

How have hydrological extremes changed over the past 20 years?

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Abstract

Severe floods and droughts, including their back-to-back occurrences (weather whiplash), have been increasing in frequency and severity around the world. Improved understanding of systematic changes in hydrological extremes is essential for preparation and adaptation. In this study, we identified and quantified extreme wet and dry events globally by applying a clustering algorithm to terrestrial water storage (TWS) data from the Gravity Recovery and Climate Experiment (GRACE) and GRACE Follow-On (FO). The most intense events, ranked using an intensity metric, often reflect impacts of large-scale oceanic oscillations such as the EL Niño Southern Oscillation and consequences of climate change. Severity of both wet and dry events, represented by standardized TWS anomalies, increased significantly in most cases, likely associated with intensification of wet and dry weather regimes in a warmer world, and consequently, exhibited strongest correlation with global temperature. In the Dry climate, the number of wet events decreased while the number of dry events increased significantly, suggesting a drying trend that may be attributed to climate variability and possible increases in irrigation and reliance on groundwater. In the Continental climate where temperature has risen faster than global average, dry events increased significantly. Characteristics of extreme events often showed strong correlations with global temperature, especially when averaged over all climates. These results suggest changes in hydrological extremes and underscore the importance of quantifying total water storage changes when studying hydrological extremes. Extending the GRACE/FO record, which spans 2002-present, is essential to continuously tracking changes in TWS and hydrological extremes.

1. Introduction

Floods and droughts have major consequences for human and ecosystem health, agriculture, and the economy. The number of billion-dollar droughts has increased substantially in recent years, raising concerns on changing hydrological extremes (<https://www.ncdc.noaa.gov/billions/>). Globally, floods and droughts affect more than 100 million people each year, with more devastating impacts in developing countries where more people live in rural areas with limited resources and fewer options to cope with extreme heat and food and water shortages (Miyan, 2015). Detailed understanding of how the frequency and intensity of hydrological extremes may be responding to climate change across different regions and climate zones would be valuable for adaptation and minimizing economic damage and human hardship.

Previous studies have reported apparent modulation of the water cycle and its extremes by climate change. Blöschl et al. (2019) attributed increases of floods in northwestern Europe to increases in fall-winter precipitation and decreases of floods in eastern and southern Europe to decreases in snowfall and annual precipitation, respectively, during 1960-2010. In Russia, increasing flooding has been attributed to increases in daily precipitation, fast spring snow melt and thawing of permafrost (Frolova et al., 2017; zolotokrylin & Cherenkova, 2017). Russia has also seen increases in severe droughts and wildfires in recent years, including in its arctic regions (Shvidenko & Schepaschenko, 2013; Frolova et al., 2017; Ciavarella et al., 2021). In the southwestern U.S., recent studies based on tree-ring data and climate reconstruction suggest that both drought occurrence and the declines in streamflow in major river basins were linked to anthropogenic warming (Woodhouse et al., 2016; Lehner et al., 2017; Williams et al., 2022; Martin et al., 2020; Milly and Dunne, 2020). In addition, incidences of weather whiplash (a rapid shift from one extreme weather condition to its opposite), as California has recently experienced, have been on the rise and are projected to increase with global warming (Huang & Swain, 2022; Zamora-Reyes et al., 2022).

However, systematic changes in hydrological extremes across continental to global scales have been difficult to confirm, as noted in global and U.S. climate reports (Douville et al., 2021; USGCRP, 2018). In fact, using streamflow data from more than 1,200 gauges in minimally altered catchments in North America and Europe over 60-80 year periods, Hodgkins et al. (2017)

showed that natural climate variability significantly affected the occurrence of floods, while linear trends associated with climate change were insignificant. On the other hand, the number of streamflow gauges is limited, especially in developing countries, and the gauges are often clustered around certain areas, making it difficult to rely on streamflow data alone for examining large-scale changes in hydrological extremes.

Soil moisture simulated by land surface models has been the basis for several studies of droughts and pluvials at continental to global scales (e.g., Andreadis et al., 2005; Sheffield et al., 2009; He et al., 2020; He and Sheffield, 2020). A shortcoming of this approach is that output from large-scale models is subject to significant uncertainty due to deficiencies in model inputs and physics (e.g., Kato et al., 2007; Xia et al., 2012). In particular, many such models do not simulate permafrost, surface water or groundwater, which are undergoing considerable changes (Rodell et al., 2018). Perhaps more relevant to the analysis of extreme events, the atmospheric re-analysis-products used to drive these models may underestimate extreme precipitation (Hu and Franzke, 2020) and are subject to large uncertainties at high elevations and during snow events (Cui et al., 2017) and therefore, are likely to underestimate the occurrence and severity of floods. In general, a major challenge to detecting changes in hydrological extremes is the lack of global-scale, spatially and temporally consistent observations.

The Gravity Recovery and Climate Experiment (GRACE) and GRACE Follow-On (GRACE-FO) satellite missions (hereafter GRACE/FO) have been mapping Earth's gravity field nearly continuously since 2002 (Tapley et al. 2004; Landerer et al., 2020). Temporal variations of gravity can be used to infer terrestrial water storage (TWS) changes which include soil moisture, groundwater, snow and ice, and surface water. Reflecting water storage change in the full surface-soil-aquifer profile, TWS data are well suited for studying hydrological extremes, especially anomalous conditions that last months to years. The effectiveness of GRACE/FO data for detecting and quantifying drought has been demonstrated in numerous contexts, including the 2003 European heat wave (Andersen et al., 2005), the Millennium Drought in Australia (Leblanc et al., 2009; van Dijk et al., 2013), the multi-year California drought in the 2000s (Weiler, 2014; Thomas et al., 2017), and drought events in the Yangtze, Amazon, and other river basins (Chen et al., 2010; Thomas et al., 2014; Zhang et al., 2015; Getirana, 2016). Zhao et al. (2017), Li et al. (2019), and Gerdener et al. (2020) developed GRACE/FO-based indicators for detecting

hydrological drought globally. Other studies have used positive anomalies of GRACE/FO TWS to detect floods in the Amazon and a small basin in Cambodia (Chen et al., 2010; Tangdamrongsub et al., 2016) and to map flood vulnerability (Reager and Famiglietti, 2009; Reager et al., 2014; Singh et al., 2021; Shah and Mishra, 2021). As TWS changes represent net fluxes between precipitation, ET and runoff, GRACE/FO TWS data have been used to examine global increases in ET (Pascolini-Campbell et al., 2021) and intensification of the water cycle (Eicker et al., 2016; Chandanpurkar et al., 2021).

In this study, we employed a spatial-temporal clustering algorithm to identify wet/dry extreme events without pre-defined boundaries. Clustering in an objective way is necessary for examining changes in the characteristics of extreme events such as extent and frequency without bias or preconceived notions. We filled the observation gap (11 months) between the two GRACE/FO missions and other missing months using TWS simulated by a GRACE/FO data assimilating land surface model (Li et al., 2019). To better understand TWS-based extremes, we examined the most intense events in each continent, determined using an intensity metric (Thomas et al., 2014), which is based on spatially and temporally accumulated TWS anomalies. Mann-Kendall trends were calculated to examine changes in the characteristics of extremes including frequency, extent, duration, severity and intensity. Correlation analysis was further performed to identify major controls of climate variability and climate change on changes in extremes in four major climate classes. In an earlier study, Rodell and Li (2023) employed the same clustering approach and intensity metric to rank the most intense wet and dry events during 2002-2021. They determined that the global total intensity of hydroclimatic extreme events was strongly and significantly correlated with global mean temperature. The purpose of this study was to perform a more thorough analysis of how hydrological extremes have been changing in different climate zones and regions around the world, including severity-area-duration analysis, with the goal of providing a more detailed understanding that will be valuable for anticipating future change and mitigating impacts.

In Section 2 we describe the data sources, data processing, the clustering algorithm and the metrics used to characterize extreme events. In Section 3 we present the most intense events in 5 continents, changes in hydrological extremes and correlation analysis results. In Section 4 we discuss the hydroclimatic and anthropogenic drivers behind the detected changes.

2. Data and methods

2.1 GRACE/FO data

The GRACE/FO data used in this study are the mascon solutions developed by the Center for Space Research (CSR) at the University of Texas (Save et al., 2016). CSR applies a time-variable regularization matrix, derived from GRACE/FO information only, to constrain the inversion of satellite ranging data to gravity fields. This approach has been shown to reduce GRACE/FO signal damping associated with spherical harmonic solutions and related post-processing (Landerer and Swanson, 2012; Save et al., 2016). The data are available on a 0.25° global grid, which facilitates delineation of study regions and signal contamination from ocean signals. However, the effective resolution of GRACE/FO observations is lower, on the order of $150,000 \text{ km}^2$ at mid-latitudes (Rowlands et al., 2005; Swenson et al., 2006) due to the limitations of the measurement system.

We excluded regions that have shown persistent, long-term TWS declines not associated with drought, because these would otherwise be identified as extreme events by the clustering algorithm. These include regions of climate change driven ice loss, such as Greenland, glaciers along the Gulf Coast of Alaska, and Patagonia, and agricultural areas where groundwater withdrawals for irrigation, in some cases in conjunction with frequent droughts, have led to groundwater depletion: California's Central Valley, Northern India and the North China Plain. We followed Rodell et al. (2018) in delineating these regions. Our study period is August 2002 to December 2021, which excludes problematic GRACE observations in April and May 2002 (June and July 2002 data are absent).

2.2 Global GRACE/FO data assimilation

There is a 11-month gap (July 2017 to May 2018) between the two GRACE/FO missions, in addition to 18 other missing months of data that occur mostly between 2011 and 2017. To create a continuous record, we used simulated TWS from a global GRACE/FO data assimilating instance (Li et al., 2019) of the Catchment land surface model (CLSM; Koster et al., 2000)

driven by the Land Information System (Kumar et al., 2006) to fill the data gaps. CLSM-simulated TWS consists of soil moisture, groundwater, snow and canopy interception. Surface water and permanent ice are not simulated by CLSM. The data assimilation method incorporates surface water storage changes into groundwater (which is tightly coupled with surface water in the real world; Winter et al., 1998), and only 18 of 221 months were filled using the data assimilation output, hence the repercussions for the results are likely to be trivial. Regions with permanent ice cover were excluded from the analysis, as previously stated. Due to CLSM's inability to simulate groundwater withdrawals, in regions where groundwater pumping intensifies TWS losses during droughts, CLSM simulated TWS may underestimate TWS dynamics. However, the effects on our results are likely small because regions with intense groundwater withdrawals were excluded as stated earlier. Nevertheless, to be cautious, we removed from our analysis any extreme event that began and ended within the 11-month gap period.

2.3 Data processing and clustering algorithm

To identify large extreme events and better align with the effective resolution of GRACE/FO data ($\sim 150,000 \text{ km}^2$ in the mid-latitudes), we first aggregated the gap-filled 0.25° data to 2° . For a given 2° grid cell and month, a wet (dry) extreme was identified if the standardized TWS anomaly, relative to location-specific monthly mean, was greater than 1.0 (less than -1.0) (i.e., a one- σ threshold). Standardized TWS anomalies were calculated as:

$$S = \frac{Y}{\sigma} \quad (1)$$

where Y represents a TWS anomaly and σ represents the temporal standard deviation of the TWS anomaly time series at a given grid cell. Given a normal distribution, the one- σ threshold implies that wet extremes occur 16% of the time and the same for dry extremes. For reference, this encompasses the exceptional, extreme, severe, and some of the moderate droughts in the US Drought Monitor's categorization (Svoboda et al., 2002; <https://droughtmonitor.unl.edu/>).

We then used a clustering algorithm, ST-DBSCAN (Birant and Kut, 2007), to delineate wet and dry events from spatially and temporally continuous groups of flagged wet and dry data points. Note that wet events only comprise wet points and dry events only comprise dry points.

The version of ST-DBSCAN used in this study employs a spatial radius (“R”) and a time interval to define a search domain for a given wet/dry cell. We set the spatial radius, R, to 250 km, long enough to encompass two adjacent 2° grid cells anywhere on Earth, and we set the time interval to one month, so that data points (wet or dry cells) from the two months adjacent to the current month would be within the search domain.

If the number of neighboring wet/dry data points for a given wet/dry data point was larger than a minimum threshold ($N_{\min}$), this data point was marked as a core point and was given a cluster label. The process was repeated for all the neighboring points of the core point, and the same cluster label was given to any neighboring core points. With the spatial radius, R=250 km, and the one-month interval, we tested three values for $N_{\min}$, 10, 12 and 14, to determine an optimal set of clusters based on intra-clustering distance, the averaged distance of all wet/dry cells to the centroid of a cluster, and inter-cluster distance, the distance between the centroids of two clusters. Ultimately, we chose $N_{\min} = 12$ based on sensitivity analysis to be discussed in section 3.1. As stated earlier, any clusters that fell entirely within the 11-month gap (July, 2017-May, 2018) between the two satellite missions were excluded from this study.

2.4 Characterization of extreme events

We defined severity (unitless) at each grid cell using standardized GRACE/FO TWS anomalies (equation (1)). The severity of an event, S_E , was computed as the weighted average severity over all wet or dry cells of an event:

$$S_E = \sum_{j=1}^T G_j (\sum_{i=1}^{N_j} W_{ij} S_{ij}) \quad (2)$$

where S_{ij} represents severity at cell, i , in month, j ; W_{ij} is the ratio of the cell area at cell, i , and the total cell area for month, j ; G_j is the ratio of total cell area in month, j , and the total cell area of all months of an event; N_j is the total number of cells of an event in month, j ; T is the total number of months during which a cell was identified as wet or dry during the event. The extent of an event was represented by the time-averaged monthly sum of wet/dry cell areas over the duration of an event.

Intensity (km^3mo) of a given event, I , was defined following Thomas et al. (2014) as:

$$I = \sum_{j=1}^T \sum_{i=1}^M A_{ij} Y_{ij} \quad (3)$$

where A_{ij} and Y_{ij} represent the cell area (km^2) and TWS anomaly (equivalent height of water relative to the mean monthly seasonal cycle of TWS, converted from cm to km) at grid cell i and time j ; M is the total number of dry or wet cells at time j ; T is the duration (number of months) of an event. A positive intensity indicates a wet event and a negative intensity indicates a dry event. Compared to metrics based on extent and duration alone, which can yield multiple rankings for a given event (Sheffield et al., 2009), the intensity metric delivers a unique ranking for each event that accounts for extent, duration, and the evolving and non-uniform severity of an event. For correlation analysis, we also calculated the inner sum of equation (3) for each month of an event, representing monthly volumetric (km^3) TWS anomalies (Section 3).

2.5 Severity-area-duration (SAD) analysis

To examine how severity changes with spatial extent and duration, we calculated the SAD curve for all the events. SAD was originally developed for upscaling point-scale precipitation to regional averages but has been adopted for analyzing hydrological extremes in previous studies (Andreadis et al., 2005; Sheffield et al, 2009; He et al., 2020).

We began the process of deriving a SAD curve by calculating the average severity (standardized TWS anomaly; equation 1) of an event for a pre-defined duration (3, 6 and 12 months in this study). The maximum severity (absolute value for dry events) and its location were then identified. To examine how severity changes with increasing area, the next maximum severity was sought in the surrounding area, equal to $200,000 \text{ km}^2$ in this study, from the location of the previous maximum severity. This process was repeated for increasingly larger areas ($200,000 \text{ km}^2$ increments) until the extent of the event at this pre-defined duration was reached. Since the maximum severity may occur at any month, the aforementioned process was repeated for all the overlapping time periods (each equal to the pre-defined duration) within the event and the maximum severity for each area and period was selected to form the SAD curve. Therefore, a SAD curve represents the maximum severities occurring within an event over increasingly

larger areas and over the pre-defined durations. For additional details on SAD, we refer to Andreadis et al. (2005) and Sheffield et al. (2009).

3. Results

3.1 Sensitivity to clustering parameters

With the spatial radius fixed ($R=250$ km in this case), the number of wet and dry clusters (events) typically decreases as the minimum number of neighboring points required to define a core point, $N_{\min}$ (top row in Fig.S1), increases. This is because larger $N_{\min}$ values cause clusters with fewer data points to be eliminated. The total number of clusters in Eurasia is more sensitive to $N_{\min}$ than in other continents because it is large, making more wet and dry grid cells available for clustering.

Increases in $N_{\min}$ lead to smaller intra-cluster distances, producing denser clusters (bottom row in Fig.S1). Inter-cluster distances decrease with increasing $N_{\min}$ in most cases (bottom row in Fig.S1), which is likely due to reduced numbers of clusters including those located near the continental boundaries. In general, the inter-cluster and intra-cluster distances are not sensitive to the choice of $N_{\min}$ given a 250 km spatial radius and the monthly interval. We also tested a larger R value (350 km), which increased intra-cluster distances considerably (for $N_{\min}=10, 12$ only, Fig.S1).

In setting the parameters we preferred large inter-cluster and small intra-cluster distances because they are associated with more distinct clusters. However, while $R=250$ km, $N_{\min}=14$ yielded denser clusters than $R=250$ km, $N_{\min}=12$, it also resulted in too few wet clusters in Australia (Fig. S1). Along with visual examination of the most intense events (which are discussed in section 3.2), we determined that $R=250$ km and $N_{\min}=12$ (and a one-month time interval) yielded appropriate numbers of wet and dry clusters for this study.

Using these parameters, the clustering algorithm yielded 505 wet clusters and 551 dry clusters (excluding those that fell entirely in the GRACE/FO gap period; Table 1). About 70% of these events lasted 6 months or shorter and less than 10% of them lasted 12 months or longer. The maximum extents and durations of events in each continent are much larger than the averages for each continent, suggesting that the events are highly variable overall (Table 1).

Table 1. Summary of wet and dry events in the five continents.

	Continent	# of events	average extent (max extent, 10 ⁶ km ²)	average duration (max duration, months)
wet events	Eurasia	239	0.38 (2.3)	6 (39)
	North America	122	0.33 (2.8)	6 (33)
	South America	66	0.53 (2.4)	6 (20)
	Africa	56	0.52 (7.8)	5 (34)
	Australia	22	0.58 (3.9)	6 (33)
dry events	Eurasia	266	0.35 (3.0)	6 (34)
	North America	112	0.34 (2.6)	6 (43)
	South America	77	0.47 (2.8)	6 (22)
	Africa	65	0.56 (2.6)	6 (25)
	Australia	31	0.49 (1.6)	5 (11)

3.2 Most intense events

The intensity metric (equation 3) integrates three aspects of an event, TWS gains or losses, extent and duration. Thus, it offers an alternative to assessing events based on spatial extent or duration, which are more common approaches (e.g., Andreadis et al., 2005; Sheffield et al., 2009; He et al., 2020). Further, hydrological extremes identified using TWS differ from those identified using soil moisture or streamflow data, in that TWS has a wider range of variability than soil moisture and its anomalies can be more persistent than those of either soil moisture or streamflow. Therefore, examining the most intense TWS events can provide new insight into the severity and how they relate to other hydroclimatic cycles and trends. In this section, we discuss the most intense wet and dry events (6 each for Eurasia and 3 each for the

other continents) ranked over each continent based on their intensity and link them with reported extremes when available.

a. Eurasia

1) Top ranked wet events

The three most intense wet events in Eurasia during 2002-2021 were located in high latitude regions (Fig.1a). The most intense wet event ($5,810 \text{ km}^3\text{mo}$), was associated with floods that occurred in Far East Russia, Southern Siberia, and Southern European Russia caused by fast spring snowmelt, ice jams and heavy snowfalls during 2017-2018 (Figs.1e & S2, Davies, 2017; Relief Web, 2017). There was also a storm surge in coastal, arctic Russia caused by delayed sea ice formation in 2018 due to warm temperature (NOAA, 2018). Although the event spread to a large area, wet conditions occurred mainly in Far East Russia (Fig.S2).

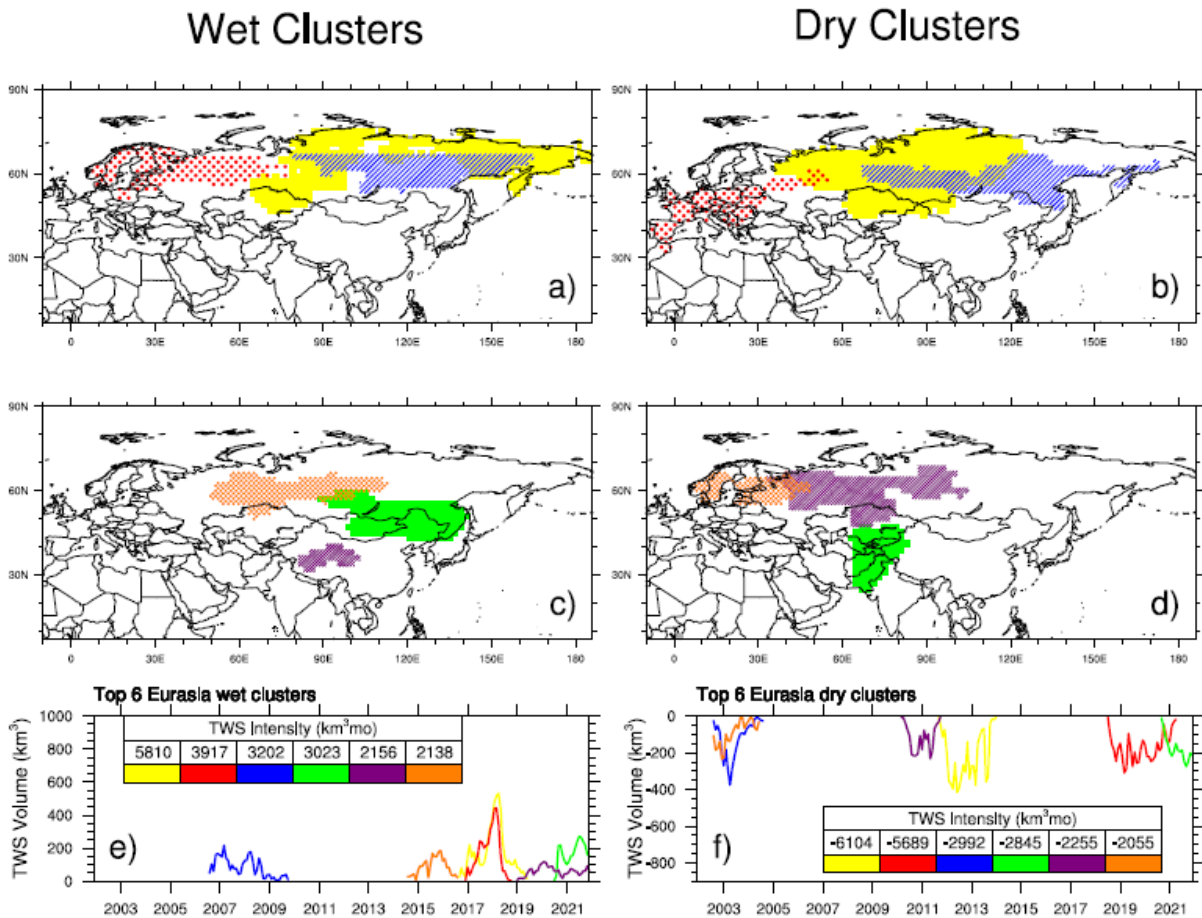


Fig.1 Spatial extents of top 6 most intense wet (panels a & c) and top 6 most intense dry events (panels b & d) in Eurasia and the associated TWS anomaly (km^3) time series (the inner sum of equation 3; panels e & f). The intensities of these events, in descending order, are given in the inset tables in panels e & f which also contain the color key for each event.

The second most intense wet event, which overlapped in time with the top most intense wet event, combined a record-breaking spring snowstorm and freezing rain in Western Russia (Blašković, 2018) and a record-breaking fall precipitation event in Norway and the Nordic countries (Figs.1a & 1e, Rønningsbakk, 2018). The third most intense wet event, which lasted more than 2 years (2007-2009), included severe flooding caused by substantial snowfall, fast spring snowmelt and ice jams in major rivers of central and eastern Russia including the Lena, Yenisei and Ob (Figs.1a & 1e., Landerer et al., 2010; Velicogna et al., 2012).

The fourth wet event was associated with severe floods in large river basins of northeastern China and the adjacent Russian and Mongolian regions during 2020-2021 (Figs.1c and 1e, FloodList, 2021). The fifth event, occurring during 2019-2021, spans the Kunlun and Qilian Mountains in western China where annual snowfall has been increasing in recent years (Figs. 1c & 1e, de Kok et al., 2019). The sixth event was associated with 2015-2016 floods caused by spring snowmelt and ice jams in central and northwestern Russia which caused significant property damages (Figs. 1c&1e, Davies, 2016b).

2) Top ranked dry events

As with the most intense wet events, the top three most intense dry events were located in the more northern latitudes (Fig.1b). The first and fifth most intense dry events were collocated with known, extensive droughts in central Russia during 2012-2014 and 2010-2011, that significantly impacted regional wheat production and global wheat prices (Figs.1b, 1d & 1f) Sternberg, 2011; Cherenkova et al., 2013; USDA, 2012). During these periods, heat waves and wildfires were also observed in Siberia, where the top event stayed the longest (Fig.S3, NASA Earth Observatory/Event 77712). The heat wave and the associated spike of global food prices in 2012 has been linked to amplified Rossby waves which can lead to simultaneous heat waves in midlatitude regions including eastern Europe (Kornhuber et al., 2020).

The second most intense dry event includes the recent European drought that ended in early 2021 with an intensity of $-5,689 \text{ km}^3\text{mo}$ (Figs.1b & 1f). In addition to abnormally low precipitation, the drought was likely exacerbated by the warmest winter temperature recorded in Europe (NASA Earth Observatory/Event 146888)).

The third most intense dry event was associated with hot and dry conditions in Far East Russia and the Sakhalin Island, where numerous forest fires occurred during the period of the event, 2002-2004 (Figs.1b & 1f, NASA Earth Observatory/Event 11787). The fourth most intense dry event encompassed severe droughts in Afghanistan and Pakistan in 2021 which triggered a humanitarian crisis in the area (Figs.1d & 1f, FAO, 2019; The New Humanitarian, 2019). The sixth intense dry event is associated with droughts in Norway, Sweden and the Baltic Republics in 2003 due to long term (12-month) precipitation deficits (Figs.1d & 1f, Spinoni et al., 2015). Increases in occurrences of severe droughts and heat waves in Northwestern Europe

may not be a coincidence: recent studies have linked them to enhanced Northern Hemisphere polar jet stream anomalies since 1960s (e.g., Trouet et al., 2018).

b. North America

1) Top ranked wet events

The most intense wet event in North America was evidenced by flooding in the major river basins of the U.S. east of the Rockies (Figs.2a & S2). The flooding started in 2019 in the Missouri and Upper Mississippi basins following record-breaking January-March precipitation and fast snowmelt (Fig.2c, NOAA 2019a). It then spread to the lower Mississippi, where the water levels were already high due to antecedent wet conditions (EOS, 2020). The event continued in the spring of 2020 with more floods in the Midwest and the southern states (NOAA, 2020) and eventually merged with wet conditions in the mid-Atlantic states (NOAA, 2019b; NOAA, 2021). The magnitude of this event ($11,896 \text{ km}^3\text{mo}$) was the second largest of all events, globally.

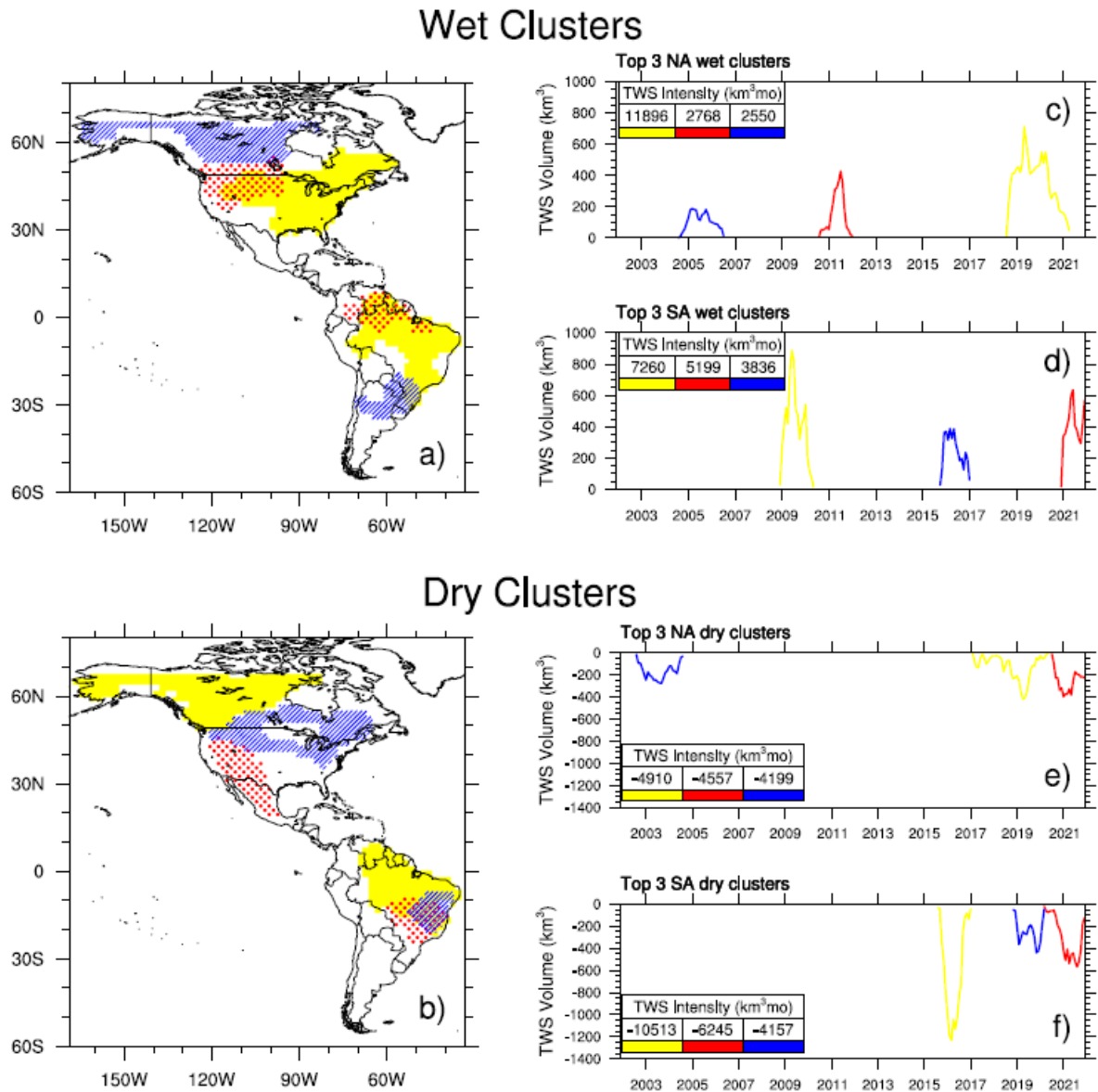


Fig. 2 Same as Fig.1 but for the top 3 most intense wet and dry events in North America and South America with maximum extents in panels a & b and associated TWS anomaly (km^3) time series in panels c-f.

The second intense wet event in North America was associated with several winter storms that hit the mountains of the western U.S. in 2010/2011 during a strong La Niña episode (Figs.2a & 2c, Wikipedia contributors, 2023a). The third most intense wet event was notable for the heavy precipitation that central Canada received in 2005 (Figs.2a & 2c, Wikipedia contributors, 2023b).

2) Top ranked dry events

The most intense dry event extended from Alaska to western Canada, but mainly affected Northern Alberta, British Columbia and the western Northwest Territories of Canada (Figs.2b & S3). This event began in the northwest with abnormally dry conditions and worsened in early 2019 due to high temperatures and below normal precipitation (Fig.2e, Canadian Drought Monitor, 2019; AGCanada, 2019). The interior of western Canada including the Arctic region has become more conducive to more intense and frequent extreme events including droughts due to shifts of atmospheric circulation patterns (Stewart et al., 2019).

The second intense dry event in North America was associated with recent droughts in southwestern North America which was the worst in the last 22 years and was partly influenced by anthropogenic climate change (Figs.2b & 2e, Williams et al., 2022). The drought condition improved in late 2021 due to atmospheric river events (WMO-No.1290) but continued into 2022 until later that year when record precipitation brought widespread floods to California and surrounding areas, abruptly ending the drought (CalMatters, 2023).

The third ranked dry event encompassed a Canadian Prairie drought in the early 2000s (Figs.2b & 2e, Hanesiak et al., 2011) and dry conditions in southern Ontario and Quebec during 2002-2003 and in the Great Lakes region of the U.S. during August-October, 2003 (see drought maps in the Canadian Drought Monitor and the US Drought Monitor).

c. South America

1) Top ranked wet events

The top three most intense wet events in South America were associated with damaging floods caused by extreme precipitation in Brazil (Wikipedia Contributors, 2023c), the Amazon (Espinoza et al., 2022) and the area encompassing Paraguay, Argentina, Uruguay and southern Brazil (Figs.2a & 2d, Davies, 2016a; Wikipedia Contributors, 2023d). The top two most intense wet events were associated with the 2009 and 2021 La Niña, and La Niñas are associated with wet December-February weather in the eastern Amazon basin (Mason and Goddard, 2001). The third most intense wet event occurred during the 2016 El Niño, and El Niños are associated with wet summer and winter conditions in Uruguay and surrounding regions (Mason and Goddard, 2001). It is noteworthy that a recent tree-ring study posited that hydrological extremes

have increased since the mid-20th century in these areas, in part due to increases in greenhouse gas emissions (Morales et al., 2020).

2) Top ranked dry events

The top three most intense dry events all occurred in recent years (Figs.2b & 2f). They affected mainly Brazil, where below normal annual precipitation had been observed in many areas since 2012 (Cunha et al., 2019). The top ranked event, also top ranked dry event globally (Rodell and Li, 2023), was a severe Brazilian drought associated with the 2015/2016 El Niño which was exacerbated by the highest annual temperature recorded in Brazil in 2015 and the record-setting global temperature in 2016 (Berenguer et al., 2021; Jiménez-Muñoz et al., 2016; World Bank, 2021).

The second most intense event represents the recent record-setting drought in central and southern Brazil where water levels in some reservoirs decreased by more than 8 m (NASA Earth Observatory/Event 148468). The third most intense dry event occurred in eastern Brazil where precipitation deficits were observed throughout 2011-2019 (Cunha et al., 2019). With a semi-arid climate, TWS changes in this region may lag precipitation changes and thus, TWS did not reach the lowest value until 2020. While droughts are frequent in Brazil due to strong coupling with the El Niño Southern Oscillation (ENSO) and sea surface temperatures in the Tropical Atlantic, land degradation and consequent desertification may have contributed to the intensity of these events (Marengo et al., 2017; Cunha et al., 2015).

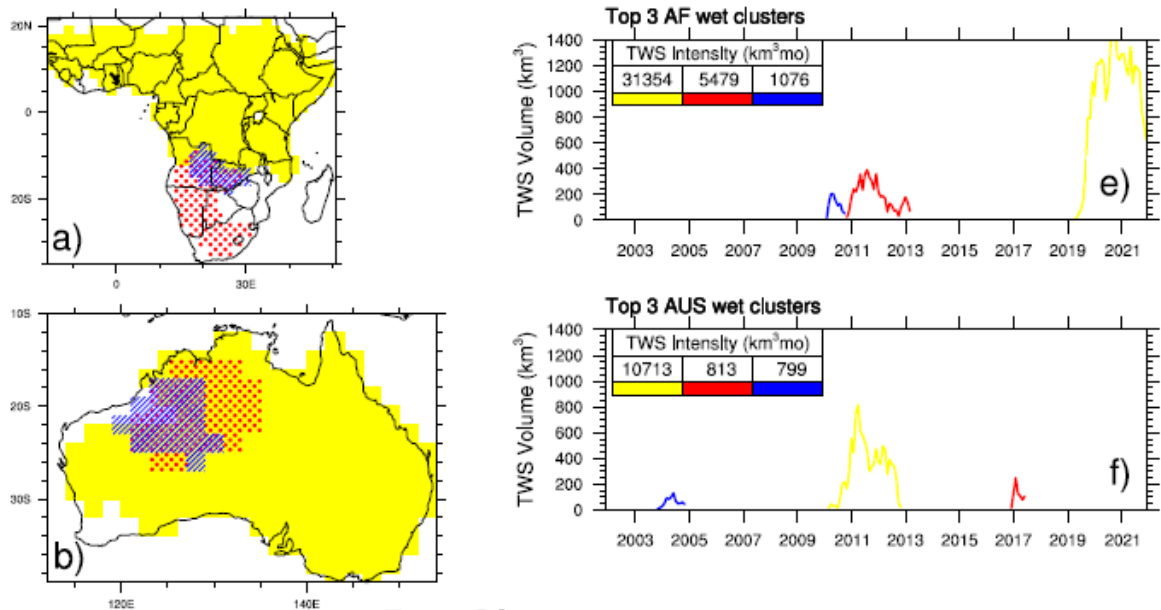
D. Africa

1) Top ranked wet events

The most intense wet event in Africa, which was massive with an intensity of 31354 km³mo, was also the most intense wet event globally (Figs.3a & 3e, Rodell and Li, 2023). It spread across the Sahel and tropical Africa and was punctuated by severe floods during 2019-2020 (FloodList, 2019; Phys, 2019). The flood in eastern Africa in late 2019 began with record-breaking precipitation in association with a positive phase in the Indian Ocean Dipole (Wainwright et al., 2020), which is a major control on rainfall in the region (Behera et al., 2005). In the western Sahel, wet conditions were likely caused by a strong Tropical Easterly Jet

(Akinsanola and Zhou, 2020). Increases in extreme precipitation in the area in the last decade have been reported in association with changes in atmospheric conditions (Vischel et al., 2019).

Wet Clusters



Dry Clusters

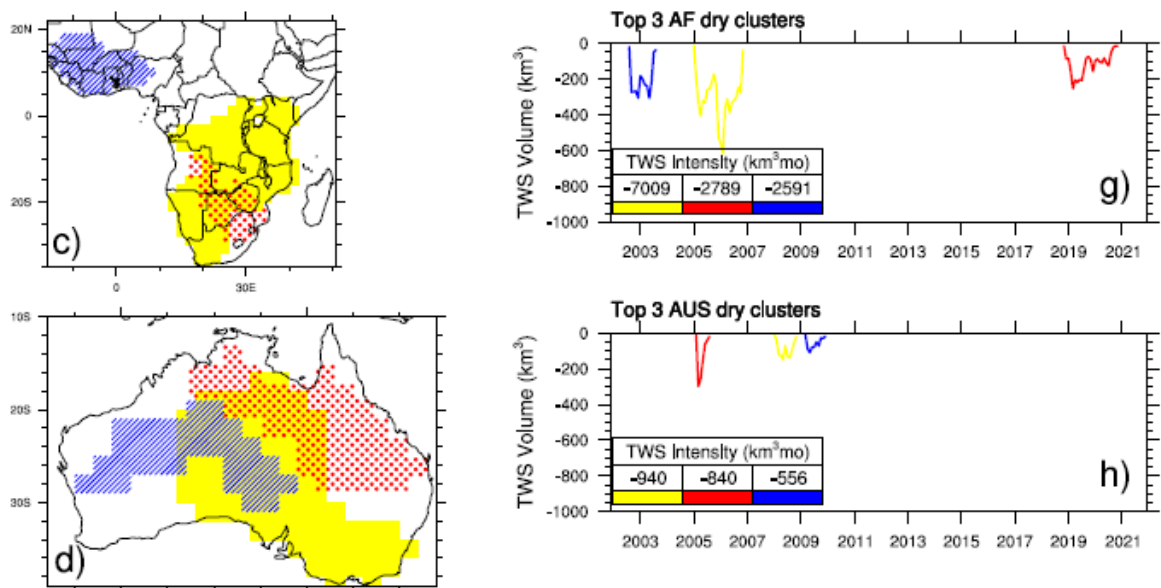


Fig. 3 Same as Fig.1 but for the top 3 most intense wet and dry events in Africa and Australia with maximum extents in panels a-d and associated TWS anomaly (km^3) time series in panels e-h

The second and third most intense wet events occurred in southern Africa, where weather is strongly influenced by ENSO (Figs.3a & 3e, Nicholson and Selato, 2000). Both started during the strong La Niña of 2010-2011, which brought heavy precipitation and flooding that caused significant loss of life and property damages (Wikipedia Contributors, 2023e).

2) Top ranked dry events

The most intense dry event encompassed the 2005 severe eastern equatorial African drought (Figs.3c & 3g, Geotimes, 2005, Hastenrath et al., 2007), which killed 40% of Kenya's cattle (Wakabi, 2006), and droughts in the Congo basin and southeastern Africa (Zhou et al., 2014; NASA Observatory/Event 15849,). The second ranked dry event, beginning around the end of 2018, featured severe droughts in southern Africa, with significant impacts on food supply, agriculture and livestock production (Figs.3c & 3g, NASA Earth Observatory/Event 146015). The third ranked dry event was located in the western Sahelian region (Figs.3c & 3g). Precipitation gauge data from Côte d'Ivoire indicates that 2002-2003 was one of the driest periods since 1970 (Santé et al., 2019).

e. Australia

1) Top ranked wet events

The most intense wet event in Australia during 2002-2021 spread across the entire continent but mainly affected eastern Australia (Figs.3b, 3f and S2). Heavy rain, including that from two cyclones, caused a series of floods between November 2010 and March 2011 and in January 2013 (Trewin, 2011; Lorrey et al., 2012; Australian Institute for Disaster Resilience, 2012; NASA Earth Observatory/Event 49779; Wikipedia Contributors, 2023f). Southern Australia also had the wettest December on record in 2011, which helped raise water levels in lakes and reservoirs back to normal after years of decline (NASA Earth Observatory/Event 76680; Jensen, 2011). Parts of Western Australia was also flooded in early 2011 (NASA Earth Observatory/Event 49779). A major driver of the heavy rains was an unusually strong La Niña in 2010-2011 and a strong negative phase of the Indian Ocean Dipole (Ng et al., 2018). Synchronization of different climate modes is known to cause extreme precipitation and droughts

in Australia (Cleverly et al., 2016). These widespread floods ended the Millennium Drought that had affected the continent since the early 2000s (Heberger, 2012; van Dijk et al., 2013).

The second and third most intense wet events were caused in part by heavy rainfall from two tropical cyclones, Blanche in March, 2017 and Monty in March, 2004 (Figs.3b & 3f, Levinson & Salinger, 2005; Aljazeera, 2017; ABM, 2004). Short-term but wet tropical storm events can cause significant TWS increases in areas that are otherwise dry in winter, such as northwestern Australia (ABM, 2015).

2) Top ranked dry events

The top three most intense dry events occurred within the Millennium Drought period, 2001-2009 (Figs.3d & 3h). The top dry event encompassed central and southeastern Australia, where the 2008 precipitation was the lowest in nearly a century. Southeastern Australia was hit the hardest by the Millennium drought based on satellite derived vegetation water content (van Dijk et al., 2013). Considering that croplands are extensive in the region, withdrawals for irrigation likely exacerbated the TWS depletion (van Dijk et al., 2013).

The second most intense top dry event was most prominent in northern Australia (Figs.3d & S3). The minimum TWS anomaly (-840 km^3) was reached in 2005, when northern Australia received low to near-record low precipitation (Fig.3h, ABM, 2006).

The third most intense dry event was centered in south-central Australia (Figs.3d & S3). The year of its minimum TWS (2009) coincided with large precipitation deficits in central Australia according to Australian Bureau of Meteorology (Fig.3h).

The intensity of these dry events was lower than that of the top wet event, owing in part to the strength of the 2010-2011 La Niña and associated heavy precipitation. Further, the magnitudes of the TWS anomalies during the Millennium drought may have been underestimated precisely because that drought persisted for nearly half of the GRACE/FO data record, thus causing the baseline mean TWS, from which anomalies were calculated, to be on the low side.

3.3 Severity-area-duration (SAD) analysis

The intensity of an event, as defined here with units of km^3mo (see equation 3), differs from severity (unitless in this case; see equation 2), which measures the degree of deviation from the mean instantaneously or over a set period. To examine severity and its relationship with intensity, we calculated SAD curves for all wet and dry events over 3-, 6- and 12-month durations (Figs. S4 and S5).

In each continent, maximum wet and dry severities occurred over the smallest areas and attained roughly the same magnitudes, between 4 and 6, with slightly higher values in Eurasia. For a given area, the most intense wet events tended to be more severe than the most intense dry events in Eurasia, Africa, and Australia, while they had similar severity in the Americas (Fig. S5). Severity generally decreases with increasing area, especially for small extent events at the 3-month duration. At longer durations (6 and 12-month), severity decreases more slowly with increasing area, indicating that the location of maximum severity can migrate as an event evolves. Note that there are fewer SAD curves for the 12-month duration sub-plots because most events last less than 12 months (Table 1).

In Africa and Australia, dry events were generally more extensive than wet events and their severity decreased more slowly with increasing area than that of wet events. This suggests that the atmospheric regimes that cause droughts are more expansive and uniform in Africa and Australia than in other continents. However, when they occur in these two continents, large-scale wet events can spread to large areas with high intensity as shown in the most intense wet (highlighted in yellow lines) events (Fig.S4).

These SAD curves are less smooth (i.e., a consistent and gentle decrease in severity from small to large scales) than those based on simulated soil moisture (Andreadis et al., 2005; Sheffield et al, 2009; He et al., 2020). Possible explanations for this include the coarse spatial and temporal scales of GRACE/FO TWS, the fact that TWS integrates multiple processes (those involved in the evolution of surface waters, snow, soil moisture, and groundwater), each of which may exhibit different temporal variability, and possibly various modeling deficiencies that could cause soil moisture variability across scales to be underrepresented.

The three most intense events in each continent (highlighted using the same color scheme as Figs.1-3) are generally more severe than others regardless duration and area (Figs.S4 & S5). The exception is Australia, where the top three dry events were middling in terms of severity for

areas less than 10^6 km^2 . This indicates that the high intensity of these three events was driven more by area and duration than by severity. Severity of top events in each continent tended to decrease more gradually with increasing area compared to other events. This is a consequence of the most intense events generally covering the largest spatial scales, and hence more potential sub-areas with great severity.

3.4 Temporal variability of extreme events

a. Annual tendencies

To examine changes in extreme events, we calculated the Mann-Kendal trend in annual characteristics (number of events, intensity, extent, duration, and severity, excluding the partial year, 2002) of extreme events in four Köppen-Geiger climate classes (Fig.4). Annual quantities were calculated by averaging (summing for the number of events) over all events in a given year, determined based on the time of the maximum/minimum TWS anomaly (km^3) of a wet/dry event. The location where an event stayed the longest (see Figs.S2 & S3) determined the climate class to which it belonged.

Significant changes in frequency of occurrence occurred in the Dry climate (Figs. 4a1 & 4a3), where the number of wet events decreased while the number of dry events increased and in the Continental climate where the number of dry events increased. Intensity of wet events increased significantly when averaged over all climates, but changes in individual climates were not significant (Fig.4b1). This seeming discrepancy is due to the most intense events skewing the global averages. Annual intensity averaged over all climates for both wet and dry events exhibited large inter-annual variability during and after the 2010-2011 La Niña episode, which was associated with several of the most intense events as discussed earlier (Fig.4c2; note that positive SOI is associated with La Niña and negative SOI is associated with El Niño).

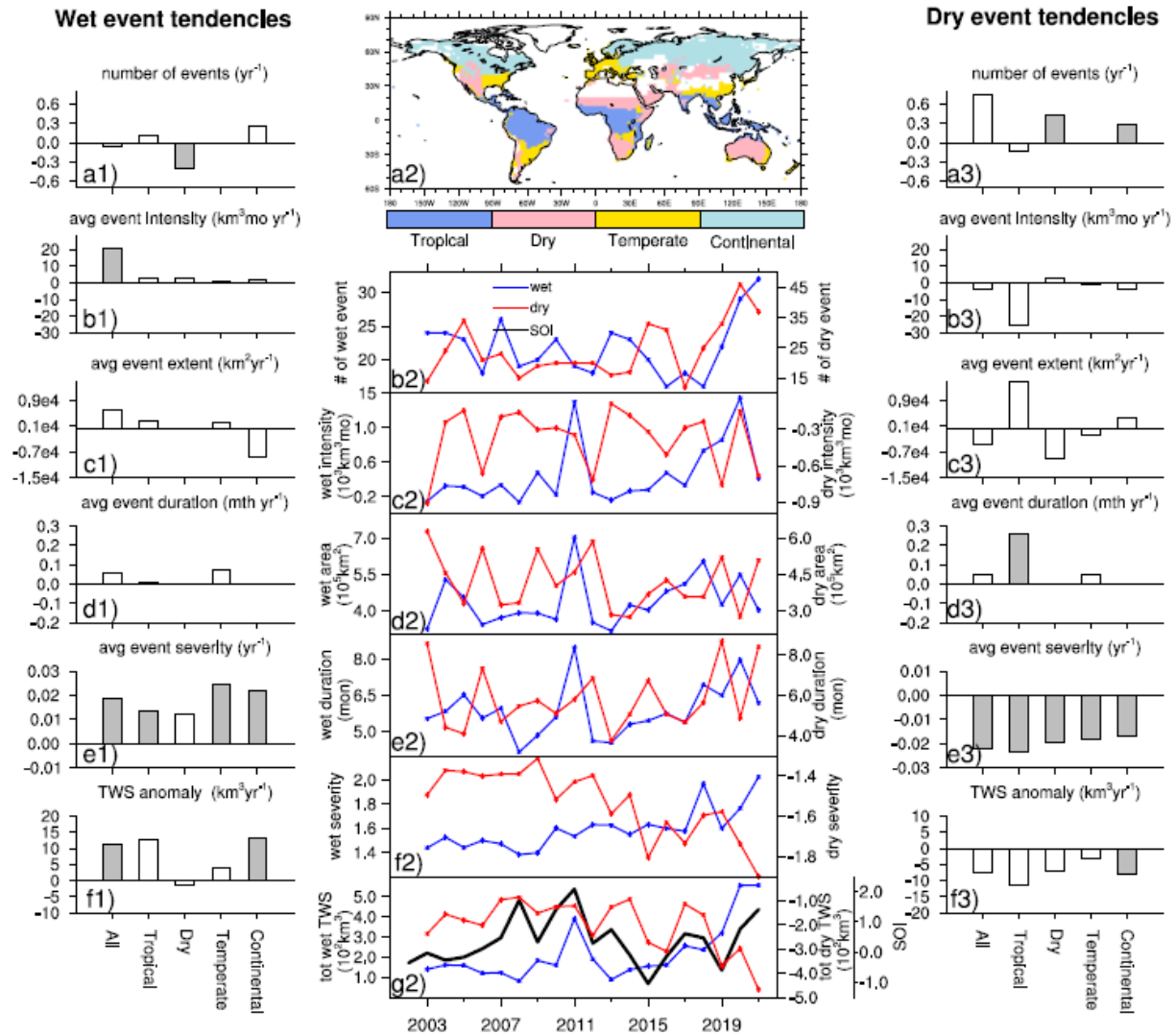


Fig.4 Spatial distribution of the four major Köppen-Geiger climate classes (panel a2), annual time series averaged over all climates (panels b2-g2) and annual tendencies of extreme event characteristics for the four and all climate classes (panels a1-f1 and a3-f3). Polar climate regions and those with significant TWS declines due to human induced groundwater depletion and losses of permanent ice are masked out in the climate class map and excluded from the analysis. Shaded bars represent statistically significant trends with $p=0.1$.

Similarly, extent and duration for all climates showed strong inter-annual variability in 2010-2011 (Figs.4d2 & 4e2) and therefore, because that is the middle of the time series, in most cases they exhibited no significant trends (Figs.4c1, 4d1, 4c3 & 4d3). Longer records will be

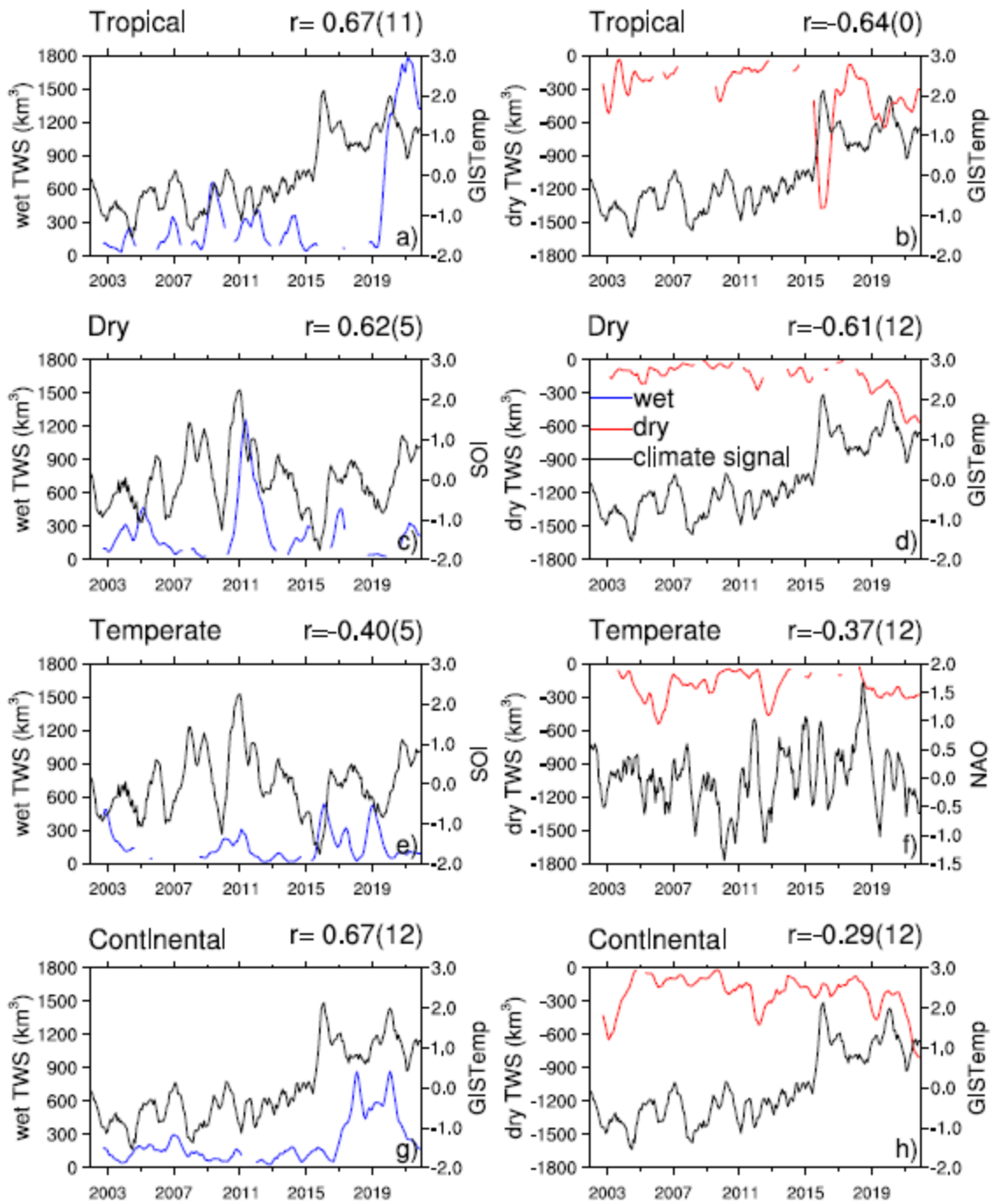
needed to identify climate change related trends in these quantities, particularly in regions strongly influenced by ENSO.

In contrast, average annual wet and dry event severity increased significantly in all cases except for wet events in the Dry climate (Figs.4e1 & 4e3). Standardization used in calculating severity makes it comparable across different sizes and durations of events. Therefore, average severity was not dominated by large events as with the other metrics. As shown in Fig.4f2, average annual severity was not affected by the 2010-2011 La Niña event.

TWS anomalies generally did not show consistent significant changes except in the Continental climate where wet TWS anomalies increased significantly while dry TWS anomalies decreased significantly, suggesting increases in the amplitude of TWS changes (Figs.4f1 & 4f3).

b. Correlation analysis

To examine the impacts of climate and climate change on TWS variability, we calculated lagged correlations (up to 12 months) between five climate indicators/signals (listed in the caption of Fig.5) and total monthly TWS anomalies in each climate class. For each climate class and event type (wet or dry), the strongest correlated climate indicator is plotted in Fig.5 along with the time series of TWS anomalies summed over all associated extreme events.



555

556 Fig.5 Monthly time series of TWS anomalies summed over wet (left column) and dry (right
 557 column) extreme events in a given climate class and the climate signal that shows the largest
 558 magnitude of correlation with those anomalies. “r” is the maximum correlation. The number in
 559 parentheses indicates the time lag (in months) of the maximum correlation. A 6-month running
 560 average was applied to smooth all plotted time series. The climate indices used for correlation

analysis are: the Goddard Institute for Space Studies (GISS) global surface temperature (GISTemp), the Southern Oscillation Index (SOI), the Trans-Niño Index (TNI), , the North Atlantic Oscillation (NAO), and the Dipole Mode Index (DMI).

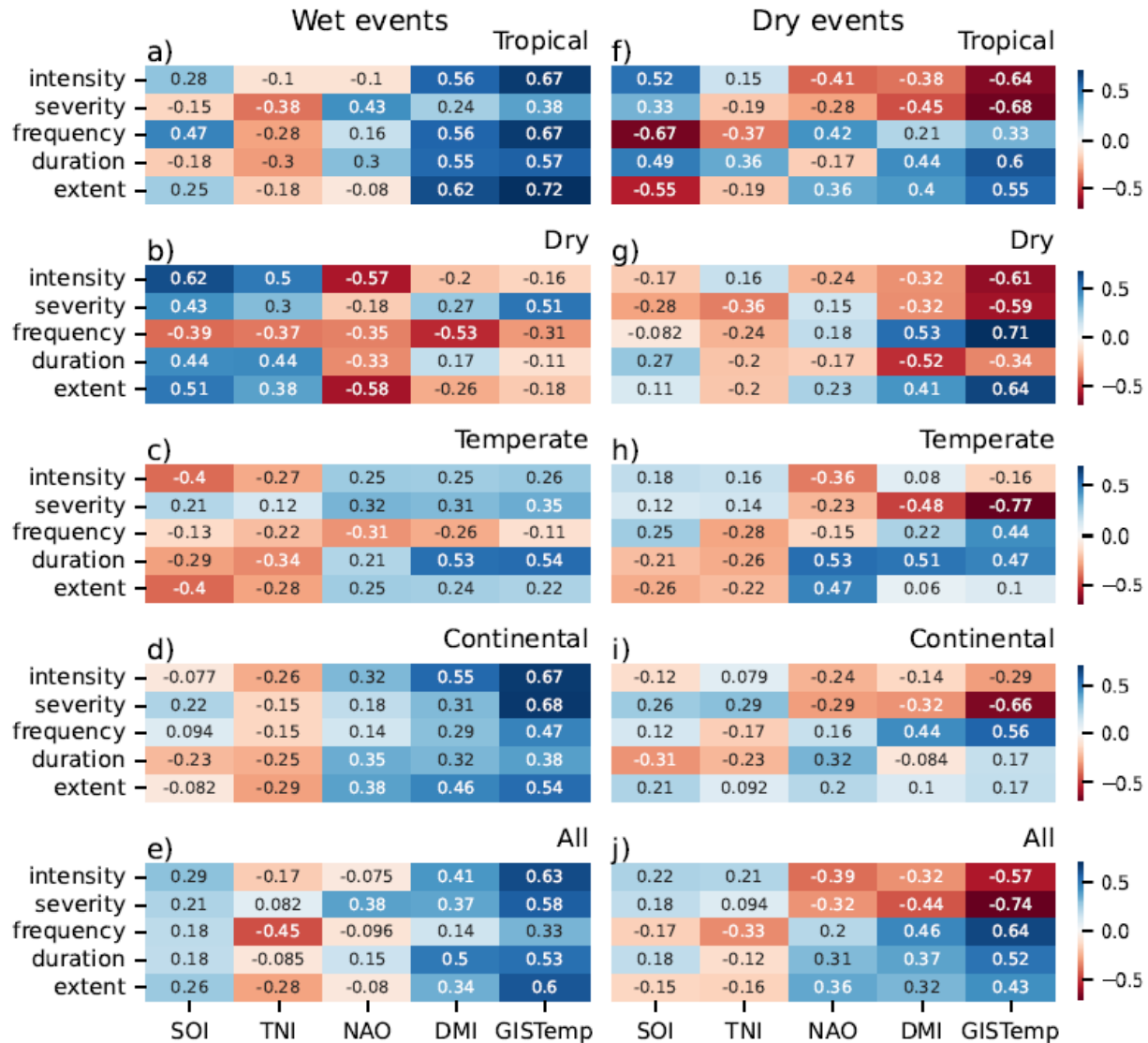
TWS anomalies of wet events in the Tropical climate class were most strongly correlated with a global average temperature index (GISTemp; $r=0.67$, Fig.5a). This result may be due to the rapid rise of TWS after 2019 associated with the worldwide top wet event that is centered in tropical Africa (Figs.3a & 3e). In the Dry climate, TWS anomalies of wet events were most strongly correlated with ENSO (represented by SOI; $r = 0.62$, Fig.5c), which is a known influence on precipitation variability in this climate (Dai & Wigley, 2000; Ng et al., 2018). TWS of wet events in the Temperate climate were also most strongly correlated with ENSO, but the correlation is much lower than that in the Dry climate ($r=0.4$, Fig.5e).

In the Continental climate, TWS of wet events were strongest correlated with GISTemp ($r = 0.67$, Fig.5g). This result is consistent with observed changes in this climate such as faster than global average increases in temperature (Trenberth et al., 2007). In addition, discharge to the Arctic Ocean from major rivers of Eurasia and North America has been increasing in the past several decades due to thawing of permafrost which releases large quantities of soil water into surface runoff (Peterson et al., 2002; McClelland et al., 2006; Ahmed et al., 2020), with implications for other processes in the region such as ocean salinity and temperature (Timmermans and Marshall, 2020). Increases in precipitation due to global warming have also been reported for northern Eurasia and may have contributed to this strong correlation (Ye, 2001; Zolotokrylin & Cherenkova, 2017).

The strong correlation ($r = -0.64$) between dry event TWS anomalies and GISTemp in the Tropical climate class is partly explained by the worldwide most intense dry event (in South America), occurred in 2016, when global average temperature reached its record high and, in another part, by the apparent trends in both time series (Fig.5b). Similarly, the strong correlation ($r=-0.61$) between dry event TWS anomalies and GISTemp in the Dry climate may be due to the apparent trends in both time series (Fig.5d). On the other hand, the apparent trends in TWS anomalies in the above cases are caused by drastic decreases in TWS in recent years when global temperature increased substantially.

591 The strongest correlations for dry events in the other two climate classes were lower than
592 0.4, so the influence of the plotted climate indicators appears to be weak. Nevertheless, it is
593 worth noting that TWS anomalies of dry events in the Temperate climate exhibited the strongest
594 correlation with the North Atlantic Oscillation (NAO) which has been linked to drought
595 occurrence in this climate zone (McCabe et al., 2004; López-Moreno & Vicente-Serrano, 2008).

596 Wet event characteristics in Tropical and Continental exhibit the strongest correlation
597 with GISTemp in 9 out of 10 cases (Figs.6a & 6d). In the Tropical, wet event characteristics
598 also show strong correlations ($r>0.5$) with DMI in 4 of 5 cases (Fig.6a). In contrast, wet event
599 characteristics in the Dry and Temperate show weak correlations with the five indicators except a
600 few cases such as frequency of occurrence in the Dry climate and duration in the Temperate
601 climate which correlated strongly with DMI ($r>0.5$), and intensity and extent in the Dry climate
602 which correlated strongly with NAO ($r>0.55$, Figs.6b & 6c).



604

605 Fig.6 Heat maps of correlations between monthly characteristics of wet (left column) and dry
 606 (right column) events and the 5 climate indicators in the 4 major and all climate classes.
 607 Monthly intensity, frequency (number of events) and extent were calculated as the sum of these
 608 characteristics over all events in a climate while monthly severity and duration were averaged
 609 over all events in a climate class.

610

611 Severity of dry events show the strongest correlation ($r > 0.58$) with GISTemp across all
 612 four climate classes (Figs.6f-6i.). Notice the negative correlations are due to severity being
 613 negative for dry events. Strong correlations are also observed between GISTemp and other

characteristics such as frequency of occurrence of dry events in the Dry and Continental climates and intensity of dry events in Tropical and Dry climates (Figs.6g & 6i). Consistent with some of these strong correlations, wildfires and severe droughts have been increasingly observed in high latitude regions of Russia and Canada (Kelly et al., 2013; Sherstyukov & Sherstyukov, 2014; Whitman et al., 2019).

Among all characteristics, severity is the only metric that is consistently most strongly correlated with GISTemp, regardless of climate and the type of extremes (wet or dry), except for wet events in Tropical (Fig.6a). As explained earlier, severity, represented by standardized TWS anomalies, can better capture changes across all events while other characteristics, when averaged, may be dominated by few large events that may be associated with climate variability and thus exhibit large inter-annual variability.

Averaged over four climates, characteristics of both wet and dry extremes show strongest and much higher correlation with global temperature than with other climate indicators, except for frequency of wet events which is more strongly correlated with ENSO (represented by TNI) (Figs 6e & 6j).

4. Summary and Discussion

We identified 505 wet and 551 dry hydrological extremes globally using the GRACE/FO TWS data for 2002-2021 and a temporal-spatial clustering algorithm. The most intense events in each continent, determined based on temporal-spatial accumulated TWS anomalies, reflected hydroclimatic variability associated with large-scale climate phenomena. These include the most intense dry event in South America, which is also the most intense one globally, occurred in Brazil in association with the 2015/2016 El Niño and the most intense wet event in Australia due to an unusually strong La Niña in 2010-2011 and a strong negative phase of the Indian Ocean Dipole in 2011. The occurrence of most intense events also showed direct impacts of global warming and climate change. These include the top 3 most intense wet events in Eurasia which were associated with increases in fall-winter precipitation, fast spring snowmelt and, in some cases, thawing of permafrost. Severity-area-duration (SAD) analysis showed the most intense

events are generally more severe (represented by standardized TWS anomalies) than others and remained so throughout their duration. Across continents, these most intense extremes often caused substantial damage to properties and agricultural production as well as loss of human life.

Trend analysis showed that both wet and dry extreme events became more severe over the course of the study period (2002-2021) across all four major climate classes. Increases in severity imply that the amplitudes of TWS changes, on average, have increased, based on the definition of severity of an event (equation 2). Increases in TWS amplitudes suggest that maximum TWS has been increasing while minimum TWS has been decreasing. These changes are likely due to the intensification of wet and dry weather regimes, with warmer air supporting higher evaporation rates during droughts and increased moisture transport during pluvials, such that wet/dry spells become wetter/drier, hence expanding the dynamic range of TWS (Douville et al., 2021; Benestad et al., 2022; Rodell and Li, 2023). Anthropogenic effects such as groundwater withdrawals and changes within the terrestrial water cycle such as degradation of permafrost, which releases subsurface water into streams, may further amplify the dynamic range of regional TWS changes. Increasing severity of both wet and dry events across all climates implies that severity of weather whiplash has also increased. Identification of drought-pluvial seesaw events and their tendencies has been challenging because previous studies relied on soil moisture (He and Sheffield, 2020). Due to its small dynamic range, soil moisture cannot represent the full depth and extent of severe droughts and floods as well as GRACE/FO TWS data does. Consistent with these trends, severity of both wet and dry events showed the strongest correlation with global mean temperature in most cases.

Robust, concurrent changes in frequency of occurrence were only observed in the Dry climate where the number of wet/dry events decreased/increased significantly, suggesting a drying trend in that climate. This apparent trend may have been influenced by the internal variability of climate. For instance, positive SOI (corresponding to La Niña events) as shown in the later study period, is known to cause dry conditions in southwestern U.S. which is located in the Dry climate zone (Mason and Goddard, 2001). As discussed earlier, global warming and associated hydroclimatic changes and anthropogenic effects may have also contributed to this drying trend.

Correlation analysis suggests strong impacts of global warming on TWS changes and all characteristics of wet extreme events in the Continental climate. These results are consistent with observed changes in northern Eurasia such as permafrost degradation, earlier and fast spring snowmelt and increases in fall-winter precipitation (Frolova et al., 2017; zolotokrylin & Cherenkova, 2017). Seasonal precipitation is projected to increase in this climate which may further increase wet TWS anomalies and severity of wet extremes (Konapala et al., 2020). A corresponding effect was seen in the warmer climates (Tropical and Dry), where TWS anomalies and characteristics of dry extremes were often most strongly correlated with global average temperature. Increases in water demands and ET in a warmer world may be a factor (WWAP, 2018). In the case of TWS anomalies of dry events in the Tropical, the strong correlation is influenced by the fact that the most intense dry event globally occurred in the warmest year on record (2016) and was located in the Tropical climate (Brazil). Averaged over four climate classes which smooths out climate variability of individual climates, characteristics of hydrological extremes show strongest correlation with global temperature in 9 out of 10 metrics. As discussed earlier, although these strong correlations may be affected by the apparent trends in the time series of global temperature and TWS anomalies, this does not diminish the impact of global warming on changes in TWS and hydrological extremes as trends in TWS were caused by abrupt increases/decreases in TWS in the last few years in responses to accelerated global warming.

A limitation of this study is the relatively short record of GRACE/FO data, which makes it difficult to put extreme events in the proper context, especially in regions with large inter-annual TWS variability. The short record also makes it difficult to separate the impacts of global warming from those of long-term climate variability. Another source of uncertainty was the use of simulated TWS output to fill gaps in the GRACE/FO data record, considering that both the model and atmospheric forcing data are imperfect. To minimize the impact of these uncertainties, we excluded events that fell entirely within the 11-month gap between the two missions. Of course, this may have affected our results. We also excluded regions with significant TWS declines associated with groundwater withdrawals. That was necessary in order to focus on non-anthropogenic extremes, but it necessitated non-global coverage, as did exclusion of ice-covered regions.

Nevertheless, this study clearly demonstrates the value of GRACE/FO data for identifying and quantifying hydrological extremes in a manner that is not possible using any other observation type. In particular, GRACE/FO data provide an integrated measure of water gains and losses at all depths on and below the surface and thus can reflect full impacts of global warming and climate change on hydrological extremes. As the global water cycle continues to evolve in response to climate change, extending the satellite based TWS record will be essential to tracking variations in TWS changes and extremes, with implications for water security and natural disasters.

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Data Availability Statement: CSR GRACE/GRACE-FO data can be downloaded at http://www2.csr.utexas.edu/grace/RL06_mascons.html and simulated TWS from the GRACE/FO data assimilation into CLSM can be downloaded at https://disc.gsfc.nasa.gov/datasets/GLDAS_CLSM025_DA1_D_2.2/summary?keywords=GLDAS_CLSM025_DA1_D_2.2). Oscillation signals can be downloaded at: <https://psl.noaa.gov/data/climateindices/list/>, https://psl.noaa.gov/gcos_wgsp/Timeseries/DMI/, and <https://data.giss.nasa.gov/gistemp/>. The python code for the ST-DBSCAN clustering algorithm was obtained from <https://github.com/gitAtila/ST-DBSCAN>.

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