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Varying Importance of Storm Types and Antecedent Conditions for Local and Regional Floods

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Key Points:

- Frontal events are the dominant storm type triggering floods in the United States
- The relative importance of different storm types only weakly differs between local and regional flood events
- Regional flood events are substantially more often related to wet antecedent conditions than local events

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Abstract Local and potentially more impactful regional floods are driven by a combination of precipitation-triggering storms and antecedent conditions. However, it is yet unclear how the importance of these flood drivers and their interplay differs between local and regional events. Therefore, we assess differences in the compounding drivers of local and regional floods in the United States using newly developed classification schemes for storm types and antecedent conditions. Our results show that the dominant storm type triggering floods is frontal events, in particular those related to mesoscale convective systems. The importance of different storm types varies by season, with frontal mesoscale convective systems being most important in summer, nonfrontal, and extratropical cyclone-related storms in winter and spring, and tropical cyclones in fall. Our comparison of the drivers of local and regional events shows that the relative importance of different storm types only weakly differs between local and regional floods, while antecedent conditions are clearly distinct. Regional events are in 75% of the cases related to wet antecedent conditions in some cases combined with snowmelt, while local events are more likely to also develop under dry conditions. Over all regions and seasons, regional events are most often the result of a frontal storm combined with wet antecedent conditions, which highlights the important role of compounding flood drivers. This finding suggests that regional flood risk and change assessments should account for the compounding nature of atmospheric and land-surface flood drivers.

Plain Language Summary Floods with a regional extent may be more impactful than local events as they potentially affect more people and assets. Both types of floods are driven by a combination of precipitation-triggering storms and antecedent conditions such as snowmelt and soil moisture. However, it is yet unclear how the importance of these flood drivers and their interplay differs between local and regional events. Therefore, we assess differences in the compounding drivers of local and regional floods in the United States. Our results show that the dominant storm type triggering floods is frontal events and that the importance of different storm types varies by season. The relative importance of different storm types only weakly differs between local and regional floods, while antecedent conditions are clearly distinct. Regional events are in 75% of the cases related to wet antecedent conditions in some cases combined with snowmelt, while local events are more likely to also develop under dry conditions. Over all regions and seasons, regional events are most often the result of a frontal storm combined with wet antecedent conditions, which highlights the important role of compounding flood drivers that should be taken into account in flood risk and change assessments.

1. Introduction

Regional floods affecting multiple catchments at once are potentially more impactful than local floods, which affect one catchment only, as they affect larger areas and more people. While these two types of events may differ in terms of impacts, they are governed by similar factors, including precipitation and antecedent conditions (Brunner, Gilleland, et al., 2020; Kemter et al., 2020). Precipitation magnitude and temporal distribution are determined by the storm type causing the event, while antecedent conditions are a result of different atmospheric and land-surface processes such as soil saturation and snowmelt taking place at longer temporal scales. Specific compounding drivers, that is, combinations of storm types and antecedent conditions, will favor flood development (Nied et al., 2014; Stucki et al., 2012).

Certain storm types and antecedent conditions have been shown to be more likely associated with floods than others (Ashley & Ashley, 2008; Hu et al., 2021; Pattison & Lane, 2012; Schlef et al., 2019; Wilby & Quinn, 2013).

For example, “Vb” cyclones have a high flood potential in Central Europe (Nied et al., 2014; Petrow et al., 2007; Stucki et al., 2012) and floods are often triggered by atmospheric rivers in different parts of the world including Great Britain (Lavers et al., 2011), the United States (Lavers & Villarini, 2013; Rutz et al., 2015), and Norway (Hegdahl et al., 2020). Large summertime convective storms play a particularly important role in generating floods in the Central U.S (Ashley & Ashley, 2008; Hu et al., 2021; Schumacher & Johnson, 2006). The importance of different flood-producing weather and storm types may vary with event magnitude. For example, the most extreme floods in the Mulde catchment in Germany are associated with Vb cyclones while smaller floods are related to westerly winds (Petrow et al., 2007). Similarly, particularly severe floods in the Mediterranean are associated with cyclonic structures (Gilabert & Llasat, 2018) and large events in the United States often result from storms related to tropical moisture exports (Schlef et al., 2019). Besides event magnitude, weather and storm patterns may also influence the spatial extent of flood events. That is, large-scale synoptic systems may more likely lead to regional flooding (Pattison & Lane, 2012) than more local storm types such as convective rainfall (Dougherty & Rasmussen, 2019; Maddox et al., 1978).

Besides precipitation-triggering storm types, antecedent conditions are an important driver of both local (Berghuijs et al., 2016; Huang et al., 2022) and regional flood events (Brunner, Gilleland, et al., 2020; Kemter et al., 2020). Previous studies have highlighted that local flood magnitudes can be much better explained by a catchment's antecedent conditions in combination with precipitation than by rainfall characteristics alone (Berghuijs et al., 2016; Brunner et al., 2021; Sharma et al., 2018; Wasko & Nathan, 2019; Ye et al., 2017). These previous studies assessed the relative importance of different flood-generation mechanisms from a hydrologic perspective only, that is, using precipitation, soil moisture, and snowmelt but no information on storm type, and relied on different approaches including comparisons of the seasonality of flood-generation processes and flooding (Berghuijs et al., 2016, 2019; Collins, 2018; Tramblay et al., 2021; Villarini, 2016; Wasko et al., 2020; Ye et al., 2017) or flood type classification schemes using streamflow observations, climate data, and output from simple hydrological model routines (Brunner et al., 2017; Sikorska et al., 2015; Stein et al., 2019, 2021a). Similarly, as previous studies have highlighted the importance of antecedent conditions for local flood formation, Brunner, Gilleland, et al. (2020) have stressed the importance of antecedent conditions for regional flood development. Specifically, they demonstrated that floods in the Rocky Mountains cooccur in different catchments because of simultaneous snowmelt contributions in late spring and early summer. Furthermore, antecedent wetness conditions explained the comparably strong spatial dependencies in flood occurrence in spring and fall. While there is substantial evidence that both storm types and antecedent conditions are important flood triggers independent of spatial flood extent, it remains unclear whether the importance of antecedent conditions, flood-producing storms, and their interplay differs between local and regional floods (Nied et al., 2017).

Here, we take an interdisciplinary perspective and investigate which factor—storm type or antecedent condition—is more important in determining the spatial extent of a flood event, that is, in determining whether a local or regional flood event is observed. Using a large-sample data set in the United States, we assess regional and seasonal variations in storm types and antecedent conditions associated with local and regional flood events. To do so, we develop two classification schemes, one for storm types and another one for antecedent conditions. The storm type classification scheme describes the synoptic forcing using cyclone climatologies and frontal identification combined with radar reflectivity over a region to assign a storm type to each day of the year. The antecedent conditions classification scheme uses information on soil moisture and snowmelt contributions to determine whether a flood event was influenced by wet antecedent conditions, snowmelt, or both types of flood-favoring antecedent conditions. Applying these two classification schemes to flood days in the conterminous United States (CONUS) allows us to disentangle the role of antecedent conditions and storm types and their interplay in determining the spatial scale of flood events.

2. Methods

2.1. Data

Our analysis of flood-triggering storm types and antecedent conditions of local and regional flood events focuses on the CONUS and relies on data sets of streamflow, meteorological variables, and land-surface variables including soil moisture and snowmelt. The hydrological flood analysis uses 671 catchments with nearly natural flow regimes part of the Catchment Attributes and MEteorology for Large-Sample studies (CAMELS) data set (Addor et al., 2017; Newman et al., 2015) (Figure 1). Daily streamflow time series for all catchments were downloaded

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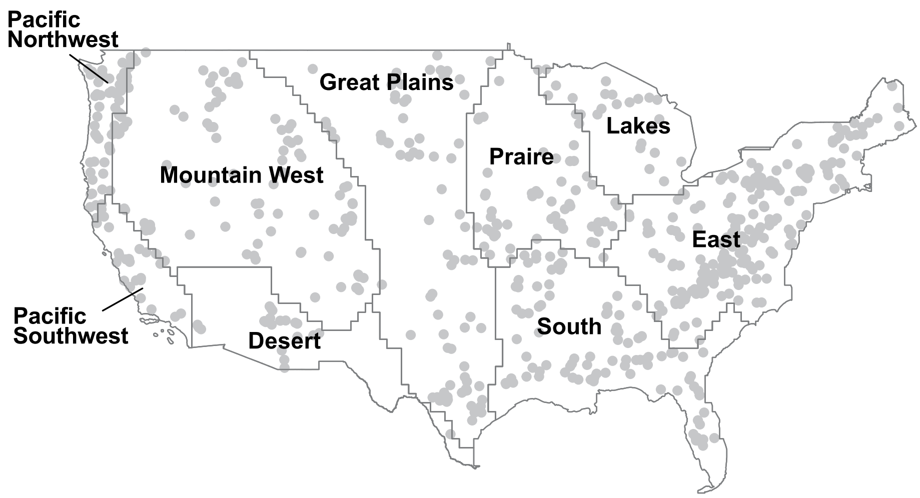

Figure 1. Nine hydroclimatic Bukovsky regions and 671 catchments used for the analysis.

from the US Geological Survey for the period 1995–2017 (USGS, 2019) and missing data were replaced by NA values. For each of these catchments, we derived time series of land-surface variables, namely soil moisture and snowmelt, using gridded daily data from the ERA5-Land reanalysis data set downloaded from the Copernicus data store (ECMWF, 2019). ERA5-Land provides information on land-surface variables including snowmelt and soil moisture for four different soil layers at a spatial resolution of 9 km for the period 1981–2020. For soil moisture, we averaged the volumetric soil moisture content over the first three soil layers, that is, the upper 1 m of the soil profile.

The storm type classification relies on a variety of atmospheric variables, including equivalent potential temperature, minimum pressure, and reflectivity derived from reanalyses and radar data sets. Fronts are identified using 850 hPa equivalent potential temperature derived from the ERA5 reanalysis data set, which has an hourly and 0.25° resolution (Hersbach et al., 2020). The data for identifying tropical cyclones (TCs) are from the Extended Best Track data set that contains 6 hourly data of Atlantic TC pressure, winds, and location coordinates (Demuth et al., 2006). Extratropical cyclones (ETCs) are identified using a cyclone climatology created by Sprenger et al. (2017) that contains hourly tracks and minimum pressures of cyclones using ERA5 data. The previous data sets identify the synoptic-scale storms, while radar data is used to characterize the rainfall and mesoscale storm characteristics. We use GridRad radar data, which is a merged Level 3 radar product with a 0.02° longitude × 0.02° latitude × 1 km altitude resolution from 125 NEXRAD WSR-88D radars over the CONUS (Bowman & Homeyer, 2017). The radar data are available at an hourly resolution from 1995 to 2017, covering the entire CONUS except the West Coast. Our analysis focuses on the period 1995–2017 for which all types of variables, that is, hydrological, land-surface, and meteorological, are available.

Both the regional flood analysis and the storm type analysis require some region definition, as we want to distinguish regional from local flood events and want to account for the spatial variability of storm types across the CONUS during a particular day. For this regional analysis, we use the hydroclimatic Bukovsky regions (Bukovsky, 2011), which subdivide the CONUS into nine different regions with different hydroclimates and represent a good compromise between hydrologically and climatologically meaningful regions (Figure 1). While alternatively relying on river basin subdivisions may have made sense from a hydrological perspective, such a subdivision would have been suboptimal from a climatological perspective because many of the storm types are larger than the river basins themselves. The hydroclimatological Bukovsky regions are used to define regional flood events and to determine storm types over a certain spatial domain as, for example, a particular day may be characterized by different weather patterns at the East and West coasts.

2.2. Event Identification

We first identify local and subsequently regional flood events using the daily streamflow time series of the 671 catchments in the CAMELS data set. The flood identification uses a peak-over-threshold (POT) approach with a threshold based on the annual maxima time series as such an annual maxima-based threshold has been shown to minimize the variability of the number of events selected across catchments (Brunner, Gilleland, et al., 2020; Schlef et al., 2019). First, local and independent POT events are identified in the daily discharge time series of the individual catchments using the 25th percentile of the corresponding time series of annual maxima as a threshold and by prescribing a minimum time lag of 10 days between events (Diederen et al., 2019). The application of this threshold resulted in the selection of 1.5 events per catchment and year on average. Please note that not all of these statistically determined high-flow or flood events are related to inundation. Second, we define regional flood events by compiling a data set consisting of the dates of flood occurrences across all catchments. We then count the number of stations affected by each event, allowing for a short time lag of 2 days between event occurrences in different catchments. Next, we retain only independent events, removing dependent events separated by less than 7 days and retaining the dates where most catchments were affected. Finally, we define regional events as events where at least 25% of the catchments in a region were jointly affected by a flood event. Please note that these regional events do not necessarily represent contiguously flooded areas but rather represent events that affected substantially more than one basin. Increasing this areal threshold leads to a very small sample size of regional flood events, which is why the threshold was kept at 25%. In a sensitivity analysis, we assessed the effect of local (percentile) and regional threshold (areal percentage) choice on the number of events retained for the analysis. Using a local threshold at the 25th percentile results in 55 events per catchment on average, while increasing this threshold to the 50th percentile halves the number of events extracted to 26. A low local threshold (25%) combined with the low areal threshold (25%) resulted in a median of 12 regional events per region, while increasing the areal threshold to 50% led to a reduction of this number to only four events. Combining a low local with a low regional threshold therefore ensures a sufficiently large-sample size for the regional analysis. Please note that an areal coverage of 25% means different areal extents in different regions and for different events as station density is irregular and affected stations may not necessarily be contiguous. To study the difference between event-triggering conditions of local and regional events, we create a local and a regional flood sample for each region. The local flood sample is generated by pooling all local flood events across the catchments within the region, and the regional sample is composed of the flood events affecting 25% of the catchments in that region.

2.3. Storm Type Classification

To assess the link between storm types and local and regional flood occurrence, we develop a storm type classification scheme, building on the classification schemes developed by Kunkel et al. (2012) and Ashley and Ashley (2008) (Figure 2a). Similar to Ashley and Ashley (2008), we consider both synoptic and mesoscale storm types associated with flooding, though over a longer time period and by using physically based indications of flooding from streamflow rather than storm reports. Additionally, we classify the convective characteristics of rainfall occurring with these synoptic storm types to provide a more comprehensive view of the rainfall associated with floods. The rainfall classification is based off of the Romatschke et al. (2010) characterization of convection in South America, as well as convective classifications from Parker and Johnson (2000).

The synoptic storm types considered are: (a) tropical cyclone (TC) if the 34 kt wind radius falls within a Bukovsky region (Knaff et al., 2007; Knaff & Sampson, 2015), (b) frontal if the smoothed 850 hPa equivalent potential temperature gradient exceeds 3.6 K for any ERA5 grid box within a Bukovsky region (0.25° latitude × longitude) which is similar to the Sprenger et al. (2017) definition, and (c) extratropical cyclone (ETC) if the cyclone track from the cyclone climatology from Wernli and Schwierz (2006) and Sprenger et al. (2017) falls within a Bukovsky region. We performed a sensitivity analysis to determine the frontal threshold that best matches observations of surface analyses from the Weather Prediction Center, and found that 3.6 K for each ERA5 grid box most closely matched observations. The cyclone track from Wernli and Schwierz (2006) and Sprenger et al. (2017) defines ETCs based on the outermost closed sea level pressure contour enclosing a local sea level pressure minima from ERA5.

In defining the main synoptic storm type, precedence is given to TCs first, since they are a distinct storm type that occurs under specific regional and environmental constraints that also contain all the other modes of convection. If the storm type is not a TC, fronts are the next storm type evaluated due to their common presence in the mid-latitudes. Preference is given to fronts over ETCs, because 86% of ETCs in our database have fronts, but only 40% of fronts have ETCs. If the storm type is not a front, the occurrence of an ETC is evaluated next. If the

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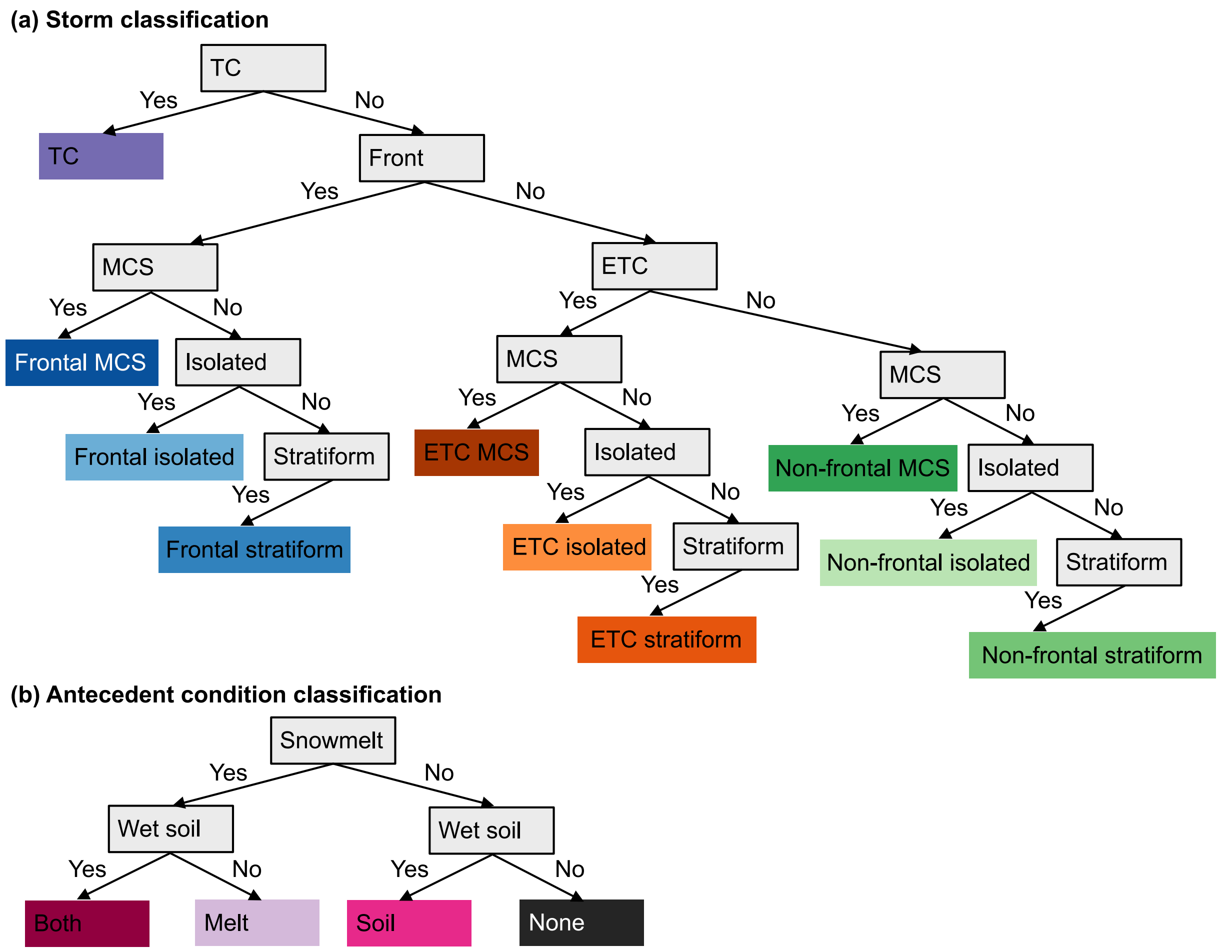

Figure 2. Decision trees for determining the (a) dominant storm type and (b) antecedent condition for each day. TC = tropical cyclone, MCS = Mesoscale Convective Systems, ETC = Extra Tropical Cyclone.

region and date does not have a TC, front, nor ETC, there is no synoptic forcing on this date, and the storm type is instead defined as nonfrontal.

These three synoptic storm types are further classified using rainfall characteristics evaluated from radar into mesoscale convective system (MCS), isolated convection, or stratiform. Rainfall is characterized as an MCS if the GridRad radar reflectivity within a Bukovsky region is ≥40 dBZ ≥100 km in one direction (similar to Orlanski (1975), Parker and Johnson (2000), Schumacher and Johnson (2005)). The rainfall is classified as isolated convection if the GridRad radar reflectivity is ≥40 dBZ for horizontal scales ≥5 km and ≤100 km, and as stratiform rainfall if the GridRad radar reflectivity is 18–40 dBZ (similar to Parker and Johnson (2000)) for scales ≥50 km to ensure clutter isn't being detected. Precedence is given to MCSs, due to their known ability to produce flooding (Ashley & Ashley, 2008; Dougherty & Rasmussen, 2019; Schumacher & Johnson, 2005), as well as their association with stratiform rainfall and isolated convection (Parker & Johnson, 2000), whereas the reverse is not true (stratiform and isolated convection can exist without an MCS present). The synoptic storm types and the rainfall characteristics class are identified using the native resolution of the data (which is hourly, except for the TC data), but are then aggregated to a daily resolution, so that each day can only have one storm type, even if it only occurs during 1 hr.

As a result of the classification procedure, a day is assigned to 1 out of 10 different storm type categories (Figure 2a): (a) TC, (b) frontal MCS, (c) frontal isolated, (d) frontal stratiform, (e) ETC MCS, (f) ETC isolated, (g) ETC stratiform, (h) nonfrontal MCS, (i) nonfrontal isolated, or (j) nonfrontal stratiform. Note that due to the lack of GridRad radar data for the Pacific NW and Pacific SW regions, storm types could only be classified as "frontal" or "ETC" in these regions.

This newly developed storm type classification scheme is applied to each region in our data set and assigns one out of these 10 storm type classes to each day of the period 1995–2017. We then focus on the days with flood occurrence to compare storm type distributions across the nine hydroclimatic Bukovsky regions, across seasons (winter: December-February, spring: March-May, summer: June-August, and fall: September-November), and for local and regional flood events.

2.4. Antecedent Conditions Classification

To assess the antecedent land-surface conditions related to flood occurrence, we develop a second classification scheme for antecedent conditions, that is, the soil and snow conditions influencing flood generation (Figure 2b). This classification scheme focuses on the important flood drivers soil moisture and snowmelt (Huang et al., 2022; Sikorska et al., 2015; Stein et al., 2019; Tarasova et al., 2019) and uses the time series of snowmelt and soil moisture derived from ERA5-Land to distinguish between four different antecedent condition classes including (a) snowmelt under dry soil conditions (melt), (b) wet soil conditions but no melt (soil), (c) both wet soils and snowmelt (both), and (d) neither wet soils nor snowmelt, that is, precipitation-driven conditions (none). Days are classified as snowmelt days if snowmelt contributions exceeded 1 mm and wet soil days if soil moisture exceeded the 80th percentile of seasonal soil moisture. The classification scheme is applied to each catchment and assigns one out of the four antecedent conditions classes to each day of the period 1995–2017.

2.5. Storm Type and Antecedent Conditions Analyses

The storm type and antecedent condition class time series derived by applying the storm type and antecedent conditions classification schemes are used to look at differences in storm type and antecedent condition distributions between the local and regional events within a region. For each flood event type (local and regional), we determine a storm type distribution which describes the relative importance of each storm type within a region. The local distribution is derived by determining the storm types of local flood days and the regional distribution by looking at the storm types of the regional floods. The antecedent condition distribution for each region and flood type is determined in the same way. We look at storm types and antecedent conditions on the day of flood occurrence because we work with small headwater catchments characterized by fast response times and want to capture convective events with potentially high impacts. We also focus on the storm type of the flood-triggering precipitation event (same day as flood event, Froidevaux et al., 2015) rather than the storm type related to the generation of antecedent conditions. We then compare the storm types/antecedent condition distributions of local and regional flood events to assess how these distributions differ between local and regional floods.

2.6. Sensitivity Analysis

Our analysis involves the selection of a range of different thresholds for defining floods and determining flood drivers. We therefore investigated the effect of the following threshold choices on the importance of the different storm types and antecedent conditions for local and regional flood formation: (a) choice of POT threshold used to define local flood events (25th percentile of AM as used in the analysis versus 10th percentile of AM); (b) areal percentage threshold used to define regional events (25% as used in the analysis versus 10% and 50% areal threshold); (c) snowmelt threshold used to classify events as snow-influenced or not (1 mm as used in the analysis versus 2 mm); and (d) soil moisture anomaly threshold used to identify events with positive soil moisture anomalies (>0.7, 0.8, and 0.9 percentiles).

3. Results

3.1. Flood-Triggering Storm Types

The importance of different storm types in triggering floods (local and regional) differs by hydroclimatic region (Figure 3). The most dominant storm types related to floods are frontal events. However, the relative importance of different precipitation types varies across regions. In the Desert and Mountain West regions, flood-triggering storms are mostly isolated convection. In all other regions, they are mostly related to MCSs, particularly MCSs associated with fronts. The Pacific NW and SW are dominated by frontal events, but note that they have different storm types than the other seven regions because no radar data were available for the analysis. ETC-related and

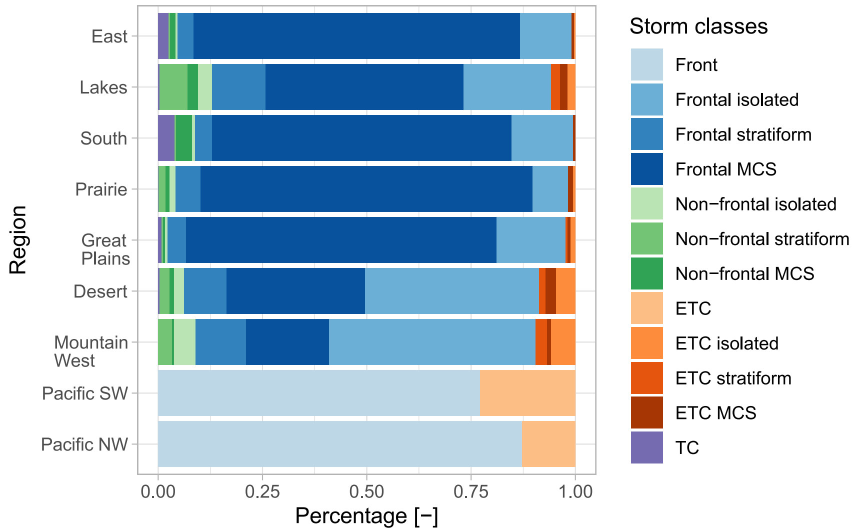

Figure 3. Regional comparison of flood-related storm types. The relative importance of each storm type across both local and regional floods is indicated for each region.

nonfrontal storms are less frequently associated with flood occurrence than frontal events and TCs are only relevant in the East, South, and GP regions.

The importance of different storm types in triggering floods also varies by season (Figure 4). Frontal MCSs are more important in summer than in the remaining seasons and nonfrontal storm types and ETC-types are most important in winter and spring. Frontal MCSs are particularly relevant in the Great Plains, Prairie, and East during the summer, where these systems tend to be frequent (Fritsch et al., 1986; Schumacher & Johnson, 2006). TC-related flood events are limited to summer and fall in the South, Lakes region, and East, which is expected due to the typical TC season being from June to November and impacting locations near the coast.

3.2. Storm Types Triggering Local and Regional Floods

Most flood events in the United States occur in winter and spring, and fewer in summer and fall (Figure 5). Regional flood events in almost all regions are most frequent in either winter or spring. Very few regional events are observed in summer and fall when floods are mostly localized. An exception is the Mountain West, where regional events frequently occur in summer because of synchronous snowmelt.

Despite the differences in the seasonality of local and regional floods, the importance of storm types in triggering local and regional floods shows little difference across all regions (Figure 6). These relatively weak differences are also confirmed by the results of Fisher's Exact test, which does not reject the null-hypothesis of equal relative frequency distributions for local and regional events at a level of significance of 0.05 in seven out of the nine regions. Some consistencies among regions show that regional events in the Mountain West, Great Plains, and South are more often driven by frontal MCSs than local events. This is in contrast to the Desert, Prairie, and Lakes regions, where frontal MCSs are more often associated with local than with regional events. In the South and East, only local events are associated with TCs. While this appears to be a small difference due to TCs being less frequent than other storm types, this minute difference is important since TCs tend to produce greater impacts (Schumacher & Johnson, 2006). Such seemingly small differences are also important in the Mountain West, where local events are more often driven by nonfrontal isolated convection as well as stratiform rainfall, with some of these rainfall types producing historic floods like the 2013 Colorado flood (Gochis et al., 2015). Therefore, while it is difficult to make generalizations about storm types causing local or regional floods on a continental scale, these differences are more important region-by-region.

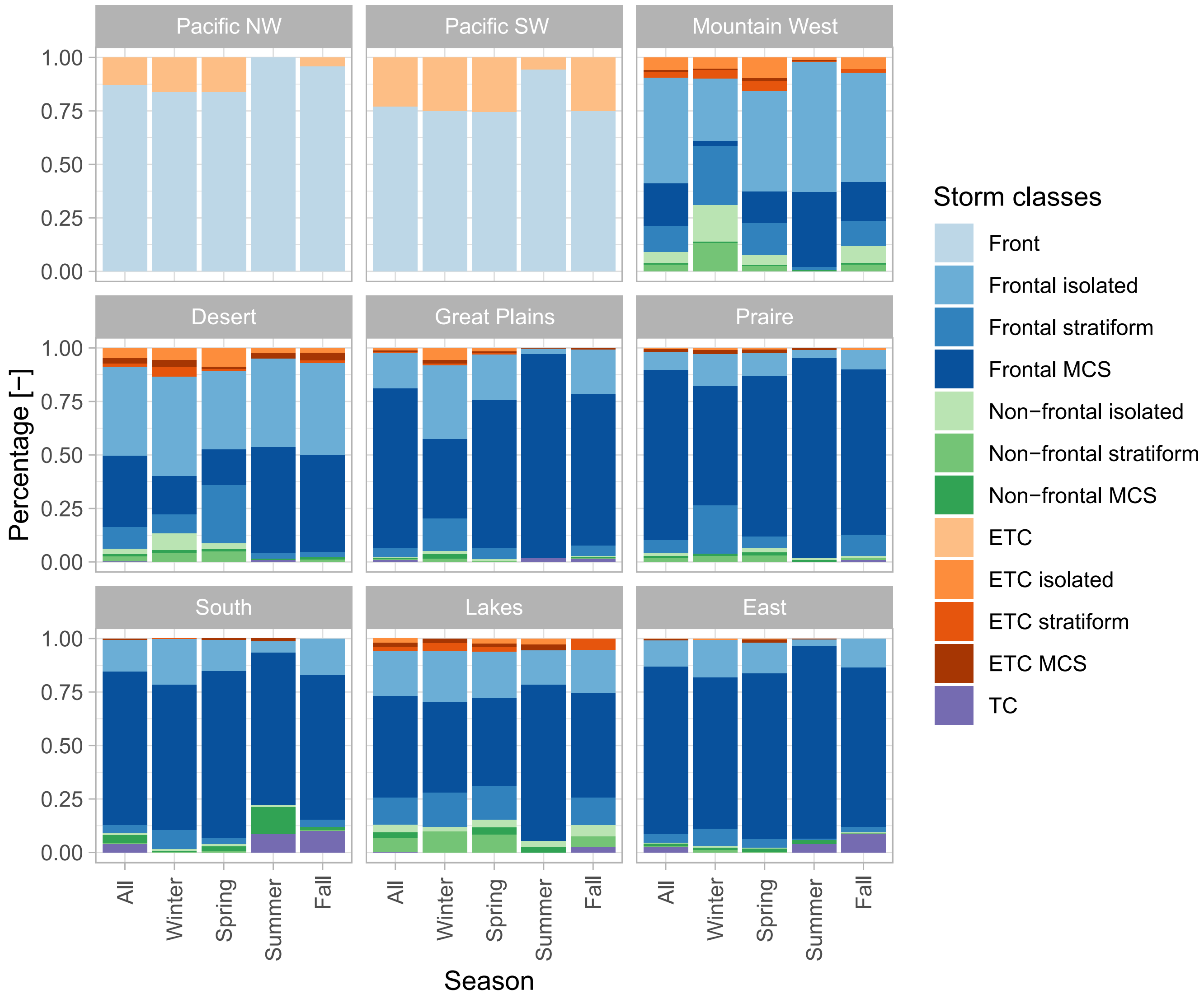

Figure 4. Seasonal comparison of flood-related storm types. The relative importance of each storm type across all flood events is indicated for each region and season.

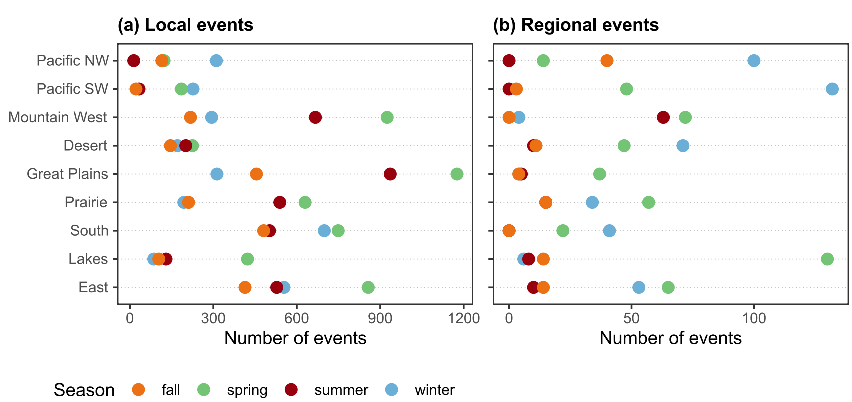

Figure 5. Number of (a) local and (b) regional flood events per season and region.

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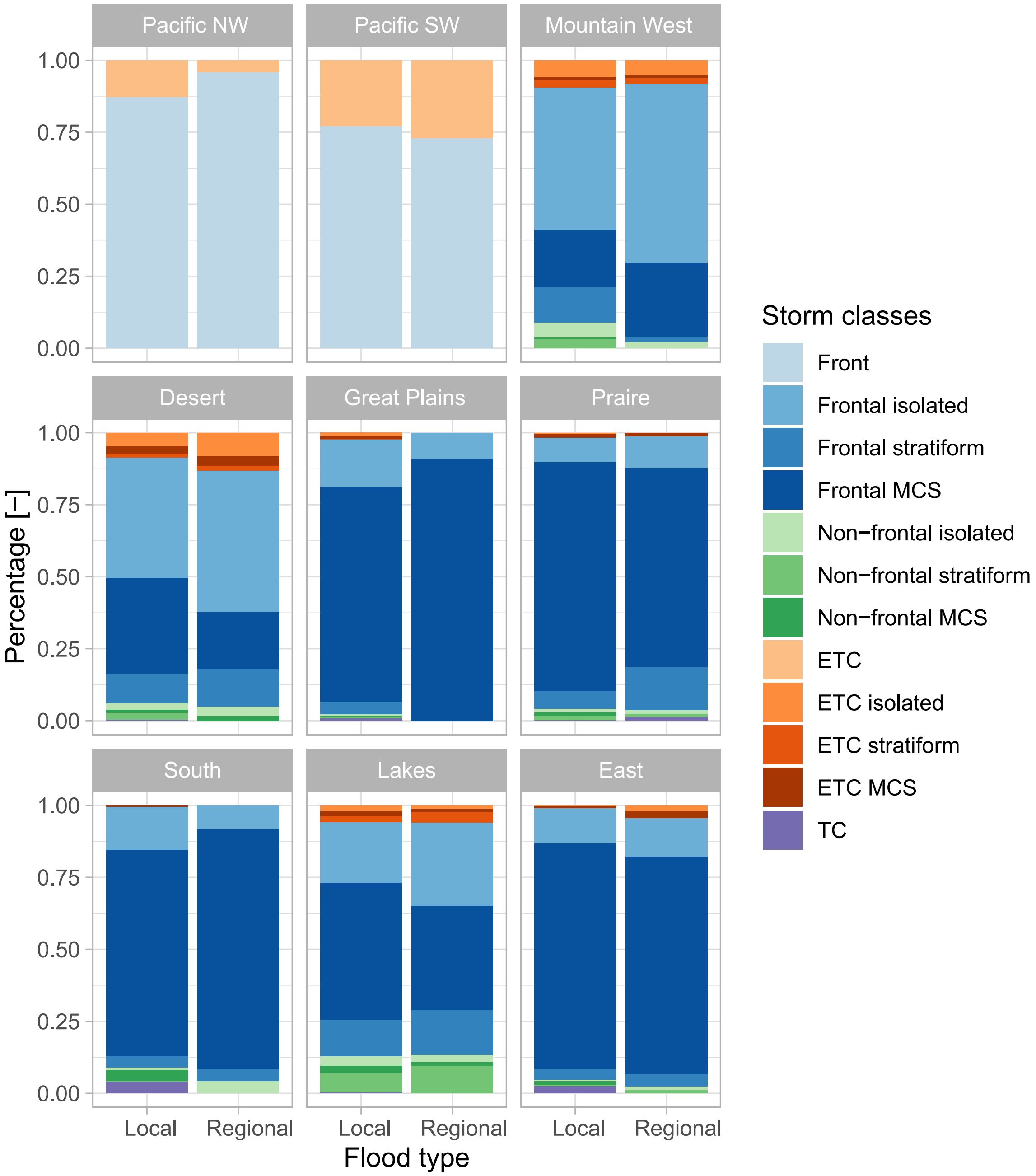

Figure 6. Relative importance of storm types triggering local and regional flood events per hydroclimatic region over all seasons.

3.3. Antecedent Conditions Related to Local and Regional Floods

In contrast to storm types, antecedent conditions vary substantially for local and regional flood events (Figure 7). These differences are confirmed by the results of Fisher's Exact test, which does reject the null-hypothesis of equal relative frequency distributions for local and regional events at a level of significance of 0.05 in all regions. Local events are equally likely under dry and wet antecedent conditions. In contrast, regional events are less likely to be purely rainfall driven and more likely to be influenced by land-surface processes including positive soil moisture anomalies, snowmelt or both. Snowmelt combined with wet antecedent conditions is an important driver of regional floods in the Pacific NW, the Mountain West, and the Lakes region, while wet antecedent conditions are an important driver of regional floods in the remaining regions.

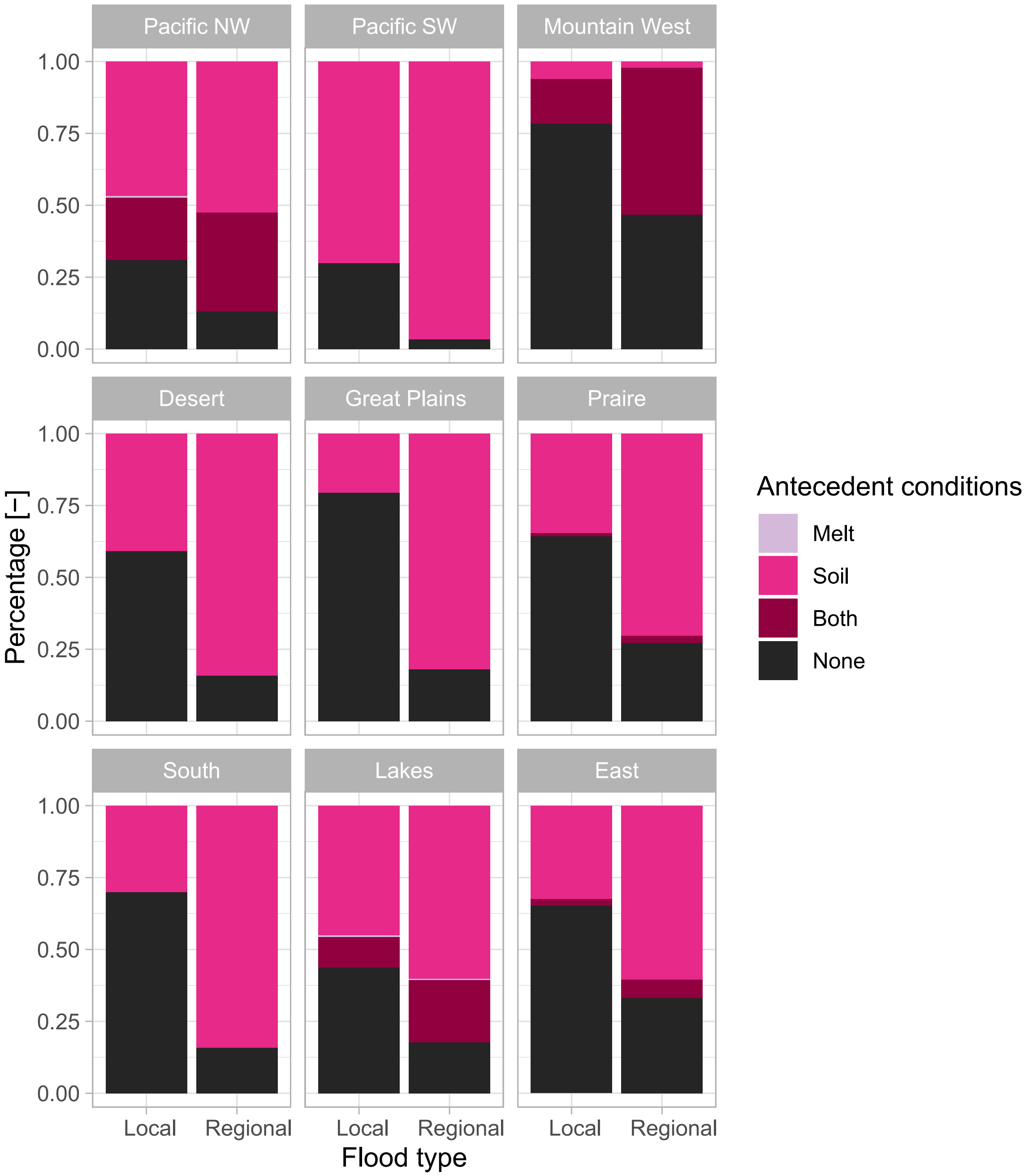

Figure 7. Relative importance of different antecedent conditions in triggering local and regional flood events per region. Antecedent conditions considered are snowmelt (>1 mm), soil moisture anomalies (>0.8 percentile), both snowmelt and soil moisture anomaly, none of the two (i.e., likely precipitation driven).

Regional events are more likely under wet antecedent conditions than during dry antecedent conditions in all seasons (Figure 8). Wet soils are particularly important for regional flood development in winter and spring, the seasons when regional floods occur most frequently (Figure 5). In the Mountain West, where regional floods also occur in summer, snowmelt in combination with wet antecedent conditions is important. In spring, snowmelt contributions together with wet soils increase the likelihood of regional flood occurrence in the Mountain West, the Lakes and eastern regions. Note that in the summer, antecedent conditions are less important for regional events.

Flood events are the result of a combination of storm type and antecedent conditions, rather than purely climate or land-surface driven. Therefore, we now look at the most frequent combinations of storm type and

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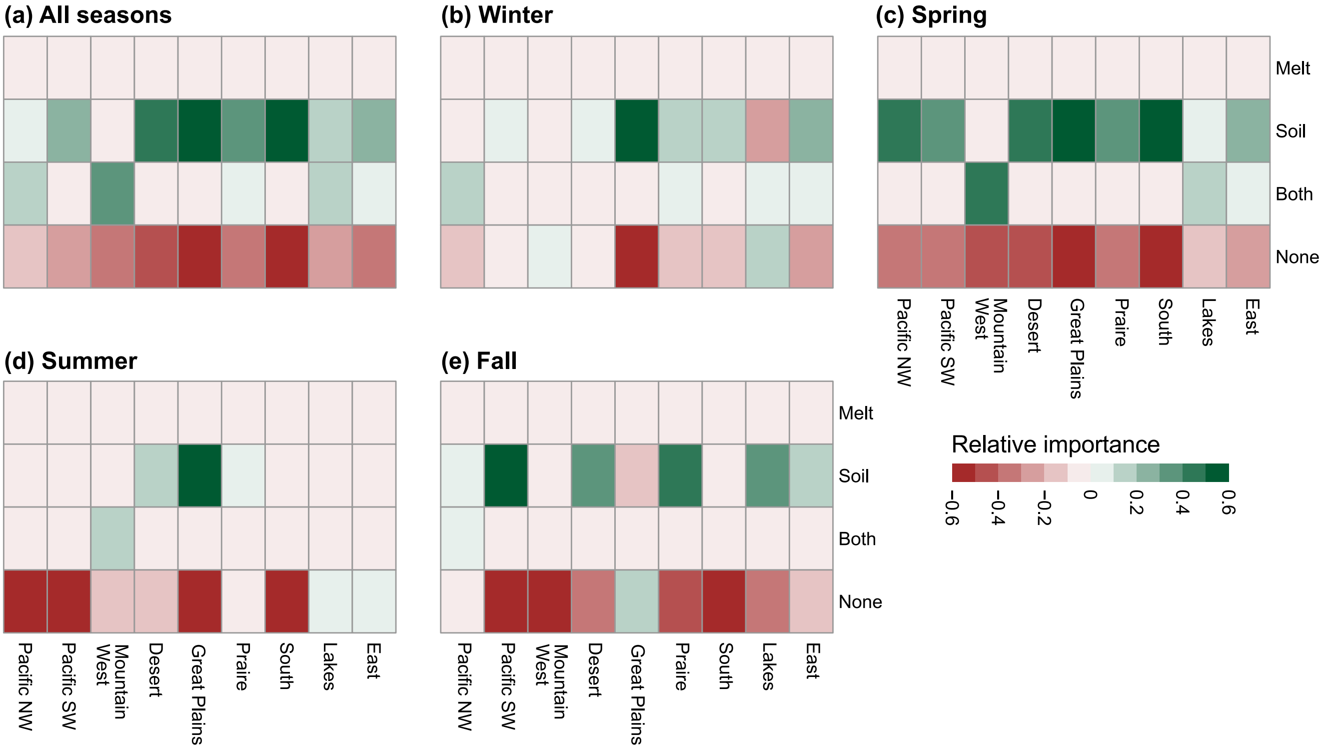

Figure 8. Difference in the relative importance of different antecedent conditions triggering regional and local flood events per hydroclimatic region and season (percentage regional—percentage local). Green and red colors indicate that an antecedent conditions class is more important during regional and local events, respectively.

antecedent-conditions for local and regional flood events. In most regions, flood events are associated with frontal events occurring under both wet and dry antecedent soil conditions (Figure 9). In the Mountain West, Desert, Great Plains, and South, local flood events commonly occur under dry antecedent soil conditions and frontal convection (isolated convection and MCSs). In the Prairie and East, local floods are frequently driven by frontal MCSs under both dry and wet antecedent soils. The Pacific NW, Pacific SW, and Lakes region have more floods occur under wet soil conditions or wet soils plus snowmelt along with fronts.

Similarly, as all floods, regional floods are still most frequently associated with frontal storm types. However, they are less likely to happen under dry antecedent conditions than local events (Figure 10). In all hydroclimatic regions, regional events are most likely under conditions where a frontal storm is combined with wet antecedent conditions or snowmelt and wet antecedent conditions. In the Pacific North- and Southwest, the dominant compounding drivers are frontal events occurring during wet soil conditions, in the Mountain West fronts with isolated convection occurring during antecedent conditions characterized by snowmelt and wet soils, in the Desert region fronts with isolated convection occurring during wet soil conditions, and in all other regions, frontal mesoscale convective systems occurring during wet soil conditions. These dominant compounding drivers have different seasonality depending on the region (Figure 11). In the Northwest, Southwest, Desert, South, Lakes, and East, the dominant compounding drivers occur in winter and spring, in the Mountain West, Great Plains, and Prairie in late spring and early summer.

4. Discussion

Our results are influenced by several methodological choices, including the design of the storm type and antecedent conditions classification schemes, the choice to sample events based on streamflow, the flood identification procedure applied, the choice to work with daily data, and the choice to work with the hydroclimatic Bukovsky regions. The storm type classification did not account for days in which multiple storm types occurred, such as a stratiform rainfall events following an MCS. While it is unlikely that multiple synoptic events (fronts, ETCs, or TCs) would occur on the same day based on their typical timescales, it is possible that multiple rainfall types

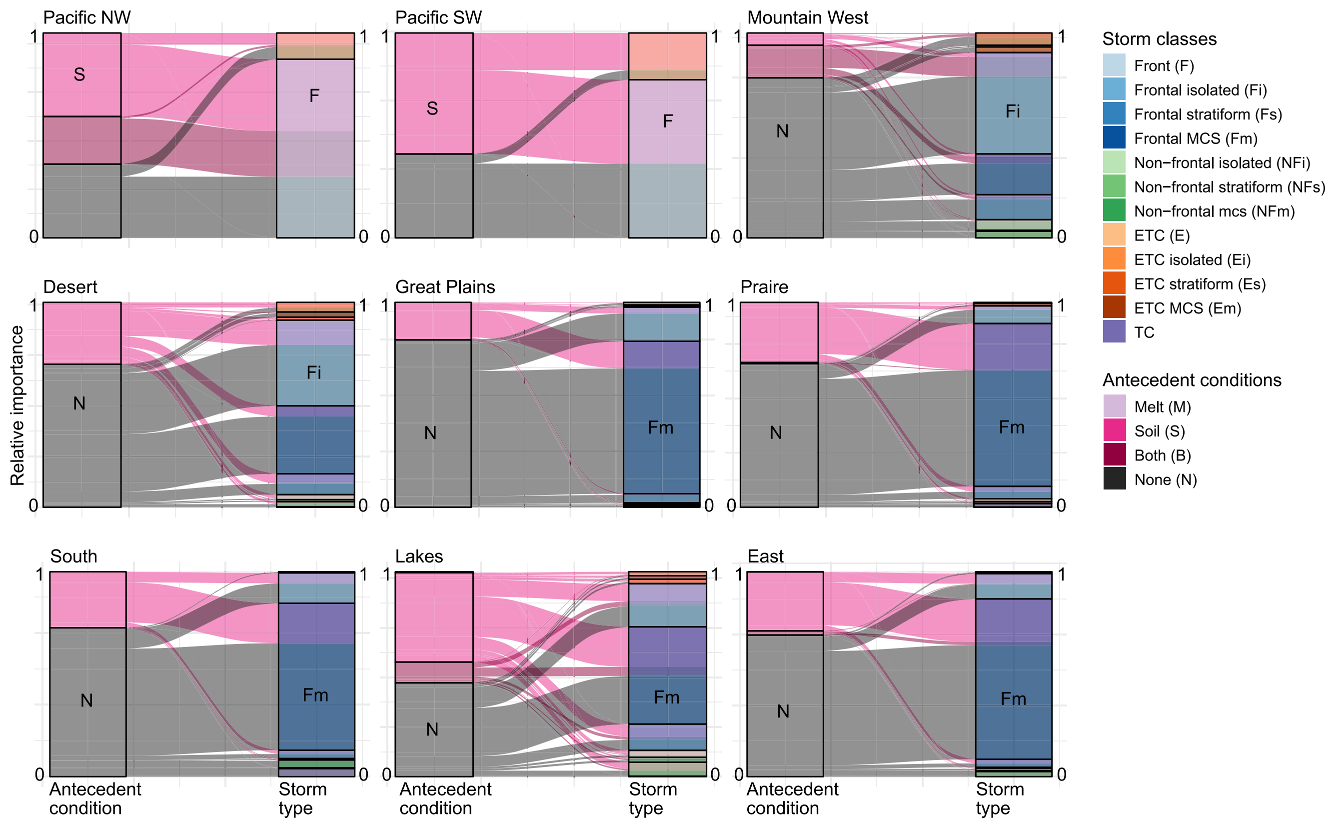

Figure 9. Co-occurrence of different storm types with different antecedent conditions during local flood events in the nine hydroclimatic regions. The thickness of the connecting line represents the relative importance of a certain antecedent condition-storm type combination. The thicker the connecting line, the more frequent the antecedent condition-storm type combination. The most important antecedent condition-storm type combination is indicated by labeling the antecedent condition on the left and storm type on the right.

could occur on the same day. Also, the storm types do not have to occur for a certain amount of time to be considered the dominant type for a particular day, and this could affect the results if a storm was only briefly in a region versus there for a longer amount of time. Additionally, the choice of the threshold used for the frontal identification could impact the results. A sensitivity test was performed for 850 hPa equivalent potential temperature gradient values between 3 and 8 K per grid cell. The stricter threshold resulted in too few fronts compared to observations, while the lower threshold produced too many. We settled at 3.6 K as the threshold, since it compared best to observations from the National Center for Environmental Prediction Center. Finally, radar data were unavailable in the Pacific Northwest and Southwest, which limited the storm type analysis in these regions. Records of long-term and reliable radar data are currently lacking from these regions, so until that is available, we cannot fully assess the storm types there.

The antecedent classification scheme relies on thresholds for snowmelt and wet antecedent conditions. Increasing the snowmelt threshold will lead to a decrease in the relative importance of melt-influenced conditions, while increasing the relative importance of wet conditions. This dependence between relative importance and snowmelt threshold is illustrated by our sensitivity analysis showing the relative importance of different antecedent conditions in triggering local and regional floods for snowmelt thresholds of 1 mm (i.e., the threshold used in our analysis) and 2 mm (Appendix Figure A1). However, independent of where the exact threshold is set, the main conclusion of our analysis, that is, that antecedent conditions are more important for regional than for local flood event development, remains unchanged. Similarly, to the snowmelt threshold, changing the soil moisture anomaly threshold will lead to a change in the relative importance of events associated with wet soil conditions compared to snowmelt-influenced and mainly precipitation-driven events (Appendix Figure A2). Our sensitivity analysis shows a decrease in the relative importance of wet antecedent conditions and a mix of wet antecedent conditions and snowmelt with an increasing percentile threshold from 0.7 to 0.9. Again, the main conclusion that antecedent conditions are more important for regional than for local floods remains unchanged. In addition to methodological

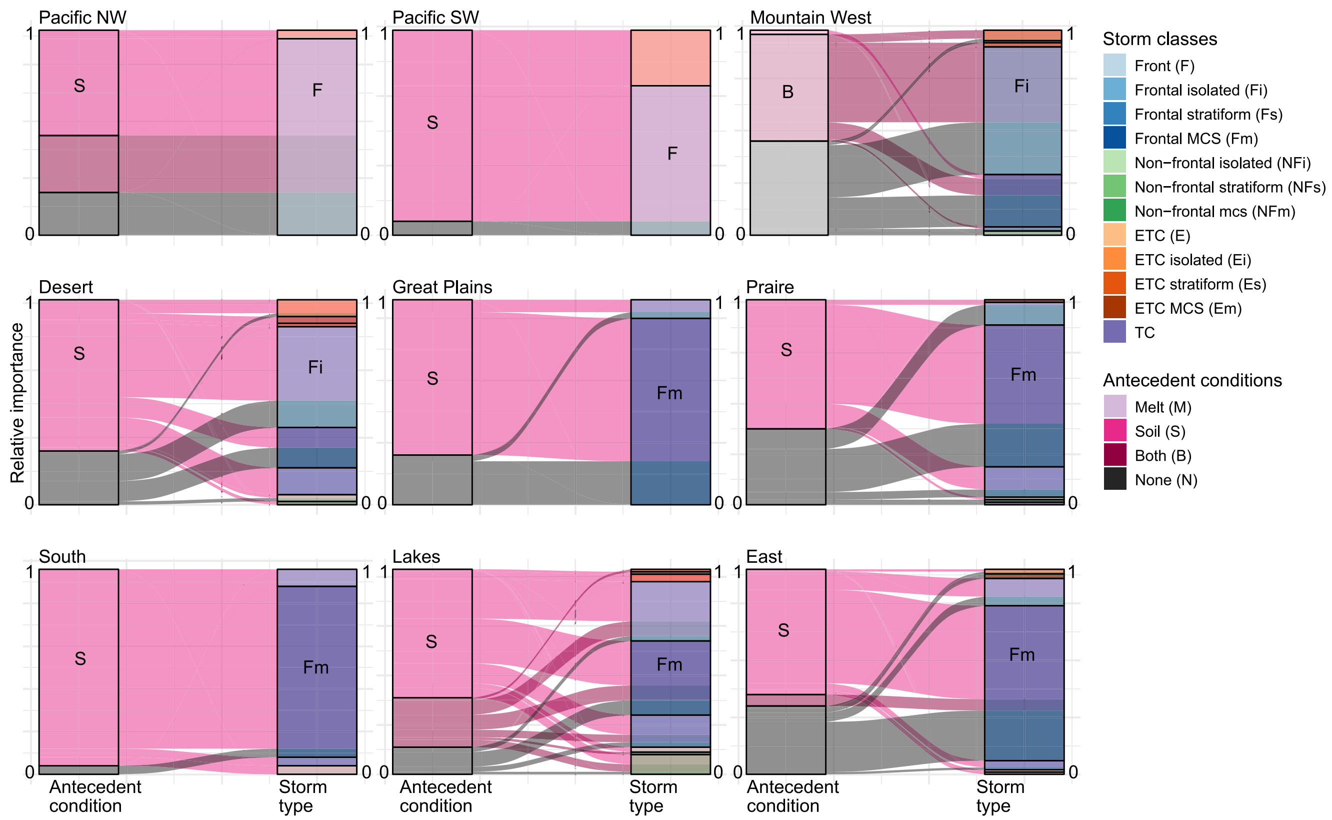

Figure 10. Co-occurrence of different storm types with different antecedent conditions during regional floods (in contrast to local floods shown in Figure 9) in the nine hydroclimatic regions. The thickness of the connecting line represents the relative importance of a certain antecedent condition-storm type combination. The thicker the connecting line, the more frequent the antecedent condition-storm type combination. The most important antecedent condition-storm type combination is indicated by labeling the antecedent condition on the left and storm type on the right.

decisions regarding the storm type and antecedent conditions classification schemes, our results to some degrees vary depending on how local and regional flood thresholds are set (Appendix Figure A3). However, independent of the threshold, storm type importance hardly differs between local and regional events while antecedent condition importance substantially differs between local and regional events. The choice of a %-coverage threshold to separate local from regional events was necessary because our analysis relied on observed streamflow data which is associated with unequal station density. While such a %-coverage threshold allows us to separate local from regional events, spatial extents of identified regional flood events will vary across regions and events because of unequal region size and because affected catchments may not be contiguous. Conditioning the sampling strategy on flooding might bias the runoff mechanisms to wet antecedent conditions (Wasko & Guo, 2022). To avoid such bias, one could condition the sampling on extreme precipitation instead. However, such a precipitation-based sampling strategy will include events that are not necessarily extreme in terms of streamflow and might miss extreme flood events which were mainly governed by other factors than extreme precipitation (Ivancic & Shaw, 2015). Our analysis neglected that a flood event is influenced not only by the storm type on the day of flood occurrence but also the storms produced a few days prior to event occurrence through their effect on antecedent conditions. As we wanted to clearly separate the storm type from the antecedent conditions analysis, we looked at the storm type on the day of flood occurrence only, and indirectly consider storm types prior to event occurrence by looking at different antecedent conditions. Our focus on storm types and antecedent conditions also neglected other potential flood triggers going beyond climatic and land-surface processes such as human flood regulation, which has been shown to influence regional flood development (Brunner, 2021), or factors related to catchment morphology such as catchment area (Stein et al., 2021b). Future analyses could focus on the relative importance of management influences on regional flood development compared to for example, the importance of antecedent conditions by studying a data set consisting of a mix of natural and regulated catchments.

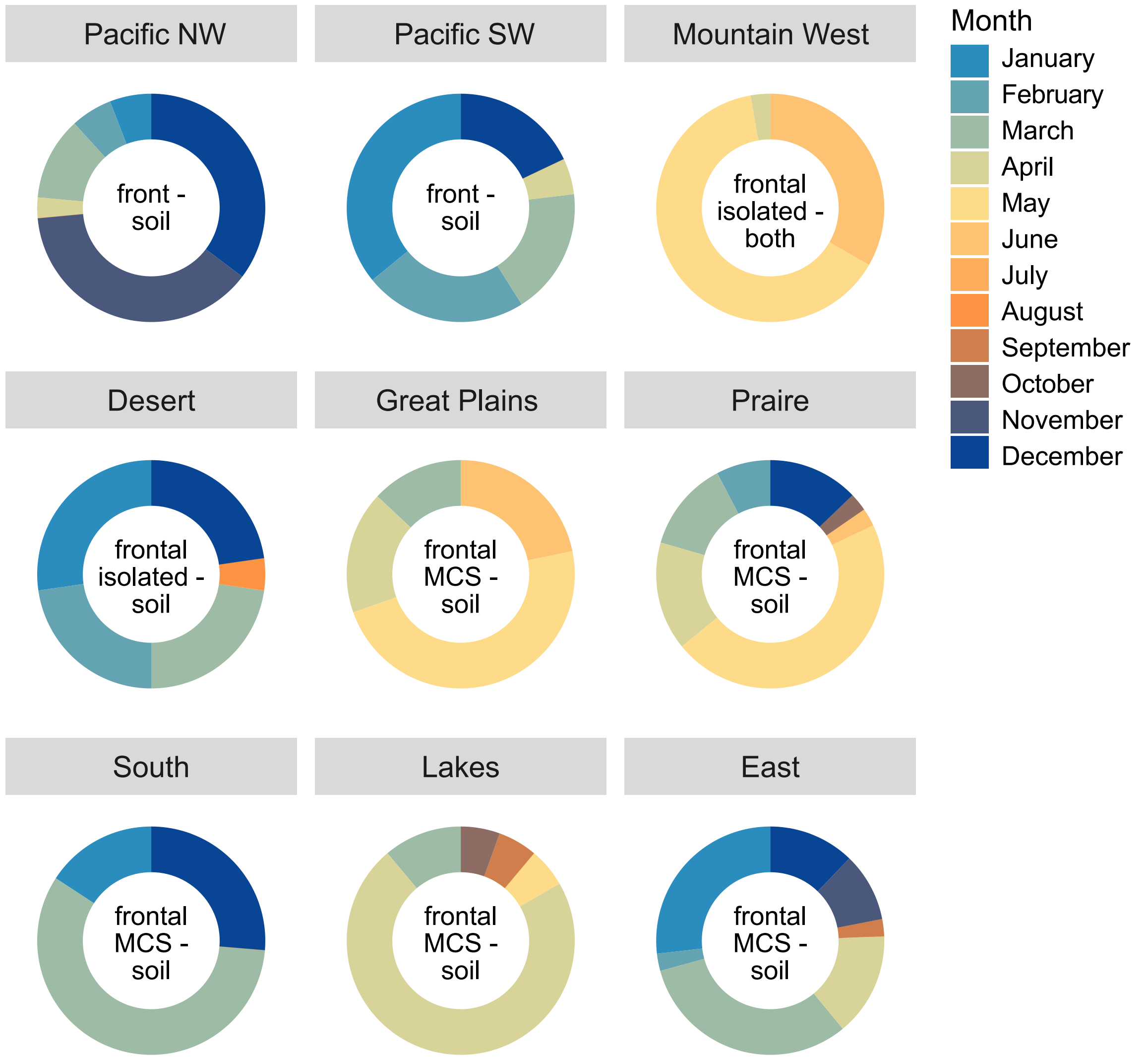

Figure 11. Seasonality of dominant compounding drivers per region.

In addition to choices related to the classification schemes and the flood identification procedure applied, our analysis is also influenced by the choice of daily streamflow data and the region definition. We used daily streamflow data to identify flood events, which means that our event selection may have missed some flood events relevant at a subdaily but not at a daily scale, such as flash floods with very fast response times. In order to include such events, one would have to use streamflow time series at subdaily resolution for event identification, while the storm type and antecedent condition classification could proceed in the same way as outlined in this study. Our analysis is also influenced be the choice of the regions used to study local and regional floods and their hydroclimatic drivers. A region definition is essential for our analysis to (a) define regional versus local flood events and (b) determine storm types for any given day. Because this is an interdisciplinary study looking at the climatological drivers of flooding, we needed a region subdivision that is meaningful both from a climatological (for defining the storm types) and hydrological (for defining the regional events) perspective. An alternative to working with the hydroclimatic Bukovsky regions would have been to use a subdivision into large major river basins (e.g., the 21 hydrologic regions follow the two-digit hydrological units delineated in the Watershed Boundary data set (USGS, 2022) or the 18 large basins used in Brunner, Papalexiou, et al. (2020)). While major river basins would have been the logical choice from a purely hydrological perspective, we did not consider such a subdivision to be the optimal choice for our analysis because it would have resulted in much smaller regions, which would have had two main disadvantages. First, some of the major river basins would have had very few unregulated gauges, which

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would have been suboptimal for the regional analysis. Second, determining storm types for such small regions would have been less sensible because the synoptic storm types (i.e., TCs, fronts, and ETCs) are large systems on the order of 1,000s of km that would have affected multiple small regions at once, leading to double-counting of such storms. Even the smaller mesoscale systems, such as MCSs, can be quite large (~100s of km), and would also present an issue in smaller river basins where their rainfall might not be entirely captured. By using larger, hydroclimatically similar basins, we attempt to avoid this issue as much as possible. While we chose to work with nine hydroclimatic regions for our analysis, the methods used and proposed in this study including the storm type and antecedent conditions classification schemes are applicable to other region definitions.

Our results highlight the dominant role of frontal storms as a flood-generation mechanism in the CONUS despite regional and seasonal differences in the importance of different frontal storm types for flood generation (Figures 3 and 4). These results corroborate findings by Schlef et al. (2019) who also showed that there are only a few distinct circulation patterns causing floods in the CONUS and by Kunkel et al. (2012) who highlighted the dominance of frontal storms in causing extreme precipitation. Analyses by Kunkel et al. (2012) also suggest that the frequency of frontal events has increased over time in several regions of the CONUS. A further increase in the number of frontal events might have potential implications for future flood occurrence because our findings stress the importance of frontal storms as a flood-triggering mechanism. Our results also show that some rarer storm types such as tropical cyclones are only relevant in specific regions such as the South and East regions, which corroborates findings by Villarini et al. (2014). The seasonal differences in the relative importance of different storm types agree with findings by Nied et al. (2014) who have observed the same for the Elbe river basin, and Dougherty and Rasmussen (2019) and Ashley and Ashley (2008) who observed similar results over the CONUS. Additionally, the dominance of MCS rainfall in causing floods supports findings from Schumacher and Johnson (2006), Ashley and Ashley (2008), and Hu et al. (2021), who suggest that MCSs are common flood-producing storm types due to their large spatial extent and high rainfall intensity. We find that this is particularly true in the spring and summer, when frontally driven MCSs combine with wet antecedent conditions to produce regional floods.

Our comparison of local and regional flood drivers shows that storm types are relatively more important for local flood development, while antecedent conditions are relatively more important for regional flood development. In addition, it shows that local and regional floods differ in their antecedent conditions more than in flood-triggering storm types (Figures 7 and 6). The finding that storm types cannot be used to differentiate between local and regional flood events supports similar findings by Pattison and Lane (2012) who showed that storm types cannot be used to distinguish between moderate and severe flood events and by Bárdossy and Filiz (2005) who found only weak relationships between large-scale features and discharge at a daily scale. Regional events are less often purely precipitation driven than local events and in more than 75% of the cases associated with either snowmelt, positive soil moisture anomalies, or both. That is, whether a flood event is local versus regional is more determined by antecedent conditions rather than by storm type. The importance of antecedent conditions in flood formation has already been stressed in previous studies for local floods (Berghuijs et al., 2016; Brunner et al., 2021; Sikorska et al., 2015; Stein et al., 2019; Tarasova et al., 2020; Wasko & Nathan, 2019; Ye et al., 2017) and for regional events (Brunner, Gilleland, et al., 2020; Kemter et al., 2020; Ivancic & Shaw, 2015). The regional variations in the relative difference between soil moisture and snowmelt as drivers of local floods (Figure 7) confirm findings by Stein et al. (2019) who have shown that soil moisture is a dominant driver of local floods in the eastern and southern United States, while snowmelt is a dominant driver in the Mountain West. Our findings also corroborate findings by Ye et al. (2017) who have shown that local floods in the Pacific Northwest are often related to wet soils while floods in the drier inland catchments are mostly driven by rainfall and less by soil moisture. In addition, our results show that both soil moisture anomalies and precipitation are an important flood driver in the South and East with rainfall being comparably more important than in previous studies by Ye et al. (2017) and Stein et al. (2021a). These differences in the relative importance of soil moisture and precipitation are likely related to the fact that our analysis looked at soil moisture anomalies while the previous studies looked at absolute soil saturation. Last, our findings stressing the importance of antecedent conditions for flood generation are in line with studies linking trends in flood seasonality, magnitude, and frequency with trends in not just precipitation but also soil moisture (Collins, 2018; Ivancic & Shaw, 2015; Neri et al., 2019).

While previous studies have highlighted the importance of antecedent conditions for local and regional flood formation, we are here able to demonstrate that antecedent conditions are even more relevant for regional than for local floods. Our results also highlight the importance of compounding flood drivers, that is, storm types and antecedent conditions, in regional flood generation (Figure 10). The conditions most favorable for regional flood development are a combination of some sort of frontal storm with wet soils or snowmelt. The importance of jointly considering multiple flood drivers has also been highlighted in previous studies focusing on local floods (Blöschl et al., 2019; Brunner et al., 2021; Sharma et al., 2018; Wasko & Nathan, 2019) but seems to be even more important when studying regional events.

The finding that antecedent conditions rather than storm types differ between local and regional floods has implications for flood prediction. Previous studies have shown that for example, snow availability can serve as a good predictor of local floods (Ossandón et al., 2022). Such information may be even more valuable in predicting regional floods as our results show that regional floods are much more likely under wet than under dry antecedent conditions. The prediction of regional floods might be improved by including more or more accurate information about antecedent conditions, for example, by assimilating remotely sensed soil moisture information in hydrological models (Behera et al., 2019). The importance of antecedent conditions for regional flood development also suggests that climate change impact assessments of regional flooding need to focus on the representation of land-surface processes and antecedent conditions in addition to looking at changes in precipitation. In summary, our results suggest that enhanced consideration and improved representation of antecedent conditions might improve both regional flood forecasting and projection.

5. Conclusions

A better understanding of mechanisms triggering local and regional floods can potentially improve change impact assessments and the prediction of both types of extreme events. Using a storm type and antecedent condition classification scheme, we assessed which storm types and antecedent conditions are related to local and regional flood occurrence in the United States. Our results show that over all regions, frontal storms, in particular those related to mesoscale convective systems, are the dominant storm type triggering floods. The relative importance of different storm types varies not just by region but also by season, with frontal mesoscale convective systems being most important in summer, nonfrontal and extratropical cyclone-related storms in winter and spring, and tropical cyclones in fall. Our comparison of flood-triggering conditions of local and regional flood events showed that storm types only weakly differ between local and regional events, while antecedent conditions are distinct. Regional flood development requires wet antecedent soil conditions which can be combined with snowmelt, while local floods are more likely to also develop under dry conditions. That is, antecedent conditions rather than storm type determine the spatial scale of flood events. Local events may develop under various combinations of storm types and antecedent conditions, while the conditions most favorable for regional flood development are a combination of a frontal storm with wet soils or snowmelt. These findings suggest that the prediction of regional flood events may be improved by using information on antecedent conditions and by improving their representation in hydrological and earth-system models, while local flood prediction can be improved by knowledge of rainfall characteristics in conjunction with antecedent conditions. We conclude that particularly regional flood risk and change assessments should account for the compounding nature of atmospheric and land-surface flood drivers.

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Appendix A: Sensitivity Analysis

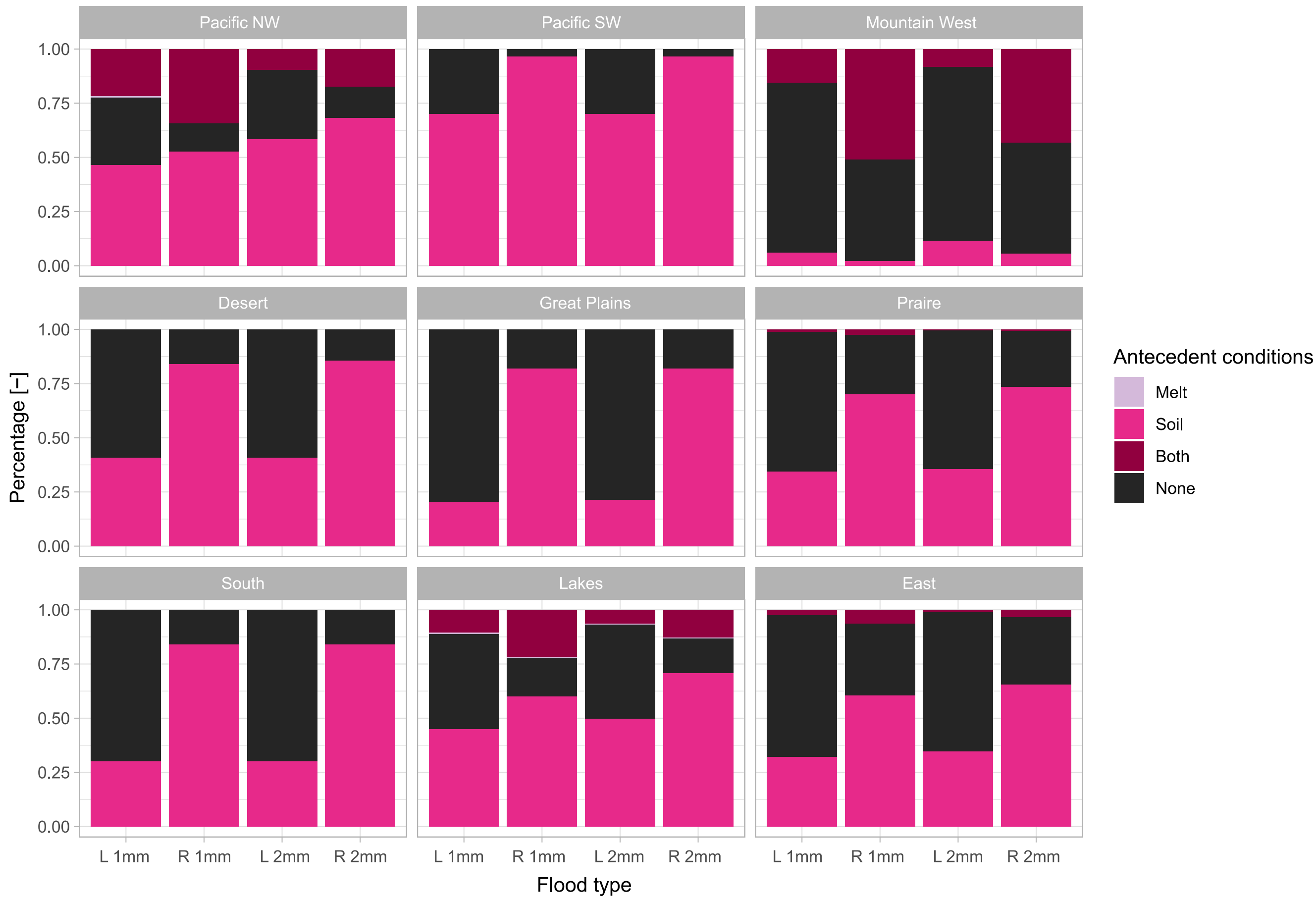

Figure A1. Sensitivity analysis toward the choice of the snowmelt threshold. The relative importance of different antecedent conditions in triggering local (L) and regional (R) flood events per region is shown for snowmelt thresholds of 1 and 2 mm while the soil moisture threshold is kept constant (>0.8 percentile).

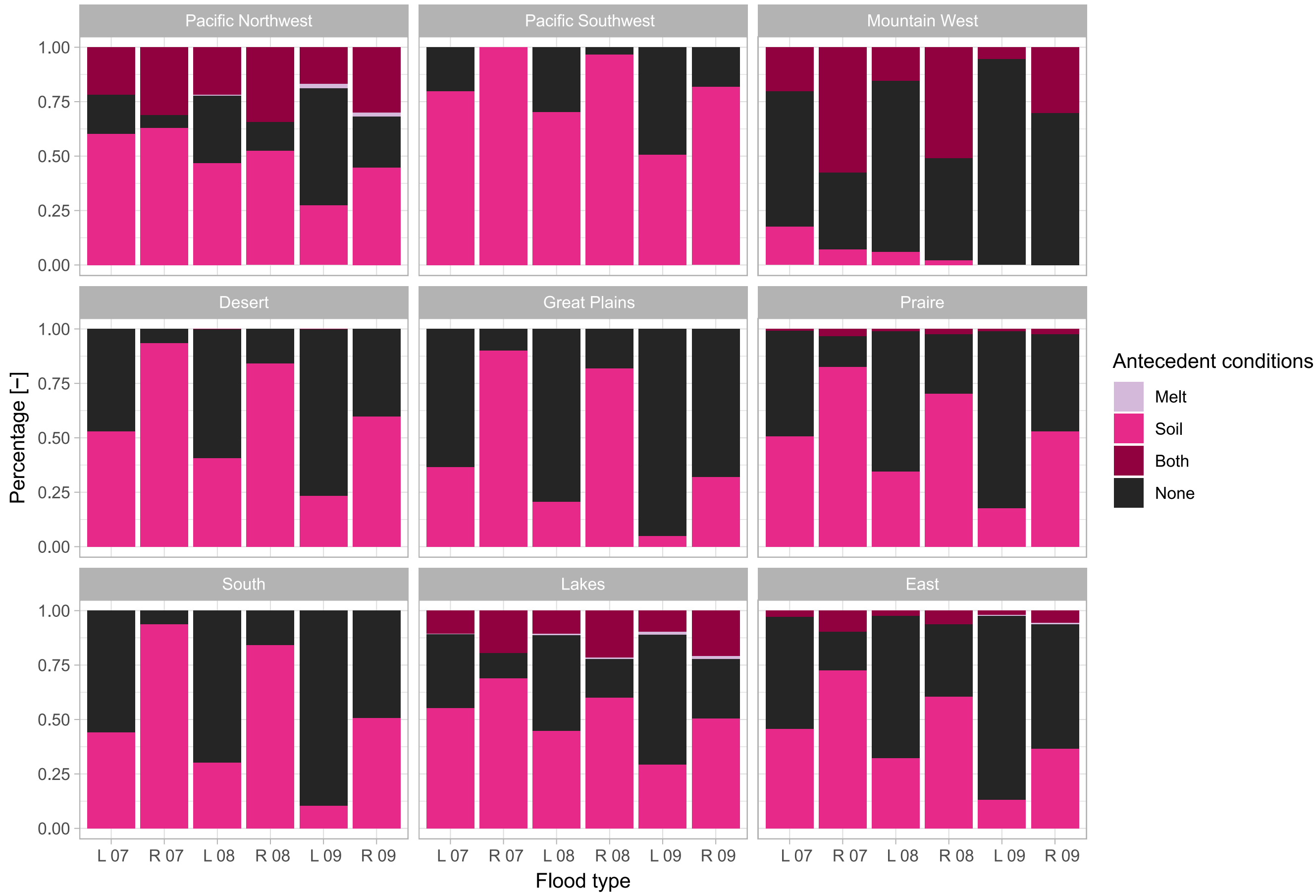

Figure A2. Sensitivity analysis toward the choice of the soil moisture anomaly threshold. The relative importance of different antecedent conditions in triggering local (L) and regional (R) flood events per region is shown for soil moisture anomaly thresholds at the 0.7, 0.8, and 0.9 percentile while the snowmelt threshold is kept constant at 1 mm.

Figure A3. Sensitivity of relative importance of storm types triggering local and regional flood events toward local and regional threshold choice per hydroclimatic region: local 25th percentile of AM and regional 25% (setting used for analyses shown in manuscript), local 10th percentile of AM and regional 25%, local 25th percentile of AM and regional 10%, and local 25th percentile of AM and regional 50%.

Acknowledgments
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Data Availability Statement

The CAMELS data set can be downloaded via https://ral.ucar.edu/solutions/products/camels (Addor et al., 2017; Newman et al., 2015). The ERA5Land reanalysis data are available through the Copernicus data store: https://cds.climate.copernicus.eu/cdsapp%23%21/dataset/reanalysis%2Dera5%2Dland%3Ftab%3Doverview (ECMWF, 2019). The ERA5 reanalysis data used to identify fronts is available from the NCAR Research Data Archive (RDA): https://rda.ucar.edu/datasets/ds630.0/ (Research Data Archive at the National Center for Atmospheric Research. Computational and Information Systems Laboratory, 2021). Tropical cyclone data from the Extended Best Track data set can be accessed through the Regional and Mesoscale Meteorology Branch: https://rammb2.cira.colostate.edu/research/tropical-cyclones/tc_extended_best_track_dataset/ (Regional and Mesoscale Meteorology Branch, 2021). The extratropical cyclone data set is available from ETH Zurich: http://eraiclim.ethz.ch/ (ETH Zurich, 2018). Radar data from GridRad can be accessed through the NCAR RDA: https://rda.ucar.edu/datasets/ds841.0/ (Bowman & Homeyer, 2017). The data sets generated in this study, that is, the identified flood events, classified storms, and classified antecedent conditions are available through HydroShare: https://www.hydroshare.org/resource/1d43baab99544e1b89eec3087da19e9a/ (Brunner & Dougherty, 2022).

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