

Supplemental Information

Atmospheric rivers that make landfall in India are associated with flooding

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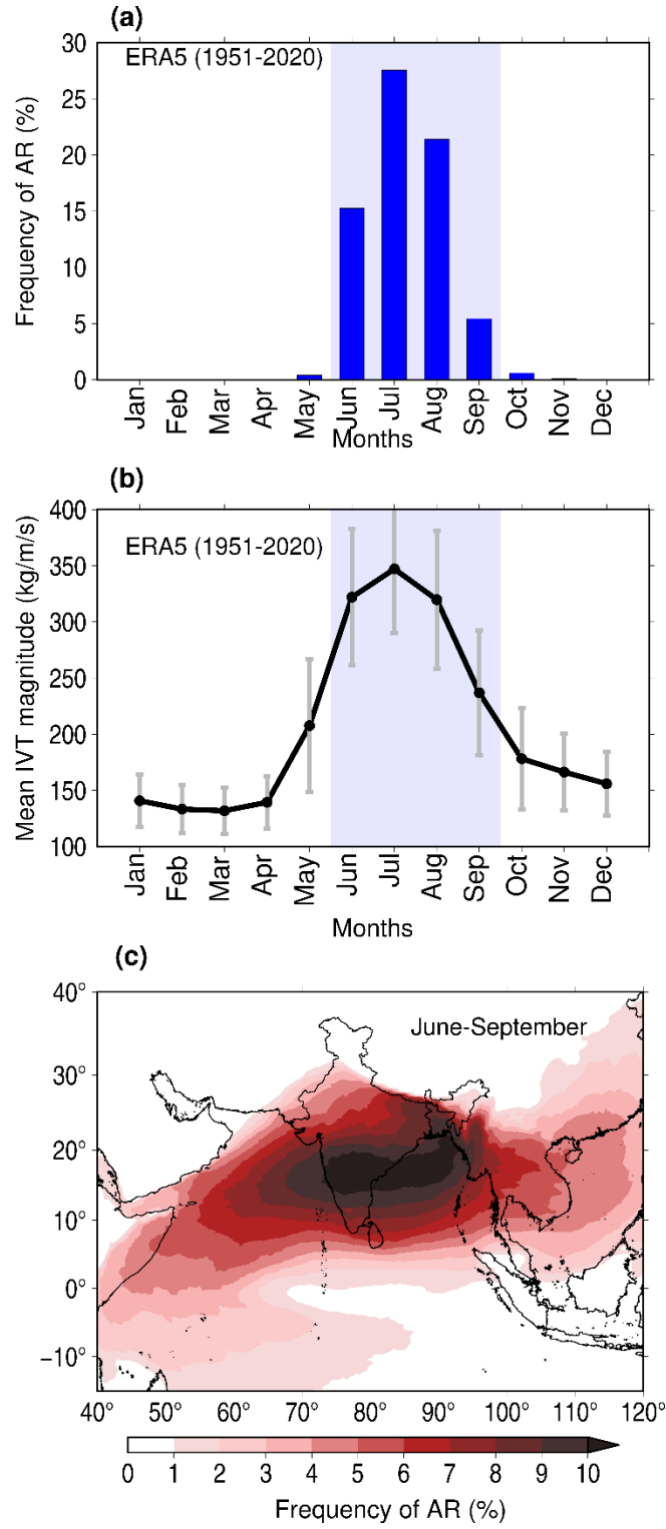


Fig. S1. Climatology of atmospheric rivers in India, 1951-2020. (a) Average monthly frequency of occurrence of ARs (% of time-step), (b) average monthly mean IVT magnitude (kg/m/s). The shaded regions in panels a) and b) show the monsoon season months (June-September), (c) Frequency of occurrence of ARs during the monsoon season (June-September) for the period 1951-2020. For each grid cell, the AR frequency is defined as the number of days on which an AR is detected, divided by the total number of monsoon days. ARs were identified using daily IVT derived from the ERA5 reanalysis (see Methods in main text for details).

Monthly IVT climatology

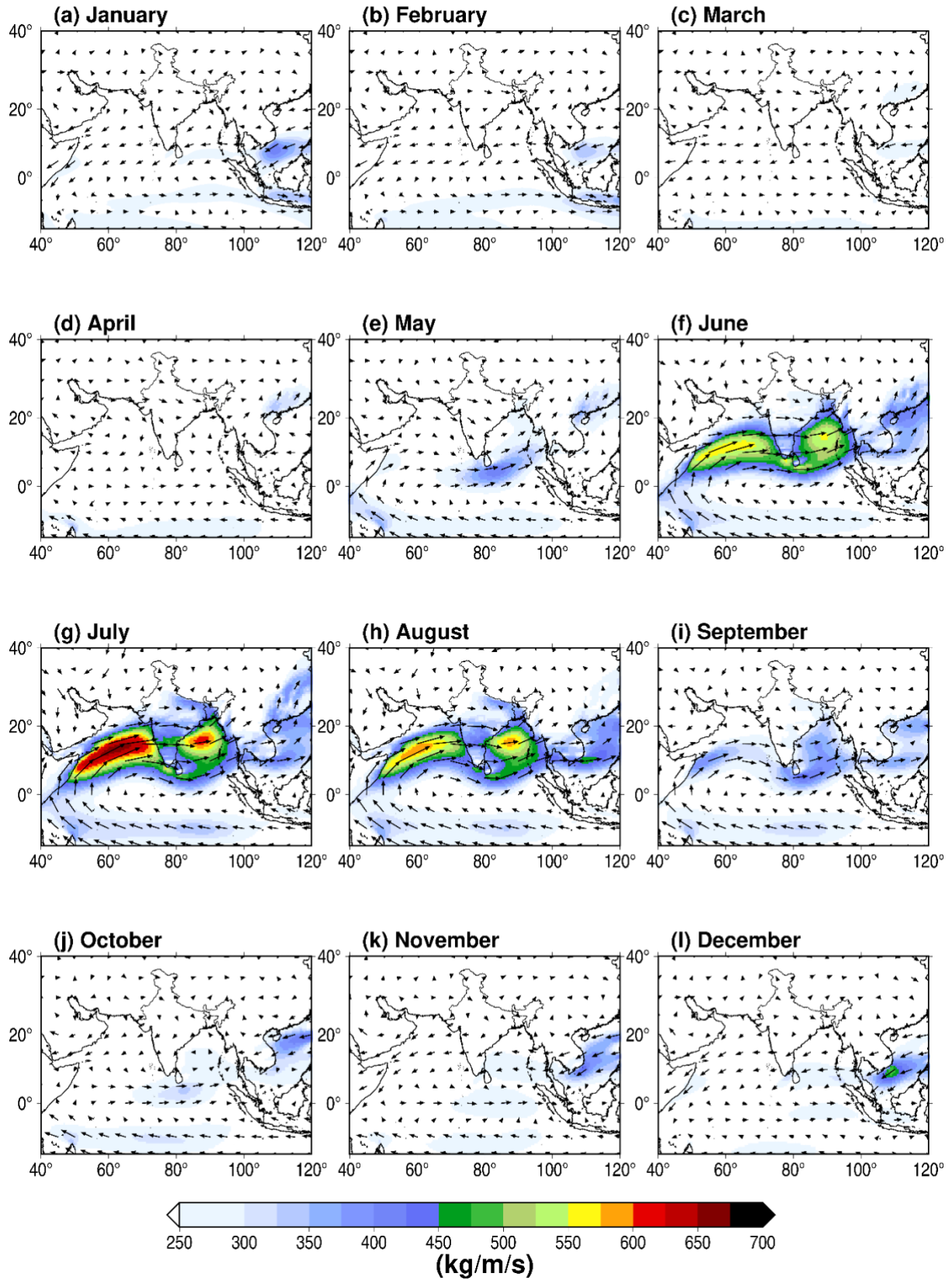


Fig. S2. Monthly climatology of IVT (kg/m/s) for 1951-2020 over southern Asia. Arrows show the direction of the wind velocity vector at 850hPa level.

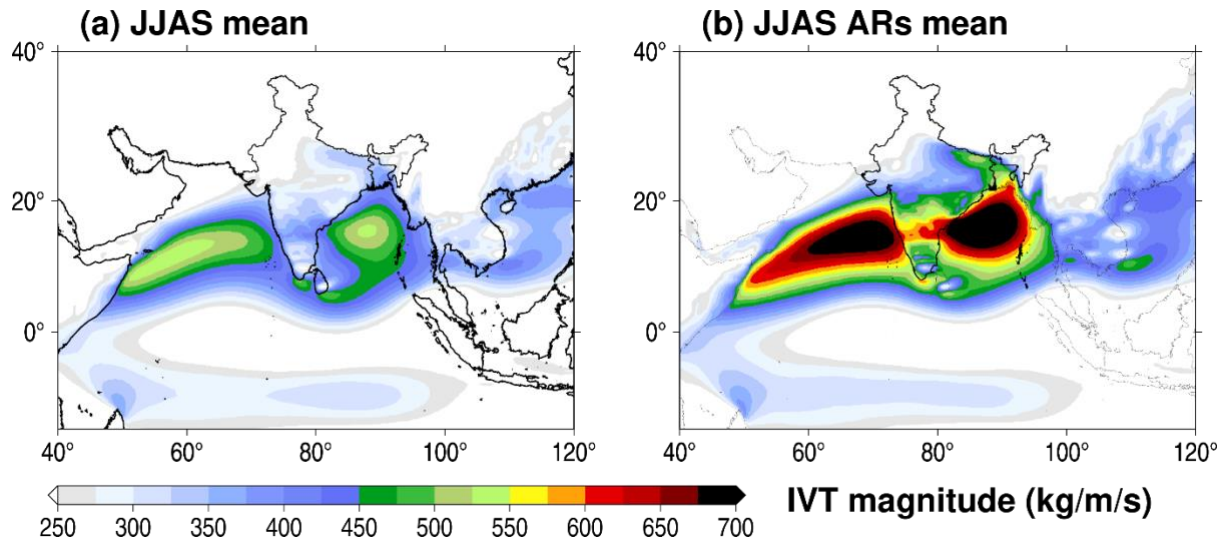


Fig. S3. Climatological mean IVT (kg/m/s) in the monsoon season during 1951-2020. (a) Non-AR days (absence of AR), (b) AR days (presence of AR).

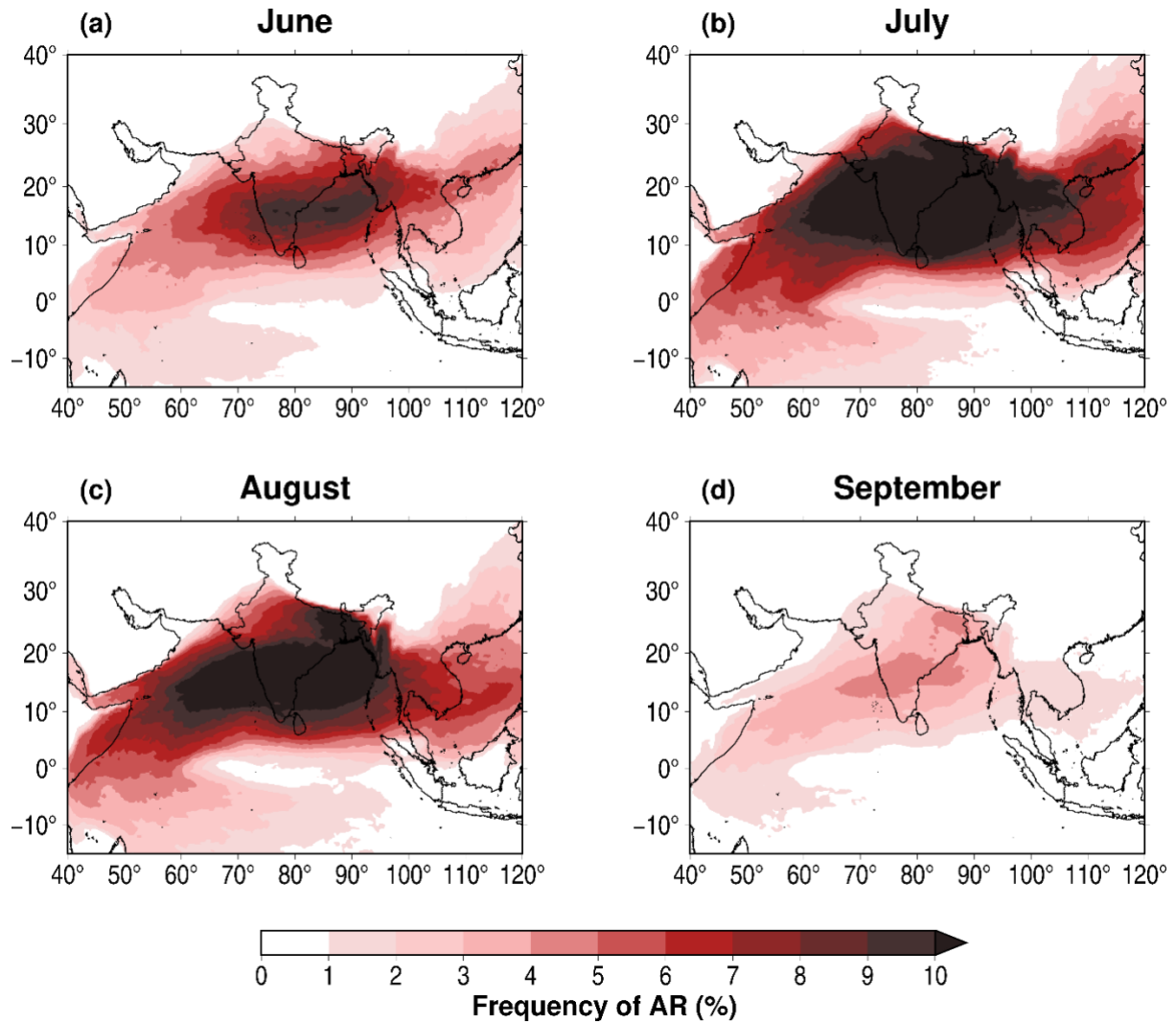


Fig. S4. Frequency of occurrence of ARs (%) in the monsoon season months during 1951-2020.

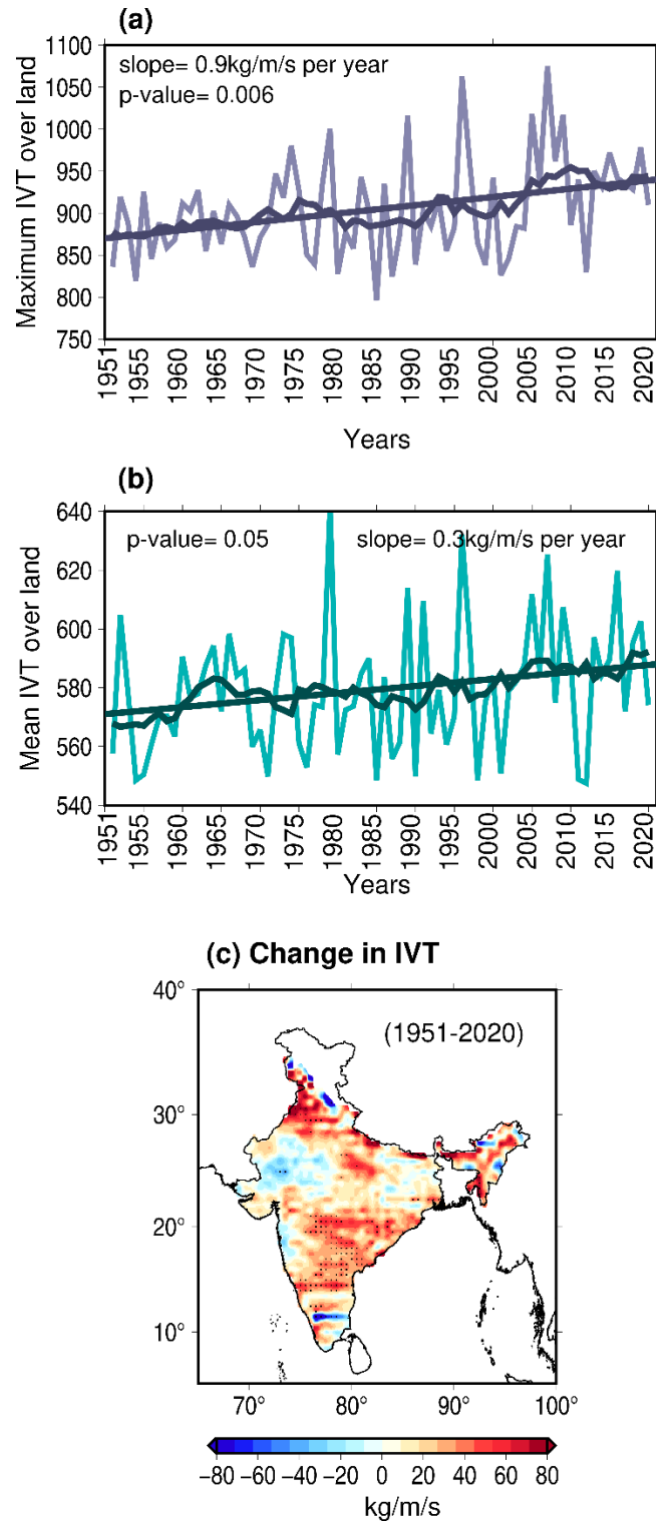


Fig. S5. Trend in IVT during atmospheric rivers in the monsoon season over 1951-2020. (a) Trend in maximum IVT (kg/m/s) averaged over the Indian landmass during 1951-2020, (b) Same as b but for mean IVT magnitude. Trend in IVT magnitude is statistically significant ($p\text{-value} < 0.05$) for the period 1965 -2020 (but not for 1951-2020). Red dots in a) and b) show the five years with maximum IVT magnitude, and corresponding year's mean IVT, respectively. Solid lines in a) and b) represent the linear trend and 10-year moving mean, (c) Long-term (1951-2020) change in the IVT magnitude in India. Stipled grids are statistically significant at 5% significance level.

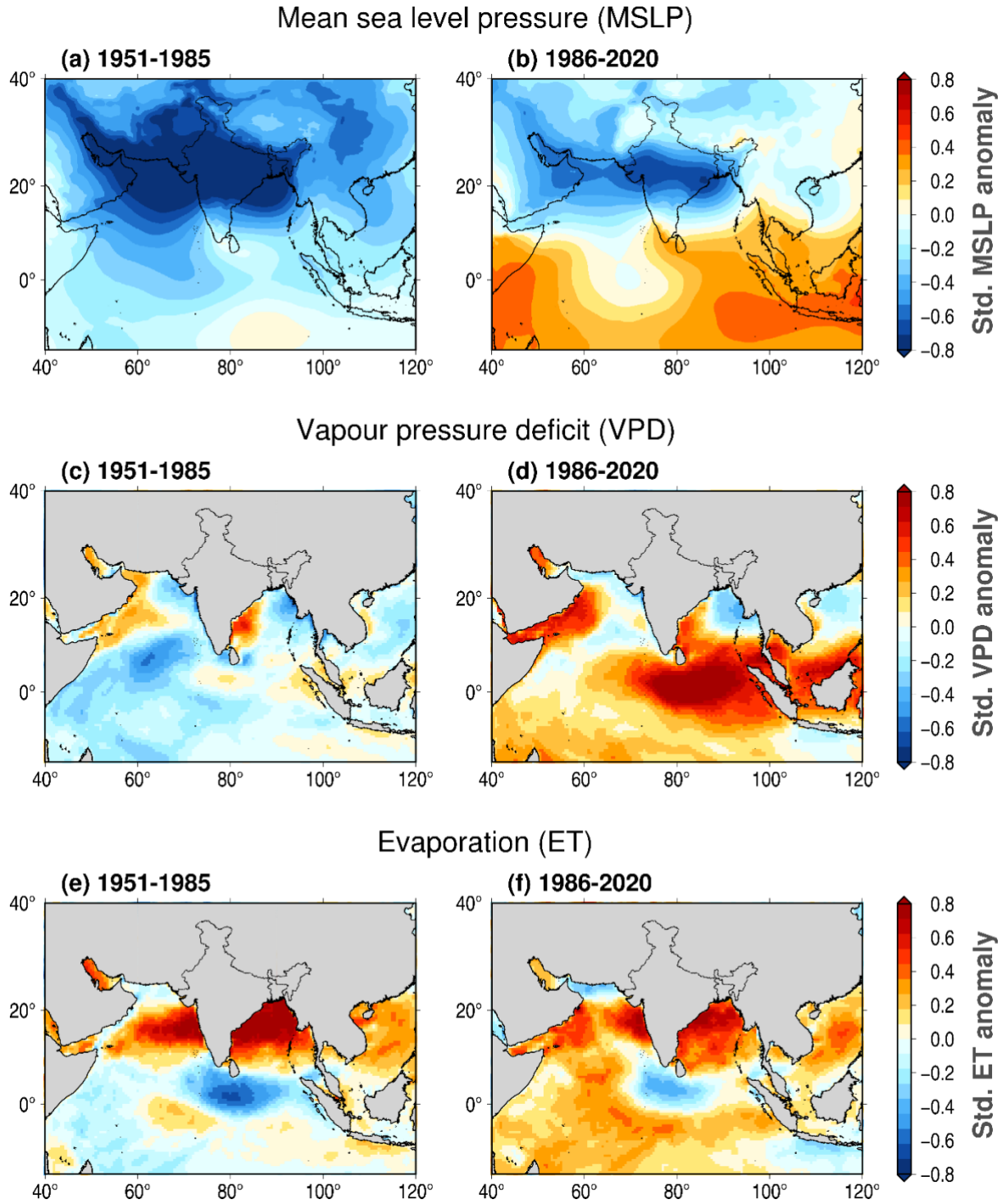


Fig. S6. Thermodynamic factors change the wind and humidity anomaly, contributing to IVT magnitude during atmospheric river in the monsoon season in India. a)-b) Standardized mean sea level pressure (MSLP) anomaly during 1951-1985 and 1986-2020. c)-d) Same as a)-b) but for vapour pressure deficit (VPD) anomaly. e)-f) Same as a)-b) but for evaporation (ET) anomaly.

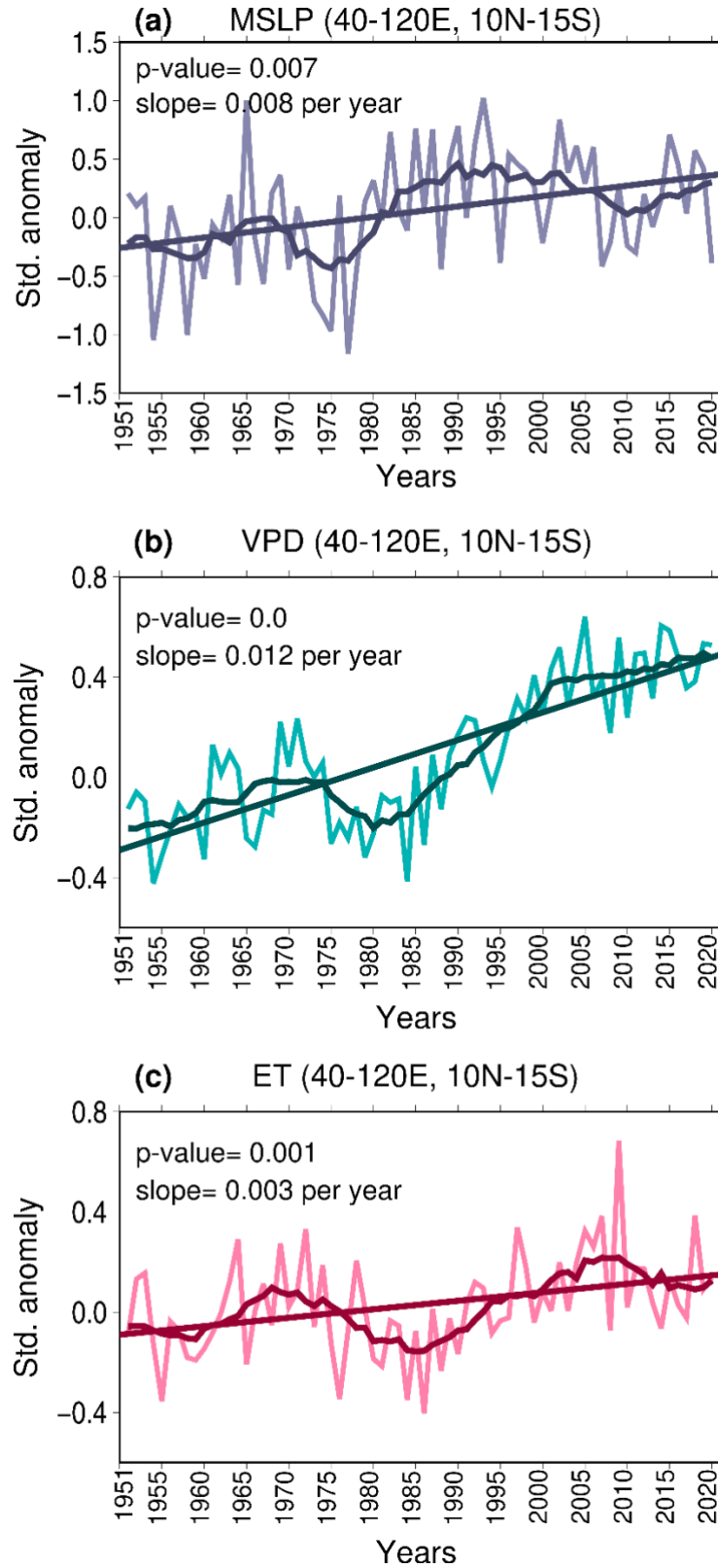


Fig. S7. Trend in thermodynamic factors responsible for change in wind and specific humidity anomaly, contributing to IVT magnitude during atmospheric river in the monsoon season in India. The values are obtained by averaging over the ocean region between 40-120E and 10N-15S (moisture source region) for each year. a)-b) Long-term trend in Standardized mean sea level pressure (MSLP) anomaly. c)-d) Same as a)-b) but for vapour pressure deficit (VPD) anomaly. e)-f) Same as a)-b) but for evaporation (ET) anomaly.

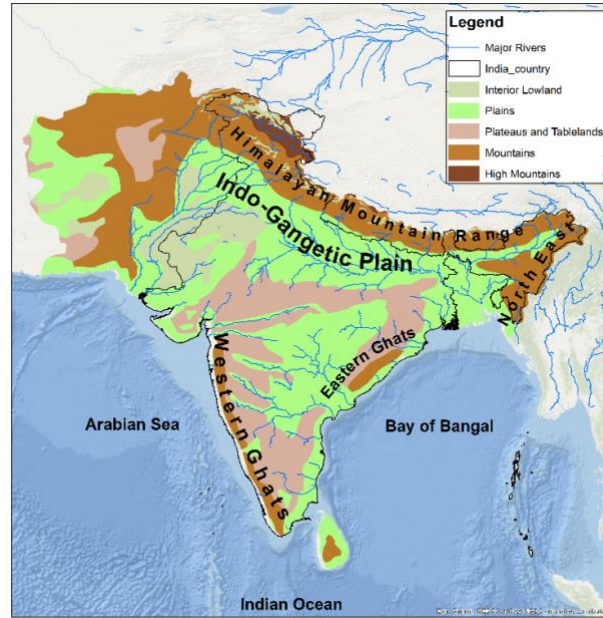


Fig. S8. Map showing the important physical features and regions of South Asian region. Base map source: <https://services.arcgis.com/>. (Esri, USGS | Esri, FAO, NOAA, USGS | Esri Data and Maps).

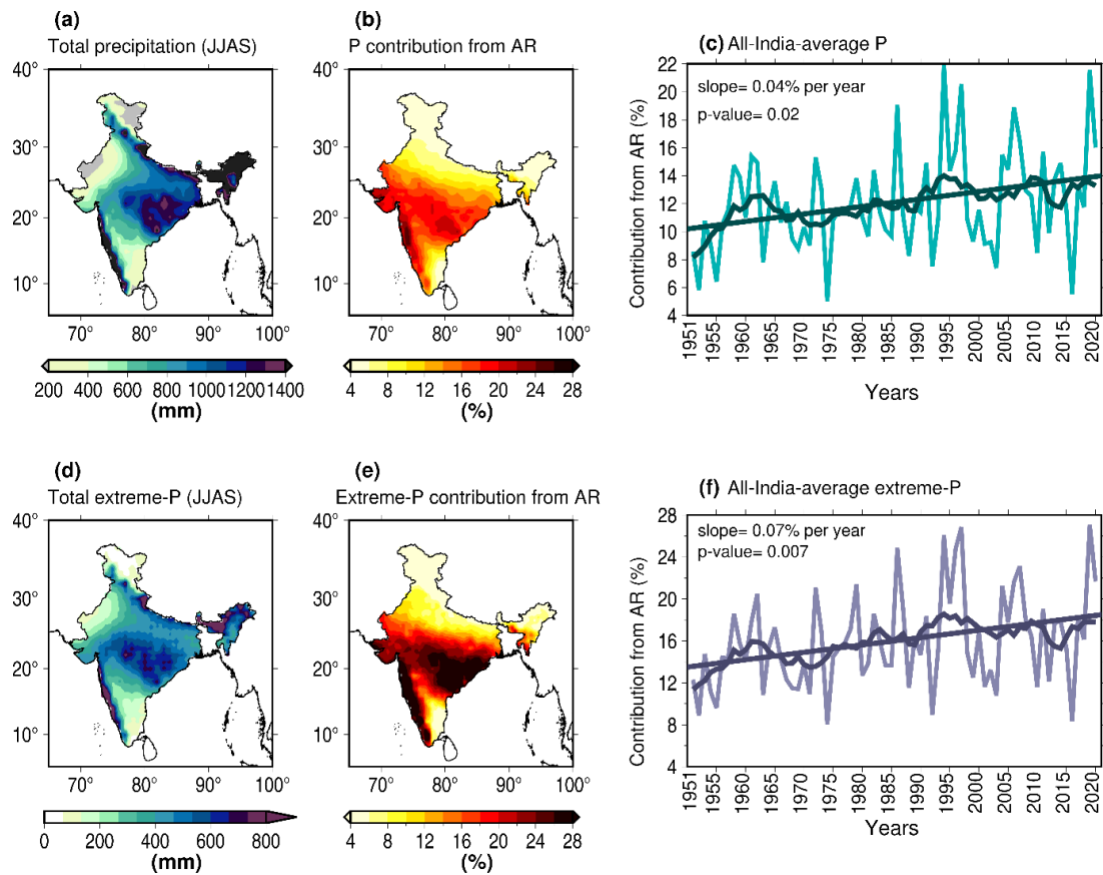


Fig. S9. Extreme precipitation contribution from atmospheric rivers in the monsoon season in India during 1951-2020. a)-c) Long-term (1951-2020) mean monsoon season precipitation (mm) across India, fraction of total precipitation (P-fraction) from the ARs, and trend in all-India average precipitation fraction from ARs, respectively. d)-f) same as a)-c) but for extreme (>95th percentile) precipitation.

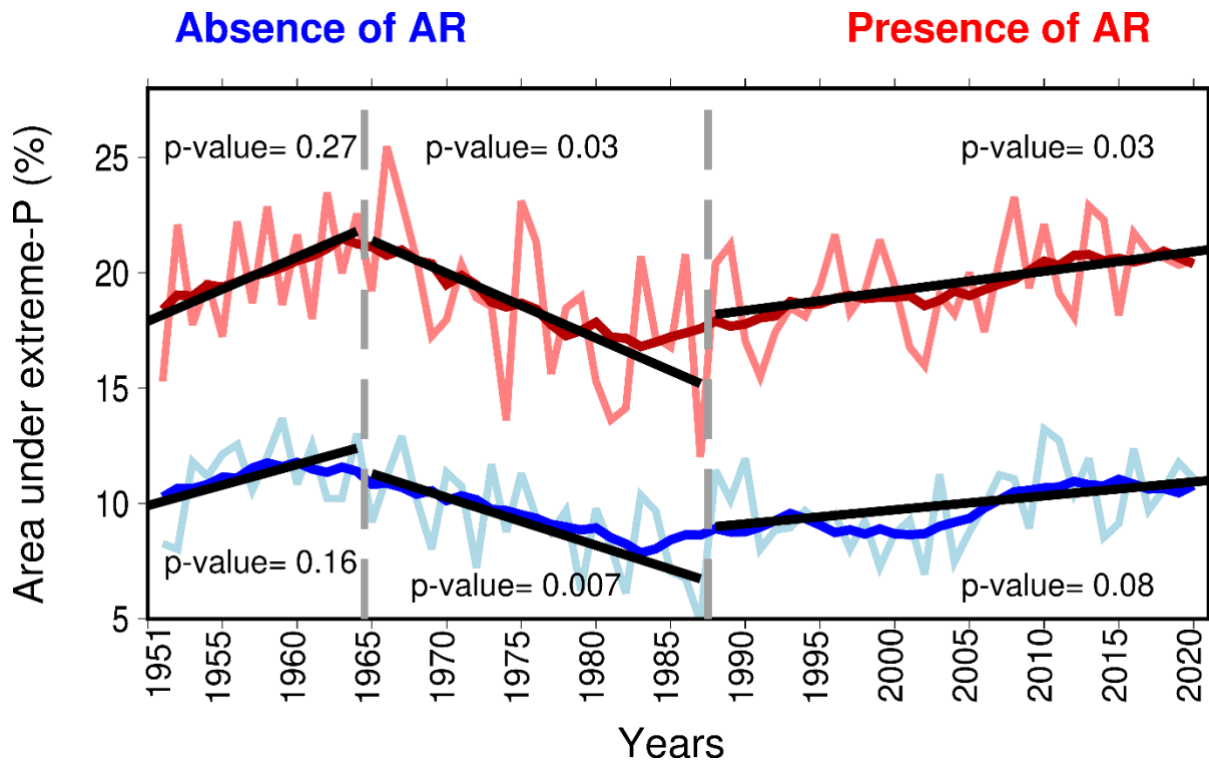


Fig. S10. Extreme precipitation contribution from atmospheric rivers in the monsoon season in India during 1951-2020. a)-b) Trend in area under extreme precipitation (%) in the absence and presence of ARs, respectively. Trends shown in a) and b) are statistically significant ($p\text{-value} < 0.05$) for the period 1980 -2020.

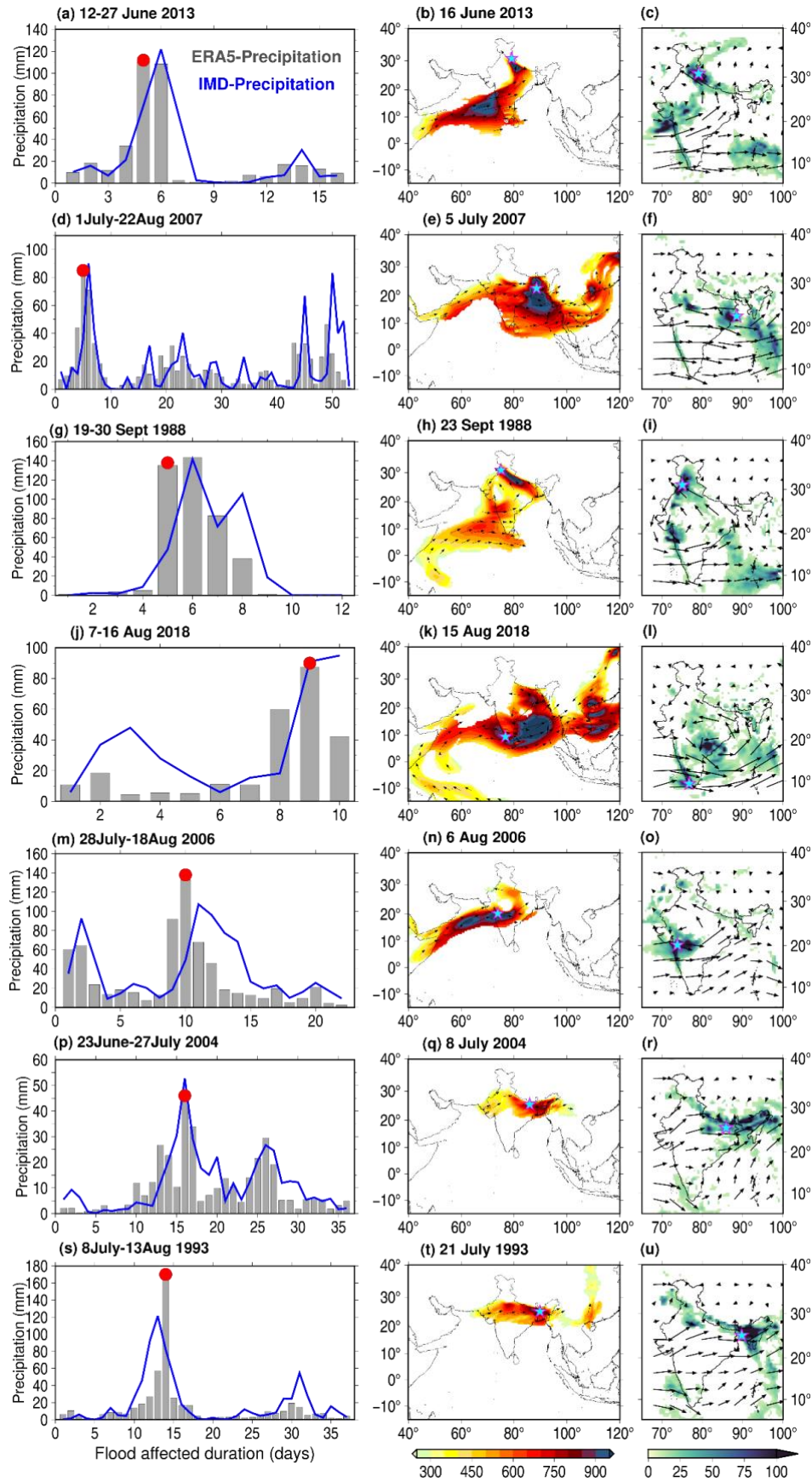


Fig. S11. Major flood events associated with atmospheric rivers. Left Panels: Spatial average precipitation (mm; ERA5 and IMD) for grid cells within $200 \text{ km} \times 200 \text{ km}$ bounding box of the identified flood location (marked by cyan color star) for given flood events. Middle Panels: IVT (kg/m/s) during the peak (red dots) of the events. Right Panels: Same as middle panels but for precipitation (mm).

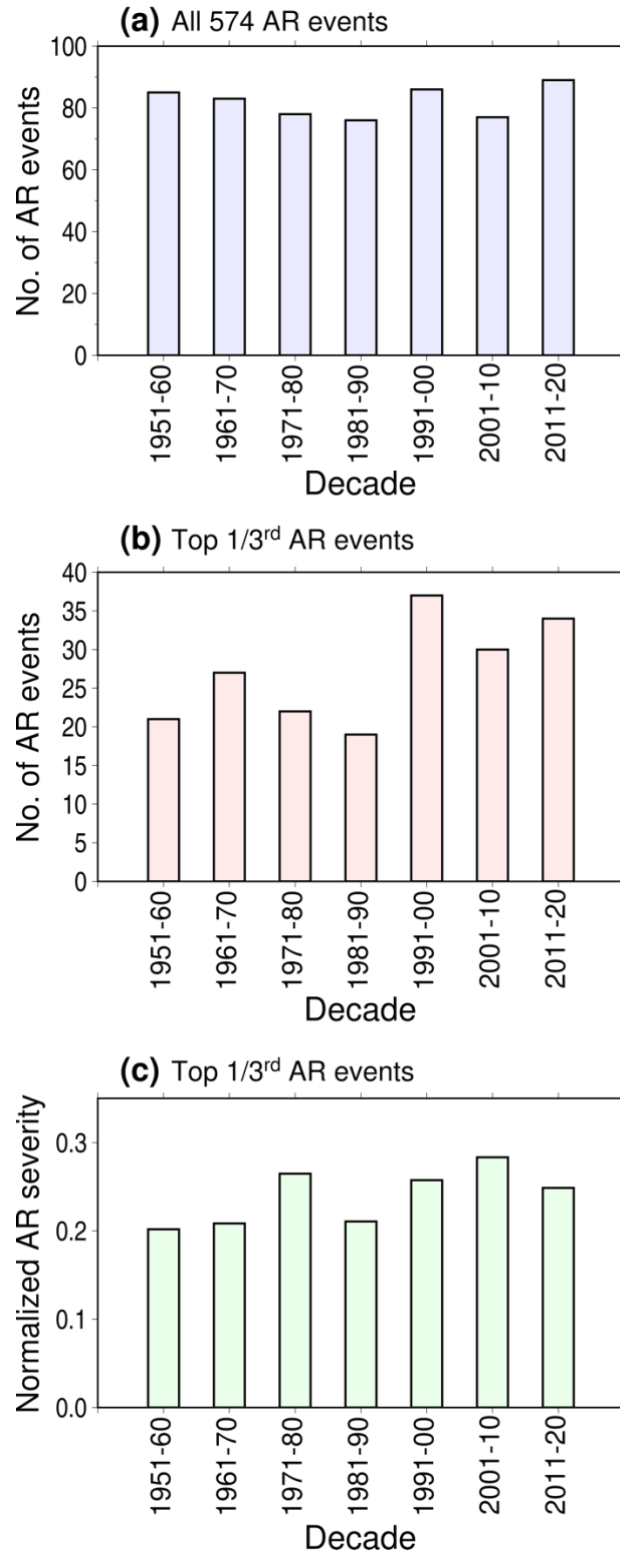


Fig. S12. (a) Decadal frequency of 574 major ARs in monsoon season in India during 1951-2020. (b) Decadal frequency of top 1/3rd (~190) AR events, sorted by decreasing order of severity score (see equation 4 for details). (c) Normalized mean severity score of ARs in each decade for the top 1/3rd events during 1951-2020 period.

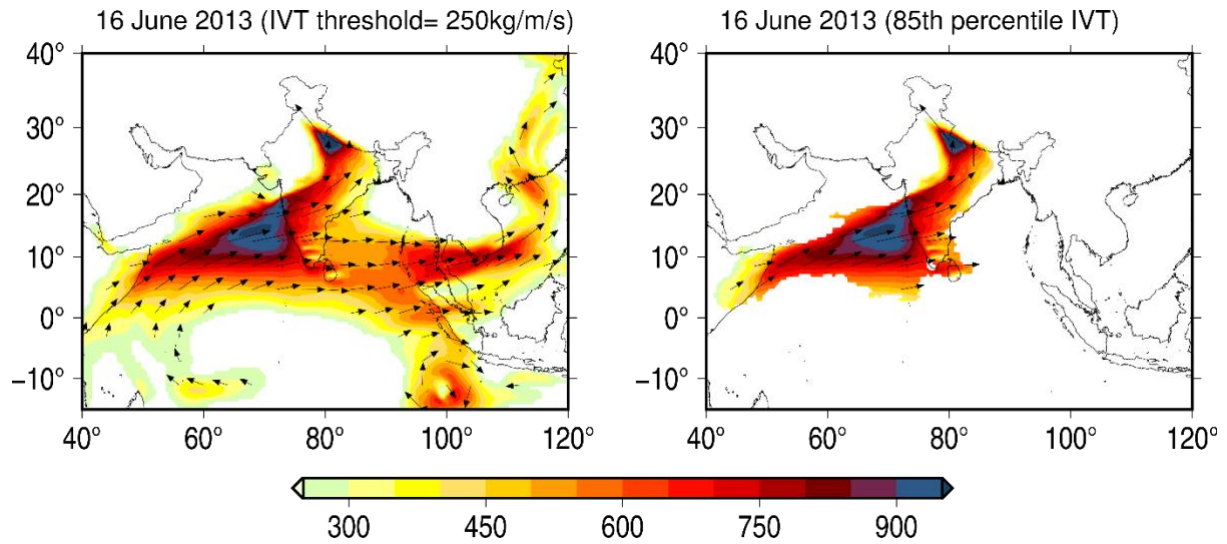


Fig. S13. Comparison of the AR during 16 June 2013 using fixed (250kg/m/s) and variable (85th percentile) IVT thresholds.

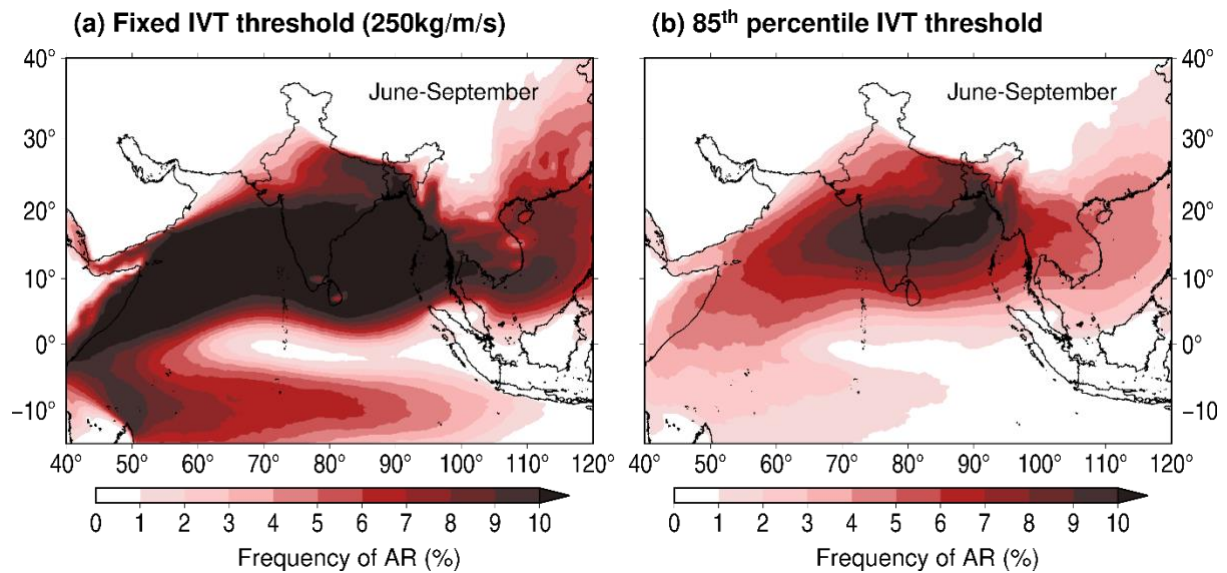


Fig. S14. Frequency of occurrence of AR using (a) variable (85th percentile) IVT threshold, and (b) fixed (250kg/m/s) threshold IVT during 1951-2020 period.

LIST OF TABLES

Table S1. List of 10 largest flood events in the monsoon season in India, 1951-2020. The list of major flood events in India was prepared based on the number of deaths reported during the flood. Flood details can be obtained from Dartmouth Flood Observatory, University of Colorado, USA (<https://floodobservatory.colorado.edu/Archives/index.html>).

Start			End			Duration (days)	Lon (°E)	Lat (°N)	Death reported	Flood Severity score (DFO)	AR Severity class of Ralph et al (2019)
year	month	day	year	month	day						
2013	6	12	2013	6	27	16	79.0669	30.7346	5748	1.5	4
1993	7	8	1993	8	13	37	89.7567	25.1622	3083	2	2
2004	6	23	2004	7	28	36	85.8918	25.4989	3000	2	3
2000	9	8	2000	9	25	18	88.5453	24.0841	1468	2	No AR
2007	6	30	2007	8	21	53	88.4871	22.6315	958	1.5	5
2008	8	20	2008	9	8	20	94.5503	27.0442	900	1.5	No AR
1988	9	19	1988	9	30	12	75.0459	30.9339	731	2	3
1985	9	13	1985	10	5	23	82.8434	26.4816	557	2	No AR
2018	8	7	2018	8	16	10	76.7275	9.39943	483	1.5	4
2006	7	28	2006	8	18	22	73.8242	20.1943	457	2	5

Table S2. Atmospheric river (AR) catalog in the non-monsoon season in India. Rest of the criteria are same as Table S1.

Non-monsoon season ARs (1951-2020)																	
Rank	Start			End			Duration (days)	total area (km2)	Total length (km)	Maximum IVT (kg/m/s)	Mean IVT (kg/m/s)	and area (km2)	Land max IVT (kg/m/s)	Land mean IVT (kg/m/s)	Flood flag	Severity score (0-1)	Severity class (Ralph et al., 2019)
	Year	Month	Day	Year	Month	Day											
1	2014	10	12	2014	10	12	1	4547500	4241	1995	539.06	925000	1995	665.73	0	0.24	4
2	2013	10	13	2013	10	13	1	4187500	3701	1393.5	512.72	1327500	1393.5	609.47	0	0.23	4
3	1995	11	9	1995	11	9	1	5802500	4746	1294.6	519.55	842500	1294.6	597.79	0	0.13	4
4	1955	10	11	1955	10	11	1	4342500	3791	1035.8	474.68	972500	1035.8	573.96	NaN	0.11	3
5	2020	5	20	2020	5	20	1	17262000	8130	1947.9	529.98	462500	1947.9	658.26	0	0.11	4
6	2009	5	25	2009	5	25	1	7502500	5749	2014.2	612.73	1070000	2000.2	538.6	0	0.06	4
7	2019	5	3	2019	5	3	1	3672500	3773	1748.6	486.73	560000	1627.5	571.02	0	0.06	4
8	1989	5	26	1989	5	26	1	10855000	6723	1611.7	476.73	672500	1534.3	546.04	0	0.05	4
9	1969	11	7	1969	11	7	1	3515000	3950	1123.2	493.85	740000	1123.2	541.26	NaN	0.05	3
10	1999	5	20	1999	5	20	1	3057500	3111	2126.3	512.63	350000	2126.3	573.23	0	0.04	4
11	1979	5	13	1979	5	13	1	4247500	3860	1091.4	479.42	1257500	1073.9	517.59	NaN	0.03	3
12	2010	5	20	2010	5	20	1	7955000	7679	1501.4	488.85	1167500	1430	518.14	0	0.03	4
13	1999	10	29	1999	10	29	1	4317500	4028	1949.2	471.7	437500	1798.4	550.06	0	0.03	4
14	1968	10	2	1968	10	2	1	4677500	3749	1261.2	533.19	1325000	1187.4	515.06	NaN	0.03	3
15	1955	5	20	1955	5	20	1	5157500	4823	1104.8	602.44	375000	1001.7	558.55	NaN	0.03	3
16	1951	10	1	1951	10	1	1	8202500	5623	1060.3	502.21	1875000	829.95	508.65	NaN	0.03	2
17	2017	10	20	2017	10	20	1	3660000	4256	1461.9	505.88	595000	1370.9	526.08	0	0.02	4
18	1987	10	16	1987	10	16	1	4885000	4628	899.67	441.49	875000	899.67	513.91	0	0.02	2
19	1970	10	23	1970	10	23	1	7105000	7197	1441.3	435.84	350000	1300.7	523.37	NaN	0.01	4
20	1956	5	31	1956	5	31	1	5612500	5914	1396	586.82	1295000	1215.9	505.54	NaN	0.01	3
21	2003	10	6	2003	10	6	1	7915000	5004	1042.7	477.47	1182500	945.65	503.07	1	0.01	2
22	2008	10	27	2008	10	27	1	6785000	4752	784.85	396.98	215000	766.3	502.57	0	0.00	2