AGU PUBLICATIONS

Geophysical Research Letters

RESEARCH LETTER
10.1002/2017GL074884

Key Point:
- Reanalysis soil moisture additions resemble spatial and temporal irrigation patterns

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Citation:
Tuinenburg, O. A., & de Vries, J. P. R. (2017). Irrigation patterns resemble ERA-Interim reanalysis soil moisture additions. *Geophysical Research Letters*, *44*, 10,341–10,348. https://doi.org/10.1002/2017GL074884

Received 14 FEB 2017
Accepted 9 SEP 2017
Accepted article online 14 SEP 2017
Published online 18 OCT 2017

Irrigation Patterns Resemble ERA-Interim Reanalysis Soil Moisture Additions

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Abstract Irrigation modulates the water cycle by making water available for plants, increasing transpiration and atmospheric humidity, while decreasing temperatures due to the energy that is needed for evaporation. Irrigation is usually not included in atmospheric reanalysis systems, but moisture can be added to the soil due to data assimilation. This paper compares these soil moisture additions to the irrigation patterns. In the ERA-interim atmospheric reanalysis, 2 m temperature observations are assimilated. A mismatch between modeled and observed temperatures is corrected by adding or removing moisture from the soil. These corrections show a clear pattern of mean soil moisture additions in many areas. To determine the cause of these increments, the spatial and temporal patterns of these soil moisture increments are compared to irrigation water demand and precipitation bias. In irrigated areas, the annual means and cycles of soil moisture increments correlate well with irrigation, and less with precipitation bias. Therefore, in irrigated areas, the soil moisture increments are more likely caused by irrigation than by the precipitation bias. In nonirrigated areas, a weak statistical relation between soil moisture increments and precipitation bias is present. Irrigation is currently not included in reanalysis systems. However, as irrigation indirectly influences the water balance in atmospheric reanalysis systems, we recommend to include this process in reanalysis models. Moreover, the influence of irrigation on the local and regional atmosphere should be taken into account when interpreting atmospheric data over strongly irrigated areas.

Plain Language Summary Irrigation makes water available for crops, increasing crop production. However, almost all of this water will enter the atmosphere through transpiration, making the atmosphere cooler and more humid. Irrigation is usually not included in the state-of-the-art atmospheric modeling systems. This research found that these modeling systems internally add moisture in the locations and the times of year that irrigation is applied in the real world. This is done to keep the atmospheric model in agreement with real-world temperature observations. Therefore, we conclude that as irrigation significantly impacts the atmosphere, it is clearer to explicitly include irrigation in these models.

1. Introduction

The current and historical state of the atmosphere is of interest for diverse applications, ranging from the hydrology to transportation and energy sectors. The best estimate of this atmospheric state is acquired by analyzing current and historical observations. However, observations are not available for all locations and variables of interest, especially going further back in time.

Reanalysis is a commonly used technique to solve this issue of the lack of observations, by assimilating available observations into an atmospheric model and to use the model to determine the state of the atmosphere where observations are unavailable. During each time step, the atmospheric model is nudged toward the observations that are available at that time and location (Dee et al., 2011). For example, if the model is too dry compared to the observations, moisture is added to the model in the reanalysis process. This procedure has the advantage that a best estimate of the state of the atmosphere is acquired globally, even in locations where no observations are available. However, a drawback is that due to the nudging (the analysis term), moisture is added to or removed from the system and the atmospheric budgets may not be conserved.

Atmospheric predictions have improved during the last decades (Bauer et al., 2015; Magnusson & Källén, 2013; Simmons & Hollingsworth, 2002). However, the modeling of the complex and chaotic interactions between the Earth system components is a very difficult task, and imperfections remain in atmospheric models. Uncertainties in the physics of the atmospheric models (the radiation, convection, interaction with the land surface, etc.) are either due to an incorrect representation or the absence of a process in the model. This can be due to a lack of fundamental knowledge about this process or the inability to resolve processes at the spatial and temporal resolutions of the modeling system.

Irrigation, the human-induced provision of water to crops, is applied to many agricultural areas around the world and is essential for the global food production, by providing better crop growth conditions and higher average yields (Siebert et al., 2005; Portmann et al., 2010). Globally 273.7 million hectares or 18% of the cultivated land is irrigated, producing 40% of the global yield (Siebert et al., 2005). Large-scale irrigation changes hydrological interactions (Tuinenburg et al., 2014) and is estimated to have increased evapotranspiration by 2.8% and decreased discharge by 5.0% (Rost et al., 2008). Irrigation affects water vapor feedbacks through latent heat transport, atmospheric water content, cloud formation, surface temperature, and precipitation.

Irrigation is not routinely taken into account in atmospheric models. However, some studies have implemented irrigation in the land surface compartments of climate models (e.g., De Rosnay et al., 2003; Leng et al., 2013, 2004) and generally found a cooling and moistening effect (Klein et al., 2006; Lobell et al., 2009; Sacks et al., 2009; Tuinenburg et al., 2014), possibly leading to better operational forecasts (Ozdogan et al., 2010). Cooler and moister atmospheric conditions could also affect precipitation, depending on the interaction between land surface, atmospheric boundary layer, and clouds (Qian et al., 2013; Santanello et al., 2013; Tuinenburg et al., 2011) or on the parametrization of irrigation in the model (Lawston et al., 2015).

ERA-interim (Dee et al., 2011) is an example of a reanalysis system with model physics that do not account for irrigation. In the ERA-interim land surface analysis, if there is a difference between 2 m temperature observations and model state, moisture is uniformly added to or removed from the root zone (first three layers) of the soil. This soil moisture analysis term is not distributed randomly around the world's land masses. In some areas, moisture is systematically added to the soil, while in other areas it is systematically removed. This could be due to a systematic error in other components of the atmospheric model. For example, if the model overestimates precipitation, the soil will be wetter than the observations and soil moisture will be removed by the reanalysis system.

In effect, this makes soil moisture a model state variable that absorbs errors from other model components, making it harder to compare the soil moisture state to actual observations. Therefore, this paper intends to determine whether the reanalysis soil moisture analysis term in ERA-interim is statistically related either to the irrigation physics missing in the model or the precipitation bias produced by the model. By analyzing a possible relevant factor for simulating the Earth system, this study aims to determine whether reanalysis systems can be improved by explicitly including irrigation. Furthermore, this study may improve the understanding of the impact of irrigation on regional climate, which can be important for local and regional atmospheric and hydrological modeling.

2. Methods

This analysis uses different reanalysis, precipitation, and irrigation data sets. The ERA-interim (Dee et al., 2011) (1990–2014) soil moisture analysis term is determined globally by comparing the 12 h soil moisture forecast and the next run soil moisture initialization (0 h forecast). The difference between these soil moisture states is due to the data assimilation. The analysis term of soil moisture of the uniform root zone (first three soil layers, 0–100 cm) depends on the difference between screen level analyzed and model state (first guess) temperatures, with correction factors for radiative and mountainous conditions (for orography above 500 m, the analysis term is linearly reduced until 300 m, above which the analysis term is zero). The analyzed screen level temperature depends on SYNOP observations of screen level temperature (European Centre for Medium-Range Weather Forecasts, 2007). If the model is warmer than the analyzed temperature, moisture is added to the soil layers in order to increase evapotranspiration and decrease the screen level temperature. If the model state is cooler than the analyzed temperature, moisture is removed from the soil to decrease evapotranspiration and increase temperatures.

The total soil moisture in the top three soil layers is used in the analysis, reflecting the layers directly impacted by the soil moisture analysis. This data set is aggregated into monthly sums. Based on these monthly values, the soil moisture variability is used to determine the relative importance of reanalysis corrections.

Second, the global map of areas irrigated areas (Siebert et al., 2005) is used. It depicts the percentage of each 5 arc min grid cell equipped for irrigation in the year 2000, based on subnational irrigation statistics.

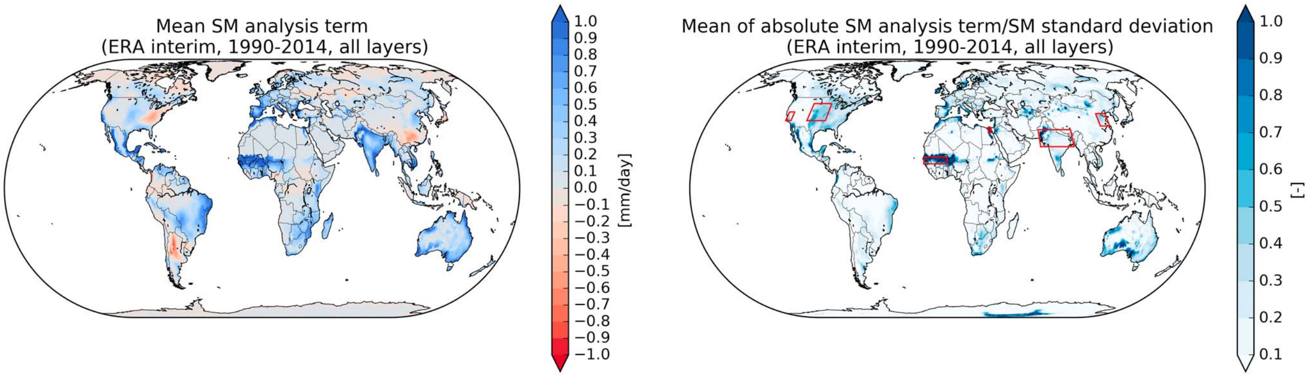

Figure 1. (left) Annual mean (1990–2014) of ERA-interim soil moisture analysis term in the top three soil layers. (right) Annual mean of ERA-interim absolute soil moisture analysis term (i.e., moisture that is added to or removed from the soil by the reanalysis system) divided by the soil moisture standard deviation, based on monthly data, for the top three soil layers. The regions that are analyzed in more detail in section 3.4 are shown in red (Figure 1, right).

Third, the monthly variations in irrigation water demand extracted from other water bodies (blue water demand) are based on Siebert and Döll (2010), who simulated the crop water demand using a global crop water model (GWCM) on 5 arc min spatial resolution. This irrigation water demand simulation provides a mean annual cycle over the period 1998–2002 and is based on monthly crop growing areas around the year 2000 provided by the MIRCA2000 global land use data set (Portmann et al., 2010), which is based on the map of irrigated areas (Siebert et al., 2005).

Finally, the ERA-interim precipitation bias with respect to the station-based observed Global Precipitation Climatology Centre (GPCC) version 7 (0.5°) precipitation (Schneider et al., 2015) is determined for the period 1990–2014 and aggregated to monthly values.

All data sets were regridded to the ERA-interim ($0.75 \times 0.75°$) grid. The Pearson correlation between the mean annual cycles of irrigation water demand and the soil moisture analysis term is determined and accepted if the probability of correlation is larger than 95%. The same procedure is performed for the correlation between the mean annual cycles of precipitation bias and the soil moisture analysis term.

3. Results

This section presents the annual mean ERA-interim soil moisture analysis term. This is compared to the total soil moisture variability (section 3.1), precipitation bias (section 3.2), and irrigation distribution (section 3.3). Subsequently, the annual cycles of the soil moisture analysis term and (I) blue water use of plants and (II) precipitation bias are compared (section 3.4).

3.1. ERA-Interim Soil Moisture Analysis Term

The mean annual ERA-interim soil moisture analysis terms are shown in Figure 1 (left). Positive values represent a net addition of soil moisture and occur in many areas. The highest positive values of 1.0 mm/d or more are in West Africa, Mexico, Morocco, Pakistan, and Egypt, although minor additions occur around the world. In some areas, notably southeast China, northern Argentina, and the eastern U.S., the soil moisture analysis term is negative, so moisture is removed from the soil. Figure 1 (right) shows the analysis term relative to the temporal soil moisture variability in the model. Analysis terms account for more than the natural soil moisture variation in the areas where the largest additions occur and for 20–30% in many other areas. For the soil layer, which is the most important one for the climate system, these values are even larger (not shown).

3.2. Precipitation Bias

A possible explanation of the structural soil moisture analysis terms is a bias in ERA-interim precipitation. If the model underestimates precipitation, the modeled soil will be drier than the soil will be in reality. In this case, any 2 m temperature observations that are assimilated into the reanalysis system will be colder than the model. The ERA-interim reanalysis system will respond by adding moisture to the soil that increases evapotranspiration and decreases the model 2 m temperature.

The annual mean precipitation bias of ERA-interim with respect to GPCC (Figure 2, left) is positive in the Congo Basin, central Africa, southeast Asia, and some parts of the Amazon and Andes, while it is negative in Borneo,

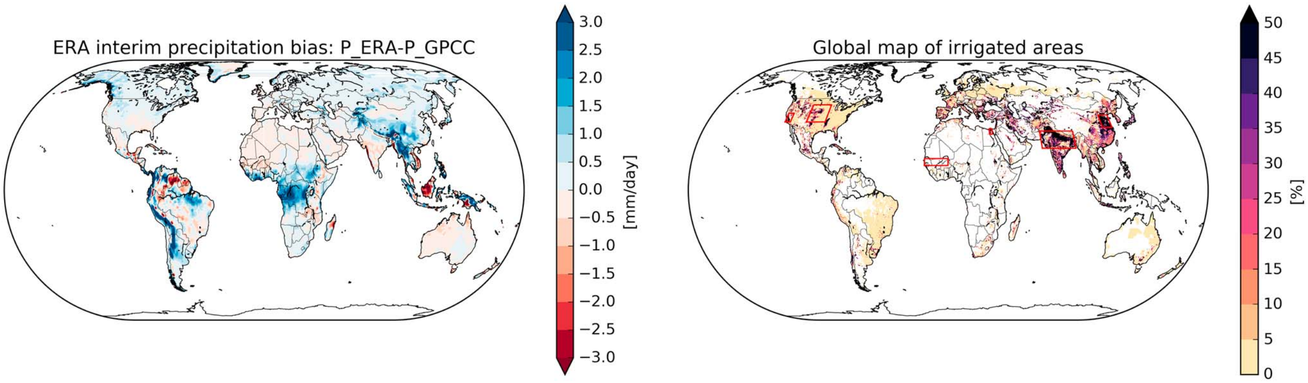

Figure 2. (left) Annual mean ERA-interim precipitation bias, compared to GPCC for 1990–2014. (right) Global map of irrigated areas (Siebert et al., 2005); percent of grid cell equipped for irrigation. The regions that are analyzed in more detail in section 3.4 are shown in red (Figure 2, right).

Vietnam, East Africa, and the Northern Amazon. As GPCC is an interpolation between station observations, the actual precipitation is uncertain due to the low gauge density in many of these areas. In temperate regions, the absolute precipitation biases are lower.

Generally, in regions with a significant precipitation bias, the soil moisture is modified in the opposite direction to correct for the bias.

3.3. Irrigation

Irrigation is another explanation for soil moisture additions in the analysis system. Figure 2 (right) shows the fractional area equipped for irrigation (Siebert et al., 2005). The highest values are found in areas where agriculture is water limited, such as India, Pakistan, Egypt, northeast China, and California. Little or no irrigation occurs in most of Africa, arid and mountainous regions, the Arctic, and the Amazon region.

This pattern is similar to the ERA-interim soil moisture addition (Figure 1); The Nile Valley in Egypt and Indus Valley in Pakistan are both very heavily irrigated, and many other heavily irrigated regions like India, northeast China, the Californian Valley, and the Great Plains in the U.S., the Mediterranean Basin and Central Asia have significant soil moisture additions. Less irrigation occurs in Mexico, Latin America, southeastern Africa, and Australia while soil moisture additions are present.

3.4. Annual Cycles

The correlations between the annual cycles of soil moisture corrections and precipitation bias (Figure 3, left column) and blue water demand (Figure 3, right column) are calculated globally, based on monthly data. The correlation with the precipitation bias is mostly negative, except in the western Amazon. The U.S. Great Plains, the Andes, and some areas in central Africa and the Sahel have a statistically significant negative correlation. The correlation of the soil moisture analysis term with irrigation (blue water demand) is positive almost

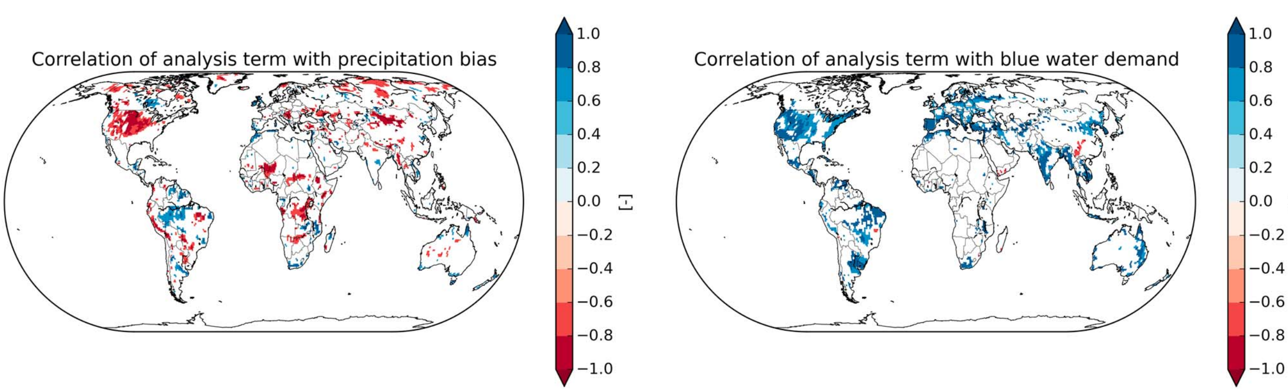

Figure 3. (left) Correlation of mean annual cycles of soil moisture analysis term (i.e. moisture that is added to or removed from the soil by the reanalysis system) and ERA-interim precipitation bias (compared to GPCC), based on monthly data. (right) Correlation of mean annual cycles of soil moisture analysis term and blue water (irrigation) demand (Siebert & Döll, 2010), based on monthly data.

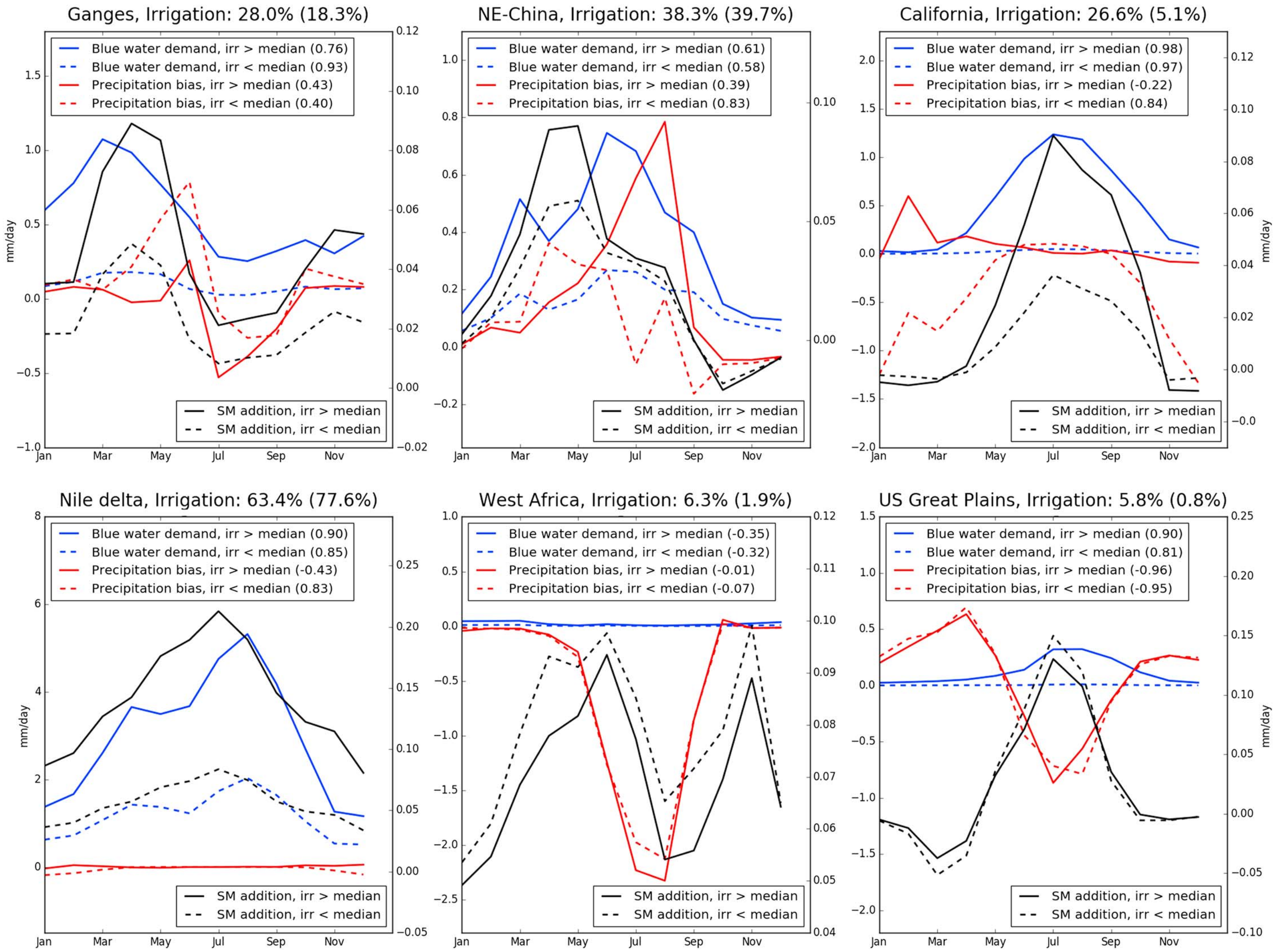

Figure 4. Mean annual cycles of precipitation bias, blue water demand (mm/d, left axes) and soil moisture analysis term (i.e., moisture that is added to or removed from the soil by the reanalysis system, mm/d, right axes) for six regions (indicated in Figures 1 and 2, with only land areas considered). For each region, the data are presented for the grid cells with irrigation smaller than the median irrigation (dashed lines) and for the grid cells with irrigation larger than the median irrigation (continuous lines). The mean and median (in parentheses) areas equipped for irrigation are indicated in the title. The correlation of soil moisture analysis terms with precipitation bias and blue water demand is indicated in the legend.

everywhere where irrigation is present. In India, the Mediterranean, northeastern China, the western U.S., Australia's east coast, and some areas in South America positive correlations are statistically significant. The negative correlation with precipitation bias and positive correlation with irrigation could both explain the soil moisture analysis terms. These are not mutually exclusive, as shown in the U.S. Great Plains. The climate model precipitation bias over the U.S. Great Plains is well known, as demonstrated by Klein et al. (2006), who found a strong warm and dry bias over the Great Plains for the summer season. However, including irrigation in climate models leads to a reduction of the warm bias over the Great Plains (Lobell et al., 2009; Sacks et al., 2009).

The annual cycles of soil moisture analysis terms, precipitation bias, and irrigation (blue water use) are compared in more detail for the Ganges Basin (21–30°N, 67–91°E), northeast China (32–39°N, 114–121°E), the Californian Valley (35–40°N, 122–118°W), the Nile Valley (28–31°N, 30–32°E), West Africa (12–15°N, 16-1°W), and the U.S. Great Plains (21–30°N, 67–91°E) (Figure 4, outlines of the areas in Figures 1 and 2). We split these regions into two parts, with irrigation intensity (GMIA) smaller and larger than the median for the given region, and show the annual cycles of both these parts to test the irrigation effect. In the strongly irrigated areas of California and the Nile Valley, correlations of soil moisture additions with irrigation are high and the precipitation bias is minimal. Moreover, the soil moisture analysis term is larger for the strongly irrigated part than for part with less irrigation. Here irrigation is likely to be causing the soil moisture addition. In other strongly irrigated areas such as the Ganges and northeast China, soil moisture additions strongly correlate with irrigation and the analysis term is larger for the strongly irrigated part, but there is a precipitation bias as well. The correlation of soil moisture addition with the precipitation bias is positive, so the precipitation bias may partially balance the lack of irrigation processes in the model.

For the U.S. Great Plains (and West Africa), the precipitation bias is larger than the irrigation water demand. Moreover, there is not much difference in the soil moisture analysis term for the strongly and weakly irrigated parts. Therefore, the soil moisture analysis terms in these areas could also be caused by the precipitation bias. For the U.S. Great Plains, subsequent analysis showed no significant differences between dry and wet years (not shown).

4. Discussion

The mean annual soil moisture analysis terms in ERA-interim have a clear and consistent pattern over the period 1990–2014, and no reduction was found after the inclusion of new observational data sets in the reanalysis system. These patterns indicate the existence of significant processes that are not yet included in the model. Some uncertainty remains about the causes of the soil moisture analysis terms. These causes could be irrigation, precipitation biases, or alternative causes, such as biases in model parameterizations that affect the water balance. These uncertainties are discussed next.

4.1. Irrigation

The distribution of irrigated areas is assessed by using the global map of areas equipped for irrigation from Siebert et al. (2005). The actual irrigated area is lower due to several reasons, and the quality of information differs per region depending on the density and reliability of the data sources.

To assess the monthly variations of irrigation, the GWCM blue water use of crops is used. These data are based on the MIRCA2000 land use data set which considers the possible difference between potential and actual irrigation (Portmann et al., 2010; Siebert & Döll, 2010). It is valid for 1998–2002, and this study assumes the same annual cycles for 1990–2014. However, irrigated areas may have increased or decreased, or the annual cycle of blue water demand may have shifted due to different cropping cycles. Moreover, because of limited accuracy of input data and process understanding, Siebert and Döll (2010) recommend not to assess this product locally but on aggregations of larger spatial units, such as countries or regions.

Mean soil moisture additions are present in most irrigated areas and are the highest during the growth seasons of plants and during the dry season in Southern Asia. As irrigation is increasing the soil moisture content, this is in line with expectations. A positive correlation between the blue water use and soil moisture addition is present in most irrigated areas, especially those with intensive irrigation or a dry climate. The heavily irrigated areas studied in more detail show similar annual cycles of soil moisture addition and blue water use, resulting in high correlations. In adjacent desert regions of the Nile Valley that have little irrigation, soil moisture additions are much smaller (not shown). These results strongly support the supposed relation between irrigation and soil moisture corrections, although the amount of moisture added to the soil is not similar to the blue water demand or precipitation bias.

However, some regions show opposite results. Some areas with little or no irrigation, notably West Africa and Mexico, have large soil moisture additions. Soil moisture is systematically removed in Southeast China, Argentina, and the eastern U.S., and the correlation between soil moisture corrections and blue water demand is negative in large parts of Southeast China. As these regions are not heavily irrigated, these divergent results are probably not caused by irrigation. The precipitation bias is not notably large in these regions, however. The explanation of these results remains therefore uncertain.

4.2. Precipitation

Another possible cause of a systematic soil moisture analysis term is a precipitation bias. In many regions, notably in West Africa and southern China, the mean annual precipitation bias corresponds to (the negative of) the mean annual soil moisture analysis term. However, the annual cycles of precipitation bias and soil moisture analysis term are not very similar. The correlation between soil moisture analysis term and precipitation is only significant in some regions. This may be due to moisture storage in other components of the large-scale hydrology that may delay the hydrological cycle. Therefore, the soil moisture is possibly altered in a different month than the precipitation bias. Moreover, in areas with a strong land-atmosphere coupling (Koster et al., 2004; Santanello et al., 2013; Tuinenburg et al., 2011), strong differences in land surface wetness could affect precipitation and including irrigation in atmospheric models could have an effect on the precipitation bias.

4.3. Other Explanations

Other factors influencing the soil moisture content, like biases in evaporation and discharge, soil conditions, and plant growth, were not analyzed. These factors potentially affect soil moisture corrections and therefore present uncertainty.

Seasonal variations in irrigation intensity, precipitation bias, and soil moisture analysis terms occur in many regions. This seasonality usually increases the correlation considered in this study. As larger seasonality increases the correlations, these may be higher in temperate regions than in the tropics.

Furthermore, an omission of irrigation or precipitation biases does not result in similar temperature biases over different soils, land covers, and atmospheric regimes.

Altogether, the results show a clear pattern of significant mean soil moisture analysis terms in many areas and a strong correlation between soil moisture additions and irrigation. The relation between soil moisture analysis terms and the precipitation bias seems to be weaker. However, these results do not imply the causality of this relation.

5. Conclusion

There is a clear pattern in the ERA-interim soil moisture analysis terms over the period 1990–2014 in many areas around the world, as well as decreases in some areas. These patterns comprise a significant part of the total soil moisture variations in the model.

In irrigated areas, these corrections are correlated to the blue water use of plants, which is a reliable indicator of irrigation. These results show a clear relation between irrigation and annual mean soil moisture additions in most regions, with larger soil moisture analysis terms for irrigated areas than for nearby nonirrigated regions. Moreover, positive correlations are found between the annual cycles of irrigation and soil moisture additions. This is especially clear in areas with intensive irrigation and little precipitation, which is where the largest effect of irrigation is expected.

The precipitation bias has a weaker resemblance to the soil moisture analysis term. In the annual mean it may explain the soil moisture additions. However, the annual cycle of precipitation bias is quite different from the soil moisture analysis term in many places.

A causal relation between irrigation and soil moisture analysis terms is not implied by this analysis. However, it is likely that this causal relation actually exists as irrigation is not implemented in the ERA-interim system but is known to influence soil moisture content and evaporation. We recommend to implement irrigation processes in reanalysis models and explicitly document the moisture additions, so that the remaining soil moisture analysis terms will be randomly distributed around zero. Furthermore, we recommend to take irrigation processes into account in interpreting atmospheric data over strongly irrigated areas as this large-scale irrigation can affect the atmosphere.

Acknowledgments
We thank the providers of the used data sets ERA-interim (http://apps.ecmwf.int/datasets/data/interim-mdfa/levtype=sfc/), GPCC (ftp://ftp.dwd.de/pub/data/gpcc/full_data/), and GMIA (http://www.fao.org/nr/water/aquastat/irrigationmap/index10.stm) for making them freely available. We thank Patricia de Rosnay for discussions on early versions of the manuscript. Furthermore, we thank two reviewers for their comments and suggestions. This project has received funding from Netherlands Organization for Scientific Research under the Innovational Research Incentives Scheme VENI (grant agreement 016.171.019).

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