Land-Atmosphere Interactions from Canopy to Troposphere

A study of similarity, roughness characteristics and scaling using data from SMEX02 and EAGLE2006 campaigns

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A study of similarity, roughness characteristics and scaling using data from SMEX02 and EAGLE2006 campaigns

by

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This document describes work undertaken as part of a programme of study at the International Institute for Geo-information Science and Earth Observation. All views and opinions expressed therein remain the sole responsibility of the author, and do not necessarily represent those of the institute.
To my wife Leila, my son Arash, and my parent
Abstract

Quantification of the relationships between land surface and the atmosphere in terms of water and energy exchange is of great importance to understand and predict the behavior of the Earth, as a system of systems. In this research, interactions of land surface and the atmosphere aloft (up to the troposphere) in terms of energy exchange were studied in the framework of flux-gradient relationships of the Monin-Obukhov Similarity Theory (MOST) and the Bulk ABL Similarity Theory (BAST) inherent in the Surface Energy Balance System (SEBS).

The main objectives of this research was to study the land-atmosphere interactions at different crop phenological and atmospheric states, comparison of SEBS modeled versus optimized effective roughness lengths, and development a disaggregation scheme for flux partitioning.

METFLUX tower and radiosonde observations from SMEX02 campaign (Walnut Creek watershed) and EAGLE2006 campaign (Cabauw Tower) were used in this research.

Profiles of temperature, wind speed and humidity from radiosonde observations were used to evaluate the effectiveness of partitioning of sensible heat flux ($H$) and to study the important affecting parameters. In addition, an analysis of the integrity of the model implemented in SEBS for estimation of roughness lengths is evaluated with comparing $z_{0m}$ and $z_{0h}$ values of this model and ones retrieved from an optimization scheme.

Results showed that roughness length parameters vary during the course of day and during the crop phenological development and are sensitive to meteorological conditions as well as the source/sink states. Also, optimized $z_{0m}$ and $kB^{-1}$ values exceeding the constant values proposed in the literatures.

Comparison of optimized roughness values with SEBS roughness sub-model showed that SEBS method is accurate; however, it needs further enhancements/improvements to include diurnal variations of $kB^{-1}$ and dependence of $z_{0m}$ into roughness sublayer and diabatic instability effects.

Results revealed that even with the best observed meteorological and crop phenological parameters required by SEBS internal roughness sub-model and with the use of direct flux-gradient equations (excluding the need for net radiation and soil heat flux), there are differences between the results of this model and optimized ones. SEBS roughness sub-model shows constant $z_{0m}$ (0.02 for soybean and 0.07 for corn) and $kB^{-1}$ (5.5 for soybean and 6 for corn) while their respective optimized $z_{0m}$ values reach to 0.11 (for soybean) and 0.6 (for corn) and corresponding $kB^{-1}$ values to 13 (for soybean) and 10 (for corn). Using SEBS roughness sub-model values instead of optimized roughness values results an average error of 27 $Wm^{-2}$ in calculation of sensible heat flux for both crops.

In addition, simulation of the land-atmosphere interactions with SEBS MOST and BAST functions revealed that implementing air temperature from ABL mixed-layer gives reasonably good estimate of sensible heat flux, particularly at noon times at SMEX02 study area. This is of potential to derive a flux partitioning scheme when good knowledge of air temperature at canopy level is not available with required spatial resolution.
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1 Introduction

Quantification of the relationships between land surface and the atmosphere in terms of water and energy exchange is of great importance to understand and predict the behavior of the Earth, as a system of systems. This importance highlights when we try to have better insight of the processes related to the exchange of heat in terms of sensible heat ($H$) and latent heat ($\lambda E$) in both local and global scales.

There are normally categorization of energy balance schemes as 1) surface energy balance (SEB) models, 2) atmospheric boundary layer (ABL) slab models, and 3) coupled SEB-Slab models.

For the first category (SEB), models like Surface Energy Balance System (SEBS) (Su 2002) or Two-source Surface flux Model (TSM) ((Norman, Kustas et al. 1995), (Norman, Anderson et al. 2003)) work well with coherent physically-based theoretical background for quantification of energy processes (See (Kalma, McVicar et al. 2008) for a review).

In the second category, mixed-layer or slab models of the atmospheric boundary layer (ABL) have long been used for coupling of the land-atmosphere water and energy balances, and the partitioning of incoming solar energy into sensible and latent heat fluxes (Porporato 2009). The slab models have been pioneered by (Tennekes 1973) and (Carson 1973), and further developed by (Tennekes and Driedonks 1981), (Driedonks and Tennekes 1984) and many others, to analyze the growth of the ABL and the dynamics of the inversion at its top. Afterwards, slab models were theoretically coupled to the surface water and energy balance models in order to justify the effects and dynamic feedbacks of vegetation and roughness conditions between the ASL and atmosphere aloft. ((De Bruin 1983); (McNaughton and Spriggs 1986); (Mahrt 2000); (Porporato 2009)).

As a distinct example of the third category (coupled SEB-Slab models), the two-source time-integrated model (TSTIM) was developed by (Anderson, Norman et al. 1997) which was an extension of the earlier TSM model of (Norman, Kustas et al. 1995) with coupling to the slab model of (McNaughton and Spriggs 1986). TSTIM and its successor, the Atmosphere-Land Exchange Inverse (ALEXI) model, couple a two source land surface model and one dimensional ABL model. Then, with the Disaggregated ALEXI (DisALEXI) algorithm of (Norman, Anderson et al. 2003), it partition the coarse resolution (5-10 km) flux estimates of ALEXI to micro-meteorological scales (~100 m).

In this research, interactions of land surface and the atmosphere in terms of energy exchange are studied in the framework of flux-gradient similarity theory functions of Surface Energy Balance System (SEBS) (Su 2002). Similarity theory formulated as standard Monin-Obukhov flux-gradient functions is the main part of many physically-based surface energy balance (SEB) evapotranspiration schemes. This scheme is utilized in the most complete form in SEBS (Surface Energy Balance System) of (Su 2002). As is originally developed, SEBS includes formulations for heat transfer in the canopy (Su, Schmugge et al. 2001), in the ASL, and in the mixed-layer (Brutsaert and Sugita 1991), (Brutsaert 1982). Therefore, SEBS includes all equations required to simulate momentum and heat transfer from canopy to troposphere (except for the roughness sublayer of tall dense canopies) and is a good choice for a coupled SEB-Slab model.

Although a full slab model for prediction of mixed-layer temperature for SEBS is not developed here, profiles of temperature, wind speed and humidity from radiosonde observations are used to evaluate the effectiveness of partitioning of sensible heat flux ($H$) and to study the important affecting parameters (i.e. roughness lengths) in such a disaggregation scheme. In addition, an analysis of the integrity of the model implemented in SEBS for estimation of roughness lengths (Su,
Schmugge et al. 2001) is evaluated with comparing $z_{0m}$ and $z_{0h}$ values of this model and ones retrieved from an optimization scheme.

In summary, the main objectives of this research are as following:

1. Study of land-atmosphere momentum and heat transfer at different crop phenological and atmospheric states
2. Optimization of effective roughness length parameters and evaluation of SEBS roughness sub-model results for $z_{0m}$ and $k_B^{-1}$
3. Optimization and analysis of roughness length for water vapor transfer ($z_{0v}$)
4. Evaluation of the effectiveness of partitioning of sensible heat flux ($H$) in a coupled SEBS-Slab framework

This research is formulated as a thesis including the following 7 chapters:

In chapter 1 (this chapter), the general introduction is given.

In chapter 2, the modeling framework of this research is introduced in details. In this chapter, dominant equations for the transfer of momentum and heat within canopy, atmospheric surface layer (ASL) and mixed-layer of SEBS are introduced and an optimization scheme for estimation of the best representative effective roughness length parameters is given.

In chapter 3, an introduction to the study area including SMEX02 and EAGLE2006 campaigns are presented. A brief introduction to each campaign, measurement protocols, and data used in this research is presented and further important references for obtaining data or their related documentations are introduced.

In chapter 4, analysis of the effective roughness parameters ($z_{0m}$, $z_{0h}$, and $z_{0v}$) retrieved from the optimization scheme is presented and comparative analysis with the modeled values of SEBS internal roughness sub-model (Su, Schmugge et al. 2001) is made.

In chapter 5, interactions of land surface and atmosphere in terms of momentum and heat exchange are analyzed from canopy level to the inversion cap using a combination of tower and radiosonde observations of Walnut Creek watershed and with SEBS MOST and BAST flux-gradient formulations.

In chapter 6, a sensible heat flux partitioning and disaggregation scheme is described with the use of radiosonde observation profiles. These profiles are then analyzed in regard to the time of the day and in consideration of the accuracy of effective roughness parameters.

In chapter 7, concluding remarks and comments resulted from previous chapters are presented, highlighting further research requirements.
Model Description

In this chapter, the modeling scheme used for simulation of land-atmosphere interactions in this research is introduced. It covers relevant equations for calculation of flux terms from the canopy to the atmosphere aloft, up to the troposphere.

First an introduction to the main important functions used for calculation of meteorological parameters is presented. Although these formulas are available in the source code of SEBS (in C++ and IDL) and in basic hydro-meteorological texts (i.e. (Campbell and Norman 1998), (Anderson and McDonnell 2005), however, a rather complete reference is desirable. Next, the general structure of the atmosphere and the index heights distinguishing the vertical domain of canopy, ASL, and mixed layer are introduced.

Formulation of the flow in the canopy (section 2.3), in the ASL (section 2.4) and in the mixed layer (section 2.5) are then described and are based on the components described in the Surface Energy Balance System (SEBS) scheme (Su 2002). Therefore, for the flow in the canopy, the method described in (Su, Schmugge et al. 2001) is used. In the ASL, formulation of Monin-Obukhov Similarity Theory (MOST) and in the mixed layer, the formulation of the Bulk Atmospheric Similarity Theory (BAST), as described in (Brutsaert 2005) are used. In section 2.6, a simple scheme used for optimization of effective roughness parameters is introduced.

Although SEBS includes functions and formulas for all parts of Surface Energy Balance System, those parts related to indirect extraction of fluxes (e.g. radiation and soil heat flux) are not presented nor used in this research.

2.1 Meteorological Parameters

Some important formulas used in canopy, MOST, and BAST formulations of SEBS are introduced as following:

**Potential temperature** (Brutsaert 2005)
The potential temperature is the temperature that would result if air were brought adiabatically to a standard pressure level \( p_0 = 1013.25 \, hPa \) and is as following (Poisson’s equation)

\[
\theta = T \left( \frac{P_0}{P} \right) \frac{R_d}{c_p}
\]

\( \theta \) Potential air Temperature (°K)
\( T \) Absolute air Temperature (°K)
\( P_0 \) Atmosphere pressure at reference level (101325 Pa)
\( P \) Atmosphere pressure (Pa)
\( R_d \) Gas constant for dry air (287.04 \( Jkg^{-1}K^{-1} \)), (Brutsaert 2005: Table 2.1)
\( c_p \) Specific heat for water vapor at constant pressure (\( Jkg^{-1}K^{-1} \))

**Specific heat for water vapor** at constant pressure (Brutsaert 2005: P 29):

\[
c_p = q \, c_{pw} + (1 - q) \, c_{pd}
\]

\( q \) Specific humidity \( (kg \, kg^{-1}) \)
\( c_{pw} \) Specific heat for water vapor (1846 \( Jkg^{-1}°K^{-1} \))
\( c_{pd} \) Specific heat for dry air (1005 \( Jkg^{-1}°K^{-1} \))
Density of moist air (Brutsaert 2005: P 25)

\[ \rho = \frac{p}{R_d T} \left( 1 - \frac{0.378 e_a}{p} \right) \]

\( \rho \) Density of moist air (\( kg \) \( m^{-3} \))
\( e_a \) Actual water vapor pressure (\( Pa \))

Virtual potential temperature (Brutsaert 2005: P 32)

Virtual potential temperature is the theoretical potential temperature of dry air which would have the same density as moist air and defined by

\[ \theta_v = (1 + 0.61q)\theta \]

\( \theta_v \) Virtual potential temperature (\( ^oK \))
\( q \) Specific humidity (\( kg \) \( kg^{-1} \))
\( \theta \) Potential temperature (\( ^oK \))

2.2 Structure of the Atmospheric Boundary Layer (ABL)

The structure of the ABL is described in many text books (e.g., Garratt 1992; Brutsaert 2005), however, the characteristic heights of each component of the ABL structure are described in Table 2.1, Table 2.2, and Fig. 2.1. Although the boundaries in ABL are not sharp (e.g. Stull 1988), the following categorizing is made here for better referencing of MOST and BAST parameters. The roughness sublayer (RSL) effects are not considered here. Important characteristics of ASL and mixed layer are explained briefly in sections 2.4 and 2.5.

Table 2.1 Shorthand notations for different parts of the ABL

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Meaning</th>
</tr>
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<tbody>
<tr>
<td>( c ) or ( s )</td>
<td>Land surface (at canopy or soil roughness height)</td>
</tr>
<tr>
<td>( asl )</td>
<td>Atmospheric surface layer (ASL)</td>
</tr>
<tr>
<td>( ml )</td>
<td>Mixed layer of the ABL</td>
</tr>
<tr>
<td>( ez )</td>
<td>Entrainment zone (or capping inversion)</td>
</tr>
<tr>
<td>( b )</td>
<td>Bottom of zone, e.g. ( z_{ez,b} ) refers to the bottom of entrainment zone</td>
</tr>
<tr>
<td>( f )</td>
<td>Floor of zone, e.g. ( z_{ez,f} ) refers to the floor of entrainment zone</td>
</tr>
</tbody>
</table>

Table 2.2 Symbols for characteristic heights of the ABL components

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>( h_s )</td>
<td>Height of soil particles</td>
</tr>
<tr>
<td>( h_c )</td>
<td>Height of canopy</td>
</tr>
<tr>
<td>( h_{asl} )</td>
<td>Height of the ASL</td>
</tr>
<tr>
<td>( h_{ml} )</td>
<td>Height of mixed layer</td>
</tr>
<tr>
<td>( h_{ez} )</td>
<td>Height of entrainment zone</td>
</tr>
</tbody>
</table>
2.3 Flow in the Canopy, the Su01 model

Roughness parameters are important in MOST and BAST equations and have great influence on the simulated sensible heat flux. Inter-dependency of equations of Obukhov Length ($L$), friction velocity ($u_*$) and sensible heat flux ($H$) in MOST and BAST exhibits how a wrong estimation of roughness length for momentum transfer ($z_{0m}$) would translate to wrong estimation of $H$ (and consequently into $\lambda E$ in full SEBS scheme). This dependency is analyzed and discussed in chapter 4.

In this section, the methods utilized in SEBS for deriving zero-plane displacement height ($d_0$), roughness length for momentum transfer ($z_{0m}$) and roughness length for heat transfer ($z_{0h}$) are presented.

If only vegetation height ($h_c$) is available, the relationship proposed by (Brutsaert 2005: P 46) as following can be used:

\[
d_0 = 0.5 \, h_c \text{ to } 0.75 \, h_c \\

z_{0m} = 0.1 \, h_c \\

z_{0h} = 0.01 \, h_c
\]

In addition, standard tables for determination of $z_{0m}$ which proposed by (Brutsaert 2005: P45) or (Wiernga 1993) can be used. However, above formulas do not give realistic values (as discussed later in chapter 4).
An alternative way used in SEBS is the framework originally proposed by (Massman 1997) and further developed by (Su, Schmugge et al. 2001). On this basis, if near-surface wind speed and vegetation parameters (e.g. $h_c$ and $LAI$) are available, the within-canopy turbulence model of (Massman 1997) can be used to estimate $d_0$ and $z_{0m}$ based on the following formulation.

**Ratio of $u^*/u_{hc}$**

$$\beta = \frac{u^*}{u_{hc}} = c_1 - c_2 \exp(-c_3 C_d LAI)$$  \hspace{1cm} (2.8)

$c_1 = 0.320, c_2 = 0.264, c_3 = 15.1$

$u^*$ Friction velocity ($m$ $s^{-1}$)

$u_{hc}$ Wind velocity at canopy top ($m$ $s^{-1}$)

$C_d$ Drag coefficient (0.2)

$LAI$ Leaf Area Index (-)

**Within-canopy wind speed profile extinction coefficient**

$$n_{ec} = \frac{C_d LAI}{2\beta}$$  \hspace{1cm} (2.9)

$n_{ec}$ Within-canopy wind speed profile extinction coefficient

**Zero-plane displacement height**

Integration of (Su, Schmugge et al. 2001: Eq. 9) yields

$$d_0/h_c = 1 - \frac{1}{2n_{ec}} \times (1 - e^{-2n_{ec}})$$  \hspace{1cm} (2.10)

$$d_0 = h_c(d_0/h_c)$$  \hspace{1cm} (2.11)

**Roughness height for momentum**

If fractional vegetation cover ($f_c$) calculated from remote sensing or filed data is less than or equal to 0, $z_{0m} = 0.005$ which is for bare soil, otherwise:

$$z_{0m} = h_c(1 - d_0/h_c) \times e^{-k/\beta}$$  \hspace{1cm} (2.12)

where $k$ is von Karman’s constant.

After determination of $z_{0m}$, the relationship between $z_{0m}$ and $z_{oh}$ is formulated as $z_{oh} = z_{0m}/kB^{-1}$ and different parameters for deriving $kB^{-1}$ are explained as following:

**Wind speed at canopy top**

$$u_{hc} = \max\left(0, u_{ref} \times \frac{\log(h_c - d_0) - \log(z_{0m})}{\log(z_{ref} - d_0) - \log(z_{0m})}\right)$$  \hspace{1cm} (2.13)

$u_{ref}$ wind speed at $z_{ref}$ ($m$ $s^{-1}$)

$z_{ref}$ measurement height($m$)

$u_{hc}$ wind speed at canopy top ($m$ $s^{-1}$)
Kinematic viscosity of the air

\[ \nu = 1.327 \times 10^{-5} \frac{p_0}{p_{\text{ref}}} \times \left( \frac{T_{\text{ref}}}{T_0} \right)^{1.81} \]  \hspace{1cm} (2.14)

- \( p_{\text{ref}} \): atmospheric pressure at reference height (Pa)
- \( T_{\text{ref}} \): ambient air temperature at reference height (°K)
- \( T_0 \): reference temperature (273.15 °C)

Roughness Reynolds Number

\[ Re_{s,s} = \frac{h_s u_{*,s}}{\nu} \]  \hspace{1cm} (2.15)
\[ Re_{s,c} = \frac{h_c u_{*,c}}{\nu} \]  \hspace{1cm} (2.16)

- \( Re_{s,s} \): Roughness Reynolds Number for bare soil
- \( Re_{s,c} \): Roughness Reynolds number for mixed canopy and soil
- \( h_s \): height of soil layer (m)
- \( h_c \): height of canopy (m)
- \( u_{*,s} \): friction velocity for soil
- \( u_{*,c} \): mixed friction velocity for soil and canopy

Heat transfer coefficient of the soil

\[ C_t^t = Pr^{-2/3} Re_{s,s}^{-1/2} \]  \hspace{1cm} (2.17)

- \( C_t^t \): heat transfer coefficient of the soil
- \( Pr \): Prandtl number
- \( Re_{s,s} \): Roughness Reynolds Number for bare soil

\( kB^{-1} \) parameter

As formulated by (Su, Schmugge et al. 2001), the \( kB^{-1} \) parameter is derived in three parts of soil, canopy, mixture of soil and canopy, and for soil as following:

\[ kB^{-1} = \frac{C_t}{4C_t \beta(1 - e^{-B/s/2})} + 2 f_c f_s \frac{k\beta z_0}{h_c} \frac{C_t^t}{C_t} + kB_{s}^{-1} f_s^2 \]  \hspace{1cm} (2.18)

- \( C_t \): heat transfer coefficient of leaves
- \( C_d \): drag coefficient of foliage elements
- \( f_c \): fractional canopy coverage
- \( f_s \): fractional soil coverage

For most canopies and environmental conditions, \( C_t \) is bounded as \( 0.005N \leq C_t \leq 0.075N \) (\( N \) is the number of sides of a leaf to participate in heat exchange). In the original SEBS code, \( C_t = 0.01 \).

As stated by (Su 2002), the first term of 2.18 follows the ‘full canopy only’ model of (Choudhury and Monteith 1988), the third term is that of (Brutsaert 1982) for a bare soil surface, while the second term describes the interactions between vegetation and a bare soil surface. For bare soil surface \( kB_{s}^{-1} \) is calculated according to (Brutsaert 1982)

\[ kB_{s}^{-1} = 2.46 Re_{s}^{1/4} - \ln(7A) \]  \hspace{1cm} (2.19)
2.4 Flow in the ASL, the Monin-Obukhov Similarity Theory (MOST)

For determination of sensible heat flux \( H \) in the ASL, the standard Monin-Obukhov Similarity Theory (MOST) is used. Based on (Brutsaert 2005), for Atmospheric Surface Layer (ASL) which refers to the lower parts of the atmosphere (normally lower 10% of ABL), the similarity relationships for the profiles of the mean wind speed, \( \bar{u}_{asl} \), the mean temperature difference, \( \bar{\theta}_c - \bar{\theta}_{asl} \), and the mean humidity difference, \( \bar{q}_c - \bar{q}_{asl} \) are usually written as

\[
\zeta = \frac{z_{asl} - d_0}{L}
\]

\[
L = -\frac{\rho c_p u \theta_v}{kg H}
\]

\[
\bar{u}_{asl} = \frac{u_*}{k} \left[ \ln \left( \frac{z_{asl} - d_0}{z_{0m}} \right) - \Psi_m \left( \frac{z_{asl} - d_0}{L} \right) + \Psi_m \left( \frac{z_{0m}}{L} \right) \right]
\]

\[
\bar{\theta}_c - \bar{\theta}_{asl} = \frac{H}{k u_* \rho c_p} \left[ \ln \left( \frac{z_{asl} - d_0}{z_{0h}} \right) - \Psi_h \left( \frac{z_{asl} - d_0}{L} \right) + \Psi_h \left( \frac{z_{0h}}{L} \right) \right]
\]

\[
\bar{q}_c - \bar{q}_{asl} = \frac{E}{k u_* \rho} \left[ \ln \left( \frac{z_{asl} - d_0}{z_{0v}} \right) - \Psi_v \left( \frac{z_{asl} - d_0}{L} \right) + \Psi_v \left( \frac{z_{0v}}{L} \right) \right]
\]

where new terms of above equations are defined as

- \( \tau_0 \): surface shear stress
- \( \rho_a \): air density
- \( k \): von Karman’s constant (= 0.4)
- \( d_0 \): Zero-plane displacement height
- \( z_{0m} \): Roughness length for momentum transfer
- \( z_{0h} \): Roughness length for heat transfer
- \( z_{0v} \): Roughness length for water vapor transfer
- \( z_{asl} \): height above ground in ASL
- \( u_{asl} \): mean wind speed at height \( z_{asl} \)
- \( \theta_c \): surface canopy temperature in K (\( \theta_s \) is relevant in case of soil surface)
- \( \theta_{asl} \): mean air temperature at height \( z_{asl} \) in K
- \( \Psi_m \): integrated form of MOST stability correction function for momentum transfer
- \( \Psi_h \): integrated form of MOST stability correction function for sensible heat transfer
- \( \Psi_v \): integrated form of MOST stability correction function for water vapor transfer (\( \Psi_v = \Psi_h \))

(Brutsaert 2005: P 50)

\( L \): Obukhov length
\( H \): cumulative sensible heat flux between \( z_{asl} \) and \( d_0 + z_{0h} \)

The equations 2.22, 2.23, and 2.21 are solved numerically to find \( L \), \( H \), and \( u_* \). Same procedure is used with equations 2.22, 2.24, and 2.21 for \( E \).
In accordance with the original SEBS formulation (Su 2002), $\Psi_m$ and $\Psi_h$ for stable conditions are based on (Beljaars and Holtslag 1991) (evaluated by (van den Hurk and Holtslag 1997)) as following. Subscripts $s$ and $u$ are referring to stable and unstable conditions respectively.

$$y_s = \frac{z_{asl} - d_0}{L}$$

$$\Psi_m(y_s) = - \left[ a_s y_s + b_s \left( y_s - \frac{c_s}{d_s} \right) e^{-d_s y_s} + \frac{b_s c_s}{d_s} \right]$$  \hspace{1cm} (2.26)

$$\Psi_h(y_s) = \Psi_v(y_s) = \left( 1 + \frac{2a_u}{3} y_s \right)^{1.5} + b_s \left( y_s - \frac{c_s}{d_s} \right) e^{-d_s y_s} + \left( \frac{b_s c_s}{d_s} - 1 \right)$$  \hspace{1cm} (2.27)

For unstable conditions, stability correction functions are used from (Brutsaert 2005: P 50) as following

$$y_u = - \frac{z_{asl} - d_0}{L}$$

$$x = \left( \frac{y_u}{a_u} \right)^{1/3}$$

For $y_u \leq b_u^{-3}$

$$\Psi_m(-y_u) = \ln(a_u + y_u) - 3b_u y_u^{1/3} + \frac{b_u a_u^{1/3}}{2} \ln \left[ \frac{(1 + x)^2}{(1 - x + x^2)} \right]$$

$$+ 3^{1/2} b_u a_u^{1/3} \tan^{-1} \left[ \frac{2x - 1}{3^{1/2}} \right] + \Psi_0$$

For $y_u > b_u^{-3}$

$$\Psi_m(-y_u) = \Psi_m(b_u^{-3})$$

$$\Psi_0 = \left( -\ln(a_u) + \frac{3^{1/2} b_u a_u^{1/3}}{6} \right)$$

and

$$\Psi_h(-y_u) = \Psi_v(-y_u) = \left[ 1 - \frac{d_u}{n_u} \right] \ln \left[ \frac{(c_u + y_u^{n_u})}{c_u} \right]$$  \hspace{1cm} (2.29)

Constants for equations (2.26) to (2.29) are listed in Table 2.3

**Table 2.3 Constants in the stability correction functions for heat and momentum transfer**

<table>
<thead>
<tr>
<th></th>
<th>For stable condition (equations 2.26 and 2.28)</th>
<th>For unstable condition (equations 2.28 and 2.29)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$a_s$</td>
<td>1.1</td>
<td>0.33</td>
</tr>
<tr>
<td>$b_s$</td>
<td>0.667</td>
<td>0.41</td>
</tr>
<tr>
<td>$c_s$</td>
<td>5</td>
<td>0.33</td>
</tr>
<tr>
<td>$d_s$</td>
<td>0.35</td>
<td>0.057</td>
</tr>
<tr>
<td>$a_u$</td>
<td>0.33</td>
<td></td>
</tr>
<tr>
<td>$b_u$</td>
<td>0.41</td>
<td></td>
</tr>
<tr>
<td>$c_u$</td>
<td>0.33</td>
<td></td>
</tr>
<tr>
<td>$d_u$</td>
<td>0.057</td>
<td></td>
</tr>
<tr>
<td>$n_u$</td>
<td>0.78</td>
<td></td>
</tr>
</tbody>
</table>
2.5 Flow in the Mixed-Layer, the Bulk Atmospheric Similarity Theory (BAST)

In the mixed layer, due to strong turbulence and perfect vertical mixing, $\theta$ and $q$ are nearly constant with height, as such one can consider them constant over the bulk of the mixed layer (Stull 1988: Ch 11). However, potential temperature in the mixed layer is normally a minimum near the middle of the ML, because heating from below and entrainment of warm air from above lead to slightly warmer potential temperature in those regions (Brutsaert 2005).

The top of the mixed layer (see Fig. 2.1) is defined as where the sensible heat flux gets negative when calculating profiles of $H$ using radiosonde observations (see chapter 5). This level is located near the middle of the entrainment zone, where we have the most strong capping inversion effect. One can say that the capping inversion acts like an edge between the mixed layer and free atmosphere (Stull 1988).

There are two causes for mixing in the mixed layer, mechanically by shears, or convectively by buoyancy. The type of mixed layer which is subject of BAST theory is one which generated by buoyant turbulence and is normally called a ‘convective boundary layer’ (CBL) or ‘convective mixed layer’ (Stull 1988).

As the convective time scale ($t_*$) in the mixed-layer is in the order of 10-20 minutes in many cases, any change in the ASL heat flux and other surface forcing can be translated to the rest of the mixed layer in a relatively short time – about 15 minute (Stull 1988).

Here, the similarity theory hypothesis for the mixed layer is formulated based on the Bulk Atmospheric Similarity theory proposed initially by (Brutsaert and Sugita 1991) and further completed by (Brutsaert 2005: Pages 50-55).

The main equations for wind speed and temperature and their appropriate integrated stability correction functions are as following

$$V_{ml} = \frac{u_*}{k} \ln \left( \frac{h_{ml} - d_0}{z_{0m}} \right) - B_w$$  \hspace{1cm} 2.30

$$\theta_c - \theta_{ml} = \frac{H}{k u_* \rho c_p} \ln \left( \frac{h_{ml} - d_0}{z_{0h}} \right) - C$$  \hspace{1cm} 2.31

$V_{ml}$ mean wind speed in the mixed layer of the unstable ABL

$h_{ml}$ height of the top of the mixed layer, that is the bottom of the entrainment zone

$B_w$ integrated form of stability correction function for momentum transfer in the mixed layer

$C$ integrated form of stability correction function for heat transfer in the mixed layer

$B_w$ has been given a subscript $w$ to indicate that the wind speed $V$ is used, instead of the wind velocity components $u$ and $v$. Therefore, $V_{ml}^2 = u_{ml}^2 + v_{ml}^2$ and $u_{ml}$ and $v_{ml}$ are characteristic horizontal wind velocity components in the x- and y-directions in the mixed layer.
The integrated stability correction functions for BAST are as following:

For moderately rough terrain, i.e. when \( z_{0m} \leq \frac{\alpha_t}{\beta_t} h_{ml} \):

\[
B_w = -\ln (\alpha_t) + \psi_m \left( \alpha_t \frac{h_{ml} - d_0}{L} \right) - \psi_m \left( \frac{z_{0m}}{L} \right)
\]

\[
C = -\ln (\alpha_t) + \psi_h \left( \alpha_t \frac{h_{ml} - d_0}{L} \right) - \psi_h \left( \frac{z_{0h}}{L} \right)
\]

For very rough terrain, when \( z_{0m} > \frac{\alpha_t}{\beta_t} h_{ml} \):

\[
B_w = -\ln \left( \frac{h_{ml} - d_0}{\beta_t z_{0m}} \right) + \psi_m \left( \beta_t \frac{z_{0m}}{L} \right) - \psi_m \left( \frac{z_{0m}}{L} \right)
\]

\[
C = -\ln \left( \frac{h_{ml} - d_0}{\beta_t z_{0m}} \right) + \psi_h \left( \beta_t \frac{z_{0m}}{L} \right) - \psi_h \left( \frac{z_{0h}}{L} \right)
\]

where \( \alpha_t = 0.12 \) and \( \beta = 120 \) (Brutsaert 2005: P50) and other terms are defined in previous sections.

In derivations of Equations (2.32) and (2.33) it was assumed that the ABL is a perfectly mixed slab layer; however, due to the entrainment of warmer air into the ABL from above under unstable conditions, \( \theta_{ml} \) tends to increase slightly with elevation, roughly from about the middle of the mixed layer (Brutsaert 2005).

The Bulk ABL Similarity Theory (or BAST) approach is practically useful to derive surface fluxes of momentum and sensible heat from sounding in the upper parts of ABL (see chapter 5). In BAST, \( V_{ml} \) and \( \theta_{ml} \) which are averages over the mixed layer, are more robust than the profiles of wind and potential temperature in ASL which are often erratic and noisy. Also, since these mixed layer variables are averages over the mixed layer extending roughly between heights of the order of 100 m and 1 km above the ground, they are better representatives for describing surface fluxes at the mesogamma scale (2 km – 20 km) (Brutsaert 2005). This concept is the bases for formulation of a disaggregation scheme for SEBS, as presented and discussed in chapter 6.
2.6 A Model for Effective Roughness Optimization (ERO model)

Determination of the effective roughness for momentum transfer ($z_{0m}$), heat transfer ($z_{0h}$), and water vapor transfer ($z_{0v}$) as appeared in the formulation of MOST and BAST equations are important in SEBS and are still the subject of research and of concern in the scientific community (Brutsaert 2005: Ch 2).

A simple iterative optimization scheme (called Effective Roughness Optimization or ERO model hereafter) is developed here to derive the best estimation of $z_{0m}$, $z_{0h}$, and $z_{0v}$, and their respective $k B^{-1}$ parameters using observations of $u_*$, $H$, and $\lambda E$ versus simulated ones derived from MOST equations.

As described in sections 2.4, MOST equations can be solved iteratively for deriving friction velocity ($u_*$) and sensible heat flux ($H$) when the knowledge of roughness parameters ($z_{0m}$ and $z_{0h}$) and wind speed, temperature and humidity is available. However, when $u_*$ and $H$ are measured, another iterative process can be applied to find the best combination of $z_{0m}$ and $z_{0h}$ (and $z_{0m}$ and $z_{0v}$ in the similar way) which gives the closest set of calculated and observed $u_*$ and $H$.

The model which used in this study is bounded to $z_{0m}$ and $k B^{-1}$ values, based on (Wiernga 1993) and (Verhoef, De Bruin et al. 1997), as Table 2.4

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Lower bound</th>
<th>Upper bound</th>
<th>Resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>$z_{0m}$</td>
<td>0.001</td>
<td>1.3</td>
<td>0.01</td>
</tr>
<tr>
<td>$k B^{-1}$ (for $z_{0h}$)</td>
<td>0</td>
<td>30</td>
<td>1</td>
</tr>
<tr>
<td>$k B^{-1}$ (for $z_{0v}$)</td>
<td>0</td>
<td>50</td>
<td>1</td>
</tr>
</tbody>
</table>

This means 3900 (and 6500) iterations for solving MOST equations of each record of observations to derive $z_{0m}$ and $z_{0h}$ (and $z_{0m}$ and $z_{0v}$). The criteria parameters for selecting the suitable $z_{0m}$, $z_{0h}$, and $z_{0v}$ are as following:

$$absErr_H = |H_{obs} - H_{sim}|$$  \hspace{1cm} \text{2.34}  

$$absErr_{u_*} = |u_{*,obs} - u_{*,sim}|$$  \hspace{1cm} \text{2.35}  

$$absErr_{\lambda E} = |\lambda E_{obs} - \lambda E_{sim}|$$  \hspace{1cm} \text{2.36}  

$H_{obs}$ observed sensible heat flux ($H$) at tower  
$H_{sim}$ calculated (simulated) sensible heat flux using MOST equations  
$u_{*,obs}$ observed friction velocity ($u_*$) at tower  
$u_{*,sim}$ simulated (calculated) friction velocity using MOST equations  
$\lambda E_{obs}$ observed latent heat flux ($\lambda E$) at tower  
$\lambda E_{sim}$ simulated (calculated) latent heat flux using MOST equations
3 Study Area and Available Data

3.1 Walnut Creek Basin

General Description
The Walnut Creek (WC) watershed (centered at 41.96°N, 93.6°W) is located near Ames, Iowa, in the United States. This watershed has been intensively monitored by the U.S. Department of Agriculture (USDA) Agricultural Research Service (ARS) National Soil Tilth Laboratory (NSTL) (Kustas, Hatfield et al. 2005). Two major studies which covering WC watershed are SMACEX (Soil Moisture-Atmosphere Coupling Experiment) and SMEX02 (Soil Moisture Experiment 2002) which are conducted during June and July 2002. Fig. 3.1 shows the spatial domains of SMACEX, SMEX02, and WC watershed.

Fig. 3.1 The SMACEX and SMEX02 experimental domain and WC watershed boundary in white color. The Background is false-color image of Landsat-7 ETM+ image (After Kustas, Hatfield et al. 2005)

A key part of SMACEX involved measurements of surface energy, water, and carbon fluxes, as well as mean and turbulent atmospheric boundary layer (ABL) properties, and the collection of very high resolution visible, near-infrared, and thermal-infrared remote sensing imagery (Kustas, Hatfield et al. 2005; Table 1)

The SMEX02 study was designed to provide direct measurement/remote sensing/modeling approaches for understanding the impact of spatial and temporal variability in vegetation cover, soil moisture, and other land surface states on turbulent flux exchange with the atmosphere (Kustas, Hatfield et al. 2005).
The intensive measurement campaign for SMACEX mainly covered the period from 15 June (DOY 166) through 8 July (DOY 189). During this period, remote sensing data were collected from ground, aircraft, and satellite platforms. The SMEX02 campaign started later, on 25 June (DOY 176), and ended on 12 July (DOY 193). During the overlap of the two field campaigns, the vegetation grew rapidly and surface soil moisture changed from dry to wet from rainfall events in early July (Kustas, Hatfield et al. 2005). Data used in this research are mainly for DOY’s 171 to 190.

The land cover in the WC study area is primarily comprised of corn- (Zea mays L.) and soybean [Glycine max (L.) Merr.] fields. A land use map of the site (Fig. 3.2) indicates that nearly 95% of the region is in corn and soybean production (Kustas, Hatfield et al. 2005).

The climate in this region is humid, with an average annual rainfall of 835 mm. In a typical growing season, the most rapid growth in corn and soybean crops is observed in the months of June and July.

Rainfall events in the spring and summer are often thunderstorms, providing brief and intense showers. A rain gauge network in and around the watershed monitored by NSTL indicates that the heaviest precipitation months are May and June (about 1/3 of the annual total).

The topography is characterized by low relief and poor surface drainage (Kustas, Hatfield et al. 2005) and soils are clay and silty clay loams, with generally low permeability (Hatfield, Jaynes et al. 1999).

Long-term hydro-meteorological observations that are collected and processed by the NSTL include 20 recording rain gauges, which also have mounted screen-level air temperature sensors placed in a grid pattern throughout the watershed (Kustas, Hatfield et al. 2005; fig. 4).

Two meteorological stations are located in the watershed and record air temperature, relative humidity, wind speed and direction, soil temperature, and solar radiation (Kustas, Hatfield et al. 2005). Five stream-gauging locations in the watershed are designed to isolate water flow and water quality for three sub-watersheds and the entire basin (Hatfield, Jaynes et al. 1999).

Ground flux measurements were collected from June 20 to July 9 2002 on 12 fields, 6 grown with corn and 6 with soybean (Kustas, Hatfield et al. 2005).
**Radiometric surface temperature**

Radiometric temperature observations above and below the canopy were made using Apogee thermal-infrared radiometers (Apogee Instruments, Inc., model IRTS-P) which have a nominal 60° field of view. This would result in an effective observation diameter \( D \) as listed in Table 3.1. Data were collected continuously throughout the study period (Jackson and Cosh 2003). Sensor height for above and below canopy for corn and soybean are in Table 3.1.

<table>
<thead>
<tr>
<th>Crop</th>
<th>Sensor Location</th>
<th>Measurement Height</th>
<th>Measurement View Angle</th>
<th>Min. Obs. Diameter</th>
<th>Max. Obs. Diameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Corn</td>
<td>Above Canopy</td>
<td>-5.00 m AGL</td>
<td>Nadir</td>
<td>-6.5</td>
<td>-10</td>
</tr>
<tr>
<td></td>
<td>Under Canopy</td>
<td>-0.35 m AGL (inside crop)</td>
<td>-45°</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Soybean</td>
<td>Above Canopy</td>
<td>-2.50 m AGL</td>
<td>Nadir</td>
<td>-4.5</td>
<td>-5.5</td>
</tr>
<tr>
<td></td>
<td>Under Canopy</td>
<td>-0.01 m AGL (inside crop)</td>
<td>-45°</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Apogee instrument records both the measured (radiometric) surface temperature and sensor housing (contact) temperature. Nominal accuracy of this instrument is ± 0.4 °C from 5 to 45 °C and ±0.1 °C when sensor body and target are at the same temperature. The wavelength range is 6.5 to 14 micrometer. Methods for calibration of temperature readings against sensor body temperature and other relevant technical descriptions are presented in (Jackson and Cosh 2003).

**Flux observations**

In total, 14 METFLUX towers provided friction velocity \( \nu^* \), sensible heat flux \( H \), and latent heat flux \( \lambda E \). Details about the measurement instrumentations, storage, and processing are properly documented in (Kustas, Hatfield et al. 2005) and (Prueger, Hatfield et al. 2009).

Data used in this thesis were originally controlled against closure of the surface energy budget by (Su, McCabe et al. 2005). As stated by (Su, McCabe et al. 2005), during SMACEX, the average closure rate during the daytime, defined as the sum of the heat fluxes \( \lambda E + H \) over the available energy \( (R_n - G) \), was 0.71 (0.84) for a typical soybean (corn) site. To circumvent the non-closure problem in this dataset, a Bowen ratio closure method is applied by (Su, McCabe et al. 2005) to correct the sensible and latent heat flux observations and the same corrected values of their work is used here (with their permission). More details about energy closure quality in WC watershed are given in (Prueger, Hatfield et al. 2005).

All observed data from METFLUX towers are imported into a database, quality controlled, and used in the modeling. Fig. 3.3 shows the location of METFLUX towers in WC study area. List of instruments and characteristics of crops for each tower is provided in Table 3.2.
Table 3.2: Configuration of METFLUX tower, WC study area (After Prueger, Hatfield et al. 2009)

<table>
<thead>
<tr>
<th>Field</th>
<th>Crop</th>
<th>Row Dir.</th>
<th>Row Spacing</th>
<th>EC Sensor</th>
<th>Radiation Sensor</th>
</tr>
</thead>
<tbody>
<tr>
<td>WC03</td>
<td>S</td>
<td>N</td>
<td>0.38 m</td>
<td>CSAT3 and LI7500</td>
<td>CNR1</td>
</tr>
<tr>
<td>WC06</td>
<td>C</td>
<td>N</td>
<td>0.76 m</td>
<td>CSAT3 and LI7500</td>
<td>CNR1</td>
</tr>
<tr>
<td>WC10</td>
<td>S</td>
<td>X</td>
<td>0.05 m</td>
<td>CSAT3 and KH20</td>
<td>REBS</td>
</tr>
<tr>
<td>WC11</td>
<td>C</td>
<td>N</td>
<td>0.76 m</td>
<td>CSAT3 and KH20</td>
<td>REBS</td>
</tr>
<tr>
<td>WC13</td>
<td>S</td>
<td>N</td>
<td>0.76 m</td>
<td>CSAT3 and KH20</td>
<td>REBS</td>
</tr>
<tr>
<td>WC14</td>
<td>S</td>
<td>X</td>
<td>0.05 m</td>
<td>CSAT3 and LI7500</td>
<td>REBS</td>
</tr>
<tr>
<td>WC151</td>
<td>C</td>
<td>E</td>
<td>0.76 m</td>
<td>CSAT3 and LI7500</td>
<td>REBS</td>
</tr>
<tr>
<td>WC152</td>
<td>C</td>
<td>E</td>
<td>0.76 m</td>
<td>CSAT3 and LI7500</td>
<td>CNR1</td>
</tr>
<tr>
<td>WC161</td>
<td>S</td>
<td>E</td>
<td>0.25 m</td>
<td>CSAT3 and LI7500</td>
<td>REBS</td>
</tr>
<tr>
<td>WC162</td>
<td>S</td>
<td>E</td>
<td>0.25 m</td>
<td>CSAT3 and LI7500</td>
<td>CNR1</td>
</tr>
<tr>
<td>WC23</td>
<td>S</td>
<td>E</td>
<td>0.20 m</td>
<td>CSAT3 and KH20</td>
<td>REBS</td>
</tr>
<tr>
<td>WC24</td>
<td>C</td>
<td>N</td>
<td>0.76 m</td>
<td>CSAT3 and LI7500</td>
<td>CNR1</td>
</tr>
<tr>
<td>WC25</td>
<td>C</td>
<td>E</td>
<td>0.20 m</td>
<td>CSAT3 and LI7500</td>
<td>CNR1</td>
</tr>
<tr>
<td>WC33</td>
<td>C</td>
<td>E</td>
<td>0.76 m</td>
<td>CSAT3 and LI7500</td>
<td>CNR1</td>
</tr>
</tbody>
</table>

Crop: C = Corn, S = Soybean
Row Dir: N = North-South, E = East-West, X = Flex Coil
CSAT3: Campbell Scientific 3-D sonic anemometer (http://www.campbellsci.co.uk/)
LI7500: Li-Cor CO₂/H₂O analyzer (http://www.licor.com)
KH20: Campbell Scientific 1-D Krypton Hygrometers/ H₂O sensor (http://www.campbellsci.co.uk/)
CNR1: Campbell Scientific Kipp & Zonen Net Radiometer
REBS: Campbell Scientific Q7*1 Net Radiometer

In all 14 FLUXMET towers, SCAT3 eddy covariance (EC) systems were operational for providing time series (high frequency) data of wind (u, v, and w component) and sonic temperature.
Radiation Observations

Radiation components were measured at 12 sites. List of radiation sensors used in these sites are in Table 3.2. For sites having CNR1 net radiometer, all four-radiation components were recorded, including incoming and outgoing short and long wave radiation.

An inter-comparison of the $R_n$ sensors was conducted by NSTL at the end of the field study and measurements were calibrated to an average output from all systems. The following equation (from CNR1 User’s Manual) used to account of sensor body temperature (Pt-100 internal sensor) for correction of longwave radiation components:

$$E_{adj} = E_{raw} \times 5.67 \times 10^{-8} \times T^4$$

where

- $E_{adj}$ Corrected longwave radiation (incoming/outgoing)
- $E_{raw}$ Raw longwave radiation (incoming/outgoing)
- $T$ Sensor body temperature

Meteorological Parameters

At each METFLUX tower, air temperature, wind speed and actual vapor pressure were measured. Instruments and sensor heights for each parameter are presented in Table 3.3.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Measurement Instrument</th>
<th>Measurement Height</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air Temperature</td>
<td>°C</td>
<td>Vaisala HMP-45C</td>
<td>~2.5 m AGL over corn</td>
</tr>
<tr>
<td>Actual vapor pressure</td>
<td>mbar</td>
<td>Vaisala HMP-45C</td>
<td>~1.5 m AGL over soybean</td>
</tr>
<tr>
<td>Wind Speed</td>
<td>m s$^{-1}$</td>
<td>CSAT3 sonic anemometer</td>
<td>before end of June:</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>~2 m AGL over soybean</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>~3 m AGL over corn</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>after: ~4 m AGL over corn</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>~2 m AGL over soybean</td>
</tr>
</tbody>
</table>

In order to use wind speed, temperature, and humidity observations in MOST calculations, it is required that we have all of these parameters in a certain elevation. Therefore, the simple and general logarithmic profile of wind (Brutsaert 2005) is used assuming constant $u_*$ and neglecting stability correction factors as following

$$u_2 - u_1 = \frac{u_*}{k} \ln \left( \frac{z_2 - d_0}{z_1 - d_0} \right)$$

$u_2$ wind speed at height $z_2$

$u_1$ wind speed at height $z_1$

$u_*$ friction velocity

$d_0$ zero-plane displacement height ($= \frac{2}{3} h_c$ )

---

1 Above Ground Level
Radiosonde Observations

Balloon-borne radiosonde measurements included upper air temperature, humidity and pressure during the balloons ascent to the upper atmosphere. Radiosonde signals were received and processed by ground equipment, which automatically computed wind speed and direction using global navigation networks. The measurements were taken from June 15, 2002 (Day of year 166) to July 9, 2002 (Day of year 190).

The site was located in central watershed area (41.00 N, 93.61 W), as showed in Fig. 3.4 with a rectangle. In this figure, location of 4 surrounding tower fluxes are show by circles and the background shows recent satellite image acquired from GoogleEarth™.

There were between 1 to 4 radiosonde measurements (depending on the weather conditions) in the study period. More details about the measurement methods and preprocessing are documented by (Eichinger 2004).

In this research, profiles of potential temperature and specific humidity were drawn to evaluate data accuracy and completeness and the situation of the atmosphere. Radiosonde data were used (as described in Chapter 5) to evaluate land-atmosphere interactions and for disaggregation scheme developed for SEBS model (see chapter 6).

Fig. 3.4 Location of radiosonde site (triangle) in WC basin.
Vegetation field parameters
Canopy height and cover information are important for estimating surface roughness, soil-plant flux partitioning, and other parameters required for modeling land-atmosphere interactions. Land-cover in the Walnut Creek Watershed consists primarily of corn and soybean fields, with some forested areas in localized riparian zones. In the intensive vegetation sampling in 31 soil moisture sampling sites within WC Watershed important parameters like stand density, vegetation height, phenology, ground cover percentage, plant water content (stem and leaf), leaf area index (LAI), and digital photos of stand collected by the filed team (Anderson 2003). Location of vegetation sampling sites is presented in Fig. 3.5.

During the field campaign, the corn and soybean crops were in their vegetative stage of growth, with leaf area index varying in the soybean fields between 0.4 and 3.7, and in the corn fields between 1.1 and 5.6 (Anderson, Norman et al. 2004), see Table 3.4 and Fig. 3.6.

Table 3.4 Minimum and maximum of VH, LAI, and VF is all sites during the study period

<table>
<thead>
<tr>
<th>Crop Type</th>
<th>Site</th>
<th>Veg. Height (m)</th>
<th>LAI</th>
<th>Veg. Fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>DOY 171</td>
<td>DOY 190</td>
<td>DOY 171</td>
</tr>
<tr>
<td>C</td>
<td>6</td>
<td>1.0</td>
<td>2.0</td>
<td>1.8</td>
</tr>
<tr>
<td>C</td>
<td>24</td>
<td>0.9</td>
<td>1.9</td>
<td>1.8</td>
</tr>
<tr>
<td>C</td>
<td>25</td>
<td>0.7</td>
<td>1.7</td>
<td>1.1</td>
</tr>
<tr>
<td>C</td>
<td>33</td>
<td>0.8</td>
<td>2.0</td>
<td>1.4</td>
</tr>
<tr>
<td>C</td>
<td>151</td>
<td>0.9</td>
<td>2.0</td>
<td>1.3</td>
</tr>
<tr>
<td>C</td>
<td>152</td>
<td>1.1</td>
<td>2.2</td>
<td>2.1</td>
</tr>
<tr>
<td>S</td>
<td>3</td>
<td>0.2</td>
<td>0.3</td>
<td>0.6</td>
</tr>
<tr>
<td>S</td>
<td>13</td>
<td>0.2</td>
<td>0.4</td>
<td>0.4</td>
</tr>
<tr>
<td>S</td>
<td>14</td>
<td>0.3</td>
<td>0.6</td>
<td>1.6</td>
</tr>
<tr>
<td>S</td>
<td>23</td>
<td>0.2</td>
<td>0.5</td>
<td>0.6</td>
</tr>
<tr>
<td>S</td>
<td>161</td>
<td>0.2</td>
<td>0.3</td>
<td>0.5</td>
</tr>
<tr>
<td>S</td>
<td>162</td>
<td>0.2</td>
<td>0.3</td>
<td>0.7</td>
</tr>
</tbody>
</table>
Precipitation and Soil Moisture
Precipitation during SMACEX occurred a few days prior to 15 June (DOY 166), with a minor rainfall event (0-5 mm) on 20 June (DOY 171). This was followed by a rain-free period for WC study area until 4 July (DOY 185). This resulted in surface moisture (0-5 cm depth) decreasing from the near-field capacity of ~25%-30% in mid-June to ~5%-10% before the rains. Near the end of the rain-free period, visual signs of water stress were evident at some field sites (Kustas, Hatfield et al. 2005).

Digital Elevation Model
A DEM of the study area extracted from National Elevation Dataset (NED) of USGS (http://ned.usgs.gov/). Elevations of each METFLUX tower were extracted from this DEM and used for calculation/adjustment of atmospheric pressure at each tower.
3.2 Cabauw Tower Site

The Cabauw site is located approximately at the central western part of the Netherlands near the village of Cabauw. In 1972 at Cabauw a 213 m high tower (Fig. 3.7) was built by the Royal Netherlands Meteorological Institute (KNMI). This tower was built to establish relationships between the state of the atmosphere boundary layer (ABL), land surface conditions and the general weather situation for all seasons (Su, Timmermans et al. 2009). The Cabauw tower is located in a polder 0.7 m below average sea level in an extensive grassland area. In the immediate surroundings of the tower (corresponding to an area of 1 ha), the grass is kept at height of 8 cm by frequent mowing. Apart from scattered villages, roads and trees, the landscape within a radius of at least 20 km consist of flat grassland. Approximately 1.5 km south of the tower runs the river Lek, which is one of the main branches of Rhine. The river Lek is a few hundred meters broad. Due to the rich supply of water and the fine grained soil, the evaporative fraction of the surrounding area rarely falls below 0.6 m.

Data available and used in this study consists of meteorological and flux measurements at different heights of Cabauw site. Of these information, air temperature ($T_a$), wind speed ($U$) and dew point temperature ($T_d$) are used in MOST calculations. Schematic levels of measurements are shown in Fig. 3.8.

![Fig. 3.7 The 213 m high Cabauw tower as seen during different weather conditions (Timmermans, Dost et al. 2008: Fig 2)](image)

![Fig. 3.8 Available meteorological and flux observations at Cabauw site at above 10 m (left) and below 5 m (right)](image)
In EAGLE 2006 database, land surface temperature is missing and therefore, this parameter is extracted from observations of long-wave upward radiations (at 1.5 m) using Stefan-Boltzmann formula as following (Brutsaert 2005: Ch 2)

\[ R_{lu} = \varepsilon_s \sigma T_s^4 \rightarrow T_s = \left[ \frac{R_{lu}}{\varepsilon \sigma} \right]^{1/4} \]

where
- \( T_s \) (absolute) land surface temperature in K
- \( R_{lu} \) longwave upward radiation (W m\(^{-2}\))
- \( \varepsilon_s \) emissivity
- \( \sigma \) Stefan-Boltzmann constant (5.6704 × 10\(^{-8}\) W m\(^{-2}\)K\(^{-4}\))

Emissivity (\( \varepsilon_s \)) was measured during the EAGLE campaign on 9, 10 and 11\(^{th}\) of June 2006 using a Two-Lid emissivity box method (Timmermans, Dost et al. 2008). An average of measured values yields 0.99 as representative of grasslands.

As only flux observations at height 5 m AGL are available, they used for calculations of optimized effective roughness (see chapter 4).


4 Effective Roughness Lengths

In this chapter, results of ERO model (section 2.6) are compared with the roughness parameterization scheme of for SEBS (section 2.3, called Su01 hereafter). The results are shown and discussed for both Walnut Creek watershed and Cabauw Tower where appropriate.

4.1 WC Watershed: Optimization of $z_{0m}$ and $z_{0h}$

The Effective Roughness Optimization (ERO) model described in Section 2.6 is used to calculate effective and representative roughness parameters ($z_{0m}$ and $z_{0h}$) for each tower in Walnut Creek (WC) watershed. Displacement height is estimated as $d_0 = \frac{2}{3} h_c$ with available vegetation height data. Then, this model is executed for all possible ranges of $z_{0m}$ and $k B^{-1}$ (see Table 2.4) and best estimations of the roughness parameters were selected as such when the lowest difference between simulated and calculated sensible heat flux ($H$) and friction velocity ($u_*$) were obtained. This way, all valid records were used in computations, regardless of the validity of MOST theory (i.e. in rainy days) to track the behavior of the equations and experience their sensitivity to non-convective situations.

Daily evaluation of effective roughness

Diurnal variations of $z_{0m}$ and $z_{0h}$ for full day (7 AM to 6 PM) are studied first to select the optimum times for the ERO model results. For this, the effective roughness parameters ($z_{0m}$ and $z_{0h}$) for Site 3 (Soybean) for 1 July 2002 (DOY 182) are shown in Fig. 4.1.

![Fig. 4.1 Roughness parameters for Site 3, DOY 182](image)

Please note that the values in Fig. 4.1 are not validated yet, as the errors produced in simulation of $u_*$ and $H$ are not evaluated yet. Therefore, we define the error between simulated and observed values of $H$ and $u_*$ as following:

$$err_H = \left(\frac{H_{sim} - H_{obs}}{H_{sim}}\right) \times 100 \quad 4.1$$

$$err_{u_*} = \left(\frac{u_{*,sim} - u_{*,obs}}{u_{*,sim}}\right) \times 100 \quad 4.2$$

The graph showing variations of $err_H$ and $err_{u_*}$ is as shown in Fig. 4.2. As is obvious in Fig. 4.2, in the early morning and late evening (before 7:30 AM and after 4:30 PM), $err_H$ and $err_{u_*}$ exhibit big values. Therefore, estimated $z_{0m}$ and $z_{0h}$ for these times of day are not acceptable.
These big errors might be due to the transfer from stable to unstable conditions in early morning (and vice versa in late evening) and due to the uncertainties in the turbulence measurements. This is common in almost all sites, during the study period. Therefore, the daily time period of analysis for roughness parameters is restricted to the times between 09:00 AM to 04:00 PM when estimated $z_{0m}$ and $z_{0h}$ are almost constant (with small variations). In addition, the acceptable $err_H$ and $err_{u*}$ for the remaining records is set to 15 percent and bigger values filtered in the subsequent analysis. The criteria selected for optimizing the roughness length parameters are listed in Table 4.1.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>$err_H$</td>
<td>$-15% \leq err_H \leq 15%$</td>
</tr>
<tr>
<td>$err_{u*}$</td>
<td>$-15% \leq err_{u*} \leq 15%$</td>
</tr>
<tr>
<td>$time$</td>
<td>$09:00 \leq time \leq 16:00$</td>
</tr>
</tbody>
</table>

Effect of advection in rainy days on optimized roughness lengths
After applying the appropriate criteria for filtering of estimated roughness parameters (see Table 4.1), time series of $z_{0m}$ were studied. A time series graph of $z_{0m}$ for site 3 (corn) is presented in Fig. 4.3. As is obvious, there are jumps in $z_{0m}$ at beginning and end of the period. Also, relatively high (un-common) values of $z_{0m}$ appeared in DOY’s 177 to 178.
Inspecting the hydro-climatological records reveals that there were rainfall events at DOY 171 and also during DOY’s 185-188. This explains the reason for unexpected values of $z_{0m}$, as MOST theory is not valid during rainy days due to the large advection effects and as the measurement instrument (eddy covariance devices) are not able to operate during rain events.

**Wind speed and $u_*$ variations**

The pattern of wind speed, friction velocity, and wind direction in all sites of the study area is almost the same. Site 13 which has the most complete data (after filtering criteria of Table 4.1) is evaluated and variations of minimum and maximum wind speed and friction velocity as well as average direction of wind speed at this site is presented in Fig. 4.4 and Table 4.2. These figures were used in subsequent sections for justification of high roughness length parameters for the days with low wind speed and friction velocity.

![Variations of Min. and Max. values of wind speed (left) and friction velocity (right) at site 13, WC watershed](image)

**Table 4.2** Average wind direction for site 13 during the study period

<table>
<thead>
<tr>
<th>DOY</th>
<th>Avg. Wind Direction</th>
</tr>
</thead>
<tbody>
<tr>
<td>172</td>
<td>S</td>
</tr>
<tr>
<td>173</td>
<td>S</td>
</tr>
<tr>
<td>174</td>
<td>S</td>
</tr>
<tr>
<td>175</td>
<td>S</td>
</tr>
<tr>
<td>176</td>
<td>SW</td>
</tr>
<tr>
<td>177</td>
<td>SW</td>
</tr>
<tr>
<td>178</td>
<td>NE</td>
</tr>
<tr>
<td>179</td>
<td>SE</td>
</tr>
<tr>
<td>180</td>
<td>S</td>
</tr>
<tr>
<td>181</td>
<td>S</td>
</tr>
<tr>
<td>182</td>
<td>SW</td>
</tr>
<tr>
<td>183</td>
<td>S</td>
</tr>
<tr>
<td>184</td>
<td>SW</td>
</tr>
<tr>
<td>188</td>
<td>SE</td>
</tr>
<tr>
<td>189</td>
<td>SW</td>
</tr>
</tbody>
</table>

Also, variations of average of the fraction of friction velocity by the observed wind speed at sensor height $u_*/U(z)$ for all soybean and corn sites are presented in Fig. 4.5. It appeared in all sites that DOY 178 experiencing a high value of $u_*/U(z)$. Also, this day has the lowest $u_*$ and wind velocity observations (see Fig. 4.4) and it is presented in the subsequent sections that for this day,
uncertainty for deriving roughness length parameters is as high that almost no valid optimized value gained. Also, site 151 (corn) showed high values of $u_*/U(z)$ after DOY 180.

Temporal variations of roughness length parameters
After applying criteria of Table 4.1 and exclusion of rainy days, time series of $z_{0m}$, $z_{0h}$, and $kB^{-1}$ are prepared. As $z_{0h}$ is a function of both $z_{0m}$ and $kB^{-1}$, the $kB^{-1}$ parameter is a better representative of this parameter. Variations of $z_{0m}$ and $kB^{-1}$ at all sites (6 soybean and 6 corn sites) are presented in Fig. 4.6 and Fig. 4.7.

These two figures show that optimized $z_{0m}$ and $z_{0h}$ are not constant and depend on phenological and meteorological parameters. This is also stated in recent investigations of roughness parameters by (Harman and Finnigan 2007) and (Harman and Finnigan 2008).

Also, the rate of change and diurnal variations of $z_{0m}$ and $kB^{-1}$ are almost the same in all sites with the same vegetation type. Therefore, site 3 is selected as representative of a soybean and site 33 is selected as representative of a corn site. These two sites are selected as they have the most valid records. These sites were examined against relationships of roughness parameters and wind direction.
Fig. 4.6 Variations of $z_{0m}$ resulted from wind and temperature equations of MOST theory in soybean (left) and corn (right) sites during the study period (after applying criteria of Table 4.1)
Fig. 4.7 Variations of $kB^{-1}$ resulted from wind and temperature equations of MOST theory in soybean (left) and corn (right) sites during the study period (after applying criteria of Table 4.1)
Dependency of roughness parameters to wind direction

Site 3, Soybean
At site 3, the crop is soybean, the row direction is North, and the row spacing is 0.38 m. Location of site 3 is shown in Fig. 4.8. Intense red color generally represents corn sites in the left map. Note that the images were not taken on the same dates; therefore the visual difference in the patterns occurred. Other differences are due to the difference in spectral bands and spatial resolutions.

Fig. 4.8 Location of site 3 (soybean) in Landsat (left) and Google Earth (right) images

$z_0m$ values are categorized for different wind directions and shown versus wind speed and $\beta$ in Fig. 4.9. As is observed, there is no distinct relationship between the variations of $z_0m$ and wind direction at this site, indicating that the measurements were representative of the local soybean canopy. However, the right graph in Fig. 4.9 shows that higher values of $\beta$ are related to SE direction where the fetch experience corn fields more.

Fig. 4.9 Variations of $z_0m$ with wind speed (left) and $\beta = u_*/U_z$ (right) in different categories of wind direction, site 3
Dependency of roughness parameters to wind direction

**Site 33, Corn**

The field in site 33 is cropped with corn, the row direction is East, and row spacing is 0.73 m. Location of site 33 is shown in Fig. 4.10. Intense red color generally represents corn sites in the left map. Note that the images were not taken on the same dates; therefore the visual difference in the patterns occurred. Other differences are due to the difference in spectral bands and spatial resolutions.

Same as site 3, $z_{0m}$ values were categorized for different wind directions and shown versus wind speed and $\beta$ in Fig. 4.11. Like the soybean site, there is no distinct relationship between the variations of $z_{0m}$ and wind speed direction for this corn site. The same goes for $\beta$ parameter. A reason for this could be the fact that most of winds come from South direction where the fetch is within the field (from 40~400 m) and is approximately 10~100 times of the measurement height.

At both sites, $z_{0h}$ and $k B^{-1}$ exhibit no relationships with wind speed, $\beta$, and wind direction.
4.2 WC Watershed: Comparison of $z_{0m}$ in Su01 and ERO models

The canopy flow model implemented in SEBS is based on the work of (Su, Schmugge et al. 2001). To evaluate the accuracy and behavior of this model (Section 2.3), roughness parameters calculated with this model are compared with the calibrated roughness parameters. This comparison is made for site 3 (soybean) and site 33 (corn) which have the most valid calibrated $z_{0m}$ and $z_{0h}$ (see section 4.1). However, it should be noted that a basic difference between optimized (with ERO model) and simulated (with Su01 model) is that in ERO model, $d_0$ is taken as $2/3$ of vegetation height, but in Su01 model, equation 2.11 is used.

Comparison of roughness length parameters ($z_{0m}$, $z_{0h}$, and $kB^{-1}$) of the ERO model (section 2.6) and Su01 model (section 2.3) is illustrated in Fig. 4.12. It is obvious that Su01 model is unable to reproduce the variations in roughness parameters and gives (almost) a constant value for $z_{0m}$, $z_{0h}$, and $kB^{-1}$. However, these constant values are in accordance with the average values of ERO model for normal days when wind speed is larger than 3 m s$^{-1}$ and $u_*$ is larger than 0.3 m s$^{-1}$.

![Comparison of roughness parameters from ERO model and Su01 model in a soybean (left, site 3) and corn (right, site 33) tower](image)
Comparison of error in flux estimations

MOST formulas (section 2.4) were iterated to calculate sensible heat flux ($H$) and friction velocity ($u_*$) with the roughness parameters ($z_{0m}$ and $z_{0h}$) given by Su01 model. Then the errors in calculation of $H$ and $u_*$ ($\text{err}_H$ and $\text{err}_{u_*}$) by equations 4.1 and 4.2) and absolute difference in calculated and observed $H$ and $u_*$ ($\text{absErr}_H$ and $\text{absErr}_{u_*}$ by equations 2.34 and 2.35) were calculated for both Su01 model (section 2.3) and ERO model (section 2.6). Results of these two models are presented in Fig. 4.13.

**Fig. 4.13** Comparison of errors in $H$ and $u_*$ due to the use of ERO and Su01 models for a soybean (left, site 3) and a corn (right, site 33) field. Parameters $\text{err}_H$ and $\text{err}_{u_*}$ in a, b, e, and f are calculated by equations 4.1 and 4.2 and $\text{absErr}_H$ and $\text{absErr}_{u_*}$ in c, d, g, and h are given by equations 2.34 and 2.35.
As is obvious from Fig. 4.13, use of roughness parameters resulted from Su01 model, even with a good knowledge of its input parameters, would result to an average error of 28 \( W m^{-2} \) of sensible heat flux in a corn site. More statistical measures are presented in Table 4.3.

### Table 4.3  Statistical parameters of Fig. 4.13

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Model</th>
<th>Site 3 (soybean)</th>
<th>Site 33 (corn)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( err_H )</td>
<td>%</td>
<td>Su01</td>
<td>Min  -356</td>
<td>Max  27</td>
</tr>
<tr>
<td>( err_H )</td>
<td>%</td>
<td>ERO</td>
<td>Min  -14</td>
<td>Max  12</td>
</tr>
<tr>
<td>( absErr_H )</td>
<td>( W m^{-2} )</td>
<td>Su01</td>
<td>0</td>
<td>78</td>
</tr>
<tr>
<td>( absErr_H )</td>
<td>( W m^{-2} )</td>
<td>ERO</td>
<td>0</td>
<td>10</td>
</tr>
<tr>
<td>( err_{u_*} )</td>
<td>%</td>
<td>Su01</td>
<td>Min  -53</td>
<td>Max  3</td>
</tr>
<tr>
<td>( err_{u_*} )</td>
<td>%</td>
<td>ERO</td>
<td>Min  -8</td>
<td>Max  8</td>
</tr>
<tr>
<td>( absErr_{u_*} )</td>
<td>( ms^{-1} )</td>
<td>Su01</td>
<td>0.00</td>
<td>0.12</td>
</tr>
<tr>
<td>( absErr_{u_*} )</td>
<td>( ms^{-1} )</td>
<td>ERO</td>
<td>0.00</td>
<td>0.05</td>
</tr>
</tbody>
</table>

However, the difference of 27 and 28 \( W m^{-2} \) in \( H \) for soybean and corn of ERO and Su01 models are relatively small and acceptable in comparison with the errors common on other terms of energy balance equation. For example, the error in observed and calculated \( H \) in original SEBS paper (Su 2002) is documented as 30 \( W m^{-2} \) for cotton, 50 \( W m^{-2} \) for shrub and 40 \( W m^{-2} \) for grass crops.

One reason for the difference of roughness parameters resulted from Su01 model to the ones estimated by ERO model is in the constants of equation 2.8 (\( c_1, c_2, c_3, \) and \( C_d \)). As is presented in Fig. 4.14, the \( \beta \) parameter estimated by equation 2.8 is almost 3 times bigger than observed \( \beta = u_* / U_z \) values for our soybean and corn sites.

To quantify the reasons for difference between the \( z_{0m} \) derived from Su01 and ERO models, the Su01 model is fed by observed values of meteorological parameters. For this purpose, first, wind speed above the canopy (\( u_{h,obs} \)) is derived by

\[
U_{h,obs} = U_{ref} \frac{\ln(h_c - d_0) - \ln(z_{0m,obs})}{\ln(z_{ref} - d_0) - \ln(z_{0m,obs})}
\]

\( U_{h,obs} \) wind speed above the canopy height (\( h_c \)) based on observed wind speed (\( ms^{-1} \))

\( h_c \) vegetation height (m)

\( z_{ref} \) measurement height for wind speed (m)
$d_0$ zero-plane displacement height

$z_{0m,\text{opt}}$ roughness height form momentum transfer from ERO model

$$\beta_{\text{obs}} = \frac{u_{*,\text{obs}}}{u_{b,\text{obs}}} \quad 4.4$$

$u_{*,\text{obs}}$ observed friction velocity (ms$^{-1}$)

Then, the values of $\beta_{\text{obs}}$ where placed in equations, 2.10, and 2.11 to derive $\eta_{c,\text{obs}}$, $(d_0/h_c)_{\text{obs}}$, and $d_0,_{\text{obs}}$. These parameters finally were placed in equation 2.12 to derive $z_{0m,\text{obs}}$. This simulates the situation where we have calibrated $c_1$, $c_2$, and $c_3$ in equation 2.8 and evaluates the effectiveness and sufficiency of assumptions and dimensional analysis background in equations 2.8 to 2.12 for giving roughness length for momentum transfer ($z_{0m}$). Above formulas were applied to the Su01 model and results are shown in Fig. 4.15.

![Fig. 4.15 Roughness height for momentum transfer resulted from ERO model, from Su01 model without observed $(u_*/u_b)$, and Su01 with observed values of $(u_*/u_b)$; for a soybean (left, site 3) and a corn (right, site 33) field](image)

However, it should be noted that the basis for calculation of $d_0$ in Su01 and ERO models are different and this could justify the reason for the differences shown in Fig. 4.15. Effect of $d_0$ is quantified in next section. As appeared in Fig. 4.15, $z_{0m,\text{obs}}$ is bigger (smaller) than $z_{0m,\text{opt}}$ in soybean (corn) site.

To justify and quantify the difference in $z_{0m,\text{obs}}$ and $z_{0m,\text{opt}}$ in Fig. 4.15, correlations between their difference and agro-meteorological parameters were studied. For soybean, this difference has no relations with vegetation parameters (LAI, VF), but for corn, after excluding of negative values of $z_{0m,\text{opt}} - z_{0m,\text{obs}}$ a good linear relationship with LAI is revealed, as is presented in Fig. 4.16.

![Fig. 4.16 Correlation between $(z_{0m,\text{opt}} - z_{0m,\text{obs}})$ and LAI for site 33 (corn)](image)

$$y = 0.0284x - 0.0269 \quad R^2 = 0.8805$$
4.3 WC Watershed: Effect of $d_0$ on calculation of $z_{0m}$ and $z_{0h}$

The zero-plane displacement height used in ERO model is in a very simple form and might be incorrect. To investigate the effect of $d_0$ in roughness length parameters derived from ERO and Su01 models, $d_0$ was simulated using the standard formulas of Su01 model (equations 2.8 to 2.11). However, to have an estimation of $\beta$ parameter, we must have wind speed at canopy height. As shown in equation 4.3, $\beta$ is dependent on both $z_{0m}$ and $d_0$. So to have a fair estimation, optimized $z_{0m}$ values of ERO model (subject of section 4.1) and $d_0 = 2/3h_c$ were used to calculate $\beta_{obs}$ (see equation 4.4).

Then, this estimation of displacement height (called $d_{0,obs}$) was used to run ERO model again to optimize roughness length parameters. Variations of $d_{0,obs}$ and $d_0$ are shown in Fig. 4.17. $d_0$ in soybean (corn) site is higher (lower) than $d_{0,obs}$. This is in correspondence with Fig. 4.15 where $z_{0m,obs}$ of Su01 model is higher (lower) than $z_{0m,opt}$ resulted from ERO model for soybean (corn). The reason is the direct relationship of $z_{0m}$ and $d_0$ in equation 2.12.

As shown in Fig. 4.18, even with the same assumption and value of displacement height (as $d_{0,obs}$), there is a difference between $z_{0m}$ values derived from Su01 and ERO models. This shows that diabatic instability and parameterization of roughness sublayer have effects on estimation of $z_{0m}$, especially in Su01 model.
4.4 WC Watershed: Optimization of \( z_{0m} \) and \( z_{0v} \)

We assume that \( z_{0v} \) has the same exponential behavior as \( z_{0h} \) in Su01 model, and hence,

\[
z_{0v} = \frac{z_{0m}}{\exp(kB^{-1})^{[m]}}
\]

With this assumption, a similar model as described in section 4.1 is developed which instead of equation 2.23, equation 2.24 (MOST standard equation for water vapor transport) is used. For estimation of Obukhov-Length \( (L) \), observed values of \( H \) are used.

This model is iterated for different boundary values of \( z_{0m} \) and \( kB^{-1} \), as described in Table 2.4, to give optimized values of \( z_{0m} \) and \( z_{0v} \). Observed values of sensible heat flux \( (H) \) were used to calculate Obukhov-Length \( (L) \) in the calculations. A constant ratio of \( d_0 = \frac{2}{3}h_c \) is used in the calculations.

This scenario was executed for two run. At first run, a maximum boundary of 30 for \( kB^{-1} \) was used (results are in Fig. 4.19 and Fig. 4.20). As it is shown, the values of \( kB^{-1} \) seems to tend to reach to values bigger than 30. Therefore, another run with upper limit of 50 for \( kB^{-1} \) was executed and results of that case were also evaluated and compared with the first run (with 30 as upper limit).

Resulted \( z_{0m} \) and \( z_{0v} \) of the both scenarios were filtered for the criteria defined in Table 4.1. A similar criteria for \( err_{\lambda E} \) (as formulated below), was developed in a same concept with equation 4.1.

\[
err_{\lambda E} = \left[ \frac{\lambda E_{\text{sim}} - \lambda E_{\text{obs}}}{\lambda E_{\text{sim}}} \right] \times 100
\]

where

- \( \lambda E_{\text{sim}} \) simulated latent heat flux using optimized \( z_{0m} \) and \( z_{0v} \)
- \( \lambda E_{\text{obs}} \) observed latent heat flux in towers

Time series of final filtered \( z_{0m} \) and \( kB^{-1} \) (for vapor transfer) derived from both scenarios (30 and 50 as upper limits of \( kB^{-1} \)) are presented in Fig. 4.19 to Fig. 4.22. Results reveal that with 30 as upper limit of \( kB^{-1} \), MOST equations fail to give valid \( z_{0v} \) values, especially for soybean sites. This means that \( z_{0v} \) values for these two crops are very small values. Experimenting 50 as upper limit of \( kB^{-1} \) would result in valid optimized \( z_{0v} \) values. However, Fig. 4.21 and Fig. 4.22 show that even smaller values of \( z_{0v} \) would be required for soybean sites.
Fig. 4.19 Variations of $z_{0m}$ resulted from wind and water vapor equations of MOST theory, in soybean (left) and corn (right) sites during the study period (after applying criteria of Table 4.1), with 30 as upper limit of $kB^{-1}$.
Fig. 4.20 Variations of $kB^{-1}$ resulted from wind and water vapor equations of MOS theory, in soybean (left) and corn (right) sites during the study period (after applying criteria of Table 4.1), with 30 as upper limit of $kB^{-1}$
Fig. 4.21 Variations of $z_{0m}$ resulted from wind and water vapor equations of MOST theory, in soybean (left) and corn (right) sites during the study period (after applying criteria of Table 4.1 with 50 as upper limit of $kB^{-1}$)
Fig. 4.22 Variations of $k B^{-1}$ resulted from wind and water vapor equations of MOST theory, in soybean (left) and corn (right) sites during the study period (after applying criteria of Table 4.1 with 50 as upper limit $k B^{-1}$).
Comparison of Fig. 4.19 and Fig. 4.20 for $z_{0m}$ shows that increasing of the boundary for $kB^{-1}$ to 50 would increase the chance for converging to a better estimation of $z_{0v}$. This reveals that $kB^{-1}$ values for $z_{0v}$ have higher ranges, even to 50 which result very low values for $z_{0v}$.

4.5 Cabauw Tower: Optimization of $z_{0m}$ and $z_{0h}$

The same methodology, as described in section 4.1 was applied to Cabauw tower data to optimize $z_{0m}$ and $z_{0h}$. Results were filtered against the criteria defined in Table 4.1 and limited to no-rain period. Optimized $z_{0m}$, $z_{0h}$, and $kB^{-1}$ values from ERO model are presented in Fig. 4.23. Although at Cabauw site, landscape is homogenous and dominant land feature is grass, there are variations in roughness length parameters.

![Variations of $z_{0m}$ (top), $z_{0h}$ (middle), and $kB^{-1}$ (bottom) resulted from ERO model for Cabauw tower on June 2006](image-url)
4.6 Effect of Roughness Sublayer

A formula developed by (Harman and Finnigan 2008) (hereafter called HF) for $z_{0m}$ includes better combination of effective parameters which would give better results. This formula (after some rearrangements) is as following:

$$z_{0m} = h_c \left(1 - \frac{d_0}{h_c}\right) \exp \left(-k \beta^{-1} \right) \exp \left\{ -\psi_m \left(\frac{h_c - d_0}{L}\right) \right\} \exp \left\{ \psi_m \left(\frac{Z_{0m}}{L}\right) \right\} \exp \left\{ \Phi_m (h_c) \right\} \quad (4.6)$$

Each of the exponential terms in 4.6 represents respectively, the impact of the canopy (i.e. the characteristics of the sources and sinks), the impact of diabatic stability and the impact of roughness sublayer. Last term (RSL effect) should be used in care as the coordinate system reference used by (Harman and Finnigan 2008) is set at canopy height.

A comparison of the $z_{0m}$ formula of Su01 model (equation 2.12) with its original form as appeared in (Massman 1997: Eq. 8) shows that the instability related terms ($\psi$) are not included and this might be a reason for the difference between Su01 and ERO models (see Fig. 4.15).

Therefore, $\frac{z_{0m, opt}}{z_{0m, obs}}$ (as discussed in section 4.2) is set to:

$$\frac{z_{0m, opt}}{z_{0m, obs}} = \exp \left\{ -\psi_m \left(\frac{h_c - d_0}{L}\right) \right\} \exp \left\{ \psi_m \left(\frac{Z_{0m}}{L}\right) \right\} \exp \left\{ \Phi_m (h_c) \right\}$$

It seems that with retrieving different parts of above equation from observed values, difference between $z_{0m, opt}$ and $z_{0m, obs}$ could be quantified, however, results showed no correlation. A reason for this could be due to the different assumptions for calculation of $d_0$ in ERO, Su2001, and HF methods, as explained in their formulations.

5 Land-Atmosphere Interactions

In this chapter, interactions of land (canopy) surface and atmosphere are analyzed using similarity theory in both ASL and mixed layer parts. Radiosonde data of WC watershed were used to derive profiles of momentum and sensible heat flux, profiles of meteorological parameters and also variations of stability parameters in different parts of land-atmosphere system, from canopy to the upper parts of atmosphere.

From radiosonde data, measurements of air temperature, relative humidity, and atmospheric pressure were used to calculate potential temperature and specific humidity. Also, ASL height of each sounding profile was detected visually in profiles from where the potential temperature becomes constant. Although (Brutsaert 2005) recommended that the ASL height is where the direction of the wind remains constant with height, real observations of radiosonde observations for some days was in contrast with this method.
Sample profiles of wind direction and potential temperature of 1 July 2002 (DOY 182) for morning and noon are presented in Fig. 5.1.

For applying of MOST and BAST formulations to derive profiles of sensible heat flux and instability parameters, an average land surface temperature and optimized roughness lengths \((z_0m)\) and \((z_0h)\) from tower 152 (see Fig. 3.4) were used. Finally, six days of radiosonde observations were selected, when valid optimizations of roughness length parameters were available. This is to use the results for evaluation of applicability of mixed layer temperature for modeling of heat flux at towers in subsequent chapter. Final date and time of radiosonde observations are listed in Table 5.1. Early morning soundings were not used, as mixed layer is not developed at that time.

<table>
<thead>
<tr>
<th>DOY</th>
<th>Early Morning</th>
<th>Morning</th>
<th>Noon</th>
<th>Afternoon</th>
</tr>
</thead>
<tbody>
<tr>
<td>175</td>
<td>05:53</td>
<td>08:58</td>
<td>11:55</td>
<td>15:12</td>
</tr>
<tr>
<td>176</td>
<td>05:58</td>
<td>09:27</td>
<td>12:11</td>
<td>---</td>
</tr>
<tr>
<td>180</td>
<td>06:07</td>
<td>10:52</td>
<td>13:17</td>
<td>---</td>
</tr>
<tr>
<td>181</td>
<td>06:00</td>
<td>09:56</td>
<td>12:34</td>
<td>---</td>
</tr>
<tr>
<td>182</td>
<td>06:02</td>
<td>10:07</td>
<td>12:40</td>
<td>---</td>
</tr>
<tr>
<td>183</td>
<td>05:58</td>
<td>10:03</td>
<td>12:37</td>
<td>---</td>
</tr>
</tbody>
</table>

ABL height is defined as the height were sensible heat flux starts to become negative (Stull 1988). Therefore, the model (system of MOST and BAST equations) were applied with setting ABL as the...
maximum height above the ground level which is available in the radiosonde observations. Then, profiles of sensible heat flux ($H$) and Obukhov length ($L$) were drawn to inspect ABL level. This level is in agreement with the level of increase of temperature above mixed layer and gives a quantitative measure when top of mixed layer in the potential temperature profile does not distinctively appear.

For the surface, data from site 152 were used. The criteria for finding the closest record to the time of sounding were based on the availability of valid $z_{0m}$ and $z_{0h}$ in tower records. This difference in time is shown in Table 5.2.

<table>
<thead>
<tr>
<th>DOY</th>
<th>Radiosonde Time</th>
<th>Tower Time</th>
<th>Time difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>175</td>
<td>8:58</td>
<td>9:00</td>
<td>0:02 before</td>
</tr>
<tr>
<td>175</td>
<td>11:55</td>
<td>12:00</td>
<td>0:05 before</td>
</tr>
<tr>
<td>176</td>
<td>9:27</td>
<td>9:10</td>
<td>0:17 after</td>
</tr>
<tr>
<td>176</td>
<td>12:11</td>
<td>12:10</td>
<td>0:01 after</td>
</tr>
<tr>
<td>180</td>
<td>10:52</td>
<td>10:50</td>
<td>0:02 after</td>
</tr>
<tr>
<td>180</td>
<td>13:17</td>
<td>13:20</td>
<td>0:03 before</td>
</tr>
<tr>
<td>181</td>
<td>9:56</td>
<td>9:50</td>
<td>0:06 after</td>
</tr>
<tr>
<td>181</td>
<td>12:34</td>
<td>12:30</td>
<td>0:04 after</td>
</tr>
<tr>
<td>182</td>
<td>10:07</td>
<td>10:10</td>
<td>0:03 before</td>
</tr>
<tr>
<td>182</td>
<td>12:40</td>
<td>12:40</td>
<td>0:00 after</td>
</tr>
<tr>
<td>183</td>
<td>10:03</td>
<td>10:00</td>
<td>0:03 after</td>
</tr>
<tr>
<td>183</td>
<td>12:37</td>
<td>12:40</td>
<td>0:03 before</td>
</tr>
</tbody>
</table>

After determination of ABL height, MOST and BAST equations were applied to each radiosonde observation to derive sensible heat flux and diabatic instability parameters. Profiles of $\theta$, $H$, and $L$ are shown in Fig. 5.2 for whole radiosonde profile covering lower parts of the entrainment zone, until the calculated sensible heat flux is negative. Start point of reduction in sensible heat flux in the profiles of Fig. 5.2 are in correspondence with the inflection point in the potential temperature profiles. This exhibits the entrainment of sensible heat flux from the entrainment zone which cause growth and widening of mixed layer.

Also, integral form of the flux-profile functions for momentum $\Psi_m(\zeta)$ and for sensible heat $\Psi_h(\zeta)$ as given by equations 2.28 and 2.29 versus $\zeta = -(z - d_0)/L$ are given in Fig. 5.3 and Fig. 5.4. These figures are comparable with (Brutsaert 2005: Fig. 2.14) and represent how diabatic instability correction terms vary in ASL in regard to the surface condition and atmospheric variables.

In addition, Fig. 5.5 exhibits bulk similarity functions ($B_w$ and $C$ as given by equations 2.32 and 2.33) versus $[-(h_{ABL} - d_0)/L]$ and are comparable with (Brutsaert 2005: Fig. 2.17 & Fig. 2.18).
Land-Atmosphere Interactions from Canopy to Troposphere
A study of similarity, roughness characteristics and scaling using data from SMEX02 and EAGLE2006 campaigns

Fig. 5.2 – Calculated $\theta$ (left), $H$ (middle), and $L$ (right) for radiosonde observations of WC watershed
Land-Atmosphere Interactions from Canopy to Troposphere
A study of similarity, roughness characteristics and scaling using data from SMEX02 and EAGLE2006 campaigns

Fig. 5.3 – Variations of integrated stability terms of MOST equations in ASL for $\Psi_m (\frac{x-d_0}{L})$ and $\Psi_h (\frac{x-d_0}{L})$ in the left, $\Psi_h (\frac{z-a_0}{L})$ in the middle, and $\Psi_m (\frac{z-a_0}{L})$ in the right; for DOY’s 175, 176, and 180 in WC watershed
Fig. 5.4 – Variations of integrated stability terms of MOST equations in ASL for Ψ_m(z - d_0)/L and Ψ_h(z - d_0)/L in the left, Ψ_h(z - d_0)/L in the middle, and Ψ_m(z - d_0)/L in the right vs. log(z - d_0)/L; for DOY’s 181-183 in WC watershed.
Fig. 5.5 – Integrated stability correction terms of MOST equations ($B_w$ and $C$) versus $\frac{ABL-d_0}{L}$ parameter for morning (left) and noon (right) radiosonde observations of WC watershed.
By determination of the profile of sensible heat flux from canopy to the atmosphere aloft, it will be possible to study the ratio of $H_{\text{radiosonde}}$ to the $H_{\text{tower}}$ at canopy level, as given by the following equation

$$H_{\text{ratio}} = \frac{H_{\text{radiosonde}}}{H_{\text{tower}}}$$  \hspace{1cm} (5.1)

This concept is used in the disaggregation scheme in the next chapter. Profiles of $H_{\text{ratio}}$ at whole atmosphere, ASL, and mixed layer are presented in Fig. 5.6. In most cases, at noon time, these profiles are linear in the ASL which exhibit convective stratified ASL. As is observed in Fig. 5.6, in the days with well-developed turbulent mixed layer, profiles of $H_{\text{ratio}}$ at mixed layer part of ABL are vertically constant and at noon times are around unity meaning that the sensible heat flux at the mixed layer and at the surface are the same. Therefore, having well developed convective ABL, information about temperature of the mixed layer would be useful to gain land surface sensible heat flux and quantify evapotranspiration using energy balance concept. This is explained with more details in the next chapter.
Fig. 5.6 – Ratio of sensible heat flux (H) of radiosonde observations at different dates to the H of ground tower (site 152) at whole profile (left), ASL (middle), and in the mixed layer until the ratio start decreasing (right)
6 A Disaggregation Scheme for SEBS

In this chapter, partitioning of sensible heat flux \( (H) \) using meteorological parameters (temperature, wind, humidity) derived from radiosonde observations is discussed.

In the use of SEBS model (MOST and BAST equations in general), it is required to define air temperature, wind speed and humidity as an input. Despite land surface temperature which is available from remote sensing, measurement of these parameters are only available in meteorological stations and normally they are assumed constant value equal to the observed values at stations for large areas or geo-statistical methods are applied to obtain spatially interpolated values. This may cause problems in estimation of sensible heat flux by MOST equations, as the difference between land surface temperature and air temperature is the main contributing factor in equation 2.23.

As we move up to the atmosphere aloft, due to more complete turbulent mixing of the air, we observe less variation in air temperature (see Fig. 5.2). As discussed by (Brutsaert 2005: P 54), temperature and wind speed in the mixed layer are more robust than in the ASL. In ASL, profiles of temperature and wind tend to be erratic and noisy. Also, temperature and wind speed in the mixed layer reflect mean surface conditions over upwind distances of the order of 1-10 km which are relevant to describe surface fluxes at the mesogamma scale (2 km – 20 km) (see (Brutsaert 2005: Table 1.5)).

Here, radiosonde observations of temperature, wind speed and humidity (see chapter 5) from ASL to the upper parts of the mixed layer are used to calculate sensible heat flux. These data are used in combination with land (canopy) surface temperature and optimized roughness parameters (see section 4.1) of each METFLUX tower in WC watershed to derive the profiles of sensible heat flux \( (H) \) and other diabatic instability parameters. This process was executed for all 12 METFLUX towers and 12 radiosonde observations of DOY’s 175, 176, and 180-183.

Selection of METFLUX tower records
Selection of tower records which are correspondent to the radiosonde observations was based on looking at valid records of optimized roughness parameters at each tower, within a temporal boundary of \( \pm 20 \) minutes. This time is in correspondence with the convective time scale \( (t_\ast) \) in the mixed layer and any change in the ASL sensible heat flux and other surface forcing can be translated to the rest of mixed layer within this time (Stull 1988).

The time differences of the METFLUX towers corresponding to each radiosonde observation is presented in Table 6.1. Empty records in this table indicate that there was no valid record (having optimized roughness parameter with acceptable error in simulating \( H \) and \( u_\ast \)) in the flux tower. In this table, records having more than 10 minute time difference are grayed.
Table 6.1 – Time difference between tower and radiosonde observations in WC watershed. Values larger than 10 minute are grayed. Cells with no value had no valid corresponding tower observation.

<table>
<thead>
<tr>
<th>Radiosonde DOY-HH:MM</th>
<th>Soybean Towers</th>
<th>Corn Towers</th>
</tr>
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<td>176-09:27</td>
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<td>0:11</td>
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<td>0:02</td>
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<td>0:13</td>
</tr>
<tr>
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<tr>
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<td>182-12:40</td>
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<tr>
<td>183-10:03</td>
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<td>0:03</td>
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<tr>
<td>183-12:37</td>
<td>0:03</td>
<td>0:17</td>
</tr>
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</table>

Land surface parameters in the selected records
Air potential temperature, land (canopy) surface temperature, simulated sensible heat flux, and optimized roughness lengths for momentum and heat transfer of tower records for each radiosonde observation (morning and noon) are grouped and graphed in Fig. 6.1 to Fig. 6.5. These parameters are used in analysis of the results in the subsequent sections of this chapter.

Fig. 6.1 – Variations of air potential temperature at towers for soybean (left) and corn (right) for morning (top) and noon (down) radiosonde observations in WC watershed
A study of similarity, roughness characteristics and scaling using data from SMEX02 and EAGLE2006 campaigns

Fig. 6.2 – Variations of canopy temperature at towers for soybean (left) and corn (right) for morning (top) and noon (down) radiosonde observations in WC watershed

Fig. 6.3 – Variations of simulated sensible heat flux ($H$) at towers for soybean (left) and corn (right) for morning (top) and noon (down) radiosonde observations in WC watershed
Land-Atmosphere Interactions from Canopy to Troposphere
A study of similarity, roughness characteristics and scaling using data from SMEX02 and EAGLE2006 campaigns

Fig. 6.4 – Variations of optimized $z_{om}$ at towers for soybean (left) and corn (right) for morning (top) and noon (down) radiosonde observations in WC watershed

Fig. 6.5 – Variations of optimized $z_{oh}$ at towers for soybean (left) and corn (right) for morning (top) and noon (down) radiosonde observations in WC watershed
Calculation of flux ratio

Here, the aim is to evaluate the applicability of using air temperature, wind speed and humidity from upper atmosphere in calculations of sensible heat flux. For this purpose, it is supposed that the profile of radiosonde observations is corresponding to each tower and sensible heat flux is calculated for each radiosonde record with setting surface parameters from tower observations and using equation 5.1. Final profiles for each tower at each time of radiosonde observation are shown in Fig. 6.6 and Fig. 6.7.

Some of profiles (i.e. 175-08:58 in Fig. 6.6) are noisy due to the direct reflection of erratic shape in the profile of potential temperature of the radiosonde observation. This shows the effect of atmospheric condition and that the presence of a well-shaped mixed layer with relatively constant potential temperature is very important in this way.

However, there are some shifts of the $H_{ratio}$ profiles for one or two distinct tower (i.e. for tower 151 in 176-12:11 of Fig. 6.6) which are due to the problems in estimation of surface parameters, especially in roughness length parameters.

Comparison of the $H_{ratio}$ profiles for soybean (left side graphs) and corn (right side graphs) in Fig. 6.6 and Fig. 6.7 shows that these profiles for soybean sites are more patched in the mixed layer, but for corn, there are distinct shifts in the profiles. This is due to the problematic estimation of $z_{0m}$ and $z_{0h}$ as the roughness sublayer effects are not considered in ERO model and inherently in the MOST equations. An especial and obvious case of this fact is for tower 151 in 176-12:11 of Fig. 6.6. A comparison of this profile with the profile of site 33 in the same graph shows that the optimized $kB^{-1}$ for site 151 is equal to zero which produce a large value of $z_{0h}$. This, directly translates to the sensible heat flux calculations of radiosonde points and cause a shift in $H_{ratio}$ profile. The main cause for the wrong optimized value of $kB^{-1}$ is that air temperature at site 151 is higher than surface temperature (for that special record, indicating a stable condition) which caused a high value of $z_{0h}$ to retrieve the observed sensible heat flux in the ERO model.

As is obvious in $H_{ratio}$ profiles of corn towers in Fig. 6.6 and Fig. 6.7, shifted profiles have normally a negative origin which represent the problem in roughness parameter estimations (see also Fig. 6.4 and Fig. 6.5).

Also, profiles related to noon time are generally closer to $H_{ratio} = 1$ with constant value in the mixed layer. This might be due to better heat exchange between the land surface and the atmosphere, as injected sensible heat from ASL (with contribution of entrained sensible heat flux from the entrainment zone) causes the growth in the mixed layer and better buoyant turbulence conditions (Stull 1988).

Apart from of problematic (shifted) profiles (explained above), other profiles for days with well developed mixed layer profile (176, 181, 182,183) exhibit that $H_{ratio}$ in the mixed layer is around 1. Visual inspections reveal that the range of $H_{ratio}$ in the mixed layer is between 0.8 to 1. So, if a good estimation of roughness length parameters gained, with meteorological parameters of the mixed layer we could obtain a good estimation of the sensible heat flux at the ground.
Fig. 6.6 – Sensible heat flux ratio between radiosonde observations and surface canopy for soybean (left) and corn (right) towers during DOY’s 175, 176, and 180. Surface temperature and optimized roughness parameters are used from valid tower data.
Fig. 6.7 – Sensible heat flux ratio between radiosonde observations and surface canopy for soybean (left) and corn (right) towers during DOY’s 181-183. Surface temperature and optimized roughness parameters are used from valid tower data.
Applicability for operational use

The method of sensible heat flux partitioning explained here has potential for application in real operational situations. As described in Table 6.2, in operational applications, a slab model can be developed to estimate mixed layer temperature using lapse rate of change in the temperature derived from early morning sounding, as developed and described by (Driedonks 1982), (Stull 1988: Ch 11), (McNaughton and Spriggs 1986), and (Porporato 2009). A sample operational use of this concept is the ALEXI/DisALEXI scheme developed by (Anderson, Kustas et al. 2007) and (Norman, Anderson et al. 2003) which benefits from dual source evapotranspiration scheme (Norman, Kustas et al. 1995). In addition, numerical model outputs might be used for atmospheric parameters of the mixed layer. Also, current advancements in atmospheric remote sensing and availability of atmospheric products (e.g. NASA AIRS\(^1\), ESA GRASS SAF\(^2\)) is promising for operational local as well as global applications of developed disaggregation methodology.

Table 6.2 – Source of information for operational disaggregation of sensible heat flux

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Data source in this study</th>
<th>Data source in real applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mixed layer air</td>
<td>Radiosonde observations</td>
<td>• Slab models&lt;br&gt;• Remote sensing&lt;br&gt;• Numerical model output</td>
</tr>
<tr>
<td>temperature</td>
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<td></td>
</tr>
<tr>
<td>Mixed layer wind speed</td>
<td>Radiosonde observations</td>
<td>• Upscaling surface wind using standard logarithmic wind equation&lt;br&gt;• Remote Sensing&lt;br&gt;• Numerical model output</td>
</tr>
<tr>
<td>Mixed layer humidity</td>
<td>Radiosonde observations</td>
<td>• Remote Sensing&lt;br&gt;• Numerical model output</td>
</tr>
<tr>
<td>Land surface temperature</td>
<td>Tower observations</td>
<td>Thermal remote sensing</td>
</tr>
<tr>
<td>Roughness parameters</td>
<td>Optimization scheme</td>
<td>Su01 model</td>
</tr>
</tbody>
</table>

\(^1\) NASA Atmospheric InfraRed Sounder (AIRS); [http://disc.sci.gsfc.nasa.gov/AIRS](http://disc.sci.gsfc.nasa.gov/AIRS)

7 General Remarks and Conclusion

In this research, interactions of land surface and atmosphere using standard formulations of MOST and BAST are evaluated for Walnut Creek watershed, Iowa. Also, roughness length parameters are estimated using an iterative optimization scheme and a comparison made between retrieved values (by ERO model) and model values (by Su01 model). Some specific conclusions in this regard are as following:

1. Su01 model for derivation of effective roughness lengths for momentum and heat transfer is accurate; however, it needs further enhancements/improvements to include diurnal variations of $kB^{-1}$ and dependence of $z_{0m}$ into roughness sublayer effect and diabatic instability effects.

2. Although the difference in calculation of sensible heat flux using roughness parameters of Su01 and ERO models are 27 W m$^{-2}$ in average, however, combining this with the uncertainty of input parameters to Su01 model (i.e. LAI and wind speed) and uncertainty inherent in estimation of other terms of energy balance equation ($R_n$ and $G_0$) may have adverse effects on the estimation of instantaneous $\lambda E$ (as evapotranspiration) in operational remote sensing applications of SEBS.

3. Air temperature from mixed layer gives reasonably good estimate of sensible heat flux, particularly at noon times at WC watershed area. This is of potential to derive a flux partitioning scheme when good knowledge of air temperature at canopy level is not available with required spatial resolution.

There are issues which are not touched in this research due to the lack of time, however, seem to be valuable for pursuing in subsequent researches. These are formulated as the following recommendations:

1. The method developed here for sensible heat flux partitioning has applicability for use as a disaggregation scheme for downscaling of low resolution thermal images to better spatial resolutions using combination of landuse/landcover and wind speed data (for resulting $z_{0m}$ and $z_{0h}$).

2. ERO model scheme used in this study is of potential as a tool for quality control of METFLUX tower observations.

3. Current advancements in atmospheric remote sensing and availability of atmospheric products (e.g. NASA AIRS$^1$, ESA GRASS SAF$^2$) is promising for operational local as well as global applications of developed disaggregation methodology (see chapter 6) with better levels of uncertainty and applicability.

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$^1$ NASA Atmospheric InfraRed Sounder (AIRS); [http://disc.sci.gsfc.nasa.gov/AIRS](http://disc.sci.gsfc.nasa.gov/AIRS)

References


