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Climate Variability and Floods—A Global Review

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Abstract: There is a strong inter-annual and inter-decadal variability in time series of flood-related variables, such as intense precipitation, high river discharge, flood magnitude, and flood loss at a range of spatial scales. Perhaps part of this variability is random or chaotic, but it is quite natural to seek driving factors, in a statistical sense. It is likely that climate variability (atmosphere–ocean oscillation) track plays an important role in the interpretation of the variability of flood-related characteristics, globally and, even more so, in several regions. The aim of this review paper is to create an inventory of information on spatially and temporally organized links of various climate-variability drivers with variability of characteristics of water abundance reported in scientific literature for a range of scales, from global to local. The climate variability indices examined in this paper are: El Niño-Southern Oscillations (ENSO), North Atlantic Oscillations (NAO), Atlantic Multi-decadal Oscillation (AMO), and Pacific Decadal Oscillations (PDO). A meta-analysis of results from many studies reported in scientific literature was carried out. The published results were collected and classified into categories after regions, climate variability modes, as well as flood-related variables: precipitation, river flow, and flood losses.

Keywords: floods; climate variability; ocean–atmosphere system; precipitation extremes; river discharge; flood loss

1. Introduction

Floods are major weather-related events that continue to cause high economic and human losses all over the Globe, reaching, on average, tens of billions of $US and thousands of fatalities per year. Hence, an understanding of mechanisms of temporal change and variability of floods and flood-related variables (such as precipitation, river discharge, flood loss) is of vast theoretical and practical interest and importance.

The search for ubiquitous, spatially coherent trends in long time-series of hydro-climatic observation records has been very successful for temperature, less successful for precipitation (including intense precipitation), and even less so for river flow. Actually, no persuading, spatially-organized long-term trends could be detected in records of maximum river discharge.

Analyses of the time series of annual maximum (or peak-over-threshold) values of river discharge at a given station (cross-section) and of flood indices do not show a convincing ubiquitous upward trend. In the absence of a gradual trend, the structure of the time series is dominated by strong, and seemingly rather irregular, inter-annual and inter-decadal variability. An intriguing question emerges—what is the mechanism of variability of flood-related variables? Perhaps there exist some links with recognized climate variability and its indices. Therefore, it is quite natural to examine whether the climate variability expressed via atmosphere–ocean oscillation indices can drive the variability of flood-related indices.

Better understanding of spatially- and temporally-organized links between climate variability patterns and flood hazard and flood risk at a range of spatial and temporal scales would be a considerable asset. Anticipating regional predisposition to river floods in a particular phase of oscillation in the atmosphere–ocean system, measured by a range of climate variability indices, could help in improving preparedness to emergency.

The aim of this review paper is to assemble a selective summary of the existing information on links of various climate-variability drivers with variability of characteristics of destructive water abundance at a range of scales. We discuss the modes of climatic variability that may have links to flood-related variables. We review publications reporting on links between variability of intense precipitation, high river discharge and flood indices and natural oscillations in the ocean–atmosphere system, starting from global scale to continental, river-basin, national, regional, to local scale.

2. Modes of Climate Variability

Many indices of inter-annual and inter-decadal climate variability have been proposed in the scientific literature in order to quantify oscillation in the atmosphere–ocean system. Some of them have been studied in the context of links with hydrological variables. Time series of characteristics of climate variability indices of concern may reflect volcanic eruptions and indices of solar irradiance, illustrated by sunspot numbers, as well as various classes of ocean–atmosphere oscillations. The first two indices from the above list are likely the drivers of climate variability. In contrast, ocean–atmosphere oscillations, being manifestations of climate variability, are likely the drivers of climate impact variability, that are the focus of this paper.

Accounting for the heat and mass exchange between the Earth's atmosphere and the oceans is absolutely necessary to understand large-scale meteorological processes and to interpret the climate variability. The latter consists of quasi-periodic oscillations in the climate system, i.e., the alternating occurrence of positive and negative anomalies of meteorological variables such as temperature or air pressure in a specific reference location, or of differences between values of these variables in two specific reference locations. These spatially defined oscillations in the ocean–atmosphere system have been found to affect the climate and various climate impact variables over large areas, including remote regions, via teleconnections.

There are four principal modes of climate variability that, according to a plethora of references, are of particular relevance for links with abundance of water—i.e., with characteristics of intense precipitation, high river discharge, and floods. They are oscillations of quasi-periodicity of several years: ENSO (El Niño-Southern Oscillation) and NAO (North Atlantic Oscillation), as well as of several decades: AMO (Atlantic Multi-decadal Oscillation) and PDO (Pacific Decadal Oscillation). Brief information about these four modes of climate variability is given below.

The ENSO is the sea surface temperature oscillation over the tropical Pacific Ocean. During the warm phase, El Niño, water off the South American coast is warmer than average (in the absence of cold upwelling), while during the cold phase, La Niña, with increased cold upwelling, warm water is further west off the South American coast than usual. Between the warm phase, El Niño, and the cold phase, La Niña, there is a neutral phase. The Southern Oscillation is the accompanying atmospheric (air pressure) component, coupled with the sea surface temperature (SST) change. Many relevant indices have been proposed and some of them were used in references reviewed in this paper. Among the indices are: ONI (Oceanic Niño Index, 3-month running mean of SST anomalies in the Niño 3.4 region, stretching from the 120° W to 170° W astride the equator, five degrees of latitude on either side; for declaration of El Niño or La Niña, the anomalies must exceed ±0.5 °C for at least five consecutive months), Niño 3.4 (5-month running mean, and SSTs must exceed ±0.4 °C for a period of six months at least), Niño 1 + 2 (0–10° S, 90° W–80° W), Niño 3 (5° N–5° S, 150° W–90° W), Niño 4 (5° N–5° S, 160° E–150° W), and the Trans-Niño Index (TNI), which is defined as the difference in normalized SST anomalies between the Niño 1 + 2 and Niño 4 regions and the event is classified as a "central Pacific El Niño" or "El Niño Modoki". Also, the Southern Oscillation Index (SOI, https://www.ncdc.noaa.gov/teleconnections/enso/indicators/soi/) has been used, expressing fluctuations in air pressure between the western and the eastern tropical Pacific, calculated based on the differences in air pressure anomaly between Tahiti and Darwin, Australia, [1,2].

The term NAO refers to cyclic air pressure changes in the Icelandic Low and Azores High as well as cyclic displacements of the center of the Azores High. If the (seasonal or monthly) value of the NAO index is positive, there is a stronger air pressure contrast between the Icelandic Low and the Azores High, i.e., the pressure value in the Azores Region is higher than the long-term average, while the corresponding pressure in the Icelandic Low is lower than the long-term average. Several indices were proposed to measure the strength of NAO, related to air pressure in various stations, such as: the Hurrell index—between Lisbon (Portugal) and Stykkishólmur (Iceland), the Rogers index—between Ponta Delgada (Azores) and Akureyri (Iceland), and the Jones index—between Gibraltar and Stykkishólmur. More detailed information on the concept and studies of NAO can be found in Wanner et al. [3].

The PDO is the decadal-scale temperature oscillation of the Pacific Ocean. Sometimes it is called a long-lived ENSO-like Pacific climate oscillation pattern. Two quasi-periodicities have been determined: of 15–25 and 50–70 years. Temperature anomalies (departures from average) in the East Pacific (off the west coast of North America) have an opposite sign to those in the West Pacific, therefore there is some compensation effect and the impact on the global temperature is small [4,5].

The term AMO refers to a coherent pattern of oscillatory changes in the North Atlantic sea-surface temperature (SST) with a period of about 60–90 years. Traditionally, indices of the AMO have been based on average annual SST anomalies in the North Atlantic. Temperature anomalies in the North Atlantic have an opposite sign to those in the South Atlantic, therefore there is a kind of compensation effect and the impact on the global temperature is small. The nature and origin of the AMO is uncertain, and it remains unknown whether it represents a persistent, quasi-periodic driver in the climate system, or merely a transient feature. A deterministic mechanism relying on atmosphere–ocean–sea ice interactions for the AMO was proposed by Dima and Lohmann [6].

There are several data sets of climate variability indices that have been collected at various sources and made publicly available (e.g., Table 1).

Table 1. Data sets of climate variability indices (monthly values) available at the US NOAA (National Oceanic and Atmospheric Administration) ESRL (Earth System Research Laboratory), under the GCOS (Global Climate Observing System) umbrella (https://www.esrl.noaa.gov/psd/gcos_wgsp/Timeseries/SOI/ or https://www.esrl.noaa.gov/psd/gcos_wgsp/Timeseries/Nino34/ or https://www.esrl.noaa.gov/psd/gcos_wgsp/Timeseries/NAO/ or https://www.esrl.noaa.gov/psd/gcos_wgsp/Timeseries/PDO/ or https://www.esrl.noaa.gov/psd/gcos_wgsp/Timeseries/AMO/).

Oscillation Pattern	Comment	Available from
ENSO	SOI, normalized pressure difference between Tahiti and Darwin	1866
	Niño 3.4 SST Index, area averaged SST from 5° S–5° N and 170–120° W	1870
NAO	Normalized pressure difference between Gibraltar and SW Iceland	1821
PDO		1900
AMO		1871

3. In Search for Links between Variability of Flood-Related Variables and Climate Oscillations

The structure of the time series of annual maximum river discharge and flood damage worldwide, does not show a persuading ubiquitous upward trend [7], even if the Clausius–Clapeyron law demonstrates that more water vapor can be stored in the warmer atmosphere, suggesting the increase of the potential for more intense precipitation (that may lead to floods) in the warmer climate. What the time series of annual maximum river discharge shows is a dominating inter-annual and inter-decadal variability that may overshadow gradual (if any) trends. High river discharges tend to be clustered in time [8].

There is a strong multi-annual and multi-decadal variability in flood-related variables. Perhaps part of this variability is random or chaotic, but there are serious arguments supporting the thesis that climate variability plays, generally, an important role in driving flood hazard over many areas of the world. Prudhomme et al. [9] examined whether the same few circulation types are systematically associated with floods at the European scale. Their results showed that, indeed, at the river basin scale and at the continental, European scale, some circulation types have significant positive frequency anomalies with flood occurrence, i.e., they are associated with a predisposition to floods. However, the results were not robust—they were shown to depend on various technicalities. Burn and Arnell [10] investigated the spatial and temporal pattern of high river flow, globally, using annual maximum discharge data for 200 gauging stations. The results of the investigation revealed that diverse regions of the world exhibit synchronous flood responses which can be related to various global climatic conditions, such as atmosphere–ocean oscillations. They also examined global temporal patterns in flooding and identified distinct periods corresponding to increased global flooding activity.

Many research works have been undertaken and reported in literature, aimed at identification of links between the climate variability and various variables related to floods. Climate variability indices can quantify some climate phenomena which can be considered as drivers of variability of such flood-related characteristics, as intense precipitation, high river discharge, flood severity and magnitude (in the sense of Brakenridge, see explanation in [11,12]), as well as flood loss (material damage, population, number of fatalities, and a combined index). Clearly, there are several climatic and non-climatic factors influencing flood risk (understood as probability times consequences, that can be disaggregated into three driving factors: hazard, exposure, and vulnerability). Non-climatic drivers are of terrestrial/hydrological (e.g., land-use and land-cover change, river regulation, and structural flood defenses), as well as social/economic nature. For instance, changes in rivers and their drainage basins, and changes in flood damage potential depend on the socio-economy (demography, wealth, development, GDP). However, the climate variability track is likely to play an important role in the interpretation of the variability in the time series of flood-related characteristics globally and, even more so, in many regions. Hence, it seems opportune to examine variability in recorded time series of flood-related characteristics and climate variability indices and seek spatially and temporally organized links between them. Improved understanding of climate-variability impacts on variability of flood-related characteristics would be of considerable value.

The expectation of discovery of absolute deterministic rules would be naïve, yet existence of probabilistic, frequency-type rules of spatially-organized validity is likely. The global spatial scale can be used, but particular focus can be put on areas where links have been found to be strong and where robust regional laws can be formulated. In many papers, authors claim to have unveiled new teleconnections (i.e., co-variability of variables at distant locations), possibly in asynchronous (e.g., lagged) mode, and/or to have found an important original interpretation.

This paper aims at building an inventory of selected information on links between climate variability indices and variability of flood-related characteristics. It is virtually impossible to embrace all the many thousands of related references. Search for the logical sum of "ENSO" and "flood" gives 32,500 hits in Google Scholar, and 733 hits in Web of Science. Search for "NAO" and "flood" gives 24,200 hits in Google Scholar, and 147 hits in Web of Science, while search for "PDO" and "flood" gives 8,020 hits in Google Scholar, and 94 hits in Web of Science. Search for "AMO" and "flood" gives 19,900 hits in Google Scholar, and 36 hits in Web of Science (updated on 13 May 2019). The gross orientation numbers given above are clearly overestimating the count, for several reasons, e.g., in some entries, Flood is an author's name, while Nao and Amo refer to geographic names and NAO—to National Audit Office. Nevertheless, the number of relevant source items is very high. In brief, the audience is inundated by information on the links between climate variability and variables related to floods, of varying strength and trustworthiness. Hence, some transparent rules of selection of entries to be included in this paper are needed. We give priority to reviewing papers that have gathered many citations, according to bibliometric indices (related to citations count) reported in Web of Science. However, we also include several papers that have not gathered numerous citations yet (some of them being quite recent), but deserve being considered. In result, bibliography contains 120 source items. In this review paper, there is usually reference to one or two papers authored by a single scientist or co-authored by a group of scientists, even if the same authors may have possibly published many other papers in the field. An attempt was made to select the appropriate paper(s) out of a larger set.

Meta-analysis (analysis of analyses) of results from selected studies reported in scientific literature is offered. The bibliography is collected and classified into categories (after regions, climate variability modes, and flood-related variables: precipitation, river flow, and flood losses). Reported results are assessed and a synthesis of findings is presented. It could improve understanding of the links of four variability modes with abundance of water and inform further studies in the area. Information is given on who studied what and whether approaches turned out to be successes or failures (though, definitely, the latter are less likely to be well represented in the scientific literature).

From the viewpoint of flood variability, the dominating mode of inter-annual climate oscillation is undoubtedly the El Niño-Southern Oscillation (ENSO), with impacts felt most strongly in the Pacific region but also in much of the world via teleconnections. Colloquially speaking, once the occurrence of a strong El Niño is declared, a range of extreme weather events worldwide, including floods, are blamed on this phenomenon in the media. Other, possibly relevant, climate variability indices examined in many references are: AMO (Atlantic Multi-decadal Oscillation), PDO (Pacific Decadal Oscillation), and NAO (North Atlantic Oscillation). Some papers tackle other variability indices, such as Northern Hemispheric Teleconnection Indices (Arctic Oscillation—AO, Polar/Eurasia Pattern, Siberian High-Intensity, Scandinavia Pattern, East Atlantic/Western Russia Pattern, East Atlantic Pattern, Pacific/North American Pattern—PNA, and Northern Hemispheric Circum-global Teleconnection—CGT), as well as Monsoon Indices (Webster–Yang Monsoon Index, South Asian Monsoon Index, East Asian–Western North Pacific Monsoon Index), see [13], Indian Ocean Dipole, see [14], and AAO (Antarctic Oscillation), see [15].

Some studies show that the overall impact of climate variability modes (e.g., ENSO and PDO) depends on the combination of ENSO and PDO. For instance, Wang et al. [16] investigated the inter-decadal modulation of the PDO upon the impact of ENSO on the EAWM (East Asian Winter Monsoon). No robust relationship was found between ENSO and EAWM on the inter-annual timescale, when the PDO is in its high phase. However, when the PDO is in its low phase, ENSO was found to exert a strong impact on the EAWM. Chan and Zhou [17] found that inter-decadal variations in the early (May–June) summer monsoon rainfall over South China are linked to the ENSO and the PDO (Pacific Decadal Oscillation), with wetter monsoon years during the periods of low PDO index.

Statistical relationships have been established between some quasi-periodic ocean–atmosphere oscillations (e.g., ENSO, NAO) and general wetness (e.g., river runoff) indices in various regions of the world (cf. [18,19]). Some research studies [19,20] reviewed connections between high river flow (in winter and spring) and the NAO index in winter over many areas. This could be particularly important e.g., in regions with snowmelt as the dominating flood generation mechanism [21].

4. Review of Links between Climate Oscillations and Flood-Related Variables—Global Studies

The El Niño-Southern Oscillation (ENSO) is perhaps the most commonly studied mode of inter-annual climate variability that was found to have an impact on river flow and flooding. Indeed, many dramatic floods have occurred in some areas during strong warm phases of ENSO (El Niño) and in other areas during strong cold phases of ENSO (La Niña). This climate variability mode largely influences the Pacific region, but its impacts can also be felt in much of the world via teleconnections, possibly of asynchronous (lagged) nature. Chiew and McMahon [18] examined global teleconnections between ENSO and river flow. They found strong and regionally consistent ENSO-streamflow teleconnections in Australia and New Zealand, South and Central America, and weaker signals in some parts of Africa and North America. They also proposed a hypothesis that the streamflow–ENSO relationship can be stronger than the rainfall–ENSO relationship (so that an amplification effect takes place), due to integrative properties of the streamflow process.

It can be stated that the occurrence of a specific stage of climate variability (e.g., El Niño) can open the door to a visit of abundant water, yet floods may or may not come. In fact, floods can happen any time, regardless of the climate variability phase. However, in the area of interest, they can be much more likely during one phase (e.g., El Niño) and perhaps more unlikely during another phase (e.g., La Niña). Sun et al. [22] postulated that the effect of ENSO on extreme precipitation is asymmetric, in the sense that a strong, significant effect is only for a single ENSO stage, and much weaker (or none) for another.

There is no doubt that the random component of climate variability as well as of variability of flood-related variables is strong. Nevertheless, Ward et al. [23,24] examined statistical links between ENSO and flooding and arrived at interesting and promising frequency-type results globally. They demonstrated that the ENSO quasi-cycle of natural variability likely has serious impacts on flood hazard in many regions of the world and called for further research to reduce uncertainty. In contrast, more recently, Emerton et al. [25] showed that the interpretation of likelihood of ENSO-driven flood hazard is more complex than perceived and reported in literature.

Ward et al. [23,24] arrived at an updated global map of prevalence of wetness (intense precipitation, flooding) for particular phases of the ENSO oscillation. It is clear that various flood-related variables may react differently to climate variability indices in different areas. The behavior of the time series of river discharge may largely differ from the time series of intense precipitation, as per suggestion of integrative properties due to Chiew and McMahon [18]. Large rivers have basins covered by multiple grid cells and the transformation of rainfall into river runoff modulates the signal and introduces a transport lag, not to forget human influence (anthropogenic effects in drainage basins and river beds) that can be substantial. However, it is not only the scale problem. In many river basins, the flow regime of the main stream differs from the regime of tributaries (e.g., pluvial versus glacial, snowmelt, or rain on snow).

There is a rich body of research aimed at connecting floods with climatic variability at the continental scale. Many relevant studies have been undertaken in Asia, North America, South America, Australia, and Europe, using ENSO, NAO, AMO, and PDO indices. Hodgkins et al. [26] examined climate-driven variability in the occurrence of major floods across two continents (North America and Europe), only in minimally altered catchments, to focus on climate-driven changes rather than changes due to catchment alterations. Temporal changes in the occurrence of major floods were shown to be dominated by multi-decadal variability (AMO) rather than by long-term trends.

The question whether one individual flood event (or a train of floods in a flood season) can be meaningfully associated with the occurrence of a particular phase of climate variability is not properly posed. A more appropriate question is whether the occurrence of a particular phase of climate variability can cause the risk of experiencing floods (predisposition to abundance of wetness) to be significantly higher or lower than average. The reported strength of correlation may vary with time (strengthening or weakening over various periods), with possible asymmetry [22]. Even the sign of correlations may change with time. This is the meaning of the so called "epochal behavior" recognized for the Mekong by Räsänen and Kummu [27]. Ward et al. [23,24] speculated that climate change may possibly be modifying the strengths of teleconnections.

Table 2 presents the essential information extracted from selected references, about the links between climate variability and floods, resulting from global studies.

Table 2. Review of links between climate oscillations and floods, reported in global studies. Aspects of reference in the rightmost column read: P—precipitation, R—runoff (or river discharge), F—flood.

Climate Oscillation	Reference	Principal MESSAGE	Aspect
ENSO	Emerton et al. [25]	Likelihood of increased or decreased flood hazard during ENSO events is much more complex than is often perceived and reported. Probabilities vary greatly across the Globe, with large uncertainties inherent in the data.	R

Table 2. *Cont.*

Climate Oscillation	Reference	Principal MESSAGE	Aspect
ENSO	Ward et al. [28]	The duration of flooding appears to be more sensitive to the ENSO index than is the case for flood frequency. At the globally aggregated scale, floods are significantly longer during both El Niño and La Niña years, compared to neutral years. At the scale of individual river basins, strong correlations were found between ENSO and both flood frequency and duration for a large number of basins, with generally stronger correlations for flood duration than for flood frequency.	F
	Ward et al. [24]	The ENSO exerts strong and widespread influences on both flood hazard and flood risk. Reliable anomalies of flood risk exist during El Niño or La Niña years, or both, in basins spanning almost half (44%) of Earth's land surface.	F
	Ward et al. [23]	Over 1958–2000, ENSO exerted a significant influence on annual floods in river basins covering over a third of the world's land surface, and its influence on annual floods has been much greater than its influence on average flows. There are more areas in which annual floods intensify with La Niña and decline with El Niño than vice versa. However, in many regions the strength of the relationships between ENSO and annual floods was found to be non-stationary during the study period.	R
	Chiew and McMahon [18]	Strong and regionally consistent ENSO–streamflow teleconnections were found in Australia and New Zealand, South and Central America, and weaker signals in some parts of Africa and North America.	P, R
AMO, ENSO	Najibi and Devineni [29]	The flood frequency across the Globe and the tropics can be largely linked to the decadal and multi-decadal climate variability, but the flood duration could not be associated with any of these climate factors. Only extreme flood duration can be partially associated with AMO for the Globe and the tropics and ENSO for the southern subtropics and mid-latitudes.	F
PDO	Dong and Dai [30]	Significant correlations between the PDO and local P are observed over Eastern Australia, Southern Africa, and the Southwest U.S. Over Northeastern Australia, P versus ENSO correlations are stronger during the PDO cold phases.	P
	Mantua and Hare [4]	During the warm PDO phase—anomalously wet conditions were found to occur in: Southeast Brazil, South-central America, West Australia, Coastal Gulf of Alaska, Southwest USA, and Mexico	P

5. Review of Links between Climate Oscillations and Flood-Related Variables—Continental, Regional, and Local Studies

Tables 3–8 present the most essential information extracted about the links between climate variability and floods, resulting from continental (and bi-continental) as well as regional or local studies, as reported in scientific literature. The tables are organized according to continental coverage of studies. Table 3 refers to Asia, Table 4—to North America, Table 5—to South America, Table 6—to Australia, Table 7—to Europe, and Table 8—to Africa. Large regions within continents are placed first, then large river basins.

A few studies examine more than one mode of climate variability. This is explicitly noted in the tables. If a study refers to more than one continent, but does not cover the Globe, it is mentioned in several tables.

Figure 1 illustrates regional predisposition to abundance of water for various phases of four modes of climatic variability. The map in Figure 1 summarizes the findings of continental, regional, to local studies reported in Tables 3–8 of this section.

Table 3. Review of links between climate oscillations and floods for Asia, as reported in literature. Aspects of reference in the rightmost column—as in Table 2.

Climate Oscillation	Range	Reference	Principal Message	Aspect
ENSO	East Asia	Lau and Weng [31]	Analysis of ENSO indices and extreme rainfall statistics between regions in East Asia and North America suggests the occurrence of two teleconnection patterns. The first pattern is associated with enhanced rainfall over the Yangtze River region. The second pattern shows enhanced rainfall anomalies over the River Huaihe, northeastern, and southern China. It is hypothesized that the first pattern may be influenced by El Niño in the preceding spring but becomes increasingly decoupled from tropical SST during the summer and fall. However, the second pattern has no significant relationship with El Niño.	P
	South-east Asia	Kripalani and Kulkarni [32]	Extreme flood situations tend to occur when the internal epochal behavior (epochs of the above- and below-normal rainfall near the Equator tend to last for about a decade, over the tropical regions, away from the Equator—for about three decades) and the external forcings of La Niña events are phase-locked.	P
	China	Lv et al. [33]	During Eastern Pacific El Niño and Central Pacific El Niño decaying years and in La Niña developing years, "wet" indices (the number of very high 24 h precipitation, the maximum 24 h rainfall and the number of consecutive wet days) all increased, suggesting an increased risk of flooding.	P
	Southwest China	Cheng et al. [34]	Extreme wet events occur during El Niño and La Niña years, with similar frequency. The frequencies of extreme wet events are lower than extreme dry events since 2001 during El Niño and La Niña years. The highest percentage levels of the frequency of the occurrence of wet events mainly occur during El Niño years.	P
	River Yangtze	Wang and Yuan [35]	Extreme pluvial floods across the Yangtze River basin in the summer of 2016 were strongly connected with intense atmospheric moisture transport after a strong El Niño winter. The predictability of precipitation and moisture flux is higher in post-El Niño summers than in post-La Niña ones, especially for flooding events. As compared with extreme precipitation, the potential detectability of extreme moisture flux increases by 20% in post-El Niño summers.	P
	River Yangtze	Zhang et al. [36]	Different phase relations were found between annual maximum streamflow of the River Yangtze and ENSO in the lower, the middle and the upper Yangtze basin. In-phase relations were detected between annual maximum streamflow of the Lower Yangtze Basin and anti-phase relations for the Upper Yangtze Basin.	R
	River Yangtze	Tong et al. [37]	In the basin of the middle and lower River Yangtze, El Niño episodes show a close relation with flood events; for the Upper Yangtze Basin, La Niña episodes are in closer relation with floods. The shorter the interval of ENSO events, the sooner the following flood responds. The longer-duration ENSO events in the Pacific result in a longer flood period.	R
	Upper and mid–lower Yangtze River	Ye and Wu [38]	The upstream floods in the Yangtze River Basin correspond to the development phase of La Niña; the mid-lower reaches tend to be linked with the decaying El Niño.	R
	River Mekong	Räsänen and Kummu [27]	Precipitation and discharge decreased (increased) during El Niño (La Niña) and the annual flood period was shorter (longer) during El Niño (La Niña). Also, decadal variations in the ENSO-discharge relationship were found.	P, R

Table 3. *Cont.*

Climate Oscillation	Range	Reference	Principal Message	Aspect
ENSO	Pakistan	Iqbal and Hassan [39]	After 1970, in Pakistan, the highest percentage of floods per year occurred during El Niño, non-ENSO, and positive Indian Ocean Dipole years.	F
	Japan	Higashino and Stefan [40]	Annual maximum precipitation and maximum flood discharges have become substantially higher in phase with the ENSO.	P, R
	Korea	Lee et al. [14]	The tropical ENSO forcing has a coherent teleconnection with September and November–December precipitation patterns, while the Indian Ocean Dipole is identified as a driver for precipitation variability in September and November.	P
	Bangladesh	Chowdhury [41]	While the relation between SOI and rainfall is strong in the upstream Ganges-Brahmaputra-Meghna basins in India, it offers limited applicability in the context of the Bangladesh climate.	P
	River Huai, China	Zhang et al. [42]	Canonical ENSO regimes tend to increase precipitation in spring and autumn, and especially in winter. Also, in summer, an increase is observed during the canonical ENSO periods. Water vapor flux is more abundant during warm episodes of canonical ENSO events in spring and summer than during cold episodes.	P
	Poyang Lake basin, China	Liu et al. [43]	The ENSO (and IOD) are the major climate indices that significantly correlated with the magnitude and frequency of floods.	R
	China	Cao et al. [44]	Influence of five El Niño–Southern Oscillation (ENSO) types (central Pacific warming—CPW, eastern Pacific cooling—EPC, eastern Pacific warming—EPW, conventional ENSO, and ENSO Modoki) on rainy-season precipitation in China was studied. Precipitation anomaly was shown to reach up to 30% above average precipitation during decaying CPW and EPW phases.	P
	Rivers Dez and Karun, SW Iran	Saghafian et al. [45]	The El Niño phenomenon intensifies March–April floods compared with neutral conditions. The opposite is true in La Niña conditions. The degree of the effect is more intense in the El Niño period.	R
PDO	Southern Mekong region	Delgado et al. [46]	A connection was found between the Western North Pacific Monsoon (WNPM) and the discharge in the Southern Mekong region. In the frequency domain, the inter-annual to decadal variance of the Mekong discharge closely follows that of WNPM. It was found that PDO plays a role in enhancing the inter-annual variability of WNPM and that WNPM is more variable during warm phases of PDO.	R
	East River Basin, China	Zhang et al. [47]	The PDO influences the variance of annual maximum streamflow. However, hydrological regulation by storage reservoir in the basin overshadows the influences of climate indices on flood processes.	F
	China	Deng et al. [48]	Large-scale climate indices were found to have more influence on frequency rather than intensity of extreme precipitation over China.	P
	Yangtze River Basin	Xiao et al. [49]	Influences of climate variability indices on the seasonal occurrence and intensity of precipitation events are complex. The negative PDO event tends to increase the spring occurrence of precipitation events in the southwestern part of the Yangtze River Basin, while the positive ENSO event a year earlier tends to increase the spring intensity of precipitation events in the east part of the Yangtze River Basin.	P

Table 3. *Cont.*

Climate Oscillation	Range	Reference	Principal Message	Aspect
NAO	Middle East	Cullen et al. [50]	Flooding period on Middle East rivers is rainfall-driven in December–March, regulated on inter-annual to decadal timescales by NAO.	R

Table 4. Review of links between climate oscillation and floods for North America, as reported in the literature. Aspects of reference in the rightmost column—as in Table 2.

Climate Oscillation	Range	Reference	Principal Message	Aspect
ENSO	US	Cayan et al. [51]	During SOI-(El Niño) years, the occurrence of two- and three-day above-threshold precipitation events has increased in the Southwest US (by twice as frequent as during neutral and SOI+ period) and decreased in the Northwest (to nearly half of the occurrence during SOI+ years). In El Niño years, days with high precipitation and streamflow are more frequent than average over the Southwest US and less frequent over the Northwest. Nearly the opposite pattern is associated with SOI+ (La Niña) episodes.	P, R
	Western US	Corringham and Cayan [52]	Links between ENSO and flood losses across the western United States illustrated by US National Flood Insurance Program (NFIP) daily claims and losses were found. In coastal southern California and across the southwest, El Niño conditions were found to be associated with more frequent and higher magnitudes of insured losses (less frequent and lower for La Niña). In the Pacific Northwest, the opposite pattern appears, though the effect is weaker, and less spatially coherent.	F
	US Midwest	Lau and Weng [31]	There is a pattern associated with above-normal rainfall over the US Midwest (as well as in a part of Asia, over the Yangtze River region) and reduced rainfall over the US Mid-Atlantic coast. It may be influenced by El Niño in the preceding spring but becomes increasingly decoupled from tropical SST during the summer and fall (see Lau and Weng, 2002 in Table 3).	P
	South Great Plains, US	Wang et al. [53]	A developing El Niño tends to increase late-spring precipitation in the South Great Plains and this effect has intensified since 1980.	P
	Lower Mississippi	Munoz and Dee [54]	In the 6–12 months preceding a flood, El Niño generates a positive precipitation anomaly over the lower Mississippi basin	R
	River Ohio	Nakamura et al. [55]	The March–May El Niño 3.4 index is weakly correlated with the years of the 20 historical spring floods events.	R
	California Coast	Andrews et al. [56]	South of 35° N along the California coast, floods are significantly larger during an El Niño phase than during a non–El Niño phase. North of 41° N, the annual peak floods during an El Niño phase were less than 70% of the geometric mean of annual peak floods during a non-El Niño phase. For exceedance probabilities from 0.50 to 0.02, the ratio of the El Niño to non-El Niño floods varies from greater than 10 near 32° N to less than 0.7 near 42° N. Latitude explains much of the observed variation in the relative magnitude of El Niño versus non-El Niño floods over the range of exceedance probabilities.	R
NAO	Eastern North America	Whan and Zwiers [57]	The observed influence of the NAO on extreme winter precipitation is largest in eastern North America, with the likelihood of an extreme rainfall event increased in the south under the positive phase of the NAO.	P

Table 4. *Cont.*

Climate Oscillation	Range	Reference	Principal Message	Aspect
NAO	River Missouri	Wang et al. [58]	The NAO climate forcing made a contribution to the magnitude of the dramatic 2011 flood event.	F
	River Missouri	Nasser et al. [59]	Joint relationships of lagged Pacific/North American (PNA) pattern and NAO with flood durations and volumes were investigated. At a 15-day lag time, a clear nonlinear dependence was found. During the long duration floods (D > 30 days), NAO and PNA are anomalous and anti-correlated, whereas the NAO and PNA anomalies were found to be mostly under neutral conditions for the short duration floods (D < 30 days).	R
	USA	Villarini et al. [60]	Over the central United States, the largest flood peaks tend to occur during the neutral and negative ENSO phases, with limited activity during El Niño years	R
PDO	Western and Central US	Dai [61]	Wet periods over much of the West and Central US, especially the Southwest were found to be associated with the warm phases of PDO.	P
	Western Canada	Gurrapu et al. [62]	Higher magnitude floods are more likely during the negative phase of PDO than during the positive phase.	R
	Northern Canada	Burn et al. [63]	Negative correlations of PDO index with annual maximum flood date and spring freshet date: during the warm phase of PDO, snowmelt shifts towards earlier spring and during the cool phase—later towards summer. Also, PDO was found to be positively correlated with winter flows and negatively with summer flows.	R
	Missouri River Basin	Wang et al. [58]	The PDO was an important precursor toward anticipating major flood events in the Missouri River Basin in 2011.	R
	Oregon, US	Beebee and Manga [64]	The DO is correlated with spring snowmelt timing and magnitude, spring and summer runoff, and timing of annual floods	R
	Nyack floodplain, Montana, US	Whited et al. [65]	Large magnitude floods and greater frequency of moderate floods were associated with the cooling phases of PDO.	R
AMO	Florida	Enfield et al. [66]	During the positive AMO phase, management priorities shift towards flood protection for the region surrounding the Lake Okeechobee (Florida).	R
	River Matawin, Canada	Fortier et al. [67]	Flood flows (magnitude and frequency) are correlated negatively to AMO upstream from the Matawin dam where the winter floods dominate, but positively downstream from the dam (spring floods). The AMO is the only climatic index that influences the inter-decadal variability of heavy floods produced by spring snowmelt.	R
	Tabasco and Chiapas, Southeast Mexico	Valdes-Manzanilla [68]	Many floods coincided with the warm (positive) phase of AMO. The odds ratio showed that floods were 1.9 times more likely to occur where the AMO index was positive.	R
ENSO, AMO	River Mississippi	Munoz et al. [69]	Multi-decadal trends of flood hazard on the lower Mississippi River are strongly modulated by dynamical modes of climate variability, particularly ENSO and AMO, but the artificial channelization has greatly amplified flood magnitudes over the past century. A multi-proxy reconstruction of flood frequency and magnitude spanning the past 500 years, reveals that the magnitude of the 100-year flood has increased by 20%, with about 75% of this increase attributed to river engineering.	R

Table 4. *Cont.*

Climate Oscillation	Range	Reference	Principal Message	Aspect
ENSO, AMO	St. Lawrence River, Canada	Assani et al. [70]	On the north shore of the St. Lawrence River Basin, magnitude of annual flow and of flooding are correlated to AMO. On the south shore they are correlated to ENSO.	R, P
ENSO, PDO	US	Hamlet and Lettenmaier [71]	Climate variability associated with PDO and ENSO affects flood risk. The largest changes are associated with years when PDO and ENSO are in phase, particularly in the southwest US.	F
	Western US	McCabe and Dettinger [72]	In the western US, ENSO teleconnections with winter precipitation are strong when SOI and NINO3 are out-of-phase and PDO is negative. ENSO teleconnections with precipitation in the western US are weak when SOI and NINO3 are weakly correlated and PDO is positive.	P
	Southwest Canada	Gobena and Gan [73]	Basins in Southwest Canada exhibit a strong response to ENSO forcing. Three of the five regions exhibited wet conditions with a consistency better than 75% during the spring and/or summer period following the onset of La Niña events. Also, ENSO-related responses were found to be modulated by PDO: the interaction between ENSO and PDO was constructive when the two are in phase (i.e., during El Niño and warm PDO, as well as La Niña and cool PDO).	R
	River Similkameen, Canada	Jain and Lall [74]	Statistically significant relationship between annual maximum floods and both winter NINO3 and PDO indices	R
	River Blacksmith Fork, US	Jain and Lall [75]	The ENSO and PDO climate indices explain 40% of the variance of the annual maximum flood series	R
AMO, PDO	Multiple gauges	Hodgkins et al. [26]	Significant negative relations between floods and AMO at large (>1000 km^2) North American catchments.	R
	Southern Mexico	Méndez and Magaña [76]	Precipitation was greater when the PDO index was in its negative phase	P
	The Upper Rio Grande, US	Pascolini-Campbell et al. [77]	The highest ranked streamflow years clustered during positive phases of PDO.	R
	River Papaloapan, Mexico	Valdes-Manzanilla [78]	Flooding had an in-phase relationship with AMO and PDO, especially when AMO and PDO were in their positive or warm phases.	R
AMO, NAO	St. Lawrence River, Canada	Mazouz et al. [79]	The timing of spring floods is correlated with NAO (positive correlation) and with AMO (negative correlation).	R
NAO, AMO, ENSO, PDO	Conterminous USA	Archfield et al. [80]	Time series of frequency, peak magnitude, duration, and volume of flood events at a gauge were correlated to the climate variability indices. Little geographic cohesion was noted, apart from the ENSO that has statistically significant correlations to flood duration and volume for approximately 25% of the 345 streamflow stations analyzed across the USA. Other climate indices (NAO, AMO, PDO) do not show widespread and strong correlations with floods (aside from New England).	R
	Central US	Mallakpour and Villarini [81]	Climate variability can play a significant role in explaining the variations in the frequency of flooding over the central United States. Different climate-modes are related to the frequency of flood events over different parts of the domain and for different seasons.	R, P

Table 5. Review of links between climate oscillation and floods for South America, as reported in the literature. Aspects of reference in the rightmost column—as in Table 2.

Climate Oscillation	Range	Reference	Principal Message	Aspect
ENSO	South America	Isla [82]	South American rivers can be classified into ENSO-affected and ENSO-dominated for those within the Arid Diagonal that are exclusively subject to high discharges during those years.	R
	Uruguay, Argentina, Brazil	Isla and Toldo jr. [83]	The ENSO-triggered floods caused significant impacts on the economies of Argentina, Brazil, and Uruguay. Floods occur approximately simultaneously in subtropical watersheds of Brazil and high-latitude watersheds of Northern Patagonia.	F
	Central America, Guatemala	Guevara-Murua et al. [84]	For the annual rainy season (May to October), only one-quarter of the wet years are coincident with La Niña. The percentage of wet events occurring during a La Niña year rises to 40% for early part of the rainy season (May to July)	P, R
	River Parana	Depetris [85]	The River Parana exhibits an active teleconnection between extreme flooding and the occurrence of ENSO events.	R
	River Parana	Prieto [86]	The ENSO is an important factor in determining inter-annual rainfall variability in South America. In 1904–2000, 11 out of 16 floods occurred during El Niño events.	P
	Ecuador, Peru	Arteaga et al. [87]	Strong El Niño events bring high rainfall and floods in Ecuador and northern Peru.	P, R
	Atacama Desert, Chile	Houston [88]	Floods in the central and northern Atacama Desert in summer are associated with La Niña, but they are caused by the summer melt of the previous winter's snow in the southern Atacama Desert which are associated with El Niño. Floods along the coastal Atacama Desert in winter are associated with El Niño.	P
	Distrito Federal, Brazil	Borges et al. [89]	Extreme rainfall indices are associated, in a complex way, with La Niña and Madden-Julian oscillation.	P

Table 6. Review of links between climate oscillation and floods for Australia, as reported in the literature. Aspects of reference in the rightmost column—as in Table 2.

Climate Oscillation	Range	Reference	Principal MESSAGE	Aspect
PDO	New South Wales and Southern Queensland	Micevski et al. [90]	The PDO modulated the flood risk in New South Wales and Southern Queensland, with flood quartiles increased by a factor of approximately 1.7 during PDO negative periods.	R
	New South Wales	Franks [91]	Identified change in flood frequency corresponds directly to an observed shift in SST and mean circulation	R
	New South Wales	Franks and Kuczera [92]	Marked multi-decadal variability is also present in flood extremes	R
ENSO, PDO	Eastern Australia	Verdon et al. [93]	Rainfall and streamflow for Queensland and New South Wales are significantly enhanced during La Niña. On a multi-decadal time scale the negative phase of PDO is associated with "wetter" conditions: La Niña rainfall and streamflow are further magnified by occurring in the PDO negative phase.	P, R
	Queensland	Cai and van Rensch [94]	The devastating southeast Queensland flood and the associated extreme rainfall in January 2011 were accompanied by an extraordinarily strong La Niña. The regional summer rainfall is affected by the ENSO cycle, but modulated by PDO.	P

Table 6. *Cont.*

Climate Oscillation	Range	Reference	Principal MESSAGE	Aspect
ENSO, PDO	New South Wales	Kiem et al. [95]	The PDO modulation of ENSO events leads to multi-decadal epochs of elevated flood risk. The flood risk in Eastern Australia is higher when the PDO is in a negative phase. PDO modulation of La Niña is related to rainfall flooding in Eastern Australia and affects both the flood magnitude and frequency. Cool-phase PDO increases flood risk.	R, F

Table 7. Review of links between climate oscillation and floods for Europe, as reported in the literature. Aspects of reference in the rightmost column—as in Table 2.

Climate Oscillation	Range	Reference	Principal Message	Aspect
NAO	Europe	Wrzesiński and Paluszkiewicz [20]	The winter floods typical of the rivers of Western and Southern Europe are markedly higher in a negative NAO phase. In the North and Northeast regions, a positive correlation can be noted between flows and the NAO indices in the winter season.	R
	Northern Europe, Atlantic countries of Europe	Zanardo et al. [96]	Links between NAO and catastrophic floods in Europe were demonstrated. The majority of winter (summer) floods in Northern Europe were found to occur during a positive (negative) NAO phase. Similar patterns were observed in individual Atlantic countries. The average flood loss during opposite NAO states were found to differ by up to 50%.	R, F
	Southern Europe	Benito, et al. [97]	See Table 8	R
	Western Iberian Peninsula	Benito, et al. [98]	Periods with more frequent floods in the western Iberian region coincide with transitions to cool and wetter conditions, and persistent negative NAO mode.	R
	North-eastern Iberian Peninsula	Moreno et al. [99]	The NAO variability at a decadal scale, modulated by fluctuation in solar radiation at a centennial-scale, are the two forcing mechanisms proposed to generate the rainfall in the Taravilla Lake catchment. The Taravilla Lake and Tagus River records (with the paleo-flood history) suggest a relationship between the occurrence of extreme hydrological events and the North Atlantic Oscillation for the Northeastern Iberian Peninsula.	P, R
	UK	Huntingford et al. [100]	Winter runoff and flood indicators have been linked to the NAO index. In the 1990s, it was strongly positive and associated with a cluster of winter floods events, contrasting with the early 1960s for which it was negative and which were correspondingly flood poor.	R, F
	UK	Hannaford and Marsh [101]	In western UK, high-flow indicators are correlated with NAO. The increasing high-flow trends since the 1960s have parallels with observed changes in extreme rainfall and they may reflect an influence of multi-decadal variability related to NAO.	P, R
	Lower Rhine	Toonen et al. [102]	Variability of flood activity correlates with NAO. Winter NAO+ phases align with increased flood frequency of the Lower Rhine, and the largest events of the last six centuries were all generated in NAO+ periods.	R
	Swiss Alps	Schulte et al. [103]	Episodes of major floods in the central Swiss Alps were triggered by negative SNAO (Summer NAO) phases during the last pulses of the Little Ice Age (AD 1817–1851 and 1881–1927 flood clusters) and by positive SNAO phases during the warmer climate since 1977.	R

Table 7. *Cont.*

Climate Oscillation	Range	Reference	Principal Message	Aspect
NAO	Swiss Alps	Wirth et al. [104]	Increased floods in the southern Alps, reconstructed by flood layers in lake deposits, were found to coincide with annual and decadal NAO- phases during the Little Ice Age. Enhanced flood occurrence in the South compared to the North took place during a NAO-state.	R
PDO, AMO	Multiple gauges	Hodgkins et al. [26]	No significant relationships, for any group of catchments, between major flood occurrence and PDO. Significant positive relations between floods and AMO at medium-sized (100–1000 km^2) European catchments.	R
ENSO, NAO	Pan-European	Nobre et al. [105]	The link between ENSO and the occurrence of extreme rainfall and intensity of extreme rainfall in Europe is much weaker than the relationship with NAO or EA, but still significant in some regions. Also flood damage and flood occurrence have strong links with climate variability, especially in Southern and Eastern Europe.	P
	River Danube	Rimbu et al. [106]	The impact of NAO and ENSO on variability of the Danube flow shows decadal variations. Winter SST from tropical Pacific and some regions from the North Atlantic are found to be significantly correlated with the streamflow variations in spring and summer.	R
	River Rhine	Ionita et al. [107]	Variability of the Rhine flow, during the transition seasons, was found to be strongly related to large-scale atmospheric circulation patterns, being driven by climate interactions at a nearly global scale in spring and more regional in autumn.	R
AO	River Elbe	Ionita et al. [108]	High anomalies of the annual Elbe flow are associated with a tripole-like pattern in the North Atlantic and with negative SST anomalies in the Central-North Pacific and positive anomalies in the Eastern and Central tropical Pacific. The pattern identified in the sea level pressure (SLP) resembles the negative phase of the Arctic Oscillation pattern.	R

Table 8. Review of links between climate oscillation and floods for Africa, as reported in the literature. Aspects of reference in the rightmost column—as in Table 2.

Climate Oscillation	Range	Reference	Principal Message	Aspect
ENSO	Africa	Nicholson, and Kim [109]	ENSO is not a major factor in rainfall variability. El Niño rather reduces rainfall over Africa than enhances it. For Sahel, it may increase rainfall early in the season but decrease it later in the season, so may not influence on seasonal totals. The signal over the rainfall is more intense, consistent, spatially and temporally coherent during the warm phase. Above-average rainfall over most of Africa, particularly during January–March and April–June may occur during the first half of the ENSO cycle. For some regions, rainfall may be enhanced during some months of the rainy season but reduced during others. For equatorial East Africa rainfall is enhanced in the 'short rains' months (October–December) of an El Niño year, but reduced in the main rainy season a few months later.	P

Table 8. *Cont.*

Climate Oscillation	Range	Reference	Principal Message	Aspect
ENSO	Africa	Li et al. [110]	Analysis of flood disaster events of 55 countries in Africa from 1990 to 2014 recorded in the International Disaster Database (EM-DAT) was undertaken. Annual flood frequencies showed a fluctuating upward trend and were in good agreement with ENSO (SOI) years: at the 0.01 level in Africa as a whole, Southern Africa, and West Africa, and at the 0.05 level in Central Africa. The larger the SOI (La Niña), the greater probability of the annual precipitation leading to flood disasters.	P, R
	Eastern Africa	Siderius et al. [111]	El Niño events are generally associated with high precipitation and floods in Eastern Africa. Kenya experienced widespread flooding during the El Niño of 1997–1998.	P
	South Africa	Quagraine et al. [15]	Broadly wet conditions have occurred in the SRR (Summer Rainfall Region) and parts of the ARR (Annual Rainfall Region) when La Niña episodes co-exist with a strongly negative AAO (Antarctic Oscillation) during summer. A shift in AAO to strongly positive drives wet conditions in Central and Northern parts of the SRR although peak conditions are centered to the east.	P
	South Africa	Weldon and Reason [112]	Nearly all the anomalously wet years over the South Coast of South Africa correspond to mature phase of La Niña years.	P
	South Africa	Alemaw and Chaoka [113]	Strong and nearly-strong positive linear correlation between annual discharges (decline) and the warm seasonal ENSO. The strong positive correlation occurs in parts of Zambia, Namibia, Mozambique, and in South Africa.	R
	Nile River Basin	Siam and Eltahir [114]	There is a significant teleconnection between the Nile flow and the SST over Eastern Pacific Ocean (ENSO explains about 25% of the inter-annual variability) and a region in the southern Indian Ocean (50°–80° E and 25°–35° S, which explains another 28% of the inter-annual variability in the flow of the Nile). Cold conditions in both oceans mean 83% probability of high flow in the Nile, and insignificant probability of low flow.	R
	Zambia	Brigadier et al. [115]	Most parts of Zambia experienced normal to above-normal rainfall (floods) during La Niña developing from autumn of the year 2010.	P
	Coastal region of Kenya and Tanzania	Gamoyo et al. [116]	There is a strong relationship between ENSO (El Niño), IOD and the October–December short rains.	P
	Zimbabwe	Mamombe et al. [117]	ENSO has a significant influence on Zimbabwe rainfall. La Niña years correspond to extreme wet summers in most parts of the country.	P
NAO	Northern Africa	Benito et al. [98]	Western Mediterranean regions (Southern Europe and Northern Africa) show synchronicity of flood episodes associated with NAO—that are out-of-phase with those evident within the eastern Mediterranean. Regional changes in flood extremes are associated with switches in predominant NAO phase, indicating their high potential to model (as covariates) climate-related impacts on flood risk.	R

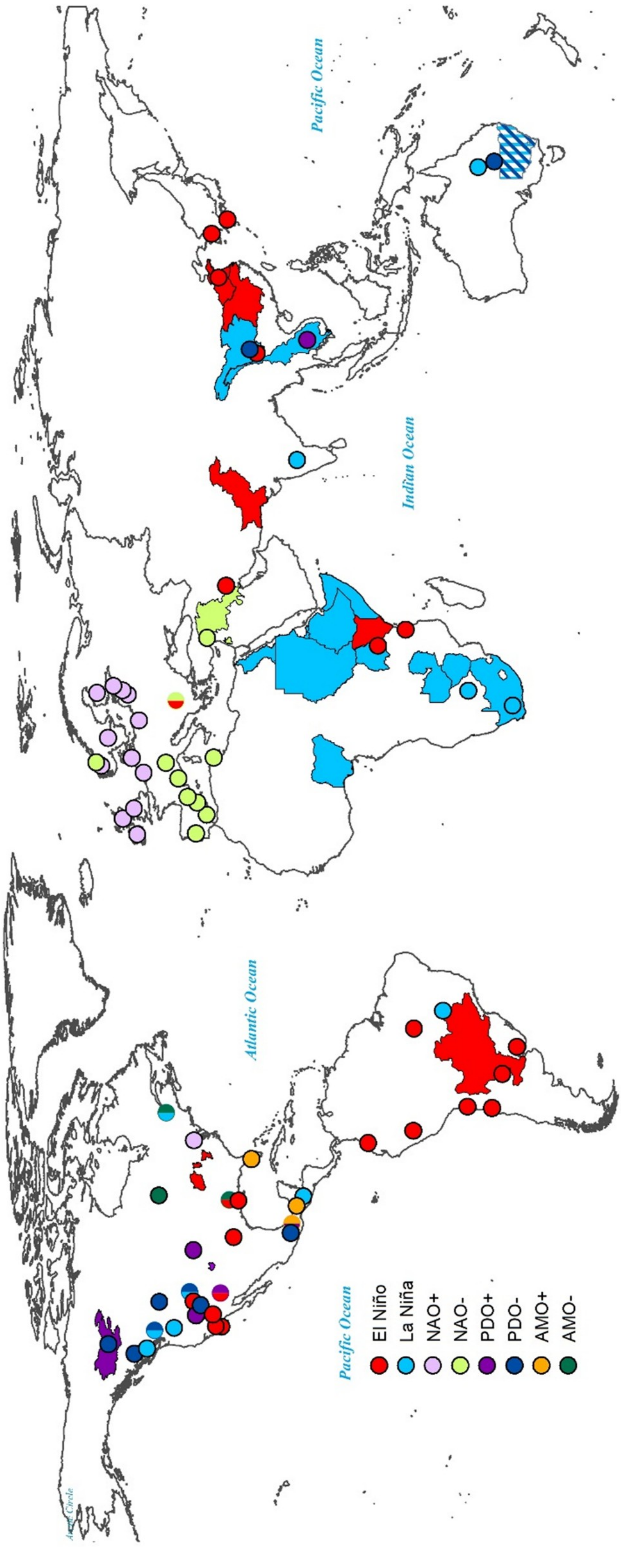

Figure 1. Map of regional predisposition to abundance of water.

6. Concluding Remarks

No persuading, and spatially-coherent, trend could be detected in long time series of flood-related variables, such as high river discharge, flood severity and magnitude, as well as flood loss. The structure of time series of river discharge is dominated by strong, and seemingly rather irregular, inter-annual and inter-decadal variability. Perhaps part of this variability can be random or chaotic, but there are serious arguments supporting the thesis that climate variability (quasi-periodic oscillations in the atmosphere–ocean system) plays, generally, an important role in driving variables related to floods over many areas of the world. Therefore, it is quite natural to examine whether there are links between the climate variability expressed via atmosphere–ocean oscillation indices and the variability of flood-related indices.

Spatially-defined oscillations in the ocean–atmosphere system have been found to affect the climate and various climate impacts over large areas, covering the oceans and adjacent continents, but also more remote (sometimes—very remote) regions, via so-called teleconnections. The strength of the link can vary from region to region and one can identify zones of influence where a climate variability mode (e.g., ENSO, PDO, NAO, or AMO) affects variables related to floods.

Many research works have been undertaken, with results reported in the literature, aimed at identification of links between the climate variability and various variables related to floods. Studying variability of properties of high river flows (e.g., timing, intensity, volume, duration, frequency) and their links with climate variability is a cutting-edge research activity, attracting broad attention due to scientific interests and practical importance. Anticipating regional predisposition to river floods in a particular phase of oscillation in the atmosphere–ocean system, measured by a range of climate variability indices, could help in improving the system of early preparedness to emergency.

The present paper reviewed published results of studies indicating links between climate variability indices and characteristics of abundant wetness (precipitation, river runoff, and flood indices) in different areas. Many studies have been found that report on the existence of such links, at a range of scales—from global (for ENSO and PDO) to local. Some references indicate the necessity to consider a combination of oscillation modes, e.g., one oscillation mode can modulate another one. Some studies combine analysis of change and variability, or seek for change points in system behavior. The list of references considered in this paper consists of 120 source items. The continents ordered after the number of source items, from highest to lowest, are: North America, Asia, Europe, Africa, South America, and Australia. Some reports on the existence of links are of a rather speculative nature, as a signal is sought among strong noise. Some findings are too complex and do not fit into the simple story of this paper.

As shown in Figure 1, the reviewed references found predisposition to abundance of water during a particular phase of one or more modes of climate variability. More consistent results are reported for South America and El Niño signals wetness there. In Africa, also ENSO is found important, while predisposition to abundance of water is related to La Niña for most areas and El Niño for some. In Europe, it is mostly NAO+ in the Northern and Western parts and NAO- in the Southern part. In Asia, links with ENSO (El Niño for some areas and La Niña for other areas) and PDO were reported. In Australia, it is La Niña and PDO-.

The situation in North and Central America looks most complex (Figure 1), because all modes: ENSO, NAO, AMO, and PDO may play a role. However, Jiang et al. [118] showed that no single index of those four, derived from the Pacific and Atlantic oceans, can explain the multi-scale temporal variability and spatial distribution of heavy precipitation in the western USA. Yet, characterization of their integrated effect, including modulation and reflecting the combined physical oceanic-atmospheric processes, allows useful links to be deciphered.

Reported links have spatial, temporal, and seasonal validity. As expected, different source items may give differing representation of links between climate variability and variables related to floods, for instance due to different definitions of indices, or due to different data windows (start-year and end-year) being considered. In brief, there are still considerable uncertainties in the understanding of the climate variability modes and their impact mechanisms on flood hazard and flood risk. This adds to the recognized general uncertainty of climate impacts on water resources [119].

Reviewed references follow various methodologies to investigate the relationship between climate oscillations and flood-related variables. Correlation and cross-correlation techniques (including time lags) are commonly used. Many papers use principal component or empirical orthogonal function (EOF) analysis (e.g., [107,118]), as well as wavelet power spectrum analysis (e.g., [107]).

Some publications report on convincing physical explanations of mechanisms behind the relationships. One of examples is in the study for North America, by Gershunov and Barnett [120], who found that the North Pacific oscillation (NPO) modulates the consistency and strength of El Niño anomalies. They hypothesized that a deeper Aleutian low (manifestation of the NPO) shifts the storm track southward while El Niño provides an enhanced eastern tropical Pacific moisture source for the storms to tap. They also demonstrated that seasonal climate anomalies over North America exhibit rather large variability between years characterized by the same ENSO phase. Interdecadal climatic anomalies in the North Pacific (the North Pacific oscillation, NPO) were shown to exert a modulating effect on ENSO teleconnections. Typical El Niño patterns (e.g., low pressure over the northeastern Pacific, dry northwest, and wet southwest, etc.) are strong and consistent only during the high phase of the NPO, which is associated with an anomalously cold northwestern Pacific.

It is hoped that the present review paper could play an important and useful role, if only because of the systematization of scattered knowledge. It could improve understanding of the links of four climate variability modes with abundance of water and inform further studies in the area.

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