Exploring wave-turbulence interaction through LES modeling

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- To study the turbulent regimes in the SBL through LES modeling
- To investigate the flow structure and the waves generated when a flow is forced to cross a small hill in the SBL

Observations of nocturnal intermittent turbulence revealed:

- Regime 1: windspeed < threshold; weak turbulence, weak wind. Turbulence generated by local shear instability. Eddies do not interact ground

- Regime 2: windspeed > threshold; strong wind above the threshold. Continuous turbulence. Eddies extent to ground

- Regime 3: windspeed < threshold; sporadic turbulence.

Category A: V oscillates around the threshold
Category B: V < threshold as a result of disturbances
Category C: top-down turbulent events into regime 1

To study the wave-turbulence interaction (intermittent turbulence) we will simulate a flow over a small hill -> under stably-stratified conditions gravity waves will be generated at the lee side of the hill
Large eddy simulation (LES) is a technique used to resolve explicitly the turbulence within a turbulent flow field while the small scale turbulent motions are modeled by a subfilter-scale stress model (SFS), also called sub-grid scale (SGS).
Simulation design

Model WRF-LES ideal v3.3.1

Two domains, 1 way nesting

<table>
<thead>
<tr>
<th></th>
<th>D1</th>
<th>D2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Grid points: 201x201 Δx = Δy = 60 m</td>
<td>Grid points: 201x201 Δx = Δy = 20 m</td>
</tr>
<tr>
<td></td>
<td>Dimension: 12.06 km</td>
<td>Dimension: 4.02 km</td>
</tr>
<tr>
<td></td>
<td>Grid points: 100 Δz = 10 m (20 first</td>
<td>Grid points: 100 Δz = 10 m (20 first</td>
</tr>
<tr>
<td>Vertical</td>
<td>levels)</td>
<td>levels)</td>
</tr>
<tr>
<td></td>
<td>Dimension: 2 km</td>
<td>Dimension: 2 km</td>
</tr>
</tbody>
</table>

12 km

D1

1 domain run

4h

Spin-up turbulence

Boundary conditions for D2

D2

1 way nesting

9h

10h

Last hour of simulation
1 second model outputs of variables (u, v, w, potential temperature, subgrid stress tensor)
Simulation design

Elliptical Gaussian hill in inner domain

\[ Z = A \exp \left( -a(x-x_0)^2 + 2b(x-x_0)(y-y_0) + c(y-y_0)^2 \right) \]

\[ A = 100 ; \ \theta = 0 ; \ \sigma_x = 1 ; \ \sigma_y = 3 ; \ x_0 = y_0 = 0 \]

\[ a = \frac{\cos^2 \theta}{2\sigma_x^2} + \frac{\sin^2 \theta}{2\sigma_y^2} \]
\[ b = \frac{\sin 2\theta}{4\sigma_x^2} + \frac{\sin 2\theta}{4\sigma_y^2} \]
\[ c = \frac{\sin^2 \theta \cos^2 \theta}{2\sigma_x^2} + \frac{\sin^2 \theta \cos^2 \theta}{2\sigma_y^2} \]

width (y) = 1 km
length (x) = 3 km
height (z) = 100 m

From Smith, 1989
Simulation design – options setup

- Diffusion vertical mixing: evaluates mixing terms in physical space stress form (x,y,z)(diff_opt = 2)

- TKE 1.5 order of closure SGS turbulence model (km_opt = 2)

- Nonlinear Backscatter and Anisotropy (NBA) sub-grid scale model (Kosovic, 1997) (sfs_opt = 2)

- Roughness length = 0.02

- Surface layer (sf_sfclay_physics = 1)

  MM5 similarity: Based on Monin-Obukhov with Carslon-Boland viscous sub-layer and standard similarity functions from look-up tables

- No parameterizations for:
  mp_physics = 0 (microphysics)
  ra_lw_physics = 0 (LW radiation)
  ra_sw_physics = 0 (SW radiation)
  sf_surface_physics = 0 (land-surface)
  bl_pbl_physics = 0 (pbl)
  cu_physics = 0 (convection)

- Tests with and without damping layer showed negligible influence of the reflections of gravity waves
Initial profiles

4 initial surface heat flux:
-0.014 K ms\(^{-1}\)
-0.010 K ms\(^{-1}\)
-0.005 K ms\(^{-1}\)
-0 K ms\(^{-1}\)

Stability

Wind speed

5 initial geostrophic wind

\(V_g = 22 \text{ m s}^{-1}\)
\(V_g = 16.5 \text{ m s}^{-1}\)
\(V_g = 11 \text{ m s}^{-1}\)
\(V_g = 8.25 \text{ m s}^{-1}\)
\(V_g = 5.5 \text{ m s}^{-1}\)

Pack of 20 simulations
Simulation design – initial conditions

<table>
<thead>
<tr>
<th>Initial conditions</th>
<th>Heat flux -0.014 K ms(^{-1})</th>
<th>Heat flux -0.01 K ms(^{-1})</th>
<th>Heat flux-0.005 K ms(^{-1})</th>
<th>Heat flux 0 K ms(^{-1})</th>
</tr>
</thead>
<tbody>
<tr>
<td>A (Vg = 22 ms(^{-1}))</td>
<td>✔️</td>
<td>✔️</td>
<td>✔️</td>
<td>✔️</td>
</tr>
<tr>
<td>B (Vg = 16.5 ms(^{-1}))</td>
<td>✔️</td>
<td>✔️</td>
<td>✔️</td>
<td>✔️</td>
</tr>
<tr>
<td>C (Vg = 11 ms(^{-1}))</td>
<td>✔️</td>
<td>✔️</td>
<td>✔️</td>
<td>✔️</td>
</tr>
<tr>
<td>Cbis (Vg = 8.25 ms(^{-1}))</td>
<td>✔️</td>
<td>✔️</td>
<td>✔️</td>
<td>✔️</td>
</tr>
<tr>
<td>D (Vg = 5.5 ms(^{-1}))</td>
<td>Runaway cooling</td>
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<td>✔️</td>
</tr>
</tbody>
</table>

Derbyshire formulation (1990)

\[
(\langle w'\theta' \rangle_0)_{max} = \frac{\theta_0 R_f g}{\sqrt{3}} |f|G^2
\]

Runaway cooling

Pack of 16 simulations
Results

- Horizontal flow panels at last time of simulation
- Cross section animations of flow fields
- Hovmoller diagrams

Spatial overview

- Statistics
- Wavelet analysis
- Turbulence relationships
- Upwind/downwind turbulence relationships

Temporal analysis in a fixed point
Results – horizontal fields

Horizontal plots at last time of simulation (10 hours)

- Southerly winds, flow is perpendicular to the hill
- The air flow rises (windward), crosses the crest and falls (leeward)

SimCbris heat flux -0.014 K m s⁻¹
Results – cross sections

Vertical wind

- simA 22 m s\(^{-1}\)
- simB 16.5 m s\(^{-1}\)
- simC 11 m s\(^{-1}\)
- simCbis 8.25 m s\(^{-1}\)

(animation)

(surface heat flux = -0.014)
Results – hovmoller diagrams

Vertical velocity at 20 m

- For a fixed z
- Time evolution
- Spatially

Decreasing wind speed

Increasing stability
Results – hovmoller diagrams

Stream wise velocity

Stream wise velocity at 20 m

Decreasing wind speed

Increasing stability
1 second time series of 
(x,y) = (100, 180)

Computation of statistics:
- Averages
- Variances
- Covariances

All fluxes averaged on time:
One data each second
5 minutes mean
1 hour averaging

\[ \mathbf{w} = \mathbf{w} + \mathbf{w}' \]
model mean turbulence (what we want)

0 2.5 5 7.5 10 minutes

\[ \mathbf{w} \]

5 minutes mean (overlapped every 2.5 min)
23 means in 1 hour

average

\[ \text{avg}(\mathbf{w}) = \bar{\mathbf{w}} \]

Variance / covariance

\[ \frac{\mathbf{w}^2}{\mathbf{w}'} = \bar{\mathbf{w}}'^2 \]

Results – results treatment

Udina, Sun, Soler, Kosovic
Wave-turbulence interaction
ICAM. Kranjska Gora, Slovenia, 3 - 7 June 2013
Results – statistics

Decreasing stability

$V$ wind

$\theta$

$-0.014 \text{ K m s}^{-1}$

$-0.01 \text{ K m s}^{-1}$

$-0.005 \text{ K m s}^{-1}$

neutral

$\text{simA}$

$\text{simB}$

$\text{simC}$

$\text{simCbis}$

Udina, Sun, Soler, Kosovic

Wave-turbulence interaction

ICAM. Kranjska Gora, Slovenia, 3 - 7 June 2013
Results – statistics

Decreasing stability

-0.014 K m s^{-1}  
-0.01 K m s^{-1}  
-0.005 K m s^{-1}  
neutral

\[ v'^2 \]

\[ w'^2 \]

Udina, Sun, Soler, Kosovic  
Wave-turbulence interaction  
ICAM. Kranjska Gora, Slovenia, 3 - 7 June 2013
Results – statistics

Decreasing stability

-0.014 K m s\(^{-1}\)
-0.01 K m s\(^{-1}\)
-0.005 K m s\(^{-1}\)
neutral

Total TKE

sgs TKE

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Results – statistics

Decreasing stability

-0.014 K m s\(^{-1}\)
-0.01 K m s\(^{-1}\)
-0.005 K m s\(^{-1}\)
neutral
Results – wavelet analysis

Wavelet analysis gives a time-frequency representation of a time series with both information (time and frequency) simultaneously.

It provides information on the evolution of different scales that take part in the events that pullulate in the SBL.

It is a useful technique to distinguish the low-frequency coherent structures, K-H waves, low-level jets, intermittent turbulence, etc.

In this study we apply wavelet analysis to the temporal series at the fixed point \((x,y) = (100,180)\) in a time-period representation of the variances per period unit.
Results – wavelet analysis

Wavelet analysis of potential temperature at 20 m

Decreasing wind speed

Increasing stability

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Results – wavelet analysis

Wavelet analysis of vertical wind component at 20 m

Decreasing wind speed

Increasing stability

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Wave-turbulence interaction

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Results – turbulence relationships

Relationships of turbulence $V$ vs $V_{TKE}$

$$V_{TKE} = [(1/2)(\sigma_u^2 + \sigma_v^2 + \sigma_w^2)]^{1/2} = \sqrt{TKE}$$

*Points and bin-averaged line*
10 m, 20 m, 30 m, 40 m

12 simulations in the SBL (4 wind regimes * 3 surface heat fluxes)
Results – turbulence relationships

Relationships of turbulence

\( V \ vs \sigma_v \)

*Points and bin-averaged line*

10 m, 20 m, 30 m, 40 m
Results – turbulence relationships

Relationships of turbulence

$V vs \sigma_w$

*Points and bin-averaged line*

10 m, 20 m, 30 m, 40 m

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Wave-turbulence interaction

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Results – turbulence relationships

Observations from CASES99

LES simulations

Sun et al. 2012 (JAS)
Results – Upwind and downwind turbulence relationships

Upwind: flow not affected by waves
Downwind: flow affected by waves
Conclusions I

- Large eddy simulations are performed to study the wave turbulence interaction and reproduce the turbulence regimes in the stably stratified boundary layer.

- Time-averaged profiles show coherent results (in accordance with literature)

- Flow reversal near the base of the hill, leeward of it, more frequently seen in simulations with weak wind and high stability

- Wavelet analysis applied to potential temperature data from model revealed that gravity waves are mainly present in simulations with high stability and weak wind

- Relationships between turbulence and wind speed from LES simulations show the general pattern of observations from CASES 99

- LES cannot reach weak wind speeds and/or high prescribed heat flux because turbulence is not solved

- Comparison between turbulence relationships upwind and downwind of the hill show higher turbulence intensity in the flow affected by gravity waves
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