Exploring a cut-cell representation of terrain for microscale idealised orographic and moist flow simulations

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With thanks to J. Steppeler, H.-W. Bitzer & U. Schaettler

Exploring a cut-cell approach to orography:

- Background to cut-cell approach
- Microscale model methods
- Results for idealised orographic flows
- Extension to moist dynamics
- On-going & future work

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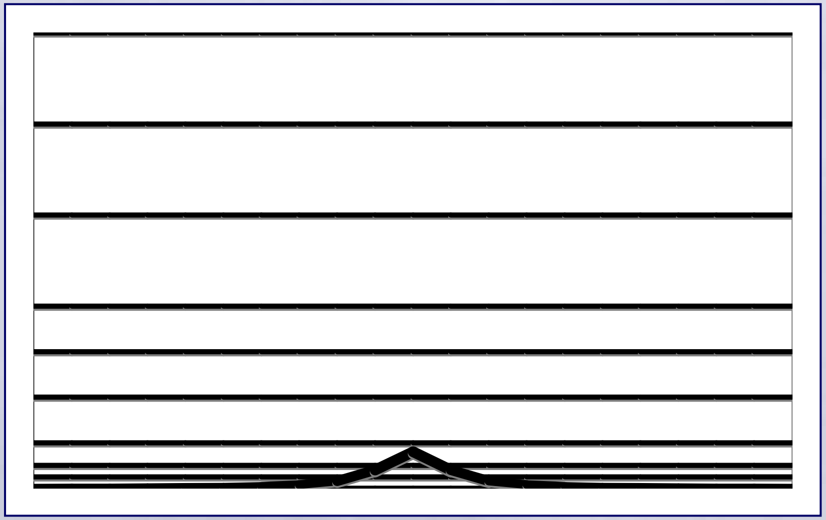
Terrain-intersecting coordinates:

What?

- vertical levels remain horizontal throughout domain *despite* any orography
- vertical levels *intersect* orography, resulting in 3 types of grid-cell:
  - those wholly *beneath* the orographic surface
  - those wholly *above* the orographic surface
  - those *cut* by the orographic surface



Why?

- growth in computing = moves to finer grid-resolutions
- finer grids = more of the variation in orographic gradients resolved by the grid

  ==> high-resolution models must be able to stably and accurately

  resolve flows over steep and complex terrain

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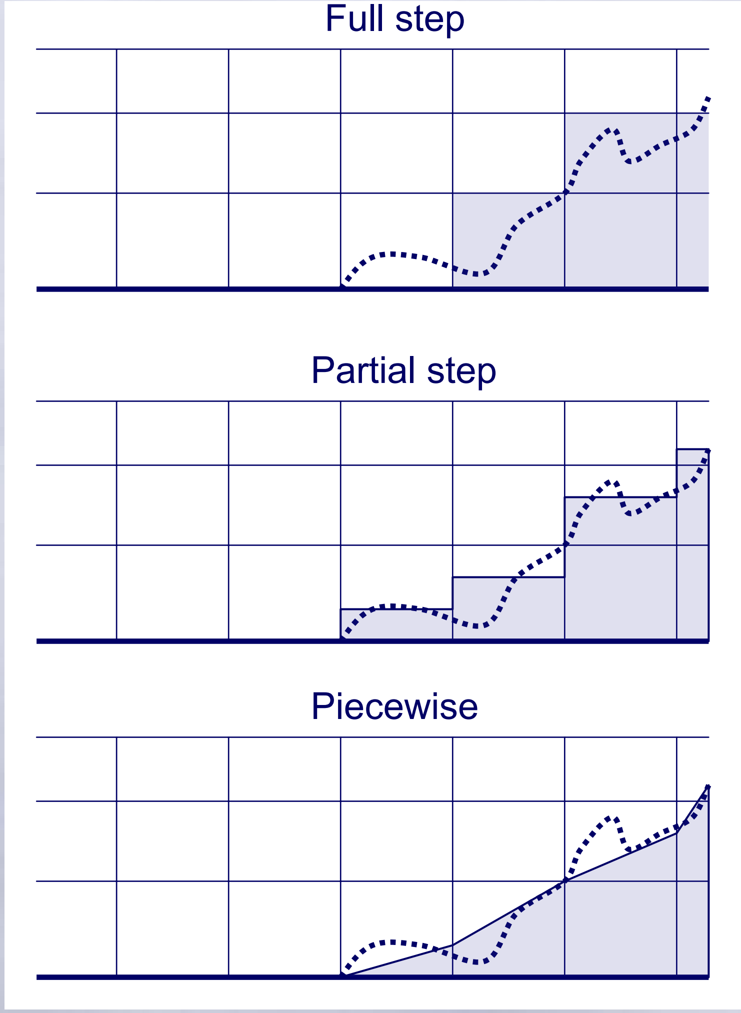
Cut-cell approach - background I:

Adcroft, Marshall, Hill (1997):

- explored cut-cells in representing irregular topography in an ocean model
- Tested 2 approaches: “partial steps” and “piecewise linear” (illustrated)
- proposed a finite-volume approach to solve flow in shaved cells
- solved 2D Boussinesq equations in flux-form => Gauss’s divergence theorem applied to fluxes in a (grid) volume
- concluded piecewise linear gives a superior representation, especially at course resolutions



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Cut-cell approach - background II:

Bonaventura (2000):

• extended cut-cell approach to compressible Euler equations

• demonstrated a simpler formulation of the finite-volume method:

only the divergence term in the pressure equation is solved by Gauss's theorem

• results from partial-step representation for a 2D bell-shaped hill showed good agreement with terrain-following model, and no evidence of spurious flows around steep orography

Steppeler et al. (2002, 2006):

• extended scheme to 3D piecewise-linear representation in a full atmospheric model (COSMO-DE)

• for dry idealised orographic flows, results compared very well with the terrain-following model

• evidence of improved precipitation forecasts from cut-cell method

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Microscale model:

What?

• a research model for very high-resolution dynamics and moist processes:

$$\Delta x = \Delta z < 100\text{m}$$

• particular focus on flows over steep/complex terrain ==> exploring potential of cut-cells

Basic model description:

• 3D, Cartesian, non-hydrostatic, fully compressible equations

• prognostic variables: u, v, w, Π', θ', q

• time-splitting integration method (Klemp & Wilhelmson, 1978) - resolves sound and gravity waves on a short time-step; all other modes on a longer step

• fully explicit discretization schemes: 2nd-order leapfrog (time) & 2nd-order centred (space)

• computation grid: staggered in horizontal and vertical (Arakawa C & Charney-Phillips)

• orographic surface represented by piecewise bi-linear surfaces

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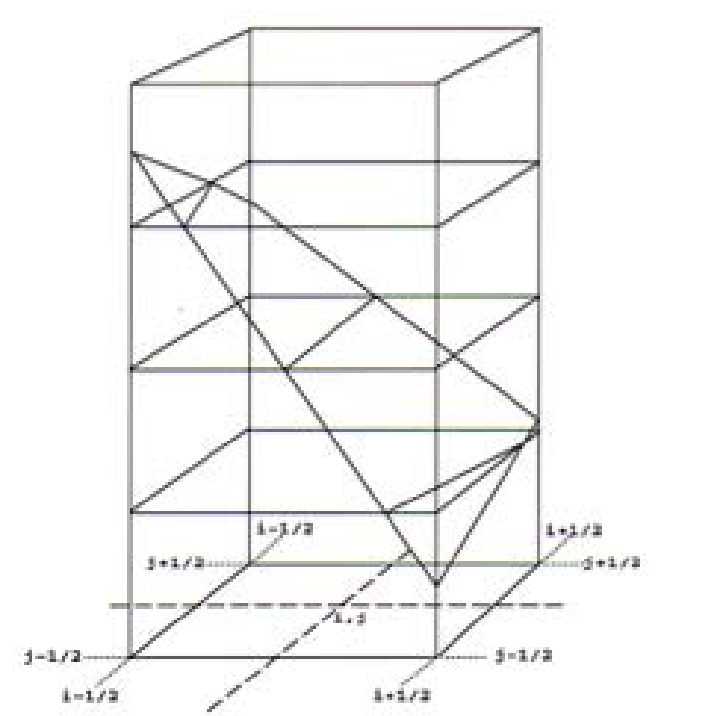
Cut-cell approach in Microscale Model:



From Steppeler et al. (2006)

Orography set-up:

- Cartesian grid, i.e. horizontal vertical levels
- define orography height at column-corners
- define unique continuous piecewise bilinear surface from four column-corner heights
- 3 types of grid-cell result:
  - i) "pure Earth" cells
  - ii) "pure air" cells
  - iii) "cut-cells" ⟶ treated with finite-volume approximation
- compute relative air surfaces/volumes in grid-cells
  - relatively simple since bilinear function means intersections are straight lines

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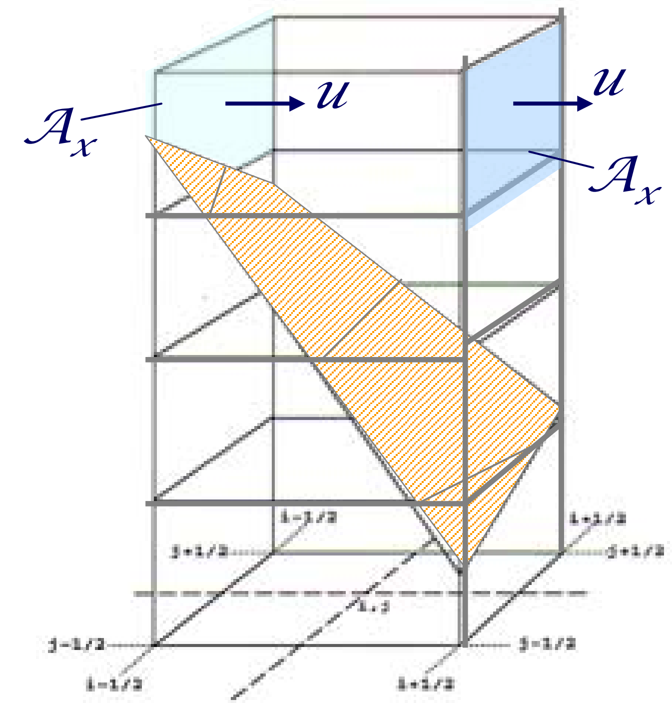
Cut-cell approach in Microscale Model:

Integration method:

- finite-volume approach =>
  values at grid-points represent
  surface/volume-averages for grid-cell

  NB grid storage point might be located beneath surface, but still needs a solution

- finite-volume approach is used to compute
  the divergence term in continuity equation,
  using Gauss's theorem



From Steppeler et al. (2006)

$$\int_{\mathcal{V}} \nabla \cdot \mathbf{u} \, \mathrm{d}\mathcal{V} = \int_{\mathcal{A}} \mathbf{u} \cdot \mathrm{d}\mathcal{A} \longrightarrow \mathcal{V}\, \nabla \cdot \mathbf{u} = \delta_x(\mathcal{A}_x u) + \delta_y(\mathcal{A}_y v) + \delta_z(\mathcal{A}_z w)$$

- in practice, finite-volume approach can be implemented in terms of
  simple multiplication factors (fractional surface areas/volumes)
  in the standard finite-difference model integrations

Results for idealised orographic flows:

2D bell-shaped hill: benchmark case, *a*=1km

2D bell-shaped hills: increasingly narrow/steep hills

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Results for idealised orographic flows:

2D bell-shaped hill: benchmark case, *a*=1km

- Gallus & Klemp (2000) - benchmark test case
- Stratified flow, $N = 0.01s^{-1}$, $U = 10ms^{-1}$
- Hill: Gaussian, $H = 400m$, $a = 1km$, $\Delta x = 200m$
- Results: comparison with analytical solution and step-approach models (Gallus & Klemp, 2000)

2D bell-shaped hills: increasingly narrow/steep hills

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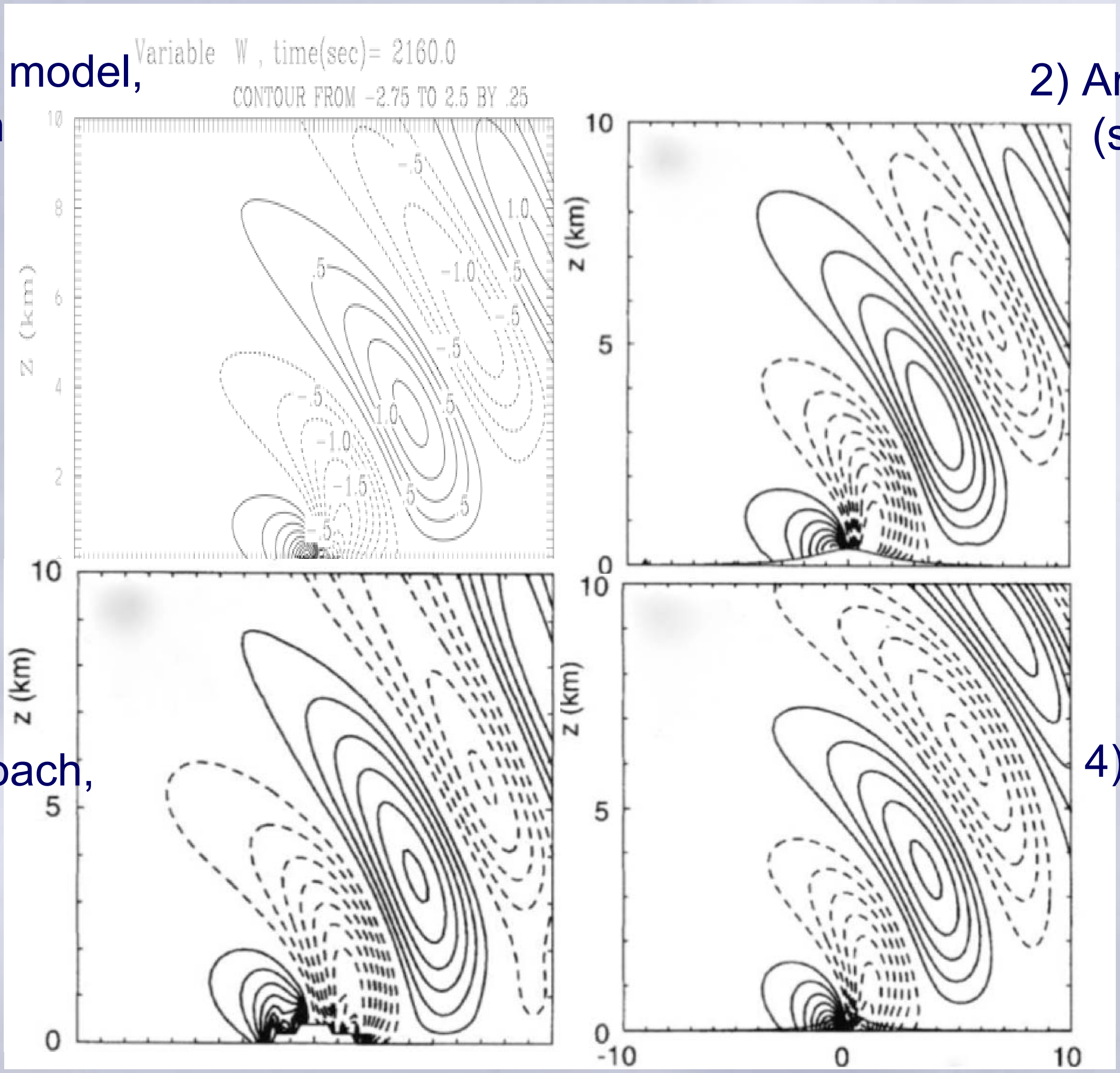
Results for idealised orographic flows - ***a*=1km** :

1) Microscale model, Δz = 200m

2) Analytical solution (smooth hill)

3) Step approach, Δz = 10m

4) Step approach, Δz = 200m



Figures 2,3,4 from Gallus & Klemp (2000)

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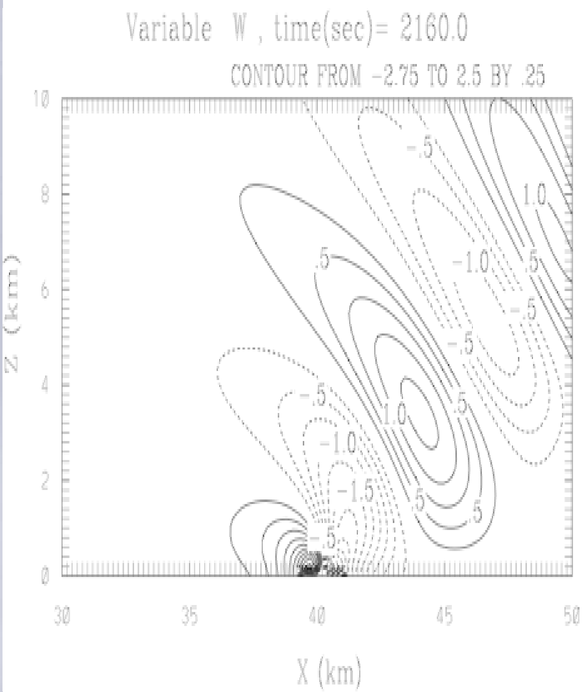
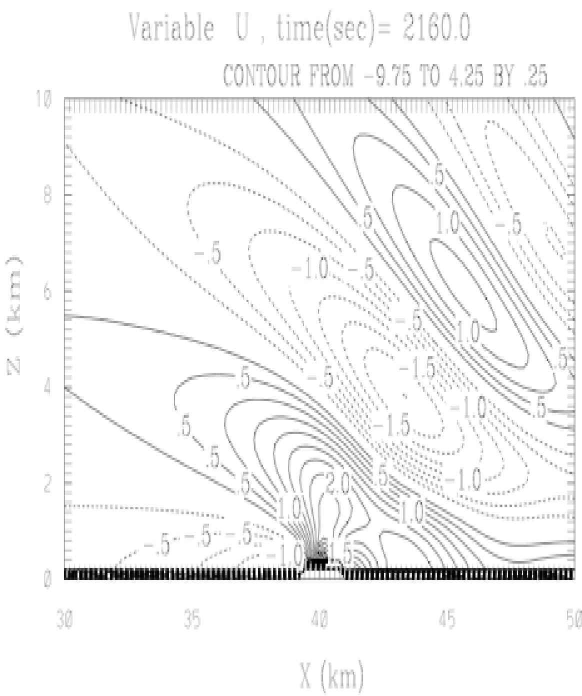
Results for idealised orographic flows - ***a*=1km** :

Microscale model (Δz = 200m)

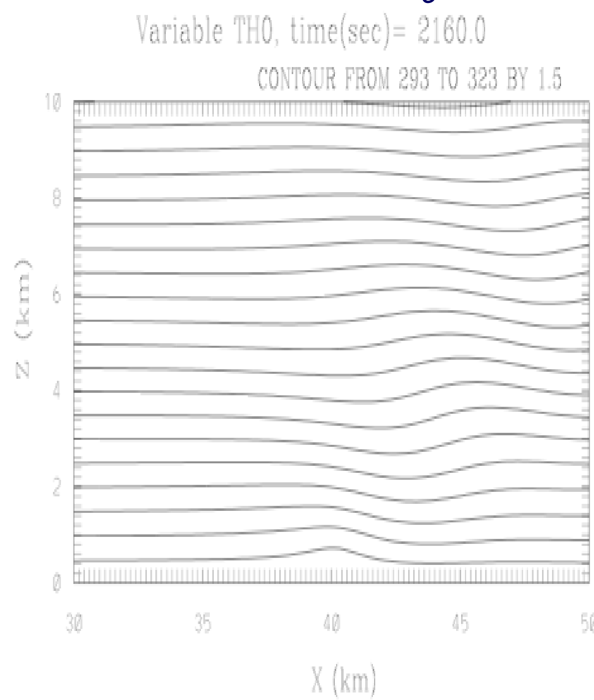
W



$U' = U - U_0$



$\theta = \theta' + \theta_0$



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Results for idealised orographic flows:

2D bell-shaped hill: benchmark case, a=1km

2D bell-shaped hills: increasingly narrow/steep hills

Continuing with similar set-up for steeper, narrower hills:

- Stratified flow, $N = 0.01\text{s}^{-1}$, $U = 10\text{ms}^{-1}$
- Hill: Gaussian, $H = 400\text{m}$, $a = <1\text{km}$, $\Delta x = 0.2a$

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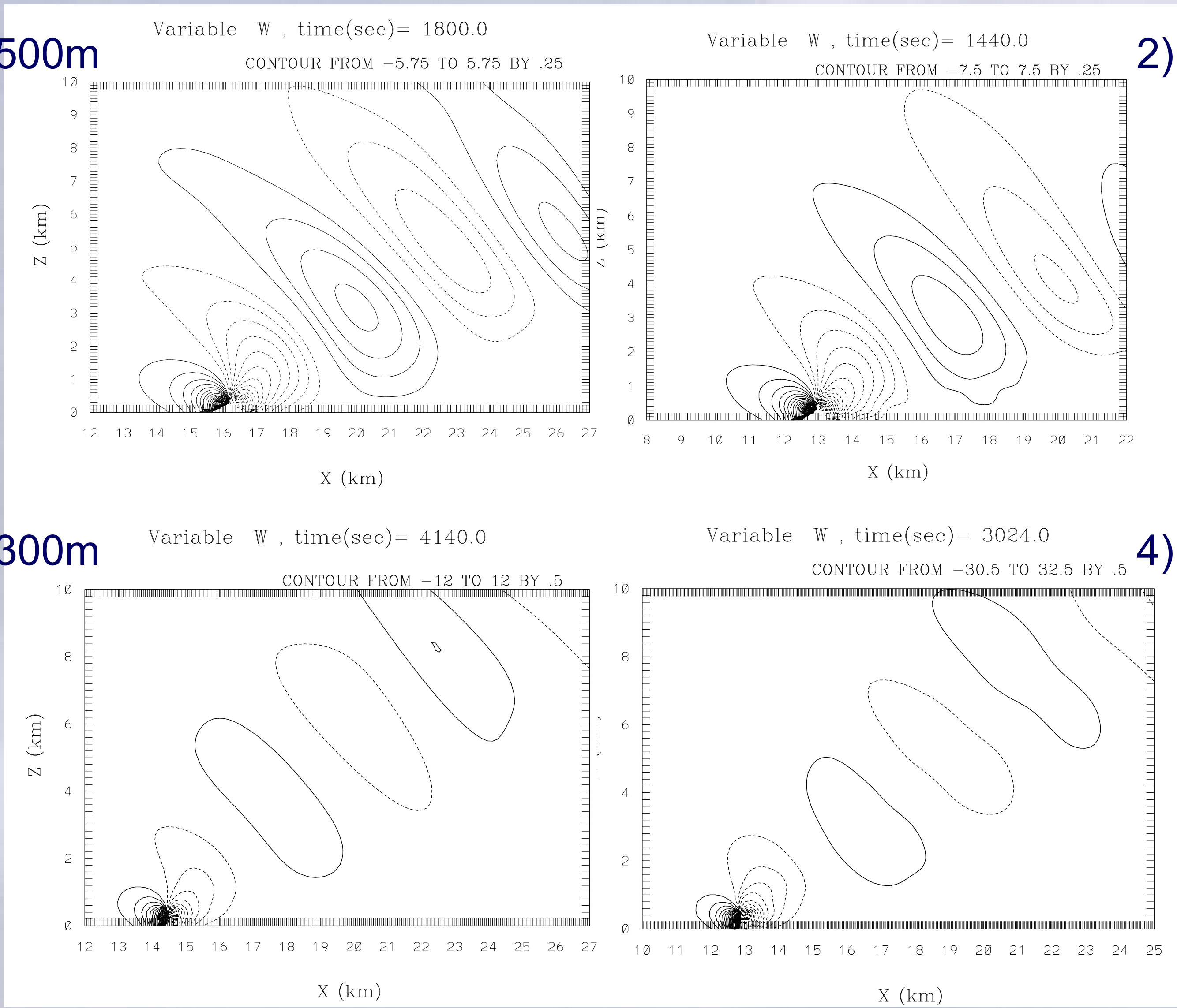
Results for idealised orographic flows - ***a*<1km** :

1) *a* = 500m

2) *a* = 400m

3) *a* = 300m

4) *a* = 200m



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Extension to moist dynamics (A. Coals):

Computing moist fields, q_v and q_l:

Contribution from latent heat to thermodynamic equation, and prognostic equations for mixing ratios for water vapour and liquid water:

$$\frac{D\theta}{Dt} = \frac{L_v C}{c_p \Pi}$$

$$\text{where } \Pi = (P/P_0)^{R/c_p}$$

$$\frac{Dq_v}{Dt} = -C$$

$$\frac{Dq_L}{Dt} = C$$

Comparison with benchmark 2D simulation (Bryan & Fritsch, 2002):

- initialised with zero winds everywhere;
- neutrally stable reference state, assuming:
  - total water mixing ratio constant at all levels
  - phase changes are exactly reversible
- warm perturbation placed at centre of domain

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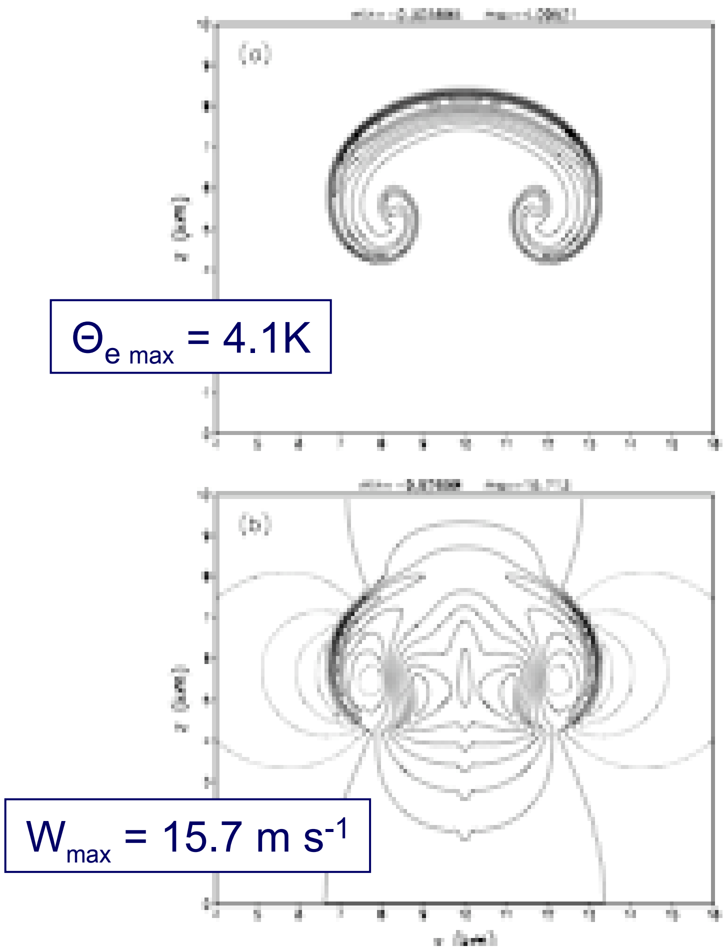
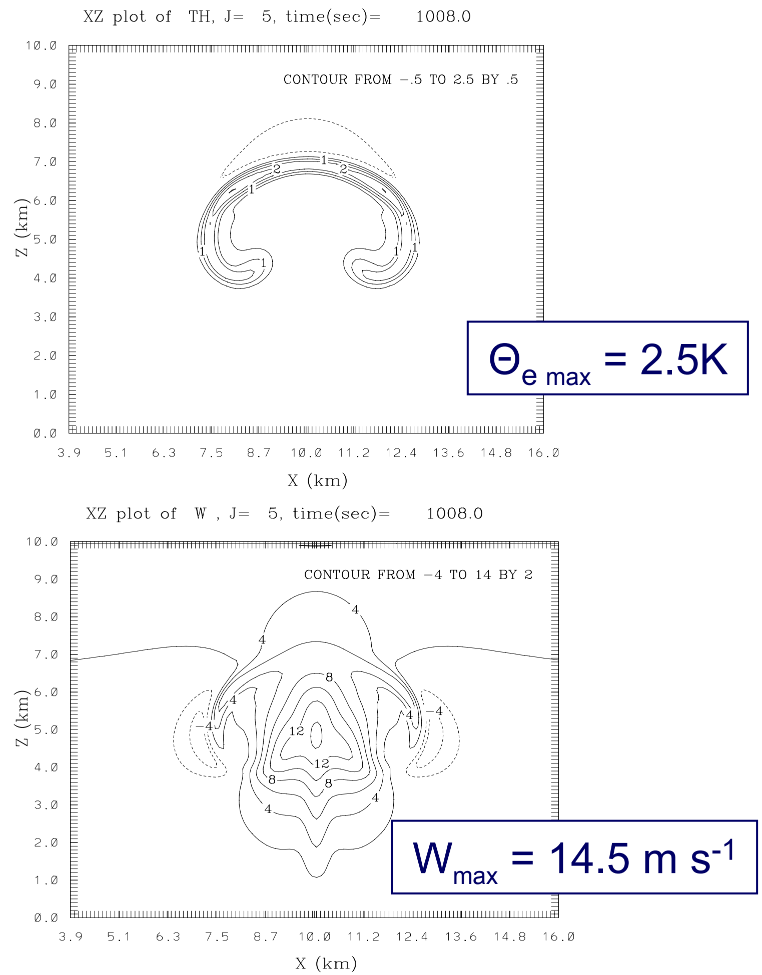
Results for idealised moist flows (A. Coals):

Comparison with benchmark simulation (Bryan and Fritsch, 2002)



Bryan & Fritsch (Fig.3, MWR 2002)



Microscale Model

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Future & current work:

Microscale model:

Exploring steeper gradients:

- What gradients is microscale model capable of?
- Rosatti, Cesari & Bonaventura (2005) & Yamazaki & Satomura (2008) - 2D idealised flows over semi-circular obstacles (i.e. flow up ~vertical walls)

Microscale moisture (A. Coals):

- exploring idealised moist flows over orography

Longer term:

- incorporate a no-slip surface boundary condition
- explore turbulence schemes
- implement warm rain parameterization schemes (developed off-line)

WRF

COPS

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Future & current work:

Microscale model

WRF:

Exploring cut-cells in "WRF" model:
- Working with Joe Klemp & Bill Skamarock on "toy" models
- Starting from 2D cut-cell height-based coordinate model
- Flux-form eqns ==> full finite-volume representation
- Working towards mass-based coordinates (consistent with WRF)

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Future & current work:

Microscale model

WRF

COPS (A. Blyth):

Convective & Orographically-induced Precipitation Study:

• observational campaign: Black Forest, Germany; Summer 2007

• using dynamical models to help "*identify the physical and chemical processes responsible for the deficiencies in QPF over low-mountain regions with the goal to improve their model representation*"

Aim: to extend the cut-cell work to investigate COPS cases

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