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# Implications of freshwater flux data from the CMIP5 multimodel output across a set of Northern Hemisphere drainage basins

**Arvid Bring[1,2], Shilpa M. Asokan[1,3], Fernando Jaramillo[1], Jerker Jarsjö[1], Lea Levi[1,4,5], Jan Pietroń[1], Carmen Prieto[1,3], Peter Rogberg[1], and Georgia Destouni[1,3]**

[1] Department of Physical Geography, and the Bolin Centre for Climate Research, Stockholm University, Stockholm, Sweden, [2] Water Systems Analysis Group, Institute for the Study of Earth, Oceans and Space, University of New Hampshire, Durham, New Hampshire, USA, [3] Navarino Environmental Observatory (NEO), Messinia, Greece, [4] Department of Land and Water Resources Engineering, KTH Royal Institute of Technology, Stockholm, Sweden, [5] Department of Applied Hydraulics, Faculty of Civil Engineering, Architecture and Geodesy, University of Split, Split, Croatia

**Key Points:**
- Freshwater fluxes better represented for cold than for warm temperate regions
- Unrealistic long-term average water balances implied by climate model output
- Attention to freshwater fluxes needed to inform climate model use in adaptation

**Supporting Information:**
- Supporting Information SI

**Corresponding author:**
A. Bring, arvid.bring@unh.edu

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**Abstract** The multimodel ensemble of the Coupled Model Intercomparison Project, Phase 5 (CMIP5) synthesizes the latest research in global climate modeling. The freshwater system on land, particularly runoff, has so far been of relatively low priority in global climate models, despite the societal and ecosystem importance of freshwater changes, and the science and policy needs for such model output on drainage basin scales. Here we investigate the implications of CMIP5 multimodel ensemble output data for the freshwater system across a set of drainage basins in the Northern Hemisphere. Results of individual models vary widely, with even ensemble mean results differing greatly from observations and implying unrealistic long-term systematic changes in water storage and level within entire basins. The CMIP5 projections of basin-scale freshwater fluxes differ considerably more from observations and among models for the warm temperate study basins than for the Arctic and cold temperate study basins. In general, the results call for concerted research efforts and model developments for improving the understanding and modeling of the freshwater system and its change drivers. Specifically, more attention to basin-scale water flux analyses should be a priority for climate model development, and an important focus for relevant model-based advice for adaptation to climate change.

## 1. Introduction

The multimodel ensemble of the Coupled Model Intercomparison Project, Phase 5 (CMIP5) and its predecessors provide critical inputs to the assessment reports produced within the Intergovernmental Panel on Climate Change (IPCC) framework [*Meehl et al.*, 2007; *Taylor et al.*, 2012; *Flato et al.*, 2013], and are also used as input for further investigations of climate change and its impacts [*Xu and Singh*, 2004]. For the freshwater system on land, and specifically the drainage basin-integrated fluxes of precipitation, evapotranspiration, runoff, and water storage change across different basins of a region, and for a sustainable human use of that water, decisive questions are whether climate change will impact flow regimes [*Oki and Kanae*, 2006; *Botter et al.*, 2013] and lead to more frequent floods and droughts, changes to water availability and quality [*Kundzewicz et al.*, 2008; *Kumar et al.*, 2013], and surplus or deficit of freshwater relative to current conditions and to the freshwater needs of humans and ecosystems. Further critical questions are how human land use and water use affect freshwater changes in addition to climate change [*Jarsjö et al.*, 2012; *Destouni et al.*, 2013] and how these effects in turn affect temperature extremes [*Seneviratne et al.*, 2006], soil moisture [*Destouni and Verrot*, 2014; *Verrot and Destouni*, 2015], evapotranspiration driven by incoming solar radiation [*Trenberth et al.*, 2009] and several other drivers within the landscape itself [*Jaramillo and Destouni*, 2014], and through that also the local–regional manifestations of climate change [*Destouni et al.*, 2010; *Asokan and Destouni*, 2014].

Some of the impacts listed above play significant roles in driving climatological processes (through various feedback mechanisms), whereas others are primarily of importance for societal and ecological concerns.

However, the fundamental driver of them all is the dynamics of freshwater and the partitioning of its precipitation input on land into evapotranspiration back into the atmosphere and runoff (surface and subsurface) through the landscape toward the sea. These freshwater interactions with both the atmosphere and the sea have significant influence on the climate system, e.g., through Arctic freshwater input that influences ocean heat and water transport [*Rennermalm et al*., 2006] and through large-scale changes in evapotranspiration resulting from changed land use and water use patterns [*Gordon et al*., 2005; *Destouni et al*., 2013]. The latter are both also major controls on freshwater availability for further human use. All of these processes are critical to understand and correctly represent at drainage basin scales, where both management and adaptation to water system change take place [*Pahl-Wostl*, 2007].

Climate models are now being used to provide multidecadal predictions of climate, in contrast to previous applications that chiefly served to project differences between hypothetical future scenarios [*Trenberth*, 2010]. With this in mind, climate model output will likely be put to a broader set of uses also outside the climate science community, e.g., in the water sector for adaptation to a changing climate, whether such uses are appropriate or not [*Kundzewicz and Stakhiv*, 2010].

Previous research indicates that there are shortcomings in climate model simulations of precipitation [*Stephens et al*., 2010] and evapotranspiration [*Mueller and Seneviratne*, 2013]. However, much of the evaluation of CMIP5 model performance so far has not been done at drainage basin scales, which precludes a direct comparison with basin-scale observations of the hydrological cycle and an assessment of model relevance for water management and adaptation measures at such scales. Among studies that have applied a drainage basin perspective, *Törnqvist et al*. [2014] evaluated all key components of the basin-scale water balance and used basin-integrated data for the single Lake Baikal drainage basin. Other studies of this type have not considered the basin-scale water-balance aspect and all the available basin data for assessing it. For example, *Deng et al*. [2013] performed an evaluation of precipitation on the watershed scale for the Yangtze river, but did not evaluate water balance. Neither did *Alkama et al*. [2013], who used watershed-scale observations to evaluate CMIP5 runoff projections. Furthermore, as their aim was global and continental-scale trend detection, they neither presented results for any particular basins nor discussed potential confounding factors, such as anthropogenic influences, on other than global scale. They also use a reduced set of the CMIP5 ensemble, consisting of only 11 models. *Siam et al*. [2013] evaluated CMIP5 data over the Congo and Upper Blue Nile basins for a similar-sized reduced ensemble, and used a watershed approach, but did also not explicitly evaluate water balance.

To our knowledge, there has been no evaluation and comparison of the watershed-scale representation of the water balance in CMIP5 data for any larger set of basins. In general, most studies that do analyze GCM output of particular relevance for the freshwater system approach the question from an atmospheric perspective, focusing on atmospheric fluxes and exchanges of moisture. For this reason, evaluating the water fluxes of climate models on the scale of physical drainage basins, which allows for basin-scale closure of the water budget, can provide information on the climate model reliability and relevance for addressing the critical freshwater-related societal questions presented above. In particular, the closure of basin-scale water budget implied by climate model output is of interest, as it aids the interpretation of the general reliability of the freshwater system representation in the climate models. It is also a complement to the focus on vertical exchanges of water and energy at the land surface discussed above, which the climate models generally represent in considerably more detail than the lateral transport and the transport beneath the surface.

To study climate effects on macroscale hydrology, a common approach is to use downscaled climate model data, computed through either statistical or dynamical methods, that is subsequently processed through a hydrological model. Although this approach can provide a higher-resolved field of climate and hydrology variables for a smaller region of interest, it cannot circumvent the fact that both the downscaled data and, in turn, the hydrological model, fundamentally depend on the climate forcing data and boundary conditions provided as output of global climate models. For example, macroscale hydrological simulations of discharge in India indicate that the selection of the climate model had greater impact on uncertainty than the parametrization of the hydrological model [*Raje and Krishnan*, 2012]. Thus, if the water fluxes do not add up over the region in the global model, biases arising from this fact will still transfer through to simulations at finer scales. For this reason, it is important to inform the hydrological modeling community, as well as other end users of climate model data, about imbalances that may exist in the original output data of global climate models.

In this study, we investigate climate model output, with regard to terrestrial water flux parameters, on drainage basin scales for a set of previously investigated drainage basins that vary in size and span a range of geographical conditions in the Northern Hemisphere. In this way, we are able to put model output in the context of actual observations at places where we also have thorough previous knowledge of which factors in the landscape, in addition to those in the atmosphere, which may be influencing these hydroclimatological changes. Thereby, we can better discuss whether global models are capturing the actually observed water changes and the effects of main change drivers in the landscape as well as in the atmosphere on management- and adaptation-relevant drainage basin scales. Furthermore, we are able to evaluate whether effects of the various geographic conditions or the basin sizes are discernible in the study results. This is an important question, as climate model output is often considered to be more reliable for larger areas [*Flato et al*., 2013].

## 2. Theory and Methods

### 2.1. Geographical Scope

For this analysis, we investigate a number of temperate basins in the Northern Hemisphere: the Aral Sea drainage basin, the eight largest rivers in the pan-Arctic drainage basin, the Greek coastal drainage basin (by which we mean all areas draining through the Greek coastline), the Sava River basin, the Selenga River basin, and a set of Swedish drainage basins. Basin outlines are shown in Figure 1 (detailed maps in Figure S5, Supporting Information). The Arctic, Sweden, and Selenga are cold temperate basins, whereas the Aral Sea, Sava, and Greek drainage basins are warm temperate. Key basin characteristics are listed in Table 1, with further detail available in the Supporting Methods and in the references listed therein. For the Greece basin, we have only limited direct observation data, but have more corresponding information from formal water management reporting in connection with the Greek implementation of the EU Water Framework Directive [*Greek Water Management Authority*, 2013] and can therefore also include Greece here for wider geographical coverage.

The main motivation for our choice of study basins is that previous studies of hydroclimatic change, carried out on watershed scales based on historical observations, are generally available and published for these basins; for some of them (Aral and Arctic), also future projections from earlier generations of GCMs have been investigated in previous studies and can be compared with the present CMIP5 assessment. This underlying basin information allows us to interpret the climate model output in the context of previous knowledge of potential change drivers and effects for the basins. For this reason, we refrain from attempting a global study here, as such a study provides limited opportunity to investigate and discuss specific basins in detail [see, e.g., *Alkama et al*., 2013].

Some of the regional basins are composed of multiple subbasins, which were aggregated to larger, common regional drainage areas for calculation of associated climate model output. For each regional basin, the included set of subbasins together comprises an area of at least around 100,000 km$^2$, and for most regions a much larger area up to several million km$^2$. As the smaller regional basins in the study are at the lower limit of areas that can be resolved with some of the included GCMs, effects of scale may influence climate model performance in these areas, but this allows us to also investigate such scale effects. This is important, as environmental managers, water planners, and decision makers often consider climate model output relevant and useful also on even smaller scales than those considered in the present investigation.

### 2.2. Theory and Methods

To address our main objective of assessing the CMIP5 representation of water fluxes on drainage basin scales, we focus here on the annual values of precipitation ($P$), runoff ($R$), evapotranspiration ($ET$; including sublimation), and net annual water balance or storage change ($\Delta S$). In addition, we also investigate temperature ($T$) as an integral measure of climate in the studied basins. The water flux components are related by the total water balance within the topographical divides of hydrological drainage basins as $\Delta S = P - R - ET$. On the long-term scales of decades, and particularly for larger basins, the average annual sum of water fluxes across the basin divide ($P - R - ET$) should normally be in dynamic equilibrium and must then equal

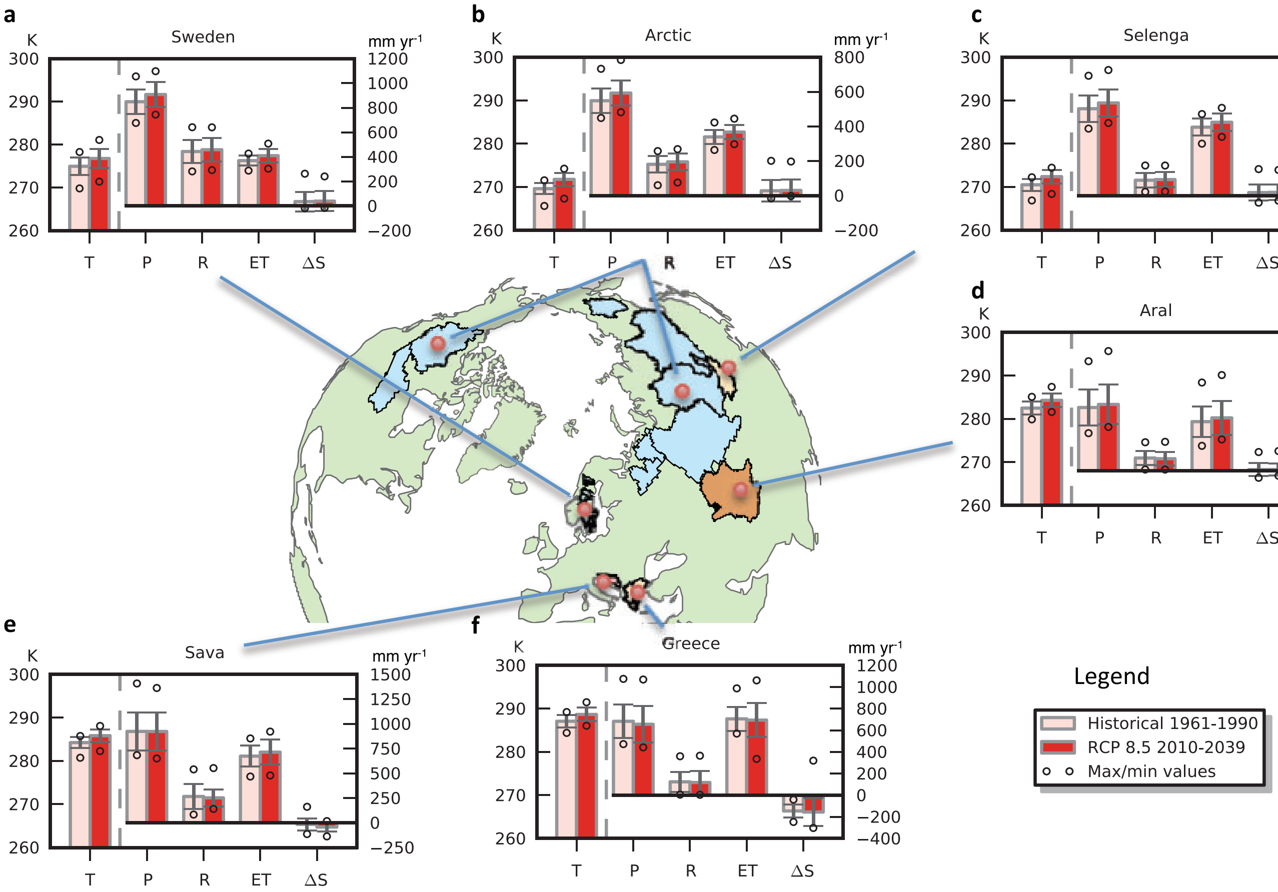

**Figure 1.** Modeled temperature and water fluxes. Ensemble mean, standard deviation, and range of CMIP5 results for temperature (*T*), and water fluxes of precipitation (*P*), surface runoff (*R*), evapotranspiration (*ET*), and net annual water balance (Δ*S*) for a set of six Northern Hemisphere drainage basin regions. Error bars denote one standard deviation of model means, and open circles the whole range of individual model results.

**Table 1.** List of Hydrological Regions and Aggregated Basin Sizes

| Region | Basin Area (km$^2$) | Reference with Basin Description |
|---|---|---|
| Aral | $1.89\times10^6$ | *Destouni et al*. [2010] |
| Arctic | $10.2\times10^6$ | *Bring and Destouni* [2011] |
| Greece | $0.19\times10^6$ | Described in Supporting Methods |
| Sava | $0.09\times10^6$ | *Levi et al*. [2015] |
| Selenga | $0.44\times10^6$ | *Thorslund et al*. [2012] |
| Sweden | $0.24\times10^6$ | *Destouni et al*. [2013]; additional basins in Table S2 are defined at the Swedish Meteorological and Hydrological Institute: Vattenweb |

zero, with intra- and interannual fluctuations in water storage change occurring around the long-term average value of $\Delta S \approx 0$. However, over periods of systematic flux imbalance, internal changes of water storage must occur and imply then nonzero Δ*S* (reflected in changed groundwater and surface water levels, as well as in changed soil moisture and surface water availability).

A long-term nonzero Δ*S* could potentially arise in a number of situations. In basins with strong anthropogenic alterations, such as sustained consumptive groundwater depletion or interbasin water transfer, the internal water storage is reduced and consequently also affects the runoff *R* from a basin, without the latter change being driven by or reflected in a corresponding change in net water input $P-ET$ to the basin. Permafrost degradation or long-term shrinkage of glaciers may also mobilize pools of new liquid water for increased $R$ and/or increased $ET$, with neither increase being driven by increased $P$; however the effect of these water phase changes in the landscape may be small on annual river flows over large scales, at least in the Arctic [*McClelland et al*., 2004; *Karlsson et al*., 2014]. Desertification leads to degraded and dryer lands, but this effect too may be small on the long-term average water balance over large scales; this process may primarily involve a changed partitioning of available $P$ between the $ET$ and $R$ terms of the water balance, and then only to a minor degree affect long-term water storage within a basin, unless there is also an element of groundwater depletion involved, as discussed above for directly human-driven groundwater depletion. For most of the world, the stored water amount in the unsaturated soil zone is quite small, and the table of the saturated, groundwater zone (where by far most of the Earth's liquid freshwater resides) lies below the rooting depth of plants [*Fan et al*., 2013] and is not necessarily significantly affected by desertification. With the exception of glacier and soil water storage, these landscape processes and changes are generally not included in global climate models, although some Earth system models are beginning to incorporate some of them.

In general, it is expected that deviations from a zero water balance over large basin scales and over time spans of several decades should be small, and at least orders of magnitude smaller than other terms [*Siam et al*., 2013]. For example, multiple reanalysis data products over the Congo and Upper Blue Nile basins mostly indicate $\Delta S$ terms of $<3\ \mathrm{mm\ yr^{-1}}$, in contrast with precipitation terms generally in excess of $1500\ \mathrm{mm\ yr^{-1}}$ [*Siam et al*., 2013]. We will therefore take as a point of departure the assumption of $\Delta S \approx 0$ for historical observations of long-term average values of water flux variables. We note, however, that qualifications to this assumption will influence our interpretation of results, which we will discuss later on.

For the other water flux variables, long-term historical observations for our study basins are relatively readily available for $R$ and $P$ for most basins, but not for $ET$. We therefore compute a water-balance-derived estimate of the historical evapotranspiration over our drainage basins as $ET_{\mathrm{wb}} = P - R$. This water-balance-derived $ET_{\mathrm{wb}}$ then also relies on the assumption of $\Delta S \approx 0$ noted above, in consistency with other recent studies of large-scale hydroclimatic conditions and changes [*Destouni et al*., 2013; *Jaramillo et al*., 2013; *van der Velde et al*., 2013, 2014; *Jaramillo and Destouni*, 2014; *Levi et al*., 2015]. Our observation-based estimate of evapotranspiration will thus include some errors in the storage change term, as well as in the observed precipitation and runoff terms, and we note that results should be interpreted with caution. However, previous studies have indicated that alternative assumptions of $\Delta S$ yielded small deviations in the estimated long-term average $\mathrm{ET_{wb}}$ based on the assumption of $\Delta S \approx 0$ from that based on different realistic, observation-based quantifications of nonzero annual $\Delta S$ [*Destouni et al*., 2013; *Jaramillo et al*., 2013].

To account for possible systematic errors in the observed precipitation data, we correct them for biases from gauge undercatch [*Adam and Lettenmaier*, 2003] and orographic effects [*Adam et al*., 2006]. Orographic corrections are based on basin water balances and variations of Budyko evapotranspiration–precipitation relationships. Although these corrections improve observations in some regions, they are also dataset specific and based on model assumptions that do not always hold, and seem to be less reliable for other regions [*Adam et al*., 2006]. We present the corrected data separately from the original, to allow for transparent evaluation of the effect of the corrections.

For the model data, the assumption of $\Delta S \approx 0$ is relaxed and neither needs to or can be made, as the CMIP5 models explicitly simulate the $ET$ parameter independently of basin-scale water balance. Thus, in addition to the $P$, $R$, and $ET$ terms, we can for the climate model output also investigate the model-implied $\Delta S$ as the residual $\Delta S = P - R - ET$. However, this term should still be expected to be zero, or close to zero, on average over our large basins and over multidecadal timescales.

As our evaluation of the model-projected $\Delta S$ is done against an assumed long-term average value of $\Delta S \approx 0$, smaller deviations are to be expected between climate model results and this assumption, which may not imply any shortcoming in model performance. We consider larger deviations, however, to be less plausible. For example, consider a long-term annual imbalance of $\Delta S = P - R - ET = 10\ \mathrm{mm\ yr^{-1}}$ for a 30-year climatological period. This implies an increase of water levels in the basin by a total of 30 cm ($10\ \mathrm{mm\ yr^{-1}}$ over 30 years) in surface waters, and around 1 m (30 cm of water distributed within an average porosity of 30%) in groundwater. Such a systematic long-term increase or decrease (rather than just seasonal fluctuations) of water levels in a landscape may pass unnoticed if it is small and water levels are not monitored. However, large systematic changes of surface water and groundwater levels should be clearly noticeable (and monitored) by water resource and environmental managers, and if large enough also by the general population. The post-1950 decrease in the Aral Sea water level, for instance, has led to one of the world's worst ecological, health, and socioeconomic disasters [*Micklin*, 2007; *Törnqvist et al*., 2011], with a water level drop in the Aral Sea of about 23 m in total [*Zavialov*, 2005], or on average about 46 mm $\mathrm{yr}^{-1}$. Note, however, that this change is manifested principally in the level of the lake, and not in significantly changed average groundwater level and storage throughout the basin [*Jarsjö and Destouni*, 2004; *Alekseeva et al*., 2009]. Comparison with this change shows that also the example of $\Delta S = 10\ \mathrm{mm\ yr}^{-1}$ implies a large flux imbalance, with associated water level changes that would not go unnoticed if sustained over several decades.

We compare model and observation values of the long-term averages of water flux variables for three multidecadal periods. In addition to the standard reference climate period of 1961–1990, we also define two 20-year periods, 1961–1980 and 1986–2005, which maximize the amount of observational data for the investigated basins and allow us to evaluate model performance for historical changes. For projections, we also evaluate model results for the periods 2010–2039 and 2070–2099 for the future scenarios RCP2.6 and RCP8.5 [*Moss et al*., 2010]. In the Supporting Information, we give a detailed account of our selection of CMIP5 models, the observational data sources, and the analysis methods we used.

## 3. Results and Discussion

Figure 1 shows ensemble mean, standard deviation, and range of CMIP5 simulations for temperature ($T$) and key water fluxes ($P$, $R$, $ET$, $\Delta S$) for our six hydrological drainage basins, and for the two time periods of 1961–1990 in the historical experiment and 2010–2039 in the RCP8.5 experiment (Figures S1 and S2 show corresponding results for individual climate models; the RCP8.5 and the RCP2.6 experiment results are very similar for 2010–2039 and only somewhat more divergent for 2070–2099, as shown in Figure S3).

Temperature is consistently projected to increase across all basins, and the intermodel standard deviation is relatively small. In contrast, the standard deviation and range are generally larger for the water fluxes, and particularly large relative to the ensemble mean result for runoff, in both the historical and the RCP8.5 experiment. Effects of basin scale on the intermodel variability of water fluxes are not evident here. For instance, standard deviation in historical evapotranspiration is identical for the Arctic and Sweden, even though the area of the former is 30 times larger.

When combining the modeled water fluxes into their model-implied long-term average net water balance or average water storage change ($\Delta S$), results exhibit even larger intermodel standard deviations around the ensemble mean model implication of $\Delta S$ (individual model results in Figures S1 and S2). Furthermore, ensemble mean model results for average $\Delta S$ imply large systematic long-term changes in average surface water and groundwater level over a whole large basin, the range of which is even larger for individual models across all basins (open circles in Figure 1).

For example, the CMIP5 ensemble mean of the historical long-term average water storage change over the whole of Greece is at $-146\ \mathrm{mm\ yr}^{-1}$, which is even larger than the corresponding runoff of $124\ \mathrm{mm\ yr}^{-1}$. Over the period 1961–1990, such a systematic, continuous average water storage change would imply a total decrease of 4.4 m in surface water level ($0.146 \times 30$) and around 14.6 m (with 30% porosity; $4.4 \div 0.3$) in groundwater level over Greece. Such systematic water level changes across the Greek peninsula have not been reported, and would undoubtedly be noticed if they had actually occurred.

Although the values for Greece are extreme, results for other basins are also typically similar to or greater than the example discussed above of a relatively large average water storage change of $\Delta S = 10\ \mathrm{mm\ yr}^{-1}$. However, the ensemble mean model-implied average water storage change $\Delta S$ of $28.1\ \mathrm{mm\ yr}^{-1}$ for the Arctic might be viewed as at least qualitatively consistent with reports of increased groundwater contribution to river flows in this region [*Smith et al*., 2007].

The causes for nonzero water balance in models likely involve several factors, which may also differ among the basins we study. For the Arctic, a contribution from model artifacts, i.e., ice accumulation in subzero grid cells, is possible but, if at all relevant, that effect should be marginal as the glaciated area of our Arctic study basins is very small [*Bring and Destouni*, 2014]. Conversely, any sizeable contribution to the multimodel mean from melting of excess ground ice is unlikely, as such factors are not included in most models

[*Lee et al*., 2014]. In any case, the long-term wetting trend for cold temperate and subpolar regions (Sweden, Selenga, and the Arctic in this study) may be viewed as consistent with increased poleward moisture transport [*Zhang et al*., 2013]. However, it is not at all certain that wetter soils and increasing water storage would follow from this—in fact, soil moisture in Swedish basins has been shown to decrease even though $P$ has increased [*Destouni and Verrot*, 2014; *Verrot and Destouni*, 2015] and in the Arctic soil moisture is generally projected to decrease as permafrost degrades and infiltration increases [*Hinzman et al*., 2013]. Nevertheless, permafrost thaw and groundwater storage change may be contributing to the positive Arctic water balance (i.e., systematically decreased water storage) implied by the models.

For warm temperate regions, the general model-implied decrease in water storage may involve other mechanisms, but still with groundwater storage change necessarily playing a crucial role, as by far the greatest amount of liquid freshwater on land exists as groundwater. Shifts in the long-term average amount of groundwater residing within a basin may then occur due to systematic consumptive water removal (e.g., for irrigation use) or nonconsumptive water addition (e.g., by permafrost thaw) that significantly alters average groundwater level and/or surface water level and occurrence within a basin and thereby also average runoff $R$ from the basin, without the latter change component being driven or explained by a corresponding change in average net water input $P-ET$ to the basin [*Milliman et al*., 2008; *Bring and Destouni*, 2011; *Karlsson et al*., 2012; *Mazi et al*., 2014]. However, such groundwater level, storage, and flux changes are a particular challenge to include and simulate properly in the land surface schemes of climate models, which focus mostly on atmospheric and oceanic change.

In general, the large water storage changes, and the large range in both magnitude and direction of these changes, as implied by the highly differing water flux results of many climate models (evident from Figures S1 and S2) indicate that there are problems with the process representations related to the freshwater balance over land in the climate models. The least unrealistic model implications in terms of net water balances are surprisingly obtained for the Arctic, where climate changes are particularly large and fast [*Christensen et al*., 2007] and climate modeling has been pointed out as particularly challenging [*Kattsov et al*., 2005], also with specific regard to the freshwater system on land [*Bring and Destouni*, 2011, 2013].

The superior performance of temperature over water flux projections applies also for historic model-observation comparison, in particular for the long-term 1961–1990 average (Figures 2a and 3a–d, individual model results in Figure S1). For the water fluxes (Figure 3), and in relative terms also for the temperature change (Figure 2b), model results are particularly problematic for the warm temperate basins studied here. Also intermodel variability of runoff (Figure 1) and additionally model-observation differences in runoff and/or evapotranspiration (Figure 3) are largest for the warm temperate Greece and Sava River basins. However, this study shows that runoff is here rather underestimated, in contrast to earlier findings for tropical basins [*Siam et al*., 2013]. In comparison, corresponding results are in our study similar for mid-latitude regions as for the fast changing and expected particularly challenging Arctic [*Kattsov et al*., 2005; *Christensen et al*., 2007], although definitions of the Arctic may vary between previous Arctic studies and ours, as we here address entire river basins draining into the Arctic Ocean.

Particularly large model overestimation of actual evapotranspiration is found for Greece (Figure 3c), and this is the main reason for the extreme Greek model-implied $\Delta S$ results (Figures 1 and 3d). This large overestimation indicates that the sea surrounding Greece overshadows the freshwater system on land and dominates the water-related representations in climate models for this area. Insufficient resolution is a well-known contributor to limited ability of resolving water fluxes in areas with complex topography [*Arakawa*, 2004; *Christensen et al*., 2007; *Stevens and Bony*, 2013; *Palazzi et al*., 2015], and a similar factor may contribute to the effect we see here for Greece, e.g. through climate model inability to resolve atmospheric moisture flux patterns along the long coastline, as also previously indicated for Africa [*Siam et al*., 2013]. Nevertheless, this mixing of water systems on land and in the sea represents a particular challenge to solve in climate modeling, both for arriving at accurate GCM output for freshwater and for practically using such output for freshwater management and adaptation in peninsular drainage basins.

For some basins, the correction factors that we included to account for potential biases in observed precipitation improve the agreement between observations and projections for $P$ and $ET = P - R$. However, for

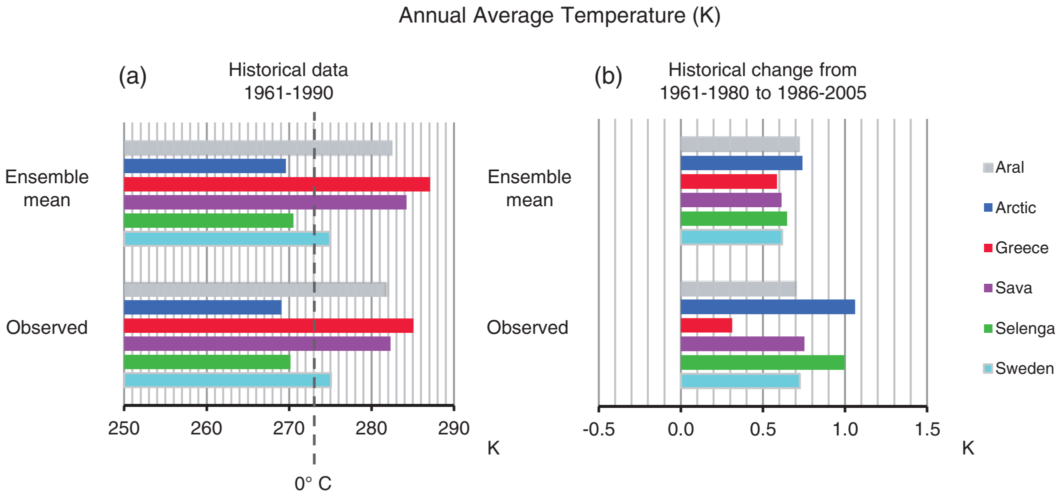

**Figure 2.** Annual average temperature. Historical annual average temperature (a) and temperature change (b) for six Northern Hemisphere drainage basin regions, from CMIP5 multimodel ensemble results and observation data.

other basins, no improvement is evident. In general, therefore, it is likely that some part of the limited agreement between models and observations for these parameters is due to errors in measurements, but it is difficult to discern to which extent. Naturally, as the corrections only apply to precipitation observations, they do not affect or improve the net water-balance problems implied by the climate models (Figures 1 and 3d).

In general, poor model-observation consistency for freshwater fluxes on land, along with unrealistic water storage (and thereby level) changes implied by the climate model results for basin-average water balance are found for basins of very different scales, with no correction strategy for precipitation observations systematically improving the physical realism of these model results and implications. These climate model problems in relation to the freshwater system over drainage basins are thus not simply related only to downscaling and data interpretation issues, although such issues may also apply to some of the regions. Nor do they reflect a new problem in the climate model evolution, as the large-scale CMIP5 model behavior is similar to that of the previous climate model generation [*Knutti and Sedláček*, 2013]. Instead, they indicate more fundamental problems with driver-process representation and resolution of the basin-scale freshwater system in the climate models.

For the mid- and high-latitude basins in our study, the model ensemble implication for long-term average net water balance is a systematic long-term increase of water storage, which also holds for most individual models. For the warm temperate areas, in contrast, the model implication for the long-term average net water balance is overall a systematic continuous loss of water from the basins, although the spread among individual models is wider for these regions. This indicates a potentially different bias in the model representation of freshwater fluxes between these two climate regions.

Although we are not aware of any earlier studies explicitly investigating the freshwater balance implied by CMIP5 models over drainage basins, some results for a 11-model subset over the Upper Blue Nile and Congo basins are possible to infer from *Siam et al*. [2013, Table 6]. Calculating the net annual water balance from their reported values yields $\Delta S$ of $-14.9$ and $-3.0$ mm yr$^{-1}$ for the Upper Blue Nile and Congo basins, respectively. These numbers are relatively small in comparison with the large rainfall amount in the region, and may indicate that water balance is more correctly simulated for tropical basins. However, their model sample is smaller than for our study, and due to rounding effects in their table, these values represent a lower bound.

In a recent study, *Mueller and Seneviratne* [2013] found systematic general overestimation of land evapotranspiration in the CMIP5 ensemble over most of the globe when compared with a synthesis observation product for the period 1989–1995. For the investigated regions, precipitation was generally also overestimated, and slightly more so than *ET*, so that these biases combined may contribute to the model-implied excess water we see here for the mid- and high-latitude basins. For the warm temperate basins with negative

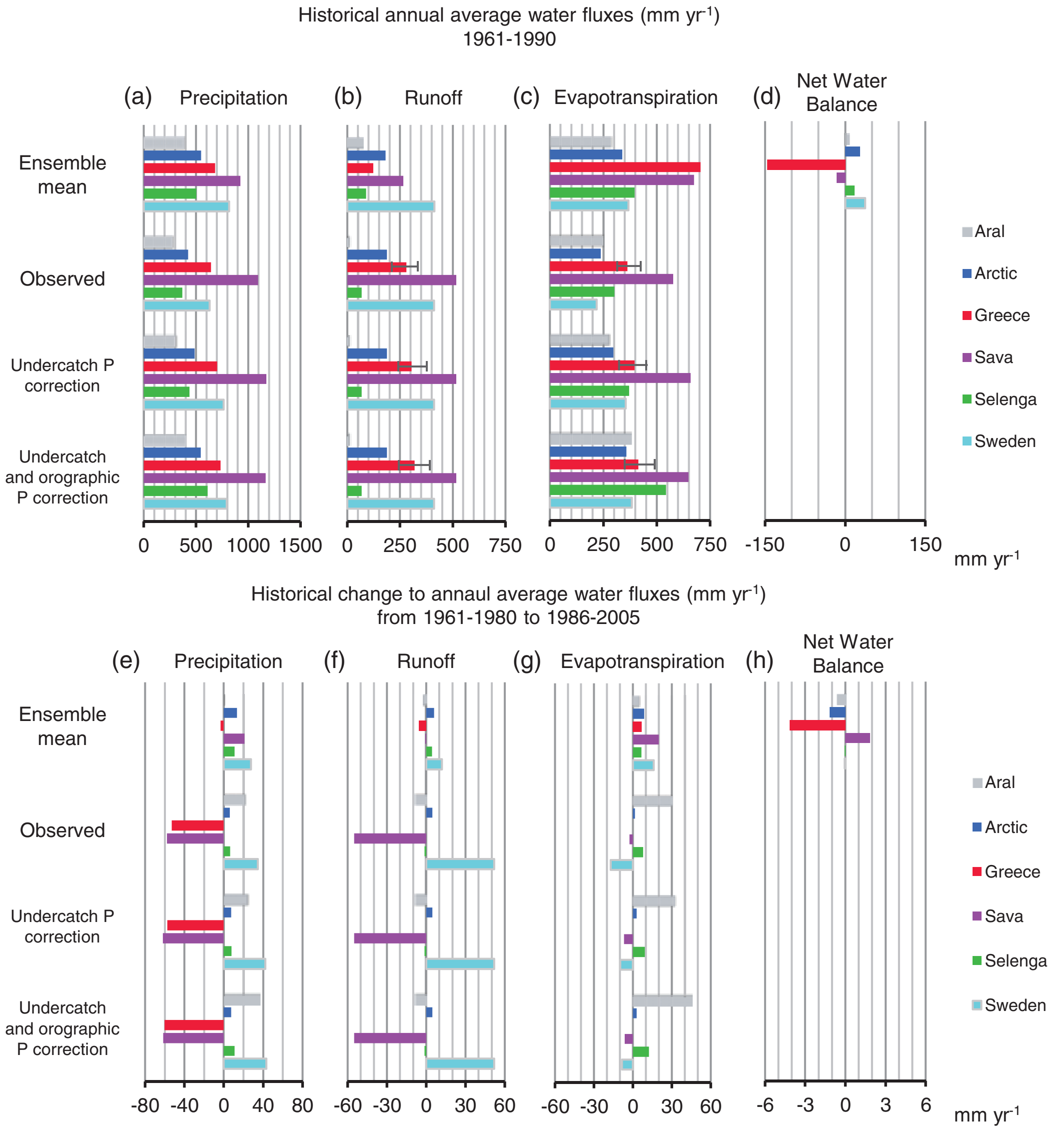

**Figure 3.** Historical annual average water fluxes. Historical annual average water fluxes (a–d) and water flux changes (e–h) for six Northern Hemisphere drainage basin regions, for CMIP5 multimodel ensemble results and observation data (the latter of direct and corrected precipitation data, with correction implications also propagated further to evapotranspiration). *Greek *ET* and *R* estimates are based on a set of smaller basins with relevant openly reported data within the larger Greek basin (see Supporting Methods), with error bars denoting maximum and minimum values of *ET* estimates and associated runoff values based on that data. In (f, g), no observed *R* or *ET* changes for Greece are shown due to the hydrological data limitations.

water balances, a large overestimation of evapotranspiration in models may in the same way contribute to our model-implied water-balance findings for these basins. However, this study also shows a consistent model overestimation of runoff for the basins with model-implied excess water, except for the Arctic, and runoff underestimation for basins where the model-implied net water balance is negative. Resolving the link and partitioning of water fluxes among these components, and their relative contributing weight to climate model biases with regard to net freshwater balance on land, requires further, detailed investigations for the individual study regions.

Although other studies have evaluated the CMIP5 performance over the Arctic [*Bintanja and van der Linden*, 2013; *Koenigk et al*., 2013], no studies have so far constrained this evaluation to drainage basins and addressed a set of multiple such basins across the Arctic. Also for other regions, more detailed investigations are motivated on drainage basin scales. A specific topic of investigation in further studies should be to directly evaluate the process representation and realism of the land surface schemes of global climate modes with regard to the freshwater system and its fluxes, comparing different model parameterizations, resolutions, and process representation approaches.

## 4. Conclusions

This study has highlighted a number of complexities with regard to the CMIP5 model representation of the surface-integrated exchanges of freshwater between land and the atmosphere and land and the sea. This has been achieved by investigating freshwater flux variables and their water-balance implications on drainage basin scales for a set of different regional drainage basins. In particular, this study is the first to explicitly evaluate drainage basin-constrained water balances for several basins, which for model ensemble means and a number of individual climate models are not realistic over the basins and regions of study.

Over the spatial scales we study here ($\sim 10^6 - 10^7$ km$^2$), we find no indication that scale is a crucial factor in the CMIP5 model performance for freshwater fluxes over hydrological drainage basins. This points to a potential limited effect of downscaling approaches in obtaining correct physically based representations of the freshwater fluxes and their change drivers on land, as the boundary conditions given by global climate models would then not necessarily be more reliable for larger than for smaller scales. Our results are also in line with previous indications that actual model resolution in a CMIP5 subset does not influence the ability to simulate annual-scale water fluxes [*Siam et al*., 2013]. Instead, the range in the deviations of freshwater-related climate model output from corresponding observations seem associated with other factors that may be specific to the present basins of study. For instance, high-latitude basins, both small and large, show positive water balances and a general overestimation of precipitation compared with observations.

The model-projected above-zero water balance for these regions is somewhat difficult to reconcile with observations of decreasing soil moisture in the Arctic [*Hinzman et al*., 2013] and in Swedish basins with increasing precipitation [*Destouni and Verrot*, 2014; *Verrot and Destouni*, 2015]. The positive flux into storage we find would rather suggest that soil moisture should be increasing with water accumulating in the basins. On the other hand, the model-implied water changes in this study show that net water balances have decreased over the historical period (Figure 3), indicating that models may still be capturing such drying tendencies. Establishing which climate models that are most adequate and which freshwater-related processes that are most reliably simulated for the high latitudes will require more detailed study over the major Arctic drainage basins, preferably also using opportunities of high observational availability [*Karlsson et al*., 2011].

Overall, the large intermodel span in modeled freshwater fluxes and model-implied net annual freshwater balance emphasizes the need for caution when using individual, or just a few, climate model results for assessing ongoing and future freshwater changes. The results for individual models (Figures S1, S2, and S4) can be more closely inspected with the aim to identify best-performance models with respect to freshwater changes for the different regions. However, caution must still be used in model choices, as reliable projections do not necessarily follow out of good alignment with historical observations.

Overall, it is difficult to find models that perform consistently well for temperature as well as for all relevant freshwater variables. Considering the large impacts of freshwater changes on human societies and ecosystems, the model-observation comparison results of this study call for further, concerted research and development of climate and Earth System models, focused on improving the understanding, and the model representation, resolution, and projection of changes to the freshwater system and their key drivers. In particular, we see the need of more detailed drainage basin studies that investigate the freshwater flux processes under the physical water-balance constrains implied by actual basin observations. This focus is important as global climate models are and will continue to be used to inform basin-scale planning and adaptation for water resources, the impacts on which are among the most critical of climate change on human society.

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