Verification of Pre-Monsoon Temperature Forecasts over India during 2016 with focus on Heatwave Prediction

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Abstract. The operational medium-range weather forecasting based on Numerical Weather Prediction (NWP) models are complemented by the forecast products based on Ensemble Prediction Systems (EPS). This change has been recognized as an essentially useful tool for the medium range forecasting and is now finding its place in forecasting the extreme events. Here we investigate extreme events (Heatwaves) using a high-resolution numerical weather prediction and its ensemble forecast in union with the classical statistical scores to serve the verification purposes.

With the advent of climate change related studies in the recent past, the rising extreme events and their plausible socio-economic effects have encouraged the need for forecasting and verification of extremes. Applying the traditional verification scores and the associated methods on both, deterministic and the ensemble forecast, we attempted to examine the performance of the ensemble based approach as compared to the traditional deterministic method. The results indicate towards an appreciable competence of the ensemble forecasting detecting extreme events as compared to deterministic forecast. Locations of the events are also better captured by the ensemble forecast. Further, it is found that the EPS smoothes down the unexpectedly soaring signals, which thereby reduce the false alarms and thus prove to be more reliable than the deterministic forecast.

1. Introduction

Reliable weather forecasting plays a pivotal role in our everyday activities. Over the years NWP systems have been employed to serve the purpose. While the NWP models have demonstrated an improved forecasting capability in general, they still have a challenge in the accurate prediction of severe weather/extreme events. Severe weather events (thunderstorms, cloudburst, heatwaves and coldwaves etc) usually involve strong non-linear interactions ,often between small scale features in the atmosphere (Legg and Mylne, 2004). For example, development of deep convection and thunderstorms in the tropics. These small-scale interactions are difficult to predict accurately (Meehl et al., 2001) and a small deviation in these could lead to completely different results, as a result of the forecast evolution process (Lorenz, 1969). The inherent uncertainty in the weather and climate forecasts can be well handled by employing ensemble based forecasting (Buizza et al., 2005). The EPS (Mureau et al., 1993, Toth and Kalnay, 1997, Molteni et al., 1996) were first introduced in the 1990s in an effort to quantify the uncertainty caused by the synoptic scale baroclinic instabilities in the medium range weather forecasting (Legg and Mylne,2004). Ensemble forecasting has emerged as the practical way of estimating the forecast uncertainty and making probabilistic forecasts. It is based on multiple perturbed initial conditions, ensemble approach samples the errors in the initial conditions to estimate the forecast uncertainty (spread in member

Summary of Comments on Microsoft Word - Temp_verification-Revised-05Apr2017

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Number: 1 Author: Bruce Subject: Highlight Date: 06-Apr-17 09:44:59

Join up with first part of abstract (no paragraph break).

Number: 2 Author: Bruce Subject: Highlight Date: 06-Apr-17 09:26:42

"etc" should be "etc." and always have a comma before it. Please correct everywhere.

Number: 3 Author: Bruce Subject: Highlight Date: 06-Apr-17 09:28:21

Please put oldest to newest. So 1993, 1996, 1997. Check entire manuscript.

Please go to the NHESS WORD TEMPLATE FOR AUTHORS and AUTHOR GUIDELINES FOR SUBMISSION as I believe that these need to be separated by ;

forecasts). The skill of the ensemble forecast shows marked improvement over the deterministic forecast when comparing the ensemble mean to deterministic forecast after a short lead time

The new EPS at the NCMRWF is now running for operational purposes. This global medium-range weather forecasting system has been adopted from the UK Met Office (Sarkar et al., 2016). Generally, the model and the ensemble forecast applications in addition to their verifications are used for prevalent events with a limited focus on the rare extreme weather events. It would be for the first time that the EPS technique has been employed from this model output for the extreme events over India to study the heatwave events. The heatwave is considered if maximum temperature of a station reaches at least 40°C or more for Plains and at least 30°C or more for Hilly regions. Based on departure from normal, a station is declared to have heatwave conditions if departure from normal is 4.5°C to 6.4°C and severe heatwave if the departure from normal is >6.4°C. In terms of the actual maximum temperature, a station is under heatwave when actual maximum temperature ≥ 45°C and severe heatwave when the maximum temperature is >47°C. There has been increasing interest in predicting such extremes, the heatwave and cold wave events in India due to the associated loss of life. An increasing number of extreme temperature events over India were documented by a few recent studies (Qin et al., 2013). [1] study conducted over the Indian sub-continent between 1969 and 1999 indicated more frequent cold and heatwave events over the Indo-Gangetic plains of India. [2]-6 heatwave events and 2-3 cold wave events are reported to occur every year in the Northern parts of the country. The global temperatures have exhibited a warming trend of about 0.85°C due to anthropogenic activities between 1880 and 2012. Similar trends were also observed in India with the annual air surface temperature rise during 20th century. This is evident from the detailed study presented in Kothawale et al (2010) based on the data from 1901-2007.

[3]he Indian mean maximum and minimum annual temperatures have significantly increased by 0.51, 0.71 and 0.27°C per 100 years respectively, during 1901-2007. However, an accelerated warming was observed during 1971-2007, mainly due to the last decade 1998-2007. [4]he study highlights that the mean temperature during the pre-monsoon season (March-May) shows an increasing trend of 0.42°C per 100 years. On the other hand, a recently reiterated IPCC report (2013) notified an "unequivocal" proof of the increasing warming trend, globally which could be associated with the variations in the climate system. This indicates a need to comprehend the heatwave events on weather and climatic scales. [5]hile there is an extensive literature discussing the heatwave events and their trends on the climatic scales, however, the literature is rather limited (especially over India) focusing such events on monthly scales. This paper thus tries to fill in the gap and attempt to demonstrate the capability and strength of predicting such events using both ensemble and deterministic forecast. This research investigates the most recent heatwave events during the summer months March, April & May (MAM) 2016 in India. This investigation considers two case studies to demonstrate the strength and weaknesses of the EPS approach in predicting such extreme events.

With these factors in mind, we can say that temperature (Minimum and Maximum both), forms a vital component of weather and climatic studies which are becoming increasingly important and challenging. Reliable projections of such changes in

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Important for entire manuscript: Where are these facts from? Check EVERY sentence, and ensure it is clear where all facts/information are from. So I look below, in next paragraph, and it is unclear.

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Avoid starting a sentence with a number. PLEASE CHECK EVERYWHERE IN MANUSCRIPT.

You could do "There are reported to occur every your in the Northern parts of the country 5-6 heatwave events and 2-3 cold wave events.

IMPORTANT: Make sure that it is clear where these facts comes from. Not clear.

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Where are these facts from?

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What study?

Number: 5 Author: Bruce Subject: Highlight Date: 06-Apr-17 09:32:59

Give half a dozen examples please.

....climatic scales (e.g., ****, ****, ****, ****). However, the literature is...

Tennant, W.J., Shutts, G.J., Arribas, A. and Thompson, S. A.: Using a Stochastic Kinetic Energy Backscatter Scheme to Improve MOGREPS Ensemble forecast Skill. *Mon. Weather Rev.*, **139**, 1190-1206, 2010.

Toth, Z., and E. Kalnay: Ensemble forecasting at NCEP and the breeding method. Mon. Wea. Rev, **125,** 3297–3319, 1997.

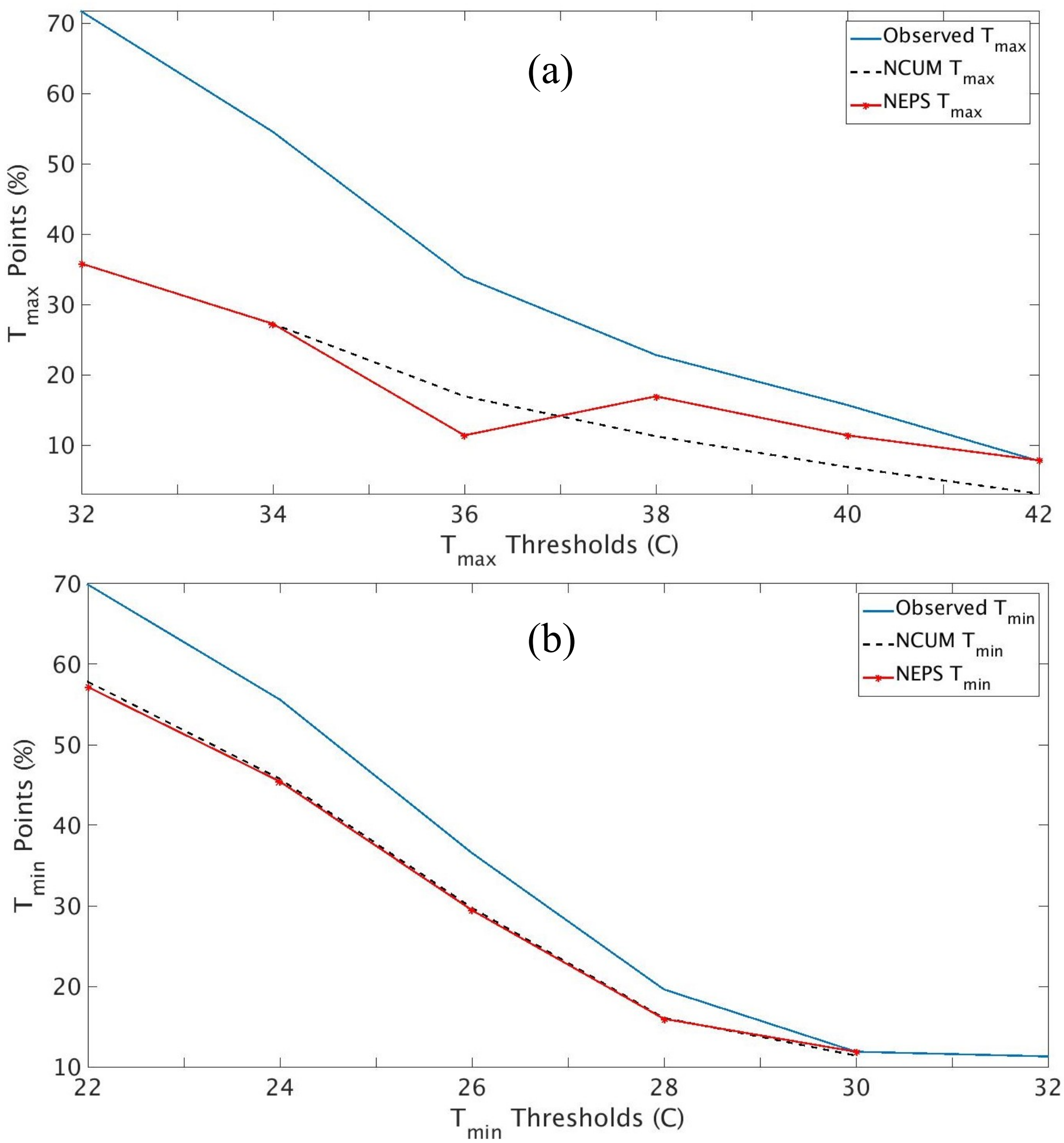

Figure 1. Frequency distribution of observed, and forecast (NCUM and NEPS) (a) *Tmax* (°C) and (b) *Tmin* (°C) over India during March-May 2016.

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For every figure, make sure it is clear WHERE the data has come from (Data from *****). This should then be in the reference list.

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For x-axis, cannot you add the same deg symbol?

For x- and y-axis here and ALL other figures, please put in italic the variables, so they are the same as in text.

Make a decision between max and min being sub-script or not sub-script, you have both (sub-script in graphs, non-subscript in text).

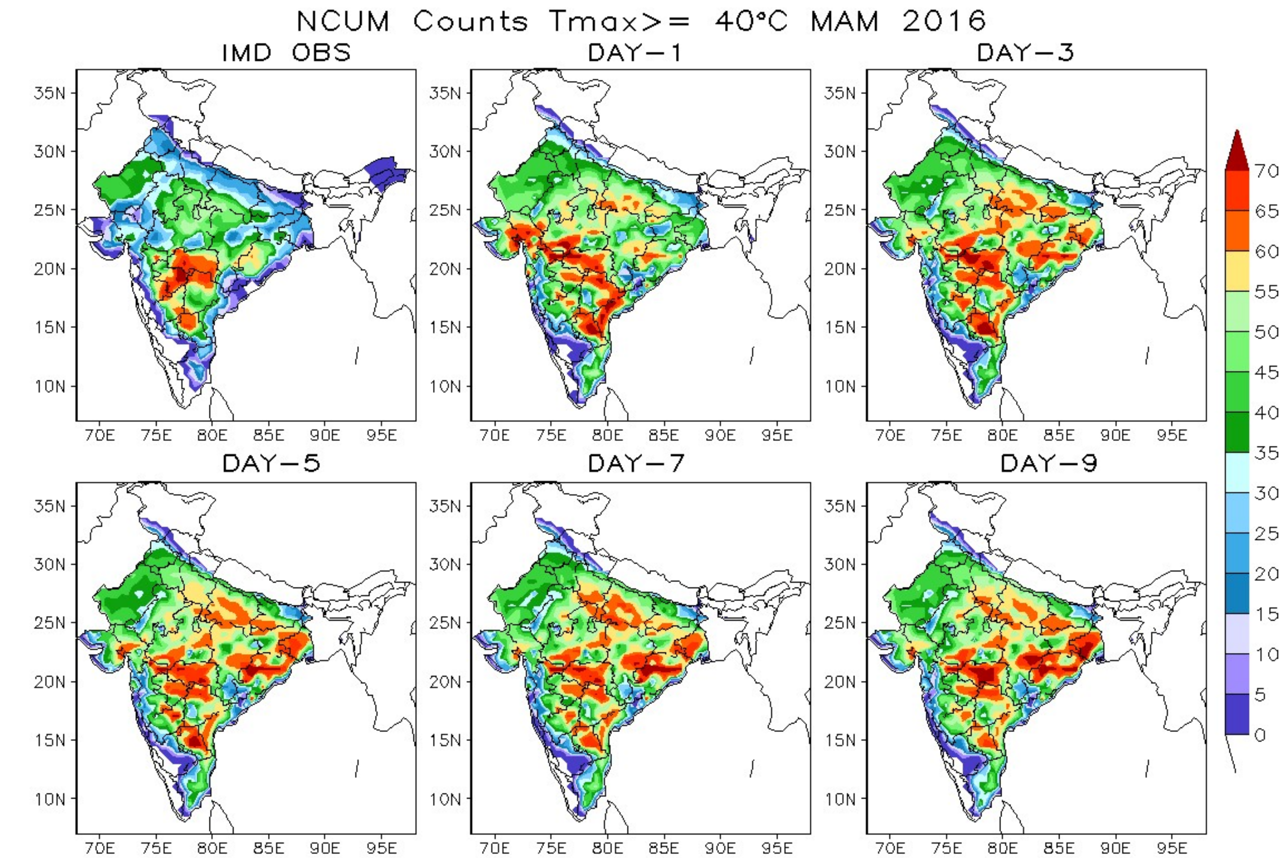

Figure 2. Spatial distribution of observed and NCUM forecasts number of days with *Tmax* ≥ 40°C during the period of March to May 2016

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Legend here and ALL figures, make sure that units are indicated.

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Please ensure that any acronyms or variables are clear and self-standing in figure captions, so reader does not have to go to text to figure them out.

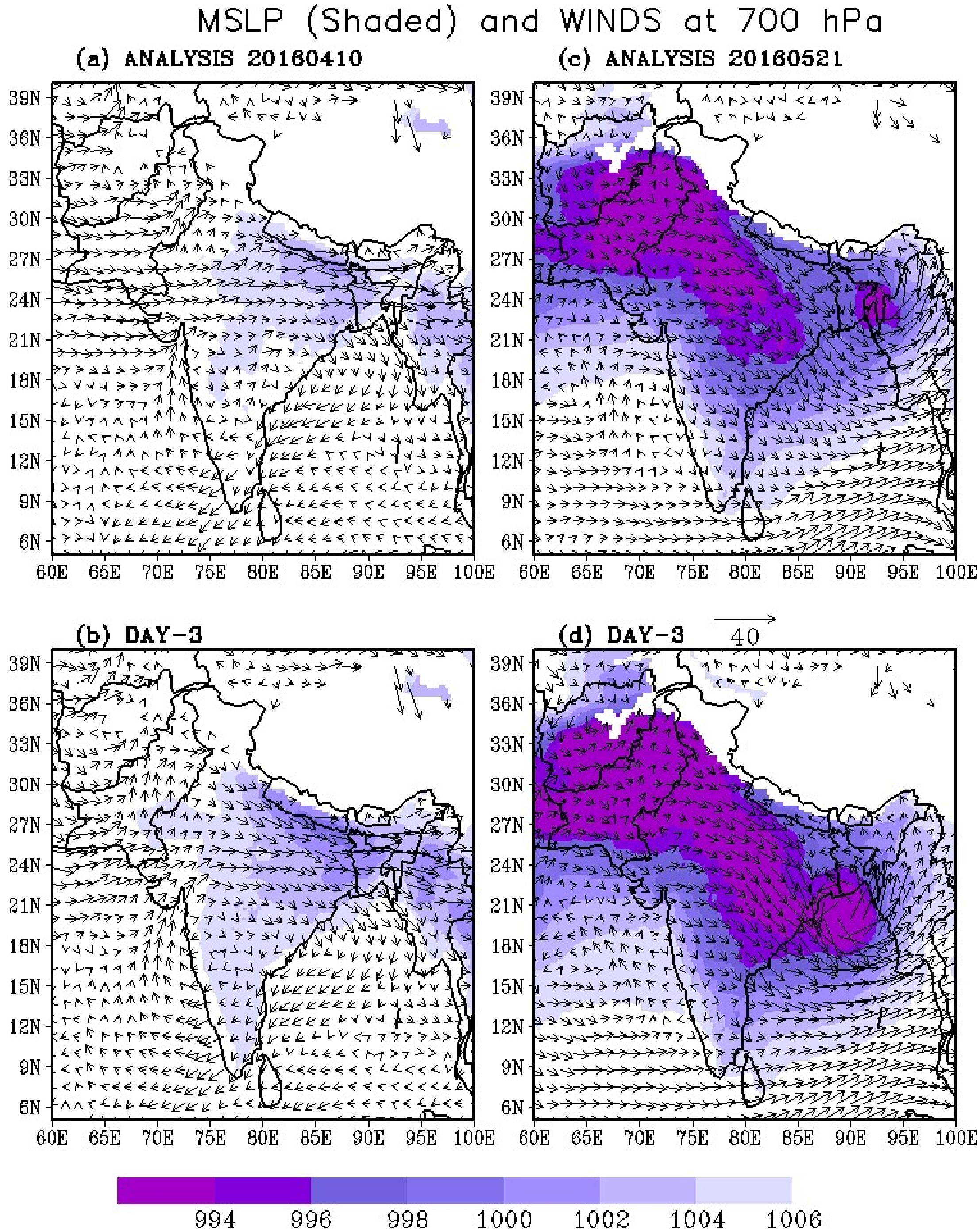

Figure 4. Mean Sea Level Pressure (MSLP) shaded and winds at 700 hPa showing heat low (a) Analysis of 20160410 (b) Day 3 forecast valid for 20160410 (c) Analysis of 20160521 (d) Day 3 forecast valid for 20160521

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Make sure that your final version of this figure is higher resolution.

Please ensure that legend has units.

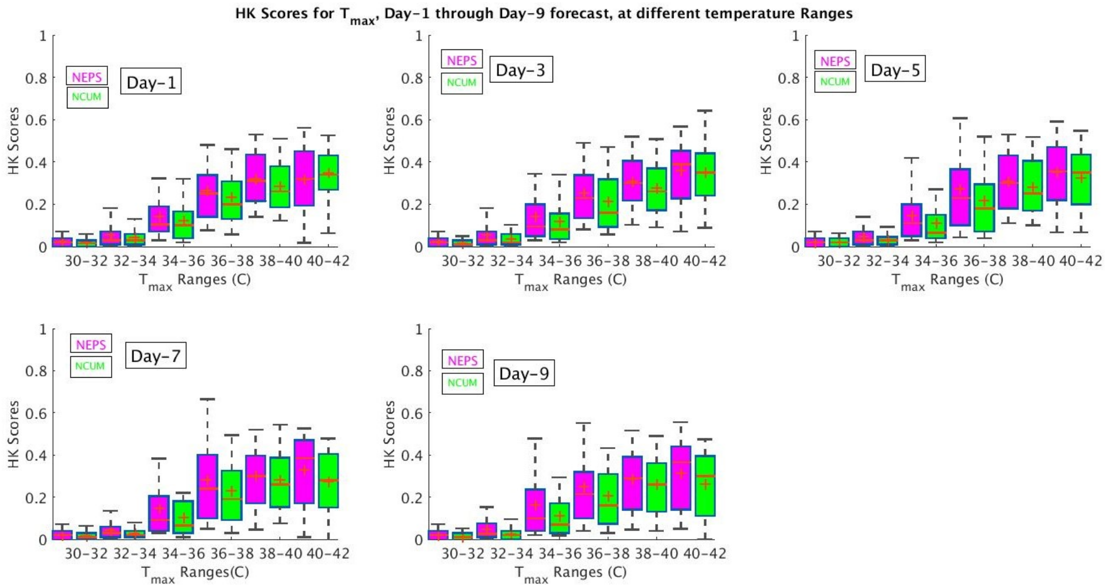

Figure 9. Box plots for HK scores for different temperature ranges (*Tmax*) NCUM and NEPS form March to May 2016

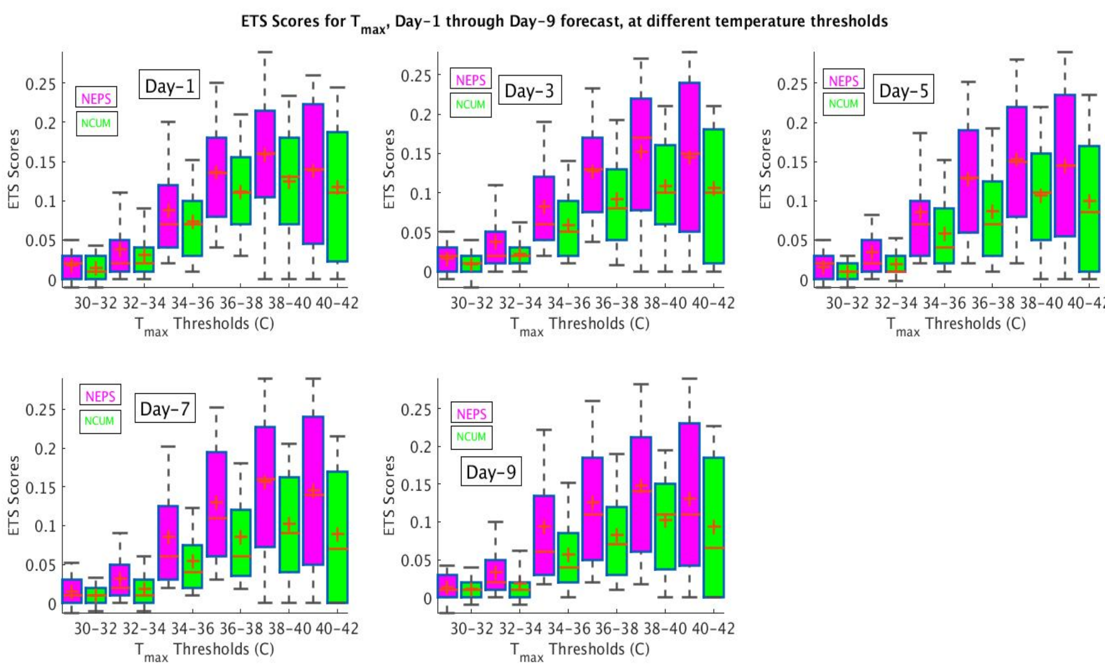

Figure 10. Box plots for Equitable Threat Score (ETS) for NCUM and NEPS form March to May 2016

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There are many kinds of box-plots. Please indicate in figure caption text, what the whiskers represent (could be max, min, could be 95% 5%), what the horizontal line represents (mode?), and what the plus represents.

Do not assume the reader will go to the text.

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Do another read through for typos like this. "Should be "from" not "form". Give this to a student to read carefully--copy-editors can only pick up so much.

Table 2. Casualities reported during MAM-2016 due to prevailing heatwaves over India

Month	State/ Region	No. of loss of lives	Total
March	Maharashtra	1	2
	Kerala	1	
April	Odisha	**88**	220
	Telangana	79	
	AP	40	
	Maharashtra	9	
	Karnataka	1	
	Tamil Nadu	1	
May	Telangana	**200**	273
	Gujrat	39	
	Maharashtra	34	

Table 3. Monthly *Tmax* > 40°C scores for NCUM and NEPS forecast with IMD observed temperature

		NCUM					NEPS				
Month	Score	Day 1	Day 3	Day 5	Day 7	Day 9	Day 1	Day 3	Day 5	Day 7	Day 9
MAR	POD	0.25	0.23	0.27	0.30	0.28	0.23	0.20	0.22	0.24	0.22
	FAR	0.81	0.71	0.75	0.75	0.79	0.49	0.54	0.53	0.53	0.43
	ETS	0.09	0.09	0.09	0.08	0.08	0.10	0.09	0.10	0.11	0.11
	HK	0.22	0.21	0.24	0.27	0.25	0.21	0.18	0.21	0.23	0.21
	SEDI	0.33	0.32	0.36	0.38	0.36	0.31	0.30	0.34	0.34	0.33
APR	POD	0.39	0.39	0.38	0.36	0.36	0.43	0.43	0.41	0.42	-
	FAR	0.66	0.65	0.66	0.66	0.66	0.62	0.61	0.62	0.61	0.62
	ETS	0.16	0.16	0.15	0.15	0.15	0.19	0.19	0.19	0.19	0.19
	HK	0.30	0.29	0.28	0.27	0.26	0.34	0.34	0.34	0.33	0.33
	SEDI	0.46	0.45	0.45	0.43	0.42	0.51	0.51	0.52	0.51	0.50
MAY	POD	0.30	0.30	0.28	0.26	0.24	0.32	0.34	0.31	0.31	0.27
	FAR	0.70	0.71	0.72	0.74	0.75	0.67	0.69	0.70	0.71	0.75
	ETS	0.12	0.11	0.11	0.10	0.09	0.14	0.14	0.13	0.12	0.10
	HK	0.22	0.22	0.21	0.19	0.17	0.25	0.26	0.24	0.23	0.19
	SEDI	0.39	0.38	0.36	0.33	0.30	0.43	0.43	0.40	0.39	0.33

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Give citation to data, what MAM means, and POPULATION of these regions (otherwise hard to put into perspective of what the loss of lives means if not normalized.

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In Table headers and figure captions, these should be self-standing. So reader should not have to go to the text to figure out what they mean. Give what the acronyms mean. Tell us where the data is from. Tell us the period of the data.