A Simple Model for the Afternoon and Early-Evening Decay of Turbulence Over Different Land Surfaces

Daniel Nadeau
ER Pardyjak, CW Higgins, HJS Fernando, MB Parlange
Objectives

- Understand the physics of decay period better
  - phenomenologically
  - quantitatively

- Understand heterogeneous terrain decay
  - roughness
  - moisture
  - albedo

- Develop a simple turbulent kinetic energy decay model

- Develop heterogeneous sensible heat flux forcing model for Large-Eddy Simulation
Turbulence Decay - Background

- Literature including laboratory work, field experiments and LES
- Most of the literature covers a limited forcing time scale range
Horizontal velocities at $z/h = 0.5$

Pino et al. (BLM, 2006)
Sensible heat flux in the atmosphere
Turbulence Decay - Background

- Literature including limited laboratory, field experiments, and Large Eddy Simulation
- Most of the literature covers a limited forcing time scale range
- Important scaling from:
  - Nieuwstadt & Brost (JAS, 1986)
  - Sorbjan (BLM, 1997)
CBL Decay Phenomena

\[ w_* = (\beta g H h)^{1/3} \]

\[ t_* = h/w_* \]

Forcing time scale \( \sim t_f \)
Some Important Decay Hypotheses

1. **Surface Heat Flux “Instantly Set to Zero”**
   The volume integrated turbulence quantities are only a function of the initial CBL state and $t/t^*$ (Nieuwstadt & Brost, JAS, 1986)

2. **Gradually Decaying Surface Heat Flux**
   Turbulent decay is dependent on 2 time scales $t^*$ and $\tau_f$ (Sorbjan, BLM, 1997)

3. **Limiting Cases** (Sorbjan, BLM, 1997)
   
   \[
   \frac{\tau_f}{t^*} \rightarrow 0 \quad \text{Instantaneous removal of H}
   \]
   
   \[
   \frac{\tau_f}{t^*} \rightarrow \infty \quad \text{Constant H} 
   \]
TKE Model Development

- Nieuwstadt & Brost (JAS, 1986) – Instantaneous removal of surface flux

\[
\frac{\partial \overline{k}}{\partial t} = -\varepsilon, \quad \varepsilon = C_{\varepsilon} \frac{k^{3/2}}{h}
\]

\[
\frac{k}{w_*^2} = \left( \frac{C_{\varepsilon} tw_*}{2} + \frac{1}{C} \right)^{-2}
\]

- Modified model to account for time varying buoyancy flux

\[
\frac{\partial \overline{k}}{\partial t} = \frac{g}{\theta_v} (w'\theta_v') - \varepsilon.
\]

Approach: Simple empirical to model approach that uses relatively easy to obtain meteorological data.
LITFASS – 2003

- Strong heterogeneities over flat terrain
- 20 x 20 km area
- Energy balance weather stations over different surface types
- Regular radiosonde launches

Beyrich and Mengelkamp (BLM, 2006)
Surface types

Surface roughness \( z_0 \)

- Range of roughness
- Range of Bowen ratios (0.75 - 8)
Solar radiation
Sensible Heat Flux

- LITFASS-2003
Collapse of Turbulence
Modeling the Heat Flux

\[ H_{\text{cos}}(t) = H_{\text{max}} \cos \left( \frac{\pi t}{2 \tau_{\text{cos}}} \right) \]

\[ H_{\text{erfc}}(t) = \left( \frac{H_{\text{max}} - H_{\text{min}}}{2} \right) \left[ \text{erfc} \left( \frac{t}{\tau_{\text{erfc}} \sqrt{2}} - \frac{3}{\sqrt{2}} \right) \right] + H_{\text{min}} \]

Incoming Solar Radiation

Sensible Heat Flux

\[ \tau_{f,\text{solar}} \]

\[ \tau_{f,\text{solar}} \text{ decay period} \]

\[ \text{start of the afternoon transition} \]

\[ \text{start of the early-evening transition} \]
Sensible Heat Flux Model Performance

Barley

Maize

Triticale

Forest

Early-evening transition

sunset
Testing the Model
Field Experiments – Suburban Salt Lake City, USA
Field Experiments – Desert Salt Flats, USA

- Very large sensible heat flux
- Very large mid-day BL depth (3 - 4.5 km)
- Very smooth
Application of the TKE Decay Model

Suburban – Salt Lake City, USA

Desert – Salt Flats, USA
Expanded Decay Picture

\[ \frac{\tau_f}{t_*} = 4.35 \]

\[ \frac{\tau_f}{t_*} = \infty \]

Sorbjan (1997)

\[ \frac{\tau_f}{t_*} = 0 \]

Salt Flats
21 July 2002

\[ \frac{\tau_{f,solar}}{t_*} = 43.3 \]
LES – Decay over Heterogeneous Terrain

- Setup SH5 from Pino et al. (BLM, 2006)
- 128 x 128 x 128
- Patches with $l/L \sim 0.72$
- Lagrangian scale-dependent dynamic model for subgrid scales (Bou-Zeid et al., PF, 2005)
Expanded Decay Picture - with LES

Sorbian (1997)
\[ \frac{\tau_f}{t_*} = 4.35 \]

\[ \frac{\tau_f}{t_*} = \infty \]

Sorbian (1997)
\[ \frac{\tau_f}{t_*} = 0 \]

LES

Salt Flats
21 July 2002
\[ \frac{\tau_{f,solar}}{t_*} = 43.3 \]
• Tremendous variability in the forcing sensible heat flux – even over relatively flat terrain
• Need to consider realistic forcing time scales
• The \textit{erfc} function does a good job of modeling the surface sensible heat flux
• Two apparent decay regimes – LES confirms
  – afternoon transition: from max heat flux to zero (slow decay)
  – early evening transition: just after the sensible heat flux changes sign (rapid decay and collapse of turbulence)
• BLAST experiment will investigate these issues in 2011
The End – Any Questions?