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Surface fluxes over Goa during Indian monsoon

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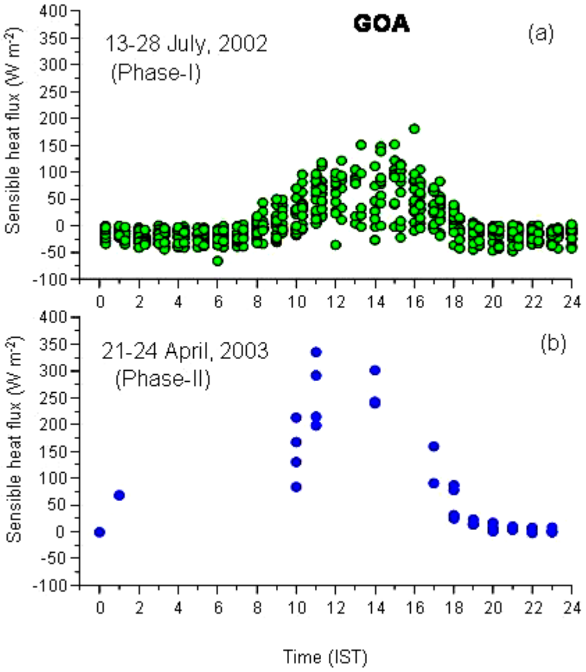
सार – इस शोध–पत्र में आरमेक्स के अपतटीय द्रोणी (चरण – I) और उष्ण जल कुँड अभियान (चरण –II) के दौरान वास्को डि गामा, (15° 21′ उ., 73° 51′ पू.) गोवा में स्थित राष्ट्रीय अंटार्कटिक और महासागर अनुसंधान केंद्र (एन. सी. ए. ओ. आर.) के परिसर में पश्चिमी तट पर सतह के संवेदी उष्मा फ्लक्सों की परिवर्तनशीलता का अध्ययन किया गया है। सतह से 5 मी. ऊपर सॉनिक एनिमोमीटर द्वारा मापे गए संवेदी उष्मा फ्लक्स 13–28 जुलाई 2002 (चरण – I) के दौरान –50 से 150 डब्ल्यू. एम.$^{-2}$ तथा 21–24 अप्रैल 2003 (चरण – II) के दौरान –5 से 350 डब्ल्यू. एम.$^{-2}$ रहे। गोवा में तटीय वायुमंडलीय धरातल की सतह अप्रैल 2003 में रात के समय में लगभग निष्प्रभावी (लगभग शून्य ताप फ्लक्स) पाई गई जबकि जुलाई 2002 में स्थिर (ऋणात्मक उष्मा फ्लक्स) पाई गई है। सतह से 2 मी. ऊपर एपले रेडियोमीटर से मापी गई सौर विकिरण के सभी घटकों का उपयोग नेट विकिरण का परिकलन करने के लिए किया गया है जो कि अप्रैल 2003 में दोपहर के समय 900 डब्ल्यू. एम.$^{-2}$ था। दिन के समय में नेट सौर विकिरण आगामिक लघु तरंग विकिरण के लगभग बराबर होती है क्योंकि धरातल से लघुतरंग विकिरण (–100 डब्ल्यू. एम.$^{-2}$) के परावर्तन के कारण हुई कमी को नेट दीर्घ तरंग विकिरण (100 डब्ल्यू. एम.$^{-2}$) पूरा करती है। देर रात्रि के समय में धरातल की सतह पर उच्च पवनों का तथा सूर्योदय के आस पास और सूर्यास्त के बाद शांत पवनों का पता चला है जिससे दैनिक वक्र में दो मिनिमा की बढ़ोतरी होती है। धरातल की ऊपरी सतह पर समुद्र समीर के प्रभाव का इसमें विवेचन किया गया है।

ABSTRACT. Variation of surface sensible heat flux over the west coast in the premises of National Center for Antarctic and Ocean Research (NCAOR), Vasco-da-Gama (15° 21' N, 73° 51' E), Goa during Offshore trough (phase-I) and Warm pool campaigns (phase-II) of ARMEX is studied. Sensible heat flux as measured by sonic anemometer at 5 m above surface is -50 to 150 Wm^{-2} during 13-28 July, 2002 (phase I) and -5 to 350 Wm^{-2} during 21-24 April, 2003 (phase II). Coastal atmospheric surface layer at Goa during night time is found to be near neutral (nearly zero heat flux) in April 2003 whereas stable (negative heat flux) in July 2002. All components of solar radiation measured by Eppley radiometers at 2 m above surface are used to compute net radiation which is 900 Wm^{-2} at noon in April 2003. Net solar radiation is nearly equal to incoming short wave radiation during daytime as net long wave radiation (100 Wm^{-2}) compensates the loss due to reflection of short wave radiation (-100 Wm^{-2}) by the ground. High winds in the surface layer are observed during late night hours with calm winds around sunrise and after sunset giving rise to two minima in the diurnal curve. Influence of sea-breeze on the surface layer over land is discussed.

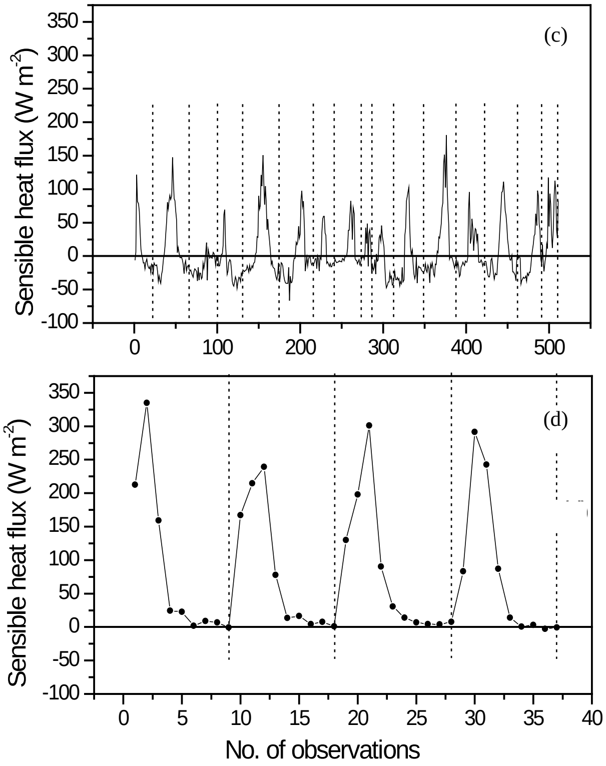
Key words – ARMEX Sensible heat flux, Land-Sea breezes, Solar radiation, Goa.

1. Introduction

Surface energy fluxes play an important role in determining the temperature and moisture profiles in the atmospheric boundary layer (ABL). The net solar energy received at the surface is partitioned into sensible and latent heat fluxes and transported vertically to higher levels in ABL by turbulence. The depth of turbulent mixing and lifting condensation level (LCL) depend mainly on sensible heat flux and evaporation at the surface respectively. Cloud cover over a region during fair weather conditions depends on the number of unsaturated surface air parcels reaching their LCLs (Stull, 1988). Land-surface processes control the surface layer energy fluxes and surface temperature. Horizontal heterogeneity of the land surface creates spatial gradients in temperature and water vapour content of the atmospheric boundary layer. Over coastal areas large gradients in air temperature due to land-sea contrast results in the formation of land and sea breezes. These local circulations change the weather on either side of the coast significantly over a few hundred kilometers. At times large-scale synoptic flow like summer monsoon may be influenced by the local circulations or *vice versa*. These small-scale processes (sub-grid scale process in large-scale numerical weather forecast models) are to be understood and parameterized to be incorporated into weather forecast models in order to reduce the uncertainty in prediction. In order to apply the surface energy flux parameterization scheme, say simplified profile method (Bolle and Streckenbach, 1993)



Figs. 1(a&b). Diurnal variation of sensible heat flux (from Sonic) during ARMEX at Goa



Figs. 1 (c&d). Time series of sensible heat flux during (c) 13-28 July, 2002 and (d) 21-24 Apri1, 2003

for inhomogeneous terrain like coastal areas, measurements over coastal areas are necessary for validation.

Measurement of surface fluxes and profiles over the west coast of India were planned for the Arabian Sea Monsoon Experiment (ARMEX) 2002-03 which aims at understanding better the heavy rainfall events on the west coast during the Indian summer monsoon. A micrometeorological tower of 9 m height was installed in the premises of National Center for Antarctic and Ocean Research (NCAOR), Vasco-da-Gama, Goa for measuring the surface energy fluxes and profiles of meteorological parameters in the coastal surface layer. Results of the analysis of data collected during the two field campaigns of ARMEX are presented in this paper.

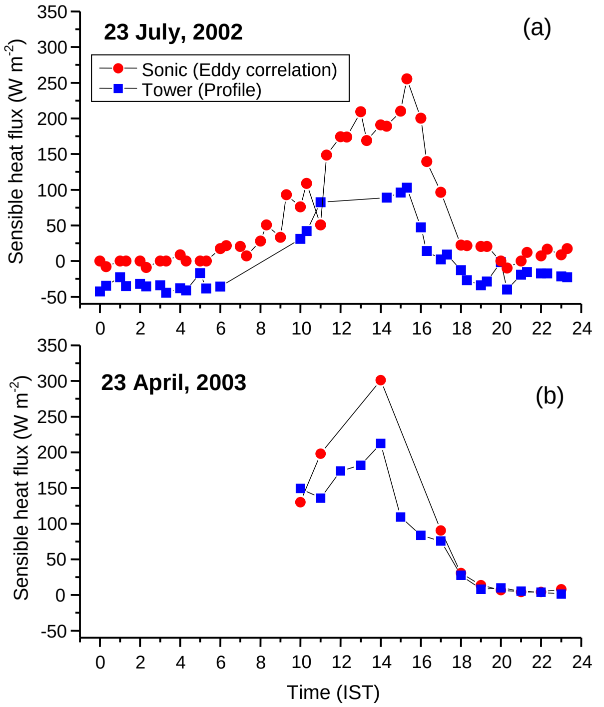
2. Experimental setup and topography of the site

The tower is located on headland (58.5 m AMSL) at 25-30 m away from the coast in the premises of National Center for Antarctic and Ocean Research (NCAOR), Vasco-Da-Gama (15° 21' N, 73° 51' E), Goa. Location of the tower with respect to the coastline of Goa can be seen in Fig. 1 of Sukumaran *et al.*, (2004) in this volume at 213-220. The base of the tower is ~ 30 m above the water surface near the coast. Meteorological parameters (wind speed, direction, air temperature, relative humidity) were measured at 1, 2, 5 and 8 m AGL. Solar radiation components were measured at 2 m AGL. Sensible heat flux is measured at 5 m AGL using sonic anemometer (Applied Tech., USA in phase-I and METEK, Germany in phase-II). Details of the experimental setup are available in IITM research report (Sivaramakrishnan *et al.*, 2003). The footprint of measurements at 5m AGL for sensible heat flux estimation by sonic anemometer covers about 250 m (50 times of measurement height) which mainly consists of the Arabian Sea coastal waters in the upwind southwest direction. NCAOR buildings are located at ~ 150-200 m away to the north of the tower.

3. Results and discussion

3.1. *Heat flux in phase I and II*

The phase-I of ARMEX (Offshore trough) was conducted during 15 June – 15 August, 2002. The phase-II of ARMEX (Warm pool) during 15 March - 15 May, 2003 is the pre-monsoon period with instability building up in the atmosphere due to intense solar heating of the surface. Surface sensible heat flux (SHF) at Goa during the two phases of ARMEX was computed by eddy correlation method using sonic anemometer data. In phase-I sonic anemometer (Kaimal's probe) manufactured



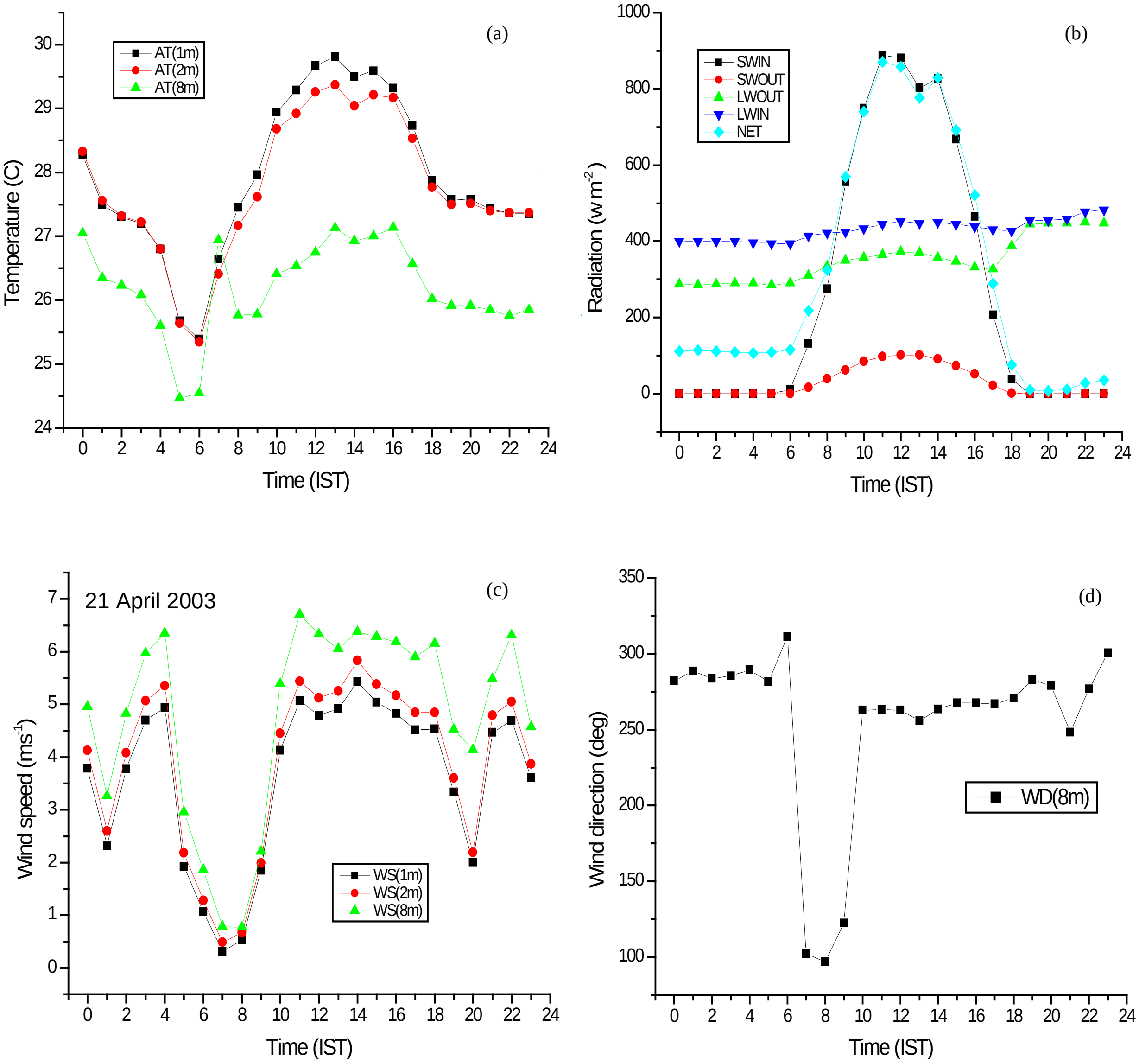
Figs. 2(a&b). Sensible heat flux by eddy correlation (at 5 m AGL) and profile (at 1.4 m AGL) methods

by Applied Tech. Inc., USA was used. It has 3 pairs of transducers in 3 perpendicular directions. METEK's (Germany) sonic anemometer that belongs to Indira Gandhi Center for Atomic Research (IGCAR) was installed in mid April 2003 for phase-II as the former one was malfunctioning. Diurnal variation of SHF during the two periods *viz*., 13-28 July, 2002 (phase-I) and 21-24 April, 2003 (phase-II) are shown in Figs. 1(a&b) respectively. No/weak offshore trough was noticed with scattered convection during 13-28, July 2002. During this period the monsoon in the Arabian sea was weak/moderate and continuous sonic data were available. Sonic anemometer gives erroneous data during drizzle/ rain. Hence sonic data were noisy during active period (4-10 August, 2002) with convection and rainfall. It was observed that peak SHF at 1400 hr (IST) during phase-II (300 Wm^{-2}) was 1.5 times of that during phase-I (200 Wm^{-2}). During night hours SHF in phase-I became negative (-40 Wm^{-2}) where as it was 10 Wm^{-2} during phase-II. It indicates that the surface layer was either unstable or near neutral during phase-II (summer 2003) and not becoming stable even during night hours. This may be due to the fact that negative temperature gradient between the ground and surface layer is maintained even after sunset due to cooler sea-breeze flowing across the shore.

Time series of SHF during phase I and II of ARMEX are shown in Figs. 1 (c&d) respectively. Vertical dotted lines indicate the days from 13th to 28th [Fig. 1 (c)]. A few hour data are not available on some days as is evident in the separation of vertical lines. During phase I SHF [Fig. 1 (c)] was observed to vary much in terms of its magnitude and the time at which it attains maximum value. This variability in the time corresponding to the peak SHF seems to be due to passing clouds in the monsoon flow over the site. Day-to-day variation of peak SHF during the period is due to variation in the intensity of monsoon activity. Clouds (that attenuate incoming solar radiation) and moderate weak monsoon flow alter surface SHF over the coast. SHF attained its peak between 1100-1600 hr (IST) during phase I. A few hour data during early morning and noon hours are not available during phase II. During 21-24 April, 2003 (Phase II) SHF attained maximum value around 1100 hr (IST). Day-to-day variation in the maximum value of SHF was around 300-350 Wm^{-2} during Phase II (21-24 April, 2003) as shown in Fig. 1 (d).

3.2. *Profile vs Eddy correlation technique*

Figs. 2(a&b) shows the comparison of sensible heat flux estimated by eddy correlation and simplified profile method (hereafter profile method) for any day, chosen arbitrarily (say, 23rd day in July 2002 and 23rd April 2003) in phase-I and II. Eddy correlation method is considered as the best (direct) method that gives very accurate estimate of sensible heat flux since contribution from all frequencies (eddy of all sizes) is measured by a fast-response instrument like sonic anemometer. Profile method uses vertical gradients of hourly/half-hourly mean parameters (wind and temperature) measured by mechanical devices (like cup anemometer) which cannot measure high frequency variations and hence results in under-estimation of flux. There are some advantages in profile method. One can check the quality of slow data (from conventional sensors) by looking at the mean profiles and then compute flux. This is not possible with turbulence data at 10/20 Hz (Foken and Wichura, 1996). Over a homogeneous terrain both the methods are supposed to agree well. Sensible heat flux (30 minute mean in phase-I and 60 minute mean in phase-II) by profile method was observed to be -50 to 100 Wm^{-2} in Phase I (23 July, 2002) and 10 to 210 Wm^{-2} in Phase II (23 April, 2003) of ARMEX Figs. 2(a&b). Over this terrain a difference ~ 100 Wm^{-2} was observed at 1300-1400 hr (IST) between the two methods Figs. 2(a&b). Under very unstable (peak SHF) conditions in the surface layer, turbulence intensity being relatively high, the contribution from high frequencies (small eddies) to the SHF seems to be significant. Cup anemometer may not be able to respond to these high frequencies which results in large under estimation of SHF by profile method during



Figs. 3(a-d). Diurnal variation of air temperature (AT), radiation (SW, LW), wind speed and direction (WD) on 21 Apri1, 2003 at Goa. Temperature and wind are given at 1, 2 and 8 m AGL. Direction at 8 m AGL. Radiation at 2 m AGL

very unstable conditions around 1300-1400 hr IST. However, at 1100 hr (IST) on 23 July, 2002 [Fig. 2(a)] profile method shows a higher value than eddy correlation method. Similar diurnal variation of SHF by both the methods was observed. Here hourly mean data at 1 and 2 m AGL were used in estimating sensible heat flux by simplified profile method (Bolle and Streckenbach, 1993). Details of this method are given in Appendix A. In eddy correlation method sonic anemometer (at 5 m AGL) data at 10 Hz were used. The top of the internal boundary layer over the site at the location of the tower (~ 25-30 m from the coastline) due to surface roughness change from sea to land lies between 2 and 5 m as inferred from '*kinks*' in wind and temperature profiles (Sivaramakrishnan *et al.*, 2003). In the profile method first two levels measurements on the tower are used as they fall within the internal boundary layer. Thus the difference in the estimates of SHF at all times by the two methods can be attributed to the existence of IBL. The foot print of the estimates at two levels *i.e.*, one within IBL and the other above IBL, is not the same due to non-homogeneous surface in the upwind direction. This could be one of the reasons for the relatively large difference in the flux estimates by the two methods.

3.3. *Land-breeze*

Land/Sea breeze is a common feature at any coastal site. At Goa, sea-breeze gets superimposed by the monsoon flow during the ARMEX phase-I period (monsoon season). It is difficult to delineate sea-breeze from monsoon flow in the tower observations. Sea-breeze can be expected to be detected in measurements on the tower during 'Warm pool' period (April 2003) because of large land-sea temperature contrast and change in the direction of synoptic flow. Figs. 3(a-d) shows the diurnal variation of air temperature [Fig. 3(a)], solar radiation [Fig. 3(b)], wind speed [Fig. 3(c)] and direction [Fig. 3(d)] on 21 April, 2003. Winds were observed to be southwesterly (260° - 280°) through out the day except during 0700-0900 hr (IST) when winds became nearly easterly (100° - 125°). This sudden change in the wind flow from the sea (sea-breeze) to the land (land-breeze) results in horizontal wind speed falling to as low as 0.5 ms^{-1} at around 0700-0800 hr (IST). This land-breeze last till 0900 hr (IST) and sea-breeze dominated again at 1000 hr (IST). Corresponding to the land-breeze during early morning hours, air temperature dropped from 27° C to 26° C at 8 m level but there is hardly any effect on the temperature at 1 and 2 m AGL. It may be due to local heating dominating very close to the ground just after Sun rise with incoming shortwave solar radiation rising from 100 Wm^{-2} at 0700 hr (IST) to 300 Wm^{-2} at 0800 hr (IST). The distinct feature at this coastal site is prevalence of high winds during late night hours and dropping steeply before Sunrise and after Sunset that caused two minima in diurnal wind speed variation [Fig. 3(c)]. More cases needed to be studied to confirm the consistency of this feature at Goa.

All four components of solar radiation *viz*., incoming shortwave radiation (SWIN), reflected shortwave radiation (SWOUT), outgoing long wave radiation (LWOUT), incoming long wave radiation (LWIN) and net radiation (NET), were measured by Eppley radiometers at 2 m AGL at the site. Net radiation is the sum of all four components (NET = SWIN + LWIN – SWOUT – LWOUT). Solar radiation energy budget is depicted on a typical day (21 April, 2003) with their diurnal variation plotted in Fig. 3(b). Normal diurnal variation of SWIN was observed between 0600 and 1800 hr (IST) with a peak 900 Wm^{-2} at 1200 hr (IST). During daytime NET and SWIN were observed to be equal. This is because the net long wave radiation (LWIN – LWOUT) of 100 Wm^{-2} compensated the loss (-100 Wm^{-2}) due to reflection of short wave radiation by the ground. That is why in many studies net radiation is taken as incoming shortwave solar radiation, assuming that net long wave radiation is nearly zero during daytime.

4. Conclusions

(*i*) Coastal atmospheric surface layer at Goa during night time was observed to be near-neutral during pre-monsoon (21-24 April, 2003) whereas stable in the monsoon season (13-28 July, 2002).

(*ii*) Net radiation (on 21 April, 2003) was found to be nearly equal to the incoming short wave radiation during daytime as net long wave radiation cancels the reflected short wave radiation.

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Appendix A

Simplified profile method (Bolle and Streckenbach., 1993) to estimate sensible heat flux (*H*)

In this method bulk-Richardson number, R_i is defined as

$$R_i = [(z_1\text{-}d)\ (z_2\text{-}d)]^{1/2}\ \ln[(z_2\text{-}d)/(z_1\text{-}d)]\ [g/\Theta]\ [(\Theta_2\text{-}\ \Theta_1)/(U_2\text{-}U_1)^2]$$

Here the stability parameter R_i is not a function of the sensible heat flux and consequently no iteration procedure is needed. In the following relations (Perrier and Tuzet, 1991; Goutrobe, 1991) this parameter is used to estimate directly the sensible heat flux under different stability conditions.

Under very unstable conditions ($R_i < -1$) *H* is estimated by (free convection expression)

$$H = \alpha\ (\Theta_2\text{-}\ \Theta_1)^{3/2}$$

With

$$\alpha = [\rho\ C_P\ (g/\Theta)^{1/2}\ C]\ /\ [3^{3/2}\ \{(z_1\text{-}d)^{-1/3} - (z_2\text{-}d)^{-1/3}\}^{3/2}]$$

where the constant C is often taken as 1.3.

Under unstable conditions close to neutral, ($-1 < R_i < 0$), *H* is obtained with

$$H = H_o\ (1\text{-}16R_i)^{3/4}$$

Under stable stratified conditions close to neutral, ($0 < R_i < 0.14$),

$$H = H_o\ (1\text{-}5R_i)^2$$

Whereas for very stable conditions ($R_i > 0.14$) *H* is given by

$$H = H_o/10$$

In the above equations, H_o is the sensible heat flux given for neutral conditions.

$$H_0 = -\ \rho\ C_P\ k^2\ [(\Theta_2\text{-}\ \Theta_1)\ (U_2\text{-}U_1)\ /\ \ln^2\ \{(z_2\text{-}d)/(z_1\text{-}d)\}]$$

ρ – air density; C_P – specific heat at constant pressure; k (=0.4) – Von Korman constant

d – displacement height; Θ_1 – Potential temperature at height z_1; Θ_2 – Potential temperature at height z_2; U_1, U_2 – Horizontal wind speed at z_1 and z_2 respectively; g – acceleration due to gravity.

It is assumed that the displacement heights for momentum and for heat are identical.