Acoustic tomography as a method to characterize measuring sites

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Summary:

The method of acoustic tomography, based on external sonic energy, is applied inside the atmospheric surface layer to observe near-surface temperature fields. Important advantages of this technique as compared to other measurement methods are their remote-sensing capacity and the possibility to directly derivate area-averaged meteorological quantities.

The needed input data for the tomographically inverse algorithm are provided by the interaction of sound waves with the scanned atmospheric layer. The resulting horizontal slices lead to statements on the inhomogeneity of the underlying surface which may result in noticeable difficulties during the analysis of measuring campaigns with conventional methods.

Zusammenfassung:

Die auf der Aussendung von Schallenergie basierende Methode der akustischen Tomographie wird in der atmosphärischen Bodenschicht angewendet, um bodennahe Temperaturfelder zu beobachten. Bedeutende Vorteile dieses Verfahrens im Vergleich zu anderen Meßmethoden sind die Fernerkundungskapazität und die Möglichkeit, flächengemittelte Werte meteorologischer Größen direkt abzuleiten.

Die für den tomographischen Invertierungsalgorithmus benötigten Eingangsdaten werden durch die Wechselwirkung von Schallwellen mit der durchstrahlten Luftschicht bereitgestellt. Die resultierenden horizontalen Schnittbilder führen zu Darstellungen der Inhomogenität der Oberfläche. Letztere können beachtliche Schwierigkeiten während der Analyse von Messkampagnen mit konventionellen Methoden hervorrufen.

1. Introduction

Sound waves propagate through the atmosphere with different sound velocities according to the air temperature and wind vector fields influenced by the environmental conditions. Therefore, acoustic parameters characterising the sound propagation lead to a spatial description of the medium properties.

In the presented study measured travel time values of sound signals between different transmitters and receivers were used as initial line-integrated values to derivate spatially averaged quantities. Because of the information content of each measurement regarding to the properties of the atmosphere radiated through, a tomographic algorithm can provide a distribution of the meteorological quantities temperature and wind vector.

Such spatially averaged meteorological quantities are needed among others for the preparation and analyses of measuring campaigns as well as for the evaluation of model-output data, e.g. Large-Eddy simulations (Wyngaard and Peltier, 1996). By using the method of acoustic travel time tomography, it is, for instance, possible to derive information on the representativeness of point measurements and the homogeneity of measuring sites and therefore on the applicability of turbulence theories in data analysis and in atmospheric models.

The following section describes the method of acoustic tomography and its applicability to measurements inside the atmospheric boundary layer. In section 3, an overview of the experimental results from a measuring campaign at the “Common measuring field” at the Meteorological Observatory Lindenberg (Germany) is given. Thereby, the degree of inhomogeneity of the measuring field will be described. The last section summarizes the results and supplies an outlook to future work.

2. Method of acoustic tomography

2.1. Application to the atmosphere

As mentioned above there is a great demand for spatially averaged meteorological data to directly validate models and to describe the characteristics of measuring sites. The needed data could be provided on one side by point measurements and a following interpolation procedure or on the other side by remote-sensing methods which yield data from a volume, an area or along a line. Acoustic travel time tomography with a specially experimental equipment and distribution of measuring devices as well as a special analysis algorithm belongs to the last group of methods (see Fig. 1).

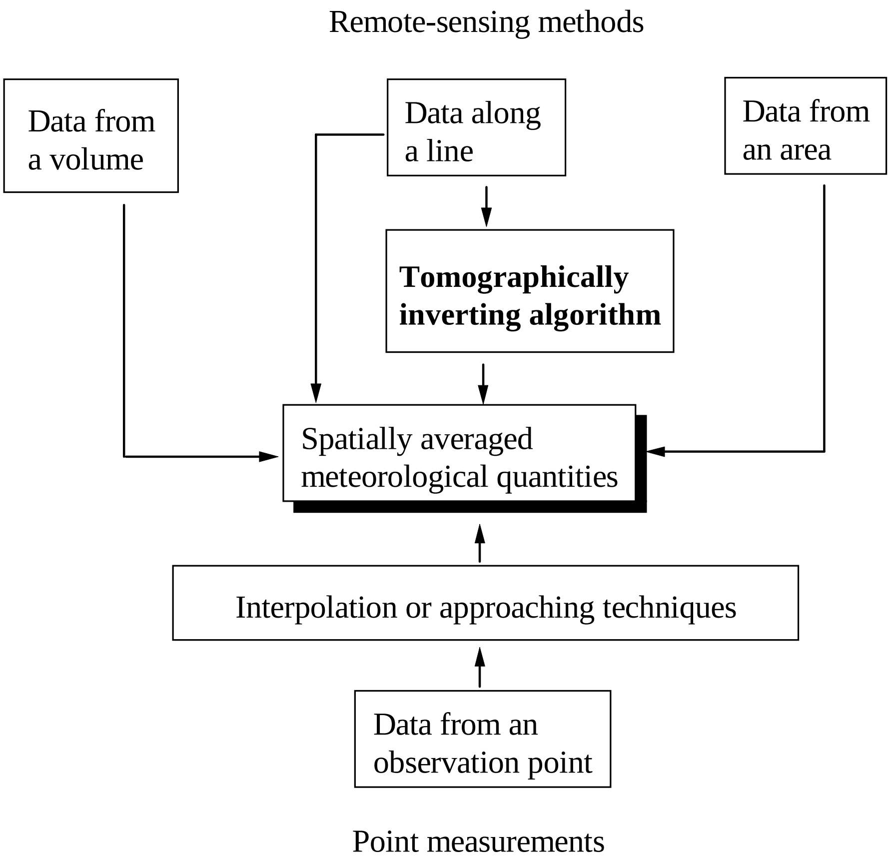

Figure 1: Possibilities to derive spatially averaged meteorological quantities.

Thereby, the acoustic travel time tomography is mainly characterised by the high accuracy regarding to other remote-sensing methods and by the creation of horizontal slices through the atmosphere (Ziemann, 2000).

In our study tomography is defined as a combined measurement and data analysis technique to reconstruct a slice through a medium using the reaction of the considered medium on an external probing energy. For the special case of acoustic travel time tomography measurements have to be performed on different ray paths between the acoustic sources and receivers. The rays must touch all parts of the experimental area, best with a quite uniform distribution. The derivation of spatially averaged values of physical parameters, e.g. effective sound speed including the influences of air temperature and wind vector, results from the inverting of all single travel time measurements.

The procedure describes the opposite situation in comparison to the traditional forward problem. Thereby, by outgoing from values of measured quantities, one can use mathematical inverting techniques to derive an estimation of the values of system parameters that explain or reproduce the experimental observations.

The possible application of acoustic travel time tomography to the atmospheric surface layer was validated by Spiesberger and Fristrup (1990) as well as Wilson and Thomson (1994). In contrast to these studies the application of an other tomographic algorithm will demonstrate how one can detect absolute values of meteorological quantities without additional information (see Ziemann et al., 1999b; Ziemann, 2000).

2.2. Simultaneous Iterative Reconstruction Technique

The measured quantity, that means the line integral of the acoustic travel time of a signal between a fixed transmitter and a receiver, can be expressed as

$$\tau = \int_{\mathrm{ray}} \frac{\mathrm{d}l}{c_{eff}} \tag{1}$$

where dl is the element of the arc length along the propagation path and

$$c_{eff} = v + c_L(T_{av}) \tag{2}$$

symbolizes the effective sound speed with the coupled influence of the virtual acoustic temperature T_{av} (c_L is Laplace’s sound speed) and the wind vector component in direction of the sound propagation v (e.g., Spiesberger and Fristrup, 1990).

Because of this relation it is possible to derive meteorological quantities like the air temperature by means of acoustic travel time tomography under the prerequisite of a high measurement accuracy which depends on the searched meteorological quantity, the sound-receiver distance and the environmental conditions.

The coupled influence of the virtual acoustic temperature and the wind vector on the effective sound speed is a difficulty in the data analysis. One possibility to distinguish between these different influences and to derive a travel time without the wind vector influence is described by Arnold et al. (2001). Thereby, one quantity (e.g., wind vector) is iteratively changed whereas the variance of the other quantity (e.g., temperature) decrease stepwise for all ray paths together until reaching a designated criterion. In the next step this procedure will be carried on with the reversed quantity. At last one obtains two data sets: one travel time set only with the temperature influence and one travel time set only with the wind vector influence.

An additional difficulty in the numerical application of the tomographic method is the dependency of the ray path itself on the unknown distribution of the effective sound speed and therefore the line integral becomes non-linear in this quantity. Usually, a linearization is applied to solve this difficulty (e.g., Bording et al., 1987). Thereby, straight lines connecting the sound source and the receiver are used to approximate the true ray path. The error made by this approximation was investigated by sensitivity tests with a sound-ray model including a generalised equation for refraction. The error found will be small enough if we use path lengths not more than 500 m over a relatively homogeneous surface (see Ziemann et al., 1999b; Ziemann, 2000).

As a result of the limited number of transmitters and receivers the tomographic algorithm has to use a tomographic array divided into grid cells of finite size.

After the linearization and discretization as well as the removing of wind influence from the travel time the system of equations, which has to be solved for *i* sound rays and *j* grid cells, results as

$$\tau_i = \sum_{j=1}^{J} l_{ij} s_j \tag{3}$$

with the so called slowness s_j (reciprocal sound velocity c_{Lj}). In the case of travel time tomography, one has to solve the inverse problem to get the spatially averaged sound speed depending on the virtual acoustic temperature. By outgoing from values of the measured travel time, an inverting technique provides an estimate of the spatially resolved temperature field that reproduces the measurements.

There are various algorithms to solve the linear equation system, for instance iterative algebraic reconstruction techniques which were developed for applications in seismic tomography (Gilbert, 1972) and for medical purposes (Herman, 1980).

Especially the Simultaneous Iterative Reconstruction Technique (SIRT) is characterised by stable convergence during the application on data sets with measuring errors, by non-significant developments of artefacts as well as simple handling during online evaluation (see Humphreys and Clayton, 1988; Ziemann et al., 1999a).

A comprehensive overview of the mathematical background of SIRT and other iterative algebraic reconstruction techniques is given by van der Sluis and van der Vorst (1987). These inverting algorithms follow a similar scheme.

An initial guess of the slowness values in the grid cells is derived from a simple back projection of the measured travel time data into grid cells using the inverse Eq. 3. By means of the so estimated reciprocal sound speed one can apply forward modelling (Eq. 3) to get a modelled travel time. Now a difference between the experimentally obtained and the simulated travel time values is provided by the model. After back projection of this difference and adding a resulting correction to the present model an updated version of the simulated travel time follows. This iterative improvement of the modelled data is continued until attainment of a convergence criterion and leads to area-averaged values of temperature T_{av}.

Using the straight-line sound rays and the described SIRT algorithm allows to derivate absolute values of the temperature without additional information in contrast to stochastic reconstruction algorithms which were used by Spiesberger and Fristrup (1990) or Wilson and Thomson (1994) in the atmospheric surface layer.

2.3. Accuracy

The travel time measurements as well as the determination of the distances between sources and receivers have to be carried out with a high degree of accuracy. Additionally, the achieved data accuracy principally depends on the examined meteorological quantity, the transmitter-microphone distance and the environmental conditions (Arnold et al., 1999; Ziemann et al., 1999b). Furthermore, the quality of the tomographic reconstruction has to be checked for the special tomographic array with synthetic data. The results of such tests of the SIRT model demonstrate the relative insensitivity of the algorithm with regard to small variations of the transmitter and receiver positions up to ±5 cm (Ziemann, 2000).

With an actual travel time accuracy of about 0.3 milliseconds the temperature field can be obtained with an indefiniteness of 0.5 K (spatial average) for one measurement.

3. Experimental results and discussion

3.1. Data analysis

The spatial resolution of a measuring field and therewith the grid cell size in the SIRT model mainly depends on the number of sound rays between transmitters and receivers, the accuracy of the travel time measurements and the differences between the sound speed values at different places inside the measuring area.

For the tomographic measuring site at the "Common measuring field" (German Weather Service Observatory Lindenberg) 70 km south-east of Berlin with a horizontal dimension of 200×240 m² we could apply a grid cell size of 50×50 m² apart from the borders (see Fig. 2).

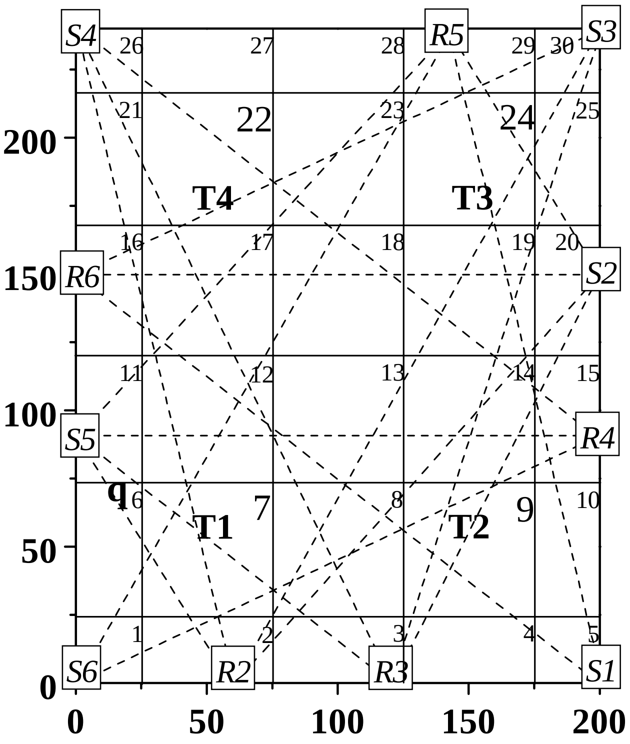

Figure 2: Tomographic array (200×240 m^2) with 6 sources (S1…S6), 5 receivers (R2…R6), 4 thermoelectric measurement devices (T1…T4), 1 measurement point for the specific air humidity (q), numbered grid cells (1…30) and sound rays (dashed lines).

By means of 6 compression drivers at a height of about 2 m using a 1000 Hz signal and 5 microphones at the same height, the travel times between the sources and receivers are determined.

Details of the experiment and the technical devices are described by Arnold et al. (2001).

To derive the air temperature depending on T_{av} the specific humidity has to be included in the calculations. For this purpose humidity measurements (one point) of the German Weather Service Lindenberg are used.

3.2. Spatially averaged values of temperature

With the adjusted travel time data (removed wind influence) area averages of the air temperature at a height of 2 m were calculated with one value for one grid cell.
Figure 3 illustrates examples of so-called tomograms, that are horizontal slices of the air temperature field at the site.
Beside the general temperature trend, for instance, the daily course of the air temperature, one can detect more or less significantly spatial differences of the air temperature (Fig. 3, left). Such pictures can lead to statements on the horizontal variability of the temperature field and additionally to statistical data inspections also to statements on the horizontal homogeneity of measuring fields.
A tomogram (Fig. 3, right) with averaged air temperatures over a time period of 24 hours demonstrates the relative homogeneity of the measuring field in relation to temperature measurements.

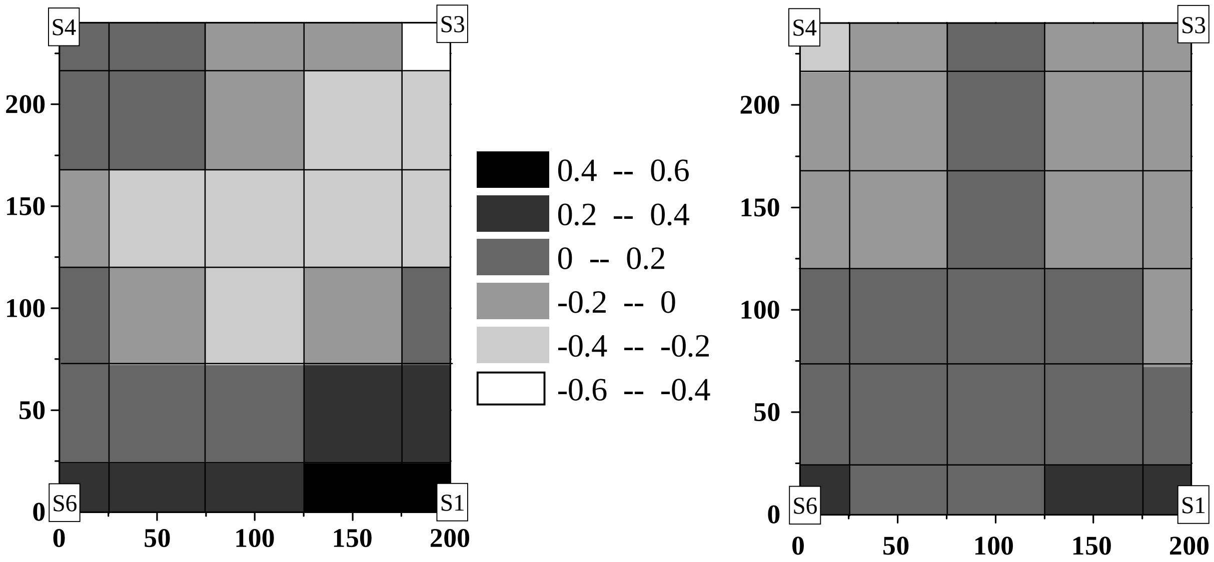

Figure 3: Tomograms of the air temperature differences between the grid cell value and the areally averaged value [K].
Left: 10-Minutes-average of the air temperature on the 24 September 1999, 1200 UTC.
Right: 24-hours-average of the air temperature on the 24 September 1999.

Figure 4 shows the comparison between two spatial differences of the air temperature measured by the thermocouples and derived by tomography (see also Fig. 2). Sometimes one can determine a qualitatively good agreement between the two methods, that means the same sign of the difference. This result especially occurs during weak wind conditions (horizontal wind speed < 2 ms^{-1}). Sometimes one has to notice a disagreement in the signs of the differences, especially in connection with higher wind speeds. The wind influence on the two measuring methods, for instance, on the effective sound speed measured by tomography as well as on advection, is one possible reason for this behaviour. Further possible explanations for the differences between the tomographic and the conventionally derived data are:

- Differences between remote-sensing method and direct measurement
- Differences between area-averaged data and data from one point
- Non-homogeneous humidity field (tomography)
- Different influence of local advection

In spite of these differences between the two methods one can detect the general agreement in the absolute values of the temperature differences and in the spatial variability of these differences. A higher variability of the spatial differences and also greater absolute values of these differences appear during the day between 0700 and 1300 UTC with a developed turbulence under convective conditions. This development was interrupted by a thunderstorm with a strong shower. The acoustic measurements has to be stopped during this period because the signal-to-noise ratio is too bad in this situation (noise of the drops on the microphone) and the microphones are not really waterproof.

Please note, that the measurement cycle during the day amounts to 30 s, whereas the measurements during the night were repeated every 5 minutes. This is in addition to the more distinct turbulence a reason for the obviously greater variability of the spatial temperature differences during the day. Furthermore, the mapped values are instantaneous values without averaging.

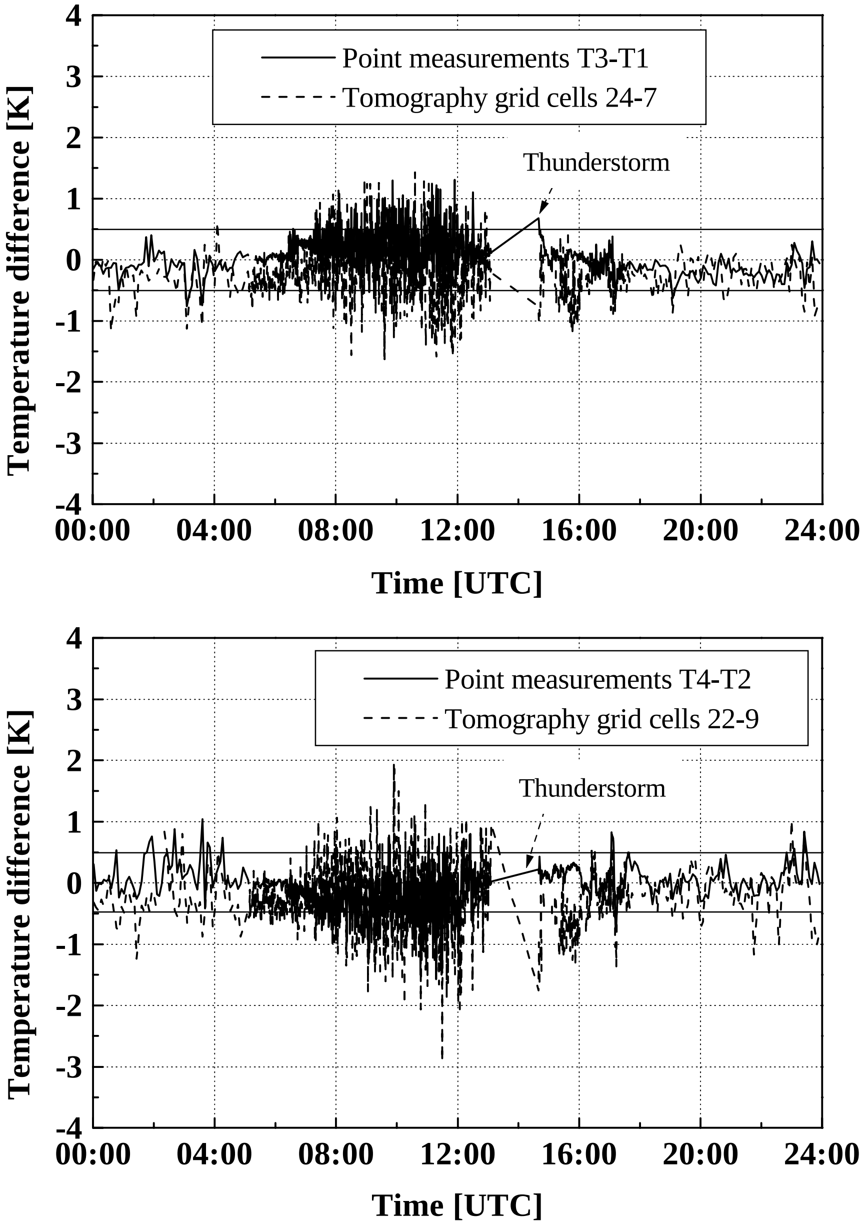

Figure 4: Spatial temperature differences (point-to-point and cell-to-cell, respectively) measured by thermocouples (solid line) and by tomography (dashed line) on the 24 September 1999) every 30 seconds during the day (05:06-17:39 UTC) and every 5 minutes during the night.

In Figure 4 the indefiniteness of the absolute temperature values measured by tomography is also indicated. However, the differences of values measured by one and the same method can reach a higher accuracy.

The calculation of statistical measures over the chosen time period is a further possibility to describe the homogeneity of the measuring field.

Therefore, the standard deviation of grid cells in relation to a spatially averaged value for the whole tomogram (see Fig. 5) and the normalised third moment (skewness, see Fig. 6) were calculated for the selected time period.

The standard deviation achieves for the most grid cells only a small value between 0.2 K and 0.4 K. That means the deviation of the single value inside the grid cell from the spatially averaged value is smaller than the indefiniteness of the measurement for one time step (ca. 0.5 K). Furthermore there are only small variations between different grid cells. Therefore, the measuring field can be indicated as horizontally homogeneous for this time period.

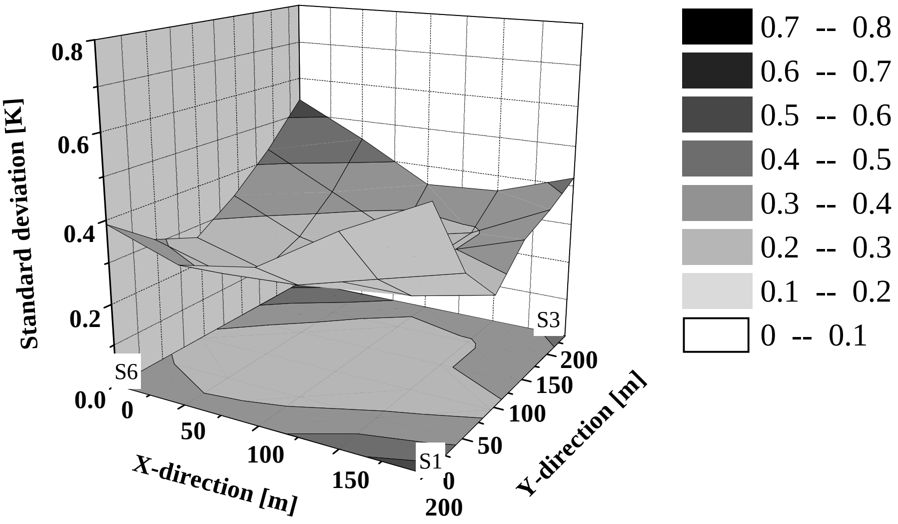

Figure 5: Standard deviation of the tomographically derived air temperature inside the grid cells in relation to a spatially averaged value, 0000-2400 UTC, 24 September 1999.

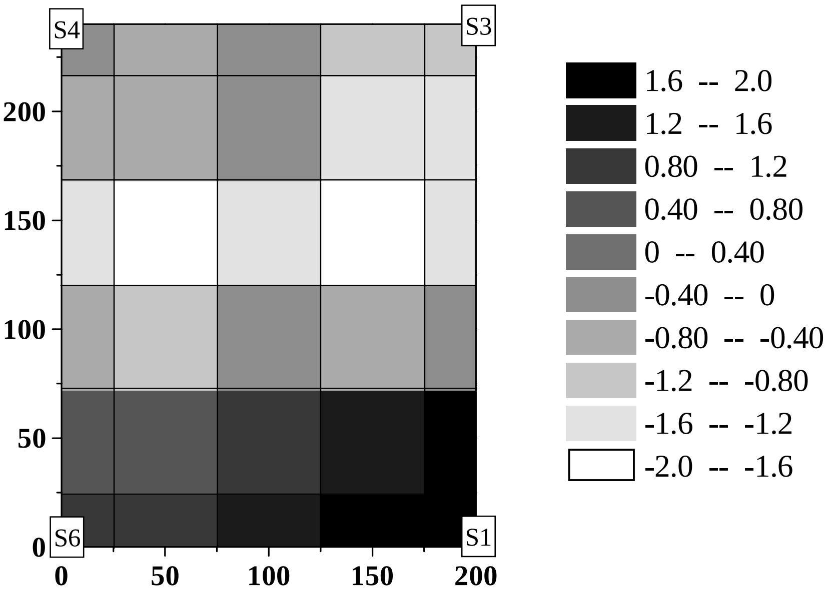

Figure 6: Momentum coefficient of skewness of the tomographically derived air temperature inside the grid cells in relation to a spatially averaged value, 0000-2400 UTC, 24 September 1999.

In comparison to this results the normalized third moment displays a spatially greater variability. This measure denotes the type of the data distribution, i.e. whether the distribution is symmetrical or not. Positive (negative) values signify that the most frequent value is smaller (greater) as the arithmetic mean. A really symmetric distribution has none skewness.

The significant spatial differences of this quantity (significance test: Madansky, 1988) point to the horizontal inhomogeneity of the measurement field. This could be a hint for different environmental conditions and turbulent processes that influence the different parts of the test site. Further investigations with other analysis methods (e.g., Fourier analysis) and by means of additional measurements are necessary to identify and quantify these processes.

4. Conclusions and outlook

The acoustic travel time tomography holds the possibility to derive statements on the variability of spatially averaged air temperature data and therefore on the possible application of the known turbulence theories to calculate vertical turbulent fluxes.

Except for the differences between point measurements and spatially averaged data the qualitatively sufficient agreement between the two methods point out the horizontal homogeneity of the measuring field in relation to the air temperature at least over time periods of several hours.

Therefore point measurements could be applied for micro-meteorological investigations over the examined area of the “Common measuring field” under convective conditions during a late summer day with the known restrictions regarding to the disadvantages of direct measurements (e.g., influence of direct radiation to absolute temperature measurements) and with sufficiently extensive averaging time intervals in mind.

The degree of inhomogeneity of a measuring field should be tomographically analysed however under different environmental conditions (e.g., meteorological situation, type of the underlying surface) to get a generalised statement on the representativeness of point measurements and the applicability of usually used turbulence theories and approximations (e.g., horizontal homogeneity and stationarity) for the calculation of turbulent fluxes.

In the future the validation of the tomographic data has to be carried on. Besides, a comparison with results from other tomographic methods will be provided to increase the quality and reliability of the reconstructed data.

Further investigations will deal with a refined separation of the wind-temperature influence on the effective sound speed to calculate also tomograms of the wind vector.

Additionally, three-dimensional tomographic measurements and algorithms will be developed to provide volume-averaged meteorological data. By using these data it should be possible to develop improved objective measures of the degree of inhomogeneity and to experimentally test such measures which were discussed in the meteorological community (see, e.g., Panin et al., 1998; Zilitinkevich and Calanca, 2000). Such investigations could be an important step to evaluate and quantify the effects of micro-scale inhomogeneity of natural surfaces on the flux measurements at one point and the determination of the energy balance of an area.

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