Precipitation and floodiness

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Precipitation and Floodiness

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Key Points

- **Indices of floodiness are introduced to assess large-scale flood hazard**
- **Precipitation anomalies do not correlate well with those for floodiness**
- **A skilful seasonal precipitation forecast may not reflect flood hazard**

Abstract

There are a number of factors that lead to non-linearity between precipitation anomalies and flood hazard; this non-linearity is a pertinent issue for applications that use a precipitation forecast as a proxy for imminent flood hazard. We assessed the degree of this non-linearity for the first time using a recently developed global-scale hydrological model driven by the ERA-Interim Land precipitation reanalysis (1980-2010). We introduced new indices to assess large-scale flood hazard, or floodiness, and quantified the link between monthly precipitation, river discharge and floodiness anomalies at the global and regional scales. The results show that monthly floodiness is not well correlated with precipitation, therefore demonstrating the value of hydrometeorological systems for providing floodiness forecasts for decision-makers.

A method is described for forecasting floodiness using the Global Flood Awareness System, building a climatology of regional floodiness from which to forecast floodiness anomalies out to two weeks.

1. Introduction

An accurate forecast that informs as to whether the upcoming monsoon season is likely to see an anomaly in terms of flood frequency and magnitude could initiate valuable flood preparedness activities [*Coughlan de Perez et al.*, 2015]. However, for decision-makers whose mandate is to respond to floods across regional scales rather than at single points in a catchment, there are no indices to reflect and therefore forecast the large-scale variability in flood hazard, termed here as floodiness. In contrast, indices do exist for assessing regional storminess (e.g. storm days [*Webster et al.*, 2005]) or drought (e.g. average area covered by drought [*Hisdal and Tallaksen*, 2003]). Floodiness indices are required to determine the degree of non-linearity between precipitation, discharge and flood anomalies and therefore decide upon appropriate methods for forecasting floodiness; are meteorological systems sufficient to approximate floodiness at large-scales, or are hydrometerological forecasting systems required to forecast floodiness for end-users that operate at large-scales?

There are numerous factors that lead to non-linearity between rainfall anomalies and the frequency and magnitude of floods. These factors include storage components such as the land surface and subsurface memory (groundwater, soil moisture, snow cover), and transfer components such as the interaction between the spatial and temporal rainfall patterns and the river network configuration and the catchment concentration time (the time it takes precipitation to reach the river mouth), as well as man-made interventions such as reservoirs. Accordingly, it follows that the most extreme amount of monthly precipitation ever recorded (for example) may not correlate with the most extreme flood.

1.1. Indices for Floodiness

Whereas flood magnitude, return period or duration can be easily assessed for a single point on a river, these do not provide a measure of the flood activity across an entire region, nor does the regional index introduced by Franks et al. [2002], the purpose of which is to account for spatial correlation in gauged data for regional flood frequency estimation. Therefore an index of floodiness is required to calculate a single value that expresses the frequency, variability and magnitude of floods across a specified region during a specified time period. While there is currently no literature examining how to measure floodiness across a region, there are obvious parallels with the literatures on storminess and drought.

One of the main parallels is that the choice of such an index is not a simple one. A multitude of indices exist for both drought [*Lloyd-Hughes*, 2013] and storminess [*Bärring and Fortuniak*, 2009] in reflection of the quantity being assessed (e.g. meteorological / hydrological drought or pressure / wind speed) and also, for droughts in particular, to represent the range of different drought impacts [*Fundel et al.*, 2013; *Lloyd-Hughes*, 2013]. Indices of storminess and drought also need to reflect intensity, duration, location and frequency [*Bärring and Fortuniak*, 2009; *Lloyd-Hughes*, 2013].

Floods similarly exhibit different intensity, duration and frequency characteristics that will equate to 'impact' for different end-users. For example, the most intense floods (greater inundation extents and flood depths) will affect more people and property, but it is the longer duration floods that may lead to higher business interruption losses for the insurance industry (e.g. 2011 Thailand floods [*Gale and Saunders*, 2013]).

For both storms and droughts a threshold is often used to define the event. Hydrological or streamflow droughts are usually characterised by indices that measure the duration, severity and magnitude (combination of severity and duration) for which an assigned runoff threshold has been exceeded [*Fundel et al.*, 2013]. Some storminess indices also take threshold-based approaches, for example calculating the number of times that a pressure threshold has been exceeded in a given year [*Bärring*, 2004; *Allan et al.*, 2009], or calculating the number of storm days, as defined by a wind speed threshold [*Fischer-Bruns et al.*, 2005].

These thresholds can also be applied over areas rather than at just a single point. For storms, the occurrence within a defined region can be quantified, such as the number of tropical cyclones per year in the North Atlantic [*Holland and Webster*, 2007]. Areal Drought Indices can take into account whether the runoff of a grid cell has exceeded a given drought threshold; and using the value for each gridcell, the mean annual drought area can be calculated as the average daily total area in drought [*Tallaksen and Stahl*, 2014] or by assessing the volume deficit for each grid cell in a given time period [*Hisdal and Tallaksen*, 2003].

In practice, different sectors will have different definitions of a flood, accordingly, different floodiness indices may eventually be required. This study provides a starting-point for a discussion on assessing floodiness, based on simulations of the Global Flood Awareness System [*Alfieri et al.*, 2013], an operational global-scale flood forecasting system.

The aim of this paper is to determine whether there is a requirement to forecast floodiness rather than using precipitation (e.g. total monthly or seasonal precipitation) or discharge variables as a proxy for potential flood activity. This aim will be met through the following objectives:

1. Derivation of directly comparable precipitation and river flow time-series, so as not to introduce uncertainty into the analysis by using observations / modelled data from different sources.
2. Discussion as to how floodiness should be assessed, and creation of such indices.

3. Quantification of the link between the time series of precipitation, discharge and floodiness

2. Methodology

2.1. Model Set-Up

The determination of the necessary forecasting systems to forecast floodiness requires an investigation into the relationship between precipitation, discharge and floodiness over time. For such an investigation it is important to isolate the effect of non-linearity in the hydro-meteorological system from the uncertainties of using non-homogenous precipitation and river flow data. In particular, though global flood datasets exist [e.g. *Adhikari et al.*, 2010], data on river flow, inundation and flood disasters are particularly sparse and also affected by reporting bias [*Kron et al.*, 2012] as well as the flows themselves being influenced by human intervention such as dams and land-use change. Here, a hydro-meteorological model is driven with a precipitation dataset, therefore any variability in correlation between modelled (naturalised) flows and precipitation is driven solely by the influence of spatial patterns in precipitation and the hydrological system.

A hydro-meteorological model covering a large spatial domain and able to run over a long time period is required to assess floodiness at scales larger than the (average) river catchment size. For this paper, the integrated hydro-meteorological forecasting chain of the operational Global Flood Awareness System [*Alfieri et al.*, 2013] is used. This system's structure links the HTESSEL land surface module [*Balsamo et al.*, 2014] of the European Centre for Medium-Range Weather Forecasts' Integrated Forecasting System (IFS) to a one-dimensional channel routing model [*Van Der Knijff et al.*, 2010]. This system therefore simulates hydrological and cryospheric processes in the land surface module, with the resultant runoff routed by the routing model to provide daily river discharge estimates at 0.1 degree resolution, equivalent to ~10km at midlatitudes.

The precipitation dataset used to drive the hydro-meteorological model is the ERA-Interim dataset [*Dee et al.*, 2011], bias-corrected using the Global Precipitation Climatology Project [*Huffman et al.*, 2009] creating the so called ERA-Interim Land dataset [*Balsamo et al.*, 2015]. ERA-Interim uses the IFS forecast model to extrapolate to where observations are unavailable, giving a gridded precipitation product at approximately 80km horizontal resolution. Though the precipitation resolution is coarser than that of the runoff modelling, high resolution in runoff prediction is of great importance, even when the precipitation is of coarser scale [*Wood et al.*, 2011]. The land surface is an integrator of precipitation, and also provides moderating processes of rainfall runoff partitioning based on land use and cover, soil and vegetation properties, slope and many other catchment factors. Here, the time period used from the ERA-Interim Land dataset is 1980 to 2010. The analyses have been performed at the global scale and within climatic regions as defined by Giorgi and Francisco [2000]: those used commonly in the climate literature and for seasonal forecasting [e.g. *Weisheimer and Palmer*, 2014], see Figure 1.

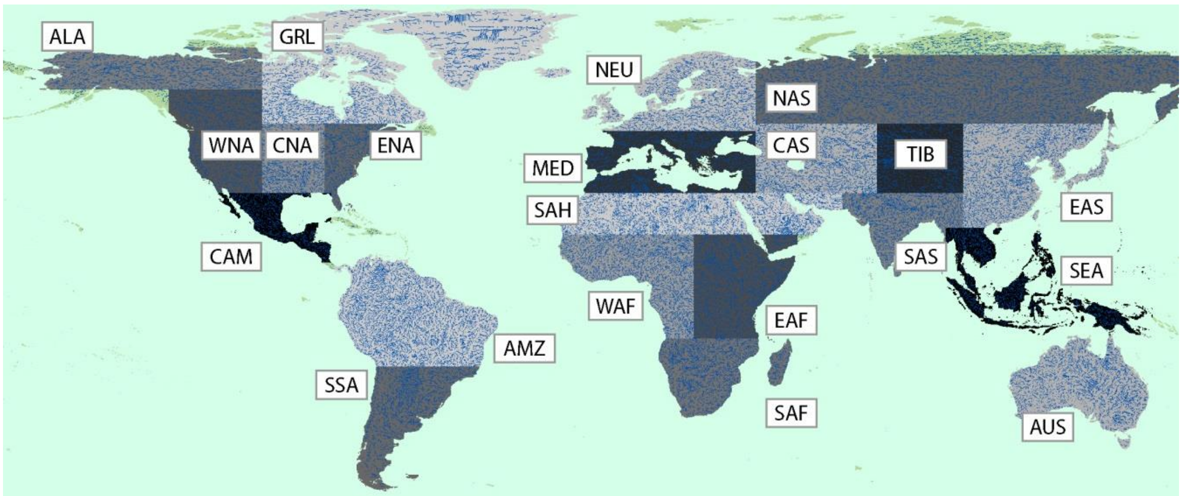

Figure 1: The GloFAS model river network, divided by the 21 regions described by Giorgi and Francisco [2000]

A comprehensive analysis of GloFAS capabilities is detailed in Alfieri et al. [2013]. A 21 year time series of simulated river discharge was evaluated against daily observations at a number of stations included in the Global Runoff Data Centre database, an international archive operating under the auspices of the World Meteorological Organisation. Findings of this analysis show that current ensemble weather predictions can enable skilful detection of hazardous events with a forecast horizon as long as 1 month in large river basins, providing that the initial conditions are estimated correctly. GloFAS was found to be skilful at 71% of discharge stations, with a maximum Nash Sutcliffe value of 0.92, but with less skill in arid and semi-arid regions due to uncertainties arising from the modelling of some hydrological processes such as evapotransipiration, infiltration and lack of simulated water withdrawals for irrigation purposes. However, the early warning capability still has utility in demonstrating anomaly from climatology.

It is important to note that the GloFAS has been designed for early warning purposes, rather than for quantitative streamflow forecasting, building on the success of continental scale early warning systems such as the European Flood Awareness System [*Pappenberger et al.*, 2008, 2015; *Thielen et al.*, 2009; *Alfieri et al.*, 2013]. Its value is the ability to assign each forecast value a correct probability of occurrence taken from its cumulative distribution function and thus identify extreme values in the upper tail of the distribution, which can possibly correspond to flooding conditions [*Alfieri et al.*, 2013]. While no replacement for local forecasting based on local conditions, the reality is that in many areas of the world these systems simply do not exist. In addition, the added value of regional overviews for disaster preparedness and earlier warning provision means that this type of early warning system has repeatedly demonstrated utility [*Pappenberger et al.*, 2015].

2.2. Derivation of precipitation and river discharge indices

This paper defines floodiness and aims to quantify the link between precipitation and floodiness at large scales. As such, indices of these variables are required for comparison. For precipitation the average monthly precipitation is averaged across all land points.

Both river discharge and floodiness are calculated for every major river pixel, here defined with a threshold of cells that have >1000km^2 upstream area; they could be assessed for every gridcell, but this would simply be an assessment of runoff rather than give an indication of an impactful river level. Within the model structure chosen, this means that approximately 10 gridcells flow into that cell, and there are 300808 river cells globally

The discharge has been calculated two ways, firstly, as the monthly mean daily discharge averaged across all major river cells, secondly, as the mean of monthly daily maximum discharge across all river cells. The first was included as a 'mass balance' type of index, whereas the second provides an index that is more equated with flood magnitude.

2.3. Definition of floodiness indices

In this paper a threshold approach is chosen to measure floodiness to reflect similar approaches described in the drought and storminess literature. The thresholds for each grid cell were calculated by fitting a Gumbel extreme value distribution to the Peaks-over-Threshold of daily flows in each gridcell, as used for the operational GloFAS [See *Alfieri et al.*, 2013].

Two threshold approaches are used in this paper to define floodiness. The first is the Percentage Floodiness; *the percentage of river cells, in a defined region, that exceed a defined flow threshold during a given time period.* Mathematically, the percentage floodiness can be defined, for any given time period, using Equation 1:

$$Percentage\ Floodiness = \frac{100}{n}\sum_{i=1}^{n} \mathbf{1}_{\{z_i > t_i\}}$$

$$where:\ \mathbf{1}_{\{z_i > t_i\}} = \begin{cases} 1 \text{ if } z_i > t_i & \text{(on at least one day during the time period)} \\ 0 \text{ if } z_i \le t_i & \text{(on all days in the time period)} \end{cases} \tag{1}$$

n, number of river cells

i, a given river cell

t_i, return period threshold for a given river cell (here defined by calculating the design flows using the full flow record)

z, river discharge

As with droughts, there will be spatial correlation in the pattern of floods (e.g. the flows in cells along the same river will be correlated), here the spatial correlation is not corrected to enable a flood along a longer river to have a higher weighting than one on a smaller river.

Here the 20 year flood threshold is chosen as the return period threshold, t_i, though other return period thresholds have been plotted in Figure S3(i).The 20 year event is chosen as this corresponds to the ‘Extreme’ flow in the GloFAS operational forecasts, and does not need to be extrapolated from the 31 year time series as would a more extreme flow. The time period used in this study is a month for the global analysis (Figures 1, 2 and 3) and a week centred around each date for East Africa in Figure 4.

Similarly for storms and droughts, the flood event duration is also important. In this study a ‘storm days’ type of approach has also been assessed to provide a potentially contrasting index of floodiness; this second index is the Duration Floodiness; *the percentage of days that a given threshold was exceeded in all major river cells in a defined region during the* *specified time period.* Duration Floodiness can be defined, for any time period, using Equation 2:

$$Duration\ Floodiness = \frac{100}{Dn}\sum_{i=1}^{n}\sum_{i=1}^{d}\mathbf{1}_{\{d,z_i>t_i\}}$$

$$where, on\ any\ day\ of\ the\ time\ period, d{:}\quad \mathbf{1}_{\{d,z_i>t_i\}} = \begin{cases} 1 \text{ if } z_i > t_i \\ 0 \text{ if } z_i \leq t_i \end{cases}$$

(2)

D, number of days in a given time period

The correlation between the variables has been assessed using the Spearman's Rank Correlation Coefficient; a non-parametric test was required due to the nature of the floodiness data.

3. Results and analysis

3.1. Comparison between different indices of floodiness and discharge

Figure S1 shows that the noisy relationship between the two floodiness indices, with the imperfect correlation indicating that they measure two contrasting properties of flood hazard (Figure S2 shows these relationships for three regions). Interestingly, the duration floodiness value is higher during the boreal autumn months, whereas the percentage floodiness index is highest during the boreal spring. This result therefore demonstrates the importance of choosing an index for floodiness that is specific to a particular application. For example, the percentage floodiness may be more important for emergency responders since it represents more people affected, but the duration index for insurers with business interruption losses directly related to the flood duration.

In contrast the plot in Figure S1 for discharge shows that the global monthly mean discharge and the global monthly maximum discharge are very well correlated. As such, these indices can be used interchangeably as a different index offers no additional information.

3.2. Comparison between floodiness, discharge and precipitation

The anomalies of the two floodiness indices, the maximum monthly discharge and the mean precipitation are compared over a 31-year time series by calculating the difference between each month's value compared to the long-term mean for that month (Figure 2, Figures S3(i-iii) for regional scales). A two-year running mean of the anomaly is also plotted, and visual comparison of the running mean between the different time series shows that precipitation and discharge appear to be relatively well correlated (for example showing similar peaks for mid-1988 to mid-1990 and troughs between mid-1990 to mid-1993). However, though there is a 1999 to 2001 peak in all the time series, in general precipitation and floodiness are not as well correlated as precipitation and discharge. While the 2-year running mean of the two different floodiness indices appears visually similar, examination of the monthly data shows that the choice of a 'floodiest' month is different between the two; this is likely to be because the two floodiness measures reflect seasonal influences on flood characteristics. Figure S1 shows the two floodiest months to be in the Boreal spring for the percentage floodiness, and the Boreal autumn for the duration floodiness.

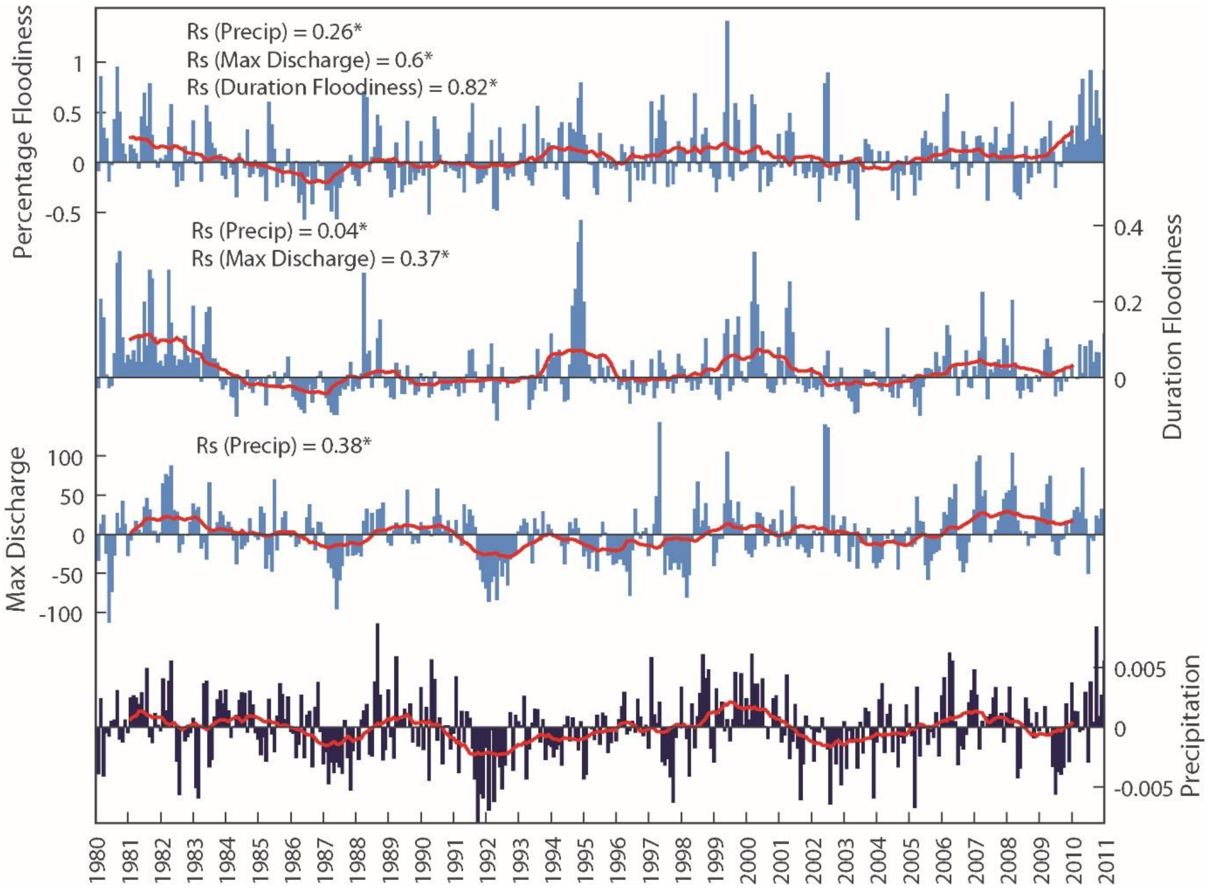

Figure 2: Time series of anomalies in Monthly Percentage Floodiness, Monthly Duration Floodiness, Maximum Monthly Discharge, and Mean Monthly Precipitation from 1980-2010 for all global major river pixels at 0.1 degree resolution. Two year running mean displayed as red line. Annotations indicate the Spearman's Rank Correlation Coefficient, with significance at 0.05 indicated by *.

Further analysis at the regional scale in different climatic regions is needed to understand the mechanisms for the differences in these indices. Figure 3, for the East Africa Giorgi Region, shows that the precipitation-floodiness and precipitation-discharge relationships are month dependent, demonstrating that precipitation will be a better approximation for floodiness in August than May. Where river flow corresponds to the previous winter's snowfall rather than spring precipitation, e.g. March to June in Western North America (Fig S4(i) and Table S1), the precipitation discharge relationship is particularly poor; further work may seek to implement snow into floodiness indices, as with drought research [*Staudinger et al.*, 2014]. The implication of using precipitation values as a proxy for flood hazard is highlighted in Figure 3b, demonstrating that an observation of an extreme precipitation value would not necessarily lead to a high floodiness value.

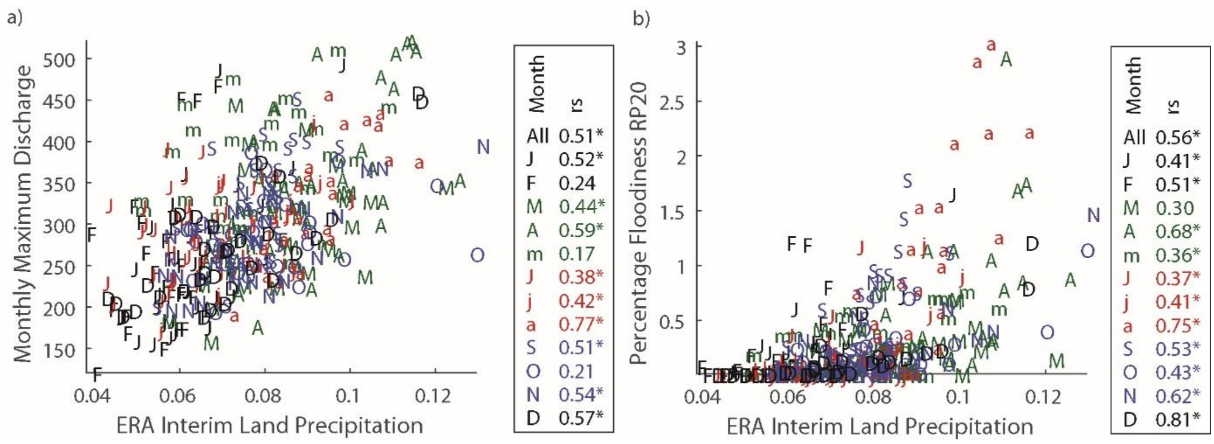

Figure 3: Correlation between precipitation and discharge (a) and the percentage floodiness index (b) for the East Africa Giorgi Region. Different months are represented by [capitalised] initials (e.g. March = M; May = m) and different seasons by colors. The legend indicates the Spearman's Rank Correlation Coefficient, with significance at 0.05 indicated by *.

This study shows the relationship between precipitation, discharge and floodiness in major rivers at global and regional spatial scales and at monthly timescales. The results demonstrate that there is significant non-linearity between precipitation and floodiness; the largest anomalies in precipitation do not correspond to the largest anomalies in floodiness. The precise correlations between precipitation and floodiness are shown to be specific to the region and month (Table S2), as well as the monthly time interval addressed in this study. Further investigation is therefore needed to determine the degree of this non-linearity over different spatial or temporal scales, considering the influence of the role of different precipitation periods for flood generation in different regions [e.g. *Froidevaux et al.*, 2015].

4. Applications of a floodiness index

The results presented here are of particular relevance to the humanitarian community; in 2008, a seasonal forecast of an augmented probability of above-normal rainfall in West Africa during the upcoming rainy season was interpreted as implying an above-normal flood risk, and subsequently led to early actions such as the pre-positioning of relief items [*Braman et al.*, 2013]. In this case, these early actions were seen as successful, saving lives and resources, but the results of this paper show that further evidence of the link between precipitation and floodiness should be established to avoid any future false alarms.

In this study two floodiness indices were used to represent the number of river cells that were flooded within a given time period, and the duration of flooding over that period. As such, a characteristic of floods that is not dealt with in this study is the number of separate flood events that occur within the specified time frame. In contrast to the counts of tropical cyclones per year, the difficulty in defining when a flood ends and another one begins makes such counts more difficult. One aspect of the duration index calculated in this study is that it does not distinguish between one flood of 10 days and 2 floods of 5 days; future studies might like to address this explicitly. Before moving onwards from this initial prescription of floodiness, scientists should initiate dialogue with different sectors; emergency response, humanitarian, insurance; to determine sector-appropriate indices of floodiness based on the relevance and importance of different flood characteristics (e.g. magnitude, duration), and to determine the region over which floodiness should be calculated / forecasted.

One application of a floodiness index is for climate purposes, with there being potential for producing a reanalysis product for floods that would allow for a better understanding of the sources of variability in floodiness at large scales, such as links with the El Niño Southern Oscillation. This could provide a regional perspective to compliment studies that have looked at links from the point or grid cell perspective [*Ward et al.*, 2010, 2014]. This information in turn could be used to provide a more robust estimation of flood frequency, allowing for flood risk decisions to be based on the current state of the climate system. A floodiness reanalysis would also act as an alternative dataset from which to determine the presence of an anthropogenic trend; trend identification from the limited observation data is difficult since these data are limited by inherent uncertainties due to the impact of improvements to flood defences and reporting biases. An analysis using the complex river network at 0.1 degrees spatial resolution represented by the Global Flood Awareness System (Figure 1), provides a valuable comparison to studies such as Dai and Trenberth [2002], which looked at only the world's largest 921 rivers.

Figure 4 provides an example application of a reanalysis dataset; here showing a daily floodiness climatology for the East Africa region. This figure clearly demonstrates the seasonality of floodiness in East Africa, with two distinct floodiness peaks, but also showing that sometimes floods of the scale seen during the main flood seasons also occur in the drier months (e.g. February). A dataset such as this can be used as a baseline climatology for forecasting; Figure 4 also displays a mock-up of a possible ensemble forecast to indicate whether floodiness is expected to be higher or lower than usual. Development of operational ensemble hydrometeorological forecasting systems, such as GloFAS, to include forecasts of regional floodiness could be of great value to decision-makers, especially where there is already useful skill in the seasonal forecasts of precipitation [*Weisheimer and Palmer*, 2014].

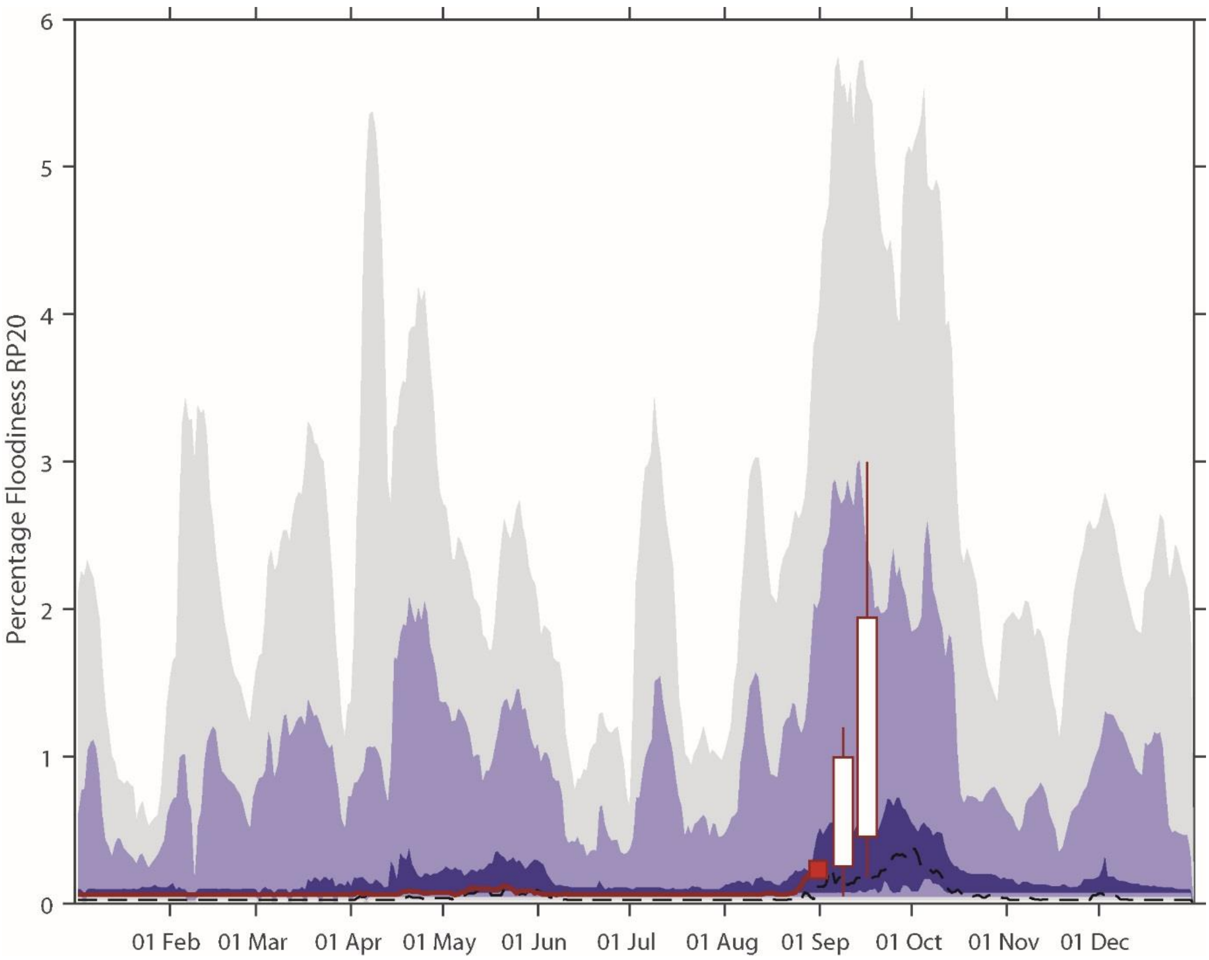

Figure 4: A climatology of 20 year Return Period percentage floodiness (1980-2010) for the East Africa (EAF) Giorgi region. Light purple = 5th to 95th percentile, Dark purple = 33rd to 67th percentiles, Light grey = full range. An mock-up weekly floodiness forecast is shown in red.

Conclusion

In this study indices of flood activity across large-scales (floodiness) have been derived, and a climatology of global-scale floodiness created for the first time by driving a precipitation reanalysis through a global-scale hydrological model. An analysis of the relationship between precipitation, river discharge and floodiness shows that global monthly floodiness is not well correlated with precipitation. For those applications that currently use a precipitation forecast as a proxy for imminent flood hazard, or for risk assessments that assume that precipitation and floodiness are driven by the same modes of climate variability, we provide evidence that demonstrates the importance of modelling the hydrological system.

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References

Adhikari, P., Y. Hong, K. R. Douglas, D. B. Kirschbaum, J. Gourley, R. Adler, and G. Robert Brakenridge (2010), A digitized global flood inventory (1998–2008): compilation and preliminary results, *Nat. Hazards*, *55*(2), 405–422, doi:10.1007/s11069-010-9537-2.

Alfieri, L., P. Burek, E. Dutra, B. Krzeminski, D. Muraro, J. Thielen, and F. Pappenberger (2013), GloFAS – global ensemble streamflow forecasting and flood early warning, *Hydrol. Earth Syst. Sci.*, *17*(3), 1161–1175, doi:10.5194/hess-17-1161-2013.

Allan, R., S. Tett, and L. Alexander (2009), Fluctuations in autumn-winter severe storms over the British Isles: 1920 to present, *Int. J. Climatol.*, *29*(3), 357–371, doi:10.1002/joc.1765.

Balsamo, G., A. Agustì-Panareda, and C. Albergel (2014), Representing the Earth surfaces in the Integrated Forecasting System: Recent advances and future challenges, *Tech. Rep.*

Balsamo, G. et al. (2015), ERA-Interim/Land: a global land surface reanalysis data set, *Hydrol. Earth Syst. Sci.*, *19*(1), 389–407, doi:10.5194/hess-19-389-2015.

Bärring, L. (2004), Scandinavian storminess since about 1800, *Geophys. Res. Lett.*, *31*(20), L20202, doi:10.1029/2004GL020441.

Bärring, L., and K. Fortuniak (2009), Multi-indices analysis of southern Scandinavian storminess 1780-2005 and links to interdecadal variations in the NW Europe-North Sea region, *Int. J. Climatol.*, *29*(3), 373–384, doi:10.1002/joc.1842.

Braman, L. M., M. K. van Aalst, S. J. Mason, P. Suarez, Y. Ait-Chellouche, and A. Tall (2013), Climate forecasts in disaster management: Red Cross flood operations in West Africa, 2008., *Disasters*, *37*(1), 144–64, doi:10.1111/j.1467-7717.2012.01297.x.

Coughlan de Perez, E., B. van den Hurk, M. K. van Aalst, B. Jongman, T. Klose, and P. Suarez (2015), Forecast-based financing: an approach for catalyzing humanitarian action based on extreme weather and climate forecasts, *Nat. Hazards Earth Syst. Sci.*, *15*(4), 895–904, doi:10.5194/nhess-15-895-2015.

Dai, A., and K. Trenberth (2002), Estimates of freshwater discharge from continents: Latitudinal and seasonal variations, *J. Hydrometeorol.*, *3*, 660–687, doi:http://dx.doi.org/10.1175/1525-7541(2002)003<0660:EOFDFC>2.0.CO;2.

Dee, D. P. et al. (2011), The ERA-Interim reanalysis: configuration and performance of the data assimilation system, *Q. J. R. Meteorol. Soc.*, *137*(656), 553–597, doi:10.1002/qj.828.

Fischer-Bruns, I., H. von Storch, J. F. González-Rouco, and E. Zorita (2005), Modelling the variability of midlatitude storm activity on decadal to century time scales, *Clim. Dyn.*, *25*(5), 461–476, doi:10.1007/s00382-005-0036-1.

Franks, S. W. (2002), Identification of a change in climate state using regional flood data, *Hydrol. Earth Syst. Sci.*, *6*(1), 11–16, doi:10.5194/hess-6-11-2002.

Froidevaux, P., J. Schwanbeck, R. Weingartner, C. Chevalier, and O. Martius (2015), Flood triggering in Switzerland: the role of daily to monthly preceding precipitation, *Hydrol. Earth Syst. Sci.*, *19*(9), 3903–3924, doi:10.5194/hess-19-3903-2015.

Fundel, F., S. Jörg-Hess, and M. Zappa (2013), Monthly hydrometeorological ensemble prediction of streamflow droughts and corresponding drought indices, *Hydrol. Earth Syst. Sci.*, *17*(1), 395–407, doi:10.5194/hess-17-395-2013.

Gale, E. L., and M. A. Saunders (2013), The 2011 Thailand flood: climate causes and return periods, *Weather*, *68*(9), 233–237, doi:10.1002/wea.2133.

Giorgi, F., and R. Francisco (2000), Uncertainties in regional climate change prediction: a regional analysis of ensemble simulations with the HADCM2 coupled AOGCM, *Clim. Dyn.*, *16*(2-3), 169–182, doi:10.1007/PL00013733.

Hisdal, H., and L. M. Tallaksen (2003), Estimation of regional meteorological and hydrological drought characteristics: a case study for Denmark, *J. Hydrol.*, *281*(3), 230–247, doi:10.1016/S0022-1694(03)00233-6.

Holland, G. J., and P. J. Webster (2007), Heightened tropical cyclone activity in the North Atlantic: natural variability or climate trend?, *Philos. Trans. A. Math. Phys. Eng. Sci.*, *365*(1860), 2695–716, doi:10.1098/rsta.2007.2083.

Huffman, G. J., R. F. Adler, D. T. Bolvin, and G. Gu (2009), Improving the global precipitation record: GPCP Version 2.1, *Geophys. Res. Lett.*, *36*(17), L17808, doi:10.1029/2009GL040000.

Van Der Knijff, J. M., J. Younis, and A. P. J. De Roo (2010), LISFLOOD: a GIS- based distributed model for river basin scale water balance and flood simulation, *Int. J. Geogr. Inf. Sci.*, *24*(2), 189–212, doi:10.1080/13658810802549154.

Kron, W., M. Steuer, P. Löw, and A. Wirtz (2012), How to deal properly with a natural catastrophe database – analysis of flood losses, *Nat. Hazards Earth Syst. Sci.*, *12*(3), 535–550, doi:10.5194/nhess-12-535-2012.

Lloyd-Hughes, B. (2013), The impracticality of a universal drought definition, *Theor. Appl. Climatol.*, *117*(3-4), 607–611, doi:10.1007/s00704-013-1025-7.

Pappenberger, F., J. Bartholmes, J. Thielen, H. L. Cloke, R. Buizza, and A. de Roo (2008), New dimensions in early flood warning across the globe using grand-ensemble weather predictions, *Geophys. Res. Lett.*, *35*(10), L10404, doi:10.1029/2008GL033837.

Pappenberger, F., H. L. Cloke, D. J. Parker, F. Wetterhall, D. S. Richardson, and J. Thielen (2015), The monetary benefit of early flood warnings in Europe, *Environ. Sci. Policy*, *51*, 278–291, doi:10.1016/j.envsci.2015.04.016.

Staudinger, M., K. Stahl, and J. Seibert (2014), A drought index accounting for snow, *Water Resour. Res.*, *50*(10), 7861–7872, doi:10.1002/2013WR015143.

Tallaksen, L. M., and K. Stahl (2014), Spatial and temporal patterns of large-scale droughts in Europe: Model dispersion and performance, *Geophys. Res. Lett.*, *41*(2), 429–434, doi:10.1002/2013GL058573.

Thielen, J., J. Bartholmes, M. H. Ramos, and A. de Roo (2009), The European flood alert system–Part 1: concept and development, *Hydrol. Earth …*, doi:doi:10.5194/hess-13-125-2009.

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*(12), doi:10.1029/2010GL043215.

Ward, P. J., B. Jongman, M. Kummu, M. D. Dettinger, F. C. Sperna Weiland, and H. C. Winsemius (2014), Strong influence of El Nino Southern Oscillation on flood risk around the world, *Proc. Natl. Acad. Sci.*, *111*(44), 15659–15664, doi:10.1073/pnas.1409822111.

Webster, P. J., G. J. Holland, J. A. Curry, and H.-R. Chang (2005), Changes in tropical cyclone number, duration, and intensity in a warming environment., *Science*, *309*(5742), 1844–6, doi:10.1126/science.1116448.

Weisheimer, A., and T. N. Palmer (2014), On the reliability of seasonal climate forecasts., *J. R. Soc. Interface*, *11*(96), 20131162, doi:10.1098/rsif.2013.1162.

Wood, E. F. et al. (2011), Hyperresolution global land surface modeling: Meeting a grand challenge for monitoring Earth's terrestrial water, *Water Resour. Res.*, *47*(5), W05301, doi:10.1029/2010WR010090.