Analysis of diurnal boundary layer development in boreal forests: measurements and simulations

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Abstract

Aims
Combining field data analysis and modeling, this study investigates factors influencing the diurnal boundary layer (BL) development in boreal forest.

Methods
Field data analysis used both air sounding and surface flux measurements collected during the Boreal Ecosystem–Atmosphere Study field campaigns in central Canada. Model study applied a non-local transient turbulence theory (TTT) to simulate the impact of the heterogeneous boundary conditions together with initial conditions on the BL development at the Candle Lake and Thompson release sites over boreal forests. Boundary conditions were characterized by the integrated surface flux measurements from different forest stands. The lake effect was included in constructing the surface fluxes at Candle Lake release site.

Important Findings
Analyses of serial upper air sounding data and tower flux data indicate strong linear impacts of surface sensible heat forcing on the diurnal BL development above boreal forests. The regression slopes on the relationship between the BL development and the surface fluxes reflect the influences of initial boundary conditions to the BL developments. Both the modeled and the measured diurnal BLs show that lakes reduce sensible heat flux, leading to a shallower boundary in Candle Lake than in Thompson. Comparison of the model results and field measurements on the BL profiles indicates that the TTT model has the capability to simulate the BL development above boreal forests for sunny, rainfall or cloudy days. This study demonstrates the importance of lake on surface fluxes and BL development. The modeling effort shows the potential to couple the transient theory with a land surface process model to study land surface and atmosphere interaction in boreal forest.

Keywords: BOREAS • transient turbulence theory • lake effects • initial patterns • surface fluxes

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INTRODUCTION

Human-induced rising atmospheric CO₂ levels and land use and land cover changes cause great concerns on the potential impact to our terrestrial ecosystem. How does terrestrial ecosystem respond to atmospheric CO₂ increase? How does anthropogenic terrestrial ecosystem change affect our climate? To understand the functioning of terrestrial ecosystems in the climate system, many studies have focused on understanding the mechanism of the biosphere and atmosphere interaction (Bonan 2008). The very fundamental aspect is to study how vegetated surfaces interact with lower turbulent boundary layer (BL). It plays an important role to aid our understanding the biosphere and atmosphere interaction and essential to understanding how future climate change will affect terrestrial carbon dioxide exchanges with the atmosphere.

Vegetated land surfaces influence weather and climate by regulating the partitioning of surface water, energy and carbon exchanges (Bonan 1995; Foley et al. 1996; Sellers et al. 1997; Williams et al. 1996). In the middle to high-latitude regions, where the land surfaces are covered by a large amount of boreal conifer forests, the interaction between land and atmosphere is hard to quantify due to high-latitude surface complexities. Forests have a lower albedo than other ecosystems, through their extensive root systems, have more access to soil water than other types of vegetation (Dong et al. 2007; Koster and Suarez 2001). Lakes can also lead to particularly strong variations in surface heat flux as lakes have a lower...
albedo, a higher heat capacity and effective conductivity and a lower roughness, so they absorb more solar radiation and emit less sensible and latent heat (Desjardins et al. 1997; Oncley et al. 1997).

Flux in atmospheric BL can be strongly influenced by the spatially varying energy exchange between heterogeneous ground surfaces and overlying air. How does the subgrid variability of vegetated land surfaces affect weather and climate by modifying the planetary BL (PBL) structure and cloud patterns in the PBL? Quantifying the subgrid variability in vegetated regions and its effects on the turbulent BL remains elusive.

The influences of land surface properties on weather and climate are usually modeled by coupling a land surface model (Huang et al. 1996; Koster et al. 2000; Mintz 1984; Pan et al. 1995; Yeh et al. 1984) with global and regional climate models at a large grid cell. The land surface model is used to simulate surface fluxes for each land cover type within a general circulation model (GCM) grid and the grid-box-averaged surface fluxes are then used as the lower BL for the PBL submodel in global and regional climate and weather models to produce the net effect of the land surface on atmospheric circulation in the troposphere.

Accurate simulations of variations in PBL depth and the vertical fluxes of momentum are important for weather prediction and climate studies as well as for carbon cycle analysis (Denning et al. 2008; Yi et al. 2001, 2004). The PBL depth has a strong impact on the vertical and horizontal distribution of CO2 in the atmosphere. The single-column model used at the Colorado State University GCM captures observed variations in PBL depth on diurnal, synoptic and seasonal time scales reasonably well in northern Wisconsin but tends to underestimate midday maximum in PBL depth (Denning et al. 2008).

Many PBL schemes often adopt the non-local mixing theory. For example, Raymond and Stull (1990) incorporated the transient theory (T-theory) into the NCAR/Penn State 15 sigma level regional primitive equation mesoscale model to replace the horizontal and vertical K-theory eddy diffusion parameterization. The model results showed that the T-theory model is much more sensitive to the way physical quantities are represented. For example, evaporative cooling of rain and cloud water now becomes extremely important. Holtslag and Boville (1993) also compared the local and non-local boundary layer diffusion schemes in a global climate model. They found that the specific-humidity profile was much better simulated with the non-local scheme, while the local scheme resulted in more moisture and a larger amount of clouds at the lower atmosphere. Holtslag and Boville (1993) recommended using the non-local scheme to study the interaction between the land surface parameterization and the PBL development, especially the entrainment process at the top of the PBL.

The purpose of this study is to use a non-local PBL model to study the impact of land surface heterogeneity on the diurnal BL development in the boreal region. To evaluate the performance of the non-local model to simulate the BL development in the boreal region over different forests, in situs measurements of sounding data and surface flux data collected over different forests from the Boreal Ecosystem–Atmosphere Study (BOREAS) experiments were used as the initial and boundary conditions.

**STUDY SITES AND FIELD DATA**

**Study sites**

Our study sites are located in the BOREAS study region of central Canada. BOREAS was designed to improve our understanding of the interactions between the boreal forest and the atmosphere in order to clarify their roles in global change. Intensive field measurements of surface fluxes and BL collected during BOREAS provide accurate parameterization schemes for modeling studies of the land surface processes and the surface–air interaction in energy, water and carbon. These test sites include two super study regions in BOREAS: southern study area (SSA) and northern study area (NSA) (Fig. 1). SSA is a 130 km by 90 km area around Prince Albert, Saskatchewan and NSA is a 100 km by 80 km area around Thompson, Manitoba. The two regions are covered with typical northern boreal forest. Forest stands include old black spruce (OBS), old or young jack pine (OJP, YJP), old and young aspen (OA, YA) and fen stands with a maximum stand age of 80 years old. The SSA site also includes various sizes of lakes. Figure 1 illustrates the locations of SSA and NSA in Canada. Two red rectangles in the upper panel are SSA and NSA, respectively. The test sites are highlighted in red dots in the two lower panels.

**Field data**

Available sounding and surface flux data are listed in Table 1. Sounding teams (AFM-02 to 06) used aircrafts, balloon and radar to measure atmospheric profiles from near the surface to above the inversion layer during the 1993, 1994 and 1996 field campaigns over the entire study region. Tower flux teams (TF-01 to 11) collected surface flux data at different locations with different dominant forest types.

Radiosonde data used in this study were collected by team AFM-05 during each intensive field campaign (IFC) in 1993, 1994 and 1996. The measured data include atmospheric parameters of atmospheric pressure, temperature, dew point temperature, wind speed and wind direction, potential temperature and equivalent potential temperature, mixing ratio, relative humidity. The data at a high-temporal frequency (almost 7–8 flights each day) is ideal to study the diurnal variability of atmospheric BL conditions (Table 2).

Serial upper air soundings were released from Candle Lake (53.73°N, 105.27°W, 503 m, in the SSA) and Thompson (55.75°N, 97.87°W, 206 m, in the NSA) at approximately six or seven sondes per day in most days, while the other sites were restricted to two or three releases per day (Table 2). Soundings were made routinely at 12:00, 18:00 and 00:00 (UTC) as well as at 14:00, 16:00, 20:00 and 22:00 (UTC) on
fair-weather days in IFCs 1, 2 and 3 at Candle Lake and Thompson. The radiosonde measurements were at a mean vertical resolution of 27 m in the BLs, and the mean ascent rate was 5.4 m/s in the BL. The release site at Candle Lake is covered by a mixture of coniferous and deciduous trees with three lakes nearby oriented in a northwest to southeast direction. Both potential temperature and mixing ratio are useful indices to identify the development of the mixing layer (ML). Figure
Table 1: summary of the methods of data collection and the measured parameters

<table>
<thead>
<tr>
<th>Team</th>
<th>Methods</th>
<th>Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>AFM-02, 03 and 04</td>
<td>Aircraft sounding</td>
<td>HT, U, V, P, T, θ, R_h, CO_2, O_3</td>
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<tr>
<td>AFM-05</td>
<td>Balloon sounding</td>
<td>HT, U, V, P, T, θ, R_h</td>
</tr>
<tr>
<td>AFM-06</td>
<td>Radar sounding</td>
<td>HT, U, V, W, T_e</td>
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<tr>
<td>AFM-08</td>
<td>Modeling</td>
<td>HT, U, V, P, T, R_h and SH, LH</td>
</tr>
<tr>
<td>TF-01 to 11</td>
<td>Tower platform</td>
<td>SH, LH, CO_2</td>
</tr>
<tr>
<td>AFM-01, 02 and 03</td>
<td>Moving window</td>
<td>SH, LH, CO_2, O_3</td>
</tr>
</tbody>
</table>

Table 2: daily measures and measured parameters performed by team AFM-05 in June 1994

<table>
<thead>
<tr>
<th>Date</th>
<th>Candle Lake, Saskatchewan</th>
<th>Thompson Zoo, Manitoba</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Flights</td>
<td>Variables</td>
</tr>
<tr>
<td>June 1</td>
<td>7</td>
<td>θ, u, v, r</td>
</tr>
<tr>
<td>June 2</td>
<td>3</td>
<td>θ, u, v, r</td>
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<tr>
<td>June 3</td>
<td>3</td>
<td>θ, u, v, r</td>
</tr>
<tr>
<td>June 4</td>
<td>7</td>
<td>θ, u, v, r</td>
</tr>
<tr>
<td>June 5</td>
<td>3</td>
<td>θ, u, v, r</td>
</tr>
<tr>
<td>June 6</td>
<td>6</td>
<td>θ, u, v, r</td>
</tr>
<tr>
<td>June 7</td>
<td>7</td>
<td>θ, u, v, r</td>
</tr>
<tr>
<td>June 8</td>
<td>8</td>
<td>θ, u, v, r</td>
</tr>
<tr>
<td>June 9</td>
<td>3</td>
<td>θ, u, v, r</td>
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<tr>
<td>June 10</td>
<td>7</td>
<td>θ, u, v, r</td>
</tr>
<tr>
<td>June 11</td>
<td>7</td>
<td>θ, u, v, r</td>
</tr>
<tr>
<td>June 12</td>
<td>3</td>
<td>θ, u, v, r</td>
</tr>
<tr>
<td>June 13</td>
<td>3</td>
<td>θ, u, v, r</td>
</tr>
<tr>
<td>June 14</td>
<td>3</td>
<td>θ, u, v, r</td>
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<tr>
<td>June 15</td>
<td>7</td>
<td>θ, u, v, r</td>
</tr>
<tr>
<td>June 16</td>
<td>7</td>
<td>θ, u, v, r</td>
</tr>
</tbody>
</table>

θ = potential temperature, r = mixing ratio, u = zonal component of wind speed, v = V component of wind speed.

2 shows the profiles of potential temperature and relative humidity measured at Candle Lake, Saskatchewan on 7 June 1994. The measurements were taken every 2 h starting from very early morning. The potential temperature θ decreased in the near surface, kept constant in the ML and increased in the entrainment layer (EL). The diurnal change of the ML depths can be used to capture the development of BL. During the daytime, both the θ values and the ML depths increased in the morning, reached a maximum value in the early afternoon and then remained constant until the late afternoon.

The ML growth was slow at early morning because of strong nocturnal inversion. The ML growth increased rapidly from midmorning to afternoon, reached maximum in the afternoon (1 600 m above ground level, AGL) and kept constant to the late afternoon. A shallow surface layer with superadiabatic lapse rate formed under a well-mixed layer of constant potential temperature. The ML growth is controlled by wind shears, buoyancy, ground dissipation and the atmospheric initial patterns. A strong superadiabatic zone under the ML, resulting from the ground heating, is a major forcing of buoyancy to drive the ML evolution.

The air–surface exchanges of net radiation, sensible and latent heat were measured above forest canopy at 11 BOREAS TF sites throughout the SSA and the NSA during BOREAS field campaigns (Table 3). Fluxes were measured with tower-mounted measurement systems. Generally, the instruments were mounted at 20 m above the ground, 7 m above the mean tree height and in the constant flux layer. The azimuth angle of the boom was altered periodically to place the instrument array into the predominant wind direction. The fluxes data were collected nearly continuously at height of 20–30 m but were recorded at a half-hour average.

MODEL REVIEW

The PBL model used in this study was developed by Stull and his coworkers (Stull 1984, 1993, 1994; Stull and Driedonks 1987). The model uses the T-theory to model the turbulent eddy movement. Ni (1997) also extended the T-theory model from the PBL to the plant canopy for further study of the effect of vegetation and soil on the atmosphere; the detailed mechanisms that affect turbulent airflow within and above the plant canopy were coupled with the original T-theory model. The study showed that the T-theory can produce the counter-thermal gradient flows within plant canopies and the model predictions agree well with field measurements in the Black Moshannon Forest in Pennsylvania (Ni 1997).

T-theory is a non-local eddy transport theory, which differs from the conventional gradient-diffusion K-theory in that in the T-theory, the energy and mass transfer is carried by the movement of the finite-sized eddies rather than down the gradient direction. Large eddies are responsible for long-distance transport; small eddies are responsible for short-distance transport. T-theory is called a non-local scheme since it comes from this long-distance interaction. T-theory was developed based on the fact that turbulence in the atmosphere is not like diffusion but more like advection. Parcels of air are moved across finite distances by eddies of varying sizes before the parcels mix with their surroundings. This is especially true for both boundary layer convection and convective clouds within the troposphere. The word ‘transient’ is based on Latin meaning ‘to jump over’, to suggest the advective rather than diffusive nature of the T-theory.

The current T-theory is a fully developed 2D/3D model. The transient turbulence was only applied in the vertical direction. In the horizontal, mixing was assumed to occur only between neighboring grid points. This should be accurate enough when accounting for local advection due to land surface heterogeneity. The 1D governing equations of atmospheric turbulent airflow for potential temperature and mixing ratio can be written as (Stull 1993)
\[ \frac{d\Theta}{dt} = -S - \frac{\partial \theta w}{\partial z}, \]

\[ \frac{dQ}{dt} = S_q - \frac{\partial q w}{\partial z} \]

in which dependent variable \( \Theta \) is the potential temperature and \( Q \) is the mixing ratio (g/kg). The governing equations for wind speed can be referred from Stull (1993). The source term \( S \) is the radiative flux divergence, \( S_q \) is the body source term associated with the mixing ratio, \( \theta w \) is the sensible heat flux and \( q w \) is the latent heat flux. \( \theta', q' \) and \( w \) are the departures of potential temperature, the mixing ratio and vertical wind speed.

The T-theory simulates the turbulent airflow transport by two transient processes: turbulence generation and turbulence mixing. Turbulence generation implies that external forcings and heat sources destabilize the flow and turbulence mixing implies that the eddy mixing relaxes the destabilization of the flow. The whole turbulent airflow transport is performed by continuously applying these two processes. The vertical mixing potential was estimated by considering wind shear, thermal buoyancy and dissipation from surface roughness. The dissipation is set as a constant through the whole simulation, and the wind shear

**Figure 2:** observed potential temperature and mixing ratio at Candle Lake release site on 7 June 1994. There were seven flights taken from the early morning (5:30 on local time) to the late afternoon (17:30 on local time).

**Table 3:** supporting information of air–surface exchanges of energy and mass at 11 tower sites
results from the difference of wind velocity between grid pairs. Because the wind speed is a predictable variable, strong mixing will lead to the uniform wind speed within the BL. Therefore, the wind shear will play minor roles in our simulations at one column domain. The thermal buoyancy will be a main forcing to drive the transient turbulence theory (TTT) model in the BL simulations.

MODEL SETUP

The simulation domain starts from ground to 3 000 m height vertically as the observed maximum PBL heights were ~2 500 m AGL on 11 June 1994 at both Candle Lake and Thompson release sites. The whole domain was divided 40 uneven grid cells with a 50 m increment for the layers below 1 000 m AGL and a 100 m increment at higher layers. The model initial profiles were interpolated from the measured radiosonde data at 5:30 am local time in each day, and the surface sensible and latent heat fluxes were obtained from the tower sites in the SSA and NSA. All the other parameters were kept the same with Stull (1993).

Initial conditions

The initial profiles of atmospheric variables represent important atmospheric structure information and are deterministic in simulating the BL growth. If the initial atmosphere is stable, the BL development requires more surface energy. If the atmosphere is unstable, even small surface energy can stimulate the BL development.

To measure the stability of the initial conditions, we developed an index based on the measured potential temperature profiles at the early morning (e.g. 5:30 am on local time) each day. It is defined as an area below each potential temperature profile as \( \sum_{i=1}^{N} \left( \theta - \theta_i \right) A Z_i \) to represent the energy requirement for the development of BL. The threshold is the potential temperature at an arbitrarily selected height. For a given threshold, \( N \) is the number of layers from the ground to the selected height and \( \theta_i \) and \( A Z_i \) are the potential temperature and thickness in the layer \( i \). If the surface can provide more energy than needed, the BL will be well developed. Therefore, the above-defined area enclosed below the profile can be considered as an index to identify the potential resistance to a BL development.

Use the index defined above, we classified the initial conditions into two groups with a predefined threshold of 4 500 for both the SSA and the NSA sites (Fig. 3). For the SSA site, the first group with the index values <4 500 has thinner near-surface layer, resulting from small radiation cooling during clear night (~347.5, -453.7, -377.3, -424.4 and -245.5 W/m² at June 7, 8, 10 and 11, respectively). The profiles of the initial potential temperature with index above 4 500 did not show the constant BLs. Their evolutions mostly result from large cooling (June 12 and 13), environmental effects (June 15) or the previous day with low flux so that the BL was not well developed (June 14 and 16).

Similarly, two groups were also separated in NSA (Fig. 3). The potential temperatures were nearly constant in BLs in the group with an index below 4 500 (June 10, 11 and 16). This pattern resulted from the low-negative sensible heat fluxes during the previous night and the well-developed BL during the previous day with the BL heights above 2 000 m. In the other group with the index above 4 500, the potential temperatures decreased with heights. The pattern in this group mostly resulted from large cooling with total sensible heat fluxes above ~200 W/m² (June 6, 12, 13 and 14), environmental effects (June 15) or the low-BL height in the previous day (June 7, 8 and 9).

Obviously, the negative sensible heat fluxes during nighttime cause BL cooling, resulting in a stable layer. One question will raise that, to what extent, the surface sensible fluxes can influence BL during nighttime. During clear night with low humidity (e.g. June 7, 8, 10 and 11 in the SSA), relative larger values of negative sensible heat result in more cooling effects and thicker near-surface stable layer. But the surface sensible heat flux is not the only factor to determine the BL evolution during night. For example, the BL potential temperature decreased much more on June 12 than that on June 10 in the SSA, but the total sensible heat flux was only ~245.5 W/m² during the night between June 11 and 12 (comparing to ~424.4 W/m² during night between June 9 and 10). Generally, the potential temperature in BL decreases through the nighttime. However, the sensible heat fluxes are not enough to influence the changes of potential temperature at the whole BL. The mechanism of the formulation of initial patterns of potential temperature or nighttime BL is still not clear. Mahrt and Vickers (2002) suggested that advection played an important role in nocturnal BL development, and the horizontal advection might be important during the morning transition from stable to convective conditions (Yi et al. 2000).

BL conditions

The surface fluxes are applied to the lowest grid point as external forcings in the transient model. The features of surface fluxes are highly dependent on land surface heterogeneity including land surface types and forest stand structure.

Features of sensible and latent heat fluxes

Figure 4 compares the flux tower measurements of net radiation, sensible and latent heat fluxes over different forest stands in the SSA and NSA. Net radiation, a critical parameter in studying the air–surface exchanges of energy, water and carbon, shows nearly the same diurnal variations among the tower sites with different vegetation types in SSA (Fig. 4c) or NSA (Fig. 4f). However, the sensible and latent heat fluxes partitioned from net radiation vary significantly among the different forest types. In the SSA, the OBS site has the largest sensible heat flux, FEN the least with YJP and OJP in between (Fig. 4a). For the latent heat flux, the FEN site shows the larger diurnal variations than the YJP and OBS sites and the OJP site shows the least diurnal

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The largest difference reaches 320 W/m² for the sensible heat fluxes between OBS and FEN in the SSA and 150 W/m² for the latent heat flux between OJP and FEN in the SSA. Similar patterns of sensible and latent heat fluxes exist in the NSA (Fig. 4d and e).

**Aggregated surface fluxes**

The boundary conditions for sensible and latent heat fluxes were aggregated from measurements over different land cover types. For the NSA, the dominant forest species is black spruce with some jack pine stands in the south and west parts of this study area. The averaged tower measurements of sensible and latent heat fluxes from black spruce and jack pine forest stands were used to represent the surface forcing at the Thompson release site. As shown in Figure 1, the Thompson release site has some distance from the flux towers, averaging of fluxes tower might not be best fluxes for the Thompson release site.

**Figure 3:** Classification on the patterns of potential temperature profiles at Candle Lake (upper row) and Thompson Zoo (lower row) release sites on June 1994. The potential temperature profiles were taken at the early morning (5:30 on local time).
For the SSA, the major vegetation types are aspen, spruce, jack pine and grassland. The release site at Candle Lake is covered by a mixture of coniferous (OBS, OJP and YJP) and deciduous (YA and OA) forests and three lakes nearby with 30% lake area fraction (Oncley et al. 1997). The surface fluxes were estimated as the area-weighted fluxes from lake and forests. Lake has large heat capacity and the sensible heat fluxes are much smaller than the latent heat fluxes, so we simply add the lake effects to the latent heat flux term. Then total sensible \(H_s(t)\) and latent heat fluxes \(\lambda E_s(t)\) were estimated as

\[
H_s(t) = (1 - LF) * H_f(t),
\]

\[
\lambda E_s(t) = (1 - LF) * \lambda E_f(t) + LF * HE_L * R_n(t),
\]

where \(R_n\) is the net radiation, \(LF\) represents lake fraction and \(HE_L\) is the heat emission ratio from lakes. \(H_f(t)\) and \(\lambda E_f(t)\) are the sensing and latent heat fluxes from forests, which were estimated as the mean fluxes from both conifer (OBS, OJP) and deciduous (YA, OA) stands.

Figure 5 shows the integrated sensible (upper panel) and latent (lower panel) heat fluxes for both the Candle Lake (solid lines) and the Thompson (dash lines) release sites. Comparison of sensible and latent heat fluxes at both sites show clear impact of lakes on surface fluxes. Lakes have a lower albedo, a higher heat capacity and effective conductivity and are smoother than land. Therefore, lake is found to be large sinks of available radiant energy leading to less emission of sensible heat. Figure 5 shows clear lower sensible heat fluxes in the SSA Candle Lake site than in the NSA Thompson site.

Figure 4: comparison of the mean values of the sensible heat flux, latent heat flux and net radiation among different forest types measured at above forest canopy in the SSA and NSA during day 6–16 of June 1994.
RESULTS

The relation between surface fluxes and BL development

Surface sensible fluxes are main forcings to drive the PBL development. First, we investigate how surface sensible heat fluxes influence the PBL evolution using field data. Figures 6 and 7 compare the BL evolution, estimated as an enclosed area between two potential temperature profiles from two radiosonde measurements, and the corresponding total sensible heat fluxes during two these radiosonde measurements for nearly every day in June 1994 for both the SSA and the NSA sites. They show clear linear relationships, indicating that sensible heat flux plays a dominant role in driving the BL development. Statistical analysis also indicates the significant linear relation between the changes of PBL potential temperature profiles and surface sensible fluxes over boreal forests.

The regression slopes vary among the different days, which may result from the different initial BL structures at the early morning in these days. A stable initial BL structure will require large sensible heat contributions for the BL development, while small sensible heat flux can easily develop a BL with an unstable initial BL structure. On the other hand, the slope can be used to identify the contributions of sensible heat flux for the BL development. The small slope values will indicate large contributions from the sensible heat flux in the BL development. The large slope in the SSA on June 15 responds to small contributions from sensible heat flux to the BL development, while the small slopes on June 7 and 10 in the SSA indicate large contributions from the surface sensible fluxes. However, the comparison for the NSA shows some scattering because the averaged sensible heat fluxes may not completely match the Thompson release site. The slope is large on June 6 (9.26) and is below 5 on other days. This indicates that the sensible heat fluxes contribute large to the PBL development in the NSA. Our result is consistent with the conclusion from Yi et al. (2001) that found the maximum PBL depth is coincident with the maximum daytime surface sensible fluxes.

Simulation results

Diurnal profile comparison

To evaluate the performance of the non-local BL model, the modeled atmospheric profiles were compared to radiosonde measurements under different weather conditions: sunny day (June 7), cloudy day (June 8) and rainy day (June 16)
in the SSA. Figure 8 shows the modeled potential temperature (first column) and mixing ratio (second column) profiles with measured profiles (third–fourth columns) for sunny (first row), cloudy (second row) and rainy (third row) days.

On June 7 (sunny day), with relative large sensible heat fluxes and small latent heat fluxes on June 7 (Fig. 5), large gradient of mixing ratio appeared between the BL (wet) and the upper layer (dry) (Fig. 8). Comparison of the measured and simulated BL profiles of potential temperature shows good agreement. Both modeled and measured mixing ratios at the top of the BL decreased before 11:30 am, indicating that the EL continued to dry the air downward. After 11:30, the mixing ratio increased because of the complement of large surface latent heat fluxes. Both model and measurements show similar dynamics of mix ratios. Comparison of the measured and simulated BL profiles of potential temperature and mixing ratios demonstrates that the model has the capability to simulate the PBL development during the clear days.

June 8 (cloudy day) is a special day with large change in potential temperature and mixing ratio above the top of the BL (Fig. 8). The mixing ratio increased because of the complement of large surface latent heat fluxes. Both model and measurements show similar dynamics of mix ratios. Comparison of the measured and simulated BL profiles of potential temperature and mixing ratios demonstrates that the model has the capability to simulate the PBL development during the clear days.

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On June 8, the continuous cloud covered for the whole day. The humidity decreased smoothly with height. The large slope of the relation between the BL development and the surface sensible heat fluxes indicates the sensible heat fluxes contribute less to the BL development (Fig. 6). Therefore, the simulated potential temperature is slightly less than the measured values. Nevertheless, both model results and measurements show reasonable agreement in potential temperature and mixing ratios for both cloudy and rainy days.

These comparisons demonstrate that the TTT model simulates diurnal potential temperature and mixing ratio relative well. However, the mechanism of the BL changes during nighttime remains challenging. Before applying the TTT model into atmospheric model for the weather forecast, we need to test the TTT modeling for the nighttime.

**Overall model evaluation in the SSA**

To evaluate the overall model performance, Figure 9 compares the diurnal modeled and measured BL height and potential temperature from 6 to 16 June 1994 for the SSA. This period includes three clear days (June 6, 7 and 10), three partially cloudy days (June 8, 9 and 11) and five rainy days (June 12, 13, 14, 15 and 16). The TTT model captures the features of the BL development. On June 16, the continuous cloud covered for the whole day. The humidity decreased smoothly with height. The large slope of the relation between the BL development and the surface sensible heat fluxes indicates the sensible heat fluxes contribute less to the BL development (Fig. 6). Therefore, the simulated potential temperature is slightly less than the measured values. Nevertheless, both model results and measurements show reasonable agreement in potential temperature and mixing ratios for both cloudy and rainy days.

These comparisons demonstrate that the TTT model simulates diurnal potential temperature and mixing ratio relative well. However, the mechanism of the BL changes during nighttime remains challenging. Before applying the TTT model into atmospheric model for the weather forecast, we need to test the TTT modeling for the nighttime.
The three clear days (June 6, 7 and 10) had largest net radiation and surface sensible heat fluxes and the three cloudy days (June 8, 9 and 11) the average net radiation between 330 and 350 W/m². The rainy days include two heavy rainfall days (June 13 and 14) with precipitation above 50 mm (average net radiation <110 W/m²) and three small rainfall days (June 12, 15 and 16) with average net radiation around 200 W/m².

For those clear days, on June 7 both the modeled BL heights and the potential temperatures are in close agreement with the measured values. On June 6, the simulated potential temperatures in the PBL are relatively smaller than the measured values, and the boundary heights match well with the measurements for the whole day. On June 10, both the simulated potential temperatures and the BL heights are slightly larger than the measured values.

These mismatches might be partially due to that the TTT model was set up with the same parameters for these three simulations. With the same model parameters indicates that the BL development and sensible heat flux were set as a fixed relation in the TTT model. On June 10, the large contributions from the surface sensible fluxes (small slope in Fig. 6) will result in the TTT model to overestimate the PBL development and potential temperature with the empirical fixed parameters. The relatively large slope (8.66) on June 6 indicates that the surface sensible heat fluxes play a relatively small role in developing the BL. With the same parameters, the TTT model underestimates the PBL potential temperature on June 6.

On the three partially cloudy days (June 8, 9 and 11), the sky was cloudy only in the morning on June 9 and around noon on June 8 and 11. The average surface sensible fluxes were 148.8, 113.8 and 143.0 W/m² for June 8, 9 and 11, slightly smaller than those values on clear days (Fig. 5). On June 8, the regression slope of the relation between the BL development and the surface sensible fluxes is 7.27 (Fig. 6), which represents that large contribution of the BL development results from the sensible heat fluxes. The current model simulations underestimate the BL heights, but the simulated potential temperature agrees with the measurements (Fig. 9). There were only three profile measurements on June 9, and the simulated potential temperature and BL heights agree well with these three measurements (Fig. 9).

The five rainy days include two heavy rainfall days (June 13 and 14) and three light rainfall days (June 12, 15 and 16). For June 12, 13 and 14 there are only three measurements per day at approximately 5:30, 11:30 and 17:30 on local time. Those heavy rain days had very low-net radiation, low-surface sensible heat fluxes (17.7 and 26.6 W/m², respectively) and low-latent heat fluxes (31.9 and 28.1 W/m², respectively) (Fig. 5). These small surface fluxes resulted in nearly no BL evolution. The relation between the BL development and the sensible

![Figure 7:](image-url)
heat fluxes is vertical (slope is nearly infinite), which represents that the surface sensible fluxes did not show any effect during heavy rain days. The TTT model captures these features, and the simulated potential temperature profiles are in close agreement to the observations (Fig. 9).

During the small rainfall days, the average net radiation was around 200 W/m² and the average sensible heat fluxes were 104.0, 36.7 and 76.7 W/m² on June 12, 15 and 16, respectively (Fig. 5). On June 16, the continuous cloud covered for the whole day. The humidity decreased smoothly with height. The large slope indicates the little contribution from sensible heat fluxes to the BL development (Fig. 6). On June 15, the extremely large slope (21.57) indicates that the BL structures have little effects from surface sensible flux. On June 12, both the simulated BL heights and the potential temperature match very well to the measured values.

Overall, the TTT model can simulate the BL development in both the BL heights and the potential temperature in the south study area of Canadian boreal forest during the sunny, cloudy and rainfall days. Some minor underestimations and
overestimations are partially due to the uncalibrated model parameters.

**Overall model evaluation in the NSA**

In the NSA, the whole simulation period includes three sunny days (June 7, 8 and 9) with large net radiation and surface sensible heat fluxes, three rainfall days (June 12, 14 and 15) with average net radiation around 200 W/m² and four cloudy days at June 6, 10, 11 and 16 with the average net radiation between 310 and 380 W/m² (Fig. 6). There were only three sounding measurements on the rainy days (June 12, 14 and 15) and there were no surface flux measurements on June 14 and only half-day flux measurements on June 11, 13 and 15. Similar to SSA, the surface fluxes were generated by taking an average among four tower sites in the NSA to represent the surface fluxes at the NSA release site.

Figure 10 compares the BL depths and potential temperature between the sounding measurements and the simulations at Thompson Zoo, Manitoba, during June 1994. Model results match reasonably well with the simulations. The TTT model tends to overestimate a little on the PBL heights in most days except June 6, 12 and 15. The relation between the BL development and the sensible fluxes suggests that the large regression slope on June 6 will result in the underestimation. In the other days, the regression slopes are smaller, which results a little overestimation. On June 11, at 15:30 and 17:30 local time the modeled and measured PBL depths and potential temperature do not match well. This may result from cloud moving in during afternoon. The mixing ratio increased for the whole column in the afternoon, and the cool wet air occupied this space and resulted in decreased potential temperature. The simulations in NSA further demonstrate that the TTT model can capture the PBL development both in potential temperature and in PBL heights, no matter what weather conditions were.

Comparison of Figures 9 and 10 shows deeper BL development and larger potential temperature in the NSA than in the SSA. Weaker BL in the SSA is due to the impact of lakes, often leading to lower sensible heat fluxes. This is another evidence to demonstrate the importance of sensible heat fluxes on BL development.
CONCLUSIONS

We analyzed upper air sounding data and TF data measured during BOREAS field campaigns and found that there is a linear relation between the BL development and the sensible heat forcing in nearly every day above boreal forests. The relationship between the BL development and the sensible heat flux can be used to identify the contribution of surface flux to the BL development. This result concords with the conclusion in Yi et al. (2001).

Further, we applied the TTT model to simulate the diurnal BL development at Candle Lake and Thompson release sites over boreal forests. Integrated fluxes from mixed forest types and lake were used as BL conditions. Thirty percent of lake at the Candle Lake release site of SSA reduces surface sensible heat fluxes and leads to less strong BL development in the SSA site comparing to the SSA site indicating lakes play an important role in BL development.

Comparison of the model results and BL field measurements indicates that land surface fluxes play an important role in BL development. Consideration of land surface heterogeneity provides accurate BL conditions and is critical for correctly modeling BL development and Good match between modeled and measured BL profiles demonstrates the capability of the transient non-local turbulent theory to model the impact of land surface on turbulent BL development. The non-local scheme has the great potential to be coupled in a land surface scheme to study the impacts of land surface heterogeneities on PBL development.

This study focused on the effects of land surface heterogeneity on the BL development in summer time. In cold season/regions, the heterogeneity of land surfaces at smaller scales leads to less net radiation and latent heat fluxes at the land surfaces when snow is under trees. Future work will use both the TTT model and the BOREAS data to study the land surface fluxes from forest with and without snow underneath.

Figure 10: comparison of the simulated and observed BL heights and potential temperature at Thompson release site during 6–16 June 1994.
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