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Masters research internship

## Analysis of 2003 Halley sodar data



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## Abstract:

According to fluid mechanics, when the atmosphere flows over the Earth surface, friction on the ground creates turbulence. But the way air temperature decreases when altitude grows, traps that turbulence into a layer called the *planetary boundary layer* (PBL), which separate the ground from the upper part of the troposphere. The boundary layer depth is an important parameter for modeling the atmosphere, as it is the layer where pollutants and aerosols remain trapped, and also the layer through which the atmosphere exchanges heat and moisture with the ground.

Acoustic radars (sodars) can record time series of turbulence profiles for the first 1000m of the atmosphere. The sodar transmits a pulse of audible frequency sound, and listen to the strength of the 180°-backscattered signal. Sound is scattered from eddies in turbulent zones, so the instrument can be used to determine the boundary layer depth. A simple sodar was running well at the UK base of Halley in 2003, providing near continuous profiles every 10s through the winter. Halley offers optimal conditions for boundary layer studies, being settled on the Brunt permanent ice shelf and surrounded by dozens of miles of flat ice. Moreover during the austral night, the sun disappears for three months, enabling us to observe the nocturnal boundary layer that has barely time to start settling down during nighttime under our latitudes.

But contrary to all expectations, even on a site as simple as Halley, the sodar charts are incredibly complex, and the atmosphere profiles hardly ever look like the ideal scheme expected by the meteorologists, with a turbulent layer near the ground and a sharp transition towards no turbulence at all above. So during the first part of this internship, I developed a system for the automated detection of some interesting types of atmosphere profiles. We were especially interested in isolating the profiles where a clear boundary layer exists because we wanted to test some empiric formula proposed to calculate the boundary layer depth from the met and turbulence data.

However, in spite of all the sorting methods I would use, we didn't observe any correlation between the boundary layer depth derived from the sodar charts and the met data measured on the neighbouring mast. This is surprising, as around Halley, the forcing conditions imposed to the PBL by the surface are homogenous on very large surfaces and rather long periods of time. What is more, in Halley, there isn't any tree or hill to account for the complexity observed on the sodar. All this suggests that, even under constant forcing conditions in time and space, the atmosphere doesn't tend to an equilibrium state with a simple boundary layer. Why and how? At this stage, we can only guess. What we think is that, even on a plane surface, air masses flow in an inhomogeneous way generating a complex horizontal structure of turbulence. What we would like to know now is, in the vertical complexity we see on the sodar, how much is merely spatial heterogeneity flowing past the sodar, and how much is due to temporal evolution?

# 1. Introduction

## 1.1. How does a sodar work?

Sodar stands for “SONic Detection And Ranging”; it’s a radar working in acoustic frequencies. Every 10s, the speaker emits a 30ms pulse of sound at 2.3kHz that the parabolic antenna direct toward the sky.

While propagating into a turbulent zone, part of the sound can be back-scattered downwards if it encounters an eddy which size is about  $\lambda/2$ , ( $\lambda$  is the sound wavelength,  $\lambda \approx 15\text{cm}$ ). That echo isn’t audible to human ears but is recorded by the microphone. It is then amplified, digitised, compressed and stored.

Let  $\Delta t$  be the time elapsed between pulse emission and echo reception. If  $c_s$  is the sound celerity, then the altitude  $z$  where the sound wave encountered a suitable eddy is given by:  $z = c_s \frac{\Delta t}{2}$

So, for each pulse emitted, the microphone records the atmospheric echo profile giving the echo strength as a function of altitude. Considering the duration of the pulses – while it’s not possible recording – and the time between two successive pulses, the altitudes covered range from 26 to 1000m. Moreover, as the quantity of data produced is huge, data is compressed on 4 bits (integer from 0 to 15) with a point every 2m.

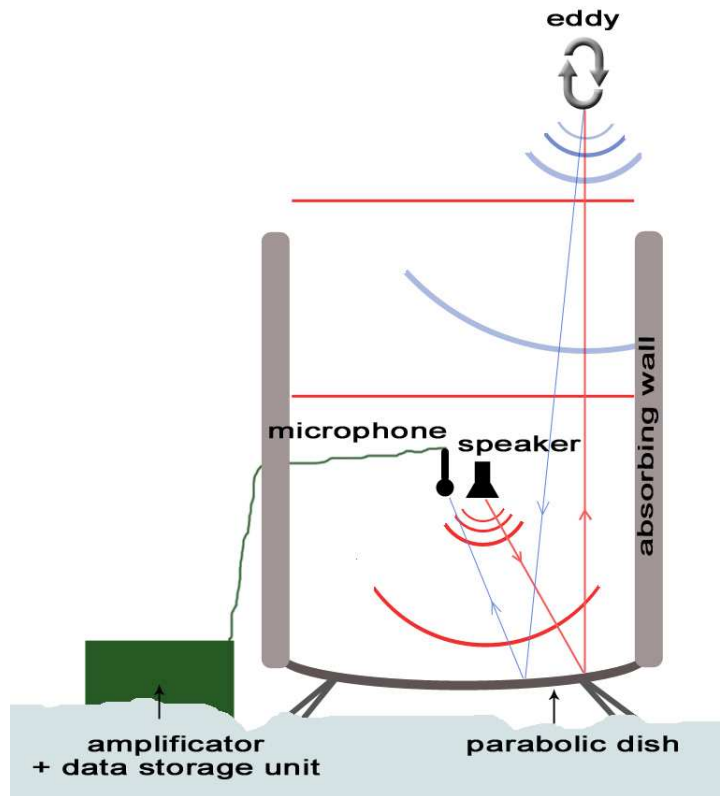


Fig. 1.1 - Scheme of Halley monostatic sodar. The absorbing wall dampens the side lobes of the pulse.

## 1.2. Types of echograms

### 1.2.1. With a boundary layer

Turbulence is created in the atmosphere by friction or convection at the contact with the ground. Most often it’s capped by a strong temperature inversion that cuts it from the upper troposphere. Thus turbulence is confined in a thin layer near the ground called the boundary layer (BL). So what the sodar hears is: strong echo near the ground in the boundary layer, then a sharp transition towards almost no echo for greater altitudes. That’s what we called “*simple profiles*” (Fig. 1.2).

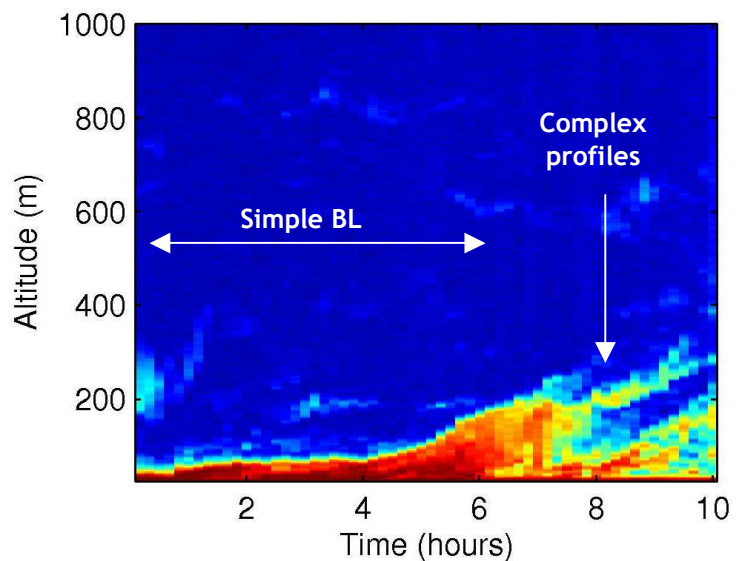


Fig. 1.2 - simple echogram

When the wind speed increases, the sodar also records the wind noise and the background noise level on the sodar charts increases as well. Simple profiles can still be seen but, as the wind noise might hide complex stratified turbulence, we will consider those “windy profiles” apart from the simple ones (Fig. 1.3).

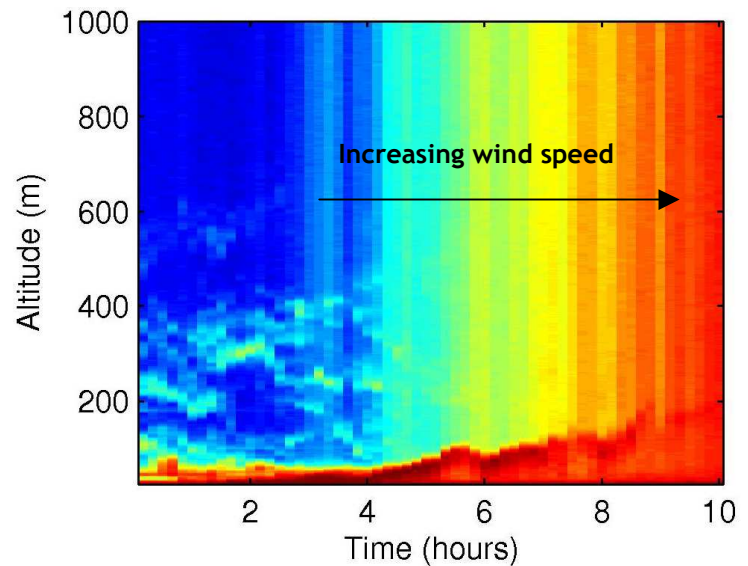


Fig. 1.3 - windy echogram

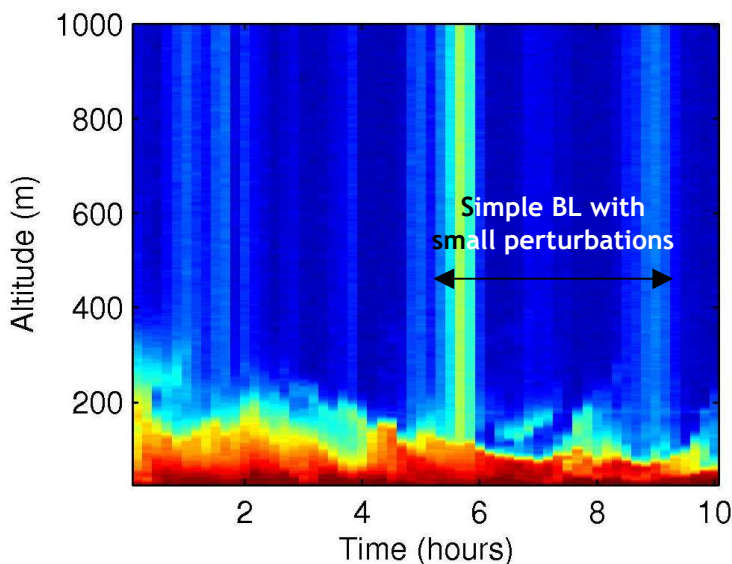


Fig. 1.4 - foamy echogram

Finally, on some occasions, weaker turbulence may exist above the boundary layer. If it's not too intense, then we can consider this is still a simple boundary layer, but with a small perturbation above, for instance due to a small irregularity on the ice surface. Those “foamy profiles” should also be included in our further study (Fig. 1.4).

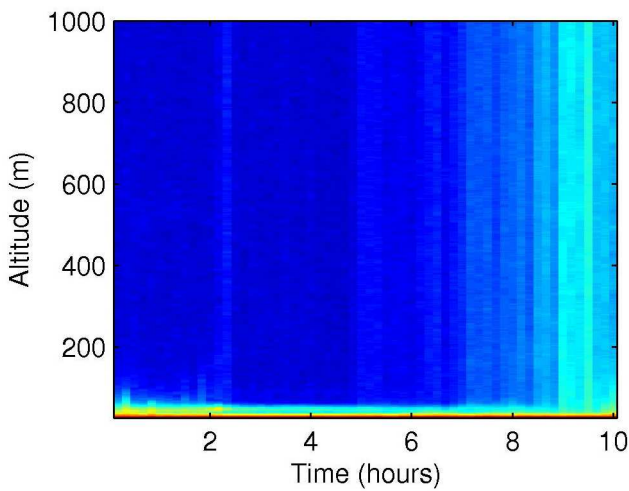
### 1.2.2. Without a boundary layer

Sometimes, no boundary layer is visible on the sodar charts (Fig. 1.5). This can happen when the boundary layer depth is below the sodar minimal range of 26m. Those are called “no echo profiles” and will have to be discarded. At other moments, horizontal lines run continuously on the bottom of the charts for  $z < 60\text{m}$  (Fig. 1.6). This occurs mainly in summer months, when the wind blows from an unusual direction and brings the sound pulse on one of the neighbouring building that reflects it toward the sodar. Those “false echo profiles” will have to be discarded as well.

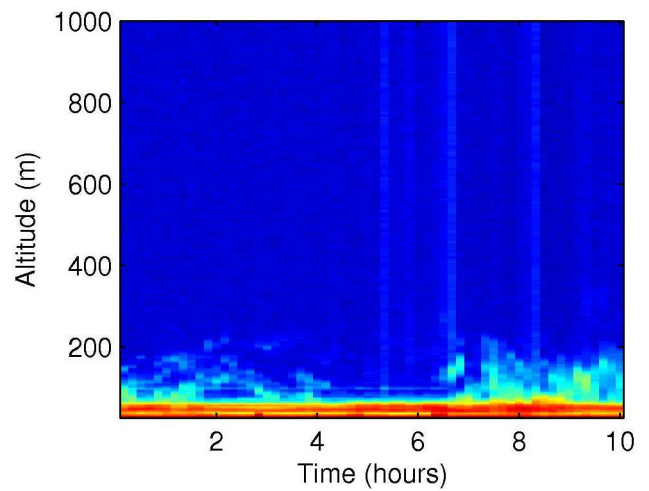
Another typical situation: during austral summer, the ice surface cools by emitting infrared radiation. The ice surface gets colder than the air above and cools the bottom of the boundary layer, creating a very strong temperature gradient. The atmosphere soon becomes so stable that all exchanges in the vertical direction are inhibited. Then vertical turbulence stops and the boundary layer splits into multiple layers that doesn't communicate with each other and can persist for several hours. We call those profiles “layered profiles” (Fig. 1.7).

Last interesting type of profile: the “spiky echogram” (Fig. 1.8). In wintertime, when the wind blows from the west, it brings over Halley an air that has travelled recently over areas of open sea. Seawater at  $\sim -1^\circ\text{C}$  is much warmer than the air above, which triggers an intense convection. As air

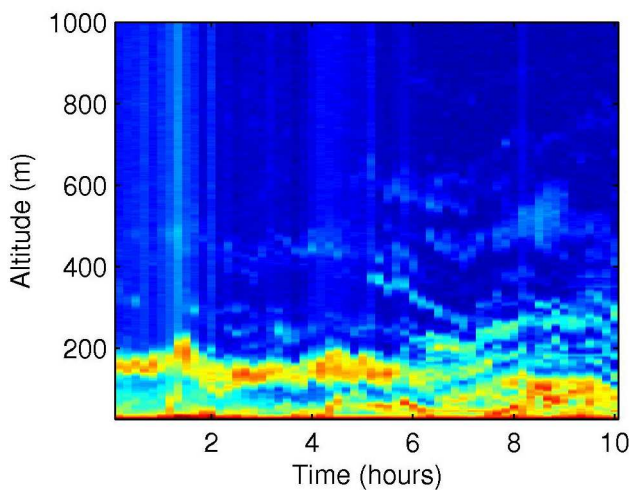
masses reach the Brunt Ice Shelf, the heat source is removed but convective plumes go on moving the air up and down for a while, and it's possible to see them passing along on the sodar charts.



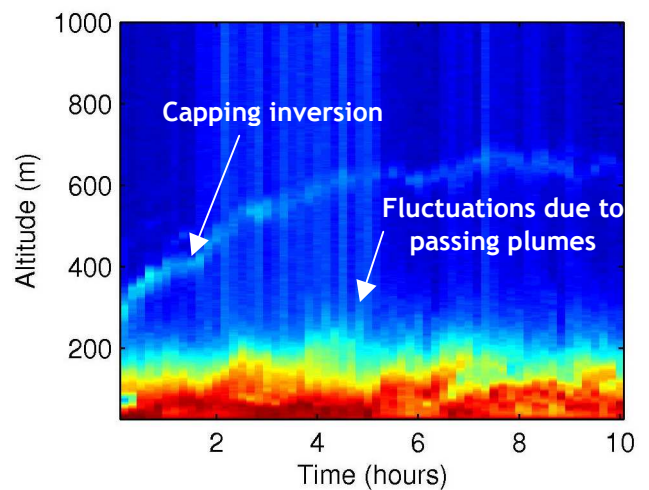
**Fig. 1.5** - no echo echogram



**Fig. 1.6** - false echo echogram



**Fig. 1.6** - layered echogram



**Fig. 1.7** - spiky echogram

Finally, everything that has not been listed above is called “*complex profiles*” and unfortunately, most of the Halley echograms are complex. This is rather surprising given that when the wind blows from the dominant direction, it brings over Halley air masses that have travelled above more than 100km of flat ice...

## 2. Characterizing the different profiles

First, I tried to set up characteristic sets of parameters for the types of profiles we wanted to sort automatically.

### 2.1. Profiles with a boundary layer

To characterize the profiles with a boundary layer, the idea was to fit them with a curve very close to a simple profile. So the fit would be very good for the simple and windy profiles, rather good for the foamy and really bad for all other type of profile. And this would give sets of characteristic coefficients.

#### 2.1.1. Fit by a hyperbolic tangent

I worked with the *tanh* function because Phil had noticed previously that it fitted the simple profiles rather well, and because it's a smooth transition that can be infinitely derived and integrated. As the profile has been compressed on integers between 0 and 15, we don't care if *tanh* is the real shape of the transition. However, I was not fitting stairs-like profiles: I had previously averaged the sodar data over 10 minute periods (or 60 profiles), as this is the frequency at which we have met data available. The fitting function is:

$$y = a + \frac{b}{2}(1 - \tanh(c(z - d)))$$

$y$  is the amplitude of echo recorded for the altitude  $z$ . The fitting parameters are  $a$ ,  $b$ ,  $c$  and  $d$ . Parameter  $a$  gives the level of background noise;  $b$  is the amplitude of the transition;  $d$  is the transition central altitude and as  $-\frac{bc}{2}$  is the tangent slope at  $z = d$ , the greater  $c$  is, the sharper the transitions will be.

To evaluate how good the fit is, I used the correlation coefficient  $cc$  between the fitting curve and the original profile. The values of  $cc$  are always very high, even when the fit is obviously bad, but this isn't surprising if we think that the interesting part of the curve is most often situated below 200m. Above, the fit looks like a straight line fitting a noisy line and that part of the curve gives very good correlations that account for 80% of  $cc$ . Fits are excellent with the simple and windy profiles, but not very good with the foamy.

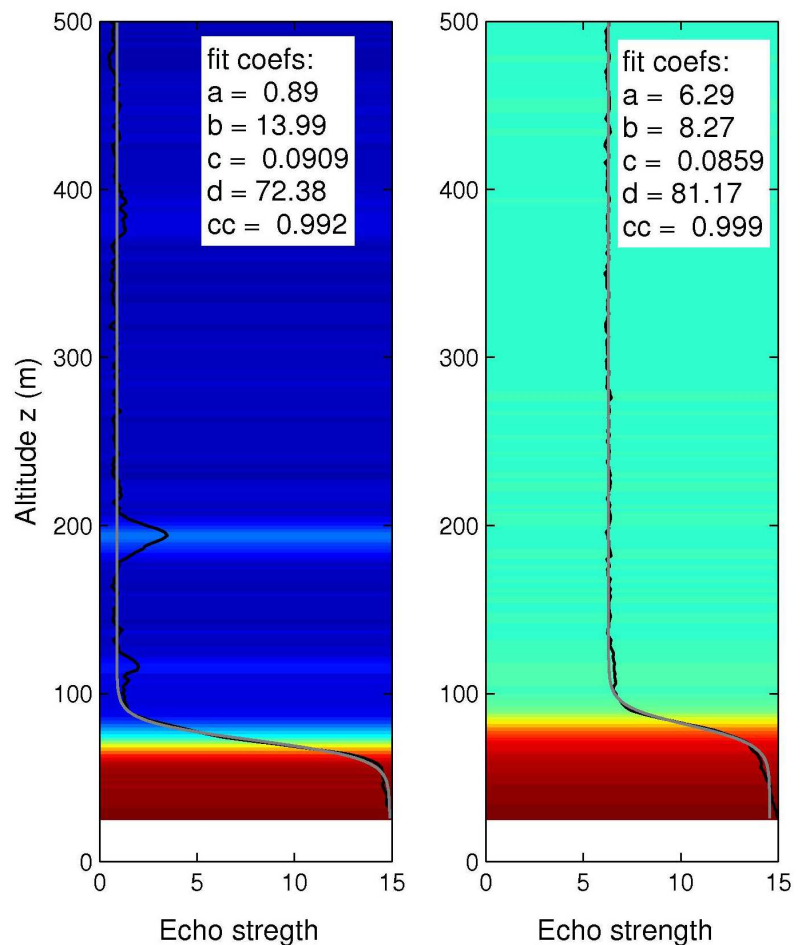


Fig. 2.1 - fit of a simple profile (left) and of a windy profile (right) by a *tanh* function.

### 2.1.2. Improvement by adding fake points

In some cases, the echo amplitude doesn't show a clear step at 15 near the ground (it might be below 26m); or for the foamy profiles, the foot of the transition is hidden by less intense turbulence. The profile looks more like an exponential curve in that case, and the  $\tanh$  fit will return absurd values of  $b$  and  $d$  (Fig. 2.2).

To force the fitting program to stick to the step, I added fake points between  $-200$  and  $26\text{m}$ , with values at  $15$ . But this didn't help to fit the foamy better as I hoped, because turbulence at the foot of the transition led to wrong values of  $c$  and  $d$  anyway.

Moreover, I realized that some complex profiles could have - by chance - very high correlation coefficient, higher than the foamy. So in the end, we can't characterize the foamy with the  $\tanh$  method.

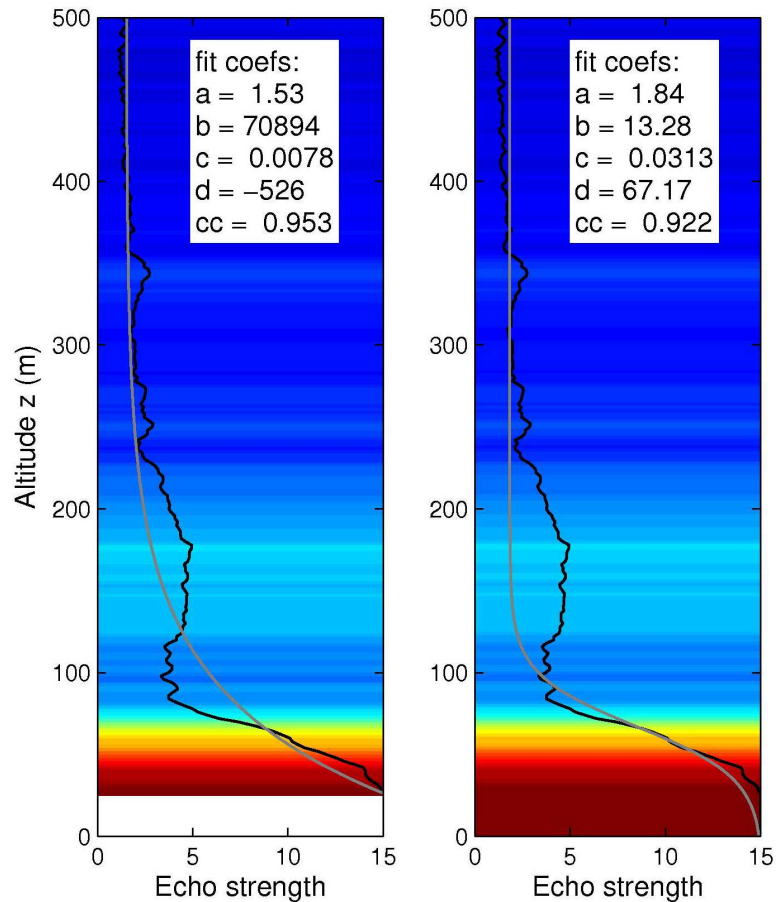


Fig. 2.2 - fit of a foamy profile. (left) simple fit; (right) fit with fake added points.

### 2.1.3. Characteristic set of coefficients for the simple and windy profiles

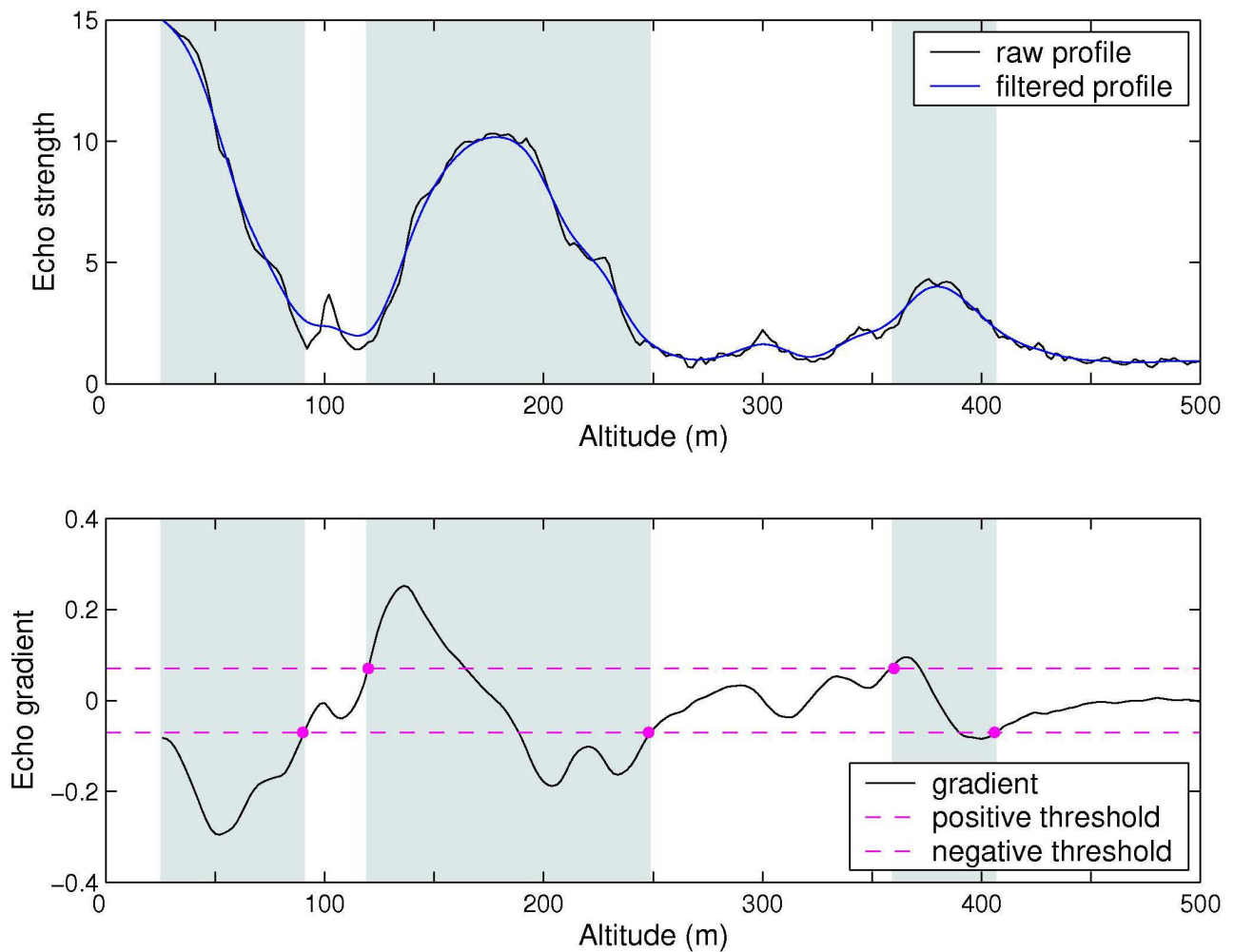
The simple and windy profiles can be characterized by a very sharp transition between the boundary layer and the upper troposphere ( $c > 0.04$ ) and a very high correlation between the  $\tanh$  fit and the original profile ( $cc > 0.98$ ). The maximum background noise level will be  $a_{max} = 3$  for the simple profiles and  $a_{max} = 9$  for the windy ones. I gave up the foamy profiles.

## 2.2. Layered profiles detection

Here, the purpose was to detect when turbulence doesn't exist only in a layer near the ground but also exist in other layers in altitude. If possible, knowing the altitudes where there's turbulence would be useful to air chemistry studies.

### 2.2.1. First algorithm

I wrote a first, rather simple algorithm using the gradient of the echo amplitude. First, the program filters the profile using a 1D linear filter (basically replacing a point by the average of the 7 closest points). This is to remove the small echo fluctuations so that the gradient will show only the large-scale echo variations. The beginning of a layer is defined as the altitude where the gradient gets greater than a threshold value  $gr_{min}$ , and the end of a layer is the altitude where the gradient becomes greater than  $-gr_{min}$ . Then, all the altitudes obtained are mixed and the program fills in a "layer" vector assuming start and end points are alternated (Fig. 2.3).



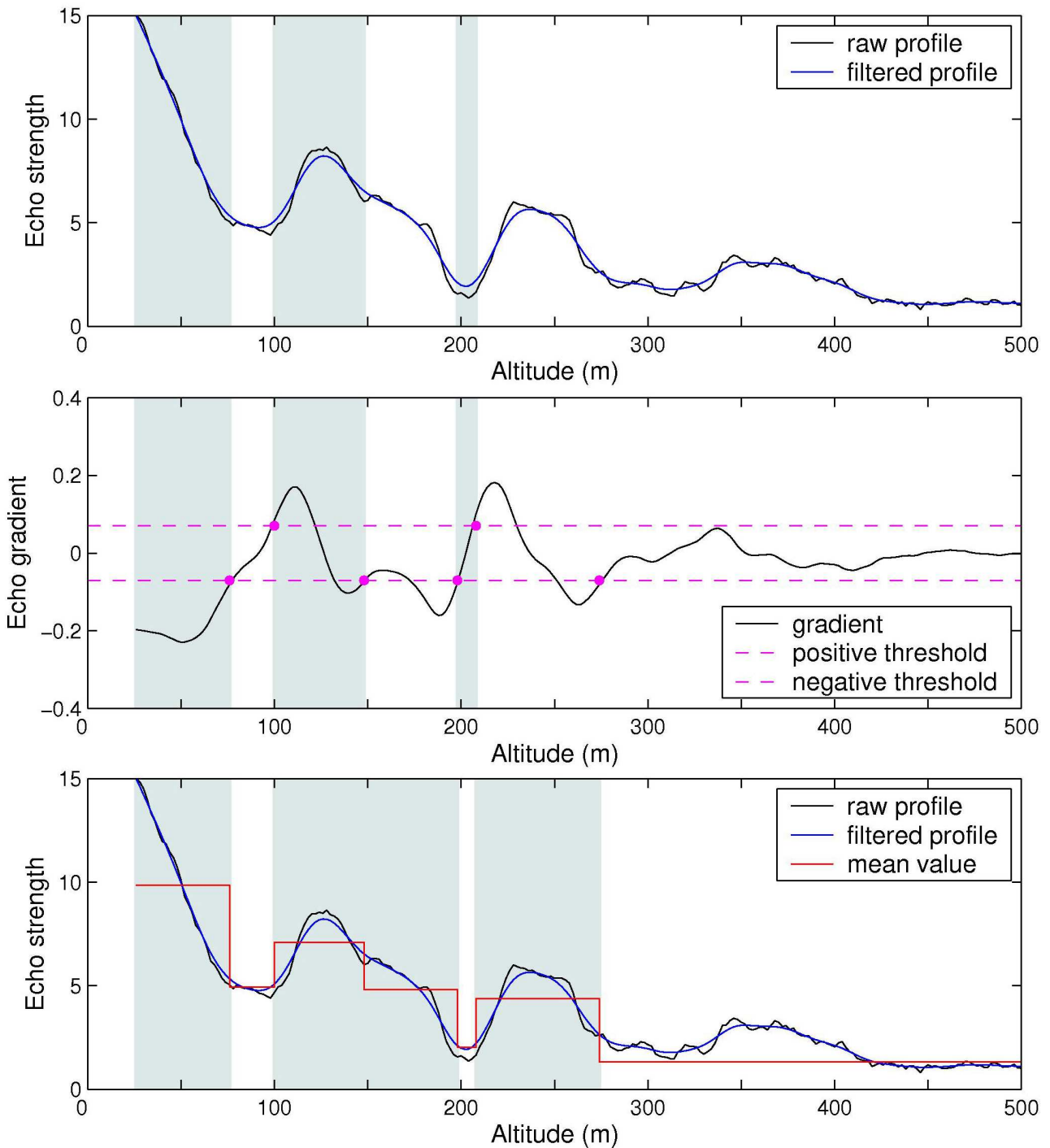
**Fig. 2.3** - layer detection with the first algorithm on a profile showing only one turbulent layer above the surface layer. (top) the raw and filtered profiles, (bottom) the gradient of the filtered profile, the threshold lines and the points detected (pink circles). Zones detected as layers are coloured in blue. Here  $gr_{min} = 0.07$

### 2.2.2. Improvements

The basic program is OK when the layers have simple shapes: the echo strength increases then decreases with strong slopes. But sometimes, when the echo strength follows more complicated patterns, for instance when there are 2 echo maxima in the same layer, the start and end points detected by the program won't be alternated. So I modified the program to enable the computer to recognize irrelevant points. The new program detects start and end points with the previous method and mixes them as well; then it calculates the echo strength mean value between the points and looks for the direction of variation of that mean value. Finally, the points situated between two variations in the same direction are discarded (Fig. 2.4).

To get a wider separation between two successive strong echo layers, it's possible to use the echo gradient extrema instead of the border point of strong echo zones. In that case, the threshold condition is to keep only the maxima greater than  $gr_{min}$  and the minima smaller than  $-gr_{min}$ . And the irrelevant point detection still works.

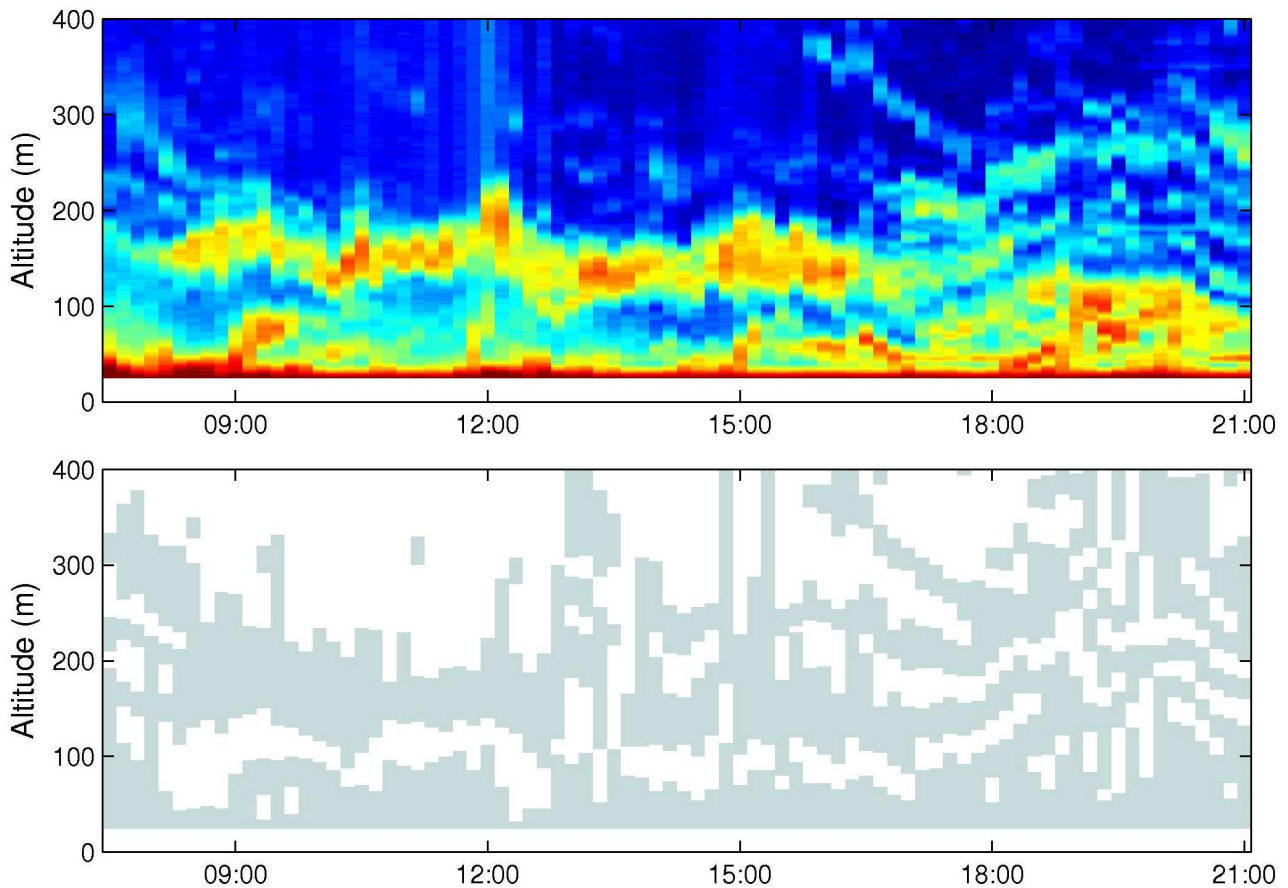




**Fig. 2.4** - layer detection with the second algorithm. (top) the raw and filtered profile and results of the first algorithm: the layer zones (in blue) are false. (middle) the echo gradient, threshold lines, and points detected: two end points come one after the other. (bottom) the profile and the mean value between the detected points: the point around 150m has been deleted as it's between two decreases of the echo mean value.

### 2.2.3. Threshold problems

The computer is now able to pick up and delete the irrelevant points, but it can't do anything when a point is missing. That can happen when an extremum is below the threshold and isn't detected so the start and end point won't be alternated. An obvious solution would be to lower the threshold value. However, no matter what value of  $gr_{min}$  is chosen, there will always be some profiles where there's a missing point; and the program will start picking up small variations that are complex patterns and not really strong echo layers (Fig. 2.5).



**Fig. 2.5** - Evolution of layers detected on June 11 2003 between 8:30 and 21:00. (top) original image from the sodar after 10' averaging. (bottom) layers detected for each profile with  $gr_{min} = 0.04$ . The long vertical bars are typical of a missing point, and some small complex patterns have been picked up as well.

To conclude on layer detection, a simple algorithm can't give a good representation of the evolution of a stratified structure in time. The altitudes given as borders for the layers are not really usable, because of the threshold problem. A two-level detection would probably be necessary: a first run with a high threshold, and if starts and ends aren't alternated, a second run with a lower threshold. But as this was not the main subject of my project, I didn't take time to compute that.

However, I think it would be possible just to detect layered days using, not the altitudes of the layers found, but merely the number of layers returned. Even if one point is missing on some profiles and the number of layers is false, if in average, the number of layers remains above a limit value  $n$  for several hours, then that period is very likely to be stratified. This should make the difference with complex days where the number of layers detected will be much more fluctuating and won't remain constantly above  $n$ . To detect days with one single strong echo layer  $gr_{min} = 0.07$  and  $n = 2$  should do. For very stratified days with multiple layers,  $gr_{min} = 0.04$  and  $n = 4$  are better.

### 3. Automated sorting of simple and windy profiles

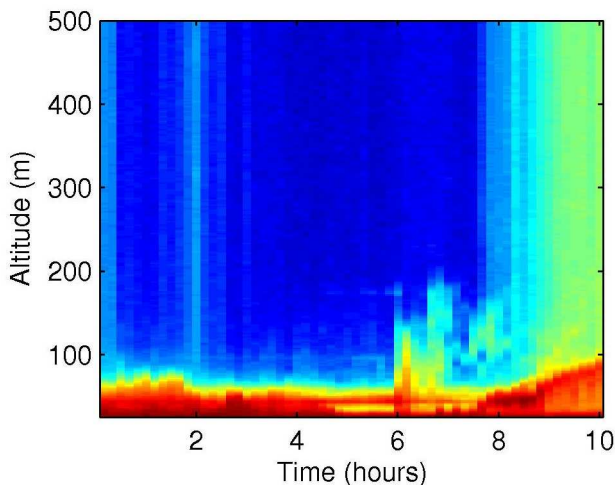
Now we have characterized the profiles showing a clear boundary layer, we'll be able to pick them up among all 2003 sodar data. Then we'll try to correlate the boundary layer depth observed on the sodar with the met and turbulence conditions measured near the ground.

#### 3.1. Sorting Method

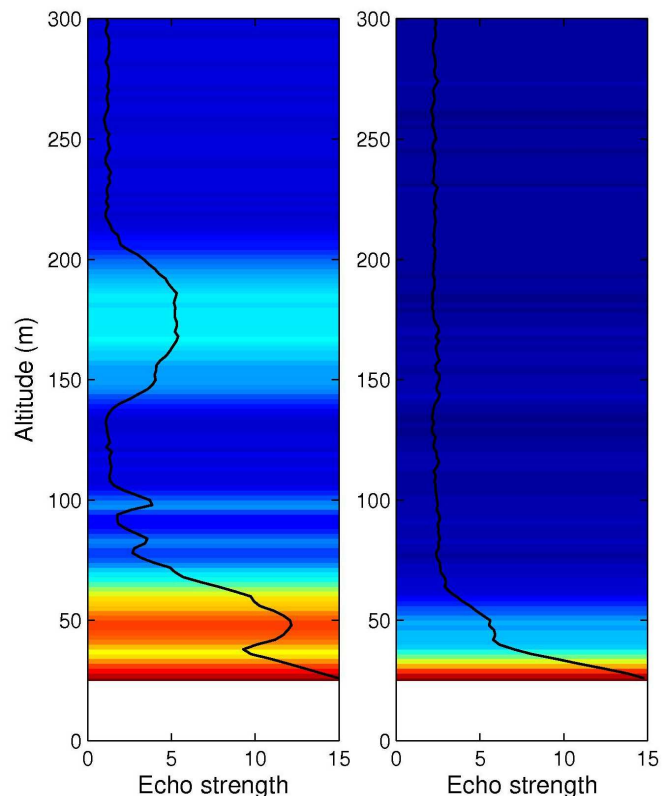
I started with a very simple algorithm just looping on all 2003 and fitting all the profiles one by one. It kept only the profiles with  $c > 0.04$ ,  $cc > 0.98$  and  $a < 3$ . Not a very fast method, but possible to run overnight. That way, I obtained 420 profiles over more than 47,000: less than 1%!! However, we were happy with only a few hundred points because too many points would just have overloaded scatter plots.

##### 3.1.1. False positive detection

But when having a closer look at those profiles, I realised that some of them were in fact false echo and no echo profiles (fig. 3.1). The false echo profiles show a characteristic increase of echo strength for  $z < 60\text{m}$  where the second false echo line begins. So to discard the false echo profiles, I wrote a simple routine looking for a big increase in echo strength below 60m. As for the no echo profiles, their only characteristic is that they show no step of echo strength a 15. This means that if those profiles are fitted without adding points, the values of the  $b$  parameter will be greater than 15. Applying these two criteria, my 420 simple profiles became 385.



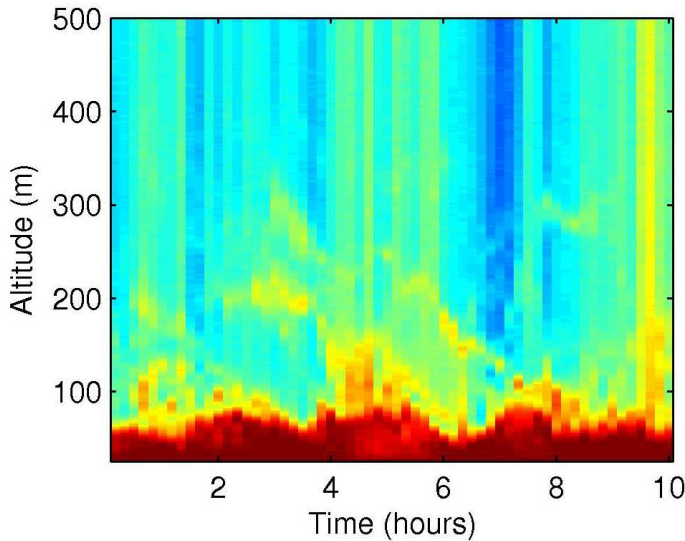
**Fig. 3.2** - a case when it's not possible to make the difference between a real boundary layer and false echo lines.



**Fig. 3.1** - two types of false positives. (left) when the echo strength doesn't drop too much between the two false echo lines,  $cc$  remains above 0.98. (right) because of added point the fit will work for no echo profiles.

Unfortunately, there will always be a few cases when false echo profiles can't be detected: when the boundary layer top fluctuates around the height of the second false echo line ( $\sim 60\text{m}$ ), then it's impossible to say if the echo transition is the top of the false echo line or the top of the boundary layer (fig. 3.2). The profiles look simple but the values of the boundary layer depth will be questionable.

### 3.1.2. Background noise limit



**Fig. 3.3** - Echogram of a complex day with strong wind. Gusts of wind can cover the sound back-scattered by turbulence above the BL and the profile will look simple.

Then I tried to sort the windy profiles and raised the background noise level allowed to 9 instead of 3. It's a rather high value, but still low enough to be able to see a clear transition if there is one. We thought that when the wind is strong, turbulence could only persist in the boundary layer where it's maintained by friction on the ground. All turbulence existing above would be quickly destroyed by the wind. So we didn't think that complex patterns could hide behind the wind noise.

However, for  $a_{max} = 9$  the computer picked up many profiles with hidden complex patterns. So I lowered the value of  $a_{max}$  to 5 to be sure that anything hidden behind would be only weak turbulence. This gives ~500 windy and simple profiles.

## 3.2. Correlation of the BL depth with met and turbulence data

Once I had produced a collection of simple and windy profiles, we wanted to test some empirical laws that have been proposed to calculate the boundary layer depth from the met and turbulence data measured on the ground. We were particularly interested in the formulations from Pollard et al. (1973) and Zilitinkevich (1972), which had both given good results for Neff et al. (2006) on a study similar to Halley experiment they carried at the South Pole base during last austral summer. So I wrote a program to go and pick up met and turbulence data for every simple profile in 2003.

### 3.2.1. Met and turbulence measurements at Halley

Met measurements at Halley come from a 32m mast settled not far from the sodar. Temperature, wind speed, wind direction and relative humidity are measured every 10 minutes at 1, 2, 4, 8, 16 and 32m heights. A radiometer gives the incoming and outgoing fluxes summed on visible and near infrared wavelengths (solar radiation incoming and reflected,  $F_{SW}^{\downarrow}$  and  $F_{SW}^{\uparrow}$ ); and the incoming and outgoing fluxes summed over far infrared wavelength (blackbody emission respectively from the atmosphere  $F_{LW}^{\downarrow}$ , and ground  $F_{LW}^{\uparrow}$ ). In that study I will also use the potential temperature gradient  $d\theta/dz$ <sup>1</sup> and the surface global radiation budget  $F^* = F_{SW}^{\downarrow} - F_{SW}^{\uparrow} + F_{LW}^{\downarrow} - F_{LW}^{\uparrow}$

Turbulence measurements are made at 4, 16 and 32m heights by sonic anemometers. Those instruments can give the values of the wind vector three components, and repeat that measure several dozens of time per second. Then, each minute, the instrument calculated the averages, variances and covariances of those components. Table 3.1 explains which quantities we used.

<sup>1</sup>  $\theta$  the potential temperature is defined as the temperature that an air parcel would have if it were brought back adiabatically from its altitude to sea level. Halley being nearly at sea level, we consider that  $\theta = T$  where T is the usual temperature in Kelvin. We approximate the gradient by  $\frac{d\theta}{dz} \approx \frac{T_{32m} - T_{1m}}{32 - 1}$

**Table 3.1** Definition of the turbulence variables we used.  $\{u, v, w\}$  are the wind speed 3 components following the directions  $\{Ox, Oy, Oz\}$ ;  $\bar{u}$  is  $u$  mean value and  $u' = u - \bar{u}$  is the turbulent part of  $u$  - same for  $v$  and  $w$ . Covariances will be noted  $\overline{\alpha' \beta'}$ .  $t$  is temperature in °C.

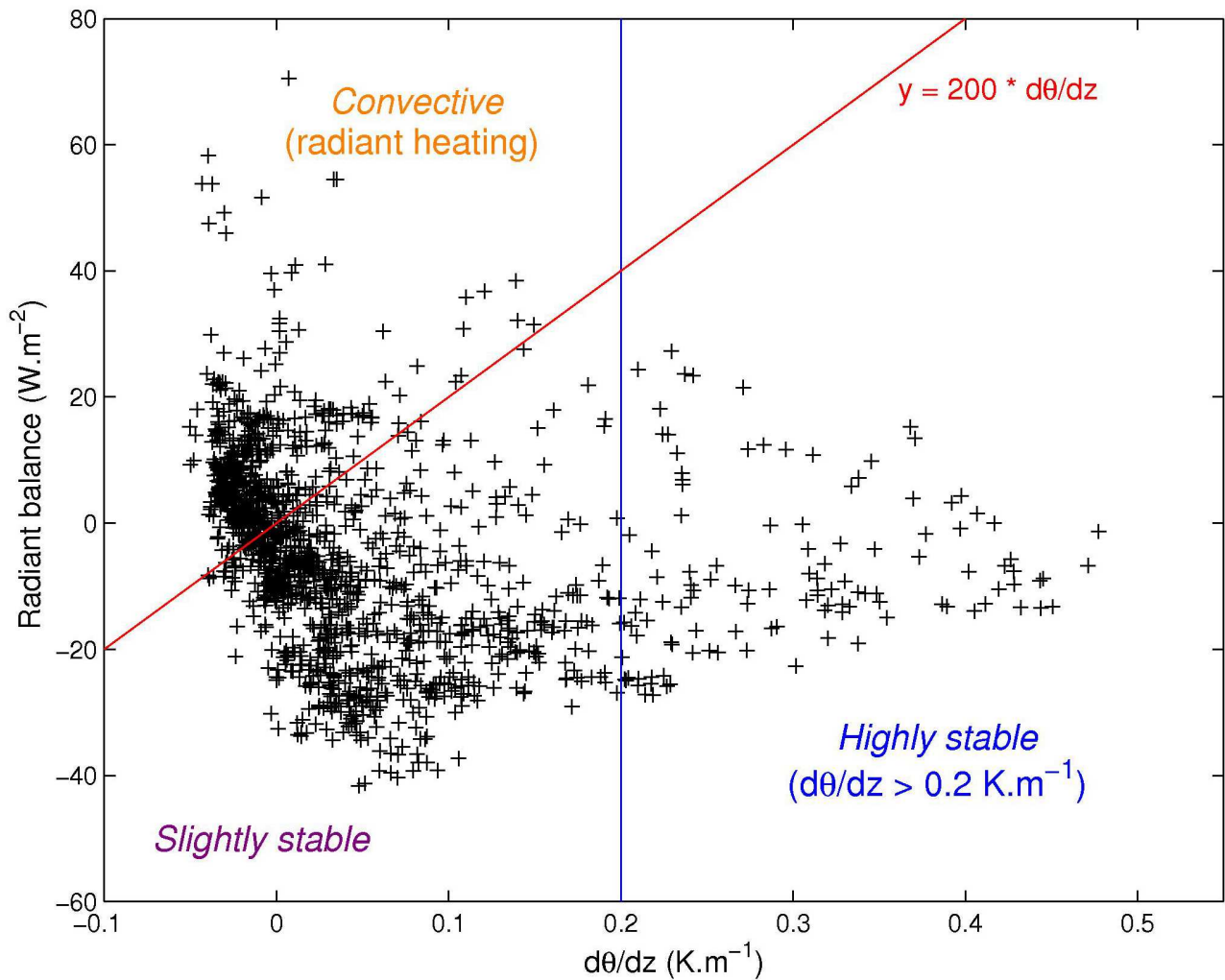
Notation	Units	Name et definition
$u_*$	$m.s^{-1}$	Friction velocity, calculated by: It's the vertical flux of horizontal momentum. $u_* = \left( \overline{u' w'^2} + \overline{v' w'^2} \right)^{1/4}$
$u_*^2$	$m^2.s^{-2}$	$u_*^2$ is proportional to the wind stress $\tau_s$ : $u_*^2 = \frac{\tau_s}{\rho}$
$TKE$	$J.m^{-3}$	Turbulent kinetic energy by unit of volume: $TKE = \frac{1}{2} \rho (\overline{u'^2} + \overline{v'^2} + \overline{w'^2})$
$\overline{w' t'}$	$K.m.s^{-1}$	Kinematic heat flux ( $\overline{w' t'} > 0$ for an upward flux). The real heat flux in $W.m^{-2}$ is $Q$ : $Q = \rho C_p \overline{w' t'}$
$\overline{t'^2}$	$K^2$	Temperature variance

### 3.2.2. Heterogeneous conditions

Once I had gathered all the data needed, I made scatter plots showing the boundary layer depth plotted against two variables chosen among: the temperature gradient  $d\theta/dz$ , the horizontal wind speed, the vertical heat flux and the friction velocity. If any correlation had existed between the 3 quantities the scatter plot should have shown a nice shading of colours; but the distribution was random. Phil suggested that the atmospheric conditions might be heterogeneous in term of stability.

Indeed, 3 types of boundary layer exist. When the ground surface is warmer than the air above, the air near the ground is heated and moves upward as its buoyancy increases: convective plumes appear. Under those conditions, the boundary layer is said to be *unstable*. At Halley, this happens during spring and summer under clear skies, when the sun is high enough to heat the ground. On the contrary, when the ground surface is colder than the air above, the boundary layer is said to be *stable*. That type of conditions is supposed to be dominant in Halley in wintertime: as the sun is gone, when there are no clouds, the ice surface cools down by emitting infrared radiations. Finally, when the wind is strong, friction effects dominate turbulence production and the boundary layer is said to be *neutral*.

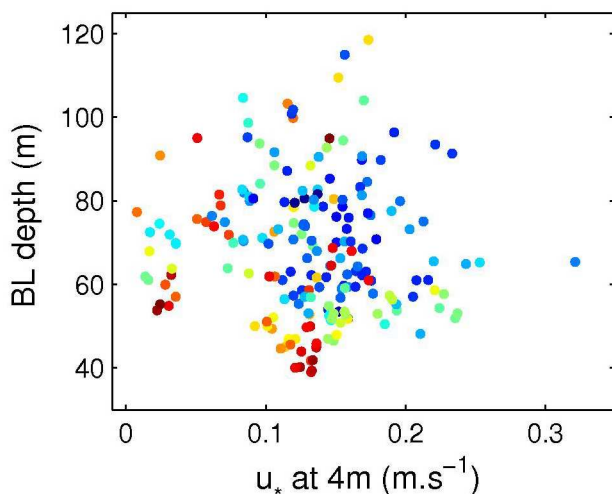
Most of our simple profiles come from the austral winter so we thought that the conditions would always be stable, or neutral when it's windy, but that it would still be possible to correlate all of them en bloc. However, if we consider the scatter plot of our profiles against  $d\theta/dz$  and  $F^*$  which characterize stability, we can see that the conditions are very heterogeneous (Fig. 3.4). So we defined borders for the 3 cases, then I sorted the sodar profiles and tried again to correlate them with the met and turbulence data. But again, we could see no correlation between the boundary layer depth and the atmospheric conditions.



**Fig. 3.4** - Scatter plot of the windy and simple profiles against  $d\theta/dz$  and  $F^*$ .

- The **highly stable** cases are when  $d\theta/dz$  is strongly positive ( $> 0.2 \text{ K.m}^{-1}$ ).
- The **slightly stable** cases are when  $d\theta/dz$  is slightly positive or neutral, and there's a radiant cooling.
- The **convective** cases are when  $d\theta/dz$  is neutral and there's a radiant heating.

The border between slightly stable and convective cases has been taken to be more or less orthogonal to the envelope curve setting the lower limit for the point locations.

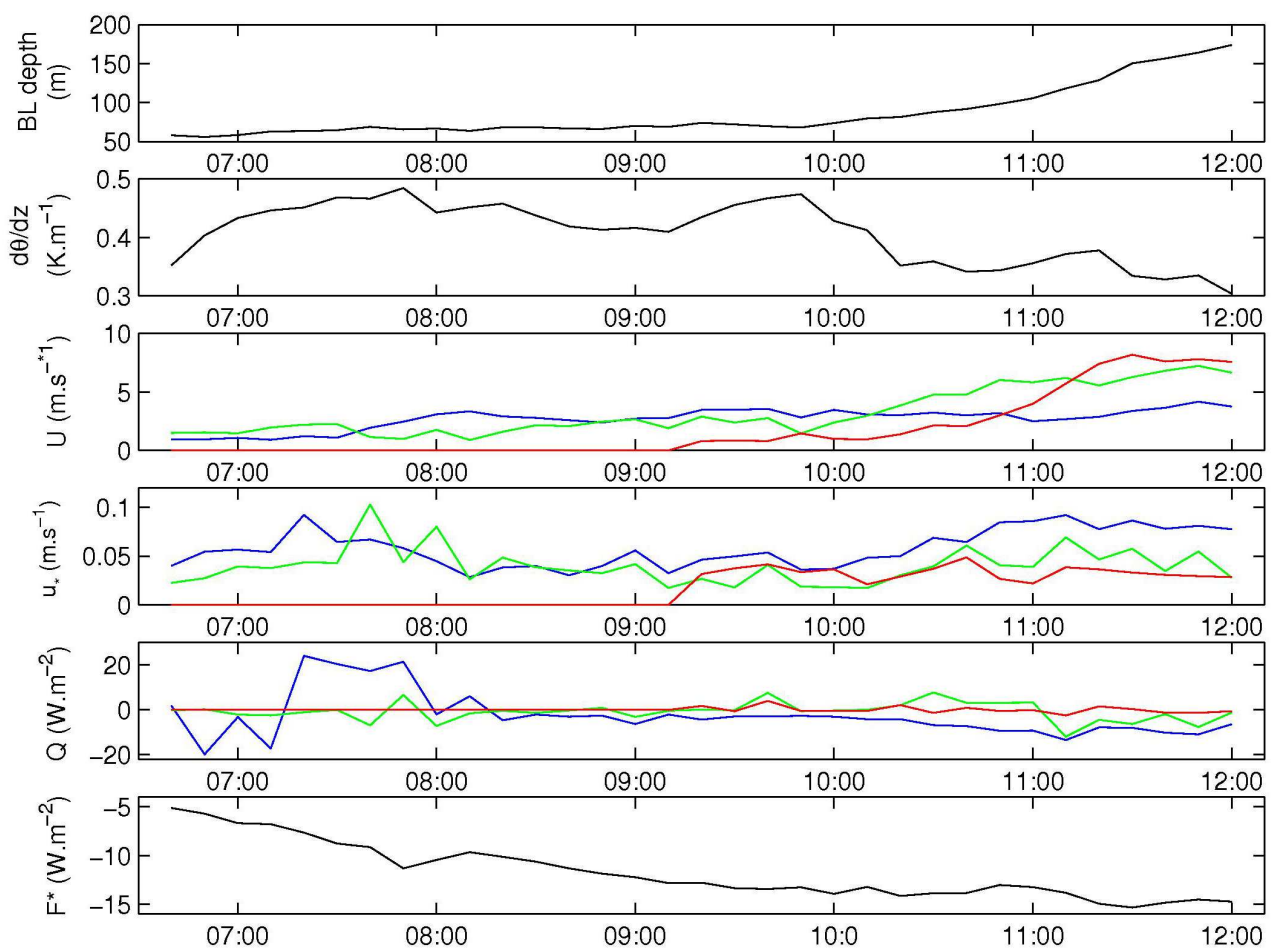


**Fig. 3.5** - A typical scatter plot. This one is for the profiles with slightly stable conditions. Colours are for  $d\theta/dz$  plotted against the friction velocity at 4m and the boundary layer depth.

### 3.2.3. Case study

At this point, the lack of any logical order in the results started to be disturbing. According to what Phil had heard from W. Neff, we could expect to get *something* on the scatter plots, even blurred. However, one might still doubt the homogeneity of our data, spread on several month of winter in bad weather conditions. So we decided to choose a few short periods of time when the boundary layer was clearly defined and to make case studies. For those cases, we observed the time series of the boundary layer depth and met and turbulence data. I show here only the case of June 10 2003, the only one for which the scatter plots aren't again complete random.

On that day, the boundary layer is well defined between 6:30 and 12:00. Its depth fluctuates around 70m till 9:50, when it starts increasing quickly up to ~180m at noon (Fig. 3.6). Then the boundary layer dislocates and the atmosphere becomes stratified. The temperature gradient is greater than  $0.3 \text{ K.m}^{-1}$  and there's an increasing radiant cooling, so the conditions are highly stable. Thus the vertical mixing is strongly limited by the temperature gradient and the vertical heat flux  $Q$  is very small.



**Fig. 3.6** - From top to bottom, time series of the BL depth, temperature gradient  $d\theta/dz$ , horizontal wind speed  $U$ , friction velocity  $u_*$ , vertical heat flux  $Q$ , and radiation budget  $F^*$ . The wind speeds come from the sonic at 4m (blue), 16m (green) and 32m (red). The increase in the BL depth seems to happen along with an increase in wind speed in altitude.

The wind is very weak, so weak that the classical anemometers return a strict 0 during most of the morning, as they must have a threshold. The sonic anemometers are more accurate but the 32m one didn't work before 9:10. Still, it's possible to see the wind speed increase in altitude at 32m and also a bit at 16m, while it remains low near the ground. Thus, the wind speed gradient and  $u_*$  increase

and the wind shear creates turbulence. When an eddy reaches the top of the boundary layer, it drags some air from the upper troposphere down into the boundary layer and the quantity of air trapped in the boundary layer increases by *entrainment*. In the end, the boundary layer gets thicker. What is more, the eddies move up the cold air created near the ground and bring warmer air down, so they reduce a bit the temperature gradient. This eases vertical mixing and maintains the process.

However  $u_*$  ends up decreasing because turbulence is making wind speed more homogeneous in the boundary layer, and the wind speed doesn't go on increasing in altitude. At some point, the wind shear is no longer strong enough to maintain turbulence. Big eddies disappear as they dissipate their energy in creating smaller eddies at their sides in a process called the *turbulent cascade*. Soon, only small eddies remain and vertical mixing drops. The temperature gradient is still very strong and ends up completely killing vertical exchanges: the boundary layer dislocates into a layered structure.

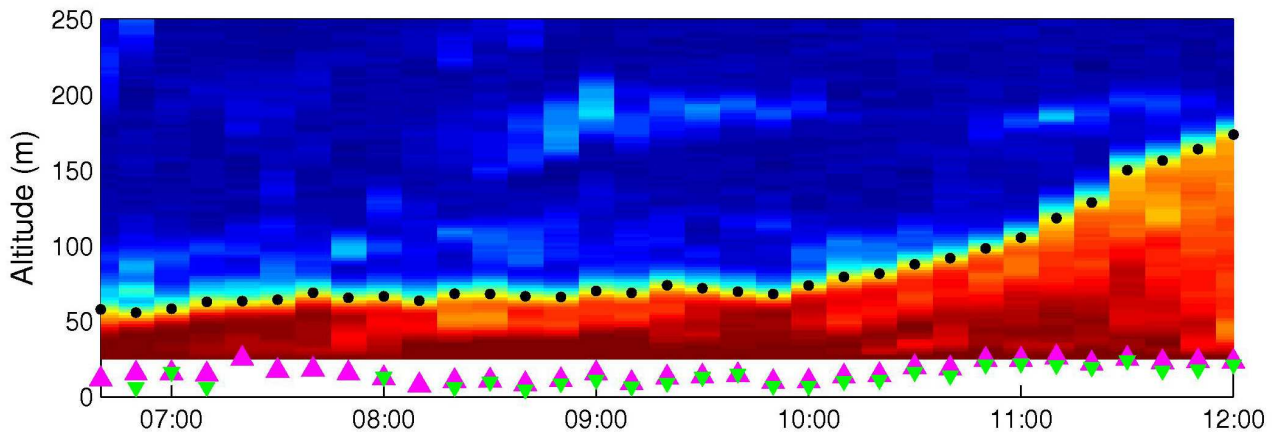
I also tried to compare the boundary layer depth read from the sodar with the value calculated from the Pollard or Zilitinkevich formulas.

According R.T. Pollard, the boundary layer depth is  $H = 1,2 \times \frac{u_*}{\sqrt{|f|N_b}}$

$f$  is the Coriolis parameter defined as  $f = 2\Omega \sin \varphi$  where  $\Omega$  is the Earth rotating speed and  $\varphi$  is the latitude of Halley.  $N_b$  is the Brunt-Väisälä frequency at which an air parcel oscillates up and down due to its difference of buoyancy with the surrounding air.  $N_b^2 = \frac{g}{T_v} \frac{d\theta}{dz}$  with  $g$  the acceleration of gravity and  $T_v$  the virtual temperature of air<sup>2</sup>.

According to S.S. Zilitinkevich,  $H = d \sqrt{\frac{u_* L}{|f|}}$  where  $L = -\frac{u_*^3 T_0}{kg(\overline{w't'})_0}$  is the Monin-Obukhov

length.  $T_0$  the air temperature just above the ground and  $(\overline{w't'})_0$  the kinematic heat flux at ground level;  $k$  and  $d$  are constants. The agreement between the two formulations is very good but the values of  $H$  are completely under evaluated (Fig. 3.7). The sodar and the turbulence measurements seem not to show the same thing.



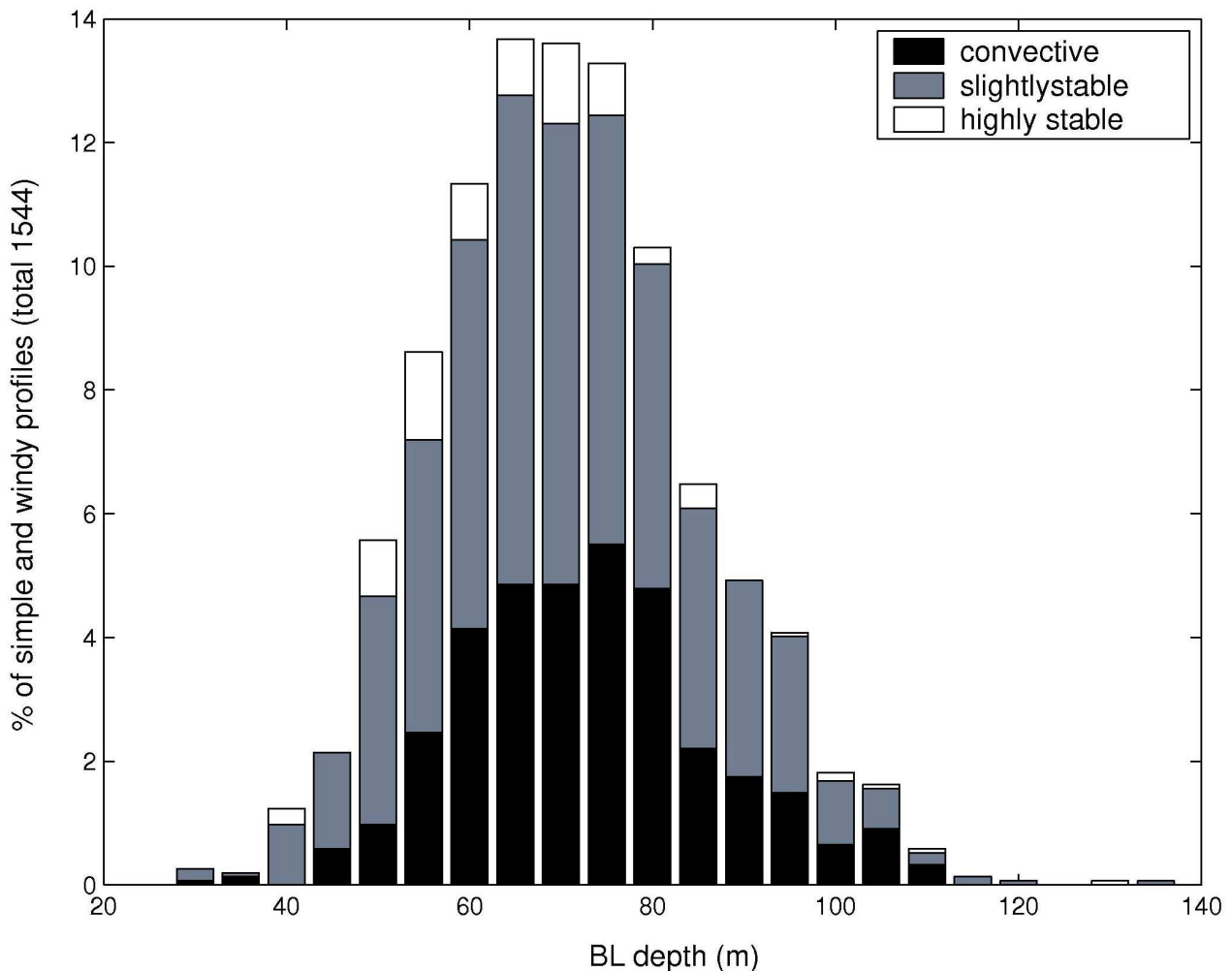
**Fig. 3.7** - (background) the original sodar image after 10-minute average. Superimposed, The BL depth from the sodar (black dots), the values given by the Pollard formula (pink upper triangles) and by the Zilitinkevich formula (green lower triangles).

<sup>2</sup> The virtual temperature  $T_v$  is used for humid air. At the same temperature as some humid air, dry air is less dense.  $T_v$  is the temperature that a dry air mass would need to raise up to in order to reach the same density than the humid air. In Halley, the air is so cold that any trace of humidity immediately condensates and we can consider that  $T_v = T$  the usual temperature in Kelvin.



### 3.2.4. BL depth repartition

We wanted to see what were the most common boundary layer depths at Halley and what the repartition looked like. So I realised the histogram of the BL depth repartition for all the simple and windy profiles. Rather strangely, the structure is very similar for the three types of boundary layer *convective*, *slightly* and *highly* stable. The most common height and the shape of the envelope are rather the same.



**Fig. 3.8** - Repartition in BL depth of the simple and windy profiles ( $a_{max} = 9$ ). The general shape of the histogram doesn't change with the value of  $a_{max}$ , it's just smoother when there are more profiles so when  $a_{max}$  is bigger. The truncated shape on the left is due to the false echo phenomenon which makes it difficult to detect BL depths smaller than 60m.

### 3.2.5. Why isn't there any correlation?

All attempt to link the height of the boundary layer to the surface conditions lies on the hypothesis that “when the forcing conditions are constant long enough and on a large enough surface, the boundary layer reaches an equilibrium state”. Thus a law linking the surface conditions to the boundary layer depth can exist.

When the surface forcing conditions change, the balance between the energy brought by forcing and the energy dissipated by turbulence takes time to re-establish. We can estimate that time  $t_{eq}$  to be about 2 hours by considering laws of similitude (see appendix A). Thus if the forcing conditions are constant for more than 2 hours, which is common at Halley during austral winter, then we can expect to see the boundary layer reach equilibrium. However, air moves with the wind and, during  $t_{eq}$  it flows over a distance  $d = U \times t_{eq}$  where  $U$  is the wind speed. So, to see the boundary layer

equilibrium, we need the forcing conditions to be constant also in space on a distance  $D \gg d$ . If we take as a typical value of  $U = 5 \text{ m.s}^{-1}$  then  $D \approx 36 \text{ km}$ . The ice shelf surrounding Halley is about 5 times bigger so we can expect to see the boundary layer reach an equilibrium state. However, as we do not see any correlation between the surface conditions and the boundary layer depth, then one of our assumptions is false. So either the ice shelf is too small to observe the equilibrium - but this is unlikely - or our first hypothesis was false and we have to admit that the boundary layer doesn't tend spontaneously to an equilibrium state, even under constant forcing conditions.

Explained another way: it is sensible to suppose that the *local* production of turbulence is related to the temperature and wind profiles as they govern convection and wind shear. But the spiky echograms show that turbulence takes time to dissipate after it's been created. So, only part of the turbulence existing at a given point and moment can be related to local conditions. However, if atmospheric conditions are homogeneous long enough and on large enough surfaces, then all the existing turbulence will have been created in the same conditions as older turbulence will have died away. Finally, the *local* surface conditions will explain *all* the turbulence present in the atmosphere, and not only the part that has been produced locally. But in that frame of mind, it's not possible to explain why the atmosphere in Halley is so complex and why we cannot see any correlation between the sodar and the met measurements.

The question arising next is: why the boundary layer doesn't tend to an equilibrium state when the forcing conditions are constant? What we think at the moment is that the moving air masses spontaneously create spatial heterogeneity and so, keep evolving without ever reaching equilibrium. However, we would need to set up an array of sodars to observe the flow at different points and determine what part is spatial heterogeneity and what part is temporal evolution on the sodar charts.

As for the very clear correlations observed at the South Pole by Neff et al. (2006), they might in fact come from the orography. The South Pole base is settled on the Antarctic plateau where the sunlight is so weak that the surface is permanently cooling down by blackbody infrared emission. Consequently, the air near the ground cools as well and those air masses - colder so more dense - fall naturally toward the coasts by gravity. That type of wind is called *katabatic* wind. Now, let's imagine that the radiant cooling gets stronger - for instance if there are less clouds. Then as the air near the ground cools down, the temperature gradient increases. But the colder the air near the ground gets, the more dense it becomes and the quicker it will fall: so the speed of the katabatic wind increases near the ground. Hence a bigger wind shear and more turbulence and in the end, this increases the boundary layer depth. And vice versa. Finally, one can observe a correlation between the temperature gradient, the wind speed and the boundary layer height but that correlation will come from the katabatic wind. And Halley being on an ice shelf and not on the mainland, the wind there is not katabatic.

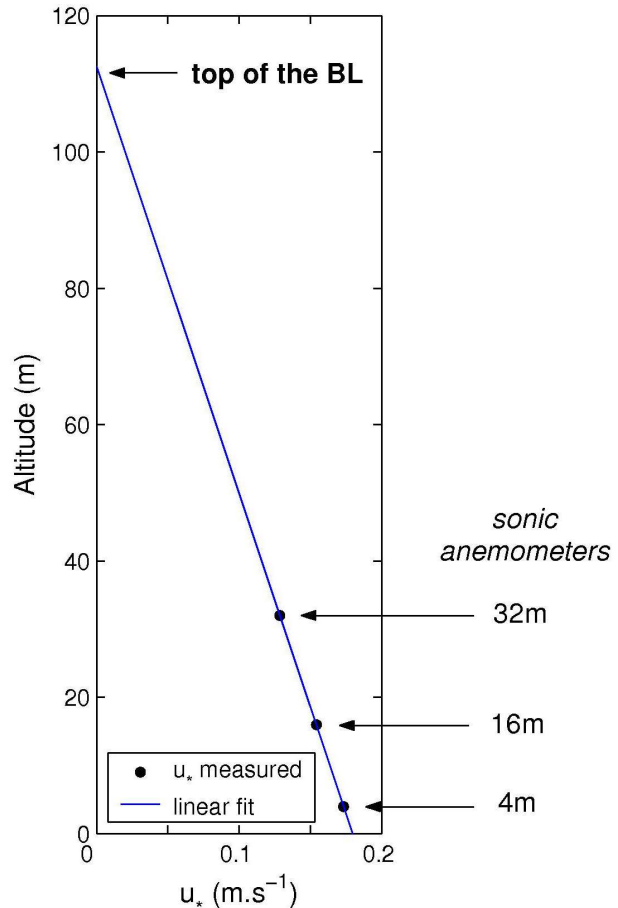
## 4. Comparing the sodar and turbulence derived boundary layer depth

Now we'd like to estimate a value of the boundary layer depth directly from the turbulence data. Then we would be able to compare it with the boundary layer height read on the sodar charts and see if there are obvious discrepancies.

### 4.1. How to assess the BL depth from turbulence measurements

In stable or unstable boundary layers, it's the temperature difference between the air and the ground that feeds turbulence; in neutral boundary layers, it's friction on the ground slowing the wind. But in all cases, turbulence is stronger near the ground and decreases with altitude up to the boundary layer top and the capping inversion where it completely stops. Thus the friction velocity, the turbulent kinetic energy, the kinematic heat flux, or the temperature variance decrease from their ground value to zero at the height of the boundary layer top. If we can make a regression from the values measured by the sonic anemometers, this will give us an idea of the altitude where the turbulence really related to the ground stops.

We lack data concerning profiles of turbulence in Halley. However, as we only want a rough assessment of the boundary layer depth - and we have only three points - we will make a linear regression. This should still allow us to compare trends and orders of magnitude with the sodar.



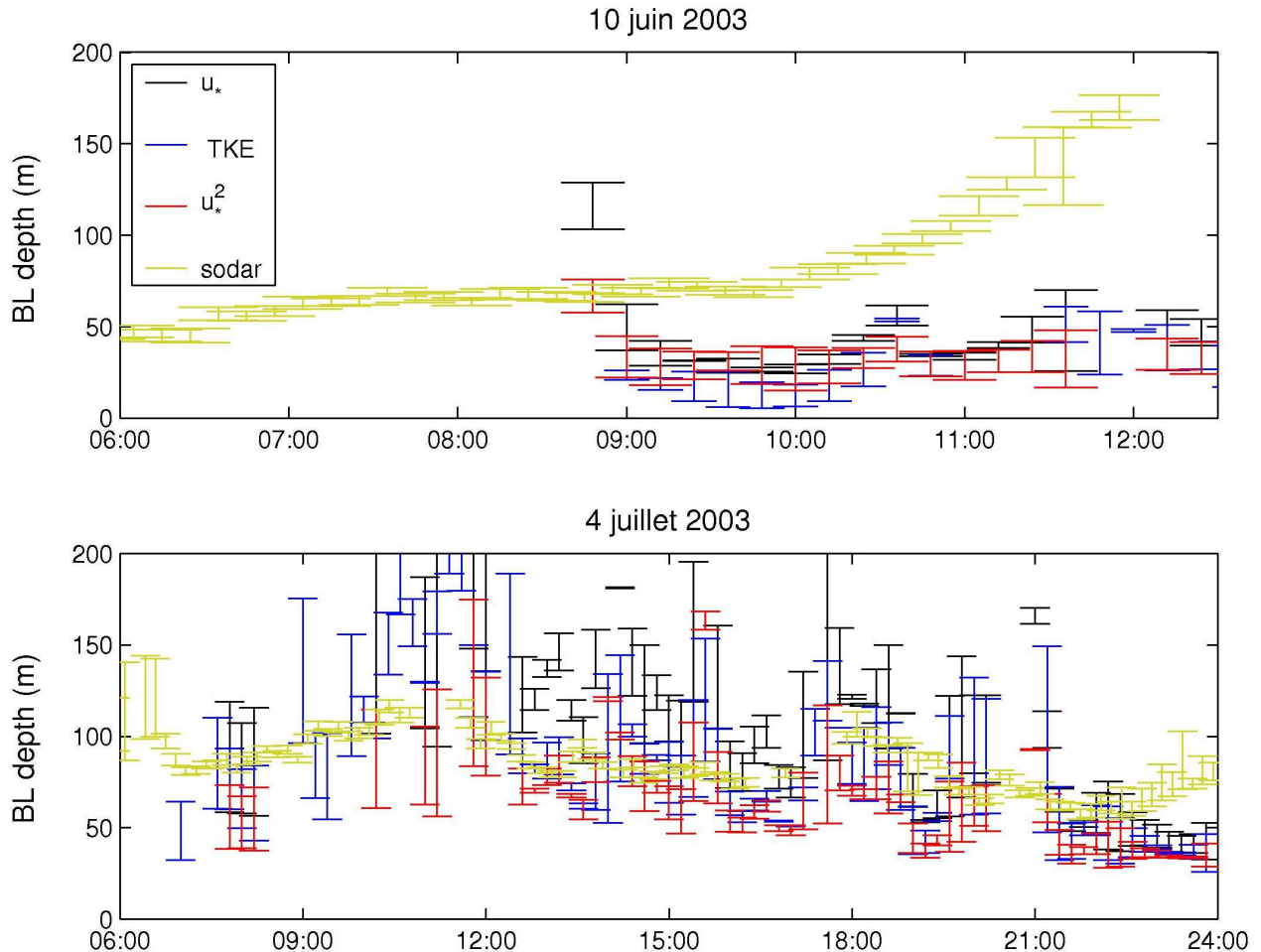
**Fig. 4.1** - the boundary layer depth can be evaluated by linear regression from the turbulence data like  $u_*$ .

### 4.2. Comparison with the sodar

For the sodar, I changed the way of calculating the boundary layer depth. The fit by a hyperbolic tangent works only in a few per cent of cases so it's not convenient to be able to compare the sodar and the turbulence in a wide variety of cases. In that part, the boundary layer height won't be the parameter  $d$  returned by the fitting program anymore, but it will be defined as the altitude where the echo strength falls below a certain level. For each profile I take the mean value between 800 and 1000m as  $a$ , the level of background noise. At those altitude there's hardly ever any complex layering. Then I look for the minimum altitude where the echo strength falls below the level  $e_{lim} = a + \eta(15 - a)$ . I take the  $\eta = 0.6$  altitude as the boundary layer depth, while the difference between the  $\eta = 0.5$  and  $\eta = 0.7$  altitudes gives the uncertainty on that value of the boundary layer depth. When the uncertainty is greater than 50m, I consider the profile complex and discard it. I also reused my subroutine to detect false echoes. Finally, the no-echo profiles can be characterized by the fact that the three altitudes obtained are grouped below 40m.

On windy days like July 4 (see Fig. 4.2), the agreement between the sodar and the turbulence derived boundary layer depth seems rather good. As we've only got three sonic anemometers, the uncertainty is often big, but we can see that the sodar and turbulence values are in the same range

and follow the same trends. However, as soon as the wind drops, the values given by the turbulence are always smaller than what the sodar shows and - worse - don't vary in the same direction. On June 10 example, the huge increase visible on the sodar (remember figure 3.8) is absolutely absent from the turbulence records. This is probably a typical case when the sodar films a spatial fluctuation passing above, while near the ground, conditions have not changed. This also explains why the Pollard and Zilitinkevich formulas give results so far away from the sodar.



**Fig. 4.2** - comparison between the BL depth from the sodar charts and from the regression of turbulence measurements. (top) the case of part 3.2.3 with very stable conditions and very light wind: the sodar doesn't fit with the turbulence measurements at all. (bottom) a windy day; the wind increases from 6:00 to 9:00 then remains strong till 20:00 when it drops. Agreement between the sodar and turbulence measurements is good when the wind is strong but gets bad when wind drops.

## 5. Conclusion

During that project, I realised a systematic study of the Halley sodar charts. Most of the echograms are complex and unexploitable but I could design a sorting method to isolate the profiles where a simple boundary layer is visible. We thought those cases showed the boundary layer reaching an equilibrium state with the surface forcing conditions. The dimensions of the permanent ice shelf surrounding Halley, on which the forcing conditions are constant, should have been big enough to allow the boundary layer to reach that equilibrium state.

However, I didn't see any correlation between the boundary layer depth read on the sodar and the temperature and wind profiles measured on the neighbouring mast. No matter I worked with all simple profiles from 2003, or that I sorted those profiles according to met conditions, or that I studied only a few hours of homogeneous data, the result was just the same: no correlation at all. At Halley, we can't invoke surface inhomogeneity to explain that the boundary layer is not coupled to the surface forcing. So we have to admit that the boundary layer doesn't tend spontaneously toward an equilibrium state, even when the forcing conditions are constant in space and time.

We think that the moving atmosphere naturally creates spatial inhomogeneity and that we see those fluctuations passing above the sodar. So the sodar records a mix of spatial inhomogeneity and temporal variations. Now what we'd like to know is how much of the fluctuations we can see are temporal and how much is merely spatial heterogeneity flowing past the sodar.

## Appendix A - evaluation of the time the BL needs to reach equilibrium

Turbulence is a complex phenomenon where thousands of eddies interact in a chaotic and non-linear way. It's not possible to find an analytical solution to that problem as a complete description of eddies motion would need an infinite number of equations. The problem has to be treated statistically and we use the variances and covariances of the wind speed components, temperature etc. as variables.

Fluid mechanics and thermodynamics give equations linking those quantities together, but the problem is not mathematically closed: there are always more unknowns than equations as adding an equation leads to introducing new variables. So, to close the system, we need to add equations by establishing some approximate links between the unknowns. The first order closure approximation

consists in taking  $\overline{u'w'} = -K_m \frac{\partial \bar{u}}{\partial z}$  and other similar equations – replacing  $u$  by  $v$  for instance.

$\{u, v, w\}$  are the three wind speed components along the axes  $\{Ox; Oy; Oz\}$  and  $K_m$  is known as the eddy diffusivity for momentum.

To simplify, we take the (Ox) axis along with the horizontal wind speed direction;  $U$  is parallel to (Ox) so  $v = 0$ .

$$\text{Then it comes: } \begin{cases} \bar{u} = \bar{U} \\ \bar{v} = 0 \end{cases} \text{ and consequently } \begin{cases} \overline{u'w'} = -K_m \frac{\partial \bar{U}}{\partial z} \\ \overline{v'w'} = 0 \end{cases}$$

Let's remember that the friction velocity is defined as:  $u_* = \left( \overline{u'w'^2} + \overline{v'w'^2} \right)^{1/4}$

So the previous approximation gives:  $u_*^2 = \overline{u'w'}$  and then  $u_*^2 = K_m \frac{\partial \bar{U}}{\partial z}$  (A1)

On the other hand, studies on wind speed and temperature profiles have shown that all profiles collapse on universal curves when they are plotted as functions of adimensional quantities. For instance, those similitude laws give for neutral conditions:

$$\frac{kz}{u_*} \frac{\partial \bar{u}}{\partial z} = 1 \quad (\text{A2})$$

where  $k$  is the Von Karman constant and  $u_*$  the friction velocity measured at the altitude  $z$ .

If we combine (A1) and (A2) then we get:  $u_*^2 = K_m \left( \frac{u_*}{kz} \right)$  so  $K_m = ku_* z$  (A3)

Another law of similitude concerning wind profiles for neutral conditions is:  $\frac{\bar{U}}{u_*} = \frac{1}{k} \ln \left( \frac{z}{z_0} \right)$  (A4)

where  $k$  is again the Von Karman constant and  $z_0$  is the roughness length that characterizes the irregularity of the surface and its capacity to create turbulence.

If we use (A4) to replace  $u_*$  in (A3) it comes:  $K_m = \frac{k^2 z \bar{U}}{\ln(z/z_0)}$  (A5)

$K_m$  characterizes the diffusion of turbulence in the depth of the boundary layer. Its dimension is  $m^2 \cdot s^{-1}$  so to evaluate  $K_m$  we need a characteristic length and a characteristic time of turbulence diffusion in the boundary layer. When the boundary layer tends to equilibrium, turbulence takes a time  $t_{eq}$  to spread the effects of surface forcing on all the boundary layer depth  $H$ . So we can take:

$$\mathbf{K}_m \sim \frac{\mathbf{H}^2}{t_{eq}} \quad (\text{A6})$$

Then we combine (A5 and (A6) and it comes:  $t_{eq} \sim \frac{\mathbf{H}^2 \ln(z/z_0)}{k^2 z \overline{U}}$

Numerical values:

- $\mathbf{H} \sim 70$  m is a typical height for the BL at Halley (middle of the repartition histogram).
- $z_0 = 50 \mu\text{m}$  is the roughness length for a smooth ice surface like the Brunt Ice Shelf.
- $k = 0.4$
- $\mathbf{U} = 5 \text{ m}\cdot\text{s}^{-1}$  at  $z = 10$  m is a typical value of the wind speed.

With those values, we get:  $t_{eq} \sim 2\text{h}$

## Bibliography

- P.S. Anderson, 2003, *Fine-Scale Structure Observed in a Stable Atmospheric Boundary Layer by Sodar and Kite-Borne Tethersonde*, *Boundary Layer Meteorology*, vol. 107 (2), p323-351.
- F. Beyrich and A. Weill, 1993, *Some Aspects of Determining the Stable Boundary Layer Depth from Sodar Data*, *Boundary Layer Meteorology*, vol. 63 (1-2), p97-116.
- A.D. Culf, 1989, *Acoustic Sounding of the Atmospheric Boundary Layer at Halley, Antarctica*, *Antarctic Science*, vol. 1 (4), p363-372.
- J.C. King and P.S. Anderson, 1988, *Installation and Performance of the STABLE Instrumentation at Halley*, *British Antarctic Survey Bulletin* 79, p65-77.
- W. Neff, D. Helmig, A. Grachev and D. Davis, 2006, *A Study of Boundary Layer Behavior Associated with High NO Concentrations at the South Pole using a Mini-Sodar, Tethered Balloon and Sonic Anemometer*, under press.
- R.T. Pollard, P.B. Rhines and R.O. Thompson, 1973, *The Deepening of a Wind-Mixed Layer*, *Geophysical Fluid Dynamics*, vol. 3, 381-404.
- *Meteorology for Scientists and Engineers: a Technical Companion Book to C. Donald Ahrens*, R.B. Stull, *Meteorology Today*, Thomson Learning. 2<sup>ème</sup> edition, 2000.
- *An Introduction to Boundary Layer Meteorology*, R.B. Stull, *Atmospheric Science Library*, Kluwer Academic Publishers, 1988.
- D. Vickers and L. Mahrt, 2004, *Evaluating Formulations of Stable Boundary Layer Height*, *Journal of Applied Meteorology*, vol. 43 n° 11, p1736-1749.
- *Atmospheric Science, an Introduction Survey*, J.M. Wallace and P.V. Hobbs, *International Geophysics Series* vol. 92, 2<sup>nd</sup> edition, 2006.
- S.S. Zilitinkevich, 1972, *On the Determination of the Height of the Ekman Boundary Layer*, *Boundary Layer Meteorology*, vol. 81 (4), p245-269.



## MATLAB<sup>®</sup> M-files list

### Making the 10 minutes average (folder 10min\_aver\)

<b>read_sodar.m</b>	The original program from Phil plus my comments. It reads and plots a daily compressed sodar file without any averaging.
<b>average_plot.m</b>	Reads a daily compressed sodar file, makes the 10-minute average, plots the result and save it into a provisional MAT-file.
<b>read_average.m</b>	A function that does the same as <b>average_plot.m</b> , except it doesn't plot anything and saves the result in a daily MAT-file.
<b>sodar_av03.m</b>	Makes the loop on months and days in 2003 and calls <b>read_average.m</b> for each day. Resulting files are now on T:\psa\sodar_av03\mmm\avYYMMDD.mat The profiles are in the matrix <b>pr_mean</b> ; <b>tsc</b> and <b>zsc</b> are the time and altitude vectors.
<b>plot_aver.m</b>	To plot a daily 10-minute averaged sodar file. Also possible to plot the BL depth as the 60% amplitude level.

### Fitting the profiles (folder profile\_fit\)

<b>profile_fit.m</b>	A function that fit a profile and returns the fitting coefficients then plots the profile and the fitting curve.
<b>profile_fit_add.m</b>	Does the same as <b>profile_fit.m</b> but adds fake points between -200 and 26m before fitting the curve.
<b>sodar_fit.m</b>	Just a program to make fits on a serie of profiles without having to call <b>profile_fit.m</b> manually.
<b>profile_fit2.m</b>	Same as <b>profile_fit_add.m</b> but without the graphic part. To be used in profile sorting.
<b>profile_fit3.m</b>	Same as <b>profile_fit.m</b> but without the graphic part. For profile sorting.

### Layer detection (folder layer\_detect\)

<b>find_lay_plot.m</b>	A function that detect and plots the layers of a profile. Choose using either the start of >0.07 gradient zones and end of <-0.07 gradient zones, or the gradient extrema. Include the mean-value improvement.
<b>find_lay_filt.m</b>	A function that detects layers using the beginning of >0.07 gradient zones and the <-0.07 minima. Include the mean-value improvement as well.
<b>find_layer.m</b>	Same as <b>find_lay_filt.m</b> except that it doesn't filter the profile before layer detection. To allow external 2D filtering.
<b>gaussian_filter.m</b>	That program convolutes the matrix <b>pr_mean</b> with a Gaussian 2D-filter. Attempt to homogenise results between successive profiles.
<b>layer_map.m</b>	Program to get a 2D map of the layer evolution during the day.

### Sorting the profiles (folder profile\_sort\)

<b>find_windy.m</b>	Program looping on months and days in 2003 and fitting each profile with <b>profile_fit2.m</b> to find the simple and windy ones. The program also needs <b>profile_fit3.m</b> and <b>false_echo.m</b> to run.
<b>false_echo.m</b>	Function to test for false echo by looking for an increase in echo strength below 60m.
<b>windy_prX.dat</b>	Resulting files produced by <b>find_windy.m</b> where X is the value of $a_{max}$ used for the sorting.

### Pulling in the met and turbulence data (folder pull\_met\_turb\)

<b>exist_met.m</b>	Small function to test the met and radiation files exist.
<b>exist_turb.m</b>	Small function to test the turbulence file exists.
<b>pull_met.m</b>	Function to pull in the met and radiation data for a requested time stamp.
<b>pull_turb.m</b>	Function to pull in the turbulence data for a requested time stamp.
<b>met_windy.m</b>	That program reads the <b>windy_prX.dat</b> file and calls <b>pull_met.m</b> for all the profiles stored in it. Then it produces a <b>windy_metX.dat</b> file to store the met data and a <b>windy_pr_clipX.m</b> file to store only the profiles that have met data.
<b>turb_windy.m</b>	Same as <b>met_windy.m</b> , but it pulls in the turbulence data as well and stores the turbulence data in <b>windy_tubX.dat</b>

### Statistic on the sorted profiles (folder statistics\)

<b>bl_rep.m</b>	That program reads <b>windy_metX.dat</b> and plots the histogram of the profiles repartition in BL depth.
<b>when_prof.m</b>	That program fills in and plot a long vector to see when are the profiles picked up and stored in <b>windy_metX.dat</b>
<b>npr_pick.m</b>	Just a small program giving the number of profiles picked up day by day.

### Scatter and error bar plots (folder scatter\_plots\)

<b>scat_err_bar.m</b>	Reads <b>windy_tubX.dat</b> and makes the scatter plots and error bar plots of the BL depth against 2 grandeurs chosen among met or turbulence data.
<b>sort_met.m</b>	Primitive version of <b>scat_err_bar.m</b> using only the 32m wind speed and $d\theta/dz$ from the scatter and error bar plots, but it can work also from <b>windy_metX.dat</b>
<b>scat_err_bar2.m</b>	Does the same job as <b>scat_err_bar.m</b> , but from a case study <b>caseYYMMDD.mat</b> file.
<b>f_ebar3.m</b> <b>f_ebar2_lines.m</b>	Functions that actually make the error bar plot and that the other programs need to run.

### Case study (folder case\_study\)

<b>case_prep_fit.m</b>	For a given day and period of time, that program prepares the <b>caseYMMDD.mat</b> file containing the profiles, the fitting coefficients, the met and turbulence data. NB: it uses <b>pull_met.m</b> and <b>pull_turb.m</b>
<b>case_prep.m</b>	Does the same job as <b>case_prep_fit.m</b> but instead of fitting the profiles, it calculates the 60%-amplitude level as the BL depth.
<b>case_met.m</b>	Plots the time series of the met and turbulence data from <b>caseYMMDD.mat</b>
<b>form_graph.m</b>	A function designed to format the time axes of the graphs produced by <b>case_met.m</b> . You've got to select manually on which case you're working.
<b>case_scatter.m</b>	That program will make the scatter plots for the BL depth plotted against $\{U_{32}; d\theta/dz\}$ , $\{u_{*4}; d\theta/dz\}$ , $\{U_{32}; Q_{32}\}$ , $\{u_{*4}; Q_{32}\}$ , $\{u_{*32}; Q_4\}$ .
<b>scatter_all.m</b>	That function actually makes the scatter plots and is needed by <b>case_scatter.m</b> to run.

### Turbulence regression (folder \regression)

<b>bl_regr.m</b>	Program that reads a daily turbulence file and makes a linear regression when possible to find an estimation of the BL depth. Reads also the corresponding 10-minute average sodar file and finds for each profile the 50%, 60% and 70% amplitude level (20%, 30% and 40% when the wind noise is above 7). Finally plots everything.
<b>sodar_stack.m</b>	A function that reads a daily 10-minute averaged sodar file and finds for each profile the 50%, 60% and 70% amplitude level (20%, 30% and 40% when the wind noise is above 7).
<b>stack_03.m</b>	Program that makes a loop on 2003 and calls <b>sodar_stack.m</b> for each day and then, stack all the data together.