**Turbulence structure of the atmosphere in a region of complex terrain and near to a major industrial installation**

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**Abstract.**

This work compares the predictions of a linearised wind flow and turbulence model with sonic anemometer data taken in a geographically complex region dominated by a large industrial site, the Sellafield nuclear reprocessing facility. The Sellafield plant, in Cumbria, has a licence to emit various forms of effluent to the atmosphere, both radioactive and stable. Understanding the turbulent structure of the boundary layer is important for modelling the dispersion of effluent. The complexity of this task is enhanced by the irregularity of the terrain, the industrial site itself and the sea-land transition, which lies within a kilometre of the plant. The results of a computer code, FLOWSTAR, are compared with field measurements of turbulence. The code divides the boundary layer into three strata and applies different approximations to each. It then finds asymptotic solutions to the linearised equations of motion in each layer. The model can consider varying terrain, surface roughness and atmospheric stability, specified by the Monin-Obukhov length scale.

The field measurements are acquired by a number of sonic anemometers, located at key points in the region. Two sonic anemometers are located on a fixed 50 m mast to the North West of the industrial site. Another 10 m portable system is situated at a number of points where the terrain is of such a nature that the model will be close to, or beyond, the limits of its validity. This technique is employed to ascertain the performance of linearised models in regions of this complexity and their application to operational dispersion modelling.

One location for the portable system is close to the summit of a small rise in the terrain. The model’s predictions display a reduction in the turbulence field at this point, at the height of the portable mast, consistent with the documented phenomenon ‘rapid distortion’ of eddies.
1. Introduction.
The Sellafield nuclear reprocessing plant in Cumbria discharges a variety of pollutants to both the marine environment and the atmosphere. Understanding the dispersion of this effluence is of prime importance for the industry, with implications for the local population. Accurate modelling of the air flow in the region is one of the key ingredients towards correct prediction of the ground level concentrations and radiation dose assessment. Work is being carried out to assess the suitability of the computer code FLOWSTAR (CERC 1993) for the task of predicting the atmospheric flow. Its predictions include details of the turbulent structure of the boundary layer of the atmosphere.

This paper will concentrate on the comparison of the predictions of these turbulence statistics at key points in the region with the values measured by sonic anemometry. It is the turbulence, quantified by the variances $\sigma_u$, $\sigma_v$, and $\sigma_w$ of the wind vector’s components that is responsible for the local dispersion of pollution and for inducing many other boundary layer changes. The high frequency variation in the wind vector brings about the necessity for rapid response equipment such as the sonic anemometer.

In section 2, an outline of the experimental set-up will be given. Section 3 describes the model FLOWSTAR and its application to this work. Section 4 compares the results from the field and modelling work and section 5 draws some conclusions.

2. Experimental set-up and data collection.
Sonic anemometers are capable of providing wind speeds, turbulent variances and covariances, a measure of the atmospheric stability, information on fluxes of heat and momentum and a temperature, all at a rapid sampling rate. See Gill Instruments (1992) for further information.

Three sonic anemometers are in use: ‘NP1’ and ‘NP2’ are located on a 50 m mast, at heights 7.5 m and 30 m. Sonic anemometer ‘WL1’ resides on a portable mast. In Figure 1, sampling sites A and B represent the positions of the permanent 50 m mast structure, located 200 m from the closest buildings on the Sellafield site. The other locations, C-E are the positions of the portable mast.

The region being studied is an area of a few square kms around the Sellafield plant. Apart from the plant itself, it includes farm land, sea and three villages. The topography undulates, gradually rising towards the Lake District.

For most of the exercise we have been using Campbell Scientific’s data loggers, with a wide range of mathematical functions for pre-processing the data. There is also a memory large enough to hold several days of processed data. A CR10 logger resides at the base of each mast, collecting means and variances of the four signals and covariances of each pair over each 10 minute interval.
Figure 1: Contour map of terrain with sampling sites, Sellafield and rivers.


FLOWSTAR has been developed in the belief that an analytical solution well representing the major features of airflow over shallow hills exists, in many cases, to the linearised equations of motion (eg. Hunt, Leibovich and Richards (1988); Hunt, Richards and Brighton (1988).) The criteria that it requires for accurate performance are a stratification that can be idealised as one of five basic forms, a Froude number greater than unity, no rapid changes in upwind conditions and no strong heating or cooling of the terrain. A mixing length relation, based on K theory, is used to calculate the turbulent momentum fluxes. Fourier transforms of the terrain heights and roughness lengths across the domain are calculated. Fourier transforms of the perturbation to the velocity field are calculated from these and the real space perturbation calculated by inverting the result. This technique saves computer time and storage space compared to a method based on the full equations of motion. It was pioneered in the 1970s, by Jackson and Hunt (1975). The code of FLOWSTAR consists of a suite of modules, executable on a PC.

Many studies have concentrated on hills approximating a cosine bell shape surrounded by flat land (eg. Mason and King 1984). In studies with such ideal
terrain, the lower atmosphere divides naturally into three layers, the inner, middle and outer layers, and the solution is calculated according to the approximations in Figure 2. The border between the lower two is defined as the height at which perturbation shear stresses become unimportant. In the middle region, wind shear is important; in the upper region stratification plays an important role and the equation for inviscid, stratified flow is solved. This highest region may contain some of the non-turbulent free atmosphere (above the boundary layer). Stratification here causes pressure changes, which in turn affect the lower level flow.

**Linearized Flow Theory for Low Hills**

This study attempts to apply this modelling technique to flow over more complex terrain, as did Inglis (1992). The region in question includes the further complications induced by the industrial site. The site will be parameterised by enhanced roughness, since there is no explicit provision for buildings within the code. Some work on modelling the region’s flow has been undertaken by Singh et al. (1993).

For this work roughness lengths of 0.1 m are being used for most of the countryside. The exceptions to this are the Sellafield site, which has been assigned a value of 0.6 m, and the sea with 0.001 m. The terrain data are supplied by Ordnance Survey, the height accurate to 1 m on a grid with spacing 50 m by 50 m. The FLOWSTAR module GRID calculates the Fourier transforms of the terrain and roughness fields. A terrain and roughness field aligned with the specified wind direction are then calculated and written to file. This procedure works best when the original files themselves are aligned with
the wind, so a program has been developed that extracts the Ordnance Survey data in a rectangular array parallel to the wind direction.

Site C was chosen for its proximity to the summit of a small rise in terrain, since the model predictions of the turbulence statistics at this point, at height 10 m, are affected by the phenomenon ‘rapid distortion theory’, which occurs in the outer regions of the inner layer.

4. Results.

The set of comparisons described is performed using a terrain grid centred on the main mast (sites A and B), with the upstream edge at sea (Westerly wind). The meteorological conditions required by the model are a friction velocity, a Monin-Obukhov length, a stratification type (0-4), a value for the Brunt-Väisälä frequency N and an estimate of the boundary layer depth. These are obtained from the 50 m mast equipment. Model predictions of turbulent kinetic energy (\( \text{TKE} = \left( \sigma_u^2 + \sigma_v^2 + \sigma_w^2 \right) / 2 \)) are compared with the values measured at the portable mast (sites C-E) averaged over periods of similar sampling conditions - subsets of similar wind direction, time of day and \( u^* \).

The value of the static stability parameter \( N \) is calculated by the following procedure for stable atmospheric conditions:

\[
R_i = \frac{N^2}{(\partial U / \partial z)^2} \Rightarrow N^2 = (\partial U / \partial z)^2 R_i
\]  

(1)

where \( R_i = (z/L)(0.74+4.7z/L) / (1+4.7z/L)^2 \) in stable conditions

(2)  

(Businger et al. 1971).

We know that \( \frac{\partial U}{\partial z} = u^* \Phi_M / k z \)  

(3)

where \( \Phi_M = 1 + 4.7z / L \) for stable conditions

(4)  

(Businger et al. 1971).

Substituting (2), (3) and (4) in (1) gives

\[
N^2 = \left( u^* / k z \right)^2 (z / L)(0.74 + 4.7z / L) \text{ for stable conditions.}
\]

We have opted to use a value of \( N=0 \) in convective conditions, assuming the surface layer lapse rate to be superadiabatic and the remainder of the mixed layer to be adiabatic.

Turbulent kinetic energy predicted by the model is in close agreement with the values measured at the portable mast. See, for example, Figure 3. Each point on this plot represents the average of all the mast data that fell into the appropriate category, viz that specified by wind direction, \( u^* \) and time of day.
Figure 1
and increasing uncertainty for more extreme stability.

Note the clustering around (1)
TKE ratio against z/L for site C in September.

Parameter z/L.

The predicted TKE ratio, measured against predicted TKE, and measured against predicted TKE.

Figure 3
Site C in September 1994.

Measured against predicted TKE.

TKE predicted by Flowstar / m².s⁻¹.
TKE measured at site C / m².s⁻¹.

Air Pollution Theory and Simulation
Distribution of TKE values observed.

The points on Figure 4 are averages of all the data measured during the appropriate conditions. Because of this, we have studied the distribution of the TKE values measured making up the points in Figure 4. For data points within the 10% bands, there is roughly a 50% chance of each measurement itself being within 10% of the predictions.

This variation in the measured TKE statistics may be due to any of a number of causes. It may be that the terrain shape is enhancing turbulence at certain frequencies. It may be that the wind is more gusty on occasions, which would affect the turbulent part of the flow linearly, but the TKE quadratically. Alternatively, the wind direction may have fluctuated more during some ten minute segments. Mast vibrations may play a part. For this last reason we are planning to collect a small quantity of raw 20 Hz sonic anemometer data from the portable mast, which we will analyse for spurious spectral peaks. (Singh 1992 noted the existence of such peaks in spectral data from a portable mast.) Lastly, of course, boundary layer structure is mostly dependent on the history of the air mass. It must be noted that this uncertainty is because of the random nature of the local atmospheric flow and not poor performance of the model.

There appears to exist a trend in the stable region of Figure 4 such that the TKE ratio decreases with increasing stability. Taking all measurements making up the data points of the stable section, there is a Pearson Product Moment Correlation Coefficient of -0.28 between the TKE ratio and z/L.

5. Conclusion and discussion.

The atmospheric flow around the Sellafield site is disturbed by the surrounding terrain in many co-existing and interacting ways, by the site itself and by the nearby sea-land transition. Attempting to model all of this on a desk-top computer is desirable for the purposes of accessibility and cost.

The model predicts TKE most accurately in neutral atmospheric conditions. Reasonable results (mean measured TKE will be within 10% of model predictions) can be expected for stability at least up to z/L=0.07, although in more extreme conditions the predictions can be erratic. The predictions for convective conditions (z/L<0) are not particularly good, although there is no explicit provision for this in the model anyway. Thus for the region of FLOWSTAR’s predictive capabilities (neutral to moderate stability) it generally succeeds. The main outlier, which is labelled on Figure 4, is the average of only two data points from the mast and experienced anomalously high levels of turbulence during these two 10 minute intervals. The correlation coefficient of -0.28 between the TKE ratio and the stability is probably not large enough to represent a significantly worse under-prediction in extremely stable atmospheres.

An alternative approach will be to run the model over terrain downwind of sites A and B. This approach will provide more accurate model boundary conditions.
(data from sites A and B), but ones from a non-ideal wind profile, having traversed a stretch of terrain.

The aims of this project concern the applicability of the model FLOWSTAR to such complex terrain and, more importantly, the nature of the atmospheric flow in the region. Additionally, it may be possible to characterise the region’s surface features in terms of roughness lengths more accurate than those currently used. Investigations will be made to discover how well a stochastic roughness length distribution performs. Such improvements will assist when meteorological input is limited without recourse to expensive particle tracking. This is done using models such as the United Kingdom Atmospheric Dispersion Modelling System (UK-ADMS), which uses FLOWSTAR for wind and turbulence field calculations.

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