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SUMMARY OF DOCTORAL THESIS

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Title: Relationship of wheat yield with temperature in large irrigation areas of Sudan
(スーダンの大規模灌漑地におけるコムギ収量と気温の関係)

Sudan is one of the most vulnerable countries to climate variability and change. In particular, agriculture is affected by climate hazards such as drought in the wet season and extremely high temperatures in the dry season. To cope with such hazards, farmers need timely and reliable climate information for agronomic management, including seed planting, fertilizer application, and irrigation scheduling. Crop yield prediction can help in coping with climate-related risks of yield reduction by taking mitigation measures. For that, the interpretation of seasonal climate forecasts is important as a way to predict crop yield before the growing season. Further, crop yield estimation is required for the process of decision-making in food policy on a regional scale. For example, the outlook for cereal production prior to harvest is crucial for the government decision-makers to plan grain imports beforehand in case of shortages. Thus, early warning systems for climate risk management in crop production have gained worldwide attention. However, the current spatial resolution of the climate forecast data is not high enough for operational use in estimating crop yield, and also high spatial resolution climate data are required for local-scale impact assessments of climate variability. The outputs of general circulation models (GCMs) are not sufficient for such local-scale studies, and therefore regional climate models (RCMs), which incorporate detailed specifications of the earth's surface such as land use and water bodies, have been broadly applied to satisfy this requirement. Weather Research and Forecasting (WRF) is a well-known RCM used for many purposes such as operational forecasting and dynamical downscaling. As local climates are regulated by global atmospheric circulations and further constrained by land surface conditions, the WRF model can be configured with multiple physics options to satisfy region-dependent climate conditions.

Wheat is one of the most important grains in the world and contributes significantly to food security in many countries. The demand for wheat production is increasing due to the increase of the world's population, and so does Sudan. In Sudan, wheat is cultivated under irrigation during the hot and dry season, but high temperature has a negative impact on the crop growth. While improving the heat tolerance of cultivars is one of the reliable measures to adapt to climate change, a yield outlook system with high spatial resolution data of seasonal forecasts is a valuable tool to cope with climate variability. The aim of this thesis was therefore to develop an approach for crop yield prediction with regard to the impact of high temperature on wheat production. The main objectives were (1) to investigate the regional-scale relationship of wheat yields with temperature for the last five decades, (2) to identify a robust configuration of the WRF model for generating high-spatial-resolution climate data for crop growing seasons, and (3) to study the feasibility of wheat yield forecasting.

First, the association between yield of irrigated wheat in hot drylands of Sudan and temperature during the growing season (November–February) was determined. Regional-scale yield data in three major wheat-producing areas (Northern State, Gezira State, and Kassala State) in 48 crop seasons (1970/71–2017/18) were used to determine the correlation of yield with maximum (TMAX) and minimum temperatures (TMIN) at representative meteorological stations (Dongola, Wad Medani, and New Halfa, respectively). Frequencies of days with maximum temperature above 35 °C (THD) and minimum temperature above 20 °C (THN) were also used for correlation analysis. In all

three areas, regression analysis detected upward trends in the growing-season temperature. The increase in temperature was particularly evident at Dongola, although no such trend has been reported previously. The yields were negatively correlated with the growing-season temperature, particularly THN in Northern State, TMAX in Gezira State, and TMIN in Kassala State. These results confirm that the recent increase in the growing-season temperature might have reduced the yield to some extent in the breadbasket of Sudan.

Second, robust configurations of the WRF model, especially cumulus parameterization schemes, for different climatic zones of Sudan were identified, focusing on wet season (June–September) rainfall and dry season (November–February) temperature, which are determinants of summer crop and irrigated wheat yields, respectively. Downscaling experiments were carried out to compare the following schemes: Betts–Miller–Janjic (BMJ), improved Kain–Fritch (KFT), modified Tiedtke (TDK), and Grell–Freitas (GF). Results revealed that the BMJ performed better for wet season rainfall in the hyper-arid and arid zones; KFT performed better for rainfall in July and August in the semi-arid zone where most summer crops are cultivated. For dry season temperature, the BMJ and TDK outperformed the other two schemes in all three zones, except that the GF performed best for the minimum temperature in December and January in the arid zone (Gezira State/Wad Medani and Kassala State/New Halfa), where irrigated wheat is produced, and in the semi-arid zone. Specific cumulus parameterization schemes of the WRF model therefore need to be selected for specific seasons and climatic zones of Sudan.

Third, statistical models for the yield–temperature relationship in the three wheat-producing areas were developed using the backward stepwise regression method. The 2-variable linear regression models were determined for the northern and eastern regions (Northern State/Dongola and Kassala State/New Halfa, respectively). The variables (predictors) selected by the stepwise regression were the growing-season THN and February TMAX in the northern region, and January TMIN and February THN in the eastern region, explaining up to about 40% of the variance for the yield. For the central region (Gezira State/Wad Medani), only one predictor (the growing-season TMAX) was selected, hence the low accuracy of the model. For the eastern region, when model performance was evaluated by classifying the yields into the above-normal, near-normal, and below-normal categories, the accuracy of the forecasted yield to the observed yield was relatively high (86%). Thus, statistical modeling using the stepwise method of multivariate analysis is a useful method for wheat yield outlook with seasonal forecasts.

The findings of this thesis are summarized as follows: (1) Irrigated wheat yield over the past half-century in the hot environments of Sudan shows an increasing trend and is negatively associated with the growing season temperature; (2) Specific configurations (i.e. physics options) of the WRF model in spatial downscaling of climate data are needed for specific seasons and climatic zones; and (3) Temperature-based statistical modeling is a useful method for wheat yield estimation in the irrigation areas of Sudan. Based on these findings, it was concluded that the yield outlook prior to the growing season is possible by incorporating high spatial resolution climate forecasts into the statistical model for yield estimation. Accordingly, the approach developed in this thesis contributes to developing an early warning system for reducing risks associated with high temperature in the wheat production areas of Sudan.