Recent progress on developing the new anelastic dynamical core for the further operational NWP model – COSMO

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Motivations and objectives

We are interested in development of new generation dynamical core, for future NWP models for very high resolutions, (as a part of research-development work of the COSMO consortium, COSMO: Consortium of Small Scale Modeling, grouping some of European national weather services)

Model requirements:
- numerically robust, allowing for representation of effects of very steep, irregular orographies of high (eg. Alpine-type) mountain ridges

- convection resolving, allowing for explicit simulation of ‘basic‘ deep convection events

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Within the frames of the COSMO priority project a new prototype model has been developed. In this new implementation the original compressible dynamical core has been replaced by anelastic one, adopted from EULAG model. This innovative approach seams to be promising as EULAG has desirable conservative properties and robustness.

Realization of the CDC plan

Task 1.7: Technical testing with COSMO by idealised cases

The correct coupling of the EULAG dynamical core into COSMO can be at first tested with the implemented idealised test cases. This testing can be performed ‘by a press of a button’ in COSMO…

…it is not necessary to perform an extended analysis of such idealised tests, but simply to check if any technical coupling problems occur.

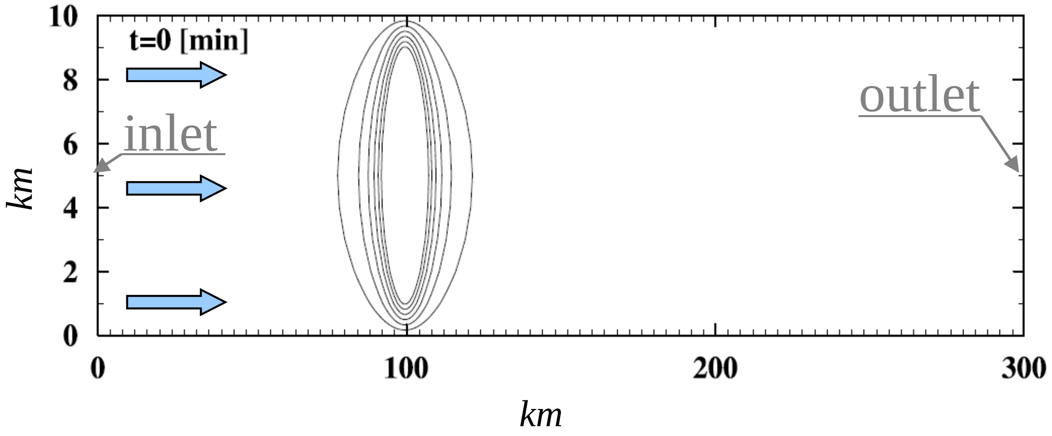
Performed tests:

1. Inertia-gravity waves (Skamarock and Klemp, 1994 and Giraldo, 2008)
2. Cold density current (Straka et al., 1993)
3. Mountain flow tests (stationary, orographic flows) Bonaventura (2000) JCP - requires terrain following coordinates

Two dimensional time dependent simulation of inertia-gravity waves

Skamarock W. C. and Klemp J. B. Efficiency and accuracy of Klemp-Wilhelmson time-splitting technique. *Mon. Wea. Rev.* **122**: 2623-2630, **1994**

Initial potential temperature perturbation



Constant ambient flow within channel 300 km and 6000 km long

Initial velocity

$$u(t=0)=20m/s$$

$$v(t=0)=0\ m/s$$

$$w(t=0)=0\ m/s$$

Initial potential temperature perturbation

$$\theta(x,z,t=0)=\Delta\theta_0\frac{\sin(\pi z/H)}{1+\left(x-x_c\right)^2/a^2}$$

Setup overview:

- domain size 300 × 10 km
- resolution 1×1km, 0.5 × 0.5 km, 0.25 × 0.25 km
- rigid free-slip b.c.
- periodic lateral boundaries
- constant horizontal flow 20m/s at inlet
- no subgrid mixing
- hydrostatic balance
- stable stratification N=0.01 s^{-1}
- max. temperature perturbation 0.01K
- Coriolis force included

Construction of the computational grid - 1st approach

EULAG U,V,W,θ

Level #	height
11	10 km
10	9 km
9	8 km
8	7 km
7	6 km
6	5 km
5	4 km
4	3 km
3	2 km
2	1 km
1	0 km

COSMO W U,V,T*

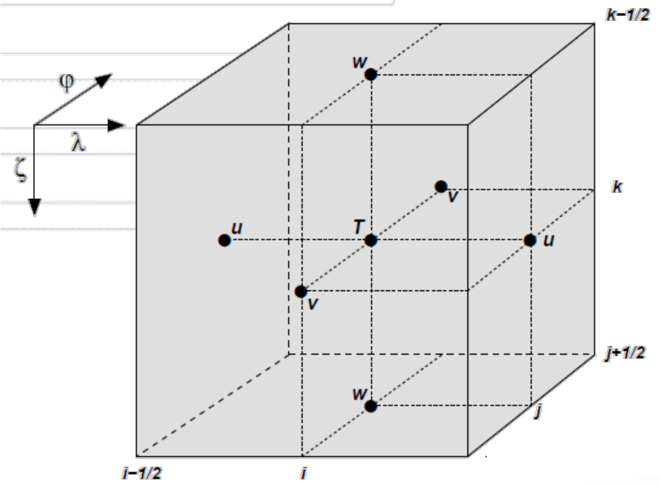
Level #	height	
11	10 km	9.5 km
10	9 km	8.5 km
9	8 km	7.5 km
8	7 km	6.5 km
7	6 km	5.5 km
6	5 km	4.5 km
5	4 km	3.5 km
4	3 km	2.5 km
3	2 km	1.5 km
2	1 km	0.5 km
1	0 km	

C&E U,V,W,θ

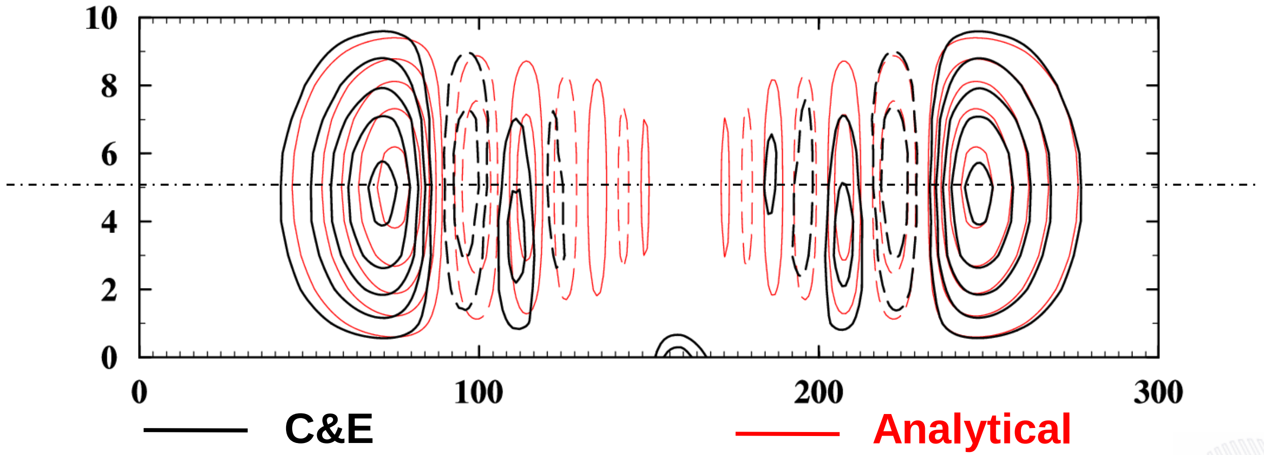
11	9.5 km
10	8.5 km
9	7.5 km
8	6.5 km
7	5.5 km
6	4.5 km
5	3.5 km
4	2.5 km
3	1.5 km
2	0.5 km
1	0 km E

E - extrapolation (U,V, θ)

Grid box volume in COSMO



Resolution 1km



Asymmetry in potential temperature distribution.

Computational grid - 2nd approach

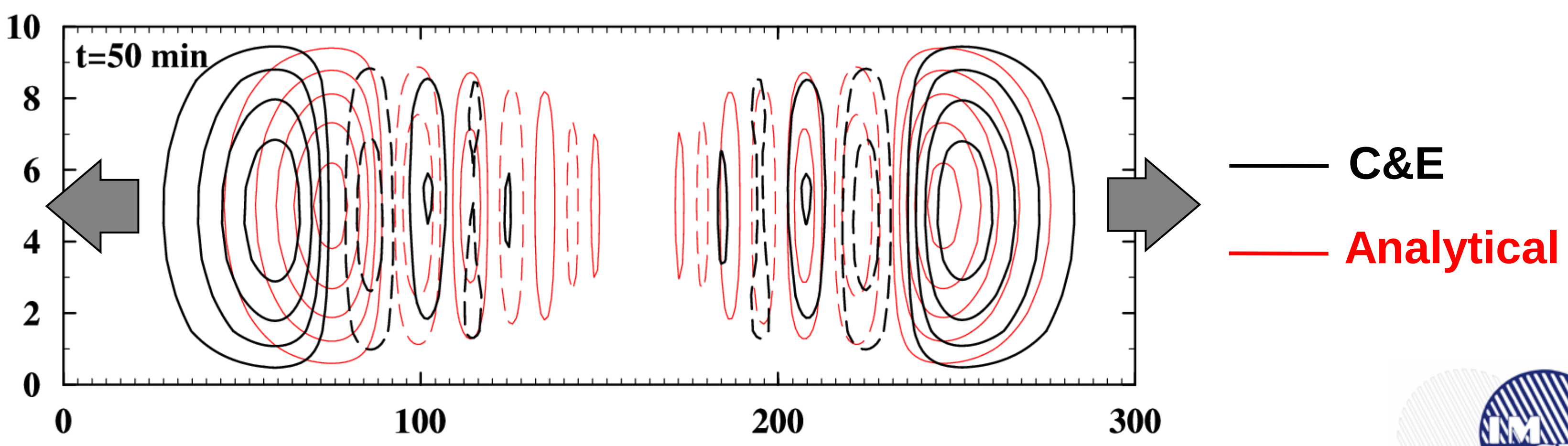
EULAG	**U,V,W,θ**
Level #	height
11	10 km
10	9 km
9	8 km
8	7 km
7	6 km
6	5 km
5	4 km
4	3 km
3	2 km
2	1 km
1	0 km

COSMO	**W**	**U,V,T***
Level #	height	
11	10 km	
		9.5 km
10	9 km	
		8.5 km
9	8 km	
		7.5 km
8	7 km	
		6.5 km
7	6 km	
		5.5 km
6	5 km	
		4.5 km
5	4 km	
		3.5 km
4	3 km	
		2.5 km
3	2 km	
		1.5 km
2	1 km	
		0.5 km
1	0 km	

C&E	**U,V,W,θ**
12	10.0 km E
11	9.5 km
10	8.5 km
9	7.5 km
8	6.5 km
7	5.5 km
6	4.5 km
5	3.5 km
4	2.5 km
3	1.5 km
2	0.5 km
1	0 km E

E - extrapolation (U,V, θ)

Resolution 1km



Wave propagates too fast

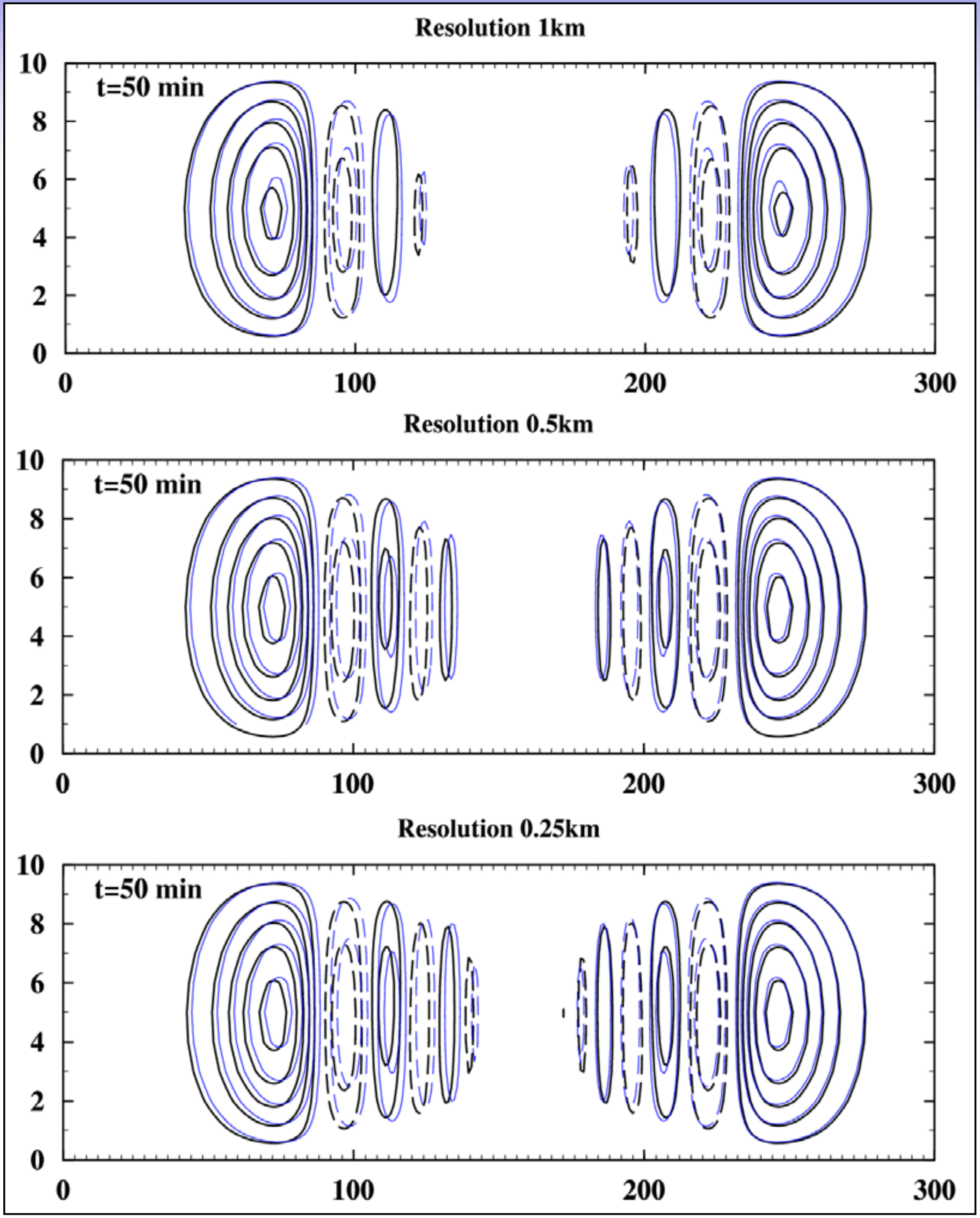
Computational grid – 3rd approach

EULAG	U,V,W,θ	COSMO	W	U,V,T*	C&E	U,V,W,θ	
Level #	height	Level #	height				
11	10 km	11	10 km	9.5 km	11	10 km	E
10	9 km	10	9 km	8.5 km	10	9 km	I
9	8 km	9	8 km	7.5 km	9	8 km	I
8	7 km	8	7 km	6.5 km	8	7 km	I
7	6 km	7	6 km	5.5 km	7	6 km	I
6	5 km	6	5 km	4.5 km	6	5 km	I
5	4 km	5	4 km	3.5 km	5	4 km	I
4	3 km	4	3 km	2.5 km	4	3 km	I
3	2 km	3	2 km	1.5 km	3	2 km	I
2	1 km	2	1 km	0.5 km	2	1 km	I
1	0 km	1	0 km		1	0 km	E

E - extrapolation (U,V, θ)

I - interpolation (U,V, θ)

Results - gravity waves in a short channel



1×1km

0.5 × 0.5 km

0.25 × 0.25 km

Eulag

C&E

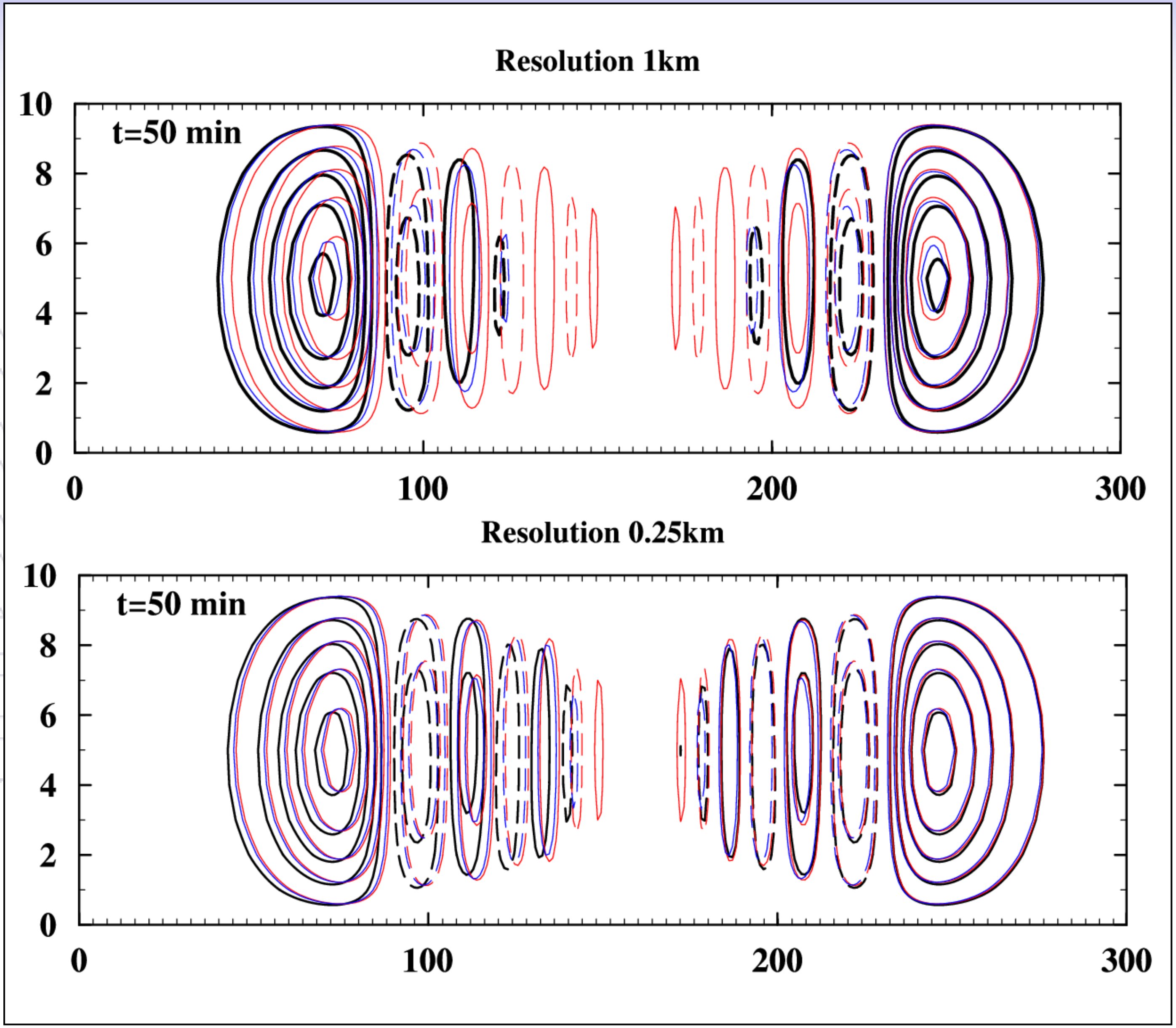
Eulag

C&E

Eulag

C&E

Comparison with analytical solution

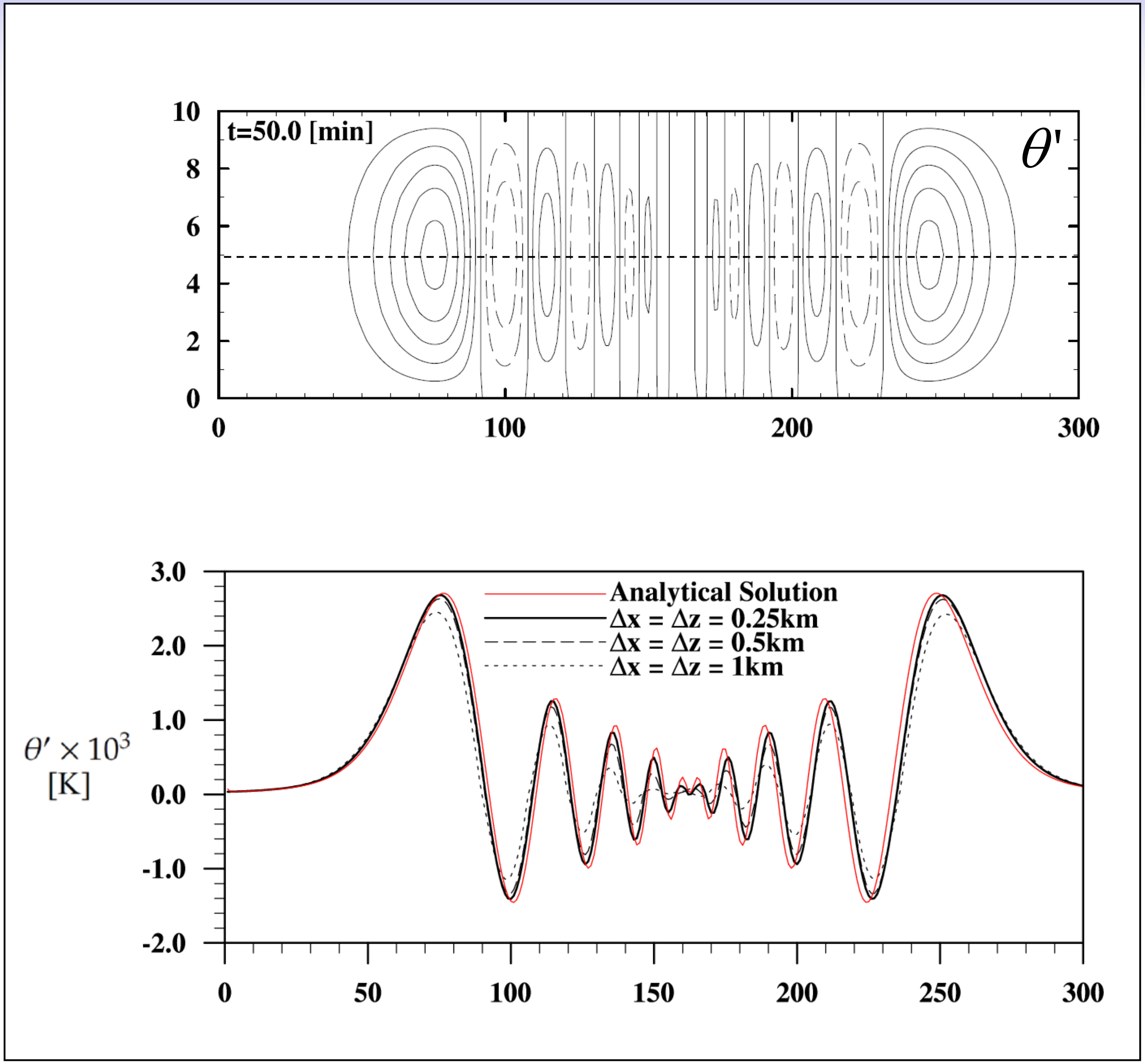


Eulag

C&E

Analytical

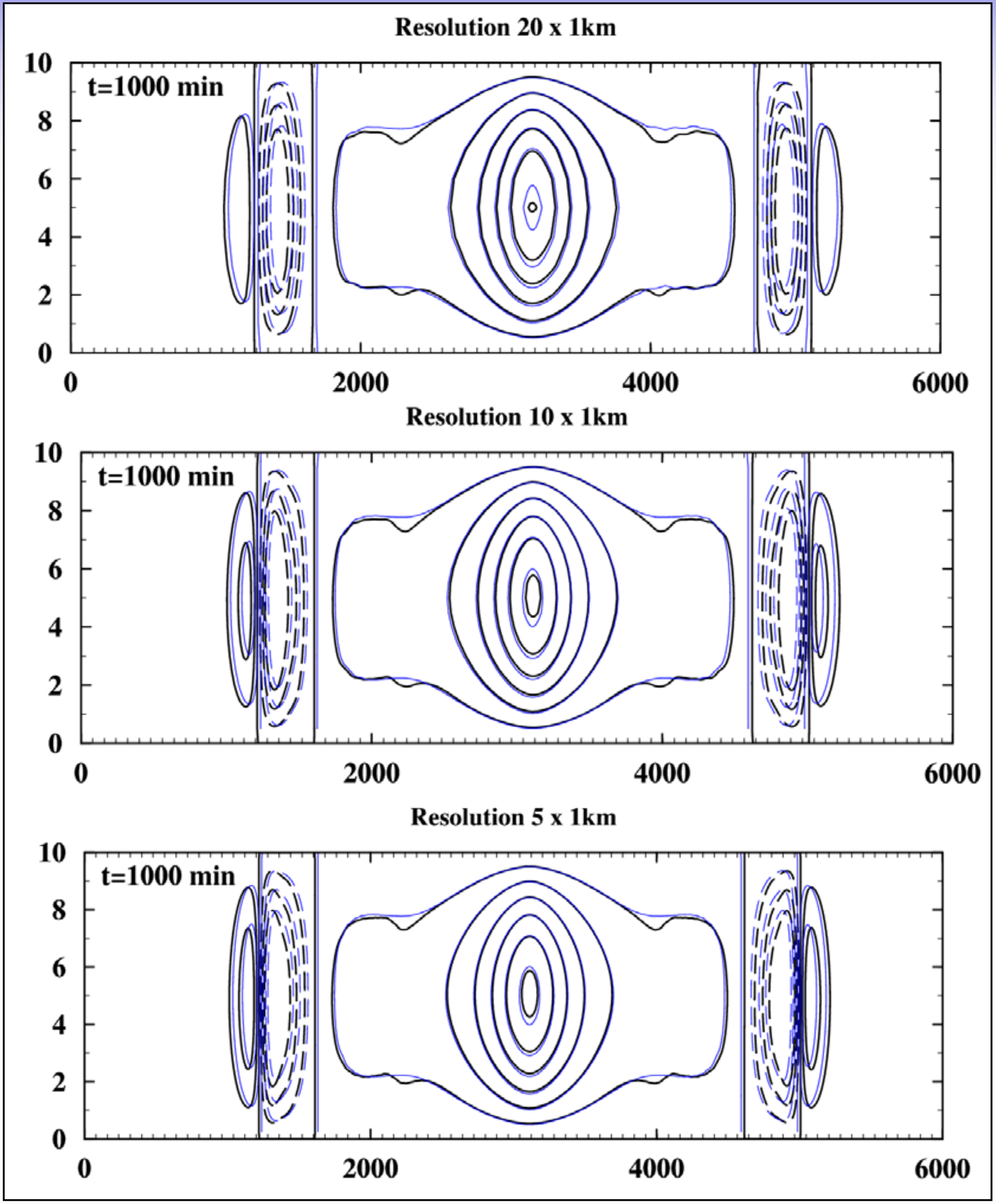
Profiles of potential temperature along 5000m height



C&E

Analytical

Gravity waves in a long channel



Eulag

C&E

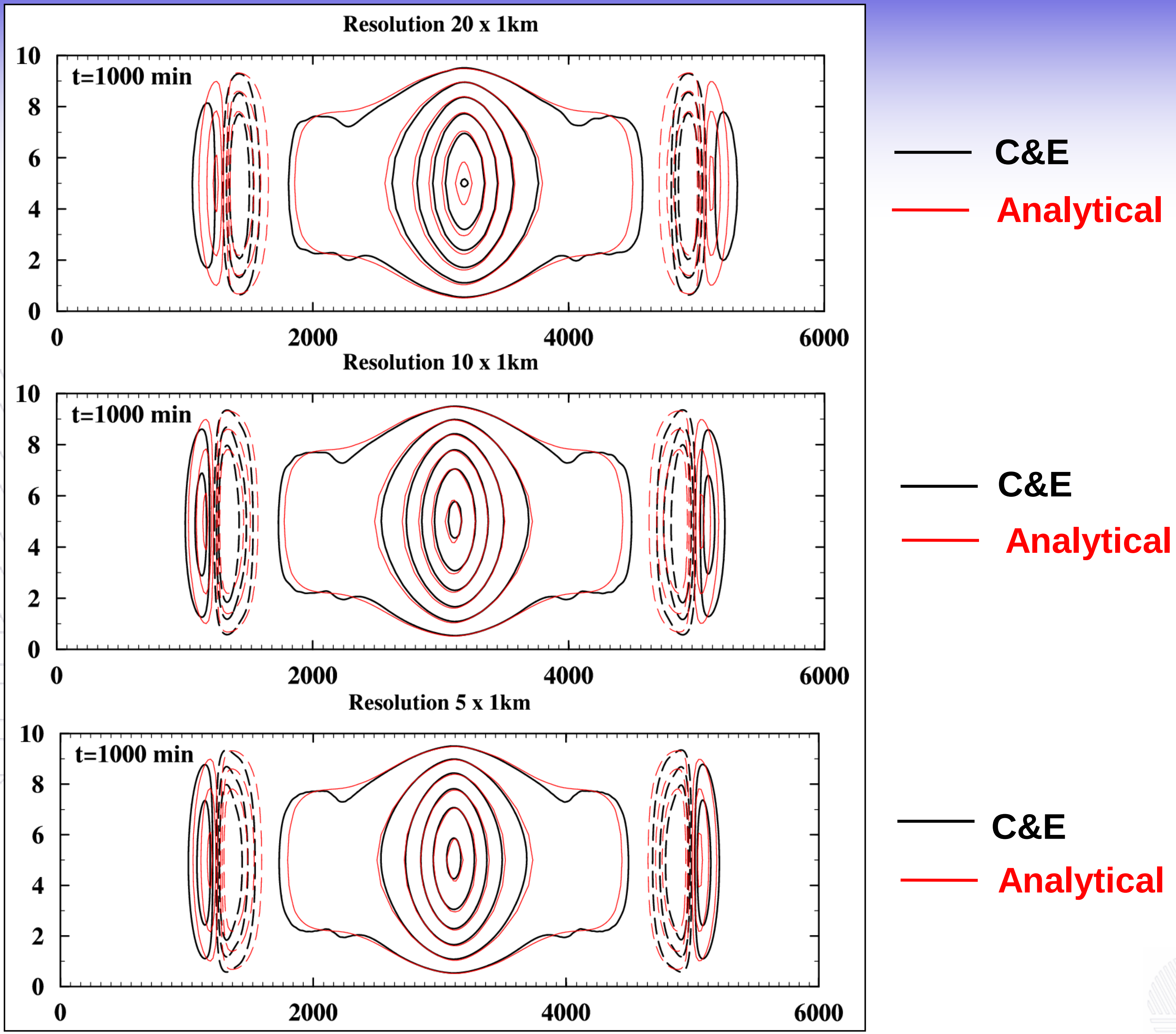
Eulag

C&E

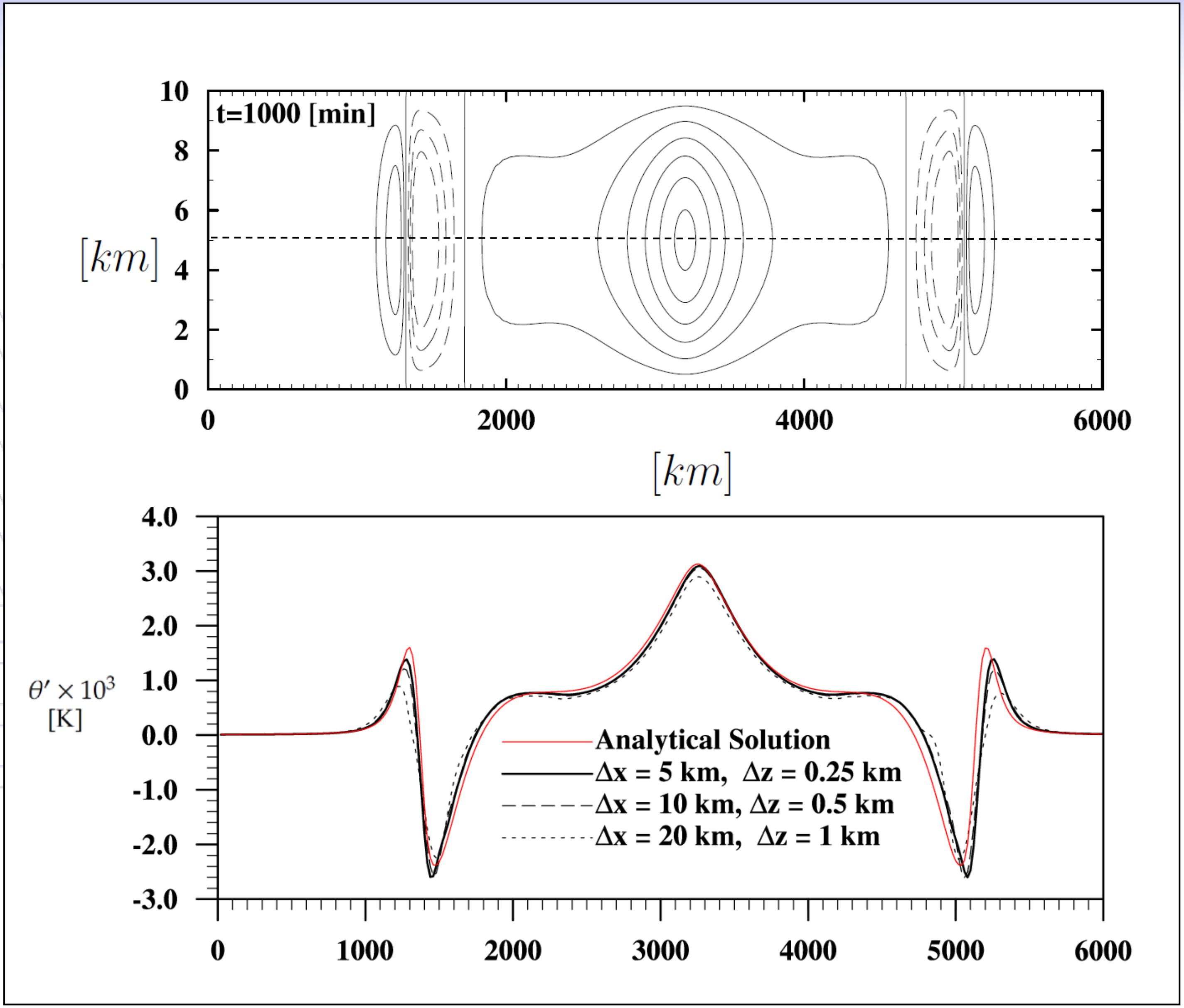
Eulag

C&E

Gravity waves in a long channel



Profiles of potential temperature along 5000m height



C&E

Analytical

Experiment 2

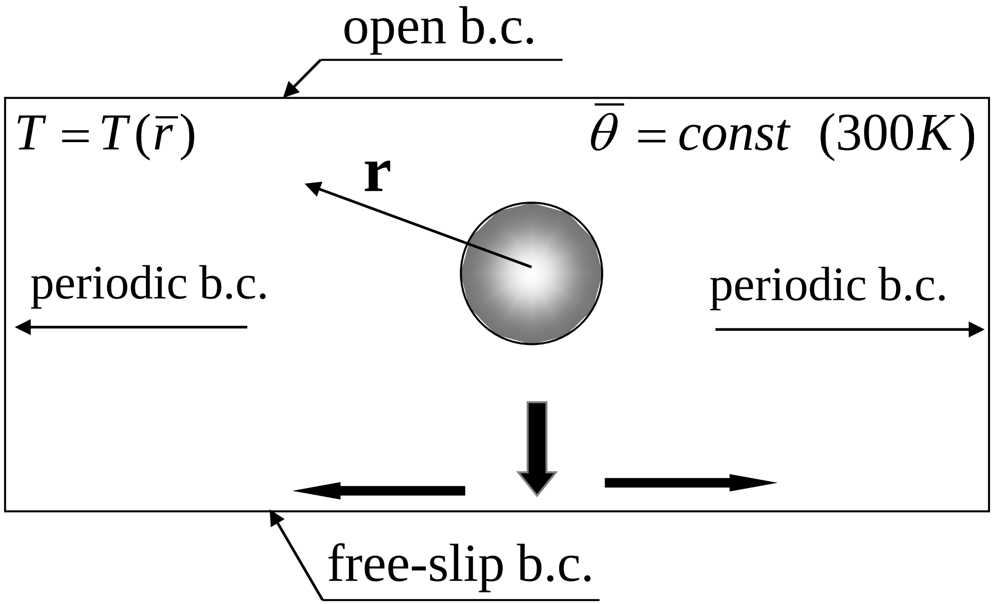
1. *Linear Gravity waves (Skamarock, Klemp (1994), Giraldo (2008))*
2. *Cold bubble (Straka et al. (1993)) (unstationary density flow)*
3. *Mountain flow tests (stationary, orographic flows) Bonaventura (2000) JCP requires terrain following coordinates*

Two dimensional time dependent simulation of cold blob descending to the ground

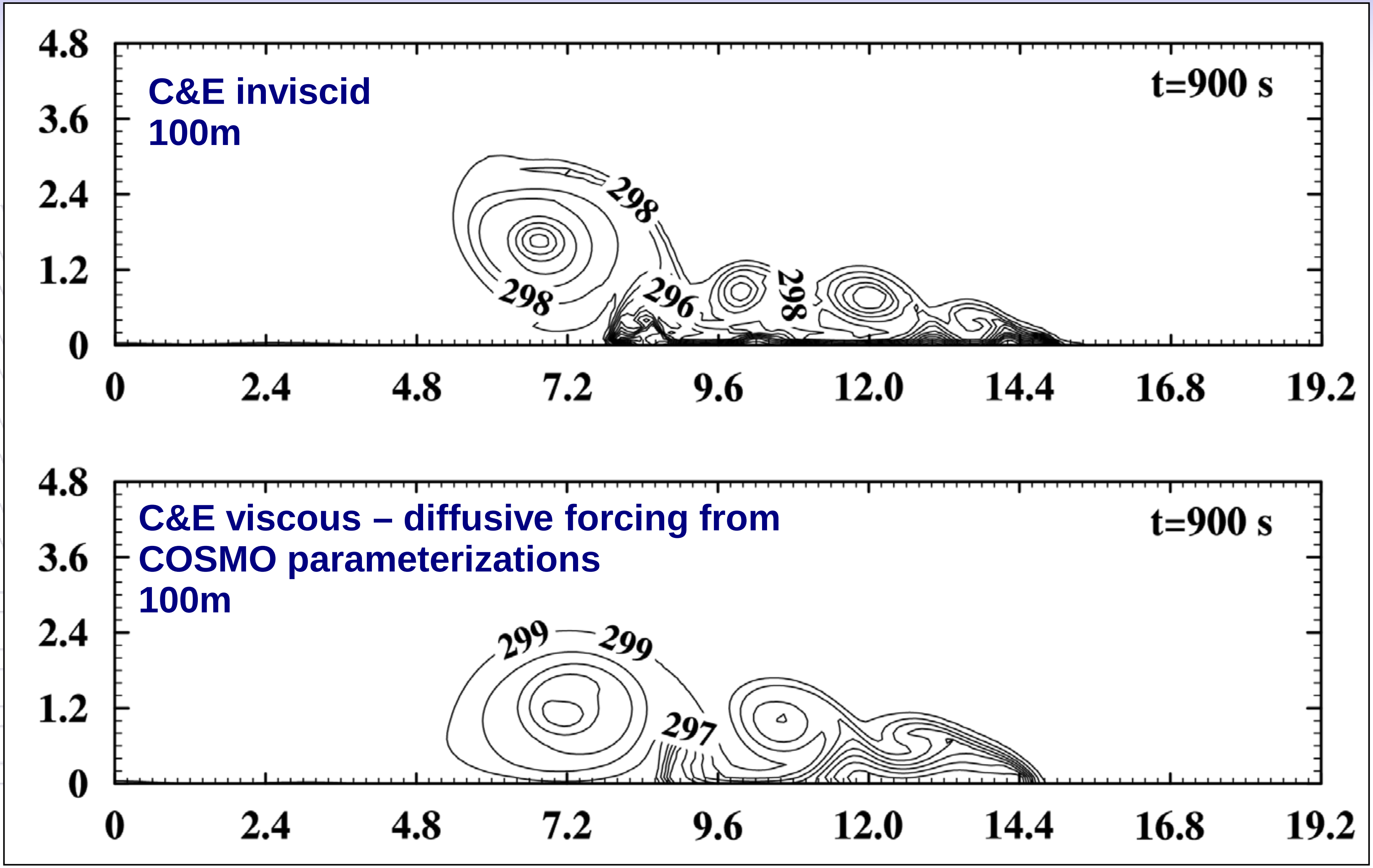
Straka, J. M., Wilhelmson, Robert B., Wicker, Louis J., Anderson, John R., Droegemeier, Kelvin K., Numerical solutions of a non-linear density current: A benchmark solution and comparison *International Journal for Numerical Methods in Fluids*, (**17**), 1993

Experiment configuration:

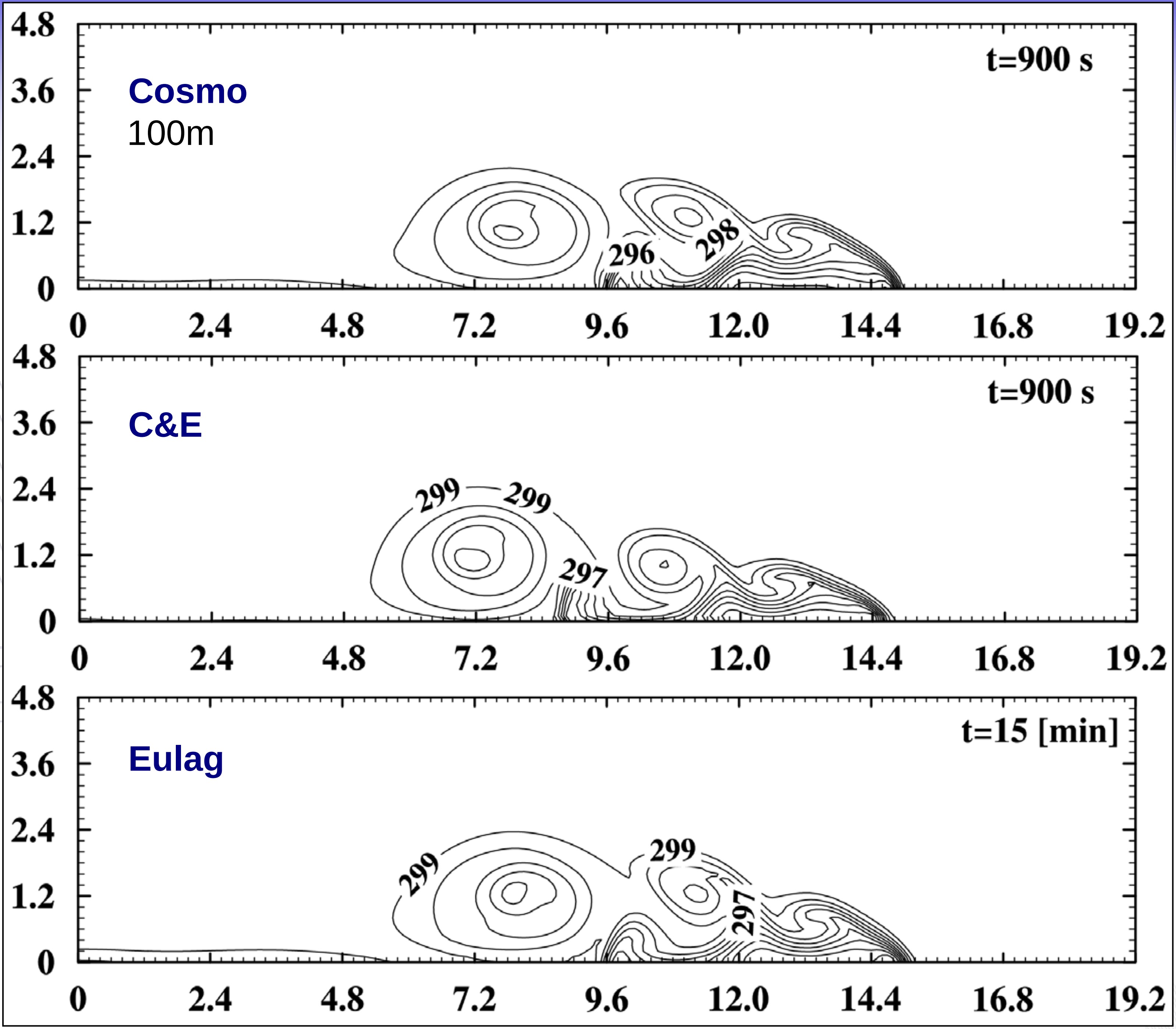
- isentropic atmosphere, $\theta(z)$=const (300K)
- periodic lateral boundaries
- free-slip bottom b.c.
- constant subgrid mixing, $K=75m^2/s$
- domain size 51.2km x 6.4km
- bubble min. temperature -15K
- bubble size 8km x 4km
- no initial flow
- integration time 15 mins



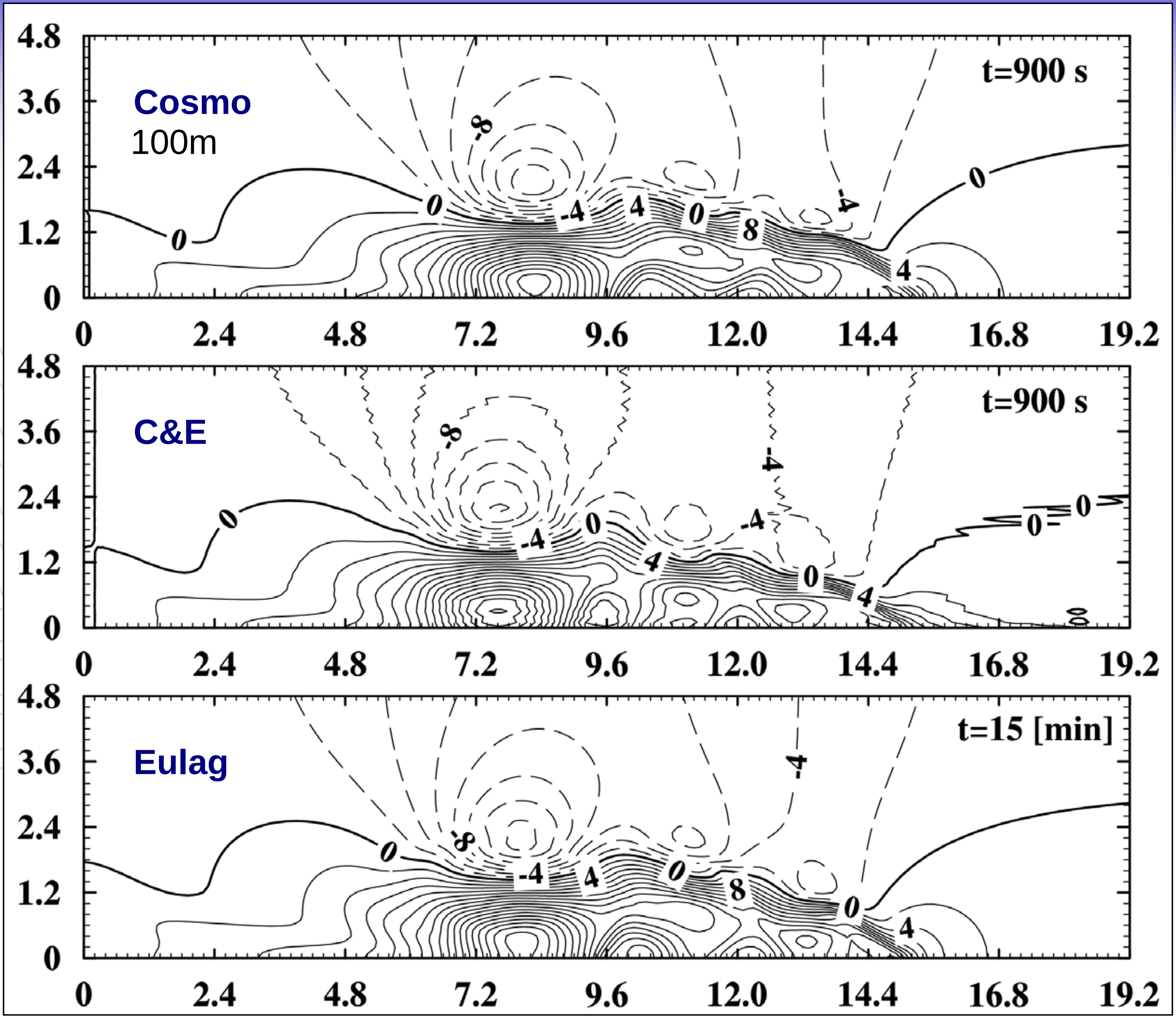
Distribution of potential temperature after 900 sec



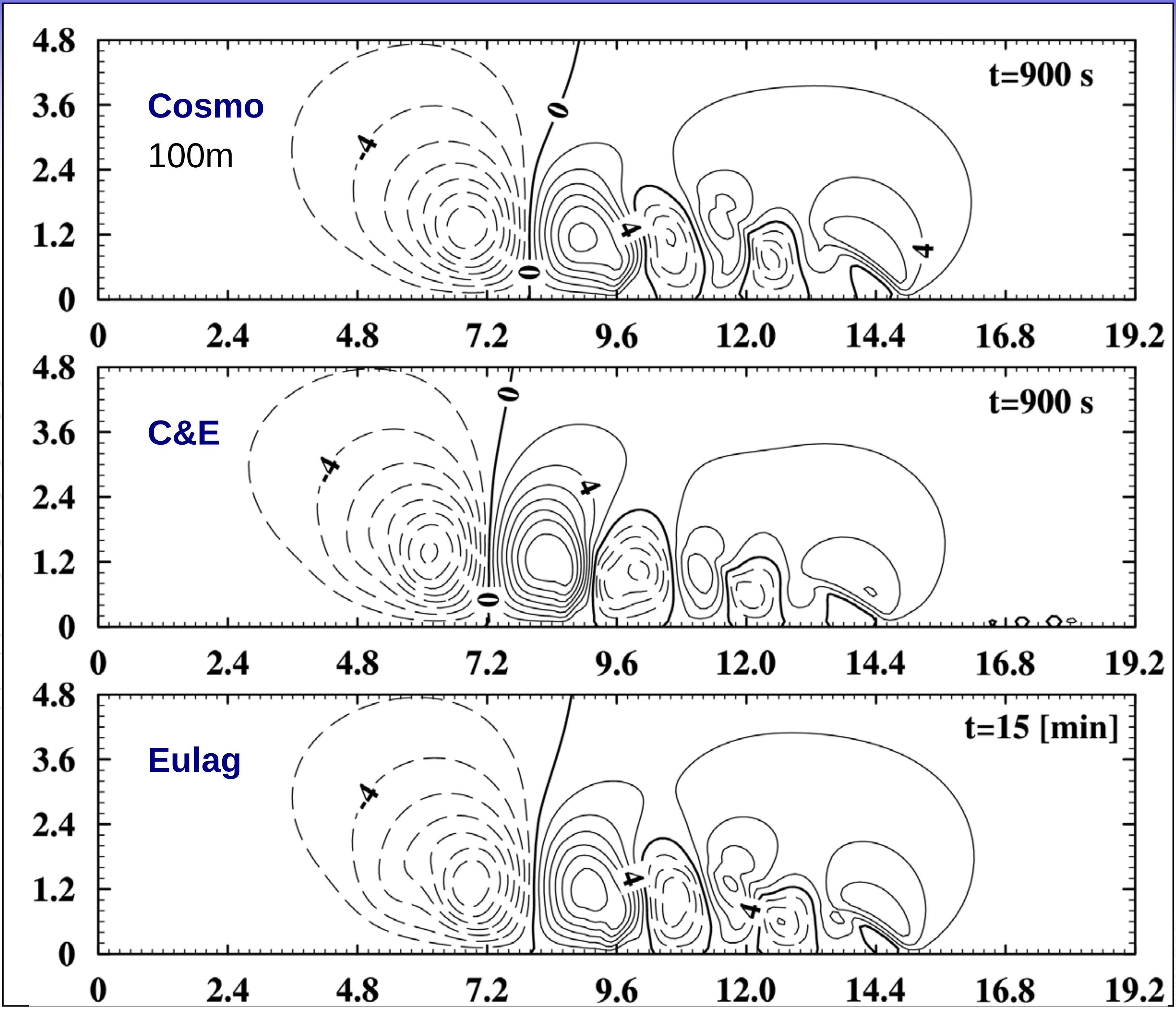
Comparison of the potential temperature distribution



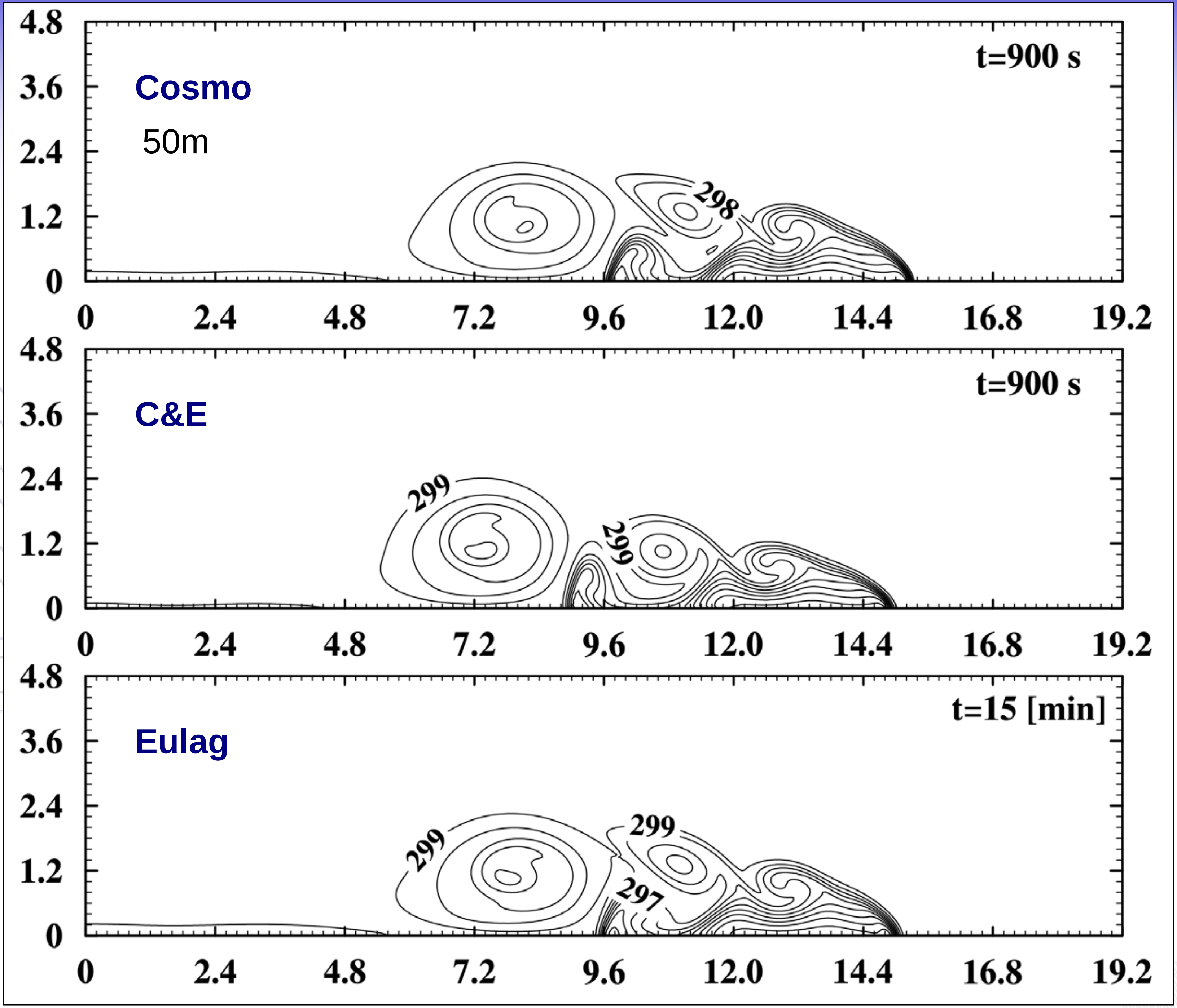
Comparison of the horizontal velocity distribution



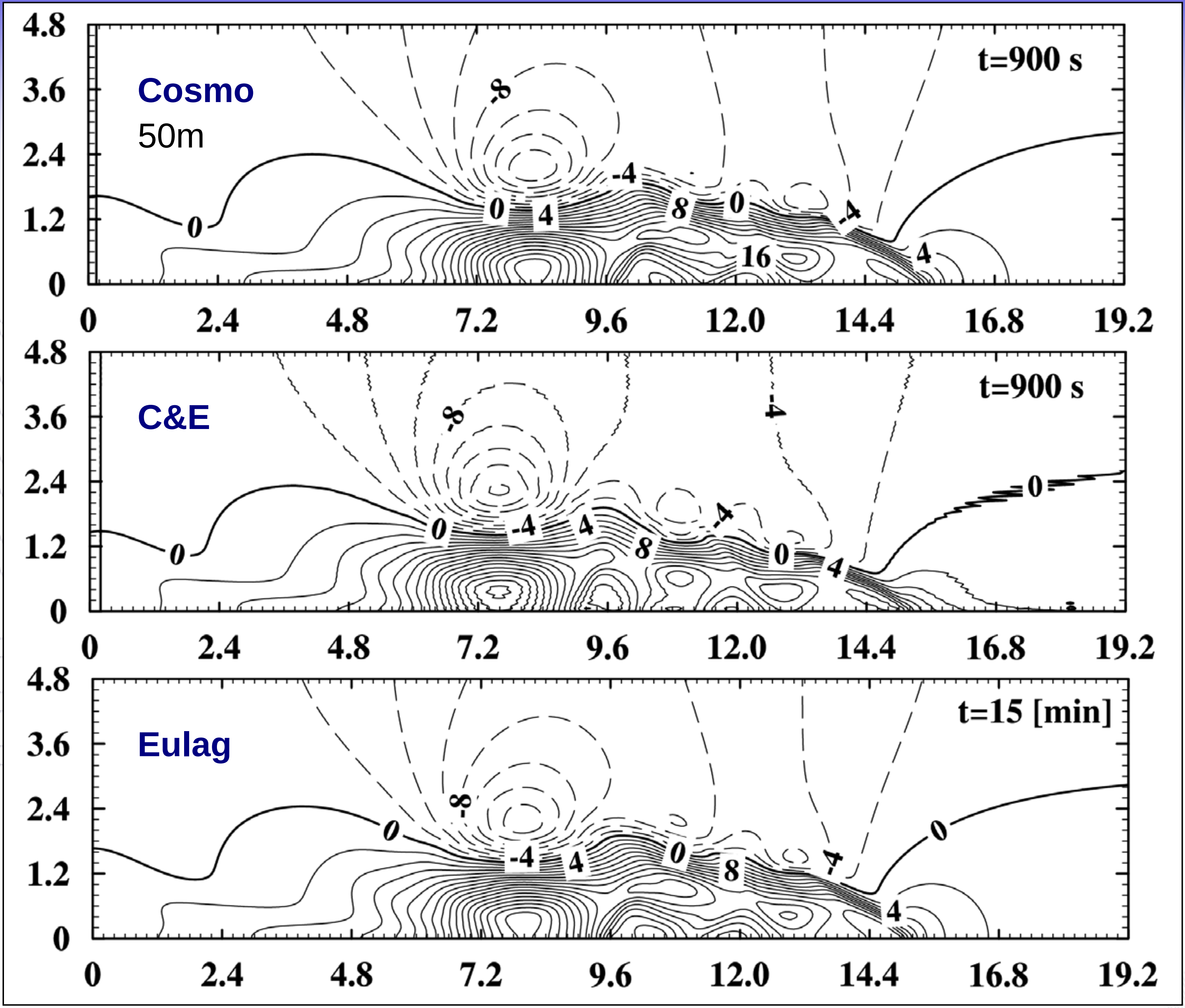
Comparison of the vertical velocity distribution



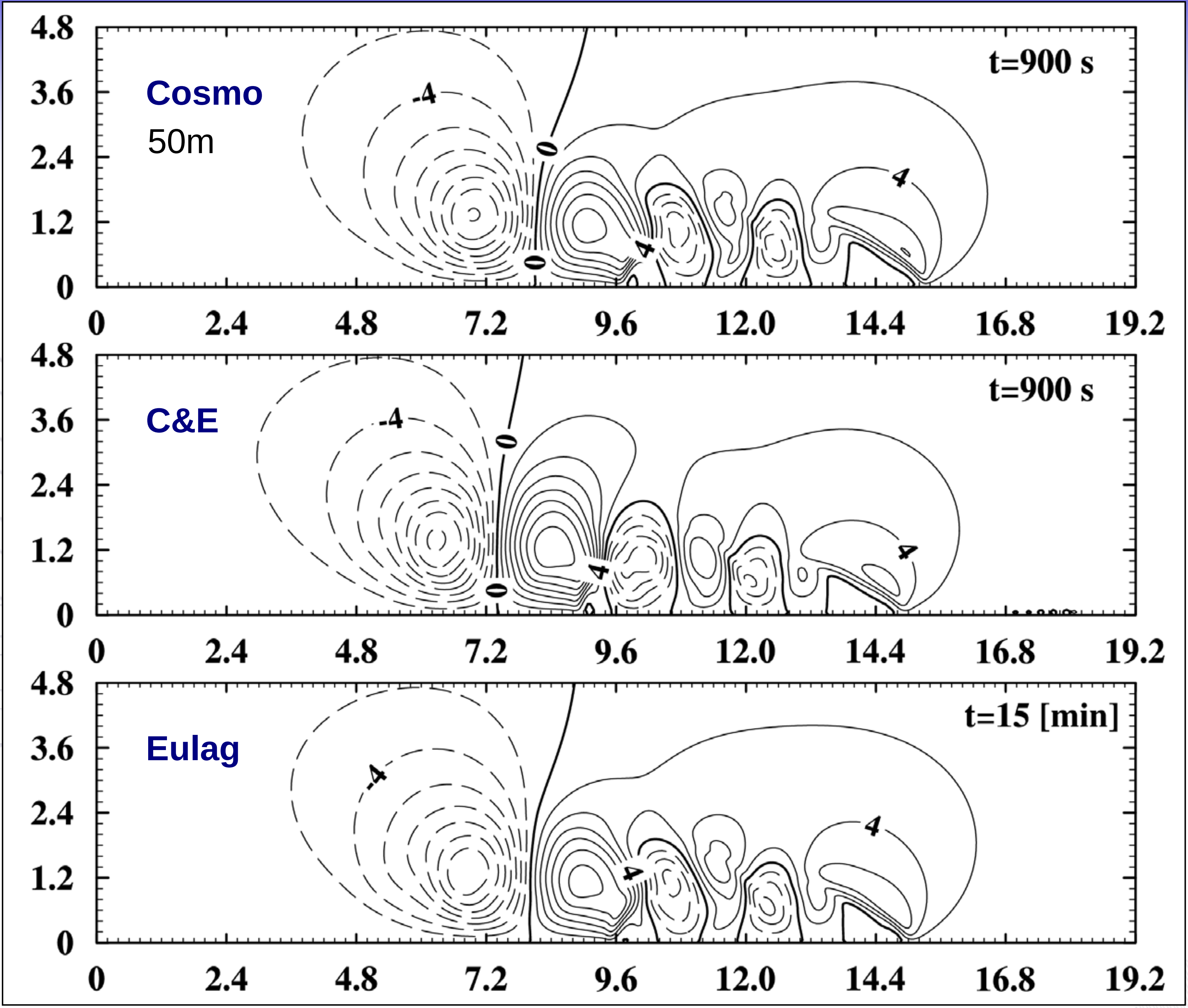
Comparison of the potential temperature distribution at resolution 50 m



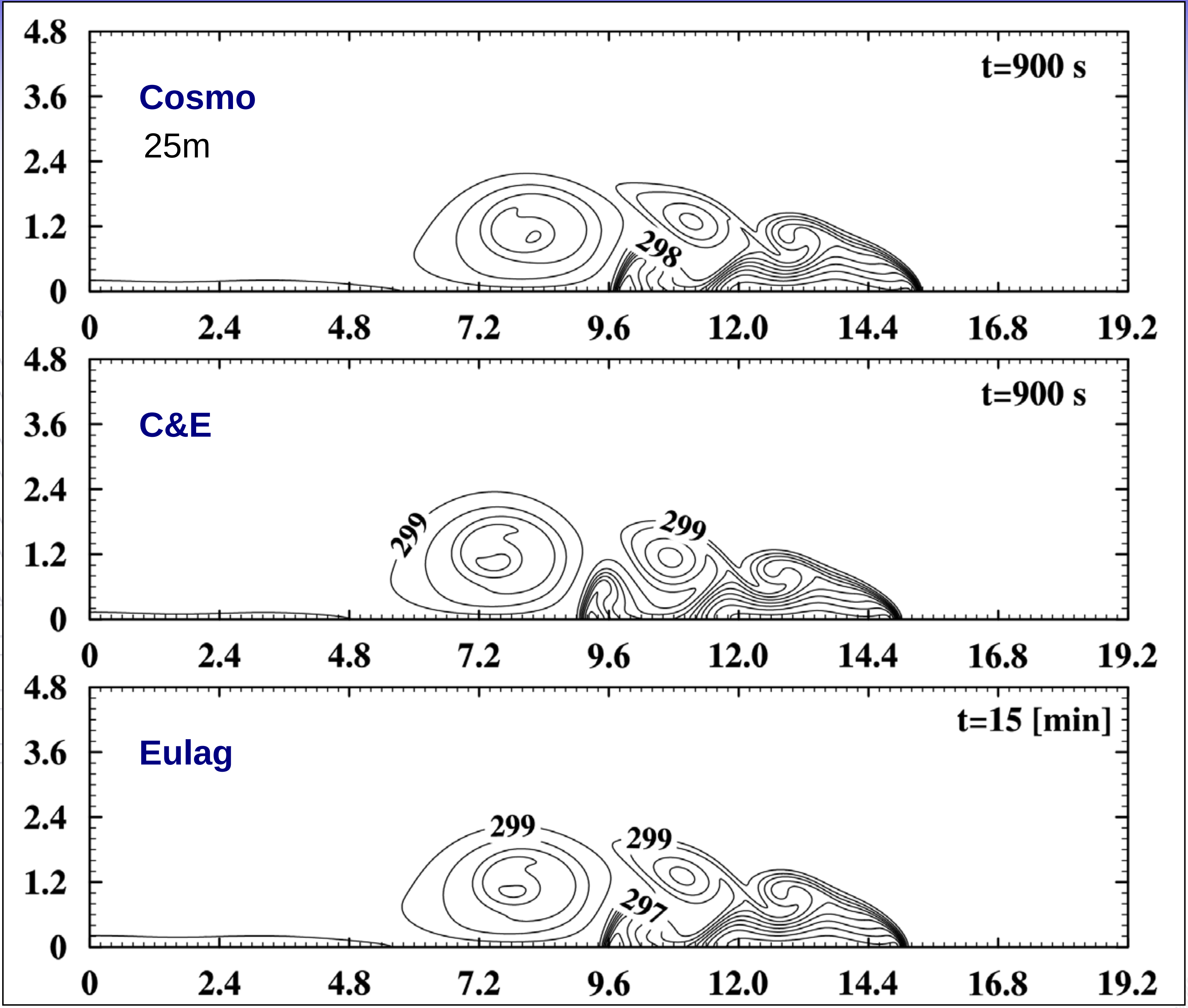
Comparison of the horizontal velocity distribution at resolution 50 m



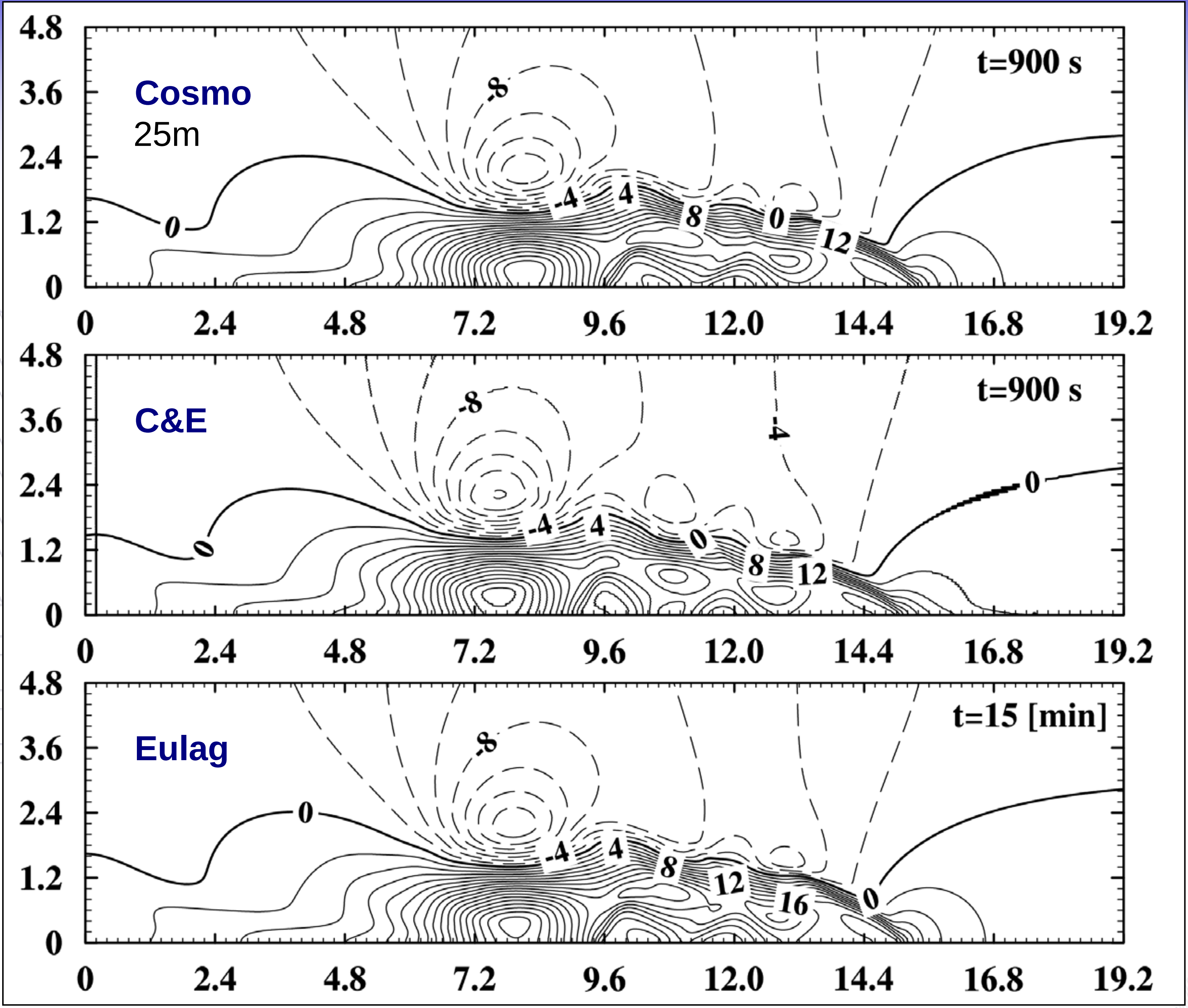
Comparison of the vertical velocity distribution at resolution 50 m



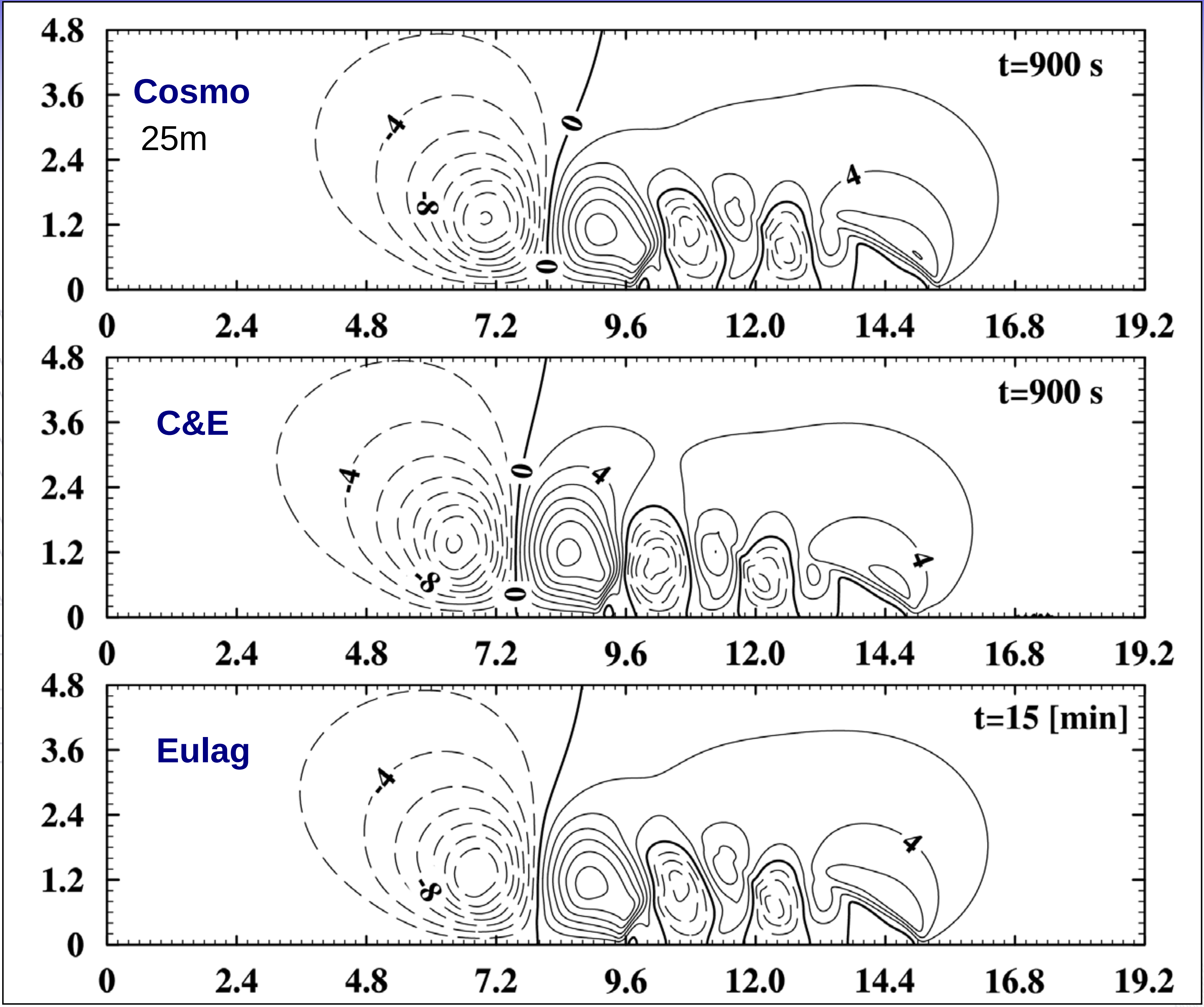
Comparison of potential temperature distribution at resolution 25 m



Comparison of horizontal velocity distribution at resolution 25 m



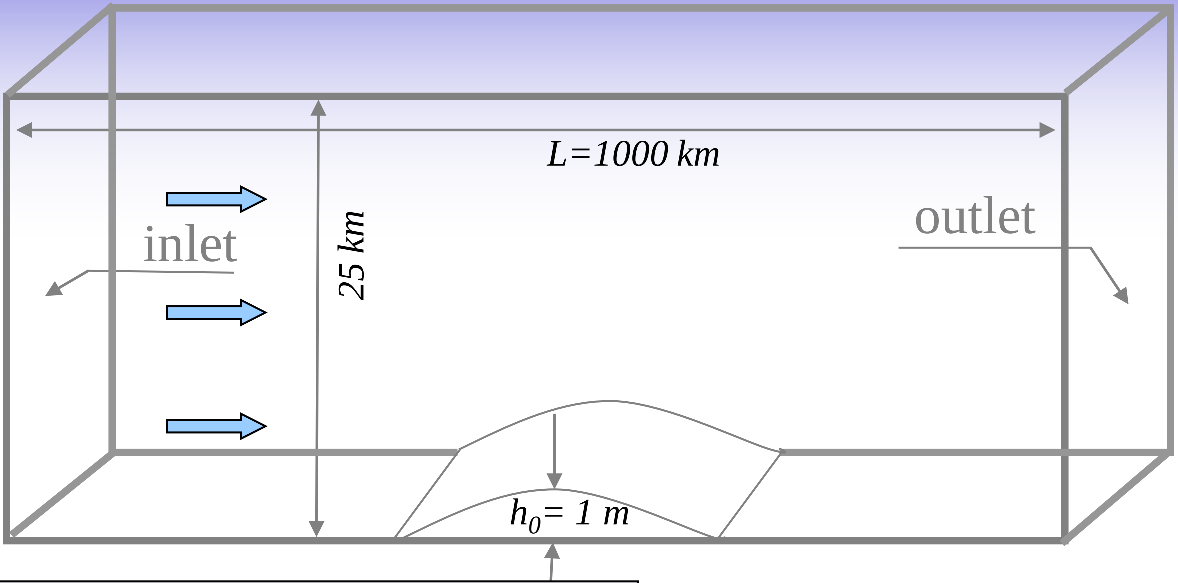
Comparison of vertical velocity distribution at resolution 25 m



Experiment 3

1. *Linear Gravity waves (Skamarock, Klemp (1994), Giraldo (2008))*
2. *Cold bubble (Straka et al. (1993)) (unstationary density flow)*
3. *Mountain flow tests (stationary, orographic flows) Bonaventura (2000) JCP requires terrain following coordinates*

Setup of the 3D simulation of hydrostatic waves generated in stable air passing over mountain.



Profile of the 3D mountain
Agnesi formula.

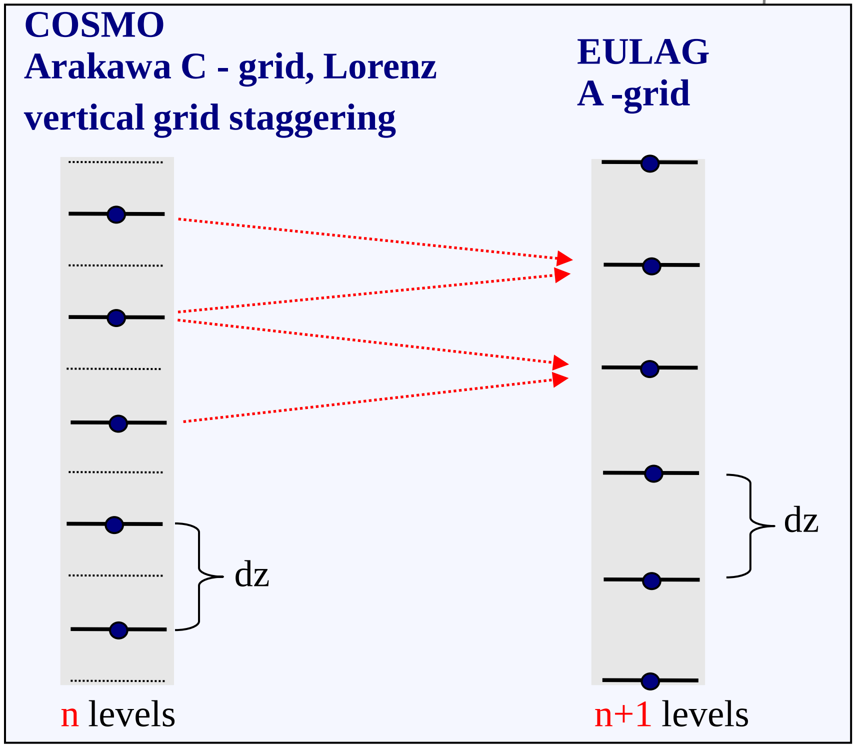
$$h(x)=\frac{h_0}{1+\left(\left(x-x_0\right)/a\right)^2},$$

$$0\le x\le L$$

$$a=16\,km$$

$$h_0N/U<<1$$

$$N=0.0187s^{-1}$$



COSMO
Arakawa C - grid, Lorenz vertical grid staggering

EULAG
A -grid

$$\theta(z)=\theta_0 e^{\frac{N^2}{g}z}$$ Clark-Farley formula

$$\rho(z)=\rho_0 e^{\frac{N^2}{g}z}\left(1-\frac{g^2}{C_p\theta_0 N^2}\right)^{\frac{Cv}{Rg}}$$ where

$$C_p=1004\,Jkg^{-1}K^{-1}$$

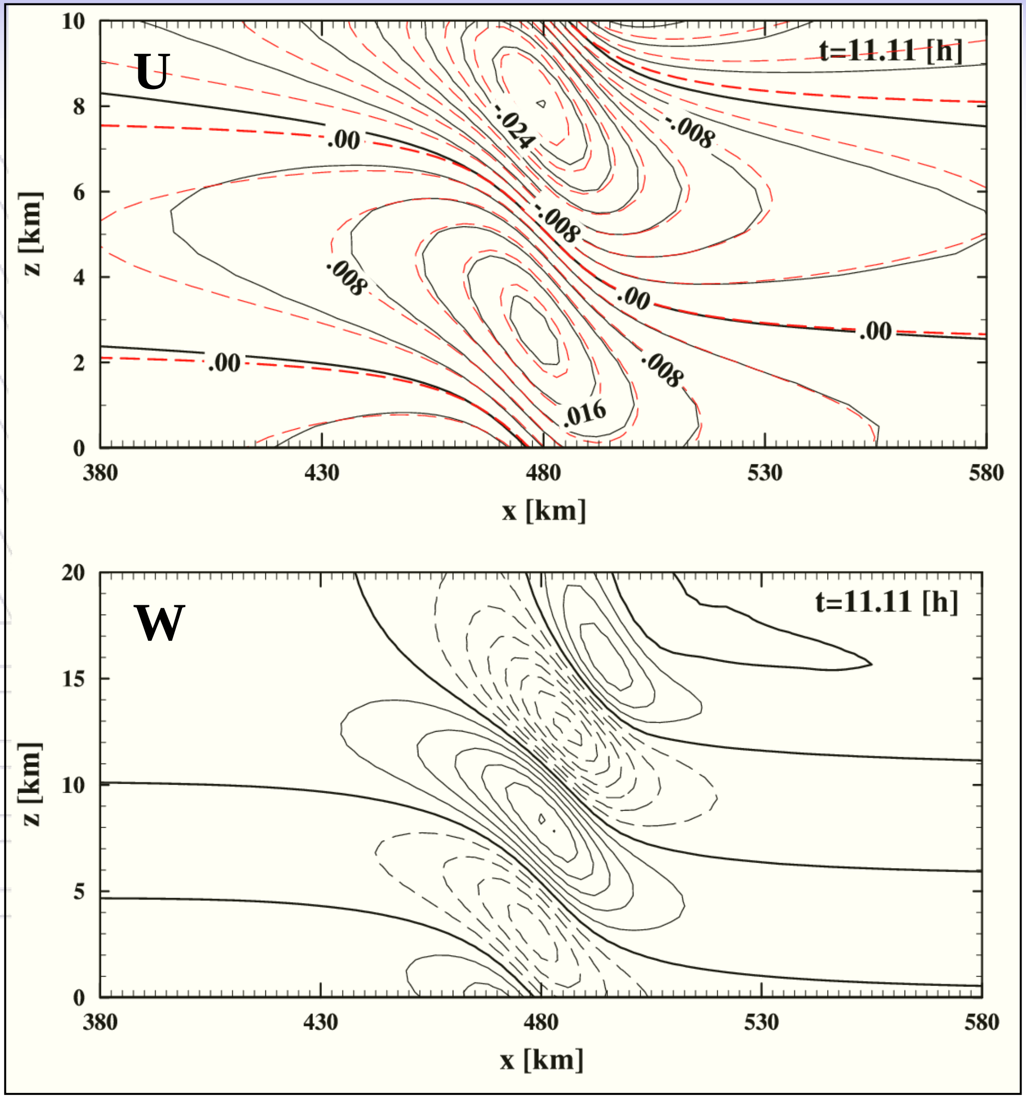
$$C_v=717\,Jkg^{-1}K^{-1}$$

$$Rg=287\,Jkg^{-1}K^{-1}$$

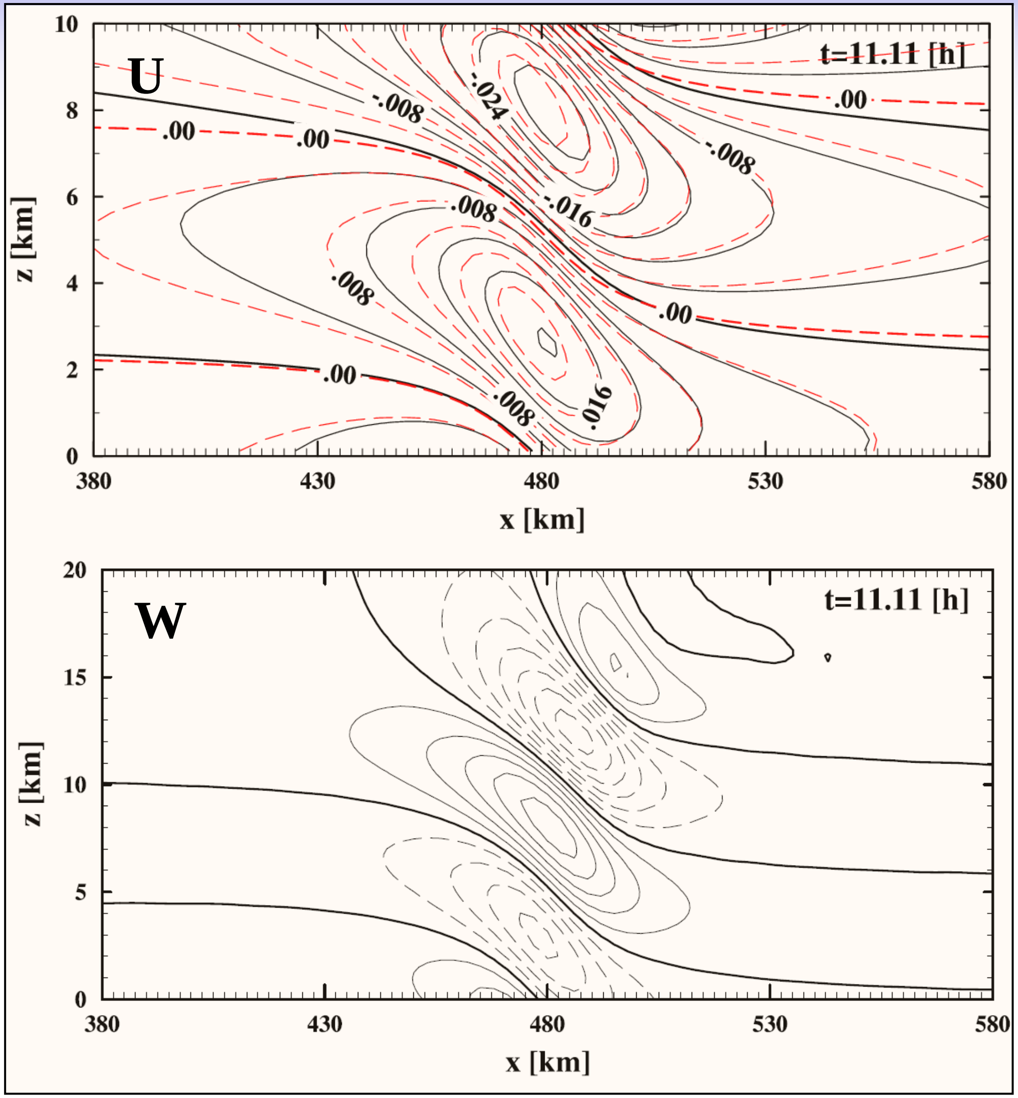
- Linear hydrostatic regime
- Initial horizontal velocity U = 32 m/s
- Grid resolution Δx = 3km, Δz = 250 m
- Time step size Δt = 40 s
- Terrain following coordinates
- Profiles of vertical and horizontal sponge zones from Pinty et al. (MWR 1995)

Linear hydrostatic regime

EULAG 2D



C&E 3D



Analytical solution in linear hydrostatic regime developed by Klemp and Lilly (JAS. 1978)

$$u(x,\theta) = Nh_0\gamma e^{C_p\theta/2R}\frac{\{\gamma x-(1-C_p/2R)\}\cos\gamma\theta+\{\gamma+(1-C_p/2R)x\}\sin\gamma\theta}{\{\gamma^2+(1-C_p/2R)^2\}x^2}$$

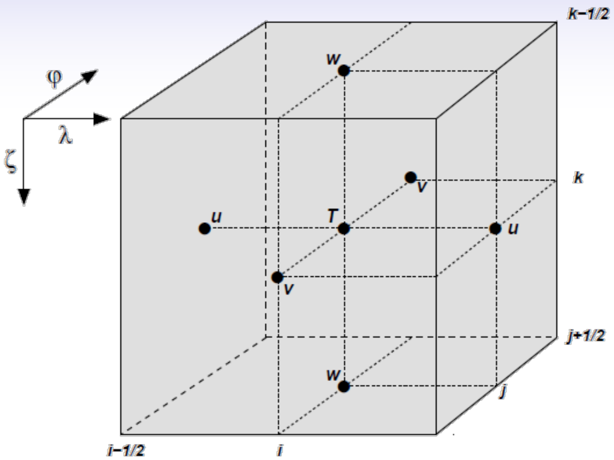
where $\gamma = \frac{\mathbf{g}}{N\bar{u}}$, $\theta = \ln(\vartheta/\vartheta_0)$, ϑ_0 is surface level potential temperature

Linear hydrostatic regime

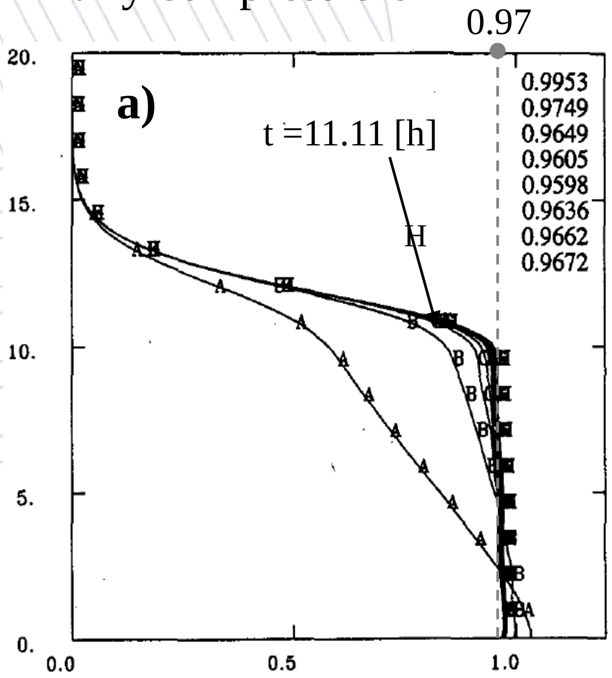
Normalized vertical flux for the hydrostatic linear case. $\left\langle \rho \left(u-\langle u\rangle\right)\left(w-\langle w\rangle\right)\right\rangle$

The flux normalized by linear analytic solution from (Klemp and Lilly JAS. 1978)

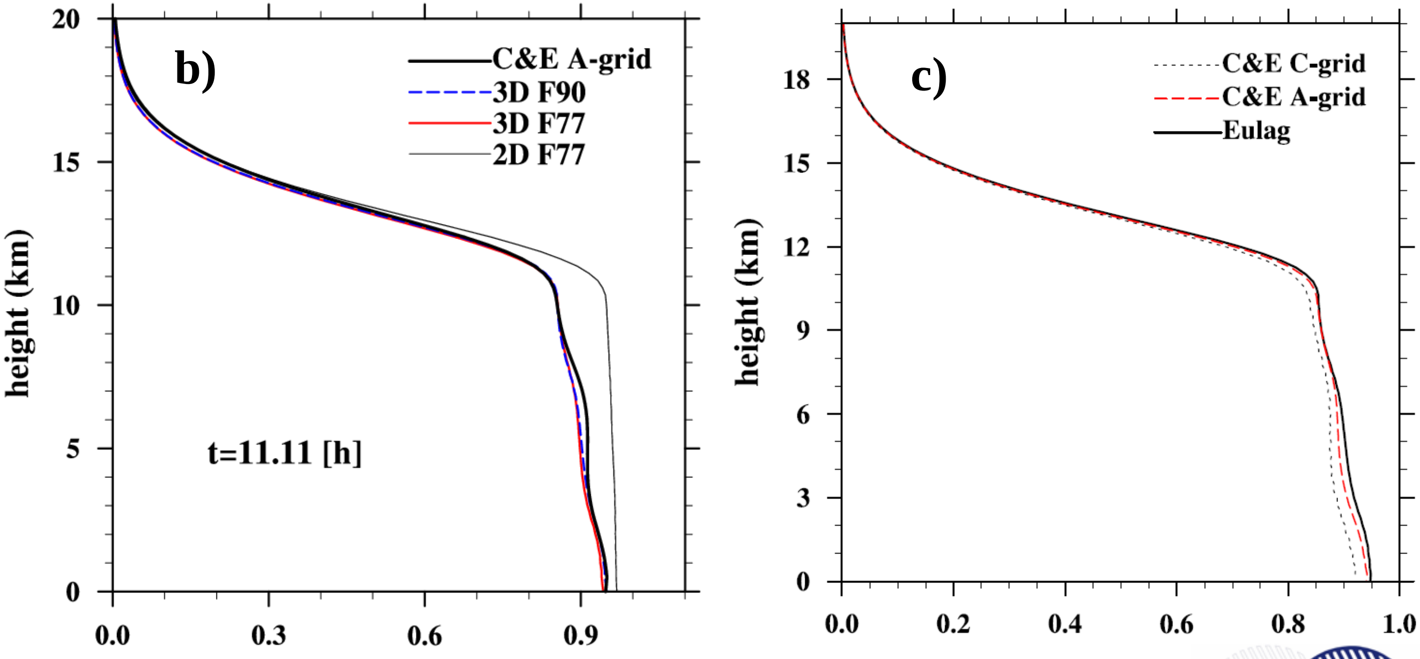
$$M_{analitic} = (\pi/4)\rho_0 h_0^2 \frac{g\gamma}{\gamma^2 + \left(1-\frac{C_p}{2R}\right)^2} \approx (\pi/4)\rho_0 N\bar{u} h_0^2$$



Pinty et al. (MWR. 1995)
fully compressible

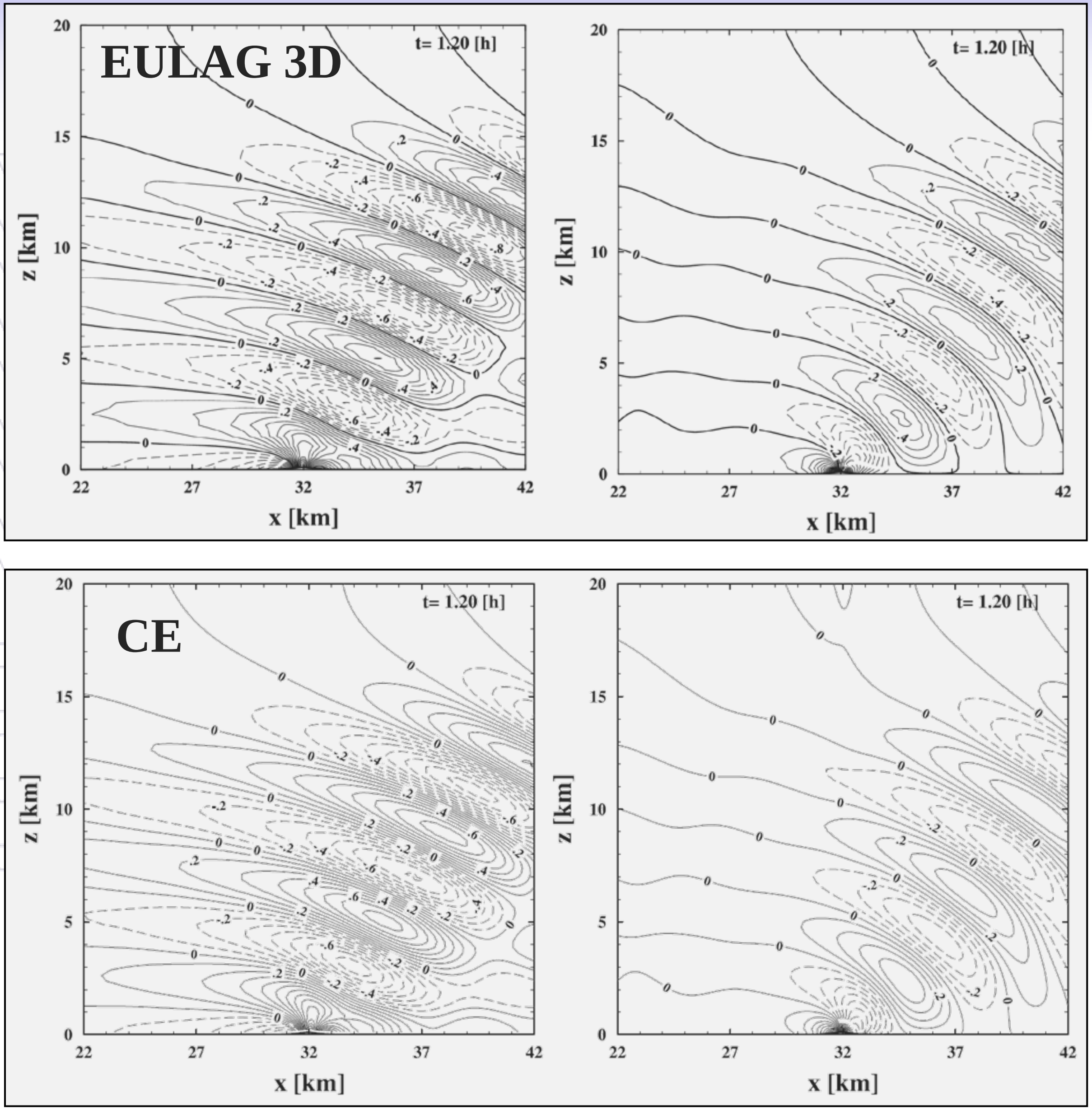


Current study



Linear non-hydrostatic regime

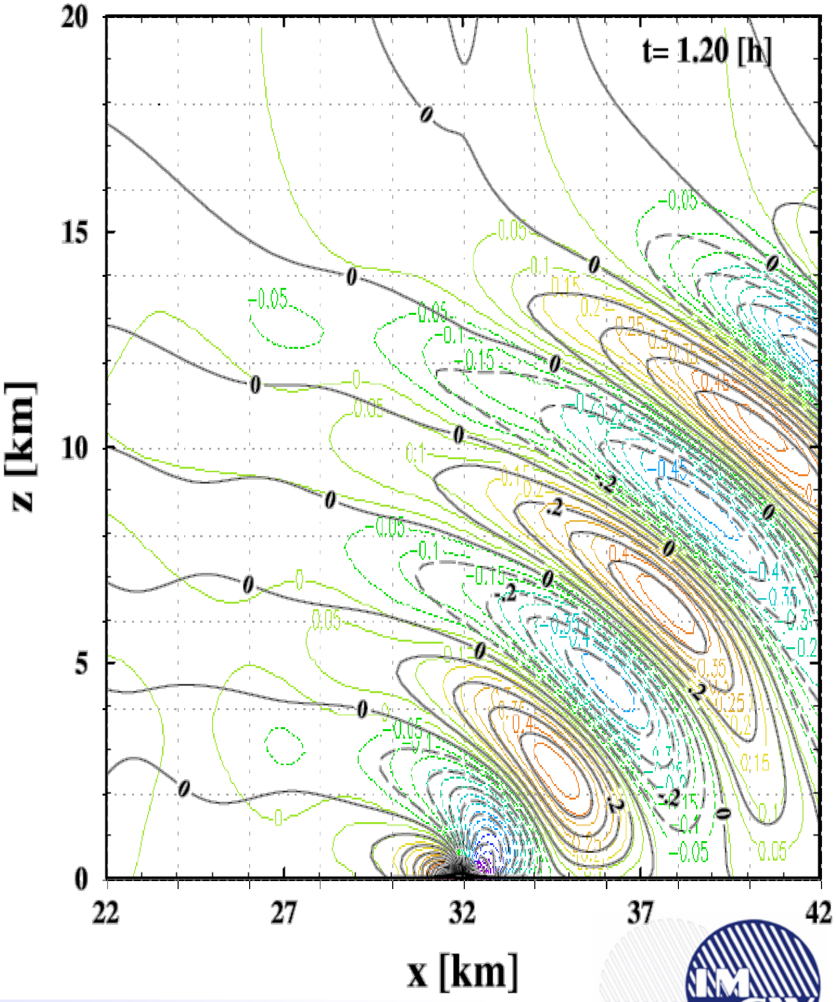
Horizontal velocity **Vertical velocity**



$a = 500\,m \quad h_0 = 100\ m \qquad aN/U \approx 1$

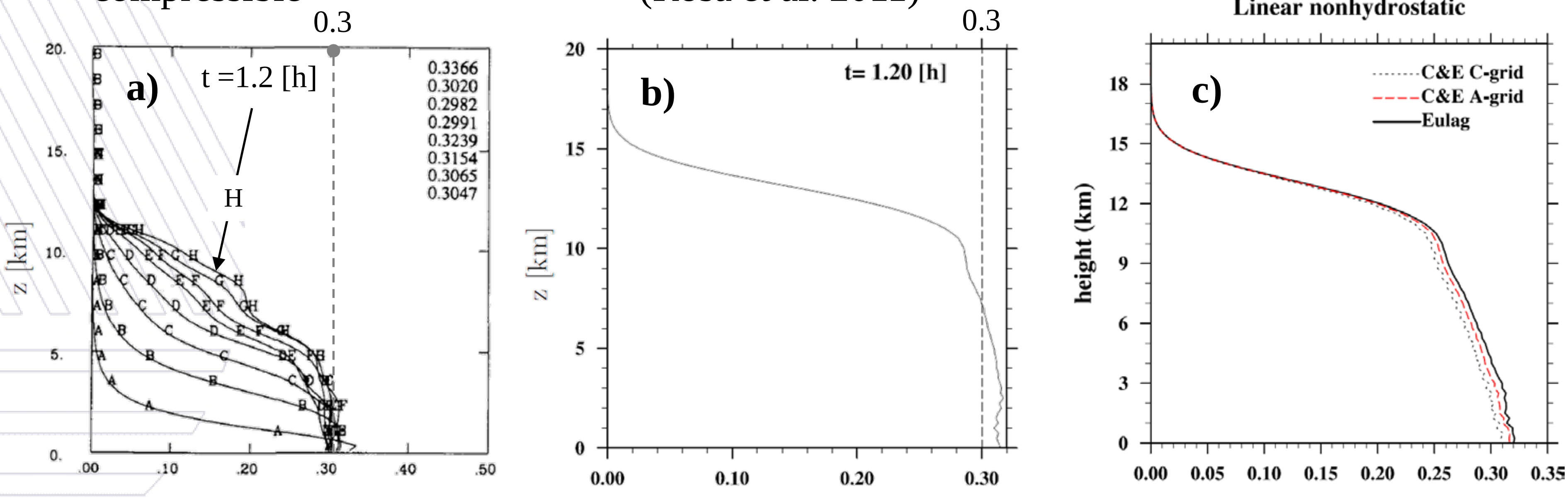
Initial horizontal velocity U = 14 m/s
Grid resolution Δx = 100 m, Δz = 250 m
Time step size Δt = 4 s

CE - COSMO



Linear non-hydrostatic regime

Normalized vertical flux for the non-hydrostatic linear case.



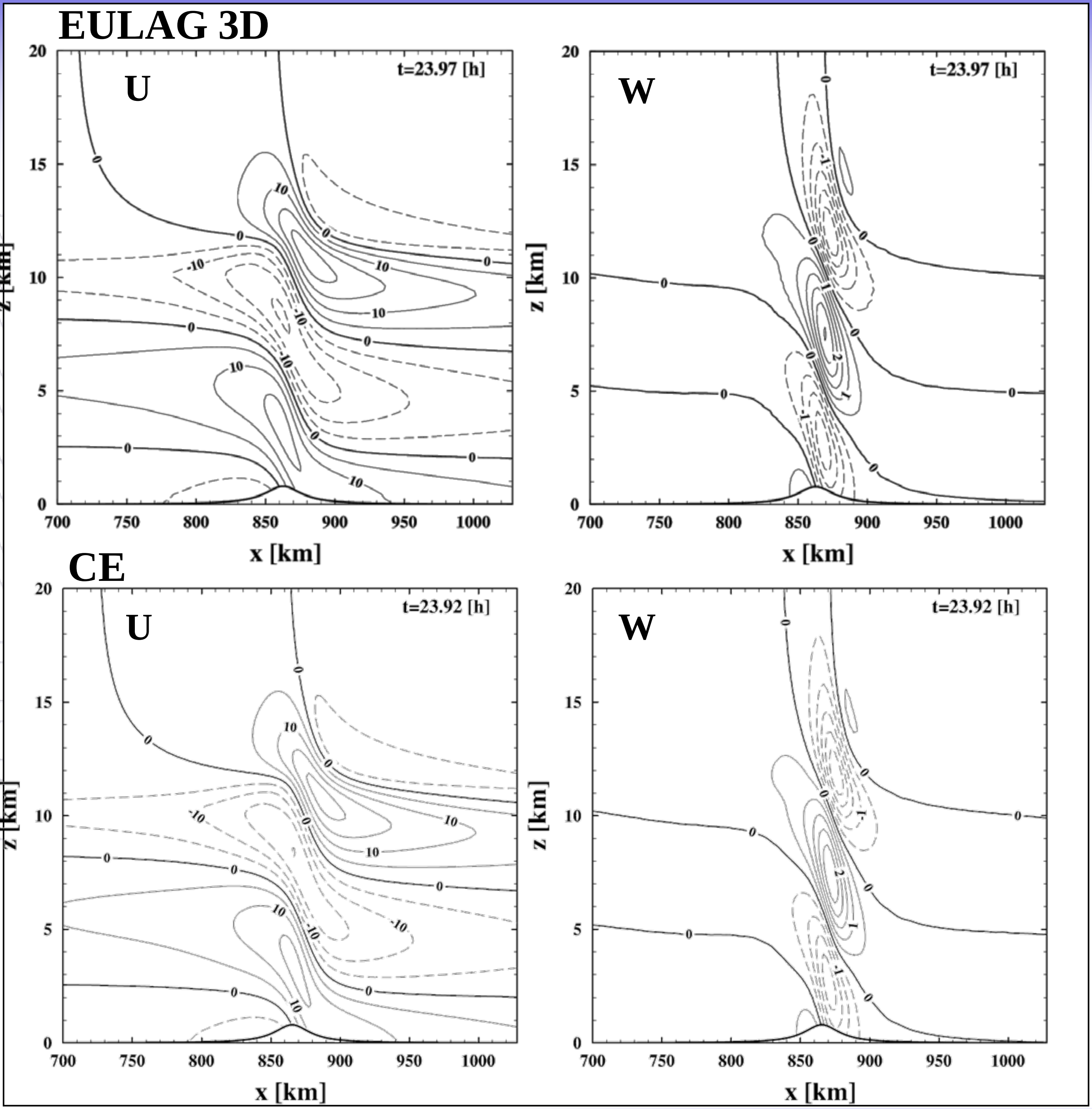
Pinty et al. (MWR. 1995) compressible

EULAG anelastic (Rosa et al. 2011)

CE 3D (2012) anelastic

The flux normalized by linear analytical solution from (Klemp and Lilly JAS. 1978)

Non-linear hydrostatic regime



$a = 16km$

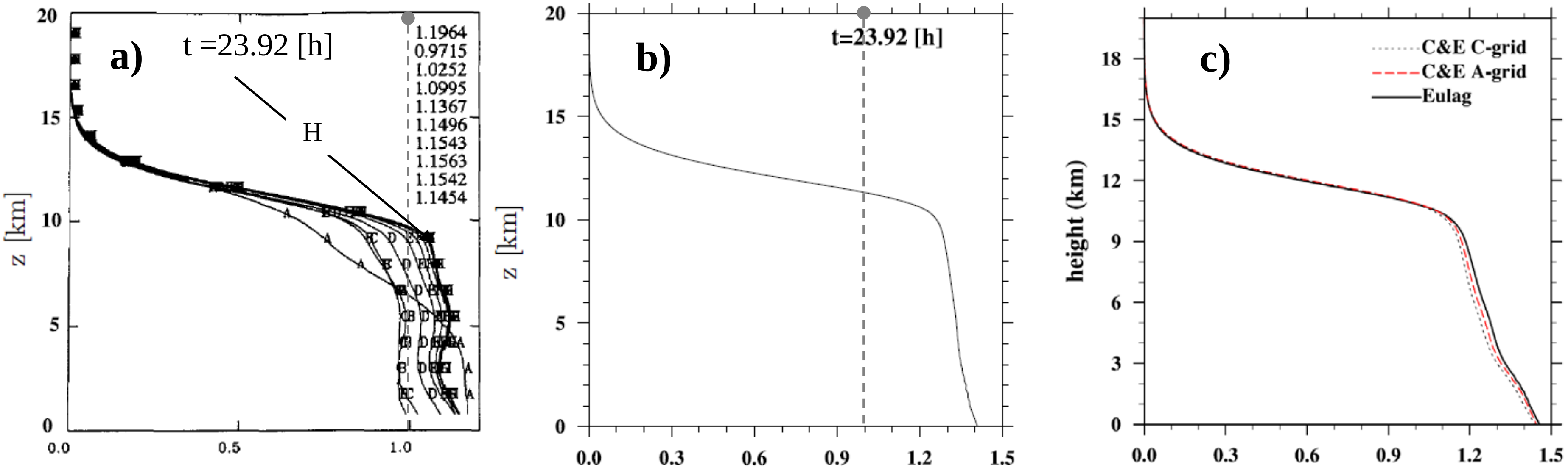
$h_0 = 800\ m$

Initial horizontal velocity U = 32 m/s

Grid resolution:
Δx = 2.8 km,
Δz = 200 m

Time step size
Δt = 30 s

Non-linear hydrostatic regime



Pinty et al. (MWR. 1995)
fully compressible

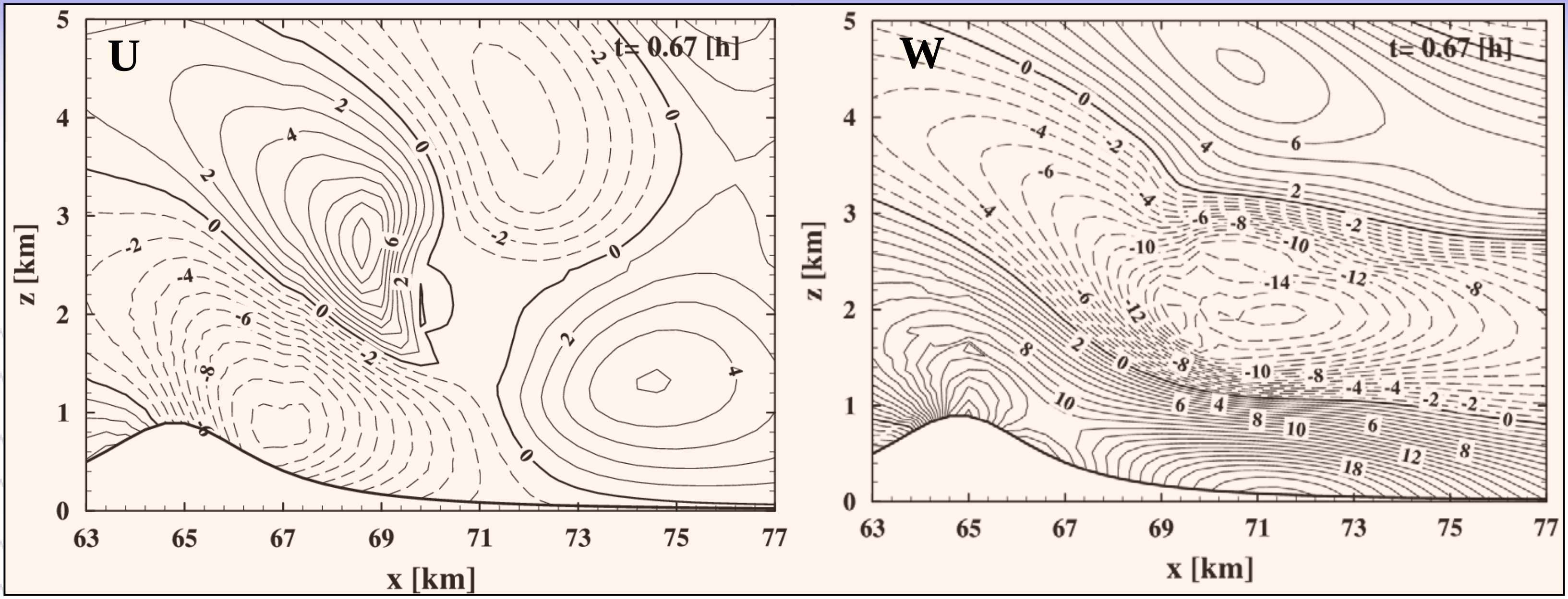
EULAG (2009)
anelastic

CE 3D (2012) anelastic

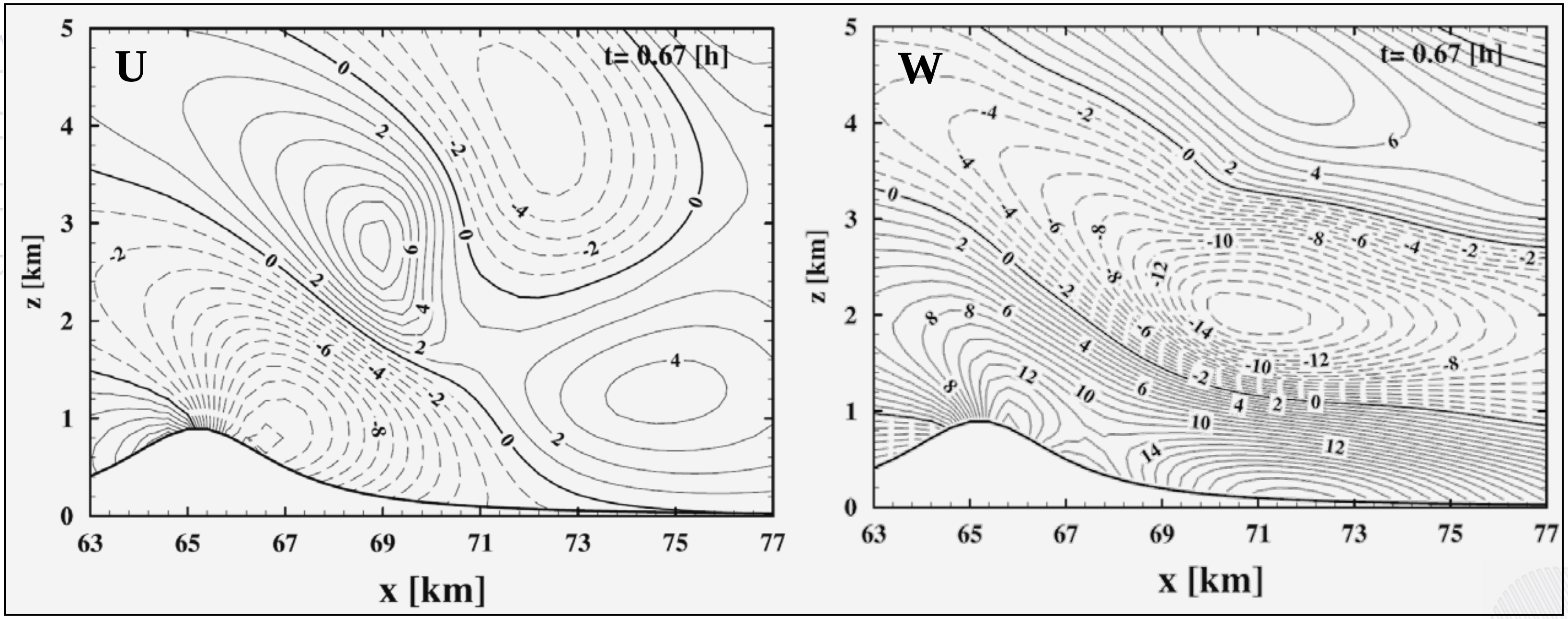
The flux normalized by linear analytic solution from (Klemp and Lilly JAS. 1978)

Non-linear non-hydrostatic regime

EULAG 3D



CE



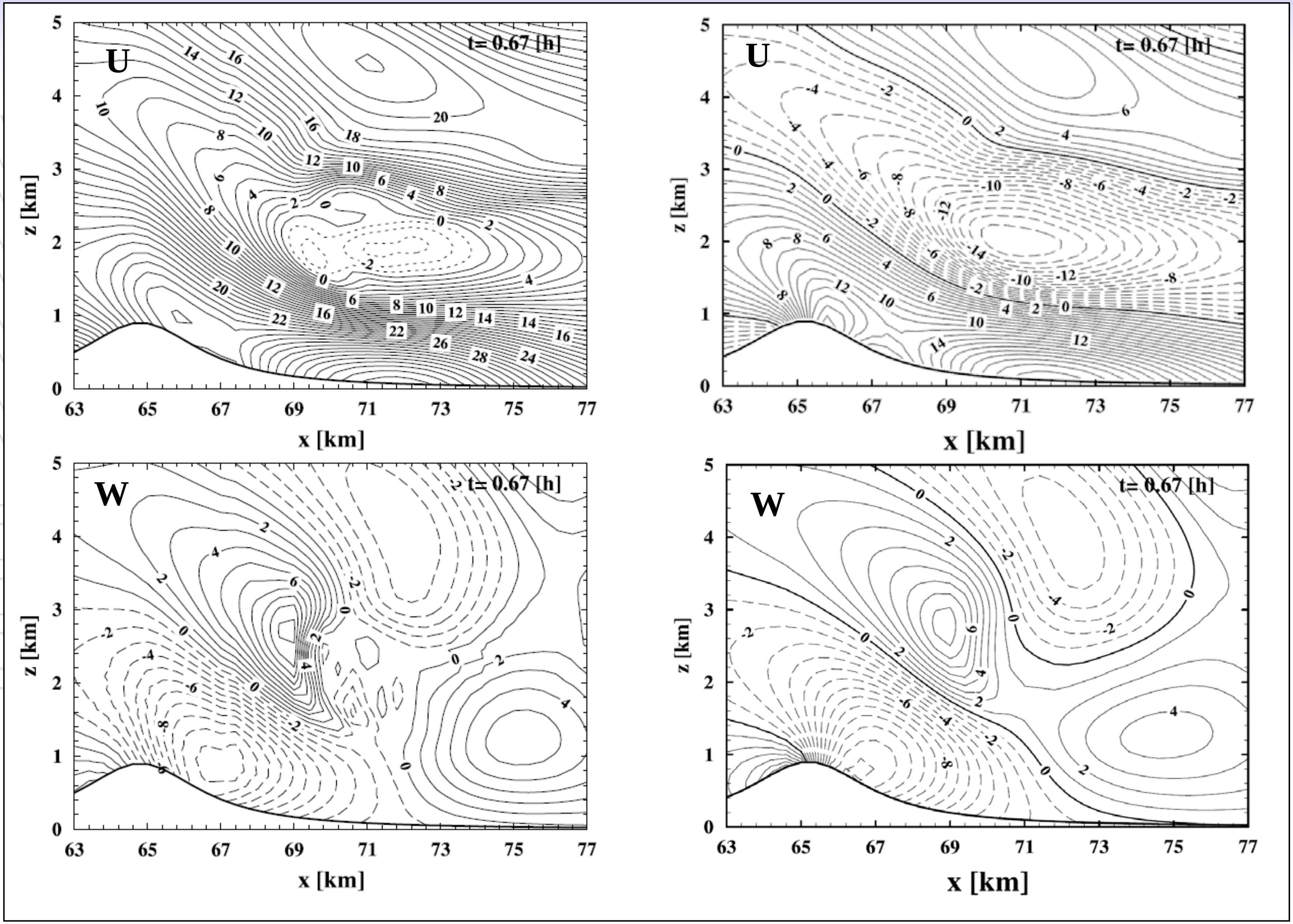
$a = 1 km$

$h_0 = 900$ m

$U = 13.28$ m/s

Non-linear non-hydrostatic regime

EULAG 2D Rosa et al. 2011 **CE 3D current study**



CONCLUSIONS

- EULAG has been successfully implemented into the COSMO model as the new conservative dynamical core.

- Developing of the hybrid model impossed a number of problems associated with coupling:
  - computational mesh
  - terrain following coordinates
  - Coriolis force
  - COSMO parameterizations (constant diffusion)

- Results of the idealized tests obtained using the hybrid CE model are in good qualitative and quantitative agreement both with reference and analytical solutions.

- Small differences indicate the need for further testing and verification of the CE code.