Changes in the Freshwater System: Distinguishing Climate and Landscape Drivers

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Abstract

Freshwater is a vital resource that circulates between the atmosphere, the land and the sea. Understanding and quantifying changes to the partitioning of precipitation into evapotranspiration, runoff and water storage change in the landscape is required for assessing changes to freshwater availability. However, the partitioning processes and their changes are complex due to multiple change drivers and effects. This thesis investigates and aims to identify and separate the effects of atmospheric climate change and various landscape drivers on long-term freshwater change. This is done based on hydroclimatic, land-use and water-use data from the beginning of the twentieth century up to present times and across different regions and scales, from catchment to global. The analysed landscape drivers include historic developments of irrigated and non-irrigated agriculture and flow regulation. The thesis uses and develops further a data-motivated approach to interpret available hydroclimatic and landscape data for identification of water change drivers and effects, expanding the approach application from local to continental and global scales. Based on this approach development, the thesis identifies hydroclimatic change signals of landscape drivers against the background of multiple coexisting drivers influencing worldwide freshwater change, within and among hydrological basins. Globally, landscape drivers are needed to explain more than 70% of the historic hydroclimatic changes, of which a considerable proportion may be directly human-driven. These landscape- and human-driven water changes need to be considered and accounted for also in modeling and projection of changes to the freshwater system on land.

Keywords: Budyko, evapotranspiration, freshwater, hydrology, hydroclimatic change, landscape change, land use, observation data, runoff, separation, water partitioning, water storage change, water use, worldwide

Svensk sammanfattning

Sötvatten är en livsnödvändig resurs som cirkulerar mellan atmosfären, land och havet. Att förstå och kvantifiera förändringar av fördelningen mellan nederbörd evapotranspiration, vattenföring och lagringsförändringar i landskapet är nödvändigt för att bedöma förändringar i tillgänglighet av sötvattet. Denna avhandling undersöker och har som syfte att identifiera och separera effekterna av atmosfärisk klimatförändring och olika långtidsverkande förändringar på sötvatten som orsakats av olika landskapsdrivkrafter. Detta görs baserat på hydroklimatisk-, markanvändnings- och vattenanvändningsdata från tidigt 1900-tal fram till nutid och för olika regioner och skalor, från lokalt till globalt. De analyserade landskapsdriverkrafterna omfattar utvecklingen av konstbevattning och icke-konstbevattnat jordbruk och flödesreglering. Avhandlingen använder och vidareutvecklar ett data-baserat tillvägagångsätt för att tolka tillgänglig hydroklimatiska och landskapsrelaterad data för identifiering av drivkrafter och effekter av vattenförändring och att utöka sättet som det appliceras på från lokala till globala skalor. Mot bakgrunden av flertalet samexisterande drivkrafter som globalt påverkar sötvattenförändringar så vidareutvecklar och identifierar avhandlingen signaler för hydroklimatiska förändringar av landskapsdrivkrafter. Globalt sett behövs landskapsdrivkrafter för att förklara mer än 70% av de historiska hydroklimatiska förändringarna, varav en avsevärd proportion kan vara direkt orsakad av människan. Dessa landskaps- och mänskliga drivna vattenförändringarna måste tas i beaktning och räknas in även inom modellering och projektioner för förändringar på sötvattensystemet på land.

Changes in the Freshwater System: Distinguishing Climate and Landscape Drivers

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This doctoral thesis consists of a summary and four papers. The papers are referred to as Papers I to IV in the summary text:

I

Jaramillo, F., Prieto, C., Lyon, S.W., Destouni, G., 2013. Multimethod assessment of evapotranspiration shifts due to non-irrigated agricultural development in Sweden. *Journal of Hydrology* 484, 55–62. doi:10.1016/j.jhydrol.2013.01.010.

II

Destouni, G., Jaramillo, F., Prieto, C., 2013. Hydroclimatic shifts driven by human water use for food and energy production. *Nature Climate Change* 3, 213–217. doi:10.1038/nclimate1719.

III

Jaramillo, F. & Destouni, G., 2014. Developing water change spectra and distinguishing change drivers worldwide. *Geophysical Research Letters* 41, 8377–8386, doi:10.1002/2014GL061848

IV

Jaramillo, F. & Destouni, G., 2014, Hydroclimatic changes worldwide: distinguishing freshwater signals of flow regulation and irrigation effects. Submitted to *Journal of Climate*.

The co-authorship of the papers reflects the collaborative nature of the underlying research. For Papers I, III and IV, I was responsible for all analysis and was the main responsible for the study design, organization and writing. For Paper II, I aquired, compiled and processed the hydroclimatic, land use and water use data for the Swedish basins, prepared the corresponding figures and contributed to their analysis and interpretation.

Abbreviations and Symbo

AET	actual evapotranspiration
AET_A	apparent actual evapotranspiration
AET/P	evaporative index
CV_P	short-term coefficient of variation of precipitation
CV_R	short-term coefficient of variation of runoff
CWOL	changes to partitioning of water on land
EET	climate-driven component of *AET*
FFR	fragmentation and flow regulation
LET	landscape-driven component of *AET*
P	precipitation
PET/P	aridity index
T	temperature
ΔS	change in water storage
$\vec{v}$	vector of total change in Budyko space
$\vec{v}_c$	vector of climate-driven change in Budyko space

Errata

There are three typos in Paper 1:

- Page 58. Table 1, Combination 1, Landbein's (1949) Potential Evapotranspiration equation is exactly as in Combination 2: $E_O = 325 + 21T + 0.9T^2$
- Page 58. Table 1, Combination 1, Turc's (1954) Actual Evapotranspiration equation is $AET_{clim1} = \frac{P}{\left[0.9 + \left(\frac{P}{E_o}\right)^2\right]^{0.5}}$
- Page 61. Table 2a, the first value of the slope for the period 1901-1940 should be 1.74 instead of 1.04.

Introduction

Freshwater is a vital resource for survival on earth. It circulates between land, the atmosphere and the sea, regulating most biogeochemical cycles (Jacobson et al., 2000). Humans use freshwater for drinking and other household, agricultural and industrial purposes; the latter not least for energy production. Much attention is then given to water availability in terms of stocks of freshwater on land. For instance, freshwater used for hydropower or irrigation is often discussed in terms of being "stored". However, it is not the stocks but the fluxes of freshwater that determine the annually renewable amount of freshwater that is available for human consumption (Oki and Kanae, 2006). Water constantly moves from the atmosphere to land by means of precipitation (*P*), which represents one of the major fluxes of the freshwater cycle. Humans can use *P* water directly, before it actually feeds into the landscape, by practices such as rainwater harvesting. However, most *P* water used by humans is taken after its introduction in the landscape; either directly or indirectly. A considerable amount of the *P* water is utilized directly through some water-use engineering, for instance, for extracting groundwater from aquifers and for diverting and storing surface water in regulated reservoirs. Such direct water use may fulfill various purposes, such as drinking supply, crop irrigation, energy production, or some combination of all of these. Humans also use *P* water indirectly by modifying the land that receives the *P* water rather than using the water itself, e.g., in rain fed (non-irrigated) agriculture. Such varied and important uses of freshwater then require understanding and quantification of the partitioning of *P* in the landscape into actual evapotranspiration (*AET*) moving water back into the atmosphere, runoff (*R*) through the landscape and eventually toward the sea, and change in water storage (ΔS) in the landscape. Such assessment is most needed now, with anthropogenic climate change also affecting the water cycle and freshwater availability (Huntington, 2006; Oki and Kanae, 2006; Zhang et al., 2007).

As climate change due to greenhouse gas emissions is modelled at the global scale, precipitation *P*, along with surface temperature (*T*) become typical outputs of climate models with major hydroclimatic relevance, which to high degree depend on large scale atmospheric processes. In general, projected climate change is expected to increase the difference between wet and dry regions and seasons in terms of *P* (Bengtsson, 2010; Stocker et al., 2013). These *P*-focused considerations of water change, which are also conveyed in policy-oriented documents on climate change such as the IPCC reports (Stocker et al., 2013), do not really address what is actually meant by drier or wetter conditions on land, so their meaning is ambiguous when also accounting for changes in *R*, *AET* and ΔS, in addition to those in *P* (Greve et al., 2014). This lack of focus on water changes on land may primarily be due to the difficulty of representing in large-scale climate models the changes in *R*, *AET* and ΔS that may arise from a variety of multiple drivers, in addition to climate-driven change; in the following, these water changes are denoted in group as changes to partitioning of water on land (*CWOL*). Drivers other than atmospheric climate change generally relate to changes in landscape conditions, also denoted landscape drivers, which may arise from changes in human land use and water use, and in landscape conditions that determine water storage or water phase changes. Although *CWOL* can be studied from any perspective of change regarding the linked *AET*, *R* and ΔS, many studies focus on *AET*. Changes in *AET* determine how much of the precipitation water remains to be partitioned between water flow and water storage change. Additionally, *AET* is a key variable that links atmospheric climate change, *CWOL*, and land use and water use change since it can be modeled from both climate and landscape perspectives.

In general, projections of forthcoming hydroclimatic change at global scales (to best knowledge) consider mostly atmospheric climate change, with these changes then being the main driver of model-projected large-scale *CWOL* and water availability (e.g., Němec and Schaake, 1982; Arora and Boer, 2001; Labat et al., 2004; Manabe et al., 2004; Milly et al., 2005; Aerts et al., 2006). Some recent studies, however, show that also changes occurring in the landscape itself may be dominant drivers of future *CWOL* change (e.g., Vörösmarty et al., 2000; Piao et al., 2007; Vörösmarty et al., 2010). Humans have transformed the surface of the earth by using both water and land worldwide (Ellis et al., 2010), thereby changing the characteristics of these resources (Jaramillo et al., 2014), with these changes also affecting *CWOL* (Lean and Warrilow, 1989; Costa and Foley, 2000; Zhang et al., 2001; Foley et al., 2005; Donohue et al., 2007; Zhang et al., 2008; Oudin et al., 2008). Accounting for the effects of these landscape changes on *CWOL* should then also be important for realistic analysis of future changes to water resources (Vörösmarty et al., 2000; Legates et al., 2005).

At local to regional scales, there is already existing evidence in the literature of the effects of several landscape drivers on *CWOL*, particularly of those related to human land and water uses. Biogeophysical properties related to vegetation on land, such as those expressed by stomatal conductance, surface albedo, roughness length, rooting depth, leaf/stem area index, control *AET* over a given surface (Zhang et al., 2001; Donohue et al., 2007; Oudin et al., 2008; Kvalevag et al., 2010). Altering vegetation type (or even variety within a species) may then change these intensive and extensive properties; land use changes that alter vegetation can thus drive *CWOL* through *AET* changes, with the change magnitude and direction depending on both the original vegetation cover and that resulting after the change in land use. For instance, conversion of forests to grasslands reduces *AET* and thus increases *R* (Bosch and Hewlett, 1982; Martin et al., 1989; Costa and Foley, 2000; Loarie et al., 2011), and conversely the opposite increases *AET* and reduces *R* (Van Lill et al., 1980; Qiu et al., 2011; Huang et al., 2003). Other studies show that changes are variable across years and that even different forest types (conifer vs. deciduous) have different water use patterns (Stoy et al., 2006).

To large degree, landscape changes on Earth involve directly or indirectly the development of agriculture (Ellis et al., 2010), so it is no wander that many of the local to regional studies of land use-driven *CWOL* are related to such development. Most of these studies focus on changes in land use and water use arising from irrigation and have generally found increases in *AET* (Boucher et al., 2004; Douglas et al., 2006; Shibuo et al., 2007; Sacks et al., 2009; Asokan et al., 2010; Destouni et al., 2010). However, non-irrigated arable land (53 351 634 km^2 or 36% of the world land area; HelgiLibrary, 2014) is much greater than irrigated arable land (3 245 566 km^2 or 2% of total land area; HelgiLibrary, 2014). Yet, studies on *AET* change driven by changes in non-irrigated agriculture are rare and have so far mostly focused on the United States Midwest (Zhang and Schilling, 2006; Schilling et al., 2008). Studies of non-irrigated agriculture in other regions have mostly focused on deforestation at the initial change stages of such development (Lean and Warrilow, 1989; Gordon et al., 2005; Loarie et al., 2011).

Additionally, not all human water uses involve irrigation. Flood control and hydropower are services that require the construction of dams and impoundment of water in reservoirs and are also related with fragmentation and flow regulation of river systems (Dynesius and Nilsson, 1994; Nilsson et al., 2005). Currently, 59% of the world's largest river systems (accounting for 60% of all global runoff) are either moderately or strongly affected by fragmentation and flow regulation of river systems (Nilsson et al., 2005) and 45,000 dams have been constructed in the world since the 1930s (World Commission on Dams, 2000). Yet few studies have assessed the possible *CWOL* related to such developments, and those that have, have done it more from an atmospheric rather than a landscape-hydrologic perspective (e.g., Degu et al., 2011).

Approaches used in the literature to study landscape-driven *CWOL* may be structured as: 1) spatiotemporal extrapolation of local *AET* rates, 2) use of models for global water assessments and 3) data-motivated distinction of climate- and landscape-driven *CWOL*, denoted hereafter as the *CWOL*-driver separation approach. The first approach compares measured or modelled estimates of local *AET* rates in some original and post-modification land covers associated with various types of landscape change. Such approach has been used to assess landscape change effects on *AET* at global scales by spatiotemporal extrapolation of the local *AET* rate estimates for specific land covers, e.g., to estimate global changes in *AET* by deforestation and irrigation (Gordon et al., 2005). This approach is limited since *AET* rates also depend on the hydroclimatic conditions where they were measured or estimated, so the spatially extrapolated *AET* rate(s) from one region to the other may or may not be realistically indicative of land cover and *AET* change function in new location(s) of *AET* assessment, even after consideration of some spatial differences. Possibilities of testing such indications and of relating resulting landscape-driven *AET* to the actual timing of land cover change are also limited. Furthermore, this approach cannot be used to study *CWOL* involving changes in landscape conditions that determine water storage or water phase changes, e.g., by human groundwater depletion (Konikow, 2011), or for spatiotemporal shifts in human water use for irrigation (Asokan et al., 2010).

The second approach uses relatively complex modelling to study the effects of particular category(ies) of landscape drivers of *CWOL*. Terrestrial biosphere models such as ORCHIDEE (Krinner et al., 2005) have been used to estimate global landscape-driven changes in *R* (Piao et al., 2007). Models such as WATERGAP (Alcamo et al., 2003) project changes in *R* driven by both atmospheric climate and some landscape changes, specifically hydropower development and irrigated and non-irrigated agriculture, which can to some degree also be tested against available *R* data series. Other model studies have also contributed with similar findings (e.g., Jia et al., 2006; Widén-Nilsson et al., 2007). Strandberg et al. (2014) has used a regional climate model (RCA3; Samuelsson et al., 2011) along with a dynamic ecosystem model (LPJ-GUESS; Smith et al., 2001) to study the direct temperature and *CWOL*-related effects of deforestation in Europe during the Holocene. The use of such models is mostly related to projections of future *CWOL* at large scales rather than to the study actually observed *CWOL* changes, for which the effects of each independent driver thus needs and remains to be distinguished. Model studies are also limited by uncertainties associated with model complexity and long-term data availability for model parameterization and validation, and usually do not quantify separately climate- and landscape-driven *CWOL* components. For example, the remote sensing-based MODIS ET product MOD16 (Mu et al., 2011) has been used to detect landscape-driven changes in *AET* from land cover transformation in Brazil related to biofuel agriculture (Loarie et al., 2011), but does then not also relate *AET* changes to possible climate change drivers and is restricted to the time period of availability of the MODIS data set (King et al., 1992).

The third approach denoted here as the *CWOL*-driver separation approach, is more data-motivated, using fundamental physical water balance-constraints to separate atmospheric climate- and landscape-driven *CWOL* components at various catchment scales. Shibuo et al. (2007) used this data-motivated approach to study water change from the perspective of observed changes in *R* and consequent water-balance determined changes in *AET*. This was achieved by assessing temporal change in total annual *AET* based on catchment-scale water balance given from observed *P* and *R* data series, and subtracting from the total *AET* a theoretical estimate of its climate-driven component of change (based on empirical relations and available *P* and *T* observation data). Denoting this climate-driven component *EET*, the remaining *AET* component after *EET* subtraction provides then an estimate of the landscape-driven component of change in *AET*, denoted *LET*. This data-motivated approach can be used where relevant data time series are available to constrain and quantify the temporal evolution of total *AET* and its atmospheric climate-driven (*EET*) and landscape-driven (*LET*) components. This approach is thus limited by the availability of long-term data for water balance closure for catchments of different scales, with the spatial resolution of the approach being limited by the scales of catchments with such data availability. Furthermore, the use of this data-driven approach has so far been limited to local-regional catchment assessments, and therefore its use for global quantification of landscape (and human) driven *CWOL* remains as a compelling research task.

This thesis uses this data-motivated method, the *CWOL*-driver separation approach, to identify and separate *CWOL*-related effects of long-term atmospheric climate change and landscape change drivers across different regions and scales, from catchment to global (Fig. 1). The use of this approach implies that historical data time series for observed and independently reported water fluxes, and atmospheric climate, land use and water use conditions are used, combined and interpreted for hydrological catchments (drainage basins) of different scales. The main objectives of this thesis, along with its included papers (Table 1), are then the following:

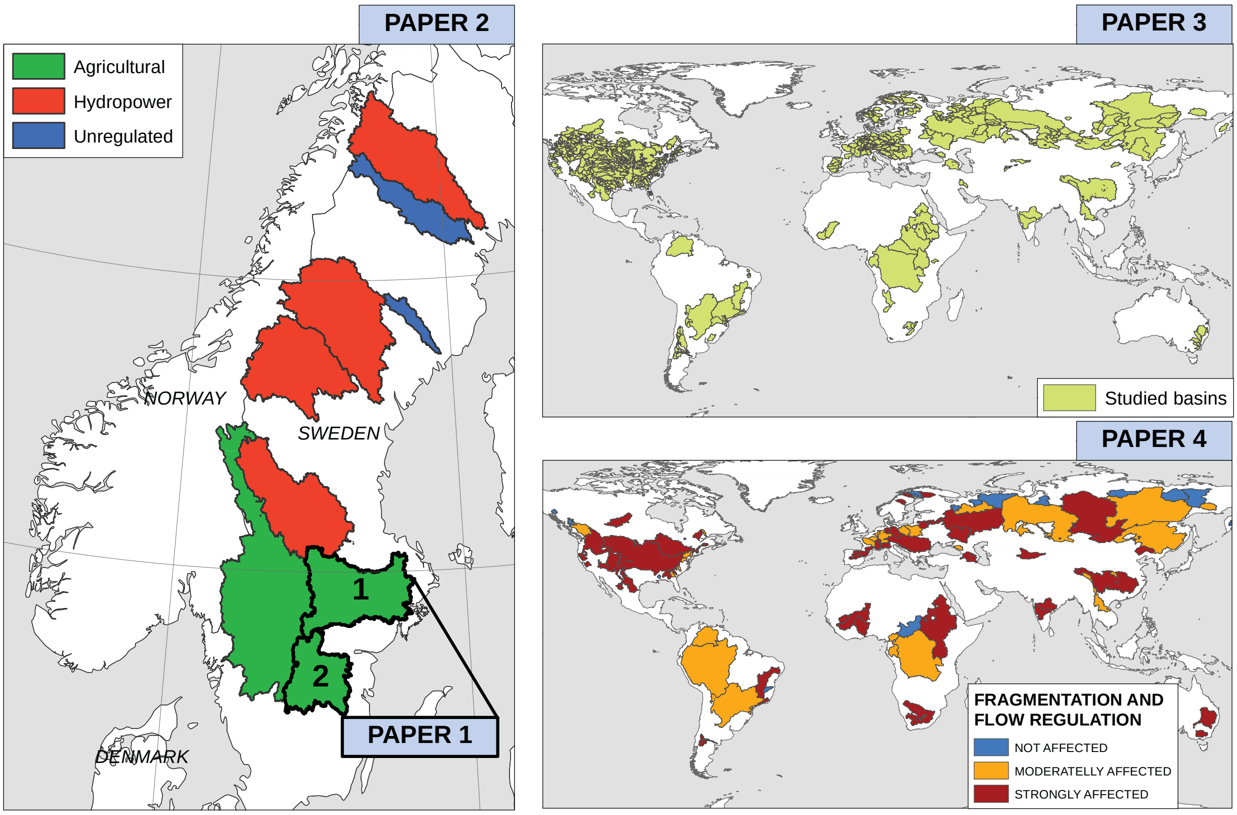

Figure 1. *Spatial scales and corresponding basins used in the analysis of the included papers; from the Norrström (1) and Motala Ström (2) drainage basins in Paper 1 to the global scales of Papers 3 and 4. Appart from the Swedish basins, Paper 2 also includes the Aral Sea drainage basin in Central Asia and the Mahanadi River basin in India.*

Table 1. *Coverage of thesis objectives by the included thesis papers.*

	OBJECTIVE	I	II	III	IV
A	Further development of the data-motivated approach for *CWOL*-driver separation	✓	✓	✓	✓
B	Basin-scale *CWOL*-driver distinction	✓	✓		
C	Continental- and global-scale *CWOL*-driver distinction			✓	✓

Objective A

One main thesis objective is to further develop the data-motivated approach of *CWOL*-driver separation. This includes accounting for a range of possible methods to estimate climate-driven *AET* (i.e., *EET*) change and thus better distinguish and quantify landscape-driven (i.e., *LET*) change, as two main components of total *AET* change in a basin. It also includes the analysis of change in other inter- and intra-annual hydroclimatic quantities, in addition to the more conventional (long-term average or actual) annual *R* and *AET*; a key such quantity was found to be the short-term coefficient of variation of runoff (CV_R) as explained further in the thesis. Overall, the aim of this approach development is to identify landscape-driven *CWOL* and various quantitative indications of it, with development of a spectrum approach (explained further in the thesis) contributing in particular to assessment of *CWOL* in multiple basins spread over continental and global scales.

Objective B

A second main aim of the thesis is to distinguish and quantify on basin-scales the *CWOL*-effects of atmospheric climate change and landscape drivers, particularly those being directly human-driven by land and water uses (Fig. 2). For the latter type of landscape drivers, the thesis considers in particular changes that have not been much investigated in this context so far, such as developments (expansion, intensification) of non-irrigated agriculture and hydropower, taking particular advantage of a large array of hydroclimatic and landscape development information and data that are available for hydrological basins in Sweden.

Objective C

The third aim is to investigate, identify and quantify effects of landscape drivers at global and continental scales. This considers such effects in general, as well as specific investigation of the possible continental- and global-scale signals of particular human drivers. The latter include specifically such drivers that are found to be dominant in the present basin-scale studies (Objective B) as well as in previous such studies of basins of other world regions (scientific literature).

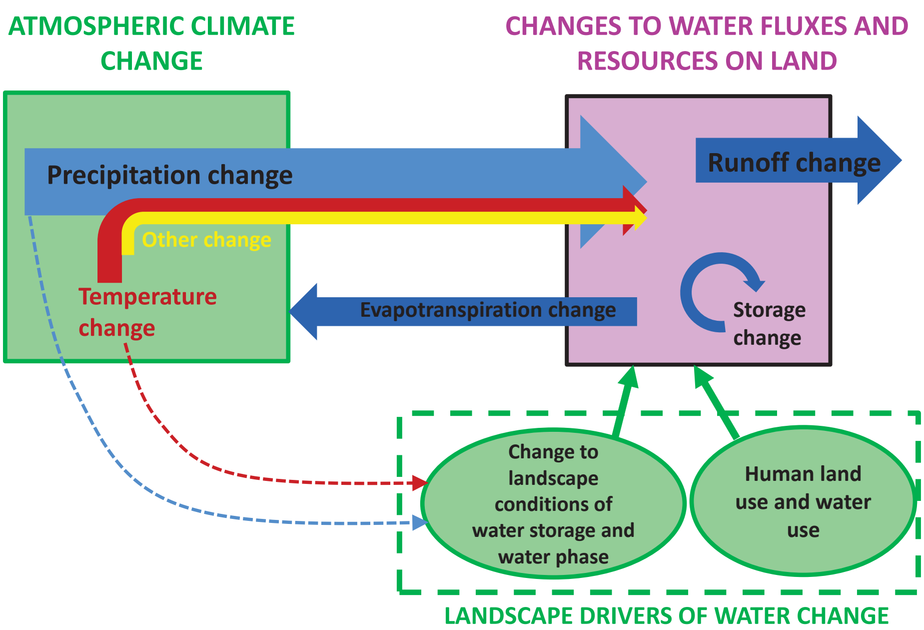

Figure 2. *Changes to the partitioning of water on land (CWOL) and their possible drivers in the atmosphere and in the landscape.*

Table 2. *Aspects accounted for in the methodology of Papers I to IV.*

ASPECTS	PAPER I	PAPER II	PAPER III	PAPER IV
Main period(s) used for the calculation of changes to the partitioning of water on land (*CWOL*)	1901-2002	Years with available and complete data in 1901-1955 and 1956-2002	Years with available and complete data in 1901-1954 and 1955-2008	Years with available and complete 1901-1960 and 1961-2009
Investigated basins (number of basins)	Norrström and Motala Ström drainage basins, Sweden (2)	Sweden (9) Aral Sea drainage basin (db) (1) Mahanadi River basin (Rb) (1)	World-scale (859 small-large basins)	World-scale (99 large basins)
Landscape drivers of *CWOL* studied in each paper (see Fig 2)	Non-irrigated agriculture	Non-irrigated agriculture Irrigated agriculture Hydropower development	Changes in landscape conditions in general	Changes in landscape conditions in general Irrigated agriculture Flow regulation
Landscape change data	Agriculture area and production (Jordbruksverket, 2011) Forest area (SLU, 2011)	Sweden Agriculture area and production (Jordbruksverket, 2011) Hydropower production (Kuhlin, 2011) Aral Sea db and Mahanadi Rb Irrigated areas (Shibuo et al., 2007)	Area of land with small human influence (Ellis and Ramankutty, 2008)	Irrigated agriculture Index and flow regulation factor (Nilsson et al., 2005)
Hydroclimatic indicators of CWOL	Change in *AET*	All regions Combination of changes in *T*, *P*, *R* and *AET* Change in *AET/P* Sweden Change in *CVR*	Change in *AET/P* Movement in Budyko space (Budyko, 1974)	Combination of changes in T, P, R and AET Change in *AET/P* Change in *CVP* and *CVR*
Hydroclimatic data	*T* and *P* (CRU; Mitchell and Jones, 2005) *R* and lake water levels (SMHI, 2010)	*T* and *P* (CRU; Mitchell and Jones, 2005) Sweden *R* and lake water levels (SMHI, 2010) Aral Sea db *R* (GRDC, 2013) Mahanadi Rb *R* (Asokan et al., 2010; further references therein)	*T* and *P* (CRU; Harris et al., 2014) *R* (GRDC, 2013)	
Empirical relations used to estimate climate-driven component of *AET*	Langbein (1949)-Turc (1954) Langbein (1949)-Budyko (1948) Priestley and Taylor (1972)-Zhang et al. (2001) Allen (1998)-Zhang et al. (2001)	Langbein (1949)-Budyko (1948) * Langbein (1949)-Turc (1954) *	Langbein (1949)-Schreiber (1904) Langbein (1949)-Ol'dekop, (1911) Langbein (1949)-Budyko (1948) Langbein (1949)-Turc (1954)-Pike (1964) Langbein (1949)-Zhang et al. (2001)	No models were used

* Used also for spatially distributed *AET* estimates based on distributed hydrological modeling by Shibuo et al. (2007) for the Aral Sea drainage basin, and Asokan et al. (2010) for the Mahanadi River basin.

Methodology

Hydroclimatic changes were studied throughout this thesis from local-regional (Papers I, and II) to continental-global scales (Papers III and IV), with each Paper focusing in a specific landscape-driver (or group of drivers) of changes to the partitioning of water on land *CWOL*, and in a specific set of indicators of *CWOL* used to assess such driving effects (Table 2). These changes were studied throughout the entire twentieth century and beginning of the twenty-first century since this is the period in which global monthly gridded data sets of *T* and *P* are available. In Paper I, and for the Swedish study section of Paper II, we used 20-year running averages of the hydroclimatic indicators (Table 2) and temporal linear regressions for three specific time periods to study *CWOL* taking advantage of the continuity of hydrcolimatic data series in Sweden. For the inter-region comparison of Paper II and in general for Papers III and IV, *CWOL* were generally calculated as the difference between the annual averages of two comparative periods for each hydroclimatic parameter (Table 2).

We studied change in absolute actual evapotranspiration *AET* and/or relative to precipitation (*AET/P*; evaporative index) in Papers I to IV. Change in *AET/P* was used as a *CWOL* indicator to eliminate the dominating effect of *P* on *AET*, and to facilitate the recognition and separation of the landscape-driven and climate-driven components of *AET* and *AET/P*. Annual *AET* was calculated by basin-scale water-balance as

$$AET = P - R - \Delta S \qquad \text{Eq. 1}$$

from available times series of *P* and *R*, and for some relevant assumption scenarios of ΔS. In Paper II, for the inter-region comparisons of *CWOL* between the basins in Sweden and the Aral Sea drainage basin and the Mahanadi River basins, we estimated spatially distributed *AET* based on the distributed hydrological modeling by Shibuo et al. (2007) and Asokan et al. (2010), respectively. In Papers III and IV, we estimated *CWOL* for each basin as the difference between the annual averages of two comparative periods for each hydroclimatic parameter (Table 2); averages are calculated only from years with mostly complete monthly or daily *R* data in order to sort out the variability and temporal discontinuity of basin *R* data present at the continental and global scales.

Furthermore, in Papers I and II, available information on lake levels that could be used to induce ΔS was used for testing different ΔS assumption scenarios. Because water level information to determine relevant scenarios of possible $\Delta S \neq 0$ was not available for most basins in the global studies of Papers III and IV, *AET* (Eq. 1) was here interpreted as an apparent actual evapotranspiration (AET_A), which may differ from actual *AET* by also including a component of non-zero water storage change ΔS, i.e., $AET_A = AET + \Delta S$ with possible $\Delta S \neq 0$.

The governing principle used in Papers I to III to quantify *CWOL* and distinguish its different drivers and components was that of the data-motivated *CWOL*-driver separation approach described in the Introduction. This principle identifies the landscape-driven component of total *CWOL* as that which cannot be readily explained by atmospheric climate-driven *CWOL*; such identification can be applied to change in any of the inter-annual variables (absolute or relative to P) of main freshwater fluxes on land (*R*, *AET*, ΔS, *AET/P*). In Papers I and II, we applied the *CWOL*-driver separation approach to *AET* by deriving a component of change in landscape-driven *AET*, denoted *LET*, as

$$\Delta LET = \Delta AET - \Delta EET \qquad \text{Eq. 2}$$

Here ΔAET is change in total *AET*, as calculated from catchment-scale water balance (Eq. 1), and ΔEET is empirically-derived change in the climate-driven component of *AET*, denoted *EET*; a representative estimate of the latter was calculated as the mean of several purely climate-related theoretical estimates obtained from empirical relations in terms of *P* and *T* (Table 2). In similar way, Papers III and IV used the same separation principle but in relation to change in evaporative index *AET/P*

$$\Delta (LET/P) = \Delta (AET/P) - \Delta (EET/P) \qquad \text{Eq. 3}$$

We also analyzed in Papers II and IV the long-term change in the coefficient of short-term variation of (daily or monthly) runoff (CV_R), and investigated the use of CV_R as an indicator of landscape-driven *CWOL*. In Paper III, we studied and compared total, landscape- and climate-driven *CWOL* from the perspective of the Budyko framework (Budyko, 1974), which uses a parameter space that relates the evaporative index *AET/P* to the potential evapotranspiration (*PET*) relative to *P* (*PET/P*; aridity index); this space links main physical principles of water and energy availability goerning the water balance. We represented the change movement of total *CWOL* in Budyko space (resulting from both atmospheric climate and landscape drivers) for each investigated basin as a vector of total change $(\vec{v})$ with horizontal and vertical components (Fig. 3), denoted as $\Delta (PET/P)$ and $\Delta (AET_A/P)$, respectively, based on the approach of van der Velde et al. (2014). In analogy, we also derived the corresponding vector of climate-driven change $(\vec{v_c})$ with horizontal and vertical components $\Delta (PET/P)$ and $\Delta (EET/P)$.

Furthermore, because significant change in intra-annual precipitation variability may also directly affect change in annual *AET* and *AET/P* (Milly, 1993; Zanardo et al., 2012; Feng et al., 2012), we investigated the coefficient of variation of precipitation (CV_P) in order to identify and discard from the landscape-driver identification analysis the basins with such possible intra-annual *P* variability effects; otherwise, these effects could be incorrectly identified as landscape-driven *CWOL*.

In Paper IV, we did not perform any *CWOL*-driver separation and restricted to the analysis of inter- and intra-hydroclimatic data in order to validate (if possible) the *CWOL*-related signals from hydropower development observed in Sweden (Paper II), and from irrigation as observed in other regions of the world. We analyzed changes in T, P, R, AET_A, AET_A/P, CV_R and CV_P as indicators of *CWOL* and related them to the categorization and parameterization of fragmentation and flow regulation (*FFR*) impact of Nilsson et al. (2005), since this study contains a homogenized dataset on worldwide irrigation and flow regulation developments.

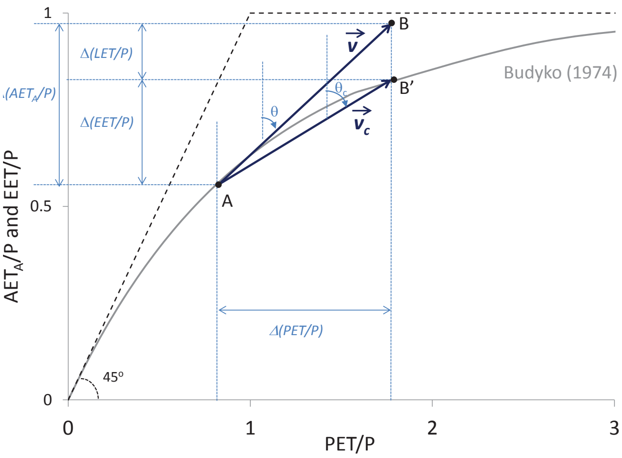

Figure 3. *Schematic representation of the water-change movement vector of a basin in Budyko space. Movement is from Point A to Point B′ for atmospheric climate change only (climate-driven change), and from Point A to Point B for total change from both climate and landscape drivers (total change).*

Results

Paper I

Jaramillo, F., Prieto, C., Lyon, S.W., Destouni, G., 2013. Multimethod assessment of evapotranspiration shifts due to non-irrigated agricultural development in Sweden. *Journal of Hydrology* 484, 55–62.

We analyzed 20-year running averages of continuous hydroclimatic and land use data during the 20th century in the Norrström and Motala Ström drainage basins in Sweden, finding for both basins shifts to a higher level of actual evapotranspiration *AET* during the first half of the century; this is exemplified for the Norrström drainage basin in Fig. 4. Specifically for this basin, the comparison between change in the water-balance constrained evapotranspiration *AET* and a range of different comparative estimates of purely atmospheric climate-driven actual evapotranspiration *EET* showed that only about 30% of the steep *AET* increase between 1901 and 1940 could be explained by atmospheric climate change alone; the latter includes then changes in temperature *T*, precipitation *P*, radiation and wind (Table 2). The remaining approximately 70% of this *AET* shift could thus not be explained by the observed atmospheric climate change, regardless of various relevant assumptions that could be made for water storage change in the basin. In consequence, this approximately 70% must have then be driven by the independently reported land use conversion from seminatural grasslands to cultivated land, and the associated enhanced productivity of herbaceous species; this conclusion is strengthened by an increase in cultivated area and/or crop production

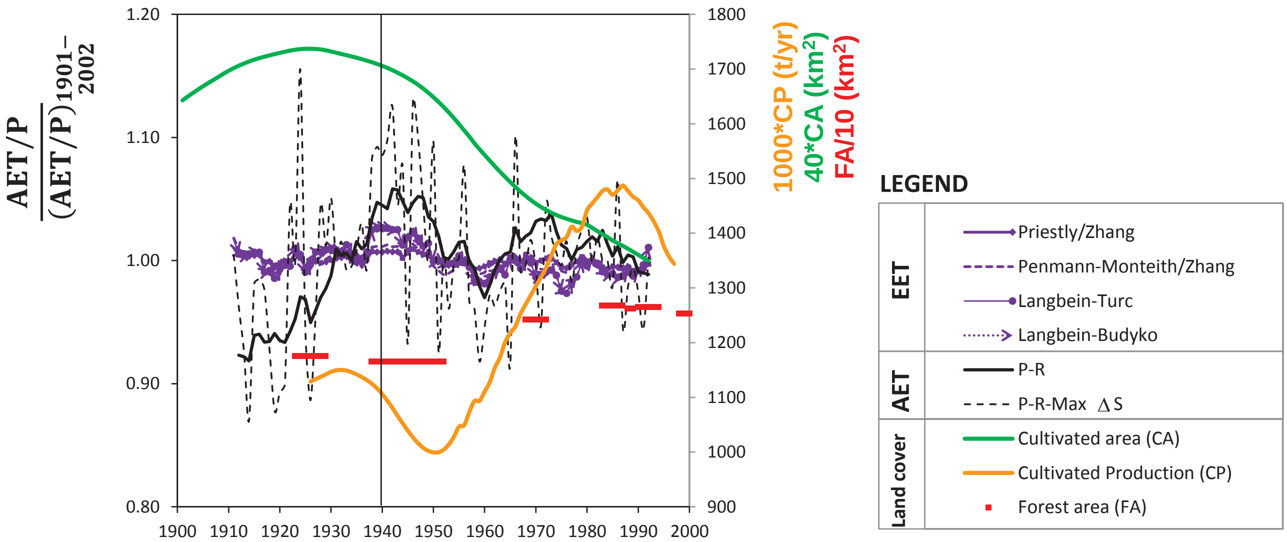

Figure 4. *20-year running averages of hydroclimatic and landscape changes in the Norrström drainage basin. Development of different estimates of water-balance constrained evaporative index (AET/P) and various methods of calculation of the climate-driven component of AET/P (EET/P), normalized by the 1901–2002 mean for each estimation method. This figure is a variation from the original figures in Paper I which rather compared total AET with the climate component of AET (EET).*

occurring temporally along with the *AET* and *AET/P* increases. An increase in forest area, which could have also increased *AET*, occurred only later in the region of the two basins during the second half of the twentieth century, when *AET* changes could actually be explained by atmospheric climate-driven change.

Paper II

Destouni, G., **Jaramillo, F.**, Prieto, C., 2013. Hydroclimatic shifts driven by human water use for food and energy production. *Nature Clim. Change* 3, 213–217.

We extended the hydroclimatic change analysis of Paper I to seven (7) additional large basins in Sweden: one (1) more agriculture dominated basin, four (4) basins with dominant hydropower development, and two (2) unregulated basins (Fig. 1a). Furthermore, we compared CWOL change evolution and its possible drivers in the Swedish basins with that in two other well-studied basins in other world regions: the Aral Sea drainage basin in Central Asia (Shibuo et al., 2007) and the Mahanadi River basin in India (Asokan et al., 2010); the hydroclimatic changes (*AET* and *AET/P* increases, and associated *R* decrease) in both of these basins had already been shown by previous studies to be primarily driven by twentieth-century developments of irrigated agriculture rather than by atmospheric climate change. In addition to changes in *AET* and *AET/P*, we analyzed here for the Swedish basins also 20-year moving averages of change in the coefficient of short-term variation (CV_R) as this change could be hypothesized to be a consequence of flow regulation associated with major hydropower developments in Sweden from 1901 to 2002. As control, we also quantified (and compared with basins with dominant hydropower development) the CV_R evolution in the Swedish basins that were dominated by non-irrigated agriculture developments and those that were both unregulated and non-agricultural. We found that in the two unregulated basins, undeveloped in terms of agriculture and hydropower, there was a natural underlying positive correlation between *AET/P* and CV_R variabilities, which could also to some degree be recognized in the agriculture-dominated basins (Fig. 5a and b).

Furthermore, the shifts to increased *AET* and *AET/P* found in Paper I for the Norrström and Motala Ström basins also extended to their neighboring mostly cultivated basin (Vänern); also in the latter, these *AET* shifts could not be explained by either of the two *EET* model calculations used for the Swedish basins in Paper II: Langbein (1949)-Budyko (1948) or Langbein (1949)-Turc (1954). We also found in the hydropower-dominated northern Swedish basins, shifts to increased *AET* and *AET/P* that could not be explained by these *EET* models (Fig. 5c). The use of hydropower production in each basin, as a proxy of possible multiple hydropower-related and/or other coevolving land and water use development effects, showed these shifts to be accompanied by a consistent decrease in CV_R. As the latter decrease was

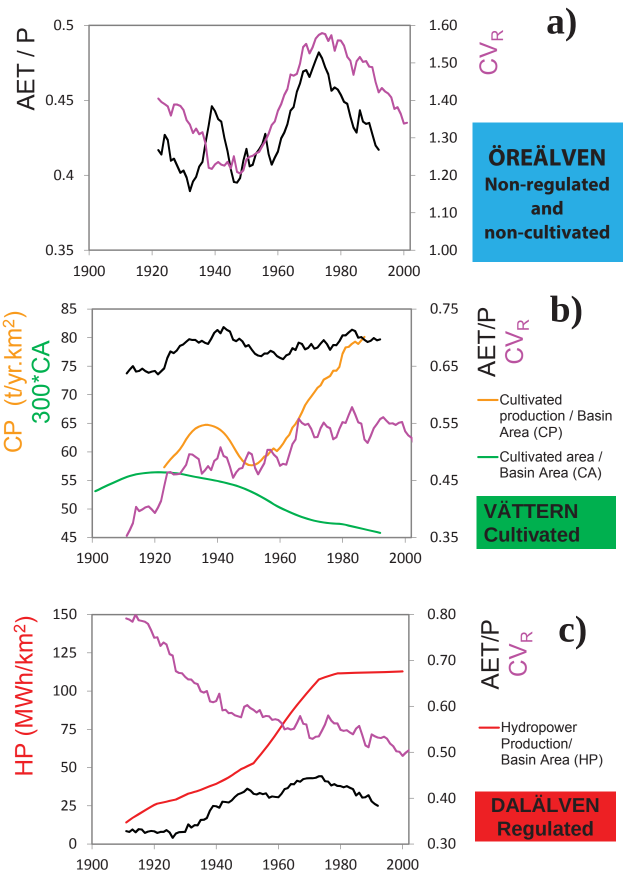

Figure 5. *Typical variable co-development for three of the Swedish basins shown in Fig. 1a, of 20-year running average of evaporative index (AET/P) and coefficient of short-term variation of runoff (CV_R) in:* ***(a)*** *an unregulated and uncultivated basin (Öreälven),* ***(b)*** *an agriculture-developed basin (Vättern) and* ***(c)*** *a hydropower-developed basin (Dalälven). The developments are accompanied by the 20-year running average of total cultivated area and production in* ***(b)*** *and normal energy production of installed hydropower relative to basin area in* ***(c)****.*

not found in agriculture-dominated basins, it was concluded that such long-term sustained CV_R decrease might be a characteristic *CWOL* effect of hydropower-related human developments and coevolving landscape changes. The analysis thus showed that a combination of *AET/P* increase and concurrent CV_R decrease could be used as an indicator to distinguish possible hydropower-related development effects on *CWOL* based on temporal analysis of basic hydroclimatic data.

Extrapolations of these results to possible world change implications estimated potential human-driven increments of *AET* by twentieth-century developments of non-irrigated agriculture (10 mm/yr) and hydropower (27 mm/yr) of similar magnitude as such increments estimated earlier for irrigated agriculture (20 mm/yr; Gordon et al., 2005). By including an earlier estimation of *AET* reductions linked to twentieth-century deforestation (23 mm/yr), the estimated net global change result was found to be a human-driven *AET* increase of 34 mm/yr on average over the world land area. As such, human-driven *AET* change may then have already overpassed a hydrological planetary boundary proposed for global

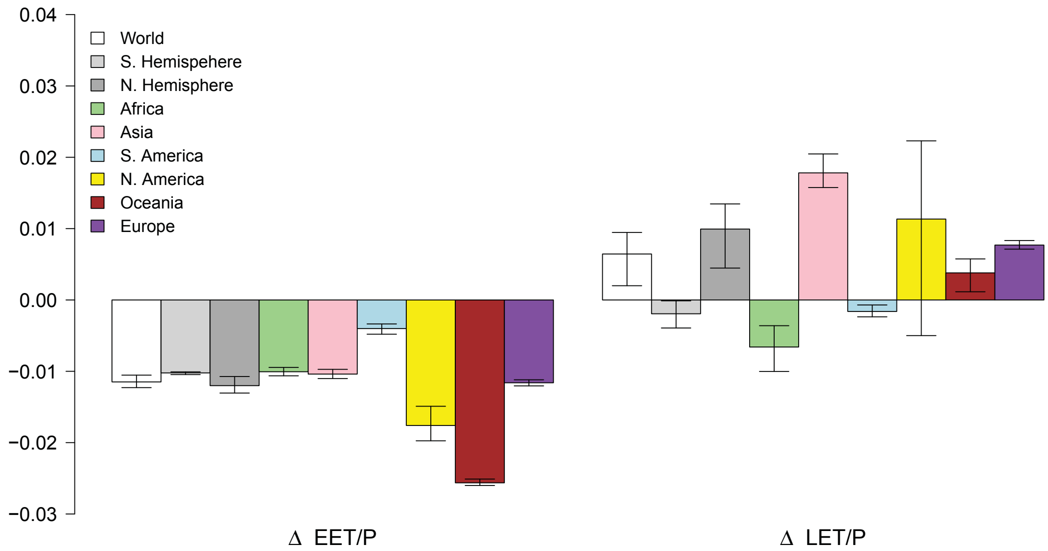

Figure 6. *Area-weighted changes in relative evapotranspiration between 1939–1954 and 1955–1979. Changes in mean climate-driven evaporative index, Δ (EET/P), and landscape-driven evaporative index, Δ (LET/P) in the 154 basins covering the largest possible land area without any basin overlap.*

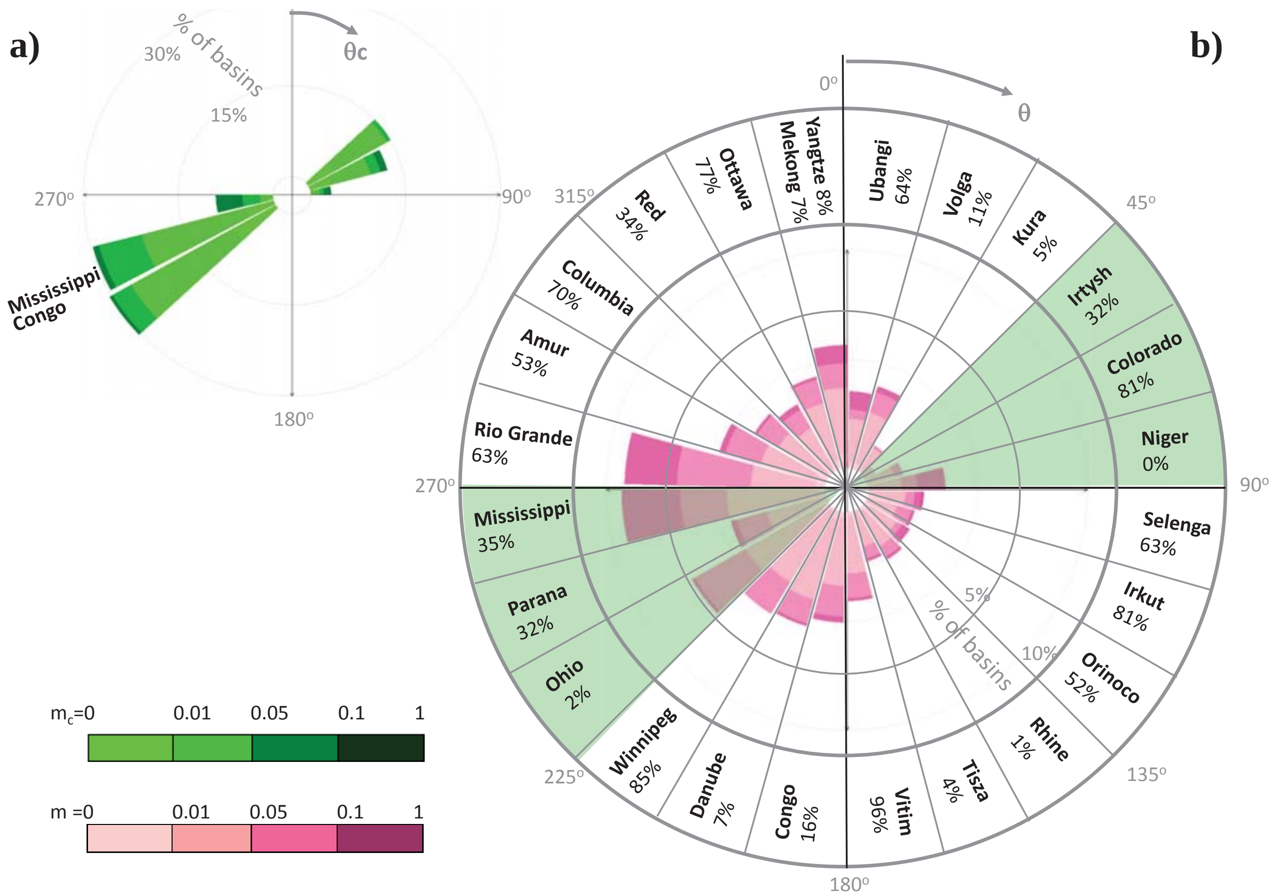

Figure 7. *Global spectra of water-change movement for 735 basins in Budyko space for:* **(a)** *climate-driven change, showing the magnitude (m_c) and direction (θ_c) of movement of climate-driven CWOL vectors ($\vec{v}_c$) (See Fig. 3) and* **(b)** *total change, showing the magnitude (m) and direction (θ) of movement of total CWOL vectors ($\vec{v}$) between at least 20-year periods from 1901–1954 to 1955–2008. Names aligned with each change direction paddle are examples of basins with change in the direction interval covered by the paddle; corresponding percentages quantify the pristine area fraction in each example basin (Ellis and Ramankutty, 2008).*

freshwater use, corresponding to 30.3 mm/yr on average over the world land area (4000 km^3 in total; Rockström et al., 2009).

Paper III

Jaramillo, F. & Destouni, G., 2014. Developing water change spectra and distinguishing change drivers worldwide. *Geophys. Res. Lett.* 2014GL061848.

We first studied in this paper the relation between the climate- and landscape-driven components of total change in evaporative index AET_A/P (in EET/P and LET/P, respectively; Fig. 3). This was done by first calculating changes between the area-weighted means of EET/P and LET/P of the 25-year periods 1930–1954 and 1955–1979, including only the basins with complete R data in all years and covering the largest possible land area without overlap. Results showed that landscape drivers in most continents and in the world have counteracted a general decrease in the climate-driven component EET/P (Fig. 6), by increasing the corresponding landscape-driven component LET/P.

We further extended the analysis to change between periods of at least 20 years from 1901–1954 to 1955–2008, including a total of 735 basins over the world; these are to some degree spatially overlapping, with each basin considered as an individual basin realization of some scale, which is variable in order to maximize statistical analysis. Such analysis is required for a statistical assessment on global scale and to increase in these statistics the number of multi-scale basin realizations in regions with limited availability of longer-term hydroclimatic data, such as Africa and South America. Previous work has shown that nested catchments of different scale within the same region may indeed exhibit quite different and even contrasting

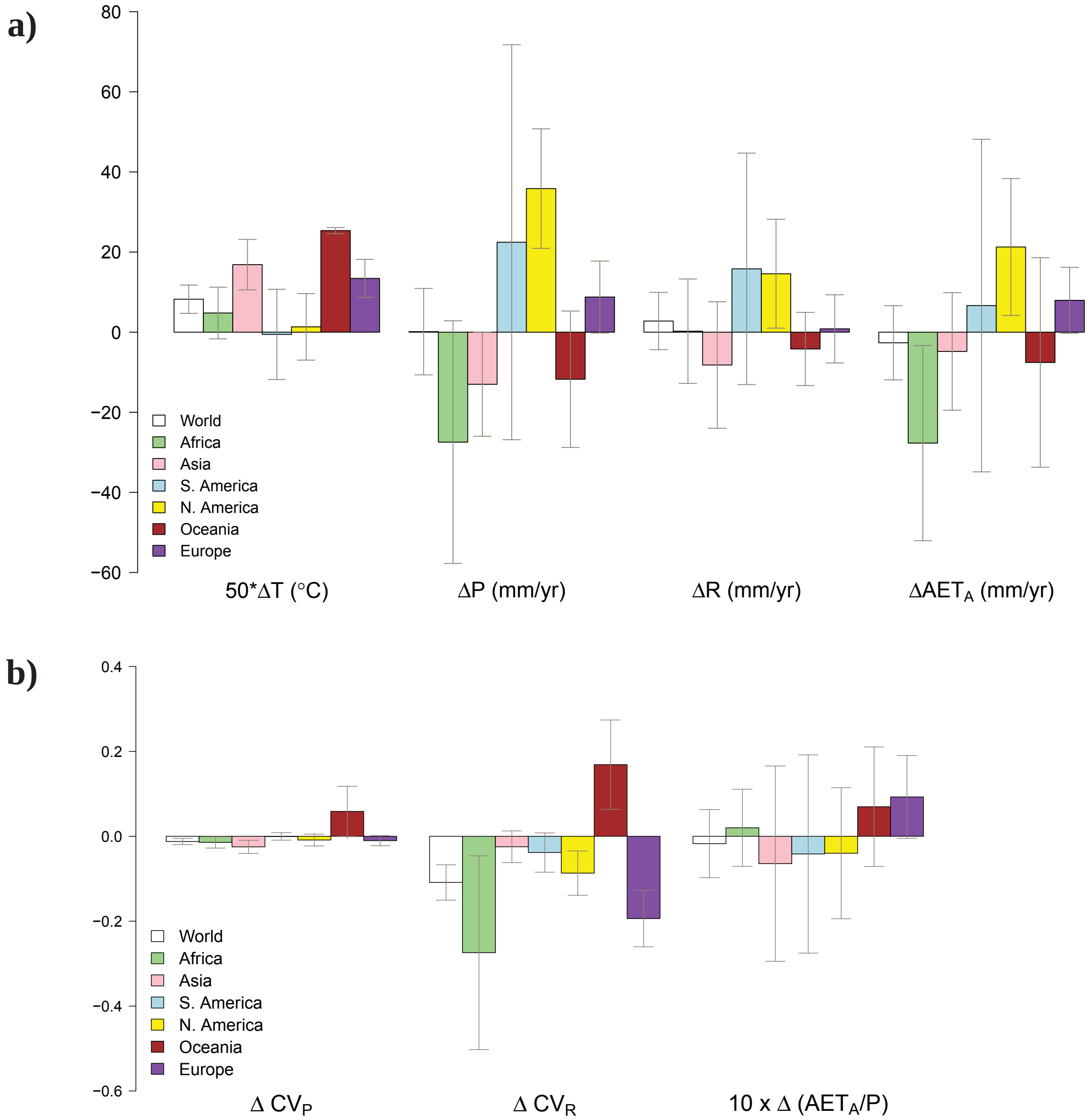

Figure 8. *Area-weighted changes in* ***(a)*** *temperature (T), precipitation (P), runoff (R), actual evapotranspiration (AET_A) and* ***(b)*** *coefficient of short-term variation of P (CV_P) and of R (CV_R) and evaporative index (AET_A/P) between the periods 1901-1960 and 1961-2009 for 99 worldwide large basins. Error bars show the spatial standard deviation among basins as derived by Hawley et al. (1988).*

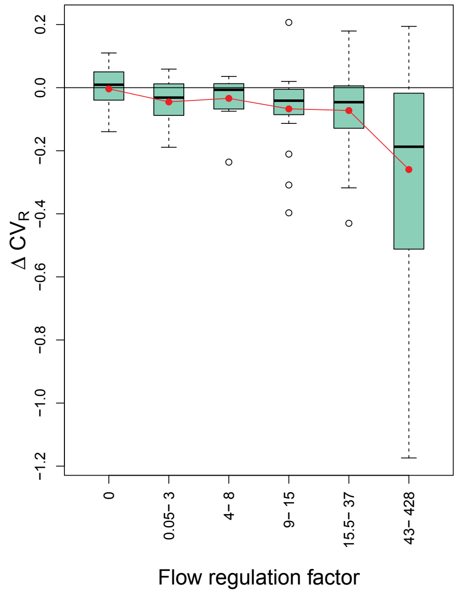

Figure 9. *Box plots of the distributions of basin-wise changes in coefficient of short-term (monthly) variation of runoff (CV_R) according to the flow regulation factor derived by Nilsson et al. (2005). Each boxplot represents the distribution of change in CV_R changes among the intervals of the 20, 40, 60, 80 and 100 quantiles of the flow regulation factor and have the typical structure showing median, outliers and whiskers representing a confidence interval around the arithmetic mean of each distribution, shown as a red dot.*

realizations of hydroclimatic change (Koutsouris et al., 2010).

The found basin changes to the partitioning of water on land *CWOL* during the period 1901-2008 were further depicted as movement vectors in Budyko space (Budyko, 1974). This was done in terms of resulting change spectra resembling the typical wind roses used in meteorology to describe wind direction and speed (Fig. 7). We grouped the movements in Budyko space for all basins at the global and continental scales in two different spectra: the first relating to climate-driven *CWOL* composed of change in *PET/P* and *EET/P*, and the second to total *CWOL* driven by both climate change and landscape drivers and composed of change in *PET/P* and apparent evaporative index AET_A/P (Figs. 7a and 7b, respectively). We found that only 26% of the basin changes in the total *CWOL* spectrum were in directions that could be explained by atmospheric climate change alone (i.e., in clockwise directions of movement between 45˚ and 90˚ or between 225˚ and 270˚, from the positive vertical axes). The remaining 74% of the basin changes were in directions that required influence of landscape drivers (apart from that of climate) for their explanation (i.e. in directions of movement between 90˚ and 225˚ or between 270˚ and 45˚).

Paper IV

Jaramillo, F. & Destouni, G., 2014, Hydroclimatic changes worldwide: distinguishing freshwater signals of flow regulation and irrigation effects. Submitted to *Journal of Climate.*

Based on the results of Paper IV, which showed that landscape-drivers were to large degree required to explain *CWOL* in at least three quarters of the investigated basins worldwide, we further investigated whether consistent signals of such drivers could be distinguished directly from the observed hydroclimatic data on the global and continental scales. In particular, we looked here for possible distinguishable signals of *CWOL* associated with fragmentation and flow regulation of river systems *FFR*, based on previous results of the *CWOL*-driver separation approach used in Papers I to III, but without actually applying that approach again on all investigated basins worldwide. With this aim, we analyzed here hydroclimatic changes in *T*, *P*, *R* and *AET* in 99 of the largest river systems of the world between the periods 1901-1960 and 1061-2009, focusing in particular on changes in *AET/P* and CV_R, based on the results of Paper II that showed these changes as possible good indicators of hydroclimatic change effects of *FFR*-related developments.

Our comparative basin analysis showed that, on average globally and particularly in the continents of Africa and Europe, the observed hydroclimatic changes (i.e., in *T*, *P*, *R*, AET_A, AET_A/P and CV_R; Fig. 8) within the period 1901-2009 required landscape-driven effects for their explanation. At the global scale, for instance, the observed combination of increased *T* and unchanged *P* cannot explain the decrease in AET_A and corresponding increase in *R*; furthermore, the large decrease in CV_R cannot be explained by the much smaller decrease in CV_P.

We additionally found consistent signals of *FFR*-driven change at the global scale, directly from observation data, and against the background of several other atmospheric climate and landscape drivers that also coexist and simultaneously influence *CWOL*. These signals include decrease in both average *R* and CV_R; these decreases are consistently greater in basins with higher flow regulation factors (Fig. 9). The signals also include an increase in AET_A/P for strongly *FFR*-affected basins, which is greater for basins with high flow regulation factors and highirrigation indexes (Figs. 10a and b, respectively).

Discussion

Objective A

Humans have modified the world's landscape and its water systems over the last three centuries for the sake of human development and expansion (Ellis et al. 2010). This fact highlights the magnitude of the possible effects that human developments may have had on hydroclimate, water availability and partitioning of freshwater in the landscape. This thesis has attempted to distinguish signals of such effects by studying changes in the water fluxes and partitioning on land *CWOL* since

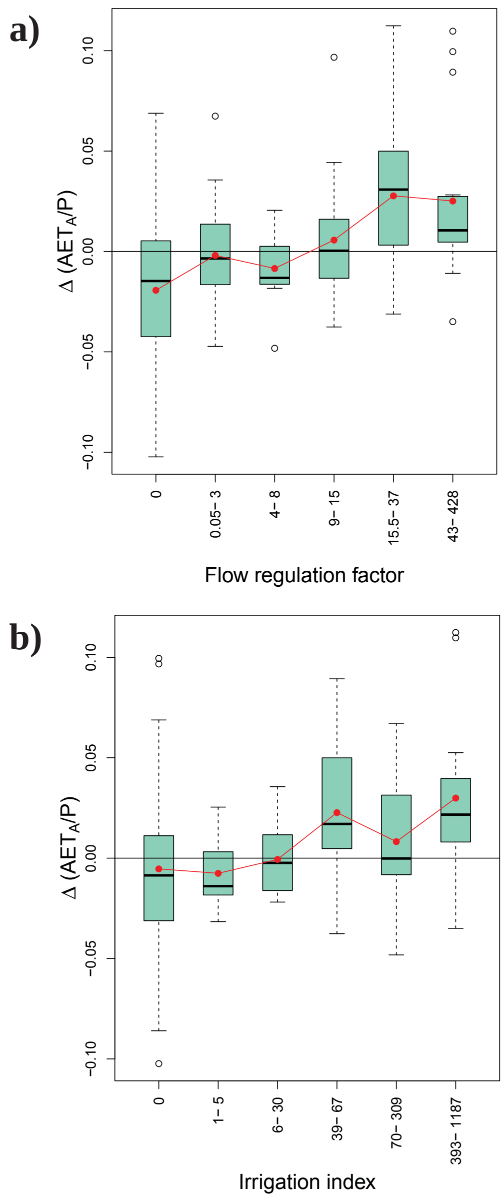

Figure 10. *Box plots of the distributions of basin-wise changes in evaporative index (AET_A/P) according to **(a)** the flow regulation factor and **(b)** the irrigation index derived by Nilsson et al. (2005). Each boxplot is structured as in Figure 9 and represents the distribution of AET_A/P changes among the intervals of the 20, 40, 60, 80 and 100 quantiles of the flow regulation factor and irrigation index, respectively.*

the beginning of the twentieth century up to present times, and their relation to possible change drivers in the atmosphere and the landscape. In order to study the latter, it has been necessary to first separate likely effects of atmospheric climate change from those of possible landscape drivers. This has been done by use of the data-motivated *CWOL*-driver separation approach.

This approach was used by Shibuo et al. (2007) to quantify the relative and combined effects of climate change and irrigation on *AET* in the Aral Sea drainage basin, based on observed hydroclimatic changes in *R*, *P* and *T*. From this perspective, the climate-driven component of *AET* was calculated by distributed hydrological modeling that estimated potential evapotranspiration *PET* by two empirical relations in terms of mean annual temperature *T* (Thornthwaite, 1948; Langbein, 1949) and used these estimates along with *P* data to calculate a climate-driven *EET* component via the Turc (1954) equation. The distributed nature of the hydrological modeling implied that water balance constraints were here honored both locally within model grid cells and overall for the whole basin. This study found that irrigation developments in this basin increased evapotranspiration, decreasing the net water flux from the atmosphere to the basin and thus leading to the major decrease in runoff from the drainage basin to the Aral Sea and directly to the dramatic decrease of the latter. Earlier studies (Jarsjö and Destouni, 2004; Shibuo et al., 2006) had then already showed that groundwater storage changes ware small over the basin, so that most of the used irrigation water was indeed lost to the atmosphere by evapotranspiration increase, rather than feeding any other major water storage change in the basin, beyond that of the Aral Sea itself; these findings were based on investigation of water balance closure (Jarsjö and Destouni, 2004) and detailed modeling of fresh groundwater and salt seawater interactions (Shibuo et al., 2006), and the coevolution of both these aspects with the Aral Sea shrinkage.

Destouni et al. (2010) further quantified the increase in latent heat flux resulting from irrigation, showing that the water use for irrigation and the associated *AET* increase cooled the atmosphere over the basin, thus affecting temperature and climate change in the region. Asokan et al. (2010) used the same modeling approach for *CWOL* driver separation as Shibuo et al. (2007) for another region, the Mahanadi River basin in India. The aim was to study the implications for *CWOL* of atmospheric climate change combined with changes in land use and water use for irrigation developments in the basin. Also here, the irrigation developments in the basin were found to increase water loss by *AET*. Based on availability of independent data for irrigation water use and land use for irrigated agriculture, this study could also explicitly show that it was the spatial distribution of actual water use rather than that of land use that actually controlled *AET* increase (Asokan et al., 2010). This thesis continues these research developments, even incorporating findings for the Aral Sea drainage basin and the Mahanadi River basin in the *CWOL* driver assessment of Paper II.

Another perspective to the *CWOL*-driver separation approach was taken by Li et al. (2007), Zhang et al. (2008), Ma et al. (2008) and Zhao et al. (2009), who separated effects of climate and landscape change for basins in China by comparing oberved *R* data with *R* change calculated from previous formulations of runoff change driven by climate variability; this was done by methods considering climate-driven *R* elasticity (Schaake, 1990;Vogel et al., 1999; Sankarasubramanian et al., 2001) or sensitivity (Koster et al., 2004; Milly and Dunne, 2002) and by climatic-streamflow model combinations developed for the basins of study. In analogy with the *AET* component determination of this thesis, a landscape-driven component of *R* was obtained here subtracting this derived climate-driven component of *R* (based on *PET* and *P*) from the total *R* (based on observed data). Additionally, statistical tests were made to determine change trends, such as the Kendall's rank correlation test (Kendall and Stuart, 1973), the Mann-Kendall test (Mann, 1945; Kendall and Gibbons, 1990) or the Pettit test for change points (Pettit, 1979); by these methods a base-line period (without landscape intervention) was distinguished from the period after landscape intervention. The studies of Li et al. (2007), Zhang et al. (2008), Ma et al. (2008), Zhao et al. (2009) showed that, in general, soil conservation measures involving afforestation had reduced annual *R* and runoff variability more than climate change alone. For Africa, Baahmed et al. (2014) has used the same statistical tools and the water balance model of Schreiber (1904) to separate the climate- and landscape-driven components of *R* change in the Macta catchment in Algeria and potentially attribute the latter component to human groundwater depletion.

Also from this perspective, Zheng et al. (2009) introduced into the *CWOL*-driver separation approach the Budyko framework (Budyko, 1948; Budyko, 1974), by expanding the calculation of the elasticity of climate-driven *R* to other water balance models (Schreiber, 1904; Ol'dekop, 1911; Budyko, 1948; Turc, 1954; Pike, 1964; Zhang et al., 2001) and separating climate and landscape-driven effects on *R* in several basins in China. For other basins in China, Xu et al. (2014) included other models to calculate runoff elasticity, such as the Choudhury–Yang equation (Choudhury, 1999; Yang et al., 2008) while Wang et al. (2009) and Ma et al. (2010) used distributed hydrological modelling to determine the climate-driven component of *R*. Xu et al. (2013) has further separated the climate- and landscape-driven components of not only annual *R*, but also baseflow and baseflow to runoff ratio, after performing a hydrograph separation.

CWOL have also been linked to movements in Budyko space. From the perspective of changes in *R*, Wang and Hejazi (2011) developed a decomposition method aiming to determine human-landscape-driven effects on *CWOL* in the contiguous United States. For 413 basins from the MOPEX database (Duan et al., 2006), this study found that the magnitude of landscape-driven *R* change could be partly explained by different proxies of human land use developments, such as population density, urban land, cropland, irrigated land and reservoir storage capacity. From an ecohydrologic perspective, the framework has also been used by Jones et al. (2012) and van der Velde et al. (2014) to link movements in Budyko space to particular effects of the interaction between vegetation, climate and human developments. Also by using the principles of the Budyko framework and the hydrological model by Zhang et al. (2001) to calculate the climate-driven component of *CWOL*, Creed et al. (2014) has recently assessed the influence of forest characteristics on water yield resilience to climate warming in North America.

Another version of *CWOL*-driver separation was presented by Tomer and Schilling (2009) for separating the effects of climate change and non-irrigated agriculture development on *AET* change in the US Midwest. They used a conceptual model to attribute changes in surpluses of water and energy to either climate and/or landscape drivers. The parameter space created for this framework is complimentary to that of Budyko (1974), but may be valid only for energy limited conditions ($PET/P<1$) since it does not take into account the orthogonality of the relationship between energy demand and water availability present at higher *PET/P* values (Fig. 3). Apart from the use of the Hargreaves et al. (1985) equation of minimum and maximum surface temperatures to calculate *PET*, this method did not determine explicitly any climate-driven component of *CWOL* and rather separated climate- and landscape-driven effects by geometric interpretations in such space. Renner and Bernhofer (2012) used this method with two other sensitivity-based models to determine climate-driven *R* change in the United States (Mezentsev, 1955; Roderick and Farquhar, 2011; Renner et al., 2012), and two other *PET* models (Hamon, 1963; Allen, 1998; Harris et al., 2014) to compare the outcomes of these models. Renner et al. (2014) further followed this work to derive a direct separation of climate- and landscape-effects on *CWOL* in the space of conformed by excess water and energy proposed by Tomer and Schilling (2009) to quantify the *CWOL*- effects from tree recuperation after air pollution damages in Germany.

Putting the present thesis in the context of various developments of the *CWOL*-driver separation approach so far, this thesis has expanded the time scale of such driver identification. Previous studies have identified change drivers occurring after 1950, and most consider only later hydroclimatic and landscape data. In Papers I and II, taking advantage of a large array of hydroclimatic and landscape development information and data that are available for hydrological basins in Sweden, we could show that major effects of landscape-drivers of *CWOL* have here occurred before 1950; i.e. effects of non-irrigated agriculture expansion and intensification, and effects related to hydropower development. Overall, this thesis separates, identifies and quantifies climate- and landscape-driven *CWOL* occurring since the early twentieth century up to the present.

By using twenty-year running averages of hydroclimatic and land-use change parameters, this thesis (Papers I and II) differentiates from other driver separation studies in tracking the actual evolution of specific land use developments in time. At the largest scales, we have also overcome hydroclimatic and landscape data limitations for such a long study period of more than 100 hundred years (Papers III and IV) by analyzing hydroclimatic changes based on only years with available *R* data, which must not necessarily be consecutive, and selecting adequate periods to assess such changes. We thus propose that global-scale analysis of hydroclimatic changes can be adequately assessed at long time scales by appropriate, justified and optimized use of available data.

We have also expanded the typical small- and regional-scale application of *CWOL*-driver separation to continental and global scales (Papers III and IV). Specifically, the development of total and climate-driven *CWOL* spectra in Paper III disentangles the complexity of using the *CWOL*-driver separation approach at continental and global scales. We have shown how such a simple tool can be used for direct quantification of climate- and landscape-driven effects on *CWOL* when combining them with the Budyko framework (Budyko, 1974). By extending the *CWOL*-driver analysis to larger temporal and spatial scales, we can better understand and interpret the impacts of human development throughout history on hydroclimate, *CWOL* and water availability; these impacts depend on actual driver timing, which may in some cases even have led to civilization collapses (Diamond, 1999; Diamond, 2011).

Stationarity is "the idea that natural systems fluctuate within an unchanging envelope of variability" (Milly et al., 2008). Hydrologists often assume stationary conditions in hydroclimate when using the water balance equation at inter-annual timescales, e.g., to calculate evapotranspiration (Eq. 1); it has also been shown that in relatively large basins and in periods longer than one year such conditions most possibly hold (Donohue et al., 2007). Since there is commonly no independent *AET* observation data available on whole basin scales and over long historic or future time periods, this stationarity assumption implies an assumption of negligible change in water storage ($\Delta S \approx 0$) in order to be able to calculate *AET*. Similarly, the energy and water availability relationships of the Budyko framework (Budyko, 1948; Budyko, 1974) are also conditioned to stationarity of both landscape characteristics and intra-annual hydroclimatic conditions.

In the Aral Sea case, several focused and detailed studies showed this assumption to be essentially valid even during dramatic, but still localized change in surface water storage, i.e., during the Aral Sea desiccation (Jarsjö and Destouni, 2004; Shibuo et al., 2006; Alekseeva et al., 2009). However, other recent research has shown that this assumption may not necessarily always be valid, particularly during times of major climate and societal changes that can both affect water storage or water phase change conditions in the landscape. Such changes may be induced directly by human water withdrawals, e.g., groundwater depletion, or indirectly by climate change, e.g., temperature-driven changes in glaciers or permafrost, or changes in vegetation stomata closure through increased atmospheric CO_2 (Haeberli and Beniston, 1998; Yang et al., 2004; Zhang et al., 2005; Gedney et al., 2006; Smith et al. 2007; Milliman et al. 2008; Bring and Destouni 2011; Karlsson et al. 2012; Mazi et al. 2014). With regard to transformation of water and land by human activities, recent studies have shown that intra-annual changes in precipitation (Zanardo et al., 2012) and even temperature (Berghuijs et al., 2014) may affect the inter-annual variability of runoff and evapotranspiration and induce non-stationary conditions of water residing within a basin. For example, an increase in seasonal *P* and *PET* variability and dry season length have been proven to decrease the evaporative index (Feng et al., 2012). Furthermore, annual *AET* can also increase because of inter-seasonal soil moisture transfer in dry climates experiencing in-phase *P* and *PET* intra-annual developments (Feng et al., 2015). By observing that in general the studies using the *CWOL*-driver separation approach have often assumed intra-annual stationarity in terms of water storage change, this thesis has also approached the stationarity assumption in various ways.

Firstly, we do consider changes of water storage and water phase change conditions in the landscape, along with changes to land use and water use, as possible main landscape drivers of *CWOL* drivers (Fig. 2). Where information on water storage change was not available, especially at larger scales (In Papers III and IV), we considered an apparent actual evapotranspiration AET_A that may also include possible systematic long-term change in water storage (average $\Delta S \neq 0$). In cases with available hydrologic data on water levels, we have further tested various $\Delta S \neq 0$ scenario assumptions and compared their result implications with those of the simple and common assumption of long-term average $\Delta S = 0$. In Papers I and II, changes in water storage due to lake regulation and soil water storage within the Swedish basins were assessed by consideration of three different scenarios of how observed water level change in the major lakes might relate to average water storage changes within the basins studied. We showed that for these cases, an assumption of long-term average $\Delta S \approx 0$ within each averaging period of study estimated reasonably well the long-term change in period-average *AET* between such periods.

Finally, also regarding effects of inter-annual hydroclimatic variability, we quantified in Paper III the coefficient of short-term variation of precipitation CV_P to to avoid misidentification of such effects as landscape-driven *CWOL*. We identified at the global scale a total of 43 basins with significant changes in CV_P and discarded them from the further analysis. Whether and how such significant CV_P changes may affect *CWOL* remains then as an interesting possible line of future research.

As one essential development of the *CWOL*-driver separation approach, this thesis has also identified (Paper I) and further checked with multiple worldwide basin results (Paper IV) the occurrence of a sustained long-term decrease in CV_R as a useful indicator of specific flow regulation effects on *CWOL* (Paper II and Paper IV). Last but not least, the thesis has considered bias correction for observed precipitation (Adam and Lettenmaier, 2003) as a further development of the *CWOL* separation approach, with maintained general *CWOL* driver conclusions for both observed and corrected *P* consideration. Other such corrections for orographic precipitation effects (Adam et al., 2006) can also be considered in future research developments.

Objectives B and C

Papers I and II have shown that major effects of landscape-drivers on hydroclimatic change occurred before 190 in Sweden; for the investigated Swedish basins these drivers include non-irrigated agriculture expansion and intensification, and hydropower development. In the particular case of non-irrigated agriculture, we have shown how its expansion and intensification coevolved with sustained increases in *AET* and *AET/P*. These findings agree with other studies in Brazil, evidencing similar increases from the conversion of pastures to sugar cane cultivation (Loarie et al., 2011) but contradict other studies in the United States, which have found such developments to decrease actual evapotranspiration *AET* and thus increase runoff *R* (Schilling et al., 2008; Raymond et al., 2008; Wang and Hejazi, 2011; Sterling et al., 2013). However, such result differences among regions are consistent with global-scale assessment of *AET* rates that points at conversion of grasslands to croplands as the land transformation for which the direction of change in *AET* exhibits the largest uncertainty (Table 1; Sterling et al., 2013). Papers I and II may contribute to reduction of such uncertainty and can inform on possible hydroclimatic consequences of agricultural developments also in other continents than continental North and South America.

Differences of *CWOL* effects of non-irrigated agriculture between Sweden and the United States may be due to the characteristics of crops being cultivated in each region (i.e., efficiency of their water use, albedo, rooting depth), the land-cover characteristics before transformation, the way and timing of expansion (area) and productivity (yield) intensification and effects of regional soil conservation measures. Xu et al. (2013) also suggest that the increase in runoff in the U.S. Midwest may also be attributed to changes in crop types (see Fig. 5) and land management practices (conservation measures and drainage improvements) rather than to agricultural expansion; changes put in place there in the second half of the twentieth century.

Such land transformation differences further suggest that spatiotemporal extrapolation of local *AET* rates among regions and even continents (e.g., Gordon et al., 2003; Gordon et al., 2005; Sterling et al., 2013) should stipulate the limits for drawing firm conclusions about actual large-scale *CWOL*. Such extrapolations should rather “encourage similar future exploration of greater basin variety” (Paper II; Destouni et al., 2013) and themselves also be subject to actual testing, e.g., by means of the *CWOL*-driver separation approach. Regarding effects of non-irrigated agriculture on CV_R, the latter was found in Paper II to increase, however, that was under conditions of increase in *AET/P*, as one result of the agriculture development. An underlying (apparent natural) coevolution of *AET/P* and CV_R in non-agricultural and unregulated control basins may then be responsible for the coevolution of increased *AET/P* and CV_R in agricultural basins, where the latter may have directly caused the *AET/P* increase with the CV_R increase then naturally following, or vice versa. To best knowledge, no other studies have presented any results that can be compared with our findings in this regard. Hence, studying the change in CV_R along with *AET/P* in other regions of the world should be a subject of future research.

The *CWOL* effects of flow regulation, e.g., by hydropower development, identified in this thesis (Paper II and Paper IV) are consistent with those of other studies. Specifically, clear spatial gradients of change have been found in convective available potential energy, specific humidity and surface evaporation from reservoirs (Eltahir and Bras 1996; Hossain et al. 2010; Degu et al., 2011), as well as decreases in intra-annual runoff variability (Poff et al., 2007; Zhang et al., 2008; Vogl and Lopes, 2009). In this thesis, increases in *AET/P*, which imply associated decreases in R, are found to coevolve with cumulative installed hydropower capacity in each basin; these change findings complement from a hydrological perspective the atmospheric change findings of Degu et al. (2011). Furthermore, a recent study of hydroclimatic and hydropower developments in the Sava Basin, Europe (Levi et al., 2013) has also found such coevolving increase in *AET/P* and decrease in CV_R, as also identified here in Papers II and IV. However, simulation of downstream runoff effects of hydropower developments in Switzerland have also found increase in runoff variation CV_R (Botter et al., 2010), suggesting that caution on interpretation and further research are needed for possible generalization of such results to different types of hydropower development and operation.

Regarding irrigation effects on *CWOL*, the findings in Paper IV of increasing *AET* and *AET/P* and decreasing *R* agree well with other regional results (of which some were also included in Paper II) on hydroclimatic effects of irrigation (Boucher et al. 2004; Douglas et al. 2006; Shibuo et al. 2007; Sacks et al. 2009; Asokan et al. 2010; Destouni et al. 2010). However, the finding of irrigation not having any significant relation to CV_R has not been investigated in the past.

Overall, the results of Papers II, III and IV point to a clear driving role of landscape conditions on continental and global hydroclimate and *CWOL*, as observed during the twentieth century and beginning of the twenty-first century. Calls for further exploration of the role of landscape drivers for the current and future water cycle have already been raised in the scientific literature (Vörösmarty et al., 2000; Legates et al., 2005; Oki and Kanae, 2006; Zhang et al., 2007; Piao et al., 2007; Vörösmarty et al., 2010). The present thesis shows that landscape drivers are needed to explain observed *CWOL* in at least 74% of the basins studied over global and continental scales, thus emphasizing these calls for further exploration of these drivers and their freshwater effects, in addition to such effects caused by atmospheric climate change (Fig. 2). Finally, Paper III shows that the water change effects of landscape drivers are mostly opposite to those of atmospheric climate change at the global and continental scales, going further than other findings that only evidenced the possible masking of climate-driven *CWOL*-related effects by those being landscape-driven (Jones et al., 2012). Our finding could have then important implications for assessment of future water cycle changes (Huntington, 2006; Oki and Kanae, 2006).

Conclusions

In general, this thesis has identified, separated and quantified, from basin-scale to continental and global scales, climate drivers and landscape drivers of changes to the partitioning of water on land *CWOL* that have been observed to have occurred over the twentieth century to the beginning of the twenty-first century.

Objective A

This thesis has developed the data-driven approach of *CWOL*-driver separation, by expanding its application in both time and spatial scales, in order to study the effects of landscape drivers on *CWOL*. The work has identified the directions of change in evaporative index *AET/P* and in the coefficient of short-term variation of runoff CV_R as potentially useful indicators for distinguishing landscape-driven *CWOL*. It has further introduced uncertainty measures to the estimation of *AET* change and its possible drivers, by multiple model consideration of climate-driven *EET* change as well as by considering both directly observed and bias-corrected precipitation *P* and its changes. Changes in the coefficient of short-term variation of precipitation CV_P have also been considered, as a possible driver of CV_R change, as well as to identify and discard basins where basic assumptions for landscape-driver identification may not be valid.

Additionally, this thesis has developed a spectrum approach for multiple basin assessment of *CWOL* over continental and global scales. This can further be used to separate climate- and landscape-driven effects on *CWOL* at any spatial or temporal scale. Finally, the thesis has also shown how signals of landscape-drivers can be identified from interpretation of changes in basic hydroclimatic variables even at continental and global scales.

Objective B

For basins in central Sweden, the thesis has shown that the development and intensification of non-irrigated agriculture is likely to have driven observed increasing shifts to higher *AET*, *AET/P* and CV_R during the period 1901-1940. For the specific case of the Norrström drainage basin, which was a first focus of this thesis work, only about 30% of the shift in *AET* could be attributed to atmospheric climate change. Unregulated agricultural and non-agricultural basins generally exhibited a positive correlation between *AET/P* and CV_R temporal evolution. In contrast, hydropower-developed basins of Northern Sweden did not exhibit such correlation; instead, shifts to increased *AET/P* coevolved here with shifts to decreased CV_R, as well as with increased hydropower development.

Objective C

The thesis has identified, across basin-scales to continental and global scales, consistent *CWOL* signals that can be related to flow regulation and irrigation developments. These signals are evident directly from observation data and against the background of several other atmospheric climate and landscape drivers that also coexist and simultaneously influence water changes on land. These findings are consistent with other thesis results showing that: i) landscape drivers are needed to explain *CWOL* in at least 74% of the studied basins worldwide, ii) hydroclimatic changes in the world and in some continents are not explainable by only atmospheric climate change, iii) a considerable proportion of the worldwide hydroclimatic changes may be directly related to human land use and water use developments in the landscape, and iv) the landscape driver effects on *CWOL* mostly counteract those of atmospheric climate change. These results show that landscape drivers of *CWOL*, and not least the direct human drivers, and their water effects need to be included and accounted for also in projections of possible future water changes on land.

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