A Virtual Wind Tunnel for flow over steep hills

Mike Revell, Stephane Popinet and Steve Reid
National Institute of Water and Atmospheric Research, New Zealand
m.revell@niwa.co.nz

Introduction

NIWA scientists Drs Stephane Popinet, Mike Revell and Steve Reid are developing a 'virtual' wind tunnel. This uses Gerris[1], a computational fluid dynamics computer code initially developed by Dr Popinet, to simulate wind flows. It has been used to model pressure loadings and flow distortion over a range of scales, from small buildings and ships to steep hills round Wellington. In this paper we describe its use to calculate the wind resource on scales of order 100 m in some of the suburbs of Wellington, New Zealand, where siting of small wind turbines has been proposed.

Model description

Gerris uses a flow dependent, adaptive grid to solve the incompressible Navier Stokes equations. This means while calculating the wind field the numerical method identifies the areas where the flows are complex and refines the grid there to capture that complexity while using a coarser grid on areas where the flows are smoother. A snapshot of a typical computation grid to estimate the flow distortion around NIWA's research vessel *Tangaroa* is shown in Fig. 1.

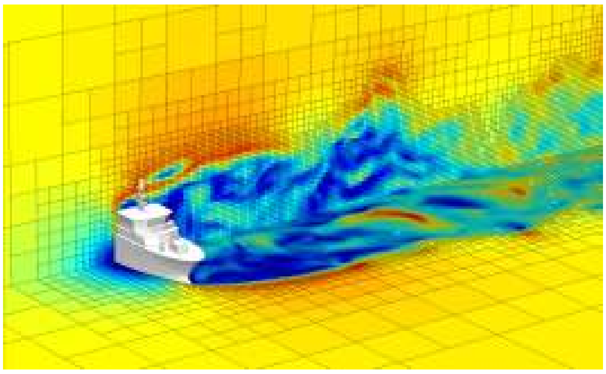

Figure 1. Grid elements and flow distortion around NIWA's research vessel *Tangaroa*.

[1] Free software (General public license) http://gfs.sf.net. Popinet (2003), J. Comp. Phys, 190.

This approach increases the computational speed by 10 to 100 times that of comparable static grid techniques with no loss of accuracy. The model does a good job of simulating the effect of upstream obstacles on wind direction at very small scales. We have also used the well observed flow round the Texas Tech building to assess how the model handles pressure loadings and wind deviation round buildings. The virtual wind tunnel results are within about 5% of field measurements for that building. The streamlines and pressure field for the Texas Tech building are shown in Fig. 2.

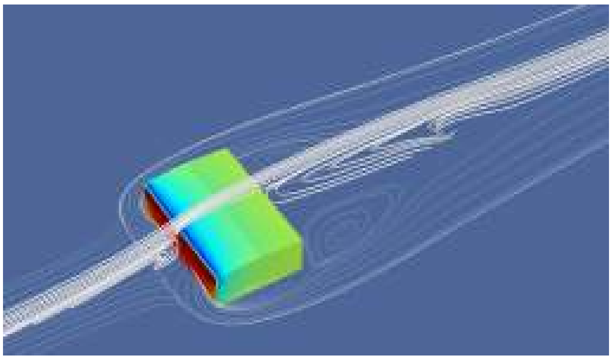

Figure 2. Streamlines and pressure field for the Texas Tech building.

Unlike most other numerical codes, the method also solves for the time varying wind thus giving an estimate of the gusts as well as the mean flow. This makes it very suitable for estimating the wind resource and turbulence in hilly sites where wind farms are proposed.

Estimating winds over hilly terrain (method)

Wellington has a reputation for being a windy city. Does it have sites suitable for power generation using small scale wind turbines? Are some suburbs better suited than others? In this paper we describe how Gerris has been used to estimate the wind resource over the Wellington region at a resolution of order 100m to answer these questions. We maintain a resolution of 100m over the built up areas but allow the resolution to decrease as we approach the boundaries. This is illustrated in Fig. 3 which shows the terrain height in the Wellington region with the coloured contours indicating the maximum resolution at that location.

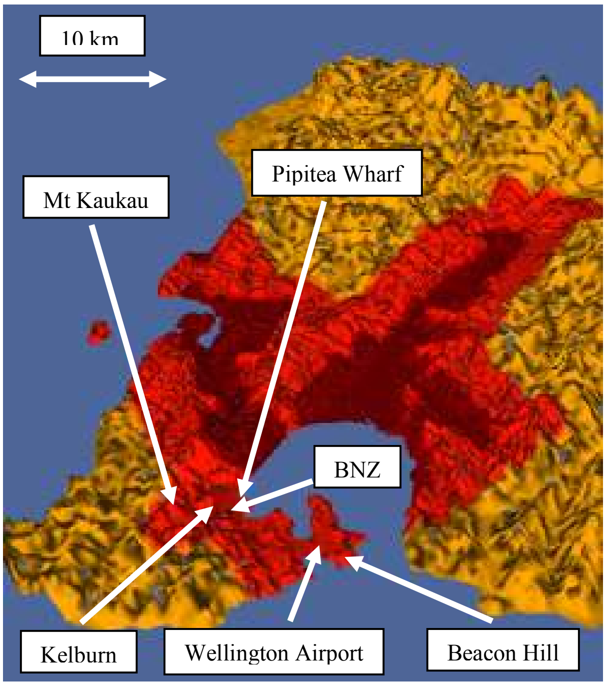

Figure 3. Wellington region terrain, key locations and coloured contours showing the maximum resolution allowed at that grid location. Brown, red and orange correspond to 100, 200 and 400m respectively.

In order to determine what inflow conditions to use for the model simulations, we first constructed wind roses for several sites in the Wellington region, including Mt Kaukau and Wellington Airport (locations indicated in Fig. 3), based on 37 years of data from the National Climate data base. As can been seen in Fig. 4, for Mt Kaukau (the other sites are similar) there are generally two predominant wind directions. In the case of Mt Kaukau these are northerlies from about 340º and southerlies from about 170º. Together these account for about 90% of the total cases. Winds from the remaining 10% of cases are generally much lighter and insignificant for power generation.

Mt Kaukau gives the best estimate of the free flow wind direction in the Wellington region (it is least affected by local topographic features) so we used inflow wind directions based on Mt Kaukau for our

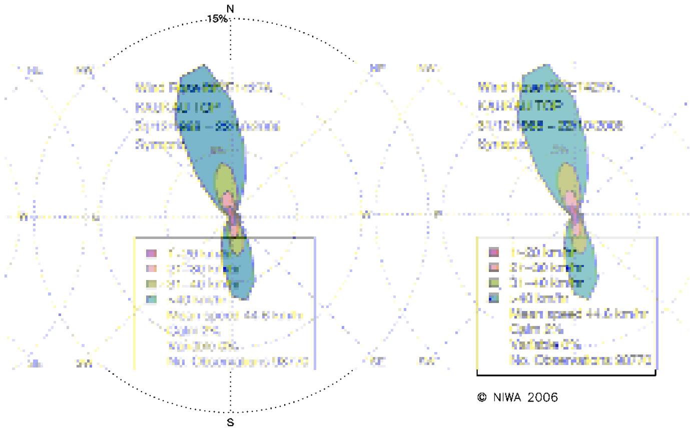

Figure 4. Wind rose for Mt Kaukau (1969 – 2006) showing the percentage occurrence of winds of a given range of strengths (colour coded) in a particular range of directions. The direction interval is 10º in this figure.

model calculations. However we consider the actual wind speeds at Wellington Airport over the last five years to be the most reliable so we used these when later estimating the mean annual wind speeds in the Wellington region.

Gerris was then run with winds from both of these wind rose directions to estimate both the speedup relative to the inflow velocity and the turbulence at each point over the grid. Gerris is well suited to this high resolution modelling at small scales. It solves the right equations, captures flow separation and eddy shedding and the adaptive grid is a very efficient way of resolving the flow where it is most turbulent. The maximum horizontal and vertical resolutions of the grid on which these calculations were made were 100m and 20m respectively. We expect this resolution to resolve the wakes due to the major topographic features in the Wellington region. The terrain model forming the lower boundary was based on high horizontal resolution contours at 20m height intervals. It does not include any trees or buildings. It was found necessary to inject some artificial white noise turbulence into the upstream flow to produce a realistic inflow boundary layer.

Finally we calculated the mean annual wind resource at Wellington Airport from the last five years of observed hourly data, since we consider this the most reliable as mentioned above. Using speedups from the above model runs for northerly and southerly directions and combining them in the appropriate proportions, according to the wind rose, the corresponding mean annual wind speed was then estimated at each of the model grid points at a resolution of 100m.

Estimating winds over hilly terrain (results)

The estimated annual mean wind at each point on the grid over the central and eastern suburbs is shown in Fig.5. The numbers are presented as a coloured spot at each grid point superimposed on an aerial orthophoto of Wellington. Speed up over the major ridges can clearly be seen by the number of yellow, orange and red dots in these locations. Regions of high turbulence tend to be in wakes downwind of the major peaks. In these downwind regions the mean wind speed is generally less.

Some comparisons of model estimated mean speeds with actual measurements at sites (with reasonably large data sets from the National Climate database) round Wellington are given in Table 1. Given that the estimates assume no trees or buildings and that most of the observation sites have some unusual features e.g. steep surrounding land or a non-standard height above ground (the tower heights are included in the table), there is generally good agreement. However, it appears the model may underestimate the sheltering in the lee of some upstream ridges by up to 20%. At steep sites like Beacon Hill or the BNZ building with its sharp corners, because of sharp gradients in velocity associated with eddy separation, movement of the location of the observation point by only a few metres could affect the wind measured by more than the difference between modelled and observed results, so this comparison needs to be viewed in this light.

Site	Model	Obs	Height
Kelburn	6.7	5.2	18
Pipitea Wharf	7.6	7.3	24
BNZ	6.5	4.6	115
Beacon Hill	11.8	9.8	12
Mt Kaukau	12.2	11.5	125

Table 1. Comparisons of model estimated mean speeds in ms^{-1} with observations (and corresponding tower heights in metres) at sites with reasonably large data sets from the National Climate data base.

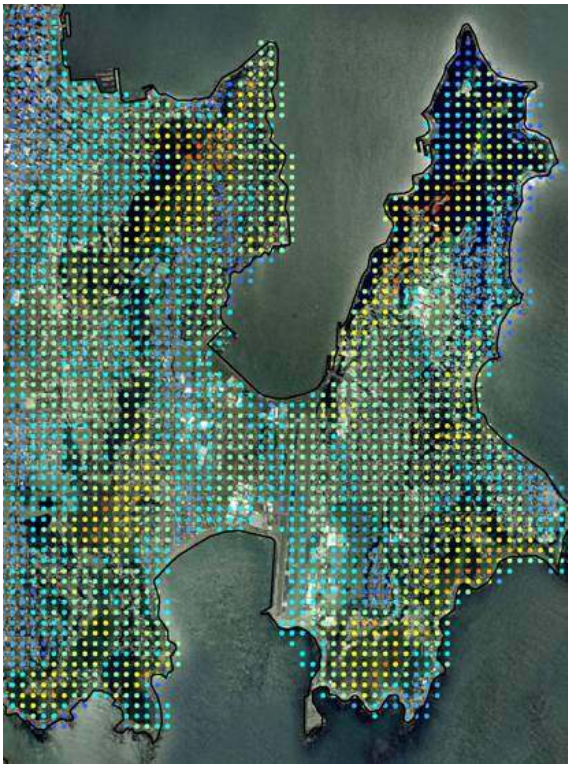

Figure 5. The estimated annual mean wind at each point on the grid over the central and eastern suburbs. Orange/red spots indicate winds over $9ms^{-1}$ and light/dark blue less than $5ms^{-1}$.

Summary and discussion

In summary, we have estimated the wind resource at a height of 10m over the Wellington region at a resolution of 100m. In general the major regions of existing housing development tend to be in the more sheltered regions – as might be expected! The upper slopes of the main ridges are clearly favourable sites for maximising the resource.

The model shows the speedup over the major ridges and the downstream wakes quite clearly. Speed up round some of the major headlands may be underestimated in these calculations due to lack of resolution. A horizontal resolution of nearer to 10m (and beyond the scope of this initial study) is probably needed to capture this effect. The modelled mean wind speeds indicate regions where one might look for the best resource. However, estimating the wind resource accurately at a specific site will require measurement or running the model at a resolution of order 10m and will need to include vegetation and the buildings themselves.