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PAGES 253–260

How Does Climate Impact Floods? Closing the Knowledge Gap

PAGES 253–254

Destructive floods impose severe consequences on societies, leaving havoc and death in their wake. Annually, an average of 9000 people are killed, and 115 million require immediate assistance or are displaced by floods worldwide. Because of population increase in flood-prone areas alone, the number of people exposed to floods in North America is expected to almost double in 2030 compared to 1970 [*National Research Council,* 2013]. It is no wonder that floods are considered serious threats by government agencies and municipal planners, but the impact of climate change on these numbers is still somewhat uncertain.

Despite the need for detailed information on how changes in flood frequency and magnitude are linked to and explained by climate change, scientific understanding of flood patterns and triggers is lacking. The reasons for this deep knowledge gap—where weather, climate, and runoff regimes merge—are manifold. Poor model resolution, short monitoring series (less than 50 years), and limited station networks hamper knowledge of broad trends in flood frequency and magnitude [*Lubchenco and Karl,* 2012].

Increasing model resolution and expanding monitoring networks are already helping to narrow this gap, but to close it scientists need to include new paleodata that capture a wider spectrum of both flood and natural climate variability than what has been available. Producing reliable flood time series that cover thousands of years requires, in turn, optimal sedimentary archives where sediments are properly understood.

New Flood Patterns and Mechanisms

The Intergovernmental Panel on Climate Change's (IPCC) latest assessment report [*IPCC,* 2013] says that the understanding of how climate relates to changing flood variability has "low to medium confidence." This is particularly worrisome considering that the anticipated acceleration of the hydrological cycle comes with a 30% increase in Northern Hemisphere precipitation, according to most IPCC estimates. Additional stress is added to this situation because according to the same report, there is "high confidence that past floods larger than those recorded since the 20th century have occurred during the past 500 years in northern and central Europe, western Mediterranean region, and eastern Asia" [*IPCC,* 2013, p. 425]. In other words, a greater span in flood variability exists than one might infer based on recent data on modern streamflow.

On a global scale the number of floods is predicted to increase, albeit with large spatial variations [*Dankers et al.,* 2014; *Hirabayashi et al.,* 2013]. Keep in mind that floods can be triggered by various causes and adaptive measures range widely among societies because of differences in existing infrastructure (dams, spillway systems, etc.), economics, and other societal factors. In lowland Europe, for example, where floods are the most frequent natural disaster [*European Academies Science Advisory Council,* 2013], rainstorms are the primary cause of repeated flooding. This type of flooding is different from flood patterns in high-latitude and mountainous landscapes, where the amount of snow is central to variations in spring and summer floods.

Because the geophysical processes overlap, drawing a straight line between various trigger mechanisms and flood patterns is tempting but futile—rainstorms, heat waves, and large snow reservoirs are not mutually exclusive. Still, if flood variability could be constrained by more lasting climate trends or semipermanent atmospheric pressure patterns such as the Intertropical Convergence Zone (ITCZ), El Niño–Southern Oscillation (ENSO), the Pacific Decadal Oscillation, or the North Atlantic Oscillation (NAO), the potential range of flood scenarios could possibly be improved.

Strengthening such a link scientifically could help stakeholders reach informed decisions about whether or not society should implement adaptive measures. Climate models are important tools that are used to assess such connections, but the task is complicated, and downscaling so that relatively small catchments can be included creates a number of challenges and uncertainties. A way to ground truth the models is to complement them—as well as modern flood time series—with paleorecords that extend thousands of years back in time (see Figure 1). Building such paleorecords can provide a more complete view of the factual range of natural variability.

Progress With Past Records

Lake sediment records have proven particularly suitable as archives of past floods because lake basins act as sediment traps for material mobilized by vigorous floodwaters. They are also purely depositional environments that can be unaffected by erosion.

Sediment cores may be subjected to various physical analyses to single out signatures of floods—for example, changes in grain size, magnetic mineralogy, or variations in trace elements that can be related to an increased transport from an upstream river source and hence be a proxy for floods—and quantify what the flood-transported sediments reveal about the magnitude of flooding. Combined with accurate age estimates, such analyses documenting past flood activities have resulted in a fast-growing body of high-resolution studies published over the past 3 years.

These studies have produced unprecedented flooding records (Figure 1) covering the past 10,000 years. The most striking, and also basic, observation in these records is that the frequency of floods changes drastically over time, with prominent trends lasting from a decade to millennia. The natural variability is, in other words, considerable compared to modern time series.

This is a valuable observation because most hydrological models based on potential future scenarios assume stationarity—the idea that "natural systems fluctuate within an unchanging envelope of variability" [*Milly et al.,* 2008, p. 573], which do not allow for variations superimposed on the underlying trend, be they gradual or stepwise.

It follows from climate change that the flood recurrence interval or return period is very much a moving target. Hence, a 100-year flood event can rapidly become a 10-year flood or vice versa as the climate shifts. This proposition caused *Milly et al.* [2008] to suggest the

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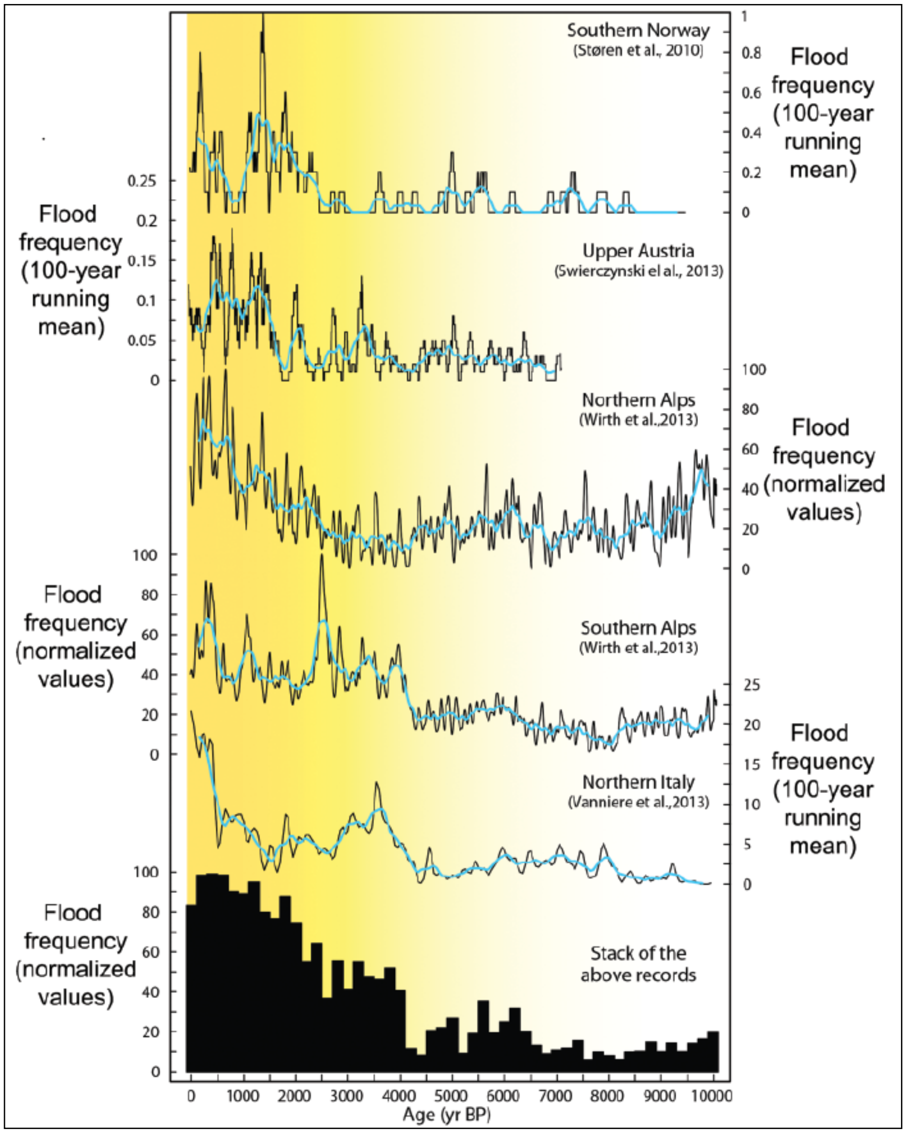

*Fig. 1. Five high-resolution time series of flood variability from southern Norway [*Støren et al., *2010] and the European Alps [*Swierczynski et al., *2013;* Vannière et al., *2013;* Wirth et al., *2013]. These new detailed reconstructions reveal how the frequency of floods has varied during the 10,000 years before present (BP). Major changes that are not easily explained by regional climate trends can be seen, yet major trends are consistent, such as the increase in floods starting around 4000 years ago. Individual time series are calculated using slightly different statistical approaches, which are presented in the corresponding references. Blue lines show 300-year running means. The stacked record is a normalized (0%–100%) sum of all five records for consecutive 200-year periods.*

death of stationarity. It also raises an equally important question: How far into the future can the past carry us [*Stedinger and Griffis,* 2011]?

Another interesting observation is that in many of these new records, periods of extremely low flood activity compared to present day occur during certain time intervals such as the Holocene Thermal Maximum (9000–6000 years ago), when summer temperatures were 1°C–2°C warmer in many parts of the Northern Hemisphere. This indicates that there are indeed dynamic thresholds in terms of catchment response if the climatic sways are large enough. The widely observed boost in floods after 4000 years ago represents such a dramatic shift (see Figure 1).

Flood Triggers in the Climate Record: Moving Beyond the Usual Suspects

The Swiss-based FloodAlp project has contributed significantly to recent progress in creating proxy records [e.g., *Glur et al.,* 2013; *Vannière et al.,* 2013; *Wirth et al.,* 2013]. For instance, *Glur et al.* [2013] use 10 lake sediment records to reveal how the frequency of floods in southern Switzerland has fluctuated throughout the past 2500 years, even on seasonal time scales. The authors link these variations to atmospheric circulation patterns—these, in theory, can explain parts of the flood variance observed. They specifically suggest that shifts in storm tracks and that the NAO have explanatory power [see also *Wirth et al.,* 2013].

Interestingly, *Støren et al.* [2012] performed a comparison of trends in flood frequency and potential shifts in atmospheric pressure patterns. Although the NAO is strongly correlated to winter precipitation along the coast of Norway, they found that in the case of southern Scandinavia, in areas where flood variability is explained primarily by the snowmelt, the NAO had little or no explanatory power; more local shifts in wintertime wind patterns, meanwhile, might have an impact on shifting trends. The NAO is typically a wintertime phenomenon; leaning toward tapping it as a candidate for explaining flood variability in the European Alps, which apparently is triggered by intense summer precipitation, seems somewhat misguided.

Although correlating proxy records to the NAO has become an almost innate reflex for climate scientists over the past 2 decades, improved reanalysis of atmospheric pressure patterns is constantly being developed, enabling a broader view. It is worth looking beyond the NAO to study mesoscale patterns as well as the spatial division of all relevant synoptic atmospheric patterns [*Barnston and Livezey,* 1987]. For the North Atlantic realm, *Cassou* [2008] shows how, in addition to positive and negative phases of the NAO, two other systems play important roles: The Atlantic ridge and Scandinavian blocking influence the spatiotemporal distribution of precipitation. A way forward for an enhanced understanding of the flood-climate connection may thus be to broaden scientific views on possible climatic forcing and increase the spatial coverage of high-resolution records of past floods.

Adapting to an Uncertain Future

Regardless of the origin of the trigger mechanisms involved and in which part of the natural system they are rooted, the new studies reveal trends that beg for an explanation that, albeit indirectly, hints at a strong climate influence on longer time scales. For example, a major increase in flood frequency around 4000 years ago (see the stacked record in Figure 1) is likely to be tied to shifting climate, and such an explanation might serve as an analogue for future scenarios.

In a new study, *Støren and Paasche* [2014] draw on records of past winter precipitation and floods to show that parts of Scandinavia can expect an increase in snow-related floods for the next 50–80 years but that the trend might be reversed within decades by a substantial changeover from solid precipitation to rain given that temperatures continue to increase. *Dankers et al.* [2014] recently used so-called impact models, combining results from nine hydrological models and land surface models, in which each impact model is forced by five global climate models to assess flood hazards. A key result is a rapid decrease in flood frequency and magnitude in areas dominated by snowmelt-driven floods, which points to a future with stronger spatial gradients in terms of flooding.

The observed shift in European flood records 4000 years ago occurred in concert with a projected southward shift in the ITCZ. This southward shift has already been implicated in slowing to a trickle runoff into the Cariaco basin just north of South America [*Haug et al.,* 2001] as well as increasing ENSO frequency and thus changing seasonal rainfall patterns over the equatorial Pacific [*Conroy et al.,* 2008]. This shift likely also had global implications and was, for example, assosiated with runoff changes in the American Southwest [e.g., *Waters and Haynes,* 2001].

From Low to High Confidence

The recent progress in reconstructing flood variability, as well as the efforts to explain the growing number of observations on longer (centennial to millennial) and shorter (annual to decadal) time scales with certain atmospheric circulation patterns, promises that flood predictions can advance from low to high confidence in the not-so-distant future.

Reaching that critical goal relies in part on better use of paleoclimatic data in model scenarios, especially in downscaling efforts, which have a better representation of local topography and climate. Using such data in models, in turn, requires dynamical climate-based explanations for the major shifts in flood patterns in the past, particularly the one that took place 4000 years ago when several of Earth's major atmospheric circulation systems changed, impacting flood frequencies and seasonal rainfall patterns not just in Europe but worldwide.

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