Sources of Uncertainties in Climate Forcing by Black Carbon Aerosol over Indian Region Using Regional Climate Model

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Abstract: ***The models of the atmospheric Black Carbon (BC) cycle are highly uncertain and the results are difficult to evaluate as they are influenced by emission inventories, the inclusion of BC ageing processes that can change BC lifetime and wet deposition that is the most uncertain process in the models. The objective of this study is to understand the various sources of uncertainties in climate models and to quantify the uncertainty in Climate Forcing due to the treatment of BC (emission and transport) in Regional Climate Model (RegCM 4.1). The methodology adopted in this study utilized emission data of June and December 2001 obtained from EDGAR. The comparative study was done between the estimated surface Radiative forcing for BC with the results obtained in similar studies done for Bangalore in December 2001 and 5 year averaged value for June and December for Kanpur. The effects on the surface temperature, surface pressure and daily precipitation rate were estimated for the months of June and December 2001 to quantify the response of the atmosphere to BC forcing in Climate models. The study concludes that the uncertainties involved in the climate models due to BC emission inventories are due to the underestimation of the emissions in EDGAR database as compared to the other emission inventories for Indian region. It was observed that the BC aerosols in atmosphere are responsible for surface cooling over the Indian region. The reduced surface temperatures in the Bay of Bengal, Arabian Sea and over Indian region act to reduce the surface pressure and precipitation over maximum parts of India.***

Keywords: BC; Radiative Forcing; Regional Climate Model; Indian Region; EDGAR

1. Introduction

Climate models use quantitative methods to simulate the interactions of the atmosphere, oceans, land surface, and ice. They are used for a variety of purposes from study of the dynamics of the weather and climate system to projections of future climate (IPCC, 2007). The degree of confidence in model results depends on some factors which produce the uncertainties in Climate models. Climate change cannot be predicted with high degree of confidence until the uncertainty range is narrowed in the Climate Models (Storelvmo, 2012). The previous findings show that these sources of uncertainties in climate models are based on the energy related emissions, Black Carbon (BC) -cloud interactions, representation of optical properties and uncertainties due to the limitations of model (Bond et al., 2013).

The goal of this study is to understand various sources of uncertainties in climate models, to quantify the uncertainty in Climate Forcing due to the treatment of BC (emission and transport) and to quantify the response of the atmosphere to BC forcing in Climate models.

BC is formed during the incomplete combustion of carbonaceous matter (fossil fuel, biomass and biofuels) that has impact on both air quality and climate change. BC can affect the climate through direct and indirect processes (Vignati et al., 2010). The “direct effect” refers to the scattering and absorption of incoming solar radiation by the BC particles suspended in the atmosphere. The absorption warms the air where the BC aerosol is suspended and results in negative forcing at the earth’s surface (Ramanathan and Carmichael, 2008). The BC affects the climate indirectly by changing cloud albedo and life times (Vignati et al., 2010). The indirect effect of the BC is considered to be the most uncertain of all climate forcings (IPCC, 2001). The main reason for this uncertainty is the General Circulation Models grid size cannot resolve the small length scale involved in cloud-BC interactions. The second reason lies in the complexity of cloud-BC interactions themselves (Nenes et al., 2003).

To assess the impact of BC at the global scale Chemistry Transport Models and General Circulation Models are used but then also the resulting studies contain large uncertainties due to the BC emissions and the treatment of physical and chemical processes affecting the BC (Cooke and Wilson, 1996; Jacobson, 2002; Stier et al., 2007). When BC is emitted it undergoes chemical and physical transformations, which are commonly referred to as “ageing” and these processes are not yet fully known therefore these are the source of uncertainties in climate models. Another important uncertainty is in the emission inventories of BC (Vignati et al., 2010). Thus, models of the atmospheric BC cycle are highly uncertain, the results are difficult to evaluate as they are influenced by: emission inventories that can have an uncertainty of a factor of 2 (Bond et al., 2004); the inclusion of BC ageing processes that can change BC lifetime by an order of magnitude (Croft et al., 2005); and finally by wet deposition that is the most uncertain process in the models (Textor et al., 2006). The interactions of BC with the climate system depend upon its microphysical properties, optical properties, and mixing with other aerosol components. This mixing can alter the optical properties of BC and influence its atmospheric lifetime and ability to form cloud droplets and ice crystals (Bond et al., 2013).

2. Model Description and Methodology

The Regional Climate Model (RegCM version 4.1) is a 3-dimensional primitive equation regional climate model. It has been applied for a wide range of regional climate studies from the process to past and future climate projections (Giorgi et al., 2006). It is a public, open source, user friendly and portable code which is supported through the Regional Climate research NETwork or RegCNET, a widespread network of scientists coordinated by the Earth System Physics section of the Abdus Salam International Centre for Theoretical Physics (ICTP).

2.1 Estimation of BC columnar burdens

For the estimation of columnar burdens (mg/m^2) the BC emissions from EDGAR emission database were used as source term in RegCM 4.1. The estimation was for the months of June and December 2001. The seasonal variations in columnar burdens were compared with the results of the studies carried out by Dey et al., 2006 over Kanpur city of India. The anthropogenic emissions of SO_2 and BC+OC (Black Carbon+Organic carbon) were also estimated for the Indian region and compared with the results of Reddy et al., 2002. The domain covers the area between 5-35° N and 65-95° E including the land mass of India and surrounding oceans with an average mixed layer height of 0.5-2.0 km and with uniformly mixed constituents. Horizontal Resolution in the model was 50.0 km.

2.2 Estimation of BC radiative forcing

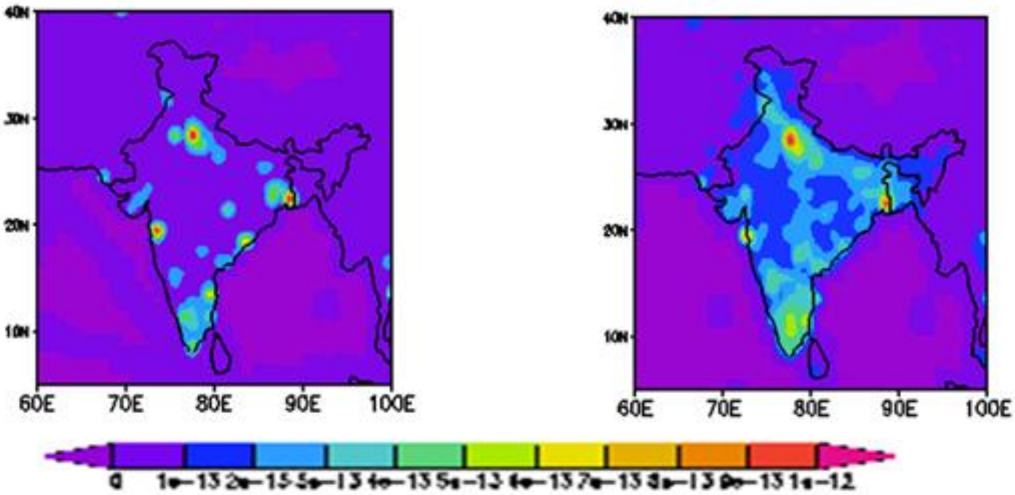
The Black Carbon emissions were used as source term in RegCM for estimation of BC Direct Radiative Forcing (W/m^2). The seasonal variations in Direct Radiative Forcing for the months of June and December 2001 were compared with the results of the studies carried out by Sarkar et al., 2005 and Dey et al., 2008 for 5 years (2001-2005) average over Kanpur city of India for the same months. The same domain area was used with the same horizontal resolution as in the estimation of BC columnar burdens.

2.3 Estimation of response of atmosphere to BC forcing

The effects on the surface temperature, surface pressure and daily precipitation rate were estimated for the months of June and December 2001 to quantify the response of the atmosphere to BC forcing in Climate models. The plots for surface temperature, surface pressure and daily precipitation rate were obtained for control (assuming no BC in atmosphere) and actual atmospheric conditions.

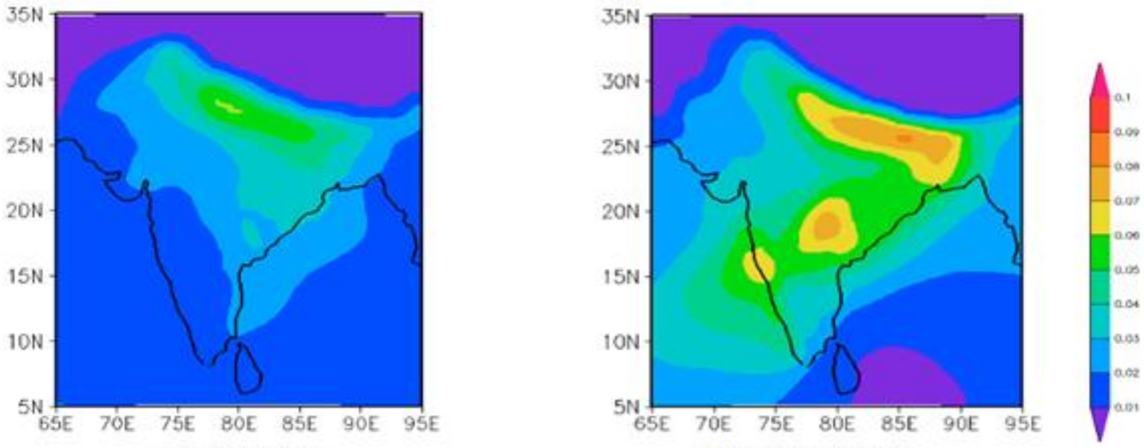
3. Results and Discussions

The spatial plots for anthropogenic emissions (Kgm^{-2}s^{-1}) of SO_2 and BC+OC over India by using the emission data of EDGAR are shown in Figure 1. The estimated integrated columnar burdens (mg/m^2) of black carbon were lower in the month of June as compared to that for the month of December 2001 as shown in Figure 2.



(a) SO_2 (b) BC+OC

Figure 1: Spatial Variation of estimated SO_2 and BC+OC anthropogenic emissions (Kgm^{-2}s^{-1}) over India by using EDGAR data.

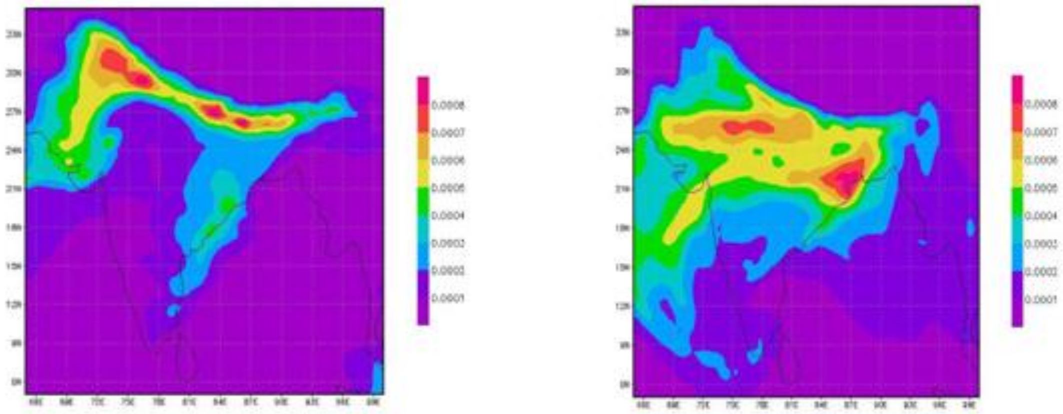


(a) June 2001 (b) December 2001

Figure 2: Estimated BC columnar burdens (mg/m^2) over India for 2001.

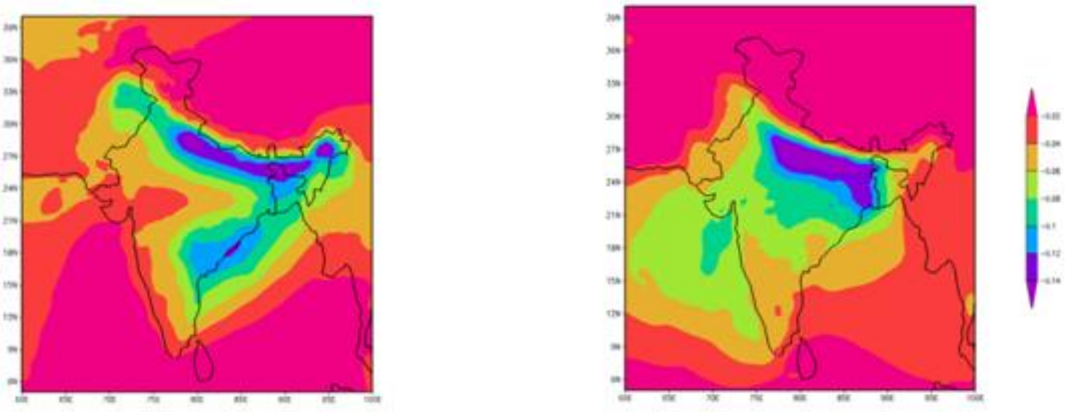
The estimated Aerosol Optical Depth (AOD) of Black Carbon for the month of June and December 2001 are as shown in Figure 3. The estimated Surface Radiative Forcing of BC over India for 2001 is shown in Figure 4.

The estimated results of surface Radiative forcing are compared with the results of similar study carried out by Babu et al., 2002 for Bangalore city. The Radiative forcing data from the study carried out by Sarkar et al., 2005 for aerosols over India was used along with the relative proportions estimated for each component to the aerosol surface Radiative forcing data in the study carried out by Dey et al., 2008 for BC aerosols over Kanpur city in India. The comparison of results for present study with these studies is shown in the table 1.



(a) June 2001 (b) December 2001

Figure 3: Estimated AOD over India for 2001



(a) June 2001 (b) December 2001

Figure 4: Estimated Surface Radiative Forcing of BC over India for 2001.

Table 1: Comparison of results of present study with various studies carried out for BC Radiative Forcing estimation during the year 2001

Reference	Model Description	Month and Year	Location	Surface Radiative Forcing	RF estimated in present study	Underestimation in present study
Babu et al., 2002	Aerosol model Developed by Hess et al., 1998	Dec-01	Bangalore	-23 W/m^2	-0.04 to -0.06 W/m^2	384 to 575
Sarkar et al., 2005	The CERES Earth Radiation budget data was taken from the NASA Langley DAAC (LARC) and used for calculation of the top of atmosphere flux for two years from January, 2001 to December, 2002.	Jun-01	Kanpur	-25 W/m^2	-0.12 to -0.14 W/m^2	179 to 209
Dey et al., 2008		Dec-01		-27 W/m^2	-0.14 to -0.16 W/m^2	169 to 193

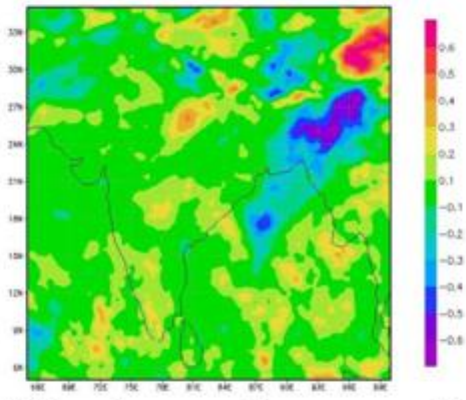
3.1 Impact of BC aerosols over Indian Region (June 2001)

Figure 5(a) shows the change in mean surface temperature due to BC in atmosphere. The results show that the northeast part of Indian region shows the maximum decrease in temperature due to negative surface radiative forcing effect of BC. The maximum temperature decrease in the range of -0.4 to -0.7K in the north-eastern part of India is because of the transport of BC due to motion and direction of wind towards northeast as shown in the Figure 5(d). The maximum parts of Indian region show slight decrease in temperature from 0.0 to -0.1K. The presence of large amounts of aerosol significantly reduces the solar flux reaching the surface and thus leads to surface cooling over the India region.

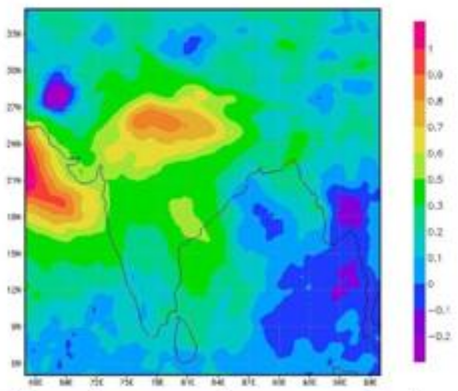
Figure 5(b) shows change in surface pressure due to BC in atmosphere. The cooling effect of black carbon shows the increase in surface pressure over the Indian landmass. The maximum pressure increase is in the range of 0.7 to 0.8 hpa over the north-western and northern parts of India including Rajasthan, Uttar Pradesh and Madhya Pradesh. Most parts of the Indian region are showing the average increase in pressure in the range 0.3 to 0.7 hpa. The slight decrease in pressure in Bay of Bengal region is because of the temperature increase in that area.

Figure 5(c) shows the change in precipitation rate over the Indian region. The result shows that the daily precipitation rate decreases in most parts of the Indian region in the range 0 to -5 kg m^{-2}d^{-1}. Some parts of India including parts of Orissa, Andhra Pradesh, Tamilnadu, Kerala and Rajasthan shows the increase in daily precipitation rate in the range 0 to 5 kg m^{-2}d^{-1}. The cooling effect over the surface and increase in surface pressure is responsible for decrease in precipitation over most of the parts of Indian region.

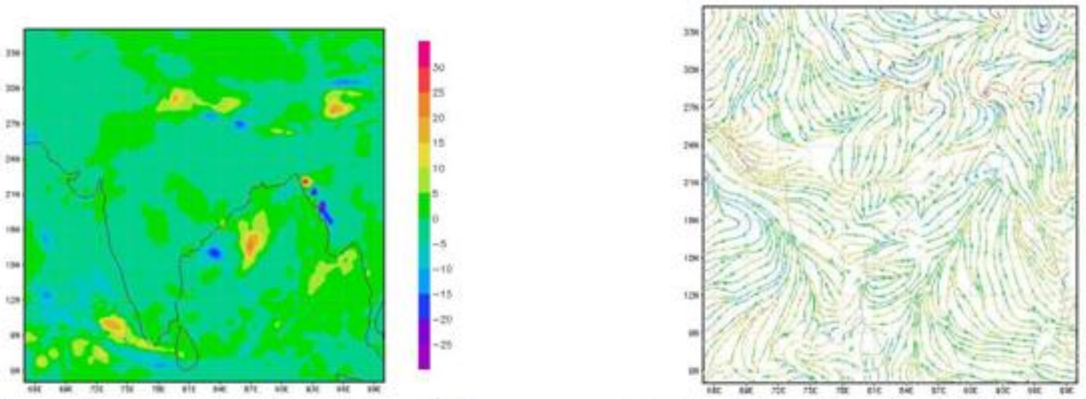
Figure 5(d) shows the streamlines of simulated wind change at the level of 850 hpa over the surface. The 2 dimensional streamlines plot is showing a series of arrows oriented parallel to wind, showing wind motion, the direction of the wind and the areas of convergence and divergence in the wind field over the Indian region which is helpful in determining the location of features within the wind pattern. The areas of Convergence depict cyclonic flow or likely areas of low pressure while Areas of divergence depict anticyclonic flow or likely positions of high-pressure areas. The transport of BC depends on the motion and direction of wind.



(a) Change in mean surface temperature (K).



(b) Change in mean surface pressure (hpa).



(c) Change in mean precipitation rate (kg $m^{-2}d^{-1}$).   (d) Streamlines of simulated wind(at 850 hpa)

Figure 5: The mean Surface pressure, surface temperature and total daily precipitation rate changes due to BC presence in atmosphere (June 2001) (BC minus Control)

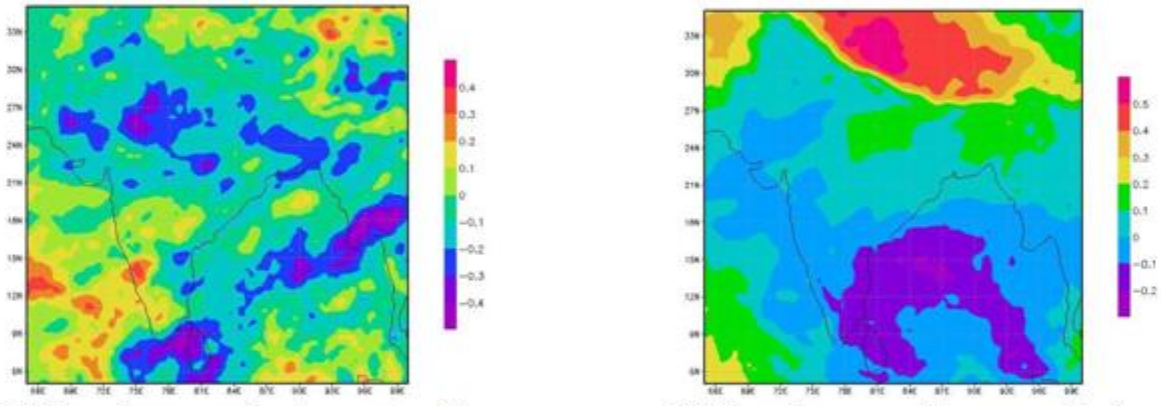
3.2 Impact of BC aerosols over Indian Region (December 2001)

Figure 6(a) shows the change in mean surface temperature due to BC in atmosphere. The results show that the North Western parts including Rajasthan, central parts including Madhya Pradesh and southern parts including Kerala and Tamilnadu of Indian region show the maximum decrease in temperature due to negative surface radiative forcing effect of BC. The transport of BC aerosol due to motion and direction of wind towards these regions are responsible for the maximum cooling. The maximum temperature decrease is from -0.4 to -0.5K in these parts of India whereas maximum parts of Indian region shows slight decrease in temperature from 0.0 to -0.2K. The presence of large amounts of aerosol significantly reduces the solar flux reaching the surface and thus leads to surface cooling over the India region.

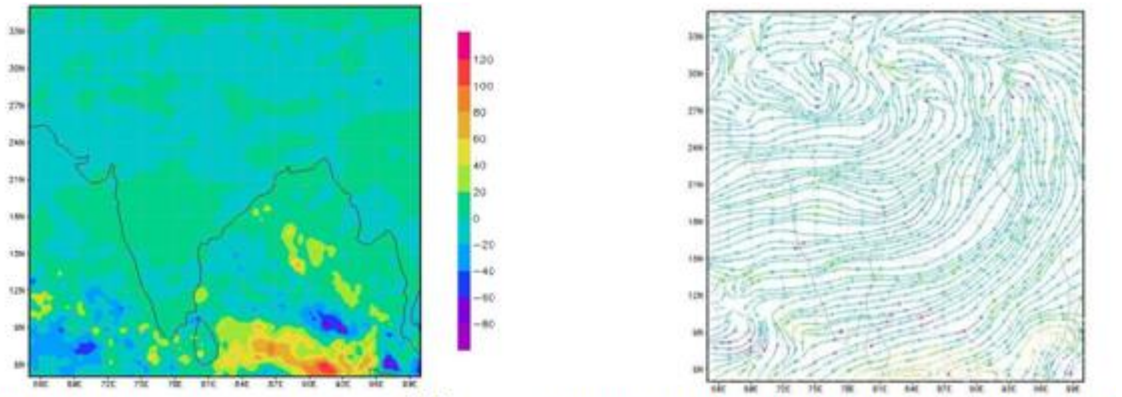
Figure 6(b) shows change in surface pressure due to BC in atmosphere. The cooling effect of black carbon is responsible for the increase in surface pressure over the Indian landmass. The maximum pressure increase is in the range of 0.1 to 0.2 hpa over the north-eastern and northern parts of India including Assam, Arunachal Pradesh, Uttar Pradesh and Madhya Pradesh. Most parts of the Indian region are showing the average increase in pressure in the range 0.0 to 0.1 hpa. The estimation shows slight decrease in pressure in the range of 0.0 to 0.1 hpa including parts of Mumbai, Andhra Pradesh, Karnataka, Orissa and Tamilnadu. The parts of Rajasthan and Gujarat also show the slight decrease in surface pressure in the range of 0.0 to 0.1 hpa. The maximum decrease in pressure is in the range of 0.2 to 0.3 hpa over the Bay of Bengal region and most of the Bay of Bengal region and parts of Tamilnadu shows decrease in pressure in range of 0.1 to 0.2 hpa.

Figure 6(c) shows the change in precipitation rate over the Indian region. The result shows that the daily precipitation rate decreases in most parts of the Indian region in the range 0 to 20 kg $m^{-2}d^{-1}$. Some parts of India including North-eastern parts and parts of Mumbai, Andhra Pradesh, Karnataka Tamilnadu, Kerala, Uttar Pradesh and Rajasthan show the increase in daily precipitation rate in the range 0 to 20 kg $m^{-2}d^{-1}$. The cooling effect over the surface and increase in surface pressure is responsible for decrease in precipitation over most of the parts of Indian region. The maximum increase in the precipitation is over the Bay of Bengal region in the range of 40 to 100 kg $m^{-2}d^{-1}$.

Figure 6(d) shows the streamlines of simulated wind change at the level of 850 hpa over the surface. The 2 dimensional streamlines plot is showing a series of arrows oriented parallel to wind, showing wind motion, the direction of the wind and the areas of convergence and divergence in the wind field over the Indian region which is helpful in determining the location of features within the wind pattern. The areas of Convergence and divergence show likely areas of low pressure and high-pressure respectively.



(a) Change in mean surface temperature (K).   (b) Change in mean surface pressure (hpa).



(c) Change in precipitation rate (kg $m^{-2}d^{-1}$).   (d) Streamlines of simulated wind change (at 850 hpa)

Figure 6: The mean surface pressure, surface temperature and total daily precipitation rate changes due to BC presence in atmosphere (December, 2001) (BC minus Control)

4. Conclusions

The result shows the estimates in this study are about 37-69 and 30-85 times underestimated for SO_2 and BC+OC respectively. This underestimation in the estimates is because of the underestimation of emissions in case of EDGAR data then the inventory constructed for SO_2, Black carbon and Organic Carbon by Reddy et al., 2002.

On comparison of the results over the Kanpur city with the results of the study carried out by Sarkar et al., 2005 and Dey et al., 2006, the BC Radiative Forcing is underestimated by the factor of 179-209 during the month of June and the same by the factor of 169-193 during the month of December. This underestimation in the estimates is because of the underestimation of emissions in case of EDGAR data then the inventory constructed for SO_2, Black carbon and Organic Carbon by Reddy and Venkataraman, 2002.

This study has investigated the climate sensitivity to emissions of BC aerosol over the Indian region. The influence of BC aerosols on climate is more complex than those of greenhouse gases. The presence of BC in the atmosphere over India is responsible for the cooling of surface similar to sulphate aerosols. However, BC aerosols differ from sulfates in their interaction with solar radiation. The sulfate aerosols radiatively cool both the surface and atmosphere by scattering the solar radiation back to space whereas BC aerosols radiatively warm the atmosphere by absorbing solar radiation but radiatively cool the surface by blocking solar radiation from reaching the surface. Due to the surface cooling effect of BC aerosol the decrease in temperature can be seen in the most of the parts of India for June and December 2001. This kind of alteration in temperature gradients is less favourable for the formation of the strong convection and leads to decrease in precipitation over the most parts of Indian region. The maximum effect on the precipitation is in the month of December.

In addition, the increase in BC emission rates could further enhance the surface cooling with increase in surface pressure and a further reduction in the precipitation over Indian region could be expected. However, regional topography and the associated climate patterns also play a role in changing the behavior of the monsoon rainfall system.

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