On the prediction of the wind field in complex orography for accident analysis

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Abstract

The work presented in this paper is part of a program to develop a method for strategic planning during industrial emergencies. The paper discusses the simulation of the wind field, for use in pollutant dispersal predictions, over a mountainous coastal region, 100 by 100 km, in north-west Wales, UK. A simple null-divergence code (AVACTA II) has been modified to allow initialization in the absence of vertical profiles of wind. The input to the simulations is limited to data that is readily available in real time, i.e. ground level wind observations and the geostrophic wind, calculated from surface pressure charts. The initialization of the wind field is of paramount importance for the accuracy of the solution obtained after the minimization of the divergence. Simulations are initialized using the geostrophic wind only, and also with the inclusion of ground level observations. The results are compared to simulations provided by a numerical model that solves the non-linear equations of motion and thermodynamics.

1 Introduction

The planning and management of accidental pollutant releases into the atmosphere requires an accurate estimation of wind speed and direction in the vicinity of the source and in the area of likely impaction. The availability of observations is, however, frequently poor and the spatial variability of the wind difficult to diagnose, particularly in regions of complex topography. Atmospheric models are commonly used to simulate the wind field distribution, with the choice of model depending on the scale of interest. A very small scale, of the order of 1 m, is necessary when simulating the flow
around a building, whereas scales in excess of 100 km are required when computing the long term dispersion of radionuclides from power stations.

In the conventional (non-nuclear) industrial field, an analysis of reported chemical incidents reveals that fatalities rarely occur at distances greater than 1 km from the source, and that the region of evacuation and the affected zone rarely exceed a distance of a few kilometres downwind. Consequently, the simulation of the low level wind field within a model domain of 20x20 km is sufficient. In contrast, nuclear accidents required a larger domain size, and the calculation of the wind field at both low and high altitude. However, for an emergency planning application, the over-riding consideration is that the method used to generate the wind field is robust and easy to use. In particular, it must be operable by users with little specific knowledge of atmospheric dispersion or numerical modelling.

This paper compares the results of two models used to simulate the wind field in the mountainous coastal region of north-west Wales (Fig. 1). The airflow in the region is likely to undergo significant topographic steering and thermal modification associated with differential heating over the land and sea. The dominant topographic feature is the Snowdonia mountain range which rises to 1000 m within a few kilometres of the coast. Observations from a network of meteorological stations (IMPLEX [1]) are available to local government emergency planning officers in real time or from the data archive. Supplementary meteorological data, e.g. the geostrophic wind speed and direction, can be calculated from surface pressure charts of the UK, updated hourly, and available by fax from the UK Meteorological Office. This relatively good data coverage ensures that the region is suitable for the model testing.

2 Numerical Models

The basic equations governing fluid flow are

\[
\frac{dV}{dt} + f k \wedge V = -\frac{1}{\rho} \nabla p + g k + F
\]

(1)

\[
c_p \frac{d \ln \theta}{dt} = \frac{\dot{q}}{T} + D
\]

(2)

\[
\frac{d\rho}{dt} + \rho \nabla \cdot V = 0
\]

(3)

where \( F \) represents frictional forces, \( D \) the viscous dissipation of heat, and the effects of moisture have been neglected. If the atmosphere is assumed to be hydrostatic, Eqs. 1 and 3 reduce to

\[
\frac{dU}{dt} + f k \wedge U = -\frac{1}{\rho} \nabla_h p + F_h \]

(4)

\[
\nabla \cdot V = 0
\]

(5)

where \( U \) is the horizontal velocity.
In emergency planning operations, the time evolution of the wind field is frequently unimportant due to the necessity for a rapid response to the incident and/or the short duration of the pollutant release. The first assumption of both wind models is therefore that the atmosphere is in steady state.

The models use a gridded topographic dataset supplied by the UK Meteorological Office. The data resolution is 30" in longitude and latitude.

### 2.1 Null-divergence code

The simplest application of the above equations is to use only the continuity equation, Eq. 5, and therefore to estimate the flow using the hypotheses of mass conservation and incompressible flow. A commercially available code, AVACTA II, has been used in this research (Zanetti [2]).

The required input for null-divergence models is the observed low level wind at several locations, the vertical profile of the wind at one, or more, station, and an estimate of the atmospheric stability, usually specified by stability class, e.g. after Turner (Stull [3]). The first approximation to the wind
field is obtained by interpolating the observations onto each of the cells in a three dimensional grid covering the region of interest. Conventionally, the interpolation method has made use of weighting functions based on \( r_i^2 \), where \( r_i \) is the distance of the observation \( i \) from the point of interest. The null-divergence condition is then applied to the flow field. The horizontal divergence of the wind is minimized, and the residual divergence removed by an adjustment of the vertical component of velocity. In performing this calculation a parameter termed 'transparency' is of paramount importance, and is dependent on the stability class of the atmosphere. If the atmospheric stability is low, the 'transparency' of adjacent grid cells will be high, and the wind field affected by the topography to a low degree. In contrast, if the atmosphere is strongly stable, then air will be forced to flow around topographic obstacles.

For many accidental releases, however, the required inputs are unavailable. Most significantly, a vertical profile of the wind is difficult to obtain in real time. Therefore, the AVACTA subroutine for simulating the wind field has been modified to reflect the routinely available meteorological observations in north-west Wales, and accordingly, the required input of the wind profile has been replaced with the input of the geostrophic wind above the level of influence of topography.

Furthermore, for general emergency management it is unrealistic to suppose the knowledge of the wind in many stations located within a few kilometres of the pollutant source. With a single low level observation included during initialization, the code produces a uniform low level wind speed over the entire domain. This is not adequate in regions of complex orography, and the interpolation method has been modified as shown below.

The wind speed, \( u \), at altitude, \( z \), is estimated using

\[
  u(z) = u_g \left( \frac{z}{z_g} \right)^p
\]

where \( u_g \) is the geostrophic wind speed, and \( z_g \) is the height at which the geostrophic wind is applied. The exponent, \( p \), is dependent on atmospheric stability, and land/sea differences can be introduced by specifying a height dependent atmospheric stability. The ground level wind speed is adjusted by interpolation of the observed wind components,

\[
  u_j = \frac{u_{0,j}}{r_0} + \left( 1 - \frac{1}{r_0} \right) u_{sg,j}
\]

where \( u_0 \) is the observed wind and \( r_0 \) is the distance of the point of interest from the observation. The sub-geostrophic wind speed at ground level, \( u_{sg} \), is calculated using Eq. 6, and its direction given by

\[
  \tan \beta = \frac{B}{\ln \left( \frac{z}{z_0} \right) - A}
\]
where a positive $\beta$ implies that the ground level wind is backed with respect to the geostrophic wind, and the constants $A$ and $B$ depend on the atmospheric stability class. Eqs. 6 and 8 are generally valid at heights between $10z_0$ and one tenth of the height of the mixed layer.

An attempt has also been made to include the effects of the thermal modification of flows in this mountainous region, by applying a correction to the ground level wind that is dependant on the terrain slope. If the terrain slope is greater than a threshold value and thermal flows are considered to have developed, an upslope or downslope correction of $1\text{ ms}^{-1}$ is applied to the initial wind field during the day or night respectively. The corrected wind field is then smoothed over a width of 6 grid cells to produce the initial wind field for the model.

The model domain is shown in Fig. 1. The grid cells are 560 m, 925 m and 55 m in longitude, latitude and height respectively, giving array dimensions of $181 \times 121 \times 38$.

It is clear that a good representation of the flow is dependent on the quality and number of observations, and more importantly, on the observations reflecting the meteorological phenomena that are acting at the time of interest. The final solution has been found to be highly sensitive to the initial wind field. Research within this study has therefore concentrated on the specification of the initial model wind field in data sparse regions.

2.2 One-level model

The model is a one layer (at the surface) sigma co-ordinate, primitive equation model. It diagnoses the ground level wind and temperature by solving the equations of motion and thermodynamics, Eqs. 4 and 2. Since only one level is used, the continuity equation, Eq. 5, cannot be solved explicitly. The equations are closed by including a parametrized layer of topographic influence where the temperature lapse rate is allowed to vary horizontally but is independent of height with a constant free atmosphere lapse rate above. This type of model was originally proposed by Danard [4] and reformulated by Mass and Dempsey [5]. The model is initialized by imposing the synoptic scale geopotential heights and temperatures of a given reference pressure level and a free atmosphere lapse rate above the boundary layer.

The model equations are solved using a finite difference technique. The initial surface wind field is calculated by balancing the surface pressure gradient, Coriolis and friction forces. The model then uses a second order Adams-Bashforth scheme to integrate the model equations, with zero diabatic heating in the energy equation, to a steady state, i.e. when the local rate of change of wind velocity and surface temperature fall below a convergence criterion. The free atmosphere lapse rate is assumed to be constant in time and space when integrating the model to steady state, as is the height of the layer of topographic influence. The lapse rate in this layer is, however, allowed to vary.
Diurnal variations in the wind circulation may be modelled by parametrizing the diabatic forcing term. After a steady state wind field, resulting from the imposition of a synoptic scale pressure and temperature field and free atmosphere lapse rate, has been attained, the diabatic forcing term may be included to simulate several hours of heating or cooling. The time of day is measured from a diurnally neutral period, around either sunset or sunrise, when the steady state wind fields are considered most applicable. The length of time that the model can be run in prognostic mode is limited by the time variability of the large scale synoptic fields.

Given the availability of data for north-west Wales, the geopotential height and temperature of a suitable reference pressure level, say 850 mb, must be simulated by assuming that the geostrophic wind is independent of height to this level, and a free atmospheric lapse rate typical of the stability class of the atmosphere. Given the size of the model domain, the spatial variation of the geostrophic wind may be significant. This is incorporated into the model by interpolating the sea level pressure measurements available from the UK Meteorological Office surface charts into the model grid, and calculating the geostrophic wind for each grid cell.

The vertical profile of the wind is then diagnosed from the ground level wind by assuming a log profile, and limiting the speed to the geostrophic value.

The model domain is shown in Fig. 1. The grid cells are 1500 m by 1500 m, giving array dimensions of 66×73.

3 Results

Figure 2 shows the observed winds on 0600 GMT, 30 November 1995. A low pressure system to the south-west of Britain, and high pressure over the North Sea, resulted in a moderate south-easterly wind flow over north-west Wales. The geostrophic wind speed was estimated to be 25 ms\(^{-1}\) from 150°.

Figure 3 shows low level wind field generated by interpolation of the geostrophic wind only and used as initialization to the null-divergence model simulation for 0600 GMT, 30 November 1995. Figure 4 shows the low level wind field after the minimization of divergence. The effects of topographic steering on the flow are readily apparent. Table 1 gives the simulated and observed winds at the meteorological stations.

The effects of the inclusion of observations in the model initialization (not shown) are localized, with an improvement in the model wind field simulation limited to the grid cells surrounding the observation point. Model runs initialized without all of the observations, fail to significantly improve the simulations at the excluded stations. Furthermore, wind speeds over the water are unaffected by the inclusion of coastal observations.
Figure 2. Wind observations at the IMPLEX stations at 0600 GMT, 30 November 1995.

Figure 5 shows the ground level wind field simulation of the one-layer model. The simulated wind at the IMPLEX stations is given in Table 1. The representation of the both the wind speed and direction is adequate at coastal stations, but is less accurate in the deep valleys of Snowdonia. The influence of topography is less marked than in the null-divergence code, and significant differences exist between the results over the sea. The later is largely due to the spatial variation of the geostrophic wind in the one-level model. The one-layer model results are sensitive to the specification of the atmospheric stability class, and to a lesser degree to the coefficients of friction imposed over land and sea.

4 Conclusions

The ‘subjective’ user input to both codes has been limited to an estimate of the atmospheric stability class and therefore, little specific knowledge is required in either case. However, for the management of small scale emergencies, the best representation of the flow can be obtained with the use of the null-divergence code, initialized using the geostrophic wind and ground level observations, which simulates the localized modification of the flow in
Figure 3. Initialization wind field for the null-divergence model simulation for 0600, 30 November 1995. Vectors are plotted for the lowest model layer, at every third model point.

Table 1. Observed and simulated wind speed (Spd, ms\(^{-1}\)) and direction (Dir, degs from) at the IMPLEX meteorological stations. The bracketed values show the range in neighbouring model grid cells.
complex topography. The simulations could be further improved at fine scales if a more detailed knowledge of the topography were available. However, this is only feasible for pollutant releases from fixed sources, e.g. factories, for which incident plans can be formulated in advance. If the movement of pollutant is required on scales in excess of 10 km, then the one-level model is likely to better represent the mesoscale flow field. The one-level model is also advantageous if low level observations in the vicinity of the incident are unavailable. Future work will concentrate on the calibration of the models under sea-breeze conditions, and on methods of incorporating forecast meteorological information into the model initial states.

Figure 4. Null-divergence model wind field simulation of the low level wind at 0600, 30 November 1995. Vectors are shown at every third model point.

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References


Figure 5. One-level model wind field simulation of the ground level wind at 0600, 30 November 1995. Vectors are shown at every second model point.