated with MHWs reaching below the mixed layer in the tropical Eastern Pacific. Clustering the MHWs with respect to their vertical propagation behaviour reveals that 20% (12%) of MHWs move downward (upward) throughout their lifetime and another 12% show a complex multi-surfacing structure. The latter occur mainly in the tropical EP during El Niño periods.

Our results serve to better understand the drivers and evolution of MHWs and can support the investigation of MHW impacts ranging from individual species to ecosystem services such as fisheries.

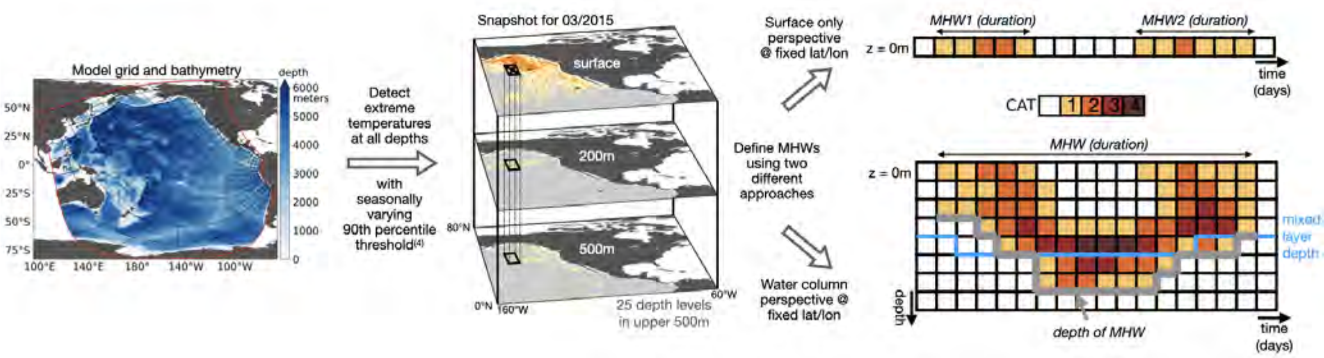


Figure 1: The methodology behind the study of MHWs. (left) Bathymetry and telescopic model grid of the ROMS hindcast, with pole located over South America, yielding highest resolution of 4km off Peruvian coast, (middle) Snapshot of extreme categories at 3 example depth levels (0m, 200m and 500m depth) in March 2015 as simulated in the ROMS hindcast, (right) Sketch of the MHW definition approach at the model grid cell level (example column from middle panel): definition of MHWs at the surface in the time dimension only (top) and allowing for vertical propagation in the time-depth dimension (bottom). The orange colors indicate the marine heatwave categories (1: moderate, 2: strong, 3: severe, 4: extreme) [7].

References

[1] Cavole et al., Biological Impacts of the 2013–2015 Warm-Water Anomaly in the Northeast Pacific: Winners, Losers, and the Future, *Oceanography* **29**, 2 (2016), doi: 10.5670/oceanog.2016.32

[2] Frölicher et al., Marine heatwaves under global warming, *Nature* **560**, 360-364 (2018), doi:10.1038/s41586-018-0383-9

[3] Oliver et al., Longer and more frequent marine heatwaves over the past century, *Nature Communications* **9**, 1324 (2018), doi:10.1038/s41467-018-03732-9

[4] Smale et al., Marine heatwaves threaten global biodiversity and the provision of ecosystem services, *Nature Climate Change* **9**, 306-312 (2019), doi:10.1038/s41558-019-0412-1

[5] Oliver et al., Marine Heatwaves, *Annual Review of Marine Science* **13**, 313-342 (2021), doi:10.1146/annurev-marine-032720-095144

[6] Scannell et al., Subsurface Evolution and Persistence of Marine Heatwaves in the Northeast Pacific, *Geophysical Research Letters* **47**, 23 (2020), doi:10.1029/2020GL090548

[7] Hobday et al., Categorizing and Naming Marine Heatwaves, *Oceanography* **31**, 2 (2018), doi:10.5670/oceanog.2018.205

Hailstone size distributions and kinetic energy flux: observations from automatic hail sensors in Switzerland during summer 2021

Jérôme Kopp[1], Alessandro Hering[2], Urs Germann[2], Olivia Martius[1]

[1]Oeschger Centre for Climate Change Research and Institute of Geography, University of Bern, Bern, Switzerland
[2]Federal Office of Meteorology and Climatology MeteoSwiss, Locarno-Monti, Switzerland

Figure 1: Automatic hail sensor.

Between 18 June and 31 July 2021, a series of exceptionally widespread and intense hailstorms occurred over Switzerland, causing historical damages as recorded by several insurance companies. While the events of 2021 caused major impacts, they also present a unique research opportunity because several measuring platforms were capturing the hailstorms:

1. a newly set-up network of automatic hail sensors (project "The Swiss Hail Network", 1) that report the size and kinetic energy of individual hailstones with very high temporal and size resolution.
2. the crowdsourcing function of the MeteoSwiss app through which users can report the largest hailstone size, the presence of a hail layer and information on potential damage along with their position, timestamp, and a picture.
3. two operational hail products of the Swiss weather radar network: the probability of hail (POH) and the maximum expected severe hailstone size (MESHS).

A first look at the data collected from those observing systems during the summer of 2021 showed that they give a coherent and comprehensive picture of both the hail footprint and hailstones diameters. However the data is numerous and remains to be fully exploited in more detailed studies.

The automatic hail sensors make it possible to capture the local duration of a hailstorm, to precisely record the timing of hailstone impacts and to infer the hailstones diameter from their measured kinetic energy. The kinetic energy flux, daily kinetic energy footprints and hailstone sizes distribution are important for hail damage assessment and modelling [1, 2]. The kinetic energy flux is directly related to the size distributions and the terminal velocity of the hailstones. An interesting research avenue is to investigate hailstone size distributions, kinetic energy flux and temporal evolution using the sensor data. More precisely, we would like to investigate the following research questions:

Are the theoretical hailstone size distributions comparable with the observed hailstones distributions at the sensor's locations during selected hail events?

Can we get better estimates of (or constraints on) the hailstone size distributions parameters using the sensor data?

What is the correlation between radar-derived MESHS and the kinetic energy flux at sensors location?

Taking advantage of the new data from 2021, we present the first results of hailstone size distributions and kinetic energy flux derived from the automatic sensor observations, as well as a systematic comparison with MESHS at the sensor's location. We also list the next steps of our research.

References

[1] A. Heymsfield et al., A comprehensive observational study of graupel and hail terminal velocity, mass flux, and kinetic energy, *Journal of the Atmospheric Sciences* **75**, 3861 (2018), 10.1175/JAS-D-18-0035.1.

[2] J. Grieser, M. Hill, How to express hail intensity—modelling the hailstone size distribution, *Journal of Applied Meteorology and Climatology* **58**, 2329 (2019), 10.1175/JAMC-D-18-0334.1.

Hotspots and drivers of compound marine heatwave and low net primary production extremes

Natacha Le Grix [1,2], Jakob Zscheischler[2,2,3], Keith B. Rodgers[4,5], Ryohei Yamaguchi[4,5], Thomas L. Frölicher[1,2]

[1]Climate and Environmental Physics, Physics Institute, University of Bern, Bern, Switzerland
[2]Oeschger Centre for Climate Change Research, University of Bern, Bern, Switzerland
[3]Department of Computational Hydrosystems, Helmholtz Centre for Environmental Research – UFZ, Leipzig, Germany
[4]Center for Climate Physics, Institute for Basic Science, Busan, South Korea
[5]Pusan National University, Busan, South Korea

Extreme events, such as marine heatwaves (MHWs), severely impact marine ecosystems. Of particular concern are compound events, i.e. situations when conditions are extreme for multiple ecosystem stressors [1], such as temperature and net primary productivity (NPP). In 2013-2015 for example, an extensive MHW, known as the Blob, cooccurred with low NPP and severely impacted marine life in the northeast Pacific, with cascading impacts on fisheries [2, 3]. Yet, little is known about the distribution and drivers of compound MHW and low NPP extreme events. We use satellite-based sea surface temperature and NPP estimates to provide a first assessment of these compound events [4]. We reveal hotspots of compound MHW and low NPP events in the equatorial Pacific, along the boundaries of the subtropical gyres, and in the northern Indian Ocean (Fig. 1). In these regions, compound events that typically last one week occur three to seven times more often than expected under the assumption of independence between MHWs and low NPP events. At the seasonal timescale, most compound events occur in summer in both hemispheres. At the interannual time-scale, their frequency is strongly modulated by large-scale modes of climate variability such as the El Niño-Southern Oscillation, whose positive phase is associated with increased compound event occurrence in the eastern equatorial Pacific by a factor of up to four.

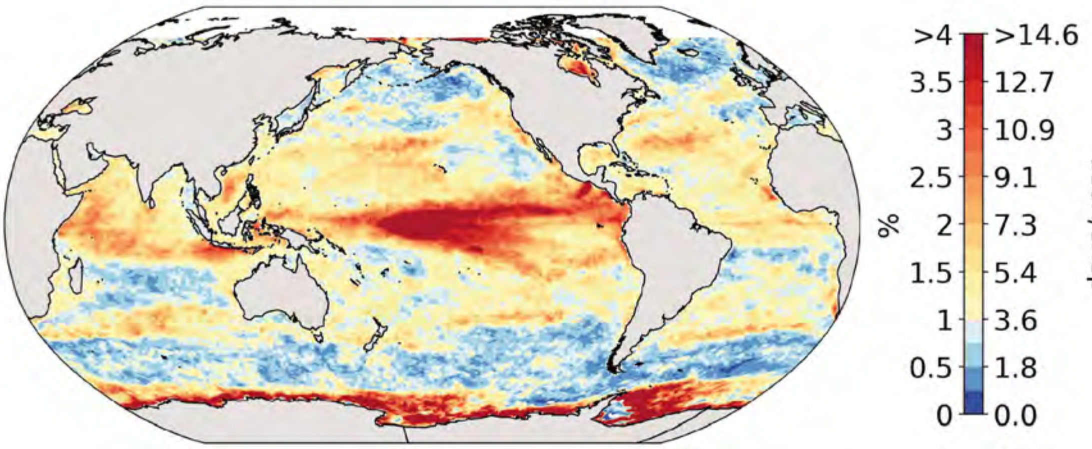


Figure 1: Mean frequency of compound MHW-NPPX events in the observation-based estimates over 1998-2018.

Using large ensemble simulations of two Earth system models, we then investigate the exact physical and biological drivers of these compound events. Both models suggest that in the low latitudes, MHWs are often associated with low nutrient concentrations at the surface of the ocean due to enhanced stratification and/or reduced upwelling, which limits the growth of phytoplankton and results in extremely low NPP. However, the models show large disparities in the high latitudes. Overall, we find that the distribution and drivers of compound MHW-NPPX events are contingent on model representation of the factors limiting phytoplankton production. This identifies an important need for improved process understanding in Earth system models used for predicting and projecting compound MHW-NPPX events and their impacts.

References

[1] J. Zscheischler et al., Future climate risk from compound events, *Nature Climate Change* **8**, 469–477 (2018), 10.1038/s41558-018-0156-3.

[2] L. Cavole et al., Biological Impacts of the 2013–2015 Warm-Water Anomaly in the Northeast Pacific: Winners, Losers, and the Future, *Oceanography (Washington D.C.)* **29**, (2016), 10.5670/oceanog.2016.32.

[3] W. Cheung and T. and Frölicher, Marine heatwaves exacerbate climate change impacts for fisheries in the northeast Pacific, *Scientific Reports* **10**, 6678 (2020), 10.1038/s41598-020-63650-z.

[4] N. Le Grix et al., Compound high-temperature, low-chlorophyll extremes in the ocean over the satellite period, *Biogeosciences* **18**, 2119–2137 (2021), 10.5194/bg-18-2119-2021.

Exploring the geochemical changes stored in impurities in polar deep ice cores using CFA-sp-ICP-TOFMS

Geunwoo Lee[1], Tobias Erhardt[1,2], Martin Tanner[3], Barbara Delmonte[4], Hubertus Fischer[1]

[1]Climate and Environmental Physics and Oeschger Center for Climate Change Research,
University of Bern, Sidlerstrasse 5, 3012 Bern, Switzerland
[2]Alfred Wegener Institute Helmholtz Center for Polar and Marine Science,
Am Handelshafen 12, 27570 Bremerhaven, Germany
[3]TOFWERK AG, Schorenstrasse 39, 3645 Thun, Switzerland
[4]Department of Earth and Environmental Sciences,
University of Milano-Bicocca, Piazza della Scienza 1 e 4, I-20126 Milan, Italy

The current global warming resulted in unprecedented extreme weather events such as heat waves, droughts, floods, and storms throughout the world. This is affecting not only atmospheric processes but also ecosystems. Aerosols (e.g., mineral dust, forest exudes, sea salt, etc.) which are produced at the Earth surface and long-range transported to the polar regions by atmospheric circulation are archived in snow/ice layers by wet and dry deposition. Thus, changes in the Earth system can be reconstructed through the analysis of aerosol components in polar ice cores.

Single Particle Inductively Coupled Plasma Time Of Flight Mass Spectrometry (sp-ICP-TOFMS; model: icpTOF R, TOFWERK AG, Switzerland) coupled to a continuous flow analysis (CFA) system [1] allows for high-resolution elemental analysis of single dust particles in ice cores over the almost full mass range. However, there are still a few technical and scientific challenges to overcome to fully leverage sp-ICP-TOFMS for the geochemical characterization of single dust particles in deep ice cores. Because ultra-trace elements like rare Earth elements (REEs) are seldomly detected in the pristine polar

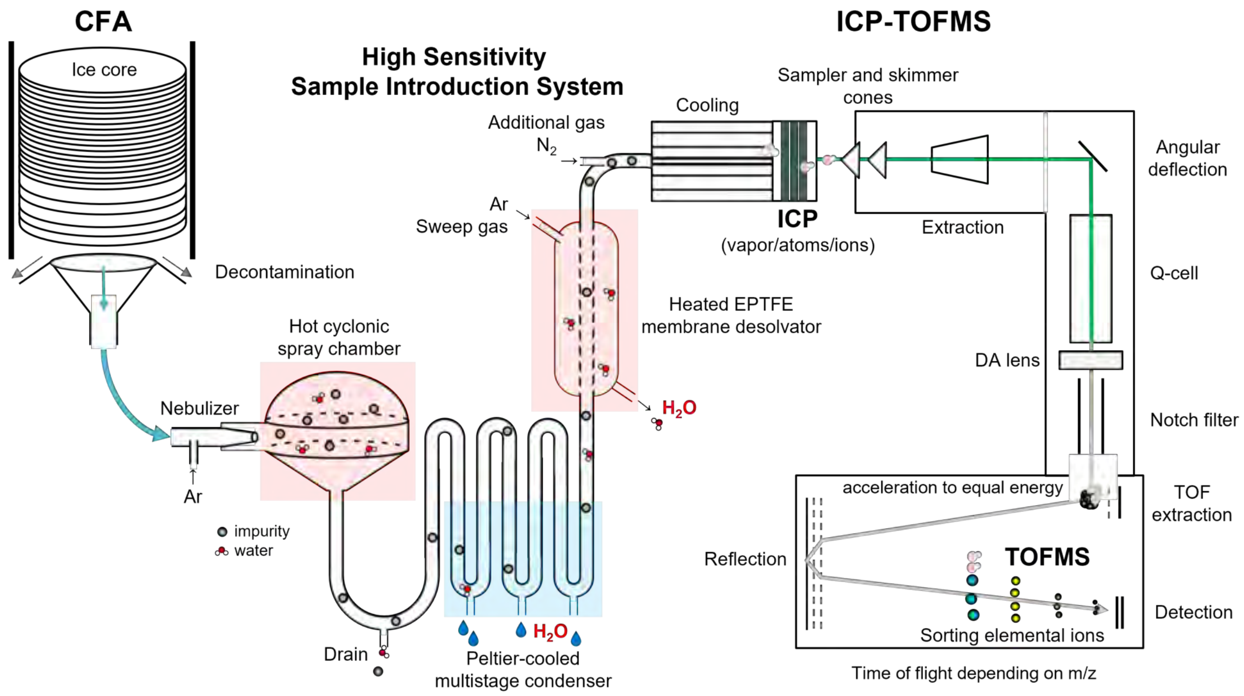


Figure 1: Schematic diagram of CFA-sp-ICP-TOFMS with desolvation unit. This high sensitivity desolvation system using condensation and membrane filtration improves the transport efficiency into the mass spectrometer, reduces water molecules from entering the plasma, and decreases oxidized polyatomic interferences noticeably in the system.

ice cores but play a crucial role in the geochemical characterization and fingerprinting of mineral dust sources [2, 3], a better analytical performance such as improved sensitivity and reduced interference formation of ICP-MS instrumentation is required to precisely quantify fluctuations in past mineral dust deposition. For example, the loss of aerosol particles from the spray chamber to the plasma limits the sensitivity of the elemental detection and has to be minimized. Moreover, H_2O from the CFA meltwater stream leads to the formation of oxides and hydrides in the ICP system, resulting in loss or interference of signal for analytes of interest. These undesirable changes in the signals could be prevented by largely removing the water before the plasma ionization. Therefore, we introduced for the first time in CFA-sp-ICP-TOFMS on ice cores a high sensitivity desolvation unit to the ICP system, which considerably improves the transport efficiency into the plasma and reduces the production of oxides in the system. A schematic diagram of CFA-sp-ICP-TOFMS with the desolvation unit is shown in Figure 1. The transport efficiency and sensitivity of sp-ICP-TOFMS increased by a factor of about five and two to five, respectively, in presence of the desolvation system.

In addition to the technical challenge, there is a scientific challenge in the rich information of multi-elemental composition data measured in single dust particles. The data dimension of the composition for individual particles varies from univariate to a few tens of measured elements and meaningful implications in the dataset can be hidden in the high dimension data set. Hence, we need appropriate dimension reduction methods for geochemical characterization of single dust particles in ice cores. First steps in this direction have been taken in this study using firn cores from Greenland.

The ultimate goal of this study is to provide the methodological and time series analytical basis for the application of CFA-sp-ICP-TOFMS on the future Beyond EPICA Oldest Ice ice core, which is supposed to extend the Antarctic ice core record to the last 1.5 million years.

References

[1] Erhardt, T., Jensen, C. M., Borovinskaya, O., & Fischer, H., Single particle characterization and total elemental concentration measurements in polar ice using continuous flow analysis-inductively coupled plasma time-of-flight mass spectrometry, *Environmental science & technology* **53(22)**, 13275-13283 (2019).

[2] Gabrielli, P., Wegner, A., Petit, J. R., Delmonte, B., De Deckker, P., Gaspari, V., Fischer, H., Ruth, U., Kriews, M., Boutron, C., Cescon, P., & Barbante, C., A major glacial-interglacial change in aeolian dust composition inferred from Rare Earth Elements in Antarctic ice, *Quaternary Science Reviews* **29(1-2)**, 265-273 (2010), https://doi.org/10.1016/j.quascirev.2009.09.002

[3] Wegner, A., Gabrielli, P., Wilhelms-Dick, D., Ruth, U., Kriews, M., De Deckker, P., Barbante, C., Cozzi, G., Delmonte, B., & Fischer, H., Change in dust variability in the Atlantic sector of Antarctica at the end of the last deglaciation, *Climate of the Past* **8(1)**, 135-147 (2012), https://doi.org/10.5194/cp-8-135-2012

Multi-model attribution of extremes in fire weather intensity and duration using CMIP6 ensembles

Zhongwei Liu[1], Jonathan Eden[1], Bastien Dieppois[1], Igor Drobyshev[2,3,4] and Matthew Blackett[1,5]

[1]Centre for Agroecology, Water and Resilience, Coventry University, Coventry, UK
[2]Southern Swedish Forest Research Centre, Swedish University of Agricultural Sciences, Alnarp, Sweden
[3]Institut de recherche sur les forêts, Chaire de recherche du Canada en aménagement forestier durable, Université du Québec en Abitibi-Témiscamingue (UQAT), Canada
[4]Forest Research Institute of the Karelian Research Centre of the Russian Academy of Petrozavodsk, Russia
[5]School of Energy, Construction and Environment, Coventry University, Coventry, UK

In response to the occurrence of a number of large wildfire events across the world in recent years, the question of the extent to which climate change may be altering the meteorological conditions conducive to wildfires has become a hot topic of debate [1]. Despite the development of attribution methodologies for extreme events in the last decade [2], attribution studies dedicated explicitly to wildfire, or otherwise extreme 'fire weather', are still relatively few. In turn, there is a lack of consensus on how to define fire risk in a meteorological context, posing a challenge for research in this subfield. Recent work has offered clarification on uncertainties associated with the choice of meteorological indicator to represent fire weather in the context of extreme event attribution [3], but there are additional sensitivities that are still not fully understood.

Here, using established statistical methodologies applied to six large (>10-member) CMIP6 model ensembles [4], we conduct probabilistic attribution of extremes in fire weather intensity and duration across the world's fire-prone regions. We assess trends in extremes in the Canadian Fire Weather Index [5] (FWI) using extreme value distributions, fitted with annual maxima in 7-day averaged FWI (FWIx7day) and the number of consecutive days for which FWI is above the 90th percentile (FWIxCD90). To investigate the dependence of the fit on global warming, the distribution is scaled with the corresponding 48-month running average in global mean surface temperature (GMST). At each grid point, a probability ratio (PR) is calculated to express how the likelihood of extreme fire weather conditions has changed between 1880-1884 and 2010-2014 as a result of global warming. Subsequently, attribution results across all six models are combined to generate a multi-model synthesis. As part of a model evaluation step, we identify models that are able to realistically reproduce the statistical properties of fire weather extremes. Models that meet the evaluation criteria are used to generate composite PR maps (Fig. 1). The results show that extremes in fire weather intensity and duration have become up to 4 times more likely since the pre-industrial era as a result of globally warming temperature in the majority of the world's fire-prone regions.

Our results also highlight the sensitivity of probabilistic fire weather attribution methodologies to the choice of climate model ensemble. In conclusion, we therefore make a set of recommendations for future attribution of extreme fire weather episodes: (i) the use (and comparison) of multiple model ensembles; (ii) robust evaluation of model capacity to represent fire weather extremes.

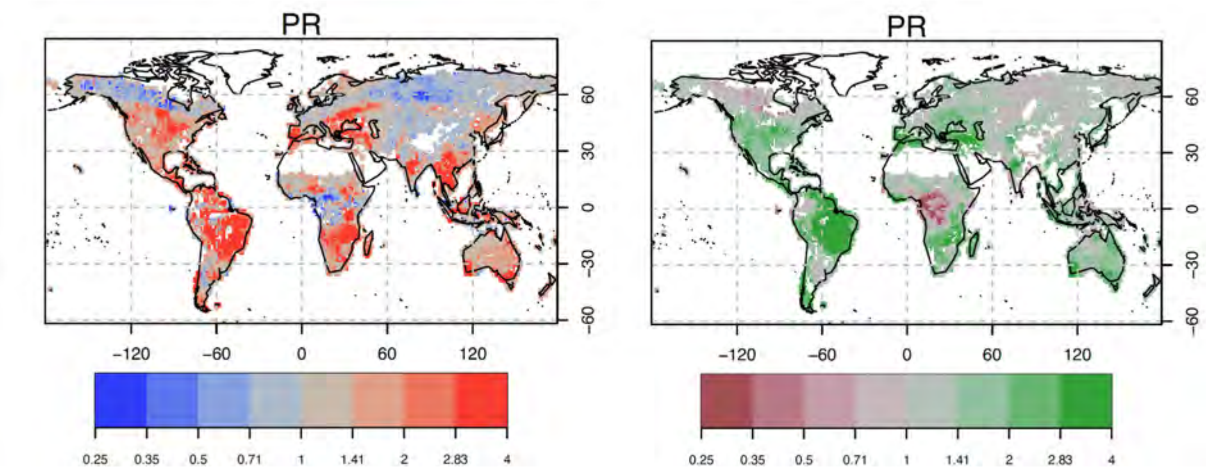


Figure 1: Composite plots showing the PR for trends in FWIx7day (left) and FWIxCD90 (right) averaged across a subset of CMIP6 models that sufficiently well-reproduce the distribution of extremes.

References

[1] T. M. Ellis et al., Global increase in wildfire risk due to climate driven declines in fuel moisture, *Global change biology* **28(4)**, 1544 (2022), 10.1111/gcb.16006.

[2] S. Philip et al., A protocol for probabilistic extreme event attribution analyses, *Advances in Statistical Climatology, Meteorology and Oceanography* **6(2)**, 177 (2020), 10.5194/ascmo-6-177-2020.

[3] Z. Liu et al., A Global View of Observed Changes in Fire Weather Extremes: Uncertainties and Attribution To Climate Change, *Climatic Change* (under review), 10.21203/rs.3.rs-1054722/v1.

[4] V. Eyring et al., Overview of the Coupled Model Intercomparison Project Phase 6 (CMIP6) experimental design and organization, *Geoscientific Model Development* **9(5)**, 1937 (2016), 10.5194/gmd-9-1937-2016.

[5] C. E. Van Wagner et al., Development and Structure of the Canadian Forest Fire Weather Index System, *Canadian Forestry Service, Forestry Technical Report*, (1987).

Global Historical Climate Database - HCLIM

Elin Lundstad[1,2], Yuri Brugnara[1,2], Stefan Brönnimann[1,2]

[1]Institute of Geography, Bern, Switzerland
[2]Oeschger Center for Climate Change Research, Bern, Switzerland

There is a growing need for past weather and climate data to support science and decision-making. This abstract describes the compilation and the construction of global monthly instrumental climate data with a focus on the 18th and early 19th centuries. We present a new instrumental monthly meteorological database prior to 1890. This database provides early instrumental data, and it is multivariable (air temperature, pressure, precipitation sum, number of precipitation days) are recovered for thousands of locations around the world for that encompasses a substantial body of the known early instrumental time series. Instrumental meteorological measurements from periods prior to the start of national weather services are designated "early instrumental data". Much of the data is taken from repositories we know (GHCN, ISTI, CRUTEM, Berkeley Earth, HISTALP). In addition, many of these stations have not been digitized before. It ends up in one database with the same format, so it is easy to use the data with a good overview of metadata. The dataset contains series compiled from existing databases that start before 1890 (though continuing to the present) as well as a large amount of newly rescued data. The first record is from 1586. All series underwent a quality control procedure and subdaily series were processed to monthly mean values. An inventory was compiled, and the collection was deduplicated based on coordinates and mutual correlations. The data are provided in a common format accompanied by the inventory. The collection totals 12452 meteorological records in 118 countries. Such datasets will allow new insights into the transition of the climate system from the Little Ice Age into the present climate, longer time series to learn from extreme events, and new opportunities to analyze the climate–society interface. This is a follow-up of work done by Brönnimann et al (2019), who built up a huge inventory of all the instrumental meteorological measurements before 1850. The data can be used for climate reconstructions and analyses. It is the most comprehensive global monthly climate data set for the preindustrial period.

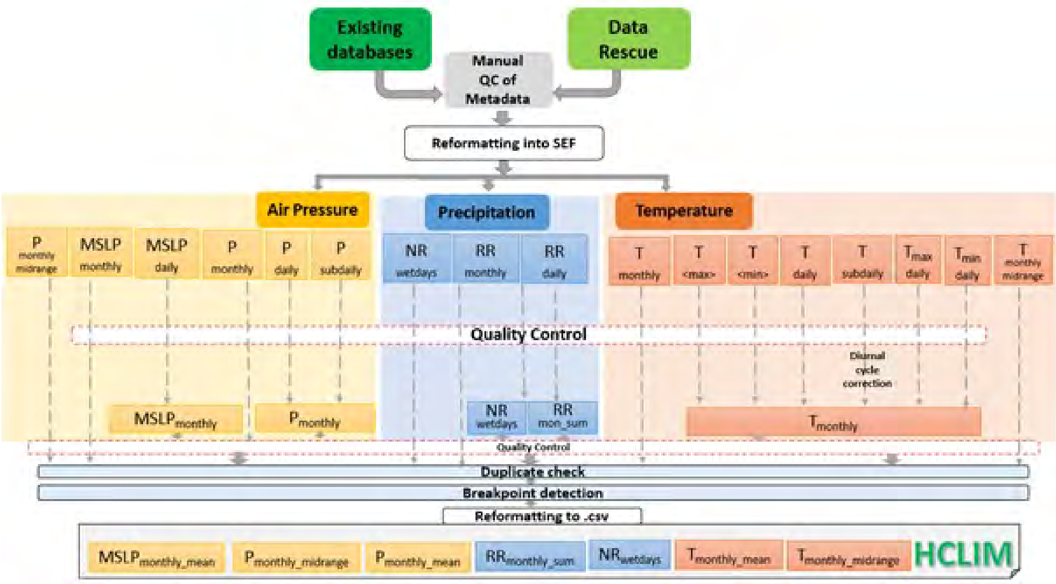


Figure 1: Schematic diagram, showing the sequence of steps involved in the data collection.

(2)

References

[1] Brázdil, R. et al., Extreme droughts and human responses to them: the Czech Lands in the pre-instrumental period. , *Clim. Past* **15**, 1 (2019), https://doi.org/10.5194/cp-15-1-2019.

[2] Cornes, R.C, P.D. Jones, Estimates of the North Atlantic Oscillation back to 1692 using a Paris-London westerly index.*International Journal of Climatology* **33**, 228 (2013), https://doi.org/10.1002/joc.3416

Rapid increase in the risk of heat related mortality

Samuel Lüthi[1, 2], Erich M. Fischer[3], Ana M. Vicedo-Cabrera[4,5], David N. Bresch[1, 2]

[1]Institute for Environmental Decisions, ETH Zurich, Zurich, Switzerland
[2]Federal Office of Meteorology and Climatology, MeteoSwiss, Zürich-Airport, Switzerland
[3]Institute for Atmospheric and Climate Science, ETH Zurich, Zurich, Switzerland
[4]Institute of Social and Preventive Medicine, University of Bern, Bern, Switzerland
[5]Oeschger Center for Climate Change Research, University of Bern, Bern, Switzerland

Heat-related mortality has been identified as one of the key climate extremes posing a risk to human health [1, 2]. Past heatwaves caught communities under-prepared, leading to excess mortality of several thousand lives within just a few weeks time. With the collision of several mega-trends – aging societies, urbanization, inequality – the need for a comprehensive heat mortality risk analysis is growing rapidly. Here, we present a probabilistic analysis of the impact of extreme heat on city-scale mortality, demonstrated for 748 locations around the world.

Building on the open-source natural catastrophe risk platform CLIMADA (CLIMate ADAptation)[3], we produce a probabilistic risk assessment for heat mortality on a city level. We combine state-of-the-art epidemiological time series analysis methods[4] with single model initial condition large ensemble (SMILE) climate model output [5]. The epidemiological analysis relies on quasi-Poisson regression time series analyses and requires daily city-level mortality data. This analysis results in city-specific risk of exceedance mortality as a function of temperature.

The SMILE approach takes a climate model and runs it multiple times with perturbed initial conditions but using the same climate scenario. It thus indicates multiple physically consistent and plausible pathways of the climate which can be used for a probabilistic risk assessment. This allows estimation of tail-risks and quantification of return-period-based mortality impacts. We used SMILE output of five different climate models, totaling 234 model runs, to estimate impacts and uncertainties of tail risks.

Across most locations, heat-mortality counts of a 1-in-100 year season in the climate of 2000 must be expected once every ten to twenty years in the climate of 2020. These return periods are projected to further shorten under warming levels of 1.5°C and 2°C, where heat-mortality extremes of the past climate will eventually become normality if no adaptation happens.

References

[1] Basu, R. & Samet, J. M., Relation between Elevated Ambient Temperature and Mortality: A Review of the Epidemiologic Evidence. *Epidemiol. Rev.* **24**, 190–202, DOI: 10.1093/epirev/mxf007 (2002)

[2] Pal, J. S. & Eltahir, E. A. B., Future temperature in southwest Asia projected to exceed a threshold for human adaptability. *Nat. Clim. Chang.* **6**, 197–200, DOI: 10.1038/nclimate2833 (2016)

[3] Aznar-Siguan, G. & Bresch, D. N., CLIMADA v1: a global weather and climate risk assessment platform. *Geosci. Model. Dev.* **12**, 3085–3097, DOI: 10.3929/ethz-b-000354305 (2019)

[4] Gasparrini, A. et al., Mortality risk attributable to high and low ambient temperature: a multicountry observational study. *The Lancet* **386**, 369–375, DOI: 10.1016/S0140-6736(14)62114-0 (2015).

[5] Deser, C. et al., Insights from Earth system model initial-condition large ensembles and future prospects. *Nat. Clim. Chang.* **10**, 277–286, DOI: 10.1038/s41558-020-0731-2 (2020).

On the Production of Expert Judgment as an Output of Climate Science

Mason M. Majszak[1,2]

[1]Institute of Philosophy, University of Bern, Switzerland
[2]Oeschger Centre for Climate Change Research (OCCR), Bern, Switzerland

The growth and development of modeling efforts has fundamentally changed the way climate science is performed. Thus, modeling as a practice has received a tremendous amount of attention by the philosophy of climate science community, with discussions ranging from general epistemic concerns to notions of confirmation [3]. However, an equally important feature has received little attention, the uses of expert judgment within climate science. In this talk, I will outline my current research into the conceptualization and epistemic evaluation of expert judgment in the climate science domain.

I will begin with a systematic examination of the various uses of expert judgment in climate science, highlight that expert judgment in this domain should be characterized as an output of science. This will lead to a discussion of methodologies for creating and further evaluating expertise as an output of science. Thus, to evaluate expert judgment we must look at the methodology of its production, structured expert elicitation then comes to the forefront of this discussion as it is, to date, the most robust approach for the creation of expert judgments [1]. This will lead to a comparison between expert judgment and other long held outputs of scientific discovery, modeling outputs and observational data. I discuss some potential differences between these scientific outputs, with one key aspect being that expert judgments are utilized when there is at least some and, in most cases, high (or deep) uncertainty. This will highlight the role of subjective elements, like individual social/political values, and the resulting epistemic concerns if these biases then influence the scientific claims [2]. I will conclude with a discussion on how the biases can and should be managed when using a rigorous elicitation methodology.

References

[1] Hanea, A. M., Hemming, V. and Nane, G. F., (2021). "Uncertainty Quantification with Experts: Present Status and Research Needs", *Risk Analysis* **42**, 254-63 , https://doi.org/10.1111/risa.13718.

[2] Martini, C. (2020). The epistemology of expertise. In M. Fricker, P. J. Graham, D. Henderson, and N. J. L. L. Pedersen (eds.) *The Routledge Handbook of Social Epistemology*, NY: Routledge. Chapter 12, 115-122.

[3] Winsberg, E. (2018). Philosophy and climate science. *Cambridge University Press*.

(De)coupling between population resistance and recovery after an extreme heat event is explained by thermal effects on life-history traits

Gerard Martínez-De León[1], Arianne Marty[1], Martin Holmstrup[2], Madhav P. Thakur[1]

[1]Terrestrial Ecology Group, Institute of Ecology and Evolution, University of Bern, Switzerland
[2]Section of Terrestrial Ecology, Department of Ecoscience, Aarhus University, Denmark

Extreme heat events lower the fitness of organisms by inducing physiological stress and increasing metabolic costs [1, 2]. Ectothermic animals are especially vulnerable to extreme heat events as their body temperatures get pushed towards their upper thermal limits [3], potentially triggering large ecological responses. Yet, little is known about the role of life-history traits, such as survival and reproduction, in elucidating population responses to extreme heat events [4]. Here, we used a trait-based approach to understand population resistance and recovery using four closely related species of Collembola, one of the largest groups of terrestrial invertebrates living in soils (Fig. 1). We first measured thermal reaction norms of life-history traits and used this information to identify ecological mechanisms linked to population resistance and recovery after an extreme heat event (one week at 26 ° C night - 30 ° C day, representing +10 ° C above control conditions). Furthermore, we investigated potential heat-induced shifts on the population size distribution to provide a mechanistic link between individual and population-level responses. We expected that the distinct climatic niches of our four study species would underlie differences in their thermal performance, which would then affect their resistance and recovery after the extreme heat event.

Figure 1: Individual of a Collembola species (*Protaphorura pseudovanderdrifti*) used to investigate population responses after an extreme heat event. The individual portrayed measures 2 mm of body length.

We show that although the population resistance remained unaltered across species, the population recovery of the most heat-sensitive species was strongly affected by the extreme heat event (-54% population change compared to control conditions). The mechanisms behind such decoupling between population resistance and recovery were elucidated by depicting that fecundity (linked to recovery) was more sensitive to extreme heat than survival (linked to resistance). In addition, the detrimental effects of heat on fecundity were most likely responsible of a decline in the number of small-sized (juvenile) individuals in the population after recovery. The lack of both resistance and recovery responses in the other species can be explained by their greater thermal tolerance, since they showed high survival and fecundity in the temperature conditions of our experiment. However, we argue that the same mechanisms causing a decoupling between population resistance and recovery in the most heat-sensitive species can be applicable to the other species under even warmer conditions. We highlight that variation in life-history responses to warming can scale to population level recovery after extreme heat events, and we thus call for a better understanding of both short and long-term responses of species exposed to climate extremes.

References

[1] M.E. Dillon et al., Global metabolic impacts of recent climate warming, *Nature* **467**, 704 (2010), 10.1038/nature09407

[2] C-S. Ma et al., Survive a warming climate: Insect responses to extreme high temperatures, *Annu. Rev. Entomol.* **66**, 1 (2020), 10.1146/annurev-ento-041520-074454

[3] C.A. Deutsch et al., Impacts of climate warming on terrestrial ectotherms across latitude, *Proc. Natl. Acad. Sci. U. S. A.* **105**, 6668 (2008), 10.1073/pnas.0709472105

[4] E.W. Neilson et al., There's a storm a-coming: Ecological resilience and resistance to extreme weather events, *Ecol. Evol.* **10**, 12147 (2020), 10.1002/ece3.6842

Unhappy triad of tropical cyclone wind, surge and rain: modelling impacts now and in a changing climate

Simona Meiler[1,2], Ali Sarhadi [3], Kerry Emanuel[4], David N. Bresch [1,2]

[1]Institute for Environmental Decisions, ETH Zurich, Switzerland
[2]Federal Office of Meteorology and Climatology MeteoSwiss, Switzerland
[3]Department of Earth, Atmospheric and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, Massachusetts, USA
[4]Lorenz Center, Massachusetts Institute of Technology, Cambridge, Massachusetts, USA

Intense precipitation from tropical cyclones (TCs), typically accompanied by wind-driven storm surges and highly destructive winds, constitutes a significant threat for compound flooding and wind-driven impacts in many coastal regions worldwide. However, most present TC risk assessment methods only consider wind as the driving hazard and thus underestimate impacts emerging from compounding TC sub-hazards. Further, it is crucial to understand how this risk will shift and intensify in a warming climate.

We thus present a coupled, physics-based modeling approach for the coastal area of Metropolitan Manila (PHL) to explicitly represent TC rainfall-induced freshwater flood, TC wind-driven storm surges, and direct impacts from TC wind for present and future climate (Fig. 1). We use a large set of synthetic TCs [1] generated from historical climate data (1985-2014) and from the late 21st century (2071-2100) SSP585 warming scenario to simulate TC wind fields [2] and rainfall [3] intensity data. Our modelling chain includes a hydrodynamical component [4] to convert TC precipitation to freshwater flood and model wind-driven storm surges [5]. We evaluate the compound socio-economic impacts from the TC sub-hazards using a state-of-the-art, open-source probabilistic damage model (CLIMADA) [6].

Modelling the joint impact from the TC flood and wind hazard is a novel contribution to the field of TC impact assessment. We hypothesize that disentangling the relative contribution of TC sub-hazard to the total risk will improve impact estimates as compared to simulating TC impacts using the wind hazard only. Furthermore, we expect different spatial patterns of TC wind and flood hazard footprints. Lastly, we suppose that these patterns changes in the future climate.

Ultimately, our advances in TC impact modelling can be applied in vulnerable coastal regions worldwide, enabling better-informed adaptation decisions and mitigation strategies.

References

[1] Emanuel, K., Sundararajan, R. & Williams, J. Hurricanes and global warming: Results from downscaling IPCC AR4 simulations, *Bulletin of the American Meteorological Society* **89**, 347 (2008), 10.1175/BAMS-89-3-347.

[2] Emanuel, K., & Rotunno, R. Self-stratification of tropical cyclone outflow. Part I: Implications for storm structure, *Journal of the Atmospheric Sciences* **68(10)**, 2236 (2011), 10.1175/JAS-D-10-05024.1.

[3] Feldmann, M., Emanuel, K., Zhu, L. & Lohmann, U. Estimation of atlantic tropical cyclone rainfall frequency in the United States, *Journal of Applied Meteorology and Climatology* **58**, 1853 (2019), 10.1175/JAMC-D-19-0011.1.

[4] Bates, P., Trigg, M., Neal, J., Dabrowa, A. LISFLOOD-FP User manual (2013).

[5] Clawpack Development Team. Clawpack Version 5.7.1, http://www.clawpack.org, (2020), 10.5281/zenodo.4025432.

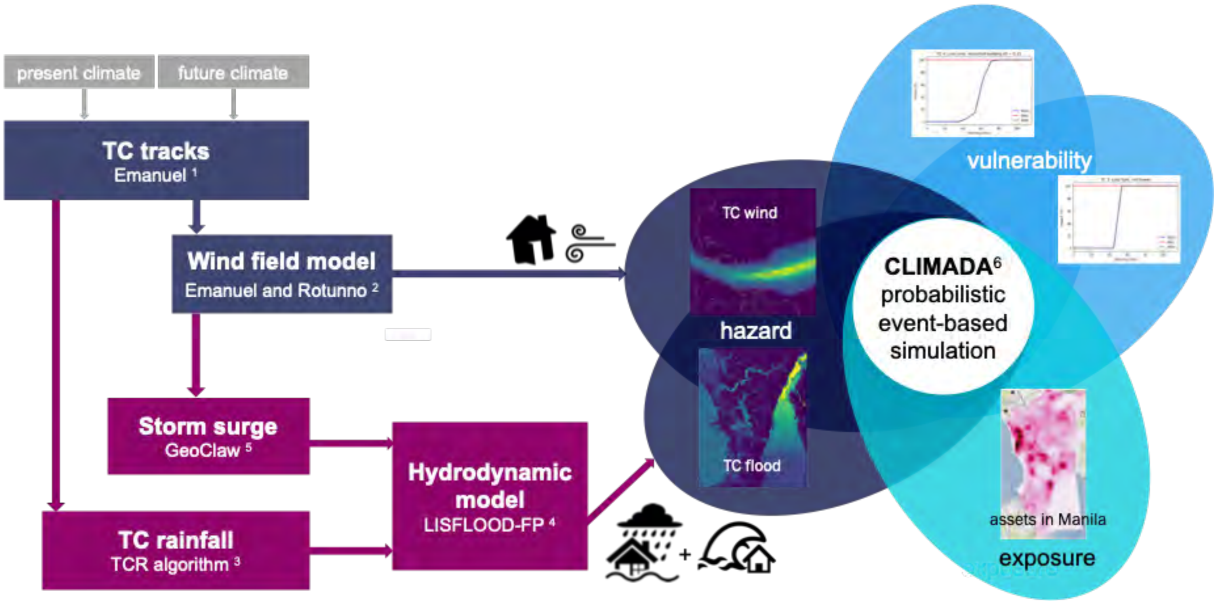


Figure 1: Overview of the chained modeling framework. Impacts in CLIMADA are calculated by integrating hazard, exposure and vulnerability data (right half of figure). The tropical cyclone sub-hazard modelling chain is shown in the left half of the figure. Rectangles in blue tones represent existing model components (wind hazard). Purple boxes correspond to new model additions (compound surge and rain hazard). 1. Emanuel et al. (2008) [1], 2. Emanuel and Rotunno (2008) [2], 3. Feldmann et al. (2019) [3], 4. Bates et al. (2013) [4], 5. Clawpack Development Team (2020) [5], 6. Aznar-Siguan and Bresch (2019) [6]

[6] Aznar-Siguan, G. & Bresch, D. N. CLIMADA v1: A global weather and climate risk assessment platform, *Geoscientific Model Development* **12**, 3085 (2019), 10.5194/gmd-12-3085-2019.

Storylines of extreme impacts and risk assessment

Henrique M. D. Goulart[1,2], Karin van der Wiel[3], Bart van den Hurk[1,2]

[1]Deltares, Delft, the Netherlands
[2]Vrije Universiteit Amsterdam, Amsterdam, the Netherlands
[3]Royal Netherlands Meteorological Institute, De Bilt, Netherlands

Extreme weather-induced impacts, while inherently rare, have high potential to cause losses, damages and disruptions to society. As the planet's climate is changing due to anthropogenic global warming, the risk of these extreme impacts is also changing. To adapt to these extreme impacts, it is essential for risk management to understand and quantify the future risk of extreme weather-induced impact events [1].

The traditional approach to estimate risk in the future relies on determining the most probable outcomes of future climate, based on different global climate model runs. This approach, while valid for many purposes, might overlook low-probability high-impact events [2].

A complementary method has recently emerged, called storylines [3], which is defined as physically self-consistent unfolding of past events and plausible future events. By focusing on plausibility rather than on probability, storylines are well-suited to simulate extreme impact events. With storylines, it is possible to create conditional explanations of events, linking impacts to specific climate conditions. This allows for the exploration of historical events under different climate scenarios.

Recent studies have used storylines for impact estimation of historical events under global warming. Yet, the suitability of storylines in generating climate information and, therefore, for risk assessment remains unknown. We aim to assess the utility of climate information obtained via storylines and its contribution to risk assessment.

In the first year of the PhD, we explored the weather conditions leading to soybean failures in the United States of America [4]. Using a machine learning model, we selected the year with largest failure and identified the weather conditions leading to this event. Then, we explored the occurrence of analogues of the historical event under different levels of global warming. The analogues were divided between events with similar or more intense weather conditions (event analogues) and events with similar or higher impacts (impact analogues). We found the impact analogues to be a better metric for future risk assessment as they detected more extreme cases and accounted for changes in the weather conditions leading to extreme impacts.

In the second year, we explored the future risks of simultaneous crop failures under climate change but considering different adaptation measures. We determined that global warming increases the simultaneous failure risk, but that adaptation measures have considerable effect in reducing this change.

Currently, we aim to explore extreme impacts due to flood events. The focus will be to use storylines to disentangle human and environmental contribution to a historical event and explore different "what if" scenarios. I would appreciate suggestions and advices on different methods of building storylines, on how to use them for generating useful climate information, and most generally, how to bridge climate science and impacts on society.

References

[1] Trenberth, Kevin E. and Fasullo, John T. and Shepherd, Theodore G., Attribution of climate extreme events, *Nature Climate Change*, 725–730 (2015), 10.1038/nclimate2657

[2] Sillmann, Jana and Shepherd, Theodore G. and van den Hurk, Bart and Hazeleger, Wilco and Martius, Olivia and Slingo, Julia and Zscheischler, Jakob, Event-based storylines to address climate risk, *Earth's Future*, (2020), 10.1029/2020ef001783

[3] Shepherd, Theodore G. and Boyd, Emily and Calel, Raphael A. and Chapman, Sandra C. and Dessai, Suraje and Dima-West, Ioana M. and Fowler, Hayley J. and James, Rachel and Maraun, Douglas and Martius, Olivia and Senior, Catherine A. and Sobel, Adam H. and Stainforth, David A. and Tett, Simon F.B. B. and Trenberth, Kevin E. and van den Hurk, Bart J.J.M. J. M. and Watkins, Nicholas W. and Wilby, Robert L. and Zenghelis, Dimitri A., Storylines: an alternative approach to representing uncertainty in physical aspects of climate change, *Climatic Change*, 555–571 (2018), 10.1007/s10584-018-2317-9.

[4] Goulart, H. M. D. and van der Wiel, K. and Folberth, C. and Balkovic, J. and van den Hurk, B., Storylines of weather-induced crop failure events under climate change, *Earth System Dynamics*, 1503–1527 (2021), 10.5194/esd-12-1503-2021.

Excess methane, ethane, and propane production in Greenland ice core samples and a first characterization of the δ^{13}C-CH_4 and δD-CH_4 signature

Michaela Mühl[1], Jochen Schmitt[1], Barbara Seth[1], James E. Lee[2], Jon S. Edwards[3], Edward J. Brook[3], Thomas Blunier[4], Hubertus Fischer[1]

[1]Climate and Environmental Physics and Oeschger Centre for Climate Change Research, University of Bern, Sidlerstrasse 5, 3012 Bern, Switzerland
[2]Los Alamos National Laboratory, Earth Systems Observation, P.O. Box 1663, Los Alamos, NM 87545, USA
[3]College of Earth, Ocean, and Atmospheric Sciences, Oregon State University, Corvallis, OR 97331, USA
[4]Centre for Ice and Climate, Niels Bohr Institute, University of Copenhagen, Tagensvej 16, 2200 København N., Denmark

Air trapped in polar ice provides unique records of the past atmospheric composition ranging from key greenhouse gases such as methane (CH_4) to short-lived trace gases like ethane (C_2H_6) and propane C_3H_8). Interpreting these data in terms of atmospheric changes requires that the analyzed species concentrations and their isotopic fingerprints accurately reflect the past atmospheric composition. Provided that, biogeochemical cycles can be reconstructed.

However, recent comparisons of Greenland CH_4 records obtained using different extraction techniques revealed disagreements in the CH_4 concentration for the last glacial. Elevated methane levels (here called excess methane or $CH_{4(exs)}$) were detected in dust-rich ice core sections measured by classic discrete melt extraction techniques pointing to an artefact sensitive to the measurement technique [1]. In targeted experiments we analyzed Greenland ice core samples for methane and other short-chain alkanes ethane and propane covering the time interval from 12 to 42 kyr using a commonly used wet extraction technique.

Here, we report our findings that the artefact production happens during the melt extraction step (in extractu) of the classic wet extraction technique and reaches 14 to 91 ppb for CH_4 excess in dusty ice samples. In addition, we document a co-production of excess methane, ethane, and propane (excess alkanes) with the observed concentrations for ethane and propane exceeding, at least by a factor of 10, their past atmospheric concentration. Independent of their produced amounts, excess alkanes occur in a fixed molar ratio of approximately 14:2:1 in all samples analyzed, indicating a shared origin. At the same time, we also discovered that the amount of excess alkanes scales linearly with the amount of mineral dust (or Ca^{2+} as a proxy for mineral dust) within the ice samples. By applying the Keeling-plot approach [2, 3] the isotopic characterization of excess CH_4 reveals a relatively heavy carbon isotopic signature of -46.4 ‰ (± 2.4 ‰) and a light deuterium isotopic signature of -318.3 (± 52.9 ‰).

With both, the co-production ratios of excess alkanes and the isotopic composition of excess methane, we established a fingerprint that allows us to confine potential formation processes. Here we see that this specific alkane pattern is not in line with a microbial origin [4, 5] but indicative for abiotic decomposition of organic matter as also found in sediments, soils, and plant leaves [6, 7]. For the first time in ice core analyses this study provides first indications for an abiotic reaction producing excess alkanes during ice core gas extraction and discusses potential mechanisms.

Moreover, we see urgent need to correct the already existing discrete records of atmospheric CH_4 for excess CH_4 contribution ($CH_{4(exs)}$, δ^{13}C-$CH_{4(exs)}$, δD-$CH_{4(exs)}$) in dust-rich intervals in Greenland ice. Especially, as we observe that in some intervals excess CH_4 is in the same range as the Inter-Polar Difference [8, 9], excess CH_4 has a significant effect on the assessments of the hemispheric CH_4 source distribution and previous interpretations of relative contributions of high latitude northern hemispheric CH_4 sources need to be revised.

References

[1] J. E. Lee et al., Excess methane in Greenland ice cores associated with high dust concentrations, *Geochim. Cosmochim. Acta* **270**, 409-430 (2020), https://doi.org/10.1016/j.gca.2019.11.020.

[2] C. D. Keeling et al., The concentration and isotopic abundance of carbon dioxide in rural areas, *Geochim. Cosmochim. Acta* **13**, 322–334 (1958), https://doi.org/10.1016/0016-7037(58)90033-4.1958.

[3] P. Köhler et al., On the application and interpretation of Keeling plots in paleo climate research – deciphering δ^{13}C of atmospheric CO_2 measured in ice cores, *Biogeosciences* **3**, 539–556 (2006), https://doi.org/10.5194/bg-3-539-2006.

[4] A. V. Milkov and G. Etiope, Revised genetic diagrams for natural gases based on a global dataset of >20,000 samples, *Organic Geochemistry* **125**, 109-120 (2018),

https://doi.org/10.1016/j.orggeochem.2018.09.002.

[5] B. Bernard et al., A geochemical model for characterization of hydrocarbon gas sources in marine sediments, *9th Annual Offshore Technology Conference, Houston, Texas* **125**, 435–438 (1977), https://doi.org/10.4043/2934-MS.

[6] F. Keppler et al., Methane emissions from terrestrial plants under aerobic conditions, *Nature* **439**, 187-191 (2006), https://doi.org/10.1038/nature04420.

[7] I. Vigano et al., Effect of UV radiation and temperature on the emission of methane from plant biomass and structural components, *Biogeosciences* **5**, 937-947 (2008), https://doi.org/10.5194/bg-5-937-2008.

[8] J. Chappellaz et al., Changes in the atmospheric CH4 gradient between Greenland and Antarctica during the Holocene, *Geophys. Res. Let.* **102**, 15987-15997 (1997),

https://doi.org/10.1029/97JD01017.

[9] M. Baumgartner et al., High-resolution interpolar difference of atmospheric methane around the Last Glacial Maximum, *Biogeosciences* **9**, 3961–3977 (2012), https://doi.org/10.5194/bg-9-3961-2012.

Reconstruction of trace element sources from Cerro Negro ice core, Central Chile

T.S. Münster[1,2], T.M. Jenk[1], A. Eichler[1], G. Lee[2], C. Jensen[2], A. Rivera[3], M. Schwikowski[1,2]

[1]Paul Scherrer Insitut, Switzerland
[2]University of Bern, Switzerland
[3]Universidad de Chile, Chile

Ice cores from alpine glaciers serve as important archives that provide information about the composition of past and present atmosphere. Due to their geographical location, they give evidences on anthropogenic emissions in addition to natural signals[1]. Trace elements (TE) in glacier ice reflect the composition of deposited aerosols and thus allow determining their origin, e.g. from oceans (sea salt), desert areas (mineral dust), volcanoes and anthropogenic pollution[2].

The analysis of mineral dust provides information on dust sources, climate (humidity conditions), circulation changes and anthropogenic land use[2]. By determining the TE composition, the source of the mineral dust can be identified and thus a reconstruction of the wind conditions and/or atmospheric circulation patterns can be achieved[3]. The climate itself plays a decisive role in the formation of mineral dust. Persistent droughts lead to the spread of deserts and therefore to a raise in dust mobilisation[4]. The anthropogenic destruction of natural vegetation for land use results in extended wind erosion of the soil surface and increased dust emission[1]. Vice-versa mineral dust and other aerosols can also affect the climate itself, through the absorption and scattering of incident solar radiation and indirectly by influencing cloud and precipitation formation[4].

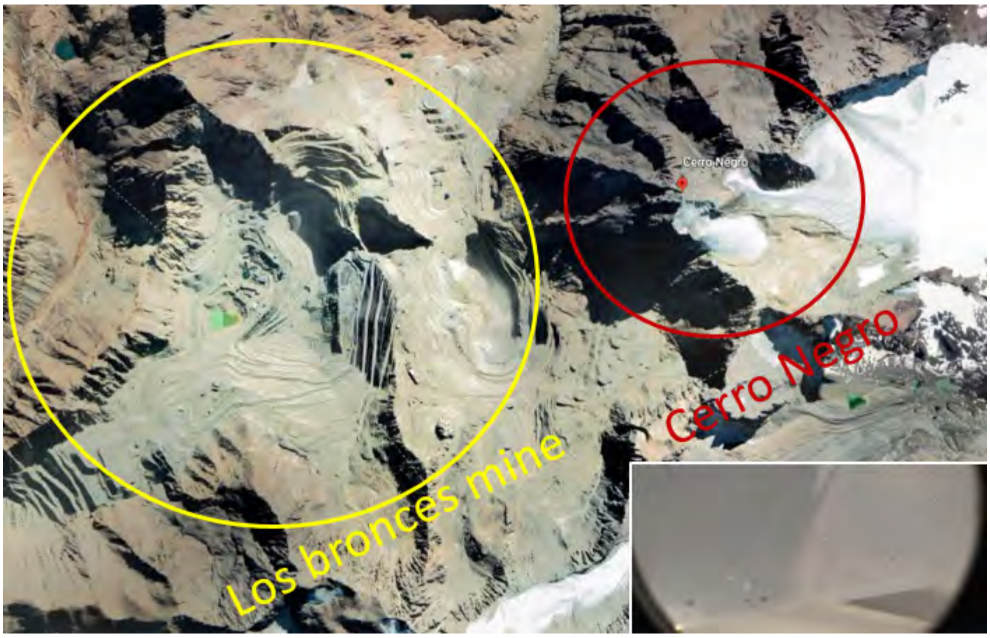


Figure 1: Cerro Negro glacier next to a copper mine. Are the particles in the ice samples coming from the mine? [5]

To determine TEs in ice cores, we use two instruments, an inductively coupled plasma-sector field-mass spectrometer (ICP-SF-MS, located at Paul Scherrer Institute) and an inductively coupled plasma-time of flight-mass spectrometer (ICP-TOF-MS, located at University of Bern). The ICP-SF-MS allows high mass resolution, is extremely sensitive and therefore often used to establish long-term TE trends, for example of anthropogenic pollution. In contrast, the ICP-TOF-MS is extremely fast, allowing measuring separately the TE composition of single particles and the dissolved fraction, which is an important information to reconstruct the mineral dust sources more precisely. We analyzed TE concentrations in a shallow ice core from Cerro Negro glacier in Central Chile with both instruments. We will present first data on single particle composition to identify TE sources (Fig. 1) and will discuss the comparability of the results (Fig. 2).

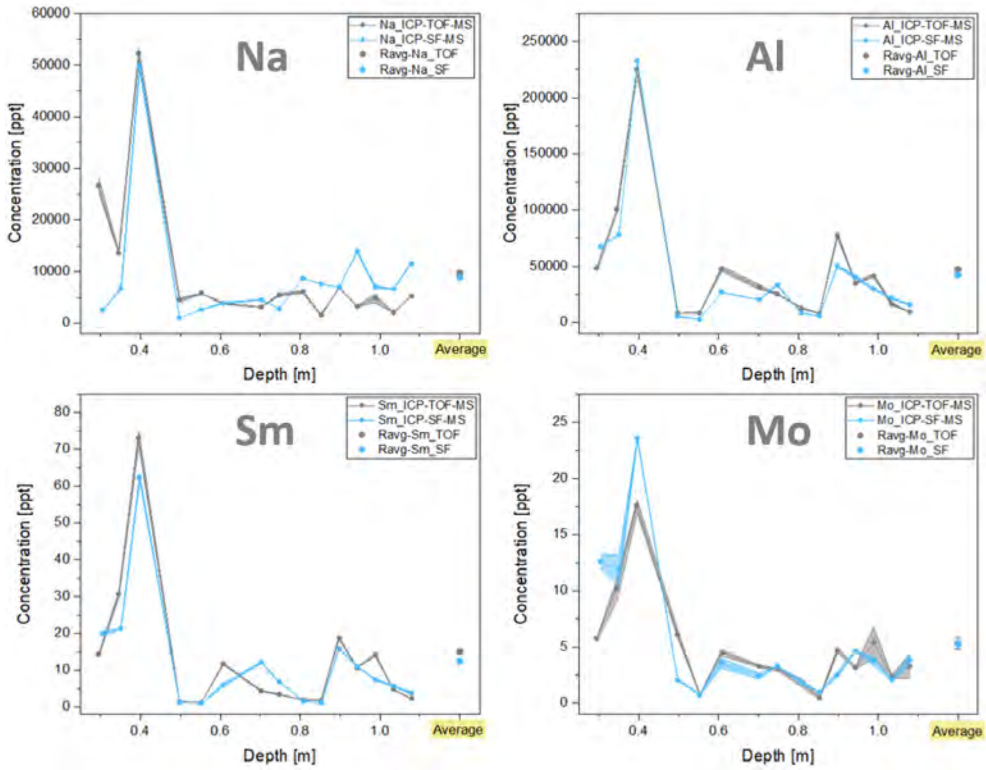


Figure 2: Comparability of the measurements with both instruments (ICP-SF-MS and ICP-TOF-MS)

References

[1] S.M. Aarons et al., Ice core record of dust sources in the western United States over the last 300 years, *Chemical Geology*, **442**, 160, (2016), 10.1016/j.chemgeo.2016.09.006

[2] F.E. Grousset, P.E. Biscaye, Tracing dust sources and transport patterns using Sr, Nd and Pb isotopes, *Chemical Geology*, **222**, 149, (2005), 10.1016/j.chemgeo.2005.05.006

[3] B. Delmonte et al., Aeolian dust in East Antarctica (EPICA-Dome C and Vostok): Provenance during glacial ages over the last 800 kyr, *Geophysical Research Letters*, **35**, (2008), 10.1029/2008GL033382

[4] R. Arimoto, Eolian dust and climate: relationships to sources, tropospheric chemistry, transport and deposition, *Earth-Science Reviews*, **54**, 29, (2001), 10.1016/S0012-8252(01)00040-X

[5] https://earth.google.com/web

Using storymaps to convey climate change impacts on the spatiotemporal dynamics of river flood events

Lukas Munz[1], Olivia Martius [1], Martina Kauzlaric[1], Markus Mosimann[1], Anna Fehlmann[2], Andreas Zischg[1]

[1]University of Bern, Institute of Geography, Mobiliar Lab for Natural Risks and Oeschger Centre for Climate Change Research, Bern, Switzerland
[2]Mobiliar Insurance, Mobiliar Lab for Natural Risks, Bern, Switzerland

Communicating flood risk information to decision makers and the public is crucial to encourage proactive action for flood protection and hazard mitigation. In order to develop a way to convey scientific insight and data on flood risk we conducted a participatory development process together with stakeholders. This process resulted in an online tool to generate storymaps of local and national extreme flood events. Our storymaps combine dynamic, interactive maps with the storyline approach. Storylines are increasingly used to convey the possible rather than the probable [1]. We have adopted this method to communicate possible river floods in Switzerland resulting from extreme precipitation events.

Data on extreme events is scarce by definition. We address this issue by selecting extreme events from a pool of hindcasts (SNSext (1998-2017, 11 members) and SEAS5 (1981-2017, 25 members)) equivalent to 8400 years of data [2]. The selected precipitation events were used as a starting point for a comprehensive model chain including a hydrological model with a river routing module, a hydrodynamic model for the inundation modelling and an impact module for assessing the flood impacts on buildings, roads, and critical facilities such as schools and retirement homes, including the number of affected people.

With the ongoing climate change, heavy precipitation events in central Europe are expected to increase in terms of intensity, frequency [3], spatial extent [4] and duration. In other words, today's extreme precipitation events are expected to occur with higher probability. It is therefore interesting to know if and where such events will have an increasing impact to our society.

As a next step, we will simulate the increasing precipitation due to the ongoing climate change and estimate the impact on the river network and the flood impacts. Therefore, we will perturb the precipitation scenarios and rerun the model chain. A sensitivity analysis of the exposed settlement area may reveal places of particular interest with regard to cost / benefit for flood protection and flood impact mitigation.

References

[1] K.M. de Bruijn et al., The storyline approach: a new way to analyse and improve flood event management, *Natural Hazards* **81**, 99 (2016), 10.1007/s11069-015-2074-2.

[2] V. Thompson et al., High risk of unprecedented UK rainfall in the current climate, *Nature Communications* **8**, 107 (2017), 10.1038/s41467-017-00275-3

[3] S.C. Scherrer et al., Emerging trends in heavy precipitation and hot temperature extremes in Switzerland, *Journal of Geophysical Research: Atmospheres* **121**, 2626 (2016), 10.1002/2015JD024634

[4] D. Matte et al., Spatial extent of precipitation events: when big is getting bigger, *Climate Dynamics* **58**, 1861 (2021), 10.1007/s00382-021-05998-0

Optimizing long-term projections of hydrometeorlogical parameters and compound events in an East Asian domain using an ensemble of bias correction methods, EAS-CORDEX models, and future scenarios

Patrick Olschewski[1], Jianhui Wei[1], Patrick Laux[1,2], Harald Kunstmann[1,2]

[1]Karlsruhe Institute of Technology - Campus Alpin, 82467 Garmisch-Partenkirchen, Germany
[2]University of Augsburg - Institute of Geography, 86159 Augsburg, Germany

Events of extreme weather have recently gained in public attention. Examples of such events are the series of heat and drought events in Central Europe during 2018 and 2019, typhoon Mangkhut causing damages in the billions in 2018, and the heatwave over Pakistan and India in March 2022, affecting the health of millions of residents. A distinct linkage between ongoing climate change and extreme events has been established [1, 2], and is also subject of discussion in the latest IPCC report [3]. This rises the need for robust and sound climate projections, especially for densely populated regions of high socioeconomic importance, such as East Asia [4, 5].

To contribute towards the establishment of a high level of protection and to finally design and implement effective adaption measures, the Sino-German project MitRiskFlood aims at optimizing regional climate projections and discussing long-term trends in hydrometeorological predictors, as well as trends in univariate extreme events and compound events. This can be achieved by consulting model output from general circulation models (GCM) and regional climate models (RCM). These models inherit systematic errors (bias) that must be addressed prior to climatological analysis. We therefore locally adapt the latest EAS-CORDEX GCM-RCM simulations and optimize the runs by using an ensemble of bias correction methods, model runs, and RCP scenarios [6, 7].

Optimized long-term projections are analyzed for 2080-2100 and compared to 1980-2000. The model mean of daily maximum 2m air temperature is projected to increase by 1.5 K in the annual mean for RCP scenario 2.6, and by nearly 4 K for RCP scenario 8.5. In terms of precipitation projections, an increase in the annual sum can be detected for scenario 8.5. Remarkable uncertainties, however, remain. Analysis of changes in specific percentile-based thresholds unveils a particular increase in the heavy tail of the distribution of both variables. The increases in the heavy tail exceed the mean increase of the corresponding variable for daily extreme events exceeding the 95^{th} percentile.
We analyse compound events of heavy precipitation (> 99^{th} percentile) and tropical cyclone force-winds (> 17.5 m s^{-1}, [8]), and consider events taking place at the same location and at the same time, while allowing for a maximum lag of one day [9, 10]. Results for 2080-2100 show a statistically significant increase in the annual number of days with compound events over the South China Sea and reaching into the densely populated coastal areas. This increase can be seen for both RCP scenarios, yet increases are amplified under scenario 8.5.

Further research questions could include a deeper understanding of changes in the physical relationship between the predictors, as well as changes in statistical dependencies [11]. Further optimization could be achieved by including additional bias correction methods, e.g. multivariate bias correction and deep learning. These methods could also be applied to station-based data to refine the obtained results on a local scale. This analysis could then be repeated with a special focus on densely populated and highly vulnerably urban locations, for example Shanghai and Shenzhen.

References

[1] J. A. Torres-Alavez et al., Future projections in tropical cyclone activity over multiple CORDEX domains from RegCM4 CORDEX-CORE simulations, *Climate Dynamics* **57**, 1507 (2021),

https://doi.org/10.1007/s00382-021-05728-6.

[2] J. Sun, J. Ao, Changes in precipitation and extreme precipitation in a warming environment in China, *Chinese Science Bulletin* **58**, 1395 (2013), https://doi.org/10.1007/s11434-012-5542-z.

[3] IPCC, Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. 2021. Cambridge University Press. In Press.

[4] S. Hanson, R. Nicholls, N. Ranger, S. Hallegatte, J. Corfee-Morlot, C. Herweijer, J. Chateau, A global ranking of port cities with high exposure to climate extremes, *Climatic Change* **104**, 89 (2011), https://doi.org/10.1007/s10584-010-9977-4.

[5] G. M. Sarica, T. Zhu, W. Jian, E. Y.-M. Lo, T.-C. Pan, Spatio-temporal dynamics948 of flood exposure in Shenzhen from present to future, *Environment and Planning B: Urban Analytics and City Science* **48**, 1011 (2021), https://doi.org/10.1177/2399808321991540.

[6] L. Gudmundsson, J. B. Bremnes, J. E. Haugen, T. Engen-Skaugen, Technical Note: Downscaling RCM precipitation to the station scale using statistical transformations - A comparison of methods, *Hydrology and Earth System Sciences* **16**, 3383 (2012), https://doi.org/10.5194/hess-16-3383-2012.

[7] A. J. Cannon, S. R. Sobie, T. Q. Murdock, Bias correction of GCM precipitation by quantile mapping: How well do methods preserve changes in quantiles and extremes?, *Journal of Climate* **28**, 6938 (2015), https://doi.org/10.1175/JCLI-D-14-00754.1.

[8] K. J. E. Walsh, M. Fiorino, C. W. Landsea, K. L. McInnes, Objectively Determined Resolution-Dependent Threshold Criteria for the Detection of Tropical Cyclones in Climate Models and Reanalyses, *Journal of Climate* **20**, 2307 (2007), https://doi.org/10.1175/JCLI4074.1.

[9] J. Zscheischler et al., A typology of compound weather and climate events, *Nature Reviews Earth & Environment* **1**, 333 (2020), https://doi.org/10.1038/s43017-020-0060-z.

[10] O. Martius, S. Pfahl, C. Chevalier, A global quantification of compound precipitation and wind extremes, *Geophysical Research Letters* **43**, 7709 (2016), https://doi.org/10.1002/2016GL070017.

[11] J. Zscheischler, P. Naveau, O. Martius, S. Engelke, C. C. Raible, Evaluating the dependence structure of compound precipitation and wind speed extremes, *Earth System Dynamics* **12**, 1 (2021), https://doi.org/10.5194/esd-12-1-2021.

Challenges in Dynamical Downscaling and Data Assimilation Within the Early Instrumental Era

Lucas Pfister[1,2], Peter Stucki[1,2], Andrey Martynov[1,2], Stefan Brönnimann[1,2]

[1]Institute of Geography, University of Bern, Switzerland
[2]Oeschger Centre for Climate Change Research, University of Bern, Switzerland

In Europe, the 19th century was characterised by several events of extreme weather, ranging from cold spells, wet summers and floods to droughts. Many of these have been analysed based on a number of early meteorological measurements, as well as on ample documentary information. For some regions, even statistical reconstructions of spatial fields with daily resolution have been conducted for a small set of surface variables. However, these datasets provide only limited information on the processes that led to such disastrous events.

In turn, dynamical downscaling methods combined with data assimilation of station records allow to combine several sources of information and to reconstruct past weather in three dimensions and on a higher temporal and spatial resolution. While this approach has so far been restricted mainly to the 20th century due to a lack of prior atmospheric boundary conditions, the newest version of the 20th century reanalysis (20CRv3) opens a new chapter, allowing us to go back in time to the early 19th century [4]. Furthermore, data rescue and digitisation activities in the last decades brought to light a vast amount of meteorological station records covering over 200 years in total [1, 2].

In our work, we assess the possibilities and challenges of this approach on the example of the summer 1816 in Europe - a particularly interesting episode due to the catastrophic aftereffects of the volcanic eruption of Mt. Tambora in the previous year [5]. We simulate one of the coldest episodes in June 1816 by downscaling data from 20CRv3. The simulation uses the Weather Research and Forecasting (WRF) model [3] with three nested domains for the greater Alpine region and provides hourly output with a 3-km resolution. In addition, we include recently digitised station series of temperature and pressure for a Three-Dimensional Variational (3DVAR) data assimilation in the innermost domain. Simulations are then validated against independent station observations.

First results suggest that dynamical downscaling and data assimilation may become a promising approach to obtain physically consistent information on past weather on a local and subdaily scale. This may hold even for extreme events in an era with a scarce network of instrumental weather observations compared to today, although erroneous results may occur. Particular attention should be paid to the data assimilation system, as early instrumental records exhibit larger uncertainties compared to today. Quality control and homogenisation efforts are therefore advisable. Furthermore, our simulations show that spectral nudging in the outermost domain leads to the most accurate results. Although further research is needed, also considering different case studies, a successful application of dynamical downscaling and data assimilation for the early 19th century might even open the door for a regional atmospheric reanalysis product that covers the last two centuries.

References

[1] Brugnara, Y. Auchmann, R., Brönnimann, S., Allan, R. J., Auer, I., Barriendos, M., Bergström, H., Bhend, J., Brázdil, R., Compo, G. P., Cornes, R. C., Dominguez-Castro, F., van Engelen, A. F. V., Filipiak, J., Holopainen, J., Jourdain, S., Kunz, M., Luterbacher, J., Maugeri, M., Mercalli, L., Moberg, A., Mock, C. J., Pichard, G., Řezníčková, L., van der Schrier, G., Slonosky, V., Ustrnul, Z., Valente, M. A., Wypych, A., Yin, X.: A collection of sub-daily pressure and temperature obser-

vations for the early instrumental period with a focus on the "year without a summer" 1816, *Clim. Past*, **11(8)**, 1027–1047, doi:10.5194/cp-11-1027-2015, 2015.

[2] Brugnara, Y., Pfister, L. M., Villiger, L., Rohr, C., Alessandro Isotta, F., Brönnimann, S., Isotta, F. A. and Brönnimann, S.: Early instrumental meteorological observations in Switzerland: 1708-1873, *Earth Syst. Sci. Data*, **12(2)**, 1179–1190, doi:10.5194/essd-12-1179-2020, 2020.

[3] Skamarock, W. C., Klemp, J. B., Dudhia, J., Gill, D. O., Liu, Z., Berner, J., Wang, W., Powers, J.G., Duda, M.G., Barker, D.M., Huang, X.-yu.: A Description of the Advanced Research WRF Model Version 4.3, No. *NCAR Technical Notes*, **NCAR/TN-556+STR**, doi:10.5065/1dfh-6p97, 2021.

[4] Slivinski, L. C., Compo, G. P., Whitaker, J. S., Sardeshmukh, P. D., Giese, B. S., McColl, C., Allan, R., Yin, X., Vose, R., Titchner, H., Kennedy, J., Spencer, L. J., Ashcroft, L., Brönnimann, S., Brunet, M., Camuffo, D., Cornes, R., Cram, T. A., Crouthamel, R., Domínguez-Castro, F., Freeman, J. E., Gergis, J., Hawkins, E., Jones, P. D., Jourdain, S., Kaplan, A., Kubota, H., Blancq, F. Le, Lee, T.-C., Lorrey, A., Luterbacher, J., Maugeri, M., Mock, C. J., Moore, G. W. K., Przybylak, R., Pudmenzky, C., Reason, C., Slonosky, V. C., Smith, C. A., Tinz, B. Trewin, B., Valente, M. A., Wang, X. L., Wilkinson, C., Wood, K., Wyszyński, P.: Towards a more reliable historical reanalysis: Improvements for version 3 of the Twentieth Century Reanalysis system, *Q. J. R. Meteorol. Soc.*, **145(724)**, 2876–2908, doi:10.1002/qj.3598, 2019.

[5] Stothers, R.B.: The Great Tambora Eruption in 1815 and Its Aftermath, *Science*, **224(4654)**, 1191-1198, doi:10.1126/science.224.4654.1191, 1984.

Modelling present and future hail damages to agricultural crops

Raphael Portmann[1], Pierluigi Calanca[1], Rebekka Adams-Selin[2], Martin Aregger[3,4], Marco Arpagaus[4], Nikolina Ban[5], Kilian Brennan[6], David Bresch[6], Ruoyi Cui[6], Marie-Estelle Demory[6], Urs Germann[4], Alessandro Hering[4], Annelie Holzkämper[1], Olivia Romppainen-Martius[3], Christoph Schär[6], Katharina Schroer[7], Timo Schmid[6], Cornelia Schwierz[4], Lena Wilhelm[3], Heini Wernli[6]

[1]Agroscope Reckenholz, Zurich, Switzerland
[2]Atmospheric and Environmental Research, Lexington, United States
[3]University of Berne, Berne, Switzerland
[4]Meteoswiss, Zurich, Switzerland
[5]University of Innsbruck, Innsbruck, Austria
[6]ETH Zurich, Zurich, Switzerland
[7]University of Freiburg, Freiburg, Germany

Hail remains one of the main climatic risks for agricultural crops and infrastructure. Forecasting hail occurence on both, the weather and climate time scale remains extremely challenging due to the complex small scale processes involved in hail formation. However, assessing the implications of climate change for hail risk is of paramount importance for informing adaptation. Within the SNF-sinergia project "Seamless coupling of kilometre-resolution weather predictions and climate simulations with hail impact assessments for multiple sectors (scClim)" we combine expertise from high resolution weather and climate modeling, climate risk modeling, observational hail research in Switzerland, agricultural research and stakeholders to provide a comprehensive assessment of hail risk in Switzerland in present and future climates [1]. The project encompasses five subprojects: A) Co-development of a hail impact assessment platform for multiple sectors, B) Hail in weather and climate modeling, C) Observations of hail, interannual variability and model validation, D) Modeling hail damage to agriculture, and E) Modeling hail damage to buildings and cars.
Subproject D), to which we contribute, focuses on hail damages to crops. One of the first key challenges in this subproject is the development of a robust approach for linking damages to field crops (Fig.1) to properties of hailfall. It is essential that the approach is able to simulate the chronological interplay between time of hailfall and crop phenology [2] and therefore account for the dynamic nature of crop exposure and vulnerability. To achieve this goal, we combine data obtained from the literature, crop phenology data and models, and loss data provided by stakeholders. The resulting dynamic model component will be integrated into the open source, event-based risk modelling platform CLIMADA [3] (Fig. 2), which will ultimately be used for post hazard and climate change impact assessments.
In the poster, we showcase the underlying risk modeling framework, discuss the challenges that the implementation of such a model chain faces and how we aim to overcome these challenges.

References

[1] scClim Website: https://scclim.ethz.ch/

[2] Schiesser, H.H.:. Hailfall: The relationship between radar measurements and crop damage, Atmos. Res., 25, 559-82, https://doi.org/10.1016/0169-8095(90)90038-E

[3] Aznar-Siguan, G. and Bresch, D. N.: CLIMADA v1: a global weather and climate risk assessment platform, Geosci. Model Dev., 12, 3085–3097, https://doi.org/10.5194/gmd-12-3085-2019, 2019.

Figure 1: Corn field damaged by a hailstorm in Summer 2021 in Switzerland. Credits: Ennio Leanza / Keystone. Source: https://www.nzz.ch/zuerich/unwetter-in-zuerich-grosser-ernte-schaden-bei-bauern-und-winzern-ld.1638842?reduced=true

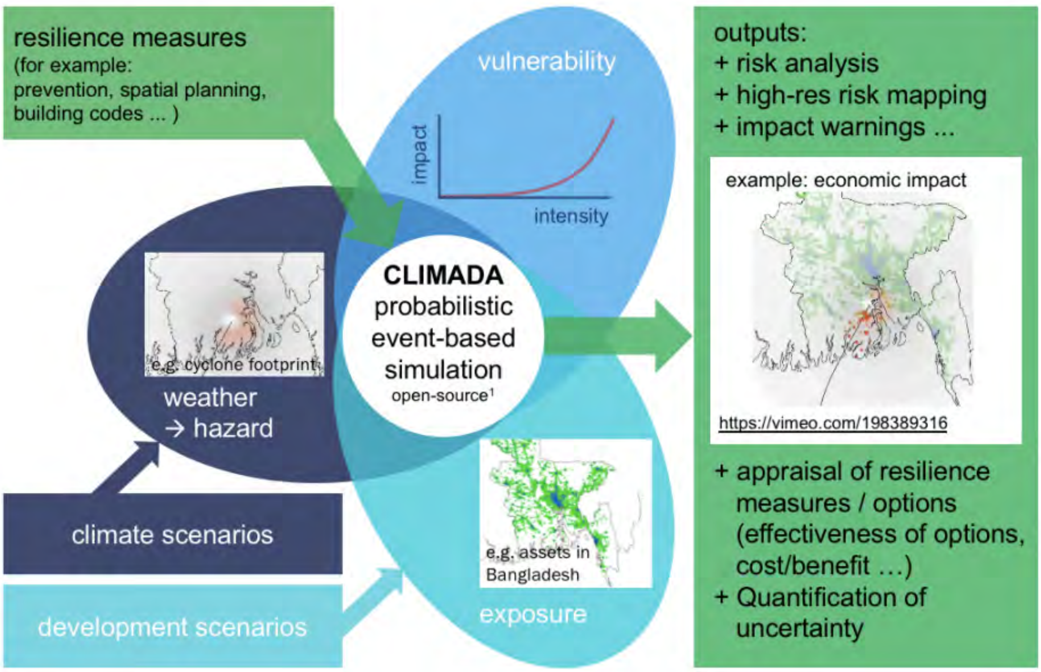


Figure 2: Schematic of the functionalities of the risk assessment platform CLIMADA. Source: https://wcr.ethz.ch/research/climada.html

A systematic review of drivers and dynamics in flood risk evolution assessments

Nele Rindsfüser[1,2], Andreas Paul Zischg[1,2], Margreth Keiler[3,4]

[1]Oeschger Centre for Climate Change Research, Mobiliar Lab for Natural Risks, University of Bern, Bern, Switzerland
[2]Institute of Geography, University of Bern, Bern, Switzerland
[3]Department of Geography, University of Innsbruck, Innsbruck, Austria
[4]Institute of Interdisciplinary Mountain Research, Austrian Academy of Sciences, Innsbruck, Austria

The future is unknown. What is obvious for all areas of modern civilization has far-reaching consequences when major decisions are to be made that affect the future.

Flood risk management is confronted with deep uncertainties in future evolution of natural and human systems. Socio-economic development, climate change or changes in the natural environment influence drivers of flood risk evolution [1, 2, 3]. Changes and dynamics of drivers of flood risk evolution pose major challenges for flood risk management strategies. Thus, new management strategies are required to ensure the safety level of humans and their assets and reduce losses from floods. Adaptive management is a strategy to cope with such uncertainties [4]. Basis for adaptive flood risk management is the knowledge and monitoring of (1) the actual system state, (2) the evolution of system components and (3) system dynamics such as interactions and feedbacks between system components.

Against this background, the first step is a scientific literature review on flood risk evolution, their related concepts and potential factors influencing flood risk evolution. Further, methods and approaches that enable the identification of those influencing factors are evaluated. Our analyses are based on a systematic search and review of scientific articles on flood risk evolution listed in SCOPUS and Web of Science since 2000. An in-depth content analysis of the selected papers is conducted in the software program MAXQDA. Coding and content analysis is based on the following guiding questions:

1. How is flood risk conceptualised in studies?
2. Which approaches, methods, and tools are used to assess flood risk evolution?
3. What is the spatial distribution of existing studies?
4. What are the main drivers of flood risk evolution, and how are they classified/characterised? Are there commonalities and differences regarding the drivers of flood risk evolution? What are the most relevant drivers of flood risk evolution?
5. Are spatial and/or temporal dimensions of flood risk evolution considered/assessed?
6. Are feedbacks and interactions between drivers of flood risk evolution considered/ assessed?

The content analysis and synthesis of the scientific literature is current work. Thus, results are not ready yet but planned until end of August. As a next step, the analysis and synthesis of the scientific literature will be conducted. This will provide important information to conceptualise an approach that enables a robust analysis of flood risk evolution including drivers of flood risk evolution and their dynamics.

References

[1] A. P. Zischg et al., Flood risk (d)evolution: Disentangling key drivers of flood risk change with a retro-model experiment, *Science of The Total Environment* **639**, 195 (2018), 10.1016/j.scitotenv.2018.05.056.

[2] F. Elmer et al., Drivers of flood risk change in residential areas *Natural Hazards and Earth System Sciences* **12**, 1641 (2012), 10.5194/nhess-12-1641-2012.

[3] A. Domeneghetti et al., Evolution of flood risk over large areas: Quantitative assessment for the Po river, *Journal of Hydrology* **527**, 809 (2015), 10.1016/j.jhydrol.2015.05.043.

[4] K. Emami, Adaptive Flood Risk Management, *Irrigation and Drainage* **69**, 230 (2020), 10.1002/ird.2411.

Using temperature and precipitation combined to detect and attribute aerosol effects on large-scale climate

Carla Roesch[1], Andrew Ballinger[1], Andrew Schurer[1], Gabriele Hegerl[1]

[1]University of Edinburgh, School of GeoSciences, Edinburgh, United Kingdom

Anthropogenic aerosols (AER) have been found to impact both Earth's energy and water cycle. Like greenhouse gases (GHG), they are an anthropogenic climate forcing that will play an important role in shaping Earth's future climate. Therefore, to improve future predictions, it is fundamental to understand and quantify the individual impacts these two forcings have on the climate system over the historical period. However, the separation of the signals is hindered by large uncertainties in the response to aerosol forcing in different climate models. To differentiate between the responses of the climate system to different forcings we are applying optimal detection methods using regularised optimal fingerprinting, which has been implemented in Python [1]. Here, model-derived response patterns (fingerprints) are regressed (total least squares) against observations to retrieve scaling factors giving the magnitude of each fingerprint in the observations. Uncertainties in the scaling factors are estimated by adding multiple samples of climate noise from the model internal variability to both the fingerprints and observations. A fingerprint is detectable if the estimate of its scaling factor is larger than zero. In this study we investigate whether combining the fingerprints of temperature and precipitation can increase the signal-to-noise ratio and better constrain the impact of anthropogenic aerosols.

Building on previous findings of aerosols effects on climate, we focus on tropical precipitation by tracking wet and dry regions (1988-2020) [2] using data from the Global Precipitation Climatology Project (GPCP;[3]), as well as changes in the interhemispheric temperature asymmetry (ITA; [4]) (1955-2020) using the HadCRUT5 dataset [5]. Large ensembles of historical simulations from three models (CanESM5, CNRM-CM6-1, IPSL-CM6A-LR) that are part of phase 6 of the Coupled Model Intercomparison Project (CMIP6; [6]) are used to derive fingerprints, including all external forcings (ALL) and anthropogenic aerosol-only forcing (AER). We also use an additional fingerprint for the remaining forcings (primarily GHG), where the AER fingerprint is subtracted from the ALL fingerprint (ALL-AER). The model fingerprints and observational time series are presented in Figure 1.

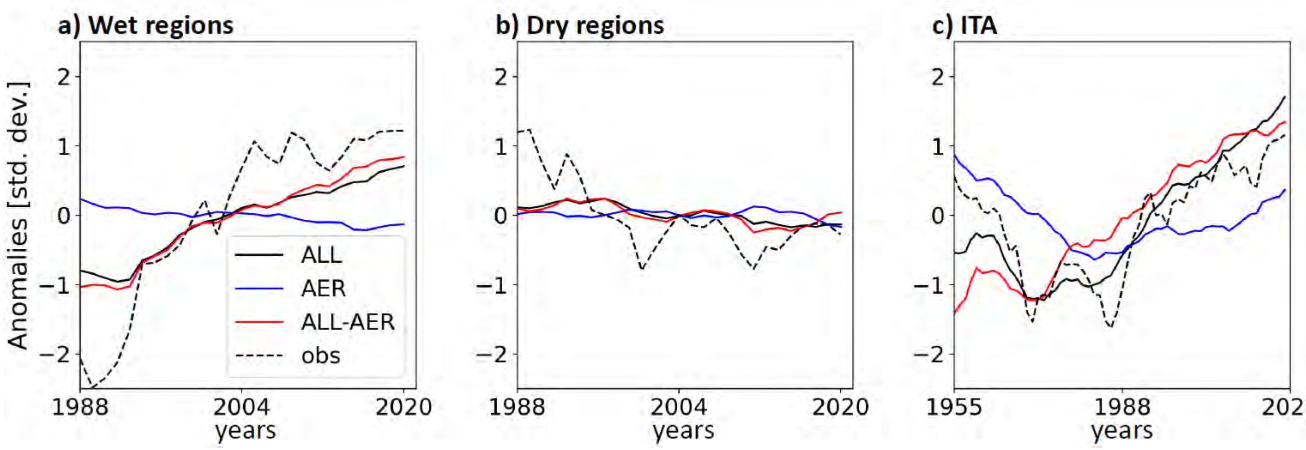


Figure 1: Time series of the ALL (black), AER (blue) and ALL-AER (red) multimodel mean annual anomalies (standardized), along with the observed anomalies (dashed black; GPCP/HadCRUT5) of **(a)** tropical wet- and **(b)** dry-region precipitation, and **(c)** the ITA. The ALL-AER signal is derived by subtracting the AER-only from the ALL-forcing signal.

Figure 2 shows the results for a 1-signal (regressing the ALL fingerprint onto the observations) and 2-signal analysis (regressing both the ALL-AER and AER fingerprints onto the observations) for the multimodel mean (MMM) and individual model means. When comparing the individual (Fig.2a-c) and the combined precipitation and temperature fingerprints (Fig.2d), we estimate a narrower range for the ALL scaling factor (in the MMM), and also for the ALL-AER vs AER scaling factors, for some of the individual models. Our preliminary findings indicate that combining temperature and precipitation information helps to quantify the aerosol impact on large-scale climate over the past several decades, yielding more robust results across models. However, these results are dependent on the precipitation sensitivity being correctly represented in the models.

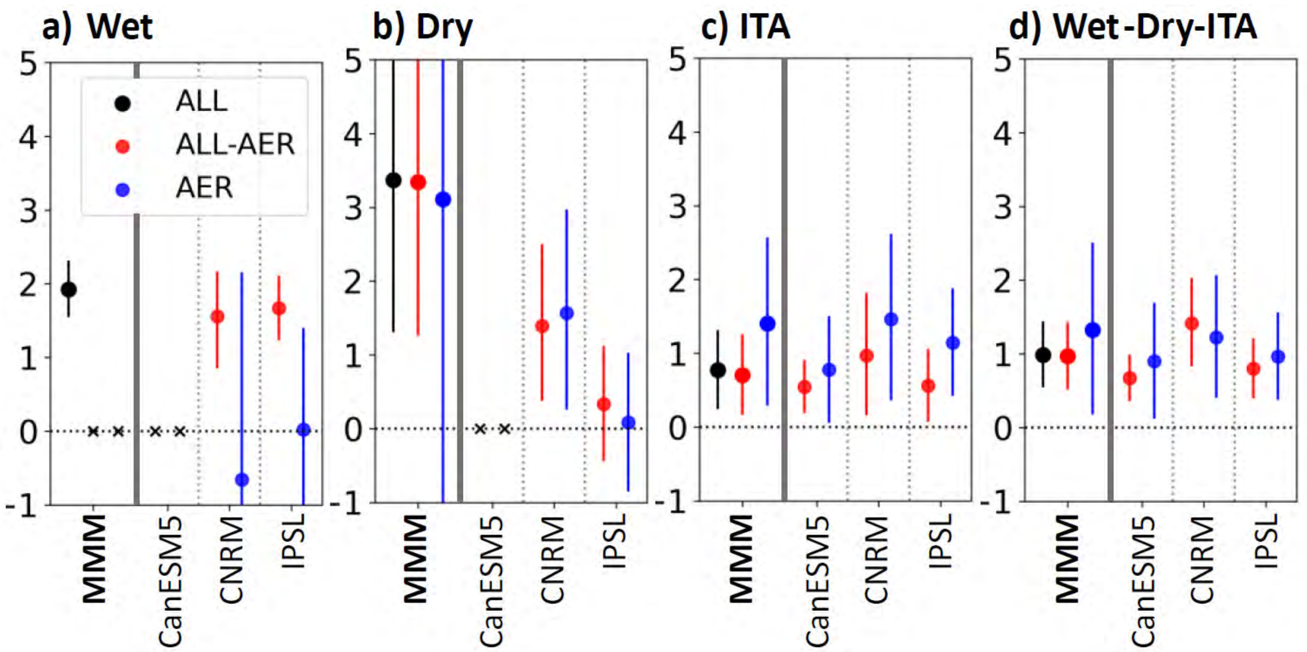


Figure 2: Detection and attribution of observed changes in tropical **(a)** wet- and **(b)** dry-region precipitation, **(c)** the ITA, and **(d)** the combined time series, from a 1-signal (ALL, black) and 2-signal (ALL-AER, red; AER, blue) total least squares regression analysis. Circles show the best estimate of the scaling factor with the vertical lines denoting the 90% confidence intervals. Crosses indicate where scaling factors cannot be retrieved.

References

[1] M. C. Kirchmeier-Young et al., Attribution of extreme events in Arctic sea ice extent, *Journal of Climate* **30**, 553 (2017), 10.1175/JCLI-D-16-0412.1

[2] A. P. Schurer et al., Human influence strengthens the contrast between tropical wet and dry regions, *Environmental Research Letters* **15**, 104026 (2020), 10.1088/1748-9326/ab83ab

[3] R. F. Adler et al., The Global Precipitation Climatology Project (GPCP) monthly analysis (new version 2.3) and a review of 2017 global precipitation, *Atmos.* **9**, 138 (2018), 10.3390/atmos9040138

[4] A. R. Friedman et al., Interhemispheric temperature asymmetry over the twentieth century and in future projections, *Journal of Climate* **26**, 5419 (2013), 10.1175/JCLI-D-12-00525.1

[5] C. P. Morice et al., An updated assessment of near-surface temperature change from 1850: the HadCRUT5 dataset, *Jour. Geophys. Res. Atmos.* **126**, e2019JD032361 (2021), 10.1029/2019JD032361

[6] V. Eyring et al., Overview of the Coupled Model Intercomparison Project Phase 6 (CMIP6) experimental design and organization, *Geos. Mod. Develop.* **9**, 1937 (2016), 10.5194/gmd-9-1937-2016

Heatwaves over Europe: Improving the forecast on the subseasonal range

Emmanuel Rouges[1,2], Laura Ferranti[1], Holger Kantz[2] and Florian Pappenberger[1]

[1]European Centre for Medium-Range Weather Forecast (ECMWF), United Kingdom (emmanuel.rouges@ecmwf.int)
[2]Technische Universität Dresden (TU-Dresden), Dresden, Germany

Heatwaves have important impacts on society and our environment. In Europe for instance, the summer of 2003 caused upwards of 40000 fatalities. They also impact the crop production, ecosystems, and infrastructures. In a warming climate, heat wave intensity and frequency are likely to increase with potentially more dramatic consequences.

Considering this, it is crucial to forecast such extreme events and therefore gain a better understanding of their triggering processes. The determination of these processes requires to identify heatwave patterns (timing and location) together with the correlated large-scale circulation patterns. This will enable to devise early warning systems, that could help mitigate the impact.

The goal is to improve the forecasts of heatwaves over the European region on the sub-seasonal scale (10 to 60 days). In the first part we evaluate links between large scale weather patterns and severe warm events over Europe. We identify 5 main heatwave types and associated atmospheric circulation by applying a k-means clustering method and using ERA5 reanalysis data from ECMWF. We further determine key characteristics of these circulation patterns influencing heat wave occurrence. We investigate the potential impact of tropical forcing on heatwaves. We use a simplified index to monitor the Boreal Summer Instraseasonal Oscillation (BSISO) and determine the importance of tropical forcing on heatwave occurrence.

In the second part, we measure the current level of predictive skill of the ECMWF model. Using reforecast data, we assess the capacity of the model in predicting extreme temperature and identifying the circulation patterns responsible for heatwaves. We then use the previous findings to estimate how the forecast of heatwaves can be improved in the sub-seasonal scale. The circulation patterns associated with heatwaves are used to infer the probability of extreme surface temperatures. The forecast is further analysed by determining the influence of the BSISO on confident and accurate forecast.

This work is part of the Climate Advanced Forecasting of sub-seasonal Extremes (CAFE) project, funded by the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No 813844.

What are the dynamical drivers of large-scale 100-year and more moderate extreme precipitation events over Central European river catchments?

Florian Ruff, Stephan Pfahl

Freie Universität Berlin, Berlin, Germany

The largest impacts of extreme river floodings are caused by very rare events with return periods on the order of 100 years. Within the last two decades, several extreme precipitation events occurred over Central European river catchments (e.g. Elbe, Oder or Danube) and triggered severe flooding events. Previous studies mainly focused on single analyses of these historical events [1, 2].

In this project, a robust analysis of the general atmospheric dynamics of 100-year precipitation extremes and their differences to more moderate extreme events (20- to 50-year) is processed. In order to do so, operational ensemble prediction data from the ECMWF with several ensemble member are used, based on the methodology of [3]. From all simulations, the daily precipitation sum of each 10th forecast day is selected. Several statistical analyses are processed beforehand which ensure the usability of the ensemble data set. These realistic but simulated daily precipitation fields add up to a time series of about 1200 years from which several 100-year and more moderate extreme events can be selected. The dynamical drivers are identified by composite analyses.

In a first step, the dynamics of 100-year extremes are identified. Such events are generally associated with an upper-level trough over Western Europe the day before the event. This trough cuts off while moving towards the southeast of the specific river catchment. This is also in combination with a surface cyclone at this position, as it is shown in Fig. 1 for events over the Danube catchment. Additionally, high atmospheric moisture is available in the lower troposphere and is mainly advected from Mediterranean areas and Eastern Europe.

In a second step, the 100-year event dynamics are compared to those of more moderate extreme events. Analyses of certain catchments like Danube show that more intense precipitation events are associated with an intensification of dynamical mechanisms like an intensified upper-level and surface cyclone. Thermodynamic characteristics do not play a major role. However, catchments like Elbe show the opposite. Here, increased thermodynamic characteristics like higher temperatures and an increased moisture supply in the lower troposphere east of the catchment are more important for intensified precipitation extremes than changes in dynamical mechanisms, as it is shown in Fig. 2.

Upcoming analyses include climate simulations of the CESM Large Ensemble in order to analyse the atmospheric dynamics of such extreme precipitation events in a warmer climate and their changes to events in the current climate.

References

[1] C. M. Grams et al., Atmospheric processes triggering the central European floods in June 2013, *Natural Hazards and Earth System Sciences* **14**, 1691 (2014), 10.5194/nhess-14-1691-2014.

[2] U. Ulbrich et al., The central European floods of August 2002: Part 2-Synoptic causes and considerations with respect to climatic change, *Weather* **58**, 434 (2003), 10.1256/wea.61.03B.

[3] Ø. Breivik et al., Wave extremes in the northeast Atlantic from ensemble forecasts, *Journal of Climate* **26**, 7525 (2013), 10.1175/JCLI-D-12-00738.1.

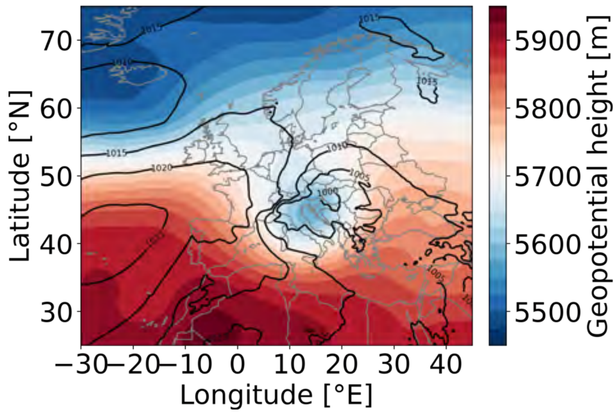


Figure 1: Composite of the geopotential height at 500 hPa with the sea level pressure composite as contours for all identified 100-year precipitation events over the Danube catchment.

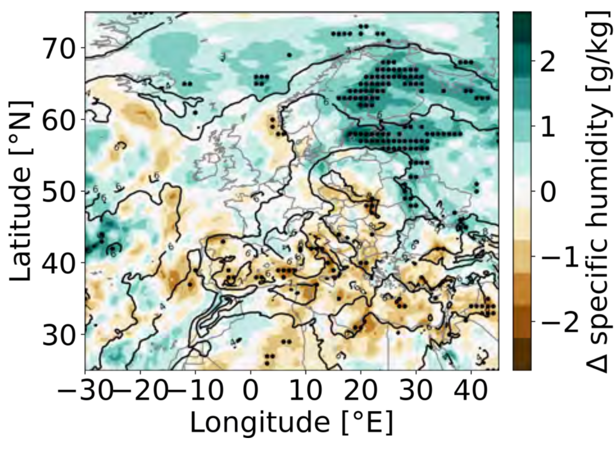


Figure 2: Difference between the 100-year and more moderate extreme event composite of the specific humidity at 850 hPa for events over the Elbe catchment. Positive (negative) values represent higher (lower) values in the 100-year composite. Significant differences are marked by black dots. The composite for more moderate extreme events is shown as black contours.

High-resolution modeling of historical forest fires in the canton of Bern

Renuka P. Shastri[1], Stefan Brönnimann [1], Daniel Steinfeld[1]

[1]Institute of Geography and Oeschger Centre for Climate Change Research, University of Bern, Switzerland

Forest fires are considered an important hazard in forested areas and a serious threat to forest ecosystem and buildings. The combination of drought, high temperatures and wind, increases the risk of forest fires. To better understand the fundamental causes and consequences of fire, we need to study the historical fire regimes. In this study, the meteorological conditions were simulated with the WRF model (Weather Research and Forecasting; Skamarock et al. 2008) for three historical forest fires, in the Canton of Bern, Switzerland (La Neuveville, April 1893, Simmenflueh, August 1911, Kirchberg, April 1915). In terms of area, these are the largest fires in the canton of Bern in the Swiss fire database. The "Twentieth Century Reanalysis" version 3 (20CRv3, Slivinski et al. 2019) was used as a boundary condition. 20CRv3 has a spatial resolution of about 75 km and a temporal resolution of three hours. Using WRF version 4.1.2 20CRv3 has now been gradually downscaled to a resolution of 1x1km^2 . Simulations suggest that the soil had dried out in the previous week and soil moisture had reached low values on the day the fire broke out. High-resolution fire weather indices are also calculated. A lack of precipitation and high temperatures led to high forest fire index values and a high to very high risk of forest fires.

References

[1] Slivinski, L. C.et al. (2019), Towards a more reliable historical reanalysis: Improvements to the Twentieth Century Reanalysis system. , *Q. J. Roy. Meteorol. Soc. 145, 2876-2908*.

[2] Pfister, L. , S. Brönnimann, M. Schwander , FA Isotta , P. Horton, and C. Rohr, (2020) Statistical Reconstruction of Daily Precipitation and Temperature Fields in Switzerland back to 1864, *Clim . past 16, 663-678.*

[3] *Skamarock , WC, et al. (2008) A Description of The Advanced Research WRF Version 3. NCAR Technical Note*.

[4] *Van Wagner, C.E. (1987): Development and Structure of the Canadian Forest Fire Weather Index System, Forestry Technical Report, Canadian Forestry Service Headquarters, Ottawa*.

Dynamical and thermodynamical contribution to contrasting trends in hot extremes over Midwest USA and Central Europe

Jitendra Singh[1], Sebastian Sippel[1], Erich Fischer[1]

[1]Institute for Atmospheric and Climate Science, ETH Zurich, Zurich, Switzerland

Previous studies have identified significant cooling of hot extremes over Midwest USA and warming over central Europe (CEU). We use multiple observations and Earth System Model large ensemble simulations to investigate whether these contracting trends are due to regional weather pattern changes dominated by dynamical and thermodynamical components. Based on preliminary analysis, we find consistent contrasting trends over these regions in various observations, although the trend magnitudes vary. Overall, model simulations reproduce the observed trend over central Europe but fail over Midwest USA. Further, we employ dynamical adjustment technique to isolate the dynamical and thermodynamical contributions to the forced trends in hot extremes. Forced trends in hot extremes is largely driven by thermodynamical component, however, circulation contribution systematically increases for longer duration events over CEU and Midwest USA in both model and observations. Further, observational dynamical adjustment analysis reveals that circulation strongly contributes to weaken the trend in hot extremes over Midwest USA and to amplify the trend over CEU.

Spatio-temporal Interactions of Socio-economic Risks due to Multiple Extreme Events in a Changing Climate

Stalhandske Z.[1,2], Steinmann C. [1,2], Schmid E. [1,2], Mühlhofer E. [1,2], Lüthi S. [1,2], Bresch D. N. [1,2], Kropf C. [1,2]

[1] Institute for Environmental Decisions, ETH Zurich, Zurich, 8092, Switzerland
[2] Federal Office of Meteorology and Climatology MeteoSwiss, Zurich-Airport, 8058, Switzerland

Climate change is transforming natural and socio-economic systems in all parts of the world, leading to changes in extreme event risks. Most areas of the world are experiencing increased frequencies and intensities of several climate extremes. We may also observe more socio-economic impacts from these events in some areas because of high population density, or because of higher vulnerability. Previous studies have assessed how extreme events are changing with the climate, and how populations' risk of being exposed to several extremes will evolve [1, 2]. This allows to investigate spatial correlations of extremes and to highlight so-called hotspots of climate change [2]. But as these climate extremes are often driven by common physical processes, they do not only tend to occur in the same geographic area, but they may also be correlated in time.

We here apply a consistent modeling framework to investigate several risk models in a changing climate, including river floods and tropical cyclones effects on infrastructure, as well as crop failures. We study historical impacts, as well as three times ranges for future climates (2030-2050, 2050-2070 and 2070-2090) under the RPC2.6 and RCP6.0 climate scenarios. The analysis builds on top of single risk models as implemented in the open-source probabilistic natural hazard platform CLIMADA [3] and on data from the Inter-Sectoral Impact Model Intercomparison Project [4]. We define events of each risk as the global yearly impact and combine these events consistently based on common physical drivers stemming from the climate model data. This allows to investigate both spatial and temporal correlations, and how these will evolve under climate change. This event-based approach additionally allows to study tail risks and return periods of combined risks. The methods are implemented in the CLIMADA framework for further analysis. To this aim, hazard and exposure data are also provided through the CLIMADA API at a global and country scale.

References

[1] Lange, S., Volkholz, J., Geiger, T., Zhao, F., Vega, I., Veldkamp, T., Reyer, C., Warszawski, L., Huber, V., Jägermeyr, J., Schewe, J., Bresch, D., Büchner, M., Chang, J., Ciais, P., Dury, M., Emanuel, K., Folberth, C., Gerten, D., Gosling, S., Grillakis, M., Hanasaki, N., Henrot, A., Hickler, T., Honda, Y., Ito, A., Khabarov, N., Koutroulis, A., Liu, W., Müller, C., Nishina, K., Ostberg, S., Müller Schmied, H., Seneviratne, S., Stacke, T., Steinkamp, J., Thiery, W., Wada, Y., Willner, S., Yang, H., Yoshikawa, M., Yue, C. & Frieler, K. Projecting Exposure to Extreme Climate Impact Events Across Six Event Categories and Three Spatial Scales. *Earth's Future*. **8**, e2020EF001616 (2020), https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2020EF00161

[2] Byers, E., Gidden, M., Leclère, D., Balkovic, J., Burek, P., Ebi, K., Greve, P., Grey, D., Havlik, P., Hillers, A., Johnson, N., Kahil, T., Krey, V., Langan, S., Nakicenovic, N., Novak, R., Obersteiner, M., Pachauri, S., Palazzo, A., Parkinson, S., Rao, N., Rogelj, J., Satoh, Y., Wada, Y., Willaarts, B. & Riahi, K. Global exposure and vulnerability to multi-sector development and climate change hotspots. *Environmental Research Letters*. **13**, 055012 (2018,5), https://iopscience.iop.org/article/10.1088/1748-9326/aabf45

[3] Aznar-Siguan, G. and Bresch, D. N. CLIMADA v1: a global weather and climate risk assessment platform. *Geosci. Model Dev.*. **12**, 3085–3097 (2020), https://doi.org/10.5194/gmd-12-3085-2019, 2019

[4] Warszawski, L., Frieler, K., Huber, V., Piontek, F., Serdeczny, O. & Jacob Schewe The Inter-Sectoral Impact Model Intercomparison Project (ISI–MIP): Project framework. *Proceedings Of The National Academy Of Sciences*. **111**, 3228-3232 (2014), https://www.pnas.org/doi/abs/10.1073/pnas.1312330110

Response of physical processes in atmospheric blocking to climate change

Daniel Steinfeld[1], Michael Sprenger[2], Urs Beyerle[2] and Stephan Pfahl[3]

[1]Institute of Geography and Oeschger Centre for Climate Change Research, University of Bern, Switzerland
[2]Institute for Atmospheric and Climate Science, ETH Zürich, Switzerland
[3]Institute of Meteorology, Freie Universität Berlin, Germany

Weather extremes are often associated with atmospheric blocking, but how the underlying physical processes leading to blocking respond to climate change is not yet fully understood [1]. Here we track blocks as upper-level negative potential vorticity (PV) anomalies [2, 3] and apply a Lagrangian analysis [4] to 100 years of present-day (∼2000) and future (∼2100, under the RCP8.5 scenario) climate simulations restarted from the CESM Large Ensemble Project runs (CESM-LENS) to identify different physical processes and quantify how their relative importance changes in a warmer and more humid climate. The trajectories reveal two contrasting airstreams that both contribute to the formation and maintenance of blocking: latent heating in strongly ascending airstreams (moist processes) and quasi-adiabatic flow near the tropopause with weak radiative cooling (dry processes), as illustrated schematically in Fig. 1. Both airstreams are reproduced remarkably well when compared against ERA-Interim reanalysis, and their relative importance varies regionally [5, 6]. Moist processes dominate in blocks over the ocean throughout the year and over the Asian continent in summer, while dry processes dominate in Ural blocks in winter, European blocks in summer, and high-latitude blocks over the Arctic.

The response of blocks to climate change is complex and differs regionally, with a general increase in the importance of moist processes due to stronger latent heating (+1 K in the median over the Northern Hemisphere) and a larger fraction (+15%) of strongly heated warm conveyor belt airmasses, most pronounced over the storm tracks. Future blocks become larger (+7%) and their negative PV anomaly slightly intensifies (+0.8%). Using a Theil-Sen regression model, we propose that the increase in size and intensity is related to the increase in latent heating, resulting in stronger cross-isentropic transport of air with low PV into the blocking anticyclones. Our findings provide evidence that moist processes become more important for the large-scale atmospheric circulation in the midlatitudes, with the potential for larger and more intense blocks.

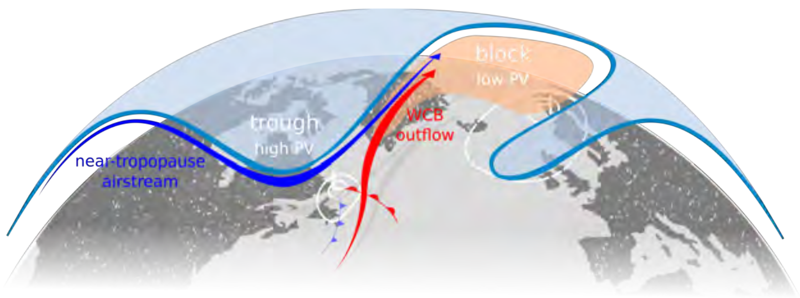


Figure 1: Schematic illustration of the dry and moist processes that contribute to the formation and maintenance of atmospheric blocking. Air masses with anomalously low potential vorticity (PV) are transported into the upper-level block either in ascending warm conveyor belt (WCB) airstreams with strong latent heat release ahead of an extratropical cyclone (red airstream) or quasi-adiabatically in near-tropopause airstreams along the amplified upper-level jet with weak radiative cooling (blue airstream).

References

[1] T. Woollings et al., Blocking and its Response to Climate Change, *Current Climate Change Reports* **4**, 278 (2018), 10.1007/s40641-018-0108-z.

[2] C. Schwierz et al., Perspicacious indicators of atmospheric blocking, *Geophysical Research Letters* **31**, L06125 (2004), 10.1029/2003GL019341.

[3] D. Steinfeld, ConTrack - Spatial and temporal contour tracking of circulation anomalies, *https://github.com/steidani/ConTrack* (2021), 10.5281/ZENODO.4765560.

[4] M. Sprenger, H. Wernli, The LAGRANTO Lagrangian analysis tool – version 2.0, *Geoscientific Model Development* **8**, 2569 (2015), 10.5194/gmd-8-2569-2015.

[5] S. Pfahl et al., Importance of latent heat release in ascending air streams for atmospheric blocking, *Nature Geoscience* **8**, 610 (2015), 10.1038/ngeo2487.

[6] D. Steinfeld, S. Pfahl, The role of latent heating in atmospheric blocking dynamics: a global climatology, *Climate Dynamics* **53**, 6159 (2019), 10.5194/10.1007/s00382-019-04919-6.

Probabilistic wildfire risk assessment of economic impacts under present and future climate conditions

Carmen B. Steinmann[1,2], Samuel Lüthi [1, 2], Samuel Gübeli[1], Benoît P. Guillod [3], David N. Bresch[1,2]

[1]Institute for Environmental Decisions, ETH Zurich, Zurich, 8092, Switzerland
[2]Federal Office of Meteorology and Climatology MeteoSwiss, Zurich-Airport, 8058, Switzerland
[3]CelsiusPro AG, Seebahnstrasse 85, Zurich, 8003, Switzerland

Wildfires are devastating events destroying large parts of physical assets exposed to them in many regions of the world. Therefore, a high-resolution hazard model is needed to accurately assess economic impacts caused by wildfires. Moreover, a probabilistic representation of the hazard covering the range and likelihood of possible wildfire seasons under certain conditions allows for a more comprehensive risk assessment, which is crucial for many applications, among others the prioritization of adaptation measures and the pricing of insurance.

In this work we build upon the existing wildfire hazard model [1] available on the open-source climate risk modelling platform CLIMADA (CLIMate ADAptation). Based on Fire Information for Resource Management System (FIRMS) satellite data and physical constraints, such as land cover and population density, a random walk generator appoints a probability of fire ignition and propagation to every grid cell. Moreover, a normally distributed regional propagation probability is calibrated to reproduce the historic inter-annual variability in burnt area in the study region. Stochastic wildfire events are then generated based on these probabilities.

The Inter-Sectoral Impact Model Intercomparison Project ISI-MIP provides the monthly fraction of burnt area from dynamic global vegetation models for present and future climate conditions. These models account for complex processes such as the accumulation of biomass (fuel load). However, their output resolution of 0.5° is too coarse for assessing economic impacts. Therefore, stochastic fire seasons under different climate change scenarios are computed by transferring changes in annually burnt area from the ISI-MIP model outputs into the regional propagation probability of the stochastic wildfire model.

Lastly, economic impacts are computed as the combination of this newly developed hazard, an exposure [2] and a vulnerability, represented by an impact function that was calibrated on historic fire damage data [1]. This results in a globally consistent model of wildfire risk to physical assets for fire prone countries under present and future climate conditions.

References

[1] S. Lüthi et al., Globally consistent assessment of economic impacts of wildfires in CLIMADA v2.2, *Geosci. Model Dev.* **14**, 7175–7187 (2021), https://doi.org/10.5194/gmd-14-7175-2021.

[2] S. Eberenz et al., Asset exposure data for global physical risk assessment, *Earth Syst. Sci. Data* **12**, 817–833(2020), https://doi.org/10.5194/essd-12-817-2020.

Model evaluation method affects the interpretation of machine learning models for identifying compound drivers of maize variability

Lily-belle Sweet[1], Jakob Zscheischler[1]

[1]Department of Computational Hydrosystems, Helmholtz Centre for Environmental Research - UFZ, Leipzig, Germany

Extreme impacts can be caused by the compounding effects of multiple drivers, such as weather events that might not individually be considered extreme[1]. An example of this is the phenomenon of 'false spring', where a combination of a warm late winter or early spring, followed by a frost once the plants have entered a vulnerable stage of development, results in severe crop damage. The relationships between growing-season climate conditions and end-of-season crop yield are complex and nonlinear, and improving our understanding of such interactions could aid in narrowing the uncertainty in estimates of climate risk to food security. Additionally, data-driven methods that are capable of identifying such compounding effects could be useful for the study of other sectoral impacts.

Machine learning is an option for capturing such complex and nonlinear relationships for yield prediction. In order to extract these relationships, explainable or interpretable machine learning has been identified as a potential tool[2, 3]. However, the usefulness of those extracted interpretations is dependent on the assumption that the model has learned the expected relationships. One prerequisite for this assumption is that the model has sufficient predictive skill. The method chosen for measuring model performance is therefore an important methodological decision, but as yet the 'best practice' when handling spatiotemporal climate data is not clearly defined.

In this study we train machine learning models to predict maize yield variability from growing-season climate data, using global climate reanalysis data and corresponding driven process-based crop model output. We assess the impact of the cross-validation procedure used for model skill measurement on each step of the modelling process: hyperparameter tuning, feature selection, performance evaluation and model interpretation. We show that the method of evaluating model skill has significant impacts on results when using interpretable machine learning methods. Our results suggest that the design of the cross-validation procedure should reflect the purpose of the study and the qualities of the data used, which in our case are highly-correlated spatiotemporal climate and crop yield data.

References

[1] J. Zscheischler et al., A typology of compound weather and climate events, *Nature Reviews Earth & Environment* **1**, 333-347 (2020), 10.1038/s43017-020-0060-z.

[2] P. Zhu et al., Uncovering the past and future climate drivers of wheat yield shocks in Europe with machine learning, *Earth's Future* **9**, e2020EF001815 (2021), 10.1029/2020EF001815

[3] A. Mateo-Sanchis et al., Learning main drivers of crop progress and failure in Europe with interpretable machine learning, *International Journal of Applied Earth Observation and Geoinformation* **104**, 102574 (2021), 10.1016/j.jag.2021.102574

Atmospheric effects and precursors of rainfall over the Swiss Plateau

W. Wang[1,2], K. Hocke[1,2]

[1]Institute of Applied Physics, University of Bern, Bern, Switzerland
[2]Oeschger Centre for Climate Change Research, University of Bern, Bern, Switzerland

In recent years, there has been growing interest in characterizing atmospheric conditions prior to rain events using integrated water vapor (IWV) derived from ground-based microwave radiometers (MWR). However, the occurrence of rainfall depends on a myriad of atmospheric parameters. This paper uses a composite analysis method to analyze various atmospheric parameters that affect rainfall over the Swiss Plateau during the period 2011-2020. 1199 rainfall events generated from the TROpospheric WAter RAdiometer (TROWARA) with a 7 s temporal resolution are combined with fields from weather station records. Different weather time evolution characteristics such as IWV, integrated liquid water (ILW), cloud-bottom infrared temperature (IRT) along with meteorological parameters, temperature, pressure, relative humidity, wind speed, and air density are identified before, during, and after rainfall. Regardless of seasonality or rainfall duration, a sharp increase in the IWV, ILW, and IRT before rain, and all the meteorological parameters reach the extreme 0.5 to 1 hour before rain starts. IWV at the end of the rain is lower than at the beginning, and it filtered by the 10-min band pass filter fluctuates significantly before rain. Air density drops 2 to 6 hours before rain starts. The true detection rate for rainfall prediction from air density alone as one of the precursors reaches 60%, as shown in Figure 1. Applying all these parameters to jointly predict rainfall is possible to obtain higher prediction accuracy.

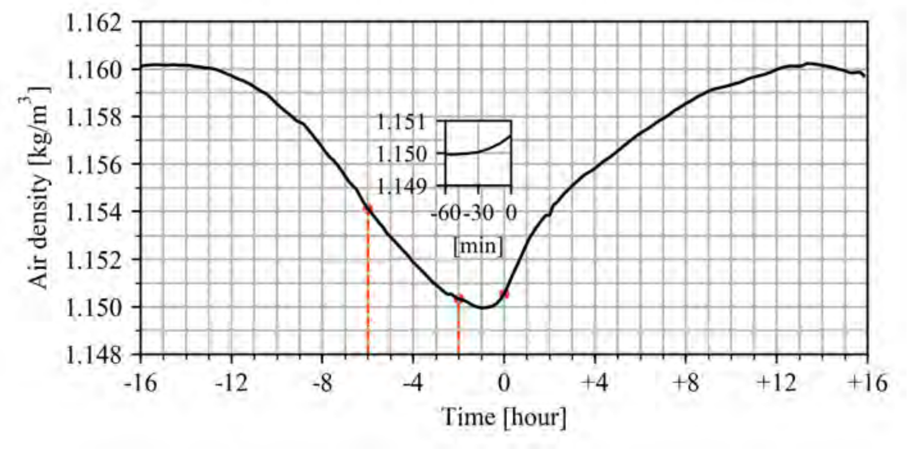


Figure 1: Composite of air density 16 hours before and during rain. Red dots represent the 6 hours, 2 hours before rain, and the onset of the rain. The subplot is from 60 minutes before rain to the onset of rain. A total of 784 rain events.

Interactive assessment of climate impacts and vulnerability hotspots using ensembles of global climate, impact, and integrated assessment models

Michaela Werning[1], Edward Byers[1]

[1]International Institute for Applied Systems Analysis, Laxenburg, Austria

In the 21st century, an increasing global population will be exposed to various risks caused by climate change, creating multi-risk hotspots in some areas. The impact of these risks on people's lives will not only depend on the geophysical climate change hazards, but also on the population's vulnerability, its spatial distribution, and its capacity to adapt. Going beyond previous climate impacts assessments by combining various climate impact indicators with socioeconomic projections from the Shared Socioeconomic Pathways (SSPs) [2, 3], Byers et al. [1] carried out a global analysis to examine this interplay for different levels of global warming. They found that although multi-sector risk hotspots are limited to a small fraction of the land surface, the number of people affected will be large, with the poorest disproportionately impacted [4] and the population exposed to multi-sector risks almost doubling between 1.5° C and 2° C [1].

Building on this work, we are using the latest Inter-Sectoral Impact Model Intercomparison Project (ISIMIP) data [5, 6] to calculate several impact indicators spanning the land-water-energy nexus. By adding indicators based on the Climate Change Indices established by the Expert Team on Climate Change Detection and Indices (ETCCDI) [7], we are extending the analysis to the impacts of atmospheric extreme events. Furthermore, we are expanding the levels at which the change in hazard between the historical baseline and future conditions is assessed to 1.5° C - 3.5° C (with the option to interpolate between these levels for even more detailed results), thereby shifting the focus to avoided impacts and the potential range of benefits that limiting the increase in global mean temperature could have.

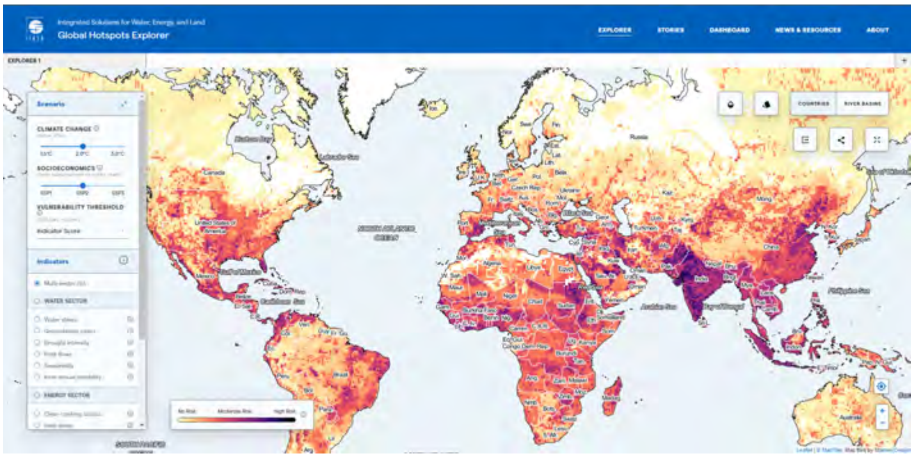


Figure 1: Global Hotspots Explorer website.

This new analysis also creates the opportunity to further explore the definition of vulnerability. Byers et al. [1] combined the multi-sector score maps with gridded socioeconomic projections of population size [8] and GDP [9] from the SSPs and used an income threshold of $10/day based on definitions from the World Bank [10] to estimate vulnerable population. By adding other vulnerability measures, such as projections of future governance, adaptive capacity [11], or inequality [12, 13] in line with the SSPs, we could provide a more complete view of risk that allows the identification of societal climate impact hotspots.

Uncovering locations that are prone to multiple risks will ultimately aid with establishing where vulnerable populations will benefit most from mitigation action. To facilitate the use by a wider public, we will be hosting the resulting global risk hotspot maps online (Fig. 1) and present the impacts alongside mitigation pathways to better contextualize the benefits, tradeoffs and avoided impacts of mitigation.

References

[1] E. Byers et al., Global exposure and vulnerability to multi-sector development and climate change hotspots, *Environmental Research Letters* **13**, e055012 (2018), 10.1088/1748-9326/aabf45.

[2] B. C. O'Neill et al., The roads ahead: Narratives for shared socioeconomic pathways describing world futures in the 21st century, *Global Environmental Change* **42**, 169 (2017), 10.1016/j.gloenvcha.2015.01.004.

[3] K. Riahi et al., The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview, *Global Environmental Change* **42**, 153 (2017), 10.1016/j.gloenvcha.2016.05.009.

[4] L. J. Harrington et al., Poorest countries experience earlier anthropogenic emergence of daily temperature extremes, *Environmental Research Letters* **11**, 055007 (2016), 10.1088/1748-9326/11/5/055007.

[5] K. Frieler et al., Assessing the impacts of 1.5° C global warming - simulation protocol of the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP2b), *Geoscientific Model Development* **10**, 4321 (2017), 10.5194/gmd-10-4321-2017.

[6] C. Rosenzweig et al., Assessing inter-sectoral climate change risks: the role of ISIMIP, *Environmental Research Letters* **12**, 010301 (2017), 10.1088/1748-9326/12/1/010301.

[7] http://etccdi.pacificclimate.org/indices.shtml

[8] S. KC, W. Lutz, The human core of the shared socioeconomic pathways: Population scenarios by age, sex and level of education for all countries to 2100, *Global Environmental Change* **42**, 181 (2017), 10.1016/j.gloenvcha.2014.06.004.

[9] R. Dellink et al., Long-term economic growth projections in the Shared Socioeconomic Pathways, *Global Environmental Change* **42**, 200 (2017), 10.1016/j.gloenvcha.2015.06.004.

[10] World Bank, *World Development Report 2014: Risk and Opportunity - Managing Risk for Development*, Washington, DC., https://openknowledge.worldbank.org/handle/10986/16092 License: CC BY 3.0 IGO.

[11] M. Andrijevic et al., Governance in socioeconomic pathways and its role for future adaptive capacity, *Nature Sustainability* **3**, 35 (2020), 10.1038/s41893-019-0405-0.

[12] M. Andrijevic et al., Overcoming gender inequality for climate resilient development, *Nature Communications* **11**, 6261 (2020), 10.1038/s41467-020-19856-w.

[13] N. D. Rao et al., Income inequality projections for the Shared Socioeconomic Pathways (SSPs), *Futures* **105**, 27 (2019), 10.1016/j.futures.2018.07.001.

Dynamical Drivers of Extreme Rainfall in Europe

Anna Whitford[1], Hayley Fowler[1], Stephen Blenkinsop[1], Rachel White[2]

[1]School of Engineering, Newcastle University, UK
[2]Dept of Earth, Ocean and Atmospheric Sciences, University of British Columbia, Canada

Sub-daily extreme rainfall events can trigger flash flooding in Europe, while daily and longer extreme rainfall can lead to fluvial flooding. Recent research has shown that the frequency and intensity of these extreme events will increase as global temperatures rise [1, 2]. This means we urgently need to improve our methods of forecasting when and where they may occur. Enhancing our understanding of the dynamical processes driving these events is essential to this, as large-scale atmospheric circulations have a much higher forecast skill (at longer lead times) than local-scale rainfall events [3]. Therefore, this project aims to identify relationships between large-scale dynamical drivers and the occurrence of extreme rainfall on different timescales.

A climatological analysis of the frequency, intensity and timing of extreme sub-daily rainfall events in Western Europe has been undertaken using a set of newly developed indices generated from the quality-controlled Global Sub-Daily Rainfall (GSDR) dataset [4]. The results of this analysis show strong seasonal and spatial patterns in the characteristics of extreme events across Europe, with a general spatial pattern of lower intensity and frequency in Northern regions moving to highest intensities and frequencies of events in Southern regions. The intensity and frequency of extreme events both peak in the same season in each region, with the timing of the peak changing from summer to autumn moving south through Europe. This work provides a climatology of the timing and distribution of sub-daily extremes to accompany existing climatologies for daily extremes.
Temporal correlation of sub-daily extreme events with large-scale weather patterns from the Met Office's set of 30 weather patterns [5] has been used to identify the large-scale conditions that tend to produce these extremes, with a small sub-set of the weather patterns so far identified as being associated with the majority of extremes. This information will subsequently be combined with reanalysis data to build an improved understanding of the specific atmospheric conditions leading to sub-daily rainfall extremes across Europe.

An on-going assessment of the connections between daily (and longer) extreme rainfall and Rossby Wave activity has so far revealed that the Local Finite-amplitude Wave Activity (LWA) metric [6] can be used to identify the local wave activity associated with periods of extreme rainfall. This will lead onto an investigation of the extent to which these connections can be utilised both in medium-range forecasting and in climate model evaluation of future extremes.

Research Questions:

- Can specific atmospheric conditions associated with certain weather patterns be identified as drivers (and predictors) of sub-daily rainfall extremes in Europe?
- Is it possible to develop sets of local wave activity patterns that frequently occur in coincidence with daily rainfall extremes using the LWA metric?
- Can the development pathway of the local wave activity associated with extremes be traced back far enough to be of use for forecasting?

References

[1] S. Westra, et al., "Future changes to the intensity and frequency of short-duration extreme rainfall", *Rev. Geophys.* **52**, pp. 522–555, (2014), 10.1002/2014RG000464.

[2] H. J. Fowler, et al., “Anthropogenic intensification of short-duration rainfall extremes”, *Nat. Rev. Earth Environ.* **2**, pp. 107–122, (2021), 10.1038/s43017-020-00128-6.

[3] D. Richardson, et al., “Linking weather patterns to regional extreme precipitation for highlighting potential flood events in medium- to long-range forecasts”, *Meteorol. Appl.* **27**, pp. 1–17, (2020), 10.1002/met.1931.

[4] E. Lewis, et al., “GSDR: A global sub-daily rainfall dataset”, *J. Clim.* **32**, pp. 4715–4729, (2019), 10.1175/JCLI-D-18-0143.1.

[5] R. Neal, D. Fereday, R. Crocker, and R. E. Comer, “A flexible approach to defining weather patterns and their application in weather forecasting over Europe”, *Meteorol. Appl.* **23**, pp. 389–400, (2016), 10.1002/met.1563.

[6] C. S. Y. Huang and N. Nakamura, “Local finite-amplitude wave activity as a diagnostic of anomalous weather events", *J. Atmos. Sci.* **73**, pp. 211–229, (2015), 10.1175/JAS-D-15-0194.1.

Wave mechanisms for heat waves in the extratropical atmosphere

Wolfgang Wicker[1], Daniela I. V. Domeisen[1,2]

[1] University of Lausanne, Lausanne, Switzerland
[2]ETH Zurich, Zurich, Switzerland

While extratropical heatwaves have been projected to become more frequent with climate change, the governing mechanisms remain uncertain [1]. To increase confidence in projections, an improved understanding of Rossby wave propagation and amplification away from source regions is necessary since persistent weather extremes are frequently associated with anomalous synoptic-scale waves [2]. Usually, synoptic-scale waves with zonal wavenumbers five to eight travel eastward around the globe with a phase speed of approximately $10\ \mathrm{ms}^{-1}$. But during episodes with concurrent weather extremes around the globe such as August 2003 or July 2010 synoptic-scale waves exhibit a large stationary component. It has been hypothesized that synoptic-scale waves are enhanced by diabatic processes via resonant amplification when these waves cease from eastward propagation and become stationary. The reason for the stalling of the waves, however, remains unclear.

In our study, we focus on the role of the extratropical waveguide to answer the question of how changes in the basic state can influence the occurrence of climate extremes. A mechanism based on barotropic dynamics and ray tracing theory has suggested that a strong and narrow westerly jet will foster future occurrences of stationary synoptic-scale waves [3]. On the other hand, this mechanism has been criticized for the applicability of ray tracing theory and the linearity approximation [4, 5]. Here we develop an idealized atmospheric model to investigate the role of baroclinic dynamics in the stalling of synoptic-scale waves during extreme events.

In addition to the process understanding gained from the idealized model, we analyze data from the atmospheric reanalysis product *ERA5* to compare the climatological wave characteristics with statistics of extreme events. Two different approaches for diagnosing wave characteristics – spectral analysis [6] and wave packet amplitudes [7] – emphasize either the circumglobal nature of waves or their locality in space and time. Both approaches are successful in identifying stationary synoptic-scale waves in the upper troposphere that are linked to temperature extremes at the surface. In reverse, we use composite analysis to relate extreme wave characteristics to changes in the basic state compared to climatology and evaluate the choice of the baroclinic model.

References

[1] T. G. Shepherd, Atmospheric circulation as a source of uncertainty in climate change projections, *Nature Geoscience* **7**, 703 (2014), 10.1038/ngeo2253.

[2] R. H. White et al., From Atmospheric Waves to Heatwaves: A Waveguide Perspective for Understanding and Predicting Concurrent, Persistent, and Extreme Extratropical Weather, *Bulletin of the American Meteorological Society* **103**, E923 (2022), 10.1175/BAMS-D-21-0170.1.

[3] V. Petoukhov et al., Quasiresonant amplification of planetary waves and recent Northern Hemisphere weather extremes, *Proceedings of the National Academy of Sciences* **110**, 5336 (2013), 10.1073/pnas.1222000110.

[4] V. Wirth, Waveguidability of idealized midlatitude jets and the limitations of ray tracing theory, *Weather and Climate Dynamics* **1**, 111 (2020), 10.5194/wcd-1-111-2020.

[5] V. Wirth, C. Polster, The problem of diagnosing jet waveguidability in the presence of large-amplitude eddies, *Journal of the Atmospheric Sciences* **78**, 3137 (2021), 10.1175/JAS-D-20-0292.1.

[6] J. Riboldi et al., Circumglobal Rossby wave patterns during boreal winter highlighted by space–time spectral analysis, *Weather and Climate Dynamics* **3**, 449 (2022), 10.5194/wcd-3-449-2022.

[7] G. Fragkoulidis et al., Linking Northern Hemisphere temperature extremes to Rossby wave packets, *Quarterly Journal of the Royal Meteorological Society* **144**, 553 (2018), 10.1002/qj.3228.

Hail time series from radar proxies for decadal variability of hail in Switzerland

Lena Wilhelm[1], Olivia Rompainnen-Martius[1], Katharina Schröer[2], Cornelia Schwierz[3]

[1]Oeschger Centre for Climate Change Research and Institute of Geography, University of Bern, Bern, Switzerland
[2]Institute of Environmental Social Sciences and Geography, University of Freiburg, Freiburg, Germany
[3]Federal Office of Meteorology and Climatology, MeteoSwiss, Zurich, Switzerland

In Switzerland hail regularly causes substantial damage to agriculture, cars, and infrastructure. However, addressing hail damage is challenging, as hail is related to severe thunderstorms, one of the most complex atmospheric phenomena due to its small spatial scale, vigorous development, and the intricate physical interactions. In a changing climate, hail frequency and its patterns of occurrence are expected to change, which can largely impact eg. agricultural hail losses. The new Swiss hail climatologies [1, 2, 3] revealed significant interannual hail variability that differs between the north and the south side of the Alps. Understanding the drivers of this variability is essential for possible adaptation strategies. In contrast to North America, where important drivers of interannual variability of severe convection are well studied (see [4, 5]) a comprehensive analysis of the long-term variability of hail in Switzerland is still missing.

Therefore, in this study, a daily hail time series for Northern and Southern Switzerland from 1950 to today is produced from radar hail proxies and ERA-5 reanalysis data. Daily POH data from MeteoSwiss is used to identify haildays in the region north and south of the Alps (see 1) from 2002 to 2021 for the hail months April - September. The decision hailday yes/no is based on surpassing a POH ≥ 80 for a certain minimum footprint area of the domains (80^{th} percentile). Next, a logistic regression model is built for each domain to predict the occurrence of a hailday depending on different environmental variables and indices. The predictors are chosen based on model performance, collinearity, and expert judgement. Seasonality, as well as long-term trends in the data, are addressed with different methods. With the two best models, haildays are then predicted back to 1950 to get the final timeseries. The time series will then be used to study the local and remote drivers of interannual variability, e.g. central European weather types, cold fronts, large-scale variability patterns, etc., as well as to study past changesand shifts in hailstorm seasonality.
With this knowledge, we could advance our understanding of the meteorological-climatological variability and change, as well as contribute to adaptation strategies to strengthen societal resilience against hail risk.

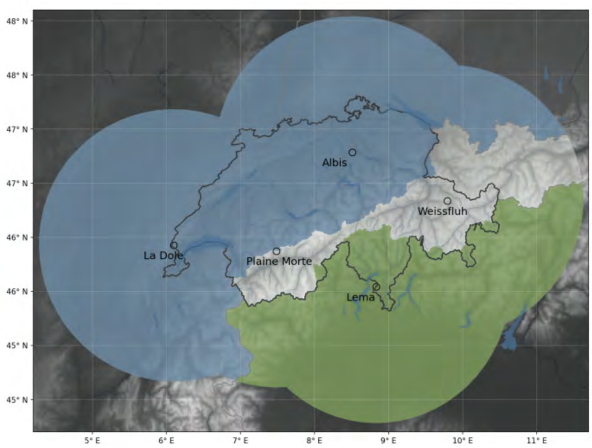


Figure 1: The domains south of the Alps (green) and north of the Alps (blue) overlaid on a topographical map. The areas fall within a 140 km radius of the five Swiss weather radar stations. Figure from [6].

References

[1] E. Madonna et al., A Poisson regression approach to model monthly hail occurrence in Northern Switzerland using large-scale environmental variables, *Atmospheric Research* **203**, 261 (2018), 10.1016/j.atmosres.2017.11.024.

[2] L. Nisi et al., A 15 year hail streak climatology for the Alpine region, *Quarterly Journal of the Royal Meteorological Society* **144**, 1429 (2018), 10.1002/qj.3286.

[3] L. Nisi et al., Hailstorms in the Alpine region: Diurnal cycle, characteristics, and the nowcasting potential of lightning properties, *Quarterly Journal of the Royal Meteorological Society* **146**, 4170 (2020), 10.1002/qj.3897.

[4] M. K. Tipett et al., Climate and Hazardous Convective Weather, *Current Climate Change Reports* **1**, 60 (2015), 10.1007/s40641-015-0006-6.

[5] J. T. Allen et al., Understanding Hail in the Earth System, *Reviews of Geophysics* **58**, (2020), 10.1029/2019RG000665.

[6] H. Barras et al., Multi-day hail clusters and isolated hail days in Switzerland – large-scale flow conditions and precursors, *Weather and Climate Dynamics* **2**, 1167 (2021), 10.5194/wcd-2-1167-2021.

Exploring the impact of different past- and present-day climatic forcings on Antarctic Ice sheet evolution and dynamics

Christian Wirths[1,2], Johannes Sutter[1,2], Thomas Stocker[1,2]

[1]University of Bern, Bern, Switzerland
[2]Oeschger Center for Climate Change Research, Bern, Switzerland

Simulations of past and future Antarctic ice sheet (AIS) evolution depend, besides the intrinsic model specific uncertainties, on the applied climatic forcing as shown by [1]. To model the past, present and future Antarctic Ice Sheet, a large set of different forcings from global and regional climate models, is available. Especially for simulation of the past, it is a common technique to use present-day high resolution forcings together with Paleo-anomalies from coarser climate models [2]. This results in uncertainties from both, the regional high resolution and coarse global forcing field. For a more complete understanding of the modeled ice sheet dynamics, it is therefore critical to understand the influence and the resulting model differences and uncertainties associated with those climate forcing choices.

In this study we examine the impact of different climatic forcings onto the equilibrium state of the AIS for past and present-day conditions. We apply past (LGM, LIG, mid-Pliocene warm period) and present-day climatic forcings from regional (RACMO2.3p3, MAR3.10, HIRHAM5 and COSMO-CLM2) and global (PMIP4 ensemble) climate models onto the Parallel Ice Sheet Model (PISM v.2.0 [3]). Further, we investigate the response of the ice dynamics, the total ice mass, its distribution, and the grounding line dynamics of the modeled equilibrium ice sheet under varying ice sheet sensitivity parameterizations. In this context we have a special interest in non-linear response of the ice sheet to the before mentioned forcings and its implication on potential model output uncertainties.

With this analysis, we aim to gain a better understanding of AIS modelling uncertainties due to the applied climatic forcings and parameterizations, which will improve the assessment of modeled past ice-sheet evolution.

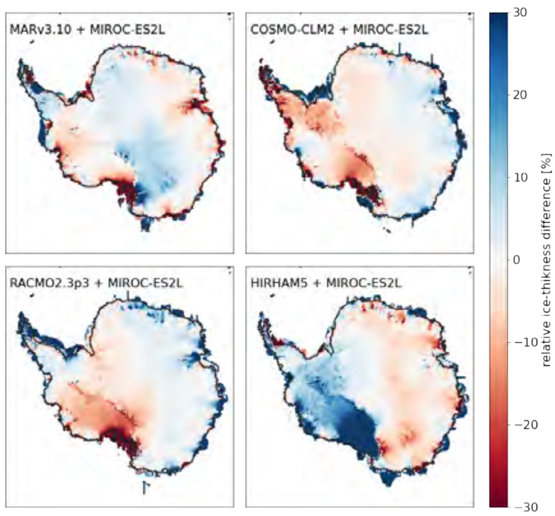


Figure 1: Relative Antarctic ice thickness deviation from mean for the LGM using MAR3.10, COSMO-CLM2, RACMO2.3p3 and HIRHAM5 model output together with MIROC-ES2L LGM anomalies.

References

[1] Hélène Seroussi et al., ISMIP6 Antarctica: a multi-model ensemble of the Antarctic ice sheet evolution over the 21st century, *The Cryosphere* **14**, 3030-3070 (2020), 10.5194/tc-14-3033-2020.

[2] Johannes Sutter et al., Modelling the Antarctic Ice Sheet across the mid-Pleistocene transition – implications for Oldest Ice, *The Cryosphere* **13**, 2023-2041 (2019), 10.5194/tc-13-2023-2019.

[3] Ed Bueler and Jed Brown, Shallow shelf approximation as a "sliding law" in a thermomechanically coupled ice sheet model, *Journal of Geophysical Research* **114**, (2009), 10.1029/2008JF001179

Characteristics of Recent Column-Compound Extremes in the Global Ocean

Joel Wong[1], Nicolas Gruber[1,2], Matthias Münnich[1]

[1]Environmental Physics, Institute of Biogeochemistry and Pollutant Dynamics
[2]Center for Climate Systems Modeling, ETH Zürich, Zürich, Switzerland

Marine extreme events can be detrimental to organisms and ecosystems across the global ocean. Marine heatwaves (MHW), ocean acidification, and low oxygen extremes occur everywhere, superimposed on the already changing trends of temperature, pH, and oxygen. When such extremes occur spatially or temporally close together, the synergistic effects of such compound events may exacerbate the impact on marine organisms[1]. While MHWs have been studied extensively, there has been less focus on extremes associated with ocean acidification (OAX) and low oxygen conditions (LOX), and even less on compound extremes. Furthermore, many studies on marine extremes are conducted only on the surface, or at a specified depth.

We use daily output from a hindcast simulation from the Community Earth System Model v1.3 for the period 1961-2020 to assess the characteristics of such compound extremes. A seasonally varying percentile threshold[2] on a moving baseline in combination with an absolute low oxygen threshold is used to identify extreme conditions in each grid cell. The vertical water column down to 300m is then identified as extreme when at least 50m is extreme with respect to each extreme type.

Our analysis shows that a large proportion of extremes in the 300m water column are driven by *El Niño* and *La Ninã* events, leading to co-located and co-temporal compound events. The results show that the tropics and subtropics have a high propensity for compounded MHW and OAX events, experiencing high habitat contraction within the vertical water column. Eastern boundary upwelling regions are also hotspots for compounded OAX and LOX events. The results of this study provide an overview of the propensity and vertical extent of compound events, motivating the postulation of their drivers and mechanisms. These drivers and mechanisms can be further investigated in higher resolution regional models.

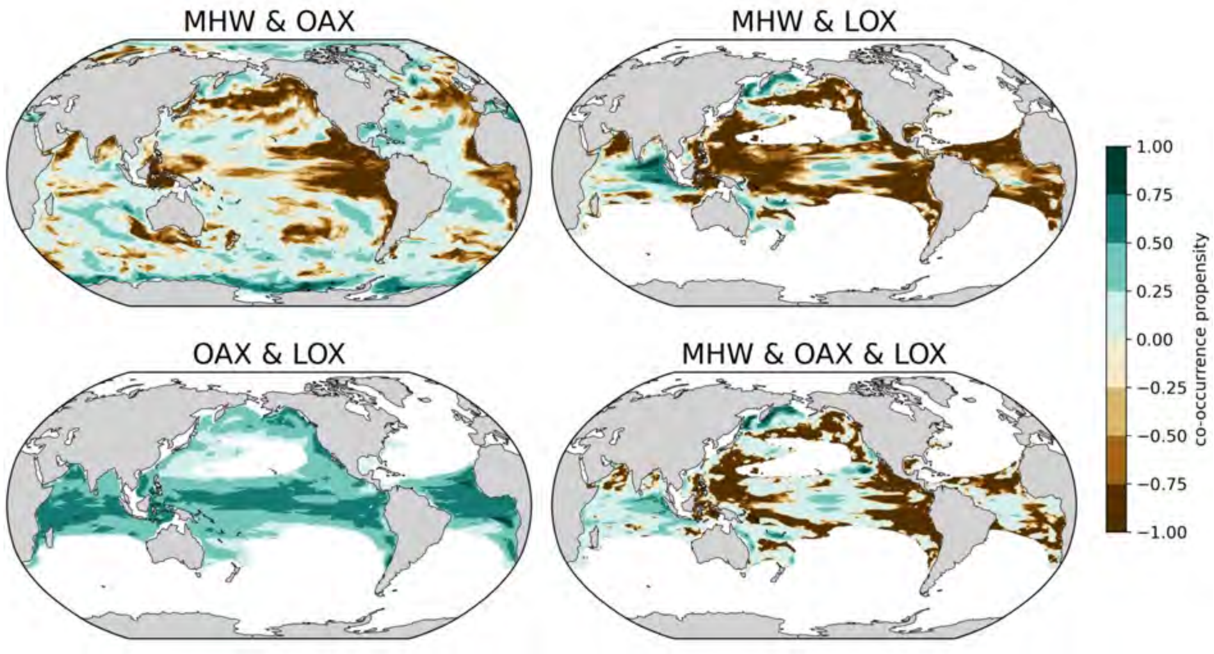


Figure 1: Co-occurence propensity of column-compound marine extreme events.

References

[1] N. Gruber et al., "Ocean Biogeochemical Extremes and Compound Events", *Nature,* **600**, pp. 395-407 (2021), doi: 10.1038/s41586-021-03981-7.

[2] A. J. Hobday et al., "A hierarchical approach to defining marine heatwaves", *Prog. Oceanogr.,* **141**, pp. 227-238 (2016), doi: 10.1016/j.pocean.2015.12.014.

Using analogues to understand future heatwave events

Emma L Yule[1], Gabi Hegerl[1], Andrew Schurer[1], Ed Hawkins[2]

[1]University of Edinburgh, UK
[2]University of Reading, UK

As global surface temperatures continue to rise, both the duration and the intensity of heatwaves across most land areas is expected to increase. In this research, past European summer heatwave events detected between 1878 and 1925 from long station data are projected into future warming scenarios using the analogue method. Heatwave activity on daily scales between 1878 and 1925 was found to be considerable and comparable in some cases to modern heatwave events in the UK. Therefore, past extremes offer an interesting case study and can be projected into future warming scenarios to understand their extent and potential impacts in a warmer world.

Temporal analogues use data from past events to serve as analogues of expected future conditions. The advantage of this approach is that events that actually occurred are used to characterize potential future events. This could provide information for local-based adaptation [1].

The analogues method is a way to estimate temperatures observed during similar pressure or 'flow' conditions to a past event developed by [2]. For each day of a summer heatwave in 1911 detected using station data, ten flow-analogues are selected from z500 pressure maps from 1981 to 2015 from the 20th Century Reanalysis in a 30-day window centered on that day. The analogues are selected by maximizing the Spearman's correlation and minimizing the Euclidean distance of daily z500 maps. The corresponding temperature is defined as the mean of the temperatures from the ten analogues [3]. The result being that the 1911 heatwave event was still anomalously warm compared to current heatwave events with a similar circulation pattern particularly in the UK and central Europe. This was expected due to the extremity of the 1911 event. The next step will be to use this event to find an anologue in historical and then future climate simulations in the model world.

The analogue method has been used in previously studies to demonstrate that present-day greenhouse gases could cause more frequent and longer Dust Bowl heatwaves in North America's Great Plains[4] and has been used to show that the cold winter of 2010/11 in Europe was an example of a cold winter in a warming world as similar dynamics were generally associated with even colder temperatures in previous years [3].

Current analogue studies tend to make comparisons between past events and present conditions. Less studies use analogues to project past events into the future which this research project aims to do. In addition, few studies that focus on how extremes are changing through time, begin with a real, observed example of an extreme event in a particular location and aim to project that single example into the future. This could provide a strong visual representation of changes due to global warming and could act as a communication tool for adaptation [1].

References

[1] Rosenzweig, Cynthia, M. L. Parry, and Manishka De Mel, eds. 2021. Our Warming Planet: Climate Change Impacts and Adaptation. Lectures in Climate Change, **vol 2**. New Jersey: *World Scientific.*

[2] Yiou, P., R. Vautard, P. Naveau, and C. Cassou. 2007. "Inconsistency between Atmospheric Dynamics and Temperatures during the Exceptional 2006/2007 Fall/Winter and Recent Warming in Europe." *Geophysical Research Letters* **34** (21): L21808. https://doi.org/10.1029/2007GL031981.

[3] Cattiaux, J., R. Vautard, C. Cassou, P. Yiou, V. Masson-Delmotte, and F. Codron. 2010. "Winter 2010 in Europe: A Cold Extreme in a Warming Climate: COLD WINTER 2010 IN EUROPE." *Geophysical Research Letters* **37** (20) https://doi.org/10.1029/2010GL044613.

[4] Cowan, Tim, Sabine Undorf, Gabriele C. Hegerl, Luke J. Harrington, and Friederike E. L. Otto. 2020. "Present-Day Greenhouse Gases Could Cause More Frequent and Longer Dust Bowl Heatwaves." *Nature Climate Change* **10** (6): 505–10. https://doi.org/10.1038/s41558-020-0771-7.

Biochemical responses of lakes to rapid climate transitions across space and time

Petra Zahajská[1], Stan J. Schouten[1], Paul D. Zander[1,2] and Martin Grosjean[1]

[1]Institute of Geography & Oeschger Centre for Climate Change Research, University of Bern, Bern, Switzerland
[2]Max Planck Institute for Chemistry, Mainz, Germany

Lakes in anthropogenically influenced environments often experience anoxia due to high nutrient inputs from agricultural activities. Recently, there has been increasing evidence of the presence of anoxic events throughout the Holocene. However, we still have little knowledge of the triggers of anoxic events in lakes in pre-anthropogenic conditions. Thus, the lake response to the driving factors such as natural abrupt climate changes (e.g., Dansgaard-Oeschger Cycles) and nutrient cycling (P, Fe, Mn) is studied to understand the occurrence of lake anoxia in pre-anthropogenic conditions.

We aim to identify anoxic events in several lakes to test the regional synchronicity and understand the impact of abrupt climate change on the lake anoxia occurrence. Further, a pattern in lake biogeochemical response to rapid warming will be described. We will investigate whether the lakes recovered to their original status before the eutrophication event. If so, we aim to determine, through high-resolution proxy records, how long it takes for a lake ecosystem to recover from a eutrophication/anoxic event.

Hyperspectral imaging will provide high-resolution data on relative changes in primary productivity and anoxic conditions, whereas HPLC pigment analysis will provide further information on the pigment producers and lake community changes. Additionally, iron, phosphorous and manganese extraction will be used to constrain the effect of changing redox conditions on nutrient cycling.

We expect to observe an abrupt response of the lake community right after the temperature increase, as well as changes in nutrient availability connected to anoxia. After the abrupt eutrophication and formation of anoxia, we expect a typical succession of restoration of the lake ecosystem across space and time.

Results of this study will bring crucial knowledge on a regional lake's response to eutrophication triggered by natural factors, such as abrupt climate change or nutrient release from the sediment. The connection between climate change and lake biogeochemical responses is essential for future projections, e.g., lake ecosystem protection strategies or drinking water reservoir management.

Physics-constrained postprocessing of temperature and humidity

Francesco Zanetta[1,2], Daniele Nerini[2], Tom Beucler[3]

[1]Institute for Atmospheric and Climate Science, ETH Zürich, Zürich, Switzerland
[2]Federal Office of Meteorology and Climatology MeteoSwiss, Locarno, Switzerland
[3]Institute of Earth Surface Dynamics, University of Lausanne, Lausanne, Switzerland

Weather forecasting centres around the world currently rely on statistical postprocessing methods for minimizing forecast error [1]. While allowing for major skill improvements, this often leads to predictions that violate physical principles and disregard dependencies between variables. However, for various impact-based applications such as hydrological forecasting or heat indices, it is important to provide forecasts that not only have high univariate accuracy, but also are physically consistent, in the sense of respecting physical principles and variable dependencies.

Achieving physical consistency remains an open problem in the postprocessing of weather forecasts, while this question has recently gained a lot of attention in the wider deep learning community and climate field [2]. Recent contributions show that physical consistency may be pursued by applying different forms of constraints to deep learning models. The most widely used approaches are to incorporate physics via regularization, by defining physics-based losses in addition to common metrics such as mean squared error, or to define custom-designed model architectures, such that the physical constraints are strictly enforced.

Building from the methodology proposed by [3] we investigate the application of the aforementioned approaches for the postprocessing of a set of variables related to surface temperature and humidity, specifically temperature, dew point, surface pressure, relative humidity and water vapor mixing ratio. As baseline, we use an unconstrained fully connected neural network. We consider the simple case of postprocessing at a single location, and we show how it is possible to incorporate domain knowledge, specifically thermodynamic relationships, via analytic constraints, to obtain physically consistent postprocessed prediction. We implement the following constraints:

$$RH = f(T, T_d) = exp\left(\frac{a \cdot T_d}{b + T_d} - \frac{a \cdot T}{b + T}\right), \qquad r = g(P, T_d) = \frac{622.0 \cdot c \cdot \exp\left(\frac{a \cdot T_d}{b+T_d}\right)}{P - c \cdot \exp\left(\frac{a \cdot T_d}{b+T_d}\right)}, \tag{3}$$

that are either incorporated in a model's architecture, or used to compute a physical violation term $\mathcal{P}$ that is then added to the loss function like the following:

$$\mathcal{L}_c = (1 - \alpha)\mathcal{L} + \alpha\mathcal{P} \tag{4}$$

where α is a hyperparameter used to scale the contribution of the physics-based loss. The considered approaches are represented schematically in Fig. 1.

We compare different approaches and demonstrate that we can enforce physical consistency without degrading performance, or even improving it, as shown in Fig. 2. Furthermore, we discuss additional advantages and disadvantages of these approaches in the context of postprocessing, besides error reduction. In line with the scope of this summer school, part of our analysis focuses on generalization and robustness to extreme values.

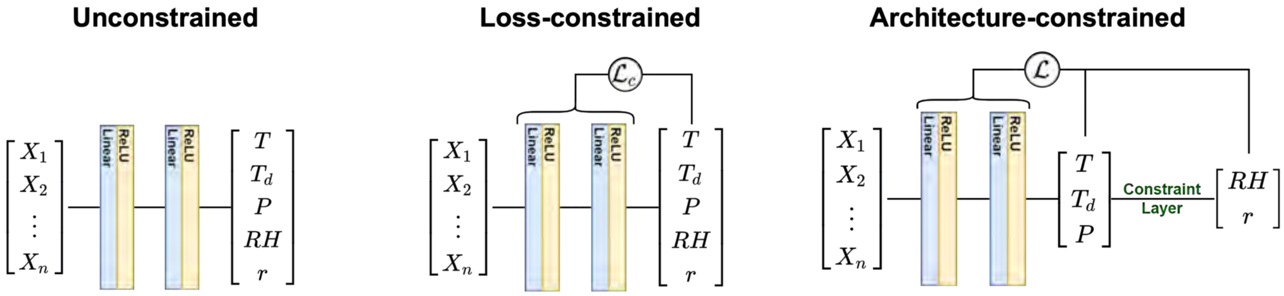


Figure 1: Schematics of three approaches for postprocessing multiple variables: a traditional, unconstrained approach, a loss-constrained model that optimizes $\mathcal{L}_c$ and a architecture-constrained model that incorporates the constraint functions in Eq. 3 in a custom layer.

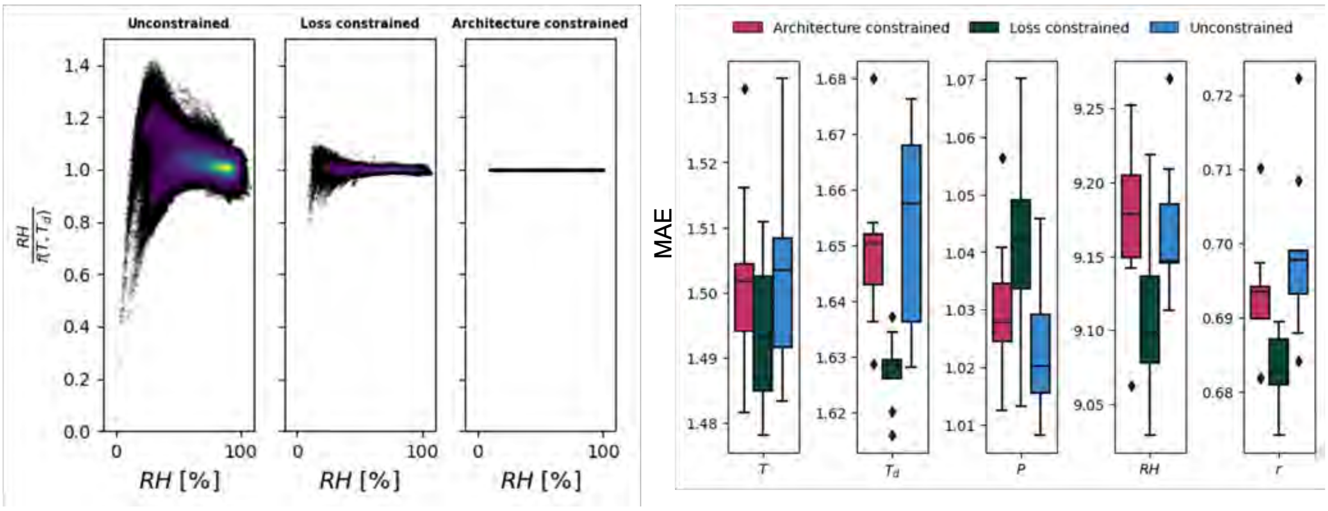


Figure 2: Left: physical consistency of predictions for the three approaches, represented by the ratio between the predicted RH and the one derived using the constraint function $f(T, T_d)$, as a function of RH. As expected, physical violations (represented by deviations from a ratio of 1) are significantly reduced by the loss-constrained approach and brought to zero with the architecture-constrained approach. Right: univariate forecast accuracy represented by the mean absolute error. Overall, the performance in comparable for all approaches, with slightly better results for the loss-constrained approach.

References

[1] Vannitsem, S. et al. Statistical Postprocessing for Weather Forecasts: Review, Challenges, and Avenues in a Big Data World. *Bulletin of the American Meteorological Society* **102**, E681–E699 (2021), https://doi.org/10.1063/1.4979042

[2] Kashinath, K. et al. Physics-informed machine learning: case studies for weather and climate modelling. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences* **379**, 20200093 (2021) https://doi.org/10.1098/rsta.2020.0093

[3] Beucler, T. et al. Enforcing Analytic Constraints in Neural Networks *Emulating Physical Systems. Phys. Rev. Lett.* **126**, 098302 (2021), https://doi.org/10.1103/PhysRevLett.126.098302

The challenges of assessing low-likelihood temperature extremes with empirical data of past events

Joel Zeder[1], Sebastian Sippel[1], Erich M. Fischer[1]

[1]Institute for Atmospheric and Climate Science, ETH Zurich, Zurich, Switzerland

Primer: The recent Pacific Northwest heatwave in June 2021 is widely considered a prime example of a record shattering low-likelihood extreme event [1], exceeding previous annual temperature maxima by large margins. The event intensity was generally perceived to be far beyond what was to be expected from historical data (c.f. Fig. 1). It has been argued that the event would have been deemed essentially impossible, i.e. having an infinite return period, if estimated based on the historical record of one-day annual maximum temperature Tx1d, even when taking the warming trend into account [2]. This raises the question whether the non-stationary extreme value modelling approach, a widely used probabilistic framework applied to assess the likelihood of such extremes, yields systematically biased estimates determining the tail characteristics of the distribution.

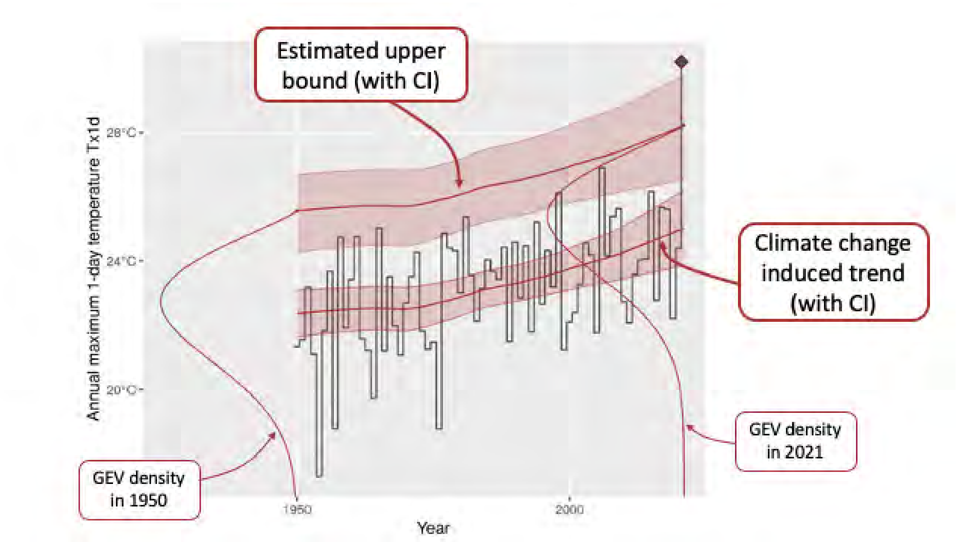


Figure 1: ERA5-Land time series of annual maxima in daily mean temperature in the Pacific North-West area. The diamond marks the value of the 2021 heatwave, further statistical estimates (conditional GEV densities, trends in Tx1d and the estimated upper bound) are also annotated.

Research objective: We here aim at understanding why the intensity of the event exceeds the upper bound of the estimated distribution when only using data up to the year before the event. We quantify the contribution of a multitude of factors for a generalized extreme value distribution GEV G_Z with a non-stationary parametrization (where the location parameter μ is a linear function of global mean surface temperature T, c.f. Eq. 1) to be too conservative in the characterisation of tail events, especially in the context of heatwaves. We analyse how physical properties of heat extremes materialise in statistical effects contributing to potential biases in the GEV parameter estimation, as well as some inherent deficiencies of the GEV in its application to heat extremes with limited sample size due to asymptotic properties.

$$Z_T \sim G_Z(z; \mu(T), \sigma(T), \xi(T)), \quad \text{where} \begin{cases} \mu(T) & = \mu_0 + \mu_1 \cdot T \\ \sigma(T) & = \sigma \\ \xi(T) & = \xi \end{cases} \tag{5}$$

Data & Methods: In order to test the respective hypotheses, we analyse climate model output of single model initial condition large ensembles (SMILEs), primarily an ensemble of 84 transient historical and RCP8.5 simulations performed with the Community Earth System Model CESM1, and an ensemble of 100 transient historical and SSP3-7.0 simulations performed with CESM2. The results are further verified using additional CMIP6 climate model and ERA5 reanalysis data.

Preliminary results and outlook: We find that non-stationary return period estimates tend to be systematically biased high when estimated on the historical records up to a year before a record-shattering event, which is a standard practice in applications of this framework. We here disentangle the reason responsible for potential biases in the estimates. We find that even in case of stationary extremes, the asymptotic nature of the GEV distribution applied to finite data favours an underestimation of the shape parameter, which has substantial effects on the characterisation of the tail, inducing biases in estimates of widely used tail measures (exceedance probabilities, return periods), and derivatives thereof (risk ratios, fraction of attributable risk). The conditional effects of non-stationary components like global warming on heatwave intensity are potentially further underestimated due to internal variability and noise in the covariates.

References

[1] Overland, J. E., Causes of the Record-Breaking Pacific Northwest Heatwave, Late June 2021, *Atmosphere* **11(12)**, 1434 (2021), `https://doi.org/10.3390/atmos12111434`.

[2] Philip, S. Y., Kew, S. F., van Oldenborgh, G. J., Anslow, F. S., Seneviratne, S. I., Vautard, R., ... Otto, F. E. L., Rapid attribution analysis of the extraordinary heatwave on the Pacific Coast of the US and Canada June 2021, *Earth System Dynamics Discussions*, 1–34 [in Review], `https://doi.org/10.5194/esd-2021-90`

Characterisation of dielectric and absorbing particles in ice cores from Northeast Greenland with the single particle extinction and scattering method (SPES)

Chantal Zeppenfeld[1], Tobias Erhardt[1,2], Camilla M. Jensen[1], Hubertus Fischer[1]

[1]Climate and Environmental Physics, Physics Institute, and Oeschger Centre for Climate Change Research, University of Bern, Switzerland

[2]Alfred Wegener Institute, Helmholtz-Zentrum für Polar und Meeresforschung, Bremerhaven, Germany

Ice cores represent archives that contain information about past climatic conditions such as the composition of the atmosphere. By melting the ice and analysing the enclosed impurities, climatic variations can be reconstructed. Of these impurities, insoluble particles are of interest due to their influence on the ocean biogeochemistry and the Earth's radiative balance. Changes in their concentration, size distribution or mineralogy reflect alterations in the source regions, transport, or deposition mechanisms [1]. The particles can be classified as dielectric or absorbing. Mineral dust is mostly non-absorbing or only very weakly absorbing. Its main source regions for Northeast Greenland ice cores are the East Asian deserts, whereas absorbing particles originate from combustion processes most likely in North America.

To investigate the particles and to quantify the past changes in their concentration and properties, the Classizer One instrument, which is based on the novel single particle extinction and scattering (SPES) method, has been incorporated into the continuous flow analysis set-up in Bern. The method allows for high-resolution continuous and simultaneous measurements of particle number, size, and refractive index in the size range of 0.2 to 2 μm [2]. This size range covers the maximum of the particle number size distribution expected in polar ice cores, which has been inaccessible by previously available continuous particle sizing methods with typical lower size detection limits of around 1 μm. Thus, while most of the mass of mineral dust was observed, the majority of the dust particles was not. Furthermore, the new method allows for a distinction between absorbing and dielectric particles for periods of low dust concentration.

The instrument was used to measure part of the main and two shallow cores drilled at the EGRIP site in Northeast Greenland. Here, we will focus on the absorbing particle concentration record obtained with this instrument for the early Holocene up to the year 8000 b2k and for the last millennial. The anthropogenic effect on the absorbing particle concentration and seasonality can be seen in both firn cores. It is characterised by an increase in concentration after the industrial revolution and a decrease to preindustrial levels after reaching its peak shortly after the turn of the century. These results are comparable to studies of black carbon in Greenlandic ice cores [3]. This and the simultaneous occurrence of peaks in the absorbing particle record and the wildfire proxy ammonium suggest that the SPES method can be used to determine the absorbing particle concentration accurately and that significant natural and anthropogenic changes in the absorbing particle number can be observed.

References

[1] M. Legrand, P. Mayewski, Glaciochemistry of polar ice cores: A review, *Review of Geophysics*, **35 (3)**, 219-243 (1997), 10.1029/96RG03527.

[2] M. A. Potenza, T. Sanvito, A. Pullia, Measuring the complex field scattered by single submicron particles, *AIP Advances*, **5 (11)**, 117222 (2015), 10.1063/1.4935927.

[3] J. R. McConnell, R. Edwards, G. L. Kok, M. G. Flanner, C. S. Zender, E. S. Saltzman, J. R. Banta, D. R. Pasteris, M. M. Carter, J. D. W. Kahl, 20th-Century industrial black carbon emissions altered arctic climate forcing, *Science*, **317**, 1381-1384 (2007), 10.1126/science.1144856.