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Some Parameterizations of Radiative Fluxes at Atmospheric Boundary Layer (ABL)

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Abstract The practicability and applicability of the most classical models for a particular location depends largely on validation against actual measurements, hence the parameterizations of the sub-grid scale process play an important role at Atmospheric Boundary Layer (ABL) for appropriate representation of model outputs. This study presents a simple parameterization for some radiative fluxes and pollution parameters at ABL in a tropical city Delhi. The characteristic of the parameterization is that the experimental data sets obtained during the experimental field campaigns are fit into a linear regression relation with the parameterized values according to the different land-use pattern and coefficients are presented, that are in comparable with earlier studies.

Keywords: *Atmospheric Boundary Layer (ABL), parameterization, net radiation, short wave radiation, long wave radiation, soil heat flux, pollutants*

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1. Introduction

The radiation/energy fluxes at the earth-atmosphere (E-A) interface are important in determining radiative warming/cooling of the ABL, in parameterizing the surface heat fluxes to soil and air in terms of net radiation etc. and to a great extent describe the state of ABL. These fluxes are used as the boundary conditions for weather forecasting and air pollution and dispersion modeling. As experimental measurements of these fluxes are skeletal in a forecast model, these fluxes have to be parameterized in terms of simple meteorological variables [28,29]. The short-wave fluxes depend principally on the solar zenith angle (varying according to latitude, season and time of day), clouds and the albedo of the surface. Long-wave fluxes depend upon the amount and temperature of the emitting medium and its emissivity. The representation of scattering and absorption effects of clouds on radiation plays an important role in the parameterization of radiative transfer [30].

The lowermost layers of the atmosphere at the E-A interface is called Atmospheric Boundary Layer (ABL). It is that layer of the atmosphere which is directly affected by the characteristics of the earth's surface and responds to surface forcing with a time-scale of about an hour or less [1]. It is formed due to the interaction of atmosphere and land (gas and solid) or atmosphere or ocean (gas and liquid). ABL is of great importance since all human and biological activities take place in this layer (of depth 1 km to 2 km) and plays a dominant role in air pollution meteorology. This boundary layer is affected by forcings which include frictional drag, heat transfer, pollutant emission and terrain differences etc. The height of ABL varies over a wide range (several tens of meters to several km.) depending upon the rate of heating and cooling of the surfaces, strengths of winds, the roughness and topographical characteristics of the surface, large-scale vertical motions, horizontal advection of heat and moisture and other factors [2]. One of the fundamental parameters characterizing the atmospheric boundary-layer is its depth, which plays an important role in boundary layer processes and environmental/air pollution meteorology, as a basic input parameter to meso- and large–scale numerical weather and climate forecasting models, and as a scaling parameter in similarity theory. Mass (water vapour, pollutants), energy (heat) and momentum exchange between ABL and atmosphere regulate a broad variety of processes which occur within it and have a direct impact on human activities and in turn are affected by these activities [3,4].

Parameterization is an approximation to nature. It is replacement of the true equations describing a value with some artificially constructed approximations. Sometimes parameterization is adopted because true physics is too complicated to use for a particular application, given cost or computer limitations. Parameterizations will rarely be perfect but it is expected that it will be adequate. It (Parameterization) involves human interpretation and creativity, which means that different investigators can propose different parameterization for the same unknown. Although there is likely to be an infinite set of possible parameterization for any quantity, all acceptable parameterization must follow certain rules [1]. Most important is that the parameterization for an unknown quantity should be physically reasonable. In addition, parameterization must have the same dimensions as the unknown, have the same tensor properties, have the same symmetries, be invariant under an arbitrary transformation of coordinate system, be invariant under inertial transformation and satisfy the same budget equations and constraints. To make the mathematical/statistical description of boundary layer phenomena tractable, one approach is to use only finite number of equations and then approximate the remaining unknown in terms of known quantities [1]. Parameterizations of turbulence and diffusion quantities at the ABL have been described by [1,5,6] in which they describe the role of radiative cooling. For stable boundary layer, [7] proposed the parameterization for mixing length theory (small eddy theory), stating that in the real atmosphere gradients are approximately linear only over small distances. [8] and [9] used this as a starting point for other parameterizations [10] emphasized the parameterization of the sub-grid scale processes (Viz. fluxes of radiation, energy and momentum) at the E-A interface for Numerical Weather Prediction (NWP) and climate models. Again mean wind and temperature profiles have been parameterized by [11] and [12] in order to incorporate them in the local and large scale models. Parameterization of the surface Ekman layer by [13-18] is well documented. The parameterization of planetary boundary layer height which varies under radiative and other forcing conditions is presented by [19,20,21] and others in their studies. The net all-wave radiation/net radiation parameterization in a complex urban terrain is presented by [22] with contrasting surface characteristics and climates over the full annual period. [23] and [24] indicated that inclusion of albedo in the parameterization of net radiation significantly affect the model performance. [25] and [26] describe the influence of canyon geometry and surface characteristics of urban areas in radiative fluxes parameterization. [27] pointed out that consideration of stability criteria and better estimate of screen height temperature may improve the parameterizations of long wave radiation and performance of surface energy-balance model.

The aim of this paper is to report on some parameterization on radiative fluxes during the daytime in a Tropical Delhi City, the capital of India with rapid urbanization and Industrialization and population growth. Utilizing data from obtained during the experimental campaigns conducted in 1997-1998 and 1998-1999 [Ministry of science and Technology, Government of India], it was possible to investigate on parameterization on radiative fluxes based on the measurement of radiation and pollution parameters. This paper outlines experimental details and data sets under material and method, gradient on radiative and pollution parameters are illustrated under the section results and discussion and in the last section, the conclusions are given.

2. Delhi-The Study Area

The study area, Delhi (latitude 28° 25$^{/}$ -28° 53$^{/}$ (N), longitude 76° 50$^{/}$ - 77° 22$^{/}$ (E) and altitude of 216-m (m.s.l.)) is situated in the north of North Indian Great plain, and influenced by the great Thar Desert in the west and the great Himalayan ranges in the north. Because of the human migrant influx, the city is dominated by a mixture of human settlements, Govt. offices, Residential and Commercial complexes with some vegetated areas. The climate of the region is controlled mainly by its inland position and continental air prevailing over most part of the year. Delhi's climate is semi-arid with extreme conditions. Winter is foggy with severe cold associated with cold waves due to western disturbances and summer with intense hot, sometimes heat wave called ('luh') also makes the life threaten. In summer dust clouds make the entire city poor in visibility. Perhaps the dust from Rajasthan desert reaches to Delhi and reduces the visibility. Unseasonal rain sometimes with gusty winds is a common feature in Delhi. Southwest - monsoon brings good amount of rainfall. The predominant wind direction in most part of the year is northwesterly except during the monsoon season (July to mid-September) when it reverses to southeasterly. Day length in this latitude ranges approximately between 10.5 hrs in winter to 13.5 hrs in summer. Maximum Global radiation occurs in May and minimum in Jan-Feb (India Meteorological Department, New Delhi [44]).

The population of Delhi is estimated to be more than 17.1 million in 2014 and expected to be crossed 20 million in 2020. It is basically an administrative center, with Govt. offices, agricultural, medical institutions etc. Lot of trading and commercial activities takes place in the city. Being a capital of the country it is linked by rails and national highways with different parts of the country. Major industries like thermal power plants (at Badarpur, Rajghat and Indraprastha), chemicals, engineering, glass and ceramics, foundries and ceramics and small industries like stone crushing, baking machine, food processing industries etc. causing air pollution. Delhi has the highest number of motor vehicles in India. The number is increasing at the rate of 14,000 per month. The vehicular population has increased phenomenally, from 2.35 lakhs in 1975 to 26.29 lakhs in 1996, and expected to touch 65 lakhs in 2015. Vehicular pollution contributes 67% of the total air pollution load (approximately 3,000 mt per day) in Delhi. Peripheral region of the city is characterized by rural population whereas, green spaces and forest areas are being scattered in southern and east central parts (Ministry of Environment and Forest, New Delhi [43]).

The average annual rainfall of the area is 625 mm, of which 95% occurs during the monsoon season (July to September). On an average, rain of 2.5 mm or more falls on 27 days in a year. Of these, 21.4 days are during monsoon months. The cold season begins at the end of November, and extends to the late February. The hot summer extends from the end of March to the end of June. The temperature is usually between 21.1°C to 40.5°C during these months. Winters are usually cold and night temperatures often fall to 6.5°C during the period between December and February. Predominant wind direction is generally W-NW but during monsoon E-SE, with a range of average speed varying from 2.5 ms^{-1} to 3 ms^{-1}. The average annual temperature recorded in Delhi is 31.5°C based on the records over the period of 70 years maintained by the Meteorological Department (India Meteorological Department, New Delhi [43]).

3. Materials and Methods

3.1. Experimental Data Sets

Data sets used are from Ministry of Science and Technology, Government of India, project report No, (DST_No.ES/048/319/95). This was an experimental campaign for radiation/energy and moisture budgets studies at the Atmospheric Boundary Layer (ABL) over tropical Delhi (India). In this campaign the year long experiments were conducted along the entire length and breadth of the capital city during the years 1997-1998 and 1998-1999, aimed at acquiring experimental data for defining the boundary layer meteorology of the urban morphology of tropical city Delhi, according to different land use pattern [29,35,39,40].

The total incoming short-wave radiation (K↓) was measured with the help of Eppley Precision Pyranometer with an accuracy of 2%-5% and output voltage of 1mV corresponding to 33.6 W/m^2. Net radiation (Q*) was measured with the help of Net radiometer (Swissteco, Type S-1) with two replaceable plastic domes and a collapsible stand, which can be adjusted to desired height. The spectral range was 0.3 µm to 100 µm with direct output voltage of 1 mV corresponding to 66.6 W/m^2. In this measurement both Eppley Precision Pyranometer (spectral range 0.28 µm to 2.8 µm) and Net Radiometer were mounted at the height of 1.5m from the surface separately on a flat surface. Albedo is obtained as a percentage ratio of the reflected radiation obtained by an inverted Pyranometer to that of upward facing Pyranometer (total radiation). Longwave radiation from the ground (upward) and the sky (downward) are obtained by exposing one side of the Net Radiometer and hermetically sealing the other side. Exposing upward gives the sky radiation (L↓) and by inverting the ground radiation (L↑) is measured. A soil heat flux plate (HFT-3, Campbell Scientific, Inc.) was used to measure the soil heat flux (G). The output voltage corresponded to 1 mV = 60.6 W/m^2, with an accuracy of 2%-5%. The Air Temperature (T_a) in the present study is measured with the dry-bulb temperature of a Whirling Psychrometer having a sensitivity of 0.01°C and standard error with 2%.

Pollution parameters viz. oxides of sulphur, nitrogen (Sox, Nox) and suspended particulate matter (SPM) were collected from Central Pollution Control Board (CPCB), New Delhi. These data are quality controlled and verified as per the norms of CPCB and certified by pollution control board of India. Methodologies adopted are best suited for Indian atmospheric conditions at par with Environmental Protection Agency (EPA), USA. Hence, further details on sampling methodology, techniques and instrument calibration procedures are not described here, and so also the sampling and monitoring of these environmental parameters are not conducted and described again in order to avoid the duplication.

However, Precautions were taken in installing the instruments to avoid the shadows of trees and other installations. Hourly observations were taken and later on averaged for daily basis for analysis at the same time outlier tests also done, following the methodologies as described in [42], to identify the values that were divergent relative to mean. Some outliers representing erroneous values were identified from the scatter plots and removed [41].

Instruments were calibrated in the Nuclear Research Laboratory of Indian Agricultural Research Institute (ICAR), New Delhi, for the consistency of the readings and accuracy of the data. They were cleaned every week during the study periods and checked simultaneously their accuracy through calibrations. The instrument errors associated with the measured terms were about 5% for net radiation and soil heat flux [29,35,39,40] details are given elsewhere.

Experimental data collected through field campaign on radiation/energy balance parameters are quality checked in the laboratory using statistical packages for data analysis and outliers and data anomalies are filtered out through the examination of scatter plots and following the suitable statistical methodologies to avoid the data artifacts as mentioned above.

4. Results and Discussions

Number of radiative flux parameterization schemes and methods have been described using conventional and non-conventional observations [22,24,38]. In the present study following simple relationships have been established between the radiative fluxes, pollution parameters and weather variables using the measured data sets during the study period.

4.1. Longwave Radiation Downwards (L↓)

In his study [31] proposed a simple parameterization scheme for incoming longwave radiation (L↓). L↓ is related to screen height temperature (T) (in K) by the equation

$$\mathrm{L}\downarrow = C_1 \mathrm{T}^6$$

where $C_1 = 5.31 \times 10^{-13}\ W/m^2\ K^{-6}$ is an empirical constant.

In the present study, C_1 showed different values in different surface characteristics. C_1 is found to be $3.31 \times 10^{-13}\ W/m^2\ K^{-6}$ for industrial and commercial sites. $C_1 = 2.31 \times 10^{-13}\ W/m^2\ K^{-6}$ for rural areas/ vegetated surfaces. It is found that at all the representative sites C_1 is less than Swinbank's approximation [31]. In their studies [28] also reported less than Swinbank's approximation [31].

This relation was tested for several locations [25]. The results indicated a difference between measured and modeled values of no greater than 5%; so this relation can be adopted for clear skies. To account for cloud cover, we employ the linear correction [37]:

$$\mathrm{L}\downarrow = C_1 \mathrm{T}^6 + C_2 N$$

where $C_2 = 60\ W/m^2$ is appropriate for mid-latitudes.

4.2. Longwave Radiation Upwards (L↑)

As suggested by [32],

$$\mathrm{L}\uparrow = \sigma \mathrm{T}^4 + C_3 Q*$$

where $C_3 = 0.12$ was found by them empirically for grass surface. σ - Stefan Boltzman's constant = 5.67×10^{-8} $W/m^2\ K^{-4}$.

In the present study, at industrial site C_3 = 0.01, at commercial site C_3 = 0.012, at residential site C_3 = 0.01, at rural area C_3 = 0.12 and at the forest site C_3 = 0.2. In this study considering earth's surface as a black body σT^4 is used. [32] also considered earth's surface as a black body and used σT^4. It is clear that C_3 is higher at the representative rural and forest areas compared to industrial, commercial and residential sites, which are rocky in nature.

4.3. Net All-Wave Radiation or Net Radiation (Q*)

According to the [32], Q* can be denoted as,

$$Q^* = [(1-a)\ K\downarrow + C_1T^6 - \sigma T^4 + C_2N]/(1+C_3)$$

For cloudless conditions i.e. C_2 = 0, we get

$$Q^* = [(1-a)\ K\downarrow + C_1T^6 - \sigma T^4]/(1+C_3)$$

where

$$a - \text{Albedo} = K\uparrow / K\downarrow,$$

or,

$$a = (K\downarrow + L\downarrow - L\uparrow - Q^*)/K\downarrow \ [33],$$

K↑ - Short wave radiation upwards and K↓ - Short wave radiation downwards.

Net radiation (Q*) estimated by the above equation (denoted as $Q^*_{(para)}$) shows high correlation (r = 0.96) with observed (Q*o), the equation being $Q^*o = 1.0937Q^*_{(para)} + 0.0186$, at industrial site, and at commercial site the equation is $Q^*o = 1.2893Q^*_{(para)} - 2.6367$, r = 0.99. The equation at residential site is $Q^*o = 1.1749Q^*_{(para)} - 0.3261$, r = 0.98. At the rural site the relation between observed and parameterized equation is $Q^*o = 1.3408Q^*_{(para)} - 2.1116$, r = 0.85. Similarly, at the forest site the regression equation between Q* estimated by above parameterized equation and observed Q* is, $Q^*o = 0.967Q^*_{(para)} - 0.8302$, r = 0.97.

4.4. Soil Heat Flux (G)

The soil heat flux is small compared to Q* in the daytime. [34] estimated G using following approximation

$$G = C_gQ^*$$

where C_g = 0.1 for the grass covered surface. In the present study C_g was found to be 0.29 on an average.

4.5. Pollution Gradient (Sox, Nox and SPM)

The variations of total and net radiation of the cities depend upon the concentration of atmospheric pollutants. The difference of the total and the net radiations between urban and rural areas give the total and net radiation gradients, denoted by ΔK↓ and ΔQ* respectively. The gradients of radiation/energy imbalances generate wind, which transport pollutants following the gradients of radiation/energy resulting in pollution gradients (ΔSPM, ΔNo2 & ΔSo2).Using the two sets of data the best fit was found out between the radiation gradients and pollution gradients and resultant regression equations are given as follows,

$$\Delta SPM = 0.0013\ (\Delta Q^*)^2 + 0.237(\Delta Q^*) - 7.562,\ r = 0.97,$$

$$\Delta No2 = 0.001\ (\Delta Q^*)^2 + 0.0596(\Delta Q^*) + 4.487,\ r = 0.87$$

and

$$\Delta So2 = 0.0005\ (\Delta Q^*)^2 + 0.053(\Delta Q^*) - 2.320, r = 0.93,$$

$$\Delta SPM = -0.0002(\Delta K\downarrow)^2 - 0.330(\Delta K\downarrow) + 61.049, r = -0.80,$$

$$\Delta No2 = 9.00E-05(\Delta K\downarrow)^2 + 0.076(\Delta K\downarrow) - 24.185,\ r = -0.81\ .$$

and

$$\Delta So2 = -1.10E-05(\Delta K\downarrow)^2 - 0.0171(\Delta K\downarrow) + 6.784,$$
$$r = -0.91$$

Regression equations indicate that there is moderate to high correlations between the radiation gradients and pollution gradients. Also it is clear that there is the increase of net radiation gradients with pollution gradients. The gradients of total radiation showed inverse relations with negative correlation coefficients indicating that with increasing pollution concentration total radiation decreases.

5. Conclusions

With the increasing understanding of the scientific knowledge in this world of rapid urbanization, industrialization and exponential population growth it's imperative to understand the changing climate and weather systems of the earth. The radiation / energy imbalances and corresponding heating, cooling in the radiation budget components pose a great concern to the climate researcher and human society. The experimental studies through field campaign over the mega tropical cities like Delhi prove useful in deducing the inferences of the sub-grid scale radiative flux parameters for further investigation. In this study simple parameterization of radiative fluxes and pollution parameters in different land-use pattern are illustrated. Results are comparable with earlier studies Parameterization of the turbulent fluxes and other ABL characteristics over Delhi are to be carried in order to approximate the complex sub-grid scale processes for better forecasting skill of the numerical weather prediction (NWP) and regional scale climate models.

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