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Discussions

Floods and climate: emerging perspectives for flood risk assessment and management

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Floods and climate

B. Merz et al.

Title Page

Abstract | Introduction

Conclusions | References

Tables | Figures

◄ | ►

Back | Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

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Title Page

Abstract | Introduction

Conclusions | References

Tables | Figures

◀ | ▶

◀ | ▶

Back | Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper

Abstract

Flood estimation and flood management have traditionally been the domain of hydrologists, water resources engineers and statisticians, and disciplinary approaches have abound. Dominant views have been shaped; one example is the catchment perspective: floods are formed and influenced by the interaction of local, catchment-specific characteristics, such as meteorology, topography and geology. These traditional views have been beneficial, but they have a narrow framing. In this paper we contrast traditional views with broader perspectives that are emerging from an improved understanding of the climatic context of floods. We conclude: (1) extending the traditional system boundaries (local catchment, recent decades, hydrological/hydraulic processes) opens up exciting possibilities for better understanding and improved tools for flood risk assessment and management. (2) Statistical approaches in flood estimation need to be complemented by the search for the causal mechanisms and dominant processes in the atmosphere, catchment and river system that leave their fingerprints on flood characteristic. (3) Natural climate variability leads to time-varying flood characteristics, and this variation may be partially quantifiable and predictable, with the perspective of a dynamic, climate informed flood risk management. (4) Efforts are needed to fully account for factors that contribute to changes in all three risk components (hazard, exposure, vulnerability), and to better understand the interactions between society and floods. (5) Given the global scale and societal importance, we call for the organization of an international multidisciplinary collaboration and data sharing initiative to understand further the links between climate and flooding and to advance flood research.

1 Introduction

Flood estimation and flood management have a long history during which dominant views have been shaped. One example is the river basin paradigm. In this, floods are seen from the catchment perspective; they are formed and influenced by the in-

teraction of local, i.e. catchment-specific characteristics of meteorology, topography, geology, vegetation etc. Another traditional view is that floods are essentially random events: typically, for statistical convenience, extreme flood occurrence and magnitude are assumed to correspond to an independent, identically distributed (iid) random pro-
5   cess represented by an appropriate probability density function.

During the EGU Topical Meeting "Floods and Climate: understanding and exploiting the link between floods and climate" on 4–5 October 2012 in Potsdam, the climate context of floods was discussed: how are floods related to climate, and in particular to climate variability? To what extent can we take advantage of linkages between climate
10 and floods? The workshop participants felt that, although the traditional views have been beneficial, they have a narrow framing, and that flood estimation and flood management could benefit from a broader perspective. For instance, the local catchment perspective needs to be complemented by the global view, since floods are embedded in a global climate context. The actual flood potential of a catchment and the character-
15 istics of floods may be influenced by global climate mechanisms. Hirschboeck (1987) offered the hypothesis that unusually large floods in drainage basins of all sizes may be related to large-scale atmospheric circulation anomalies. Nakamura et al. (2013) show that 20 major flood events over the last 100 yr in the Ohio River Basin have nearly identical storm tracks, moisture source and delivery patterns. Such persistent
20 anomalies may in turn reflect modulation of the storm tracks by identifiable climate phenomena such as the El Niño Southern Oscillation (ENSO) and Pacific Decadal Oscillation (PDO). Consequently, it seems necessary to complement the local catchment perspective with a global view, to investigate whether floods are purely random and whether the widespread iid assumption holds, and to develop flood risk assessment
25 methods which are capable of taking advantage of such extended perspectives.

New perspectives are emerging even more clearly in the field of flood risk management. Traditionally, flood management strategies have focused on reducing the flood hazard, i.e. the probability of flooding. Hence, flood research has centred on the physical processes within catchments and river systems. Over the past two decades there

has been a shift from the hazard-focused view to the broader risk-based perspective, including societal processes and implications (Merz et al., 2010). Flood disaster risk results from the interaction of hazard, exposure and vulnerability. Hazard represents the probability and intensity of flooding, exposure describes the elements-at-risk, for example, the people and their assets that may be affected by flooding, and vulnerability describes the susceptibility or propensity of elements-at-risk to be adversely affected. This concept is at the heart of the Global Assessment Reports of the United Nations Office for Disaster Risk Reduction (UNISDR, 2011, 2013), and the IPCC SREX report (2012) adopted it for analysing risks related to climate change.

It is taken for granted that changes in climate or human interventions in catchments and river systems may change flood hazard and, as a consequence, flood risk. Within this view, floods are evaluated from a hazard perspective, focusing on hydrologic/hydraulic parameters such as discharge, water level or inundation extent. Societal processes are often neglected, which implicitly means they are assumed to be constant or, if random, a stationary process. However, some socio-economic processes, like population growth and economic development, may change at a faster pace than long-term physical changes (for example, the impacts of climate change on discharge), and exposure and vulnerability to floods can be highly dynamic. Against this background, societal processes need to be addressed within a risk-based approach, where next to the hazard, societal exposure and vulnerability play a decisive role. A particularly interesting question is how space-time variations in flood hazard that may be related to climate variability and change intersect with the changing nature of the flood exposure and vulnerability. As an example, globalization leads to potential pathways of supply chain disruption as seen with the long duration floods in Thailand (2011), Queensland (2010, 2011), Indus (2010), and Mississippi (2012), that led to significant local and global economic impacts.

Table 1 contrasts the traditional narrow framing of floods with the broader perspective that is emerging from an improved understanding of the climatic context of flood generation. The different aspects of Table 1 are closely linked. This becomes obvi-

ous in Sect. 2 which focuses on understanding climate–flood linkages. In Sect. 3, we discuss how this broader framing may be used for improved flood estimation and risk management. In particular, we explore how an improved process-based understanding of climate–flood linkages at multiple scales can be exploited to address critical man-
5 agement and societal issues in a rapidly changing world.

2 Understanding climate–flood linkages

Climate–flood linkages operate across multiple spatial and temporal scales determined by (i) the nature of the meteorological and climatic processes that drive the atmospheric components of the hydrologic cycle and (ii) the nature of the hydrologic land-surface
10 and subsurface processes within which a flood develops. As implied in Table 1, the traditional approach for linking atmospheric components to flood analysis has been primarily hydro-meteorological, i.e., framed by local weather events of recent decades interacting with current catchment characteristics. The emerging view of climate–flood linkages is process driven and seeks to understand and analyze flood events in the
15 context of their long-term history of variation – in magnitude, frequency, and seasonality – and within the *climatic* framework of the global and regional atmospheric circulation patterns and processes that drive changing combinations of meteorological elements at the catchment scale. In the following, we discuss these contrasting perspectives.

2.1 Randomness or causality?

20 Floods are typically seen as events that are generated by the random superposition of processes in the atmosphere, catchment and river system. The idea of very strong or even complete randomness prevails in the history of flood prediction. Much effort has been spent on describing flood occurrence and magnitude by probability distributions, a large share of the flood research has been focused on statistical aspects, and the role
25 of randomness has been emphasised. This avenue has been shaped by the pioneers

of flood frequency analysis; for example, in 1941 Emil Julius Gumbel mentioned about the flood estimation problem: "The author believes it is possible to give exact solutions, exactitude being interpreted from the standpoint of the calculus of probabilities.", (Gumbel, 1941, p. 163).

5   Figure 1 provides examples of the atmospheric moisture transport averaged across the top 10 floods over a 60 yr period in 4 regions of North America. It is clear that there is a distinct large-scale circulation pattern with different moisture sources and storm tracks associated with these extreme events. Such determinism is not restricted to the mid-latitudes. The 2011 persistent flooding in Thailand was marked by 5 typhoon

10   landings over a period of 100 days, and the typhoon tracks were very similar over this period with a similar area of origin and path. The prevailing La Niña conditions in the Western Pacific (the source region of the storms) and phase of the Madden Julian Oscillation (20–40 day) period are thought to have interacted to produce the convergence of moisture into Thailand per event. To be sure, causality may also be

15   found in other aspects of the climate-catchment system. For example, Nied et al. (2013) show that floods in the Elbe catchment in Central Europe are preferably initiated by specific large-scale soil moisture patterns, and Sivapalan et al. (2005) demonstrate that the flood peaks increase notably if seasonality of rainfall and antecedent soil moisture are in phase.

20   If one takes a causal approach, arguing that flood occurrence and magnitude contain a significant fraction of determinism, then identifying the signatures of major floods in terms of the associated climatic and catchment mechanisms becomes important. A fruitful direction of research could be to identify the dominant mechanisms associated with regional floods, and to see how the occurrence and intensity of those mech-

25   anisms lead to the space and time expression of floods. The analysis would move from annual maximum or peak over threshold floods to looking at extreme floods in terms of discharge, volume and duration and their space and time structure over perhaps a season or a decade or longer as could be informed by the nature of the underlying mechanisms. The volume and duration of flooding are directly tied to inundation

characteristics and hence represent how the strength and recurrence characteristics of the large-scale atmospheric fluxes that bring moisture into the region interact with catchment hydrologic processes. These, in turn, determine how the static and dynamic aspects of topography, soils, channel networks and flood control infrastructure process the atmospheric inputs. Given the uncertainties attendant to all these processes, the integrated causal view could provide a basis for better probabilistic modelling of floods from a physical as well as statistical perspective.

2.2 Local or global?

Frequently, floods have been understood as local phenomena, driven by the perspective of flood management at the local level, e.g. at the municipal or county scale. Within the last two decades there have been many attempts to reconcile the spatial frame of this societal lens with the traditional hydrological view. Here, floods are considered through the local catchment lens, and are shaped by catchment meteorology, hydrology and river processes. The emerging view extends this spatial framework to the continental and global scale to accommodate the interactions between local flooding and global climate mechanisms.

Probably the most famous and well-studied global linkage between large-scale climate oscillations and hydro-meteorological variables is ENSO, with variations on a 2–7 yr time scale. For example, linkages can clearly be seen between ENSO indices and gridded precipitation datasets. Such an analysis has been carried out by Becker et al. (2013) using global land-surface precipitation of the past 110 yr at a spatial resolution of 0.5° (Schneider et al., 2011). At this scale, the data are capable of resolving global and synoptic-scale precipitation patterns. Over this longer than centennial time period, the correlation of each grid cell against the negative Southern Oscillation Index (i.e. the occurrence of La Niña events) reveals that years with strong ENSO phases (such as the La Niña years 2010 and 2011) feature precipitation anomaly patterns in the same overall ENSO sensitive regions. Therefore, these predictable anomaly patterns point to regions where extreme precipitation events (Thai-

land, Queensland/Australia, El Salvador) or droughts (Northern Mexico, Southern US, South-East Africa, Hong Kong) have also occurred (Fig. 2) during a specific year or period.

ENSO has been linked to floods in Peru (Waylen and Caviedes, 1986), the United States (Cayan et al., 1999; Jain and Lall, 2000, 2001; Pizaro and Lall, 2002; Sankara-subramanian and Lall, 2003), China (Lin et al., 2005; Zhang et al., 2007), Australia (Kiem et al., 2003) and generally to the extra tropics (Ward et al., 2010), as well as to precipitation anomalies in Europe (Bichet et al., 2014). PDO and the North Atlantic Oscillation (NAO) have been shown to influence precipitation and flood regimes and to lead to flood episodes of varying intensity in various regions (e.g. Cayan, 1996; Jain and Lall, 2000; Bouwer et al., 2006; Kingston et al., 2006; Maraun et al., 2010; Bichet et al., 2011; Rana et al., 2011; Gregersen et al., 2013). Moreover, Ward et al. (2010, 2014) examine correlations between observed peak discharge and the Southern Oscillation Index (SOI) at the global scale and show that peak discharges have a strong sensitivity to ENSO in catchments over large parts of the globe.

In Mediterranean Europe, most of the weather systems causing intense and/or persistent rainfall originate over the Atlantic Ocean and are carried towards the Mediterranean region by westerly winds. These systems can interact with regional topography and produce localised extreme precipitation (Rudari et al., 2005; Pinto et al., 2013), inducing severe river floods. In the upper troposphere over the Euro-Atlantic region, the westerly flow is characterised by two jets: the Atlantic jet, which crosses the ocean with a north-easterly trajectory, and the African jet, which flows above the coast of North Africa. The cross-jet circulation of the Atlantic jet favours storm activity in its exit region, while the cross-jet circulation of the African jet suppresses this kind of activity in its entrance region. It follows that the rainfall distribution downstream of these cross-jet circulations is strongly influenced by their relative positions (Gaetani et al., 2011; Toreti et al., 2010). Specifically, in autumn, rainfall is copious and more persistent in the western Mediterranean basin, when the Atlantic jet is relatively strong but its north-easterly tilt is small, and the African jet is in its easternmost position. In winter, rainfall

Floods and climate

B. Merz et al.

Title Page

Abstract | Introduction

Conclusions | References

Tables | Figures

◄ | ►

◄ | ►

Back | Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

is abundant in the eastern Mediterranean basin; this is when the Atlantic jet reaches the Scandinavian peninsula and the African jet is in its westernmost position. In spring, when the two jets weaken, the Atlantic jet retreats over the ocean, but the African jet stays in its winter position, and rainfall is more persistent and abundant in the Alpine region and in the Balkans. Therefore, the origin for many floods is not necessarily local, but is related to large-scale circulation patterns like ENSO or jet stream tracks.

These examples show that the investigation of global climate processes might help to understand and predict local floods. However, the potential benefit goes further. Linkages across different hazards and across large distances are possible, since the flood and drought potential for far catchments may be related. Specifically, one can hypothesize that persistent spatial patterns of surface temperature in the tropical oceans lead to enhanced probabilities of regions where strong convection takes place and provides a moisture source that could lead to floods in certain areas. The same anomalous surface temperature patterns could also lead to suppression of convection in other tropical areas, and also to changes in the position and strength of the mid-latitude jet stream and the eddies that are coupled to it. The net result could be that persistent centers of low and high pressure are set up in the mid-latitudes, such that tropical moisture is funnelled repeatedly into the persistent low pressure regions leading to floods, and droughts persist associated with the atmospheric blocks associated with the high pressure centers. The net result may be synchronous flooding and drought patterns at seasonal to annual scales across the world. Some examples are indicated in Sect. 2.2. The potential dynamics of such a system at a global scale under a changing climate are discussed in Karamperidou et al. (2012, 2013).

2.3 Stationary or time-varying random variables?

Traditional flood frequency analysis assumes stationarity. This assumption implies that flood characteristics fluctuate around a constant value, and that flood quantiles can be determined from data collected over relatively short time periods, typically a few decades. It is assumed that the flood generating processes remain constant in time,

and that flood probability represents the long-term natural variability of the climate-catchment system. Changes in flood characteristics are expected to result from anthropogenic interventions in this system, such as human-induced climate change, land-use change or river training.

Stationarity implies that each flood record has the same probability of occurrence at any time. However, Sects. 2.1 and 2.2 suggest that there may be periods with distinct flood peak distributions for catchments with strong climate–flood links. Analyses of long observation data and historical flood records give evidence that floods tend to cluster in time in many regions, and hence, that the traditional assumption of time-invariant probability distribution does not hold. Periods with higher or more frequent floods can be differentiated from periods with minor flood activity (e.g. Jacobeit et al., 2003; Schmocker-Fackel and Naef, 2010). This is attributed to low-frequency climate variability, as climate has well organized modes of interannual, interdecadal and lower-frequency variability modulating atmospheric moisture uptake, transport and deposition (precipitation) processes, and hence, flood conditions (Hirschboeck, 1988). Knox (2000) studied the effect of climate variability on flood probability at the Mississippi River. He divided the 120 yr long observation period into four decadal-scale sub-periods according to their prevailing global circulation patterns and calculated flood quantiles for each sub-period separately. The 50 yr-flood was approximately 50 % larger during episodes with more frequent meridional circulation patterns than in periods with more common zonal circulation patterns. This approach of stratifying the flood sample into sub-samples with different climate modes has been repeated, for example, by Kiem et al. (2003) for 40 flood gauges in New South Wales, Australia. The stratification of a regional flood index according to ENSO and the Interdecadal Pacific Oscillation (IPO) leads to very marked differences in flood quantiles. In flood frequency estimation such variations will show up as a bias as well as an underestimation of the uncertainty of projecting future flood hazards because the interdecadal and longer oscillations are ignored.

Consequently, even in the absence of human-induced changes, the statistical properties of flood time series may vary significantly over time. Flood characteristics may

not be fixed but may float dynamically in time. These regime-like patterns with quasi-cyclic behaviour of flood-rich and flood-poor periods need to be understood, and those regions and conditions under which marked regimes exist need to be identified.

An interesting research question is whether flood regimes occur in accordance across large distances. If the flood behaviour of large regions responds in a similar way to large-scale or global climate regimes, this should be seen in concurrent flood-rich clusters and flood-poor periods. For instance, Schmocker-Fackel and Naef (2010) find that large floods tend to synchronously occur in different regions of Europe since 1500 (e.g. in Switzerland and the Czech Republic). In the late 19th century, central Europe was particularly affected by recurring large and destructive floods (e.g. Pfister, 1999; Mudelsee et al., 2006; Brazdil et al., 2005; Schmocker-Fackel and Naef, 2010). Using an atmospheric GCM, Bichet et al. (2014) found that this 15 yr period of destructive floods in Central Europe was induced by a change in the atmospheric circulation (positive PNA-like (Pacific-North American) pattern and negative summer NAO pattern), itself driven by changes in the tropical SSTs (Eastern tropical Pacific and Indian Ocean Sea Surface Temperatures). Although the impact of tropical SSTs on European precipitation has previously been documented in the literature (e.g. Bronnimann, 2007), there is still no clear understanding of how and under which circumstances the SST signal transmitted from the tropics to Europe can lead to precipitation extremes associated with flooding. Although other parts of the world were also affected by above average precipitation in the late 19th century (Gergis and Ashcroft, 2012), the reasons why this period was so exceptional in Europe are still unclear.

2.4 Recent or long-term?

Traditionally, understanding of flood characteristics and flood frequency analysis have been focused on data from the most recent decades, based on the idea that flood characteristics result from current catchment characteristics. From a long-term perspective, it must be recognised that flood characteristics are the result of an interplay of climate, geology, topography, vegetation (biology), and humans. As an example, consider the

Title Page

Abstract | Introduction

Conclusions | References

Tables | Figures

◄ | ►

Back | Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

way precipitation and catchment time scales are related to flood time scales. Figure 3 (from Gaál et al., 2012) illustrates some of the factors that influence these three time scales. Note that Fig. 3 could be extended by feedbacks in the climate system and the role of humans as strong floods may lead people to build flood control systems that modify hydrology (Di Baldassarre et al., 2013). The time scales shown in Fig. 3 are not independent and the interplay amongst them can be interpreted differently at different time scales, from hours to millennia. The events that produce the maximum annual floods are those for which the storm duration is close to the concentration time of the catchment, because the catchment-response time scales filter the distribution of all storms to produce the distribution of flood-producing storms (Viglione and Blöschl, 2009). This is the reasoning behind the rational method for flood estimation and it applies at the event scale (e.g. Pilgrim and Cordery, 1993, p. 9.13). At the seasonal time scale, flood characteristics tend to be closely related to the seasonal water balance and, conversely, runoff event types affect the seasonal water balance through rainfall and snowmelt (Sivapalan et al., 2005). At the time scale of decades, however, the flow paths as well as soil moisture affect erosion during floods and soil evolution (modulated by differences in geology), while soil depth and permeability affect flow paths and therefore the flood response at the event scale. At the landscape evolution time scale there are further interactions (Abrahams and Ponczynski, 1984; Tucker and Bras, 2000). To fully understand floods, this long-term interplay has to be disentangled. Because of the coupling between different processes across many spatial and temporal scales, the interplay between climate and catchments has to be seen as complex system (Rihani, 2002; Raupach, 2005; Kumar, 2007; Blöschl and Merz, 2010), i.e., systems with a large number of strongly interdependent variables at multiple space and time scales.

One promising avenue to better understand this long-term interplay and the role of climate for flood characteristics is the use of historical and geological archives (e.g. Kochel and Baker, 1982; Baker, 2008; Glaser et al., 2010; Gilli et al., 2012). Historical archives provide exact dates of catastrophic floods often together with detailed descriptions of the hydro-meteorological conditions and the resulting damage. How-

ever, these archives are limited to regions that were populated over a long period and only reach back a couple of centuries. Millennial-scale variations from potentially all regions world-wide can be revealed from river and lake sediment records (e.g. Benito et al., 2003c; Swierczynski et al., 2012, 2013; Wilhelm et al., 2012, 2013). While river sediments typically reflect periods of both accumulation and erosion and thus mainly reflect highest-amplitude floods, lakes represent ideal natural traps which continuously collect suspended detrital sediments transported by floods. In case of annually laminated sediments even the seasons of paleofloods can be precisely determined by the micro-stratigraphic position of a detrital layer within the annual succession of lake deposition (Mangili et al., 2005; Czymzik et al., 2010).

Figure 4 shows exemplarily the reconstruction of spring and summer floods from laminated sediments of Lake Mondsee, Austria. The amount of temporal variability in the occurrence of floods is striking. There is a period of more than 200 yr (21 BC–216 AD) without any flood documented, whereas the average frequency is 0.04 floods yr^{-1} yielding 9 floods for such a time interval. Similar fluctuations are seen in other paleoflood records (e.g. Ely et al.,1993; Knox, 2000; Benito et al., 2003a, b).

Combining flood reconstructions with climate reconstructions has a great potential to better understand climate–flood linkages. However, interpreting sedimentary paleofloods records requires the precise timing of detrital flood layer deposition and a detailed understanding of the mechanisms from the sediment source to the sink. The entire chain of processes needs to be captured, from the hydro-meteorological event and the resulting erosion in the catchment to sediment transport into the lake and distribution of suspended material within the lake basin. This, in turn, requires both detailed investigation of the lacustrine sediment formation including the influence of land-use and vegetation changes on catchment erosion and sedimentation, and calibration of flood layer deposits with meteorological and hydrological observations. Such a detailed understanding allows an assessment of the completeness of the paleoflood record and whether certain flood types are missing.

Where very long flood time series extending over millennia can be reconstructed with sufficient reliability, they provide a data-based approach to separate the impact of anthropogenic climate change on floods from natural climate variability. Given the large uncertainty of today's models to simulate floods under changing climate, reliable paleoflood reconstructions have an exciting potential to determine the natural variability of the flood activity, to better constrain flood projections under climate change, and to better assess flood recurrence times and flood–climate relations for various climate states and time scales.

This long-term view has been successfully used for flood management in dam safety considerations by defining upper limits of flooding through paleoflood and documentary studies (Enzel et al., 1993; Levish, 2002). However, the systematic integration of paleo and historical records into flood frequency analysis has been limited. An argument that is often raised is that if climate is now changing, the long-term record is of little benefit because the past is no longer the key to the present. However, even with a changing climate, from a meteorological/mechanistic perspective, the laws of physics which result in rain, snow and floods are time invariant. Non-stationarity is produced by changes of these processes in their frequency, magnitude, location, persistence, intensity, and clustering. These are driven by the interplay described earlier and are partially deterministic (Sect. 2.1). Hence the extreme events of the past are indeed important indicators of what the atmosphere-catchment system is capable of, given the right interplay of factors. They have left evidence in the landscape of the occurrence of a real event (not something emerging from modeling). Floods – by their very nature – are rare events, hence there is a need to identify them in all temporal contexts (paleo, historical and systematically gauged) and explain them from a mechanistic understanding of causal drivers.

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

3 Exploiting climate–flood linkages to better manage flood risk

How can a better understanding of climate–flood linkages be used for improved flood risk management? In the following we contrast the traditional approaches for flood estimation, flood projections under climate change, and for flood management with emerging perspectives based on this improved understanding of floods in their climatic context.

3.1 Flood estimation: process-neutral or process-based?

Flood estimation does not traditionally differentiate between flood event types and flood generation processes and can be termed process-neutral. The main approach to estimate flood probabilities is based on extreme value statistics, i.e. fitting distribution functions to ordered sequences of observed flood peaks, ignoring the underlying processes, and extrapolating the tails of the distribution to low exceedance probabilities. It is typically assumed that the flood data used are independent and identically distributed. This has been popular largely because most common statistical methods for the analysis of extreme values make this assumption. Consequently, even in locations where a mix of mechanisms such as frontal storms, localized thunderstorms and rain-on-snow events, that have very different space and time attributes, lead to floods, most analyses focus on finding a single best distribution to fit them instead of identifying and modelling the mixtures. Flood heterogeneity has been shown to invalidate the iid assumption in different catchments (e.g. Murphy, 2001; Todhunter, 2012). Further, flood clustering may introduce serial correlation in the time series and may invalidate the independence assumption.

Even more disturbing is the possibility that climate-related fluctuations may significantly bias flood quantile estimates. Franks and Kuczera (2002) point to the need to distinguish between conditional and unconditional flood probability. The unconditional, long-term probability averages across different climate states, whereas the conditional probability depends on the current climate state. Traditional flood frequency analysis

results in sound estimates of unconditional flood probability only if the observed data accurately represent the different climate states. Moreover, it may seriously over- or underestimate flood probability in a given year. In a comparison of unconditional and conditional flood probability, Kwon et al. (2008) found that the conditional 100 yr flood fell outside the confidence interval of the unconditional estimate. Jain and Lall (2001) explore how the long-term, ENSO-related climate variability impacts the exceedances of flood thresholds. From their bootstrap analysis they conclude that there is a much higher chance of obtaining substantially different numbers of exceedances of the design flood derived from the iid assumption. Hence, low-frequency fluctuations may lead to fat tails of flood distributions and may increase the potential for surprise.

The contrasting, process-based perspective is founded in the premise that flood events of different types occur in a given catchment, and that flood characteristics are linked to the hydro-meteorological processes driving the water input into catchments, to the runoff generation processes, and to the flood routing processes. The expectation is that process-based approaches can inform flood probability estimation and allow more reliable and catchment-specific characterisation of the flood hazard.

The analysis of flood events in terms of their meteorological causes is an important starting point for understanding how flood-climate linkages can influence flood probability distribution functions (Hirschboeck, 1988). Different storm types can trigger completely different flood processes in the same catchment. For example, in the Southwestern United States (Fig. 5), intense summer convective thunderstorm cells interact selectively with a watershed's drainage network and topography, typically generating flashy flood hydrographs. In contrast, synoptic-scale winter storms deliver snow and rain to large areas and tend to generate flood hydrographs characterized by sustained and cumulative flows. Catchments with flood peaks generated by a mix of climatic mechanisms may exhibit complex heterogeneous frequency distributions, but stratifying the flood record according to climatic cause (Fig. 5) reveals useful information about the individual processes that shape the catchment's overall flood frequency distribution. If marked climate–flood linkages can be identified, it allows improving flood estimation

and design. Kwon et al. (2008) stress the reduction in uncertainty of the 100 yr estimate when they include climate information. This reduction can be used to decrease the costs of over- or underdesign. However, in order to benefit, there is a need for more statistical and theoretical analysis of temporal variability in extremes, to understand how temporal clustering or existence of a range of stochastic processes or mixture of distributions affect the tails of flood distributions.

The reasoning that better process understanding improves flood estimation can be extended further along the chain of flood processes. Runoff able to generate floods is produced in three main ways: (1) at the surface by infiltration excess (Hortonian overland flow) due to low or no infiltration intensities of the soil or surface, (2) by saturation excess (saturation overland flow) due to saturating the porous soil matrix, or (3) by fast subsurface flow, usually triggered by a variety of mechanism and conditions (Bachmair and Weiler, 2011). Based on the specific setting of a given catchment (geology, soils, topography, vegetation cover, land-use, etc.), the three processes interact differently, therefore in conjunction with the hydro-meteorological conditions, different runoff generation processes can dominate the flood generation (Weiler et al., 2009; Steinbrich and Weiler, 2012). Rogger et al. (2012) give the following example which illustrates the benefits of understanding the dominant controls on flood probability. Empirical distribution functions of flood peaks in small catchments sometimes show discontinuities in the slope, that is, the largest flood peaks are significantly larger than the rest of the record. For Austrian alpine catchments Rogger et al. (2012) suggest that these step changes are the consequence of a threshold of storage capacity being exceeded, which causes fast surface runoff in large parts of the catchments. This step change effect is not captured by flood frequency statistics which tends to underestimate floods in these catchments.

Another example of the effect of runoff processes on the flood distribution function is shown in Fig. 6. The left graphs show the flood frequency curve and the associated event runoff coefficients for the Weißach catchment at Zwing located in West-Austria (Merz and Blöschl, 2008a). Owing to orographic enhancement of north-westerly air-

Floods and climate

B. Merz et al.

flows, rainfall is high and persistent and runoff coefficients tend to be constantly high. As rainfall becomes more extreme, runoff coefficients only increase moderately as they are already close to unity, and the flood frequency curve of the catchment shows a downward curvature. Assuming that the rainfall regime remains similar, and on the basis of

5 the runoff coefficients, one would expect that the trend continues as one extrapolates to higher return periods. In contrast, runoff coefficients of Wulka at Schützen in the dryer eastern part of Austria are much lower and increase with increasing return periods. The flood frequency curve shows an upward curvature and, on the basis of the analysis of the runoff coefficients, one would expect that this trend continues, assuming

10 the rainfall regime remains similar. Hence, the information on runoff coefficients gives more confidence in extrapolating to higher return periods.

The idea that the flood frequency curve is a fingerprint of important processes can finally be extended to flood routing and river-floodplain interactions. Apel et al. (2009) show for the Lower Rhine in Germany that dike breaches lead to significant retention

15 effects by pruning the flood waves which, in turn, modify the flood frequency curve downstream of breach locations. This effect only occurs beyond a certain (extreme) threshold, and it is typically not contained in observed time series. Hence, a process-neutral, purely statistical approach, i.e. not including this specific process in the extrapolation to extreme floods, results in significant overestimation of large flood quantiles.

20 We conclude that the past dominance of process-neutral approaches to the flood estimation problem should be substituted by more process-based avenues. We support the reasoning of Merz and Blöschl (2008a, b) who argue that much better use should be made of the wealth of knowledge on hydrological processes in estimating flood probabilities and have introduced the concept of *flood frequency hydrology*. It is

25 based on a systematic expansion of information on flood processes beyond the flood sample at the site of interest, in order to derive more informed estimates of flood frequencies. By combining local flood data statistics with additional temporal information on historic floods, spatial information on floods in neighbouring catchments, and causal information on the flood processes, the subtleties of the flood characteristics at the site

of interest can be more fully captured and the uncertainty of the flood quantile estimation reduced. It is important to note that the complete spectrum of processes – in the atmosphere, catchment, river system and floodplains – should be included in a process-based flood estimation. This is a very broad definition of flood frequency hydrology and subsumes, for example, elements of the flood hydro-climatology concept of Hirschboeck (1988).

3.2   Climate change: model chain vs. model chain augmented?

Anthropogenic climate change is perceived as particularly relevant by authorities responsible for flood design and management. Therefore, in this section the benefit of understanding climate–flood linkages for projections of future floods under climate change is elaborated.

The typical approach for deriving future flood hazard scenarios under climate change is to implement model chains consisting of the elements: "emission scenario → general circulation model (GCM) → downscaling, possibly including bias correction → hydrological catchment model → flood frequency analysis" (e.g. Dankers and Feyen, 2009; Kay et al., 2009; Ott et al., 2013), with the emission scenarios stemming from scenarios of future economic and social development (Nakicenovic and Swart, 2000). IPCC has changed the climate change impact modelling concept slightly with the introduction of the concept of representative concentration pathways (Moss et al., 2008), but this will not affect the above mentioned modelling chain except replacing the initial element from "emission scenario" to "representative concentration pathways" (Moss et al., 2010). In either case the natural variability in the general circulation models is produced without a link to the observed timing of variability mode stages. The "pure" climate change signal can thus be analysed in ensembles of model simulations. Multi-model ensembles can reduce the uncertainties associated with deviations of individual model climatologies. However, uncertainty is still large in projected flood changes, and IPCC SREX (2012, p. 178) states that "overall there is low confidence in projections of changes in fluvial floods." One of the main uncertainty sources is the problem all GCMs have

in simulating regional and local rainfall. Causes for these shortcomings are influences of local orography and land-surface that are not resolved and small-scale processes which cannot be represented by a GCM. It is thus not recommendable to infer future changes in flooding directly from the GCM produced rainfall at individual grid points.

Statistical downscaling can be used to estimate the local rainfall from large-scale parameters. It can, for example, be based on the relationship between extreme rainfall and large-scale atmospheric circulation patterns (Arnbjerg-Nielsen et al., 2013). Circulation patterns or weather types, either subjectively (e.g. Hess and Brezowsky, 1952) or objectively (e.g. Philipp et al., 2007) derived, can take different atmospheric variables into account (e.g. direction of flow, atmospheric humidity, temperature). Climate change signals in the relevant weather types, in particular in the frequency of occurrence and persistence, can then be identified for the individual climate change simulations. Instead of (or in addition to) using weather types, it is also possible to identify cyclone tracks which are associated with extreme precipitation and enhanced flood risk in specific regions. A well-known example of a pathway associated with major flooding in Central Europe during summer is van Bebbers Vb track (e.g. Kundzewicz et al., 2005).

Where a strong climate–flood link can be identified for a given catchment, this link can be used to directly project future flood changes. For river gauges in the Mekong basin, Delgado et al. (2012) identify a statistical relationship between flood variance and the Western Pacific monsoon variance. A non-stationary flood frequency model is developed where the monsoon variance drives temporal changes in flood quantiles (Delgado et al., 2013). For climate change scenarios, the variance of the monsoon is extracted from GCM runs. The simplicity of the monsoon–flood link allows the derivation of large ensembles of flood projections under climate change almost immediately, when GCM output is available. Such approaches are promising – and complement the above mentioned climate change model chains – because they bypass precipitation which is poorly simulated by global and regional climate models. Rather, they are based on circulation-linked atmospheric variables, such as large-scale pressure fields

and wind velocities, which are frequently much better represented by climate models. Problems with this approach, as in all statistical downscaling procedures, occur when there is non-stationarity in the link between the scales and parameters, a lack of data for estimating them, or a need of extrapolation to situations far from the area for which the statistical link has been derived.

Notwithstanding the approach that is selected, one has to be aware of the current limitations of global and regional climate models which go beyond errors in simulating precipitation. For example, SSTs are one of the most important drivers for precipitation on decadal timescales (e.g. Bichet et al., 2011). The spatial patterns of SSTs are particularly relevant in driving regional precipitation. This is an issue of concern, considering that coupled atmosphere-ocean GCMs from the Coupled Model Intercomparison Project Phase CMIP3 and CMIP5 globally predict warming of SSTs that is too uniform (e.g. Shin and Sardeshmukh, 2011).

Another approach with great potential beyond the typical use of model chains is the development of process-based scenarios of flood response to realistic shifts in climate. For instance, in the US Southwest, where different flood-generating storm types dominate in different seasons (Fig. 5), the circulation features associated with each storm type are distinctly different. This information can be used to design alternative scenarios for a catchment's flood response to climate change. A poleward shift in the latitude of the current winter storm track, an increase or decrease in the magnitude or frequency of eastern North Pacific tropical cyclones, or an expansion of the low latitude tropical moisture belt that enhances the summer thunderstorm season would each have a profound impact on the overall probability distribution of flood peaks in southwestern US watersheds. Catchment-based future flooding situations, constructed by sampling observed floods within each of these flood types could be used to develop alternative planning scenarios for different regional atmospheric circulation responses to changing global climate drivers based on GCM output or projected circulation regime shifts (Fig. 7).

Floods and climate

B. Merz et al.

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Such scenarios could be derived via simulation or via data analysis, for example relying on historical periods with analogous conditions in the same catchment. Or one could derive possible future flood changes by investigating catchments which have a climatic regime that is similar to the regime we expect in the future in a specific catchment. Such process-based scenario approaches do not need to be based on the relation between floods and atmospheric moisture transport or storm tracks. They can be applied more directly to surface hydro-meteorological variables. For example, in several European regions human-induced climate change is associated with an increase in winter precipitation and a higher snow line. Although we may not be very confident about the actual future precipitation, we might be confident about the general trend of increasing winter precipitation and decreasing fraction of snowfall. Indeed watersheds in mountainous areas of the Western United States that rely on seasonal snowpacks are already vulnerable to shifts in the timing of runoff and increases in early spring flooding because warmer temperatures promote an earlier snowmelt season and more precipitation falling as rain instead of snow.

Such process-based scenarios might provide a space of possible future flood characteristics, conditioned on our current knowledge. This possibility space of flooding characteristics in a given catchment could be compared to the vulnerability of the elements-at-risk, separating catchments which require special attention from those which are less vulnerable to the conceivable changes in climate. Prudhomme et al. (2010) have introduced the closely related "scenario-neutral approach to climate change impact studies". It is based on sensitivity analyses of catchment response to a plausible range of climate changes. An advantage of this approach and related ideas, such as what-if analysis or cause-and-effect analysis, is that it is much easier to understand and interpret changes in flood behaviour. On the contrary, the complexity of the typical climate model chains impedes the understanding of how changes in climate propagate to changes in flood characteristics. Hence, in parallel to improving climate model chains and their reliability for flood projections under climate change, a better understanding of climate–flood linkages has a large potential for flooding under climate change.

Currently, human-induced climate change and natural climate variability are not operationally incorporated into flood management practice, in part because floodplain managers are constrained by the absence of accepted alternatives to standard stochastic methods. To overcome this impasse, there is a need for methods that can incorporate realistic, process-based climate change scenarios into the statistics of gauge records in ways that demonstrate an improvement on the traditional flood frequency analysis approach. Probabilistic methods now being used with paleoflood data present one approach, but they are not directed toward future climate change and are limited by the availability of paleoflood indicators in the landscape. Methods are needed that can augment existing flood peak records in ways that reflect how the climatic drivers of local hydro-meteorological processes have changed and will change in the past, present and future.

3.3 Flood risk management

What is the benefit of an improved understanding of climate–flood linkages for flood risk management? In the last two decades, flood change research has been dominated by studies looking at changes in flood hazard, for instance due to human-induced climate change (e.g. Feyen et al., 2012; Ott et al., 2013; Ward et al., 2013a), land-use change or river training (e.g. Bronstert et al., 2007). Today it is recognized that all risk elements are dynamic through time, not only hazard (IPCC, 2012; Jongman et al., 2012). Amongst other factors, the vulnerability and exposure of people and economic assets are determined by phases of development. Further, a single driver may influence different risk components. For example, the societal perception of flood risk may be strongly influenced by a damaging flood which may trigger investments in structural flood defence, such as flood retention basins, and may change flood hazard. In parallel, it may change exposure by flood-affected companies and private households migrating out of heavily flooded areas, and vulnerability by triggering private precaution in the flooded areas (Petrow et al., 2006; Kreibich et al., 2011). Bubeck et al. (2012) show that societal responses are critical in understanding how vulnerability to floods changes over

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time. This study surveyed 752 households along the River Rhine in Germany that experienced floods, with two major floods in 1993 and 1995. The results indicate that flood damage mitigation measures were implemented by households gradually over time, with major flood events being important triggers for an accelerated implementation. Especially in the aftermath of the severe flood in 1993, a remarkable increase in the number of undertaken measures was observed.

In addition, spatio-temporal interdependencies between vulnerability, exposure, and hazard have to be expected. Current risk assessments, if they include dynamics at all, often examine dynamics in one of the components, whereas the interdependencies could be crucial (Di Baldassarre et al., 2013). For example, flood protection by dikes aimed at reducing the flood hazard can lead to increased development behind dikes, thus increasing exposure, the so-called levee effect (Tobin, 1995). In areas with high protection standards by dikes, individuals and societies may have low risk perceptions, and thus be less prepared for floods, in other words, they may have high vulnerability (Bubeck et al., 2012; Zaalberg and Midden, 2013). Spatio-temporal changes in all of these factors influence the overall flood risk.

Another factor that has received little attention in flood risk studies is the role of climate variability. As discussed earlier, many studies have found linkages between climate variability and extreme streamflow. A number of studies are now taking the step of examining whether such linkages can be detected between climate variability and flood losses. A preliminary analysis of recorded economic flood costs in Australia shows these to be sensitive to climate variability. Table 2 illustrates that average flood damages in Australia are significantly higher in La Niña years than in non La Niña years. This signal appears to be robust to the loss data used, with significant differences for both loss data sets (EM-DAT, CRED, Belgium, and data on insured losses from the Insurance Council of Australia).

The work of Ward et al. (2010, 2014) on relationships between ENSO and river flooding at the global scale is currently extended to assess the impacts of ENSO on risk (rather than discharge). Using the global flood risk modelling framework described

in Ward et al. (2013b), preliminary results presented at the EGU Topical Meeting in Potsdam show that there are clear and significant regional patterns of ENSO influence on disaster risk, in terms of both affected population and economic damage. Hence, socio-economic risks may to some extent be linked to climate regimes which could have major implications for the insurance and re-insurance industry. For example, clustering of flood events increases the likelihood of a high number of damage claims within a short period of time – an issue which is aggravated if clustering is spatially coherent and damaging events occur at different locations within a short time interval.

Figure 8 visualises the concept of dynamic flood risk and dynamic risk management, based on the climate informed risk management approach of Pizarro et al. (2009). Since all components of risk vary in time, flood risk itself is dynamic. Some aspects of flood risk dynamics may be predictable, many others not. For example, changing climatic boundary conditions at inter-annual to decadal to century scales may be due to structured natural variability or anthropogenic factors or their interaction. Some of these changes may be smooth and potentially predictable over some time scale, while others (e.g. a reversal of the Atlantic Gulf Stream) may be abrupt and can be anticipated but not predicted. Given the fact that ENSO events are predictable to some extent across seasons (Cheng et al., 2011), it appears worthwhile to test the predictive skill for seasonal flood forecasts in those regions where Ward et al. (2014) have shown a strong sensitivity of peak discharges to ENSO. Drivers other than climate may be predictable to some extent, as well. For example, exposition in the tourism and agricultural sector may vary regularly in the course of the year.

The potential predictability of flood hazard and risk varying at seasonal to decadal time scales opens the door for a dynamic risk management paradigm. Assume that one can quantify the climate mechanisms that result in changing flood characteristics over a certain future time period. Then one could use the projected statistics and their uncertainty distribution to inform risk reduction measures. For example, if one knows that a flood rich period is active in a given region, and that one has to expect higher probabilities for damaging floods during the next few years, this knowledge can be used

to optimize disaster management (optimized strategies in Fig. 8). Relief stocks and emergency capabilities could be temporarily increased, reservoir water levels could be temporarily lowered to allow for more flood retention volume, temporary levees could be built or floodplain zoning rules for different activities could be temporarily imposed. The predictability of the climate–flood link would allow optimizing the portfolio of risk reduction measures.

On the other hand, many future flood risk changes are expected to be severe but are not predictable. In such cases robustness is an important criterion for designing risk management strategies. Robustness describes how well a measure performs under different possible but initially uncertain future developments. Flood proofing strategies, such as elevated configuration of buildings, sealing of buildings to prevent water entrance, or the use of building materials in such a way that the impact of inundation is minimized, are robust in the sense that these measures will lower the damage in case of flooding, regardless of the exact future development of the flood hazard (Merz et al., 2010). Another example is the enhancement of risk awareness and self-protecting behavior of people at risk. If residents are aware of their flood risk and of their possibilities to undertake effective precautionary, adverse flood impacts will be reduced under different possible but initially uncertain future developments. Risk reduction measures that are designed to be robust differ from measures that are the result of an optimization for the most likely future development. They represent trade-offs and are associated with real or opportunity costs (Heltbert et al., 2009). Hence, the degree of predictability of future changes in flood hazard and risk influences the role that different criteria play in designing risk management measures (Blöschl et al., 2013).

As an example, consider seasonal flood forecasts in the insurance and reinsurance industry. Companies try to take short-term changes in loss probabilities into account in managing their lines of business. If, for instance, a wet year with above-average flood losses is expected in a certain region (such as in Northeastern Australia during La Niña), less business may be written to reduce accumulation risks. Apart from underwriting-related reactions on seasonal forecasts, preparation on high/low losses

in terms of management of reserves may be done; short-term liquidity for flood losses can be raised or reduced. Also, reinsurers and insurers "like" to provide services to their clients in the form of recommendations based on the characteristics of the upcoming flood season, not least to show their expertise. The advantage the insurance sector derives from seasonal forecasts results from the fact that it does not deal with a specific, localized issue. For an emergency planner in a city a shift in event probability of a few percent is almost without meaning; in the case of a (re-)insurance company this shift concerns a whole portfolio with a large number of exposed items, hence even a small shift in probability may be traced in the total amount of losses.

4   Conclusions: broader framing and global initiatives

Traditionally, flood estimation and flood management have mainly been the domain of hydrologists, water resources engineers and statisticians, and disciplinary approaches have abound. Embedding floods in the climate context, as laid out in this paper, requires to extend this narrow framing. It is timely to bring together the different aspects of floods at the interfaces of the climate–catchment–society system. The discussions during the EGU Topical Meeting on "Floods and Climate" converged to a common understanding that extending the perspectives in flood research opens up exciting possibilities for better understanding and for providing improved tools to flood risk assessment and management. The conclusions can be summarized as follows:

4.1   Extend the system boundaries

We argue for extending the traditional system boundaries (local catchment, recent decades, hydrological/hydraulic processes) in flood estimation and management. Extension in space goes beyond the inclusion of regional information which has proven beneficial in regional flood frequency analysis. Floods are embedded in global climate mechanisms, and deciphering these relations promises to improve flood estimation

and management, such as better understanding the tail behaviour of flood distributions or improved flood forecasting. However, it has been found that catchments respond rather differently to global climate variability (e.g. Glaser et al., 2010, for 12 major rivers in Europe for 1500–today). Hence, there exists a large variety of climate–flood link-ages, and the existence of a marked climate–flood relation within one catchment does not automatically allow transferring it to other catchments in the same region. This extension of perspective concerns the temporal system boundaries as well. For example, new technological developments allow reconstructing millennial-scale flood time series differentiating between floods in different seasons. The integration of systematic measurements with historical and paleo-data offers exciting prospects for quantifying flood variability and extremes at very different time scales, from the decadal to the millennial time scale. And finally, it is noted that a richer understanding of floods requires considering the interplay of climate, geology, topography, vegetation (biology), and humans. Experiences, methods and data from a variety of scientific disciplines, e.g. meteorology, climatology, paleo-hydrology, geography, economics, and from practitioners, e.g. insurance, disaster management, water authorities, need to be integrated.

4.2 Understand the dominant processes

We argue that different societal needs, such as flood estimation and forecasting, benefit from better understanding the processes that dominate the tail behaviour of flood distributions. Although statistical approaches have played and will play an important role, they have to be complemented by the search for the causal mechanisms and dominant processes in the atmosphere, catchment and river system that leave their fingerprints on flood characteristics. Understanding the dominant processes is expected to increase the reliability of extrapolation to rare floods and to reduce the potential for surprise. It is also an avenue for flood projections under climate change – complementing the widespread model chain approach. Understanding the different flood event types that occur in a given catchment and their dominant processes may provide an opportunity to hypothesize from a causal, mechanistic perspective about possible future flood

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changes. For example, spatial shifts in storm tracks or changes in the snowfall fraction may impact flood characteristics in certain ways.

4.3 Quantify the role of natural variability

One of the core concepts of this paper is that natural variability has an important role to play in flood estimation and flood management – besides delivering the random component. We argue that flood characteristics vary in time, that this variation may be partially quantifiable and predictable, and that knowledge about this structured variability may be exploited in flood estimation and management. It is necessary to understand the ratio of structured variability to random variability, and how this ratio varies in space, with flood types, with flood magnitude. For example, the structured variability for most regions in Europe is significantly smaller than in the US. One task is to identify regions for which predictable climate–flood links play a significant role and regions where randomness dominates. Another mainly open question is how the type and strength of climate–flood linkages vary with flood magnitude. Floods of different magnitude may correspond to different climate modes (for an illustrative example see Jain and Lall, 2000), and these variations need to be understood. Maybe the most important aspect is the persistence of climate–flood linkages: how stable are linkages between climate and floods? Results are mixed: for instance, flood favouring circulation patterns have been found in many studies, but it has been found as well that during different flood-rich periods of a given river different circulation patterns have dominated (Schmocker-Faeckel and Naef, 2010). This is part of the more general discussion on the evidence of cycles in climate phenomena: as Burroughs (2003, p. 5) states in his comprehensive treatise on such cycles: "...a fundamental weakness of many apparently convincing examples of 'weather cycles': they come and go in a most tantalising manner." The central question for a dynamic flood risk management concept which considers climate–flood linkages is, whether these linkages constitute a sufficiently large part of the observed variability to be exploited in risk management strategies. Although there are some con-

vincing examples, the potential of climate informed risk management needs still to be explored.

4.4 Integrate hazard with societal aspects

Although the focus of this paper is on the role of climate, we stress the tremendous role of society. Ideally, risk assessment and management consider changes in hazard *and* societal aspects, and varies according to the predictability with which short- and long-term changes in flood risk can be quantified. Increasing efforts are needed to fully account for factors that contribute to changes in risk, which implies that changes in vulnerability (e.g. early warning, building codes) and exposure (e.g. population growth, spatial planning) need to be considered when interpreting records of observed flood losses. However, the understanding of the interplay between changes in hazard, exposure and vulnerability is hampered by data scarcity. The knowledge on disaster costs is incomplete and fragmented, with many cost types unaccounted for in current analyses, and a heavy focus on direct losses and less complete understanding of longer-term impacts and indirect costs (Merz et al., 2010b). While changes in the number of exposed assets and people can be reasonably accounted for, temporal changes in vulnerability that are critically important are poorly understood and quantified. The interactions and feedbacks between society and floods are little understood. For instance, is the societal response to floods different for clustered events compared to random events? Here, we support the call for socio-hydrology which explicitly studies the co-evolution of humans and water (Sivapalan et al., 2012).

4.5 Organize data and knowledge exchange globally

The advancement of flood research in the discussed broader framework is fundamentally dependant on (1) access to and exchange of fit-for-purpose data on a global scale and (2) increased international and national collaboration between different disciplines, in particular hydrologists and meteorologists/climatologists. On a global level the iden-

tification of climate-driven changes in river flow is hindered due to a lack of long qual-ity data from rivers limited from artificial human disturbances (Whitfield et al., 2012). Therefore, in the past 15 yr several countries have established reference hydrologic networks (RHN) with the sole purpose of assessing hydrological responses to fluctu-ations in climate (Hannaford and Marsh, 2008; Whitfield et al., 2012; Murphy et al., 2013). Despite these efforts the majority of regions across the globe have yet to es-tablish such databases. Data users have a responsibility to promote the need of such data for their analyses in order to increase the global distribution of RHN like networks. However, significant economic and institutional barriers to the open access of hydro-meteorological data remain (Viglione et al., 2010; Hannah et al., 2011) and need to first be overcome. Hydrologists could learn from the climate community that actively advocate open data access and support data exchange (Hannah et al., 2011). Given the global scale and societal importance, we call for the organization of an international multidisciplinary collaboration and data sharing initiative to understand further the links between climate and flooding. This would require the integration of meteorological, cli-matological and hydrological expertise in conjunction with increased access to coupled RHN and meteorological databases. While this is ambitious, discussions need to take place now for such an initiative to ever be realised even within medium-term flood risk planning horizons.

There have been some initiatives for studying floods in their global context. One of the earliest was the Natural Disaster Hotspots study of the World Bank (Arnold et al., 2005), which prepared a preliminary map of global flood hazard frequency, and exam-ined mortality and economic risk. Recently, modelling efforts are undertaken with the aim of assessing global flood hazard and risk (UNISDR, 2011; Hirabayashi et al., 2013; Ward et al., 2013b; Winsemius et al., 2013). A different and very interesting path has been initiated by the earthquake risk community by launching the Global Earthquake Model (GEM, www.globalquakemodel.org). GEM is a collaborative effort and involves scientists and stakeholders from around the globe. Data, models, open-source soft-ware, and knowledge are shared with the final aim of expanding the science of earth-

quake risk, informing decision making and increasing earthquake resilience worldwide. We feel that the flood research community should foster global approaches and should study physical and societal mechanisms of flooding within their global interconnectedness. This global perspective would not only improve our understanding and exploitation of linkages between climate and flooding, but would also help to understand and mitigate far-distance impacts of flooding, such as the disruption of global supply chains.

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Title Page

Abstract | Introduction

Conclusions | References

Tables | Figures

◀ | ▶

◀ | ▶

Back | Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

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Title Page

Abstract   Introduction

Conclusions   References

Tables   Figures

◀   ▶

◀   ▶

Back   Close

Full Screen / Esc

Printer-friendly Version

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Title Page

Abstract | Introduction

Conclusions | References

Tables | Figures

◄ | ►

◄ | ►

Back | Close

Full Screen / Esc

Printer-friendly Version

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Floods and climate

B. Merz et al.

Title Page

Abstract | Introduction

Conclusions | References

Tables | Figures

◄ | ►

Back | Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

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Title Page

Abstract | Introduction

Conclusions | References

Tables | Figures

◀ | ▶

◀ | ▶

Back | Close

Full Screen / Esc

Printer-friendly Version

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Title Page

Abstract | Introduction

Conclusions | References

Tables | Figures

◀◀ | ▶▶

◀ | ▶

Back | Close

Full Screen / Esc

Printer-friendly Version

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Floods and climate

B. Merz et al.

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5

Table 1. Contrasting traditional views with emerging perspectives on flood hazard and risk.

|	Aspect	Traditional view	Emerging perspective
Understanding climate–flood linkages	Randomness	**Random**: Floods are random events with flood magnitude quantified by a probability distribution.	**Causal**: Flood occurrence and magnitude depend on a causal network of processes in atmosphere, catchment and river system. A fraction of the flood variability is described by deterministic processes, for example, by using climate information as co-variates in flood probability distributions.
	Spatial perspective	**Local**: Floods are events that can be described fully by processes on a catchment scale.	**Global**: Floods occur within spatial framework of large-scale circulation patterns, and global climate mechanisms.
	Natural variability and floods	**Stationary**: Flood characteristics are stationary and represent the long-term natural variability of the climate-catchment system.	**Time-varying**: Flood characteristics change in time due to climate variability at different time scales.
	Temporal perspective	**Recent**: Flood characteristics result from current catchment characteristics and are derived from recent observations.	**Long-term**: Flood characteristics result from the long-term interplay of climate, geology, topography, vegetation (biology), and humans. To fully understand floods, this long-term interplay has to be disentangled.
Exploiting climate–flood linkages	Flood estimation	**Process-neutral**: Flood estimation does not differentiate between different flood event types and processes. Flood frequency analysis is based on iid assumption.	**Process-based**: Flood events of different types occur in a given catchment. Knowledge on flood generation processes informs flood probability estimation.
	Flood projections under climate change	**Model chain**: Flood scenarios are the result of model chains, from emission scenarios through climate models to flood frequency estimation.	**Model chain augmented**: In addition to model chains, a range of approaches for assessing climate-related flood changes are used, such as assessing historical climate variability, or using ocean source –atmospheric moisture transport – flood linkages.
	Flood risk management	**Hazard-focused, static**: Flood management focusses on flood hazard reduction within a static framework, principally using structural or zoning flood proofing or financial instruments (insurance).	**Risk-oriented, dynamic**: Risk management takes into account changing hazard, exposure and vulnerability, and the combined application of financial, structural and non-structural measures. The best way to mitigate floods depends on how well changes in flood risk can be predicted at short and long time scales.

Table 2. Average economic flood losses in Australia stratified according to ENSO phase. Analysis based on data from EM-DAT (CRED, Belgium) for 1971–2010, and insured loss data normalised for changes in wealth from the Insurance Council of Australia, for 1967–2010 (for method see Crompton et al., 2008). T test and Mann–Whitney U test were applied indicating the significance of the differences in average losses.

Dataset	N	Average damage		t test	MWU test
		La Niña	Non La Niña		
EM-DAT [mn US$]	57	1070	142	$p = 0.026$	$p = 0.014$
Insurance Council of Australia [mn AUS$]	50	369	61	$p = 0.014$	$p = 0.024$
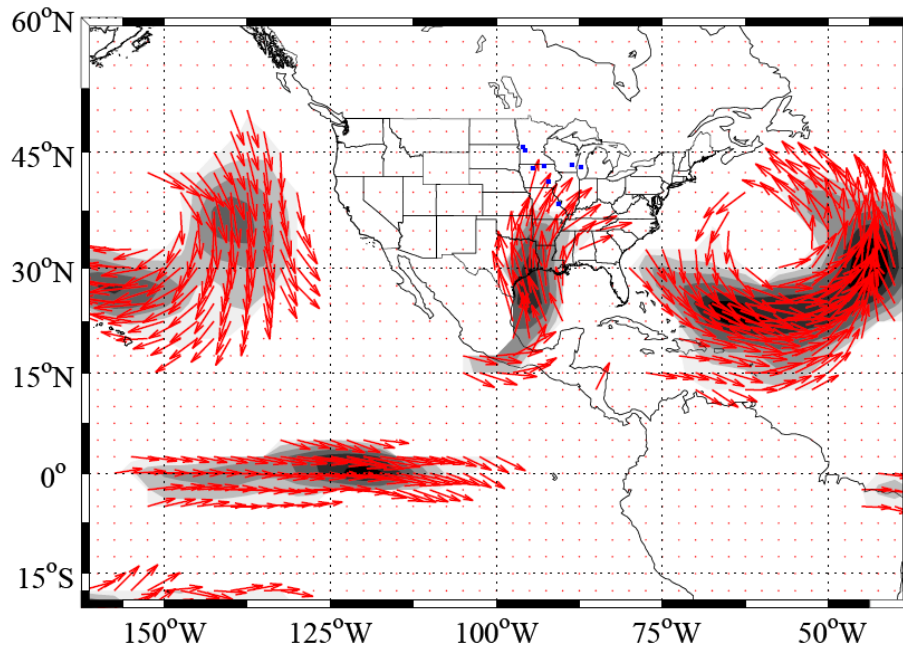
Fig. 1. Vertically integrated moisture flux averaged over the dates of the 10 largest floods in the Ohio River Basin in North America from 1948 to 2005. The flux is computed daily over 1000–850 mb, using the NOAA-NCEP re-analysis data set. The arrows show the wind direction while the shading shows the intensity of the moisture flux. Only pixels whose moisture flux magnitude is in the top 5 % of the visible map are shown. Note that a large-scale meridional low level flow into the region is active averaged across these 10 events.

Mississippi Floods in middle west following a wet Spring and strong snow melt

Texas, Northern Mexico: Extreme draught together with the hottest summer ever => 21,000 bush fires, 1500 real estates burned down

El Salvador, Huzucar: 1653 mm rain from 10.-15. October 2011

Brasil, Venezuela and Columbia: wide spread too wet

Simbabwe, Botswana, Namibia, Angola, northern RSA: January until March, 2 - 4 times above average

East-Africa: Extreme Drought from October 2010 ,til September 2011 Later, however, ways to much precipitation occurred for the rest of the year. More than 13 Mio. people become dependent on humanitarian aid.

South-East-Asia: Extremely long und strong monsoon season (Mid May until October). Catastrophic flooding along rivers **Mekong** and **Chao-Praya** including **Bangkok**. Death toll in **Cambodia and Thailand** exceeding 1000. Wettest year ever in the latter country.

Philippines & Indonesia: wide spread too wet

China: Much too dry Southeast: **Yangtse Ebene** 47% of average (record); **Hongkong**: 60% of average

Australia: Third wettest year ever.

All time record for two-years total 2010/2011

February: YASI, Kat.4 Hurricane in Queensland

Fig. 2. Centennial climatology of ENSO sensitive regions with regard to the global land-surface precipitation from 1901–2010. Blue (red) areas have enhanced (reduced) precipitation during La Niña periods. In addition, the circles and boxes point to extreme hydro-meteorological events (including devastating floods) which occurred during the strong La Niña year 2011.
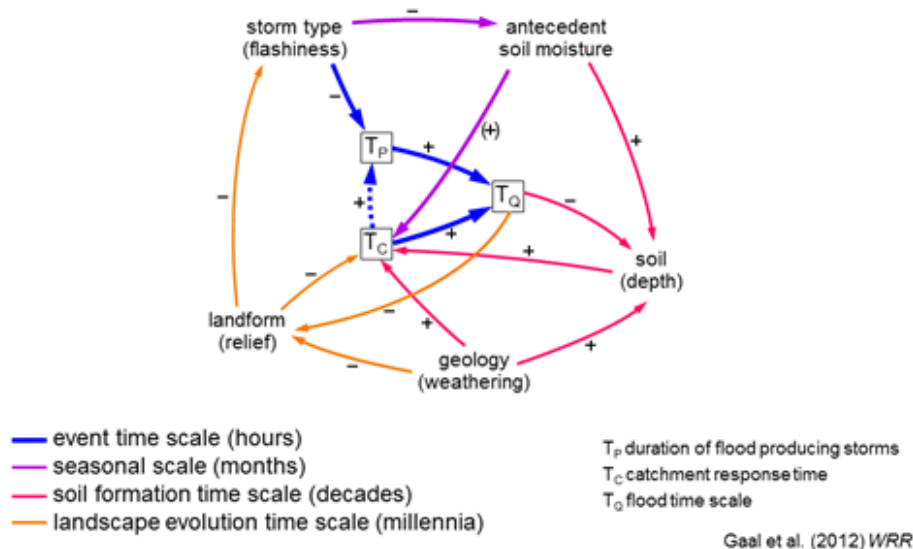
Fig. 3. Schematic of the coupling of process controls on the flood time scale. Plus and minus signs indicate whether coupling is positive or negative, i.e. whether an increase in a variable increases or decreases another variable. T_P: precipitation time scale, characteristic duration of rainfall producing a maximum annual flood; T_C: catchment response time scale, time delay of catchment routing; T_Q: flood time scale, characteristic flood duration (from Gaál et al., 2012).
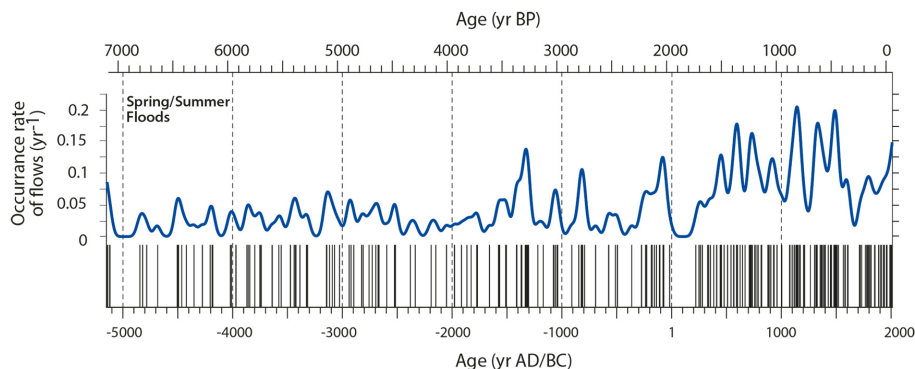
Fig. 4. 7000 yr reconstruction of flood events from Lake Mondsee, Upper Austria. Lower panel: occurrence of flood events. Upper panel: occurrence rate calculated by using a Gaussian kernel regression with a 30 yr bandwidth (data from Swierczynski et al., 2013).

Title Page

Abstract   Introduction

Conclusions   References

Tables   Figures

|◄   ►|

◄   ►

Back   Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion
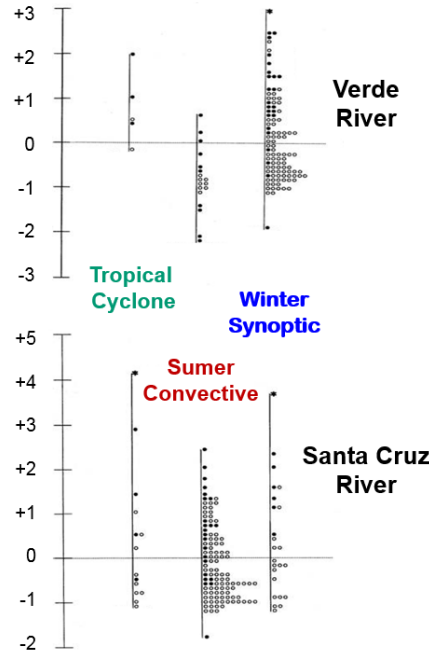
Fig. 5. Stratification of flood events according to climatic mechanism. Climate-based flood heterogeneity is evident in two Arizona watersheds when observed flood peak distributions are stratified according to the three dominant flood-producing mechanisms in the Southwestern United States. Shown are histograms of instantaneous peaks-above-base, plotted as standardized dimensionless z-scores for comparison. The Santa Cruz River at Tucson floods most frequently in response to summer convective thunderstorm rainfall, but the two largest peaks of record were produced by tropical cyclone-enhanced rainfall and precipitation from winter synoptic storms, respectively. In contrast, in the Verde River below Tangle Creek, some 300 km to the north, the most frequent and largest floods are produced by winter precipitation events (based on House and Hirschboeck, 1997).
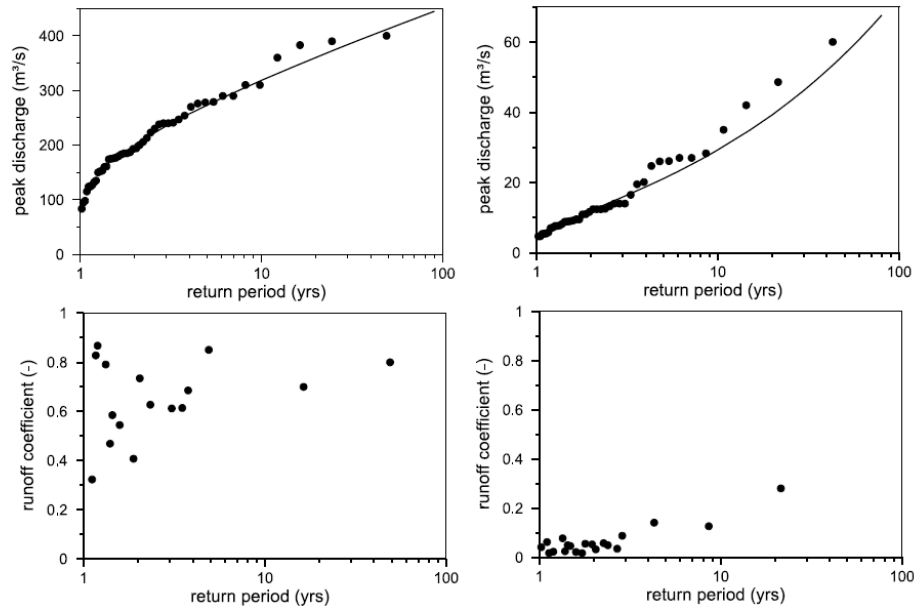
Fig. 6. Flood frequency plots (top) and runoff coefficients (bottom) of the associated flood events for (left) Weißach at Zwing (199 km^2) and (right) Wulka at Schützen (383 km^2) (from Merz and Blöschl, 2008a).
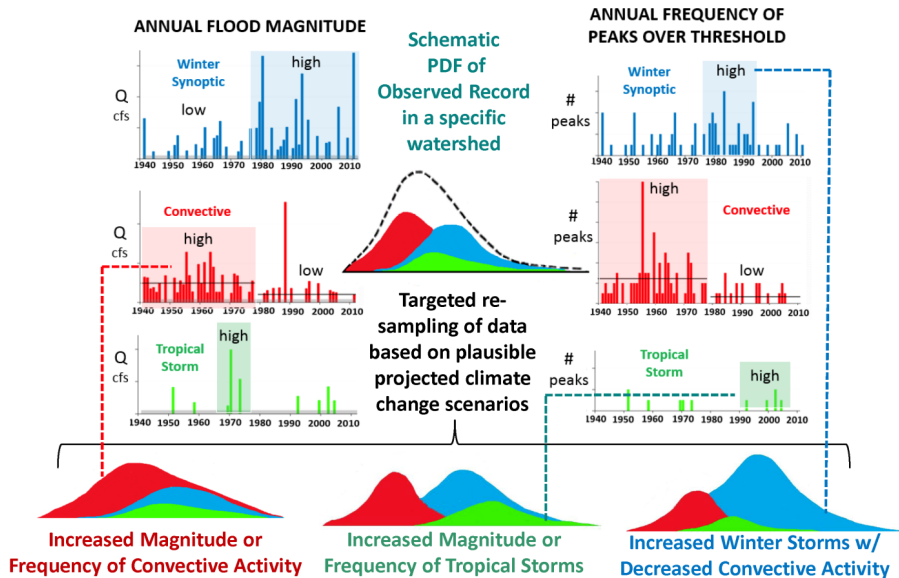
Fig. 7. Schematic illustration of a proposed method for the development of process-based flooding scenarios by re-sampling distinctive segments of the observed flood record. Extreme flooding variability often occurs as clusters or episodes of high or low magnitudes of annual flood maxima (left-hand side of figure), and/or high or low frequencies of flood peaks that exceed a defined threshold (right-hand side of figure). To use these modes of variability in scenario development, the flood record can be partitioned into separate time series for each atmospheric circulation-linked flood-generating process (i.e., winter synoptic, convective, or tropical storm), and then analysed using subjective and objective methods (e.g., change-point analysis) to identify statistically significant and climatically unique episodes of extreme flooding behaviour (shaded segments of flood time series). The magnitude and frequency attributes of the flood peaks in each unique episode can then be iteratively sampled and recombined to simulate new modes of flood-generating behaviour during plausible projected climatic shifts (e.g., increased magnitude and frequency of winter synoptic storms combined with decreased frequency of convective activity).

Title Page

Abstract | Introduction

Conclusions | References

Tables | Figures

|◄ | ►|

◄ | ►

Back | Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

Full Screen / Esc

Printer-friendly Version

Interactive Discussion
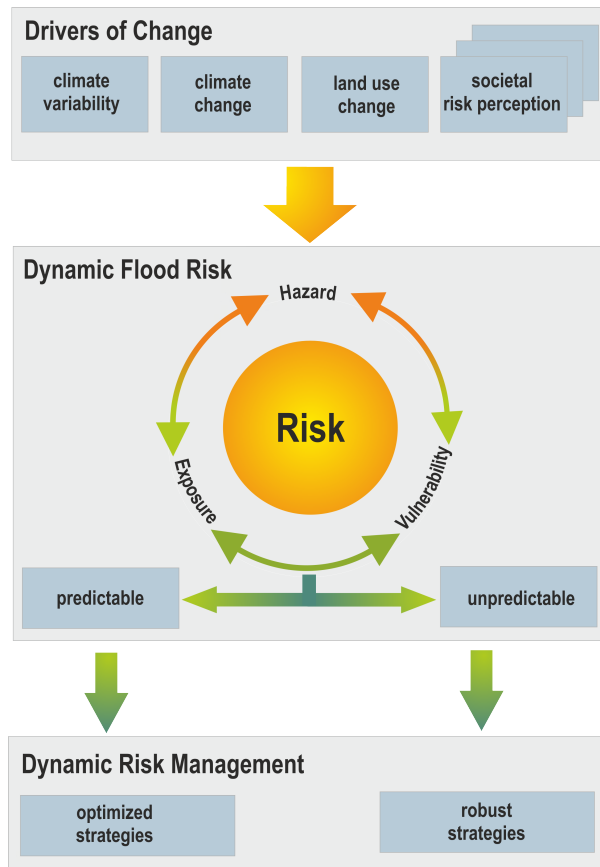
Fig. 8. Drivers of flood risk change, dynamic risk and dynamic flood risk management.