Science of the Total Environment 647 (2019) 29–36

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Urbanization and climate change: Insights from eco-hydrological diagnostics

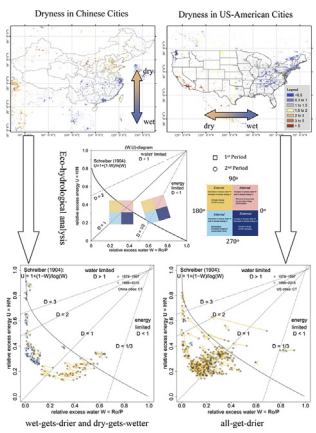
Danlu Cai [a,*], Klaus Fraedrich [b], Yanning Guan [a,*], Shan Guo [a], Chunyan Zhang [a], Xiuhua Zhu [c]

[a] Institute of Remote Sensing and Digital Earth, Chinese Academy of Sciences, Beijing, China
[b] Max-Planck-Institute for Meteorology, Hamburg, Germany
[c] KlimaCampus, Hamburg University, Hamburg, Germany

HIGHLIGHTS

- Nighttime lighted urbanization is subjected to eco-hydrological analysis.
- Urbanization shows differences between developing and developed countries.
- Bi-modal and uni-modal distributions characterize Chinese and US-American cities.
- Chinese cities follow climate induced 'wet-gets-drier' and 'dry-gets-wetter' changes.
- Global urbanization develops towards uni-modality.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 24 October 2017
Received in revised form 16 July 2018
Accepted 23 July 2018
Available online 23 July 2018

Editor: R Ludwig

Keywords:
Urban climate
Rainfall-runoff chain
Climate and anthropogenic induced changes
Developing and developed countries

ABSTRACT

To quantify how urbanization induced long-term changes have altered the evolution of urban climate, a novel eco-hydrological diagnostic is introduced and applied globally, to a developing and a developed country (China and US-America). Urban areas are (i) geographically identified by remote sensing based nighttime light, (ii) physically embedded in state spaces spanned by suitable combinations of surface energy and water fluxes comprising the rainfall-runoff chain, and (iii) dynamically characterized by the time evolution of the surface fluxes at geographically fixed locations, analyzed as trajectories in state space, and interpreted by an attribution model separating anthropogenic from climate induced causes. The results describe the long term climatological settings of urban areas in a net radiation versus dryness diagram, while the attribution of change is diagnosed in a state space spanned by energy and water excess: (i) Cities in China are characterized by a bi-modal distribution separated by the boundary between water and energy-limited (northern and southern) regimes while US-American cities are assembling unimodally on this boundary, and globally the urbanized areas are also aligned along this boundary between water and energy-limited regimes. (ii) Attribution of eco-hydrological changes of urbanized regions to climate and human-induced causes shows also basic differences between the developing and developed country: urbanization in Chinese cities is characterized by a 'wet-gets-drier' and 'dry-gets-wetter' paradigm of the climate-induced contributions, due to which cities tend towards a unimodal state as it is observed for US-American urban areas. Finally, implications for large scale city planning are discussed in the outlook.

* Corresponding authors.
E-mail addresses: caidl@radi.ac.cn (D. Cai), guanyn@radi.ac.cn (Y. Guan).

https://doi.org/10.1016/j.scitotenv.2018.07.319
0048-9697/

1. Introduction

Although global and regional climate changes are known to have an impact on altering the urban surface climate, urbanization is one of the most evident aspects of human modification of natural landscapes and climate (Cai et al., 2017; Fan et al., 2017). Urbanization, which can be interpreted as anthropogenic induced change in surface fluxes, includes the effects of increasing atmospheric greenhouse gas concentration, aerosol emission, and land use and land cover change, is a major driver for the formation and evolution of urban climates (Grimm et al., 2008; Wu and Yang, 2013). Numerous observational studies have reported that cities experience urban heat island effect and pollutant emissions a decade ahead of the global average (Briber et al., 2013; Carreiro et al., 2009; Dentener et al., 2006; Friedlingstein et al., 2006; George et al., 2007; Zhou et al., 2017). These long-term changes may have altered the ecology or evolution of urban organisms in ways that can occur outside the cities in the future (Carreiro and Tripler, 2005; Youngsteadt et al., 2017).

Current approaches are limited in analyzing effects of urbanization/anthropogenic induced surface driven parameter changes (e.g. temperature, carbon and nitrogen) on response variables (e.g. biomass and water) over ecologically relevant spatial and temporal scales (Youngsteadt et al., 2017). Experiments are inevitably constrained by the number of driver variables to be tested simultaneously (Leuzinger et al., 2011). And, as the number of change drivers increases, understanding the interacting mechanisms causing a particular net response becomes much more difficult (Larsen et al., 2011). Contrarily, quantitative analyses of rainfall–runoff chain dynamics on watershed scales as part of the climate system will physically relate water demand to supply by combining the energy and water flux balances (Cai et al., 2016; Cai et al., 2015).

The rainfall–runoff chain dynamics is subjected to an analysis based on the Budyko framework (Budyko, 1974), which has inspired physical insights on the control of the water and energy balance, employing a functional relationship between water demand by net radiation (or potential evapotranspiration) and water supply by precipitation. It reduces the complex mutual interactions between climate and hydrological processes to a single parameter, the dryness as the ratio of two fluxes: mean annual net radiation versus precipitation (Donohue et al., 2009; Fraedrich and Sielmann, 2011; Potter et al., 2005; Williams et al., 2012, for a theoretical analysis, see Fraedrich (2010)). In addition, the coupled water–energy budget and the separation of its respective variables into water and energy related flux ratios provide an eco-hydrological diagnostics that can attribute total change to impacts of external or climate and internal or land-use/watershed change (Tomer and Schilling, 2009; Wang and Hejazi, 2011; Zhan et al., 2014).

Thus, embedding urbanization processes into the changing rainfall–runoff chain with the aim to quantify how urbanization induced long-term changes have altered the evolution of urban climate for a developing and a developed country (China and US-America), has to our knowledge not been performed. In a broader sense, this study expands on the quantitative analyses of urbanization. Commencing with basic measures characterizing the thermal climate effected by urbanization (Cai et al., 2017), a more comprehensive metric is now being employed to embed urbanization into its eco-hydrological environment. In this sense (as a big image) urbanization analysis emerges as a three-step scheme conditional on geographical and economical structures, which are based on night-light clustering and on the separation between developed and developing countries (US-America and China): First, urbanization (as human habitat) is embedded in the thermally effected climate (Cai et al., 2017). This is followed by an eco-hydrological urbanization analysis to attribute causes of change to climate and/or human induced forcing employing causality models based on the Budyko framework. As an outlook, the subsequent next focus will turn towards biodiversity as it can be measured by species and endangered species.

That is, after describing urbanization and the thermal environment of Chinese and US-American cities, we now analyze urbanization and climate change to gain insights from an eco-hydrological diagnostics employing the Budyko framework. Although varying subsurface storage in the catchment water balance is neglected, it provides a simple subgrid closure relation that quantifies how spatial heterogeneity affects average annual evapotranspiration at catchment scales (see Freund and Kirchner, 2017). It is this scale-sensitive aspect which requires special attention. Urbanization and effects on the living world will be considered in the further work.

Thus, after identifying urban areas by remote sensing based nighttime light, urban areas are physically embedded in state spaces spanned by the coupled eco-hydrological conceptual models (Section 2) comprising the rainfall-runoff chain. The dynamical time evolutions of the surface energy and water fluxes of China and America are analyzed as trajectories in state space, and interpreted by separating anthropogenic from climate induced causes (Section 3) before a concluding summary (Section 4).

2. Data and methods of analysis

The geographical setting of urban regions is described by nighttime light signals derived from the Defense Meteorological Satellite Program's Operational Line Scan System (DMSP/OLS). The nighttime light data provides striking remotely sensed information as the basis to analyze global spatiotemporal changes of urbanization processes (Elvidge et al., 1997; Small and Elvidge, 2011; Small et al., 2005; Sutton, 2003). Spatially contiguous lighted pixels obtained from global nighttime stable light products 2012 with digital value number $DN \geq 12$ are defined as cities. The DN-threshold reduces the effects of over-glow usually caused by anthropogenic activities in undeveloped areas, which is excluded from the urban development statistics (Elvidge et al., 1997; Small et al., 2005). Urbanization dynamics are analyzed within the Budyko framework (Fig. 1a–b) to describe hydro-ecological setting and evaluate the changes. They are based on the balanced land surface fluxes net radiation, precipitation and runoff averaged over the following two almost twenty year periods (1979 to 97 and 98 to 2015) ERA-Interim of ECMWF (Balsamo et al., 2012). For detailed calculations, see Cai et al. (2017) and for descriptions of data quality control and threshold selection, see Small et al. (2011).

2.1. Budyko's diagram of climate forcing

The rainfall–runoff chain receives a total supply of water and energy which, interpreted as forcing fluxes, are balanced by a flux partitioning. That is, rainfall P is balanced by runoff Ro and evapotranspiration E, and net radiation N or potential evapotranspiration, which, representing atmospheric water demand, is balanced by the sensible heat flux H and evapotranspiration E:

$$P = Ro + E \text{ and } N = H + E \tag{1}$$

The forcing flux ratio of energy-over water supply, that is of net radiation N over rainfall P, has been introduced by Budyko (1974) as dryness $D = N / P$. It separates energy-limited regimes ($D < 1$ or $N < P$) from water-limited ones ($D > 1$, $N > P$) at $D = 1$. Note that, for compatibility, energy fluxes are given in terms of water equivalents (m/year).

Budyko's geobotanic climate (N,D)-diagram is a surface climate state space spanned by net radiation versus dryness (Fig. 1a). It represents the climatological forcing and, in a qualitative and idealized sense, the meridionality (from polar to equatorial latitudes) and zonality (from wetter western to drier eastern parts in the mid-latitudes) of continental climates. Moreover, climate variables can be displayed, such as precipitation, presented by the slopes of lines through the origin, $N = D P$, or the total supply, $N = (P + N)[D / (D + 1)]$, as isolines which attain the slope $N + P$ at the origin ($N = D = 0$). Finally, the dryness index or