Remote Sensing Applications: Society and Environment 8 (2017) 193–198

Contents lists available at ScienceDirect

Remote Sensing Applications: Society and Environment

journal homepage: www.elsevier.com/locate/rsase

Effect of urban surface albedo enhancement in India on regional climate cooling[☆]

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ARTICLE INFO

Keywords:
Energy balance
Land surface temperature
Radiative forcing
Urban surface albedo
White roof

ABSTRACT

In this work, the impact of surface albedo change (by using white paint on roofs in India) on radiative forcing and land surface temperature change has been quantified based on the principles of Physics using energy balance equation and one-layer atmospheric model. The reduction in temperature from enhanced surface albedo was related to the offsets in temperature increase due to carbon dioxide concentration change from pre-industrial to present times. For Indian region, land surface temperature was found to decrease by ~0.63 ± 0.04 K considering water vapour feedback effect and total outgoing radiation increased by ~1.314 W/m^2, for an increase in area weighted surface albedo by 0.0037. However, in order to take into account all the feedback effects and the effect of ocean, the mesoscale model, Advanced Research Weather Research and Forecasting (WRF) model version 3.7 was used and the effect of urban albedo enhancement on the land surface temperature change was simulated and it was found to be in the range of −1 to +1 K with the mean value of −0.043 K. Radiative forcing due to Carbon dioxide concentration change from pre-industrial to present times was calculated as 1.797 W/m^2 and corresponding land surface temperature change estimated was ≈0.86 K. The results obtained by the analytical model were found to be the subset of the results obtained using WRF model. The study concluded that use of cool roofs in India can compensate the heating due to increase in CO$_2$ concentration (from pre-industrial times to present times) by ~5% by taking into account the average value of temperature change obtained by using WRF model.

1. Introduction

Surface temperature of the Earth results from the net balance of incoming solar (shortwave) radiation and outgoing terrestrial (longwave) radiation (Kiehl and Trenberth, 1997). In order to offset the effects of elevated greenhouse gas, especially carbon dioxide (CO$_2$) concentrations, current radiative forcing has to be rectified. The options are either (Lenton and Vaughan, 2009): (1) reduce the amount of solar (shortwave) radiation absorbed by the Earth, or (2) increase the amount of longwave radiation emitted by the Earth. The shortwave options (1) can be subdivided into (a) those that seek to reduce the amount of solar radiation reaching the top of the atmosphere (by injecting stratospheric Sulphur, Crutzen, 2006), and (b) those that seek to increase the reflection of shortwave radiation (albedo) within the atmosphere or at the surface. The longwave options (2) primarily involve removing CO$_2$ from the atmosphere and preventing (at least some of) it from returning there. They can be subdivided into the enhancement or creation of (a) land and (b) ocean carbon sinks. Either way, accurate quantifications of potential climate cooling effects are crucial. Amongst the available options, modification of the land surface albedo is one of the options to reduce the shortwave radiation absorbed by the surface. The effectiveness of this option will highly depend upon the applied area and the achievable albedo enhancement magnitude. The greater the albedo, the less the radiative energy absorbed by the surface. Cool roofs have been studied as a means to cool surface temperatures and reduce cooling energy loads for buildings. In this study, an attempt has been made to assess the potential of urban surface albedo enhancement (by applying white acrylic paint on roofs in India) option for climate cooling.

Globally, a few studies have been carried out on the computation of surface cooling because of the urban surface albedo enhancement (Taha et al. 1999; Akbari et al. 2009, 2012; Menon et al. 2010; Oleson et al. 2010; Salamanca 2012; Rossi 2013). Taha et al. (1999) quantified the possible meteorological impacts of large-scale increases in surface albedo and vegetative fraction on 10 U.S. regions with a three-dimensional Eulerian mesoscale meteorological model (CSUMM). In the model, they increased the albedo from 0.25 to 0.55 for residential roofs and from 0.25 to 0.70 on office roofs. They focused only on temperature and found that the increase in albedo and vegetation can reduce the

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[☆] This work was supported by our own organisation i.e. Space Applications Centre (ISRO).

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http://dx.doi.org/10.1016/j.rsase.2017.09.004
Received 13 August 2016; Received in revised form 5 April 2017; Accepted 16 September 2017

temperatures in most of the study areas by about 1–2 °C. Akbari et al. (2009) concluded that for a 0.01 mean increase in global albedo the average global radiative forcing was calculated as $-1.27\ \mathrm{W/m^2}$. The estimate of the global emitted CO_2 offset potentials for cool roofs and cool pavements was calculated to be about 24 Gt of CO_2 and 20 Gt of CO_2, respectively, giving a total global emitted CO_2 offset potential range of 44 Gt of CO_2 by increasing the roof and pavement albedo by 0.25 and 0.15 respectively across all urban areas on the Earth. Using the land component model (CLSM) of the NASA GEOS-5 climate model, Menon et al. (2010) quantified the change in radiative forcing and land surface temperature due to increased albedo in urban areas by performing simulations. GSWP-2 was used to collect meteorological forcing and were not allowed to respond to changes in surface albedo. Increasing urban albedos by 0.1 for all global land areas resulted in increase in the global average outgoing radiation by 0.5 $\mathrm{Wh/m^2}$ and the surface temperature was found to decrease by ≈ 0.008 K during the boreal summer (June-July-August). For the continental United States, the average outgoing radiation was found to increase by 2.3 $\mathrm{Wh/m^2}$ and the surface temperature would decrease by ≈ 0.03 K for the same increase in urban albedo.

The regional climate impact of large-scale cool roof deployment was studied by Millstein and Menon (2011) by using a regional atmospheric model (WRF) with a fully coupled representation of land-surface and atmospheric system. Their study showed that the cool roofs and pavements over the continental U.S. have the potential of decreasing the afternoon summer time temperatures in urban locations. However, at some rural areas, increase in temperature was also found. They associated the increase in temperature with lower soil moisture, fewer or thinner clouds, and less precipitation. The study carried out by Jacobson and Ten Hoeve (2012) concluded that a worldwide conversion to white roofs, accounting for their albedo effect only, have the potential of cooling population-weighted temperatures by 0.02 K but there is a warming effect of the earth overall by 0.07 K. In India, Bala and Nag (2012) investigated the hydrological consequences of enhancing albedo over land surface. However, their study did not intend to realistically represent future albedo modification over land. In the present study, quantification of land surface temperature change by using cool roofs in India has been done by solving the energy-balance equations for Earth-atmosphere system.

2. Data used

Top of the atmosphere (TOA) and surface shortwave radiation data products from the Clouds and the Earth's Radiant Energy System experiment (CERES, which is an on-going NASA climatological experiment from Earth orbit) and monthly Land Surface Temperature (LST) product of MODIS (MOD11C3) have been used in this study. This LST product provides monthly composited and averaged temperature and emissivity values at 0.05 degrees latitude/longitude grids, as well as the averaged observation times and viewing zenith angles for day time and night time LSTs. The value of the TOA incident shortwave radiation ‘S’, used in this work, is obtained by using relevant CERES data product specified in Table 1.

Table 1
CERES Data description.

CF variable name, units:	TOA Incident Shortwave radiation (rsdt), $\mathrm{W/m^2}$
Spatial Resolution:	1°X 1°
Temporal resolution and extent:	Monthly averaged from 03/2000 to 12/2010
Coverage:	Global

3. Methodology

Changing albedos of urban surfaces and changing atmospheric CO_2 concentrations, both result in a change in radiative forcing. In this work, using the available data, we first estimate the change in the urban surface albedo that can be obtained by applying white acrylic paint to roofs in Indian region. After that, using the energy-balance equation and one-layer atmospheric model, theoretical calculations have been done to find out the change in radiative forcing and corresponding land surface temperature change due to change in urban surface albedo. In order to incorporate the effect of all the feedbacks and the ocean, the mesoscale model, Advanced Research Weather Research and Forecasting (WRF) model version 3.7 (Skamarock et al., 2008) was used and the effect of urban albedo enhancement on the temperature change was simulated. It is a limited area, non-hydrostatic primitive equation model with multiple options for various physical parameterization schemes. The time split integration uses a third order Runge Kutta scheme with smaller time step for acoustic and gravity wave modes. The WRF model physical options used in this study consist of the WRF model Single Moment 6-class simple ice scheme for microphysics (Lin et al., 1983); the Kain-Fritsch scheme (Kain, 2004) for the cumulus convection parameterization, and the Yonsei University planetary boundary layer scheme (Hong and Dudhia, 2003). The Rapid Radiative Transfer Model (Mlawer et al., 1997) and Dudhia scheme (Dudhia, 1989) are used for long wave and shortwave radiation respectively. More details about WRF model and selection of physics options are opt from Kumar et al. (2014a, 2014b). The model domain extends between 61.5°E to 104.5°E zonally and 2.15°N to 41°N meridionally, which covers the Indian landmass consisting of 740 by 740 grid points with 6 km spatial resolution. ECMWF global model analysis data on $0.125^\circ \times 0.125^\circ$ spatial resolution at every 6 h interval is used for the initial and boundary conditions. Further, change in radiative forcing and land surface temperature change due to change in the CO_2 concentration from pre-industrial to present times have also been calculated.

3.1. *Estimation of surface albedo change due to painting the existing roofs white ($\Delta\alpha_s$)*

In order to find out the change in surface albedo by painting the existing roofs white, firstly we estimated the total area under roofs in India. For this, Land use/land cover statistics from NRSC has been used. Table 2 shows the spatial distribution of built-up classes (Level-3) in

Table 2
Spatial distribution of various built-up classes in India.

Level 2	Level 3	CODE	Area in sq km.	% to TGA
Urban	Residential	010101	11720.88	0.37
	Mixed builtup	010102	8429035	0.27
	Recreational	010103	191.37	0.01
	Public/Semi Public	010104	577.78	0.02
	Communication	010105	12.20	…..
	Public utilities/ facility	010106	105.76	…..
	Commercial	010107	352.59	0.01
	Reclaimed	010108	163.48	0.01
	Vegetated area	010109	1396.59	0.04
	Transportation	010110	1784.24	0.06
Rural	……	010201	58653.89	1.85
Mining/ Industrial Area	Industrial	010301	2661.89	0.08
	Mine/Quarry	010302	2722.15	0.09
	Industrial/Mine dump	010303	415.54	0.01
	Ash/ Cooling pond	010304	135.20	……
	Abandoned Mine pit	010305	23.86	……
	Land fill area	010306	17.04	…….