TKE decay and budget in the afternoon transition

Erik Nilsson[1,4], Marie Lothon[1], Fabienne Lohou[1], Clara Darbieu[1] Eric Pardyjak[3] , Fleur Couvreux[5] , Guylaine Canut[5] and Larry Mahrt[2]
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We are studying TKE decay and budget in the surface layer and above during the BLLAST field campaign

- What governs TKE decay in the afternoon transition?

Outline:

1. TKE budget for the surface layer and observed non-local influences on dissipation
2. Present a 'simple' 1D boundary layer model for TKE
3. Evaluation of the model for 1 IOP day
4. A comparison of near-surface wind speed and TKE in AROME
5. Conclude

Measurements used:

Erik Nilsson[1,4], Marie Lothon[1], Fabienne Lohou[1], Clara Darbieu[1] Eric Pardyjak[3] , Fleur Couvreux[5] , Guylaine Canut[5] and Larry Mahrt[2]
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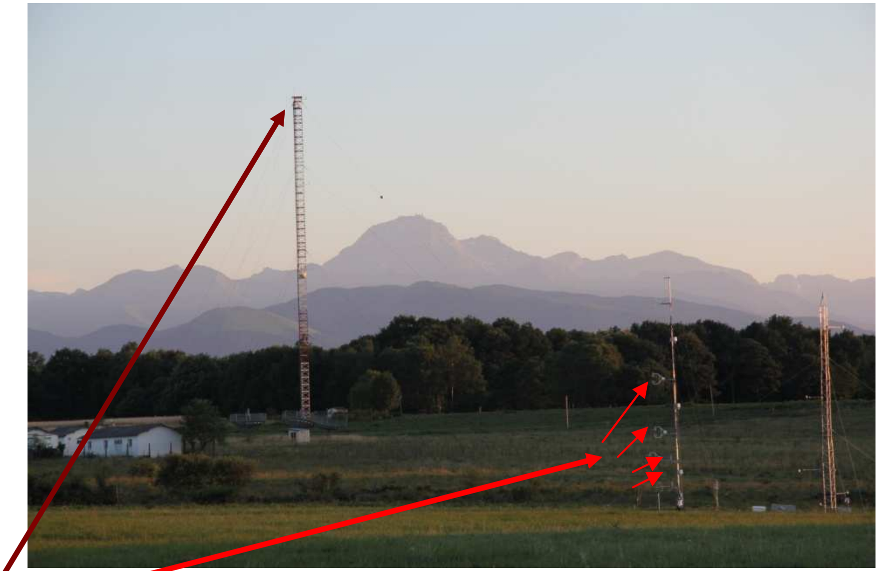
To achieve our objectives:

•We use field measurements from the Boundary Layer Late Afternoon and Sunset Turbulence field campaign that took place in June and July 2011 in southern France.

•High frequency (20 Hz) measurements of velocity and temperature from CSAT sonics at 4 levels in the surface layer on a small tower is analysed. The levels are 2.2 m, 3.2 m, 5.3 m and 8.2 m

•We also use some data from the 60 m tower as well



•We use all 10 Intensive Observation Period days with measurements at this tower

•We also use UHF, lidar and radiosoundings from Site 1

Turbulence kinetic energy budget during the afternoon transition

Erik Nilsson[1,4], Marie Lothon[1], Fabienne Lohou[1], Clara Darbieu[1] Eric Pardyjak[3], Fleur Couvreux[5], Guylaine Canut[5] and Larry Mahrt[2]
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Shear production

Buoyancy production

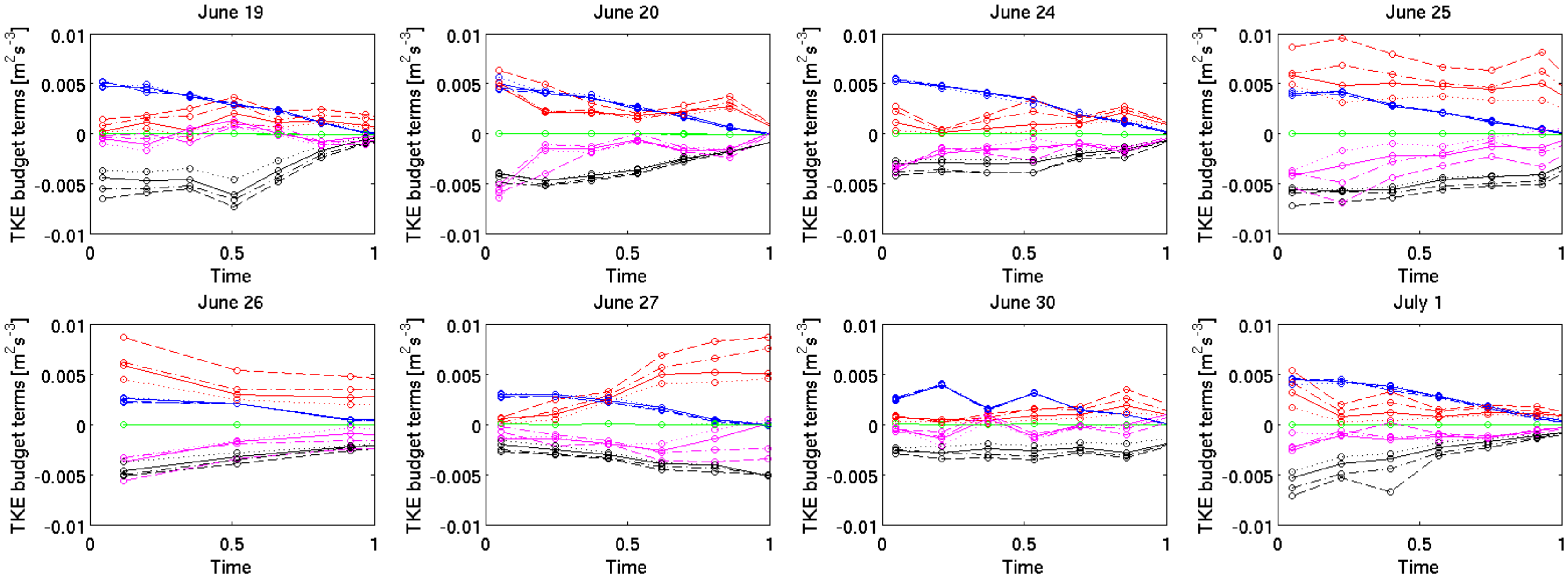
TKE tendency

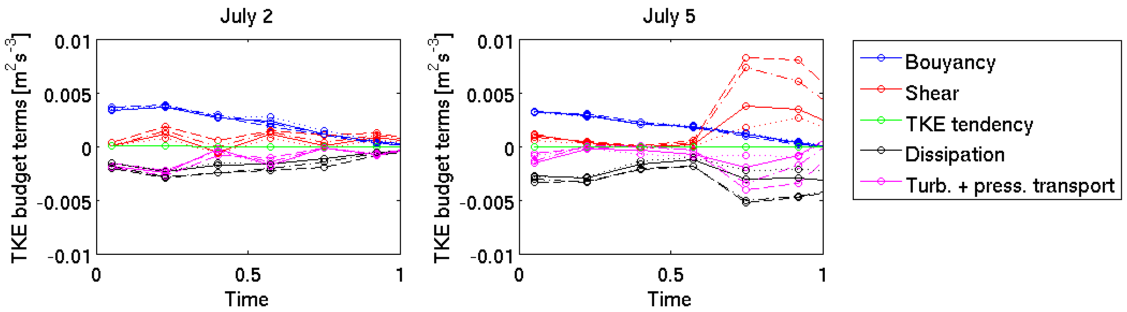
$$\frac{\partial E}{\partial t} = -\left[\overline{uw}\frac{\partial U}{\partial z} + \overline{vw}\frac{\partial V}{\partial z}\right] + \frac{g}{T_0}\overline{w\theta_v} - \frac{\partial \overline{wE}}{\partial z} - \frac{\partial \overline{wp/\rho_0}}{\partial z} + \epsilon, \quad (3.1)$$

Turbulent and pressure transport

Dissipation

TKE budget from 12 UTC (t = 0) to zero buoyancy flux (t = 1) at 2.2, 3.2, 5.3 and 8.2 m for 10 IOPs





Categories: higher (h), moderate (m) and weaker (w) was formed based on the mean afternoon value of the TKE budget terms.

Limits used in classification (A scale factor 10^{-3} applies on all terms.)

Shear: h > 3.5, 3.5<m<2.0, 2.0>w   Buoyancy: h > 2.5, 2.5>m

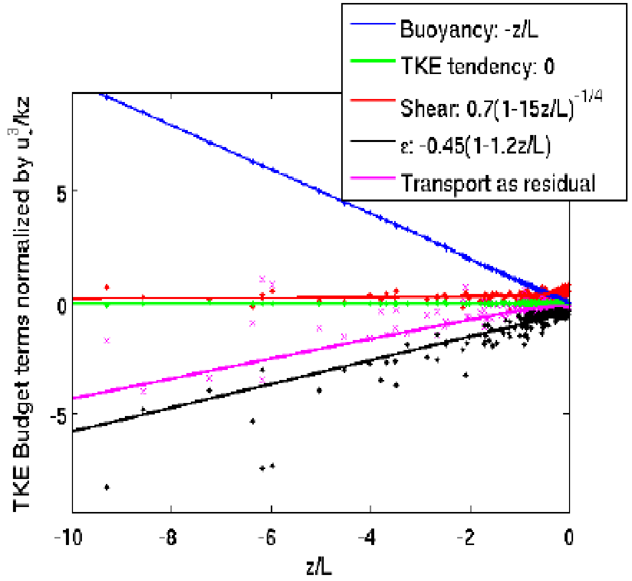
Dissipation: h < -4.5, -4.5<m<-3.5, -3.5<w   Transport: h < -2.5, -2.5<m<-1.5, -1.5<w

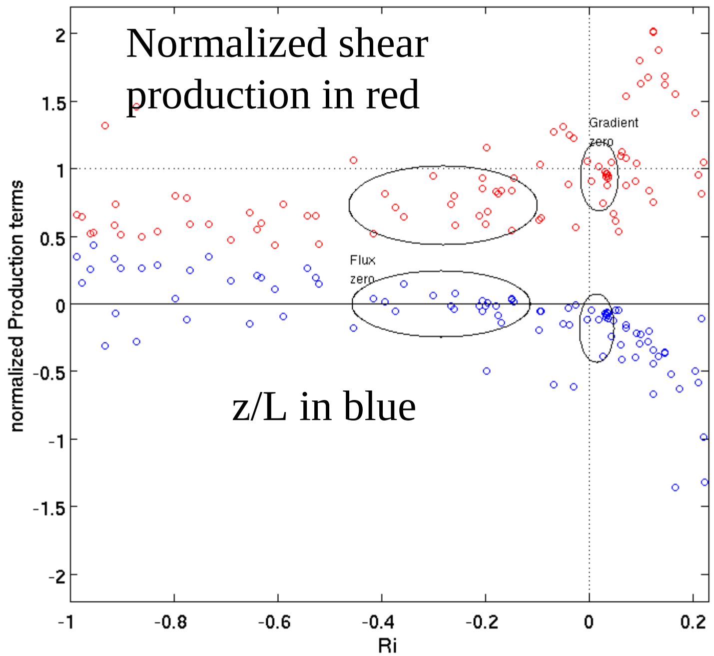
	Wind speed			Shear production			Buoyancy production		Transport			Dissipation		
Category	h	m	w	h	m	w	h	m	h	m	w	h	m	w
June 19		X			X(pl)		X				X	X		
June 20	X(p)			X(p)			X(p)		X(p)				X	
June 24		X(pl)			X(pl)		X			X(pl)			X(pl)	
June 25	X			X				X(p)	X			X		
June 26	X(p)			X				X	X(p)			X(p)		
June 27	X(p)			X(p)				X		X			X(inc)	
June 30			X			X		X(p)			X			X
July 1		X(pl)			X(pl)		X(p)				X		X(ph)	
July 2			X			X		X(p)			X(p)			X
July 5		X(ph)			X(ph)			X		X(pl)				X (inc)

Normalization of TKE budget terms

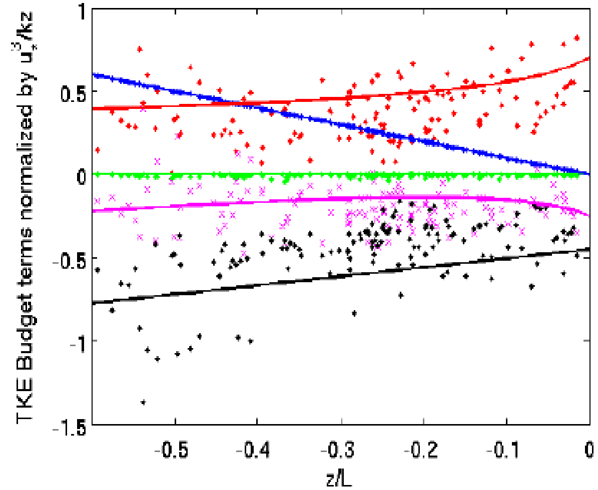
We note both similarities and differences in results to some previous studies regarding the budget terms after normalization.

Low shear production in near-neutral conditions might be linked to non-zero Ri number during the end of the afternoon transition. When both the heat flux and temperature gradient is small a mean value of about 1.0 is observed after normalization of the shear production with u_*, z and k=0.4





$$Ri = \frac{g \frac{d\theta}{dz}}{\left(\frac{du}{dz}\right)^2}$$



Things to remember about the budget

(for later modelling assumptions)

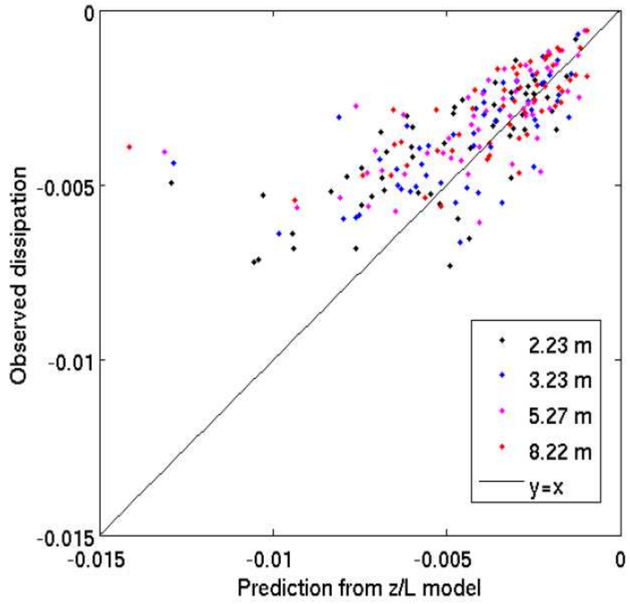
Neutral

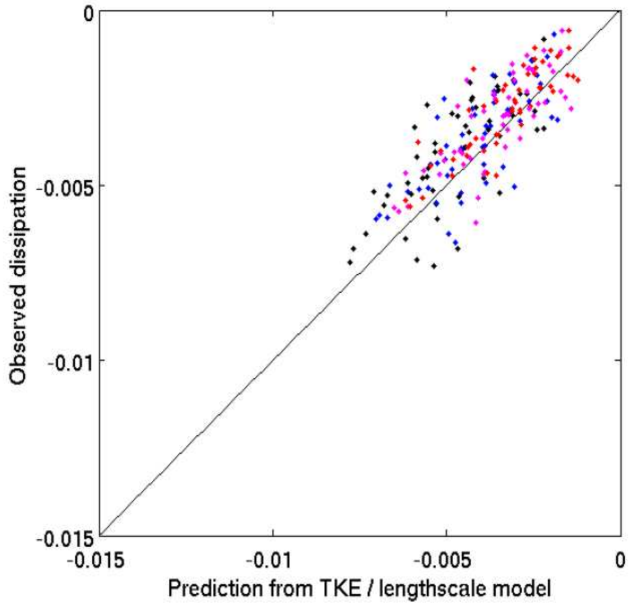
- Normalized dissipation about -0.45
  assuming normalized shear production 1.0
  gives transport at neutral of about -0.55
  so to simplify about 50 to 60% of shear production goes into transport
  and 40 to 50% goes into local dissipation

More convective

- Normalized buoyancy production equals z/L
  Dissipation at very convective about $-0.54z/L$
  Transport at very convective about $-0.46z/L$
  so to simplify about 40 to 50% of buoyancy production goes into transport
  and 50 to 60% into local dissipation

Evaluation of two dissipation models





$$D = -\frac{u_*^3}{kz}\left(0.45(1 - 1.2z/L)\right)$$

$$D = -\frac{E^{3/2}}{l_\epsilon} = -E^{3/2}\left(\frac{2.2}{z_i} + \frac{0.006}{z}\right)$$

Error statistics:

Bias:	$-9.3*10^{-4}\ m^2s^{-3}$	$-4.9*10^{-4}\ m^2s^{-3}$
CRMS difference:	$1.8*10^{-3}\ m^2s^{-3}$	$0.93*10^{-3}\ m^2s^{-3}$
Correlation:	0.70	0.80

A 'simple' TKE model

- 1-Dimensional model (only vertical direction)
- TKE budget for each vertical level used to calculate TKE tendency dE/dt
  dE/dt = S + B + T + D

  and thereby update E = TKE

$$\frac{\partial E}{\partial t} = -\left[\overline{uw}\frac{\partial U}{\partial z} + \overline{vw}\frac{\partial V}{\partial z}\right] + \frac{g}{T_0}\overline{w\theta_v}$$

$$- \frac{\partial \overline{wE}}{\partial z} - \frac{\partial \overline{wp/\rho_0}}{\partial z} + \epsilon, \quad (3.1)$$

T

- 1 m vertical resolution
- 1 s time step

Some assumptions regarding the height variation of budget terms:

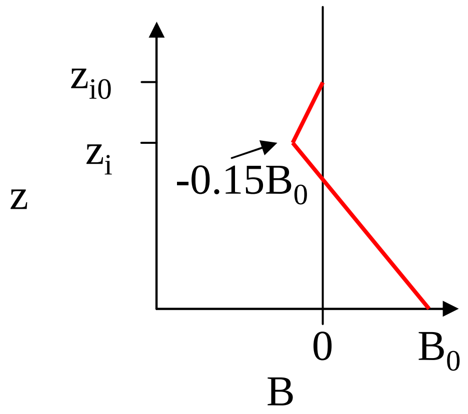
- Assumes vertical profiles for **TKE budget terms with shape of idealized simplified quasi-steady profiles** (inspired by profiles for a barotropic CBL, Wyngaard 2010)

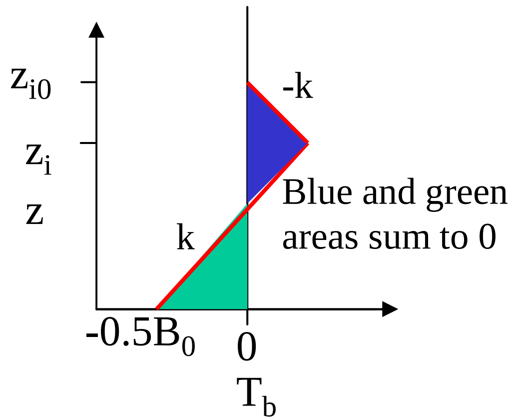
  -linearly decaying surface fluxes with height (momentum, bouyancy)

- **Dissipation calculated with TKE/length scale model:**

$$D = -\frac{E^{3/2}}{l_\epsilon} = -E^{3/2}\left(\frac{2.2}{z_i} + \frac{0.006}{z}\right)$$

Some assumptions regarding the height variation of budget terms:





Buoyancy term B

and

Transport related to buoyancy production T_b

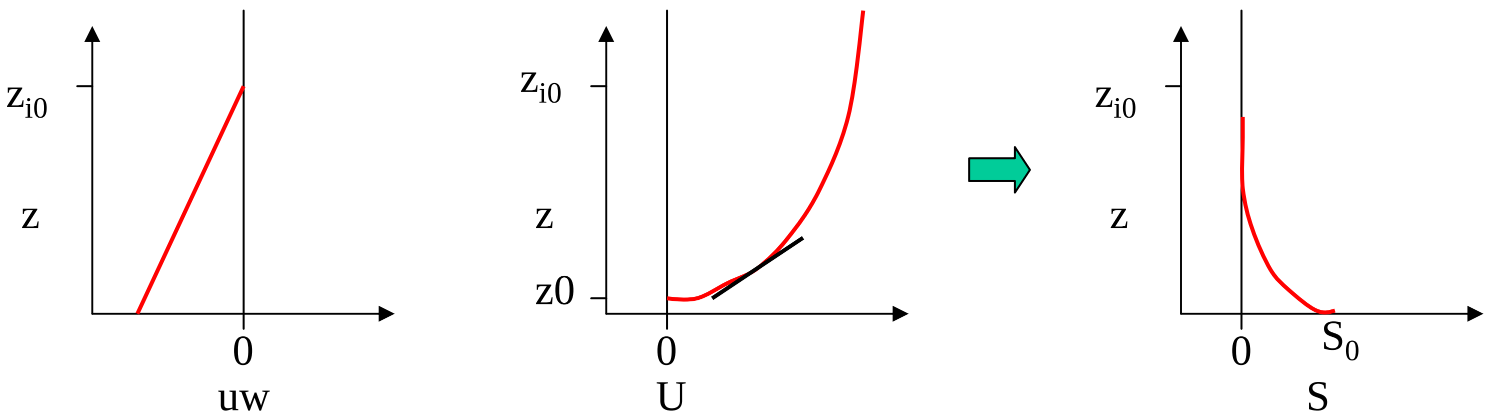
•**Minimum buoyancy flux is set to -0.15*surface buoyancy flux** at the boundary layer height (-0.15 taken from LES simulation by Clara Darbieu for June 20)

•A **linearly varying transport due to buoyancy produced turbulence** up to zi is used
- **Transport surface value** due to buoyancy is set to **-0.5*(surface buoyancy term)**

•A symmetric transport term with **a k, -k slope assumption is used to calculate height of no turbulence** z_{i0}

Some assumptions regarding the height variation of budget terms:

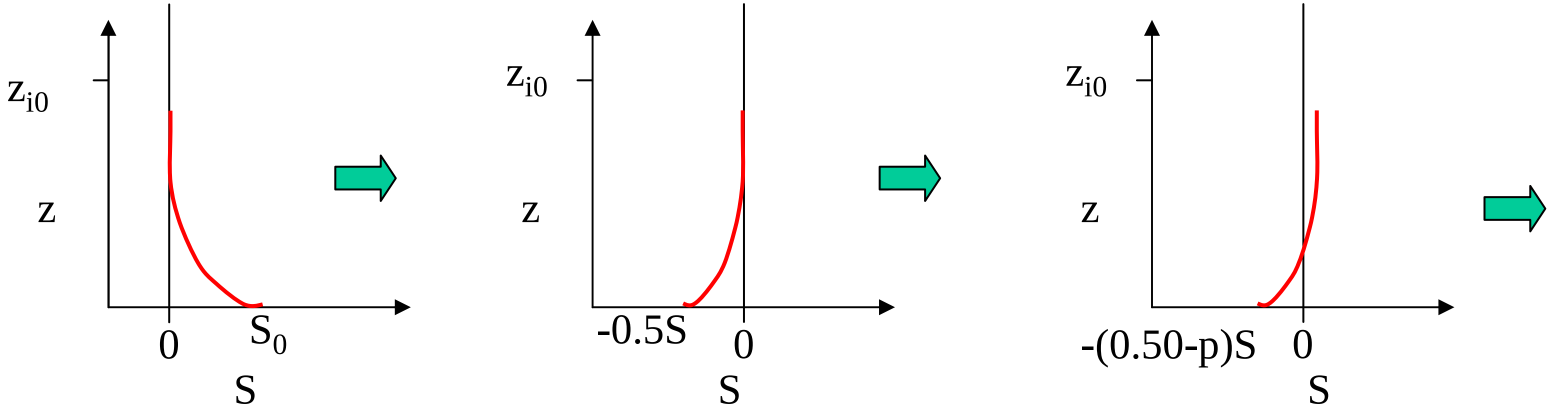
Momentum flux + Wind gradient Shear term S



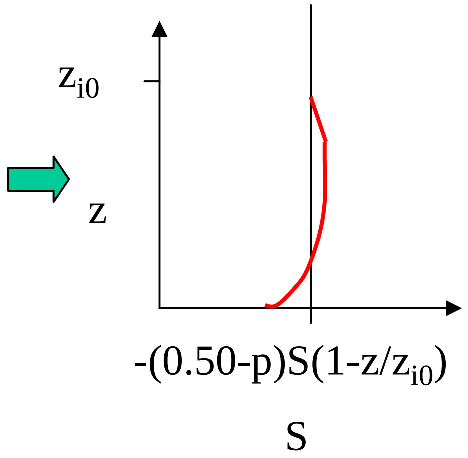
•**Wind speed profile is assumed nearly logarithmic** (a z0 value of 0.02 m was used and a correction to the wind gradient near the surface was applied, MO type of correction)

Some assumptions regarding the height variation of budget terms:

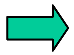
T_s Transport related to shear production

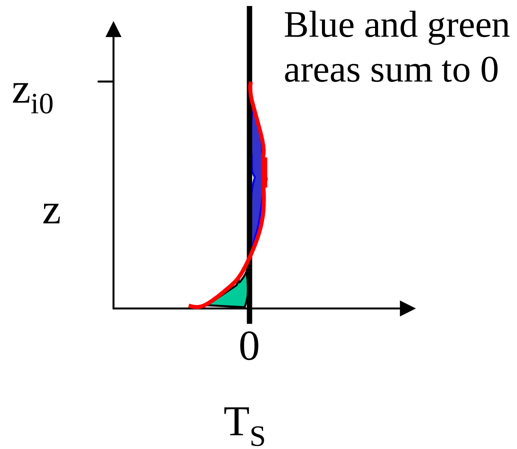


• **Transport surface value** due to shear produced turbulence is set to **-0.5*(near surface shear term value)**



Check that areas match if not adjust p



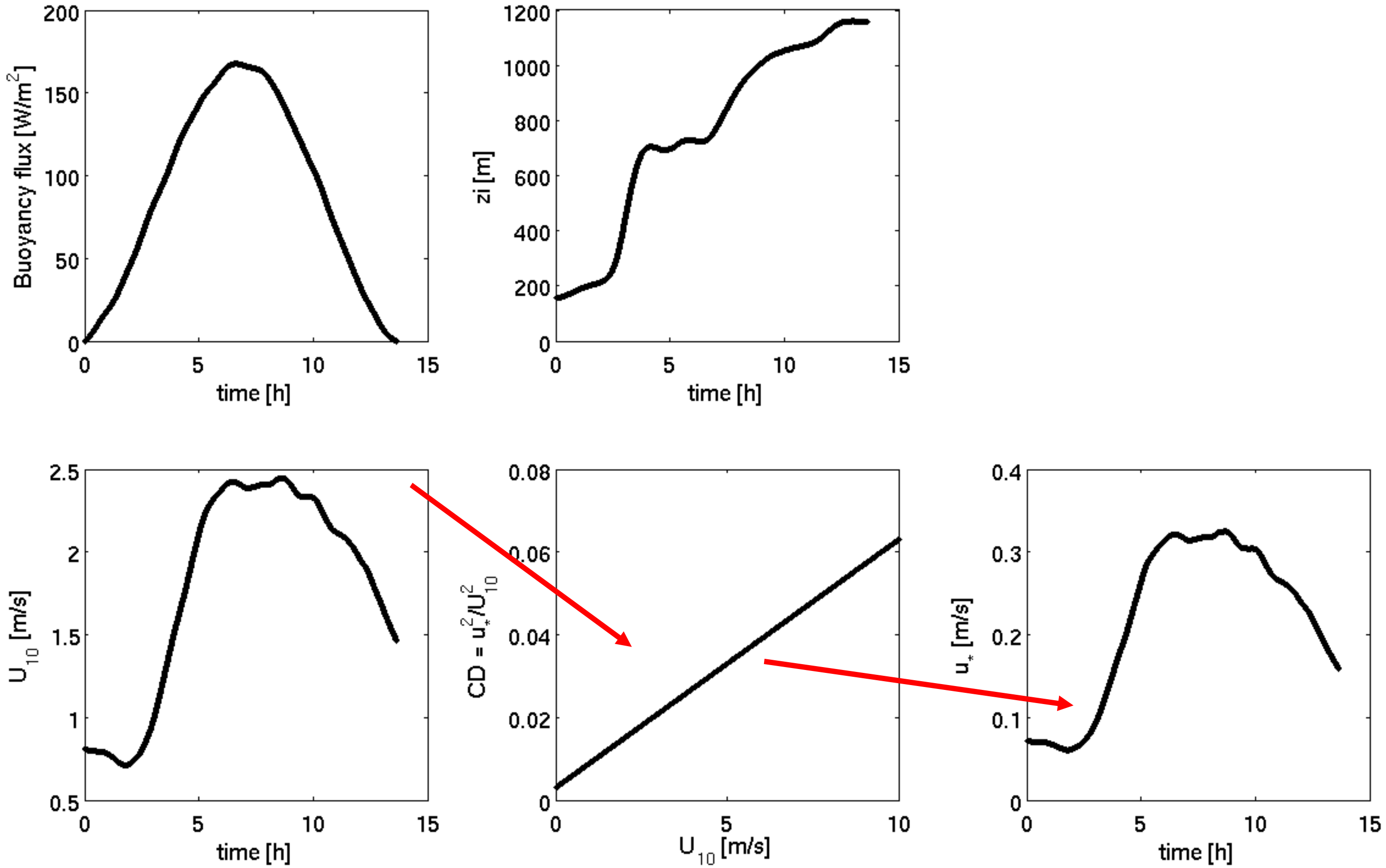


Numerical experiment A: June 20

Input forcings to run the model:

- Prescribed zi development (from smoothed lidar measurments)
- Prescribed surface buoyancy flux (from smoothed measurements at 2.23 m)
- Prescribed wind speed (from smoothed measurements at 8.22 m)

(surface momentum flux is then calculated using a simple CD curve approach)

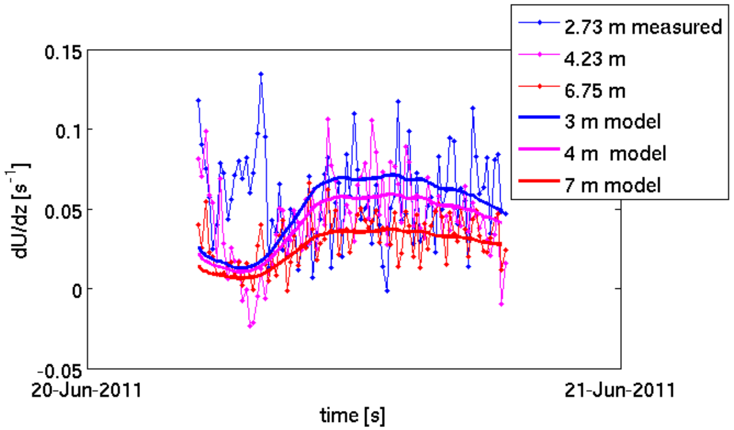


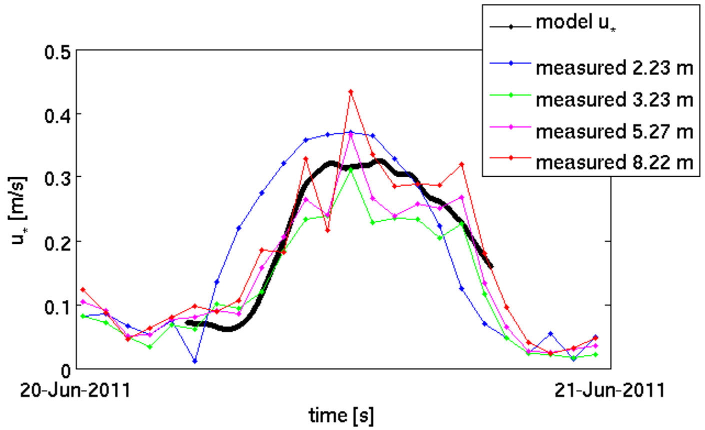
Numerical experiment A:

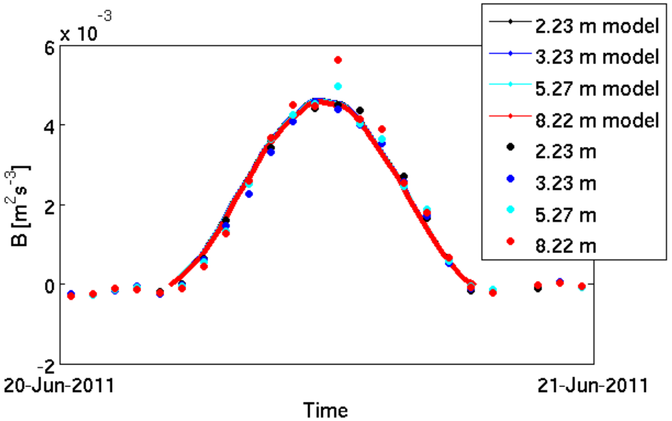
First confirming that the forcings are roughly consistent with measurements

Near surface wind gradient

u_*







u_* may overestimate somewhat (ignoring the estimate from the lowest measurement height which did not correspond well with the mean wind speed at 8.22 m)

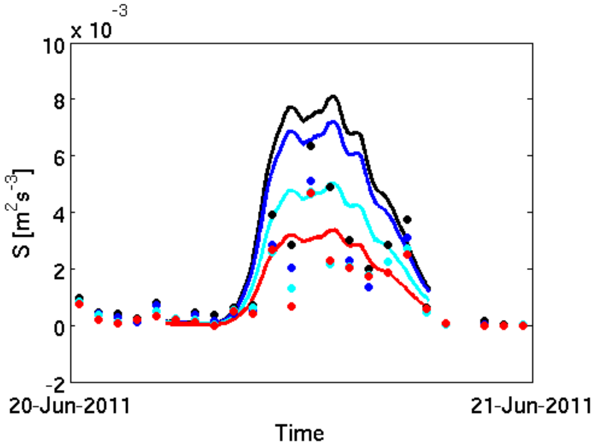
Near surface Buoyancy production

Numerical experiment A:

Outcome of other TKE budget terms compared to hourly measured budget values

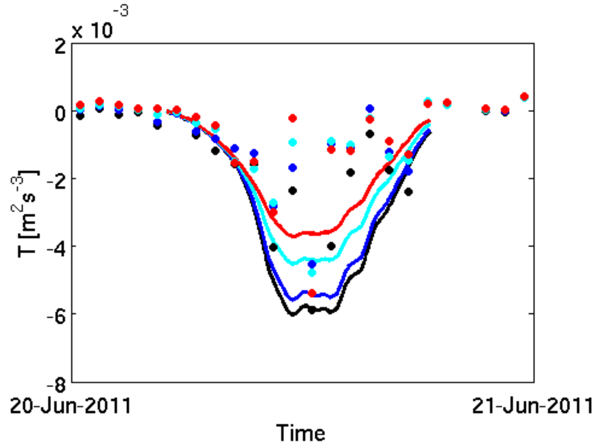
Shear production

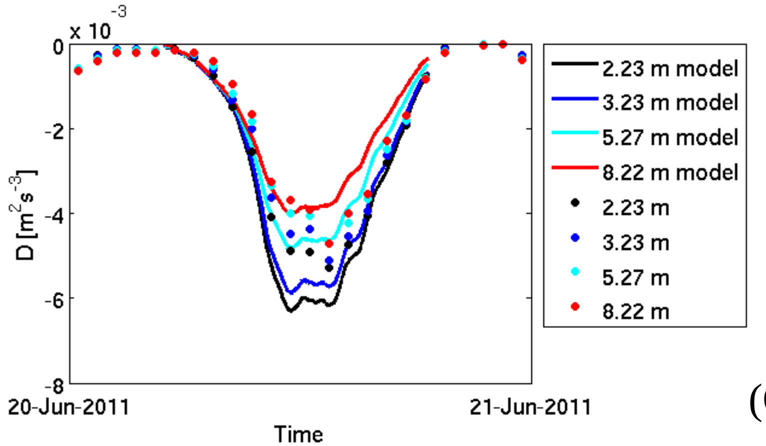
(Overestimating slightly)



Transport

(Overestimating slightly)



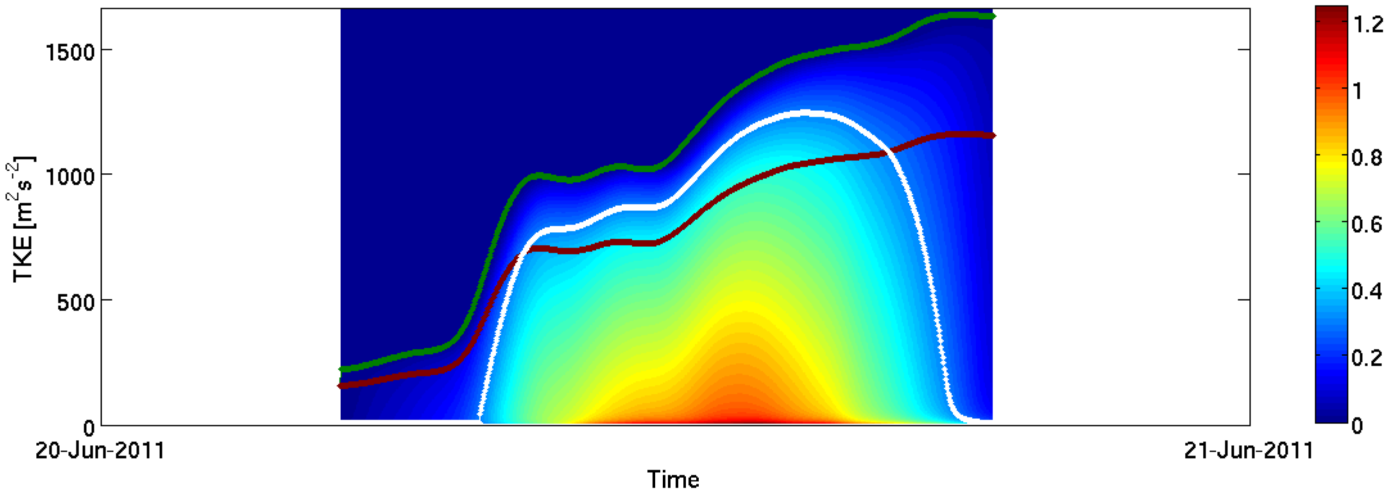


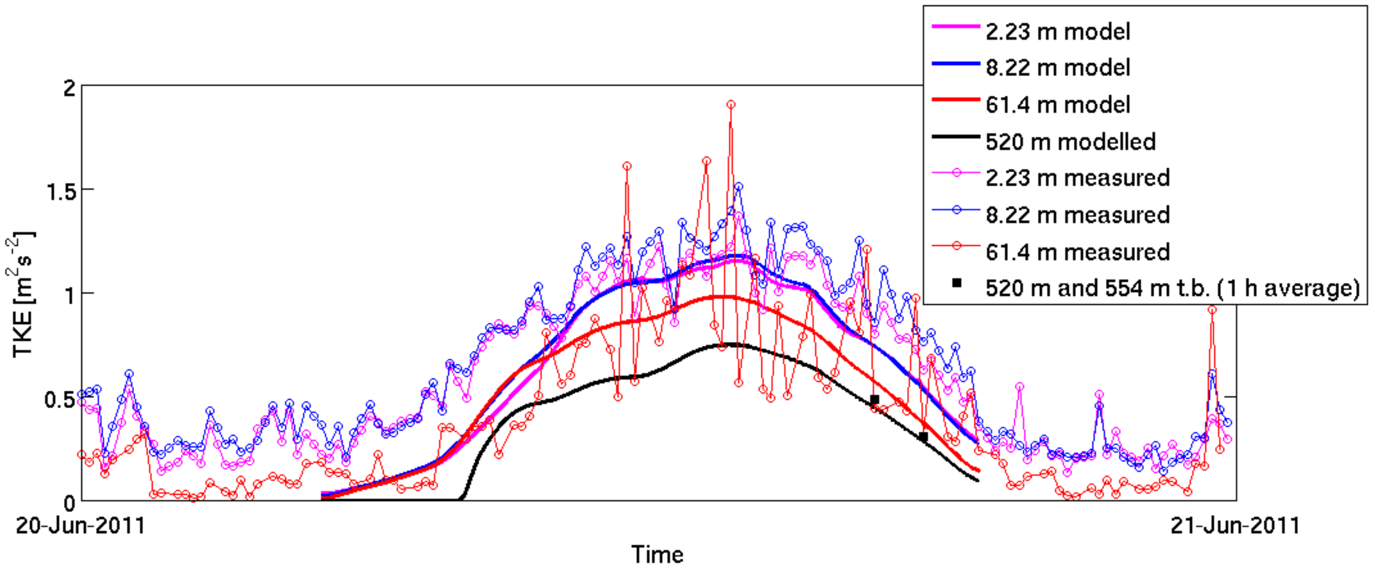
Dissipation

(Overestimating slightly)

Numerical experiment A:

How is the TKE?





Underestimating somewhat (big scatter in 10 min values at the 60 m tower)

Numerical experiment A:

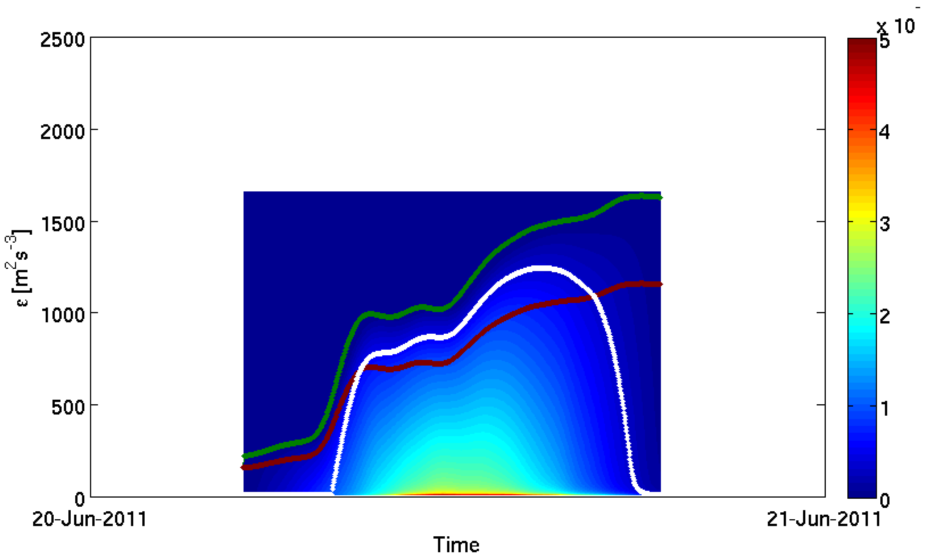
How is the dissipation rate?

Many features is lacking

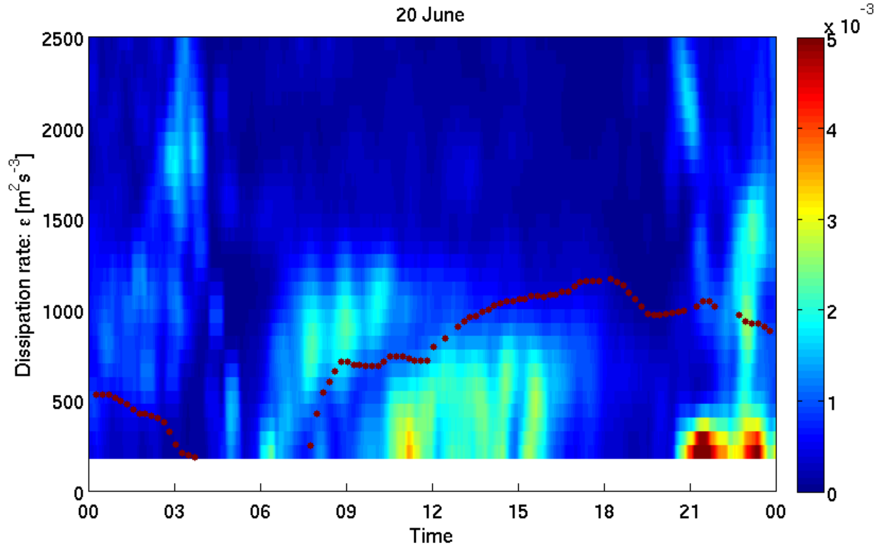
Dissipation rate is somewhat underestimated from 175 m and up to the entrainment zone (most of the time)

Model is lacking wind shear at the top of the boundary layer. This could also increase the TKE and overall dissipation in the boundary layer once it has been included

Modelled



Estimated from UHF



Numerical experiment A:

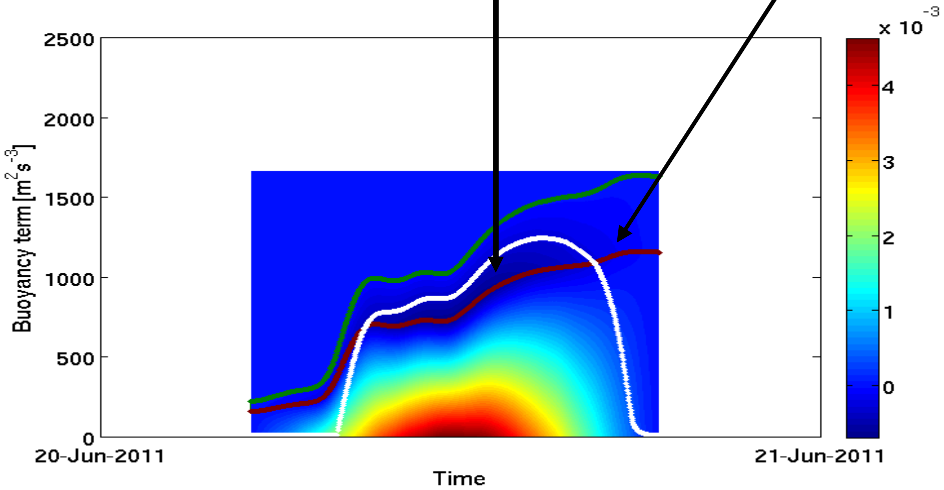
Turbulent Convective Mixed Layer

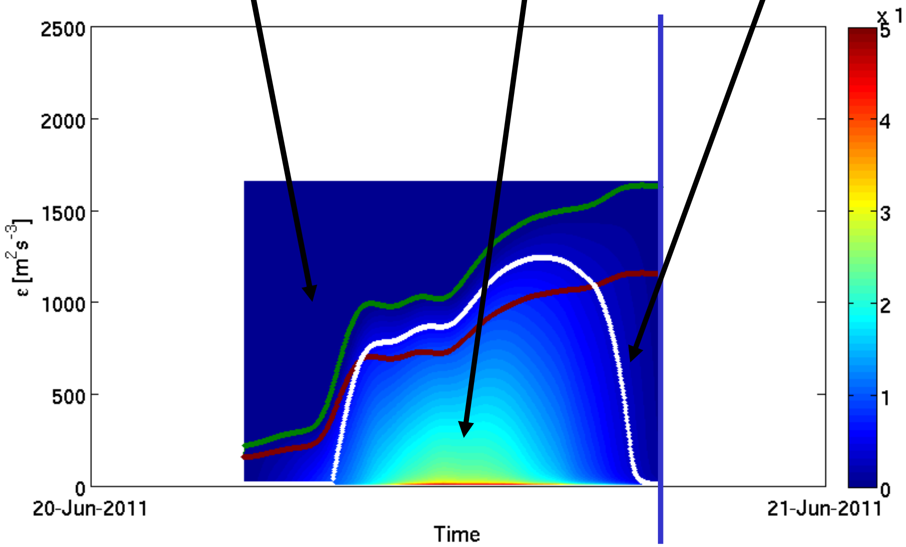
Entrainment zone

Residual layer definition?

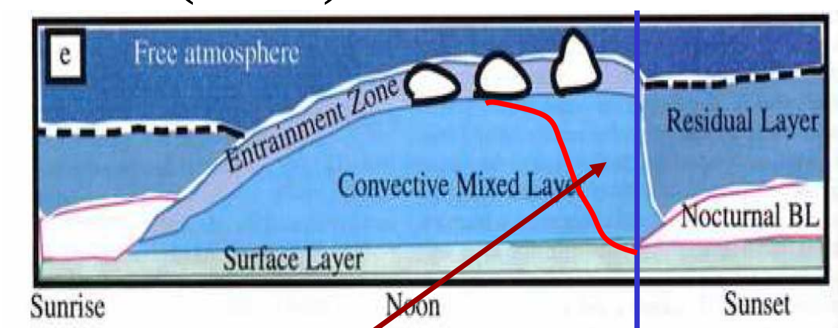
Very weak EZ

Free atmosphere





Stull (1988) sketch revisited

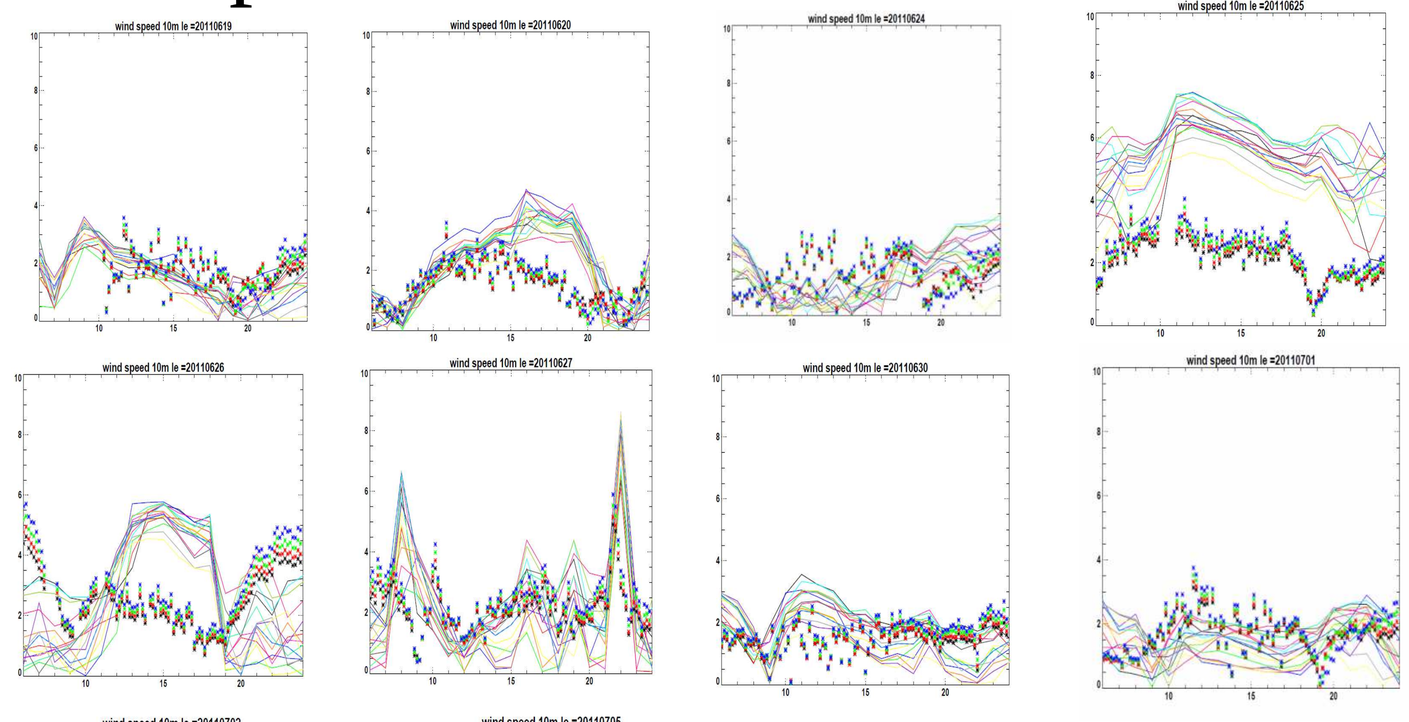


Zero buoyancy flux

'Pre-Residual Layer'

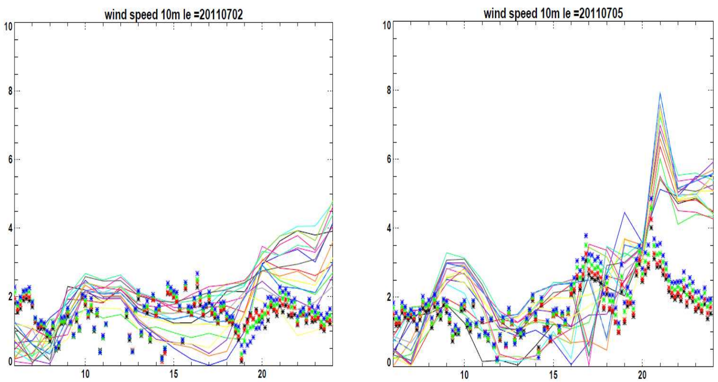
Zero buoyancy flux

How well does the meso-scale model AROME predict wind and near-surface TKE?



Figures from Fleur Couvreux

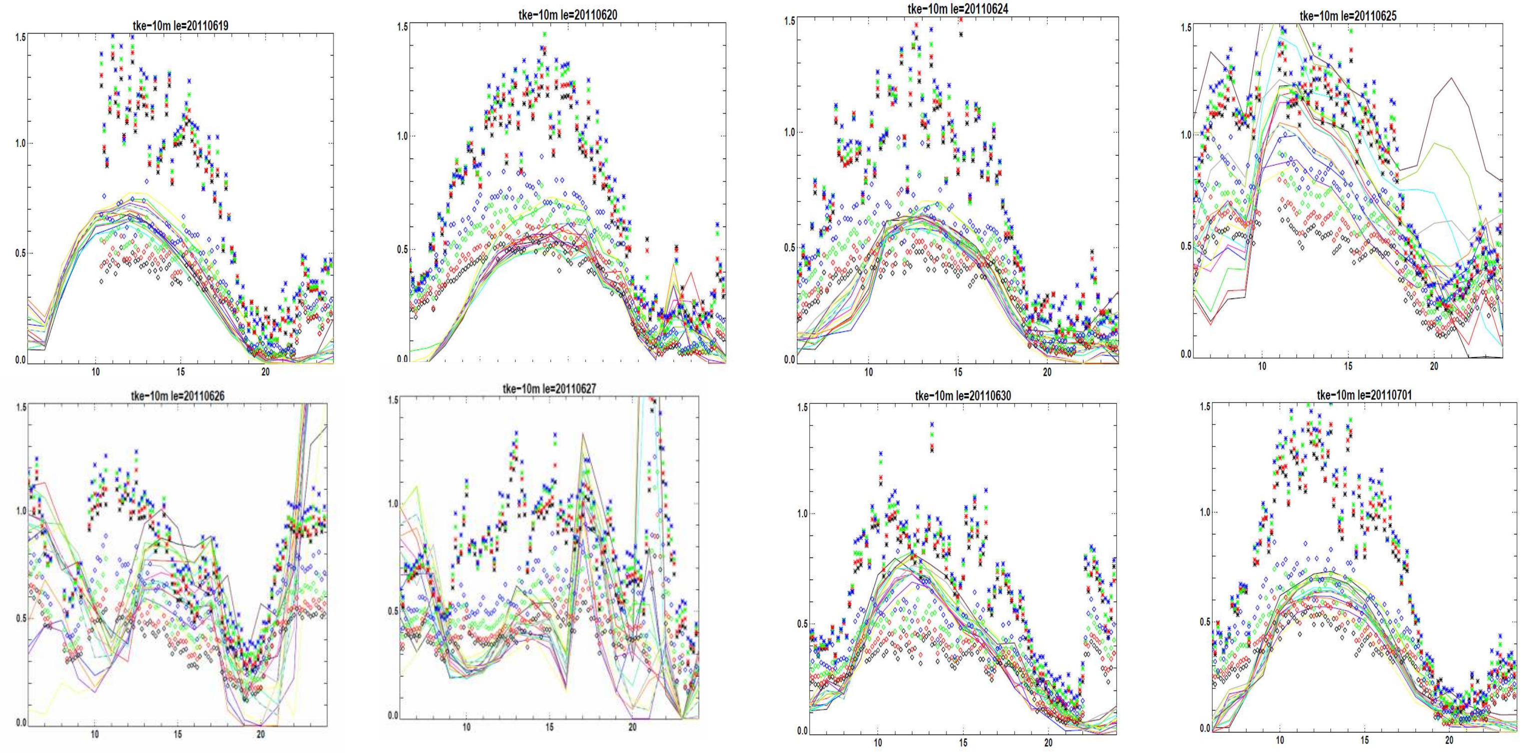
2.5 km horizontal resolution in AROME



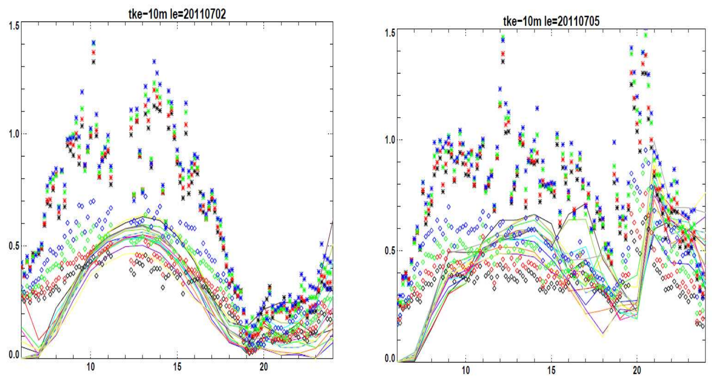
Wind speed overall decently predicted. Some days better than others

We should remember the difficulty of comparing grid box averages to one-point measurements

How well does the meso-scale model AROME predict wind and near-surface TKE?



Figures from Fleur Couvreux



The model TKE (lines) is compared to measured TKE (*) = $(u^2+v^2+w^2)/2$

and an 'w only TKE' = $(3w^2)/2$

in (open squares)

Conclusions

- A TKE budget has been presented from measurements for 10 IOP days

  - **Classification** of the days reveal a variety of **different amounts of Shear production**, **transport** and **dissipation** for the different afternoon periods

- **A simple TKE model was developed** based on: 1. Very idealized vertical profile assumptions, 2. TKE budget results 3. Some LES results.

  - The simple **model** was shown to **reproduce TKE and dissipation rate relatively well** for one of the IOP days. Exp A.

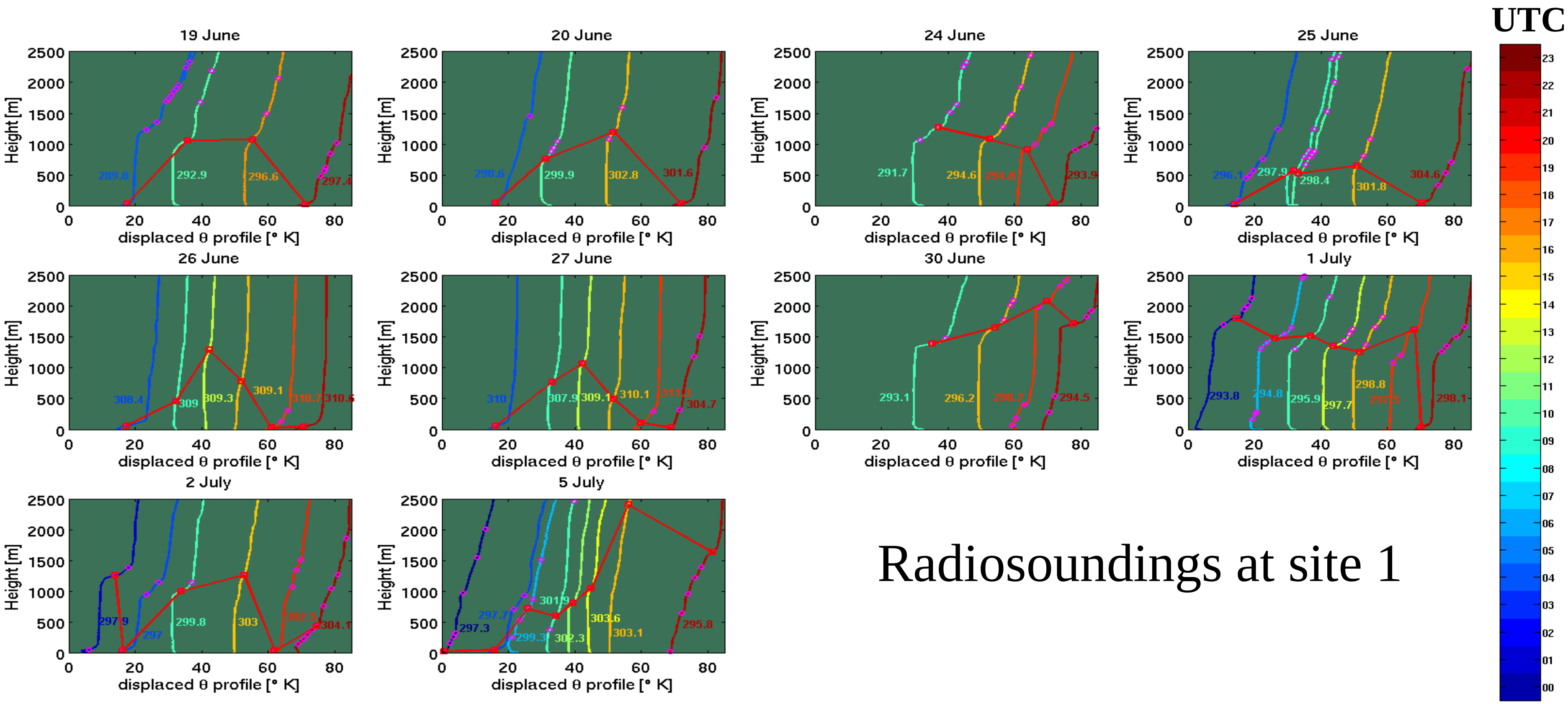
- Definition of z_i at the site and the sketch of Stull (1988) was discussed.

- An **initial evaluation of** how well a **meso-scale model AROME** predicts wind speed and TKE was presented

  - The **TKE near the surface is underestimated in AROME** and is more consistent to a TKE calculated from purely vertical wind variance.

More material for discussion

Vertical profiles of potential temperature



Radiosoundings at site 1

Vertical profiles are shifted along the x-axis and color coded according to the starting time of each radiosounding

Strongest gradient below 2500 m is marked with red squares. Gradients stronger than 1 K/100 m are also shown by purple circles.

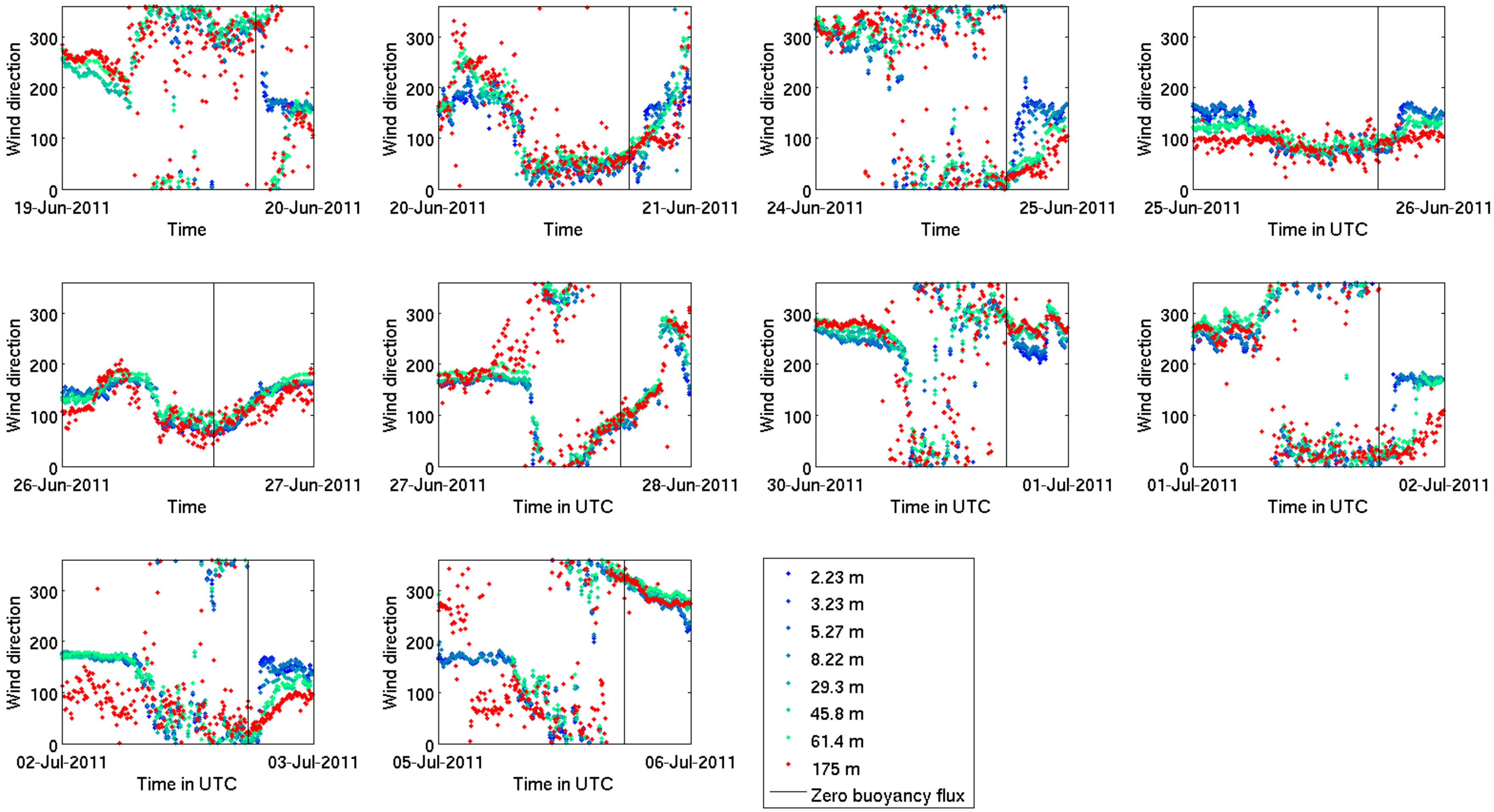
Theta value at 500 m is displayed for each profile sometimes shifted for readability

Wind direction at Site 1

In the evening the small tower measurements at 2 to 8 m (in bluish colors) can sometimes differ 180 degree in direction in comparison to the larger tower measurements at 29 to 61 m (in greenish).

The 60 m tower measurements usually are more representable for the boundary layer flow and agrees better with the lowest level of the UHF at 175 m (in red)

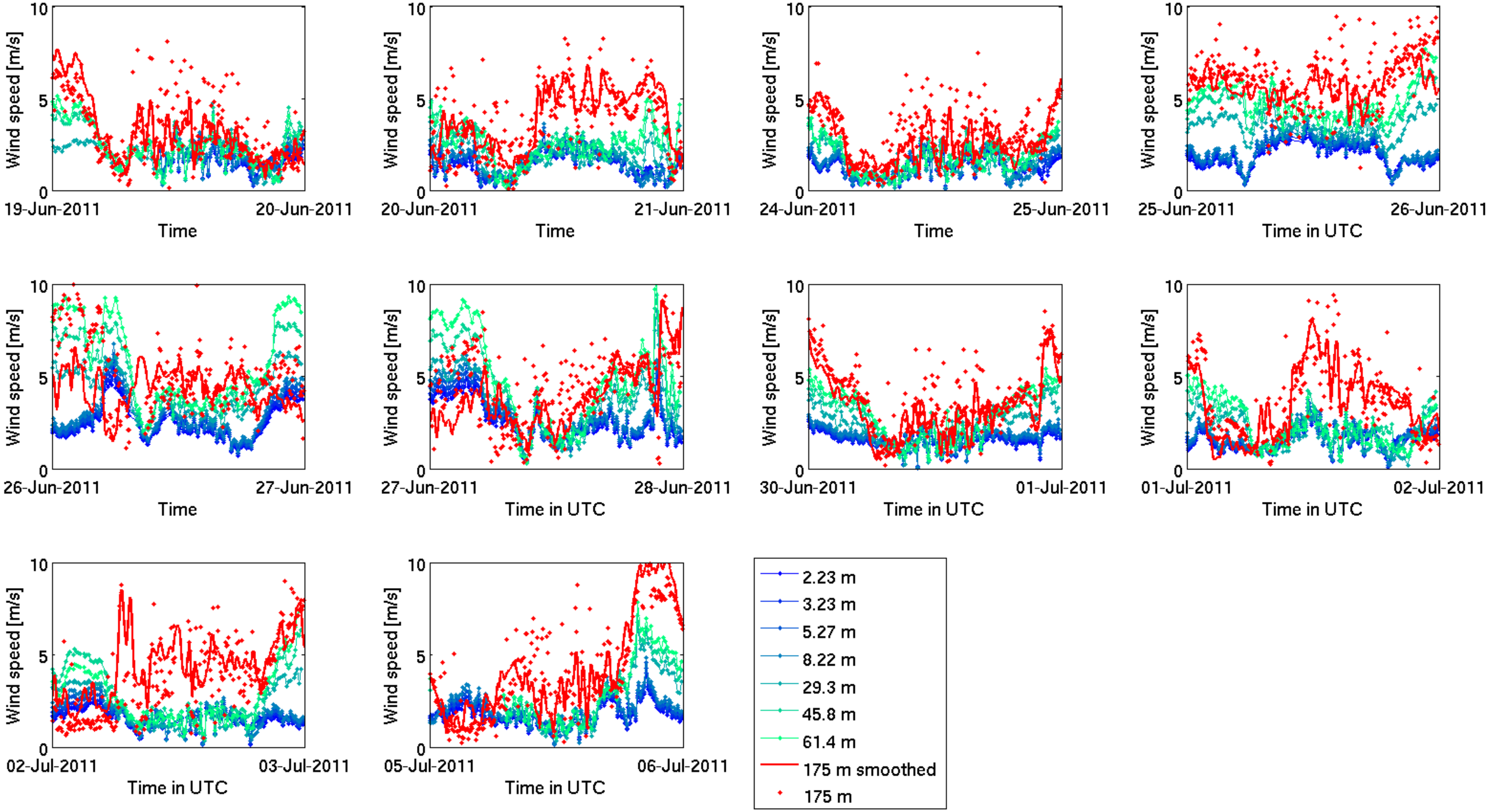
In daytime before the buoyancy flux becomes very small the small tower measurements mostly agree with the observations at higher levels on the tall tower. The TKE budget derived at surface can therefore potentially inform us about some of the dynamics that takes place also in the lower part of the boundary layer.



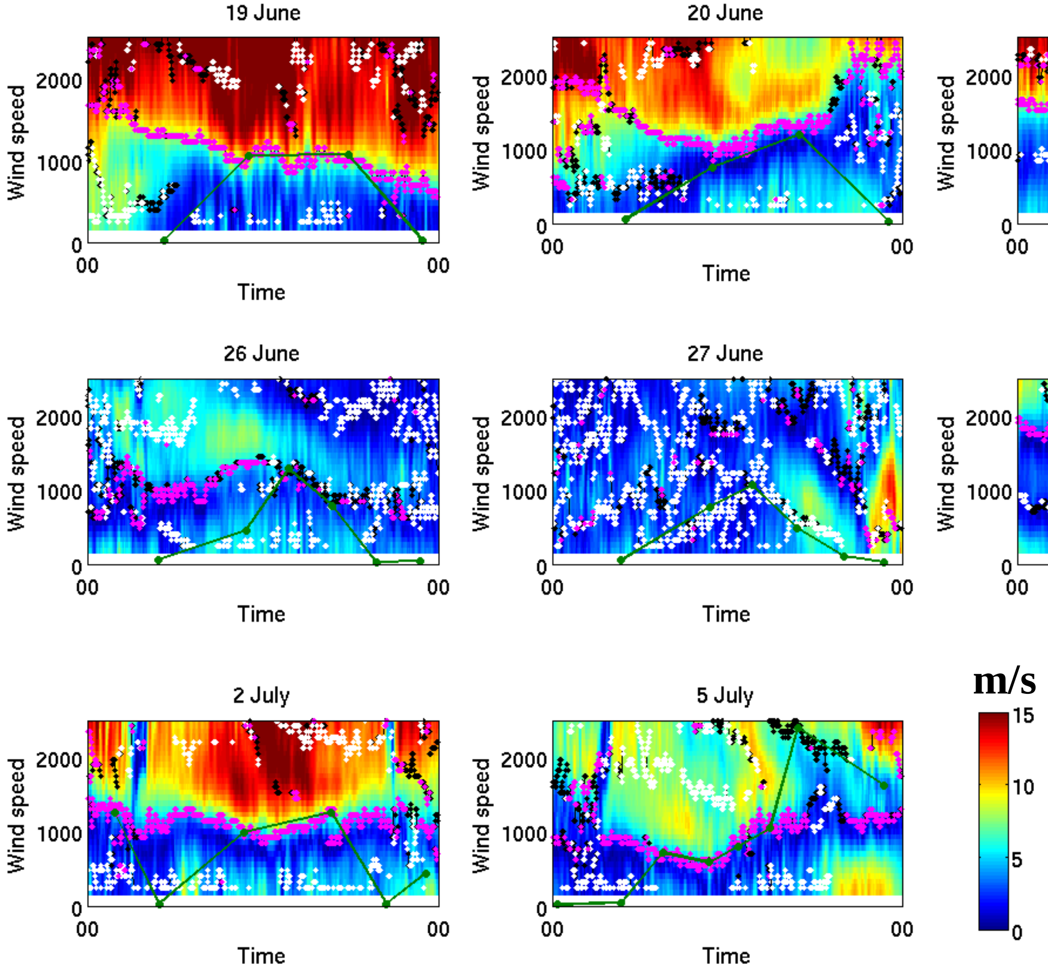
Wind speed at Site 1

The wind speed measurements are significantly more consistent between levels at the small tower (2 to 8 m) and at the large tower (30 to 60 m) than between the 8 m and 30 m level on the different towers which are separated by about 400 m.

But most of the time (ignoring non-stationarity, temporary fluctations and large scatter in UHF data) the measurements are reasonably consistent in daytime between the different data sources.



Smoothed and gapfilled wind speed from UHF



I borrowed some software from the Computational statistics community to smooth and gapfill data (but also apply some extra smoothing by running mean value procedures)

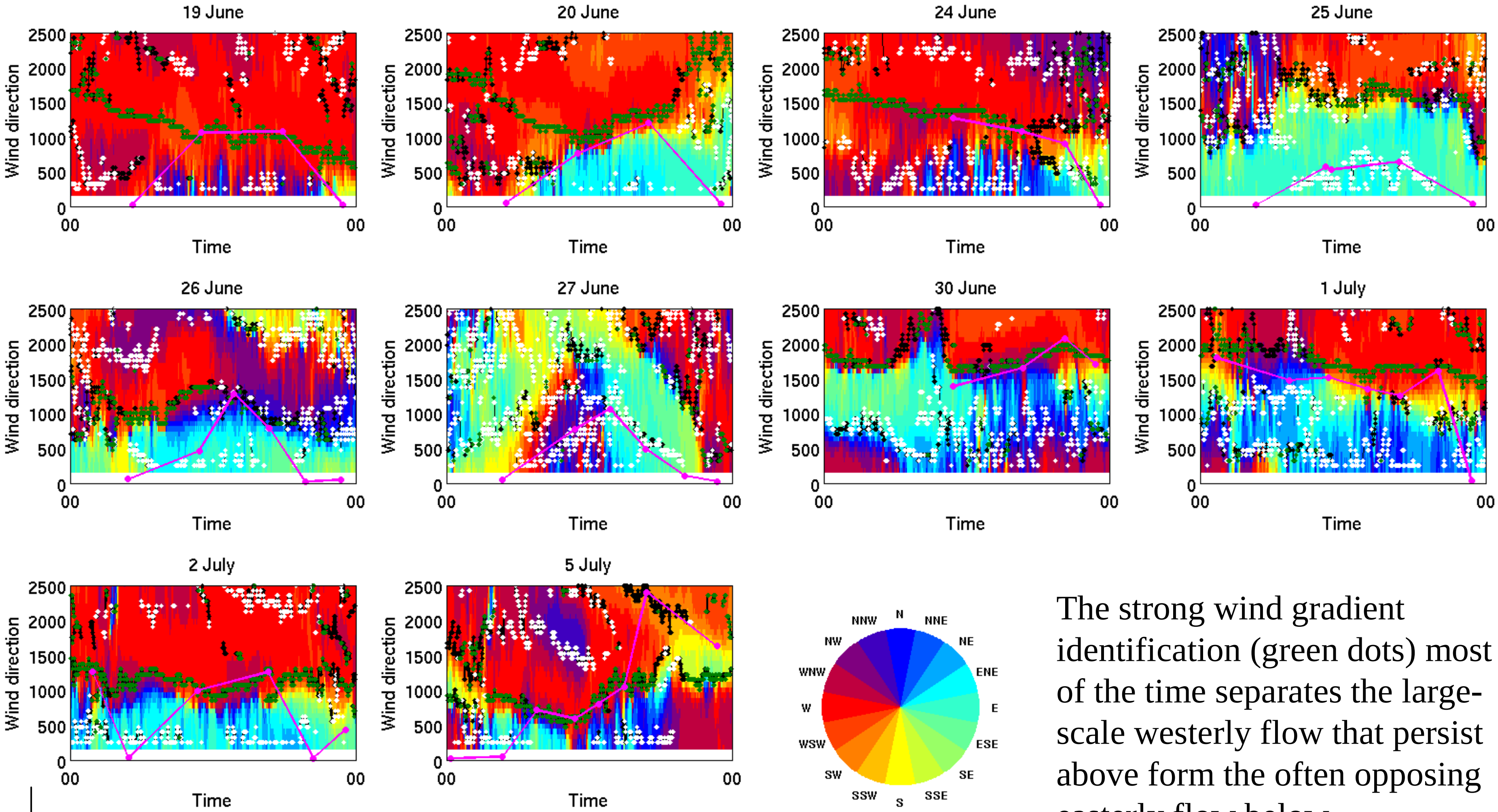
Garcia D, Robust smoothing of gridded data in one and higher dimensions with missing values. Computational Statistics & Data Analysis, 2010.

Strong local maximas in wind gradient (more than 1 m/s change in 100 m) shown in purple.

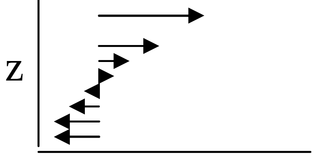
Moderate in black and weak in white (<0.5 m/s change in 100 m).

Strongest theta gradient from radiosounding shown in dark green.

Wind direction from UHF



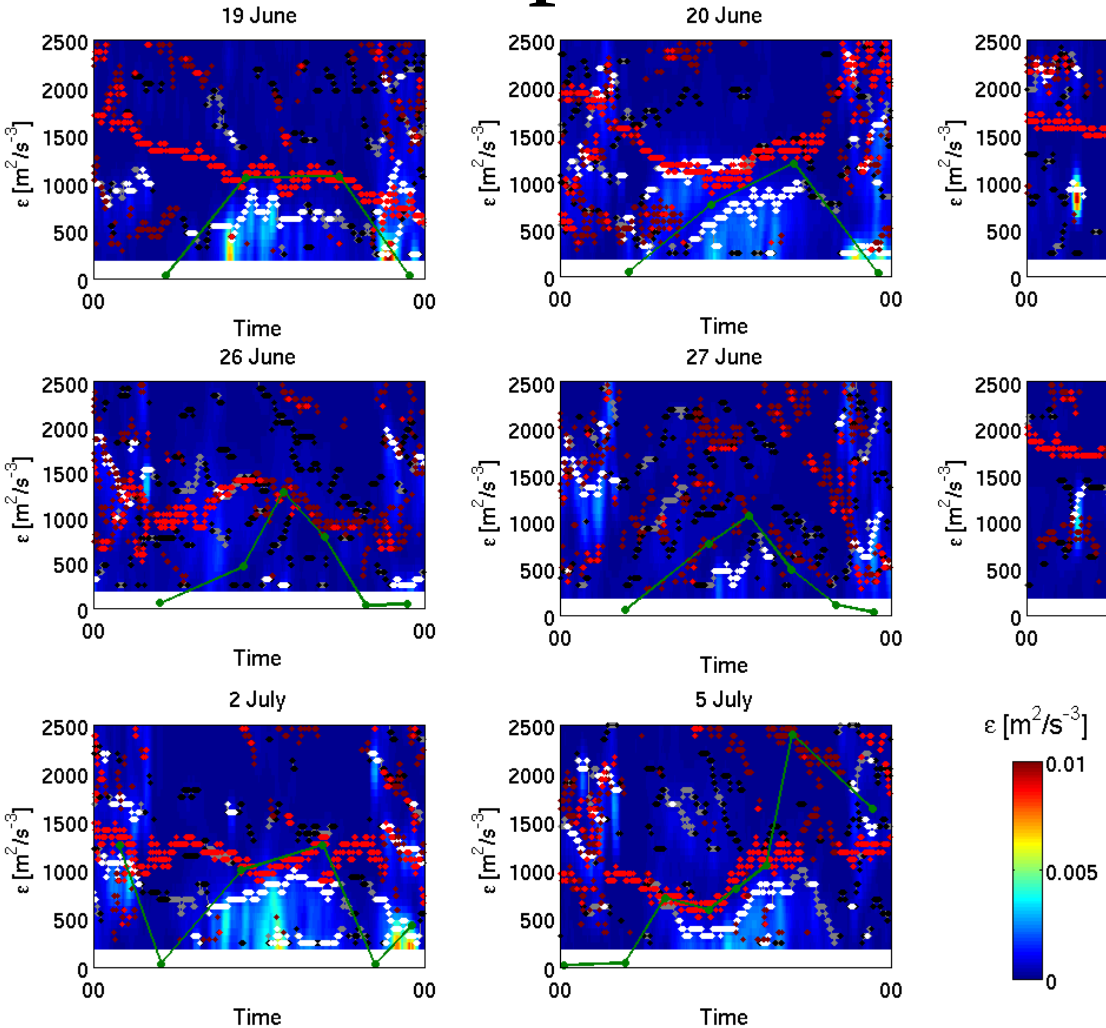
The strong wind gradient identification (green dots) most of the time separates the large-scale westerly flow that persist above form the often opposing easterly flow below



Idealized wind vectors

The figure emphasize the actual complexity that exist at the site

Dissipation rate from UHF



Strong wind gradient (in red) and strongest theta gradient (green) are similar on June 19, 24, (26), 30, and July 2, 5 for the afternoon. Otherwise theta gradient criteria are lower.

Epsilon gradient criteria (white) even lower. June 25, 26, 27 have lower dissipation rates than the other days

Strongest gradient in dissipation rate in white less than: -0.2*10^-5 ms^3

Wind gradient in bright red more than: 1 m/s per 100 m

Estimation of the terms in the budget:

Shear production

$$-\left[\overline{uw}\frac{\partial U}{\partial z} + \cancel{\overline{vw}\frac{\partial V}{\partial z}}\right]$$

Buoyancy production

$$\frac{g}{T_0}\overline{w\theta_v}$$

Momentum and heat fluxes 30 min averaging time on filtered time-series (10 min running mean) to remove long time-scale ’non-turbulent’ fluctuations

Wind gradient from fitted profile between wind speed and logaritmic height to obtain estimates at all 4 heights. Comparison to finite difference computation for 3.2 and 5.3 m level was performed.

8.2 m temperature chosen as reference temperature

Subsequent averaging of each term over each hour centered at 12.30, 13.30 ... was applied

Estimation of the terms in the budget:

TKE tendency	$\frac{\partial E}{\partial t}$	TKE = E determined for 10 min averaging time (no pre-filtering). A running 1 hour mean time-series was calculated before a second-order finite difference approximation was applied to obtain TKE tendency for the times 12.30, 13.30 ...
Dissipation	ϵ	Dissipation was calculated from spectra using fit to the inertial subrange and a Kolmogorov constant of 0.52. 8 periods of 7.5 min was used for each hour. Linear interpolation was used to gap fill time-series. Subsequent averaging of the dissipation term over each hour centered at 12.30, 13.30 ... was applied and standard deviation was calculated.

Estimation of the terms in the budget:

Turbulent and pressure transport

$$-\frac{\partial \overline{wE}}{\partial z} - \frac{\partial \overline{wp/\rho_0}}{\partial z}$$

Transport = Tendency - Shear
- Buoyancy - Dissipation

Attempts were made to estimate the turbulent transport term directly but estimates was found to be uncertain. The profile of estimated wE was found to be mostly non-monotonic regardless of choice of averaging time, pre-filtering procedure...

An attempt to calculate pressure-velocity correlation was performed using Microbarometer data and a vertically separated sonic anemometer at the small-scale heterogenity site. No clear leveling-of was found in Ogive curves.

Therefore we choose to calculate the sum of turbulent and pressure transport as a residual from the other terms in the budget.

Data screening and treatment:

•Out-of-range values above 100 or below -100 of any wind component or sonic temperature was removed from all time series.

•Outliers outside plus/minus 4 standard deviations from the mean value for each hour was also removed before further calculations.

•Each hourly time-series u, v, w and t was manually checked and suspicios ’noisy’ periods were error-flagged.

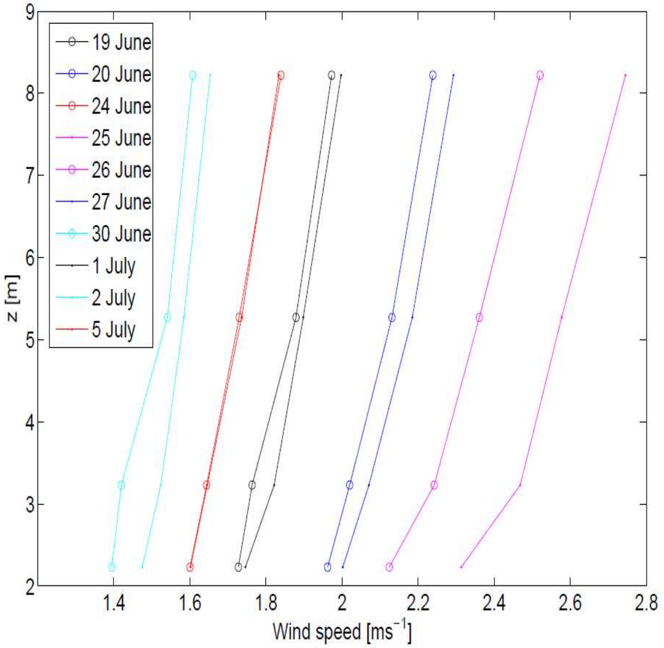
•If any 10 minute period of data had less than 90% data the hour was excluded from our hourly budget calculations.

•Linear interpolation was applied when needed

• Times with hourly reverse or non-monotonic wind gradient in stable conditions (mostly related to shallow drainage flow) requires special treatment for a reliable estimate of shear production. These times are therefore not included in the present analysis and budget calculations.

Classification of the 10 IOP afternoons

	Wind speed at 2.23 m	Shear production	Buoyancy production	Transport	Dissipation
Unit and scale factor	(ms^{-1})	(10^{-3} m^2s^{-3})	(10^{-3} m^2s^{-3})	(10^{-3} m^2s^{-3})	(10^{-3} m^2s^{-3})
June 19	1.73 (0.48)	2.3 (0.7)	3.2 (1.5)	-0.2 (0.7)	-5.4 (1.7)
June 20	1.96 (0.35)	3.8 (1.6)	2.9 (1.6)	-2.8 (1.9)	-4.0 (1.3)
June 24	1.60 (0.54)	2.1 (1.1)	3.4 (1.7)	-2.1 (1.1)	-3.5 (0.8)
June 25	2.31 (0.24)	7.8 (1.2)	2.4 (1.5)	-4.3 (1.7)	-6.1 (0.9)
June 26	2.12 (0.26)	6.9 (2.4)	2.1 (0.1)	-4.6 (1.6)	-4.5 (0.9)
June 27	2.00 (0.50)	4.3 (3.2)	1.9 (1.1)	-2.5 (1.3)	-3.7 (0.9)
June 30	1.39 (0.42)	1.5 (1.1)	2.2 (1.2)	-0.4 (0.7)	-3.3 (0.3)
July 1	1.75 (0.57)	2.6 (1.5)	2.8 (1.6)	-1.1 (0.8)	-4.3 (2.4)
July 2	1.47 (0.53)	1.1 (0.6)	2.3 (1.4)	-1.2 (0.9)	-2.1 (0.7)
July 5	1.60 (0.69)	3.0 (4.0)	1.9 (1.2)	-1.5 (1.8)	-3.4 (1.3)



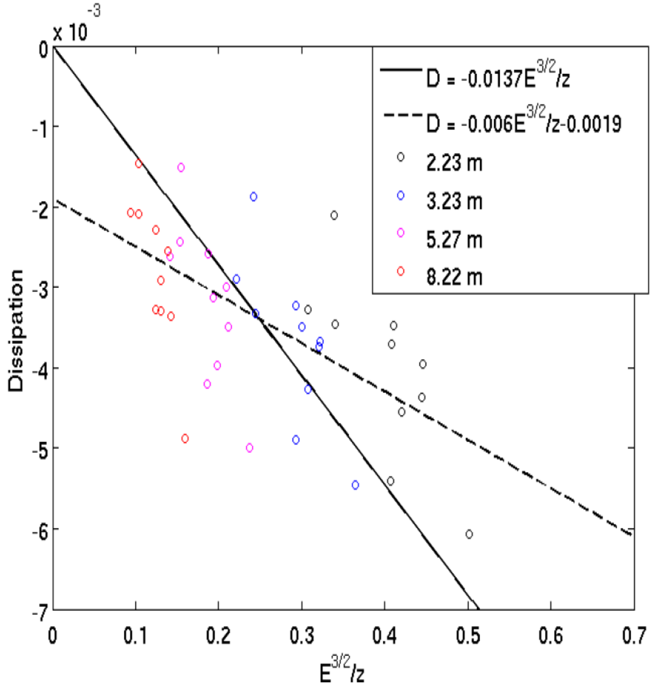
Categories: higher (h), moderate (m) and weaker (w) was formed based on the mean afternoon value of the TKE budget terms. Standard dev. in ( ) indicate variability of hourly values.

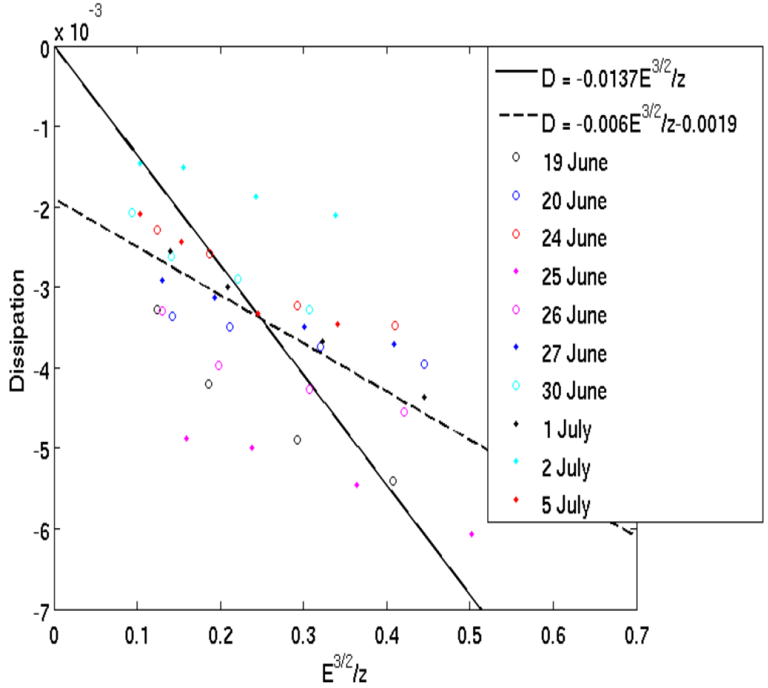
Limits used in classification (Note that a scale factor 10^{-3} applies on all terms.)

Shear: h > 3.5, 3.5<m<2.0, 2.0>w   Buoyancy: h > 2.5, 2.5>m

Dissipation: h < -4.5, -4.5<m<-3.5, -3.5<w   Transport: h < -2.5, -2.5<m<-1.5, -1.5<w

Alternative interpretation of observed near-surface dissipation





It is reasonable that dissipation decrease as TKE decrease and it is height dependent (higher dissipation close to the surface). $D = -0.006E^{3/2}/z + A$

At a large distance away from the surface we could expect mixed-layer dynamics to be related to variations in dissipation.

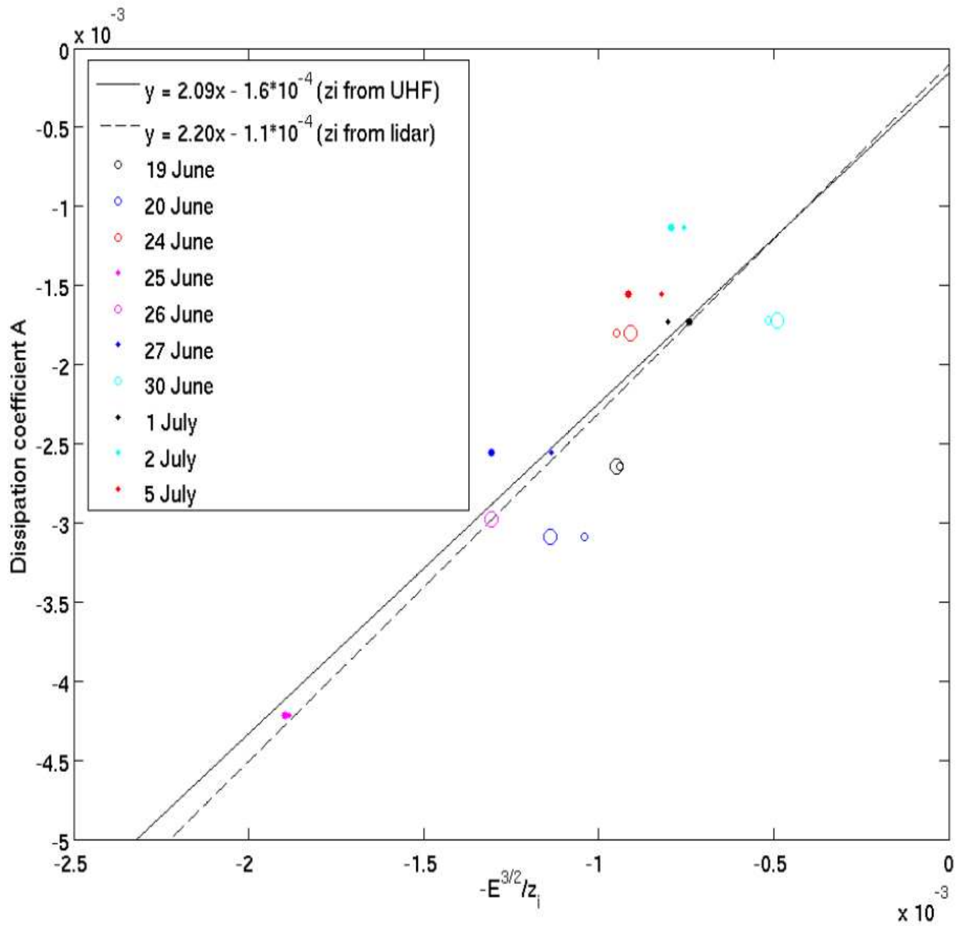
For each afternoon a linear fit $y = kx + A$ was performed and variations in the intersection value with the y-axis (A values) was investigated.

Variations in dissipation (weakly dependent on measurement height) was found to correlate with TKE and boundary layer height.

The best fit lines suggest:

$A = 2.1E^{3/2}/z_i$ – small number

$A = 2.2E^{3/2}/z_i$ – small number



Which give us an expression for dissipation:

$$D = -\frac{E^{3/2}}{l_\epsilon} = -E^{3/2}\left(\frac{2.2}{z_i} + \frac{0.006}{z}\right)$$

Where we suggest that both z_i and z influences a dissipation length scale which together with TKE determines the dissipation

(Nadeu et al. 2011 previously suggested: $D=-2E^{3/2}/zi$)