Abstract

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Title: “Modeling and Data Analysis of Large-scale Atmospheric Dynamics associated with Extreme Weather”

In the last decades the frequency and intensity of extreme weather events like heat waves and heavy rainfall have increased and are at least partly linked to global warming. These events can have a strong impact on agricultural and economic production and, thereby, on society. Thus, it is important to improve our understanding of the physical processes leading to those extreme events in order to provide accurate near-term and long-term forecasts. Thermodynamic drivers associated with global warming are well understood, but dynamical aspects of the atmosphere much less so. The dynamical aspects, while less important than the thermodynamic drivers in regards to large-scale and long-time averaged effects, play a critical role in the formation of extremes.

The overall aim of this thesis is to improve our understanding of patterns, variability and trends in the global atmospheric circulation under a changing climate. In particular, in this dissertation I developed two new data-driven methods to quantitatively describe the dynamics of jet streams, Hadley cells and storm tracks. In addition I introduce and validate a new statistical-dynamical atmosphere model that can be used to efficiently model the large-scale circulation.

First, I developed a scheme based on the Dijkstra ‘shortest-path’ algorithm to identify jet stream cores. Using reanalysis data, I found a significant change in jet stream strength and position over the last decades: Specifically, a decrease in wind speeds and a spatial shift toward the poles. This work also shows that the splitting or merging of the polar front jet stream and the subtropical jet stream depends on the season and longitudinal position. In a follow-up study, I analyzed trends in the latitudinal position of the poleward edge of the Hadley cell and subtropical jet stream core for all longitudes. These trends depend strongly on longitude and thus the impacts of tropical expansion might be pronounced in some regions and absent in others.

The second approach was to develop an empirical forecast method for European and Mediterranean winter precipitation. This prediction algorithm innovatively incorporates the spatial patterns of predictors in autumn using clustering analyses. I identified the most important precursors (snow cover in Eurasia, Barents and Kara sea ice concentrations as well as sea surface temperature in the Atlantic and Mediterranean regions) for the precipitation prediction. This forecast algorithm had higher forecast skills than conventionally employed methods such as Canonical Correlation Analysis or operational systems using climate models.

The last approach was to examine the atmospheric circulation using the novel statistical-dynamical atmosphere model Aeolus. First, I validated the model’s depiction of the large-scale

circulation in terms of Hadley circulation, jet streams, storm tracks and planetary waves. To do so, I performed a parameter optimization using simulated annealing. Next, I investigated the sensitivity of the large-scale circulation to three different temperature components: global mean temperature, meridional temperature gradient and zonal temperature gradient. The model experiment showed that the strength of the Hadley cell, storm tracks and jet streams depend almost linearly on both the global mean temperature and the meridional temperature gradient, whereas the zonal temperature gradient is shown to have little or no influence. The magnitude of planetary waves is clearly affected by all three temperature components. Finally, the width of the Hadley cell behaves nonlinearly with respect to all three temperature components.

These findings might have profound consequences for climate modeling of the Mediterranean region. The latitudinal poleward trend of the Hadley cell edge position might become stronger under climate change according to the results with Aeolus. These changes would lead to a substantial reduction of the winter precipitation in the Mediterranean region. In this case seasonal empirical forecast methods, like the clustering-based prediction scheme, will play an important role for forecasting seasonal droughts in advance such that water managers and politicians can mitigate impacts.