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E-mail: damian.insua@usc.es**Keywords:** floods, moisture tracking, extreme precipitation, vegetation, transpirationSupplementary material for this article is available [online](#)**Abstract**

Plants play a key role in the hydrological cycle, yet their contribution to extreme rainfall remains uncertain. Here we show that more than half of the vast amounts of water accumulated in the recent Germany and Belgium floods were supplied by vegetation (41% from transpiration, 11% from interception loss). We found that intercontinental transport of moisture from North American forests (which contributed more than 463 billion liters of water to the event) was a more important source than evaporation over nearby seas, such as the Mediterranean or the North Sea. Our results demonstrate that summer rainfall extremes in Europe may be strongly dependent on plant behavior and suggest that significant alterations in vegetation cover, even of remote regions, could have a direct effect on these potentially catastrophic events.

1. Introduction

Vegetation exerts a fundamental control on climate as, among other things, it takes up soil water through its roots [1] and releases it into the atmosphere, ultimately feeding rainfall. Globally, it is estimated that 40% of terrestrial precipitation originates from continental evapotranspiration (ET) [2], most of which comes from plant transpiration [3, 4]. At the regional scale, researchers have focused their efforts on quantifying the precipitation recycling ratio [5, 6] as a way of assessing the potential impact of land use changes on the regional rainfall regime. For this purpose, moisture tracking techniques have proven to be a powerful tool, especially in the Amazon basin, where different scholars have used this methodology to investigate how tropical forests sustain rainfall [7–9]. At the local scale, some studies have attempted to estimate the role of continental ET in some cases of torrential rains [10, 11]; nevertheless, the most widespread moisture tracking techniques, based on spatio-temporal tracking of individual fluid particles, do not allow for accurate quantitative analysis in specific case studies [12]. For this reason, little is still known about the contribution of land ET to individual extreme precipitation events and even less is known about

the role of vegetation as moisture source during such events.

In the current context of climate change, it is particularly important to have a good understanding of the contribution of recycled moisture to these precipitation extremes. Anthropogenic global warming is increasing the water-holding capacity of the atmosphere, which raises the odds of heavy rainfall [13, 14]. On the other hand, recent studies have revealed a greening trend of the land surface [15, 16], especially in Europe, where the forested area has increased considerably [17]. Therefore, knowledge about the contribution of moisture from continental origin to extreme rainfall would provide a measure of the extent to which current changes in vegetation cover may be affecting the increasing number of heavy precipitation events.

In July 2021, one of these catastrophic events struck central Europe leaving the world stunned by its devastation [18]. On 12 July, a low-pressure system from the Atlantic moved into Europe (see the atmospheric configuration in figure S1 of the supplementary material (available online at stacks.iop.org/ERL/17/064053/mmedia)) causing flooding in an area of 2470 km² [19]. Heavy rainfall, potentially enhanced by global warming [20], spread

from France north-westwards and peaked late on 14 July in south-western Germany and eastern Belgium. The worst affected areas were the Belgian province of Liège and the German states of Rhineland-Palatinate and North Rhine-Westphalia where rainfall exceeded 150 mm in just 24 h causing enormous material damage [21]. More than 200 people died, making it one of the worst flood disasters in recent European history [22].

In the days following the catastrophic floods, different media outlets proposed that the rains had been caused by the large amounts of moisture that the low-pressure system had picked up from the Mediterranean Sea and then transported towards northern Europe. Motivated by this claim, we wondered: was the rain really fed by maritime moisture? In this study we use a state-of-the-art moisture tracking technique coupled to an atmospheric model [23] and calculate precise figures for the contributions of all possible sources. Furthermore, we partition terrestrial ET into its three components, which allows us to quantify the fraction of precipitation fed by moisture supplied directly by vegetation (transpiration plus interception loss) and the fraction coming from soil evaporation.

2. Methods

The atmospheric model used in this study is the Weather Research and Forecasting (WRF) version 3.8.1 [24]. The model code has been modified to enable atmospheric moisture tracking. This modified version, called WRF-WVTs (where WVTs stands for water vapor tracers), has been thoroughly validated showing high precision [23]. The coupling of a highly accurate Eulerian moisture tracking strategy with a state-of-the-art atmospheric model, which considers in detail all physical processes affecting atmospheric humidity, guarantees a rigorous analysis of the moisture sources feeding rainfall. Importantly, the WRF model incorporates a spectral nudging technique [25] that, when activated, prevents large-scale atmospheric fields from drifting away from the observation, i.e. from reanalysis. This ensures that the model continues to provide realistic results even several days after simulation initialization, making it particularly suitable for analyzing moisture sources in past extreme precipitation events. Initial and boundary conditions for the WRF simulations were taken from the 5th generation of The European Centre for Medium Range Weather Forecasts global reanalysis (ERA5 [26]) and updated every 6 h. For a more detailed explanation of the model setup, please refer to the Extended Methods section in the supplementary material.

The surface parameterization selected to run WRF is the Noah land surface model [27]. In this parameterization, which employs Leaf Area Index (LAI; shown in figure 2(b)) from the Moderate

Resolution Imaging Spectroradiometer (MODIS) [28], the ET flux is calculated from the sum of different components:

$$ET = T + C + D + S, \quad (1)$$

where T is transpiration, C is canopy evaporation or interception loss, D is direct soil evaporation and S refers to snow sublimation (see section 3 in Chen and Duthia [27] for a detailed formulation of the different terms). In order to track moisture coming from a given region R, the source term in the prognostic equations for moisture due to ET (QFX) is modified as follows:

$$TRQFX = QFX \cdot M, \quad (2)$$

where M is a binary array with values of 1 in the region R of interest and 0 in the rest. QFX can refer to ET, T, C, D or S. As an example, if we were interested in tracking all moisture, QFX would correspond to ET, while if we only wanted to track transpired moisture, QFX would correspond to T.

Moisture is tracked until it precipitates, so a new variable corresponding to tracer precipitation (TP), i.e. coming from the source region R of interest, is defined (for further details on the moisture tracking technique, see extended methods section in the supplementary material). The rainfall fractions shown in figures 1(c) and 2(c) are therefore calculated as:

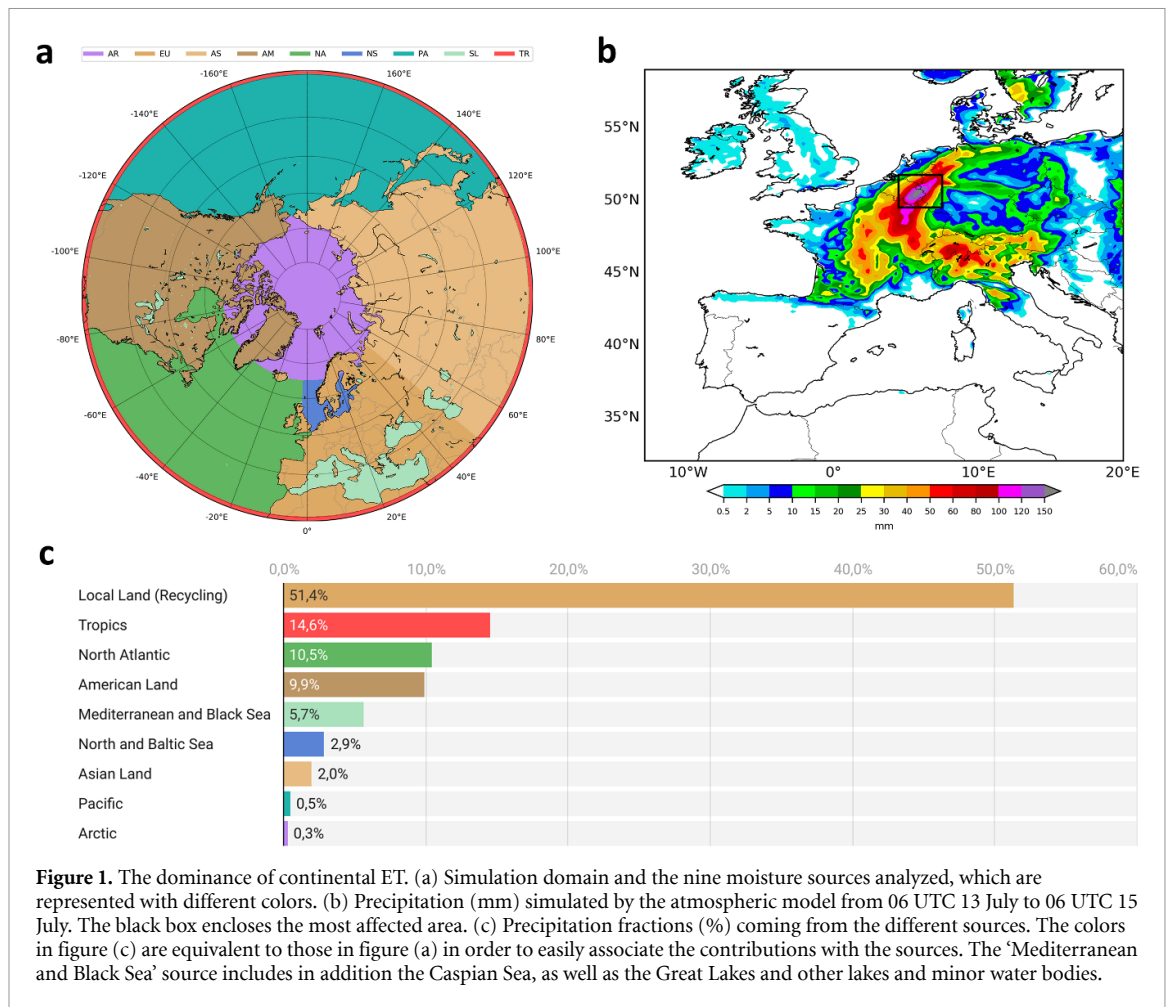
$$F = \frac{\sum_{i,j} TP_{i,j}}{\sum_{i,j} P_{i,j}} \forall i,j \in A, \quad (3)$$

where in our case $i,j \in A$ refers to all model grid cells contained in the area marked with the black box in figure 1(b) (49.5° – 51.75° N, 4.5° – 7.5° E) and P is total precipitation.

Finally, we note that WRF-WVTs allows tracking both 2D and 3D moisture sources. Of the nine analyzed sources (figure 1(a)), all are 2D except for the tropical one (red in figure 1(a)), which is 3D. This type of source, unlike a 2D source, not only tracks moisture from surface ET, but also moisture at any level above, within the same atmospheric column. In our case, this 3D source is used to track all incoming moisture from the domain's boundary following the 30° N parallel, i.e. from tropical latitudes (below 30° N).

3. Results

Figure 1(a) shows the simulation domain together with the analyzed moisture sources. Figure 1(b) depicts the simulated precipitation for the extreme event (see figure S1 for a validation of the model results). Finally, in figure 1(c) we present the fraction of precipitation coming from the different moisture sources. These fractions have been calculated over the

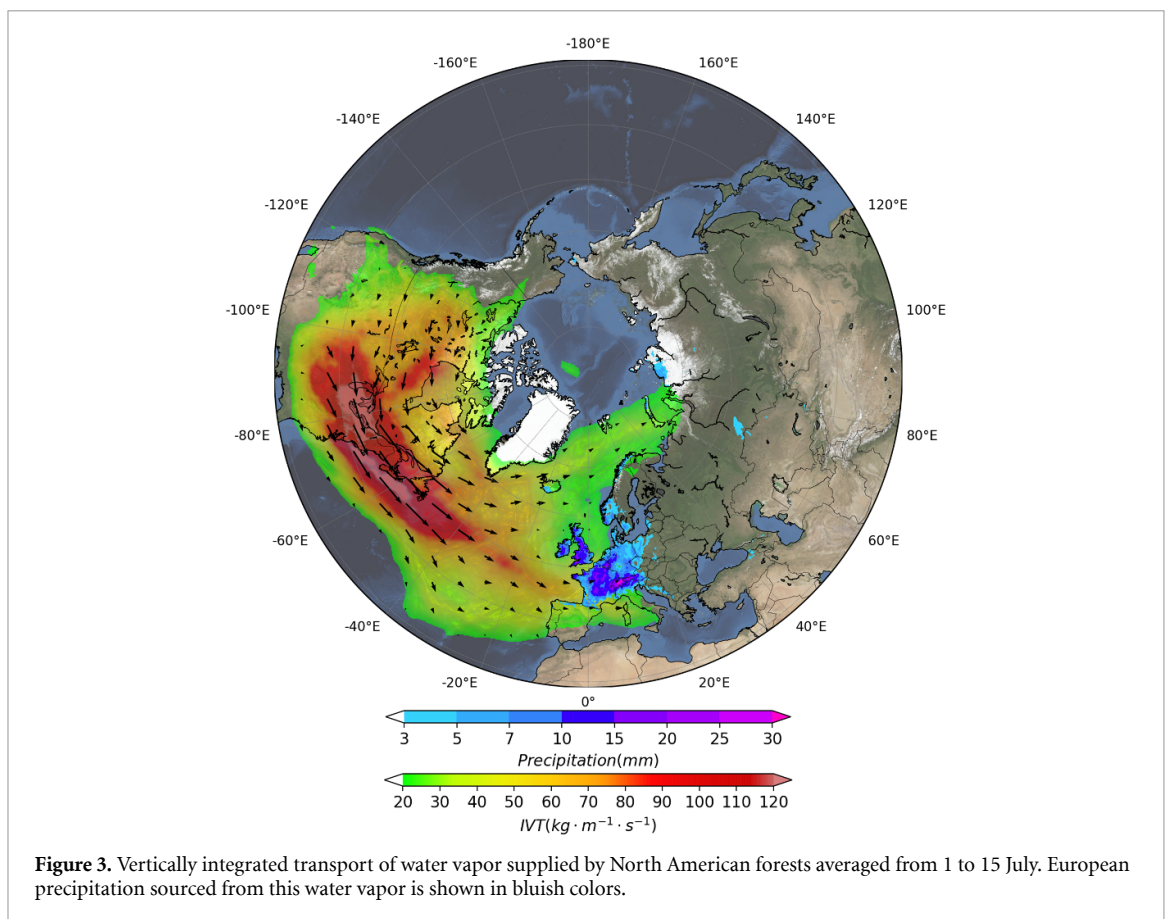
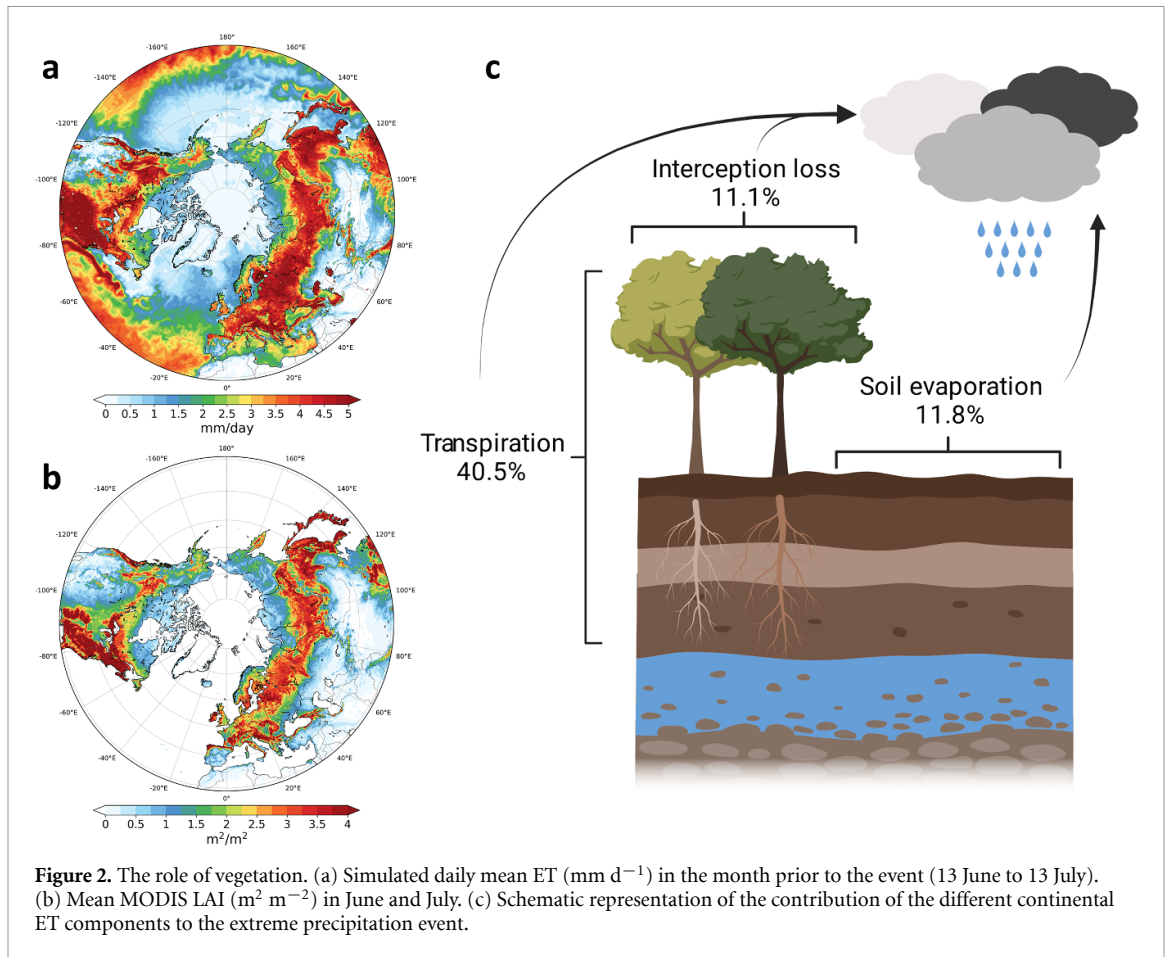


black square in figure 1(b) enclosing the area most affected by rainfall. We have divided the continental part of the domain into three sections, roughly coinciding with the European, Asian and American landmasses. Most of the rainfall (51.4%) was recycled, i.e. fed by moisture from nearby (European) lands. Despite being far away, North America contributed significantly to the event (about 10% of the total precipitation). In contrast, Asia had a smaller contribution (2%) due to its downstream position. In total, these three sources accounted for more than 60% of the moisture, demonstrating the dominance of continental versus maritime sources. The nearby seas (North Sea, Baltic, Mediterranean and Black Seas), notwithstanding their proximity and anomalously high surface water temperatures in the days leading up to the event (see figure S2), had generally smaller contributions. The main oceanic source was the North Atlantic, with about 10%. The tropics acted as a major precipitation enhancer, providing nearly 15% of the recorded rainfall. The contributions of the Arctic and Pacific Oceans were negligible.

The dominant role of continental ET as feeder of the flood event is already foreseeable when examining the daily mean ET field in the days preceding the event (figure 2(a)). In almost all of Europe, the ET rate is much higher than in the surrounding seas, such

as the Mediterranean. The subtropical Atlantic shows higher ET values, but still lower than those in Europe and the boreal forests of Asia. The maximum ET rates are observed in eastern North America, which explains its prominent contribution to extreme rainfall (figure 1(c)) despite its distant location. When comparing ET with the LAI (LAI = leaf area/ground area; figure 2(b)), the link between floods and vegetation becomes evident. The maximum values of continental ET occur where the LAI is also high, i.e. in places with a significant vegetation density.

We have been able to quantify this floods-vegetation link by separately tracking the different ET components. We find that 40.5% of the rainfall in Germany and Belgium (black box in figure 1(b)) came from plant transpiration (33% from Europe, 6.2% from North America and 1.3% from Asia), 11.1% from interception loss or canopy evaporation, and 11.8% from soil evaporation (figure 2(c)). Thus, more than half (51.6%) of the water in precipitation was supplied by vegetation, demonstrating its central role. The rainfall from continental origin adds up to 63.4% of the total, with transpiration alone representing almost two thirds of this figure. Good *et al* [4] recently found a very similar transpiration contribution fraction on a global scale using a completely different approach, which underpins the robustness of



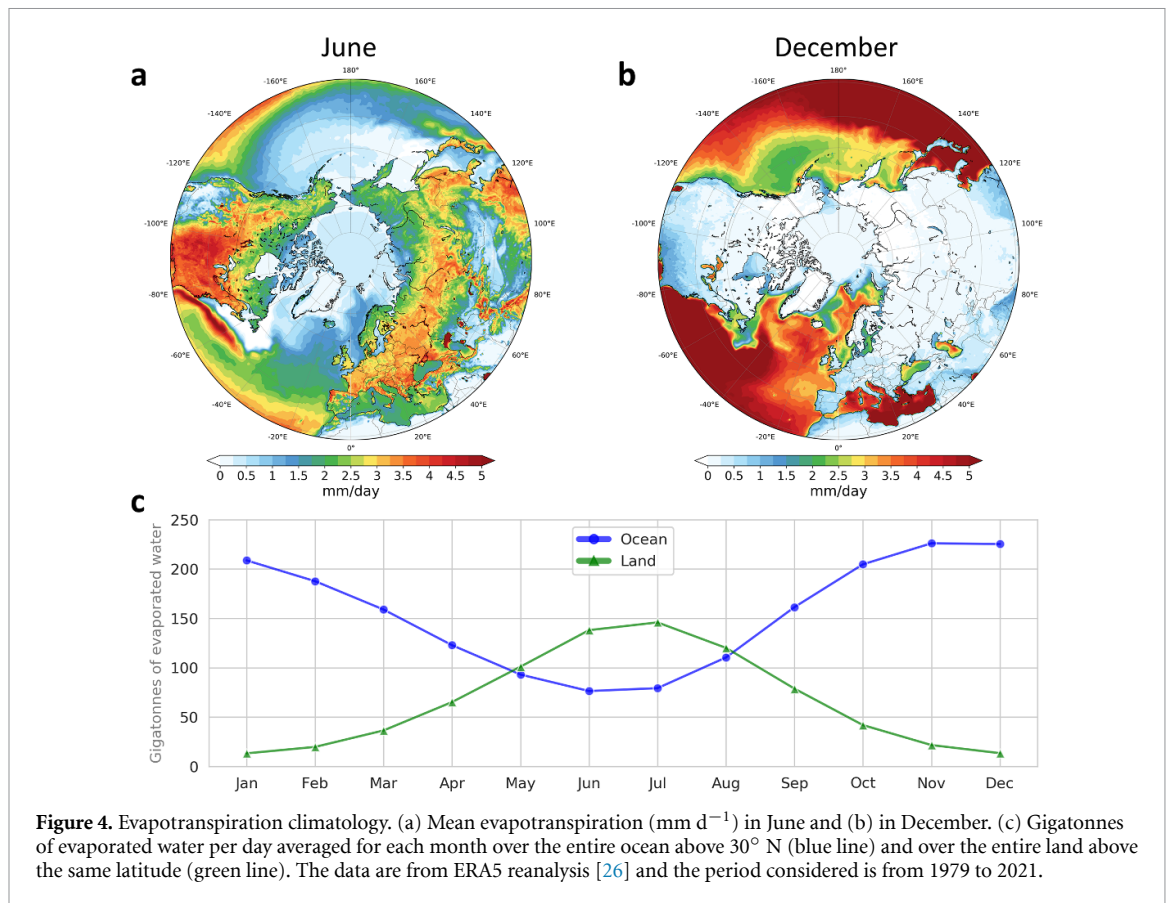


Figure 4. Evapotranspiration climatology. (a) Mean evapotranspiration (mm d^{-1}) in June and (b) in December. (c) Gigatonnes of evaporated water per day averaged for each month over the entire ocean above 30° N (blue line) and over the entire land above the same latitude (green line). The data are from ERA5 reanalysis [26] and the period considered is from 1979 to 2021.

our ET partitioning. The continental ET input could even be somewhat higher if we consider that a part of the rainfall with tropical origin (14.6%, figure 1(c)) could also come from land sources, mainly from tropical Africa.

Finally, we would like to highlight the role of North American vegetation as moisture source. The sum of transpiration and interception loss over this continent explains up to 7.5% of the total precipitation that fell during the event (see table S1 for a clarification of all continental contributions). Therefore, this extremely distant source significantly enhanced heavy rainfall, more so than nearby seas, e.g. the Mediterranean (5.7%, figure 1(c)). The North American contribution increases to 10% when direct soil evaporation is added, as shown in figure 1(c). It is a small fraction, but by no means negligible: we estimate that in the 48 h period between 13 and 15 July, a total of 617 billion liters of water from North America (of which 463 were supplied by vegetation) fell in the area most affected by the event (black box in figure 1(b)). The relevant role of this intercontinental moisture transport between North America and Europe, analogous to the transport of soil dust from Africa to South America [29], is still poorly understood. Figure 3 exemplifies this phenomenon. It shows the integrated transport of water vapor supplied by North American vegetation and the precipitation fed by this source for the first half of July (see also supplementary video). Moisture from North

American vegetation flows into the Atlantic with a maximum south of Newfoundland and some of it manages to cross the ocean following the prevailing westerly circulation. Eventually this moisture precipitates over Europe, affecting not only the countries most impacted by the flood event, but also other areas such as the British Isles.

4. Discussion

Our results show that not only tropical rainfall depends on forests, but also mid-latitude rainfall extremes can be highly dependent on moisture provided by vegetation. This dependence indicates that water amounts recorded during European summer flood events can be very sensitive to vegetation cover changes. The results extracted for this study could actually be the norm for summer precipitation extremes in Europe, as other authors have found high moisture contributions of continental origin in other cases of this type [10, 11]. This would be consistent with the fact that, at mid- and high latitudes, average ET over the continents during summer is higher than evaporation over nearby seas, just the opposite of winter (figure 4). Nevertheless, we intuitively tend to assume higher evaporation rates from water bodies, which shifts attention to the contribution of seas, lakes and reservoirs to the detriment of that of land. In addition, we found that ET rates around the area most affected by the event and on dates close to it (late

June and early July) were close to their climatological value (see figure S3). This would indicate that the high terrestrial contribution to heavy rainfall was not due to an anomalous or extraordinary continental moisture supply, which reinforces the idea that such high recycling ratios may be the norm in these summer extreme events.

Our findings highlight the need to consider the role of vegetation as moisture source in summer flooding when designing land-management strategies [30, 31], such as reforestation. This practice has been shown to have high benefits in the context of climate change [32]. As an example, a very recent study [33] indicates that a realistic reforestation scenario in Europe would lead to an increase in summer precipitation of $7.6 \pm 6.7\%$, which in turn would help mitigate the effects of increased frequency and severity of droughts in this area [34, 35]. In addition, it is known that an increase in leaf area can limit temperature rise [36], especially in summer and in low and mid latitudes [37]. Both processes are related to the increase in ET fluxes at the expense of sensible heat fluxes, which reduces the Bowen ratio [38]. However, based on the high continental moisture contributions found, we hypothesize that this increase in ET could also considerably intensify extreme rainfall. Therefore, our results suggest that these positive effects could be counterbalanced by a flood-enhancing (negative) effect. We nevertheless acknowledge that further research is needed to quantify the extent to which land surface greening has the capacity to intensify European summer flooding.

Data availability statement

All other data generated during the current study are available on request from D I C.

The data that support the findings of this study are available upon reasonable request from the authors.

Code availability statement

The WRF-WVTs model code is freely available for download at <https://github.com/damianinsua/WRF-WVTs>.

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Author contributions

D I C designed the experiment, performed the simulations, created the figures and wrote the first manuscript draft. M S R was in charge of part of the data analysis. G M M, M S R and M C L L contributed with ideas, interpretation of the results, and manuscript revisions.

Conflict of interest

The authors declare no competing interests.

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