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A Dissertation

Nocturnal Wave-Like Air Motion in Forests
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Changming Hu and Songjuan Dun

and my parents

This thesis is dedicated to my wife Yong Lin
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As dynamics, the two-layered wave model was first developed while I took this class. As
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more continuing projections on the global changes.

data. These researches will be extremely useful in building realistic models to make
variation (Coulson et al., 1986a), have been studied by measuring the hourly CO₂
variation (Szysmata et al., 1996), annual cycle (Hickel et al., 1996), and internal
est systems to the climate variability in a range of temporal scales, such as seasonal
role of a particular forest ecosystem in the global carbon cycle. The responses of for-
continuous measurement (Selker et al., 1995) provides opportunities to identify the
cess was sufficient to understand the ecosystem-level exchange. The long-term
ried to use measured CO₂ flux to examine whether the knowledge on leaf-level pro-
ecosystem-atmosphere exchange of CO₂ in a temperate forest. Hollinger et al. (1994)
and the canopy-atmosphere interfaces, Wogel et al. (1993) estimated the annual net
the CO₂ concentration profile and the CO₂ fluxes across the soil-atmosphere
flux over boreal forests with airborne eddy covariance instruments. By measure-
 ample, Desjardins et al. (1982, 1986) and Asefo et al. (1984) measured the CO₂
term net ecosystem exchange of CO₂ between forests and the atmosphere. For ex-
by the anthropogenic CO₂, there have been increasing practices to quantify the long-
Since the early 1980’s, with the concern of the potential environmental changes caused

Preface
20 meters above the leaves. The existence of a constant flux layer between the
potted plants and the atmosphere is suitable for measurements in forests, in order to get good
results. Developed for forest measuring applications (Shields et al., 1999).

For lower-based measurements in forests, in order to get good
results. Developed for forest measuring applications (Shields et al., 1999).

The influence in the atmospheric boundary layer (Bush et al., 1989; Balbo et al., 1996; Balbo et al., 1996).

The experimental design, such as the sampling frequency, instrument height, fetch,
and layout has been advanced tremendously. Nowadays, fast-response instruments are
are available to measure the atmospheric turbulence and fluxes of chemical species.

Over the last four decades, knowledge of the influence in the atmospheric boundary
layer has increased tremendously. Fast-response instruments are

The proportion in the application of micrometeorological techniques in the tropics

Models and the calibration of satellite observations (Shields et al., 1997).

The parameterization of the land-surface exchange in the atmosphere (Gurney, 1997).

Such high temporal and spatial resolution data sets are of great importance to improve
the understanding of the sources. Secondary, it is an important area over a surface area that
is several hundred meters to about 1 kilometer in the sampling direction.

Improving the instrument height, hourly lower-based measurements represent
environment of the source. Therefore, it is important to measure the fluxes without disturbing the natural
measurement method, it is possible to measure the fluxes without disturbing the natural
factors. Compared with the "source force" method, most field measurements employ microelectromechanical techniques to quantify the
fluxes of CO2 and other scalar entities across the canopy-atmosphere interface. There
The uptake of the forest in the daytime. The nighttime CO₂ fluxes measured by the
released by respiration activities is comparable to magnitude to the photosynthesis
the nocturnal exchange processes over the forests. For example, the nighttime CO₂
enough attention in the past. However, there are compelling reasons to understand
fluence diffusion. As a result, the nocturnal exchange over forests has not received
nocturnal radiation cooling at the canopy top would significantly suppress the tur-
compared with the rigorous daytime influence on the estimated nocturnal exchange,

Carbon sequestration

underlying forest systems and may cause uncertainty in the estimate of the long-term
Under such conditions, the measured CO₂ flux may not represent the output from the
fluence background decreases from the surface (Marra, 1999; Wofsy et al., 1999).
conditions, the canopy flux layer may be very shallow or does not exist at all, and
represents the exchange processes under stable conditions at night. Under very stable
is often optimized for unstable or neutral conditions in the daytime. The data poorly
been established. In fact, the setup of current tower-based flux measurement systems
interactions between plant canopies and the air, similar guidelines have not
the to the inherent complexity of the nocturnal atmospheric boundary layer and the
atmospheric influence dominates the exchange process. Under stable conditions,
version designs are well established for unstable and neutral conditions when regional
those from the underlying systems. A host of the considerations guiding the option-
canopy top and the instrument height guarantees that the measured fluxes represent

3
Wave-like motion is a common type of air motion in forests. At 40%, 49.8%, and 49.9% (Brown et al., 1990; Mustonen et al., 1989; Fitzgerald and Hoorelbeke, 1990), it is safe to say that the 49% of the nighttime observations. Along with other observational studies (Michalski et al., 1990), we found wave events with various intensities in a boreal forest (Leclair and Part, 1998) have demonstrated that wave-like motions were often observed in a variety of plant canopies. From short crops to tall forests, the field measurement in Pauw et al. (1999) have demonstrated that wave-like motions were often observed in boreal forests, we find that the importance of the frequency observed wave-like motions, especially in understanding of the nocturnal exchange processes in forests.

When focusing our attention to the nighttime atmosphere exchange processes in forests, wave-like motions have a negative effect on nighttime (Schmid and Wodzicki, 1972). All other applications demand a better understanding of the nocturnal exchange processes at night. Certain fungal spores are released and transported at the forest floor. Fungal spores are released in the canopy due to the night (Kaplan et al., 1988; and Defrense, 1996; Whithaker, 1972). NO$_x$ and other biogenic emissions important in forests is one way to estimate the respiration rates of forest ecosystems (Woolward et al., 1997). For instance, the nighttime building of carbon dioxide concentration within forests is one way to estimate the respiration rates of forest ecosystems (Woolward et al., 1997). The high levels of CO$_2$ in forests implies an increase in the contribution of respiration to the nighttime CO$_2$ flux in forests. The uptake of CO$_2$ by forests implies on clear and calm nights (Black et al., 1999; Coulson et al., 1996b; Lee et al., 1997; 1998).
It is well established that waves can significantly affect the global atmospheric ener-
gy. Superimposed on patterns are the manifestations of mountain waves (Smith, 1979). In
frontal systems and general synoptic scale weather, mountain clouds and some oro-
o- of scales. For example, waves associated with the jet stream form the mid-latitude
atmospheric phenomena are the direct or indirect results of waves on a wide range
of scales. The wave community, the importance of the atmospheric

Outside the microclimate community, the measurement of wave activity,
resolution is just simply not enough to capture the whole wave activity.
measurements are made at only one or at most a couple of heights. The wave vertical
which generates zero mean vertical fluxes. In addition, most of the lower-bound flux
the wave components of scalars are in quadrature with the vertical wind fluctuation,
perception that pure horizontal gravity waves do not transport scalar quantities because
only very small fractions of their daytime values. Another reason is the wide-spread
of most microclimateological quantities, such as momentum, heat and water vapor, are
been fully understood yet. The neglect is mainly due to the fact that nighttime fluxes
 dynamics, wave-canyon interaction, and associated transport processes have not
canopy waves (Paw U et al., 1989; Fitzgerald and Moore 1990; Lee et al., 1997). The wave
waves. Only a few simple models have been developed to explain the mechanism of
were not many field experiments designed specifically for the study of canopy
more; they have not received enough attention from the microclimateology community.
Although waves are frequently found in the field observations for flux measure-
waves is revealed. Background knowledge of canopy-canyon influence and KH
mechanical canopy-flow model. In Chapter 1, the current state of knowledge on canopy
structures was described. The wave dynamics with a single wave (i.e., a simple model) is not
suitable for simulating the exchange of energy and momentum between the surf and the
water surface. This is especially true for the exchange of energy because energy is
transferred from Kelvin-Helmholtz waves to the air-water interface. These waves are
important in the study of the exchange of energy and momentum between the surf and the
water surface. In Chapter 2, the current state of knowledge on canopy-canyon influence
was described. The model of canopy-canyon influence was developed by Remehill (1996).
In Chapter 3, the numerical model of canopy-canyon influence was developed and
implemented in a general purpose software. In Chapter 4, the numerical model of canopy-
canyon influence was implemented in a general purpose software. In Chapter 5, the
numerical model of canopy-canyon influence was implemented in a general purpose software.
summarized in the Construction and future works are suggested.

model to reproduce the salient wave features is demonstrated. Finally, the results are
model is used to simulate the flow structure of the canopy wave. The ability of this
investigated. In Chapter 4, a two-dimensional eddy-resolved numerical canopy flow
wave model is developed. The effect of the canopy drag on the wave dynamics is
anomalous data from a boreal forest. In Chapter 3, a two-layered hierarchy canopy
is investigated by analyzing the high-resolution temperature profiles and the sonic
instabilities is presented. In Chapter 2, the flow structure of the wave-like air motion
Canopy Flow

The Organized Structures in the

Chapter I
forest environment because the structure of canopy influence differs from that of
and spatial variation of sources and sinks, the commonality used in theory falls in
as the result of the non-local transport by the canopy influence and the temporal
shifts for wind, temperature, humidity, CO2 and other scalars show erratic patterns
the organized structures with scales of the canopy heights. The flux-gradient relation
by high influence intensity. The downward momentum transfer is mainly done by
seen larger when approaching the canopy tops. Within canopies, wind is characterized
conceptually treated as evolved solid surfaces. The departure to surface layer profiles
the canopy tops, Monin-Obukhov similarity relations still hold if plant canopies are
from Monin-Obukhov similarity theory is expected. Several canopy heights above
short vegetation. Depending on the proximity to the canopy tops, a departure
characteristics in this layer differ greatly from those over bare soil or surfaces with
are usually located within the canopy influence sublayer. The observed influence
expected compared to the instrument heights in most micrometeorological measurements
fourth dimension, In contrast, over tall forests, for the practical interest and the lo-
The observation heights are well above the characteristic heights of the underlying
itary theory were performed over bare surfaces or surfaces with short vegetation.
The micrometeorological experiments for establishing the Monin-Obukhov sim-
above surface layer is widely known as the y'-theory.
extension of the eddy-diffusion concept to the influence exchange in the ana-
exchange coefficients, the counterparts of viscosity, conductivity, and diffusivity. The
Introduced.

Layer analogs for the ramp-like structures and the near wave models will also be

described in Section 1.3. The plane-mixing

observed features of the ramp-like coherent structures and canopy waves, A brief

rotational variables in forests is given in the Section 1, followed by a review of the

In this chapter, a brief description of the unique distribution of common mean-

into the complex interaction between the airflow and plant canopy.

theoretical studies. The study of the wave-like analogy will provide further insight

motion, by its well-organized structure, is especially suitable for mathematical and

motion has not attracted much attention yet. The wave-like and

structures (Kuang et al., 1999). In contrast with daytime coherent structures, the

strong wind shear at the canopy top is responsible for the generation of these coherent

strong downward motions (sweeps). Numerous observational studies have provided

of section-sweep cycles, that is, slow upward and motions (sections) followed by

can be identified in time series of wind velocity components as repeated patterns

cohesive structures, with the length scale of the canopy height. The coherent structure

within and just above plant canopies, influenced is characterized with the intermittent

the canopy roughness layer is far from random. It is now widely recognized that

Observations over the last two decades have established that the influence in

the surface layer influences

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1.1.1 Leaf Area Index and Leaf Area Density


\[ \int_{y_1}^{y_2} p(z) \, dz = \int \]
The dynamic pattern of the net radiation above the canopy with clear sky in a homogeneous spruce forest with average tree height of about 30 m in Figure 1 shows the vertical distribution of mean net radiation on a selected day.

Net radiation determines the net exchange of energy at the canopy surfaces and the surroundings. The heat exchange processes determine the net radiation at the canopy surfaces. The net radiation can be measured directly with heat flux meters and the ground. The shortwave and the longwave components of the net radiation are determined by the vegetation and the weather conditions.

A detailed description of the net radiation transfer in the plant canopy can be found in the literature. Solar radiation, cloud type and amount, and aerosols, only add more complexity. Other external factors, such as the changes of the direction and the intensity of net shortwave and longwave energy of the stand architecture and the individual tree structure, are important and have a significant impact on the net radiation transfer in forest canopies.
Figure 1.1: The typical daily variation of the net radiation in a forest.
Detailed measurements of the various components in forests (Thorn, 1972) demonstrated that the energy balance at a reference level above the ground can be written as

\[
S' + V + G + F + H = \eta \%
\]

The air temperature in plant canopies is determined by the energy balance. The

### 1.3 Temperature

10% of that at the open.

While the lower canopy and the trunk space, the \( \eta \) values initially be less than

\[ \text{where } \eta = \text{only } 40\% \text{ of the value at the canopy in the daylight and } 20\% \text{ at } \%
\]

where the \( \eta \) is only 40% of the value at the canopy in the upper canopy,

and not only about one hour before sunset, within canopies, the reduction of the \( \eta \%

patterns occur at sunrise and sunset. The \( \eta \) becomes positive shortly after sunrise

dropping through the night. Transitions between the night and the daytime

sky, the net radiation is negative and the air temperature in the canopy layer keeps

of canopy elements is usually greater than the effective radiative temperature of the

of the canopy (and of the ground if the forest is sparse). Since the temperature

\( \eta \) is determined by the atmospheric longwave radiation and the longwave emission

residuals that of the solar radiation. At night, without the shortwave component, the

direct insolation is the dominant radiation component and the \( \eta \) variation essentially

follows the same pattern as that above a open surface. In the daytime, the solar
net radiation by modifying the shortwave radiation and the atmospheric longwave.

Other factors can change the above scenario. Clouds can significantly disrupt the

with height.


can be found in sparse forests. The temperature are expected to continuously decrease from the ground can escape from the canopies. No unstable temperature structure is located at the upper canopies. It is also the location of the temperature minimum that radiation is received in all yellow of the ground and the maximum radiation difference. The atmospheric longwave radiation is usually smaller than the canopies emission. The net

On clear nights, canopies emit the longwave radiation almost like blackbodies. The

canopies cannot be established.

forests, more solar radiation can penetrate deeper. Stabile never found in closed

the height of the temperature maximum, there usually is a stable layer. In sparse

the mid-canopy is usually a few degrees higher than at the ground level. Below

the large daily temperature variation. At midnight in summer, the temperature near

canopy experience a daily change of the difference of the net radiation. As a result, canopy tops experience

In closed canopies, the uppermost part of the crown is the place with pronounced

the remaining terms, the energy budget is dominated by $\frac{H}{H}$ and $\Delta\varepsilon$.
canopies can usually be divided into three layers according to Campbell and Norman stand structure and density (Fig. 1.2, from Physiologia, 1989). Flow regime within

Within canopies, wind profiles show great variations because of the variability of

possible.

of the plant height. Stable layer correction for $z_0$ of the logarithmic model is also
simulation (Shaw and Peter, 1982), and $z_0$ are often estimated to be 0.7 and 0.1
roughness height. Both $p$ and $z_0$ depend on the stand density, from the numerical
where $n = 0.11$ is the von Kármán constant, $n$ is the friction velocity, and $z_0$ is the

\[
\left( \frac{z_0}{p - z} \right) \log \left( \frac{y}{z_0} \right) = (z) n
\]

is given by

due to an extra parameter, $\gamma$, the displacement height. Thus, mean wind at height $z$
canopies, the famous logarithmic formula for mean wind can be modified by intro-
upward. Under neutral conditions, by taking into account of the influence of plant
experiment has a similar shape to that above a bare surface, except that it is shifted
the structure is significantly reduced by plant canopies. The wind profile above a
compared with that above the surrounding bare surface, wind within and just above

1.1.4 Mean Wind

reduced by the enhanced atmospheric longwave radiation associated with clouds.
longwave radiation. At night, the radiative cooling of stands can be significa-
ected by blocking the direct solar
Figure 1.2: Mean wind profiles in various plant canopies. Where h is the height above the ground, H is the height of the top of the canopy, L is the wind speed and U is the wind speed at the height of the free top. Line 1 is dense cotton, 2 is Douglas fir forest, 3 is dense hardwood juniper with understory, and 6 is isolated conifer stand.
the activities of CO$_2$ sources and sinks are moderate and so is the daily variation
carbon dioxide sources and sinks over time and height can be identified. In April,'
forest for three different months (Gagnon et al., 1981). The effects of the different
Figure 1.3 shows the average CO$_2$ concentration distributions in an 80-year-old pine

1.1.5 Carbon Dioxide

Roughness

Loosening profile above the canopy except for using the forest floor surface
wind maxima, sometimes called minima, are often found.
wind speed within the leaf layers. For stands without understory, secondary
is associated with a more open canopy. The presence of an understory affects
then the shear driven by the airflow aloft. A large within-crown wind speed
motion within the canopy is primarily the result of the pressure gradient rather
above the canopy; in both speed and direction. It is believed that the horizontal

2. In the second layer ($p > z > H$), wind can be quite unidirectional to the wind
where the attenuation coefficient $a$ can be related to the canopy structure,

\[
\alpha(z) = \left[ \frac{1 - \eta/z}{\eta} \right] \exp(\eta) n = (z) n
\]

above canopies. Wind in this layer is usually given by an empirical relation

1. The top layer ($\eta > z > p$) is the layer that exerts most of the drag on the wind
Figure 1.3: Daily CO₂ variation in forests. (a) April; (b) August; (c) December.
1.2 The Organized Structures in the Canopy Flow

wave events, which has not been paid much attention previously.
the next chapter, it is found that CO2 concentration can be highly changeable during
Only a slight minimum by photosynthesis occurs during the early afternoon hours. In
wet or dry periods, the algae and algae in the canopy are more active, and the detritus of the organic
matter in the soil. Observations have been made at the carbon dioxide concentration
concentration within the canopy is mainly caused by the strong photosynthetic mixing of
the pronounced minimum during the late afternoon. At night, the uptake by the
August, evidenced with the rapid decrease of the concentration after sunrise and
of CO2 concentration. There is a strong photosynthetic carbon dioxide uptake in
structures in each patch. The phase difference between adjacent patches is arbitrary. Each patch of coherent wave-like structures. There are 2 or 3 individual wave-like patches in the canopy flow. When homrain waves take place, the field is divided into down- and upward moving patches in a particle field (O'Brien and Nihrmann, 1978), and in a wave field measurements in a particle field (O'Brien and Nihrmann, 1978) show a similar evidence that the organized structures exist. Further detailed study of the planar elasticity confirming some experiment results persistently. Further detailed study.

Ocean-wave-like motions have been documented and named by Jones (1975). Homrain crops on windy days, the phenomenon of homrain, the organized and persistent pattern, have been observed over short agricultural fields. Over both within and above the canopy, a series of ramps give rise to an oatleaf apples (Lu and Fitzgerald, 1994). The ramps occur simultaneously at several levels, and of these ramps is typically about several tens seconds, with somewhat seasonal variances. In the front, there is a fast downward motion (sand, downwind, east) followed by an upward motion (ejection, updraft) proceeds the arrival of the scalar front. Following a slow drop (or jump) in just a couple of seconds (Figure 14. From Gao et al., 1989). A sharp drop by a gradual increase (or decrease) in the magnitude of the scalar followed by a sharp decrease. Water vapor and CO2, typically, a ramp-like structure is characterized by a few characteristics. The structure patterns in the time traces of scalars such as wind.

In the daytime observations, the organized structures in the canopy, influence many...
Figure 1.1: Ramp-like structures in the time traces of temperature.
A negative mean vertical gradient, then, tends to ease the inverse-ramp structures.

measured translation speed is close to the wind speed at the top. For a scalar with
short-term components, the vertical velocity occurs almost simultaneously at all levels.
Then
microstructure. After the arrival, the strong downward motion is most noticeable. The
microstructure. After the arrival, the strong downward motion is most noticeable. The
the forest, the vector flow field shows weak upward motions before the arrival of the
direction. This can be explained as the result of the wind shear. Near the top of
behind those at higher levels, which makes the microstructure clear to the downward
only a few seconds across microstructures. The passage of a microstructure at each level
forest canopy as scalar microstructures. The temperature drops a couple of degrees in
unstable conditions, it is clear that the ramp-like structures within and just above
of temperature and wind horizontal vectors (Figure 3, from Caio et al., 1989). Under
Over tall forests, the common structures are best revealed in the time-height plot.

Almost all of the downward momentum transfer is done by those gusts.
the boundary layer, bending over a succession of slabs in their downward passage,
high streamwise momentum. They sweep down to the surface. From an outer part of
1978b) have proposed that horizontal waves are recorded of the passage of gusts within
about twice of the mean velocity at the top of the canopy: Predict and Monitor
about direction. If remains its identity for about 2 s after. The average phase speed is
extends about 20 canopy heights in the streamwise direction and 7 m across the
even as direction, giving the impression of waves moving through the canopy. A patch
the small phase difference between adjacent planes varied smoothly in the stream-
Within patches, individual planes varied at their common natural frequency, while
The phenomenon reinforces the concept that the coherent structures occur frequently normal water vapor ramps occur because the atmosphere is humidified by evaporation by photosynthesis during the daytime. Recent periods, whereas, at the same time, in the daytime, the CO2 ramps are inverted because this scalar is depleted in other scalar fields, such as water vapor and CO2 (Cao et al., 1989). However, they can be seen because of the presence of a temperature gradient. However, they can be seen in neutral conditions, the ramp patterns are not observable in all temperature regimes.

Page 24
Fluxes associated with the ramp-like structures, which are supported by the analyses in the next chapter of this thesis, demonstrate both ramps and wave-like structures are signatures of the same coherent structures, which is supported by the analyses in the previous chapter. Although the detailed connection has not been established, Lee et al. (1988) have suggested that the interaction between the two are significant. The work of the ramp structures are closely associated with wave-like structures. The ramp quickly replaces the cooler air, resulting in a sharp rise in the surface temperature. A strong sweep associated with the coherent structure occurs, warmer air from aloft within the plan canopies, allowing the air to be cooled by the plan elements. When two or more of the structure phases of a coherent structure, which is in the upper boundary layer, move across the ramp to the inverse scalar ramps described above, the slow temperature drop near the canopy tops. The step-like propagation of the ramp-like structures are generally believed to be the ramps. As noted, under stable conditions, temperature inversion usually occur.
and above canopies alone with ramp-like structures at other levels, the connection

of the wave-like structures are often observed at certain levels within

instrumental setup in most of the field observations are selected for the daytime con-

mon nocturnal motion type in forests has not been widely accepted yet. The usual

structures have not been fully understood. The fact that wave-like motion is a com-

the fluctuations in the time traces of temperature, wind speed, water vapor, CO2 and

nighttime micrometeorological measurements over plain canopies often find wave-

1.2.2 The Wave-like Structures

flux-gradient relationships within canopies (Shaw, 1977; Priemé, 1979; Denmead

intermittent fluxes in the sweep phase are suggested to be responsible for the erratic

contributions from the two become almost equal, like that in the surface layer. These

the fluxes in the sweep phase are much lower. At higher levels above the canopy, the

canopy, Compared with those in the Ejection phase within and just above the canopy,

monotonic and heat flux at the higher level and 70-80% of the fluxes within the

canopy and become equally dominant above several canopy heights. For example,

within the canopy, while Ejection events become increasingly important above the

occur both in the Ejection and sweep phases. Sweeps evolve dominate flux transport

Denmead and Hoggiston, 1989). The transfer of momentum, heat and mass

Priemé, 1979a, 1979b; Haendel, 1981; Baldocchi and Novais, 1988; Gao et al.,
wave-like fluctuations at other levels. Above the canopy, there were no discernible
canopy, sometimes the inverse temperature ramps were found to coexist with the
shows that wave-like fluctuations are most noticeable within the canopy. Within the
of surface or sensible, under low wind conditions. Their observation in an oriental
found in the temperature and vertical velocity time series, especially near the time
in a variety of plant canopies, from short crops to tall forests. Wave fronts have been

wave-like fluctuations because of the radiative cooling.

wave-like fluctuations would be most noticeable just above the crop tops, the height with large
the wind shear at the canopy tops, in turn, resulted in intermittent influence. The
wave in the atmospheric boundary layer above canopy height periodically enhances
force drives the wave-like motion near the crop tops. It might be that the gravity
wind speed at crop tops, the rather longer periods indicate that a periodical external
ions mimic, Compared with the time scale estimated from the crop height and the
analysed reveals that the wave-like motions have periods from a few minutes to several
wind and temperature measurements over a rose and a sorghum field. Their special
wave-like fluctuations, most noticeable at the top of crop canopies, in the nighttime
canopy wave. Khalili and Khalili (1984) and Khalili (1989) have reported persistent
During the last two decades, these have been sporadic observational studies on the

Phenomena

Resolutions.
above the tree-tops. Most of the waves were found on nights when the wind over the
wind direction, with a speed matching the background wind speed at a few meters
was not available in previous observations. Figure 1.6, from Lee et al. (1997), Figure 1.7,
have been directly measured by a horizontally separated thermal couple array, which
indicated that the ramps were parts of the same wave event. Key wave parameters
between ramp-like patterns and wave-like patterns in the layers above and below
the layer near the tree-tops were often measured as inverse ramps. The higher center-
line wave thermal couples (Figure 1.6, from Lee et al. (1997), The temperature in
wave features were revealed by the high-frequency temperature profile measured by
where were found in over 40% of the nighttime observations in a boreal forest. Striking
The recent observation by Lee and Park (1998) showed that waves of various heights
of the wind speed, which was consistent with the appearance of clouds.
minute, the sporadic occurrence of wave episodes seemed to correlate with increase
the tree-tops. The wave patterns were persistent and usually lasted for several hours
from 65 s to 80 s. They were most noticeable in the upper canopy and just above
wind speed for the occurrence of these waves. The periods of these waves ranged
by the sporadic increase of the wind above the forest. It seems there was a threshold
Ambrozik and Moroz (1990) have observed wave episodes on clear nights in an
Figure 1.6 and Figure 1.7 have observed wave episodes near the canopy tops.
are gravity waves trapped in the strong inversion layer near the canopy tops.
the mid-canopy to just above the canopy tops. They have postulated that the waves
wave-like fluctuations, which suggests the waves were located in the thin layer from
Figure 1.6: Wave-like patterns in the nighttime micrometeorological observation in a boreal forest. The tree height was 21 m. The temperature traces at 8 heights are shown in the left panel. The horizontal velocities and the vertical velocities at 3 heights are shown in the right panel.
The wave centers were significantly larger than those measured at the upper edges of the
experiments. As a result of the strong radiative cooling, fluxes measured at the height of the
temperature inversion near the tree tops, were usually strong temperature inversion mixing within the waves. The mixing can also be inferred from the much reduced
the waves suggested that convection instability would lead to irreversible impact on the vertical variation of the wave structures. Hn and Lee (1998) have shown a case of
the vertical variation of the wave structures. This is a clear indication of the non-conservation vertical fluxes due to
the tree tops. The observed better than those measured at the higher level in terms of fluxes
contain convective and radiative knowledge. They also found that the fluxes measured near
Federal QO fluxes associated with wave events, which is difficult to interpret with
temperature forest by Lee et al. (1996). Moreover, Lee et al. (1996) found the counter-
vertical motion of the wave events. Significant CO fluxes have also been observed in a
wave episode. Similar cases with enhanced CO fluxes have also been observed in a
wave episode. Shigeuchi et al. (1996) reported that there were enhanced downward heat fluxes in the upper
role in the vertical mixing in the canopy, which is of great interest. Fitzpatrick and
With the possibility that the canopy wave is a common motion type in forests, its

Fluxes associated with the wave-like motions
were found when the equivalent Richardson number was less than 1.5.
are 1.61, 1.72, 1.80, and 0.07 Hz, respectively. Over 90% of the wave energies
wave speeds, the wave length, the wave vertical displacement, and the wave frequency
forest was moderate and radiative cooling was very strong. The median values of the
between the canopy, flow, and plant canopies. Knowledge of these models are helpful in understanding the complex interaction.

However, the applicability of these models to natural flows in canopies is rather limited. The direct comparison between theories and experiments is extremely difficult. Some qualitative results are limited in the near-wake and well-developed flows in the canopy, but such as the impact of wind profile and the dynamic instabilities of the Kelvin-Helmholtz type. The basis of these models are so far, most models treat ramp-like structures and wave-like structures as hydro-


tures in the Canopy Flow

1.3 Theoretical Models on the Organized Structure of the Near-Earth Layer

of the NEE of carbon dioxide.

Experiments on these waves, the uncertainty is even severe for the long-term measurement. Between forests and the atmosphere during wave events, considering the high thence might be uncertainty in the measured nighttime net carbon exchanges CO₂ and other scalars are often too coarse to resolve this vertical partition. If implies concern raised by Fitzgerald and Moore (1990), that the current profiling systems for height-dependent even over a short distance above the canopy tops, This results in waves. One can draw the conclusion that the influence mixing associated with waves is
be triggered by the KH instability (Phillips, 1961).

and conclusions in the stratified environment. In addition, other motion types can
KH instability plays an important role in the redistribution of momentum, heat, mass,
(Thorpe, 1969). The irreversible mixing associated with the undulation collapse of the
ocean (Edwards, 1969), in the atmosphere (Alves et al., 1970) and in the laboratory
lines form a "cell" pattern. The KH form is robust and has been observed in the

determined the stability criterion of this type. Kelvin later showed that the stream
up-churns of vorticity, called Kelvin-Helmholtz instability (KH) is Helmholtz who first

In an incompressible flow, the instability typically takes the form of periodic rolls.

Influence.

Here are a finite amplitude, and the flow appears to evolve directly to fully developed
short-wave three-dimensional disturbances. This secondary instability does not eng-
finite amplitude. This state can be considered as a new basic state, it is unstable to
understood by further perturbations, the long waves eventually equilibrate at some
rolls. Larger overturning occurs with stable unstable structures within billof cores. If
the centers of the rolls. Narrow bands with large gradients appear to separate the
flow with a rapid redistribution of fluid near the shear core. Fluid accumulates at
primarily waves. The crests of the waves are normal to the shear direction. The waves
lead unidirectional shear flow becomes unstable to the growth of long two-dimensional
begins with a sequence of instabilities, a sufficiently high Reynolds number, the ini-

In a simplified picture, the transition from the laminar shear flow to the turbulence flow

1.3.1 A Brief Description of the Kelvin-Helmholtz Instability

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to dominate the flow structure. The ratio of the wave velocity of the least growth to the speed of the medium is expected to differ from the speed of the medium’s gravity wave, which has a phase speed that is fundamentally different from a buoyancy gravity wave. In this point, it is important to note that the mean flow, the disturbances and the secondary frames move with the mean flow, the disturbances of the mean flow. In a reference phase speed of an unstable mode in an unbounded symmetrical shear layer is equal.

Instability in the free shear layer (Klaassen and Peltier, 1991). The real part of the Richardson number is greater than the critical value of 1/4, which is in agreement at the saturation stage (Frisch and Rasmussen, 1983). No instabilities are found when number will suppress both long waves and short waves and their maximum amplitudes waves with large wavelengths. With stable stratification, the increase of Richardson number will suppress both long waves and short waves and their maximum amplitudes with a vortex sheet, the finite depth of the shear layer effectively suppressed the instability with the proper velocity and length scales. With non-stratification, compared with the proper velocity and length scales, the finite depth of the KH instability are proved to be universal if key variables are not included by Hazel (1972). Despite the difference in the details of the problems, a number of references to the paper of Thomas and Howard (1965) and the teddy function and their stability diagrams are car-

approximations by hyperbolic tangent functions and their stability diagrams were car-

layer of finite depth with a continuous density distribution was given by Coldstream and Read (1981). After Henningson’s study of the stability of a vortex sheet, extensive literature exists concerning the shear stability of parallel shear flows.
that develops between two co-moving streams of different velocities. Many observed

MIXING LAYER INFLUENCE IS GENERALLY AROUND THE INHOBITATIONAL MEAN WIND PROFILES.

The inhomobitational mean wind profiles canopies resemble the plane-mixing flow because of the instabilities associated with one other, near neutral or unstable conditions, the influence peaks in plane surfaces of plane models (Rampard et al., 1989). Rampard et al. (1996) have pointed


generated structures in the atmospheric surface layer influence (Arnold et al., 1997; driven by wind shear (Paw et al., 1992). The same mechanism explains the or observations have led to the conclusion that the coherent structures are essentially

1.3.2 Plane-mixing Layer Analogy

(Davis and Peltier, 1979).

strained environment may destabilize the flow to modes of an entirely different type in evidence of the stabilizing effect of the ground. The presence of the ground in a rate and the phase speed of the KH instabilities is reduced (Davis and Peltier, 1976; fixed ground are more realistic. For a shear flow close to the ground, the growth waves less stable. For the atmosphere application, shear flows bounded by the lower can have a stabilizing effect for short waves. However, the boundaries can make long reaction can alter the above scenario. Hazel (1972) has shown that rigid boundaries

Besides the shear and the boundary, boundaries and the contribution of shear-

mode to the shear layer depth is about 7.5;

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Additional secondary instabilities will destroy the primary instability and finally lead to local instability which develops in such a background flow to a finite amplitude. Then, established by the canopy drag within the large-scale inertial eddy, the primary inertial quasi-horizontal influence. An inertial wind profile will be rapidly established by large-scale inertial quasi-horizontal influence. The predicted picture is that the canopy influence is modulated by large-scale inertial quasi-horizontal influence.

- With the production from the mixing-layer analogy,
  - The length scales of the coherent structures from observations are in agreement
  - Mixing Layer
  - The behavior of the inertial energy balance is similar to that in the plane
  - The role of eddies and sweeps in the transport processes are similar
  - The ratio of the eddy diffusivities for heat and momentum in the canopy tur.
  - The canary influence are similar to those in the plane-mixing layer influence
  - The observed ratios between the components of the Reynolds stress tensor in
    in the canopy roughness layer

Inertional instability probably determines much of the coherent eddy structure

- The mean wind profile has a strong interaction near the canopy top, the
  - Surface Layer influence
  - The supporting evidence includes
    - which provide an explanation of the differences between the canopy influence and
A Brief Review of Current Canopy Wave Models

1.3.3 The Canopy Wave Models

Here, 1984; Thorpe, 1985, 1987; Cane and El. 1996.

The nonlinear vortex interactions and background small-scale turbulence (Ho and
includes several additional instability processes, such as three-dimensional instabilities
subsequent nonlinear development of the mixing layer toward a fully turbulent state
less grow to finite sizes from infinitesimal perturbations in a rather short time. The
unstable conditions. In the cylindrical, the above instability hydrodynamic instabilities
across a wide range of buoyancy conditions, from weakly stable to neutral, and to
the unimodal eddy structures near the top of forest canopies share similar features
dynamic ground level or zero-plane displacement (Wintner, 1968). Qualitatively
buoyant production of turbulence energy, which increases with height above the zero-
above the canopy is strongly unstable. The justification is that the ratio of shear to
In the plane mixing layer analogy, buoyancy effects are ignored, even when the air
vertical scales of the original primary instability,

To the full turbulence state, the observed organized structures are believed to be the
waves although this is beyond the scope of Lee's layer model
of KH instability, which explain the observed enhanced fluxes associated with
thermore, the irreversible mixing associated with the subsequent nonlinear processes
mechanism, which is not possible with the other two models mentioned above. For
and aspects. The main attraction of Lee's model is that it gives a wave generation
canopy effect and the proximity to the ground modify the KH instability in sev-
shocks that canopy waves share features of a Kelvin-Helmholtz (KH) instability. The
of for the canopy influence (Hampson et al., 1996) to stable conditions. This model
The internal canopy wave model by Lee (1997) extends the plane-mixing layer and
Layer mechanism.

The internal canopy wave model by Lee (1998) have presented a wave even with much reduced temperature inversion
layer dynamics. The role of the canopy is limited in maintaining the strong
simple model has its limitations. First, the canopy effect is not directly included
wave parameters inferred from their model are in accord with their observation, this
spread gravity waves in the nighttime inversion layer near the canopy top. Although
In the three-layered model (Paw U et al., 1989), canopy waves are treated as
much insight into the wave dynamics.

much insight into the wave dynamics.
\[(1.1.3)\]

\[
\frac{\partial}{\partial t} \mathbf{V} + \nabla \cdot (\mathbf{V} \mathbf{V}) - \frac{1}{\rho} \nabla \rho = -\mathbf{V} \nabla \phi + \mathbf{G} + \mathbf{F}
\]

...
k and complex phase speed c can be solved for a given set of background profiles.

With properly specified boundary conditions, the eigenvalue problem for wave number

\[ \frac{\Delta p}{\partial p} \frac{\Delta q}{\partial q} + (c - \eta) \frac{\Delta q}{\partial q} = 0 \]

The structure functions are given by

\[ n \eta \phi + (c - \eta) \frac{\Delta q}{\partial q} = 0 \]

\[ n \eta \psi + (c - \eta) \frac{\Delta q}{\partial q} = 0 \]

with auxiliary variables

\[ \frac{\Delta p}{\partial p} \frac{\Delta q}{\partial q} + (c - \eta) \frac{\Delta q}{\partial q} = 0 \]

A modified Taylor-Goldstein equation can be derived as

\[ \frac{\Delta p}{\partial p} \frac{\Delta q}{\partial q} + (c - \eta) \frac{\Delta q}{\partial q} = 0 \]

by a factor of c. It is also called a folding time.

The reclosure of this parameter is the time needed for a small disturbance to grow

\[ \frac{\Delta q}{\partial q} = 0 \]

defined as

If \( c^* = 0 \), the growth rate, \( c^* \) taking the exponential growth in the linear stage, is

part of the phase speed \( c^* \). A mode is stable if \( c^* > 0 \), unstable if \( c^* < 0 \), or neutral complex conjugate. The stability properties of a mode are determined by the immediately

where\( \eta \) is the wave number, \( c = \eta + ic \) is the complex phase speed, and \( c \) denotes the
and presents

of the fastest growing mode to the half shear layer depth agrees with previous theory. The transition depth, where the maximum shear is found, the ratio of the wavelength to the height of the forest. The phase speed of the canopy wave is greater than the mean wind speed at profile, except a strong stabilizing effect on wave motions, particularly in a sparse wind profile. The ground, which is close to the Inception Point of the mean wind canopy, does in the wave dynamics is to maintain an Inception Point in the mean. The Inception and shear features of the Kelvin-Helmholtz wave. The main role of the Lee's analogy indicates that canopy waves are generated by the wind shear near
At the same time, like the trend in the turbulent study in general, the importance of
mistaken detail of the canopy flow in the early observations and theoretical works.

It becomes clear that the failure of the y-theory results from the neglect of the

canopy layer.

there exists a simple first-order "y-theory" for momentum in the
this combined with a zero or negative velocity gradient. It implies that there cannot
stably would behave entirely in the existence of a vertical downward momentum
Wilson and Shaw (1977) and Raupach (1979) have pointed out that the eddy diffu-
correlations raised the question about the efficiency of the y-theory. For example,
even diffusion process and characterized by eddy diffusivity, known as y-theory. Later
and the reference mean velocity. The canopy transport was simply treated as a gradient
have those means to the boundary conditions of the flow field, the canopy geometry
concerned with the mean turbulence statistics. Which effort has been devoted to re-
A quarter century ago, measurements of influence in plant canopies were mainly

Wave-like Motions in Forests
Flow Structures of Nocturnal

Chapter 2
the shear instability

which states that organized structures in canopy influence is the manifestation of

operational studies lead to the plane-mixing layer anode (Rempel et al., 1986).

Icon stability conditions have been summarized by Pau \\

el al., 1992). All of these

structure of the gases over tall forests has been revealed by further observations (Cao

canopy turbulent transport, which explains the failure of Y-theory. The micro-fron-

tance of scalar profiles. Their measurement indicates the non-local nature of the

Over a tall forest, Downard and Bradley (1986) have described intermittent gusts with

height (Anthonio et al., 1979). In the experimental studies of canopy influence, the

studies of organized structures result from wind shear rather than from differential

Burges, 1983). However, further measurement indicates that the scalar ramps as

of the thermal plume has been detected (Wicker and Skamar, 1990; Wicker and

sphere surface layer, the temperature ramps have been analyzed and the structure

the front wall, the dominant mechanism transporting momentum to the surface is the

layer. It is also a feature of the rough-wall boundary layer (Gress, 1971). Close to

eddy have been shown to dominate the smooth surface of the laboratory boundary

organized structures has been widely recognized (Larner, 1973). The sweep-effect

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waves and its implication to CO\textsubscript{2} flux measurement will also be discussed.

Wave structures and inverse ramp structures will be stressed. The mixing ability by

temporal and spatial resolution temperature measurement. The difference between

(1980)' and Cao et al. (1989), wave structures will be analyzed in detail with the high

will be investigated by a procedure analogous to those used by Weihek and Timm

In this chapter, the two-dimensional flow structures of nocturnal canopy waves

for nocturnal wave-like motions over forest remain largely unknown.

by Hn and Lee (1998). However, unlike daytime ramp-like structures, how structures

nighttime observation in a boreal forest. The wave-associated mixing was suggested

structures. They also demonstrated that waves of various strength dominate the

that both waves and ramps were the signatures of the same underlying oscillation

two has not been established yet. The observation by Lee and Par

indicated

with ramp-like structures (Cao et al., 1989, Cao et al., 1992). Frequently, wave-like motions and/or

waves were usually believed to be the minor images of those in the daytime condi-

storms were usually found near canopy tops. inverse ramps identified in temperature

and neutral conditions. At night, in weakly stratified unstable, temperature inver-

Timm (1980), the instrument setup in these observations were mainly for unstable

organized structures in canopy turbulence was similar to the approach by Weihek and

The method used by Cao et al. (1989)', regression and Hestes (1961) to analyze
Height Dimensions

2.2 Flow Structures of Wave-Like Motions in Time...

details of the observation can be found in Lee et al. (1997).

Detailed information of salient wave structures can be inferred from the temperature measurements were estimated to be 0.008-0.0028 K and 0.01-0.033 K, respectively. 39.1 in. per minute sampled at 6 Hz. The precision and the accuracy of the temperature in Fig. 26 are the measured temperature (diurnal-comparative, the flux measurement. There were 12 for each measurement and CO₂ sensors were mounted at 39.1 in. for levels. The least response water vapor and CO₂ sensors were mounted at 39.1 in. from ground level. There were 3 some microphones mounted at 2.5, 27.7, and 39.1 in. from ground level. The total response water vapor and CO₂ sensors were mounted at 1.5 in. while the stand density was about 50 per hectare. There was a thick stand of trembling aspen (Populus tremuloides) about 21 m tall. Canopy base


easel, Canada (32°42'N, 106°17'W), The forest was an extensive 70-year-old Ecosystem Atmosphere Study, Selkirk, 1999 at Prince Albert National Park.

The data was collected during the 1994 field campaign of the BOREAS (Boreal...
Wind direction was moderately small. Just before sunrise, in general, wind was from the NW sector and the variation of the wind was calm. The wind speed was steadily picking up and reached above 3 ms⁻¹ at the end of the night. Shortly after sunset and remaining strong for the whole night, except for the 12-hour period of clouds at midnight and around 0300. July 12. Just after sunset the 0500, 13 July, 1994 will be presented to illustrate the salient wave features. Waves were measured at intervals of 34 in minutes that the net radiation reached about 70 W/m². Short term measured net radiation at 34 in minutes that the net radiation reached about 70 W/m². Short term measured net radiation at 34 in minutes that the net radiation reached about 70 W/m². Short term measured net radiation at 34 in minutes that the net radiation reached about 70 W/m². Short term measured net radiation at 34 in minutes that the net radiation reached about 70 W/m². Short term measured net radiation at 34 in minutes that the net radiation reached about 70 W/m². Short term measured net radiation at 34 in minutes that the net radiation reached about 70 W/m². Short term measured net radiation at 34 in minutes that the net radiation reached about 70 W/m². Short term measured net radiation at 34 in minutes that the net radiation reached about 70 W/m². Short term measured net radiation at 34 in minutes that the net radiation reached about 70 W/m². Short term measured net radiation at 34 in minutes that the net radiation reached about 70 W/m². Short term measured net radiation at 34 in minutes that the net radiation reached about 70 W/m². Short term measured net radiation at 34 in minutes that the net radiation reached about 70 W/m². Short term measured net radiation at 34 in minutes that the net radiation reached about 70 W/m². Short term measured net radiation at 34 in minutes that the net radiation reached about 70 W/m². Short term measured net radiation at 34 in minutes that the net radiation reached about 70 W/m². Short term measured net radiation at 34 in minutes that the net radiation reached about 70 W/m². Short term measured net radiation at 34 in minutes that the net radiation reached about 70 W/m². Short term measured net radiation at 34 in minutes that the net radiation reached about 70 W/m². Short term measured net radiation at 34 in minutes that the net radiation reached about 70 W/m². Short term measured net radiation at 34 in minutes that the net radiation reached about 70 W/m². Short term measured net radiation at 34 in minutes that the net radiation reached about 70 W/m². Short term measured net radiation at 34 in minutes that the net radiation reached about 70 W/m². Short term measured net radiation at 34 in minutes that the net radiation reached about 70 W/m². Short term measured net radiation at 34 in minutes that the net radiation reached about 70 W/m². Short term measured net radiation at 34 in minutes that the net radiation reached about 70 W/m². Short term measured net radiation at 34 in minutes that the net radiation reached about 70 W/m². Short term measured net radiation at 34 in minutes that the net radiation reached about 70 W/m². Short term measured net radiation at 34 in minutes that the net radiation reached about 70 W/m². Short term measured net radiation at 34 in minutes that the net radiation reached about 70 W/m². Short term measured net radiation at 34 in minutes that the net radiation reached about 70 W/m². Short term measured net radiation at 34 in minutes that the net radiation reached about 70 W/m². Short term measured net radiation at 34 in minutes that the net radiation reached about 70 W/m². Short term measured net radiation at 34 in minutes that the net radiation reached about 70 W/m². Short term measured net radiation at 34 in minutes that the net radiation reached about 70 W/m². Short term measured net radiation at 34 in minutes that the net radiation reached about 70 W/m². Short term measured net radiation at 34 in minutes that the net radiation reached about 70 W/m². Short term measured net radiation at 34 in minutes that the net radiation reached about 70 W/m². Short term measured net radiation at 34 in minutes that the net radiation reached about 70 W/m². Short term measured net radiation at 34 in minutes that the net radiation reached about 70 W/m². Short term measured net radiation at 34 in minutes that the net radiation reached about 70 W/m². Short term measured net radiation at 34 in minutes that the net radiation reached about 70 W/m².
12 is probably not good since the wind speed was very low. From 23:30 to
expected to be smaller than that in Figure 2.3. The accuracy of R before 23:30, July
maximum wind shear was near the turbines; the minimum Richardson number was
and 31.4 in. If is the averaged value for the layer between 1.7 and 2.1. Since the
5-minute-averaged wind speeds at 39.1 m in and 27.7 m in temperatures at 39.1 m
The Richardson number (Figure 2.3) has been calculated with the
measurement.
peaks of $c_0$ above the canopy and the well-organized wave patterns in the temperature
exhibited the characteristics of turbulence. There was a good correlation between the
with the wind speed. The vertical velocities measured above the canopy
vertical velocities were active (Figure 2.3). In general, $c_0$ tended toward decreasing
Waves were usually found near the turbines when the standard deviations of the

Figure 2.1: Background wind speed (arrows) and net radiation (shading)
Figure 2.3: Richardson number

Figure 2.2: The standard deviations of vertical velocities at three levels
of about 730 ppm was found at approximately 02:00, July 13. About 740 ppm, from 12:00 to 02:00, it decreased to 400 ppm. Later another peak of the suppressed tumble mixture. Around midnight, it reached its peak value of a large variation. After sunrise, it was steadily building up, presumably as the result of a consistent negative gradient. The concentration at the ground level exhibited a concentration at 34 in and 39 in were roughly constant throughout the whole night.

The 30-minute averaged CO₂ concentration plot (Figure 2.4) shows that CO₂ with the sequences of wave activities, which shall be discussed later.

![Figure 2.4: 30-minute-averaged CO₂ concentration at three heights](image-url)
below 24, wind fluctuations at 27 had good correlation with those near the lee tops. The fluctuations, which depicted the wave structures, indicated that waves were confirmed at the time of well-organized waves (Fig. A-1, A-2). The potential temperature was characterized by repetitive wave events. The 0°C peaks (Fig. A-2) occurred from 22:30, July 12 to 01:45, July 13, wave activities were moderated. This period which first appeared when the wind began to increase.

Reduced. This nurture be the result of the mixing associated with the wave structures, gradually decreased, and the strength of the temperature inversion was gradually near the lee tops by the near-neutral layers above and below. The inversion layer structures appeared in the thin inversion layer. These wave structures were confirmed by the level of mixing. As time progressed, the wind speed began to pick up and wave during 600 s to 1200 s as the result of the continuing radiative cooling and the decomposition between 400 s and 600 s. The strength of the inversion layer was slightly near the neutral, the signature of the residual layer. The inversion layer was slightly lower at the lee tops (Fig. A-1), above and below the inversion layer, the air was averaged value was (5°C), a strong temperature inversion was found in the thin layer. Shortly after sunrise, when the wind speed at 39.1 m was low (the 30-minute radiation and the wind speed above the lee tops, activities showed a number of distinctive slices in response to the changes of the net high-vertex vertical-resolution temperature profiles (Fig. A-1, A-2 in Appendix A). Wave salient wave structures are best revealed from the time-height plots of cover-bases.
Inversion at the tropopause was enhanced by the continuing strong radiative cooling and escape periods; the vertical wind fluctuations were much reduced. The temperature depressions were shorter, typically from several minutes to about 10 minutes. In the ground depression of each wave episode, the relatively gentle escape periods to separate the wave from the tropopause were usually lasted for about several tens minutes. Compared with the temperature depressions of the enhanced radiative cooling.

As a consequence of the enhanced radiative cooling, the temperature depressions mainly because of the steep temperature gradient at the tropopause layer. The evolution of the wind speed (Figure 2), and the standard deviations of vertical velocities in the minimum of the wind speed (Figure 1) and the standard deviations of vertical velocities at the top inversion layer was re-established. This occurred concomitantly with both the top inversion layer seemed to be destroyed and the near-amplitude scale. The layer appeared by wave activities extended from the mid-canopy was gradually reduced. From 23:10 to 23:20, the wave seemed to reach a steady phase at the same time, the inversion layer was gradually deepened by the temperature gradient and the temperature inversion layer's vertical amplitude apparently began to grow. In the net, from 22:50, July 12 to 23:10, July 13, small disturbances appeared in the net. In Figure 2 and Figure 3, a complete cycle of a wave event can be seen.

In Figure 2 and Figure 3, a complete cycle of a wave event can be seen. The cycle at 1.3h was considerably larger than that at 1.9h. Even with wind fluctuations measured at only three levels, it is speculated that the source of the wind fluctuations was located near the tropopause, not from the layer well above.
much like those in the early part of the night, except that the wave periods were much
than those at 1.3/2 (Figure 2.2). The waves were again confined below 2'/ and were
radiation was about 80 W/m² to 70 W/m² (Figure 2.1) and the wind at 1.9/ was smaller
from 01:00 to 02:30, July 13, the wind at 1.9/ diminished to 3.2 ms⁻¹ and the net
relative greenhouse inversion layer was found from 03:30 to 04:00.

exhibited irregularly-spaced structures the reminiscence of the original waves. A
07:45 to 08:40, the destruction of the waves begins. The remaining temperature field
the wave activities extended above 2'/ and was probably limited to below 2'. From
the temperature-temperature common phase. From 07:20 to 07:45, the layer affected by
the same magnitude, coincidently with the increase of wave amplitudes identified from
However, the difference was shrinking. Eventually, the 0° at the two levels were of the
described above. During this period, the 0° of the two levels were at their minimum. From 01:45 to 02:20, waves were similar to those
vectors were at their minima. From 01:45 to 02:45, waves were stronger than those
when the lower inversion layer was quiet and the standard deviations of the vertical
in the early part of the night. Thus, wave events probably started at 01:45, July 13,
the appearance of clouds. Wave activities at this time were much stronger than those
of wind speed implies the occurrence of an outer scale event, likely associated with
from 02:00 to 04:00, July 13, the reduction in the net radiation and the increase
periods of the waves.

and Nicholson (1989) were probably the periods of the external forcing rather than the
ience of the waves. The rather long wave periods observed by Nicholson et al. (1984)
reduced mixing. The peaks and valleys in Figure 2.2 actually revealed the intermit-
The lower edges of the wave cores. The cooler air was entrained in the cores and was
received further downstream, which resulted in a spread, higher-temperature, warmer surface. At
the following several waves, the warmer air seemingly went down deeper and was
with a positive spanwise vorticity just above the crests, close to the shear maximum.

Impression that the warmer air and the cooler air were spinning around each other
up out of the canopy and was speed up by the ambient air. Together, they gave the
was slowed down by the canopy drag. At the same time, the slow cooler air went
the wave around 0.22, the warmer air above the canopy dropped into it and then

There were very interesting temperature structures within the wave cores. In the core of

steep.

were more diffuse, and the temperature gradients at trailing edges were usually
both the leading edges and their trailing edges. For some waves, the leading edges
characterized by rather broadened cores, defined by steep temperature gradients at

These gave the wave hints a look similar to that of billow waves. These billows were
the impression that the waves leaked in the downstream direction. The rise of the phase
gravity waves. A phase shift occurred in the thin layer near the crests, which gave
observed phase relations typically exceed the possibility of vertically propagating
phase. For vertically propagating gravity waves, these phase lags are exceeded. The
upper edges of the waves, the temperature fluctuations were also more or less in

The temperature fluctuations within the canopy were more or less in phase. At the

\[ 2.3 \] Temperature Fluctuations

shorter.
For some waves, the temperature gradients in both the leading edges and the

from the lower layer above the canopy, and the motion was confined in the lower layer
result in the square-wave-like patterns. Apparently, the disturbance did not originate
would periodically bring cool air in, which would generate dips in the temperature and

eddy from sensors located in the layer would be the same. The undisturbed motions
dispersion in the layer, where the air above 2θ in this particular half-hour, Temperature
in the layer of temperature. A conjecture can be made that there were little

where the eddy were moved. Temperature levels, Short separations among the eddies
the various eddies in the layer. The various eddies in the layer, Temperature levels were
and wave-like structures, has been frequently found in the temperature levels and
waves are usually limited at several levels. Variations of patterns, including ramp-like

the canopy. In most meteorological observations in the canopy roughness layer, measure-
mixing associated with the wave overturning if the advection effect could be excluded,
cores was actually getting a bit warmer. If mixing be the consequence of the important
indeed, in spite of the continuing radiation cooling, the eddies are in the subsequent
expected, similar to those found in the laboratory experiment by Thoore (1969).
structures are statistically unstable; fluctuations from spatially uncorrelated instability would be

evenly distributed from the cooler air within the canopy. Since such overturning
mean wind direction. Five five-minute sequences of the data from 01:45 to 04:00,

concerns. The coordinate rotation has been performed to align the x-axis to the
horizontal and vertical fluctuations of velocity vectors on the time-temperature

In this section, the wind velocity fluctuations will be examined by superimposing the

2.2.4 Velocity and Scalar Fluctuations

underlying canopy waves.

Lei and Burt (1998) that both of the signals patterns are manifestations of the same
were treated as different motion types. Here, the examination supports the argument by
noted and the interactions between the two have been suggested. However, they
noted that the interactions between the two have been suggested. However, they

Il deserves to be pointed out that, in previous observations (e.g., Paul & al.

loss of sinusoidal waves.

the wave trains. At the middle of the canopy and lower, the structures were more or
the temperature fluctuation within the canopy was closely related to the strength of
the inverse ramps in the temperature excess measured at that level. The strength of
more diffuse than those at the canopy edges. Such wave structures would result in
centers of some of the waves, the temperature gradients at the leading edges were

their persistence and well-defined periodicity. Usually, just above the canopy, at the
ramps, ramp-like structures were typical. They differ from the daytime ramps by

patterns which crossed waves passed over the canopy. From the mid-canopy to just above the
of the waves were rather rotational. Temperature sensors detected square-wave-like

leading edges had opposite signs and were roughly of the same strength. The cores

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The fluctuations, rather than from above,

or in a previously well-mixed layer. Together with the behavior of the measured wind

near any parcel at that height, 1.9\% could also indicate that the sensors were located

concentrations of CO\textsubscript{2} and H\textsubscript{2}O at 1.9\% could indicate that little vertical displace-

ejection and the sweep had similar magnitude in this case. The remarkable constant

to an ejection. In contrast to the downflow ramps, where sweeps are dominant, the

air motion shared features of a sweep. Following the ramp, the motion was similar

which backed and in the direction of the mean flow. Before the arrival of the infor-

intermediate that the temperature fluctuation, while the downflow coherent structures

edge. The temperature sensors near 1.9\% would detect inverse ramp-like signals. It is

edge of the wave was characterized with a steeper temperature gradient than in the trailing

temperature microturbulences (for example, between 01:15 and 01:17). The leading edge

that at 1.9\%, larger wind fluctuations and distinctive patterns were associated with

identical. At 1.3\%, wind fluctuations were also weak. Nevertheless, it was observed that

fluctuations at 1.9\% was small, the distinctive periodic pattern can still be visually

used fluctuations were found mainly below 2\%. Although the magnitude of the wind

induced from Figure 2.3, the wave activity was weak in this example. The tempera-

Example 1

measured at 1.9\% during the same periods will also be presented for reference.

Here meaningful results will be presented. The time traces of CO\textsubscript{2} and water vapor

July 13, when the wind fluctuations at both 1.3\% and 1.9\% were strong enough to
Figure 2.25: Velocity and Scalar Fluctuations (a) Scalar Fluctuations

![Graph showing scalar fluctuations over time with axes labeled for water vapor and CO2 at 1.9h (kPa)].

Legend is 0.2k.

The contour interval of the maximum wind fluctuation is 0.79 m/s. The contour interval of the wind fluctuations is superimposed on temperature contours. The mean wind direction is indicated.
This dear reader,
can be interpreted as the result of condensation on the ground and plant elements on
resolvable spikes in water vapor measurements indicated a downward gradient, which
certainly enhances positive spikes in the CO₂ trace measured above the canopy. The
canopy by the respiration of leaves, understory bushes, and the soil, waves would
in spikes in the scalar time traces. Since a high CO₂ concentration is expected within
particles with high CO₂ and less humidity to the instrument height and would result
was in a previously well-mixed layer. Waves with large amplitude would bring air
the heat baselines in CO₂ and H₂O does suggest that the sensor at this level
associated with the strength of the wave activity revealed by the temperature contours
the distributions in CO₂ and H₂O time traces (Figure 2.6(b) at 1.9h were closely

as those of resonant waves.

means little or sensitive heat flux. The phase relations here bear the resemblance
hvaculation was also found to be quadrature with the vertical vector's fluctuation, which
the mean momentum flux, n,m ̇, is averaged over one wavelength. The temperature
magnitude of the wind fluctuations, little net momentum flux would be resolved in it
hvaculation n,m. More specifically, led n,m ̇, by π/2. In spite of the relatively large
vector fluctuations were approximately in quadrature with the horizontal velocity
cores, away from the maximum shear. The vector pattern indicated that the vertical
20h. The source anomaly at about 1.9h was located above the upper edge of the wave
for waves with moderate strength (Figure 2.6), the wave cores were confined below

Example II
momentum flux at this height. In other words, momentum flux is generated only at
the wave cores. It was these sweeps and ejections that effectively generated downward
components of sweep patterns. Following the sweeps were ejections located mainly in
the leading edges where temperature gradients were steeper, and fluctuations were
the measurement inside the hollow cores in general has the sweep-ejection pattern. At
cores, ρ and w were in quadrature as were those in the previous example. Part of
the wind anti-rotation in the wave cores and outside the cores. Outside the wave
strong wave activity was found in Figure 27. The same anomalous at L 9h measured

Example III

One of the features of the entire behavior of the measured fluxes.
Lee et al. (1996) believed, a better understanding of these waves would be instan-
etable gradients that patterns associated with waves have been previously reported by
The momentum flux at L 9h was also affected by the background wind gradient. Similar
during this five-minute period was upwind, which was apparently counterclockwise.
between the vertical velocity and the temperature was positive. The thermal flux at L 9h
other in the momentum transport. It should be noted that the moderate correlation
swells dominate, then the sweeps and ejections associated with waves of the same
To generate a large downward momentum flux, unlike in the daytime ramps, where
relationship between the horizontal component and the vertical component are favorable
messenger, patterns of sweeps and ejections can be identified at this level. The phase
Compared with those at the upper level, wind fluctuations at L 9h were larger and
The same anomaly at L 9h was studied near the center of the wave cores.
Figure 26: Velocity and Scalar Fluctuations (II)

(b) Scalar Fluctuations

(a) Wind fluctuations superimposed on temperature contours. The major wind speed is 0.2 m/s. The contour interval of the maximum wind fluctuation is 0.1 m/s. The contour interval

Water Vapor at 1.9h (KPa)

CO₂ at 1.9h (ppm)

Mean Wind Direction ←
Figure 2.7: Velocity and Scalar Fluctuations

(b) Scalar Fluctuations

![Graph showing CO₂ and Water Vapor fluctuations over time](image)

Legend: 0.2K

Note: In the mean wind direction is 1.79 m/s. The contours represent the max/min wind fluctuation is 1.99 m/s. The mean wind direction is superimposed on temperature contours. The mean wind direction is labeled at the bottom of the graph.
were found in the time traces of CO₂ and water vapor for a considerate fraction of a wave period. As a result, much broader disturbances of well-mixed wave cores with high CO₂ and low humidity could touch the sensors at 1.9h. Waves in this figure had larger amplitudes than those in the previous figure. The that of the classical KH wave from the linear canopy wave model by Lee (1998), which is qualitatively similar to above, the polariization relations between n and m, are in accord with the prediction part of the canopy layer, waves are of an evanescent type. Together with the discussion fluctuations, one can infer that n/2 = m by approximately. Visually inspecting the wind vector another moment at 2.5 in (0.26h) was meaningful. The wind during this period was strong and the measurement from the sonic anemometer at 3m above the canopy was strong around each other to generate overturning structures, are in cores. Such a pattern of the velocity field supports the conclusion that cooler momentum fluxes. There were generally slow upward motions in the region of cooler KH instability. The heightly correlated wind components generated large downward the wind fluctuations more or less resembled that found in the shear center of a KH instability. The phase difference between n and vertical m was approximately 70°. Qualitatively, between sweeps and ejection occurred relatively in the center of the core regions. The phase difference between n and vertical m was approximately 70°. Qualitatively, in the trailing half of the cores, motions were of the ejection type, shear instabilities a distinctive pattern. In the leading half of the cores, sweeps were noticeable. At 1.3h, the level in the middle of the wave core's velocity fluctuations were of a fraction of a wave cycle at this height.
The temperature field, however, their patterns were closely correlated with
the scalar fluctuations at 1.9h were rather chaotic. The heat baseline in CO2 and
H2O time traces disappeared. However, their patterns were closely correlated with
zone influenced from the wave cores vertically expanded and horizontally merged.
The time traces of CO2 and H2O reflected the wave activity. As the influence
was in accord with the inverse temperature ramp described by Py & al. (1992),
the strength of the sweep was stronger than that of the section. In general, this event
of the microturbulence, the motion was more or less of the sweep type. The
of the microturbulence at both levels above the canopy, the air motion was of the section
the lenses assumed the patterns of inverse temperature ramps. Before the arrival
temperature front was found around 02:58. The temperature lenses measured above
temperature field were the remnant intrusive of the previous waves, a downwind ridge
of similar magnitude as those at 1.3h. The dominant organized structures in the
introduced as the waves were being destroyed. The wind fluctuations at 1.9h were
percolation eddies, which determined the waves, began to disappear. Inertia was
vertical fluctuation reached the maxima of the ridge (Figure 2.2). The steep top-
on July 13, 1994, during this period, wind at 1.9h was getting stronger. The vertical
Another example shown in Figure 2.8 is from the period between 02:35 and 03:00

Example 17
Figure 2.8: Velocity and Scalar Fluctuations (Tv)

(b) Scalar Fluctuations

Legend is 0.2K.

Water Vapor at 1.9h (KPa)

CO₂ at 1.9h (ppm)

Wind fluctuations superimposed on temperature contours. The mean wind direction at 1.9h is 0.2K.
Figure 2.9: Velocity and Scalar Fluctuations (c)

(c) Scalar Fluctuations

Legend is 0.2K.

Water Vapor at 1.9h (kPa)

CO₂ at 1.9h (ppm)

Wind Fluctuations shown imposed on topographic contours. The mean wind direction is 0.2K.
motion type in forests. Indeed, in this study, the signal enhanced visual inspection of
and Bart (1998) have proposed that the nocturnal wave-motion is a common
-40 Wm-². The two conditions are usual for boreal forests on clear nights, i.e.
-2°C m-³. Second, the radiative cooling was strong with the net radiation
below.

of canopy waves. First, the wind above the canopy was moderately strong, about
other nights at this site, two background conditions were essential for the occurrence
in the canopy turbulence layer in a boreal forest. By surving time the wave energies at
The data presented above shows that wave-like motions of various strengths dom-

2.3.1 The Mechanism of Canopy Waves

Discussion

address this issue.

wave evens of influence events. But this one-point lower measurement cannot
CO₂ concentration might be the result of the mixing associated with the previous
increased from 31.92 ppm to 326.0 ppm. This increase of background atmosphere
increased from 31.92 ppm to 326.0 ppm. This increase of background atmosphere
in the second half of the two-hour period. Finally, the examples above covered the various stages of a wave event. It is interesting
indicated that waves were weak and could not influence the air layer at 1.9h.
In the final example (Figure 2.9), the waves were weakening. Weak fluctuations at

Example A
not likely to be generated by the direct obstacle effect. The spatial observation by Lee
forests create background conditions favorable to the wave-like motions. Waves are
Another candidate often populating is the roughness structure of forests. Simply,
that waves were from some preferential directions as expected for le waves,
tried with the mean flow (Lee and Hatt; 1998). Moreover, there was no evidence
by the lower based time-height measurement. In addition, waves were observed to
the crested lee wave by Leopold's frequency should be stationary and cannot be detected
the effect of forest edges or obstacles in the measurement far beyond the edges. However,
propagate several kilometers downstream, the lower-based sensors might experience
generate the disturbances. Since the disturbances in the stable boundary layer can
kin at this site. It was not likely that any obstacles within the homogeneous fetch
this observation satisfied the fetch requirements for eddy covariance flux measurement
that are not favorable to topographic effects. The setup of the instruments at
Although there are no direct observations related to these a number of arguments
may suspect that canopy waves are formed at the crested lee waves generated by topography.
The possibility that waves are generated from the layer well above is excluded. One
be highly consistent with the obvious occurrence of wave-like motions, the mechanism of canopy waves
With the frequent occurrence of wave-like motions, the mechanism of canopy waves
their postulation.
and $\rho$, near the terrace, there are examples showing the phase difference between
from the terrace, where the maximum shear is found, $n_1$ is in quadrature with $n_2$ according to Lee's model (1972), which embeds the HHI hypothesis. Specifically, away
Secondly, the polarization relation among wind fluctuations and scales are in

Study supports Lee's argument in several aspects. Firstly, clear cycles of wave energy
above the critical value (\(a \approx a_1, 1970\)). The measured eddy Richardson
observation in the atmosphere (\(a \approx a_1, 1970\)). The measured eddy Richardson
layer and/or (Bartels et al., 1998) to stable conditions. The data analyzed in this
in the instability of the Kelvin-Helmholtz type (Lee, 1972), which extends the plane-mixing
A more plausible explanation is that canopy waves originate from hydrodynamic
from the obstacle effect by canopies is not negligible.
Furthermore, canopies are more porous than might be expected. The possibility of secondary waves
the free height and the fetch scale characterizing the horizontal separation of trees,
above canopies, the order of the wavelength is about 100 m. It is much larger than
in fall. With an observed mean wave period of about 1 minute and moderate wind
match the wind speed a couple of meters above the lee slopes of a forest about 21
and Bart (1998) has found that waves travel at the mean wind direction at the speed
I. Quiescence Phase

The wave evolves in several distinct stages:

1. Based on current knowledge of canopy waves, it is possible that the wave is generated by the Kelvin-Helmholtz instability. The observations in forests have demonstrated that canopy waves evolve in stages that are consistent with the predictions of theoretical models.

2. The wave is characterized by the temporal and spatial variations in the canopy structure. These variations are caused by the interaction of the wind with the canopy, leading to the development of a complex wave pattern.

3. The wave is influenced by the temperature profile in the canopy. The temperature profile affects the stability of the canopy layer and, consequently, the propagation of the wave.

4. Chapter 4 of this thesis, Wind and Temperature Dependence of Canopy Waves, presents numerical simulations of canopy waves and discusses their relationship with the temperature profile in the canopy. The simulations show that the wave characteristics are influenced by the temperature profile and the wind speed.

5. The wave is characterized by the interaction of the wind with the canopy, leading to the development of a complex wave pattern. The wave is influenced by the temperature profile in the canopy, and the wave characteristics are influenced by the temperature profile and the wind speed.
Propagation buoyancy gravity waves whose speeds do not give them a critical matching the wind speed near the lee tops. In this aspect, KHI waves differ from introduced by overturning. The waves will travel at the speed of the mean flow, as a result of the wave folding, which is enhanced by the convergent mixing two of these lee edges. During the growth, distinctive rotational cores appear since the available energy is finite and the stable stratification is strong, the

3. Saturation Phase

and the dissipation of the wave. How, which is partitioned among the kinetic energy, the wave potential energy. The growth of the wave is fed by the energy extracted from the background grows. The wave potential energy held of the stable stratified flow, the canopy layer and warm air above will spin around each other as the wave and parallel shear flow and create periodic vorticity maxima. Cool air within dominate the flow structure. The fastest growing wave will break the orographic wave manifold and complex inversion will be favorable to the wave of other than wavelength, and this wave has largest growth rate. It will eventually to the ground and complex inversion will be favorable to the wave of certain disturbances grow on such background shear. The wind shear, the proximity

2. Growth Phase

canopy drive.

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It is well established from observations that a strong wind shear is usually found
in the vicinity of the shear center to the right of the ground can modify the dynamics of a
specifically the flow. The role of canopies in wave dynamics would be easy to understand
well-known that the shear is to destabilize the flow while the stable shear stabilization is to
wave-heights are more significant. For the KH instability, it is

Thus, the long-lasting primary wave structures are preserved.

The persistence of the observed wave trains indicates that the strong stable
structures in the previous studies (e.g., Cao et al., 1989; Paw et al., 1992).

The leading edge of the wave, instability will first destroy the leading edge of the
caused unstable structure formed during the wave overturning is first found in the

4. Destruction Phase

Level
waves since the initial shear layer is thin. As the initial instability grows to the finite
value of 0.2', the initial instabilities would be of a smaller scale than the observed
coupling. The strong wind shear can bring the Richardson number below the critical
canopies. Although the temperature inversion is strong due to the strong radiative
shear generated by the canopy, drag would be found in the lower layer in the upper
very short time the wind shear at the canopy tops would be established. The initial wind
mixing length will be reduced by a half. For a forest with a dead canopy, the scale of the
leaves uniformly distributed from ground to canopy tops, initial wind speed of

\[ \frac{2}{\pi n} = z \rho_{\text{canopy}} = \frac{2}{\pi n} \]

Shimmin (1962), that is,

for the canopy drag, which is slightly different from the formulation in Shaw and
The time scale of establishing the shear can be estimated with the empirical formula
of momentum by the canopy elements will create a wind shear near the canopy tops,
how since the small-scale influence would exist in the beginning, the absorption
of momentum by the canopy elements will create a wind shear near the canopy tops.
This background flow initially could be treated as a laminar
canopy roughness layer. This background flow initially would speed up background wind in the
breakdown of the nocturnal low-level jets, would speed up background wind in the
same inversion is found near the canopy tops. Topographic effects, such as the
to be modified. Initially, the wind within and above canopies is calm and the temper-
ear the canopy top. The process to establish the shear at the canopy top deserves

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more holistically. For example, scaling of a (2000) found that the CO₂ source building
internal exchange of CO₂ when there is little apparent influence patterns at the instru-
Another problem can be both in underscoring the importance of
occurred fluxes.
edge of wave dynamics will shed light on understanding the apparent counter-gradient
are associated with the overturning and mixing in the wave cores. A thorough Knorr-
This study has demonstrated that the flux-gradient relationships
Canopy waves deserve more attention from experimentalists doing eddy-covariance
considering the large CO₂ gradient maintained by the nighttime respiration.
the mixing is limited in the vertical direction, the result is expected to be significant,
irreversible mixing occurs only in the thin layer below 2 or 3 wave heights. Although
in the downward direction. Because the waves have limited finite amplitudes, the
wave cores travel with the background mean flow, the excess CO₂ will be advected
the CO₂ within canopies can be mixed with the air above the canopy. Since these
the observation, the overturning wave cores extend to about 2 wave heights. Presumably,
Of most practical interest is the mixing ability associated with canopy waves. From

2.3.3 The Implication to the Eddy-Covariance Flux Measure

choice of the basic flow for these stability analyses is not straightforward.
previous smaller waves. Since the background flow is always being modulated, the
a larger scale might be increased in the broadened the shear layer by the merging
slight and finally are destroyed, the initial shear layer is broadened, instabilities with
have been analyzed in the time-height dimensions. The results show that wave-heights are as

In this descriptive study, the authors show that wave-heights are motions in forests

2.4 Summary

eddy-covariance systems.

mean of the net ecosystem exchange of CO$_2$ between forests and the atmosphere by

would be significant. It raises great uncertainty regarding the long-term measure-

mixing process. Given the frequent occurrence of wave events, the accumulated effect

height. Clearly, the current setup of instruments cannot adequately quantify this

mixing in the thin layer just above the canopy, which might be below the instrument

amount of CO$_2$ could be flushed out of canopies by the wave-induced irreversible

fraction velocity. Nevertheless, the examples shown in this study suggest that certain

relationships similar to those seen in canopied waves would generally lead in momentum. That is, little

wind and scalar fluctuations can be detected at instrument height, the perturbation

associated CO$_2$ effluxes. For waves with moderate strengths, although considerable

the instruments simply cannot detect the underlying wave activity and the

the flux measurements have instrument-mounted an about two or three lee heighths,

diminues. The clear-felled canopy waves might be responsible for it. Since most of

There are several explanations of such missing CO$_2$ flux at low fraction velocity con-

for low fraction velocity conditions (e.g., Condon et al., 1996; Young et al., 1997).

ion velocity. Others have developed empirical methods to estimate the CO$_2$ release

in the early morning was significantly reduced at midheight with little measured fre-
The popular eddy-covariance technique, the estimation of the long-term net ecosystem-atmosphere CO2 exchange by using current instrumental setups. Thus, it raises the potential significant uncertainty in
with a depth of 1 to 2 tree heights. This flux cannot be satisfactorily quantified by
irreversible mixing can push CO2 out of canopies to the layer just above the leaves.
unmixing and mixing inside the waves. It has been pointed out that wave-induced
 evidence that counter-gradient fluxes are associated with the highly non-linear over-

The influence mixing associated with canopy waves has been discussed. There is

Mixing from downgradient instability is correlated with the measured upwind
structures been found inside the overturning waves. The convection of important
at limited heights were in accord with those of KH waves. The stably unstable
associated with the distinctive wave structures. The polariation relations measured
leaps in time series, including both wave-like and ramp-like signal patterns, could be
of the waves resembled those of finite-amplitude KH waves. A variety of signal pat-
the changes of the background wind and the radiative cooling. The convection leads
those of KH waves. The wave were characterized by their prominent response to
above the leaves was moderate. The life cycles of wave events bore resemblance to
motions were dominant in the canopy roughness layer on clear nights when the wind
motions.
Chapter 3

3.1 Introduction

Model

A Two-Layered Canopy Wave
\[(\varepsilon_{\text{3.2}})\]

\[\begin{array}{l}
\begin{cases}
\eta < z & 0 \\
\eta \geq z & 1
\end{cases}
\end{array}\]

\[= \mathcal{F}\]

Wave-induced fluctuations. The canopy drag term \(\mathcal{F}\) is given by

the air density, and \(d\) is the gravitational acceleration. The primed quantities are the
where \(n\) and \(m\) are the horizontal and the vertical velocities, \(d\) is the pressure,

\[\eta = \frac{\eta_{\text{d}} n + \rho_0 d}{\eta_{\text{d}} n + \rho_0 d} \]

\[\eta = \frac{\eta_{\text{d}} n + \rho_0 d}{\eta_{\text{d}} n + \rho_0 d} \]

The governing equations with the canopy drag term is heared as

at the leaves:

\(\partial \nabla - \) constant. Within the canopy the air density \(\rho\) and there is a density jump of
is \(u\) and the wind speed in the layer above is \(w\). The air densities in each layer are
the leaves and the leaf area index \(T = l\). Within the canopy, the wind speed
the canopy layer is of height \(\eta\), with uniform leaf area density \(a\) from the ground to

\section{3.2 Model Description}

much easier to identify the role of the canopy drag in the wave dynamics.

behave, the simple flow configuration and the simple canopy structure will make it
physical interpretation of observations. In this canopy wave model, with the same
 phenomena over limited regions of the atmosphere. Their simplification exactly aids in the
that layered models provide a remarkably good prediction of observed wave prop-

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Propagating gravity wave solution in the upper layer (atmospheric) transport is given by the equation of the same low system with a

\[
(\psi - \frac{1}{2n}) \exp(-\frac{1}{2}) \exp(x - 1) = (\psi - \frac{1}{2n}) \exp(-\frac{1}{2})
\]

In equation 3.2.1, the community of \( \eta \) at height \( \eta \) requires

The vertical displacement of the interface at the reference of the form B is that the

\[ \eta = 0 \]

where satisfies boundary condition at the field ground \( \eta \) is of the form B, then the

\[
\{(\eta - z) \psi \exp(\frac{1}{2}) \exp(x - 1) - [(\eta - z) \psi - 1] \exp(x - 1) \} = \varphi
\]

is in the form of

where \( \varphi \) is a constant which will be determined later. Within the canopy, the solution

\[ (\psi - \frac{1}{2n}) \exp(x - 1) = \varphi \]

layer above the canopy \( \psi \), that is,

Based on the observation (Chapter 2), the evanescent wave solution is chosen for the

\[
\left\{ \begin{array}{l}
\eta \geq z \\
\eta < z
\end{array} \right.
\]

\[ = \varphi \]

where

\[ \varphi = \varphi \exp(x - 1) \]

A modified Tropospheric equation can be derived as

where \( f \) is the structure function and \( c_x \) denotes the complex conjugate. After

\[
\left( (\psi - x') \exp(x - 1) \right) = \varphi
\]

in the form of

where \( \varphi = 0 \) is the canopy the evanescent given by the observation (Shaw, 1988).
\[
0 = \eta \beta - \eta \frac{\gamma}{\nu} \nabla + \eta \gamma n \nabla z - \eta \frac{\gamma}{\nu} \beta - (\eta \gamma + 1) \psi
\]

For the reference frame moving at the speed of \(n\), the above equation is transformed

\[
0 = \eta \left[ \beta - \eta \frac{\gamma}{\nu} (c - \varepsilon n) \right] + \left[ \eta \frac{\gamma}{\nu} + (c - \varepsilon n) \right]
\]

For a long wave, \(\eta\) is small and tanh \(z\) is small, the equation 3.2.14 is simplified to

which describes an instability of the Kelvin-Helmholtz type.

\[
\frac{1}{c} \left( \frac{z}{n \nu} \right) - \frac{\eta}{\beta} = \psi
\]

In the coordinate moving at the speed of the mean flow, we have

\[
\beta = \eta \frac{\gamma}{\nu} (c - \varepsilon n) + \eta \frac{\gamma}{\nu} (c - \varepsilon n)
\]

Without the canopy, that is, \(A \ll \eta\) 0, the above equation is reduced to

\[
0 = (\eta \eta) \tanh \left[ \beta - \eta \frac{\gamma}{\nu} (c - \varepsilon n) \right] + \left[ \eta \frac{\gamma}{\nu} + (c - \varepsilon n) \right] (c - \varepsilon n)
\]

The relation is given by

By manipulating the matching conditions (equation 3.2.11 and 3.2.12), the dispersion

\[
\frac{\beta_\nu}{\nu} = \beta
\]

where the reduced gravitational acceleration is given by

\[
\eta \frac{\beta_\nu}{\nu} + \varepsilon d = \gamma d
\]

The dynamic boundary condition at the interface requires
speed for the same flow configuration but without the canopy drag will be the same as the 
canopy drag parameter, $\varphi$. The phase speed is hard to solve. Here the phase 
canopy drag parameter, $\varphi$. The dispersion relation with the canopy drag is given 
by the phase speed $C(\varphi, y)$ is a function of both the stability parameter, $\eta$, and the 

3.3 Results and Discussion

(3.3.23) \[ \varphi/\sqrt{1 + \eta^2} = \varphi \]

Parameter is defined as

is a stability parameter analogous to the Richardson number. The canopy drag

(3.3.22) \[ (\varphi n \nabla z)/\eta \varphi \equiv H \]

Where

(3.3.21) \[ 0 = H - \frac{\varphi}{1 + \varphi (1 - \varphi \iota)} + \varphi \]

Equation 3.2.19 becomes

\[ n \nabla / \varphi = \varphi \]

(3.3.20)

\[ \left( n \nabla / \varphi \right) = \varphi \iota \]

\[ \left( n \nabla / \varphi \right) = \iota \iota \]

Hereafter, in the following discussion we will use normalized velocities

(3.3.19) \[ \frac{\varphi}{\varphi \nabla / \varphi} - \frac{\varphi}{\eta \varphi} = \frac{\varphi}{\varphi \nabla / \varphi} + n \nabla \varphi - \varphi \]

With the assumption that $\eta = 1$, the above equation is simplified to
Section 3.2 shows that the second reference state (the slower neutral wave mode and those departures from this base state by introducing canopy changes of various

especies when \( \gamma > 1/4 \) and the decaying mode when \( \gamma < 1/4 \). Figure 3.1 shows the first reference state (the

results are presented in two figures. Figure 3.1 shows the first reference state. The

over a range of Richardson numbers for several typical canopy drag parameters. The

\[
(3.3.2) \quad \frac{\partial T}{\partial \tau} = C + i \gamma
\]

possible solutions for \( C \). We will immediately solve

For a given Richardson number and a canopy drag parameter, there are two

phase speed. Modify the stability property by altering both the real and imaginary part of the

For the classical KH instability in the absence of the canopy, the canopy drag will

will become unstable if the imaginary part of the complex phase speed is positive. This

result in a complex phase speed. Thus, the neutral waves in the absence of the canopy

It is conceivable that the inclusion of the canopy term in equation 3.2 will always

other is stable. The transition occurs at the critical Richardson number \( \gamma = 1/4 \).

The two modes move at the speed of the mean flow. One of them is unstable and the

when the other one. When \( \gamma > 1/4 \), these are two modes according to the equation.

When \( \gamma < 1/4 \), the equation will give two neutral wave solutions. One moves faster

\[
(3.3.1) \quad \frac{\partial T}{\partial \tau} \left( \frac{1}{\epsilon - \gamma} \right) \mp \frac{\gamma}{\epsilon} = (0, \gamma) C
\]

solutions.

reference state. In the absence of canopy term, that is \( \gamma = 0 \), we have the familiar

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unstable when approaching the critical Richardson number 1/4. Since the instability
drives cause larger growth rates, the original neutral wave becomes more and more
larger when $Y > 1/2$, the original slower moving neutral wave becomes unstable. Larger
slower moving neutral wave becomes stable when $Y < 1/2$. However, in the range
in the range 0 $\leq Y < 1/2$, larger canopy drives cause more reductions. The original
stability of the flow. Figure 3.2 illustrates much more interesting features. In 3.2(a),
the original decay mode is even faster. Overall, the canopy drives in this case is to
the original neutral instability, part of the phase speed. Thus, the decay of
in sensitivity to the increase of $Y$. When $Y > 1/4$, canopy drives increase the instability
more effective reducing the original neutral wave. When $Y$ is large, $\gamma^g$ is almost
camped out after introducing the canopy. Dense canopies with large $\gamma^g$ will be
of the canopy drives. The faster neutral wave in the absence of the canopy would be
part of the phase speed is unrealistic and the modification increases with the increase
no significant modification of $C^T$. In Figure 3.1(q), when $Y < 1/4$, the instability
larger canopy drives bring larger increases. For very strong stratification, there is
the real part of the phase speed, in the range of the canopy
Figure 3.1(a), compared with the reference state, the reduction of the canopy

states for the following discussion.

the solid curves are cases without the canopy drives. They will serve as the reference
base state by introducing canopy drives of various strengths. In both of the figures,
when $Y < 1/4$ and the growing mode when $Y > 1/4$. (d) and those departures from this

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Figure 3.1: The influence of canopy drag on phase speed. The reference line is the reference speed.

(a) The imaginary part of the complex phase speed.

(b) The real part of the complex phase speed.
lower neutral wave mode when \( \gamma > 1/4 \) and the growing mode when \( \gamma < 1/4 \).
can either destabilize or stabilize the flow. To summarize, depending on the stability parameter, the canopy drag reduction will result in a reduction of $C_e$ compared with the original unstable mode, $y$ for the range of canopy drag parameters considered here. Further reduction of $y$ for the range of canopy drag parameters considered here. The growth rate of the original unstable mode in this range is enhanced until $y$ is less than 0.22. Roughly constant increase of $C_e$ by the canopy drag is confirmed. The growth rate of the original unstable mode. Close to the critical value $y = 1/4$, the growth rate of the original unstable mode. The critical value $y = 1/4$, the canopy drag can either enhance or reduce the number $1/4$ for the stability properties of the flow without canopies.

number $1/4$ for the canopy drag enhances the stability, which is the case for a range of critical Richardson number for the canopy drag increases the stability. Thus, the critical value $y = 1/4$, corresponding to the critical Richardson number for the canopy drag, is the critical strength. The zero $C_e$ separates the canopy drag instability and to the canopy drag, respectively. The zero $C_e$ separates the canopy drag instability and to the canopy drag, respectively. It becomes according to equation 3.2.21, the two solutions are.

\begin{align}
C_e &= 0, \\
C_r &= 1/2.
\end{align}

According to equation 3.2.21, the two solutions are.

The canopy drag is in general called the canopy drag instability. At $y = 1/2$, in the above expression, the parameter $y$ appears solely as the result of introducing...
and stabilize the flow. Several simplifications have been adopted in the formulation contrary to the common intuition that the canopy drag would damp our disturbances.

In this context, the otherwise stable background conditions without canopies. This is

This two-layered canopy were model indicates that the canopy drag can integrate

at a speed less than that of the mean flow. The unstable mode, when the number, the canopy drag may stabilize the flow by reducing the growth rate of

numbers, the canopy drag may stabilize the flow by reducing the growth rate of

mode is further destabilized by the canopy drag. For even smaller Richardson

drag, when the stability parameter is close to the critical value 1/4, the unstable

Richardson number.

than the mean speed of the flow and the speed increase with the decrease of

of reducing the canopy drag. The canopy drag initially moves more slowly

When 1/4 < R < 1/2, the canopy drag initially appears solely as a result

sense, the canopy drag is to stabilize the flow.

When R < 1/2, no neutral waves are allowed with the canopy drag. In this

Specifically, the canopy drag causes following changes:

the phase speed of a normal mode is generally complex because of the canopy drag.

In contrast to the flow system without the canopy, this layer indicates that

3.4 Conclusion

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is made and the module of the canopy drag.

Research should focus on the choice of background states on which the parameterization might not be suitable for direct comparison with realistic canopy flows. Further, this model, which makes it unable to predict the fastest growing mode. The model
The linear canopy wave model developed by Lee (1992) is more realistic. This model, derived from these models are in accord with observations. Among these models, u et al. 1990; Fitzjarrald and Moore, 1990; Lee, 1997, the basic wave parameters.

To date, several linear models have been developed to interpret canopy waves (Fitzjarrald and Moore, 1990).

Important cases.

quantifying the nighttime forest-atmosphere exchange of CO2 and other biologically
the transport mechanism associated with canopy waves is of great practical interest in
and Lee, 1998), which may lead to the irreversible mixing. A better understanding of
1996). Irresistible thermal structures have been found in the overturning waves (Fitzjarrald and
Moore, 1990). But the flux-gradient relations exhibit erratic behaviors (Lee et al.
have been found during the wave episodes in an Amazonian forest (Fitzjarrald and
motions are common on clear nights in a boreal forest. Enhanced turbulent fluxes
The observational study by Lee and Bart (1998) has demonstrated that wave-like an

4.1 Introduction

Wave-Like Motions in Forests

A Numerical Simulation of

Chapter 4
canopy wave model. The justification for a two-dimensional model is that the primary

observations are limited.

features in the linear range. Thus, the applicability of linear analysis to interpret field

that nonlinear processes favor the development of waves longer than those that linear

models. Furthermore, the numerical simulation by Pan and Pe (1996) has found

models, observed waves are probably not in the linear regime described by the linear

word, observed waves are probably not in the linear regime described by the linear

highly nonlinear phenomenon, in reality, wave-like modes can be visually identified

profiles have shown the evidence of turbulent mixing (Hin and Lee, 1998), which is a

process, which is beyond the scope of linear models. Furthermore, the measured

constant background. However, the observed wave patterns seldom resemble those

linear wave models describe the evolution of small wave-like disturbances in a

waves is expected to be an important transport mechanism on clear nights in forests.

The irreversible mixing process in the nonlinear development stage of K-H

that it gives a wave generation mechanism, which is not possible with other linear

instability in several aspects. One of the main attractions of this model is

Helmholtz (K-H) instability, canopy effects and the proximity to the ground model.

1996) to stable conditions. It shows that canopy waves share features of the Kelvin-

extends the plane-mixing layer and/or for the canopy influence (Pan and Pe, et al.}

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The data in time-dependent contour plots (Gao et al., 1989), the same method has been
daytime coherent structures have been revealed as scalar interactions by resolving
structures can be revealed by the lower-based probe measurements. For example,
from the point of view of observation, some features of two-dimensional flow
ions, the quality of the influence closure model is no critical for this purpose.
of primary interest are essentially determined by initial profiles and boundary cond-
in which a crude influence closure scheme will be used. Since the macro-structures
respond to major canopy wave structures with a two-dimensional influence model,
decay of the influence can be reasonably simulated. The goal of this chapter is to
billows. The breakdown of the roll-up vortex layer and the subshear spread and
been employed to describe the three-dimensional small-scale influence within KH
numerical study by Squires and Lewellen (1982), a second-order closure scheme has
waves has been calculated by these early numerical studies. In the two-dimensional
phase speed and the growth rate of the primary mode. The structure of the growing
el al., 1978) have substantiated the predictions of the linear analyses, such as the
simulations of the instabilities of a parallel shear flow (C.4, Parent et al., 1976, Becker
near how to influence flows (Ilerassen and Pedler, 1982), two-dimensional numerical
be the vestige of the primary instability in the early stage in the transition from lamin-
the presence of small-scale fluctuations. These structures are commonly believed to
Furth, 1979), even then the coherent large-scale structure is observed to persist in
strong motions appear only after primary waves reach the saturated stage (Wyngaard and
KH wave is two-dimensional and gulf persistent in the initial stage. Three dimen-

68
equations for momentum, heat and mass balance. Within the canopy, additional
space. The Boussinesq approximation has been made to simplify the Navier-Stokes
and Shummann, 1992), except that the computation is performed in x-z dimensions in
formulation is similar to that of the large eddy simulation of canopy flows (e.g., Shaw
grid size explicitly, and the effects of the sub-grid-scale motions are modeled. The
This two-dimensional eddy-resolved model solves motions with scales larger than the

4.2.1 Basic Equations

4.2 Model Description

Results can be found in Hu and Lee (2000),
tures and velocity fields are compared with observations. Some of the preliminary
and by the proximity of the critical level to the ground. The detailed internal stoc-
particular the modification of the classical KH instability by the canopy elements,
ary is covered with leaves. Several aspects of the KH wave growth will be investiga-
red in a stable stratified boundary layers will be presented. Specifically, the lower bound-
here a sequence of numerical simulations of the instability of a parallel shear flow
waves.

atmospheric and canopy processes could reproduce the major observed features of the canopy
three-dimensional model couched in the current understanding of the interaction between the
be a powerful tool in visualizing organized flow structures. We expect that this two-
Barr, 1998; Hu and Lee, 1998; Chapter 2 in this thesis). It has been demonstrated to
applied to the nighttime high-frequency temperature profile measurements (Lee and
Kolmogorov Relation

scale turbulent kinetic energy. The eddy viscosity is obtained from the Prandtl-

where \( \mu^w \) is the subgrid eddy viscosity of momentum, and \( \varepsilon \) is the subgrid-

\[
\begin{align*}
\tilde{\varepsilon} \frac{\varepsilon}{\nu} = \left( \frac{x_\theta}{\nu} + \frac{\nu}{\Phi} \right) \mu^w = \frac{x_\theta}{\nu} \mu^w - \frac{\nu}{\Phi} \mu^w = \tilde{\varepsilon}
\end{align*}
\]

The subgrid-scale momentum flux can be written as

\[
\text{Coefficient } \tilde{\varepsilon} \text{ is set to be 0.15 based on the field measurement (Shaw et al., 1998).}
\]

where \( \Lambda \) is the integral scale, \( \tilde{u}_\theta \) is the lab area density, \( \Lambda \) is the draft

\[
\begin{align*}
\tilde{u}_\theta \tilde{u}_\theta = \tilde{I}
\end{align*}
\]

that in Shaw and Shinman (1999).

from the adiabatic background, the drag force by canopy elements \( F \) is modeled as

d Telegram. The overbar denotes the grid cell average. The \( \theta \) and \( \tilde{u}_\theta \) are the deviations

\[
\begin{align*}
\bar{u}_\theta \bar{u}_\theta = \bar{I}
\end{align*}
\]

when \( n \) is the velocity component in the \( \theta \) direction, \( \bar{u}_\theta \) is the velocity

\[
\begin{align*}
\frac{\varepsilon}{\nu} &= 0 = \frac{x_\theta}{\nu} \\
\left( \frac{\theta}{\nu} \right) \frac{x_\theta}{\nu} &= \left( \frac{x_\theta}{\nu} \right) \frac{x_\theta}{\nu} + \frac{\nu}{\Phi} \\
\frac{\nu}{\Phi} &= \frac{x_\theta}{\nu} + \frac{\nu}{\Phi} \\
\begin{align*}
\left( \frac{\theta}{\nu} \right) \frac{x_\theta}{\nu} + \frac{\nu}{\Phi} &= \frac{x_\theta}{\nu} + \frac{\nu}{\Phi}
\end{align*}
\]

Plane. The grid-cell-averaged governing equations are:

\( \frac{z - \infty}{\varepsilon} \) are the major variables located in the center of grid cells in the \( x \) plane. These terms are included to account for the canopy drag and the heat exchange between
Compared with standard upwind different methods, the scheme coupled the spatial
with avoids any cell Reynolds number stability restriction for high Reynolds flows.
Second-order upwind method is adopted to describe the non-linear advection terms, a
specialized
velocity equations to predict the intermediate velocities, and then projects these
modified projection method is a fractional step scheme. It first solves the advection-
processes in a stenographic marine boundary layer (Stevens et al., 2000). The
the MATLAB flow solver for solving the model equations is developed by Stevens et

4.2.2 Numerical Method

In the above equation,

with empirical constant \( \alpha = 0.93 \). The canopy drag effect is included in the last term

\[
(A.2.8)
\]

\[
\frac{f_x}{n \theta} \left( \frac{f_x}{n \theta} + \frac{f_x}{n \theta} \right) \frac{w}{y} + \left( \frac{f_x}{n \theta} \frac{w}{y} \right) \frac{f_x}{n \theta} = \frac{f_x}{n \theta} + \frac{n}{n} \frac{f_x}{n \theta} + \frac{f_x}{n \theta}
\]

The turbulent kinetic energy is computed by solving the following prognostic equation

\[
(A.4.4)
\]

\[
\frac{z}{l} \left( z \nabla \cdot x \nabla \right) = 1
\]

\( \nabla \cdot \nabla \times x \nabla = 1 \) 

The horizontal and vertical grid sizes and \( z \) \( l \) are empirical constant \( w_l = 0.1 \). The characteristic length scale \( l \) is related to

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where $z$ is height, $y$ is the root height, and $L$ is leaf area index. The free height in the

$$
(4.2.10) \quad \left[ \left( \frac{z}{0.12} \right) / \left( \frac{0.62}{y} - \frac{y}{z} \right) \right] \exp \left( \frac{2z - 0.12}{y} \right) = \left( \frac{z}{0} \right)
$$

density

up this two-dimensional simulation. A Gaussian distribution describes the leaf area

The same problems in the linear canopy wave model (Teo, 1997) are used to set

opment.

carbon far away from the maximum shear. It has negligible effect on the flow devel-

compensation domain height is set to be 6 leaf heights. The upper boundary is suff-

boundaries are treated as rigid walls and no-flux conditions are implemented. The

boundary mode predicted by the linear wave model (Teo, 1997). The upper and lower

the length of the compensation domain is set to be one wavelength of the fastest

The lateral boundaries are periodic, which is suitable for the simulation of waves.

Boundary Conditions, Initial Profiles and Initialization

(4.2.9)

$$
\max \left( \frac{z}{y}, \frac{x}{n} \right)
$$

Thus, the time-step constraint is the common Courant-Friedrichs-Levy condition

interpolation is needed to compute model statistics, such as momentum flux and heat

compounds are located in the centers of the grid cells. One of the benefits is that no

Unlike the widely-used staggered grid layout, all of the primary variables to be

It leads to a robust higher order discretization with excellent phase-averaged propertie,

and temporal discretization to attain second-order accuracy in both space and time.
Parameters used in the numerical simulation.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$h$</td>
<td>Height of the computation domain</td>
</tr>
<tr>
<td>$l$</td>
<td>Length of the computation domain</td>
</tr>
<tr>
<td>$w$</td>
<td>Width of the test chamber</td>
</tr>
<tr>
<td>$v$</td>
<td>Wind speed at the top</td>
</tr>
<tr>
<td>$y_n$</td>
<td>Real area index</td>
</tr>
<tr>
<td>$y$</td>
<td>Area index</td>
</tr>
<tr>
<td>$z$</td>
<td>Vertical grid size</td>
</tr>
<tr>
<td>$\n$</td>
<td>Horizontal grid size</td>
</tr>
</tbody>
</table>

The parameters used in the simulation are listed in Table 4.1. The minimum Richardson number of 0.112 is found just above the tornado, which is below the critical value of 0.2.

The momentum equation for the Reynolds-Averaged Navier-Stokes (RANS) equation assumes the following form:

$$\frac{\partial}{\partial t}(\rho u_i) + \nabla \cdot (\rho u_i u_j) = -\frac{\partial p}{\partial x_i} + \mu \left( \frac{\partial^2 u_i}{\partial x_j \partial x_j} + \frac{\partial^2 u_i}{\partial x_k \partial x_k} - \frac{2}{3} \frac{\partial^2 u_i}{\partial x_m \partial x_m} \right) + \frac{\partial}{\partial x_j} \left[ \rho (u_i u_j - u_i u_j) \right]$$

The temperature profile is set up to make the Blunt-Wedge RANS calculation possible:

$$\frac{\partial}{\partial x} \left[ \rho C_p T \right] = 0$$

The Richardson number is defined as:

$$R_i = \frac{\Delta}{\Delta_w} = \frac{\rho u^2}{\nu g}$$

where $\Delta = \frac{\rho u^2}{\nu g}$ is the characteristic scale of the flow, $\rho$ is the density, $u$ is the velocity, $\nu$ is the viscosity, and $g$ is the acceleration due to gravity.

By assuming that the wind speed at the top is $u_n$, the following equation is given by

$$\frac{\partial}{\partial x} \left[ \rho C_p T \right] = 0$$

The initial mean wind speed is given by

$$u_0 = \frac{20}{2} \text{ m/s}$$
\[
\frac{\varepsilon \rho}{(3.4) z''} = \left( x p \left[ v_{\text{in}} + (1 - n) \right] \right) z p \int_{H}^{0} f = \left( \gamma \right) \Phi
\]

where the \( \gamma \) is the wavelength of the primary mode. The total perturbation profile

\[
(3.4) \quad x p (z, x) n \int_{1}^{0} \frac{v_{\text{in}}}{t} = \langle n \rangle
\]

(Parmer et al., 1997)

mean of the horizontal velocity in the two-dimensional plane is defined as

linear theory (Le, 1997). To estimate the apparent linear growth rate, the horizontal 2D simulation. The apparent growth rate and phase speed can be compared with the is chosen to be sufficiently small and the apparent growth rate can be computed by the canopy and without canopy, respectively. The amplitude of the initial perturbation for the parameters listed above, simulations have been performed for the flow with

\textbf{Comparison with the Linear Theory}

4.3 Results and Analysis

流量 of the result to the exact form of the initial perturbation. (e.g., Peller et al., 1978; Sikes and Loweller, 1982) have demonstrated the important

does not influence the flow structure at the finite-amplitude stage. Previous studies growing mode. The initial perturbation is chosen to be sufficiently small so that it is used to study the initial conditions. At about 200\( s \) after the initialization, the lower half looks like the first partial convective field. Other variables adjust themselves gradually to the pert-

Simulations are initialized with small-amplitude where noise added to the initial
The simulation without canopies is about 0.01 s⁻¹, nearly identical to the prediction of Peiter et al. (1978). The steady growth rate for the simulation without the canopy has been established after about four linear time constants. The growth rate for the canopy growth rate and without the canopy growth are the result of the initialization with white-noise, similar to those observed by inspection of Figure 4.1 shows that linear growth stages, characterized with con-

\[
\frac{\mu}{p} \cdot \frac{\mathcal{A}}{\mathcal{B}} \frac{\mathcal{C}}{\mathcal{D}} = \mathcal{E}
\]

The result is shown in Figure 4.1.

\[
\text{Figure 4.1: The Linear Growth Rates for the Flow with Canopies (solid line) and Without canopies (dashed line).}
\]
canopies. The phase speed is about 1.50 m s⁻¹, smaller than the prediction of the linear growth stage, which is in agreement with the linear analysis. For the flow without canopies and without canopies, the phase speeds for the flow without canopies is about 1.61 m s⁻¹. In the 2D com-
The inspection of the flow structures shows that the couple of shear time constants. The growth rate decreases to zero rapidly within a
getting narrower and more adjacent to the edge of the core. As for the broad, which is of maximum strength, from 0 to 60's, the amplitude of the wave is shown

If most noticeable just above the core, where wind shear is reduced, the stratification is gradually distorted. At the center of the wave, vertical temperature heterogeneity grows, the horizontal homogeneity.

At the starting line, a small disturbance is added to the background potential

Flow around a small disturbance of potential temperature field for a growing wave.

Potential Temperature and Wind Fluctuations

4.3.2 The Two-Dimensional Wave Evolution

At the increased speed of the mean flow of a broadened shear layer, to about 1.9 m/s, it could be understood as the result of the saturated wave moves, wave becomes saturated in amplitude. At the same time, the phase speed increases...
Figure 4.3: The evolution of a canopy wave in the potential temperature field. The contour interval is 0.2 K.
velocity profile is symmetric and the spread of the mean flow is found at the shear.

Further above, motions of the ejection type persist throughout the bridge. There is
sweep-ejection pattern is prominent from the upper canopy to about two tree heights.
The transition between the ejection and the sweep occurs at the bridge, which would
be the counterpart of the vortices found in the daytime coherent structures. The
bride and ejection-like downward motions whose counterpart would be the sweeps.
are similar to the ejections observed in the daytime coherent structures. Following
located. Near the leeward, before the arrival of the bridge, the slow upward motions
are expected. Large wind fluctuations are found at the layer where the wave core is

This eooenomous wave feature is expected because of the way in which initial Philip,
vortical structures, which would generate large vertical momentum and heat fluxes.
wave core, the vortical feature is in quadrature with the horizontal vorticity and po-
area well at the time when the wave reaches its maximum amplitude above the

In Figure 4.4, wind fluctuation vectors are superimposed on the potential temper-
structural. With such thermal structure, in immediate instrument lower would record
definition, the core, the leading edge is more diffuse and the trailing edge is more

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Figure 4.4: Wind fluctuation vectors and potential temperature contours. The contour interval is 0.2K.
closed streamlines gradually moves upward. At the later stage of the linear growth, as the verticality associated with the initial shear, as the wave grows, the center of the reference frame moves with the mean flow, the fluid circulates in the same fashion initially appear at about 1,379, where the minimum Richardson number is found. In the absence of streamlines is presented in Figure 4.3. The closed streamlines

\[ (4.3.4) \quad \overline{\psi}(r - \eta) \int = \phi \]

defined as will be changed. In the co-ordinates moving with the wave, the stream function is

evolved (Drazin and Reid, 1982). Here the streamlines for the simulated canyons vary

determined with a closed streamline pattern, which is widely known as the "carts" In the reference frame moving with the mean flow, the classical KH instability is

Streamline Pattern


health of the core center. This is in agreement with the observation by Lee and Park

speed calculated in section 4.3.1 is consistent with the background wind speed at the

core is at about 1.3 lee height, a few meters above the shear maximum. The phase

ground. Furthermore, by visual inspection it is found that the center of the wave

ground. The growth of the lower half of the wave is significantly limited by the rigid

profile is anti-symmetric. Second, the shear maximum at the lee side is close to the

maximum. This simulation differs from the two in several aspects. First, the wind
Figure 4.5: The evolution of streamlines.
Revealed how near the ground at the maximum stage is infinite. The momentum
creates secondary wind maximum within the canopy (Fig. 4.6(a)). The
Cassie distribution used in this model (Equation 4.1.1) reduces the distribution of canopy elements, the
Canopy drag (Equation 2.3.1) is related to the distribution of canopy elements, the
primarily done by the canopy drag. Since the half life of the wind speed reduction by
strength near the tree tops. Within the canopy, the reduction of the wind speed is
the tree tops diminishes little. The direct result of this reduction is to reduce the shear
profile remains zero throughout the growth phase. Thus, the wind speed just above
the reduction of horizontal wind speed in the layer below 2h is noticeable. The most
is found at about 2h, the height with the maximum divergence of Reynolds
the first closed streamlines at that time (Fig. 4.3). At the maximum amplitude,
characteristics that the two profiles are modified in correspondence approximately
amplitude, the modification becomes prominent as the wave grows to the maximum
people and the mean potential temperature profile until the wave reaches its maximum
Figures 4.6(a) and 4.7(a) illustrate the modification of the mean horizontal wind

Due to Mixing

4.4 Wave-Mean Flow Interaction and Wave Inte-
Figure 4.6: Background horizontal wind profile and horizontally averaged momentum flux.
Figure 4.7: Background potential temperature profile and horizontally averaged heat flux.
4.5 Discussion and Summary

and potential temperature are completely unaffected by the wave. They are revealed. The figures with Figure 4.6 and Figure 4.7 in Chapter 2, options be excluded either. Above three lee edges, the background profiles of both wind structure formed during the overturning of the wave. But the numerical effect cannot that found in the momentum flux. It is probably created by the stably stratified unstable e.g. et al. (1976). The zigzag pattern of the heat flux near the ground is similar to canopy, similar to the spilling of the original inversion layer reported by Peters. Two secondary inversion layers appear both above the canopy and in the lower result, two secondary inversion layers appear above the canopy and above two lee edges is much reduced. As a layer between the upper canopy and above two lee edges is much reduced. As a downstream heat flux. At the maximum amplitude, the temperature gradient in the downward heat flux, the divergence of the heat flux above the lees is as well as the boundary layer exchange with the surrounding wave. The divergence of the heat flux above the lee bars the potential temperature profile by the eddy heat flux is modification of the original potential temperature profile by the eddy heat flux is

(\text{Figure 4.7(a) (Figure 4.7(b)) responsible for the potential temperature profile)}

The low heat Fluxes (Figure 4.7(b)) observed by Peters et al. (1976). But the numerical effect from ventilation of the lee-moving fluid into the flow moving lower layer similar to that

flux at the same time exhibits a zigzag pattern. This might be the effect of the
Successes that the observed canopy waves are shear-generated Mw waves, resemblance between the numerical simulation and the lower-based field observation boundary conditions, that are of primary interest at the present time. The qualitative it is the macro-structures which are essentially determined by the initial profile and present wind conditions. In the wave cores in Figure 2.6 and Figure 2.7. Nonetheless, two-dimensional model. For example, this model cannot reproduce the observed in the cores is three-dimensional in nature, which cannot be resolved by this development of spanwise secondary instability in the brems and gravitational waves. However, this two-dimensional numerical simulation has its limitations. Further...
Quantitative details of the evolution of the flux field and impulse statistics are

can produce how structures that qualitatively bear resemblance to observations, the

Although this numerical model, with a crude sub-grid influence decrease scheme,
estimate of the long-term net ecosystem exchange of CO2 measured by such systems,

Figures 7 and 8 show how the mean behavior, with differing from normal

a scenario is true, most of the cumulative lower-layer eddy-correlation systems cannot

helps. The escaped CO2 might be advected down-stream by the mean flow. If such

the mixing is limited to the thin layer just above the canopy and below to 3 tree

were is expected to push CO2 out of the canopy and mix it with the air above. But

Forest-atmosphere interaction is usually found. The mixing process associated with the

potential temperature profile, a large positive CO2 concentration gradient across the

the strength of the temperature inversion. On clear nights, similar to that of the

the secondary convective instability in the statically unstable structures, will reduce

layer and simultaneously release cooler air out of the canopy. The irreversible mixing, by

heated up. The role of the canopy wave is to entrain warmer air above into the canopy

same time, the air in the canopy layer, most noticeable in the upper canopy layer, is

below above the canopy is reduced by the downward transport of sensible heat. At the

of the KH wave below these canopy heights. The potential temperature in the thin

waves, the simulation indicates that considerable mixing occurs during the growth

from the modification of wind profile and potential temperature profile by canopy

The mixing of scalars, especially the nocturnal respiratory CO2, can be ignored

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The large-eddy simulation of the nocturnal canopy flow, in a three-dimensional large-eddy simulation, which is expected with the advance of stratospheric (Schling and Janssen, 1992), ultimately, the simulation should be done in a similar to the study of the particle dispersion due to H.M. instability in the lower transport-transportation models (e.g., Ramach, 1988) to investigate the wave-introduced mixing and Lwoff (1985). The improved turbulence statistics can be used by Lagrangian closure can be done, such as the second-order closure scheme employed by Sykes et al. (1981). Within the 2D frame work, further improvement in sub-grid influence is not realistic.
Conclusions
Implication of these results to the field observation has also been discussed. The non-stationary property of the mixing process associated with the wave, the observation verifies the results of KH waves. The numerical simulation, however, reveals unimodal mode. The numerical model also indicates that the motion of shear and observed the structures. These results, therefore, suggest that the wave overrunning in the ionosphere among the wave components is reproduced in the numerical calculation. The temperature gradient. Away from the shear maximum, the observed phase lead of KH waves on shear is characteristic with reasonable cores determined by slope-compared. The numerical results bear major resemblance to the observation. Specifically, the influence due to shearing strain, the detailed flow field information of the wave evolution is needed. In an effort to reproduce flow structures of canopy waves, a two-dimensional numerical model has been developed. With the prescribed initial profiles and a coarse grid, motions of KH waves on shear inherent indicate that the forest environment is favorable to the occurrence of wave-like air motions in the otherwise stable background conditions without canopies. The model results canopies. A new type of instability has been found solely as a result of the canopy drag or destabilizes the flow in preference to the flow with the same configuration but without the flow system. By modifying the growth rates, the canopy drag can either stabilize or wave mechanism, the influence of the canopy drag changes the stability properties of a two-layered canopy model has been developed to investigate the
Time-height Dimensions

Wave-like Air Motions in

Appendix A
Figure A.1: Time-height potential temperature contour plot (22:30-23:00, July 12, 1994).
Figure A.2: Time-height potential temperature contour plot (23:00-23:30, July 12, 1994).
Figure A.3: Time-height potential temperature contour plot (23:30-24:00, July 12, 1994).
Figure A.4: Time-height potential temperature contour plot (00:00-00:30, July 13, 1994).
Figure A.5: Time-height potential temperature contour plot (00:30-01:00, July 13, 1994).
Figure A.6: Time-height potential temperature contour plot (01:00-01:30, July 13, 1994).
Figure A.7: Time-height potential temperature contour plot (01:30-02:00, July 13, 1994).
Figure A.8: Time-height potential temperature contour plot (02:00-02:30, July 13, 1994).
Figure A.9: Time-height potential temperature contour plot (02:30-03:00, July 13, 1994).
Figure A.10: Time-height potential temperature contour plot (03:00-03:30, July 13, 1994).
Figure A.11: Time-height potential temperature contour plot (03:30-04:00, July 13, 1994).
Figure A.12: Time-height potential temperature contour plot (04:00-04:30, July 13, 1994).
Figure A.13: Time-height potential temperature contour plot (04:30-05:00, July 13, 1994).
Figure A.14: Time-height potential temperature contour plot (05:00-05:30, July 13, 1994).
The correlation theorem states

\[
\Phi(\phi) \Leftrightarrow \Phi(\phi)
\]

(10.3)

(10.2)

The Fast Fourier Transformation (FFT). The Fourier transformation pairs are denoted by \( \phi \) and \( \phi' \). The correlation is computed by an algorithm based on the convolution between \( \phi \) and \( \phi' \). The correlation can be estimated by finding the maximum of the spatial core.

(10.1)

\[
\frac{\nabla \phi}{\nabla \phi'} = c
\]

Then the phase speed is given by

\[
\nabla \phi = \phi' (x, z, t) - \phi (x, z, t)
\]

For a suitable quantity such as the potential component of the vertical velocity field,

Phase Speed

The Algorithm for Computing the

Appendix B
(B.0.5)
\[
\frac{\theta_0}{\theta} + \theta_0 x = p \nabla
\]

of \( p \). The better-than-the-end-size estimate of the displacement is

square method. The maximum of this parabola curve is presumed to be the best estimate

is pleased with a number of data points adjacent to the discrete maximum by a least

(B.0.4)
\[
\gamma + (\theta \phi - x) \theta + \theta (\phi - x) \theta = (x) \nabla
\]

the discrete maximum of \( \text{corr} (\phi, \phi) \) is found at \( x = 0 \) for a parabola curve

The estimate of \( \nabla \phi \) can be further improved by an empirical method. Given that

according to the correlation theorem.

not change much. The correlation is calculated by the inverse FFT transformation

of data with a properly chosen time delay, so that the primary flow structure does

where the asterisk denotes the complex conjugate. In practice, we take two frames
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