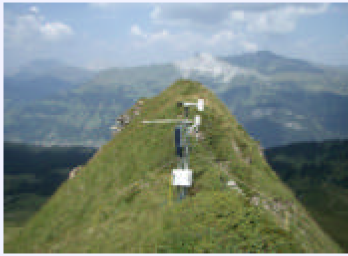
”The development of Micro-Scale Meteorological Modelling in UK universities”

Alan Gadian, Stephen Mobbs, David Woodhead, Xianyun Wen, Juma Al-Maskari, Sarah-Jane Lock & host of others



Typical micro-scale meteorological problems

- Airflow over sharp objects / steep terrain / buildings
- Local scale forecasting (Weather forecasting?)
- Cloud Physics studies

Content

- *Why am I here?*
- Application of terrain co-ordinate model. Does it work?
- Development of terrain intersecting approach
- Current progress and plans.

Why?

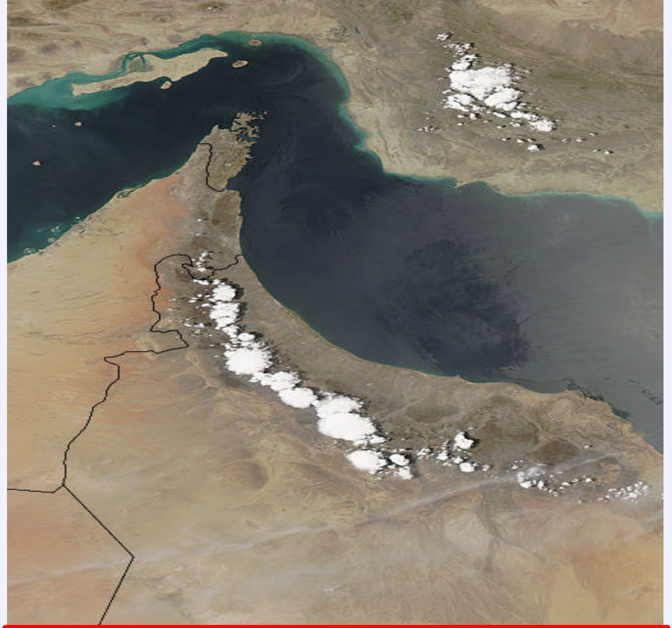
- The UK universities, in collaboration with interested parties, has set up a project to develop high resolution micro-scale models, to address both “urban” and “meteorological” atmospheric modelling issues.
- A UK consortia application has been made to bring observational equipment for the 2007 COPS project. There will also be considerable modelling expertise applied to the project (decision on funding in June 2006)
- An EU Marie Curie fellowship has been applied for to apply the UK Unified model and the Lokal model to COPS and CSIP data (Karlsruhe and Leeds)
- An unsuccessful EU STREP application, has been followed by a successful application to hold a 2 day ESF funded workshop in Hohenheim, to look at possible collaborative developments using terrain intersecting / cut cell approaches

The aim is to show some of the work (which we are now starting!)

N.B.
As this is an LM workshop, I am taking the opportunity of showing how we are using some LM data in a research project at Leeds.

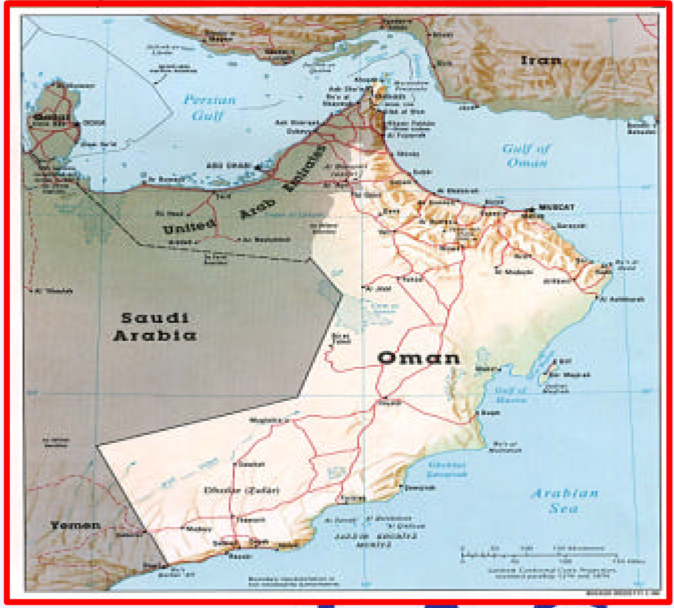
Understanding orographical convection over Oman

Juma Al-Maskari

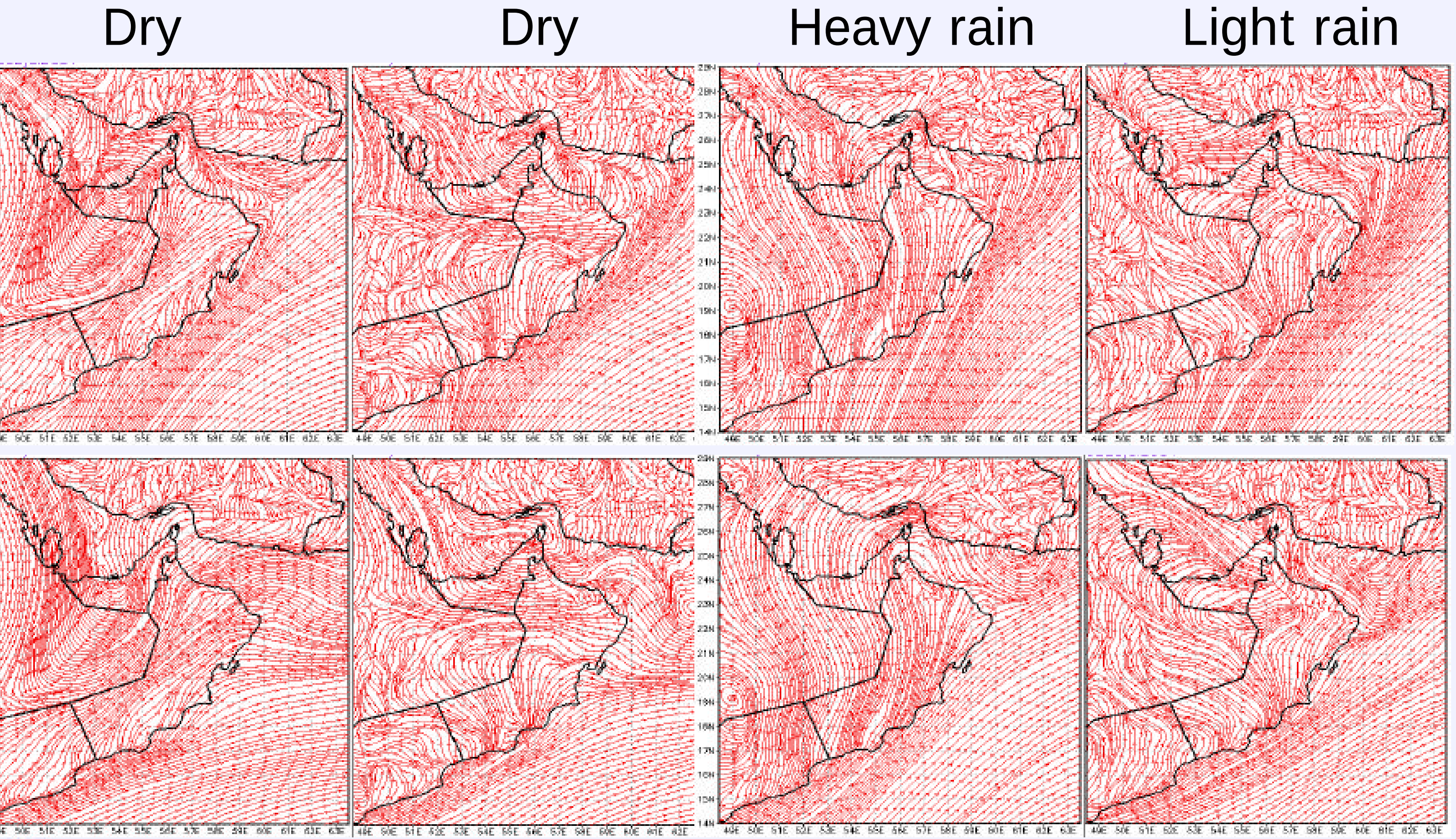


- Small field campaign
- Use LM hydrostatic model to derive large scale fields
- Apply Smolarkiewicz meso-scale anelastic model to look at the processes which control convection.

We have obtained consistent explanation of the major factors determining convective precipitation over the Hajar mountains.

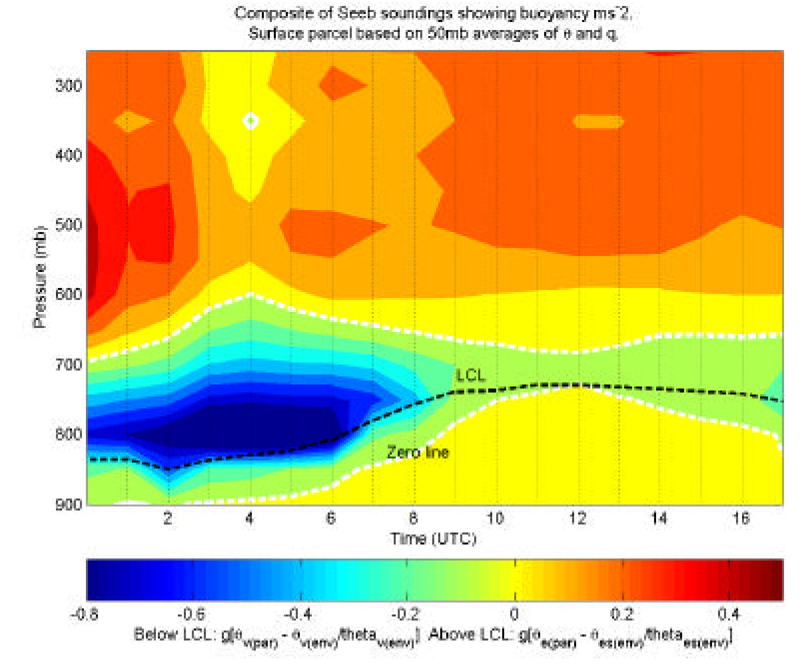


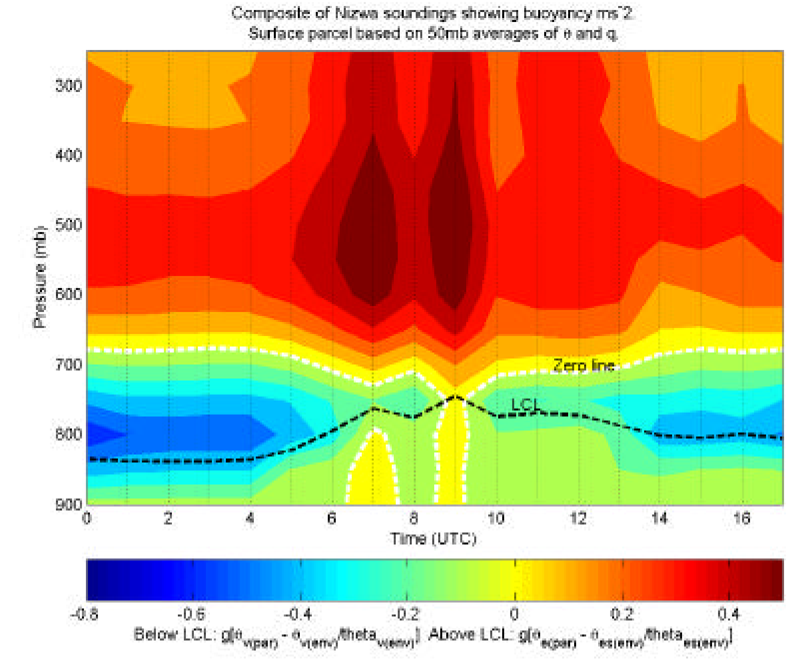
Stream lines for surface & 900 hPa at 09 UTC

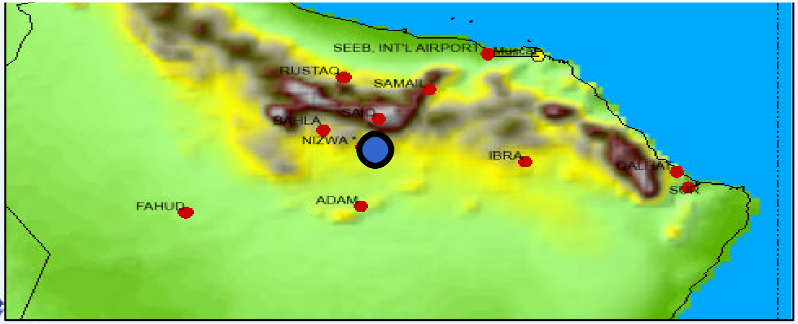


Buoyancy (Nizwa profiles) 12 July 04

left (hydrostatic model) right (EULAG model)







Hydrostatic, 7 km resolution
EULAG , 2 km resolution

Background:- The micro-scale model project

This is a UK National Environmental Research Council (NERC) project, for the atmospheric science community.

Aims:

- To provide expertise in University Atmospheric Science Community
- To use existing / create a new micro-scale model for the UK Universities weather Research Network (UWERN), resolving dynamical scales down to a few metres, and assimilating and interfacing data from larger scale models (UM).
- The model will enable a subset of science applications, particularly in the areas of orographic flows and the atmospheric boundary layer.
- The approach will be modular and flexible, allowing further development.

Background:- Map of Falklands and location of airport

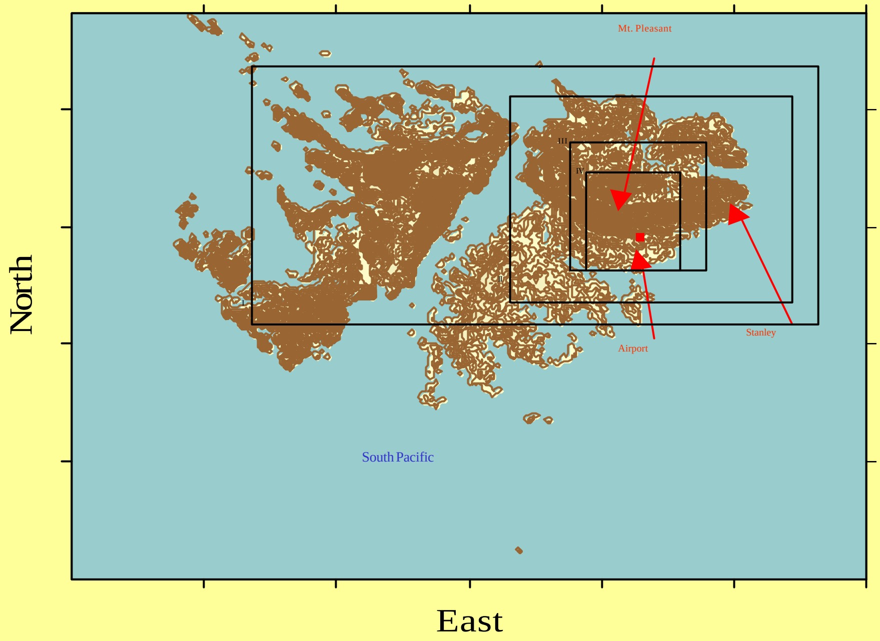


Figure 1a : Overview over the Falkland Islands and position of the 4 nested model domains. The domains are nested with a grid resolution ratio of 1:4, the outer domain being at 4 km resolution.

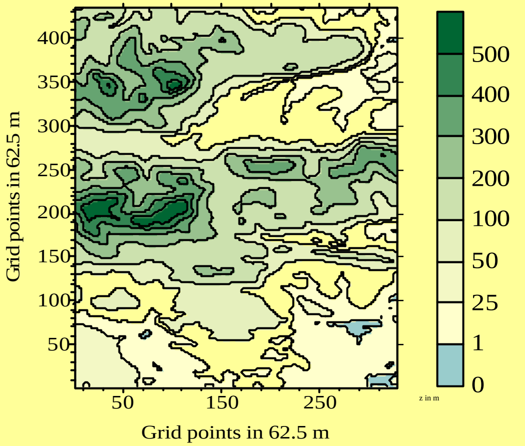


Figure 1b. Zoom of the topography of the 4th domain with a grid-resolution of 62.5 m in the horizontal. In the vertical the grid is stretched. The highest vertical resolution is 9m close to the surface, and 1500 m in the upper troposphere.

Background:- Falkland Island Rotors

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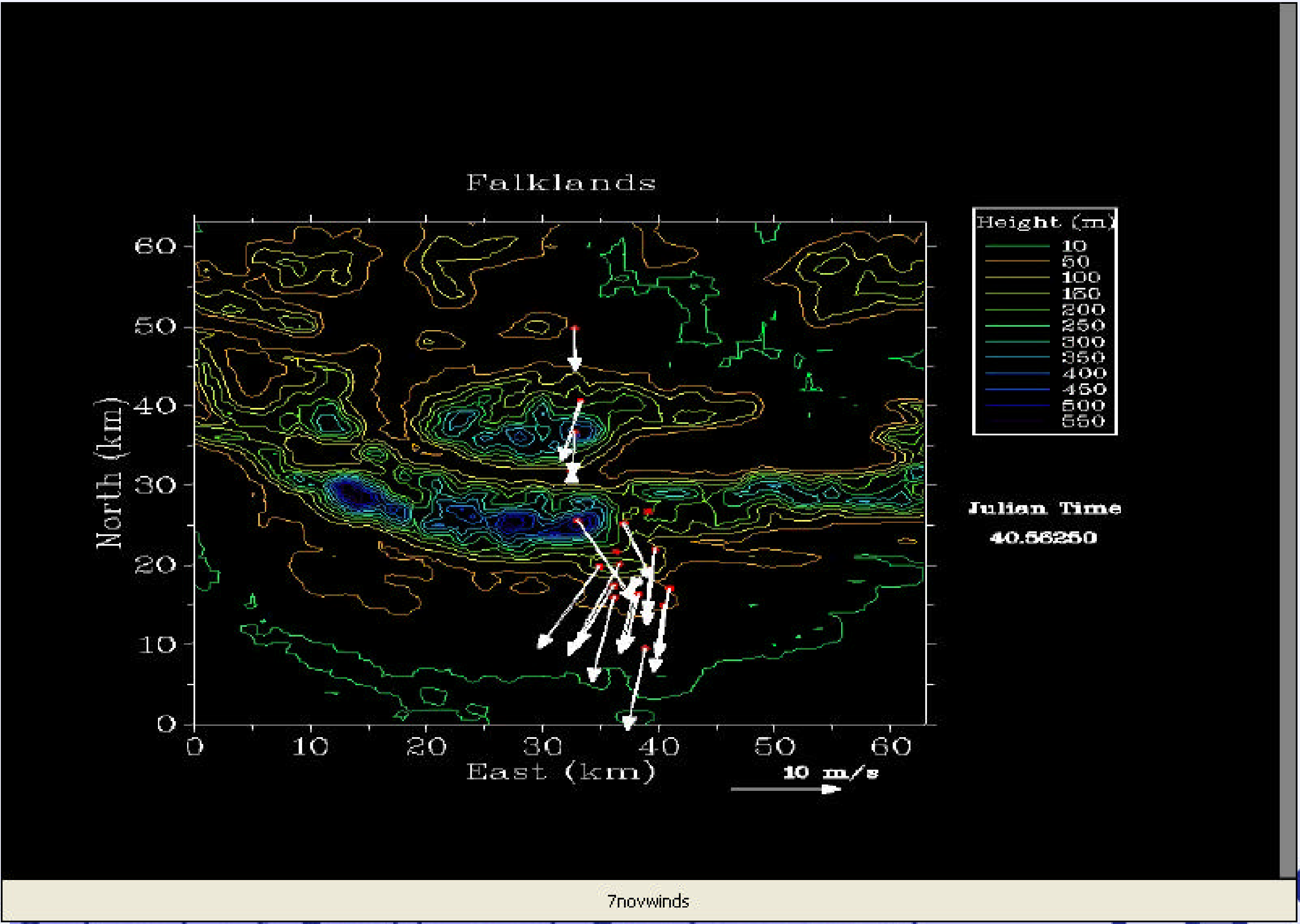
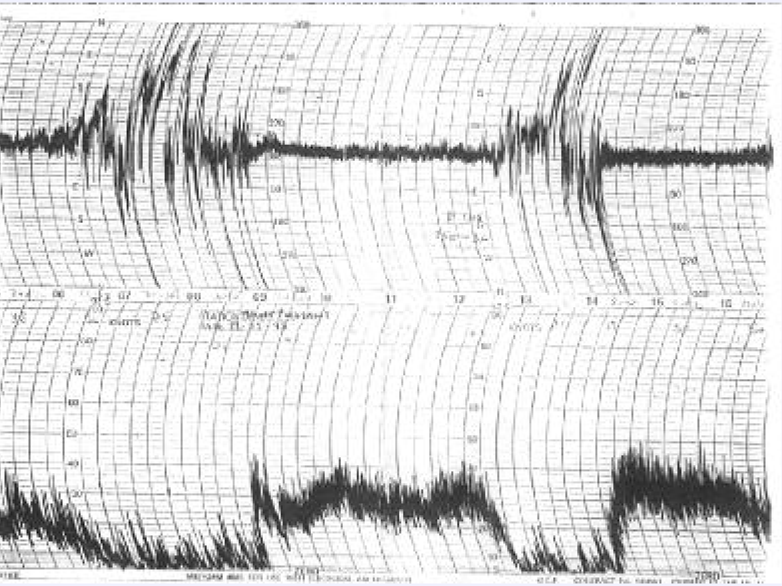
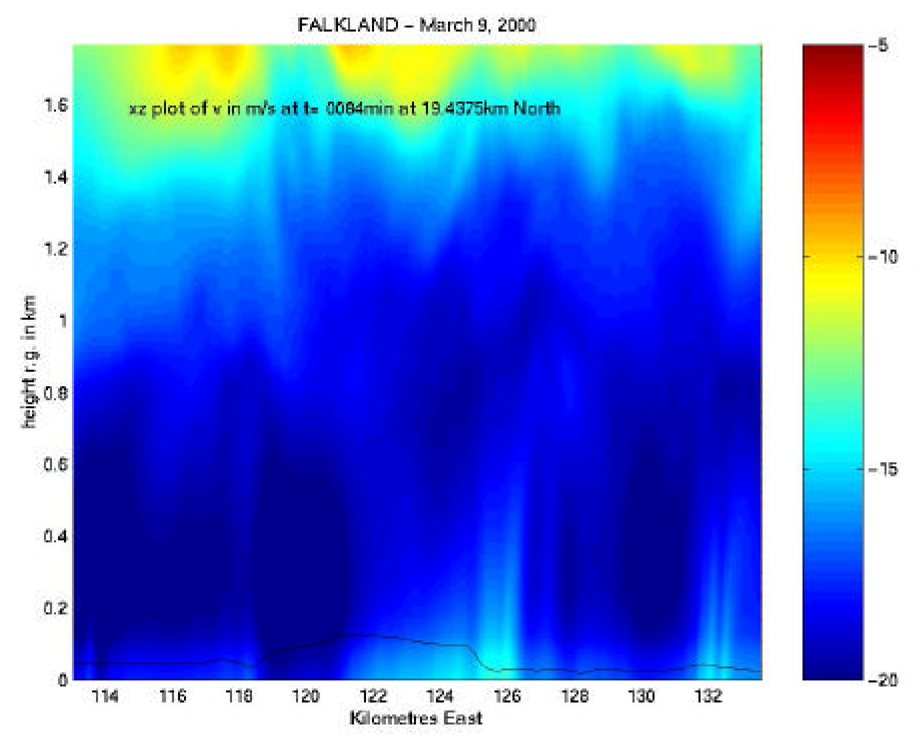


Background:- Falkland Island Airport Winds.
Anemograph of rotor events …. Model Northerly winds over the airport





Terrain following co-ordinate models

Can terrain following co-ordinates of flow over steep hills, street canyons or 5 sided buildings, work? Can the problems associated with anisotrophic cells be overcome?

One such model is the Smolarkiewicz model, anelastic developed from the Clark-Hall code. Critical importance of pre-conditioner to obtain a solution for slopes over ~ 45^0. (Now implemented in other models)

Gal-Chen (1975) terrain following co-ordinate system (or sigma system in pressure co-ordinates

$$x = \tilde{x}$$
$$y = \tilde{y}$$

$$z = \frac{\tilde{z} - \tilde{z}_s(\tilde{x},\tilde{y})}{1 - \tilde{z}_s(\tilde{x},\tilde{y})/H_D}$$

For any function φ , a Jacobian is needed to evaluate:

$$G^{1/2}\frac{\partial j}{\partial \tilde{z}} = \frac{\partial j}{\partial z}$$

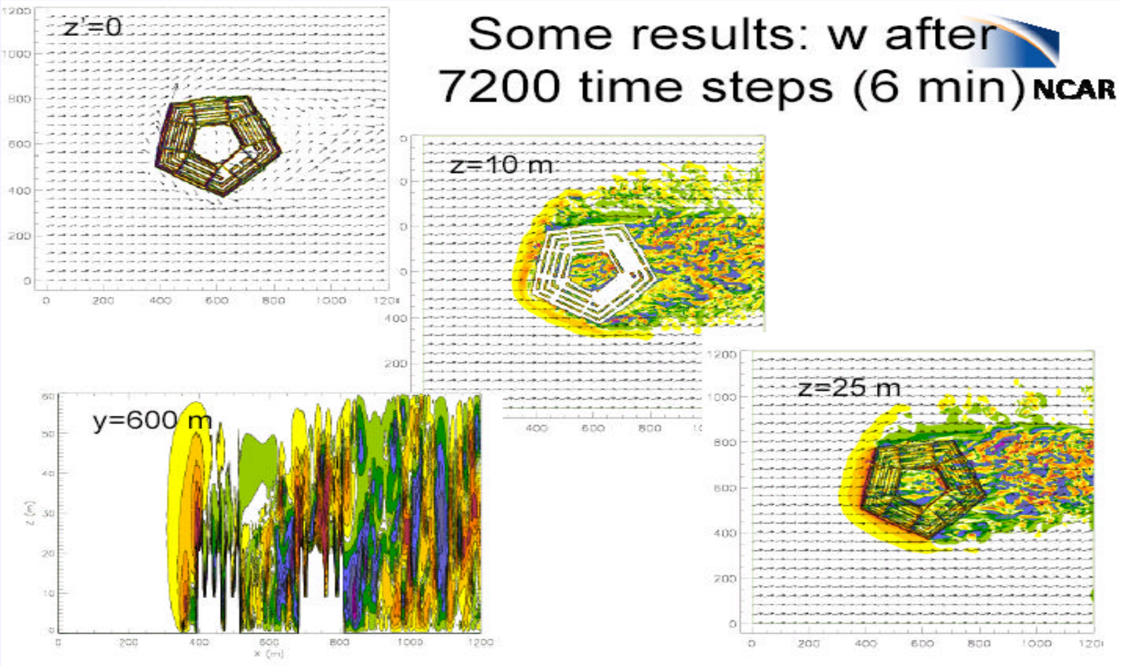
LHS new co-odinate, RHS cartesian

http://www.rap.ucar.edu/projects/shield/resources/gmu04/EuLag_gmu.pdf

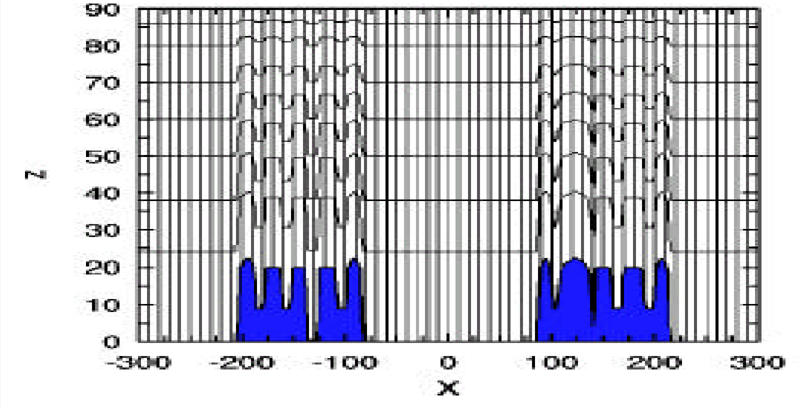
High resolution flow around buildings

Pentagon setup

- Boundary-fitted representation
  $z' = H(z-h(x,y))/(H-h(x,y))$
- $600 \times 600 \times 31$ @ $\Delta x=\Delta y=\Delta z=2$m
- 7200 time steps @ $\Delta t=0.05$ s
- Rigid upper boundary
- Eulerian option 2nd order in space and time
- sgs 1 ½ order closure
- Specified CD on building and sfc.
- Neutral with prescribed velocity profile from previous LES simulation (Moeng and Sullivan)
- NCAR supercomputer ("older" IBM MPI using 200 processors): 10 ½ hrs wallclock time for 7400 time steps (with 3 tracers)



Some results: w after 7200 time steps (6 min) NCAR



Street Canyon modelling using a terrain co-ordinate model. (S-J.Lock)

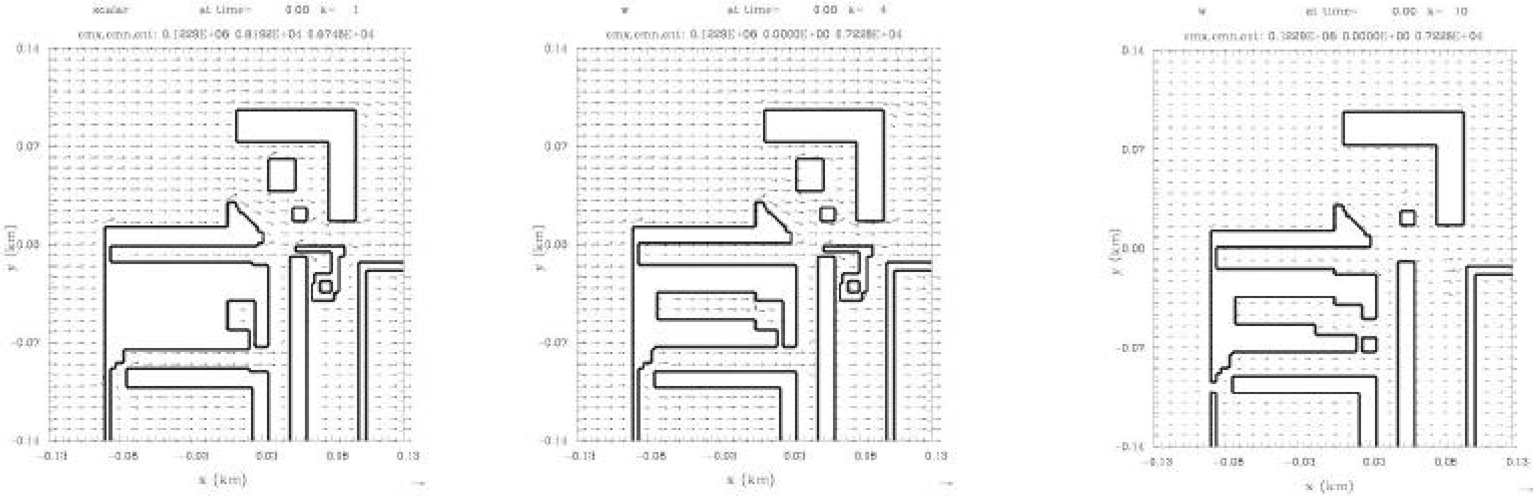
Aim:- to use the Smolarkiewicz anelastic model to look at flow in a street (Gilly Gate) in York (a small town) and to compare with data from observations.

- Set up required dt=0.025s, **dx**=1.0m; dimensions ~200*200*60, with a sponge > 50m, u00=5m/s.
- A source of inert tracer, reprsenting the traffic is being compared with some measured chemical.
- Open / cyclic to present a typical urban profile.

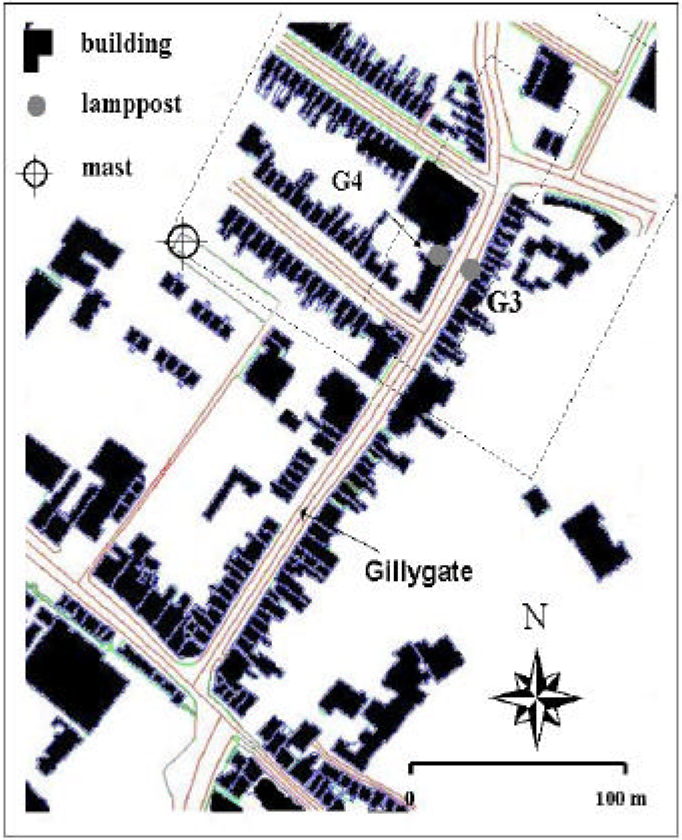
Currently we are evaluating wind characteristics.

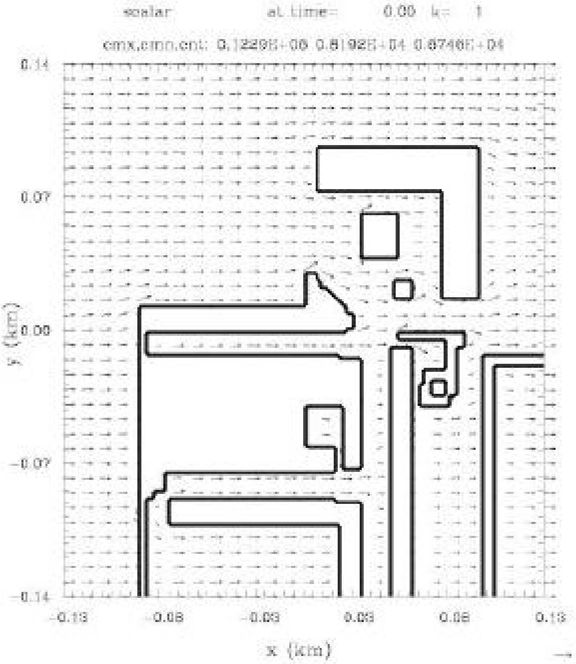
Representativity of the flow looks good.

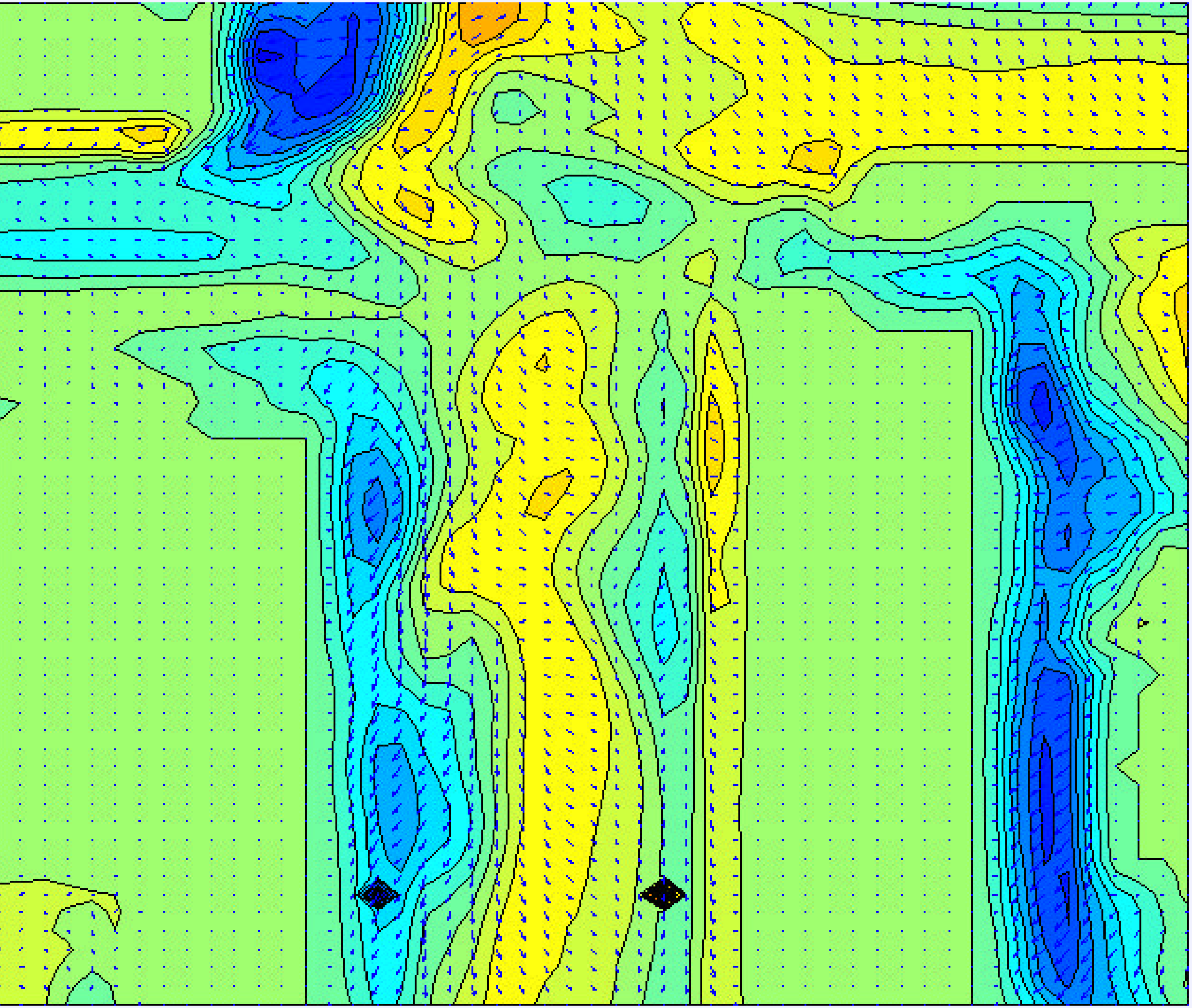
Plan of street at z = 1m , z = 4m and z = 10m at time 0s



Some results: Flow in a street canyon in York (data by Alison Tomlin)



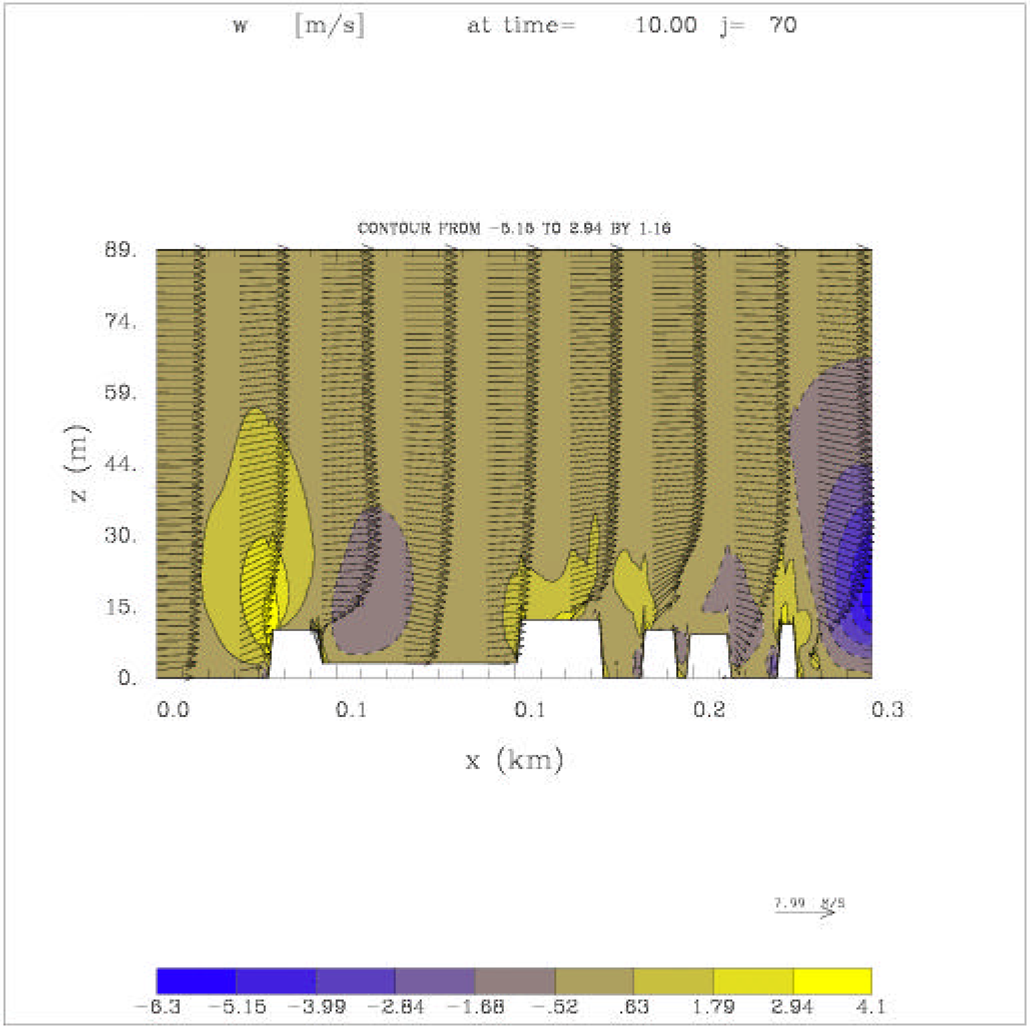




Vertical velocity field.
(red = +2m/s, blue= -2m/s)
of flow over Gillygate,

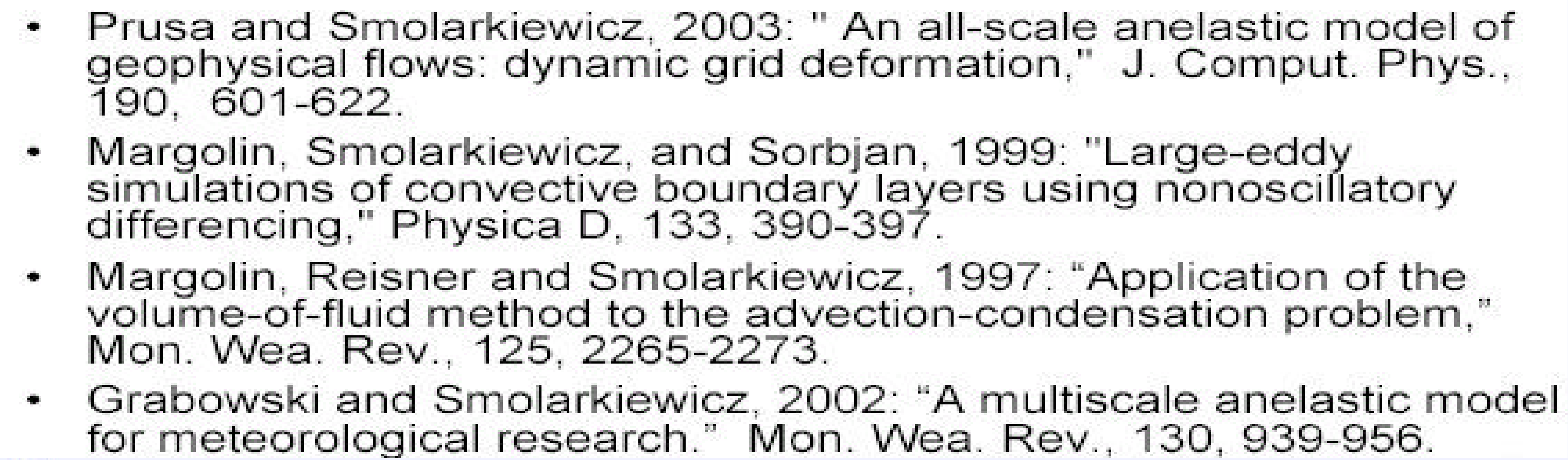
Time step =0.5s for 20s
duration.

The two lamp posts ar
marked, ~ 12m apart.


w [m/s] at time= 10.00 j= 70
CONTOUR FROM -5.15 TO 2.94 BY 1.16
z (m)
89.
74.
59.
44.
30.
15.
0.
0.0
0.1
0.1
0.2
0.3
x (km)
7.99 M/S
-6.3
-5.15
-3.99
-2.84
-1.68
-.52
.63
1.79
2.94
4.1

Some references for Smolarkiewicz. anelastic, meso / micro scale model, which shall be used for the following examples.

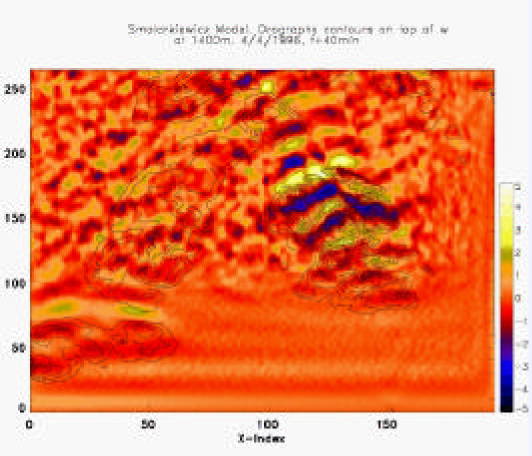
.. Non-hydrostatic, anelastic $\nabla .\ r(z)\, \underline{u} = 0$ Navier Stokes Equations
.. Eulerian or Semi Lagrangian
.. Multi-dimensional positive definite advection
.. Terrain following
.. Pre-conditioner for generalised conjugate gradient residual solution of elliptic pressure equation. (Stephen Thomas et al., 2003, MWR, 131, 2464-78)

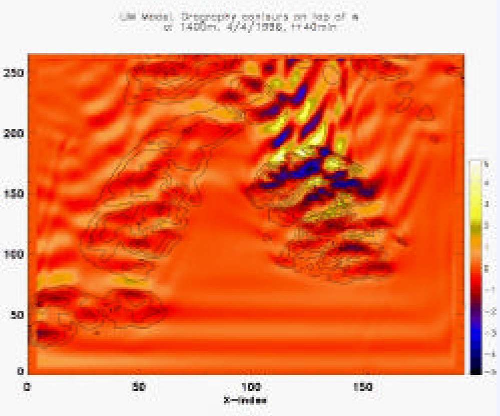


- Prusa and Smolarkiewicz, 2003: " An all-scale anelastic model of geophysical flows: dynamic grid deformation," J. Comput. Phys., 190, 601-622.
- Margolin, Smolarkiewicz, and Sorbjan, 1999: "Large-eddy simulations of convective boundary layers using nonoscillatory differencing," Physica D, 133, 390-397.
- Margolin, Reisner and Smolarkiewicz, 1997: “Application of the volume-of-fluid method to the advection-condensation problem,” Mon. Wea. Rev., 125, 2265-2273.
- Grabowski and Smolarkiewicz, 2002: “A multiscale anelastic model for meteorological research.” Mon. Wea. Rev., 130, 939-956.

Summary --- terrain following co-ordinate applications

- Results applied to steep sided hills, indicate good inter-comparison with data. Aircraft results c.f. with model simulations. (Al-Maskari)
- Preliminary observations from a street canyon in York look very promising (S-J Lock)
- Intention to compare with terrain intersecting approach.





2 … Atmospheric Flow Over Complex Topography; developments with a terrain intersecting code

Woodhead, Gadian, Mobbs & Wen

Aim : To develop a model that can efficiently simulate atmospheric flow over geometrically complex and steep orography

- non-hydrostatic, compressible equation set, rather than anelastic system, based on the “RAMS equation set” , wall function type stress, and split explicit time-step to overcome sound wave / advection limitations..

Can this be successfully used in 3-d simulations?

Explicit time split method

The fully elastic, non-hydrostatic, compressible equation set is used

- severe restrictions on the time step are imposed due to the presence of sound waves

The explicit time split approach numerically integrates the slower advection, diffusion, and Coriolis terms and the faster sound and gravity waves using alternate techniques with appropriately chosen time steps

- a very small explicit time step is required to solve for the the sound waves

- negates the solution of a 3-d elliptic pressure equation

Momentum and pressure equation for dry atmospheric motion

[illegible]

[illegible]

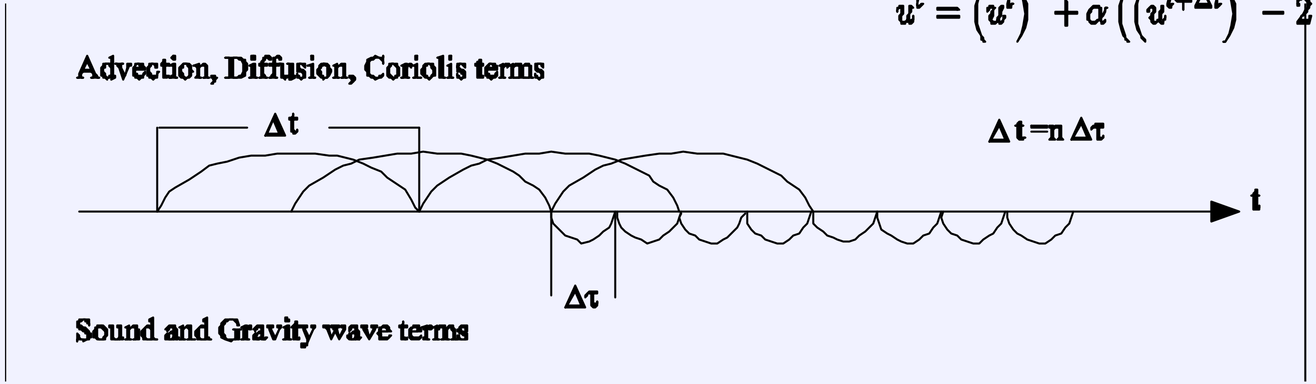
[illegible]

[illegible]

The L.H.S are the terms responsible for the sound waves and the R.H.S are the advection, diffusion & Coriolis terms

The slower phase speeds are solved over the time step Dt using a leapfrog scheme where Dt must satisfy the CFL condition. Every step has an additional binding condition to prevent time splitting.

$$u^t = \left(u^t\right)^* + \alpha\left(\left(u^{t+\Delta t}\right)^* - 2\left(u^t\right)^* + u^{t-\Delta t}\right)$$



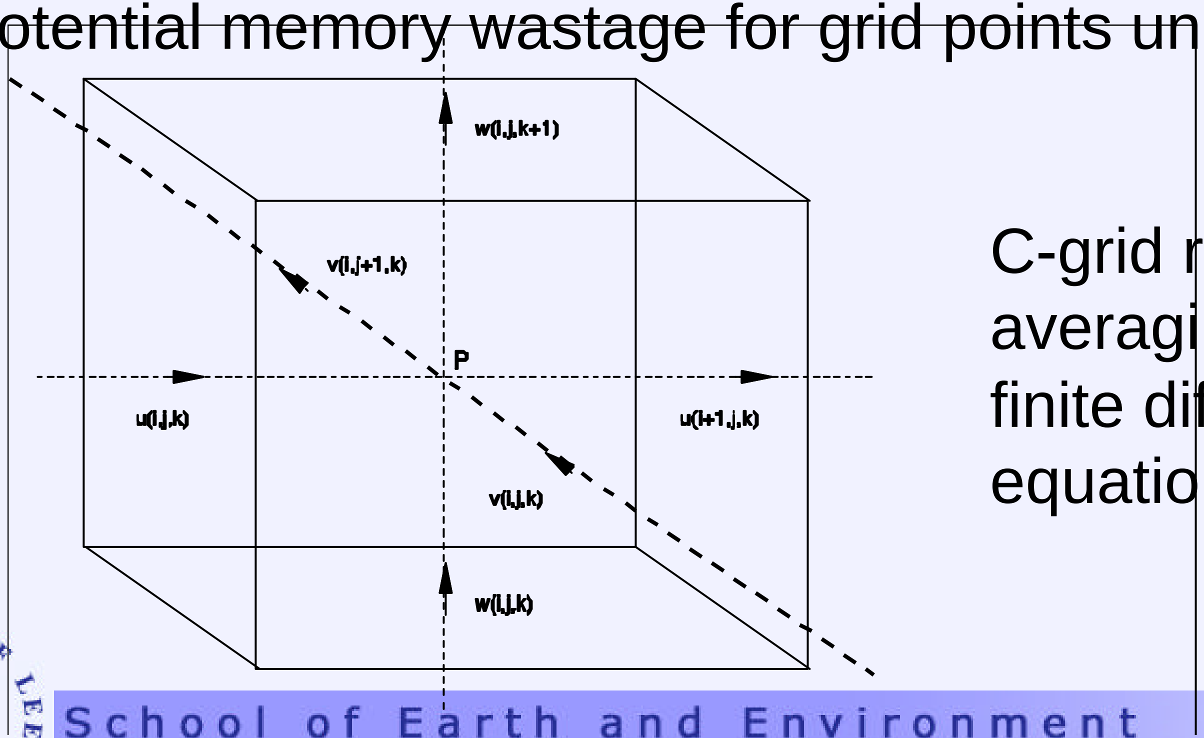
Terms responsible for the faster phase speeds are solved 2n times over time step Dt . Advection, diffusion and Coriolis are kept constant at a central time position

Grid Structure is a staggered, terrain intersecting mesh

- reduced storage requirements compared to non-orthogonal grids

- no need to adapt equation set when implementing grid nesting or stretching

- potential memory wastage for grid points under the ground



C-grid requires less averaging for the finite difference equations

Boundary Conditions

- the inlet has a fixed velocity profile

- the top boundary can be an open top where normal velocities vanish or a rigid lid where the velocities are fixed

- the outlet must allow disturbances to propagate out with minimal reflection hence the radiative condition is used

[illegible]

Lower Boundary

The wall stress u^*_i is expressed as a set of polynomial functions of distance s along the ground.

$$u_i^* = a_1 + a_2 s_i + a_3 s_i^2 + \cdots + a_n s_i^{n-1}$$

where the coefficients a_i are calculated using information *local* and *interior* to the section of ground s_i.

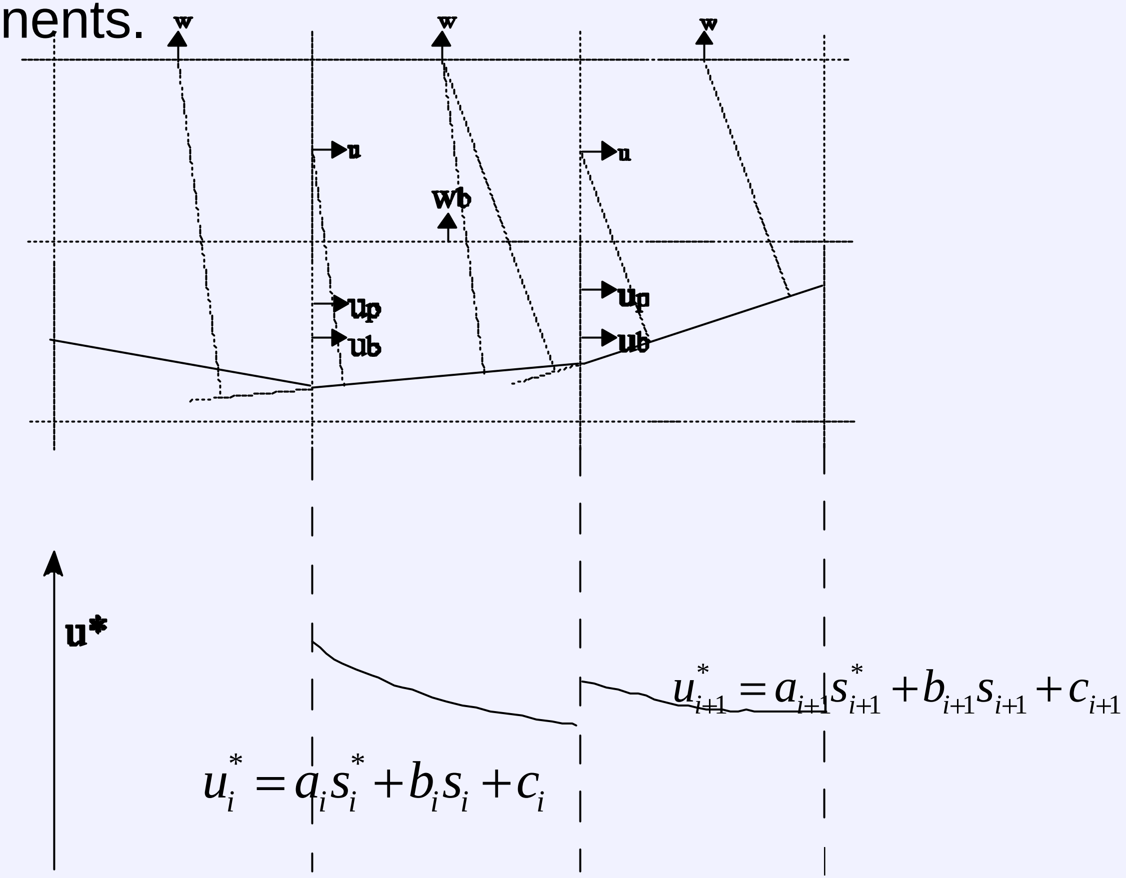
Once a_i have been approximated the tangential and normal velocity components can be calculated using equations derived from the *log law of the wall* and *mass continuity*.

$$u_t = \frac{u^*(s)}{k}\ln\left(\frac{n}{z_0}\right)$$

$$u_n = \frac{du^*(s)}{ds}\frac{-z_0}{k}\left\{\left(\frac{n}{z_0}\right)\ln\left(\frac{n}{z_0}\right)-\left(\frac{n}{z_0}\right)+1\right\}$$

velocity components *close* to s_i are then easily calculated

Consider *n=3*. The quadratic expression for u* requires 3 interior velocities, these are two vertical (w) and one horizontal (u) velocity components.



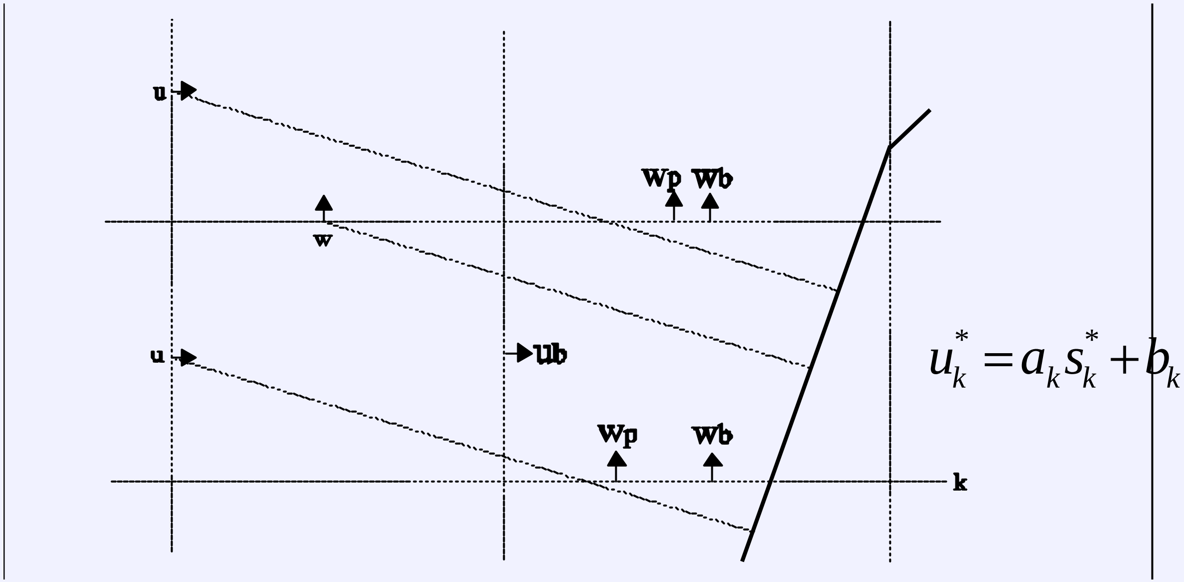
$$u_{i+1}^* = a_{i+1} s_{i+1}^* + b_{i+1} s_{i+1} + c_{i+1}$$

$$u_i^* = a_i s_i^* + b_i s_i + c_i$$

Using the equations for u_n and u_t , a_i,b_i & c_i can be approximated. The horizontal boundary points u_b and part cell points u_p can be calculated from u*.

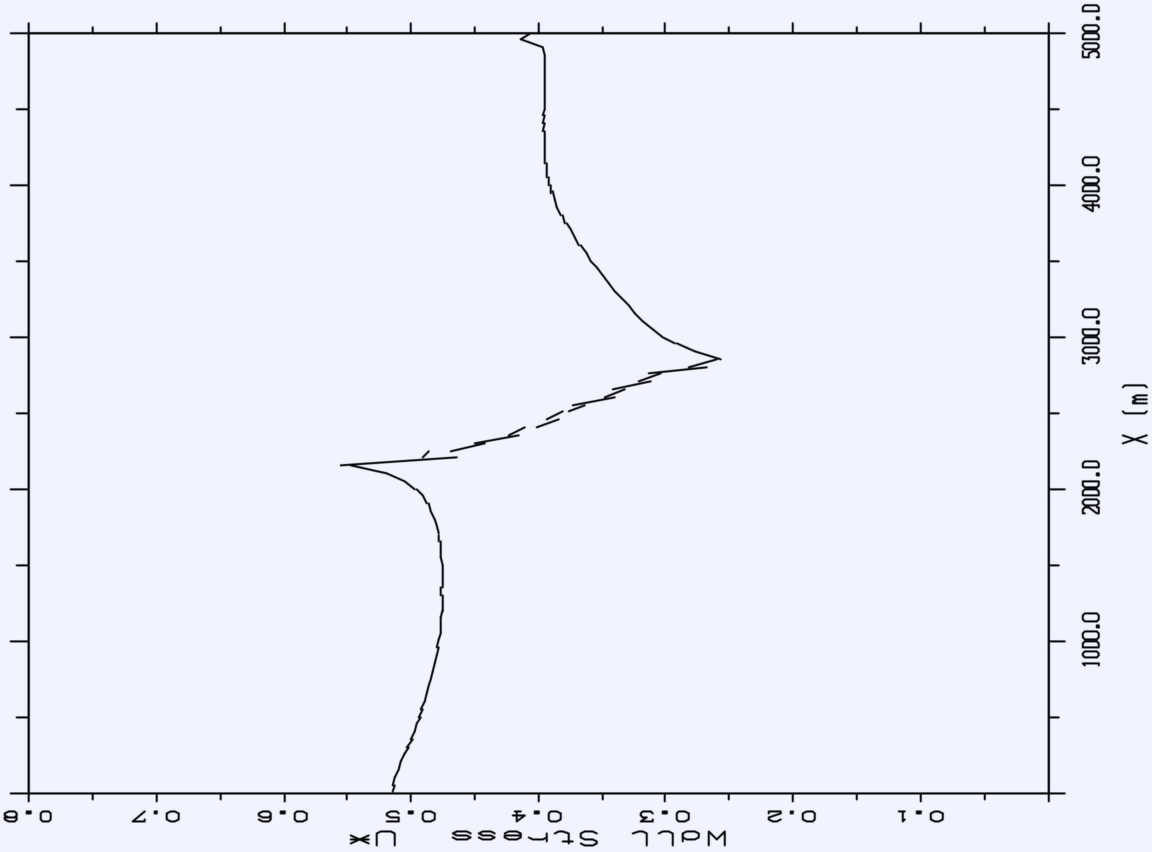
For hill gradients $-p/4<q<p/4$, points u_b and u_p are calculated and w_b is then derived such that mass is conserved in every cut cells

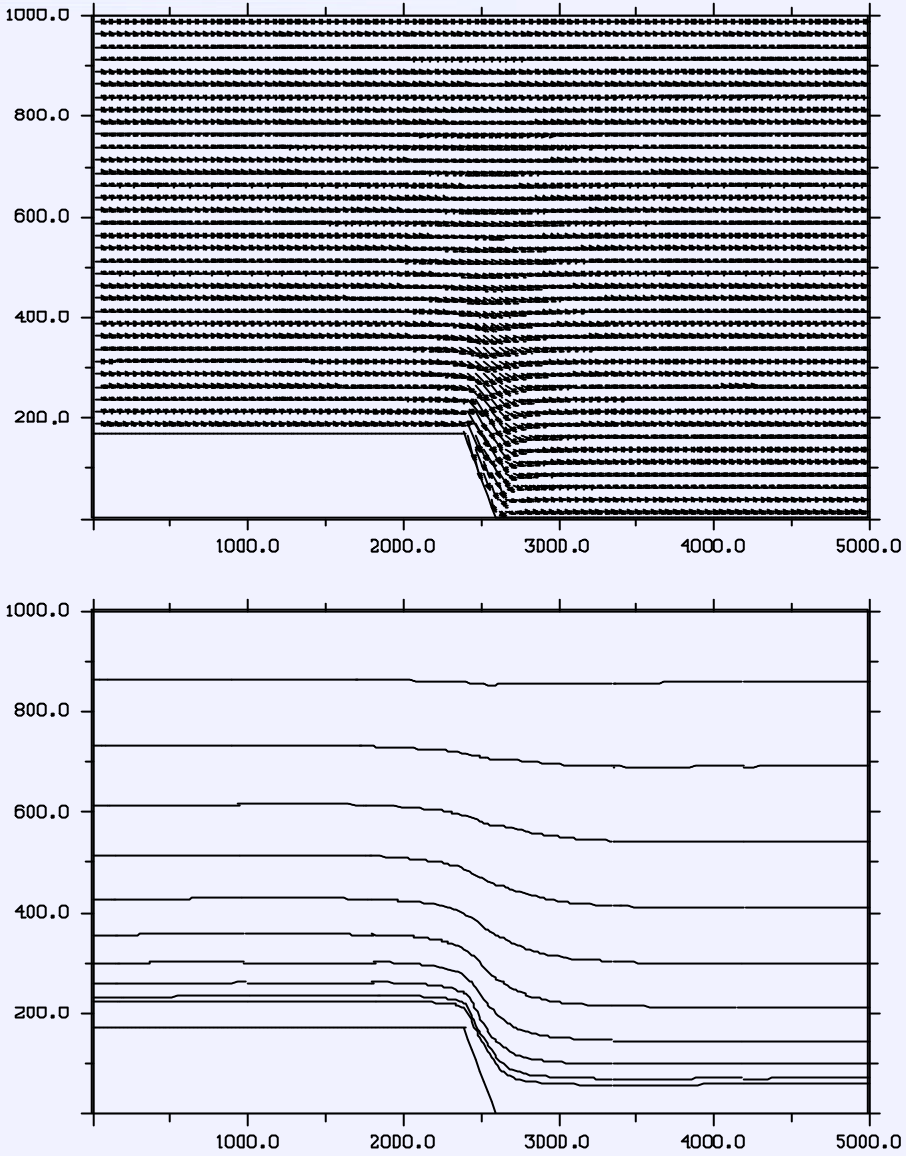
For steeper gradients the equation set is switched. a_k, b_k and c_k are approximated using two u and one w interior velocity points, w_b and w_p are then calculated using u^*_k and u_b is found by applying mass continuity to the cut boundary cell.



$$u_k^* = a_k s_k^* + b_k s_k + c_k$$

The discrete quadratic wall stress functions for flow over a small down slope

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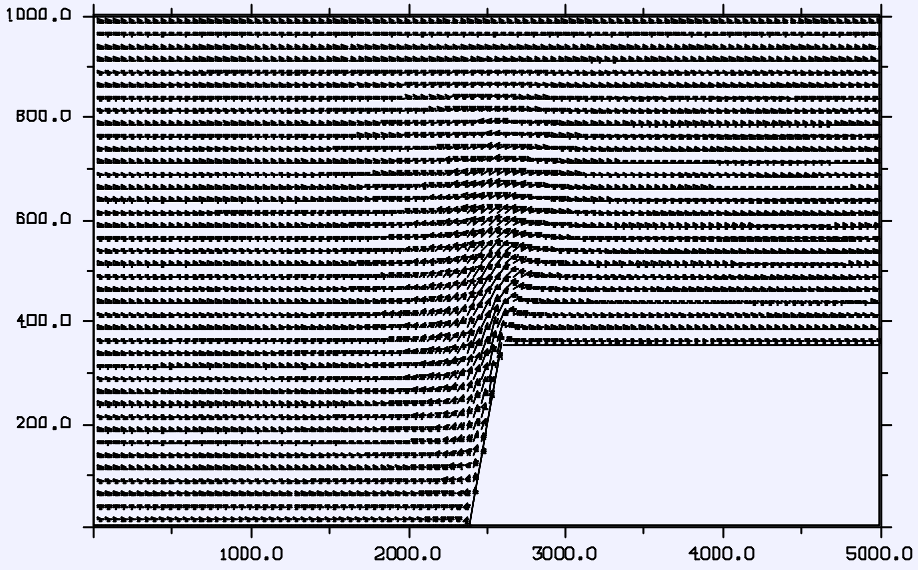
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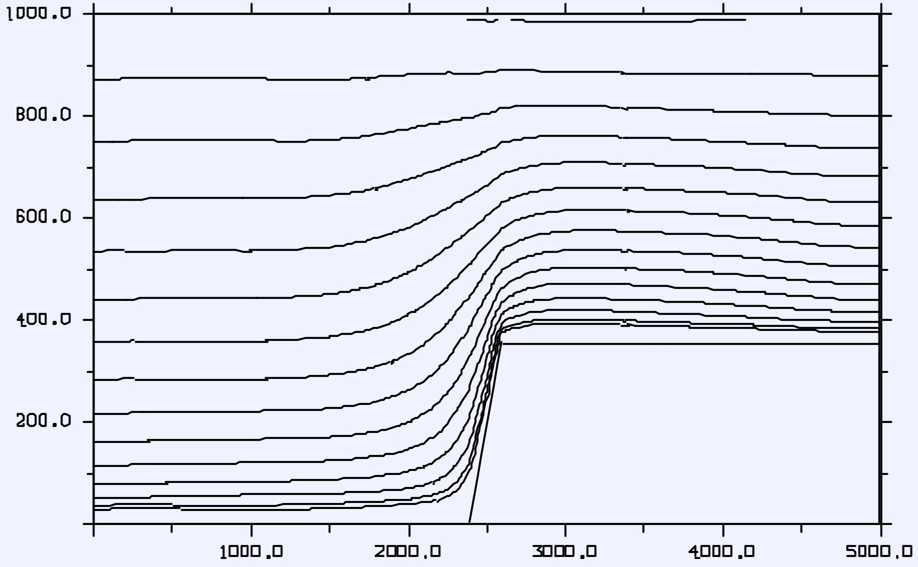
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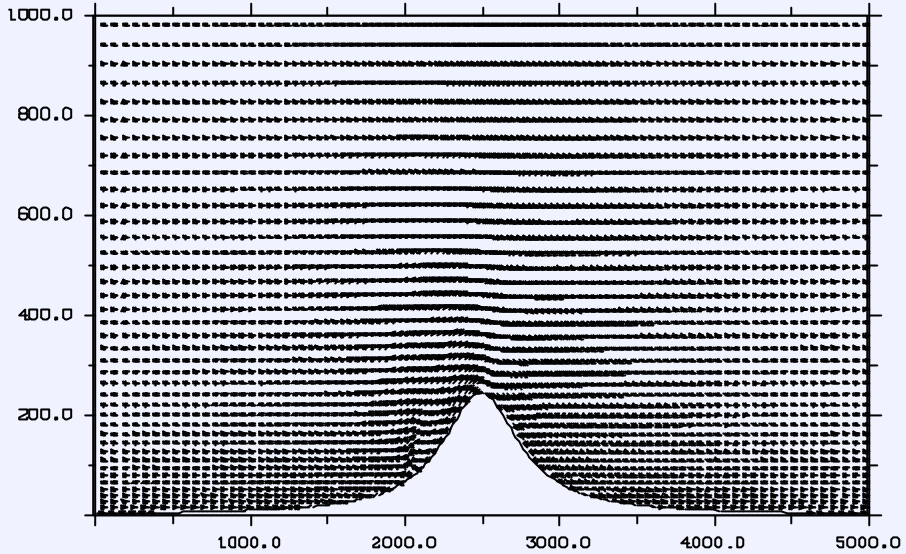
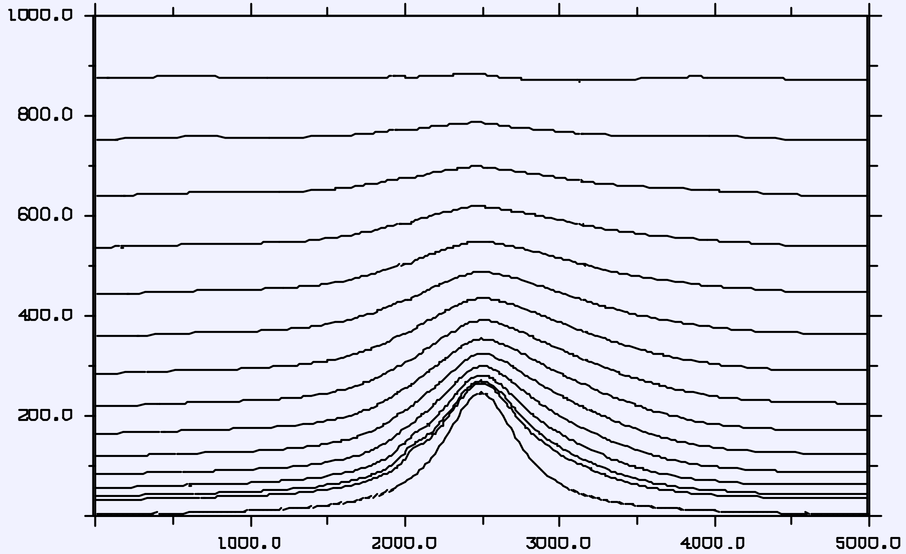
Stretched mesh

Dx = 15m…70m

Dz = 10m…40m





Concluding Remarks

This technique produces good results for small hills and smooth terrain. Using an explicit time split approach the model remains efficient even though sound waves propagate throughout the domain. And with a terrain intersecting mesh stretching can be implemented with minimal effort and increase accuracy in areas of interest.

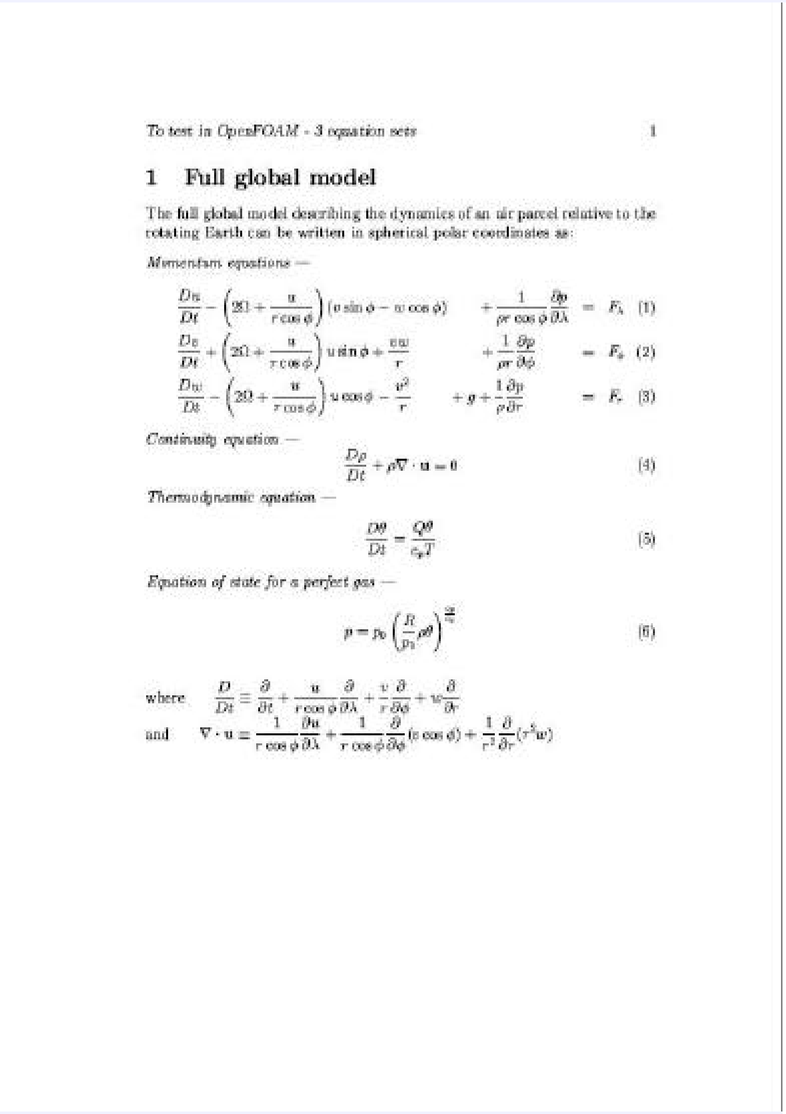
However when the terrain becomes steep or has sharp peaks or troughs the choice of *local* points becomes difficult, u* can be poorly represented and consequently results can be distorted or unstable.

Future Work

At present I am looking into applying a smoother across several wall stress functions. The potential disturbances caused by a poorly represented wall stress function could then be dispersed over several grid cells.

Model developments (S-J Lock)

- Modification of the equation set to be consistent with the UK Met Office UM forecasting equation set.
- Extend the wall function terms to 3-d
- Use of a pressure solver in comparison with the split time stepping routines.
- Issues still exist in enabling terrain of over 70^0 to be handled well.
- Verification and inter-comparison of the relevant equation sets.
- Inclusion of advection of scalar terms, and moist processes.



To test in OpenFOAM - 3 equation sets 1

1 Full global model

The full global model describing the dynamics of an air parcel relative to the rotating Earth can be written in spherical polar coordinates as:

Momentum equations —

$$\begin{aligned}
\frac{Du}{Dt} - \left(2\Omega + \frac{u}{r\cos\phi}\right)(v\sin\phi - w\cos\phi) \quad & + \frac{1}{\rho r\cos\phi}\frac{\partial p}{\partial\lambda} &= F_\lambda \quad (1)\\
\frac{Dv}{Dt} + \left(2\Omega + \frac{u}{r\cos\phi}\right)u\sin\phi + \frac{vw}{r} \quad & + \frac{1}{\rho r}\frac{\partial p}{\partial\phi} &= F_\phi \quad (2)\\
\frac{Dw}{Dt} - \left(2\Omega + \frac{u}{r\cos\phi}\right)u\cos\phi - \frac{v^2}{r} \quad & + g + \frac{1}{\rho}\frac{\partial p}{\partial r} &= F_r \quad (3)
\end{aligned}$$

Continuity equation —

$$\frac{D\rho}{Dt} + \rho\nabla\cdot\mathbf{u} = 0 \qquad (4)$$

Thermodynamic equation —

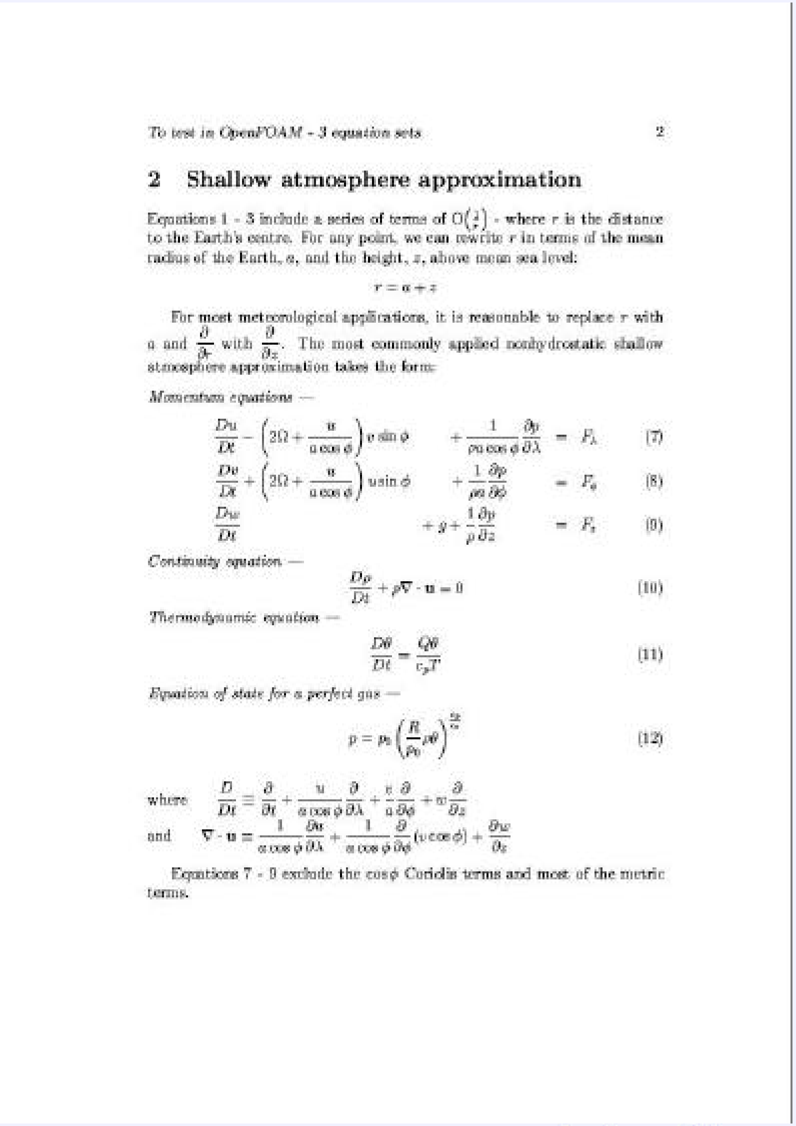
$$\frac{D\theta}{Dt} = \frac{Q\theta}{c_pT} \qquad (5)$$

Equation of state for a perfect gas —

$$p = p_0\left(\frac{R}{p_0}\rho\theta\right)^{\frac{c_p}{c_v}} \qquad (6)$$

where $\quad \frac{D}{Dt} \equiv \frac{\partial}{\partial t} + \frac{u}{r\cos\phi}\frac{\partial}{\partial\lambda} + \frac{v}{r}\frac{\partial}{\partial\phi} + w\frac{\partial}{\partial r}$

and $\quad \nabla\cdot\mathbf{u} \equiv \frac{1}{r\cos\phi}\frac{\partial u}{\partial\lambda} + \frac{1}{r\cos\phi}\frac{\partial}{\partial\phi}(v\cos\phi) + \frac{1}{r^2}\frac{\partial}{\partial r}(r^2w)$



To test in OpenFOAM - 3 equation sets 2

2 Shallow atmosphere approximation

Equations 1 - 3 include a series of terms of $O\left(\frac{1}{r}\right)$ - where r is the distance to the Earth's centre. For any point, we can rewrite r in terms of the mean radius of the Earth, a, and the height, z, above mean sea level:

$$r = a + z$$

For most meteorological applications, it is reasonable to replace r with a and $\frac{\partial}{\partial r}$ with $\frac{\partial}{\partial z}$. The most commonly applied nonhydrostatic shallow atmosphere approximation takes the form:

Momentum equations —

$$\begin{aligned}
\frac{Du}{Dt} - \left(2\Omega + \frac{u}{a\cos\phi}\right)v\sin\phi \quad & + \frac{1}{\rho a\cos\phi}\frac{\partial p}{\partial\lambda} &= F_\lambda \quad (7)\\
\frac{Dv}{Dt} + \left(2\Omega + \frac{u}{a\cos\phi}\right)u\sin\phi \quad & + \frac{1}{\rho a}\frac{\partial p}{\partial\phi} &= F_\phi \quad (8)\\
\frac{Dw}{Dt} \quad & + g + \frac{1}{\rho}\frac{\partial p}{\partial z} &= F_z \quad (9)
\end{aligned}$$

Continuity equation —

$$\frac{D\rho}{Dt} + \rho\nabla\cdot\mathbf{u} = 0 \qquad (10)$$

Thermodynamic equation —

$$\frac{D\theta}{Dt} = \frac{Q\theta}{c_pT} \qquad (11)$$

Equation of state for a perfect gas —

$$p = p_0\left(\frac{R}{p_0}\rho\theta\right)^{\frac{c_p}{c_v}} \qquad (12)$$

where $\quad \frac{D}{Dt} \equiv \frac{\partial}{\partial t} + \frac{u}{a\cos\phi}\frac{\partial}{\partial\lambda} + \frac{v}{a}\frac{\partial}{\partial\phi} + w\frac{\partial}{\partial z}$

and $\quad \nabla\cdot\mathbf{u} \equiv \frac{1}{a\cos\phi}\frac{\partial u}{\partial\lambda} + \frac{1}{a\cos\phi}\frac{\partial}{\partial\phi}(v\cos\phi) + \frac{\partial w}{\partial z}$

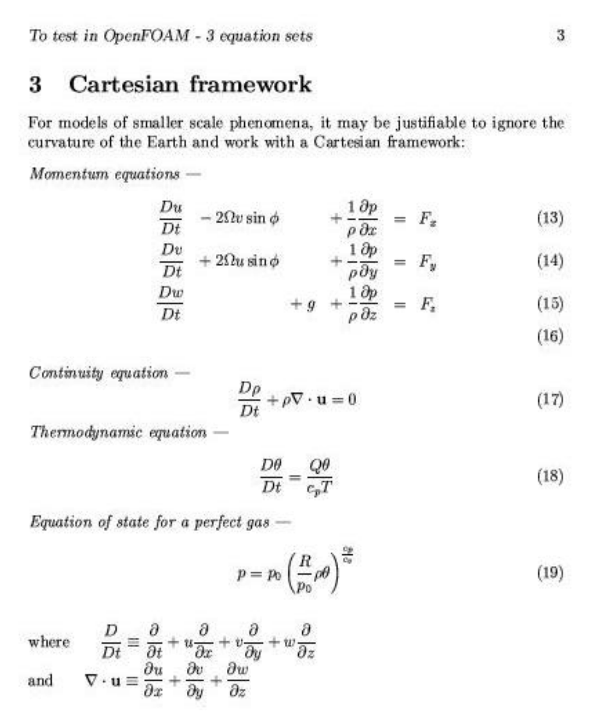
Equations 7 - 9 exclude the $\cos\phi$ Coriolis terms and most of the metric terms.

Cartesian equation set being used in the modified model.

“a” and “c” -grid formulation.

A simple pressure solver will be used, for sound waves.

Application to field experiment observations over steep orography.



To test in OpenFOAM - 3 equation sets 3

3 Cartesian framework

For models of smaller scale phenomena, it may be justifiable to ignore the curvature of the Earth and work with a Cartesian framework:

Momentum equations —

$$\frac{Du}{Dt} - 2\Omega v \sin\phi + \frac{1}{\rho}\frac{\partial p}{\partial x} = F_x \tag{13}$$

$$\frac{Dv}{Dt} + 2\Omega u \sin\phi + \frac{1}{\rho}\frac{\partial p}{\partial y} = F_y \tag{14}$$

$$\frac{Dw}{Dt} + g + \frac{1}{\rho}\frac{\partial p}{\partial z} = F_z \tag{15}$$

$$\tag{16}$$

Continuity equation —

$$\frac{D\rho}{Dt} + \rho\nabla\cdot\mathbf{u} = 0 \tag{17}$$

Thermodynamic equation —

$$\frac{D\theta}{Dt} = \frac{Q\theta}{c_p T} \tag{18}$$

Equation of state for a perfect gas —

$$p = p_0\left(\frac{R}{p_0}\rho\theta\right)^{\frac{c_p}{c_v}} \tag{19}$$

where $\frac{D}{Dt} \equiv \frac{\partial}{\partial t} + u\frac{\partial}{\partial x} + v\frac{\partial}{\partial y} + w\frac{\partial}{\partial z}$

and $\nabla\cdot\mathbf{u} \equiv \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z}$

Future?

- Examining funding opportunities with other established groups with other groups involved with "terrain-intersecting" techniques
- Further examination and use of terrain following procedures to examine their applicability, and for use in cloud process studies
- New project (Stephen Belcher, Alan Robins) cfd unstructured grid methods for flow over steep orography. (STAR CD)