GOTHAM Summer School detailed report

GOTHAM (Globally Observed Teleconnections and their role and representation in Hierarchies of Atmospheric Models) is a Belmont Forum/JPI-Climate funded project that aims to better understand teleconnection patterns using novel techniques in combination with super-ensembles of atmospheric models realized within distributed computing at the citizen-science platform climate*prediction*.net (CPDN).

Within the context of GOTHAM, an International Summer School was held at the Potsdam Institute for Climate Impact Research, Potsdam, Germany, from 18-22 September 2017. It hosted 27 aspiring young scientists and a number of experts on teleconnection patterns, methods and data science. As the GOTHAM project itself, the program was divided into different climatological topics including mid-latitude flow, stratospheric teleconnections, El Niño/Southern Oscillation (ENSO), and monsoons, but also focused on the interplay between these different teleconnections and the associated climatological regions.

In more detail, during the 5 days of the school, recognized international scientists (both from GOTHAM partner institutes and external keynote speakers) presented the recent advances in climate science and climate data analysis and discussed various significant issues, including the following research questions:

- **Mid-latitude weather extremes and the interplay of tropical, extratropical and Arctic drivers:** More prolonged wave-resonance events and double jet-streams were discussed as there is evidence of a dynamically induced increase in summer heat extremes over Eurasia. On the other hand, winter circulation seems to be characterized by more frequent weak polar vortex states resulting in colder extremes in Northern Hemisphere mid-latitudes (Dim Coumou). Arctic-mid-latitude interactions were also discussed. The Arctic Amplification, which is most pronounced in autumn and winter and near the surface, can contribute to changes in the frequency of occurrence of certain circulation states. For instance, when Arctic sea-ice concentration is particularly low in autumn, the Scandinavian blocking pattern is favored in early winter (December-January), while a pattern similar to the negative phase of the North Atlantic Oscillation (NAO) is favored during the following later winter/early spring (February-March). Atmospheric models with well-implemented sea-ice forcing are able to reproduce the observed negative NAO signal in (late) winter and the related dynamical processes (Doerthe Handorf). NAO and seasonal predictability and forecast skill were discussed in more detail. There are large uncertainties in models' forecasts, due to underestimation of the Arctic Amplification, low signal-to-noise rations in predictability of extratropical atmosphere and complex interactions with the tropics. The fact that a positive NAO phase is better reproduced by the models, does not guarantee a similarly good performance in the future during possible periods with more negative NAO winters (Antje Weisheimer). A recurring issue is the role of the different NAO definitions, especially on different time scales. Moreover, the Pacific/North America (PNA) pattern seems to have an effect on NAO via the Newfoundland storm track when the former is in its negative phase, resulting in a downstream enhancement of the Atlantic storm track in the subsequent months (Uwe Ulbrich). More generally, it was pointed out that the averaging of ensemble members does not make sense for atmospheric circulation, due to the pronounced regional differences of the relevant parameters. Furthermore, the importance of causal attribution of atmospheric teleconnections was underlined (Ted Shepherd).

- **Stratosphere dynamics and stratosphere-troposphere interactions**: The Quasi-Biennial Oscillation (QBO) is one of the most regularly repeating and thus predictable phenomena in the atmosphere. As such, it could help reaching a significant improvement of seasonal forecasting. Modelling of the

QBO remains a big challenge for contemporary General Circulation Models (GCMs), as only a few of them (e.g., 4 GCMs among the CMIP5 model ensemble) include a good representation of it. Observations show a robust relationship between the phase of QBO and the strength of polar vortex, but this teleconnection, although of the same sign, seems to be much weaker in the models. Moreover, the unexpected disruption of the QBO in 2016 was discussed, when an unprecedented westward jet was formed during the QBO's eastward phase in the lower stratosphere. It seems that the primary cause of this unprecedented behavior was wave momentum transport from the Northern Hemisphere. This fact is interesting as the possibility of more frequent occurrences of similar disruptions is projected for a warming climate (Scott Osprey). A network-based approach to analyze and predict the stratospheric polar vortex using causal discovery algorithms was also presented (Marlene Kretschmer).

- **ENSO and extreme El Niños** and their global consequences: It was underlined that there are not enough well-studied El Niño events in order for sophisticated statistical analysis to be conducted. Thus, one has to rely on physical understanding of the phenomenon. Nevertheless, it is certain that there will be a doubling of the number of occurrences of extreme El Niños in case of unmitigated climate change (RCP8.5 scenario), and global warming will contribute to greater effects/impacts (Eric Guilyardi). An open topic is the asymmetry between El Niños and La Niñas, but also the differences among events of the same type. There is an ongoing debate regarding proposed classifications of ENSO events, as the East (EP or classical) and Central Pacific (CP or Modoki) El Niño and La Niña types. The use of complex climate networks can contribute in this direction to objectively distinguish between such different ENSO flavors (Reik Donner).

- The topic of **Monsoon** changes under climate change was discussed. Generally, although moderate Monsoon events show a decreasing trend, heavy and very heavy events have been increasing recently (1950-2000). The weakening of the Summer Indian Monsoon seems counterintuitive given that there is more intense rainfall and floods over the western part of the Himalayas and Pakistan, but different factors contribute to this. For instance, a weakened Monsoon circulation/moderate-active Monsoon conditions juxtaposed with equatorward penetrating extratropical circulation/southerly moisture transport and enhanced upper-air trough activity, favors intense flood-producing rainfall in this area. Orography of the region also plays a role in amplifying precipitation amounts. Moreover, a long-standing scientific question is whether Indian Ocean dynamics can influence the occurrence of long-lasting "breaks" in the monsoon rainfall over India (Raghavan Krishnan, Ramesh Vellore). The role of the Western North Pacific anomalous anticyclone (WNPAC) in linking El Niño and East Asian monsoon was highlighted as well. Both internal (Interdecadal Pacific Oscillation, IPO, and Atlantic Multidecadal Oscillation, AMO) and external (greenhouse gases, aerosols) forcings contribute to changes in the East Asian Monsoon, but their relative contributions remain unclear (Tianjun Zhou, Bo Wu). Also, a network-based prediction scheme for long-range forecasting of the onset and the withdrawal of the Indian Summer Monsoon was presented (Elena Surovyatkina).

- **Complex networks and causal discovery methods**: Complex systems based approaches for climate data analysis covered a large part of the summer school. Climate data are characterized by non-stationarity, non-linearity, multi-scale variability and internal dynamics, as well as external forcings. Thus, classical time-series analysis may not be suitable to study such data. Complex networks provide a prospective tool as they contain a solid theory of statistical evaluation, efficient numerical algorithms for estimating complementary measures, and existing results on the interrelations between structure and dynamics of networked systems. They are, hence, potentially useful in studying teleconnections. Nevertheless, there are still various conceptual challenges to be tackled (Reik Donner). For this purpose, the Python-based software package pyunicorn (http://www.pik-potsdam.de/~donges/pyunicorn/) provides various functions for generating network structures from climate data and employing various methods of complex network theory and nonlinear time-series analysis (Catrin Kirsch). Another important issue in the context of climate research in general, and teleconnections in particular, is the question of causality. In order to detect causal links and quantify causal interactions, the Python package tigramite provides state-of-the-art algorithms (https://jakobrunge.github.io/tigramite/). Causal effect networks (CEN) were presented as an example of how to identify potential drivers of certain atmospheric processes using concepts from causal discovery (Marlene Kretschmer).

- **CPDN data:** *Climateprediction.net* is a platform that uses distributed computing power provided by volunteers (citizen science) to run super-ensembles of climate model simulations. This way, very large ensembles of simulations are generated, which are very useful to study extreme weather and climate. Two talks presented the way the platform works and how it can be used (Sarah Sparrow, David Wallom).

- **Poster sessions**: 27 posters were on display for the whole duration of the summer school.

- **Practical sessions**: During the practical sessions, students were acquainted with the CPDN platform and how to extract data from the CPDN simulations. Then the two network tools, pyunicorn and tigramite, were presented and the students applied them on different datasets, including CPDN simulations, QBOi and CMIP5 modelled data.