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The estimation of surface fluxes from heat balance equation for the city of Delhi

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सार — दैनिक मौसम विज्ञान संबंधी सतही प्रेक्षणों पर आधारित विकिरणी, भू-ऊष्मा, गुप्त ऊष्मा और सुग्राह्य सतह ऊष्मा अभिवाहों (फ्लक्सों) के अभिकलन के लिए सरलीकृत आनुभविक सूत्रों का प्रयोग किया गया है। इन आनुभाविक सूत्रों से हम अनेक जटिल निविष्ट प्राचलों को सम्मिलित किए बिना, इन अभिवाहों को परिकलित कर सकते हैं। ये अभिकलन दिल्ली शहर में एक वर्ष की ऋतुओं के चार प्रतिनिधि महीनों के लिए किये गये है। तुलना करने पर नेट विकिरण और गुप्त ऊष्मा अभिवाह का अनेक प्रेक्षित मानों के साथ अच्छा मेल दिखाई देता है। इसके अतिरिक्त, वायुमंडल में परिवर्ती अविलता द्वारा निष्पादित सुग्राहिता परीक्षण से पता चलता है कि आविलता में दुगुनी वृद्धि दिन में अनेक बार नेट विकिरण में 15–50 प्रतिशत परिवर्तन का कारण बन सकती है।

ABSTRACT. Simplified empirical formulae have been used to compute radiative, soil heat, latent heat and sensible surface heat fluxes based on routine meteorological surface observations. These empirical formulae enable us to compute these fluxes without involving too many complicated input parameters. Computations have been performed for the four representative months of the season of a year for the city of Delhi. On comparison, net radiation and latent heat flux show good agreement with their observed values. Furthermore, a sensitivity test performed by varying turbidity in the atmosphere shows that a two-fold increase in turbidity may cause a change of 15-50% of the net radiation at various times of the day.

1. Introduction

The heat balance equation for the earth and earth-atmosphere system can be written as

$$R = LE + H_{sg} + G \tag{1}$$

The surface fluxes of soil, heat and water vapour are useful for many purpose, *viz.*, the estimation of stability near the ground, the determination of evaporation rate useful in hydrology, agriculture and for various air pollution problems.

In India, though a good network of observational stations exist, but the radiation measurements are done only at very few stations. These measurements are available fully or partly only at eighteen stations in India (Mani 1980). In the absence of such measurements, estimation of net radiation and associated surface fluxes is based on some formulae using many input parameters which are usually not available. With this objective, the present study deals with the computation of net radiation, in addition to the G, LE and H_{sg} by making a choice from the available simplified formulae using routine meteorological surface observations for four representative months of the season for the city of Delhi. These formulae have been verified against the observations with highly sophisticated computations by other authors.

2. Flux computations

List of symbols

ϕ	Latitude of the place under study
δ	Declinition to the sun
ϵ	Decadic absorption coefficient ($dm^2 mol^{-1}$)
δ_2	Emissivity constant, .95
σ	Stefan-Boltzman constant, 5.998 x 10^{-8} wm^{-2}
γ	Psychrometric constant, .66 mb k^{-1}
ρ	Density of air
β	Constant used for latent heat flux, 20 wm^{-2}
a'	Accounts in fractions the moisture content in soil (a) .65 for dry periods, (b) .95 for normal periods.
τ	Transmissivity coefficient in clear air including Rayleigh and Mie scattering.
A	Albedo of the surface
ABS_{NO_2}	Amount of energy depleted from NO_2 absorption
C_B'	Coefficient for low cloud layer, .15
C_C'	Coefficient for middle cloud layer, .50
C_H'	Coefficient for high cloud layer, .70
c_p	Specific heat capacity of dry air at constant pressure, 1005 J Kg^{-1} k^{-1}
e	Vapour pressure at the surface (mb)
δe	Vapour pressure deficit
E	Evaporation rate
E_{NO_2}	Amount of energy transmitted after NO_2 absorption
G	Soil heat flux (wm^{-2})

H_{sg}	Sensible surface heat flux (wm^{-2})
I_0	Net longwave radiation with cloudless skies (wm^{-2})
k	Turbidity coefficient
LE	Latent heat flux (wm^{-2})
l	Pathlength, 10000 dm
L	Latent heat of evaporation (wm^{-2})
N	Absorption due to cloud cover
$[NO_2]$	Molar concentration of NO_2 (mol dm^{-3})
P	Surface pressure (mb)
r	Mixing ratio
r_s	Saturation mixing ratio
R	Net radiation or radiative flux (wm^{-2})
R_s	Total incoming shortwave radiation
RH	Relative humidity in fractions
rc	Surface resistance, (a) 60 sm^{-1} for normal periods, (b) 120 sm^{-1} for dry periods
r_a	Aerodynamic resistance (sm^{-1})
S	Slope of the saturation vapour pressure *versus* temperature curve
T	Air temperature at screen height (K)
U_1	Total pressure corrected precipitable water vapour (gm cm^{-2})
W	Water vapour pathlength in cm
Z	Zenith angle.

Sign convention—The value of G is considered to be positive if it designates an income of heat to the underlying surface and all other fluxes are considered positive if they designate disbursal of heat from the surface.

2. 1. Following meteorological input parameters are required for the flux computations :

(1) Diurnal variation of mean monthly surface temperature,

(2) Diurnal variation of mean monthly relative humidity,

(3) Mean monthly cloud cover,

(4) Albedo of the surface and

(5) Surface pressure.

These data have been obtained from Mani (1980) and Mani and Rangarajan (1982) and are based on climatological mean of around twenty years.

(*i*) *Radiative flux*

The total incoming shortwave radiative flux after taking into account the attenuation by various species present in the atmosphere can be given as follows :

$$R_s = S_0 \cos Z\, (\tau - A_W)\, N \exp\,(- k/\cos Z)\, E_{NO_2} \tag{2}$$

(*a*) *Absorption by permanent gases, Rayleigh and Mie scattering*

According to Atwater and Brown (1974), the transmissivity coefficient in clear air including scattering is given by the formulae :

$$\tau = 1.021 - 0.0824 \left[\frac{949 \times 10^{-6} \times P + .05}{\cos Z} \right]^{\frac{1}{2}} \tag{3}$$

(*b*) *Absorption by Nitrogen dioxide*

NO_2 is an efficient absorber of visible radiation as is shown by its pronounced brown colour. NO_2 absorption has been parameterised, based on Beer-Lambert's law, where loss of irradiance after transmission through pathlength l can be given after Campbell (1977) as follows :

$$\frac{I_L(\lambda)}{I_0(\lambda)} = 10^{-\epsilon(\lambda)\,[NO_2]} \tag{4}$$

$$ABS_{NO_2} = \int_{\lambda = 290\text{ nm}}^{410\text{ nm}} I_0(\lambda) - I_0(\lambda)\, 10^{-\epsilon(\lambda)\, NO_2\, l/\cos Z}$$

$$= E_{NO_2} \tag{5}$$

$$E_{NO_2} = 1 - ABS_{NO_2}/S_0 \tag{6}$$

Absorption of NO_2 is considered only in visible region from 290-410 nm wavelength at 10 nm interval because $\epsilon(\lambda)$ is significant in this region. Typical values of $[NO_2]$ and $\epsilon(\lambda)$ is obtained from Campbell (1977). Maximum irradiance is found to be 15% of incident irradiance at 400 m.

(*c*) *Absorption by aerosols and dust particles*

It has been taken into account by turbidity coefficient k and the overall effect is accounted by the exponential factor in Eqn. (2).

(*d*) *Absorption due to water vapour*

The relative absorption of solar beam due to water vapour can be given after Mani and Rangarajan (1982) :

$$a_1 = .110\, (u_1 - 6.31 \times 10^{-4})^{0.3} - .0121 \tag{7}$$

It is cumbersome to obtain and use the total pressure corrected water vapour on hourly basis so a simple parameterisation of the same have been used after McDonald (1980) based on surface observations as follows :

$$A_W = .077 \left(\frac{W}{\cos Z} \right)^{0.3} \tag{8}$$

where W is approximated after Perrin de Brichambault (1968) by the relation $W = .17e$. Details of the calculation of e from RH is given in Appendix I.

The value of A_W based on observations, using Eqn. (7) is found to be .124. From Eqn. (8) used for the present study, the value of A_W is found to vary between .114 & .165 during day time. While the A_W is .124 at 10 IST which is in a very good agreement with Eqn. (7).

(*e*) *Depletion of solar radiation due to clouds*

Absorption of incoming solar radiation by clouds may be given after Haurwitz (1948) as follows :

$$N = \prod_{i=1}^{3} 1 - C_i\,(1 - T_i) \tag{9}$$

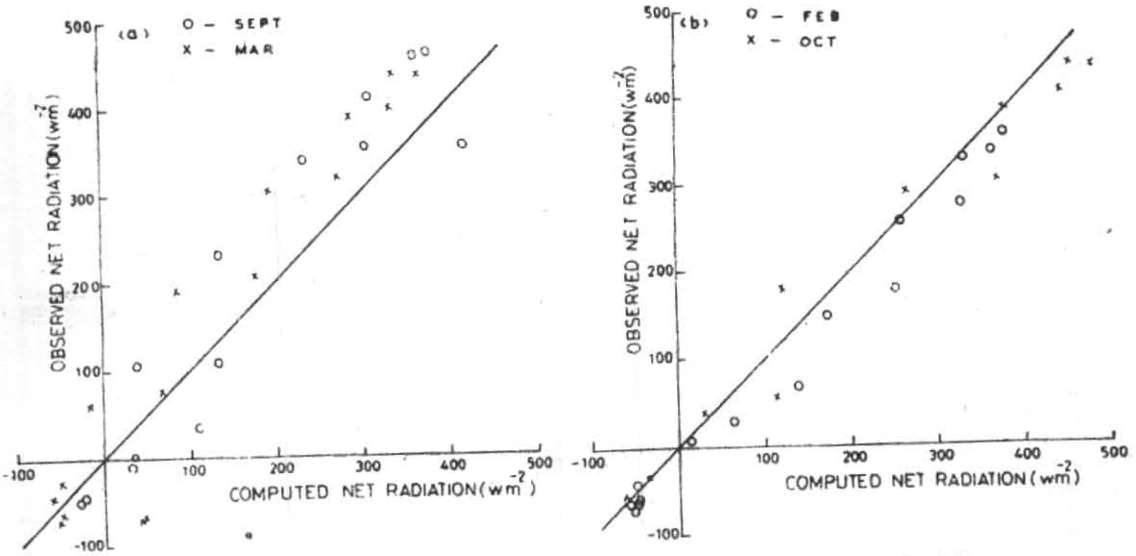


Fig. 1(a)

Fig. 1(b)

Figs. 1(a&b). A plot between observed and computed net radiation for the four months of the year for the city of Delhi

Here $i = 1$, 2, and 3 represents low, medium and high cloud types respectively. C_i is the cloud cover of each category, T_i values may be obtained from Schayes (1982).

(*i*) *Net longwave radiation* — According to Budyko (1974), the dependence of net longwave radiation on humidity is given as :

$$I_0 = \delta_2 \, \sigma T^4 \, (.254 - .0066 \, e) \tag{10}$$

The effect of cloudiness on net longwave radiation is usually accounted for by the following formula :

$$I = I_0 \, [1 - (C_B' C_1 + C_O' C_2 + C_H' C_3)] \tag{11}$$

Finally the net radiation is given as :

Net shortwave radiation (R_0) *minus*

Net longwave radiation (I)

(*ii*) *Ground heat flux* — Following empirical relations for G based on Nickerson and Similey (1975) have been used :

$$G = .19 \, R \text{ (daytime)} \tag{12}$$

$$G = .32 \, R \text{ (night time)} \tag{13}$$

(*iii*) *Latent heat flux* — The following formula after DeBruin and Holtslag (1982) have been used for the estimation of latent heat flux :

$$LE = \alpha' \frac{S}{S+\gamma} (R - G) + \beta \tag{14}$$

Appendix I contains the details for the computation of S.

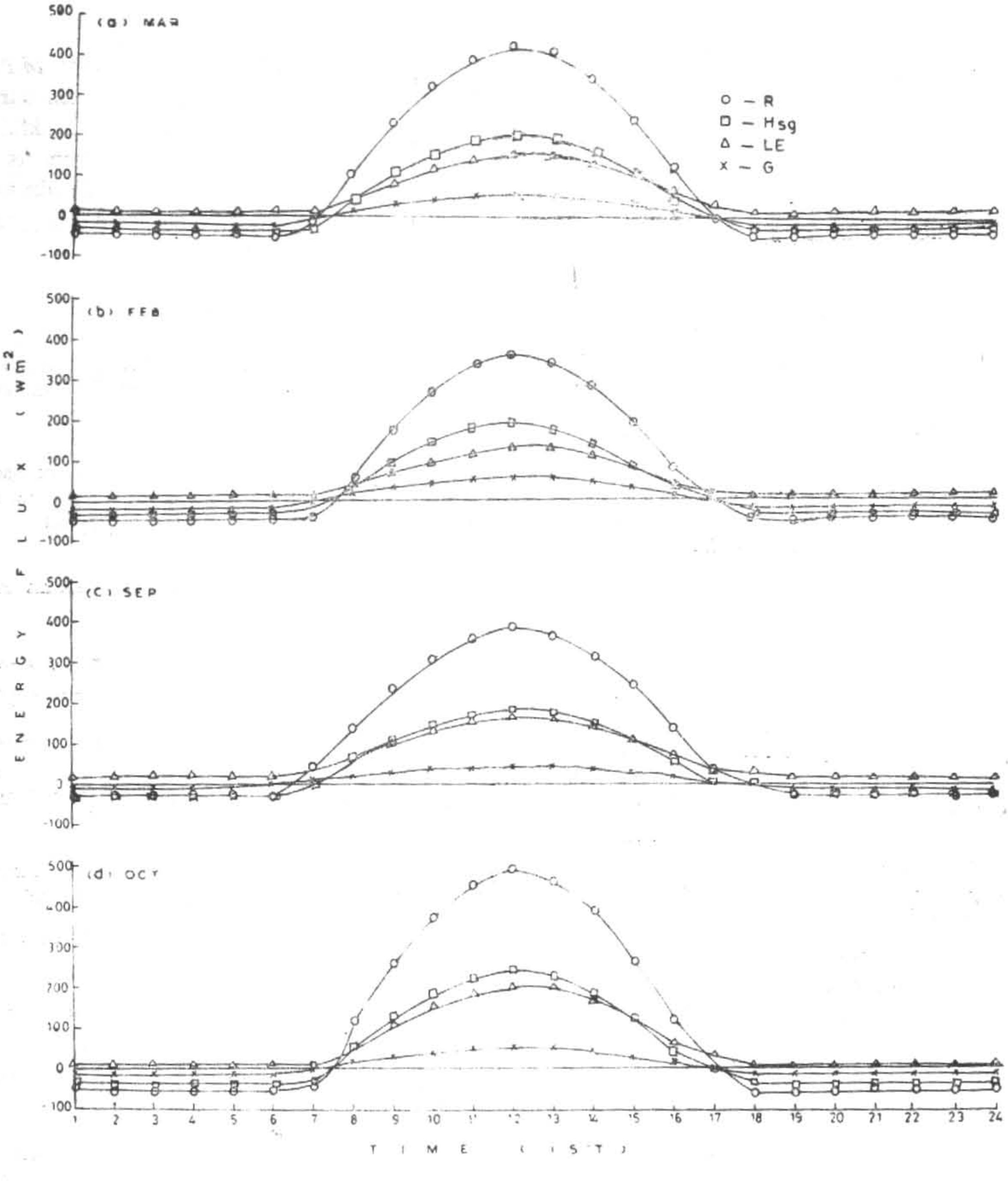
(*iv*) *Sensible surface heat flux* — From Eqns. (1) and (14) we get the following for the estimation of sensible surface heat flux :

$$H_{sg} = (1 - \alpha') \frac{S}{S+\gamma} (R - G) - \beta \tag{15}$$

4. Results and discussion

Computed net radiation has been verified with the observations given by Mani (1980), for October, February, March and September selected as four representative months of the season for the city of Delhi. The plots in Figs. 1(a) and 1(b) between observed and computed net radiation, show that most of the points lie close to the straight line region. The correlation coefficient for October, February, March and September is .9879, .9893, .9881 and .9872 respectively implying a good agreement of R with observations.

Figs. 2(a-d) show the diurnal variation of R, G, LE and H_{sg} for the month of March, September, February and October respectively. The maximum amount of R is noted in the month of October followed by March, September and February. We find that rest of the fluxes follow more or less the same trends in their diurnal variation.



Figs. 2(a-d). Diurnal variation of R, H_{sg}, LE and G for the four months of the year of the city of Delhi

In the daytime, relatively large positive values of the radiation balance are converted to latent heat, sensible heat and heat exchange in the soil. In this situation, the latent heat flux is noticeably larger than the sensible surface heat flux, and the heat inflow into the soil is considerably less than either the latent heat flux or the sensible heat flux.

At night R, G and H_{sg} are negative which are comparatively small in their absolute values, and the heat expense due to evaporation is very small as there is no source of energy at night. Outgo of radiative heat is compensated by the gain of heat from the turbulent sensible heat flux and heat outflow from the soil.

Table 1 shows the comparison between observed and computed values of twentyfour hours integrated latent heat flux for the four representative months of the season. Observed values of latent heat flux from Pan evaporimeter in mm has been obtained from evaporation data of the observatories published by India Meteorological Department, New Delhi. The results show that computed LE is less than the observed LE. This suggests that the value of β in Eqn. (13) from DeBruig and Holtslag (1982) should be more than 20 wm^{-2} at this latitude. The flexibility for the value of β can also be observed from the scatter in their data set which varies between -10 and $+100$ wm^{-2} for summer conditions. Based on observations, it appears that the value of β of 35 wm^{-2} will be more appropriate for summer conditions and $\simeq 30$ wm^{-2} for winter and pre-monsoon season and 25 wm^{-2} for monsoon season.

A release of pollutants, *viz.*, particulate matters, aerosols etc leads to an increase in atmospheric turbidity. A sensitivity test for the month of March shows that increasing the turbidity causes a significant amount of depletion in net radiation. For instance, an increase of turbidity by a factor of two decreases the net radiation from 14% (12 IST) to 50% (8 IST).

5. Conclusions

With the help of simple empirical formulae and routine meteorological surface observations diurnal variation of radiative, soil heat, latent heat and sensible surface heat flux have been computed for the four representative months for the city of Delhi. R has been computed after taking into consideration all possible kinds of attenuation from the various species present in the atmosphere. R and LE on comparison shows a good agreement with observations.

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Appendix I

The saturation vapour pressure at air temperature T is given as :

$$e_s = e_0\, 10^{A'(e_0) - (B')e_0/T} \tag{1}$$

where $e_0 = 10$ mb, $A'(e_0) = 8.4051$ and $B'(e_0) = 2353$.

The vapour pressure e is defined as (Gill 1982)

$$e = p.r/(.62197 + r) \tag{2}$$

where r is given by the relation

$$r = RH.\, r_s \tag{3}$$

Putting $e = e_s$ in Eqn. (2), we get following expression for r_s:

$$r_s = .62197.\ \ x/1 - x \tag{4}$$

where $x = e_s/P$.

Slope of saturation vapour pressure *versus* temperature curve can be given as :

$$S = \partial e_s/\partial T = e_0\ 10^{A'(e_0) - B'(e_0)/T}\ \frac{B'(e_0)}{T^2} \tag{5}$$

$$S = \frac{e_s B'(e_0)}{T^2} \tag{6}$$