Spatial mapping of temperature and wind fields using sound propagation

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Introduction

Numerical simulations represent a solution of the hydrodynamic equations over a discrete grid structure. In comparison with such numerical data, horizontally integrated measurements are able to provide data sets in a consistent structure. Acoustic travel time tomography is a technique which can be used to observe area-averaged air temperature and wind fields in their horizontal and temporal variability. This technique basically uses the dependence of sound speed on temperature and wind to derive the distribution of these quantities within the measuring area. Such observations are used to decide whether the point measurements produce data which are representative for the whole experimental area, and thus for the simulations. Furthermore, the acoustic travel-time data can rearranged in a structure which is comparable with the numerical grid structure of simulations.

Acoustic Tomography

The acoustic tomographic system consists of several sound transmitters and receivers, which are distributed within a landscape [1].

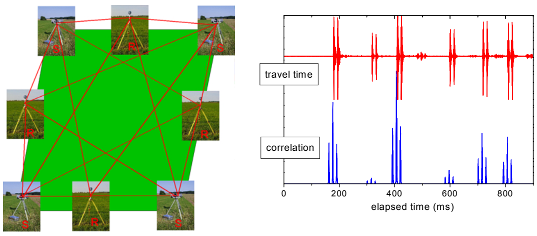

Figure 1: Schematic view (left side) of the tomographic system around the area of investigation. The connecting lines between transmitters (S) and receivers (R) represents the sound paths. The right side illustrates an example of the received signal (6 sound sources) at one microphone and the calculated travel times (correlation).

The receivers and transmitters were arranged in order that the covering of the investigation area with sound paths is optimal and to avoid an overlapping of the recorded different sound-source signals at any one receiver.

Figure 2: The sound source, a system consist of three compression driver (left side) and the receiver unit (right side), a microphone with a wind screen.

All sources simultaneously transmit a sine burst (e.g. double peak with frequency of 1000 Hz, duration of 4 ms). The travel time of each signal is estimated from the recorded data by cross correlation between the received and the transmitted signal. Each peak of the cross correlation is associated with a separate ray path. The delay time corresponds to the travel time of the transmitted signal [1].

Sound speed data

The acoustic measurements produced a data set of travel times of the sound signals along the different sound paths. The lengths of the sound paths were exactly determined during the set-up of the array, therefore the sound speed for each sound path can be calculated. In the (unrealistic) case of non-moving air the speed of sound can be calculated according to the Laplace approximation.

$$c_L = \sqrt{\gamma_L R_L T} \tag{1}$$

where c_L is the speed of sound, γ_L is the specific heat ratio, R_L gas constant for humid air and T is the temperature. In the atmosphere the specific heat ratio depends on the temperature, air composition and humidity.

$$\gamma_L(T) = \frac{c_{pa}(T) + m c_{pW}(T)}{c_{Va}(T) + m c_{VW}(T)} \tag{2}$$

where c_p and c_V are the specific heats at constant pressure and volume and m is the mixing ratio (Indices: a dry air, *W:* water vapour). Because dry air is a mixture of different gases, the specific heat at constant pressure has to considered for each gas component according to the molar contribution:

$$c_{pa}(T) = \sum_i \frac{c_{pai}(T)\Psi_i M_i}{\overline{M}} \tag{3}$$

where M is the molar mass contribution and Ψ is the mole fraction.

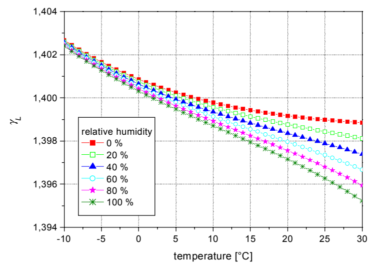

Figure 3: The variation of specific heat ratio of humid air with temperature at various relative humidity. The deviation to the standard value of 1.4 cause a change of the speed of sound in the range of 0.3 ms^{-1} at -10°C and 0.5 ms^{-1} at +30°C (80% humidity).

The temperature dependence of the specific heat at constant pressure can be estimated be use of quantum physics or empirical approximation. Here the constant pressure specific heat approximation of [2] were used.

In the realistic case the effective sound speed has to considered, which is a superposition of the wind field and the Laplace sound speed field.

$$\vec{c}(T,\vec{v}) = c(T(t,x,y,z)) + \vec{v}(t,x,y,z) \qquad (4)$$

To separate the different influences on the sound speed several methods are applicable [3] e.g. the iterative solution or and bi-directional sound propagation between two orthogonal source-receiver combinations. During the iterative algorithm the wind vector is changed until the variance (of all sound paths) of the Laplace sound speed reach a minimum. This algorithm provide only an averaged value of the wind-vector for the considered area.
A spatial sub-division of the wind field is possible by use of the bi-directional propagation between several sound sources and receivers which were arranged perpendicular. Analogous to a sonic anemometer the wind components along the propagation path in both orthogonal directions as well as the sound speed c_L were determined independently.

STINHO-2 field experiment

A micrometeorological field experiment within the scope of the STINHO-project (STructure of turbulent transport under INHOmogeneous conditions) was performed at the boundary layer research field of the Meteorological Observatory Lindenberg (DWD, German Meteorological Service) in the summer of 2002 to investigate the interaction of an inhomogeneously heated surface with the turbulent atmosphere. The intention was to compare conventional meteorological point and vertically integrated measurements with area-covering observations and numerical simulations.

The central investigation area had an extension of 300 m × 440 m. One part was a meadow (grass) and the other part was a recently ploughed field (bare soil; see Figure 4). In the STINHO-2 experiment, the acoustic tomography covered an area of grassland (300 m × 440 m) including a recently ploughed field of bare soil (90 m × 300 m).

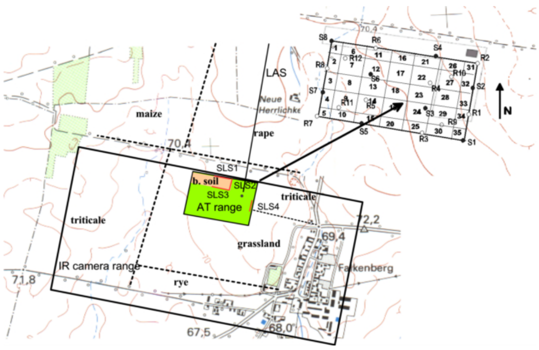

Figure 4: Area for the acoustic tomography (AT), and infrared surface temperature observations (black rectangle). The scintillometer are labelled SLS1 to SLS 4 and LAS. The arrangement of air temperature cells (70 m x 70 m) as well the positions of the acoustic receivers (R) and transmitters (S) are shown in the upper part.

The upper part of Figure 4 shows the arrangement of the sound sources and receivers and the subdivision into 35 grid cells for the temperature field. Be use of the bi-directional sound propagation the wind velocity and direction can be estimated for nine individual cells.

Figure 5 demonstrates an example of the resulting temperature and wind distributions at different time. The warming up in the morning is clear visible. However, spatial temperature differences due to the variation in land use were not observed.

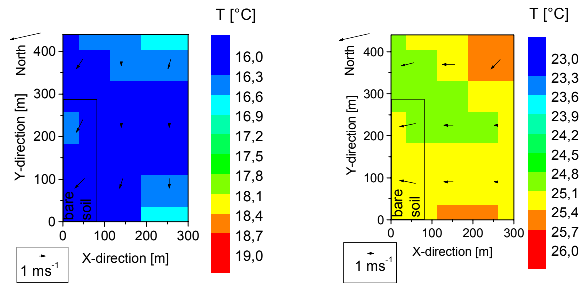

Figure 5: Horizontal slices through the acoustically-determined and 10-min-averaged air temperature and wind field (arrows) at a height of 2 m above the ground on July 06th, 2002 at 05:30 UTC (left) and at 10:50 UTC (right).

A clear signal of the heterogeneous surface conditions was identified in the sensible heat fluxes which were determined with the surface layer scintillometer [4]. The turbulent heat fluxes above the bare soil are significant higher than above the grassland.

Acknowledgements

The STINHO project was performed as a part of the VERTICO (VERTIcal transports of energy and trace gases at anchor stations under COmplex natural conditions) network which has been funded by the German Federal Ministry of Education and Research (BmBF) in the framework of the AFO-2000 research programme (grant No. 07ATF37).

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