# ZHydro Seminar 2020

Seminar in Hydrology

## Program and teasers for the presentations

November 25th, 2020
Virtual meeting

Organisation: Christoph Schär and Christian Steger, Climate and Water Cycle, Institute for Atmospheric and Climate Science, ETH Zürich

Info: schaer@env.ethz.ch, christian.steger@env.ethz.ch

Website: https://iac.ethz.ch/edu/courses/master/electives/seminar_hydrology.html

## General information

The ZHydro seminar (Seminar in Hydrology) provides a platform to foster exchange and interaction between different research groups in the Zürich area working on hydrology-related topics.

Due to the special circumstances regarding COVID-19, this year's seminar will be held in a virtual format. We invite all researcher, students and other interested people to join. Please register; a Zoom-link will be sent around on November 24. There is no registration fee.

Please find below the seminar's schedule and a list of oral presentation abstracts. Oral presentations will either be 10' or 20', followed by 5' discussion.

Poster contributions will be provided on the seminar's website (in a password protected domain). During the seminar, there is an opportunity to briefly advertise the posters in a pitch and there is room to discuss them in a chat. If you would like to contribute a poster, please send details (title, lead author, affiliation) to christian.steger@env.ethz.ch no later than November 11. A digital version of the poster should be sent to the same e-mail address until November 22. The poster should be a one-page pdf-file (A4 landscape).

We opened a website for the event, where we will also host the posters. For the moment it is in the webspace of the IAC.

**Please register until November 22 at:**

https://iac.ethz.ch/edu/courses/master/electives/seminar_hydrology.html

## Schedule

| Time | Title | Presenter |
|---|---|---|
| | **Introduction** | |
| 09:00 | Welcome | Christoph Schär, Christian Steger |
| | **Hydrology-vegetation interactions** | |
| 09:05 | Soil hydraulic constraints on transpiration and physiological adaptations | Andrea Carminati |
| 09:20 | The response of natural vegetation and rainfed crops to rainfall anomalies as a function of soil texture | Surya Gupta |
| 09:35 | Are hydrologic and vegetation droughts disconnected in the Alps | Harsh Beria |
| 10:00 | Poster pitches | |
| 10:10 | Coffee break | |
| | **Mixing processes and fluid flow** | |
| 10:30 | High-frequency concentration time-series reveal novel insights into pesticide dynamics | Daniele la Cecilia |
| 10:55 | Impact of water saturation on chemical reactions in soils: insights from Magnetic Resonance Imaging | Ishaan Markale |
| 11:20 | How stimulated fault zones reorganize fluid flow: New experimental and theoretical insights | Bernard Brixel |
| 11:35 | Integrated Borehole Flow Logging Technique using Active Heating: An Experimental and Numerical Study | Nima Gholizadeh Doonechaly |
| 11:50 | Lunch break | |
| | **Hydrology and hydrological modelling** | |
| 13:00 | The origin of sediment matters: combining geomorphic mapping and hydrology-sediment modelling | Giulia Battista |
| 13:25 | Intelligent parameter sampling for flood uncertainty estimates at low computational costs | Anna Senoner |
| 13:50 | Flow Prediction in Ungauged Catchments Using Probabilistic Random Forests Regionalization and New Statistical Adequacy Tests | Cristina Prieto |
| 14:15 | Hydrogeological Explorations using Remotely Sensed Data | Nicole Burri |
| 14:40 | Fish's movement behavior during simulated hydropeaking conditions – An imaging-based tracking approach | Robert Naudascher |
| 14:55 | Poster pitches | |
| 15:05 | Coffee break | |
| | **Climate and Glaciers** | |
| 15:25 | Observed changes in dry-season water availability attributed to human-induced climate change | Ryan Padron |
| 15:40 | Dryness stress on ecosystem production globally: Soil moisture supply vs. Atmospheric water demand | Laibao Liu |
| 15:55 | The scaling of extreme hourly and sub-hourly precipitation intensities over the Alps under climate change | Jesus Vergara Temprado |
| 16:20 | Sustainable ablation of glaciers in High Mountain Asia | Evan Miles |
| 16:45 | Outlook 2021 and Goodbye | Christoph Schär, Christian Steger |

# Soil hydraulic constraints on transpiration and physiological adaptations

**Andrea Carminati**[1]

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The current trend towards linking stomata regulation to plant hydraulics emphasizes the role of xylem vulnerability. However, a recent meta-analysis show that the primary driver of stomatal closure is the loss in soil hydraulic conductivity, rather than that of the xylem.
In this presentation I will discuss 1) the soil hydraulic constraints on transpiration and 2) physiological mechanisms that enable plants to plastically adapt to such constraints. These adaptations include short time stomatal regulation and rhizosphere plasticity. A new model of stomatal regulation that allows plants to adapt to variable conditions will be introduced.

# The response of natural vegetation and rainfed crops to rainfall anomalies as a function of soil texture

**Surya Gupta**[1], Peter Lehmann[1], Sara Bonetti [2], Dani Or[3]

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The sensitivity of rainfed crops to soil texture guides many agronomic operations (timing, crop selection, inputs), particularly in water-limited regions. In contrast, natural vegetation undergoes continuous trait and species selection to better adapt to local soil and climatic conditions. We hypothesize that natural vegetation becomes insensitive to variations in soil texture whereas the response of crops to rainfall anomalies is accentuated or diminished based on local soil texture. We systematically examined the responses of natural and rainfed cropped vegetation to rainfall anomalies across biomes and scales using field observations and remote sensing information. At local scales (0.1 km), crop yields were obtained from literature data, whereas natural vegetation's gross primary productivity (GPP) was deduced from FLUXNET sites. At regional scales (>250 km), we extracted information from remote sensing-based GPP. Results confirm a lack of response of natural vegetation productivity (GPP) to soil texture across biomes and rainfall anomalies at all scales. In contrast, crop yields show correlation with soil texture at local scales in dry years (in agreement with conventional agronomic practices). The correlation with soil texture vanishes at larger scales (250 x 250 km) based on remote sensing products (GPP). Interestingly, for the same remote sensing products at smaller scales (25 x 25 km), crop GPP sensitivity to soil texture becomes more prominent in dry years. Results suggest that natural vegetation across biomes adapts to local climatic conditions and becomes independent of soil texture limitations, whereas rainfed crops retain dependency on soil texture as manifested at local field scales, but such dependence becomes obscured at larger scales (where topography, aspect, and other sources of uncertainty confound the dependency). The study (i) provides new insights into the meaning of natural vegetation in climatic equilibrium, (ii) highlights the potential of cumulative adaptation of soil structural alterations that diminish soil texture influence relative to annual cropped fields, (iii) suggests different water stress functions for crops and natural vegetation, and (iv) reveals the role of scale in expressing such sensitivities in Earth System models.

# Are hydrologic and vegetation droughts disconnected in the Alps?

**Harsh Beria**[1,2]

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The 2003 European drought was one of the longest and hottest rainless periods in recorded history and popularized the concept of "drought paradox", where precipitation deficits reduced streamflow without significantly impacting vegetation. However, the drought paradox wasn't reproduced in the 2018 drought, which was broadly comparable in terms of meteorological conditions, but had a very adverse impact on tree mortality. This points to a large knowledge gap, wherein the underlying drivers of landscape response to droughts are not well understood in the Alps. This is likely to become more relevant in a warmer climate where rapidly evolving atmospheric dynamics, such as reduced snowfall leading to lower snow accumulation and earlier snowmelt, are expected to accentuate streamflow droughts in the Alps. In this context, it is imperative to understand how much streamflow and vegetation water uptake depend on different precipitation phases (rainfall versus snowfall), and what factors control the relative proportion of rainfall and snowfall that are ultimately used by vegetation (versus that flow to streams). This will help us understand how precipitation deficits during periods of drought affect the partitioning between streams and vegetation within mountainous landscapes.

This presentation will provide a broad overview of the current state-of-art in drought research in mountainous regions, highlighting the differential role of seasonal precipitation on water partitioning in the Swiss Alps. I will outline my research plan to understand the propagation of precipitation deficits into streamflow and evapotranspiration in drought years using an array of different datasets derived from multiple sources such as remote sensing products, stable water isotopes, and plant phenology.

# High-frequency concentration time-series reveal novel insights on pesticide dynamics

**Daniele la Cecilia**[1], Anne Dax[1], Michael Stravs[2], Christoph Ort[3], Heinz Singer[1], Christian Stamm[1]

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We present the results from the on-site platform MS2field quantifying hundreds of pesticides with 20 minutes temporal resolution continuously. In 2019, MS2field was deployed in a small agricultural catchment in the Swiss Plateau close to Lake Constance for 41 days of observations from the 27th of May until the 7th of July.
We targeted 60 pesticides among fungicides, herbicides and insecticides having widely different physical and chemical properties and mode and time of application. Eventually, 32 pesticides exceeded their corresponding levels of quantification during the monitoring period; these pesticides were further analysed. The high temporal resolution together with a comprehensive data set of different pesticides promised to yield insights about potential PPPs sources and pathways.
The time-series encompassed several rain events of different intensities and three dry periods. During wet periods, supply limitation and transport limitation mechanisms in the mobilization of pesticides were evident. A close look to the most intense rainfall revealed the occurrence of two consecutive peaks for some herbicides, 4 hours apart, which are possibly due to two pathways delivering pesticides at different speed.
In dry periods, we identified for the first time diel concentration fluctuations of some pesticides but not others. The former attained high concentrations and persisted for days. Such peculiar patterns excluded the occurrence of known pathways including spray drift, wind erosion and dry deposition. We show that the time-series of PPPs concentration are time-lag correlated with water levels measured at the same location. Therefore, we speculate that the diel patterns are caused by intra-daily exchanges at the interface between surface water and groundwater.

To close this knowledge gap, we recently carried out a 1 day field campaign in a dry period to collect water samples every 6 hours from the stream at 6 different locations and from 4 outlets of active tile drains discharging in the stream. Tentatively, we will present the results of the target campaign, which may pinpoint contamination hot spots, quantify the contribution of tile drains in delivering pesticides and support or discard the hypothesis that diel fluctuations can re-occur in the experimental catchment.

Finally, there are still many potential candidates in the mass spectrometer (MS) spectra to be analysed. Inspired by recent application of signal analysis tools to MS intensities, we tested whether these tools can drive process discovery in pesticide dynamics without the need of supervision.

# Impact of water saturation on chemical reactions in soils: Insights from Magnetic Resonance Imaging

**Ishaan Markale**[1,2], Gabriele Cimmarusti[3], Melanie Britton[3], Joaquin Jimenez-Martinez[1,2]

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Transported chemical reactions in unsaturated porous media are relevant across a wide range of environmental and industrial applications. Widely used dispersive models are often based on equivalent parameters derived from analogy with saturated conditions, and cannot appropriately take into account processes such as incomplete mixing, which intrinsically occurs at pore scale. Yet, it is unclear how the third dimension controls mixing and reactions in unsaturated porous media. We obtain 3D experimental images of the phases distribution and of transported chemical reaction by Magnetic Resonance Imaging (MRI), for which an immiscible non-wetting liquid as a second phase and a fast irreversible bimolecular reaction were used, respectively. We use this to systematically study, varying the flow rate and keeping the Peclet number constant, the impact of phases saturation on the dynamics of mixing and of the reaction front. By measuring the local concentration of the reaction product, we quantify temporally resolved effective reaction rate. We successfully describe the effective reaction rate using the lamellar theory of mixing, which explains faster than Fickian rate of product formation by taking into account the deformation of mixing interface between the two reacting fluids. Our experiments reveal that for a given Peclet number, although stretching and folding of the reactive front are enhanced as saturation decreases, enhancing the product formation, the magnitude of the global reaction rate, and therefore of the mass of product, is larger as saturation increases, i.e., volume controlled. However, after breakthrough, the extinction of the reaction takes longer as saturation decreases due to the larger non-mixed volume behind the front. These results are the basis for a general model to better predict reactive transport in unsaturated porous media not achievable by the current continuum paradigm.

# How stimulated fault zones reorganize fluid flow: New experimental and theoretical insights

**Bernard Brixel**[1], Qinghua Lei[1], Paul Selvadurai[2], Federico Ciardo[2], Antonio P. Rinaldi[2], Hannes Krietsch[3], Linus Villiger[2], Nathan Dutler[4], Maria Klepikova[5], Clément Roques[5], Mohammadreza Jalali[3], Simon Löw[1].

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Faults control the transfer of fluids, mass and energy in the upper crust and their hydromechanical state often determines whether deep, anthropogenic fluid injections generate large earthquakes or not. Increasing the permeability of the crust, while keeping seismicity as low as possible, constitutes for example a major challenge to extract deep geothermal energy. While models abound in the literature to explain the role of fluids during earthquakes and faulting, few direct observations exist to systematically relate the hydrological state of faults and seismicity. Here, we show from in situ tests performed before and after fault stimulation experiments at the Grimsel Rock Laboratory, Switzerland, that fault reactivation simultaneously increases and decrease permeability to enhance fluid flow, and that seismicity is directly related to the magnitude of net permeability changes. Using simple flow models to fit our observations, we find that the hydraulic properties of fault zones sustain significant, non-reversible changes. While stimulated locations experienced an increase in permeability, permeability along-strike can be reduced by more than one order of magnitude, indicating that fault slip and shear-induced dilation impacts permeability differently depending on location. To explore how shear dilation impacts the spatial distribution of post-slip permeability on and off-fault, we model the effects of an edge dislocation in an infinite, homogeneous, linear elastic and isotropic material and show that mechanically-driven compression affects the distribution of effective normal stresses in the near-field, changing its permeability both positively and negatively depending on location. Finally, comparing our results with the maximum earthquake magnitudes and rupture areas observed during stimulation reveals that strong correlations exist between the net permeability enhancement sustained and the near-field seismicity. Such a link suggests that the hydraulic performance of fault stimulations (i.e. the ability to enhance permeability) could be predicted from knowledge of their hydraulic properties

# An Integrated Borehole Flow Logging Technique using Active Heating: An Experimental and Numerical Study

Matthias Meier[1], **Nima Gholizadeh Doonechaly**[1], Simon Löw[1]

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It is of crucial importance to identify the flowing zones/fractures in a (newly drilled) borehole for reservoir characterization/development studies. The thermal anomalies within the borehole, amongst other features, have been used frequently in the past as one of the main signatures of flowing intervals, since the flowing fluid often bears thermal contrast against the embedding rock. However, the magnitude of such a contrast is not always large enough to decisively pinpoint the flowing zones. By applying active heating in the borehole, otherwise known as heat dilution test, this study aims to amplify the natural in-situ thermal contrast to be able to identify the flowing zones in a borehole drilled in crystalline rock at the Bedretto Underground Laboratory for Geo-Energies (BULG) in Switzerland.
For this purpose, a hybrid cable composed of a Fiber Optic-Distributed Temperature Sensing (FO-DTS) as well as a heating element is lowered into the borehole. Once installed, large enough current is flowed into the heating cable for a fixed duration of time using a power supply unit at the surface. The temperature of the system is continuously monitored with the FO-DTS part of the cable both during- and after- the heating process. The rapid temperature changes with such as active heating approach provides us with a notable thermal contrast in the flowing zones, much larger than the in-situ conditions. The qualitative observation from this experiment are then supported by the numerical inversion analysis, appreciating the flow rates measured during drilling of the nominated borehole at the surface as boundary constraints.
The results show that the heat dilution test can be used as a powerful tool for the analysis of the location-, inflow rate- and inflow temperature-of flowing fractures in the borehole. It was possible to detect inflows that contribute as small as 10-4 m/s to average fluid velocity in the borehole.

# The origin of sediment matters: combining geomorphic mapping and hydrology-sediment modelling

**Giulia Battista**[1], Fritz Schlunegger[2], Paolo Burlando[1] and Peter Molnar[1]

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Knowledge about the sediment provenance at a river basin outlet is of fundamental importance not only to identify the locations of most active erosion, but also to interpret denudation rates based on cosmogenic radionuclide (CRN) dating. Approaches based on sediment fingerprinting are widely used for this purpose, however they only provide limited information about the actual sediment paths and the temporal dynamics of the sediment provenance. Here we show the potential of combining spatially explicit modelling with geomorphic mapping of localized sediment sources, to track sediment from the sources to the outlet.

In the hydrological model TOPKAPI-ETH we introduced two components for sediment mobilization and transport. They account for hillslope overland flow erosion and mobilization of sediments from localized sources, which we further classified into landslides and deeply incised areas. The model routes the sediment flux components in parallel from the sources to the outlet, allowing tracking of the sediment load provenance at the basin outlet and its temporal dynamics. To describe the gully competence on landslide surfaces we introduced a new parameter allowing the model to shift between channel-process and hillslope-process dominant behavior. We show that this parameter can be estimated from a topographic analysis of surface roughness, or from sediment tracing with $^{10}$Be concentrations, which were measured in source areas and at the outlet in previous studies.

The application of the model to the pre-Alpine Kl Emme river basin showed that accounting for localized sediment sources is essential to capture the sediment dynamics. The estimates of the gully competence parameter indicate that channel-processes are likely dominant in the case study. Finally, we show how this approach can guide optimal CRN sampling for denudation rate estimates, and in the future could complement fingerprinting methods in the analysis of sediment dynamics in mountain environments.

# Intelligent parameter sampling for flood uncertainty estimates at low computational costs

**Anna E. Sikorska-Senoner**[1]

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Uncertainty of a hydrologic model is often communicated in the form of a simulation ensemble derived through resampling of the probable parameter space. The major limitation of this approach is that it involves running the hydrologic model with resampled parameter sets before its resulting ensemble can be characterized, e.g. with prediction intervals. Hence, each application to new settings requires re-running the model to derive the simulation ensemble and the prediction intervals for new conditions. As the ensemble can consist of thousands or more members, re-running the model for all these members may become timely and computationally intensive. This is particularly the case if many different meteorological inputs of long time series should be analysed or for (semi-)distributed models. To overcome this computational issue and to reduce the number of model simulations needed, some kind of a parameter set pre-selection would be very desirable.

This study proposes a novel method for such an intelligent selection of the representative parameter sets of a hydrologic model that relies on analysis of hydrological model responses in the flood frequency space. By examining the variability and similarity of the ensemble members in the frequency space, representative parameter sets can be selected. These representative sets selected in the frequency space should enable for deriving reliable prediction intervals for extreme flood simulations. The proposed methodology is applied to annual maxima and demonstrated on a small Swiss catchment (Dünnern at Olten, 196 km$^2$) based on 10’000 years of continuous daily pseudo-discharge observations. These synthetic data are generated with a hydrological model (HBV) fed with meteorological scenarios generated with the weather generator. The proposed method is particularly suitable to be used in complex settings that require multiple and computationally intensive model runs at high temporal resolutions. Potential practical applications include all studies using large data sets, flood frequency analysis, medium to short-range forecasting, operational systems, and designing flood constructions.

# Flow Prediction in Ungauged Catchments Using Probabilistic Random Forests Regionalization and New Statistical Adequacy Tests

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Flow prediction in ungauged catchments is a major unresolved challenge in scientific and engineering hydrology. This study attacks the prediction in ungauged catchment problem by exploiting advances in flow index selection and regionalization in Bayesian inference and by developing new statistical tests of model performance in ungauged catchments. First, an extensive set of available flow indices is reduced using principal component (PC) analysis to a compact orthogonal set of “flow index PCs.” These flow index PCs are regionalized under minimal assumptions using random forests regression augmented with a residual error model and used to condition hydrological model parameters using a Bayesian scheme. Second, “adequacy” tests are proposed to evaluate a priori the hydrological and regionalization model performance in the space of flow index PCs. The proposed regionalization approach is applied to 92 northern Spain catchments, with 16 catchments treated as ungauged. It is shown that (1) a small number of PCs capture approximately 87% of variability in the flow indices and (2) adequacy tests with respect to regionalized information are indicative of (but do not guarantee) the ability of a hydrological model to predict flow time series and are hence proposed as a prerequisite for flow prediction in ungauged catchments. The adequacy tests identify the regionalization of flow index PCs as adequate in 12 of 16 catchments but the hydrological model as adequate in only 1 of 16 catchments. Hence, a focus on improving hydrological model structure and input data (the effects of which are not disaggregated in this work) is recommended.

# Hydrogeological Explorations Using Remotely Sensed Data

**N. M. Burri**[1,2], C. Moeck[1], M. Schirmer[1,2]

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Groundwater (GW) recharge input and discharge output are important components of a catchment's water storage. However, these components are often challenging to quantify due to the complexity of hydrogeological processes and limited observations. Although remotely sensed (RS) data present an attractive and promising tool in hydrological studies, in particularly because of the spatiotemporal availability of many RS products, its application for calculating water storage for meso-scale catchments (typically 10 – 104 km2) is still limited. However, when coupled with ground-based observations, RS data could provide a more complete understanding of the hydrogeological system. We investigate the capability of a data-assimilation approach for the Thur catchment in Switzerland (~1700 km2). The Thur River, with its naturally variable discharge rates (3 m3/s - 1129 m3/s), has 10 long-term operational gauging stations, and readily available groundwater level data. Combined with readily available historic precipitation data, and RS evapotranspiration estimates from MODIS, used in conjunction with hydrological discharge data, 20 years (2000 - 2019) of water storage was calculated for the Thur catchment. Using a water balance approach, we determined the spatiotemporal water available for storage.

Our working hypothesis suggests that, when coupled with groundwater level fluctuation data and geological information, the remotely sensed water storage can be used to determine the physical processes governing the timing and amount of water available for groundwater recharge and discharge in the Thur catchment. We demonstrate the usefulness of data-assimilation techniques, using open source software and readily available data, in determining catchment-wide water distribution, and groundwater storage capacity and changes. Understanding a catchment's spatiotemporal water distribution will help determine where water bodies could be suitably buffered, either through the rehabilitation and protection of wetlands and river reaches or via managed aquifer recharge, in order to abate the effects of increasing water demand, and climate and land use change on the catchment's water budget.

# Fish's movement behavior during simulated hydropeaking conditions – An imaging-based tracking approach

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High-head storage hydropower is deemed to be the ideal renewable energy source in Alpine regions to meet the increasing demand for daily peak electrical energy and serve as a battery for other renewable energy sources. In Switzerland this trend is further enhanced by the recent governmental decision to phase out nuclear power production. However, the common mode of operation - called hydropeaking - can imply severe hydrological, thermal and hydromorphological alterations that affect the ecosystem downstream of such facilities. Hydropeaking is characterized by rapid alterations in discharge that threaten in particular the early life-stages of riverine fish species. Broadly characterized by low water depths and low flow velocities, their habitat is spatially relocated during hydropeaking events. The migration rate needed to respond to hydropeaking depends on the local gravel bed inclination and the slope of the rising and falling limb (ramping rate) of the river hydrograph. A fish’s ability to survive hydropeaking events is strongly linked to its ability to relocate along spatial gradients of flow depths and flow velocities during these periods of rapid change in discharge. If relocation is ineffective, individuals may drift away with the current (during the rising limb of the hydrograph) or fatally strand on the gravel bed (during the recession limb of the hydrograph). Traditionally, the severity of ramping rates has been quantified by counting the number of drifted and stranded individuals for specific gravel bank arrangements in hydraulic flume experiments. In this study, we use state-of-the-art imaging-based tracking techniques to quantify the movement behavior of 1-month-old river trout on artificial river substrate in a flume. We quantify changes in behavior during discharge alterations and investigate the local hydrodynamic cues that are associated and potentially trigger behavioral changes. This work aims to provide a mechanistic understanding of fish movement behavior in drastically altered river flows in order to determine why certain flow alterations provoke stranding or drift of individuals.

# Observed changes in dry-season water availability attributed to human-induced climate change

**Ryan S. Padrón**[1], Lukas Gudmundsson[1], Bertrand Decharme[2], Agnès Ducharne[3], David M. Lawrence[4], Jiafu Mao[5], Daniele Peano[6], Gerhard Krinner[7], Hyungjun Kim[8], and Sonia I. Seneviratne[1]

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Human-induced climate change impacts the hydrological cycle and thus the availability of water resources. However, previous assessments of observed warming-induced changes in dryness have not excluded natural climate variability and show conflicting results due to uncertainties in our understanding of the response of evapotranspiration. Here we employ data-driven and land-surface models to produce observation-based global reconstructions of water availability from 1902 to 2014, a period during which our planet experienced a global warming of approximately 1 °C. Our analysis reveals a spatial pattern of changes in average water availability during the driest month of the year over the past three decades compared with the first half of the twentieth century, with some regions experiencing increased and some decreased water availability. The global pattern is consistent with climate model estimates that account for anthropogenic effects, and it is not expected from natural climate variability, supporting human-induced climate change as the cause. There is regional evidence of drier dry seasons predominantly in extratropical latitudes and including Europe, western North America, northern Asia, southern South America, Australia and eastern Africa. We also find that the intensification of the dry season is generally a consequence of increasing evapotranspiration rather than decreasing precipitation.

# Dryness stress on ecosystem production globally: Soil moisture supply vs. Atmospheric water demand

**Laibao Liu**[1, 2], Lukas Gudmundsson[1], Mathias Hauser[1], Dahe Qin[2], Shuangcheng Li[2], Sonia I. Seneviratne[1]

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Dryness stress can limit vegetation growth and is often characterized by low soil moisture (SM) and high atmospheric water demand (vapor pressure deficit, VPD). However, the relative role of SM and VPD in limiting ecosystem production remains debated and is difficult to disentangle, as SM and VPD are coupled through land-atmosphere interactions, hindering the ability to predict ecosystem responses to dryness. Here we combine satellite observations of solar-induced fluorescence with estimates of SM and VPD and show that SM is the dominant driver of dryness stress on ecosystem production across more than 70% of vegetated land areas with valid data. Moreover, after accounting for SM-VPD coupling, VPD effects on ecosystem production are much smaller across large areas. We also find that SM stress is strongest in semi-arid ecosystems. Our results clarify a longstanding question and open new avenues for improving models to allow a better management of drought risk.

# The scaling of extreme hourly and sub-hourly precipitation intensities over the Alps under climate change

**Jesus Vergara Temprado**[1], Nikolina Ban[2], Christoph Schär[1]

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Over hourly and sub-hourly time scales, extreme precipitation events play a critical role for many sectors impacted by climate change; however, it is unclear how these events will evolve in a warmer climate. Here, we perform climate simulations using a regional climate model over the greater Alpine region at kilometer-scale resolution. By analysing precipitation intensities with various accumulation times, we show that the model can capture the observed percentiles of extreme hourly and sub-hourly precipitation measured at surface rain-gauge stations. Then, by simulating the future climate, we show that the associated increases in intensity of sub-hourly extreme precipitation events grow with the intensity of the events but tends asymptotically towards 6.5 % per degree warming. This suggests that the most extreme intensities scale with the Clausius-Clapeyron scaling rate that represents the ability of a warmer atmosphere to hold more water vapor. It should be expected that these changes will lead to increased risks of flash flooding, land-slides and erosion over the Alps and Europe in a warmer climate.

# Sustainable ablation of glaciers in High Mountain Asia

**Evan Miles**[1], Michael McCarthy[1,2], Amaury Dehecq[1,3], Marin Kneib[1,4], Stefan Fugger[1,4], Francesca Pellicciotti[1,5]

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Glaciers in High Mountain Asia have experienced intense scientific scrutiny in the past decade due to their hydrological and societal importance. Despite advances in assessing their net mass loss, our understanding of accumulation and ablation rates remains limited to a few individual sites. Here we combine ice thickness and surface velocity datasets to adjust observed glacier thinning for mass redistribution, and estimate altitudinal mass balance across the region's glaciers. After testing at sites for which in situ observations are available, we apply our approach to 5527 glaciers across the region. The altitudinal mass balance results allow us to determine the annual ablation budget for each glacier, resolving the portion compensated by annual accumulation.
Our results indicate that very little of the region has a healthy ablation balance, with only 60+/-4% of the regional ablation compensated by accumulation annually. In the Ganges-Brahmaputra basin, just 48% +/- 7% of ablation is sustainable, while the ablation balance is severe for the Lake Balkash (43+/-6%) and Gobi Interior (39+/-5%) basins to the north of the Tien Shan. However, we find that the most important and vulnerable glacier-fed river basins (Amu Darya, Indus, Syr Darya, Tarim Interior) are currently supplied with >50% sustainable glacier ablation due to the extensive accumulation areas of the glaciers affected by the Karakoram Anomaly. However, our results indicate that even without additional climate warming, these basins are likely to experience strong changes in glacial meltwater supply.