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Title: A meteorological discourse on Extreme Storm Events driven by Asian Slum Emissions

Abstract: Increasingly the world over, climate modelers have suggested that local emissions may well affect cyclonic storms. The eastern coast of India, home to mega cities, is routinely battered by such storms over the period October- December. Additionally, these cities house millions of slum dwellers who cook their meals from unseasoned firewood yielding substantial amounts of biomass particles. These particles chemically age within a polluted air mass rendering them active as cloud condensation nuclei (CCN). This first study shows the genesis, progression and evolution of one such tropical disturbance, Hurricane Thane, which was modulated by these transient emissions, devastating the coast of Tamil Nadu on 30th December 2011.We show that auto-conversion rates converting cloud water to rain water are significantly altered by up to 12% when such emissions are included. Carefully designed numerical experiments using the Weather Research and Forecasting (WRF) model show an increase of 20.5% in the cloud water amounts when these effects are included. Emissions from Asian slums may well alter cyclonic activity elsewhere in South Asia. This study, using a state of the art numerical weather prediction model, indicates how local effects can be quickly obtained through offline modeling. In a nation of continental proportion where

millions of under privileged persons live close to the most vulnerable coastal locations, quick alerting mechanisms by local institutions with limited resources (Government Colleges and Engineering Institutes) may well form a support system linking ordinary citizens with the local coast guard for purposes of mass evacuation well in advance.

Keywords: Aerosols and particles, Cloud physics and chemistry, Pollution-urban and regional, Precipitation

1. Introduction

Chennai city, a major manufacturing hub, has 2 million of its population residing in dilapidated hovels spread out over 1202 slums present within the city limits – the slums span an area less than 2% of Chennai city whilst comprising of 25% of the city's population. The main source of fuel for this slum population is cow dung cakes and unseasoned wood which release soot and black carbon diurnally. A study of the wavelength exponent of aerosol absorption in the atmospheric column at ground level showed two peaks, one in the morning and one in the evening, indicating an undisputed contribution from cook stove emissions (Aruna et al. 2013; Habib et al. 2004). Local soot and black carbon emissions from millions of archaic cook stoves over Asian megacities mix in a multi component environment comprising of the well-known sea salt and sulphate signatures. The effects of these anthropogenic aerosols on climatic trends such as global warming, tropical cloudiness and radiative forcing have been extensively studied [Ramanathan and Carmichael, 2008; Satheesh and Ramanathan, 2000; Ackerman et al. 2000]. However, the scientific question addressed in this paper is whether this carbonaceous aerosol loading is affecting cyclonic activity over the region by modulating the CCN activation?

Studies quantifying local impacts from congested slum aerosol aggregates on the microphysical characterization of extreme weather patterns such as storms and cyclones are sparse (e.g. Goff et al. 2006). Over the Indian subcontinent, Evan et al. (2011) analysed the effect of transient emissions from BC and other aerosols on tropical cyclones over the Arabian Sea. An increase in propensity of cyclones over the Arabian Sea is attributed to the six fold increase in anthropogenic emissions over South Asia. Cyclone development in the Arabian Sea is limited by the vertical wind shear and atmospheric monsoon circulation modulated by these emissions. On the contrary, Latham et al. (2012) analysed the weakening of hurricanes with injection of seawater as cloud condensation nuclei in regions of hurricane genesis. No study however provided a quantification of cloud water amount or precipitation changes induced by transient emissions from unseasoned biofuel combustion from cook stoves. This is a major cause of concern over many overpopulated developing countries and a closer look on their climatic imprint is warranted.

These local impacts need to be quantified, particularly during seasons in which storms develop – if soot and black carbon emissions modulate the partitioning of cloud and rain water, then with a foreknowledge of such emissions, the source can be adapted suitably, if this partitioning is found to induce major changes.

2. Discussion and Relevance

Studies quantifying local impacts from congested slum aerosol aggregates on the microphysical characterization of extreme weather patterns such as storms and cyclones are sparse (e.g. Goff et al.2006). Over the Indian subcontinent, Evan et al. (2011) analyzed the effect of transient emissions from Black Carbon (BC) and other aerosols on tropical cyclones over the Arabian Sea. An increase in propensity of cyclones over the Arabian Sea is attributed to the six-fold increase in anthropogenic emissions over South Asia. Cyclone development in the Arabian Sea is limited by the vertical wind shear and an atmospheric monsoon circulation modulated by these emissions. On the contrary, Latham et al. (2012) analyzed the weakening of hurricanes with injection of seawater as cloud condensation nuclei in regions of hurricane genesis. It is not just Arabian Sea where cyclonic activity abounds-the Bay of Bengal also is a repository of cyclonic activity. Cyclone Phailin, a Bay of Bengal storm, was categorized by the India Meteorological Department as a *very severe cyclonic storm.* It was indeed classified as a Category 5 tropical cyclone affecting more than 12 million people in India and neighbouring countries of Myanmar, Thailand and Nepal. There are other examples illustrating how the eastern coast of India is routinely devastated by severe tropical cyclones (e.g. Cyclonic storm Thane (Dec 2011), Nilam (Oct 2012), Viyaru (May 2013), Phailin (Oct 2013) and Hudhud (Oct 2014). This article focuses on Cyclone Thane (25–31 December 2011) which wreaked havoc along southeastern coastal India.The coast is home to highly populous cities – many of them vulnerable, with a risk of flooding, affecting 13 million people. No study, however, provided a quantification of cloud water amount or precipitation changes induced by transient emissions from unseasoned biofuel combustion from cookstoves in any cyclone based study. This is a major cause of concern for many overpopulated developing countries and a closer look at their climatic imprint is warranted.These local impacts need to be quantified, particularly during seasons in which storms develop – if soot and black carbon emissions modulate the partitioning of cloud and rainwater, then with a fore knowledge of such emissions, the source can be adapted suitably, if this partitioning is found to induce major changes. In the next section, we provide details of the procedure that has been followed in this paper.

3. Methodology

We present a unique procedure to ascertain the magnitude of this partitioning using the WRF offline. In this study, we start with a WRF-ARW model run (Version: 3.8.1) which is a fully compressible and non-hydrostatic model. The input dataset has been retrieved from the research data archive of the Computational andInformation Systems Lab (National Centre for Atmospheric Research- NCAR / University Corporation for Atmospheric Research- UCAR).At the outset, we propose that the estimation of cloud and rainwater amounts from localized regions, including a variety of sources, be done offline. If this partitioning were made online it would be restricted only to large institutions – there is an increasing effort in getting weather forecasts at the level of individuals and local communities particularly within Asian countries where the government-run meteorological forecasts are accessible only through radio and television, and are often hard to access with crippling power cuts. Obtaining precipitation tendencies locally is non-trivial requiring a government backed satellite meteorological support which slows down the procurement and dissemination of data. Climate model runs with detailed microphysics are very computer intensive and cannot run offline, severely limiting the number of potential users worldwide. A quick process has been described in this paper which involves optimizing transient emission effects within the easy to use Kessler formulation (Kessler 1969) (this run is 6 times faster than a comparable WRF-Chem run[a]. The modified Kessler scheme is efficient and amenable for easy incorporation within a standard WRF framework without sacrificing accuracy. We have looked at the effect of these emissions on a major cyclonic disturbance – Hurricane Thane over the Bay of Bengal, which battered the coast of Tamil Nadu on 30th December, 2011. We show a definition sketch of the main steps followed in figure 1.

Hurricane Thane was designated as Very Severe Cyclonic Storm Thane by the India

Meteorological Department (IMD) and was the strongest tropical cyclone of 2011 within the North Indian Ocean. Its genesis was a tropical disturbance developed within the monsoon trough near Indonesia (Unattributed, 2011; Khole et al. 2011). Thane had an extensive cloud cover (543,753 km^2) with moderate precipitation intensity (Saini et al. 2013) - Figure 2 shows an optimized WRF predicted cloud fraction amounts. The novelty of our approach is in the effective incorporation of transient emissions in the WRF model by using the modified Kessler scheme. In the original Kessler (1969) scheme, the

[a] WRF-Chem uses spectral bin microphysics for computing the aerosol-cloud interactions. The computing time associated with spectral bin microphysics is more than 5 times the time associated with a bulk microphysics scheme. In addition, the number of advected variables involved in a WRF-Chem cloud-aerosol interaction model mechanism required for effectively computing the effects of transient emissions on cloud water and rainwater is 323, assuming eight spectral bins. In comparison, a simple meteorology scheme like the Kessler scheme involves only 11 advected variables resulting in majorly reduced computation time and invariably computational costs (Gustafson et al. 2005).

deciding factors that partition cloud water into rain water are the autoconversion rate and the autoconversion threshold -the autoconversion threshold defines the minimum cloud water amount required for the conversion of cloud water to precipitation while the autoconversion rate is the reciprocal of the conversion time of the cloud water. These parameters are accounted for within WRF's microphysical modules using the standard Kessler parameterizations which cannot account for any variation in droplet spectral distribution – although WRF has other microphysical options they are computationally complex and are unsuited for local forecast run offline by individuals. Most Bay Of Bengal (BOB) storms are mediated by warm rain microphysics – this justifies the use of the Kessler scheme which efficiently models warm rain processes (Fovell and Su, 2007; Roy et al. 2013). The Kessler parameterization is still widely used the world over in many climate models.

An earlier study by Ghosh and Jonas (1998) pointed out that another widely used scheme proposed by Liu and Daum, (2004) overpredicts the cloud water conversion rates. This prompted us to 'optimize' the standard Kessler scheme within the WRF scheme to account for multiple aerosol effects. In order to optimize the Kessler Scheme for cyclone Thane, cloud droplet number concentrations and the droplet spectral spread values were used (see Figure 3) to compute the dispersion parameter. This was used to calculate the autoconversion rate and threshold- which was explicitly calculated for all five aerosol modes over Chennai city shown in Figure 3, i.e. global sulphate, global biomass, transient biomass, salt film, and salt jet modes. The transient biomass mode represents the biomass emanating from unseasoned cookstove emissions, whilst the two salt modes depend on wind-driven sea spray (de Leeuw et al. 2000). A sophisticated Chemical Parcel Model (CPM) by O'Dowd et al. (1999) was used to grow the given modes into cloud droplets. The model is Lagrangian with explicit microphysics and uses dynamic growth equations to have the aerosol solution droplets grow through water vapour condensation. This results in a size-resolved droplet spectrum (Pruppacher and Klett 1998). Both the curvature and solution effects are included along with corrections for the continuum approximation close to the droplet surface (Ghosh et al. 2007a,b; Varotsos and Ghosh 2016; Ghosh et al. 2017; Kolb et al. 2010; O'Dowd et al. 1999b). The CPM model runs initialized with the cloud base temperature, pressure, vertical updrafts and relative humidity values obtained from the WRF (shown in Figure 2), yielded radii of the grown cloud water droplets accurately after integration. From the aerosol size distribution observed in Figure 5, we see from the aerosol size distribution observed in Figure 5, we see a very high concentration of aerosols over submicron and micron-sized radii comprising of sulphate and sea salt- film modes. These yield concentrated solution droplets where the assumptions of ideality are not valid.*Pitzer* formulations are invoked to resolve the inherent non-ideal effects present over such small sizes (O' Dowd et al.). These effects can be significant because droplet numbers can soar up to 1200 cm^{-3}at the smallest sizes. The fully grown aerosol cloud spectra obtained from the CPM was fitted to a lognormal curve – this provided the new values of the mean, standard deviation and number concentration for the grown spectra. A comparison of the time rate of change of cloud water amounts between the Kessler (1969) andBerry (1968) equations (which incorporates aerosol dispersion) provided the best fit of the two curves - the point of convergence of the two schemes indicated the optimum value for the autoconversion rate and threshold (see figure 3.) . This optimized Kessler framework with the parameters was input into the

WRF's standard Kessler Scheme -the autoconversion rates and thresholds for all 5 modes are tabulated in Table 1.The Kessler parameters for the WRF runs were obtained through a weighted average method taking into account the aerosol number concentration and the corresponding weight obtained by the product of the number concentration and the mean radius.

3. Results

In order to quantify the effect of transient emissions two contrasting WRF runs were performed without (Run A) and with (Run B) the effects of transient emissions. Weighted averaging of modes for Run A provided values of 1.82 x 10-3 s-1 for k and 3.9 x 10-4 kgkg-1 for a, while Run B yielded 1.63x 10-3s-1 and 0.396x 10-3 kgkg-1 as the autoconversion rate and threshold respectively.We wish to emphasize that Thane’s morphology and dynamics were well characterized through this procedure. The cloud water content for the duration of cyclone Thane is shown in Figure 4. The higher than average sea surface temperature of the Bay of Bengal led to a greater accumulation of water vapour. This water vapor, as it rose, condensed and resulted in intense precipitation in the surrounding regions.A maximum difference of the order of 20% (0.35 gkg-1) in the cloud water mixing ratio is obtained when transient emissions are accounted for in WRF. The accumulation of water vapour due to the cyclone's vorticity is visible in Figure 4(i) and Figure 4(ii). The rotational vorticity of the cyclone combined with its intensity draws in the water vapour from the surrounding area into the storm radius. This accumulated water vapor influenced by the eye wall up-draught rises and coalesces to form liquid water droplets. Upon striking the Tamil Nadu coastline, the source of heat is extinguished leading to cyclonic dissipation - this weakening led to the spreading of the water vapor accumulated by Thane over the surrounding region as seen in Figure 4(iii). In contrast, there is a decrease in the precipitation tendency characteristics where we see higher precipitation when transient emissions are excluded (see Figure 5). This decrease is expected as the presence of the transient emissions would lead to higher number of cloud condensation nuclei (soot and black carbon are normally hydrophobic, however over Chennai city they are rendered partially hydrophilicas they have aged in a sulfur rich environment hence increasing the water droplet concentration but decreasing the droplet sizes (Ghanti and Ghosh, 2010). This reduction in size causes a reduction in collection because the 20μm critical radius threshold is not attained for these smaller droplets that are present in high concentration (Ghosh et al. 2005).

Precipitation tendencies (mmhr-1) using the optimized microphysical scheme have been compared with NASA's TRMM satellite precipitation imagery – the presence of multiple bands of precipitation centered around Thane's eye is clearly evident in the TRMM image. The maximum value of precipitation is better captured when these transient slum emissions are included – the 45 mmhr-1 maximum observed in the TRMM compares well with the 44 mmhr-1 value obtained from Run B. When these are not included the amounts are under-predicted (the maximum is ~40 mmhr-1 in this case). An additional caveat is that the loose clustering of cloud bands indicating the presence of convective spirals is better captured in Run B.

4. Conclusion

There have been reports emanating from the world's press about novel ways of containing the wrath of cyclones. Evan et al. (2011) credited the increase in the propensity of cyclones in the Arabian Sea to the six fold increase in the anthropogenic emissions. However, a recent study by Wang et al. (2014) indicates that aerosols may operate differently than greenhouse gases in terms of influencing hurricanes - they tend to weaken such storms contrary to the belief that they intensify cyclones. This gives us all the more reason to look at cloud water conversion amounts – this result shows higher cloud water amounts with the inclusion of transient emissions. Increase in cloud water indicates a decrease in rain water amounts – tropical storms, where precipitation bands are suppressed pertain to increased wind speeds – sometimes reaching 150 kmph wreaking havoc in their wake. Slums and Shanty towns are ill equipped to withstand the onslaught of these high wind-speeds. In addition, for the water scarce region of Southern India suppression of precipitation is undesirable.

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Figures:

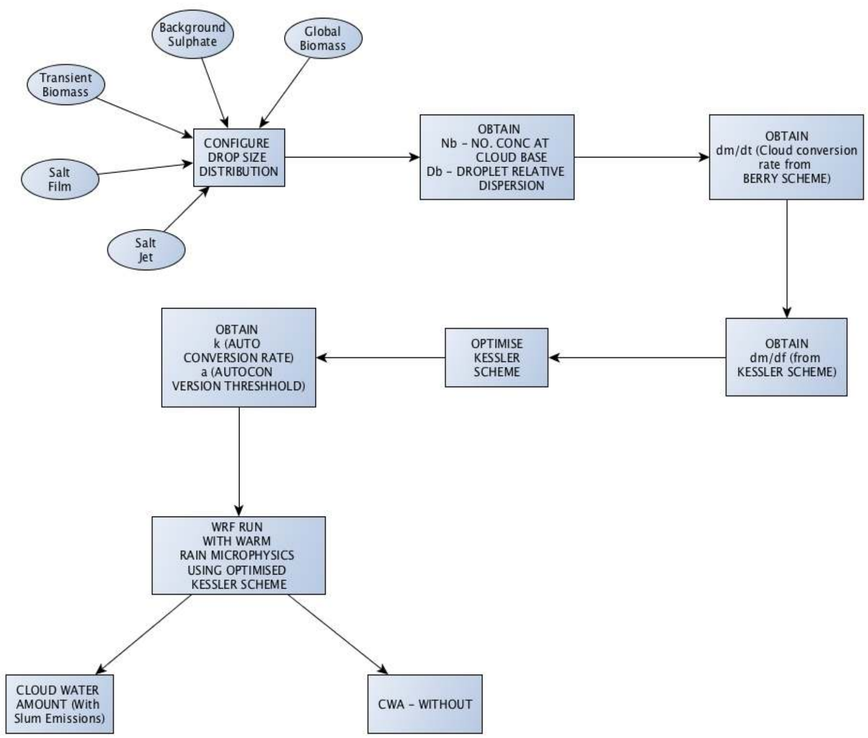

Figure 1. Definition sketch of the main steps adapted.

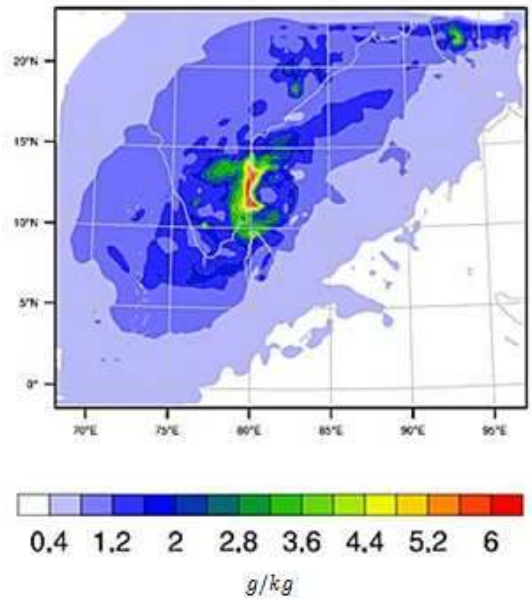

Figure 2. WRF optimized image of cyclone Thane on 28th of December, 2011. The image depicts the cloud water content over the Indian Subcontinent during Thane. The sudden increase in shear and loss of the heat source upon landfall caused the cyclone to dissipate and cause precipitation.

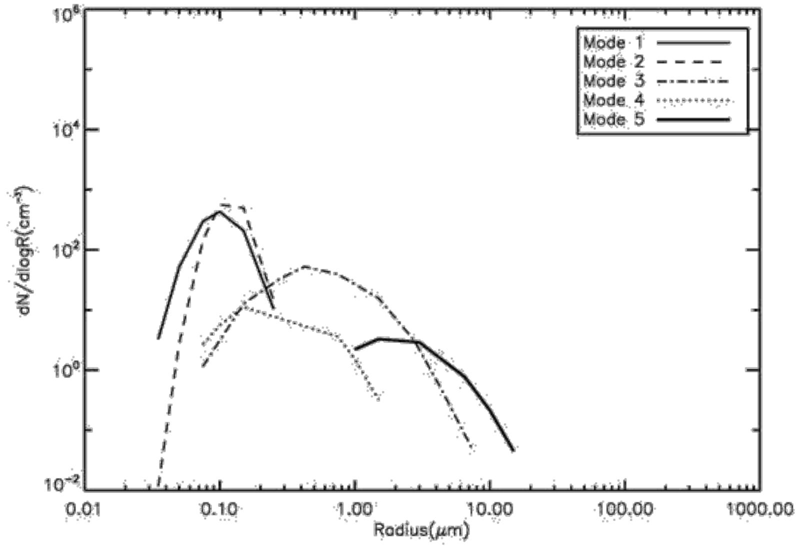

Figure 3. The input spectra of the five aerosol modes. The modes in numerical order are sulphate, background biomass, transient biomass, salt film and salt jet. The modes 1 and 2 indicate the global background emissions obtained from Ghosh et al (2007) while the modes 4 and 5 indicate salt modes over the Bay of Bengal obtained from Ghanti and Ghosh (2010). The transient biomass mode (mode 3) was obtained for Chennai from Sathish et al (2011).

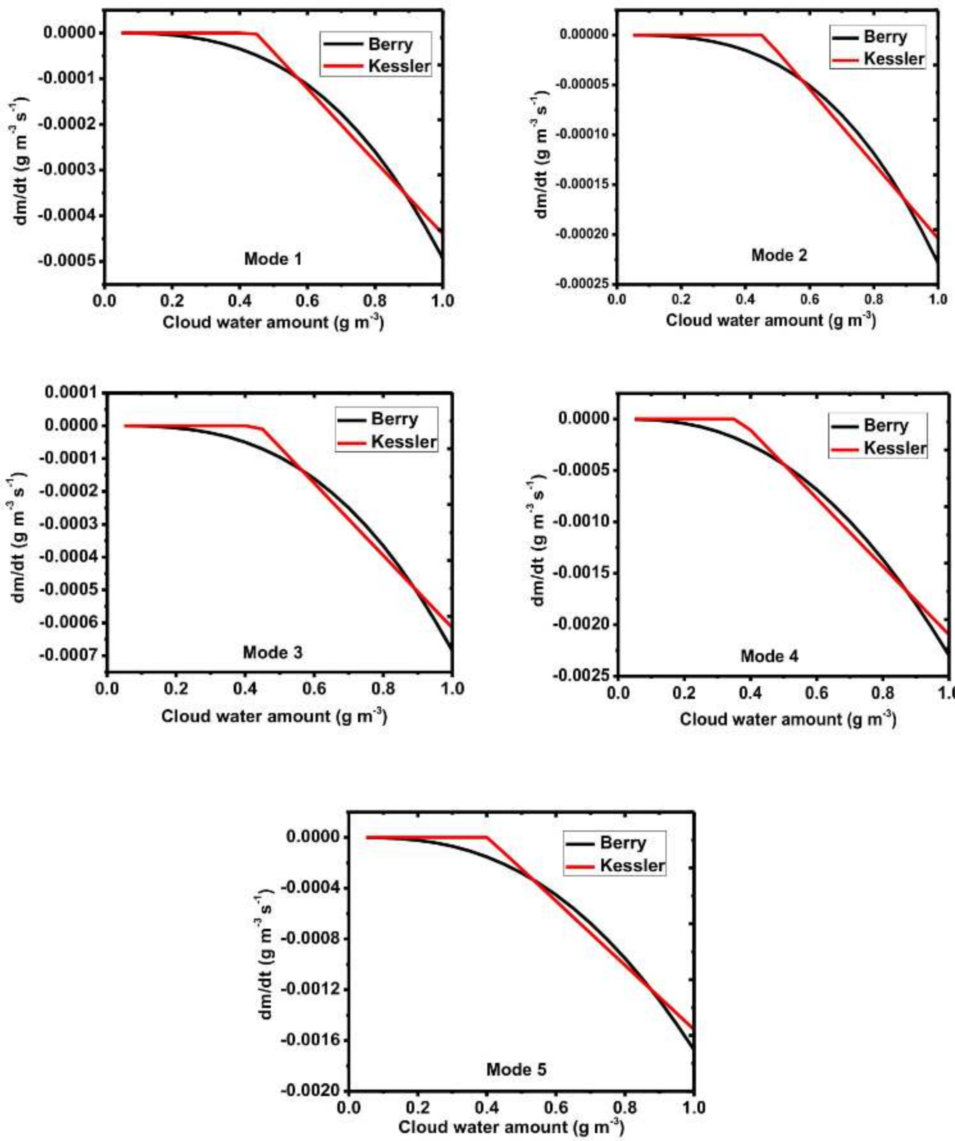

Figure 4. Autoconversion rate and threshold for modes 1-5 are obtained from a best fit of Kessler and Berry Schemes. The modes in the ascending order are sulphate, background biomass, transient biomass, salt film and salt jet. The curved black line and linear red line indicate the Berry and Kessler curve respectively. The best fit of the two schemes indicates the optimum value of autoconversion rate and threshold for each of the 5 modes.

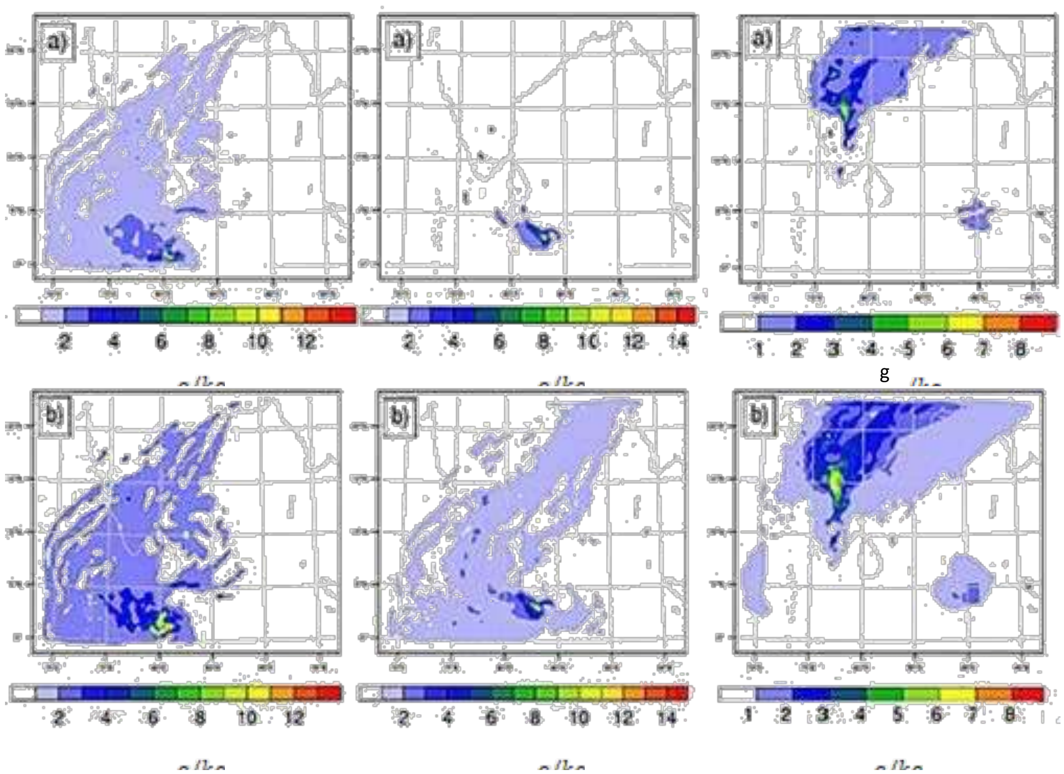

Figure 5. Cloud water mixing ratio (g/kg) obtained from WRF for cyclone Thane for the Run A (**A**) and Run B (**B**) over the Indian subcontinent during cyclone Thane. A sharp increase is seen when transient emissions are accounted for in the WRF simulation. The increase in the aerosol numbers effectively increases the cloud water conversion rate leading to the higher mixing ratio.

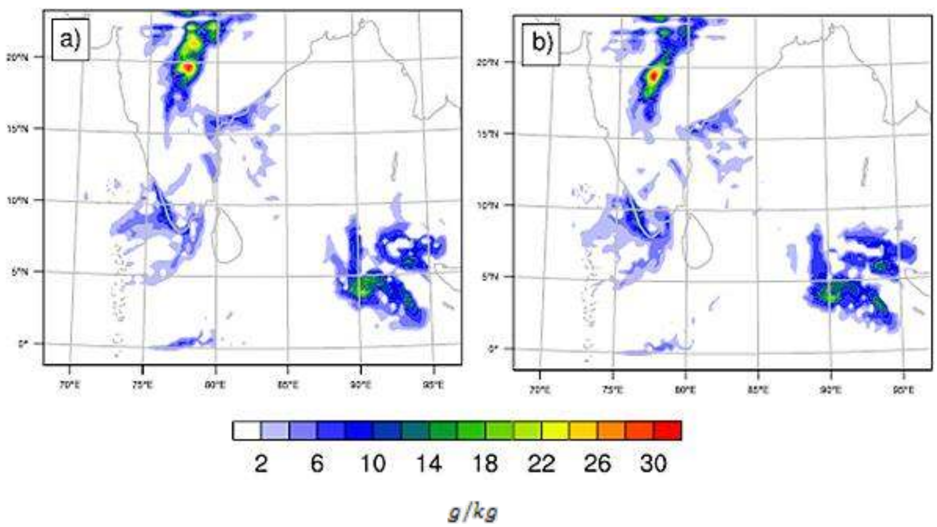

Figure 6. Total precipitation tendency (mm) on 31st of December, 2011 obtained from WRF for the Run A (**A**) and Run B (**B**) over the Indian sub-continent. A contrasting trend to that of cloud water mixing ratio is seen where higher precipitation tendency is observed (note the more extensive green and red patches in (**A**)) in Run A as compared to the Run B – this can be attributed to the higher number of aerosol particles in the atmosphere.

Tables:

Table 1: Autoconversion rates and thresholds for grown aerosol modes obtained from the CPM. Nb represents the number concentration, Db is the dispersion parameter defined as standard deviation/mean and, k and a stand for the autoconversion rate and threshold respectively.

Mode	N_b (number cm^{-3})	D_b	k (s^{-1})	a ($g\ m^{-3}$)	Mean Radius (μm)
Mode 1 - Sulphate	372	0.472	7.95×10^{-04}	0.447	0.9
Mode 2 – Background Biomass	575	0.310	3.74×10^{-04}	0.455	1.5
Mode 3 – Transient Biomass	241	0.456	1.10×10^{-03}	0.441	5.2
Mode 4 – Salt Film	42	0.684	3.32×10^{-03}	0.368	3.7
Mode 5 – Salt Jet	83	0.612	2.53×10^{-03}	0.402	23.4