Flux Measurements in Complex Terrain: old problems and new ways forward

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1. **The problem of advection**
   - Interpretation of time series and time-averaged data

2. **Topography and fluxes in neutral (and unstable) flows**

3. Topography and fluxes in stable flows

4. **Using models and measurements together**

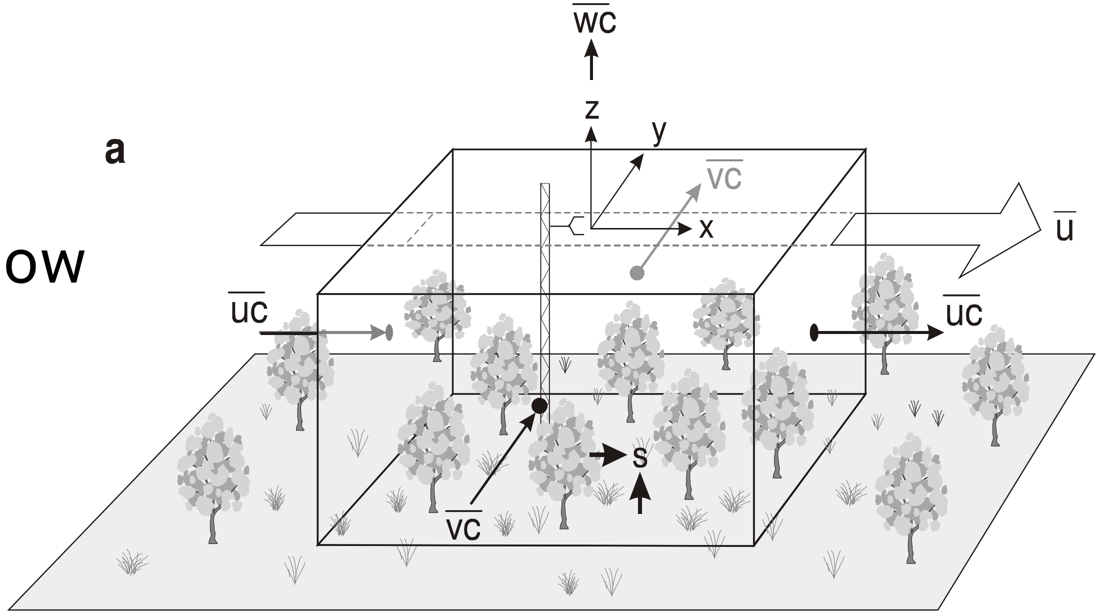
5. **Next steps?**

Fundamental concepts of measuring surface exchange aerodynamically: The mass balance in a control volume

horizontally homogeneous flow

x axis parallel to u

a



Advective and eddy flux divergence terms represent net transport through the walls of the control volume

Storage	*Advective Flux Divergence*	*Eddy Flux Divergence*	*Surface exchange*

$$\iiint_{Vol}\left[\overline{\frac{\partial c}{\partial t}} + \frac{\partial \bar{u}\bar{c}}{\partial x} + \frac{\partial \bar{v}\bar{c}}{\partial y} + \frac{\partial \bar{w}\bar{c}}{\partial z} + \frac{\partial \overline{u'c'}}{\partial x} + \frac{\partial \overline{v'c'}}{\partial y} + \frac{\partial \overline{w'c'}}{\partial z} = S(x,y,z)\right] dxdydz$$

On a single tower, only the terms in black can be measured

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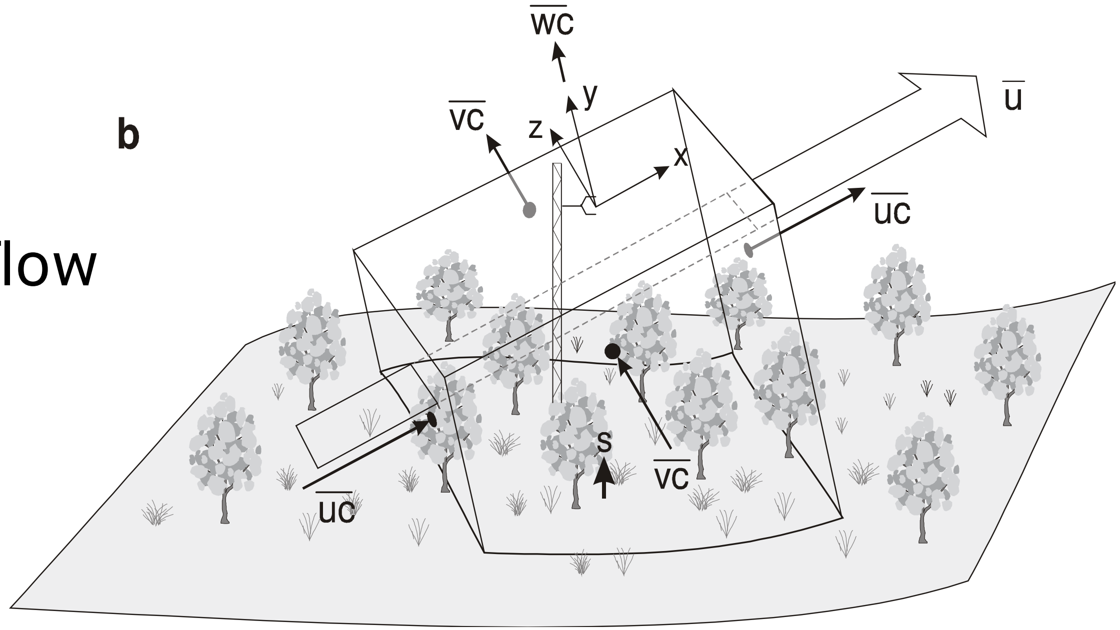

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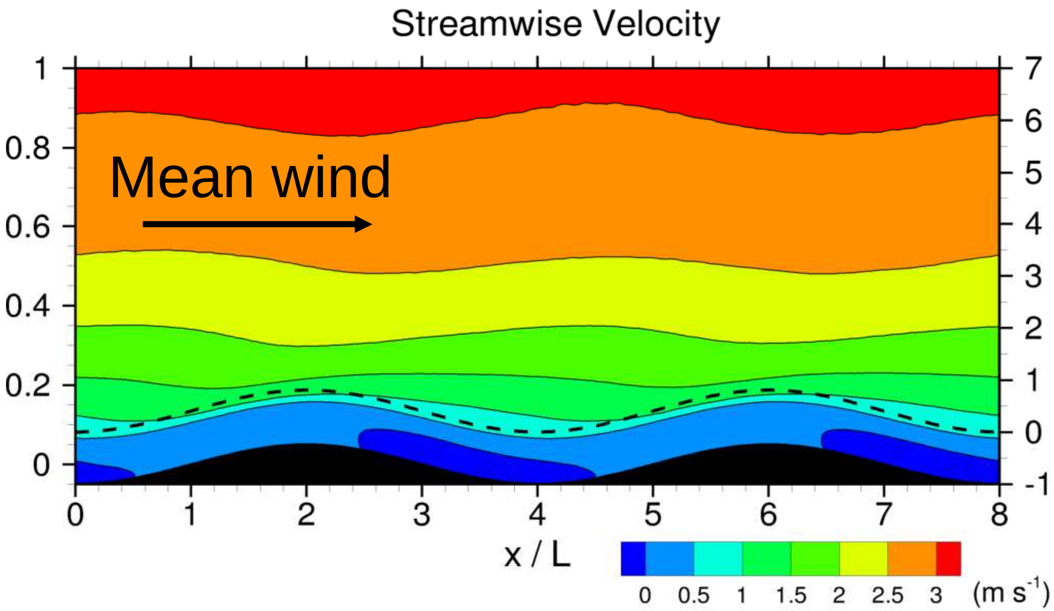
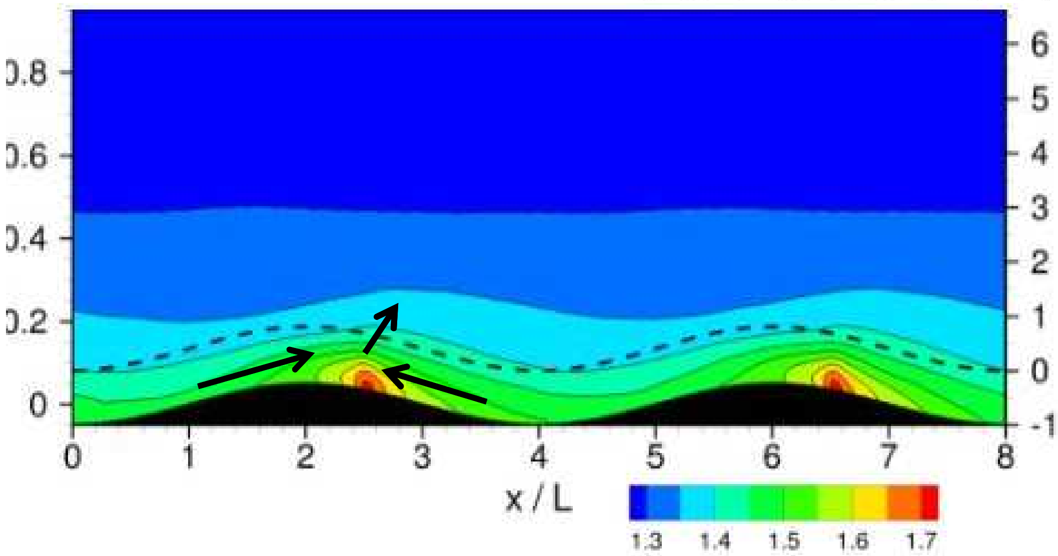
LES time averages

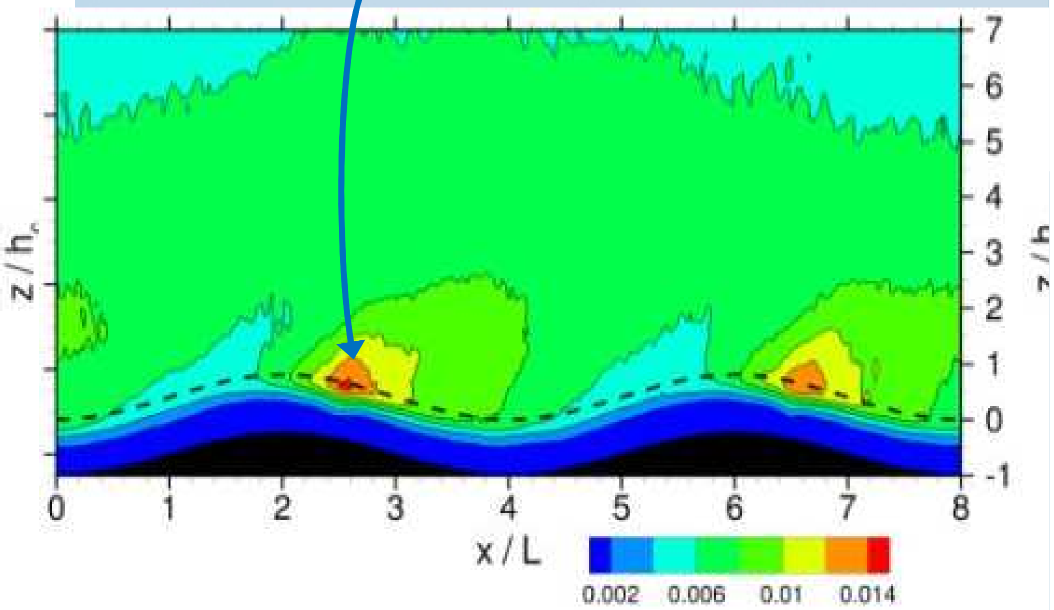


LES of neutral flow over small, low hill; dense canopy

flow field from Patton and Katul (2009): max slope 4.5°



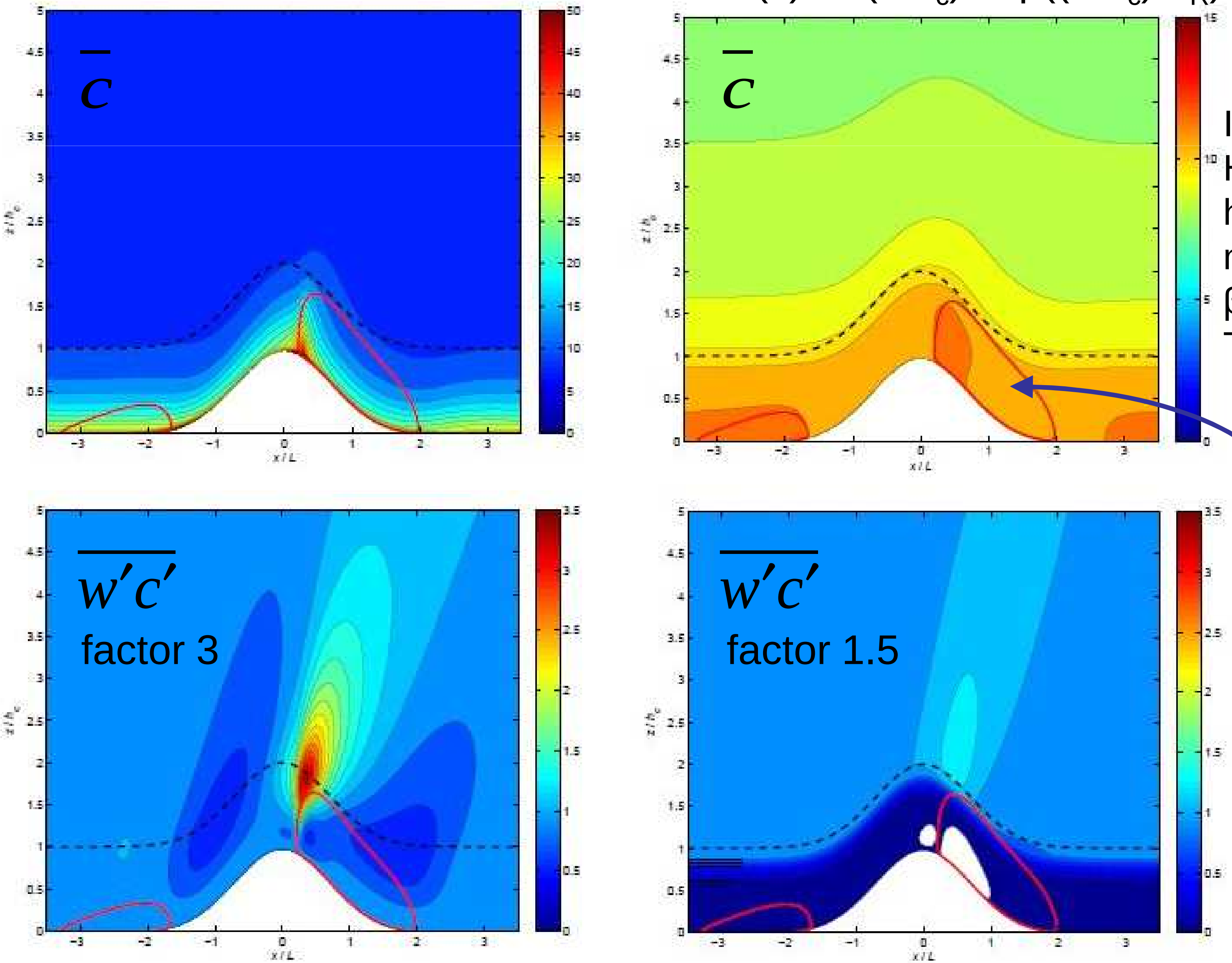
factor 1.8!



The convergence in the lower canopy affects ground sources more than those in the crown space

Ground source

Radiation source –
$S(z)=A\,(z-h_c)\,\exp((z-h_c)/L_R)$



Isolated Gaussian hill
H=10m, L=200m;
h_c=10m, L_c=10m, LAI=4;
max slope = 2.5°
$\beta=u_*/U(h_c)=0.3$;
Total source S_0 = 1

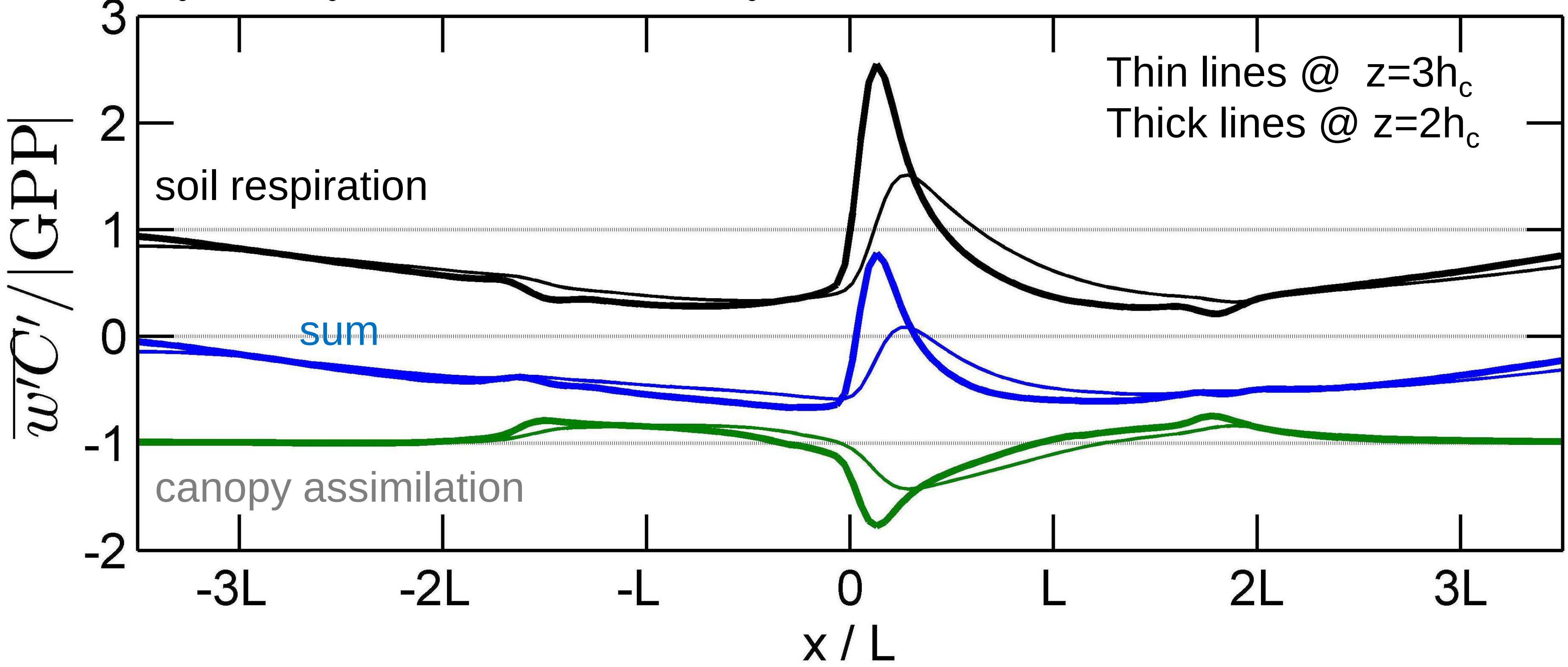
region of reversed flow

Harman and Ross, *in prep*

Consequences for flux measurement

In this example the respiration source at the soil surface equals the net assimilation sink in the canopy

Isolated Gaussian hill H=10m, L=200m;
h_c=10m, L_c=10m, LAI=4; $\beta=u_*/U(h_c)=0.3$;

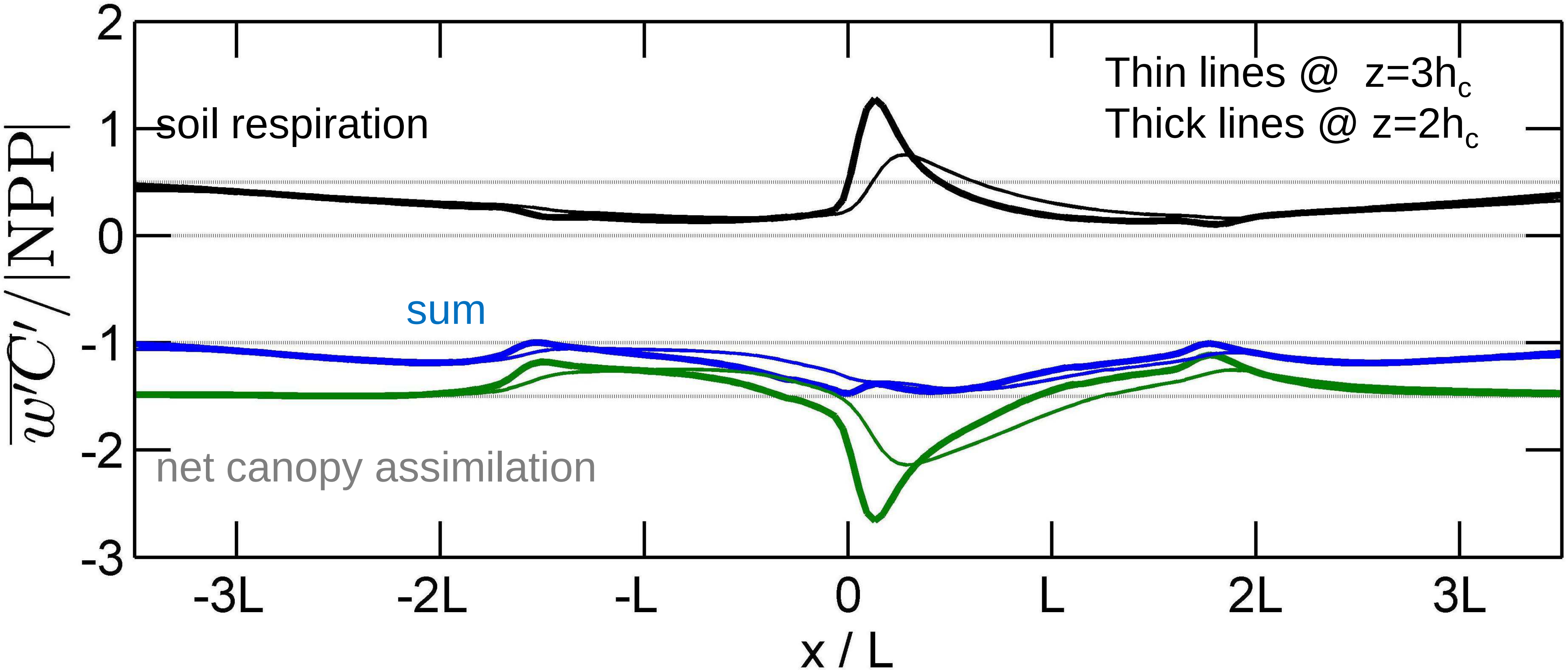


Harman and Ross, *in prep*

Consequences for flux measurement

In this example, net canopy assimilation is three times larger than soil respiration and so is typical of midday in temperate forests.

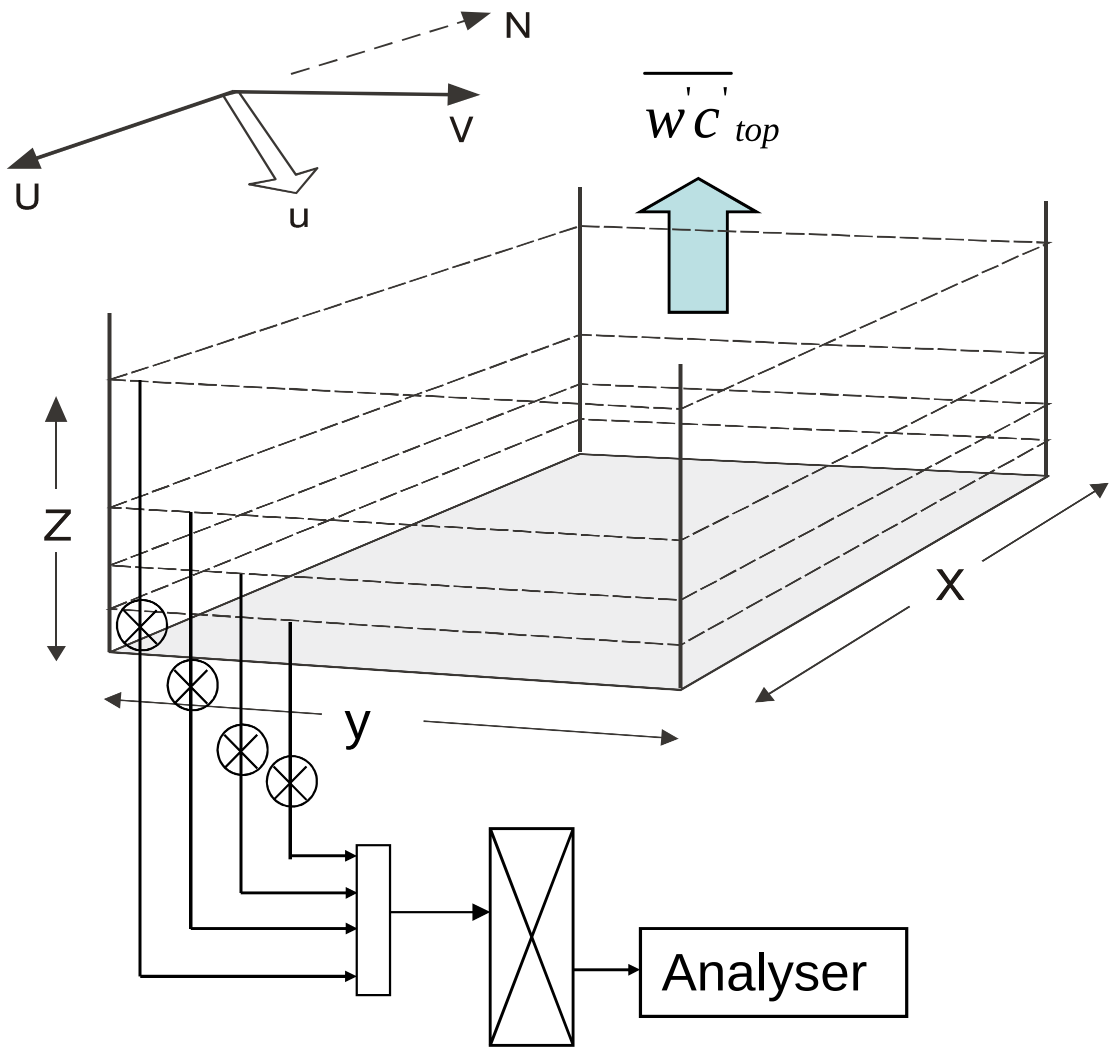
Isolated Gaussian hill, H=10m, L=200m;
h_c=10m, L_c=10m, LAI=4; $\beta=u_*/U(h_c)=0.3$;



so net carbon flux observation is biased yet instrumentation (u_*) indicates all is ok

Harman and Ross, *in prep*

Why not measure advective divergence terms directly? ADVEX plus others



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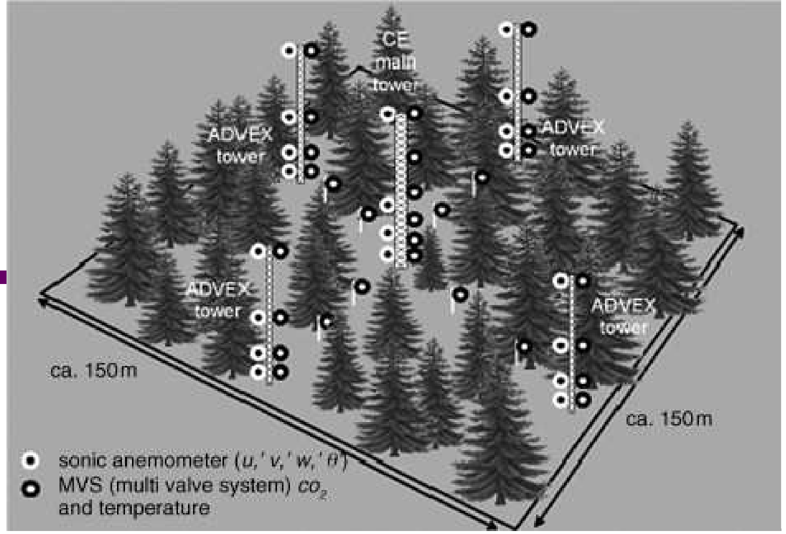
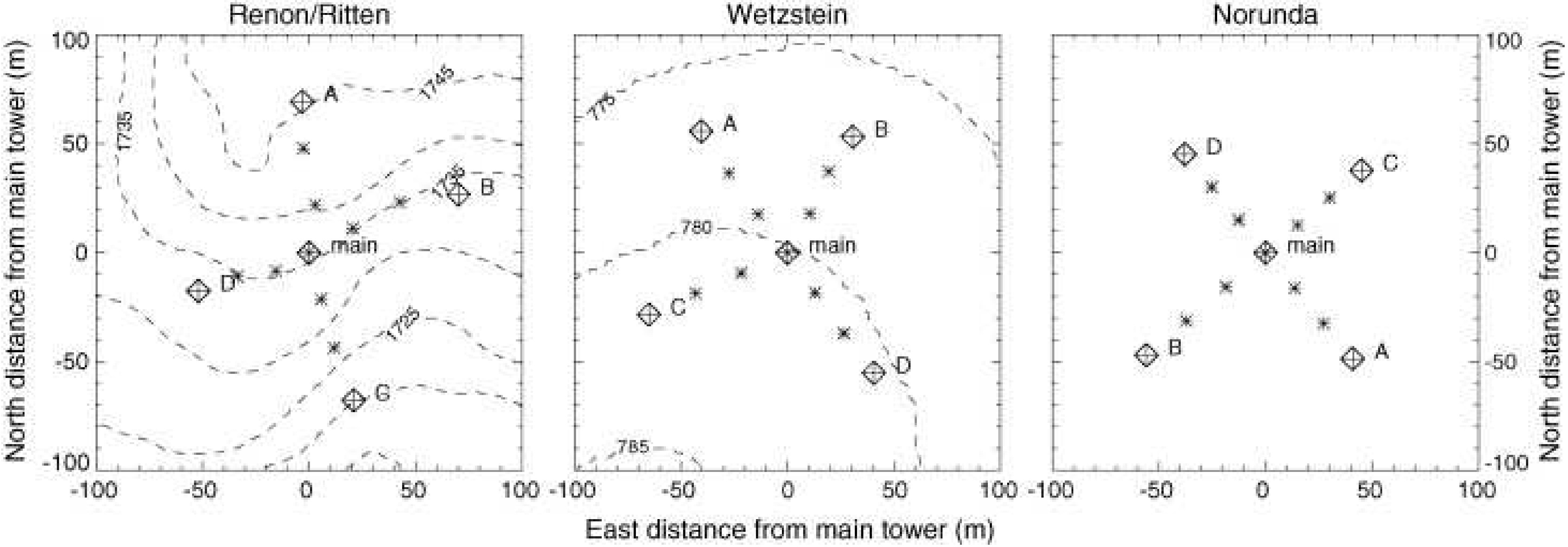


An attempt to measure advection directly using multiple towers at three contrasting Carbo Euro Flux sites (Feigenwinter et al. 2008)



attempting to measure advection directly by adding more towers to a site "**did not help to solve the night time CO_2 closure problem**" (Aubinet, 2009) **or the daytime energy balance closure problem** (Finnigan et al., 2009)

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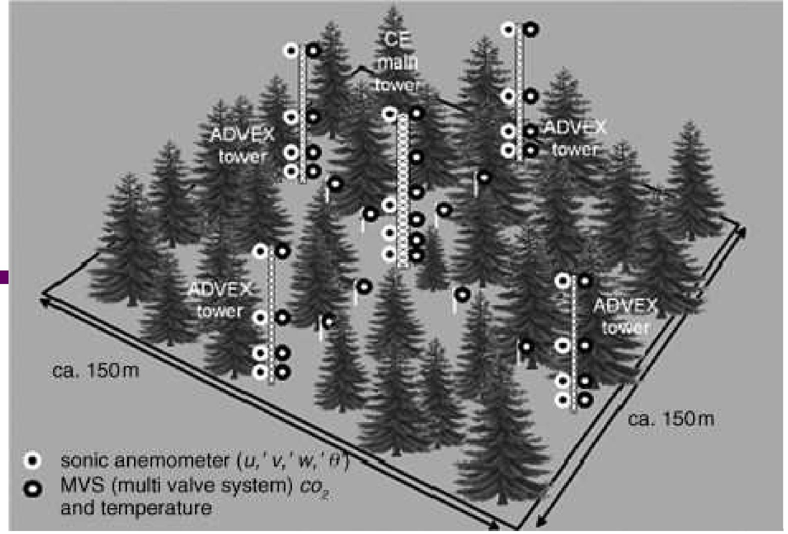

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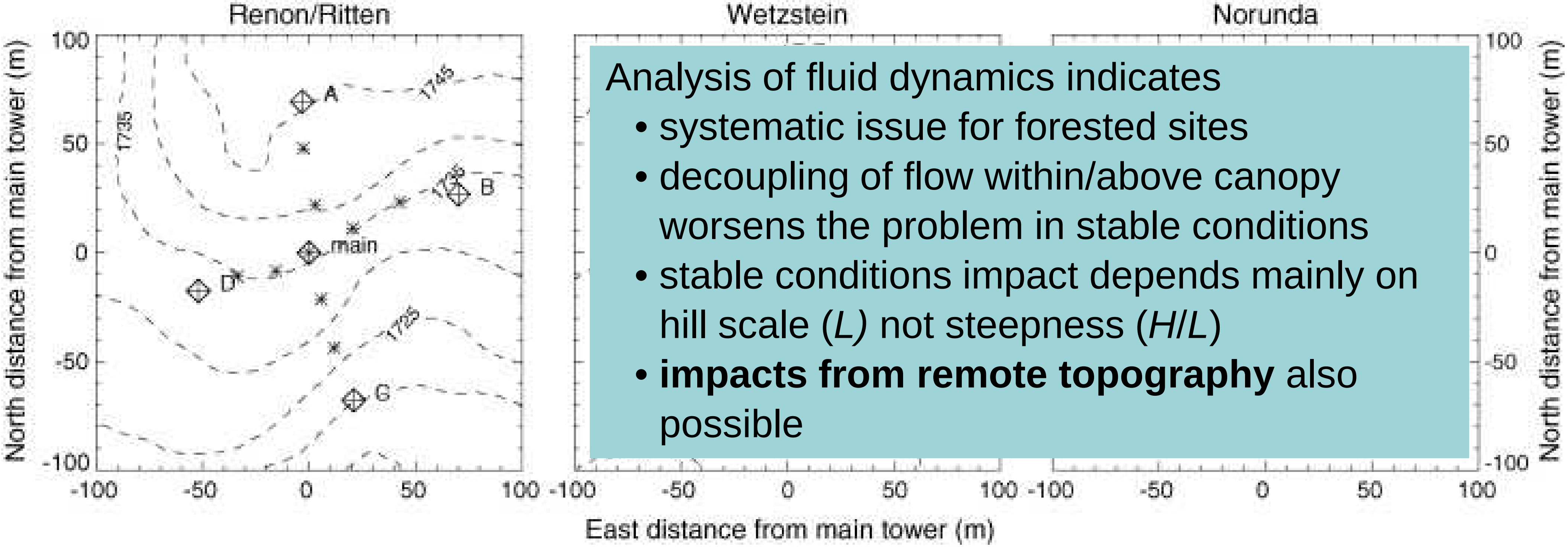

Analysis of fluid dynamics indicates

- systematic issue for forested sites
- decoupling of flow within/above canopy worsens the problem in stable conditions
- stable conditions impact depends mainly on hill scale (*L*) not steepness (*H*/*L*)
- **impacts from remote topography** also possible

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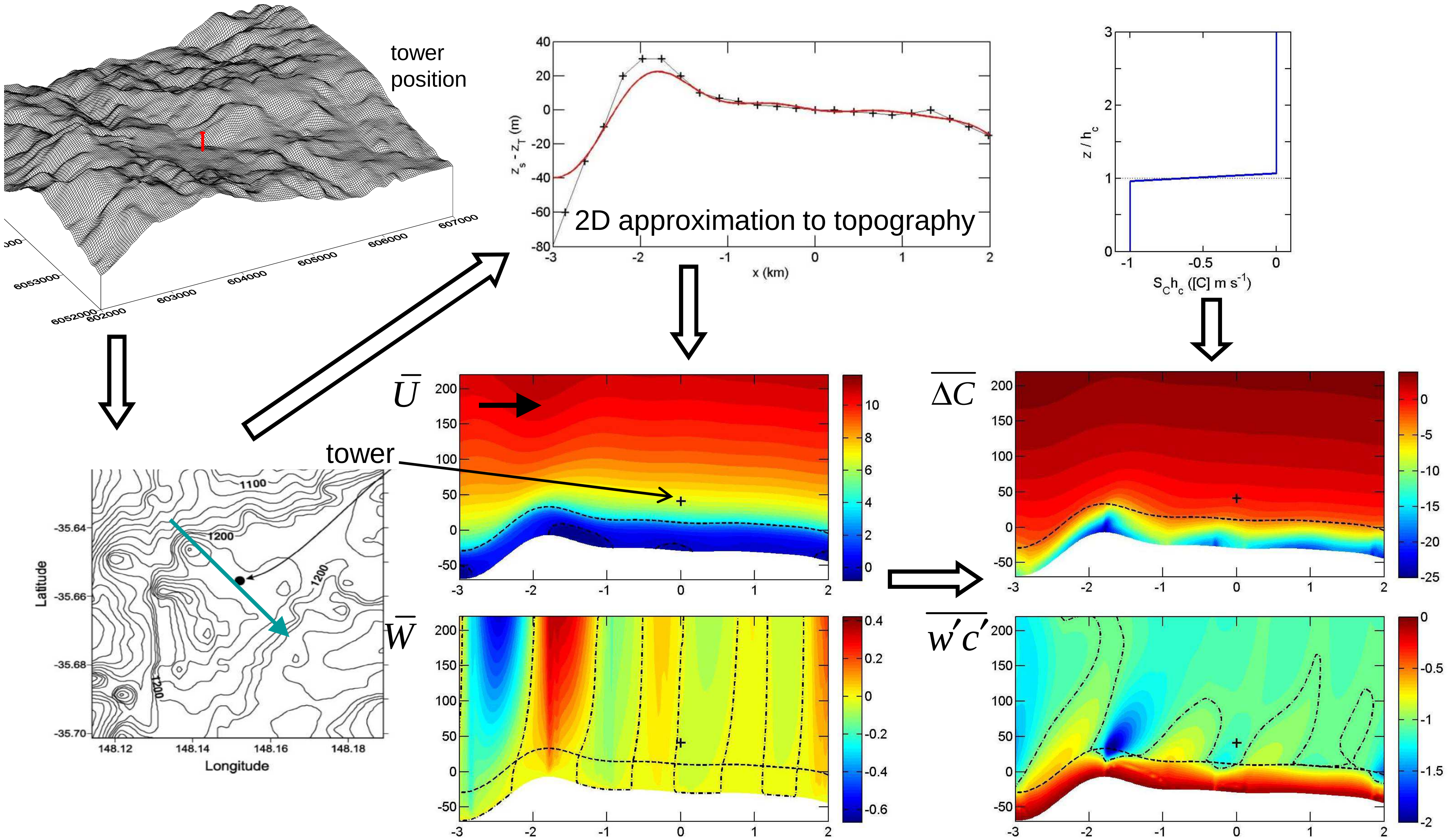
Practical difficulties of closing the budget by direct measurement

- Matching the measurement locations with the co-ordinate frame in which the mass balance is constructed
- Rotating measured wind vectors into the co-ordinate frame in which the mass balance is constructed
- Measuring mean w (small residual flow acting on large scalar gradient)
- Errors in measurements of any quantity with a large spatial gradient when the location of the measurement is uncertain
- Contamination of scalar concentration gradient measurements due to proximity to individual sources
- Problems in constructing spatial derivatives by finite differences given few measurement locations and variability
- WPL in 3D
- Unsteadiness: changes to spectral characteristics of wind and scalars
- Changes to instrumentation footprint
- *...*
- *...*
- ***Plus*** all the normal problems of instrumental calibration, error and resolution

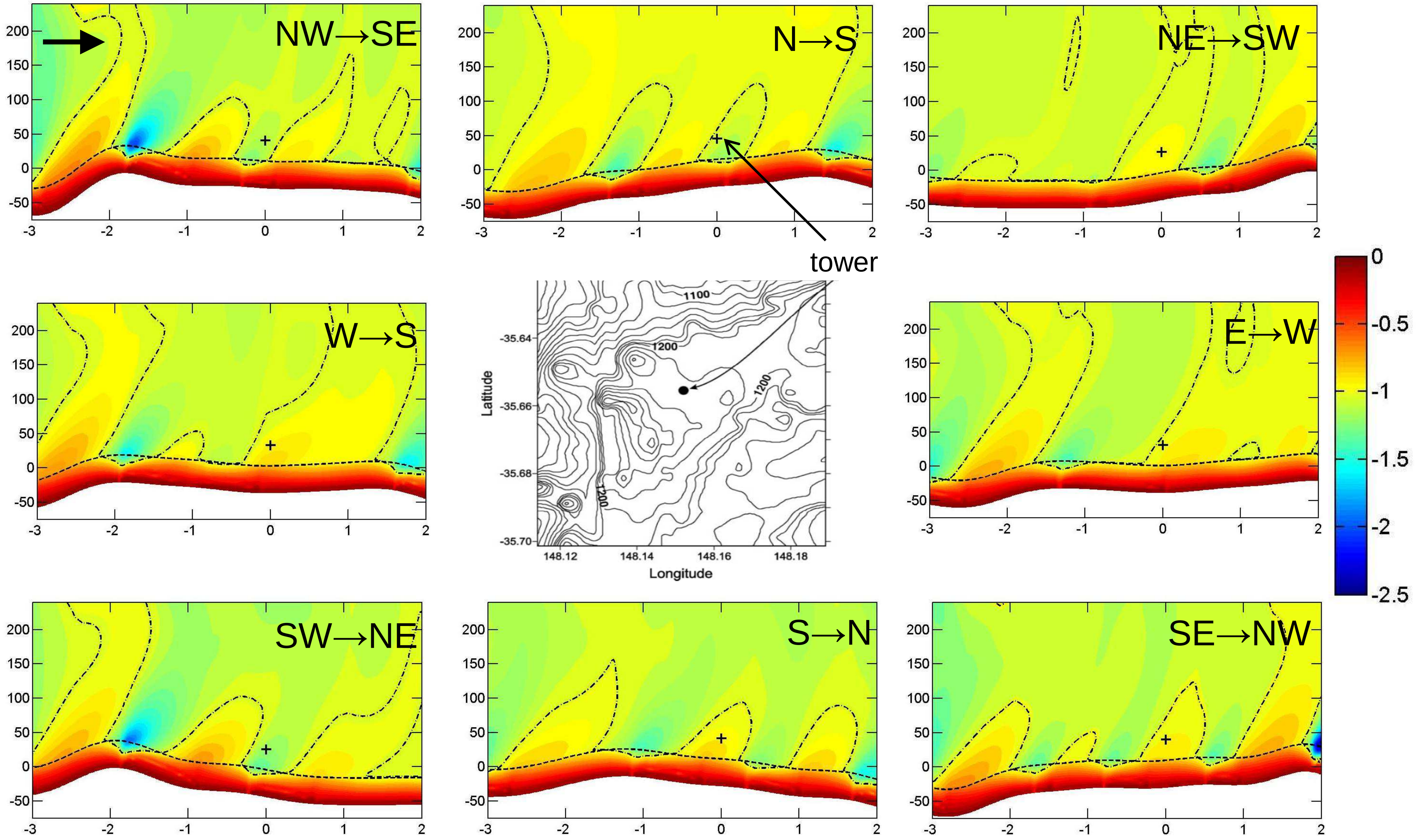
Combining models and measurements (1)

Using Models as a Site diagnostic



Local perturbations to measured flux due to local and remote topographic features

Site diagnostic: Impacts on scalar fluxes



Combining models and measurements (2)
Using models for data assimilation

The fundamental model can be stated as:
$[C(x,y,z), F(x,y,z)] = \Lambda_C(U)\, S(x,y,z)$
where Λ_C is a differential operator, i.e. a flow and transport model, which relates *C* and *F* to the source distribution *S*

The Forward Problem: $\left[C(x,y,z), F(x,y,z)\right] = \Lambda_C . S(x,y,z)$

Given a distribution for S and a known transport model, what are the corresponding *C* and *F* fields and the likely errors around them? e.g. Katul et al. (2006).

The Inverse Problem: $S(x,y,z) = \Lambda_C^{-1}(U)\left[C(x,y,z), F(x,y,z)\right]$

Given observations of *C* and *F* and estimates of their errors, what is the corresponding source distribution and the likely errors around it?

Combining models and measurements (2)

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FLUXNET: Quantify the inverse problem

$$S(x,y,z) = \Lambda_C^{-1}(U)\left[C(x,y,z), F(x,y,z)\right]$$

This is very sensitive to error/variability.

Alternative: Use the Forward Problem then match data and model

$$\left[C(x,y,z), F(x,y,z)\right] = \Lambda_C . S(x,y,z)$$

Balance uncertainties in observations and model for best agreement in S

Combining models and measurements (2)
Using models for data assimilation

The fundamental model can be approximated as:
$[C(x,y,z), F(x,y,z)] = \Lambda_C(U)\ g(z)\ S_0$
where Λ_C is a differential operator, i.e. a flow and transport model,
which relates C and F to the source strength S_0,
given a source distribution $g(z)$

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Summary and caveats

- Advection caused by topography can be a problem even on sites that are not obviously ‘challenging’ – in neutral/unstable and stable conditions
- Additional fluid mechanics that occur within canopies in complex terrain
  - In neutral or unstable conditions, the hydrodynamic pressure field caused by the hill affects the near ground and upper canopy flows differently. Reverse flow can occur in the lee of the hill even on very gentle slopes if the canopy is tall or dense enough. This affects the balance of assimilation to respiration fluxes measured on a tower
  - In nighttime stable conditions, radiative cooling can cause the within-canopy flow to become very stable, turbulence collapses and the canopy flow decouples from the boundary layer above. Gravity currents, driven by the balance of hydrostatic and stability modified hydrodynamic pressure gradients, advect respired CO_2 laterally.
- Flow and transport models can be used in two ways to address this problem
  1. a site diagnostic tool to put realistic error bounds on data
  2. as a basis for data assimilation to correct data automatically
- 2D terrain leads to larger impacts than 3D terrain
- Within limits – yet to be assessed – the results of variational or relativistic analyses should be robust

A challenge for the (Oz)Flux community

- Data remains king – more flow and profile data
- Direct measurement of the advection terms remains impractical.
- Data assimilation into *appropriate conservation models* offers a way forward
- Flow and transport models encapsulate our knowledge of turbulent flow in many situations but our current models are inadequate and need both development and testing – none are set up for DA
- Only a few isolated groups are engaged in model building; engagement with the flux community is less strong than it needs to be (and less than at the Corvallis Ameriflux meeting in 2002).
- A concerted effort seems to be required that will involve the **measurement community, model builders, data assimilation experts and end-users** and would need to include rigorous exploration and testing in both the field and at scale.

- Has the time arrived to embrace the challenge?