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Interactive comment on "Long-term trends of instability and associated parameters over the Indian region obtained using radiosonde network" *by* Rohit Chakraborty et al.

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Replies to Reviewer #3 Comments/Suggestions

First of all we wish to thank the reviewer for providing constructive comments/suggestions which significantly improved the content of the manuscript. The authors have addressed all the comments raised by the three reviewers and incorporated in the revised manuscript.

Main Comments:

Figure 3d: The changes in EL, LI, and CAPE between 1980 and 2016 are difiňĄcult to

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Discussion paper

believe and if true compelling. Have other studies shown such huge changes?

Reply: There have been multiple papers which reported highly increasing trends of various thermodynamic instability parameters both globally and over India in the last few years. Gettlemann et al (2002) has showed a ∼20% increase per decade in CAPE from tropical radiosonde stations globally during 1958-1997. Murugavel et al. (2012) has shown a steep rise in CAPE during the monsoon season of 1984-2008 with a slope of 38 J/kg over India. Thus, a very prominent rise in CAPE over India in the last 37 years is not an unexpected result. Some portions of this have been incorporated in the revised manuscript as follows:

It may appear at certain sections of this analysis that the trends of CAPE and EL are exorbitantly high; but it is not the actual case because previous studies by Murugavel et al (2012) and Gettlemann et al. (2002) have also shown almost comparable trends in convective severity both in India and abroad.

Changes in aerosol loading and subsequent changes in the morphology of clouds due to the aerosol indirect effect are not discussed and should be considered when examining trends in stability and precipitation over the Indian region. Please discuss the role of aerosol forcing may play in explaining these trends.

Reply: In this study, we have tried to understand the association of several natural and anthropogenic factors responsible for the drastic growth in atmospheric instability and thunderstorms in the recent years. In this connection, there also has been an attempt to show the direct forcing effect of aerosol components in generating a weak inhibition to convective activities as already discussed by previous researches. But on the other hand, the relationship between indirect aerosol forcing and instability is comparatively complex (Connoly et al. 2012). Some recent studies have revealed that a higher concentration of aerosols may lead to stronger updrafts velocities by altering the latent heat release resulting in growth of CAPE and TSS (Tao et al. 2012; Storer and van den Heever, 2013). However, this is a season and location specific phenomena and hence it is not expected to impact the yearly trend of CAPE and TSS as strong as the upper tropospheric cooling effect projected in this study. But in future, an exhaustive analysis of cloud and aerosol components involving both in-situ and modelled data can to be done to investigate its contribution on the total CAPE, TSS and SRF trends over the Indian region. This has been mentioned in the conclusion section of the revised manuscript as follows:

On the other hand, this study also introduces the effect of direct aerosol heating on instability and convection; but the probable impact of indirect aerosol loading in modulating the cloud lifetime and convective severity has not been discussed here. This is because, the relationship between indirect aerosol forcing and instability is still unclear and complex (Connoly et al. 2012). A few researches in the recent years have hypothesized that a higher concentration of aerosols may lead to stronger updrafts velocities by altering the latent heat release resulting in growth of CAPE and TSS (Tao et al. 2012; Storer and van den Heever, 2013). However, this is a season and location specific phenomena and hence it is not expected to impact the yearly trend of CAPE and TSS as strong as the upper tropospheric cooling effect projected in this study. But in future, an exhaustive analysis of cloud and aerosol components involving both in-situ and modelled data can to be done to investigate its contribution on the total CAPE, TSS and SRF trends over the Indian region.

The authors look at trends in 16 different variables derived from radiosonde data. That makes for a difïňĄcult read. Might make sense to condense the variables to 8-10 by removing highly correlated variables.

Reply: We have considered reducing the number of parameters shown in the manuscript but ended up with the dilemma that for a complete understanding about the morphology of upper tropospheric instability, all the instability parameters are required; hence the number of parameters used in this study cannot be condensed. However, to reduce the confusion of readers, main parameters like LFC, EL, CAPE, CINE, PWV, T100, TSS and SRF are to be retained in the main figures while their complementary aspects such as LCL, LI, VT, MLC, PWL, WSH, TSO and WRF are kept in supplementary sections. This has now been mentioned in the revised manuscript as follows:

However, it should be noted that Fig 3 provides too much detailed and cumbersome results related to all 16 parameters and the complexity of the analysis is expected to increase further when similar analysis will be presented for all the Indian regions together. But on the other hand, for a complete understanding about the morphology of upper and lower tropospheric instability, all the instability parameters will be required. Hence, to reduce further chances of confusion and to make the results more compact, all 16 parameters will be discussed together but only a few of them will be presented in the main study. After a thorough consideration with respect to the main objective of the present attempt, 8 parameters namely LFC, EL, CAPE, CINE, PWV, T100, TSS and SRF are to be retained in the main figures while their complementary aspects such as LCL, LI, VT, MLC, PWL, WSH, TSO and WRF are shown in the supplementary sections.

It is difiňĄcult to determine the regional trends from the plots. Perhaps the means/trends for the 3 regions (coastal, interior, and other) can be separated vertically as opposed to stacked on top of each other in plots 4-6 and 8-9.

Reply: The authors humbly suggest that showing the means/trends of these three common sub-division types is not reasonable as it will become difficult to compare the difference between these regions. On contrary, the existing approach makes it easier to identify that coastal regions have more variability and trends compared to the others. Further, with the reduction in number of subplots, the readability of the figures has also improved significantly; hence now it may not be difficult to understand the regional trends.

SpeciïňĄc Comments L36 to L48: I would suggest limiting your references to studies that focused on India. Alternatively, you need to explicitly state for what region and what time period the results you cite are valid.

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Discussion paper

Reply: The authors have tried to give equal preference to studies both within and outside India to highlight the global perspective of the research problem. As per reviewer suggestion the references which are very much similar to our studies are only added in the revised version.

Over the Indian region, Manohar et al. (1999) studied the latitudinal variation and distribution of thunderstorm frequency and CAPE over 78 Indian stations during 1970-1980 and he postulated that the ambient temperature at 100 hPa pressure level has a strong relationship with it. Dhaka et al. (2010) utilized radiosonde observations during 1958-1997 and obtained very prominent autocorrelations on both yearly and seasonal basis between convection strength (CAPE) and upper troposphere temperatures at 100 hPa (T100). Later, Murugavel et al. (2012) studied the long term trends of CAPE from 32 radiosonde stations during 1984-2008 and revealed an alarming growth in monsoon CAPE over India with a slope of 38J/kg/year. However, they additionally stated that the low-level moisture and solar cycle can have additional impact on the increasing CAPE. Recently, using reanalysis datasets Chakraborty et al. (2017a) and Saha et al. (2017) reported that lower tropospheric instability is reducing over few Indian stations after 1980 due to increasing levels of pollution.

L54: Increases in air pollution and greenhouse warming may have opposing effects on lower atmospheric stability. Don't group them together here.

Reply: The authors have made the necessary corrections in the revised manuscript as:

Recently, Chakraborty et al. (2017a) and Saha et al. (2017) reported that lower tropospheric instability is reducing at certain Indian stations predominantly due to pollution.

L88-90. This sentence is confusing. Are you saying that typically a station has 2-7 gaps with each gap being less than one month in length? If yes, please say so. Reply: The authors have clarified the confusion created by these lines in the revised manuscript as follow:

When an in depth investigation is done on the data continuity by plotting the temperature and humidity profiles for all days, a set of monthly gaps were noticed in the data. Most of the stations had data gaps of 2-7 days in some months but, on the whole, except for very few cases, the duration of these individual data gaps are mostly limited to less than 1 month. However, these small data gaps are not expected to provide any significant impact on the long-term seasonal or annual average variation of (37 years x 12 months) span.

Figure 1: Identify the sites with the serial number from Table 1A.

Reply: Necessary corrections have been done in the revised manuscript.

Figure 2: SufïňĄcient space is available at the top of each plot to replace the acronyms with the actual names, e.g., CI –> Central India

Reply: The authors have modified the figure caption text to remove any possible confusion.

Figure 4: This set of plots confuses me. a) By inspecting these plots, is it possible to separate the west coast from the east coast and central India from Peninsula-India? b) Shouldn't there be a separate box and whisker plot for each region? c) I'd suggest ïňĆipping the vertical pressure coordinates so that high pressures are located near the bottom and low pressures near the top. d) How can the mean for a region be located at the 5th or 95th percentile? e) Why do I only sometimes see "whiskers"?

Reply: (a) The number of subplots has been reduced to half now hence the symbols corresponding to various regions can be easily being resolved and understood. (b) Grouping and separation of regions cannot be done as already explained before. (c-d) This has been done in the revised figures. (d) The average values of parameters for all six sub-divisions along with total Indian region average are shown in form of a distribution to give a feel to the readers about the general instability conditions across the Indian region. The regions in the percentiles indicate more extreme weather conditions on average. (e) If a quartile is present very close to the total mean value, then no whisker can be seen, hence these visual effects.

L114-116: Is rainfall or lightning required or is the determination strictly based on wind speed?

Reply: IMD reports strictly classify thunderstorm intensities based on the basis of maximum surface wind speeds (http://imd.gov.in/section/nhac/termglossary.pdf). L135-136: "VT is found to lie exactly in the middle ..." Arguably, TTI or CT is more in the middle than VT.

Reply: It is true that VT is not solely at the centre in all cases. However, as VT indicates the temperature difference between 850 and 500 hPa hence, it better represents the lower tropospheric instability compared to other parameters. Consequently, VT has been given additional preference for selection towards the long-term analysis. This has been mentioned in the revised manuscript as follows:

Since VT is found to lie exactly in the middle of the rest of the parameters, and it also represents the lower tropospheric instability in a much more suitable way; hence this parameter can also be used to represent the population in a convenient way.

L163: I do not see a trend in PWL. C2

Reply: The discussion on PWL trend has been removed from that line as per reviewer comments.

A decreasing trend in VT and a strengthening of CINE with LI is noticed which indicates a reduction in the lower atmospheric instability.

L168: "intensiïňĄcation in EL". This is confusing. Go with "increase in the height of the EL".

Reply: This has been corrected in the revised manuscript.

Table 1: Since the p tests always yield the same results, i.e., signiïňĄcant , I would

suggest replacing those columns with columns that indicate the percent trend. I would also suggest adding a column that indicates the units.

Reply: This has been corrected in the revised manuscript and the corrected lines are as: The p values are calculated at 95% confidence limits for ttest analysis on all instability parameters over the Indian sub-divisions and interestingly, all the values are found to be below 0.05. Hence the time series variations to be presented in subsequent sections will always be statistically significant in nature. So, to have a better quantitative measure of the trend significance, the total changes in each of these parameters are presented in percentage form in place of the p values in the table. This process will enable an easy identification of regions experiencing more accelerated convective growth. But on the other hand, while analyzing the results of the trend analysis in statistical form, the absolute trend has to be given more importance as the % change depend on the magnitude of the long term mean.

L247: "TSS is found to increase drastically". What are the units for TSS. What do you mean by increasing drastically. L261-262: Chicken and egg question: Is "more convective rain" the cause or consequence of changes in the LFC?

Reply: TSS is the frequency of severe thunderstorms and it does not have any unit. By “drastic” it meant to depict that the change in TSS is much higher compared to TSO. However, the TSS (Fig.5g) is found to increase at a much higher rate compared to TSO especially in the coastal regions.

This line has been modified to get rid of extra confusion.

However, this ascent is more prominent in the monsoon and post-monsoon season.

L271: What does it mean for T100 to strengthen?

Reply: The authors wanted to refer to a “small cooling effect” there. The word “strengthen” has been replaced in the revised manuscript.

L290: I ïňĄnd it questionable to look for periodicities of 16-20 years in a data set that is only twice that long.

Reply: In this study, the time series datasets are not checked by FFT analysis but by EMD and LSP which considers the full time period unlike half of the dataset in the former. Additionally, significant changes in the trends of instability and related parameters are observed most prominently between the years 1996-2004; consequently the relative contribution of this periodicity over the instability trends are found to much higher compared to the other periods. Hence this periodicity has been selected for analysis.

L318: "Drastic" can mean different things to different people perhaps use a different adjective. Also, be speciïňĄc as to which instability parameters showed "drastic" changes.

Reply: This line has been modified in the revised manuscript as follows: In the previous section, the annual averaged time series of many parameters such as EL, LI, VT, CAPE, CINE, T100, TSS, WRF and SRF has showed very significant changes with respect to MCO.

L325: EL –> EL height

Reply: This line has been modified in the revised manuscript. L356: ozone breakup –> ozone decreases

Reply: This line has been modified in the revised manuscript.

L358: cooling effect –> cooling effect due to a reduction in downwelling long wave radiation

Reply: This line is correct and it does not need any correction.

L395: What do you mean by "strong cooling due to ozone decomposition?"

Reply: This line has been corrected in the revised manuscript as follows: . . .the upper troposphere and lower stratosphere (UTLS) where it undergoes prominent cooling due to ozone reduction.

L398: Why would the dearth of transported moisture affect that rate of pollutant dispersion by the winds?

Reply: This line was wrongly written as moisture has nothing to do there. Changed as: However, in the inland regions the layer of absorptive aerosols and greenhouse gases cannot be dispersed amply due to the dearth of strong lower level winds.

L423: CAPE increases in all regions not just near the coast. Please rephrase bullet point 1. Also, "suffer" is a poor choice of words.

Reply: These lines have now been corrected in the revised manuscript as follows: The coastal regions experience the most significant increase in Convective Available Potential Energy. . . .

L426: "drastic" is a qualitative term - be more quantitative C3

Reply: This word has replaced as “significant” in the revised manuscript.

L439: Are you certain this leads to a strong cooling effect in the troposphere? The increases in OH would lead to increases in the oxidation rates of CO and methane, which could lead to more ozone in the presence of NOx.

Reply The authors humbly accept that they are no experts in UTLS chemistry. However, a cooling in UTLS, reduction of ozone and a simultaneous increase in water vapor indicates some complex mechanism initiated by moisture intrusion which eventually leads to ozone breakup. On the other hand, as pointed out by the reviewers, OH molecules may also have a probability to both increase and decrease the ozone concentration. So, to clarify this confusion, the phrase involving OH radical effect has now been faded out of the conclusion section. The modified conclusion result is as follows:

In the coastal regions, ample amount of water vapor is advected into the mid-troposphere from the surrounding seas which in presence of strong lifting goes up to upper troposphere and lower stratosphere (UTLS) where ozone depletion occurs leading to a strong cooling effect. This cooling effect enables the ascent in EL resulting in much stronger LI and CAPE values, hence more TSS and SRF.

TEXT S1: S6: Free condensation –> Free Convection S11: Parcel may continue moving past the EL due to upward momentum. S24: Add a reference to the supercell comment S25-32: "lifted from the LFC to the lowest 100 mb of the troposphere". This is incorrect. Please re-phrase this. I believe the moisture and temperature proïňĄles are averaged over the lowest 100 hPa and then the resulting parcel is lifted to the LCL. S42: calculated as th –> calculated as the S48: resaerch –> research

Reply: All these corrections have been done in the revised manuscript.

Minor comments

L32 showed –> shown L39: due to surface heating –> due to increases in surface heating L46: extreme precipitations –> extreme precipitation events L46: intense convections –> intense convection L54: lower instability is reducing –> lower tropospheric instability is decreasing L58: studies over India has –> studies over India have L108: upto –> up to L171: reduction VT –> reduction in VT L192: higher in the coasts –> higher at the coasts L195: "higher", Do you mean "more negative?" L217: "ttset" –> test L223: "all the regions" –> not true in the NE region L224: is minimum –> is smallest L227: "also show an enhancement " –> become more negative L243-244: Smallest changes in the NE and NW regions. The difference between inland and coast regions isn't that large (2 versus 2.375 degrees) L376: a dominant increase –> an increase L380: resulting more –> resulting in more L382: To prove this hypothesis –> To test this hypothesis L383: increasing prominently –> increasing L383: expand DLWRF acronym

Reply: All these corrections have been done in the revised manuscript.

We thank the reviewer once again for providing detailed suggestions which made us to improve the manuscript content significantly.

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Please also note the supplement to this comment:
https://www.atmos-chem-phys-discuss.net/acp-2018-565/acp-2018-565-AC1-supplement.pdf

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Interactive comment on Atmos. Chem. Phys. Discuss., https://doi.org/10.5194/acp-2018-565, 2018.