(Relatively) Simple Models of Flow in Complex Terrain

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Topography and Roughness variations

The term, "complex terrain" includes both topography and variations in surface roughness and thermal properties. The scales that are affected can differ and there are some advantages to modeling them separately.

We often find that one type of complexity is the most significant at many sites.
Internal Boundary Layers

$U_g$

Wind

Land

Water

Internal Boundary Layer

Unmodified flow

$\delta$

$x$
A 2-D numerical model of boundary-layer flow over single and multiple surface condition changes

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Wall layer

ABSTRACT
Based on the 1-D planetary boundary layer model of Weng and Taylor with E–ε turbulence closure, a 2-D numerical model is developed to study the atmospheric boundary-layer flow over single or multiple changes in surface conditions. These changes can include surface roughness, thermal and moisture properties. A constant flux wall layer is used within which approximate forms for the velocity, temperature, moisture and turbulent kinetic energy profiles are obtained by analytic solution with the assumption of production equal to dissipation of turbulent kinetic energy. We also use a simple, analytic model dealing with the surface roughness change effects in neutral stratification based on the concept of an internal boundary layer. Model results for roughness changes are discussed and compared with other models and published field data.

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Long fetches, heights around 100m.
PBL model, neutral or stratified

With Boundary-layer approximations, and in 2D, we solve the RANS and Continuity equations,

\[
\begin{align*}
U \frac{\partial U}{\partial x} + W \frac{\partial U}{\partial z} &= f (V - V_g) - \frac{\partial \langle uw \rangle}{\partial z} \\
U \frac{\partial V}{\partial x} + W \frac{\partial V}{\partial z} &= f (U_g - U) - \frac{\partial \langle vw \rangle}{\partial z} \\
U \frac{\partial \Theta}{\partial x} + W \frac{\partial \Theta}{\partial z} &= - \frac{\partial \langle w \Theta \rangle}{\partial z} \\
\frac{\partial U}{\partial x} + \frac{\partial W}{\partial z} &= 0
\end{align*}
\]

...together with closure hypotheses for Reynolds stresses and fluxes. Details in Weng et al. JWEIA
RANS Closure hypotheses, TKE and length scale equations

\[
\langle uw \rangle = - K_m \frac{\partial U}{\partial z}, \quad \langle vw \rangle = - K_m \frac{\partial V}{\partial z}, \quad \langle w \theta \rangle = - K_h \frac{\partial \theta}{\partial z},
\]

\[
K_m = \ell_m (\alpha E)^{1/2}, \quad K_h = \ell_m (\alpha E)^{1/2} / \text{Pr},
\]

\[
U \frac{\partial E}{\partial x} + W \frac{\partial E}{\partial z} = -\langle uw \rangle \frac{\partial U}{\partial z} - \langle vw \rangle \frac{\partial V}{\partial z} + \beta g \langle w \theta \rangle - \frac{(\alpha E)^{3/2}}{\ell_d} + \frac{\partial}{\partial z} \left( K_m \frac{\partial E}{\partial z} \right)
\]

\[
L = - \frac{\left( \langle uw \rangle^2 + \langle vw \rangle^2 \right)^{3/4}}{\kappa \beta g \langle w \theta \rangle}
\]

Stable Stratification

\[
\frac{1}{\ell_m} = \frac{1}{\kappa (z + z_{0m})} + \frac{1}{\ell_b} + \frac{\beta_m}{\kappa L},
\]

Neutral or Unstable Stratification

\[
\frac{1}{\ell_m} = \frac{1}{\ell_d} = \frac{\phi_m}{\kappa (z + z_{0m})} + \frac{1}{\ell_b}
\]

\[
\ell_b = 40m - 100m \quad \zeta = z/L
\]
Canadian Wind Atlas, 80-m height average winds
A typical Southern Ontario onshore flow situation. Neutral stratification. Significant reductions at 80m start about 1 km inland.
Offshore flow: maybe from Toronto over Lake Ontario? Neutral stratification.
Note increase at 80m requires fetch > 1 km and equilibrium takes 100 km
Scarborough Bluffs, Toronto

The Toronto Hydro platform, installed in Lake Ontario, May 2010 with ZephIR lidar.
A 3-D model

\[
U \frac{\partial U}{\partial x} + V \frac{\partial U}{\partial y} + W \frac{\partial U}{\partial z} = f(V - V_g) + \frac{\partial}{\partial y} \left( K_{my} \frac{\partial U}{\partial y} \right) + \frac{\partial}{\partial z} \left( K_{mz} \frac{\partial U}{\partial z} \right)
\]

\[
U \frac{\partial V}{\partial x} + V \frac{\partial V}{\partial y} + W \frac{\partial V}{\partial z} = f(U_g - U) + \frac{\partial}{\partial y} \left( K_{my} \frac{\partial V}{\partial y} \right) + \frac{\partial}{\partial z} \left( K_{mz} \frac{\partial V}{\partial z} \right)
\]

\[
U \frac{\partial \Theta}{\partial x} + V \frac{\partial \Theta}{\partial y} + W \frac{\partial \Theta}{\partial z} = \frac{\partial}{\partial y} \left( K_{hy} \frac{\partial \Theta}{\partial y} \right) + \frac{\partial}{\partial z} \left( K_{hz} \frac{\partial \Theta}{\partial z} \right)
\]

\[
\frac{\partial U}{\partial x} + \frac{\partial V}{\partial y} + \frac{\partial W}{\partial z} = 0
\]

\[
U \frac{\partial E}{\partial x} + V \frac{\partial E}{\partial y} + W \frac{\partial E}{\partial z} = -\langle uv \rangle \frac{\partial U}{\partial y} - \langle uw \rangle \frac{\partial U}{\partial z} - \langle vv \rangle \frac{\partial V}{\partial y} - \langle vw \rangle \frac{\partial V}{\partial z} - \langle vw \rangle \frac{\partial W}{\partial y} - \langle ww \rangle \frac{\partial W}{\partial z}
\]

\[
+ \beta g \langle w \Theta \rangle - \varepsilon + \frac{\partial}{\partial y} \left( K_{my} \frac{\partial E}{\partial y} \right) + \frac{\partial}{\partial z} \left( K_{mz} \frac{\partial E}{\partial z} \right)
\]

\[
\langle uv \rangle = -K_{my} \frac{\partial U}{\partial y}, \quad \langle uw \rangle = -K_{mz} \frac{\partial U}{\partial z}, \quad \langle vv \rangle = \frac{2}{3} E - 2K_{my} \frac{\partial V}{\partial y}, \quad \langle vw \rangle = -K_{mz} \frac{\partial V}{\partial y}, \quad \langle vv \rangle = -K_{mz} \frac{\partial W}{\partial y},
\]

\[
\langle ww \rangle = \frac{2}{3} E - K_{my} \frac{\partial U}{\partial y}, \quad \langle w \Theta \rangle = -K_{hz} \frac{\partial \Theta}{\partial z}, \quad \varepsilon = \frac{(\alpha E)^{2.3}}{\ell_d}
\]

K's and turbulence length are formulated as in 2-D.
$\log_{10} z_0$ for Cleveland area, lake $z_0=2 \times 10^{-4} \text{m}$, upstream $z_0 = 0.05 \text{m}$ contours are for $\log_{10} z_0 = -3, -2, -1, 0$. 
3-D model results, 80m wind speed for S flow near Cleveland CRIB site, Geostrophic wind speed 15 ms$^{-1}$.

Upstream wind speed at 80 m with $z_0 = 0.05$m is approx 10 m/s. Flow slows over the city then slowly accelerates over the lake. Far downwind, the 80m equilibrium speed is close to 13 ms$^{-1}$ while it is only 9.5 ms$^{-1}$ at the CRIB site for these South winds. Results for 210 degrees would be similar.
Flow over hills and other topography: Askervein, 1982/83
The linear Mixed Spectral Finite-Difference (MSFD) and non-linear (NLMSFD) models for surface boundary-layer flow over complex terrain have been extended to planetary boundary-layer flow over topography. This allows for their use for larger scale regions and increased heights. The models have been applied to successfully simulate the Askervein hill experimental case and applied to more complex terrain, typical of some Canadian wind farms.

2.1 The model equations

For the PBL boundary-layer flow, the model uses the Reynolds-averaged equations for steady-state, neutrally stratified incompressible flow. They are, in tensor notation including use of the summation convention,

\[
U_j \frac{\partial U_i}{\partial x_j} = -\frac{1}{\rho} \frac{\partial p}{\partial x_i} + f \epsilon_{ij3} \left( U_j - U_{gj} \right) - \frac{\partial \langle u_i u_j \rangle}{\partial x_j}, \tag{1}
\]

\[
\frac{\partial U_i}{\partial x_i} = 0, \tag{2}
\]

where \( U_i \) and \( u_i \) are the \( i \)-th component of the mean and turbulent flow respectively; \( f \) is the Coriolis parameter; \( \epsilon_{ij3} \) is the alternating unit tensor; and angle bracket \( \langle \rangle \) denotes an ensemble mean. The pressure gradient force consists of a nonhydrostatic mesoscale pressure component, \( P \), and a synoptic-scale component, \( f \epsilon_{ij3} U_{gj} \), where \( U_{gj} \) is the \( j \)-th component of the geostrophic wind.
Report: MSRB-83-8

ASKERVEIN '82: Report on the September/October 1982 Experiment to Study Boundary-Layer Flow over Askervein, South Uist

by P.A. Taylor and H.W. Teunissen

Research Report: MSRB-84-6


by P.A. Taylor and H.W. Teunissen

BASIC Askervein 1982, 1983 reports at:
http://www.yorku.ca/pat/research/Askervein/index.html
NLMSFD-PBL and Askervein revisited. Contour plot of wind speed at $z = 80$ m from NLMSFD-PBL calculation. Base calculation was for terrain differences scaled by a factor of 0.9. Linear solution is adjusted by the ratio $(1.0/0.9)$ and the non-linear component is scaled by $(1.0/0.9)^2$. The set up is $z_0=0.03$ m, $|U_g|=18.5$ m/s and wind direction is 210 degrees.
More complex terrain:

A typical BC or Quebec wind farm site.

Winds from W
MSFD-PBL

Fractional speed-up ratio, $\Delta S$

$\frac{(U-U_0)}{U_0}$

$Z = 100\text{m}$
Velocity profiles at 9 grid locations

Log plot

Contour Plot of Computational Domain - Inner Region

(Averaged edge value subtracted)

-10000
-5000
0
5000
10000

Easting (m)

-10000
-5000
0
5000
10000

Northing (m)

10
0
1
10
100

Height, z (m)

10
0
1
10
100

100
1000
10000

Wind speed (m s⁻¹)

0
4
8
12
16
20

U0
U (x=0, y=0)
U (x=-5000, y=0)
U (x=-5000, y=-5000)
U (x=0, y=-5000)
U (x=0, y=-5000)
U (x=-5000, y=-5000)
U (x=5000, y=-5000)
U (x=5000, y=0)
U (x=5000, y=5000)
U (x=0, y=5000)
U (x=-5000, y=5000)
Contour Plot of Central Portion of the Computational Domain

MSMicro-PBL test terrain and tower locations – central part of domain
Contour Plot of $\log_{10}(z_0)$ - Central Portion

MSMicro-PBL test; roughness and tower locations – central part of domain
Fractional speed up ratio caused by topography, $|\Delta S_T| = |U_T - U_0|/|U_0|$ at 80 m above the terrain (in the central part of the computational domain). Upstream surface winds are from 270 degrees. Geostrophic wind speed 15 ms$^{-1}$, roughness length, $z_0$=0.3 m, neutral stratification.
Fractional speed up ratio caused by roughness variations, $|\Delta S_R| = |U_T - U_0|/|U_0|$ at 80 m above the terrain. Upstream surface winds are from 270 degrees. Geostrophic wind speed 15 ms$^{-1}$. Upstream roughness length $z_0 = 0.153$ m, neutral stratification.
Left: Ratios of MS-Micro-PBL model predictions to mast measurements of ratios of averaged wind speeds at different measurement masts as they vary with mast location separation. Four cardinal wind direction sectors.

Right: Scatter plot of winds (> 5 ms$^{-1}$) in the W sector. A good case for one mast pair.
Left: Ratios of MS-Micro-PBL model predictions to mast measurements of ratios of averaged wind speeds at different measurement masts as they vary with mast location separation. Four cardinal wind direction sectors.

Right: Scatter plot of winds (> 5 ms\(^{-1}\)) in the W sector. A good case for one mast pair.
Observed and Predicted wind speed ratios at mast pairs versus mast location separation. Wind Speeds > 5 ms\(^{-1}\).
A scatter plot of simultaneous 10-min wind speeds at pairs of towers with ratio of ratios > 1.25.

A case with poor agreement.
Warm air blowing over cold water - Grand Banks fog

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AGU Fall Meeting 2016

The condensation of water vapour into droplets and the formation of fog in the Earth's atmospheric boundary layer involves a complex balance between horizontal advection and vertical turbulent mixing of heat and water vapour, cloud microphysical processes involving the numbers and size of available condensation nuclei and radiative transfers of heat, plus the impact of water droplets, and sometimes ice crystals, on visibility. It is a phenomenon which has been studied for many years in a variety of contexts. Over the waters offshore from Newfoundland a key factor is the advection of moist air from over warm gulf stream waters to colder Labrador current water - an internal boundary-layer problem. Some basic properties can be learned from a steady state 2-D (x-z) model.

Supported by NSERC Engage program and AMEC-Foster Wheeler
Upstream/initial conditions: a 1-D time dependent model.

Heat and Momentum

Water Vapour, $Q_v$

Liquid water droplets, $Q_l$, diffusion + settling, $V_T$.

Long wave and solar radiation absorption, emission

Surface cooling, $dT_s(t)/dt < 0$, so $q_s(T_s)$ also decreasing. Water surface is a water droplet sink, $Q_l = 0$, and potential source or sink of $Q_v$. Settling velocity (Nakanishi, 2000 proposes $V_T = 10^6(Q_l/N_0)^{2/3}$ ms$^{-1}$ - an empirical equation! with $N_0$ fixed at $10^8$m$^{-3}$). Typical values, $Q_l = 10^{-4}$, $V_T = 0.01$ms$^{-1}$.
1-D model has 201 grid points, uniform spacing after log-linear z to $\zeta$ transform. Top of model at 3 km.

Surface cooled at 2°K per hour for 6 hours, 100% RH at surface
Linear scale in $z$

Results with Long Wave radiation, More $Q_l$ due to radiative cooling.

- Total water content, $Q_w$ (g kg$^{-1}$)
- Liquid water content, $Q_l$ (g kg$^{-1}$)
- Relative humidity, $Q_v/Q_s$

Time (hr):
- 0
- 1
- 2
- 3
- 4
- 5
- 6
No LW radiation in model, less fog, later start.
a) **Project Title:** Ontario's Regional Climate: Surface Weather and Upper Level Winds

b) **Project Objective(s):** The primary objective of the proposed research is to secure a better understanding of the relationship between regional climates of upper level wind (primarily 500hPa and 250hPa) and surface weather. This will be based on past records, mostly upper level NCEP-NARR (US National Centres for Environmental Prediction – North American Regional Reanalysis) analyses and surface AHCCD (Adjusted and Homogenized Canadian Climate Data), and include correlations on multiple time scales, seasonal variability and trend. Beyond this initial objective we plan to apply the regional relationships obtained to climate model predictions (generated elsewhere and potentially available from, e.g., NCEP, IRI (International Research Institute for Climate and Society at Columbia University), ECMWF (European Centre for Medium Range Weather Forecasts), ECCC (Environment and Climate Change Canada) or the OMECC Climate Change Data Portal) on seasonal and long term bases.
Jet Streams, MCI and the Polar Vortex

Figure 1. Latitude-pressure cross-section of horizontal wind magnitude at 90°W, valid at 00 UTC on January 20th, 2014.
Figure 2. 250-hPa vector winds, valid at 00 UTC on January 20th, 2014.
The Graduate Program in Earth and Space Science (ESS) is a multidisciplinary research program associated with the Department of Earth and Space Science & Engineering (ESSE) and the Centre for Research in Earth and Space Science (CRESS). The graduate program provides postgraduate instruction and research experience for graduate students working towards either MSc or PhD degrees. Research is carried out under the supervision of ESS faculty members, who are drawn from a number of science departments within York University or Adjunct Faculty Members appointed to the Graduate Program.

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