Development of a numerical model for studying microscale atmospheric dynamics

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With thanks to S. Mobbs[1], D. Woodhead[1]

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National Centre for Atmospheric Science
NATURAL ENVIRONMENT RESEARCH COUNCIL

7th SRNWP-workshop, Bad Orb, 5th-7th November 2007

Project aims:

The “microscale model” project was developed to:

- investigate modelling approaches for very high-resolution studies;
- explore the applicability of full atmospheric models for flows on scales of O(<100m);
- provide an accessible research model;
- provide a resource to help improve our understanding of small-scale dynamics/processes

Model details:

- **equation set:**

  3D, Cartesian, non-hydrostatic,

  fully compressible

- prognostic/diagnostic variables

- time-stepping:

  time-splitting method

- numerical schemes:

  fully explicit (horizontal & vertical)

  1st-order forward-in-time

  1st-order upwind scheme

- grid: Arakawa-C (horizontal)

  Charney-Phillips (vertical)

- lower boundary:

  LMz immersed boundary scheme

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Prognostic variables:

u, v, w	wind velocity
π'	Exner pressure pert.
θ'	potential temp. pert.
q	(moist version)

Diagnostic variables:

ρ	density
Π	Exner pressure field
Θ	potential temp.
p	pressure
T	*in situ* temperature

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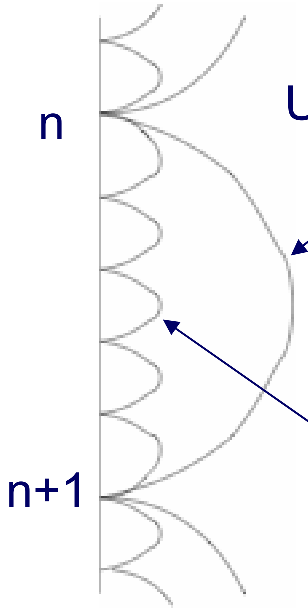
Based on Klemp & Wilhelmson (1978):

Equations take the form

$$\frac{\partial \phi}{\partial t} = s_\phi + f_\phi$$

where s_ϕ = fast modes
f_ϕ = slow modes



Update slow modes on long time-step (Δt)…

…and fast modes on intermediate short steps ($\Delta \tau$)

Model equations (time-split form):

$$\begin{aligned}
\frac{\partial u}{\partial t} + c_p\bar{\theta}\frac{\partial \Pi'}{\partial x} &= -\mathbf{u}\cdot\nabla u + fv - Fw + D_u \\
\frac{\partial v}{\partial t} + c_p\bar{\theta}\frac{\partial \Pi'}{\partial y} &= -\mathbf{u}\cdot\nabla v - fu + D_v \\
\frac{\partial w}{\partial t} + c_p\bar{\theta}\frac{\partial \Pi'}{\partial z} &= -\mathbf{u}\cdot\nabla w + Fu + g\frac{\theta'}{\bar{\theta}} + D_w \\
\frac{\partial \Pi'}{\partial t} + \frac{\bar{c}^2}{c_p\bar{\theta}}\nabla\cdot\mathbf{u} &= 0 \\
\frac{\partial \theta'}{\partial t} &= -\mathbf{u}\cdot\nabla\theta' - w\frac{d\bar{\theta}}{dz} + S_\theta
\end{aligned}$$

(as in KW78)

LHS: fast modes
(acoustic only)

RHS: slower modes
(inc. gravity, advection, …)

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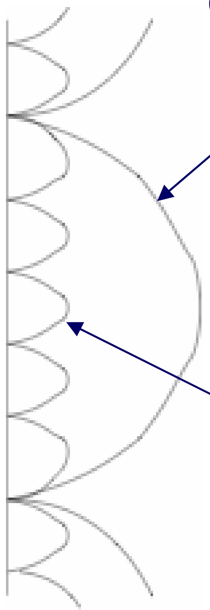
Currently using simple schemes:

For time-differencing:



On the long step,
1st-order forward-in time

$$\phi^{n+1} = \phi^n + \Delta t\left({F_\phi}^n\right)$$

On the short step,
1st-order forward-backward

$$u^{n+1} = u^n + \Delta\tau\left({F_u}^n + {G_\pi}^n\right)$$

$$\pi^{n+1} = \pi^n + \Delta\tau\left({F_u}^{n+1} + {G_\pi}^n\right)$$

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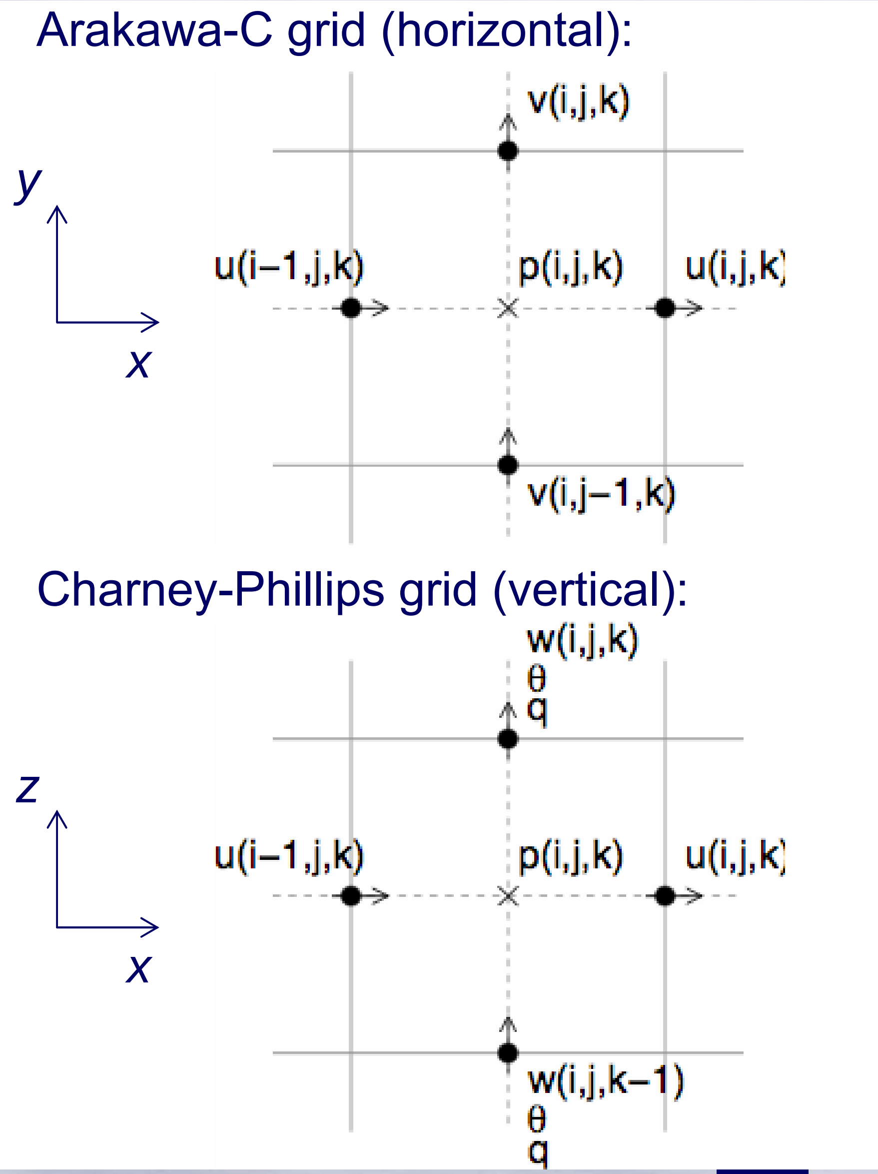
Arakawa-C grid (horizontal):

Charney-Phillips grid (vertical):



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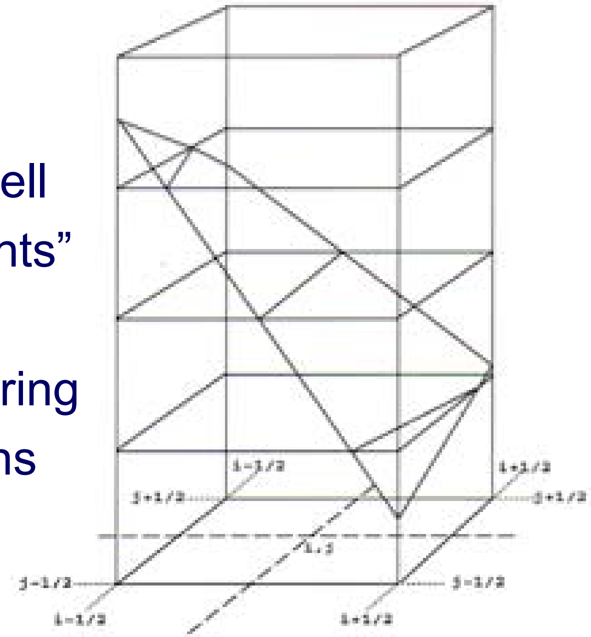
LMz immersed boundary scheme:

- Vertical levels remain horizontal
- Orography cuts through grid cells
- Shape defined by bilinear function
- Finite volume method for flow through cut-cells
- Calculate "weights" for each cell
- Use "weights" as simple factors during integrations



From Steppeler et al. (2006)

Some early results :

- **Neutral flow over a 2D sinusoidal ridge**

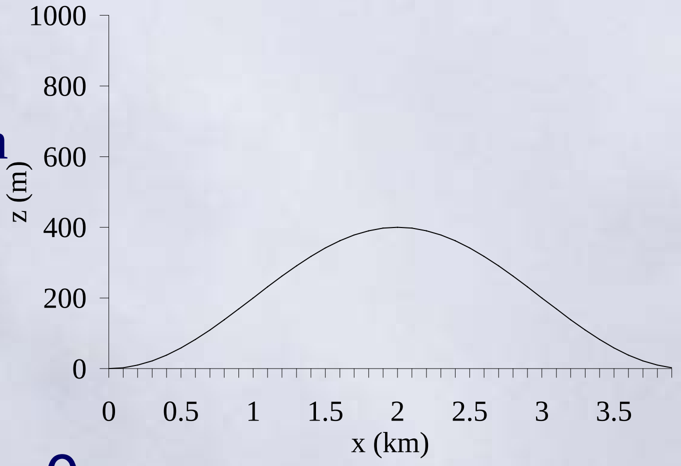
  - domain: Δx = 100m (n=40), L = 3900m

    Δz = 100m (l=60), H = 5900m

  - hill:

    $$h(x) = \frac{h_0}{2}\cos\left[\pi\frac{2x}{L}\right] + \frac{h_0}{2}$$

    h_0 = 200m, $h(x)$ = [0,400] m

  - initial conditions: u=10ms^{-1}, v=w=0

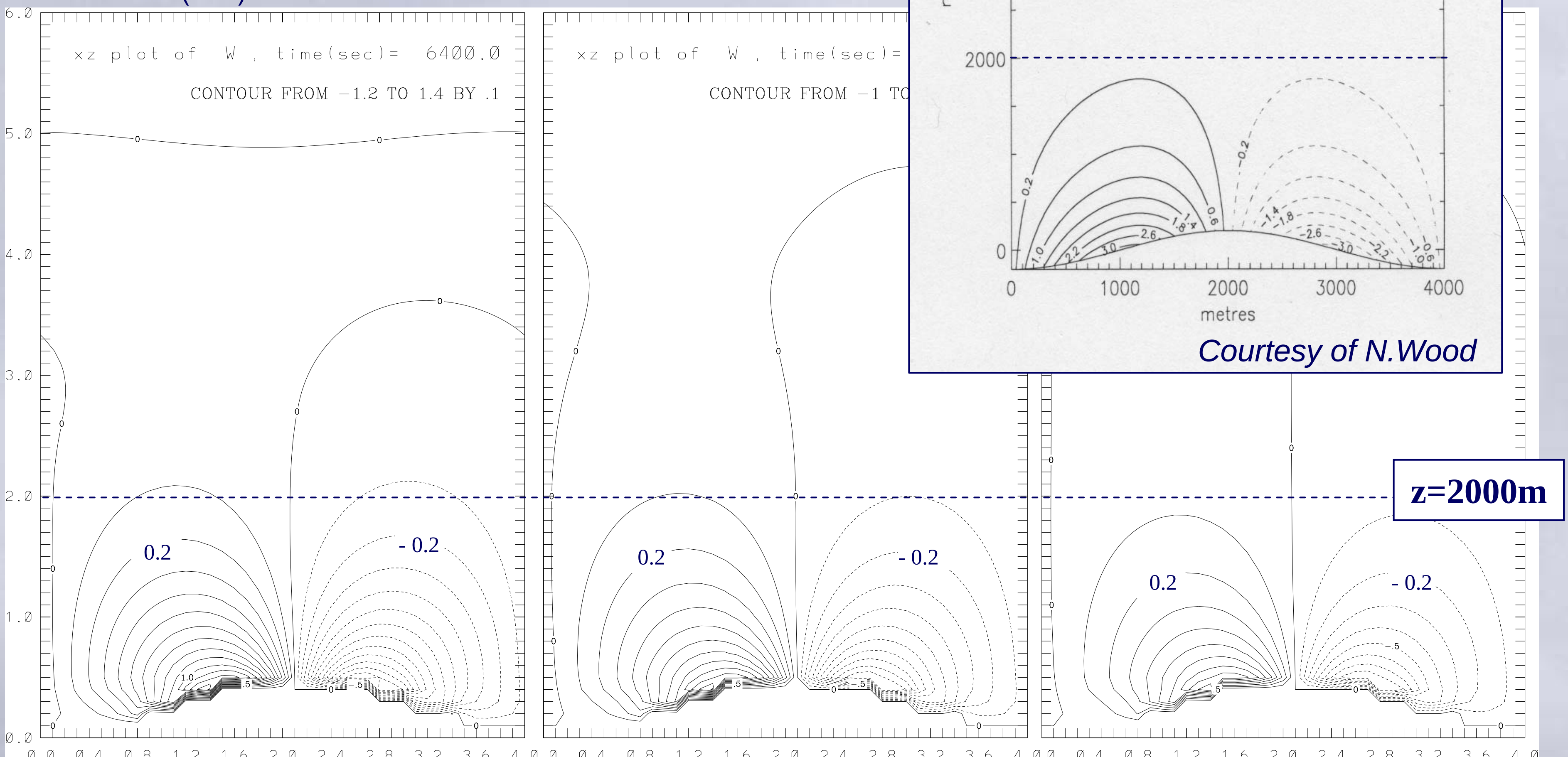
  - periodic lateral boundaries

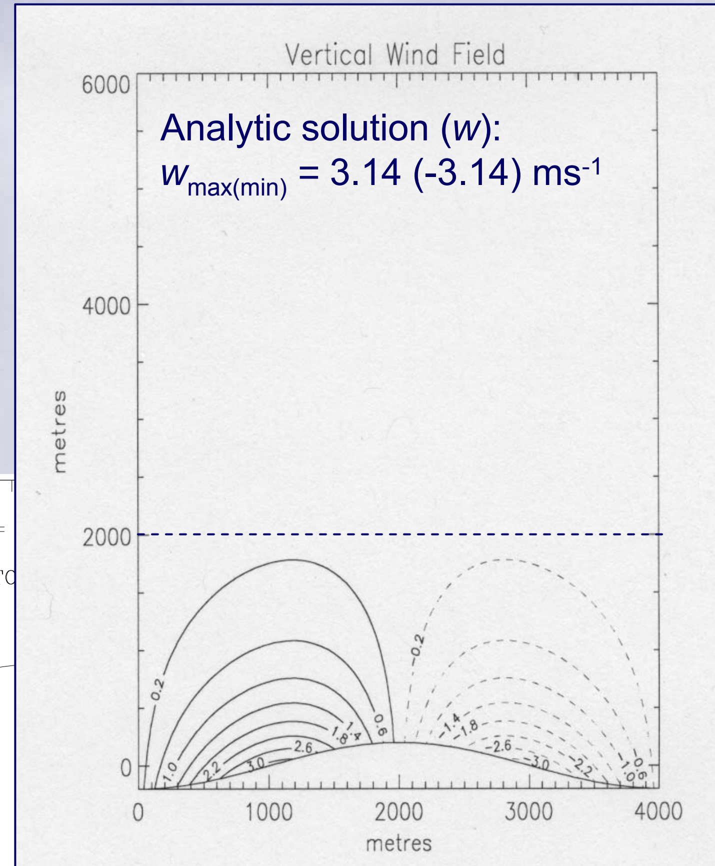
- Moist version tests

Neutral flow over 2D sinusoidal

Vertical wind field (*w*) results:

- results for 6400s, 12800s, 32000s
- contour intervals 0.1ms^{-1}
- shows flow deceleration
  - $w_{max(min)}$: from 1.4 (-1.3) to 1.0 (-0.9)



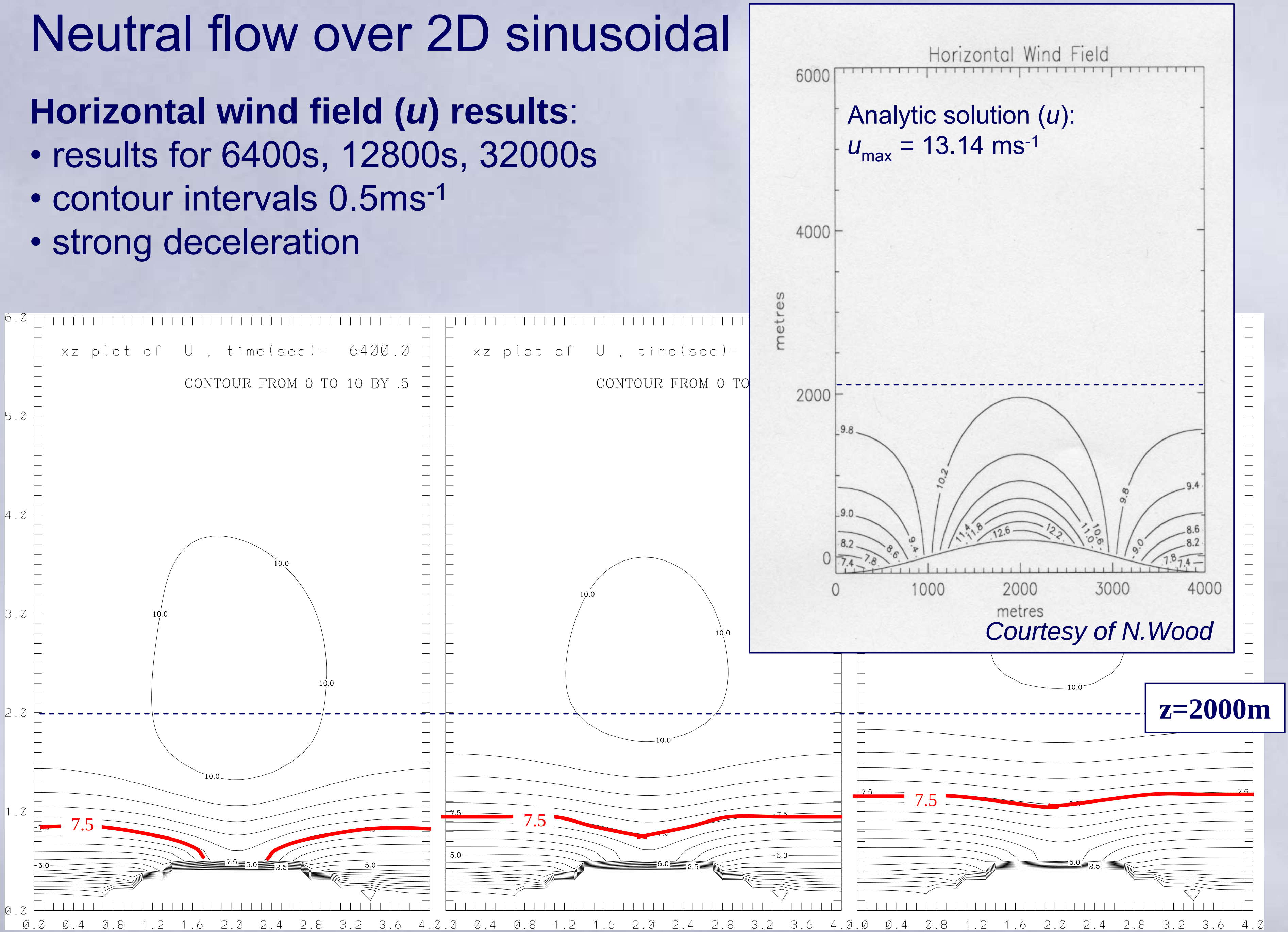


Courtesy of N.Wood

Neutral flow over 2D sinusoidal

Horizontal wind field (*u*) results:

- results for 6400s, 12800s, 32000s
- contour intervals 0.5ms^{-1}
- strong deceleration



Some early results :

- Neutral flow over a 2D sinusoidal ridge
- **Moist version tests**

  - contribution from latent heat release

Neglecting terms due to diffusion or precipitation, equations for potential temperature and mixing ratios of water vapour and liquid water can be written

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

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

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

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

where C is rate of change of liquid water due to condensation and L_v is latent heat of vapourization

Moist test over flat topography :

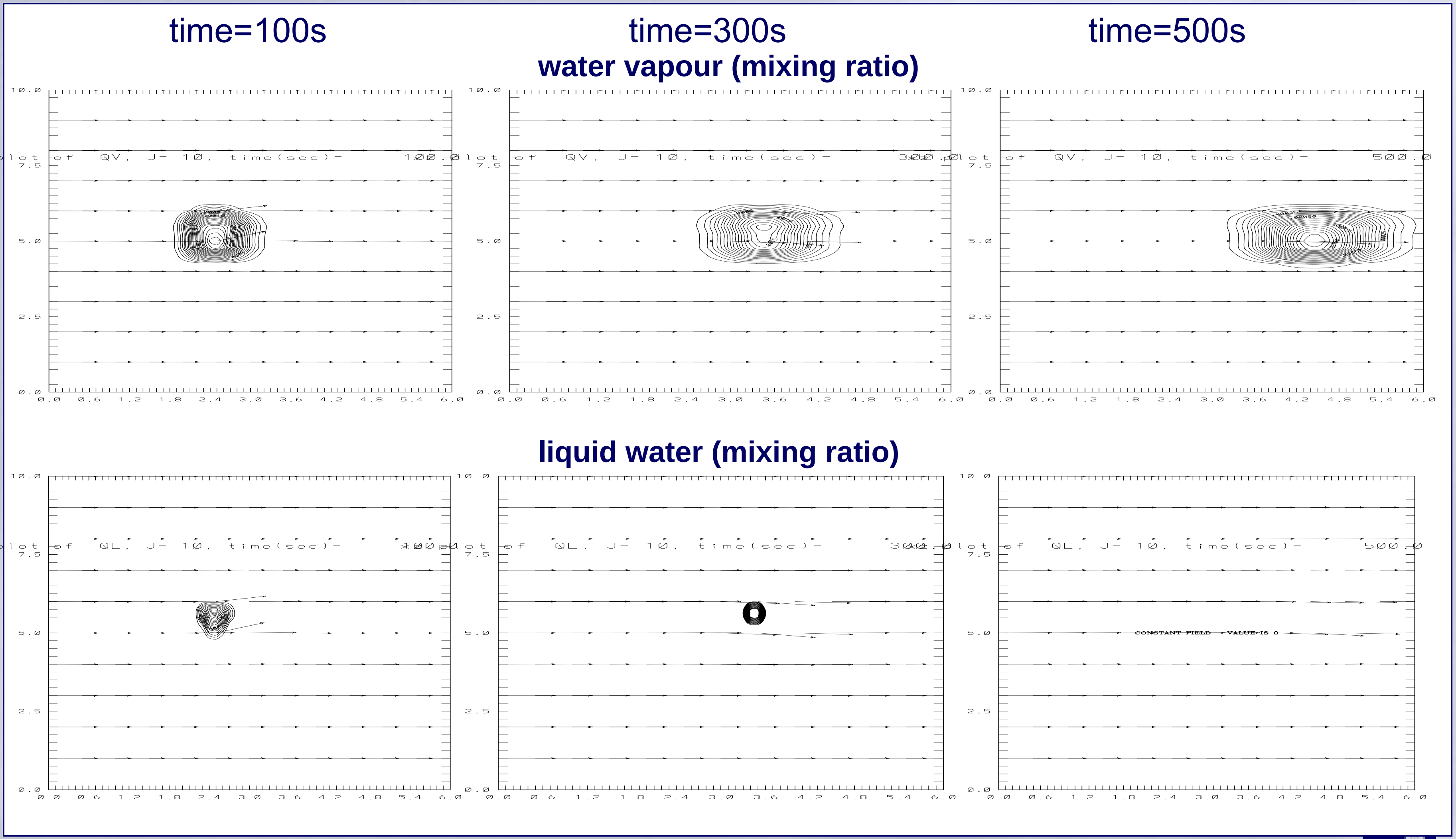
Model set-up

- domain: $\Delta x = \Delta y$ = 100m (n=60, m=100);
  Δz = 250m (l=40)
- no orography
- initial conditions: u=5 ms^{-1}, v=w=0
- periodic lateral boundaries

- linearly-varying background profile
- ‘bubble’ of water vapour (0.004 kg kg^{-1})at 5x5x5 grd-pts
- calculation of condensation (dq_L/dt)

Moist flow over flat topography: advection of vapour ‘bubble’

- results at 100s, 300s, 500s (vertical slice through centre of y-domain)
- contour intervals 0.0001 kg kg^{-1}



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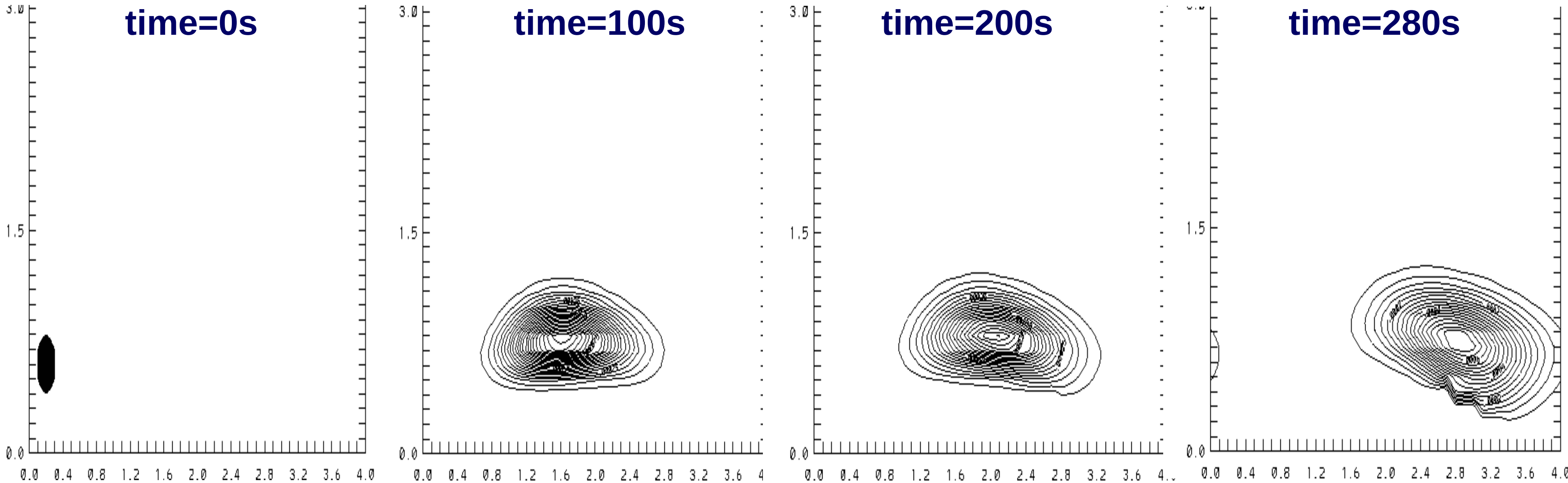
Moist version – on-going work:

Moist flow over 2D sinusoidal ridge: advection of vapour ‘bubble’

- set-up as for dry 2D sinusoidal ridge, with linearly varying background theta
- ‘bubble’ of water vapour (0.015kg kg^{-1}) of 1x1x5 grid-points
- calculation of condensation (dq_L/dt)
- contour intervals 0.0001 kg kg^{-1}



Unfortunately, we have not managed to produce any cloud with this set-up (so far…)

- find more appropriate test cases for moist flow over idealized orography

Future work:

On-going / short-term plans:

• consider free-slip / no-slip lower boundary condition

• improve advection schemes with “flux-corrector” method

• implement LES sub-grid turbulence scheme

• warm rain parameterization, based on Kessler, 1974 scheme

– includes autoconversion, accretion and evaporation processes

• continue comparisons with analytic solutions / other models

– both dry and moist

Long-term plans:

• application to real data e.g. Gaudergrat Experiment

• three-phase (ice) microphysics

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