Supplementary Material

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S.1 August 2022 Pakistan precipitation event

Pakistan is a region suffering from heavy rain and floods, and there is evident increasing trend of precipitation in past 60 years (Hussain et al., 2022). The major mechanism that causes above normal rainfall in Pakistan is South Asian Summer Monsoon (SASM), but SASM is a quite complex system with many different scale of drivers. One major process is that a consistent intensified South Asian High (SAH) will enhance mid-troposphere ascent, thus enhanced convective process. The Rossby wave pattern and 200hpa cut off low also leads to cold air's intrusion into the warm subtropical region, enhancing the ascent and extreme precipitation (Ullah et al., 2021).

For the August 2022 extreme event, studies show that there is strong anomalous southwesterly from the Arabian Sea and easterly winds associated with the strong Western North Pacific Subtropical High (WNPSH), and the convergence of the two wind near Pakistan provide a favorable condition for convection (Hong et al., 2023). In this study, 18th Aug 2022 is chosen for moisture tracking study, the study region is 30N-24N, 67E-71E (see the pale yellow boundaries in Fig. S 3).

S.2 October 2023 Scotland precipitation event

European precipitation is connected with large scale mean sea-level pressure (MSLP) fields, which can be expressed as circulation indexes (Lavers et al., 2013).Precipitation in Scotland has a significant relationship with North Atlantic Oscillation (NAO) index (Wang et al., 2024), as the "jet stream" occurs from larger pole-to-equator temperature gradient, especially in winter, and extratropical cyclones develop from these jet stream regions, then Atmospheric Rivers within extratropical cyclones transport huge amount of moisture from North Atlantic Ocean northeastwards to Europe, causing extreme precipitation and floods (Lavers et al., 2013; Lavers and Villarini, 2015).

The October 2023 extreme event is in Scotland autumn, near winter. 75mm of rainfall over 48h was reported in a wide area from the Scottish Environmental Protection Agency, which is not as heavy as Australia and Pakistan events in this study, but also quite heavy for this region. An atmospheric river and a quasi-stationary front are thought to be the leading reason

(Graham et al., 2023). In this study, 7th Oct 2023 is chosen for moisture tracking study, the study region is 60N-52N, -8E--1E (see the pale yellow boundaries in Fig.S4Figure S 6 The same as Figure 3 but for the Scotland event.).

S.3 Parcel release number

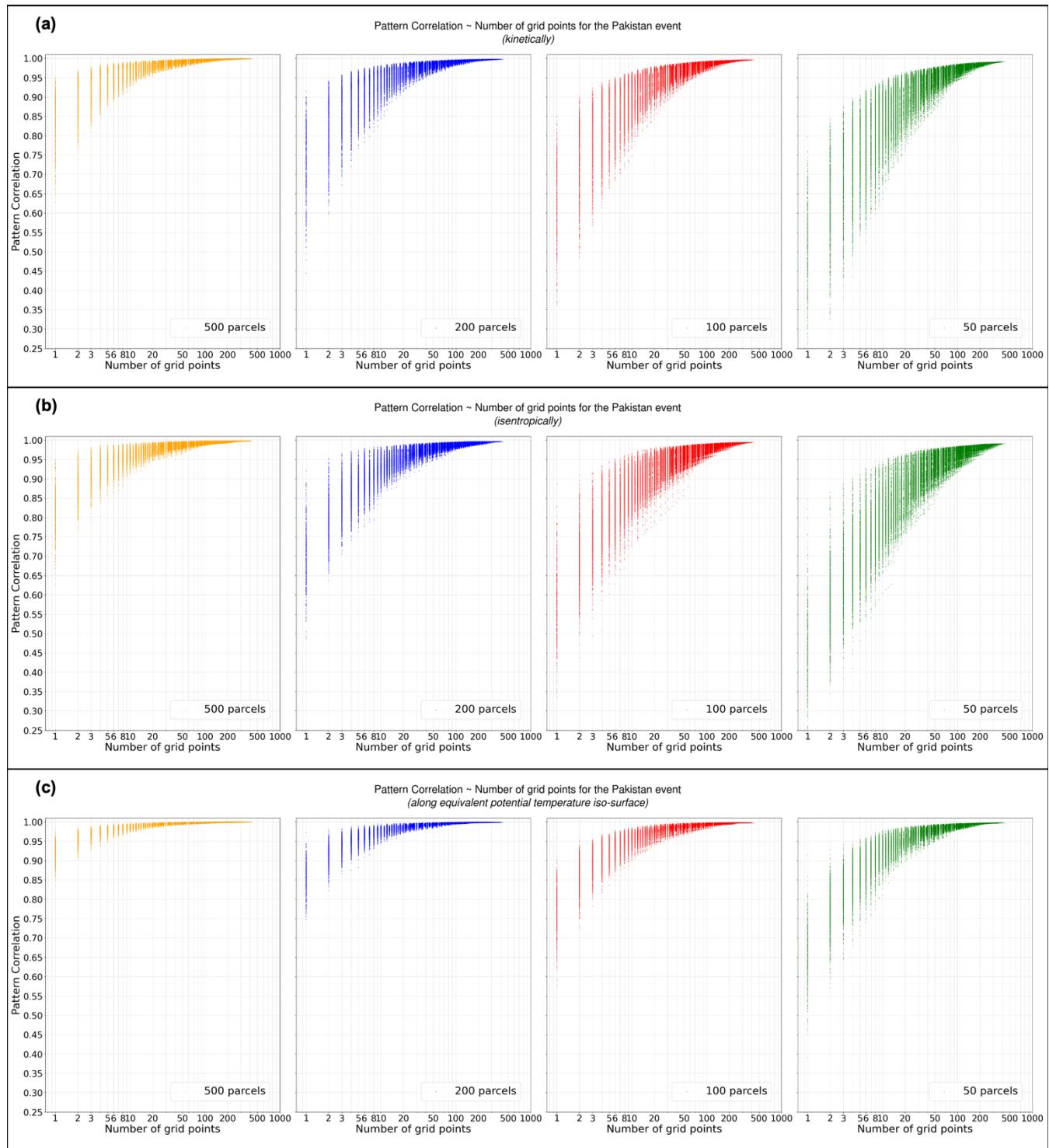



Figure S 1 The same with Figure 1 but for the Pakistan event

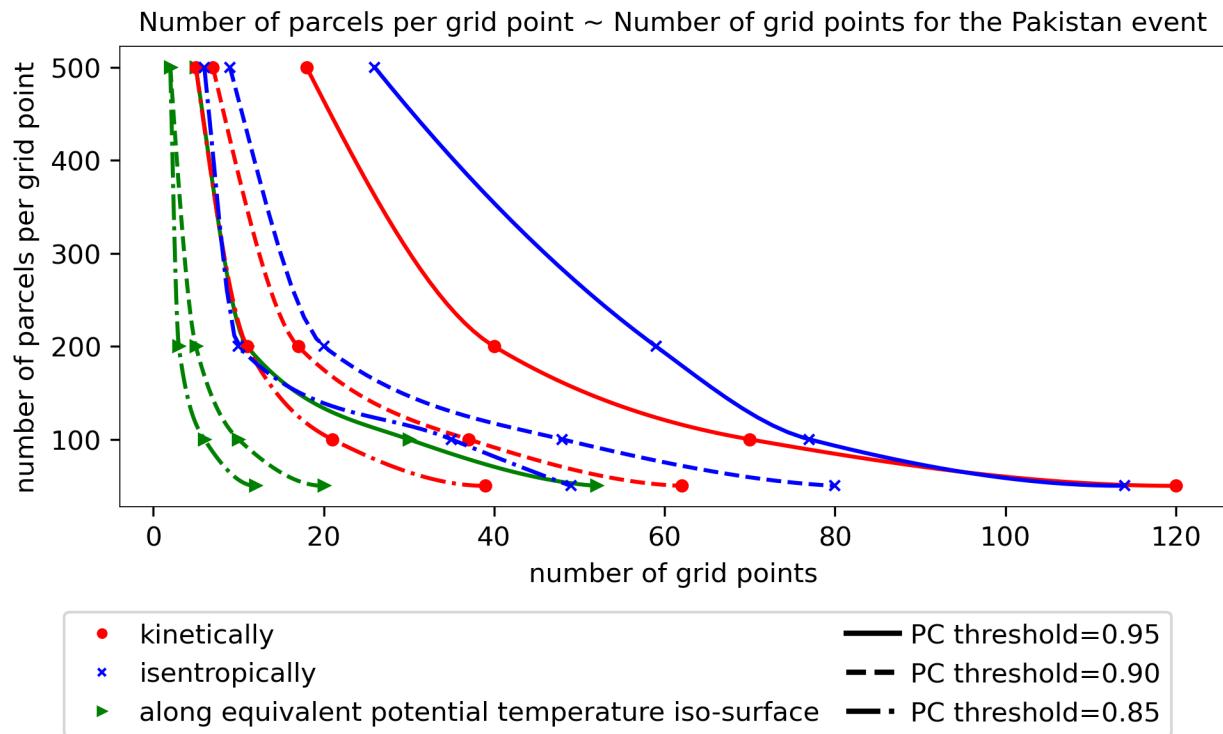



Figure S 2 The same with Figure 2 but for the Pakistan event

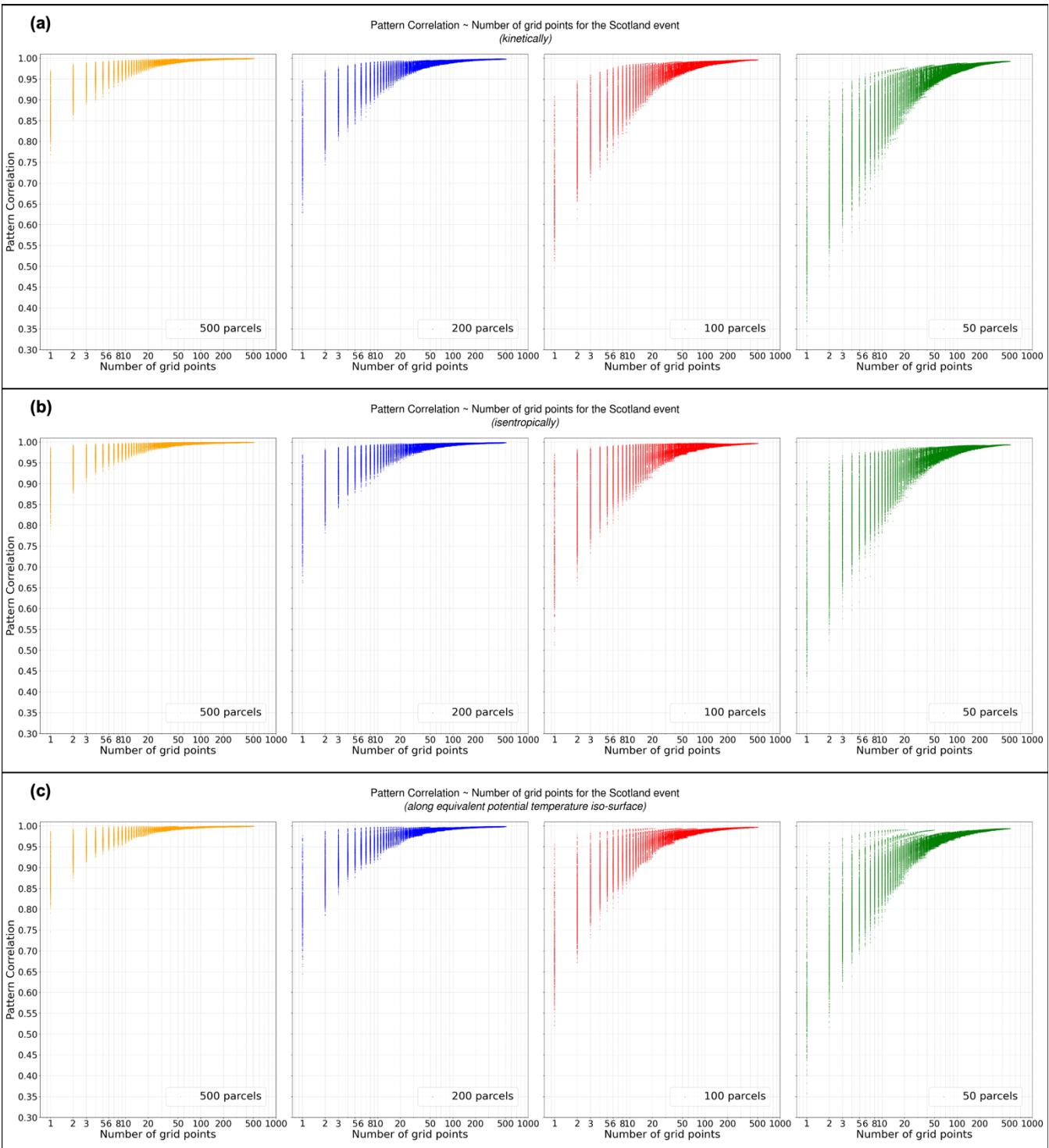



Figure S 3 The same with Figure 1 but for the Scotland event.

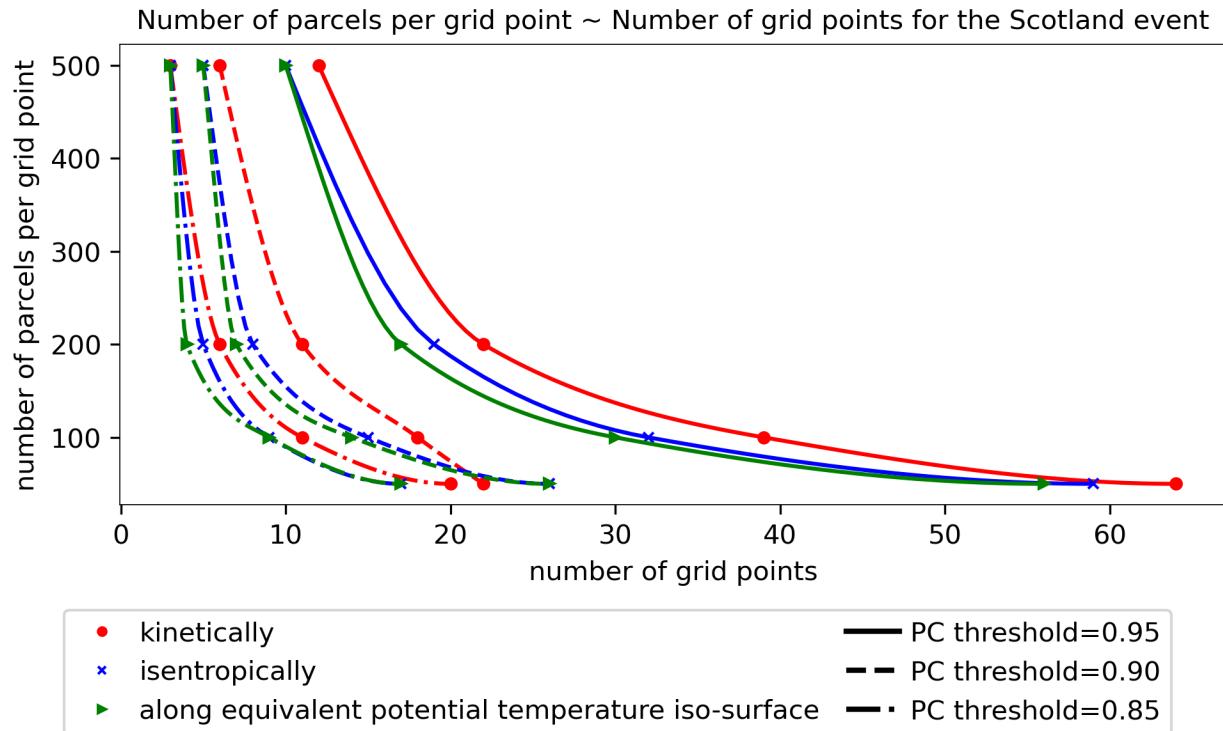



Figure S 4 The same with Figure 2 but for the Scotland event.

S.4 vertical movement

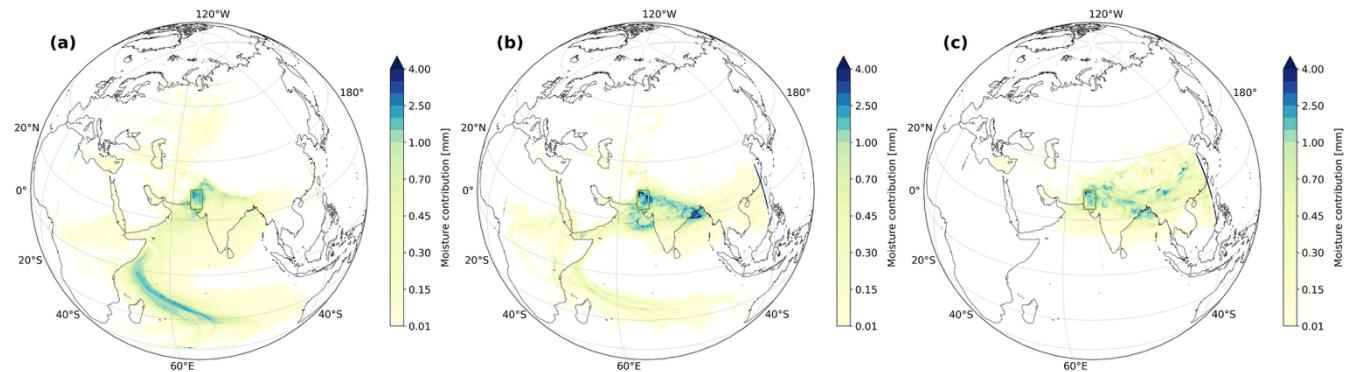



Figure S 5 The same with Figure 3 but for the Pakistan event.

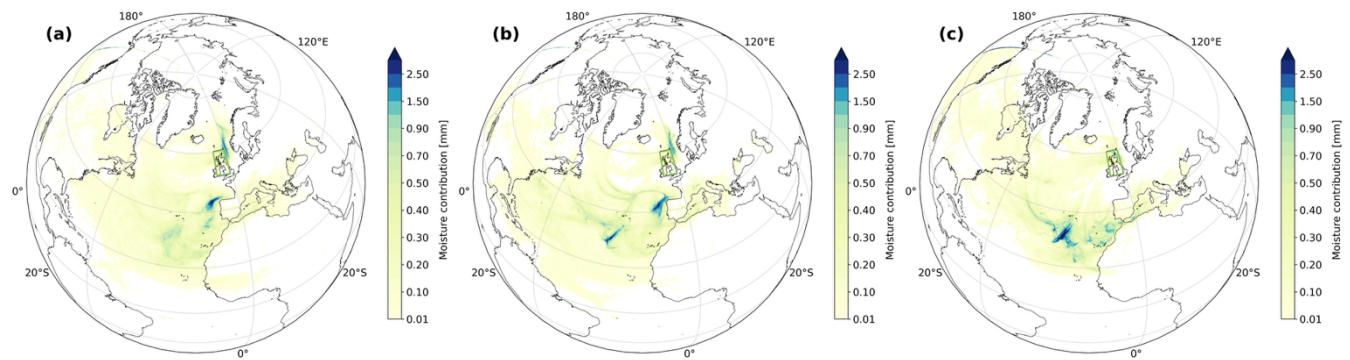
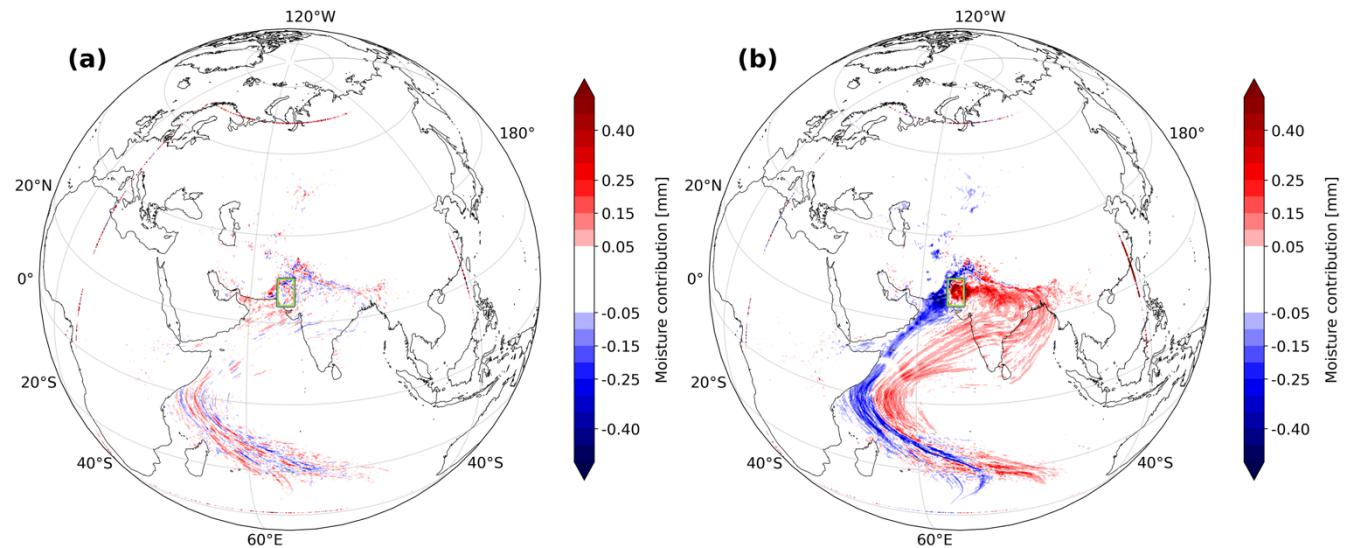



Figure S 6 The same as Figure 3 but for the Scotland event.

S.5 Parcel release height

50   **Figure S 7 the same with Figure 4 but for the Pakistan event**

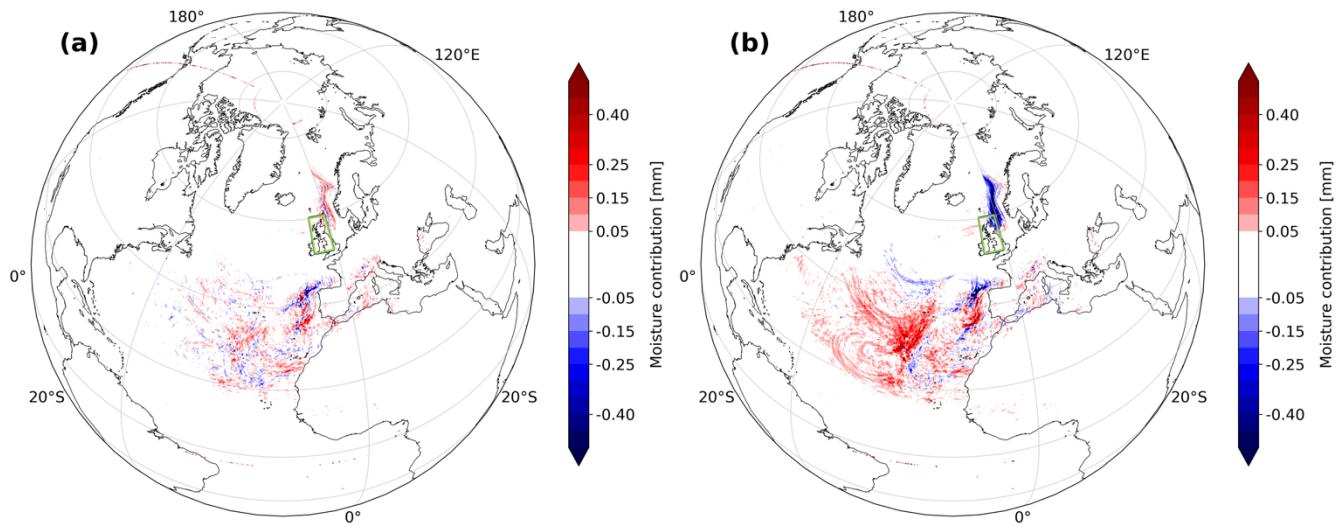
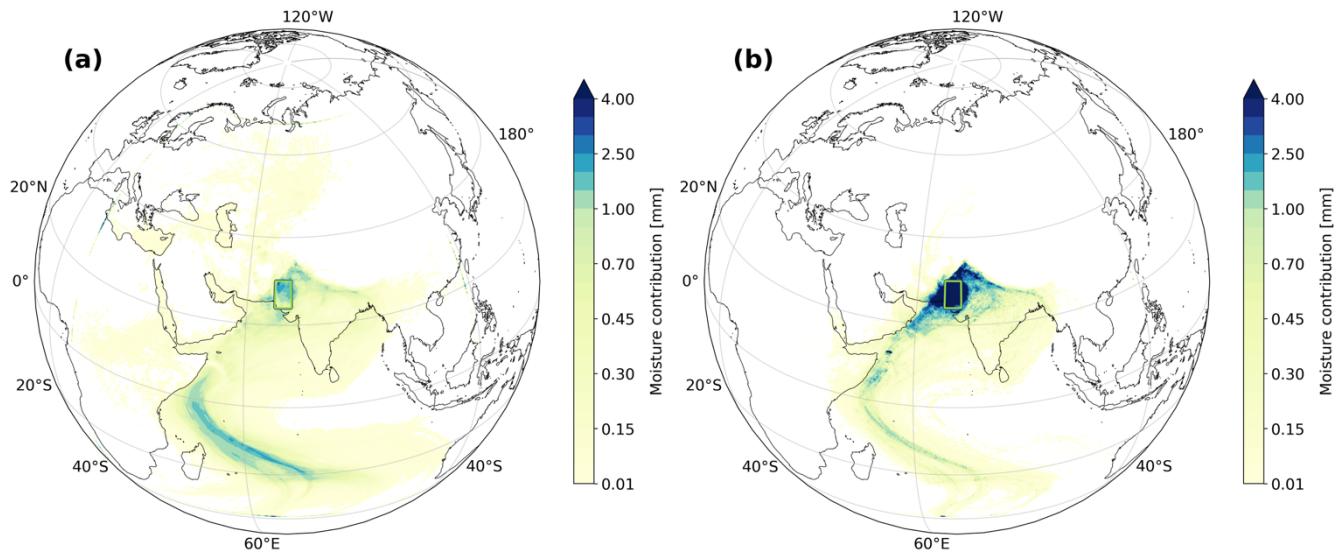



Figure S 8 the same with Figure 4 but for the Scotland event

S.6 Well mixed assumption and moisture identification method

55 **Figure S 9 the same with Figure 5 but for the Pakistan event**

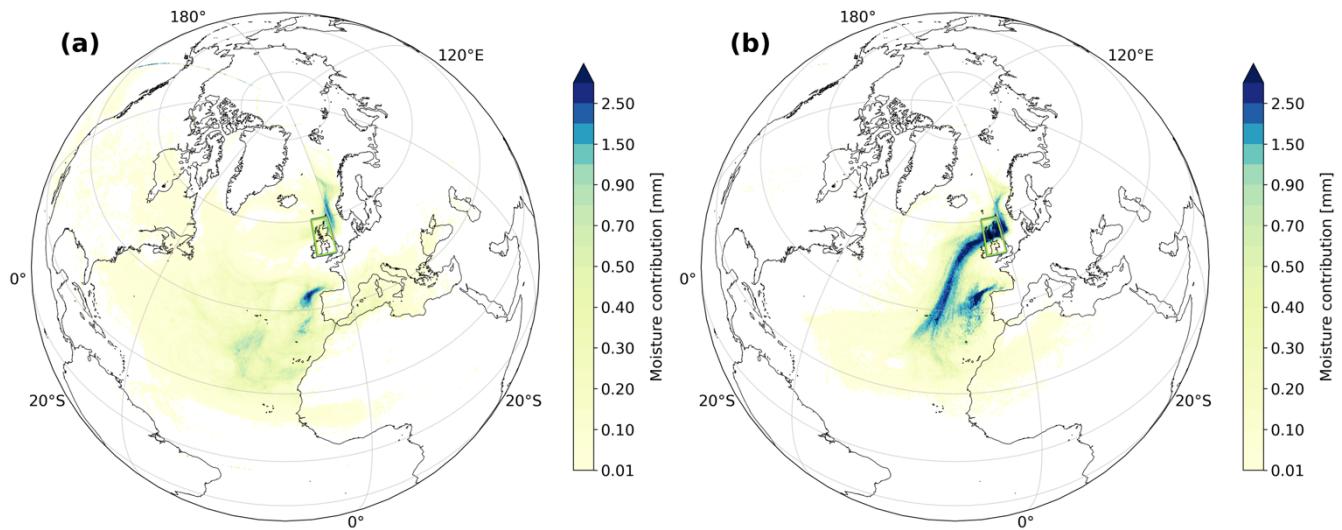



Figure S 10 the same with Figure 5 but for the Scotland event

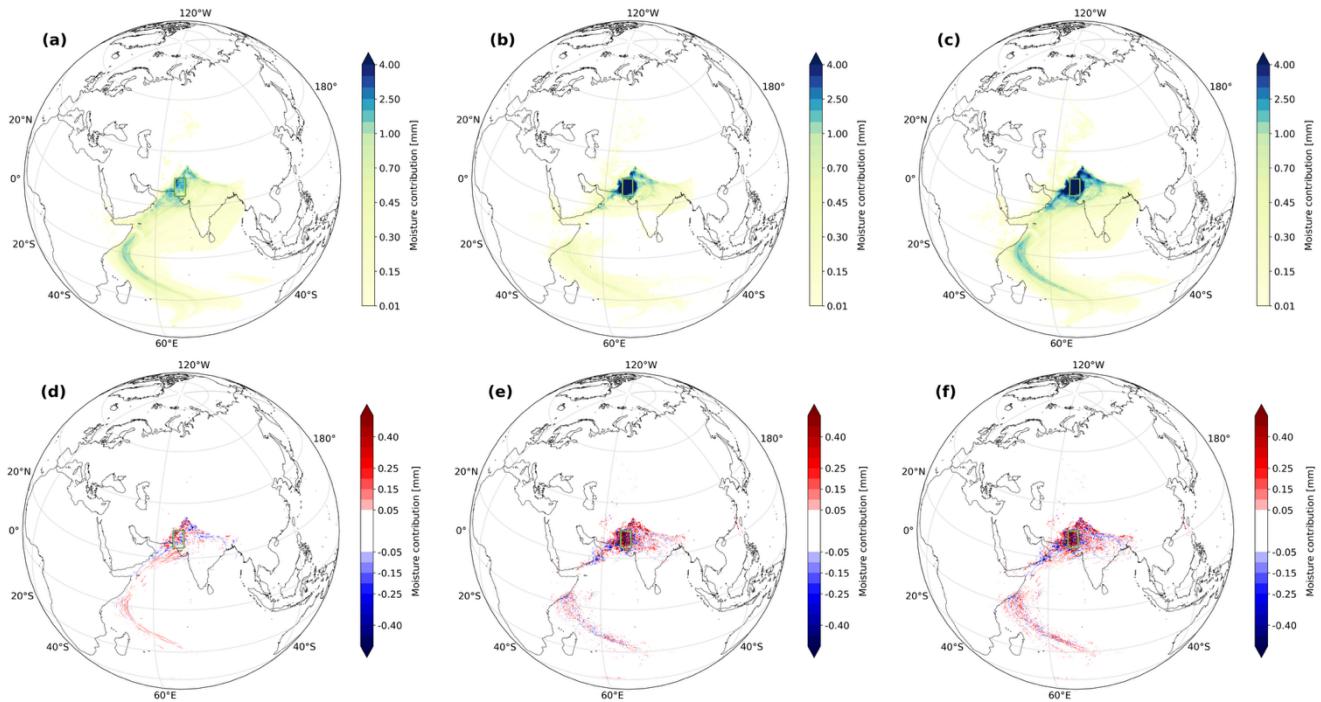



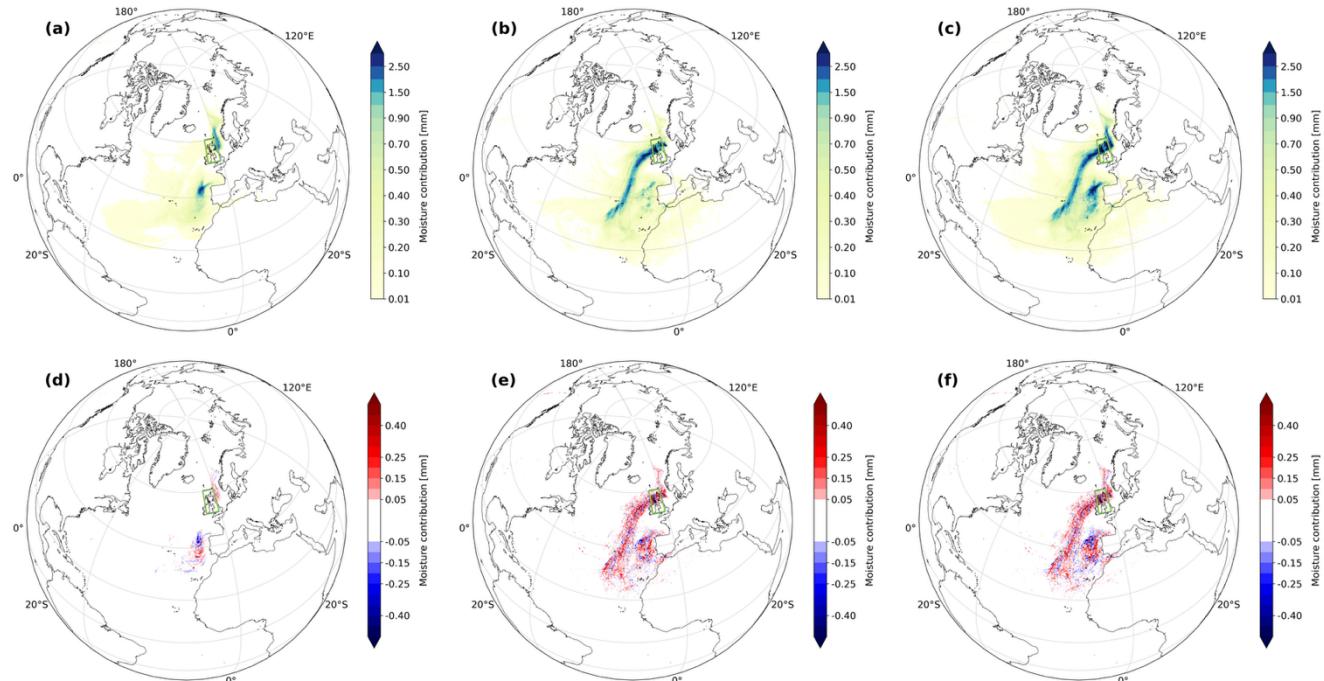
Figure S 11 the same with Figure 6 but for the Pakistan event

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Figure S 12 the same with Figure 6 but for the Scotland event

S.7 Subgrid interpolation method
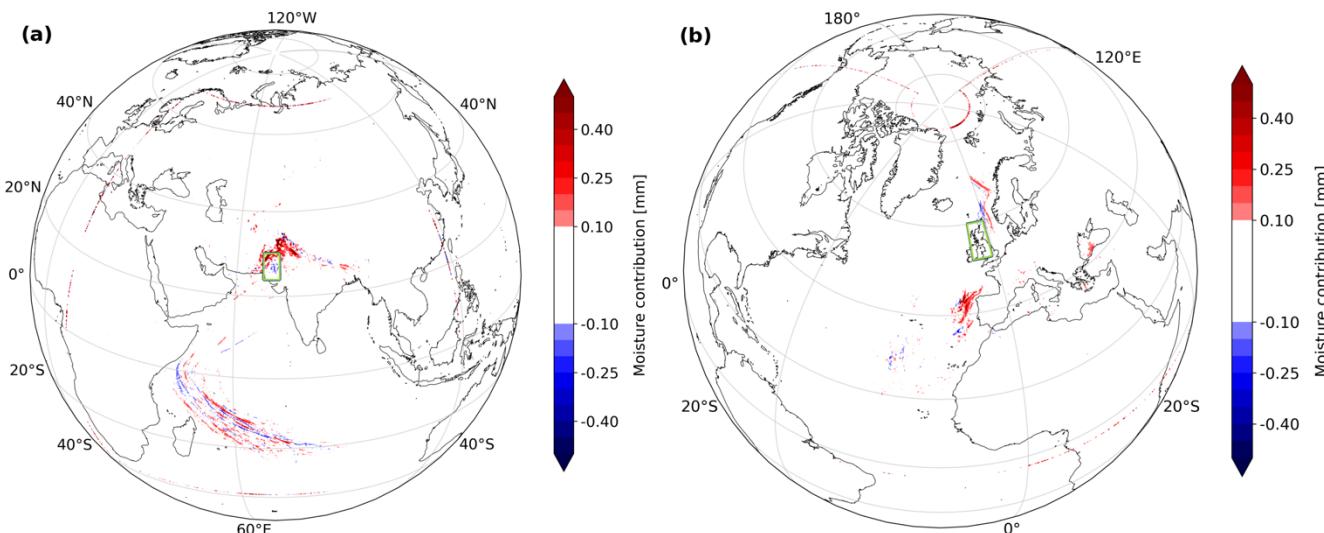
Figure S 13 the same with Figure7 but for the Pakistan event(a) and the Scotland event(b)

 S.8 Time step
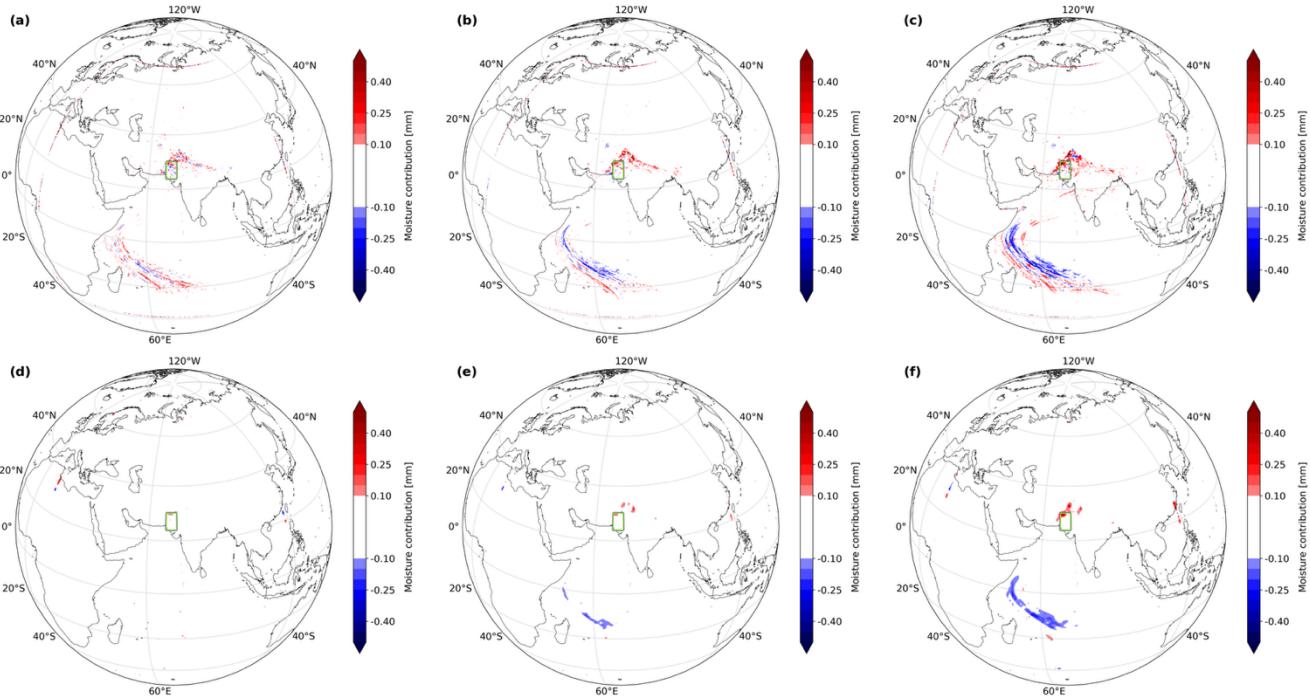
Figure S 14 the same with Figure 8 but for the Pakistan event
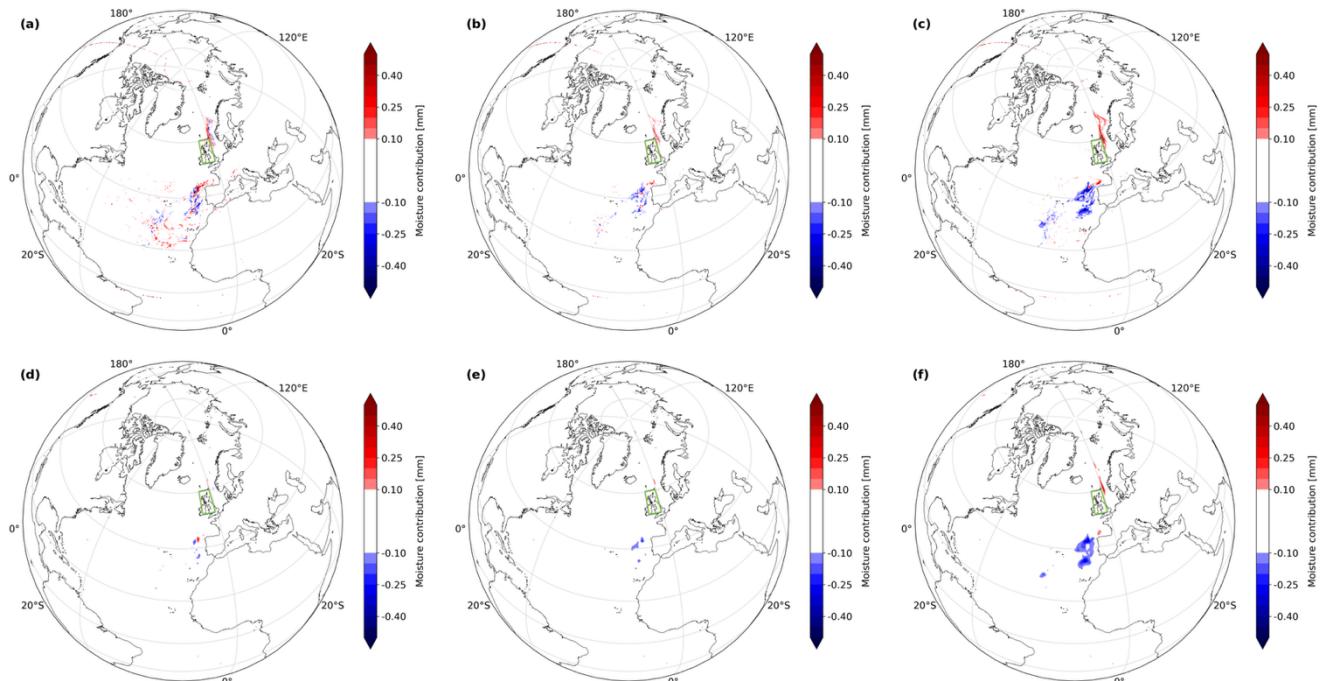
Figure S 15 the same with Figure 8 but for the Scotland event

70

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90