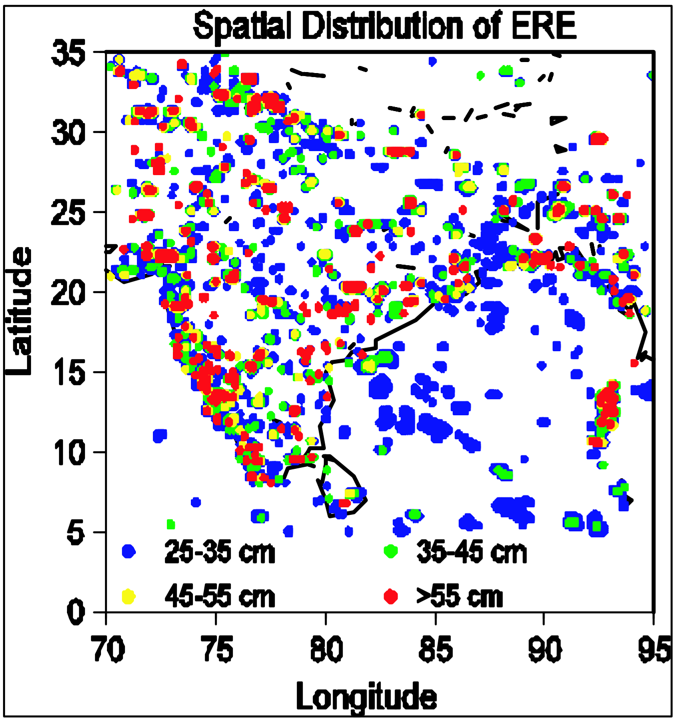
Extreme Rainfall Events: Vulnerability Analysis for Disaster Management and Observation System Design



P Goswami and K V Ramesh

CSIR Centre for Mathematical Modelling and Computer Simulation
Wind Tunnel Road, Bangalore-560 037, India

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CSIR Centre for Mathematical Modelling and Computer Simulation
Wind Tunnel Road, Bangalore-560 037, India
Tel No: +91 80 25224667   Fax +91 80 25220392
Website: http://www.cmmacs.ernet.in
E-mail: goswami@cmmacs.ernet.in

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Abstract

Extreme rainfall events today pose a serious threat to many populated and urbanized areas worldwide; an accurate estimate of frequency and distribution of these events can significantly aid policy planning and observation system design. We report here a first-ever high-resolution (10 KM) analysis of heavy rainfall episodes (defined as 24-hour rainfall exceeding 250 mm) over the Indian region. The data set, recently developed by National Oceanographic and Atmospheric Administration, USA (NOAA), provides daily composite rainfalls for the period 2001-2006 at locations approximately 10-km apart. A category-wise analysis reveals a number of hot spots of vulnerability in terms of annual average number of extreme rainfall events; in particular, the semiarid region in the north-west India emerges as a high vulnerability area in terms of extreme rainfall events. These findings have important implications for a number of areas like vulnerability assessment and meso-scale forecasting. The high-resolution analysis also clearly reveals the corridor of the monsoon trough (Continental Tropical Convergence Zone), lined by a flower-pot distribution of extreme rainfall events along the flanks; this can be a valuable input for precision design of field experiments on the continental trough or on localized extreme events like thunderstorms.

Introduction

The last few decades have seen rapid, large-scale, and often unplanned urbanization in many parts of the world, especially in India. More than 60% of the world population is projected to be urban by 2020, with India poised to develop a number of mega cities [1-3]. A serious consequence of such urbanization, and associated land use, is anticipated to be enhanced susceptibility and vulnerability of the urban population to high-impact weather events like episodes of intense rainfall, especially for high-density cities like those in south Asia. An example is the heavy rainfall event of 26-27 July, 2005 over Mumbai, India, which alone caused a loss of more than 1500 lives and considerable loss of property. Vulnerability and agricultural sustainability are primarily local issues, and depend critically on the amount and temporal distribution of rainfall received over a region. Thus rainfall patterns need to be examined in a local perspective.

Applications like pro-active disaster management and observation system design, however, require inputs at resolution, precision and accuracy not provided by isolated and sporadic measurements. Model forecasts can be valuable, and sometimes the only tool for generating information that goes into design and (pro-active) response. However, for such forecasts to be effective, the models need to have proven (statistical) skill at required temporal and spatial resolutions. Similarly, quantitative estimates of the geographical distribution of vulnerability as well as reliable projection of future changes in the frequency, intensity and distribution of extreme rainfall events (hereafter ERE) require detailed observational inputs and other constraints. Such observational features of ERE with high spatio-temporal resolution were unavailable until recently, especially for the Indian region. Although there have been several studies on occurrence and distribution of rainfall events over India [17], these studies have been primarily based on isolated station data and thus do not provide a large-scale picture[5-6].

Data set and Analysis

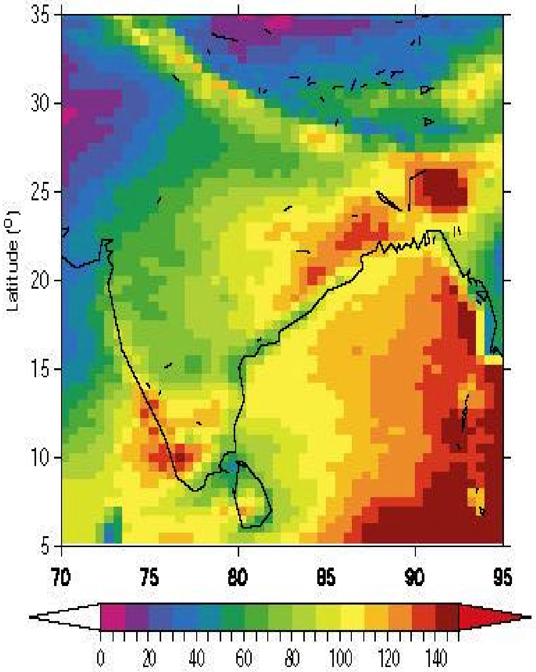
Recently, beginning May 01, 2001, the Climate Prediction Center (CPC) of NOAA (National Oceanographic and Atmospheric Administration, USA) initiated a project to produce real-time analyses of daily precipitation on a 0.1° latitude/longitude grid over south Asia (70°E-110°E; 5°N-35°N). The inputs include GTS station data, as well as geostationary infrared cloud top temperature fields and polar orbiting satellite precipitation estimates from SSM/I and AMSU-B microwave sensors. Analysis of daily precipitation was generated by merging 4 kinds of observation-based individual datasets using the algorithm of Xie and Arkin [4, 7]. The extreme rainfall events at a grid point were then categorized based on the 24-hour accumulated rainfall.

A quantity essential for an assessment of vulnerability is the density distribution of events at a given location. We have quantified this in terms of the accumulated (2001-2006) number of events with intensity higher than 25 cm/day at a given grid point. In order to quantify the degree of vulnerability, we have categorized the ERE further based on their intensity, as given in Table 1. While these categories are somewhat arbitrary, it needs to be emphasized that even the lowest intensity considered here (25 cm) is a high-impact event, especially over a populated location. In fact, events of higher intensity considered here are rarely revealed by coarse-resolution data sets like NCEP Reanalysis (~250 Km resolution) [15] or even the 1°x1° gridded daily rainfall recently prepared by the India Meteorological Department (IMD). [16] We have thus not considered these data sets here. In addition to the category-wise analysis of the ERE, we have also examined their duration (in terms of 24-hour accumulated rainfall) to assess the duration of their impact.

Results and Conclusions

The spatial distribution of occurrence (figure 1) clearly shows the existence of certain hot spots (circled) of vulnerability, with the annual average number of ERE exceeding 5. While many of these hot spots lie over the coastal regions (Gujarat, Mumbai, Mangalore and Orissa), as expected, a significant number are also found over land, especially over north India. Over the ocean, the ERE are not uniformly distributed, but are clustered around island masses and the mean position of the Inter-Tropical Convergence Zone (ITCZ).

(a) Number of rain events (greater than 5 mm/day) during May, 2001 - August 2006



(b) Occurrence of extreme rainfall events during years (2001-2005)

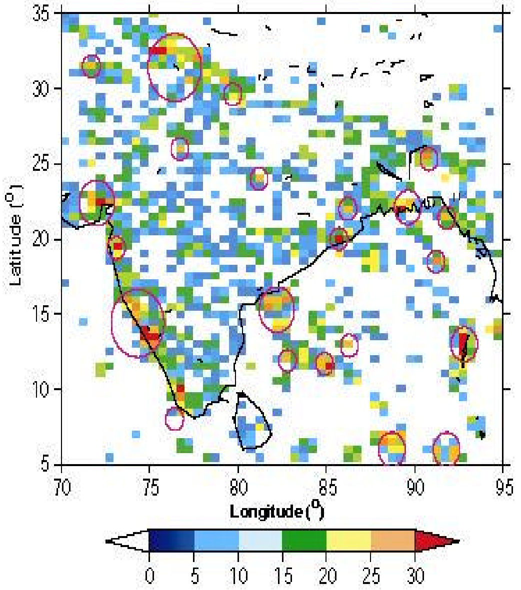


Figure 1: **(a)** Spatial distribution Number of rainy days (X 100) and **(b)** ERE of different categories accumulated over five years (May 2001-August 2006) over the Indian region. Two prominent features are the relatively large number of hot spots over India and absence of events of higher intensity (more than 35 cm/day) over the ocean.

Distribution of extreme rainfall events of different intensities (Figure 2) for two seasons: March-May (MAM, left panels) and June-August (JJA, right panels) reveals the strongly localized nature of their occurrence. In fact, most EREs in the June-August period of intensity greater than 35 cm/day are confined to a narrow longitudinal band that extends from the west coast of India to 35N in a more or less continuous fashion. The south-north extent of this band, from coastal region to the continent at interior, emphasizes the relatively minor role of the oceanic environment in the genesis and evolution of these extreme events (table 2).

Year-wise distributions of ERE's for five years pertaining to two seasons March-May and July-August are shown in figure 3. While the general pattern of distribution (figure 2) is clearly obvious for each of the years, there is also a significant interannual variability. The interannual variability of ERE's, further highlighted in Table 1, shows their number for the June-August period for each of the categories for the five years. While the average number of events per year is 489, the standard deviation is 159, almost 32.5% of the mean. While the minimum number of ERE (given by the total in Table 1) is 271 (2006), the maximum is 634 (2003); however, it is the maximum number that is critical in terms of preparedness to ERE.

With respect to their lifetimes most ERE's appear to be short lived, as expected. Table 3 shows that almost all of them during the five year period were from rainfall episodes that lasted 24 hours or less (which can not be determined from the daily rainfall). Significant seasonality in the number of ERE, as seen from figures 2 and 3, strongly suggests that the large-scale environment exerts significant control over the genesis of ERE; it has been shown that large scale systems do have significant influence on the dynamics of small scale systems [8,9]. There is also a widespread concern regarding possible increase in the number and intensity of heavy rainfall events in response to global warming

[10-12]. However, very strong spatio-interannual variability of ERE, poses a significant challenge to quantify and ascertain such a change. Finally, the strongly localized nature of the ERE hot temporal variability, especially the strong spots indicates the need for horizontal resolution far beyond what is employed today, especially in global and climate simulations.

Table 1 Interannual variation in the number of extreme rain events (JJA)

Category (cm/day)	**Number of extreme rainfall events for year**							
	2001	**2002**	**2003**	**2004**	**2005**	**2006**	**Mean**	**Standard deviation**
25- 35	447	332	547	186	405	220	356	137.94
35-45	86	81	57	55	75	24	63	22.88
45-55	38	42	16	26	39	10	29	13.32
> 55	39	56	14	44	78	17	41	24.13
Total	610	511	634	311	597	271	489	159.39

Table 2 Regional occurrence of number of extreme rainfall events in different category (2001-2006)

Category (cm/day)	**Number of extreme rainfall events per 100 km^2**	
	India (74-83E, 12-35N	**Bay of Bengal (85-95E, 5-17N)**
25-35	0.0976 (1396)	6.4 (768)
35-45	0.0254 (363)	0.0083 (1)
45-55	0.01042 (149)	0
> 55	0.2147 (307)	0

Table 3 Life time of number of extreme rainfall events in different category during May, 2001-August, 2006

Category (cm/day)	**Number of extreme rainfall event with duration**		
	1 day	**2 days**	**3 days**
25-35	4356	19	0
35-45	1080	4	1
45-55	469	1	0
> 55	823	5	0

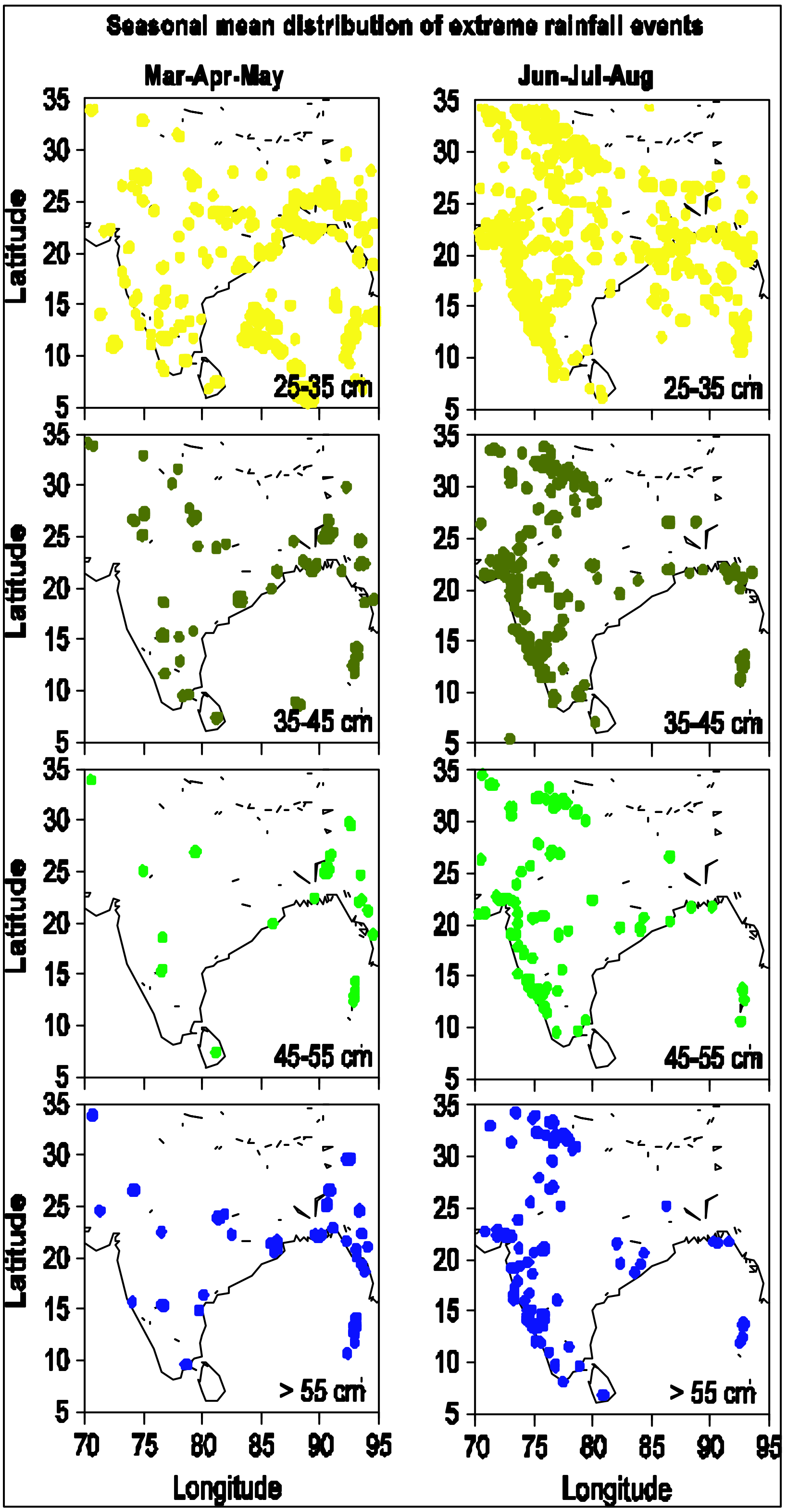


Figure 2: Distribution of (5-year average 2001-2006) ERE for different categories over south Asian region. The left (right) panels represent seasonal average for March- May (June-August). Two prominent features are the conspicuous absence of high intensity events over the ocean in both the seasons, and the narrow south-north band of extreme events in June-August season.

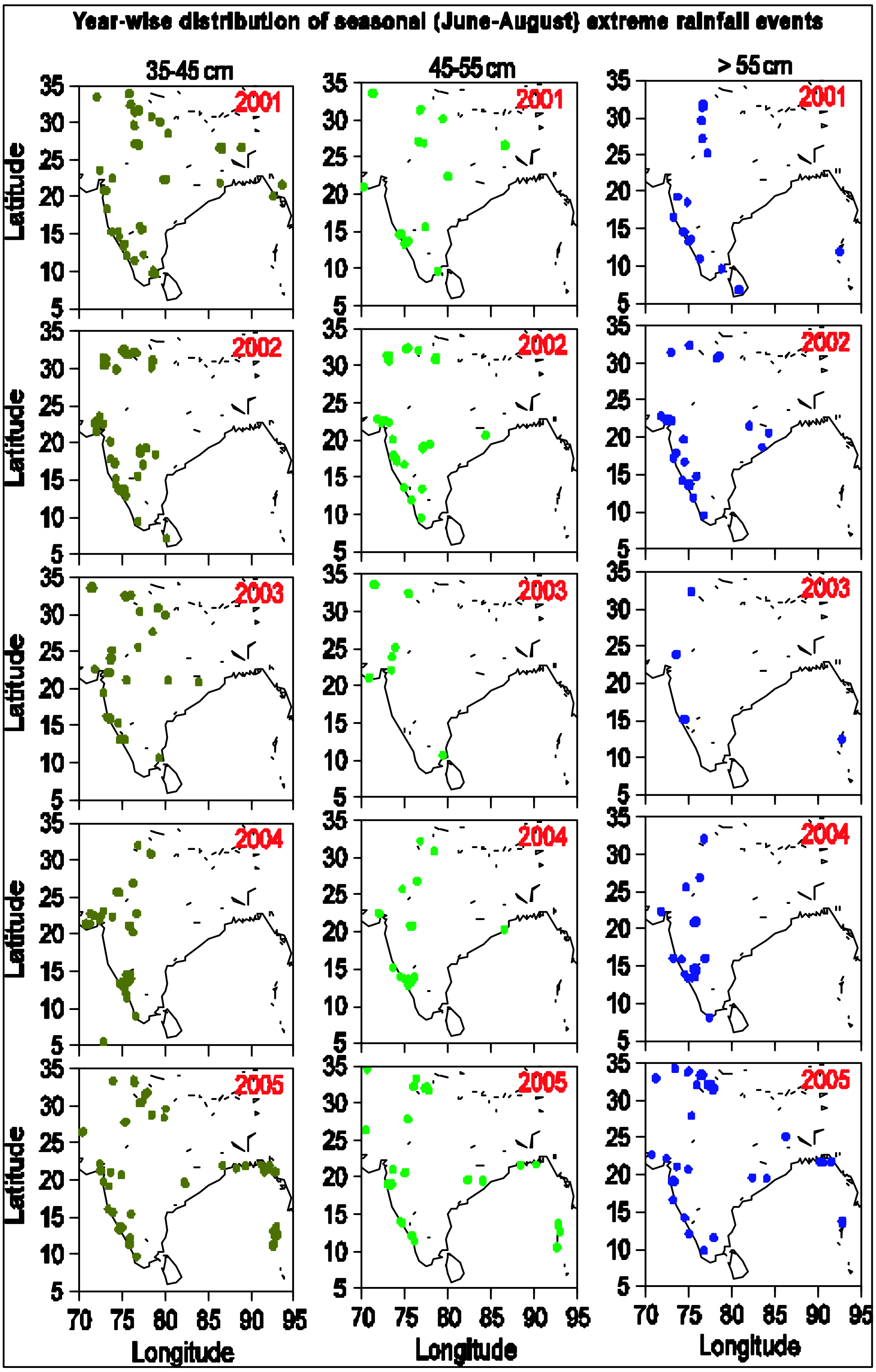


Figure 3: Year-wise distribution of extreme rainfall events of different intensities for June- August period for the five years. The left, middle and the right panels show, respectively, ERE with 24-hour accumulated rainfall in the range of 35-45 cm/day, 45-55 cm/day and more than 55 cm/day rainfall. The strong interannual variability in the number and distribution of these events is noticeable.

The highly localized nature of ERE as revealed by our analysis highlights the importance of sufficiently high resolution for simulation of these events. A dataset like the NCEP Reanalysis [15] with a horizontal resolution of about 250 Km, or the daily gridded rainfall at about 110 Km recently prepared by the India Meteorological Department (IMD) [16], for example, can not adequately represent the distribution and the degree of vulnerability to these high-impact events.

An important application of such high-resolution analysis can be in the area of precision observation design. From figure 4, we note that the distribution of ERE clearly marks the corridor of the monsoon trough (Continental Tropical Convergence Zone, CTCZ) over the Indo-Gangetic plane, in the same way that the (lower intensity) ERE mark the mean position of the ITCZ over the ocean. The structure of the CTCZ, as represented by the ERE, however, reveals interesting fine structures. In particular, the ERE of highest intensities are not found deep inside the corridor, but are distributed in a flower-pot pattern along the flanks of the CTCZ. This pattern is dynamically consistent, as the sharpest pressure gradients (and hence the strongest convergence and secondary circulation) are expected to be found along the line that separates the low-pressure trough from the surrounding area. Our analysis, however, marks this corridor and the flanks with a precision hitherto unachievable; as such, these analyses can be important inputs for precision (10 km-resolution) design of field experiments, for example, the CTCZ field experiment currently being planned, in terms of location of observation platforms, or the STORM field experiments over the eastern and the north-eastern India.

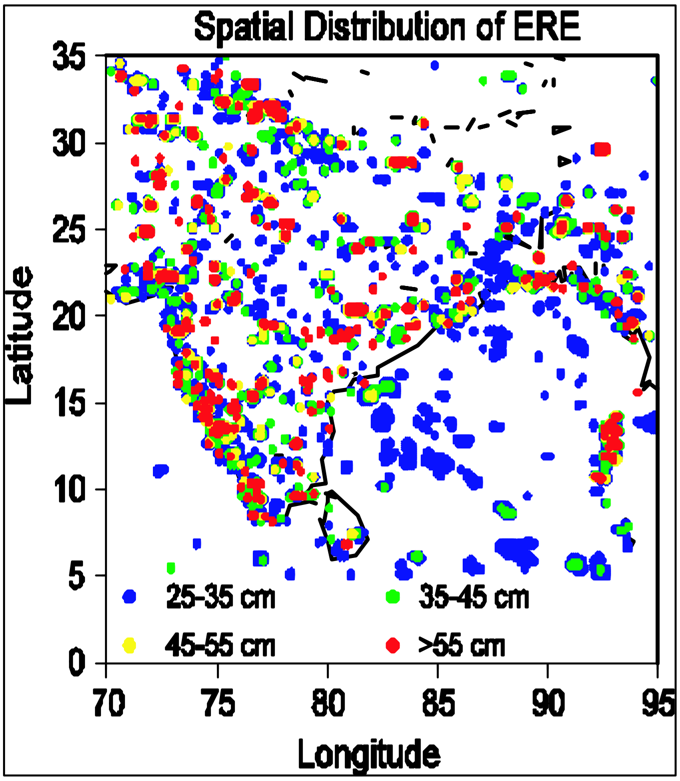


Figure 4: Spatial distribution of ERE of different categories accumulated over five years (2001-2005). The high density of ERE over the west coast and along the flanks of the monsoon trough is prominent.

Although the NOAA data set used here allows us much more precise and accurate assessment of spatial and temporal distribution of ERE and thus associated degree of vulnerability, a more comprehensive analysis requires collocated measurements of other dynamical, surface and sub-surface parameters. Based on the precision distribution of the ERE revealed by our analysis, such measurements can be made by placing Automated Weather Stations (meteorological towers) over these locations. Such measurements, supplemented by other observation platforms like remote sensing and upper-air soundings can allow analysis and forecasting of these high-impact events at precision and resolution that can be effective in applications like pro-active disaster management.

In terms of vulnerability assessment and disaster management, however, rainfall amount (or category) is only one of the (critical) inputs. The forecast of rainfall needs to integrated, with appropriate weight for reliability of the forecast, with models of impact and logistics which require detail information on infrastructure, population and other parameters over the location. Although a critical area, such models, which are necessarily location-specific, are in their infancy, especially in India.

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