On the importance of horizontal turbulent transport in high resolution mesoscale simulations over cities.

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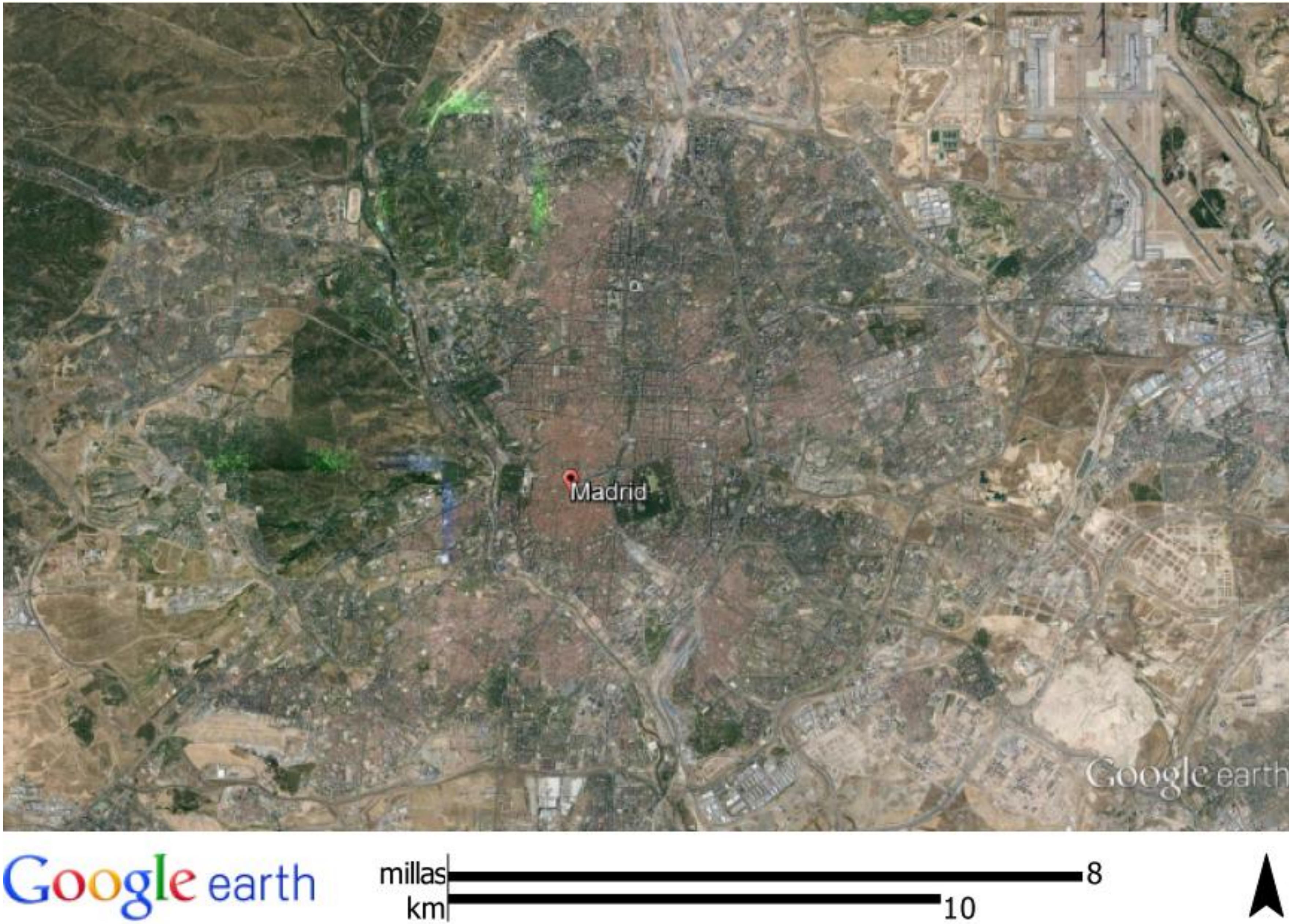
In an urban area, surface hetereogeneitis have a spatial scale of few kilometers



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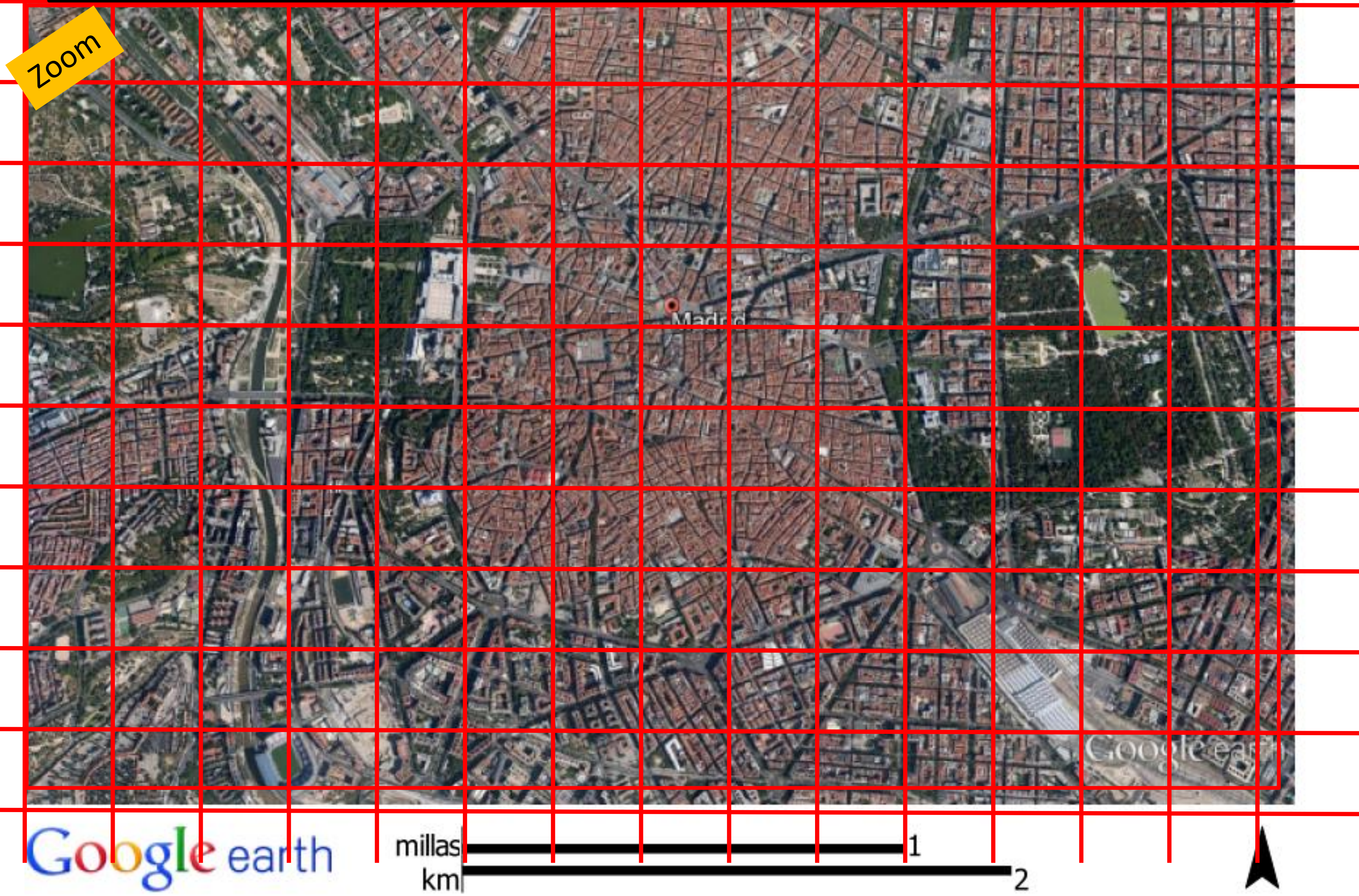
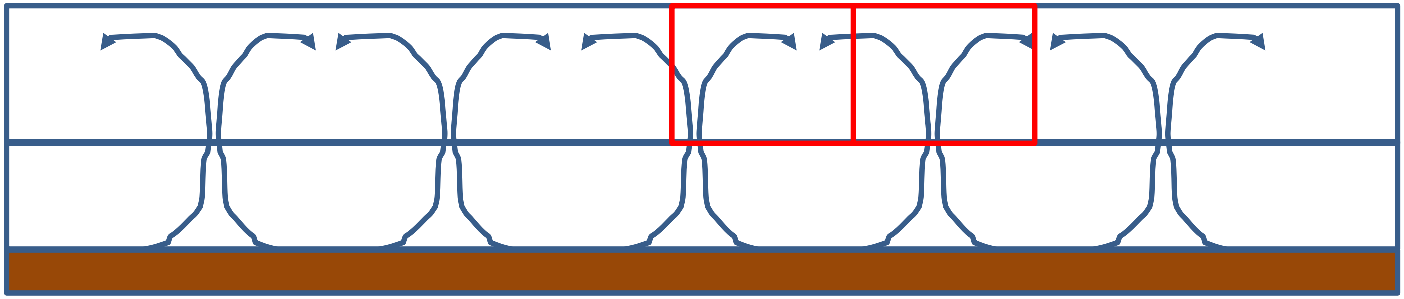
To resolve them we need a resolution of the order of several hundreds of meters



When resolution becomes of the same order of the integral scale of turbulence (or less), the conditions where volume and ensemble averages can be considered equal are not fulfilled anymore. A choice must be done.



We choose to consider the mean as an ensemble average.

However, we have shown in

Convectively Induced Secondary Circulations in Fine-Grid Mesoscale Numerical Weather Prediction Models

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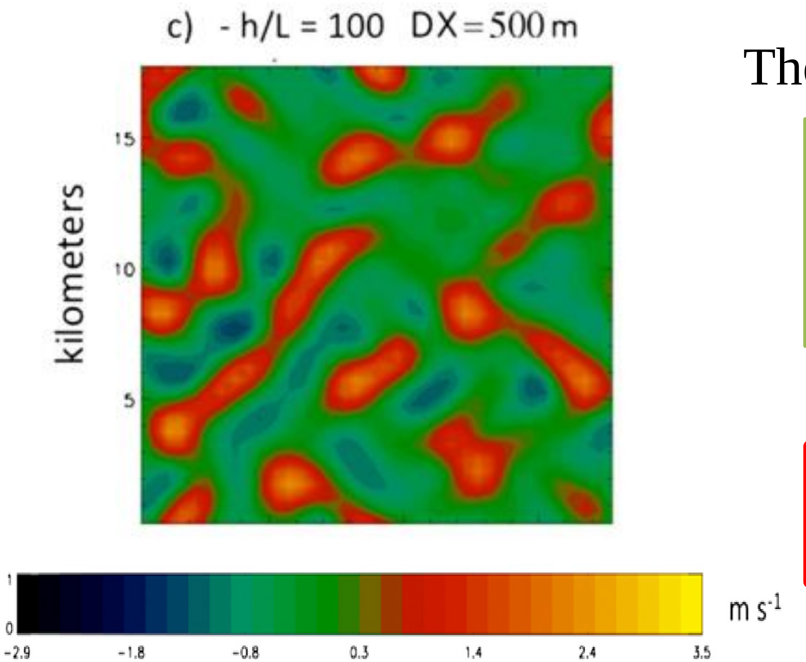
MONTHLY WEATHER REVIEW

that when the resolution is of the same order or less than the integral scale of turbulence spurious circulations form over flat and homogensous terrain (even if they should not).



The causes of this problem are:

The fact that the “standard” PBL schemes are not efficient enough to transport heat in the vertical to reduce the superadiabaticty

The lack of a proper parameterization of the horizontal turbulent fluxes.

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Traditionally, only the vertical component of the turbulent flux is usually parameterized

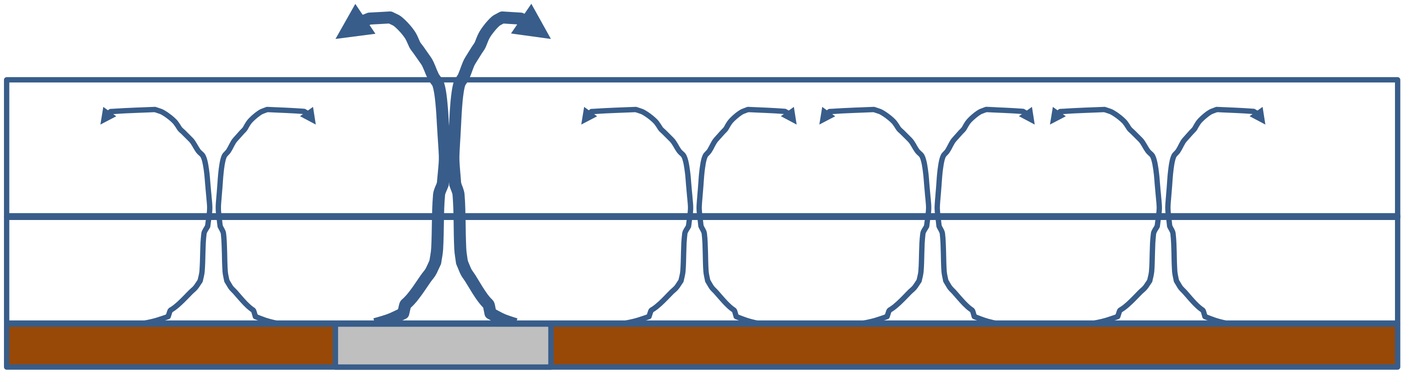
$$\overline{u'w'}, \overline{\theta' w'}$$

With PBL closures that are based on ***ensemble*** averages.

Little attention has been given to the horizontal components of the turbulent fluxes, which in general is :

- neglected,
    - modelled with an horizontal diffusion coefficient that can be:
        - Constant and "ad hoc"
        - Based on the deformation of the flow and the model grid size (similar to Smagorinsky, which is the approach used in LES – ***volume*** averaged models).

Is the divergence of the horizontal turbulent fluxes important over regions with high variability in surface fluxes? How can we parameterize them?



$$\frac{\partial \rho \overline{u'u'}}{\partial x}, \frac{\partial \rho \overline{u'v'}}{\partial y}, \frac{\partial \rho \overline{u'\theta'}}{\partial x}, \frac{\partial \rho \overline{v'\theta'}}{\partial y}$$

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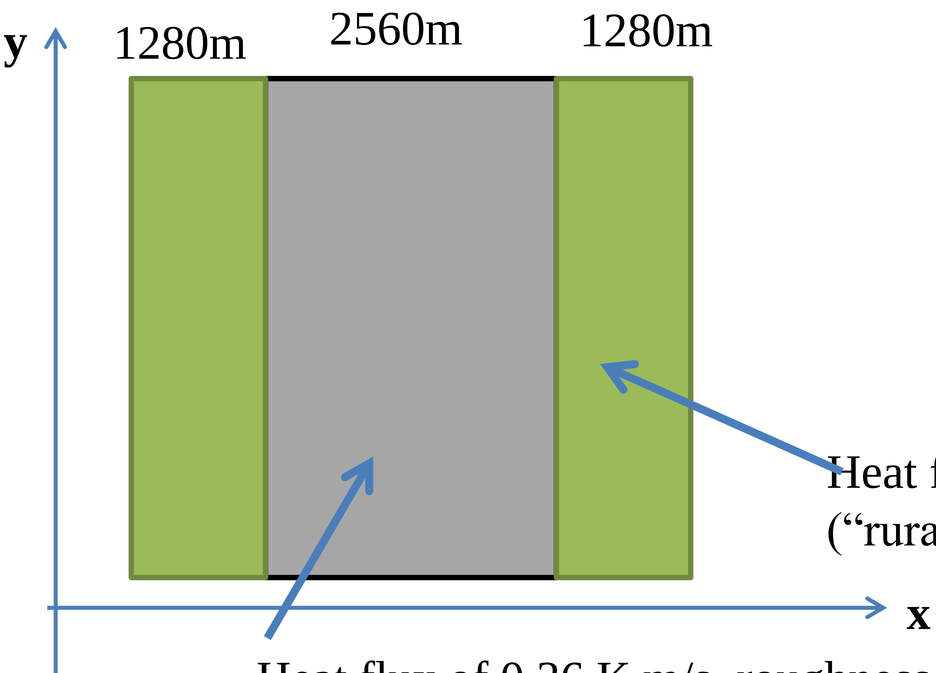
Tool to investigate this problem:

Large Eddy Simulations (Sullivan and Patton, 2011) applied to a case with strong horizontal hetereogeneity in surface fluxes.



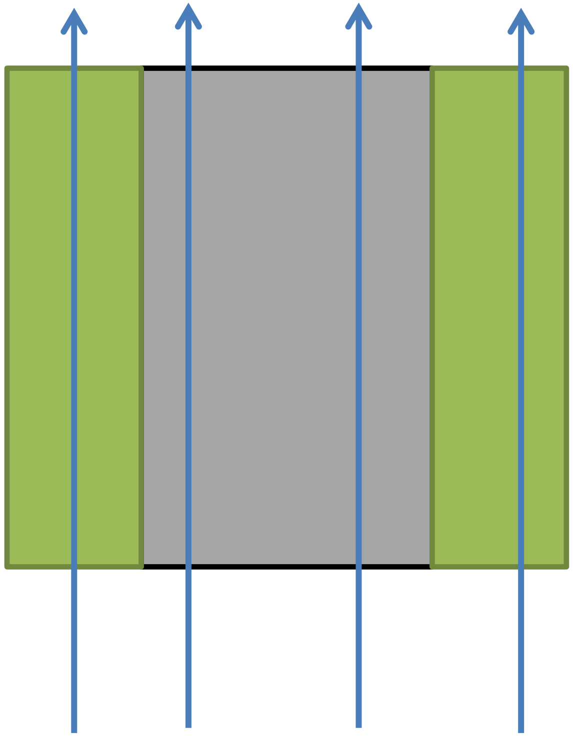
Horizontal resolution is 20m, and vertical resolution is 8m.

256 X 256 X 256 grid points.

Heat flux of 0.12 K m/s, roughness length of 0.1m ("rural")

Heat flux of 0.36 K m/s, roughness length of 1m ("city")

Technique to recover the **mean**



Due to the horizontal homogeneity in the ***y*** direction, averages over ***y*** and over time are performed to get the mean.

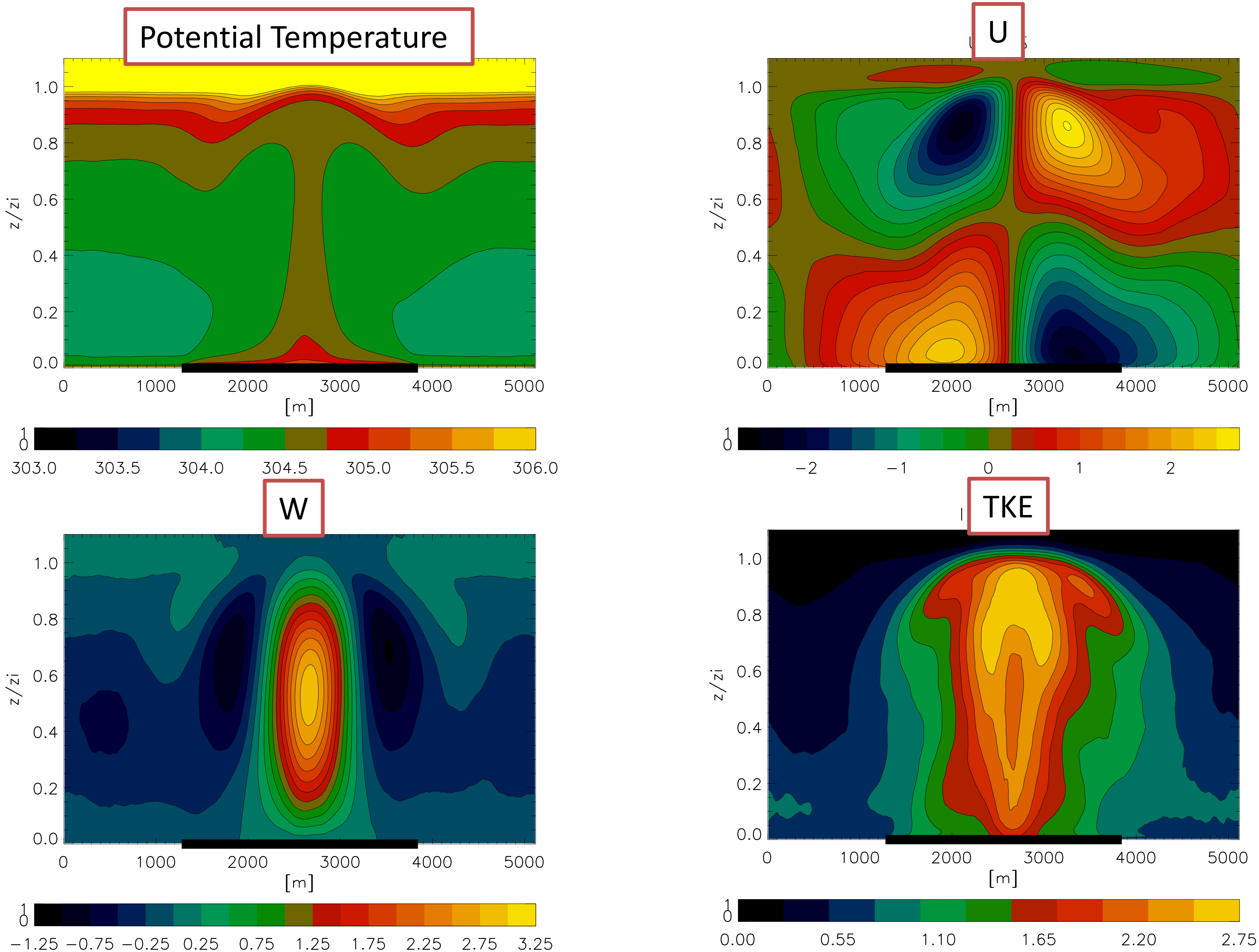
Istantaneous values are stored every 30 seconds, for a period of approximately 2.5 hours (300 outputs).

For each output, horizontal averages (***y*** direction) are performed and turbulent fluxes are calculated

$$\langle u(ix,iz,n)\rangle = \frac{1}{NY}\sum_{iy=1,NY} u(ix,iy,iz,n)$$

Results are averaged over the 300 outputs

$$\bar{u}(ix,iz) = \frac{1}{tend - tstart}\sum_{n=tstart,tend}\langle u\ (ix,iz,n)\rangle$$



Potential Temperature
U
W
TKE
z/zi
[m]
0 1000 2000 3000 4000 5000
0.0 0.2 0.4 0.6 0.8 1.0
303.0 303.5 304.0 304.5 305.0 305.5 306.0
−2 −1 0 1 2
−1.25 −0.75 −0.25 0.25 0.75 1.25 1.75 2.25 2.75 3.25
0.00 0.55 1.10 1.65 2.20 2.75

Horizontal section of the four terms of the flux divergence of **potential temperature** at three different heights

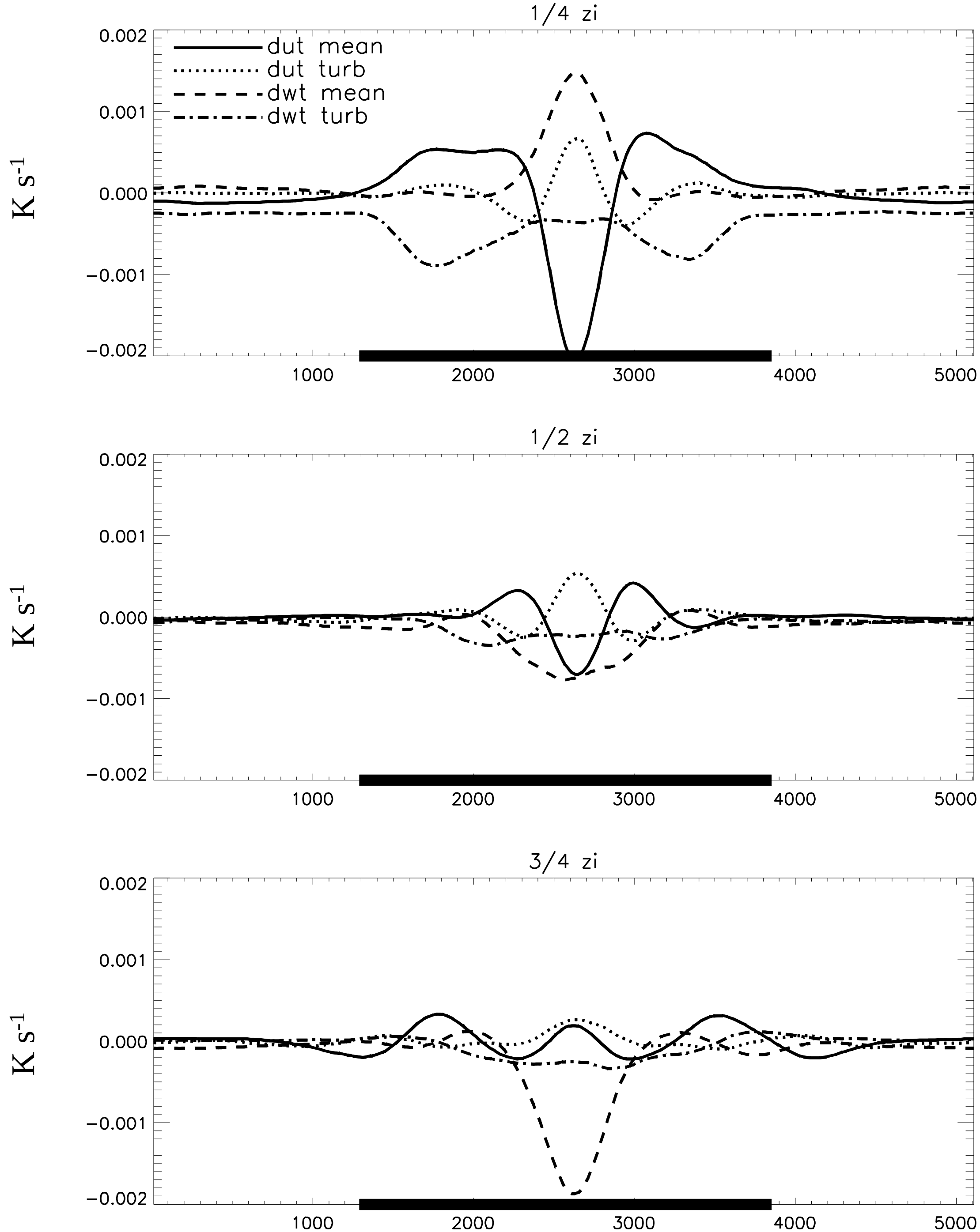
$$-\frac{\partial \rho \bar{\theta} \bar{u}}{\partial x}$$

$$-\frac{\partial \rho \overline{\theta' u'}}{\partial x}$$

$$-\frac{\partial \rho \bar{\theta} \bar{w}}{\partial z}$$

$$-\frac{\partial \rho \overline{\theta' w'}}{\partial z}$$

Smoothed over 260m.



The divergence of the horizontal turbulent transport is at least as significant as the one for the vertical.

Wyngaard (2004) proposed an approach to parameterize the horizontal turbulent fluxes that in 2D reads like (for temperature – a similar formulation can be derived for momentum):

$$\overline{u'\theta'} = -T\left(\overline{u'\theta'}\frac{\partial \overline{u}}{\partial x} + \overline{w'\theta'}\frac{\partial \overline{u}}{\partial z} + \overline{u'^2}\frac{\partial \overline{\theta}}{\partial x} + \overline{w'u'}\frac{\partial \overline{\theta}}{\partial z} \right)$$

$$\overline{w'\theta'} = -T\left(\overline{u'\theta'}\frac{\partial \overline{w}}{\partial x} + \overline{w'\theta'}\frac{\partial \overline{w}}{\partial z} + \overline{w'^2}\frac{\partial \overline{\theta}}{\partial z} + \overline{w'u'}\frac{\partial \overline{\theta}}{\partial x} \right)$$

T is a time scale of the order of $l / \sqrt{tke}$

And it arises from the assumption that the pressure correlation term can be modelled as

$$\overline{\theta'\frac{\partial p}{\partial x_i}} = \frac{\overline{u_i'\theta'}}{T}$$

Two relevant questions:

How good is the assumption on T?

$$\overline{\theta' \frac{\partial p}{\partial x_i}} = \frac{\overline{u_i'\theta'}}{T}$$

Future work

Can we find a way to parameterize T? Is it the same for all the variables?

Are all the terms important?

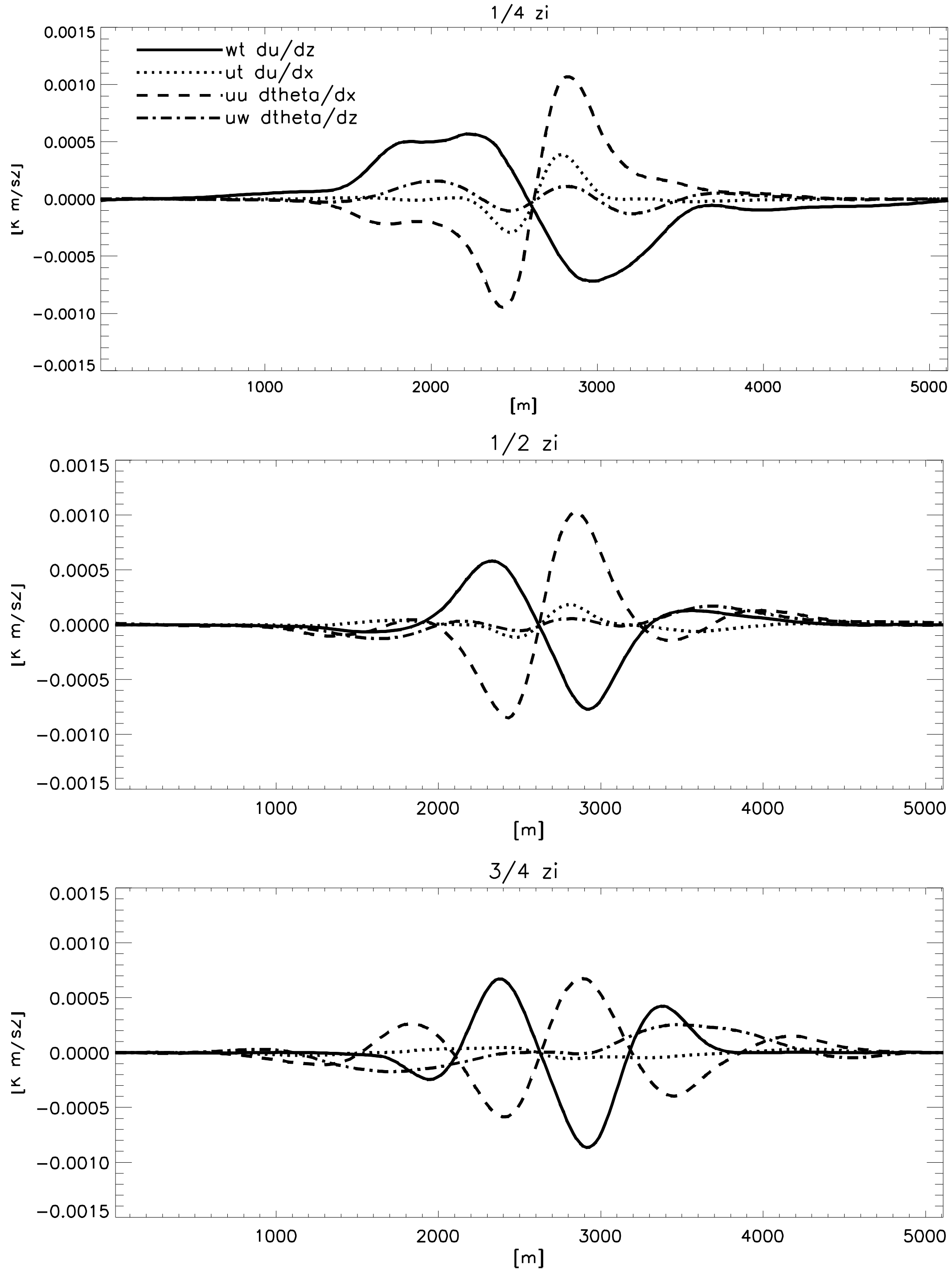
Horizontal section of the four terms for $\overline{u'\theta'}$

$$\boxed{\overline{w'\theta'}\frac{\partial \bar{u}}{\partial z}}$$

$$\overline{u'\theta'}\frac{\partial \bar{u}}{\partial x}$$

$$\boxed{\overline{u'^2}\frac{\partial \bar{\theta}}{\partial x}}$$

$$\overline{w'u'}\frac{\partial \bar{\theta}}{\partial z}$$



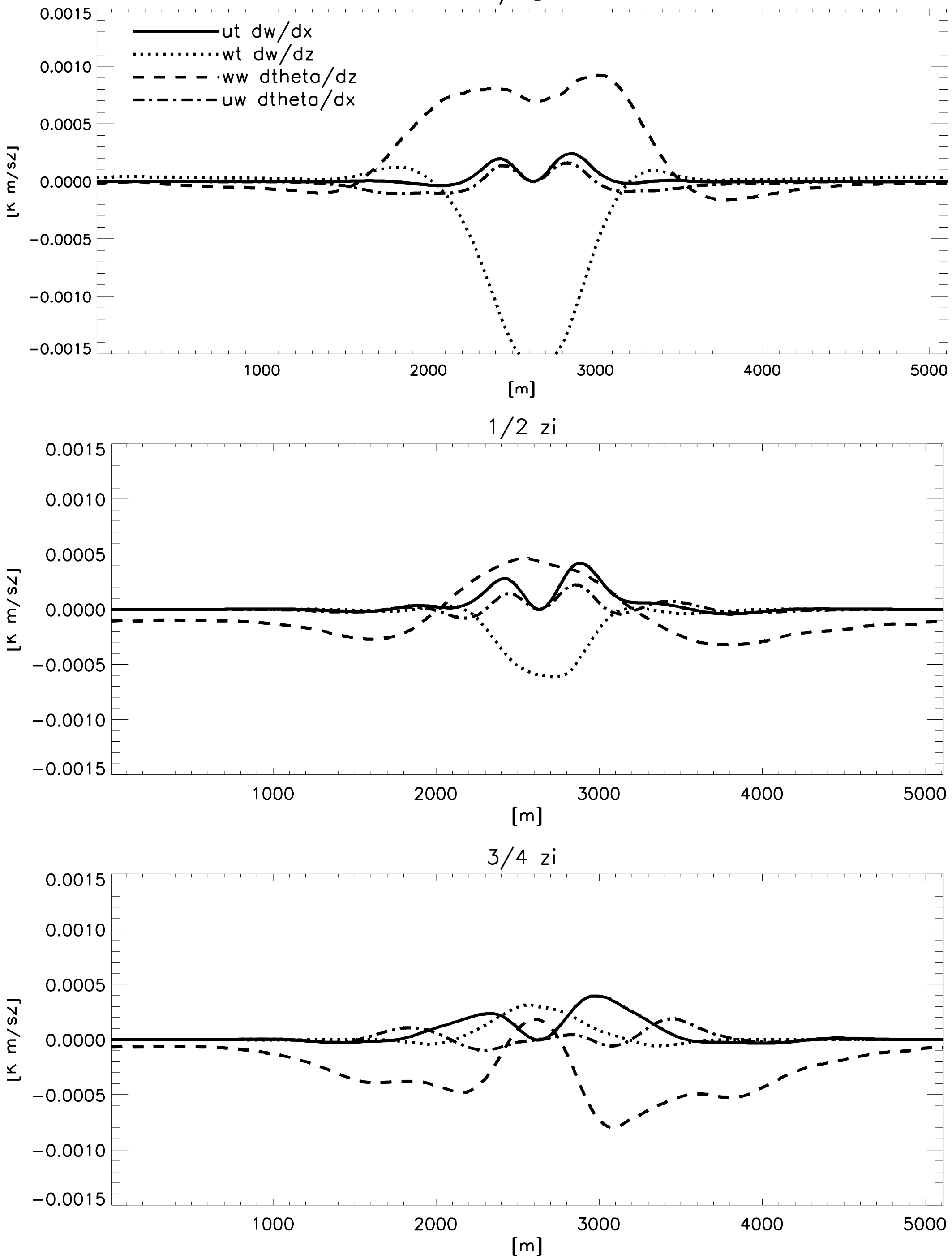
Horizontal section of the four terms for $\overline{w'\theta'}$

$$\overline{u'\theta'}\frac{\partial \overline{w}}{\partial x}$$

$$\boxed{\overline{w'\theta'}\frac{\partial \overline{w}}{\partial z}}$$

$$\boxed{\overline{w'^2}\frac{\partial \overline{\theta}}{\partial z}}$$

$$\overline{w'u'}\frac{\partial \overline{\theta}}{\partial x}$$



Guidance, possible simple approach for a parameterization:

$$\overline{u'\theta'} = -T\left(\overline{w'\theta'}\frac{\partial \overline{u}}{\partial z} + \boxed{\overline{u'^2}\frac{\partial \overline{\theta}}{\partial x}}\right)$$

$$\overline{w'\theta'} = -T\left(\boxed{\overline{w'^2}\frac{\partial \overline{\theta}}{\partial z}}\right)$$

Downgradient term

Different coefficients for the horizontal and the vertical

Similar approach can be developped for momentum

Conclusions

LES simulations over surfaces with hetereogeneous fluxes can give guidance for the development of a physically based parameterization of the horizontal turbulent fluxes.

These results suggest that a first attempt can be to represent the heat horizontal fluxes by mean of a downgradeint term (but with a coefficient different than the one used for the vertical), and a term function of the vertical heat flux and gradient of wind.

This new develpment is expected to:

- Improve the repsentation of surface flux hetereogenities in mesoscale models
- Improve the results of mesoscale models at subkilometer resolution, (Ching et al. MWR, 2014).

Thank you

The presence of hetereogenities in the surface fluxes has two important consequences:

Horizontal homogeneity is broken

Needs for high resolution models

The conditions where volume and ensemble averages can be considered equal are not fulfilled anymore. A choice must be done.

We choose to consider the mean as an ensemble average.

Basic equations solved in a mesoscale model (in flux form)

$$\frac{\partial \rho \overline{u_i}}{\partial t} = -\frac{\partial \rho \overline{u_i}\,\overline{u_j}}{\partial x_j} - \frac{\partial \rho \overline{u'_i u'_j}}{\partial x_j} - \frac{\partial p}{\partial x_i} - \delta_{i3} g \frac{\overline{\theta} - \theta_o}{\theta_o}$$

$$\frac{\partial \rho \overline{\theta}}{\partial t} = -\frac{\partial \rho \overline{\theta}\,\overline{u_j}}{\partial x_j} - \frac{\partial \rho \overline{\theta' u'_j}}{\partial x_j}$$

Overbar represents "mean". Traditionally, **"mean"** has been intended as "***ensemble average***" or as "***volume average***" over the grid cell (or a volume of the size of the spatial filter).

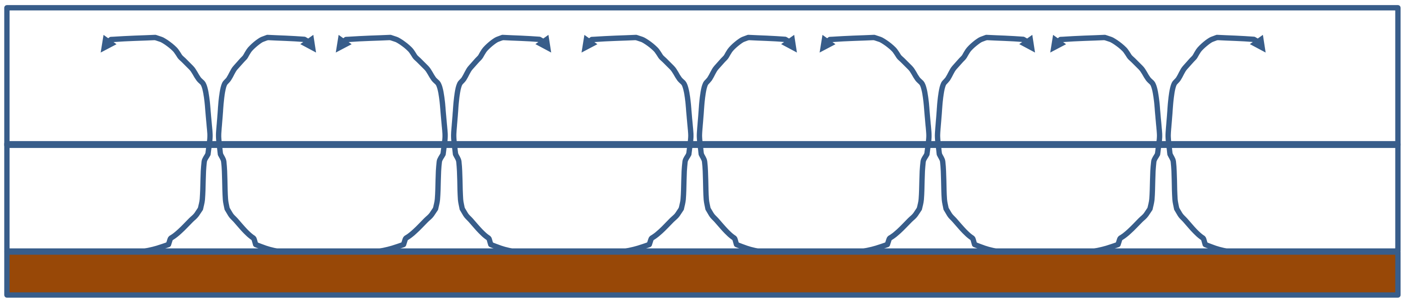
$$\langle U(\vec{x},t)\rangle = \lim_{N\to\infty} \sum_{\beta=1}^{N} U(\vec{x},t,\beta)$$

$$\langle U(\vec{x},t)\rangle = \int_{-\infty}^{\infty} v(\vec{x},t)\, f\,(v(\vec{x},t))\,dv$$

Where f is the p.d.f.

$$\overline{U}(\vec{x},t) = \int_{x_3-\Delta x/2}^{x_3+\Delta x/2} \int_{x_2-\Delta x/2}^{x_2+\Delta x/2} \int_{x_1-\Delta x/2}^{x_1+\Delta x/2} U(\vec{x}+\vec{x}',t)\,dx'_1 dx'_2 dx'_3$$

Wyngaard (2004) justified this confusion saying that for resolutions of several kilometrs (typical of mesoscale models till some years ago), the integral scale of turbulence is in general smaller than the grid size, so within one grid cell there are several large eddies –the volume average can be considered equivalent to the ensemble average.



Strictly speaking this is true only when turbulence is (quasi-)horizontally homogeneous, which implies horizontally homogeneous surface fluxes of heat and momentum.

Horizontal section of the four terms of the flux divergence of **U** at three different heights

$$-\frac{\partial \rho \bar{u}\bar{u}}{\partial x}$$

$$-\frac{\partial \rho \overline{u'u'}}{\partial x}$$

$$-\frac{\partial \rho \bar{u}\bar{w}}{\partial z}$$

$$-\frac{\partial \rho \overline{u'w'}}{\partial z}$$

Smoothed over 260m