Doctoral Thesis

Understanding and characterizing past, present, and future hydroclimatological change

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Understanding and characterizing past, present, and future hydroclimatological change

A thesis submitted to attain the degree of

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presented by

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Abstract

Changes in the hydroclimatological conditions of the land surface induce widespread impacts on a variety of socio-economic sectors. Assessing past and projected hydroclimatological changes is therefore essential. Nonetheless, the substantial complexity of the hydroclimatological system and the associated data and methodological uncertainties do often not permit conclusive assessments. Also, the wealth of metrics and definitions regularly create conflicting results. In order to foster a clear communication of changes in dryness/wetness to policymakers and the public, observed and anticipated changes are occasionally summarized into simple catchphrases, like e.g. the ‘dry gets drier, wet gets wetter’ paradigm. However, such summaries carry the risk of oversimplifying the governing relationships.

This thesis consists of two parts both separated into two chapters. The first part of this thesis aims at identifying regions of robust past and projected trends in dryness/wetness using observations-based data for the 2nd half of the 20th century and model data for the 21st century, respectively. Dryness and wetness changes are assessed through the joint analysis of water availability (precipitation - evaporation, $P - E$) and aridity (ratio of potential evaporation and precipitation). The statistical approach used allows to determine the geographical distribution of significant hydroclimatological trends.

Regarding the assessment of past changes (Chapter 2), the large amount of existing datasets and possible dataset combinations is evaluated using the Budyko framework as a reference model. By doing so, the selection of physically consistent dataset combinations is enabled and reliability is added to the trend assessment. The trend analysis then reveals that for ca. 3/4 of the global land surface no robust trends are detectable. For the remaining 1/4, significant wetting is identified in parts of North and South America, and drying is found in many parts of Africa, East Asia and the Mediterranean. Using the aridity index to classify regions as either humid or arid allows the evaluation of the ‘dry gets drier, wet gets wetter’ paradigm. It is found that for less than half of the area with robust trends the paradigm is confirmed. Thus, the paradigm is in total supported for ca. only 11% of all land area.

Regarding future changes (Chapter 3), it is first shown that the widely-used $P - E$ (water availability) metric alone is not adequate to assess land
drying/wettening. Trends in water availability are identified as significant only in some northern high latitude regions over land. Additionally considering aridity reveals more regions experiencing significant drying, especially located in the Mediterranean and adjacent regions. However, jointly considering both metrics, still ca. 70% of the land surface show no robust trends. Validating the ‘dry gets drier, wet gets wetter ’ paradigm using both metrics reveals that the paradigm is not supported for ca. 1/3 and supported for ca. 2/3 of the remaining land area. Overall the paradigm is accordingly confirmed for only ca. 20% of all land area, mainly for regions in southern Europe and the northern high latitudes. It does not explicitly apply to the remaining 80% and a few cases of expanding drylands into adjacent regions are identified that specifically invalidate the paradigm. In summary, we conclude that the ‘dry gets drier, wet gets wetter’ paradigm does not serve as a valid summary of observed and projected hydroclimatological changes over global land areas.

The second part of the thesis is dedicated to the Budyko framework. The Budyko framework is a well-established, semi-empirical and simple hydrological model to relate mean annual aridity and water availability. Due to its simplicity it is widely recognized as a powerful hydrological tool and is used to validate and to test datasets on physical consistency in Chapter 2 of the present thesis. However, it is still subject to certain limitations. Two of these limitations are addressed in the second part of the thesis: (i) the nonlinearity of the underlying Budyko space in combination with the deterministic nature of the Budyko curve (Chapter 4) and (ii) the limitation to steady-state conditions (Chapter 5).

By using a formulation of the Budyko curve that includes a free parameter, the first issue is addressed by developing a probabilistic representation of the framework. For this new representation, the free parameter \( \omega \), which represents the combined influence of landscape and climatic characteristics of a catchment is assumed to follow a probability distribution. This step allows the formulation of a probabilistic Budyko model. The distribution of the parameter is further estimated from a set of catchments in the United States, suggesting that the parameter follows a gamma distribution.

In a second assessment, the same formulation is used to derive a Budyko framework implicitly accounting for the case of nonstationary water balance conditions and to enable its use on other than mean annual catchment scales. The new formulation is derived by relaxing the boundary condition that represents the supply limit. By doing so, an additional parameter, which is physically well defined, is obtained. The remaining first parameter is indeed very similar to the single parameter of the stationary Budyko curve. The new framework is evaluated against a standard set of datasets. By doing so, a reasonably good performance at monthly time scales is shown.

In conclusion, this thesis shows that both past and future changes in
hydroclimatological conditions over land are subject to major uncertainties, which do not permit an identification of robust trends for the majority of global land areas. Further, the widely-used ‘dry gets drier, wet gets wetter’ paradigm is determined to not represent observed and anticipated changes. The second part of this thesis further highlights that addressing major limitations of the Budyko framework is potentially of greater importance in order to enhance the fundamental knowledge and range of potential applications, than the yet not conclusive assessments aiming to identify potential physical controls determining the basic characteristics of the Budyko framework. In this context, two expansions of the Budyko framework are introduced: (i) a probabilistic, rather than deterministic, and (ii) a nonstationary, rather than stationary framework.
Zusammenfassung


Durch die Verwendung einer Formulierung des Budyko-Modells, welche eine freien Parameter beinhaltet und aus einfachen Grundannahmen analytisch hergeleitet wird, ist es möglich ein probabilistisches Budyko-Konzept


Im zweiten Teil wird argumentiert, dass die grundsätzliche Untersuchung von Limitierungen des Budyko-Konzepts wichtiger sein könnte die zukünftige Nutzung des Konzepts voranzubringen als die bisher nicht abschliessende Zuordnung von möglichen physikalischen Kontrollprozessen. In diesem Zusammenhang wird eine probabilistisches, im Gegensatz zum traditionell deterministischen und ein nicht-stationäres, im Gegensatz zu einem stationären Konzept eingeführt.