The budget of turbulent kinetic energy within and above a sparse Lodgepole Pine stand

Andreas Christen¹
Michael D. Novak²
Andy T. Black²
Mathew Brown²

¹ University of British Columbia, Department of Geography / Atmospheric Science Program, Vancouver, BC, Canada.
² University of British Columbia, Faculty of Land and Food Systems, Biometeorology, Vancouver, BC, Canada.
Motivation

- How do changes in stand density and structure control turbulence and turbulent exchange?
- Essential for modelling canopy microclimates. Here: in the context of forest management strategies to combat the Mountain Pine Beetle outbreak in British Columbia.
- Method: Studying the physical processes that create, remove and relocate turbulent kinetic energy (TKE) in stands of different structure.
- Interestingly, most full-scale studies of the TKE budget focussed on dense canopies. Less information is available for sparse canopies.
The budget of turbulent kinetic energy (TKE)

- Shear Production
- Wake Production
- Buoyancy Production
- Dissipation
- Turbulent Transport
- Pressure Transport
- Advection
Previous studies

- Meyers and Baldocchi (1991) conclude for a dense forest (LAI ~ 5) that ‘below $z/h = 0.75$, the magnitudes of the various components [of the TKE budget] are small compared to their values near the top of the canopy’.

- Lesnik (1974) highlighted the role of turbulent transport of TKE as a significant sink at canopy top and a source in the canopy itself.

- Dwyer et al. (1997) concluded in their LES study of a sparse canopy that pressure transport is important: It is a source well above the forest, a sink at canopy top and an important source in the trunk space.
‘Kennedy Siding’, 60 km South of MacKenzie, interior British Columbia, Canada.

- 83 year old canopy with $h = 16$ m, 1551 stems ha$^{-1}$ and open trunk space.

- Low canopy cover of only 24.3% and cumulative LAI of 1.38.

- Flat terrain, with fetch of at least 1 km in all directions.
Experiment

- Vertical profile of eight simultaneously operated ultrasonic anemometers-thermometers (Campbell Scientific CSAT-3) and fine-wire thermocouples.

- Four weeks of measurements between Aug 22 and Sep 17, 2007.

- 30-min block averages based on 10 Hz measurements with 1 global rotation.
Vertical wind profile

Selected stabilities (tower top)
- Convective (-10 < z/L (top) < -1)
- Unstable (-1 < z/L (top) < -0.05)
- Neutral (-0.05 < z/L (top) < +0.05)
- Stable (+0.05 < z/L (top) < +10)

All data
- 25%
- 75%
- No of 30min blocks
- Median
Comparison to other studies
Reynolds stress

Selected stabilities (tower top)
- Convective (-10 < z/L (top) < -1)
- Unstable (-1 < z/L (top) < -0.05)
- Neutral (-0.05 < z/L (top) < +0.05)
- Stable (+0.05 < z/L (top) < +10)

All data

25% 75% No of 30min blocks

Median
Comparison to other studies
Shear Production

\[ P_s = -\langle u'w' \rangle \frac{\partial \langle u \rangle}{\partial z} \]

Selected stabilities (tower top)
- Convective (-10 < z/L (top) < -1)
- Unstable (-1 < z/L (top) < -0.05)
- Neutral (-0.05 < z/L (top) < +0.05)
- Stable (+0.05 < z/L (top) < +10)

All data

No of 30min blocks
- 25%
- 75%
- Median
Wake Production

\[ P_w = -\langle \bar{u} \rangle \frac{\partial \langle u'w' \rangle}{\partial z} \]

Raupach et al. (1986), BLM., 35, 21-55.

Selected stabilities (tower top)

- Convective (-10 < z/L (top) < -1)
- Unstable (-1 < z/L (top) < -0.05)
- Neutral (-0.05 < z/L (top) < +0.05)
- Stable (+0.05 < z/L (top) < +10)

All data

25% 75% No of 30min blocks

\( P_w \frac{k \cdot h}{u_{* \text{top}}} \)
Sensible heat flux

Selected stabilities (tower top)
- Convective (-10 < z/L (top) < -1)
- Unstable (-1 < z/L (top) < -0.05)
- Neutral (-0.05 < z/L (top) < +0.05)
- Stable (+0.05 < z/L (top) < +10)

All data
- 25%
- 75%

No of 30min blocks
Median

Buoyancy Production
TKE production for convective cases

Convective cases with $z/L$ at tower top $< -0.1$
Dissipation of TKE

Based on ‘regular’ intertial subrange spectra (Kolmogorov).

No MKT (Finnigan, 2000)
Vertical turbulent transport of TKE
Divergence of turbulent transport ($T_t$)

$$T_t = -\frac{\partial \langle u'_i u'_i w' \rangle}{\partial z}/2$$

- **Net export of TKE**
- **Net import of TKE**

**Selected stabilities (tower top)**
- Unstable ($-1 < z/L$ (top) < -0.05)
- Neutral ($-0.05 < z/L$ (top) < +0.05)
- Stable ($+0.05 < z/L$ (top) < +10)
Comparison to other studies.
Neutral TKE budget

- **Shear Production**
- **Wake Production**
- **Dissipation**
- **Turbulent transport**
- **Residual**

**Remove TKE**

- **Create TKE**

**z/h**

**k h / u_*$^3$**
Unstable TKE budget

- Shear Production
- Wake Production
- Buoyancy Production
- Dissipation
- Turbulent transport
- Residual

Remove TKE

Create TKE

$z / h$

$k h / u^3_*$
Key findings

- **Shear production** dominates production with peak at canopy top $z/h = 0.96$ (inflection point). **Wake production** is most important at $z/h = 0.75$.

- On average, magnitude of **buoyancy production** (or suppression) is typically less than 15% of shear and wake production together.

- Excess turbulence from canopy top and above ($z/h > 0.9$) is exported down to the canopy and trunk space ($z/h < 0.9$) by **turbulent transport** of TKE.

- Residual term indicates that **pressure transport** relocates excess TKE from upper canopy and canopy top to higher layers of the atmosphere.
Discussion

TKE budget does not differ significantly from dense canopies, however some points are notable:

- Shear and wake production are important in the whole upper canopy (i.e. above $z/h < 0.5$), not just at canopy top.
- Normalized peak shear production is $\sim 4$, which is lower compared to other forests (6 in Leclerc et al., 1990; 20 in Meyers and Baldocchi, 1991).
- Turbulent transport is dominating source in the lower trunk space.
- The residual term indicates that likely pressure transport is removing TKE from upper canopy to higher layers - this observation is supported by LES results (Dwyer et al., 1997).
We thank Jonathan Bau, Rick Kettler, Zoran Nesic, and Andrew Sauter for their excellent support in the lab and/or the field.

This research activity has been made possible by: NSERC Discovery Grants (Christen, Novak, Black) and NSERC RTI (Christen). The long-term infrastructure tower was funded by CFCAS (Black) and BC Forest Science Program Grants.