AGU PUBLICATIONS

Geophysical Research Letters

RESEARCH LETTER
10.1002/2015GL066929

Key Points:
- High correlation between climate oscillations and river discharge anomalies
- Strong agreement between correlation patterns in observed and modeled discharge
- High predictability in discharge for many regions based on last 110 years of data

Supporting Information:
- Figure S1
- Figure S2
- Figure S3
- Figure S4
- Figure S5
- Figure S6
- Figures S1–S6

Correspondence to:
N. Wanders,
nwanders@princeton.edu

Citation:
Wanders, N., and Y. Wada (2015), Decadal predictability of river discharge with climate oscillations over the 20th and early 21st century, *Geophys. Res. Lett.*, *42*, 10,689–10,695, doi:10.1002/2015GL066929.

Received 6 NOV 2015
Accepted 6 DEC 2015
Accepted article online 10 DEC 2015
Published online 23 DEC 2015

Decadal predictability of river discharge with climate oscillations over the 20th and early 21st century

Niko Wanders[1,2] and Yoshihide Wada[2,3,4]

[1]Department of Civil and Environmental Engineering, Princeton University, Princeton, New Jersey, USA, [2]Department of Physical Geography, Utrecht University, Utrecht, Netherlands, [3]NASA Goddard Institute for Space Studies, New York, New York, USA, [4]Center for Climate Systems Research, Columbia University, New York, New York, USA

Abstract Long-term hydrological forecasts are important to increase our resilience and preparedness to extreme hydrological events. The skill in these forecasts is still limited due to large uncertainties inherent in hydrological models and poor predictability of long-term meteorological conditions. Here we show that strong (lagged) correlations exist between four different major climate oscillation modes and modeled and observed discharge anomalies over a 100 year period. The strongest correlations are found between the El Niño–Southern Oscillation signal and river discharge anomalies all year round, while North Atlantic Oscillation and Antarctic Oscillation time series are strongly correlated with winter discharge anomalies. The correlation signal is significant for periods up to 5 years for some regions, indicating a high added value of this information for long-term hydrological forecasting. The results suggest that long-term hydrological forecasting could be significantly improved by including the climate oscillation signals and thus improve our preparedness for hydrological extremes in the near future.

1. Introduction

Extremely high and low discharge can be hazardous for society, water supply, food production, hydropower generation, and flood protection, challenging our societal resilience to extreme events [*Vörösmarty et al.*, 2010].The annual damage caused by floods and droughts combined is estimated at 100 billion U.S. dollars worldwide [*Aon Benfield*, 2014]. However, our current capability to forecast these extreme events is limited to short time periods (e.g., days or weeks). For example, the 2011/2012 devastating drought in the Horn of Africa was not predicted accurately, which delayed local food aid and other international help and aggravated the aftermath [*United Nations*, 2011]. This consequently led to an increased number of fatalities (depending on the source between 50,000 [*Associated Press*, 2013] and 260,000 [*Checchi and Courtland Robinson*, 2013]) and economical damage (e.g., crop failure and livestock losses). This drought event clearly shows the need for a forecasting system that allows for decision support systems to accurately monitor and predict hydrological extremes at a continental scale and at long time scales (e.g., intra-annual and inter-annual or decadal).

While a long-term hydrological forecast could improve our resilience and preparedness to these extreme hydrological events, our skill is still limited due to large uncertainties inherent in hydrological models and relatively low reliability of long-term predications of meteorological conditions [*Weisheimer and Palmer*, 2014]. The reliability substantially decreases as a lead time becomes longer, which prevents accurate long-term predictions of hydrological extremes. Importantly, river discharge is a dominant water supply for agriculture, industry, and drinking water for many regions of the world [*Wada and Bierkens*, 2014]. Thus, accurate long-term predictions will increase the preparedness and reduce vulnerability to prolonged periods of drought and associated water supply shortage.

Climate oscillations tend to have strong correlations to regional hydrological states and hence provide valuable additional information for long-term hydrological forecasting [*Kiladis and Diaz*, 1989]. Recent studies show that climate oscillations correlate well with annual river discharge anomalies [*Dettinger et al.*, 2000] and regional flood events [*Ward et al.*, 2010]. However, these studies mostly focus on the EL Niño-Southern Oscillation (ENSO) and the annual time scale and are limited to specific regions of the world. No study has taken into account other climate oscillations at the global scale and time lag correlations since previous studies use only relatively short periods of time to investigate the relationship between climate oscillations and river discharge anomalies.

Time lag correlation can provide valuable information to advance our capability of hydrological forecasting into intra-annual and interannual or even decadal prediction. The long-term hydrological forecast is largely influenced by the quality of the meteorological input data. However, the persistency in the hydrological conditions is not only determined by the persistence in the meteorological conditions. Additional valuable information for long-term hydrological forecasts can be derived from the climate oscillation modes and associated time lag correlations, especially when multiple indicators are combined. Up till now little is known on the correlation between river discharge anomalies and different climate oscillations.

Here we present a first global assessment that investigates the long-term correlations between climate oscillations and river discharge anomalies over the 20th and the early 21st century (1901–2010). By correlating climate indices with monthly time series of streamflow we show strong teleconnections between river discharge anomalies and climate oscillations in many regions of the world. We evaluate the correlation between four different climate oscillation indices (derived from NOAA) and observed and simulated discharges, obtained from the Global Runoff Data Center (GRDC) and a global hydrological model, respectively. We assess the uncertainty by using four climate reanalysis data sets (Princetonv3, GWSP3, WATCHv2, and WFDEI from ISI-MIP2.1 modeling framework) in combination with four different climate indices (El Niño–Southern Oscillation, North Atlantic Oscillation, Antarctic Oscillation, and Pacific Decadal Oscillation) over the period 1901–2010. We calculate the correlation between the four climate oscillation anomalies and observed and modeled monthly discharge over the same period. The level of agreement between observed and modeled discharges and their correlation with the climate oscillations is evaluated on the global scale, for the entire period and separate seasons. Finally, we investigate the lagged correlation (up to 5 years) between climate oscillations and river discharge anomalies.

2. Material and Methods

Four different climate oscillations are used and compared to observed monthly discharge anomalies that are obtained from the GRDC observation archive (total of 8962 stations). The average record length of the GRDC observations is 26 years, where the station data with at least 15 years of the record are included into the analysis. Modeled discharge anomalies are derived from a multiensemble simulation of the PCR-GLOBWB model [*Wada et al.*, 2014] that simulates global streamflow or river discharge at a grid of 0.5° by 0.5° (roughly 50 km by 50 km at the equator) over the land area excluding the Antarctica. PCR-GLOBWB has been extensively validated against observed discharge and has been used in many applications in global hydrological modeling. A median anomaly correlation of 0.67, between modeled discharge and observations, was found for PCR-GLOBWB forced with the four reanalysis forcing data sets used in this study. A more detailed validation and evaluation of PCR-GLOBWB can be found in *Wada et al.* [2014]. The simulated river discharge is obtained from the natural simulations, indicating that human influences (e.g., irrigation and reservoirs) are not included. PCR-GLOBWB has been forced with four reanalysis forcing data sets of Princetonv3, GWSP3, WATCHv2, and WFDEI from the ISI-MIP2.1 modeling framework [*Warszawski et al.*, 2014]. The forcing data are produced for the period 1901–2010 at the same spatial resolution (0.5° by 0.5°).

The four climate oscillations include El Niño–Southern Oscillation (ENSO), North Atlantic Oscillation (NAO), Antarctic Oscillation (AAO), and Pacific Decadal Oscillation (PDO). Historical time series data of the climate oscillations are obtained from the archive of the National Oceanic and Atmospheric Administration (NOAA). The correlation between the climate oscillation time series and observed and modeled discharge anomalies are evaluated over a 110 year period using equation (1). A t test is used to determine whether correlations are deemed significant. Additionally, the lagged cross correlations between climate oscillations and river discharge anomalies are calculated to identify the memory in the hydrological system. This also provides valuable information on the maximum time duration up to which climate oscillation could improve long-term hydrological forecasts.

The (lagged)-correlation (R_i) is given by

$$R_i = \frac{1}{T-1} \frac{\sum_{t=1}^{T} \left(\mathrm{CO}(t) - \overline{\mathrm{CO}}\right)\left(Q(t+i) - \overline{Q}\right)}{\sigma_{\mathrm{CO}}\sigma_Q} \tag{1}$$

where i is the correlation lag (months), T is the total length of the time series, CO is the climate oscillation indicator (e.g., ENSO), $\overline{\mathrm{CO}}$ is the average of CO, σ_{CO} is the standard deviation of CO, Q is the observed or simulated

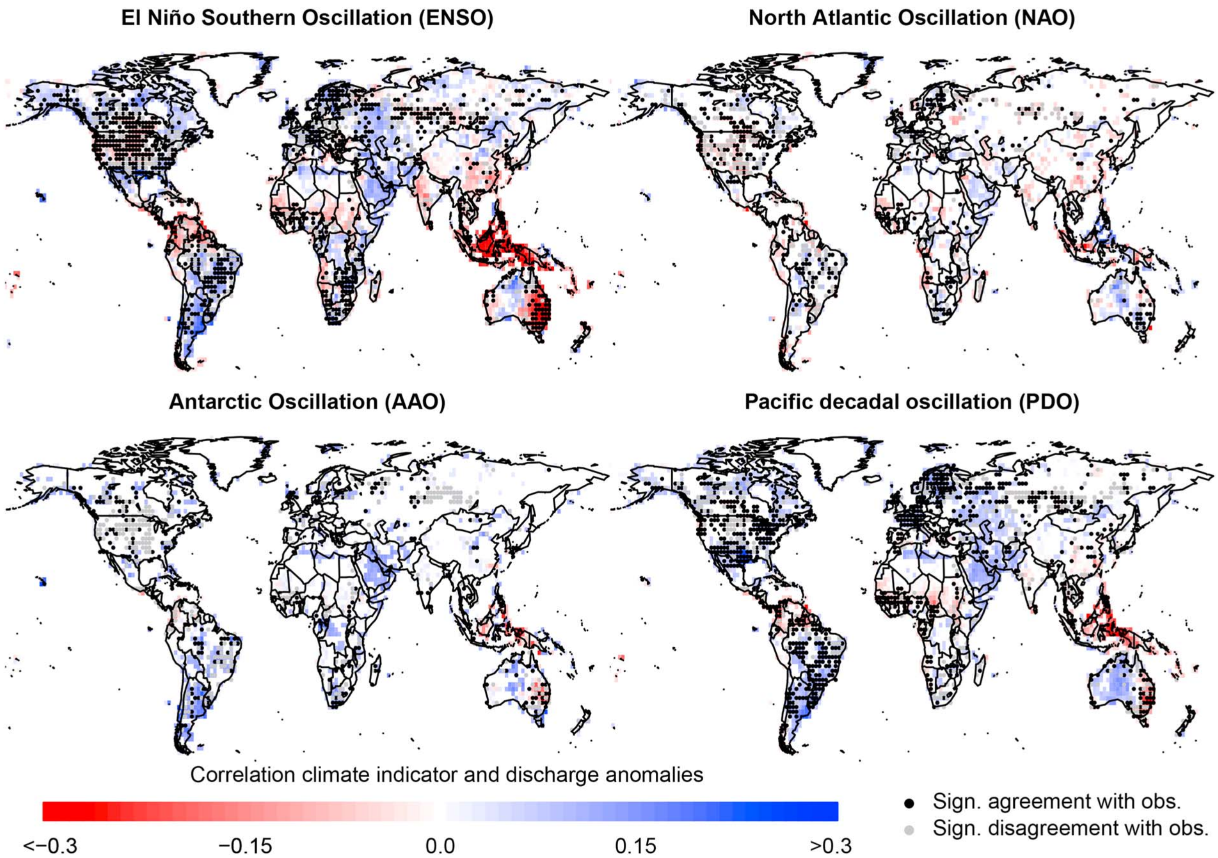

Figure 1. Annual average correlation between climate oscillation anomalies and modeled river discharge anomalies (*Rm*), overlaid by the agreement with observed discharge anomalies. Each plot provides the ensemble mean significant correlation (95% confidence level, $Rm > 0.054$) for a 100 year period, derived from four climate forcing data sets.

river discharge, and $\overline{Q}$ and σ_Q are the average and standard deviation of Q. Correlations between climate oscillations and observed discharge are given as Ro_i, and we use Rm_i for the correlation between climate oscillations and the modeled discharge.

Because seasonal impact with opposing signs can remove the year-round signal, a seasonal decomposition of the time series of both climate oscillations and river discharge is also performed. This seasonal decomposition is only performed for Rm_0, where $|Rm| = 0.2$ is seen as a weak correlation that is used as a reference level for comparison and was found by other studies as the average correlation between ENSO and river discharge anomalies [e.g., *Ward et al.*, 2010]. Results show that the median *Rm* over the different climate forcing data sets is shown in all results unless stated otherwise.

3. Results

In Figure 1, we show that ENSO has the highest correlation with observed and modeled discharge, especially in Indonesia, Western Australia, and Central and South America where the median correlation is moderate ($|Ro| > 0.22$ and $|Rm| > 0.3$), where in 69% of the locations the observed and modeled discharge correlations agree on the spatial pattern. The correlation found for NAO, AAO, and PDO is lower, and they often show a positive correlation. Especially, PDO shows positive correlations with observed and modeled discharge for the Middle East and South America ($Ro > 0.26$ and $Rm > 0.2$), which are also consistent with the observed discharge (63% spatial agreement). Similar correlation between the ENSO signal and observed discharge were found by *Ward et al.* [2010], where the tropics showed an average positive sensitivity to ENSO and the extratropical regions showed a lower sensitivity for mean annual discharge. This confirms the spatial patterns found here, although results cannot be directly compared, due to different metrics used in both studies. NAO and AAO show year-round low correlations with both modeled and observed discharge

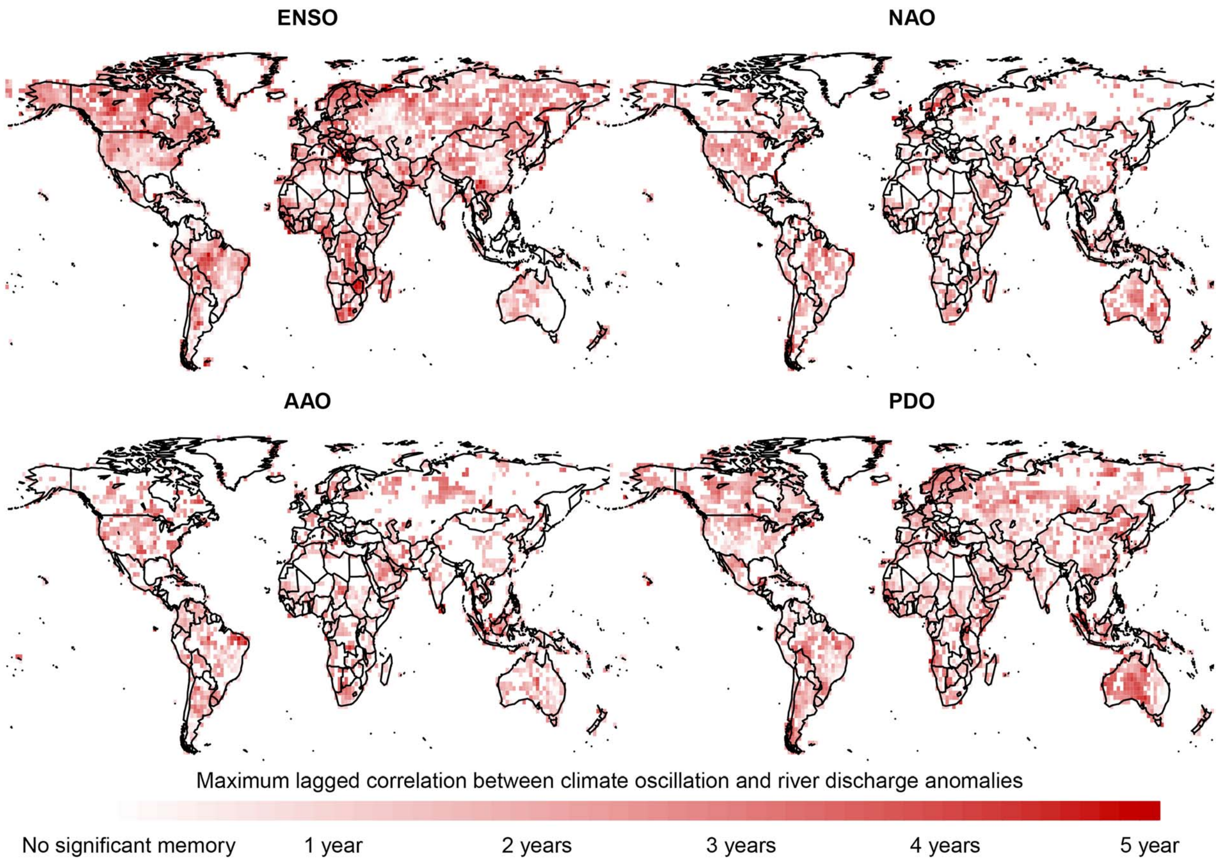

Figure 2. Maximum time up to which lagged correlation (Rm_i) is still significantly positive (95% confidence level) between climate oscillation mode and modeled river discharge anomalies.

indicating that their potential added value for forecasting systems is limited ($-0.09 < Rm < 0.16$ and $-0.1 < Ro < 0.15$). From these results it is concluded that ENSO shows the highest potential for long-term hydrological forecasting.

A spatial evaluation of the maximum significant lag time between climate oscillation time series and modeled discharge indicates that for some regions the memory in the hydrological system and its correlation with present ENSO anomalies can be over 60 months (Figure 2). Similar strong lagged correlations between climate oscillations and precipitation or temperature are not found, in general. The strongest lags were found between temperature and the ENSO signal (Figure S1 in the supporting information), while the lagged correlation for precipitation was almost absent (Figure S2). This suggests that the lagged correlation is primarily related to slow groundwater response times to climate anomalies (e.g., slow precipitation propagation to groundwater systems and subsequently to base flow). This lagged cross correlation could potentially provide us with improved insight on the forecasting ability of discharge anomalies in drought prone regions and the time that is required to recover from extreme hydrological events.

The correlations found between monthly discharge anomalies and the ENSO signal is strongest for the winter season (December-January-February, 8.9% global land area, $|Rm| > 0.2$) and lowest for the summer season (June-July-August, 3.7% global land area, $|Rm| > 0.2$, Figure 3). The seasonal patterns show significant resemblance with the year-round pattern, although the seasonal signal is more pronounced. For the NAO, AAO, and PDO similar patterns are found, where winter correlations are strong, where the global land area is with a $|Rm| > 0.2$ is 7.8%, 12.7%, and 18.5%, respectively. Detailed analysis for the other oscillation types can be found in the supporting information including the lagged correlations (Figures S3 and S4). This information implies that for long-term seasonal hydrological forecasting the climate oscillation anomalies have the highest added values in winter, while the lowest global average correlation is found for summer. These climate indicators show higher seasonal correlations with discharge anomalies than those from the ENSO

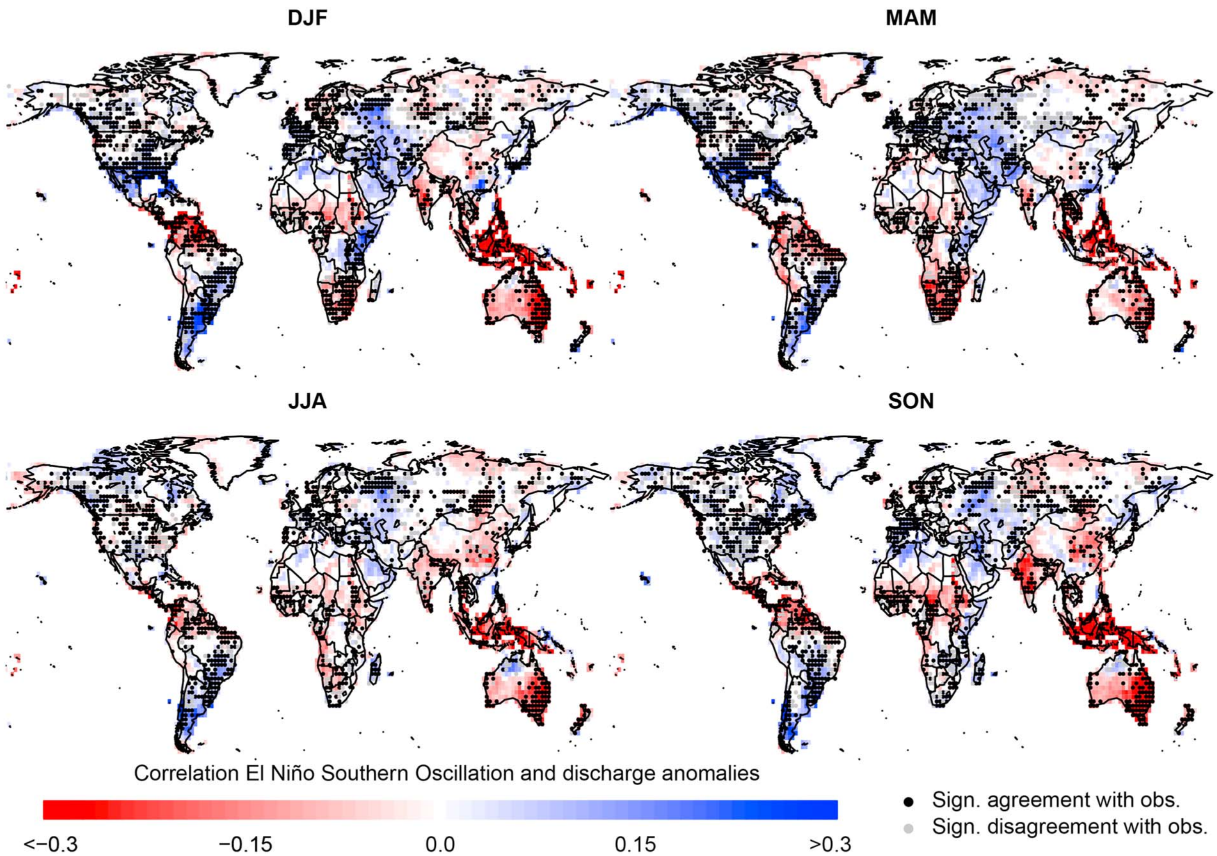

Figure 3. Seasonal correlation (*Rm*) between the ENSO oscillations and river discharge anomalies in both modeled and observed discharge. Only significant correlations are shown (95% confidence level, $Rm > 0.108$). Highest absolute correlation can be found in December-January-February for the tropical regions.

signal, indicating that although the year-round correlation for these climate oscillations is lower, their applicability for long-term hydrological forecasting is higher.

With this additional seasonal correlation between discharge anomalies and NAO, AAO, and PDO the signal is not only restricted to highly seasonal river discharge anomalies in the subtropics but also can be extended to the higher northern and southern latitudes, where NAO and AAO have a higher correlation with discharge anomalies. *Sun et al.* [2015] showed that a similar seasonal pattern can be found in the extreme precipitation effects for the northern latitudes. This seasonal dependency of both discharge and extreme precipitation extends the possible regions of interest and enhances long-term forecast quality. Since the winter season is the most dominant period of groundwater recharge in the Northern Hemisphere, it also warns for potential drought-related problems when groundwater recharge is below normal, leading to abnormally low groundwater level and higher drought vulnerability or abnormally high level leading to an increased risk of flood [*Eckhardt and Ulbrich*, 2003]. These hydrological extremes could be detected

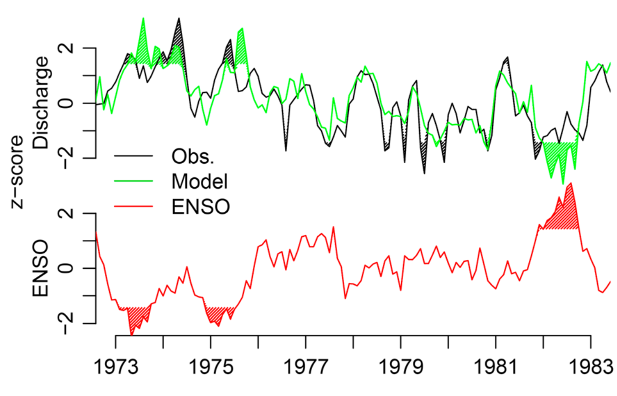

Figure 4. Example of anomalies in ENSO climate oscillations and observed and simulated river discharge for the Murray River (Australia); exceptional anomalies are indicated by shading. The correlation between modeled discharge and the ENSO climate oscillation, *Rm*, is as low as −0.46 and comparable to the correlation between observed discharge correlation, $Ro = -0.44$. Furthermore, Rm_5(correlation with a 5 month lag) is as low as −0.28, indicating substantial memory in the system.

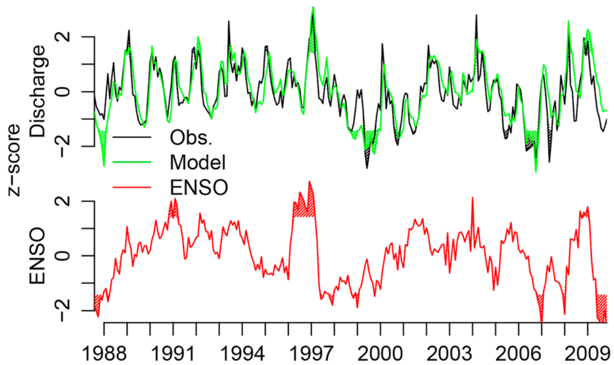

Figure 5. Example of anomalies in ENSO climate oscillations and observed and simulated river discharge for the Mississippi River (United States); exceptional anomalies are indicated by shading. The $Rm = 0.33$ and $Ro = 0.37$, indicating substantial correlation between extremes in ENSO conditions and extremes in the hydrological system.

in advance by looking at the (lagged time) correlation of climate oscillation anomalies to seasonal river discharge anomalies, increasing the lead time up to several months for summer droughts.

With respect to the different forcing reanalysis data sets, the level of agreement is high for the anomaly correlations (identical for other climate oscillations, see appendix), where the obtained patterns are almost identical to the ensemble mean year-round correlation (Figure S6). One outlier exists in the WATCHv2 data set that shows opposing signs in the anomaly correlations, especially for vast regions in Russia, where discharge anomalies are associated with the timing and quantity of the snow melt. This is a reason for concern, since most studies focus on one reanalysis data set only, thereby underestimating the uncertainty caused by the differences in these forcing data sets.

At the regional scale, the Murray Darling river basin in Australia is an area prone and vulnerable to severe flood (e.g., 2010) and drought events (e.g., 2006) [*Van Dijk et al.*, 2013]. A strong negative correlation is found between ENSO climate oscillations and the river discharge anomalies (Figure 4, $Rm = -0.46$ and $Ro = -0.44$). This example clearly shows that prolonged period with low ENSO anomalies coincide with high discharge anomalies and vice versa. Additionally, the lagged correlation between the ENSO signal and the memory in the hydrological system is found for prolonged periods of high or low discharge anomalies. A significant negative correlations are found for a period of 5 months, both Rm_5 and $Ro_5 < -0.25$, indicating that the current ENSO anomaly can increase long-term forecast quality, up to lead times of 5 months in advance over this region.

Another example where our results would provide useful information for forecasting hydrological extremes is given in the Mississippi basin, where floods (e.g., 2011) and drought events (e.g., 2012) have a severe impact on society and food production. In contrast to the previous example, the Mississippi shows a clear positive correlation with the ENSO signal (Figure 5, $Rm = 0.33$ and $Ro = 0.37$). Especially, the extreme events are well captured indicating that for both flood and drought events the added value of ENSO is high.

4. Discussion and Conclusions

Previous studies mainly focused on the relationship between ENSO and flood events, with either observations or a model simulation forced by a single reanalysis data set for short periods (e.g., 30 years). We provide the century-long multireanalysis model assessment with four climate oscillations, compared to modeled and observed discharge anomalies. We show that the climate oscillations show a strong correlation with modeled and observed global discharge anomalies with seasonal fluctuations providing additional valuable information. On the other hand, the anomaly correlation between climate oscillations and discharge can show a prolonged lag time, indicating a high potential for increasing skill in intra-annual and interannual and even decadal hydrological forecasts. By combining the (lagged) correlations of climate oscillation anomalies and hydrological simulations in a data assimilation framework, long-term hydrological forecast can be improved. This additional information on the hydrological state and the persistence in this state for some regions can be used to correct the forecasted hydrological state and hence improve our ability to forecast hydrological extremes at longer timescales. Moreover, the findings from this work provide new insight in the mechanisms that influence the onset and recovery from hydrological extremes. Forecasts of climate oscillation modes (e.g., from the U.S. Climate Prediction Centre of NOAA) could now also be used to improve the forecasting of hydrological extremes. When strong changes in climate oscillations are forecasted, this indicates the onset or recovery from an extreme event which in turn will help to increase the preparedness and reduce resulting societal disruption and economic damage.

Acknowledgments

NW is funded by NWO GO-AO/30 and NWO Rubicon 825.15.003, Y.W. is funded by JSPS 2014-878. The authors would like to acknowledge Balázs Fekete and Cédric H. David for reviewing the original manuscript and for their constructive comments. The Princetonv3, GWSP3, WATCHv2, and WFDEI will become available from the ISI-MIP2.1 archive. The hydrological model PCR-GLOBWB is an open source hydrological model that can be obtained from Utrecht University (http://www.globalhydrology.nl/models/pcr-globwb-2-0/), and the discharge observations are obtained from Global Runoff Data Centre (http://www.bafg.de/GRDC/EN/Home/homepage_node.html).

References

Aon Benfield (2014), Annual global climate and catastrophe report impact forecasting—2013. Global Catastrophe Recap report.

Associated Press (2013), Famine toll in 2011 was larger than previously reported, New York Times. Retrieved 3 May 2013.

Checchi, F. and W. Courtland Robinson (2013), Mortality among populations of southern and central Somalia affected by severe food insecurity and famine during 2010–2012, Tech. Rep. FAO/FSNAU and FEWS NET, Rome, Wash., 2 May.

Dettinger, M. D., D. R. Cayan, and G. J. McCabe (2000), Multiscale streamflow variability associated with El Niño/Southern Oscillation, in *El Niño and the Southern Oscillation—Multiscale Variability and Global and Regional Impacts*, edited by H. F. Diaz and V. Markgraf, pp. 113–147, Cambridge Univ. Press, Cambridge, U. K.

Eckhardt, K., and U. Ulbrich (2003), Potential impacts of climate change on groundwater recharge and streamflow in a central European low mountain range, *J. Hydrol.*, *284*, 244–252, doi:10.1016/j.jhydrol.2003.08.005.

Kiladis, G. N., and H. F. Diaz (1989), Global climatic anomalies associated with extremes in the Southern Oscillation, *J. Clim.*, *2*, 1069–1090.

Sun, X., B. Renard, M. Thyer, S. Westrac, and M. Lang (2015), A global analysis of the asymmetric effect of ENSO on extreme precipitation, *J. Hydrol.*, *530*, 51–65, doi:10.1016/j.jhydrol.2015.09.016.

United Nations (2011), Humanitarian requirements for the Horn of Africa drought 2011, Tech. Rep., Office for the Coordination of Humanitarian Affairs (OCHA), New York and Geneva.

Van Dijk, A. I. J. M., H. E. Beck, R. S. Crosbie, R. A. M. de Jeu, Y. Y. Liu, G. M. Podger, B. Timbal, and N. R. Viney (2013), The Millennium Drought in southeast Australia (2001–2009): Natural and human causes and implications for water resources, ecosystems, economy, and society, *Water Resour. Res.*, *49*, 1040–1057, doi:10.1002/wrcr.20123.

Vörösmarty, C. J., et al. (2010), Global threats to human water security and river biodiversity, *Nature*, *467*, 555–561, doi:10.1038/nature09440.

Wada, Y., and M. F. P. Bierkens (2014), Sustainability of global water use: Past reconstruction and future projections, *Environ. Res. Lett.*, *9*, 104003, doi:10.1088/1748-9326/9/10/104003.

Wada, Y., D. Wisser, and M. F. P. Bierkens (2014), Global modeling of withdrawal, allocation and consumptive use of surface water and groundwater resources, *Earth Syst. Dyn.*, *5*, 15–40, doi:10.5194/esd-5-15-2014.

Ward, P. J., W. Beets, L. M. Bouwer, J. C. J. H. Aerts, and H. Renssen (2010), Sensitivity of river discharge to ENSO, *Geophys. Res. Lett.*, *37*, L12402, doi:10.1029/2010GL043215

Warszawski, L., K. Frieler, V. Huber, F. Piontek, O. Serdeczny, and J. Schewe (2014), The Inter-Sectoral Impact Model Intercomparison Project (ISI–MIP): Project framework, *Proc. Natl. Acad. Sci. U.S.A.*, *111*(9), 3228–3232, doi:10.1073/pnas.1312330110.

Weisheimer, A., and T. N. Palmer (2014), On the reliability of seasonal climate forecasts, *J. R. Soc. Interface*, doi:10.1098/rsif.2013.1162.