The Influence of Atmospheric Stability on the Budgets of the Reynolds Stress and Turbulent Kinetic Energy within and above a Deciduous Forest

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(Manuscript received 25 September 1989, in final form 19 March 1990)

ABSTRACT

This paper shows that the inclusion of thermal effects is necessary to correctly interpret the physical processes involved in the generation or suppression of Reynolds stress and turbulent kinetic energy inside a forest canopy. In both of these budgets, thermal effects are largest in the upper third of the canopy where the foliage is densest and the radiation load highest. The magnitude of the buoyant production term in both these budgets increases almost linearly with instability in the upper region of the canopy. The onset of stability exerts a strong influence on the behavior of the shear production in both the budgets of Reynolds stress and turbulent kinetic energy. In strong thermal stratification, the shear production term becomes a sink of Reynolds stress and turbulent kinetic energy in the lower half of the canopy.

1. Introduction

The budgets of the Reynolds stress and turbulent kinetic energy (TKE) behave differently inside vegetation than in the atmospheric surface layer. The most noticeable changes are the increased importance of turbulent transport rates within the canopy and the additional effect of drag due to canopy elements. These budgets have been investigated in model plant canopies (Lesnicky 1974; Raupach et al. 1986) and in real canopies (Wilson and Shaw 1977; Shaw and Seginer 1985), where attention is drawn to the significance of large observed turbulent transport rates and canopy drag. The only attention given to the importance and effects of atmospheric stability on the terms in such budgets inside vegetation was (as noted by Pereira and Shaw 1977) in the work of Legg and Monteith (1975), in which they use a gradient Richardson number to show that buoyancy is an important mechanism contributing to the production or destruction of TKE. This paper examines the role played by atmospheric stability on the budgets of Reynolds stress and turbulent kinetic energy within and above a deciduous forest canopy.

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2. Methods

The data were collected at Camp Borden, Ontario, Canada in the fall of 1986 inside and above a deciduous forest. The leaf area index (LAI) of the Camp Borden forest was approximately 1.6 in early October and 0.3 in late October (Neumann et al. 1988). The forest was approximately 18 m tall, although individual trees/tree clusters sometimes extended up to 22 m. Seven three-dimensional fast response sonic anemometers were used. Four of these were placed on an 18 m scaffolding tower at heights of 5.9, 10.5, 15.4, and 17.6 m. The remaining three anemometers were placed on a 43 m tower at 17.9, 34.2, and 43.1 m. A complete description of the site and instrumentation is included in Shaw et al. (1988). A coordinate transformation was performed on the data so that the mean vertical and transverse velocities were zero. The data from the two anemometers near the canopy top were averaged together.

Atmospheric stability regimes are classified using a stability parameter $h/L$ (Leclerc and Shaw 1988; Shaw et al. 1988; Leclerc et al. 1990) where $h$ is the canopy height and $L$ is the Obukhov length calculated at canopy top. The validity of this parameter has been discussed by Leclerc et al. (1990). Individual 30 minute periods have been averaged for each stability class. The number of periods used in the calculations of both budgets is shown in Table 1. All budget terms have
been nondimensionalized by $h/u^2_\| (h)$, where $u_\|$ is the friction velocity at $h$. For consistency, calculations of all terms including terms whether or not involving derivatives were taken at the midpoint between two observation levels.

Since there are inherent uncertainties in the measurements of turbulence statistics due to finite sampling time, an analysis of the error in the mixed second moment $u'w'$ and in the third moment $u'w'^2$ was made. We have followed Lumley and Panofsky's (1964) criterion to estimate the uncertainty caused by a sampling time of 30 minutes for observations made at 43.1 m in neutral conditions and have found the uncertainty estimate of the $u'w'^2$ term to be about 25% and for $u'w'$ about 10%.

3. Results

a. The Reynolds stress budget

Assuming horizontal homogeneity and steady state conditions, the budget of the Reynolds stress reduces to

$$
\frac{\partial (u'w')}{\partial t} = -w^2 \frac{\partial u}{\partial z} + \frac{g}{T} (u' \theta') - \frac{\partial u'w'^2}{\partial z} 
$$

(i)

$$
+ \frac{p'}{\rho} \left( \frac{\partial u'}{\partial z} + \frac{\partial w'}{\partial x} \right) - \frac{1}{\rho} \frac{\partial (p'u')}{\partial z} + \nu \frac{\partial^2 (u'w')}{\partial z^2} 
$$

(vi)

$$
- 2\nu \left( \frac{\partial u}{\partial x} \frac{\partial w}{\partial x} \right) 
$$

(viii)

(1)

where an overbar indicates a mean, and a prime indicates a fluctuation from the mean. Here $u$ and $w$ are the streamwise and vertical velocity components, respectively; $\theta$ is the potential temperature; $T$ the air temperature; $p$ the static pressure; $\rho$ the air density; $\nu$ the kinematic viscosity; and $g$ the gravitational acceleration. Term (i) is the local rate of change of $u'w'$. Terms (ii) through (viii) represent, in order, shear production, buoyant production, turbulent transport, pressure destruction and pressure transport, viscous transport and viscous dissipation. Viscous transport is assumed to be negligible. The turbulent transport and production terms were measured directly. The relative importance of these terms, pressure transport, pressure destruction, and viscous dissipation within the canopy is not known and these, together with measurement errors inherent in the other terms, were combined to form the residual term.

Shear production indicates the production of Reynolds stress by the interaction of the vertical velocity variance and the mean wind shear, and it is usually a source term. The remarkable influence of atmospheric stability on the behavior of the shear production term is illustrated in Fig. 1. In a nondimensional form, the onset of stability dramatically enhances the rate of shear production in the upper portion of the crown and above but has little effect below except in strong stable stratification ($h/L > 0.25$), where shear production becomes a destruction term. This arises where the velocity gradient is negative; i.e., in regions of secondary wind speed maxima, which occur when the divergence of transport of Reynolds stress is opposite in sign from and larger in magnitude than the pressure velocity gradient correlation (Shaw 1977).

The buoyant production term (Fig. 2) is a source of Reynolds stress in unstable conditions and a sink in stable conditions everywhere inside the forest except in the lower half of the canopy where it contributes to the production of the Reynolds stress in very stable conditions ($h/L > 0.20$). This coincides with vertical positive heat fluxes in the lower canopy during very stable conditions. Such occurrences of nighttime upward heat fluxes and their associated mechanisms have been discussed in Leclerc et al. (1990).

The effect of atmospheric stability on the momentum flux has already been demonstrated in Shaw et al. (1988). The turbulent transport term, mathematically described as the vertical divergence of the flux of the Reynolds stress, is depicted in Fig. 3 and generally exhibits a weak dependence on stability. This term represents the vertical transport of $u'w'$ to or from other regions. Above the canopy turbulent transport generally represents an export of Reynolds stress, and values are typically positive with little dependence on stability. The large variability in the estimates of this term at 26 m, calculated from observations at 18 and at 33 m, may well reflect the effect of the uneven forest height. Estimates of this term made at 38.5 m are closer to zero and generally better behaved. The turbulent

<table>
<thead>
<tr>
<th>Group number</th>
<th>Stability range</th>
<th>Stability groups</th>
<th>Number of periods averaged</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$h/L &lt; -0.5$</td>
<td></td>
<td>3</td>
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<tr>
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<td>4</td>
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Fig. 1. Nondimensional rate of shear production of Reynolds stress as a function of stability within and above the forest. Closed circles represent estimates at 26 m and open circles represent estimates at 38.5 m.
transport term estimated in the upper portion of the crown also suffers from a lot of scatter and no clear trend is identifiable. The turbulent transport term in the upper two-thirds of the canopy represents an import of Reynolds stress. Thermal stability does not influence the behavior of the transport term in that region but appears to suppress the import of Reynolds stress almost entirely in strong thermal stratification \((h/L > 0.4)\) at the lower observation level.

The residual term (Fig. 4) exhibits a weak dependence on stability. In the lower two-thirds of the canopy, strong stable stratification \((h/L > 0.25)\) markedly damps the strength of the residual to near zero values, while above the forest (38.5 m), the residual increases with increasing thermal stability, although the scatter is large, similar to surface layer observations (Wyngaard et al. 1971).

b. Profiles of the terms in the budget of the Reynolds stress

The impact of thermal effects on the behavior of each term in the Reynolds stress budget is demonstrated in Fig. 5. As expected, the contribution of such effects on the production/ destruction of \(u'w'\) (when presented in dimensionless form) is most pronounced in stable conditions where large velocity gradients are present. In this regime, the buoyant production term represents a sink as strong as the sum of the viscous dissipation, pressure transport, and pressure destruction terms combined (i.e., the residual). These sinks act to destroy imported (through the turbulent transport term) or locally generated (through the shear production term) Reynolds stress inside the forest. In the upper portion of the crown during these stable regimes, shear production is the only source term and by midcrown, shear production and turbulent transport are nearly equal. In the lower canopy the turbulent transport is much reduced and shear production becomes a sink of Reynolds stress (though small) imparted by the negative velocity gradient present in this region. In unstable regimes the contribution of the buoyant production and turbulent transport terms is small when compared with the large shear production or residual terms. At the lowest observation level the Reynolds stress is primarily imported through the turbulent transport term. In neutral conditions shear production remains the dominant source term in the upper canopy and above, in agreement with results of Wilson and Shaw (1977) and Raupach et al. (1986).

c. Turbulent kinetic energy budget

Assuming horizontal homogeneity, the turbulent kinetic energy budget for a free surface layer is

\[
\frac{1}{2} \frac{d\bar{q}^2}{dt} = -\bar{u}'w' \frac{\partial \bar{u}}{\partial z} + \frac{g}{T} \bar{w}' \theta' - \frac{1}{2\rho} \frac{\partial \left( \bar{w} \bar{q}^2 \right)}{\partial z} \tag{i}
\]

\[
- \frac{1}{\rho} \frac{\partial \bar{w}' \bar{p}'}{\partial z} - \nu \left( \frac{\partial \bar{u}'_x \partial \bar{u}'_x}{\partial x} \right) \tag{ii}
\]

where \(q^2 = \bar{u}'^2 + \bar{v}'^2 + \bar{w}'^2\).

The notation is the same as with the Reynolds stress equation. These terms represent the contribution from (i) shear production, (ii) buoyant production, (iii) turbulent transport of turbulent kinetic energy, (iv) pressure transport, and (v) viscous dissipation. The pressure transport is believed to be small but nonnegligible. The dissipation term represents the rate of conversion of TKE into internal energy. In Eq. 2, the terms on the right-hand side contribute to a gain in TKE when positive and a loss when negative. The transport and production terms of the TKE budget have been calculated directly while the combination of viscous dissipation and pressure transport form the residual together with the cumulative errors due to canopy inhomogeneity and measurement errors inherent in the other terms.

The shear production term represents the transfer of kinetic energy from the mean flow to the turbulent component of the flow. The shear production term in the TKE budget like in the Reynolds stress is normally a source term. It is negative in the Reynolds stress equation (Fig. 1) and positive in the turbulent kinetic energy budget (Fig. 6). In both cases the influence of thermal stability on the shear production terms are alike. In the upper portion of the canopy and above, the normalized shear production increases dramatically with the onset of stability. Shear production in the lower two-thirds of the canopy is very small and largest in slightly unstable conditions. The magnitude of shear production decreases with increasing \(h/L\) and becomes a very weak sink of TKE during very stable regimes. Though this loss of TKE is small, it is significant because it suggests a conversion of TKE into mean kinetic energy.

The buoyant production term (Fig. 7) contributes in unstable conditions to the production of turbulent kinetic energy by a conversion of potential energy. This term also behaves like its counterpart in the Reynolds stress budget. A notable difference is the behavior of this term in unstable conditions. While that term in the Reynolds stress budget is independent of stability when the flow is thermally unstable, the buoyant production term in the TKE budget exhibits a quasi-linear relationship with thermal stability over the spectrum of stabilities encompassed. Buoyancy occasionally represents a loss in unstable regimes and a gain in stable...
Fig. 2. Nondimensional rate of buoyant production of Reynolds stress as a function of stability within and above the forest. Closed circles represent estimates at 8.2 m and open circles represent estimates at 16.5 m.
Fig. 3. Non-dimensional rate of turbulent transport of Reynolds stress as a function of stability within and above the forest. Closed circles represent estimates at 26 m and open circles represent estimates at 38.5 m.
Fig. 4. Non-dimensional rate of the residual term in the Reynolds stress equation as a function of stability within and above the forest. Closed circles represent estimates at 12.95 m, above canopy; open circles represent estimates at 15.5 m.
Fig. 5. Vertical profiles of the budget of Reynolds stress in nondimensionalized form for three stability groups within and above the forest. Unstable conditions are represented by group 4 (−0.5 < h/L < −0.2), neutral by group 6 (−0.05 < h/L < 0.0) and stable by group 11 (0.5 < h/L < 0.65).
Fig. 7. Non-dimensional rate of buoyant production of turbulent kinetic energy as a function of stability within and above the forest (closed circles represent observations at 26 m and open circles represent observations at 38.5 m).
stratification. This reversal of the buoyant contribution to TKE production arises when the heat flux within the canopy is opposite that at the canopy top.

Figure 8 shows the vertical profiles of the flux of TKE. This flux is downward within the canopy, reaching a maximum in the upper region of the canopy. The TKE flux inside the forest shows a strong relationship to stability where the largest negative fluxes occur in thermally unstable conditions. In very stable conditions, the TKE flux approaches zero in the lower two-thirds of the canopy indicating the absence of downward transport of TKE to the lower portion of the canopy. Above the canopy, the flux of TKE is positive for stable and unstable conditions but becomes zero in neutral conditions. In the upper part of the crown, the turbulent transport (Fig. 9) exhibits a lot of run-to-run variability, but no clear trend can be detected. The turbulent transport represents an import of TKE in the lower canopy whose extent is limited by the thermal stratification. Above the canopy, the turbulent transport is a loss of TKE except in very stable conditions.

Within a canopy work is done on the mean flow by canopy elements producing form drag. This process may be mathematically represented in a spatially and temporally averaged momentum equation, and appears in the spatially averaged TKE equation as a wake production term \( \langle u'w'(d\bar{u}'/dz) \rangle \) (Wilson and Shaw 1977; Raupach and Shaw 1982). The angle brackets represent the horizontally averaged flow and double primes are fluctuations from that average. Assuming that dispersive and molecular contributions to the shear stress are negligible, wake production can be rewritten as \( \langle u'(d < u'w'/dz) \rangle \) (Raupach et al. 1986). Although the term represents spatially averaged quantities, we have assumed that the temporal average will approximate the spatial average. In the upper third of the canopy, the onset of stability increases the production of wake turbulence (written in a normalized form and depicted in Fig. 10) since thermal stratification enhances vertical gradients in the Reynolds stress. Not surprisingly, this effect decreases with increasing depth of penetration into the canopy, as the effect of thermal stability has been most pronounced in the upper third of the canopy for most other terms studied.

d. Profiles of the budget of turbulent kinetic energy

The role played by atmospheric stability on the magnitude of the shear and wake production terms is illustrated in Fig. 11. In strongly stable conditions, both shear and wake production terms, which are about the same magnitude near the treetops, are about twice as large (once again, in dimensionless form) as in neutral or unstable conditions. The size of the residual in these conditions is nearly three times larger than in neutral or unstable conditions. The buoyant production term in unstable conditions constitutes an important gain of TKE. The influence of stability is most clearly seen in the upper third of the canopy while in the lower portion of the crown, the magnitude of each term is typically small and thermal effects play a secondary role.

e. Shear turbulent kinetic energy

The TKE equation in the absence of thermal effects consists of two production terms, shear and wake production. Shear production extracts energy from the mean flow, and wake production is caused by work done by the flow on canopy elements, forming wake motions. Because eddies produced by shear scale with canopy height and those produced by wake motions scale with canopy elements, wake eddies will be much smaller than shear eddies. Although shear and wake production rates are nearly equal in neutral conditions, the turbulent wake kinetic energy is dissipated more rapidly than turbulent shear kinetic energy, as production of smaller eddies accelerates the eddy cascade. The influence of wake production on the total effective turbulent kinetic energy is thus small. The TKE budget has been separated into two distinct scales of motion following Shaw and Seginer (1985) and Wilson (1988). We have included the buoyant production term as an important contributor of large scale turbulence. Sources and sinks of large scale eddies can be examined with the budget of turbulent shear kinetic energy (SKE) while sources and sinks of small scale eddies can be examined with turbulent wake kinetic energy (WKE) in the following equations (Shaw and Seginer 1985).
Fig. 9. Non-dimensional rate of turbulent transport of turbulent kinetic energy as a function of stability within and above the forest (closed circles represent estimates at 26 m and open circles at 38.5 m).
Fig. 10. Nondimensional rate of wake production of turbulent kinetic energy as a function of satellite within the forest.
Fig. 11. Vertical profiles of the budget of turbulent kinetic energy in nondimensionalized form. Unstable conditions are represented by group 1, neutral by group 6, and stable by group 12.
Fig. 12. Nondimensionalized canopy drag as a function of stability within the forest.
FIG. 13. Vertical profiles of the budget of shear turbulent kinetic energy in nondimensionalized form within and above the forest. Unstable conditions are represented by group 1, neutral by group 6, and stable by group 12.
SKE = \frac{u'w'}{\partial z} \frac{\partial \bar{u}}{\partial z} - \frac{\partial w'q^2}{\partial z} + \frac{g}{T} (\bar{w'}) - \bar{W} - \epsilon_s = 0 \tag{3}

\text{WKE} = r \bar{W} + \bar{u} \frac{\partial p'}{\partial x} - \epsilon_w = 0 \tag{4}

where \( \bar{W} \) (canopy drag) represents the rate of work done by large scale turbulence against the drag on canopy elements, and \( r \) is the fraction of \( \bar{W} \) which contributes to wake turbulence only. The term \( \bar{u} \partial p'/\partial x \) represents the rate of work by the mean flow against drag and is a “wake production” term (Wilson and Shaw 1977). Viscous dissipation rates for shear turbulence and wake turbulence are represented by \( \epsilon_s \) and \( \epsilon_w \), respectively. Canopy drag is easily measured when rewritten in terms of the velocity components as (Shaw and Seginer 1985):

\[ \bar{W} = -\frac{\partial}{\partial z} \bar{u}'w'(V^3 / \bar{u}V - \bar{u}) \tag{5} \]

where \( V \) is the instantaneous scalar wind speed.

Shear production, buoyant production, and turbulent transport terms are the same in both the turbulent kinetic energy equation and the shear turbulent kinetic energy equation and have been presented above. The loss of shear kinetic energy due to canopy drag replaces the gain of turbulent kinetic energy due to wake motions in the budget of SKE. The canopy drag is small in the lower two-thirds of the forest (Fig. 12) and approaches zero with increasing stability in the lower half of the canopy. In the upper region of the canopy the drag is large but there is a large amount of scatter present.

\textit{f. Profiles of the budget of shear turbulent kinetic energy}

Canopy drag is the primary destruction term within the canopy (Fig. 13) in agreement with findings of Shaw and Seginer (1985) in a corn canopy. Thus, the conversion of the energy of large eddies to small scale motions plays an important role in the balance of turbulent energy. In stable conditions the canopy drag remains the predominant destruction term of the SKE budget, demonstrating the large influence of canopy elements on the breakdown of large scale eddies and indicating an accelerated dissipation rate of TKE. In addition to canopy drag near the treetop, TKE is also lost through turbulent transport and dissipation terms. Shear production is the predominant source of SKE in the upper canopy and turbulent transport is the largest source of SKE at middle and lower canopy. The residual term is positive in the middle and lower canopy, perhaps indicating sources of SKE due to pressure transport. With increasing atmospheric stability in the densest part of the canopy, canopy drag, buoyant production, turbulent transport, and residual contribute to the destruction of SKE in the stable environment. As with the TKE budget, shear production and turbulent transport contribute to the gain of SKE in the lower two-thirds of the canopy.

\textit{4. Summary and conclusion}

The influence of atmospheric stability on the budgets of Reynolds stress and turbulent kinetic energy has been investigated for the first time inside a forest canopy. In both of these budgets, thermal effects are largest in the upper third of the canopy where the foliage is densest and the radiation load highest. The onset of stability exerts a strong influence on the behavior of the shear production term in both the budgets of Reynolds stress and TKE. The strength of this term appears to increase linearly with increasing stability in the upper portion of the canopy. Our results indicate that, however, the shear production term acts, in strong thermal stratification, as a sink of Reynolds stress and TKE in the lower half of the canopy. The wake production term, a major contributor of TKE, increases rapidly with increasing stability (for \( h/L > 0 \)). The buoyant production term in both budgets is, as expected, a strong function of stability and provides a significant sink of Reynolds stress in very stable conditions. When the TKE is separated into two frequency bands, the shear kinetic energy and the wake kinetic energy, the canopy drag, the turbulent transport, the buoyant production, and the residual terms all remove shear kinetic energy in stable conditions.

Since neutral conditions are seldom observed outdoors, the inclusion of the buoyant production term in the budgets of Reynolds stress and turbulent kinetic energy is significant. Even more important is the inclusion of the pronounced effect of thermal stability on these budgets. The exclusion of thermal effects may easily create unrealistic interpretations of the physical processes involved in the creation of turbulence.

\textit{Acknowledgments}. The experiment was conducted by Atmospheric Environment Service (G. den Hartog and H. H. Neumann had overall responsibility for the experiment) in conjunction with the University of California at Davis (R. H. Shaw) and the University of Guelph (G. W. Thurtell, G. E. Kidd, M. Y. Leclerc, and G. Shi). The experiment was funded by Atmospheric Environment Service and the data reduction and analysis were funded by a Faculty Research Grant of Utah State University.

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