Universitat de les Illes Balears

Grup de Meteorologia

TRAM
(Triangle-based Regional Atmospheric Model)

A New Nonhydrostatic Fully Compressible Numerical Model

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COASTEPS

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EUROPEAN UNION
EUROPEAN REGIONAL DEVELOPMENT FUND
"A way to make Europe"

MOTIVATION

> WHY NOT our own model ? (e.g. GLOBO-BOLAM-MOLOCH)

> Mostly for RESEARCH and ACADEMIC purposes, but potentially for "FORECASTING" as well

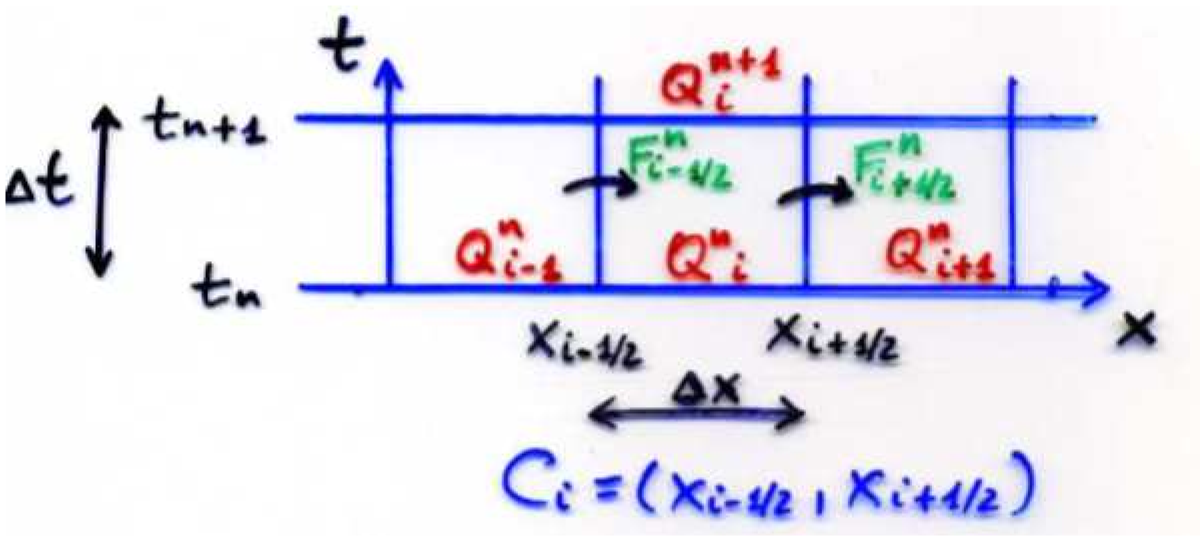
> Aimed at MESOSCALE applications and IDEALIZED experiments(high resolution and regional contexts), although naturally suited to SYNOPTIC scale

> The new numerical model must necessarily involve ORIGINAL aspects and pass some benchmark TESTS

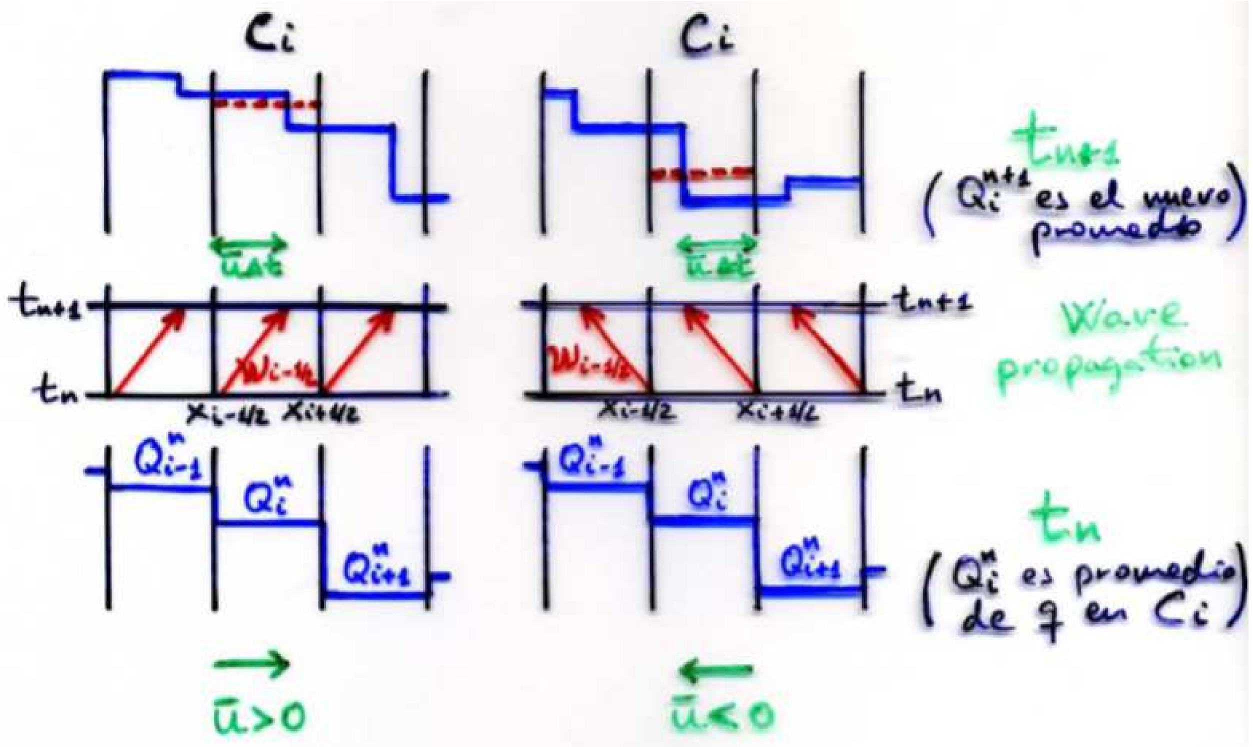
> $\partial_t q = -\bar{u}\,\partial_x q$ **expressed in flux form is** $\partial_t q = -\partial_x(\bar{u}\,q)$

> **The new cell average** Q_i^{n+1} **would be approximated as**

$$Q_i^{n+1} = Q_i^n - \frac{\Delta t}{\Delta x}\left(F_{i+1/2}^n - F_{i-1/2}^n\right)$$



> **REA (Reconstruct-Evolve-Average) point of view**



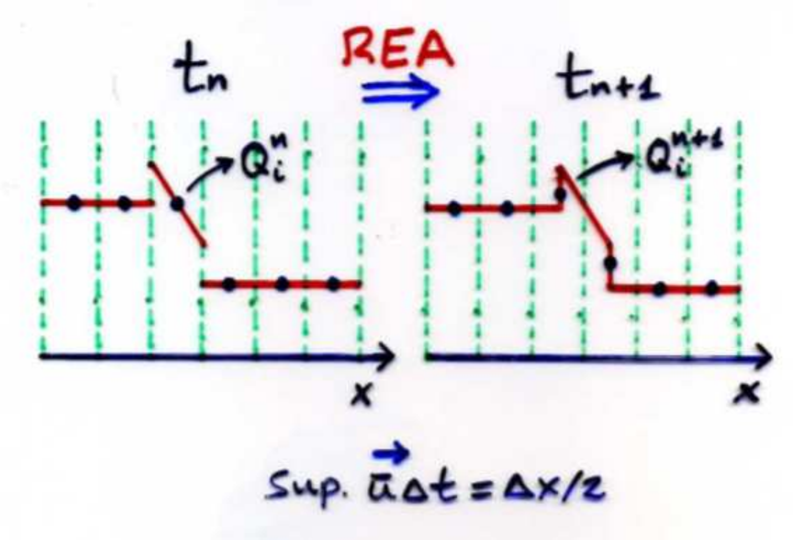
> **Classical choices for the slopes**

$$\sigma_i^n = 0$$
UpWind

$$\sigma_i^n = \frac{Q_{i+1}^n - Q_i^n}{\Delta x}$$
LW

$$\sigma_i^n = \frac{Q_i^n - Q_{i-1}^n}{\Delta x}$$
BW

$$\sigma_i^n = \frac{Q_{i+1}^n - Q_{i-1}^n}{2\Delta x}$$
Fromm



> **Slope-Limiter methods**

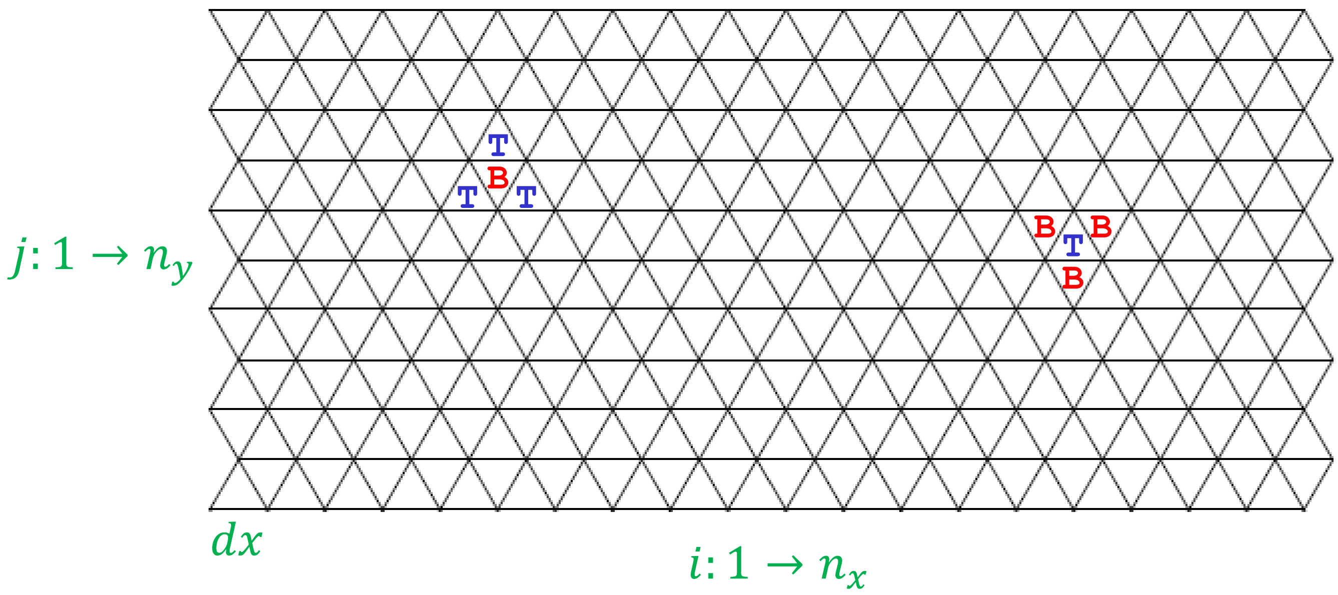
$$\sigma_i^n = minmod\binom{LW}{BW} \qquad \sigma_i^n = minmod\begin{pmatrix} 2\,LW \\ 2\,BW \\ Fromm \end{pmatrix} \qquad \sigma_i^n = maxmod\begin{pmatrix} minmod\binom{LW}{2\,BW} \\ minmod\binom{2\,LW}{BW} \end{pmatrix}$$

Minmod *MC* *Superbee*

> **REA also for** $\partial_t q = -\boldsymbol{u}\partial_x q$ **(e.g.** $q = u$**) using** $U_{i+1/2}^n = \frac{U_i^n + U_{i+1}^n}{2}$

> **Linear profile for wind within cell:** $x' = U_{i+1/2}^n + Ax$

> Triangular-based mesh



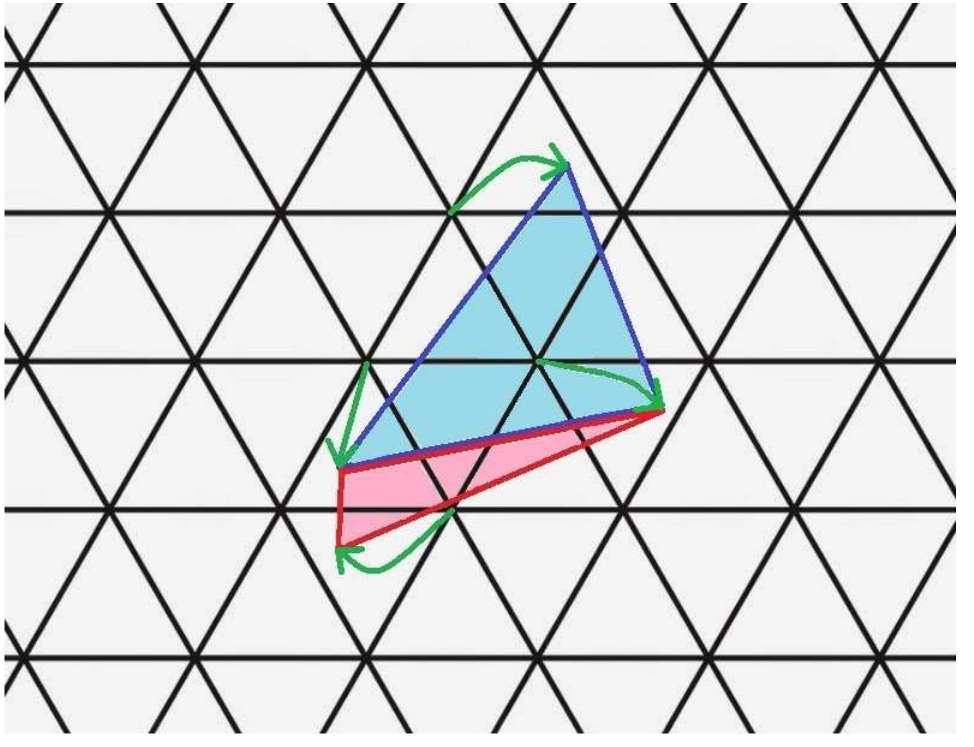
> Actual resolution (square-based domain) is $\approx \frac{2}{3} dx$

> All variables defined at triangle barycenters: T_{ij} B_{ij}

> 1st derivatives (slopes) at T/B from neighbor B/T

> 2nd derivatives (e.g. diffusion) using all four T/B

> True 2D REA instead of dimensional splitting



> MC Slope Limiter, using local and neighbor slopes

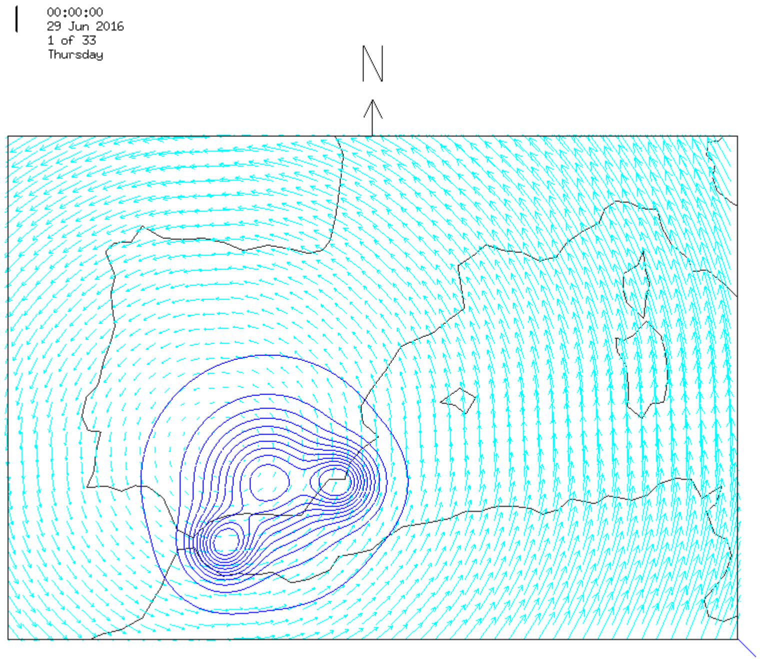
> 6-cell average wind at corners $\bar{U}_{ij}^{n}$ $\bar{V}_{ij}^{n}$

> Linear profile for wind within cell: $\begin{cases} x' = \bar{U}_{ij}^{n} + Ax + By \\ y' = \bar{V}_{ij}^{n} + Cx + Dy \end{cases}$

> Rotating Gaussians

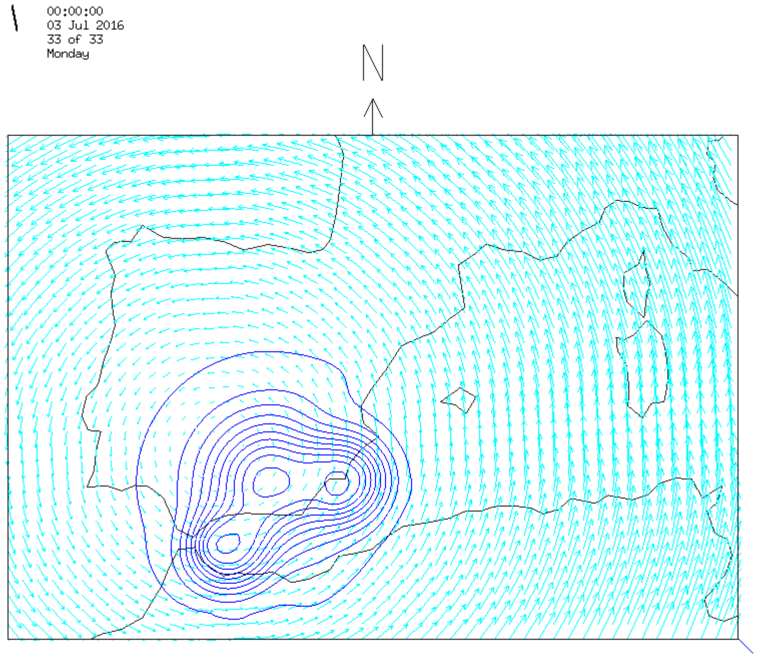
(dx=20km,dt=60s,4revs/4days)

(NO wind profile)

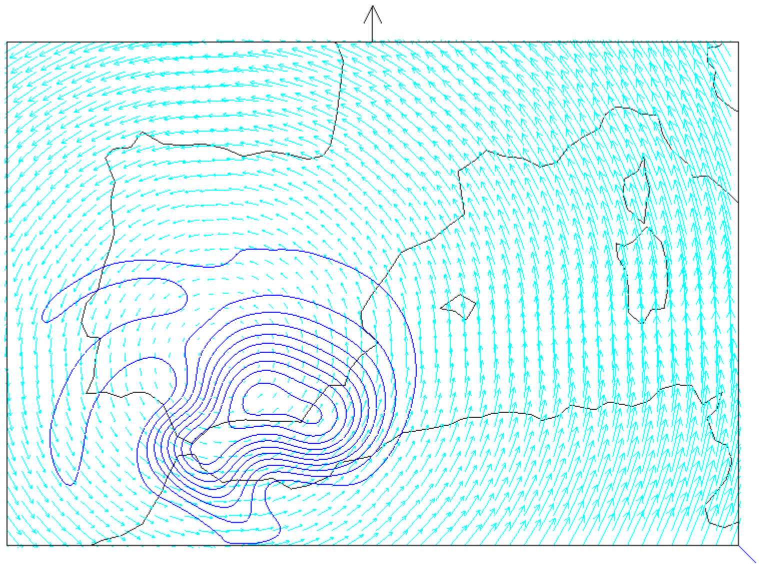


Initial

MC



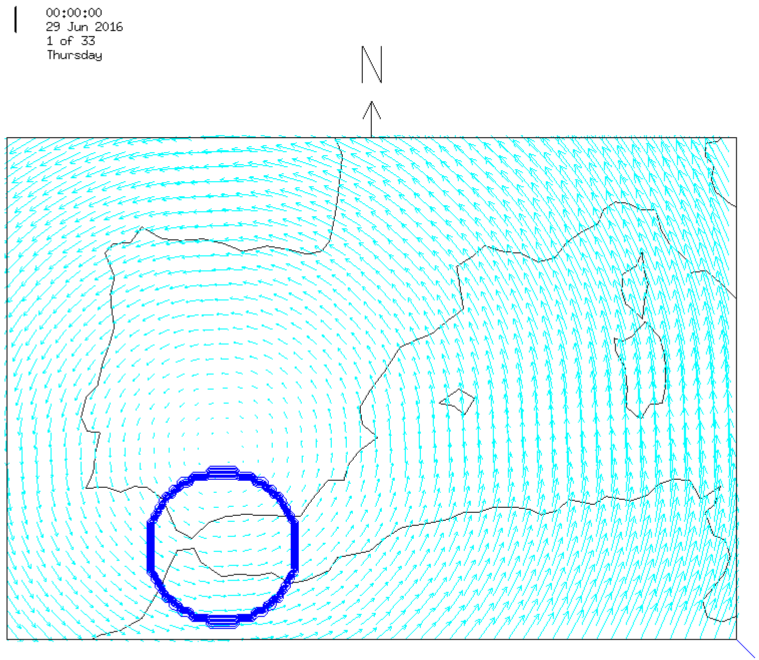
LW



> Rotating Cylinder

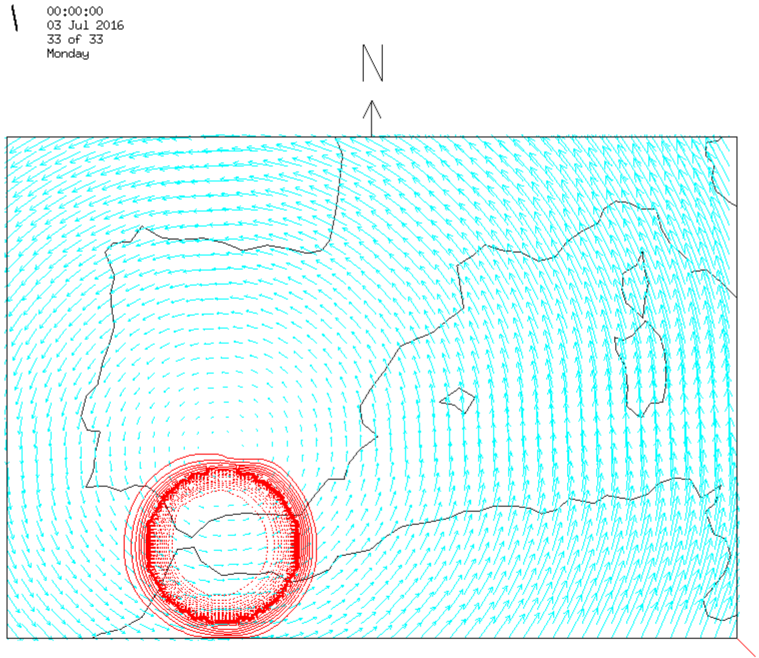
(dx=20km,dt=60s,4revs/4days)

(+ wind profile)

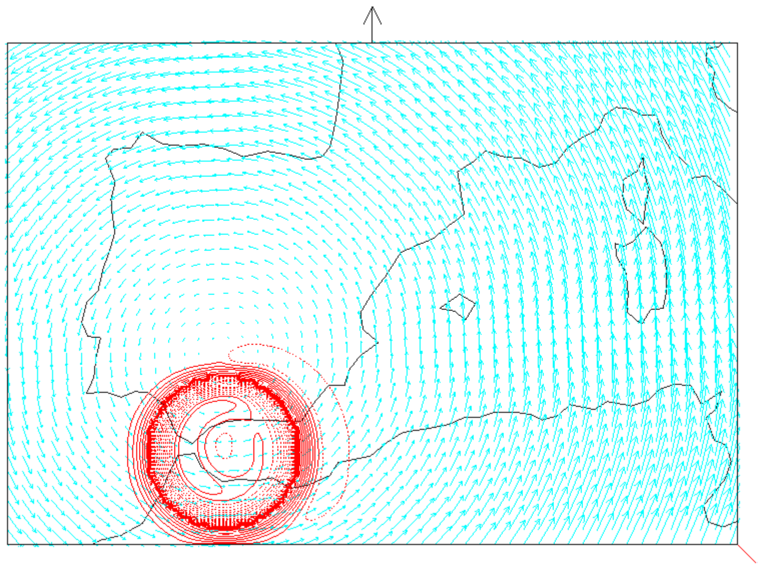


Initial

MC



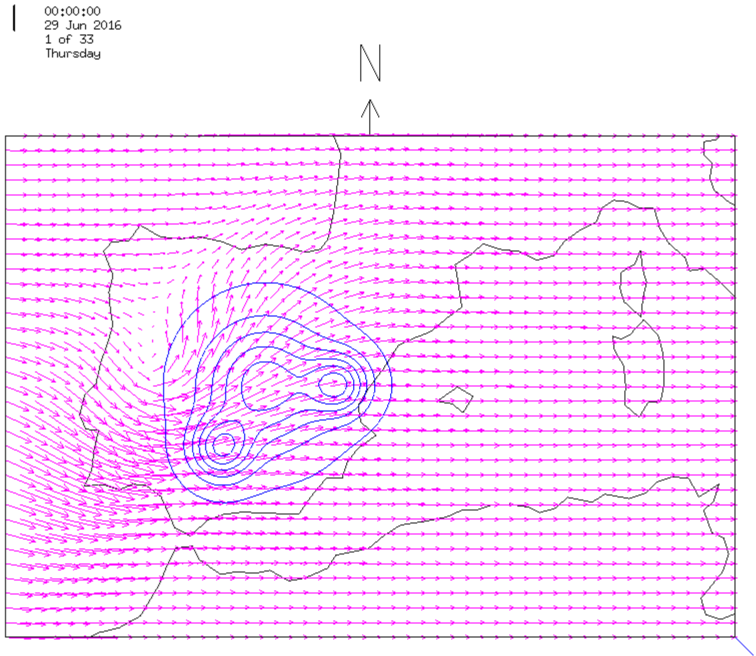
Fromm



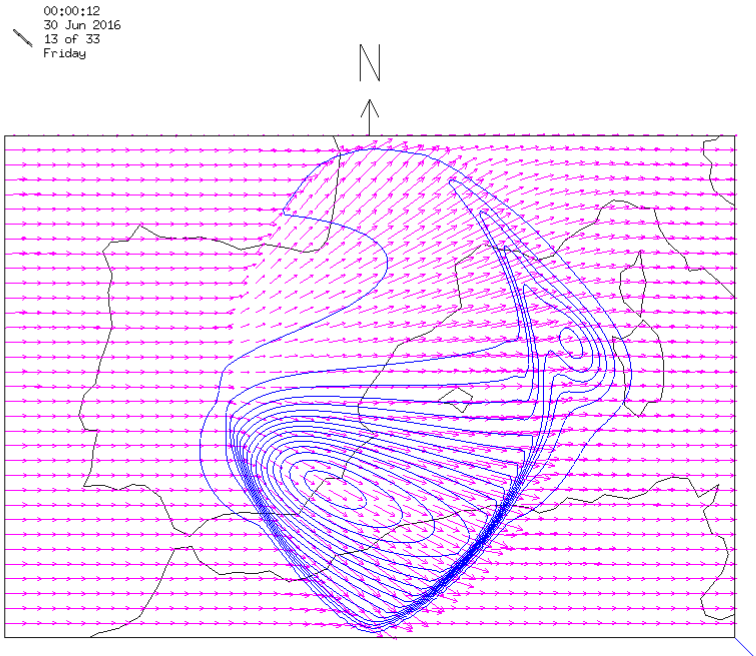
> Vortex in zonal flow

(dx=20km,dt=180s,Periodic BCs,4days)

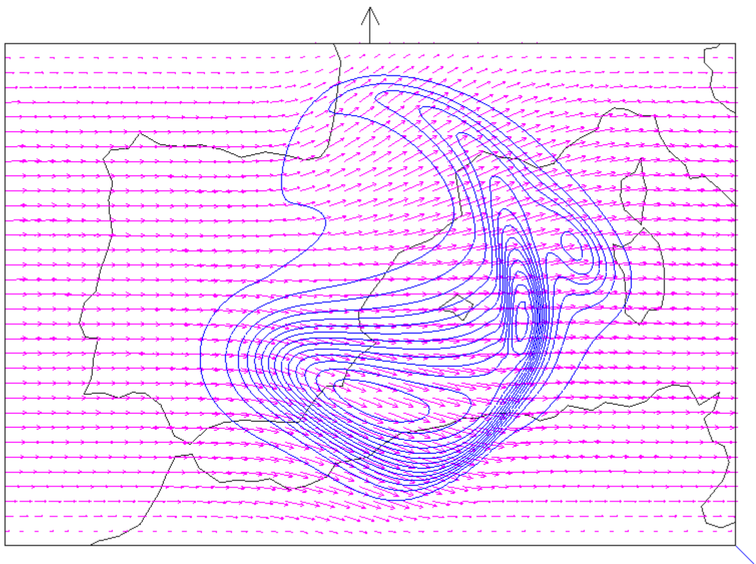
(+ episodic source S)



Initial



NO $\vec{D}$



+ $\vec{D}$

$$\frac{d\vec{V}}{dt} = \vec{D} \quad \begin{cases} \partial_t u = -u\partial_x u - v\partial_y u + k\nabla^2 u \\ \partial_t v = -u\partial_x v - v\partial_y v + k\nabla^2 v \end{cases}$$

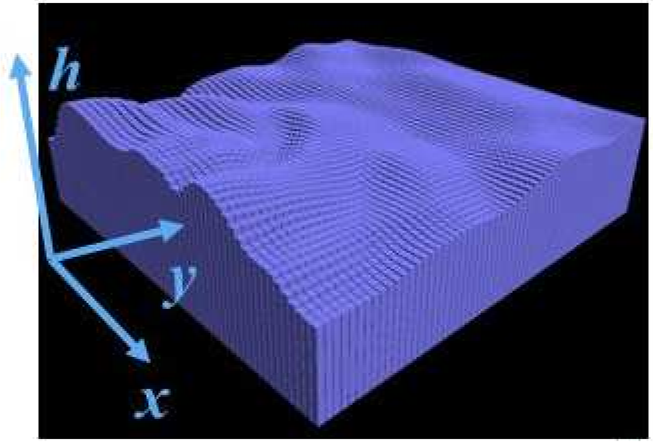
$$\partial_t \phi = -u\partial_x \phi - v\partial_y \phi + S$$

> Governing equations

$$\frac{\partial h}{\partial t} = -u\frac{\partial h}{\partial x} - v\frac{\partial h}{\partial y} - h\left[\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y}\right]$$

$$\frac{\partial u}{\partial t} = -u\frac{\partial u}{\partial x} - v\frac{\partial u}{\partial y} - g\frac{\partial h}{\partial x} + fv - bu + \mu\nabla^2 u$$

$$\frac{\partial v}{\partial t} = -u\frac{\partial v}{\partial x} - v\frac{\partial v}{\partial y} - g\frac{\partial h}{\partial y} - fu - bv + \mu\nabla^2 v$$



> Numerical implementation

* Forward-Backward integration of "forcings" in RK cycle

RK2 $\begin{cases} \phi^* = \phi^n + \frac{\Delta t}{2}F(\phi^n) \\ \phi^{n+1} = \phi^n + \Delta t F(\phi^*) \end{cases}$ SSPRK2 $\begin{cases} \phi^* = \phi^n + \Delta t F(\phi^n) \\ \phi^{**} = \phi^* + \Delta t F(\phi^*) \\ \phi^{n+1} = \frac{1}{2}(\phi^n + \phi^{**}) \end{cases}$ CFL $\xrightarrow{\sqrt{gH}}$ Δt

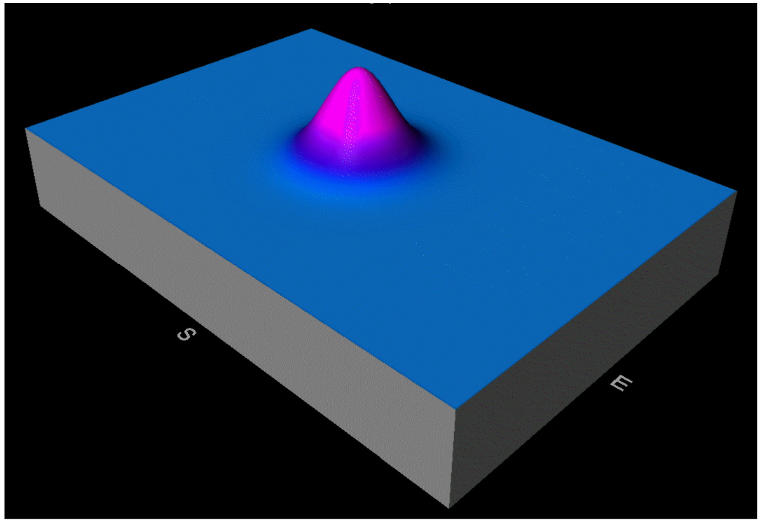
* REA integration of advective terms at end of timestep

* Rigid Wall BCs at the 4 boundaries

> Gaussian Bump in H=10m

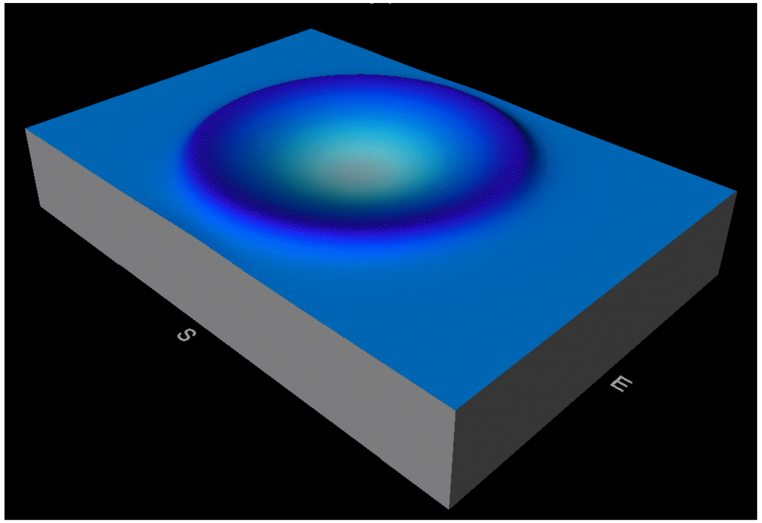
(dx=20km,dt=180s,2000x1600km,10days)

(NO Coriolis/Drag/Diffusion)

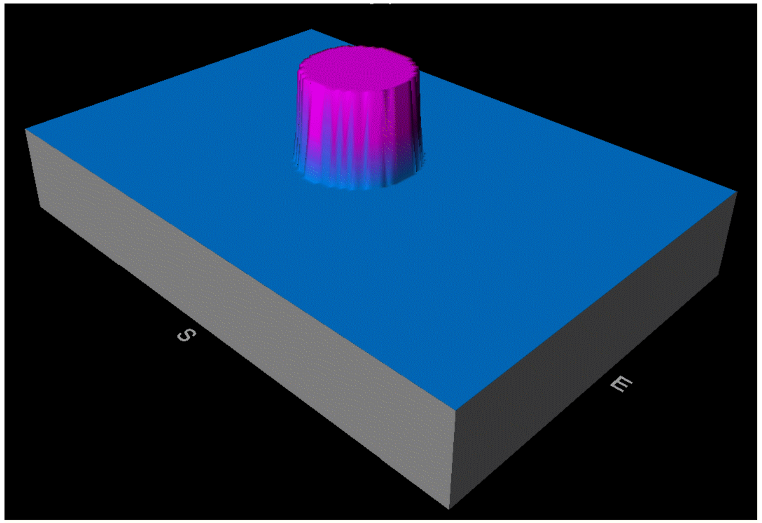


Initial

RK2



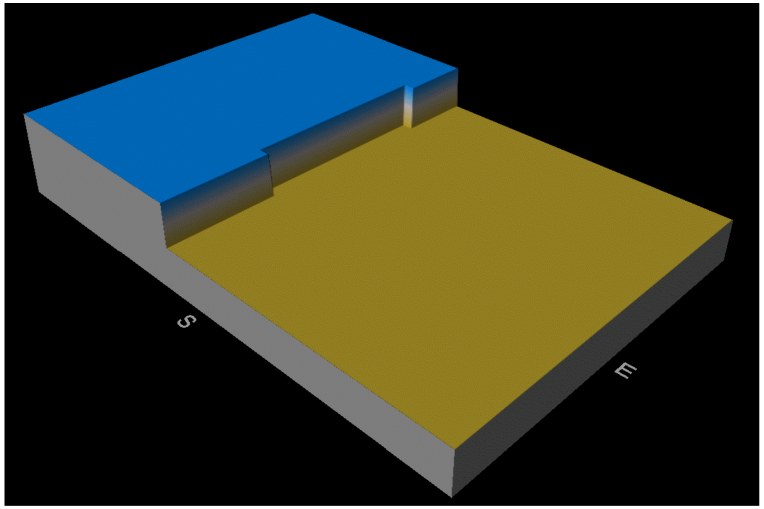
SSPRK2



> Partial Dam Break 10-5 m

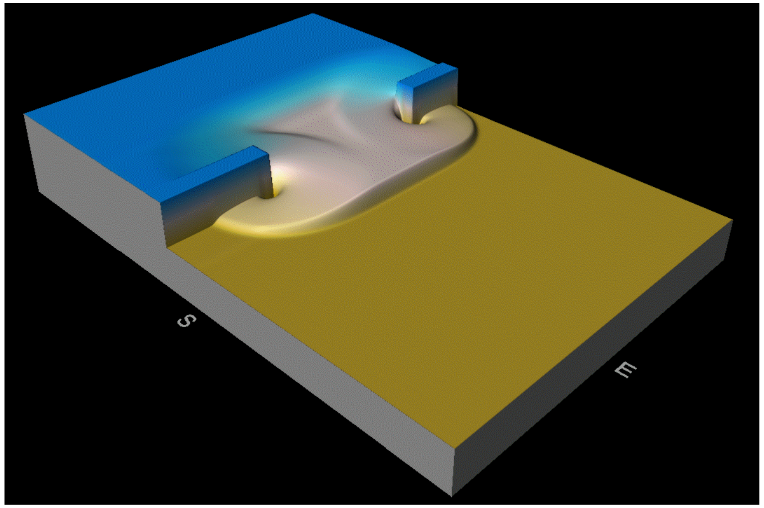
(dx=5km,dt=180s,2000x1600km,10days)

(NO Coriolis/Drag/Diffusion)

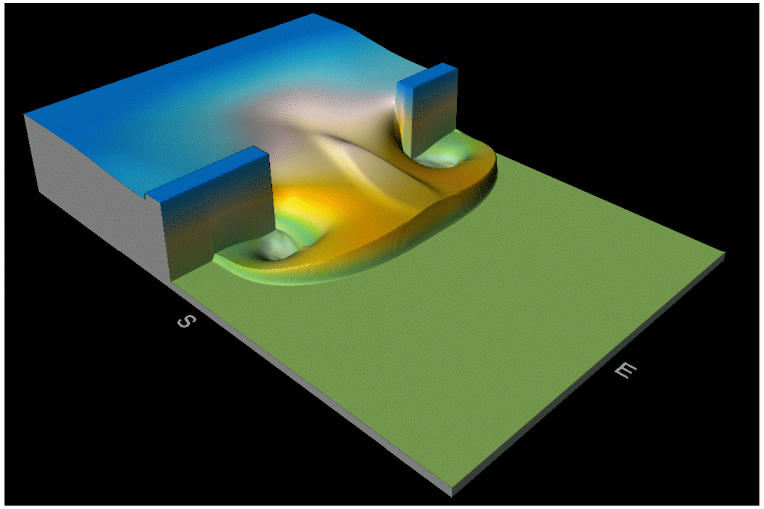


Initial

SSPRK2



10-1 m



Non-Hydrostatic Fully-Compressible Equations

> **Combine the fundamental principles**

$$\frac{dT}{dt} = \frac{1}{c_p \rho}\frac{dP}{dt} \qquad P = \rho R T$$

Adiabatic atmosphere

$$\frac{d\rho}{dt} = -\rho\left[\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z}\right]$$

No moisture

$$\frac{du}{dt} = -\frac{1}{\rho}\frac{\partial P}{\partial x} + fv - \hat{f}w$$

Inviscid flow

$$\frac{dv}{dt} = -\frac{1}{\rho}\frac{\partial P}{\partial y} - fu$$

$$\frac{dw}{dt} = -\frac{1}{\rho}\frac{\partial P}{\partial z} - g + \hat{f}u$$

> **in terms of the following variables**

Exner pressure: $\boldsymbol{\pi} = \left(\frac{P}{P_0}\right)^{R/c_p}$ **Potential temperature:** $\boldsymbol{\theta} = \frac{T}{\pi}$

Non-Hydrostatic Fully-Compressible Equations

> **Alternative version of Euler equations**

$$\frac{\partial \pi}{\partial t} = -u\frac{\partial \pi}{\partial x} - v\frac{\partial \pi}{\partial y} - w\frac{\partial \pi}{\partial z} - \frac{R}{c_v}\pi\left[\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z}\right]$$

$$\frac{\partial \theta}{\partial t} = -u\frac{\partial \theta}{\partial x} - v\frac{\partial \theta}{\partial y} - w\frac{\partial \theta}{\partial z}$$

$$\frac{\partial u}{\partial t} = -u\frac{\partial u}{\partial x} - v\frac{\partial u}{\partial y} - w\frac{\partial u}{\partial z} - c_p\theta\frac{\partial \pi}{\partial x} + fv - \hat{f}w$$

$$\frac{\partial v}{\partial t} = -u\frac{\partial v}{\partial x} - v\frac{\partial v}{\partial y} - w\frac{\partial v}{\partial z} - c_p\theta\frac{\partial \pi}{\partial y} - fu$$

$$\frac{\partial w}{\partial t} = -u\frac{\partial w}{\partial x} - v\frac{\partial w}{\partial y} - w\frac{\partial w}{\partial z} - c_p\theta\frac{\partial \pi}{\partial z} - g + \hat{f}u$$

> **Apply the following decomposition**

$$\left.\begin{aligned}\pi(x,y,z,t) &= \bar{\pi}(z) + \pi'(x,y,z,t)\\ \theta(x,y,z,t) &= \bar{\theta}(z) + \theta'(x,y,z,t)\end{aligned}\right\} \quad c_p\bar{\theta}\frac{\partial \bar{\pi}}{\partial z} = -g$$

Hydrostatic balance

Non-Hydrostatic Fully-Compressible Equations

> **FINAL** version of Euler (Navier-Stokes) equations

$$\frac{\partial \pi'}{\partial t} = -u\frac{\partial \pi'}{\partial x} - v\frac{\partial \pi'}{\partial y} - w\frac{\partial \pi'}{\partial z} - w\frac{\partial \bar{\pi}}{\partial z} - \frac{R}{c_v}(\bar{\pi}+\pi')\left[\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z}\right]$$

$$\frac{\partial \theta'}{\partial t} = -u\frac{\partial \theta'}{\partial x} - v\frac{\partial \theta'}{\partial y} - w\frac{\partial \theta'}{\partial z} - w\frac{\partial \bar{\theta}}{\partial z} + \mu\left[\nabla^2\theta' + \frac{\partial^2(\bar{\theta}+\theta')}{\partial z^2}\right]$$

$$\frac{\partial u}{\partial t} = -u\frac{\partial u}{\partial x} - v\frac{\partial u}{\partial y} - w\frac{\partial u}{\partial z} - c_p(\bar{\theta}+\theta')\frac{\partial \pi'}{\partial x} + fv - \hat{f}w + \mu\left[\nabla^2 u + \frac{\partial^2 u}{\partial z^2}\right]$$

$$\frac{\partial v}{\partial t} = -u\frac{\partial v}{\partial x} - v\frac{\partial v}{\partial y} - w\frac{\partial v}{\partial z} - c_p(\bar{\theta}+\theta')\frac{\partial \pi'}{\partial y} - fu + \mu\left[\nabla^2 v + \frac{\partial^2 v}{\partial z^2}\right]$$

$$\frac{\partial w}{\partial t} = -u\frac{\partial w}{\partial x} - v\frac{\partial w}{\partial y} - w\frac{\partial w}{\partial z} - c_p(\bar{\theta}+\theta')\frac{\partial \pi'}{\partial z} + g\frac{\theta'}{\bar{\theta}} + \hat{f}u + \mu\left[\nabla^2 w + \frac{\partial^2 w}{\partial z^2}\right]$$

> **Numerical implementation 3D** [CFL $\xrightarrow{c_s > 300\ m/s}$ $\Delta t \approx 2\ \Delta x(\Delta z)$]

* **Forward-Backward** integration of "forcings" in **RK2** cycle
* **REA (V and H)** integration of **advection** every 6-10 **Nsteps**
* Rigid **Wall BCs** at W/E S/N B/T boundaries

Non-Hydrostatic Fully-Compressible Equations

> FINAL version of Euler (Navier-Stokes) equations

$$\frac{\partial \pi'}{\partial t} = -u\frac{\partial \pi'}{\partial x} - v\frac{\partial \pi'}{\partial y} - w\frac{\partial \pi'}{\partial z} - w\frac{\partial \bar{\pi}}{\partial z} - \frac{R}{c_v}(\bar{\pi}+\pi')\left[\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z}\right]$$

$$\frac{\partial \theta'}{\partial t} = -u\frac{\partial \theta'}{\partial x} - v\frac{\partial \theta'}{\partial y} - w\frac{\partial \theta'}{\partial z} - w\frac{\partial \bar{\theta}}{\partial z} + \mu\left[\nabla_x^2\theta' + \frac{\partial^2(\bar{\theta}+\theta')}{\partial z^2}\right]$$

$$\frac{\partial u}{\partial t} = -u\frac{\partial u}{\partial x} - v\frac{\partial u}{\partial y} - w\frac{\partial u}{\partial z} - c_p(\bar{\theta}+\theta')\frac{\partial \pi'}{\partial x} + fv - \hat{f}w + \mu\left[\nabla_x^2 u + \frac{\partial^2 u}{\partial z^2}\right]$$

2D (NO rotation)

$$\frac{\partial w}{\partial t} = -u\frac{\partial w}{\partial x} - v\frac{\partial w}{\partial y} - w\frac{\partial w}{\partial z} - c_p(\bar{\theta}+\theta')\frac{\partial \pi'}{\partial z} + g\frac{\theta'}{\bar{\theta}} + \hat{f}u + \mu\left[\nabla_x^2 w + \frac{\partial^2 w}{\partial z^2}\right]$$

> Numerical implementation 2D [CFL $\xrightarrow{c_s > 300\ m/s}$ $\Delta t \approx 3\ \Delta x(\Delta z)$]

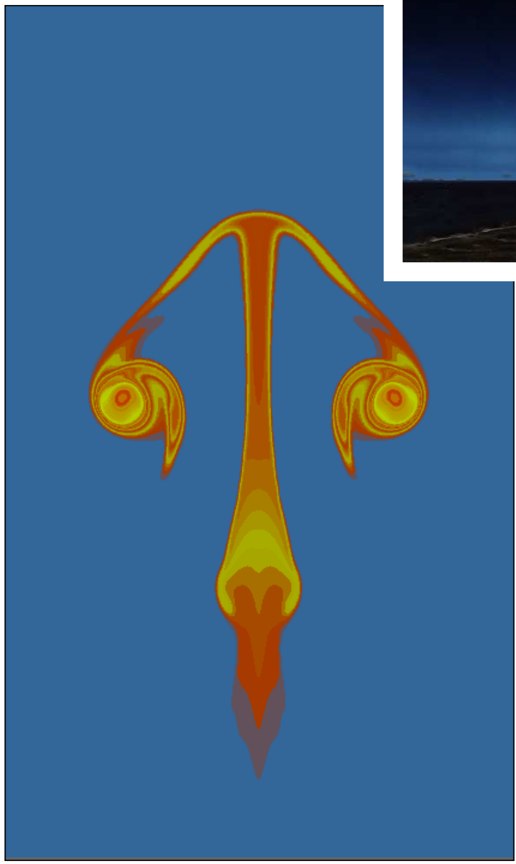
* Forward-Backward integration of "forcings" in RK2 cycle
* REA (V and H) integration of advection every 6-10 Nsteps
* Rigid Wall BCs at W/E B/T boundaries

> Rising Thermal Bubble (calm and neutrally-stable environment)

(dx=dz=100m, dt=0.2s, Nstep=10, 50min)

(NO Coriolis/Diffusion)

Initial



3D

* Check of *MASS* & Total *ENERGY*

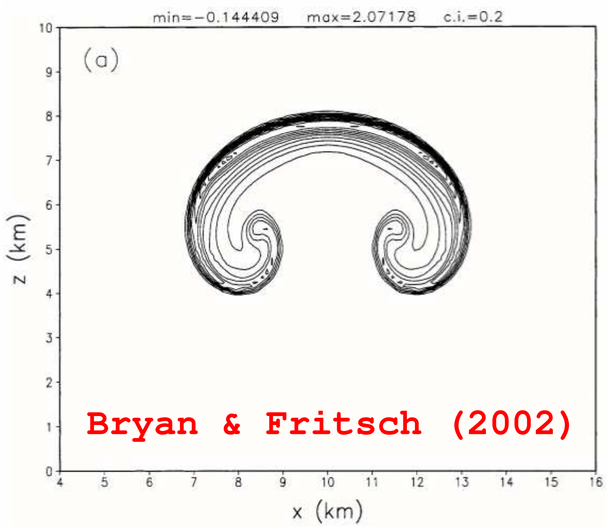
ΔM = −0.002 %

ΔE = −0.0005 %

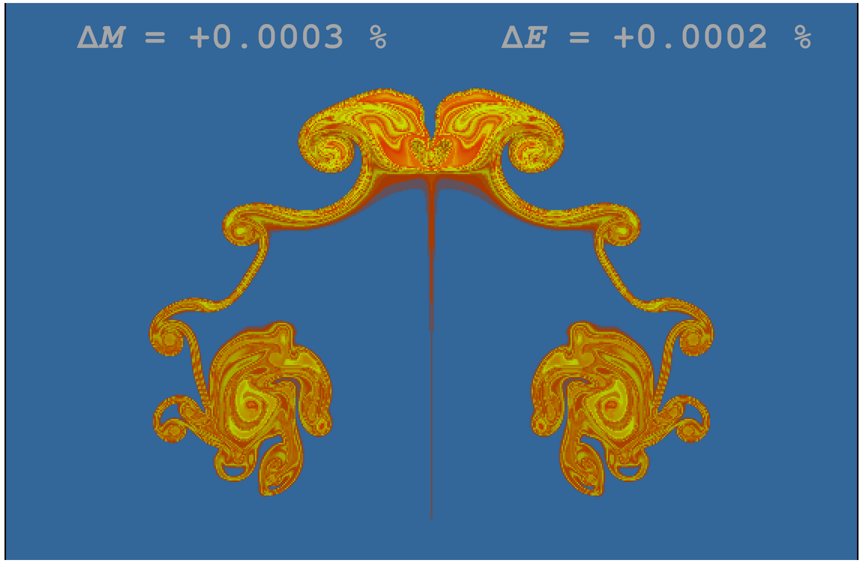
> Rising Thermal Bubble (2D)

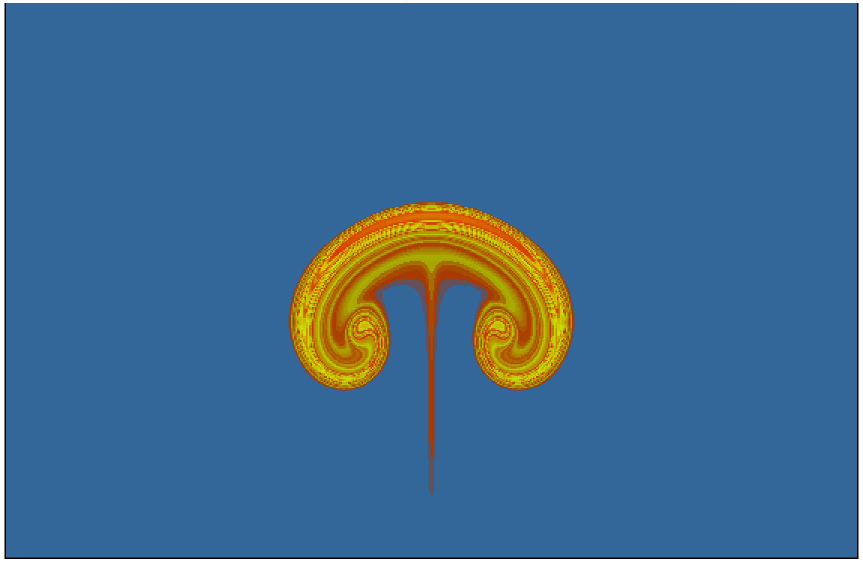
(dx=dz=50m, dt=0.125s, Nstep=10, 55min)

Double resolution t=33min

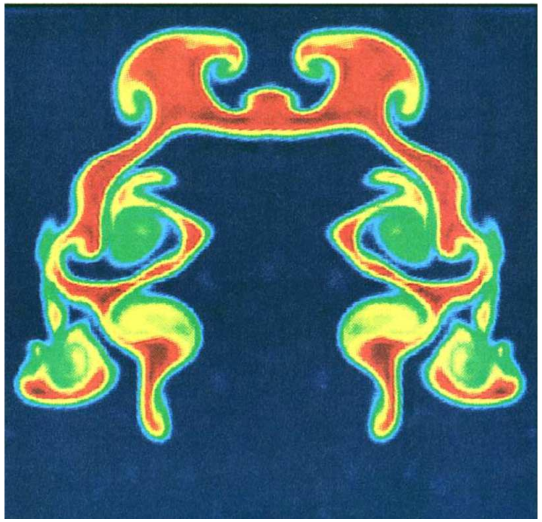


Bryan & Fritsch (2002)





t=17min



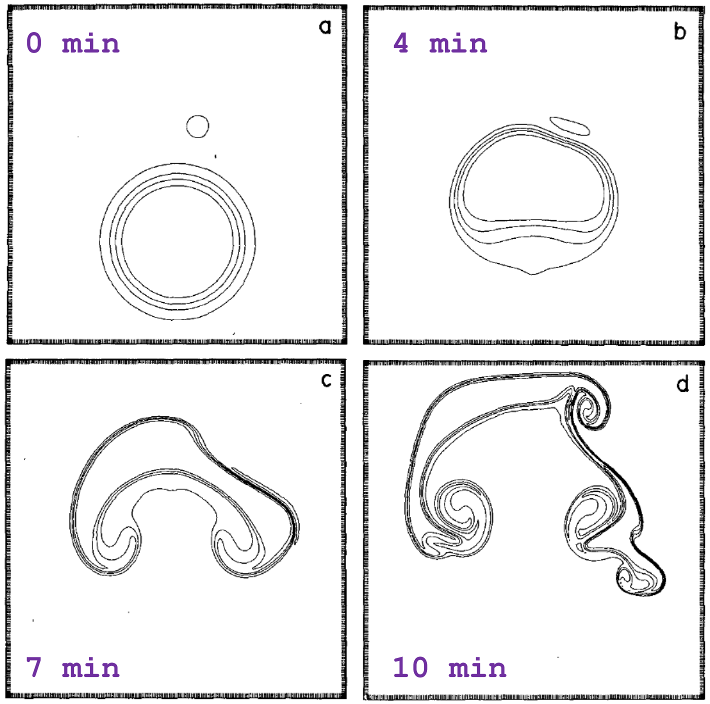
Robert (1993)

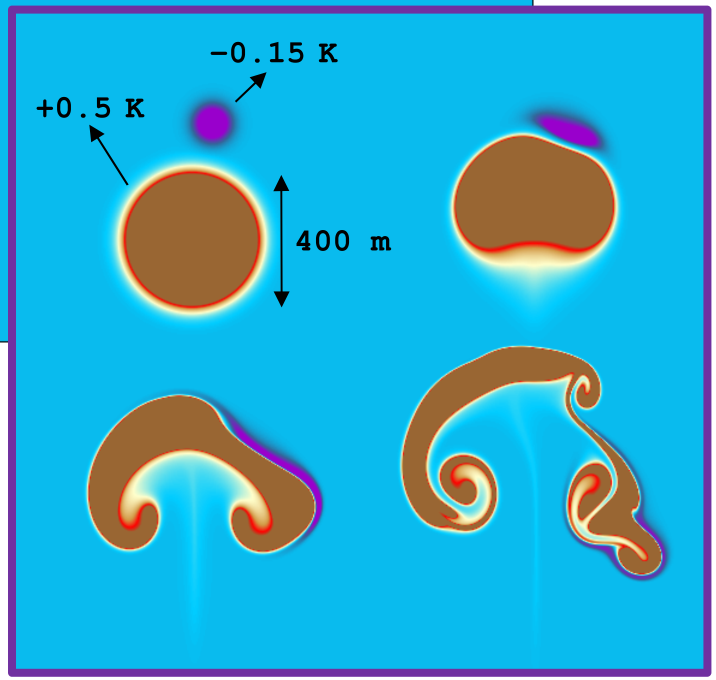
> Large Warm & Small Cold Bubbles

(dx=dz=2.5m,dt=0.00625s,Nstep=10,40min)

Initial

Robert (1993)





ΔM = −0.00007 %

ΔE = −0.0001 %

Animation

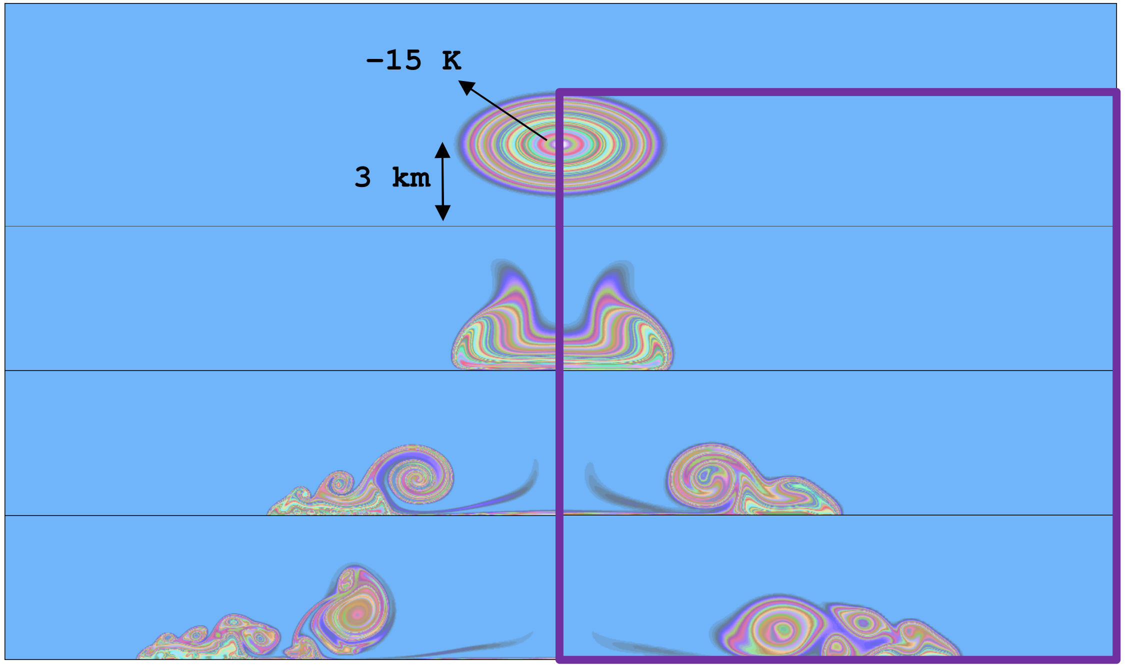
> Density Current

(dx=dz=100m,dt=0.25s,Nstep=10,3h)

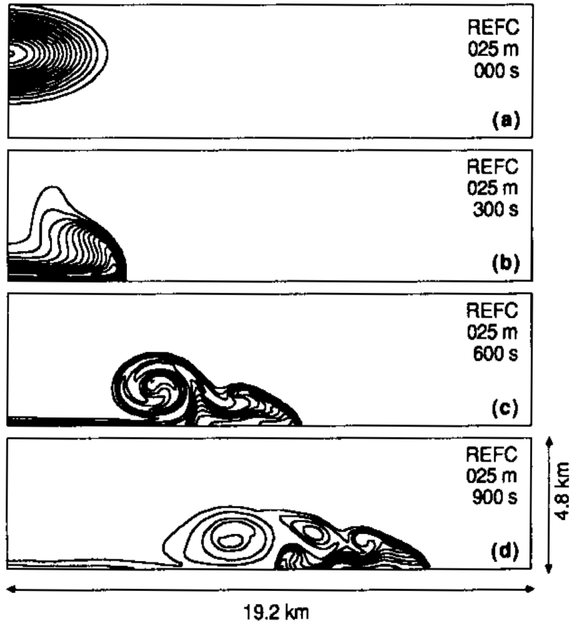
ΔM = −0.46 %
ΔE = −0.56 %

Quadruple resolution

Initial



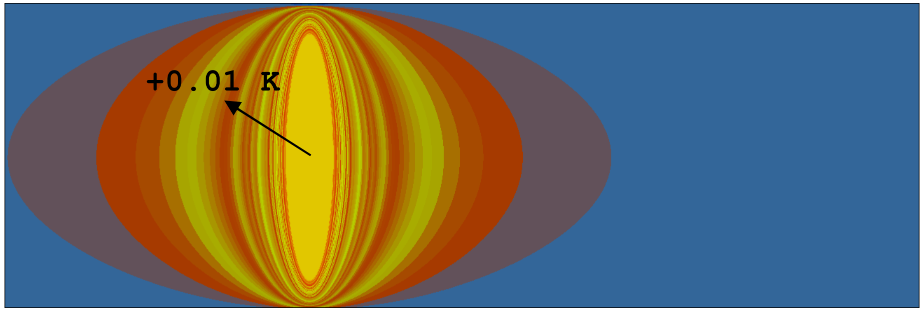
Straka et al. (1993)



ΔM = −1.6 %
ΔE = −2.0 %

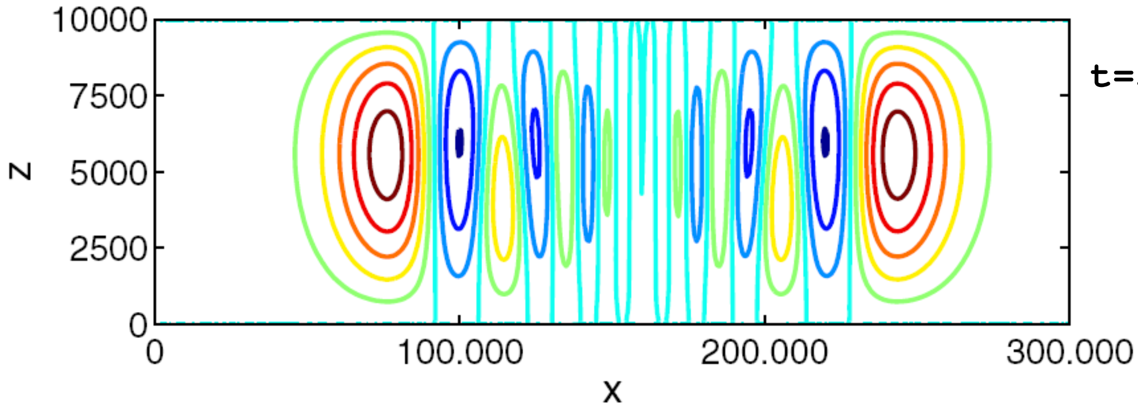
> Inertia-Gravity Waves (uniform wind/stability: $U=20ms^{-1}/N=0.01s^{-1}$)

(dx=dz=125m, dt=0.3125s, Nstep=10, 1h)

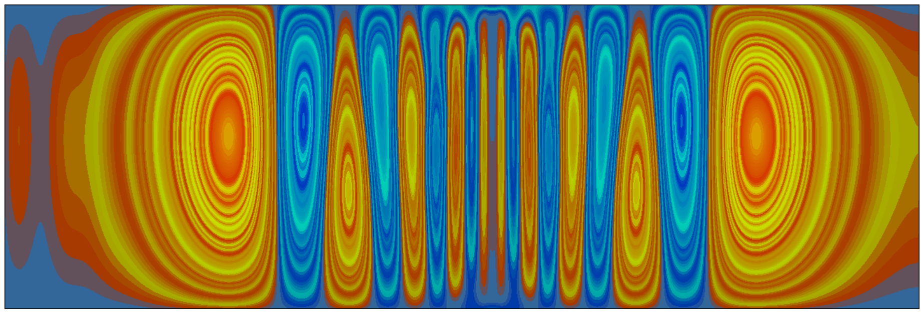


Initial

Giraldo & Restelli (2008)



t=50min

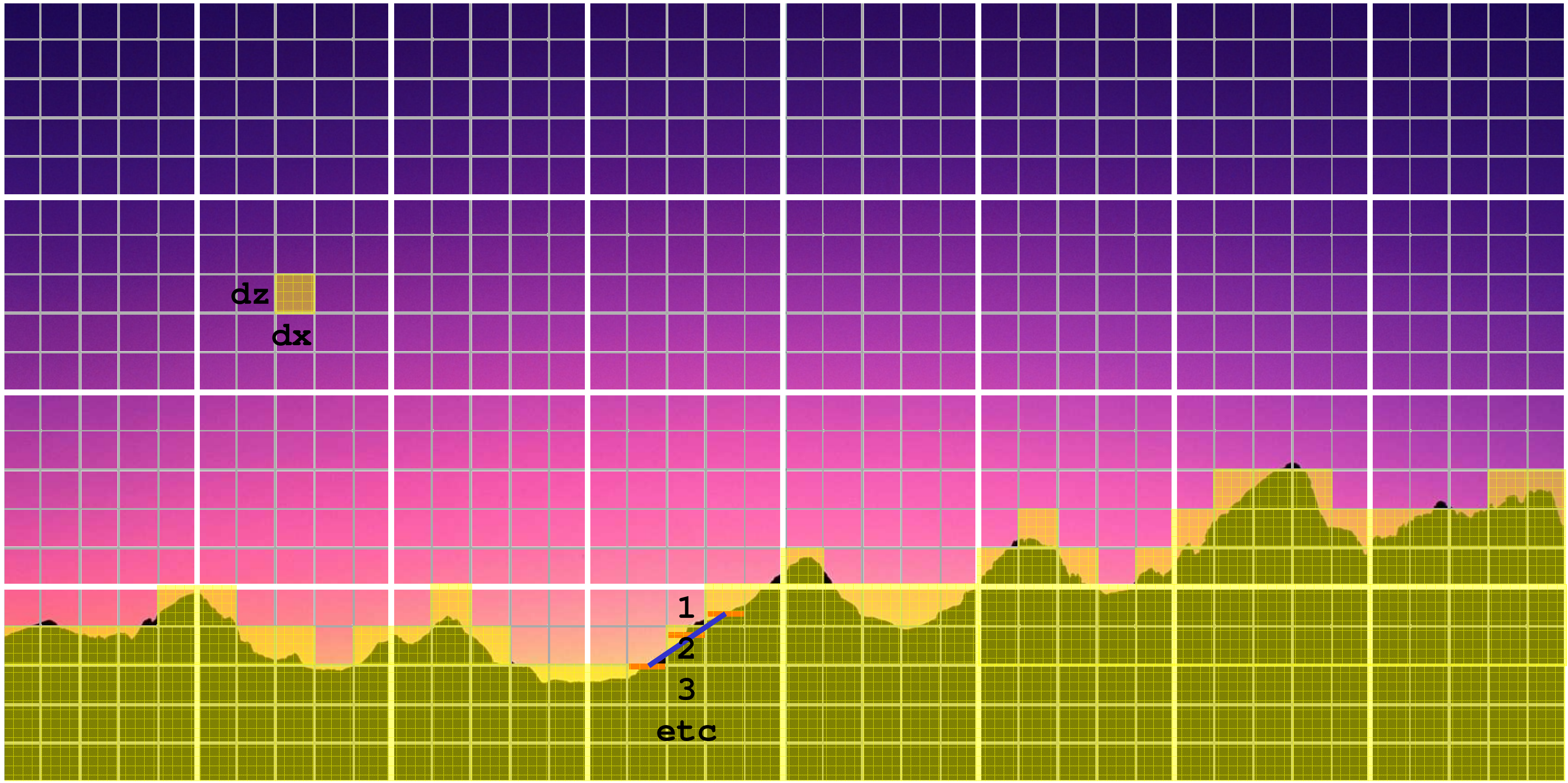


ΔM = +0.00001 %

ΔE = +0.000005 %

Animation

> Use **mean terrain height** over grid cell



> **Terrain-following Bottom B.C.**

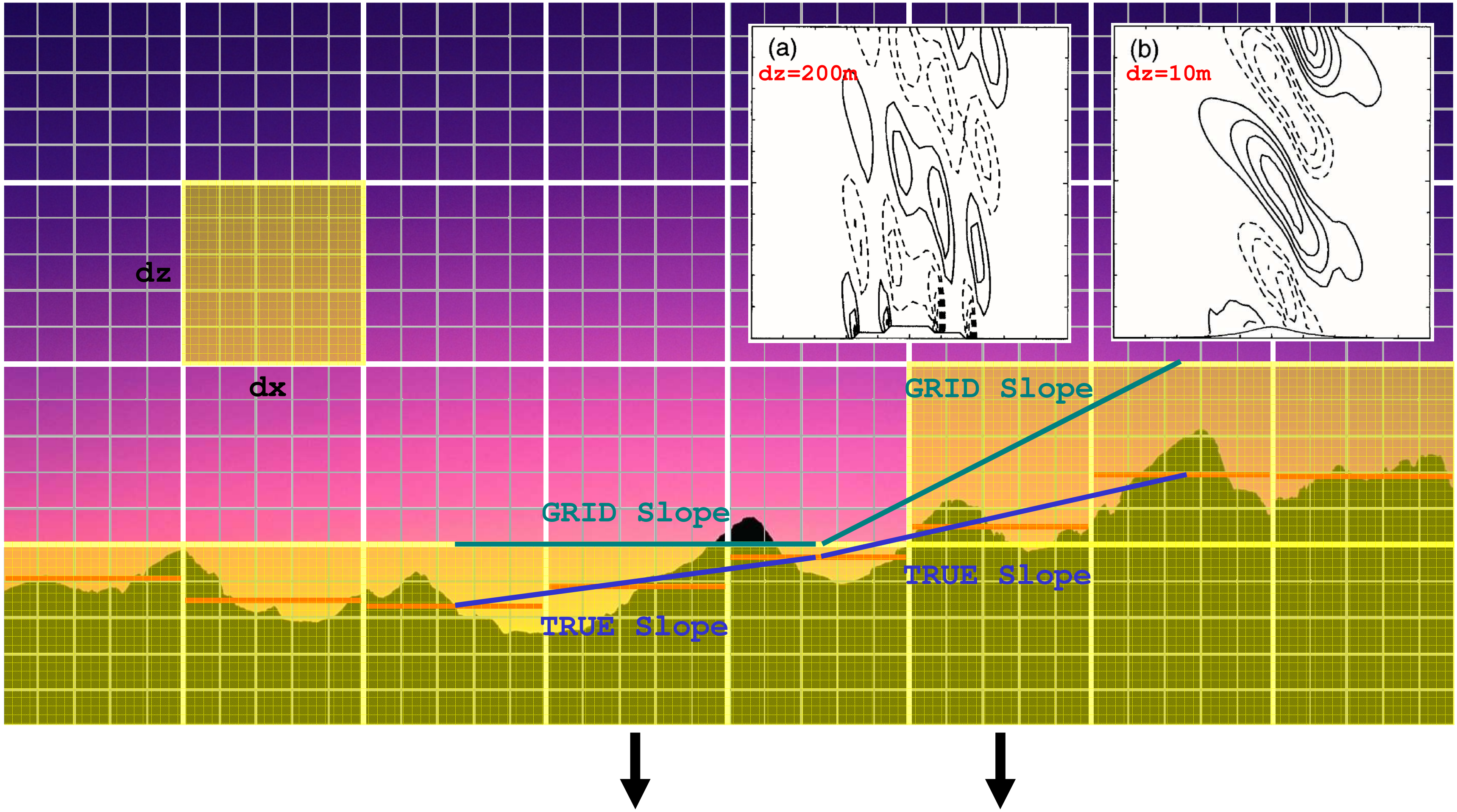
Vertical velocity: $w_2 = (u_1, v_1) \cdot \overrightarrow{slope}$ *Linear extrapolation underneath*

Other fields: $(u_i, v_i) = (u_1, v_1)$ $(\pi'_i, \theta'_i) = (\pi'_1, 0)$

> TRUE-terrain slope *vs* GRID-based slope

ETA MODEL

Gallus & Klemp (2000)



NO forcing !!!

CORRECT forcing

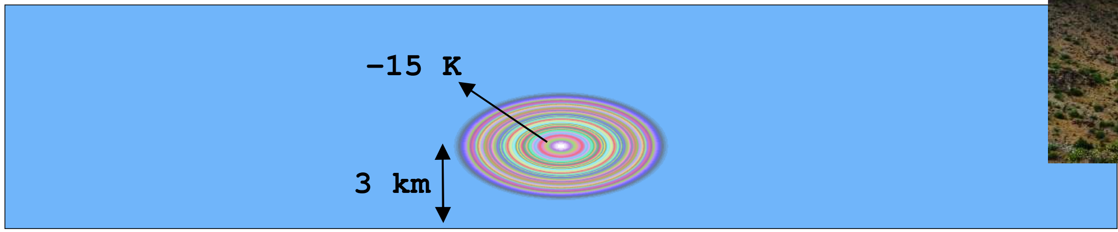
TOO MUCH forcing !!!

CORRECT forcing

> Density Current Comparison

(dx=dz=50m,dt=0.125s,Nstep=8,3h)

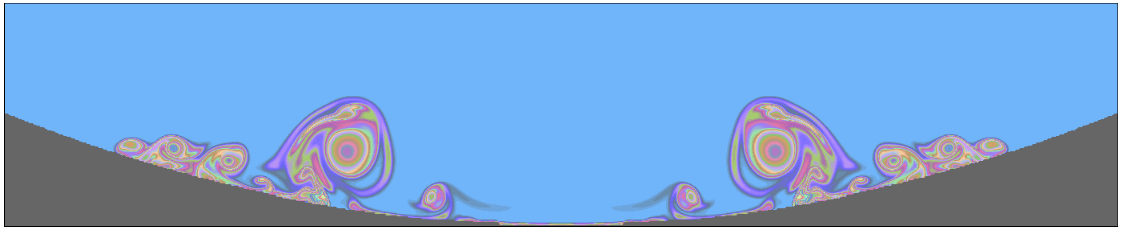
Initial



Flat terrain

ΔM = −0.85 %

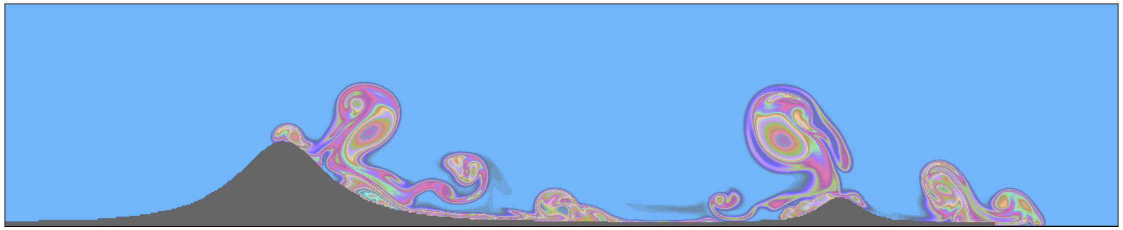
ΔE = −1.06 %



Parabolic slope

ΔM = −0.94 %

ΔE = −1.09 %



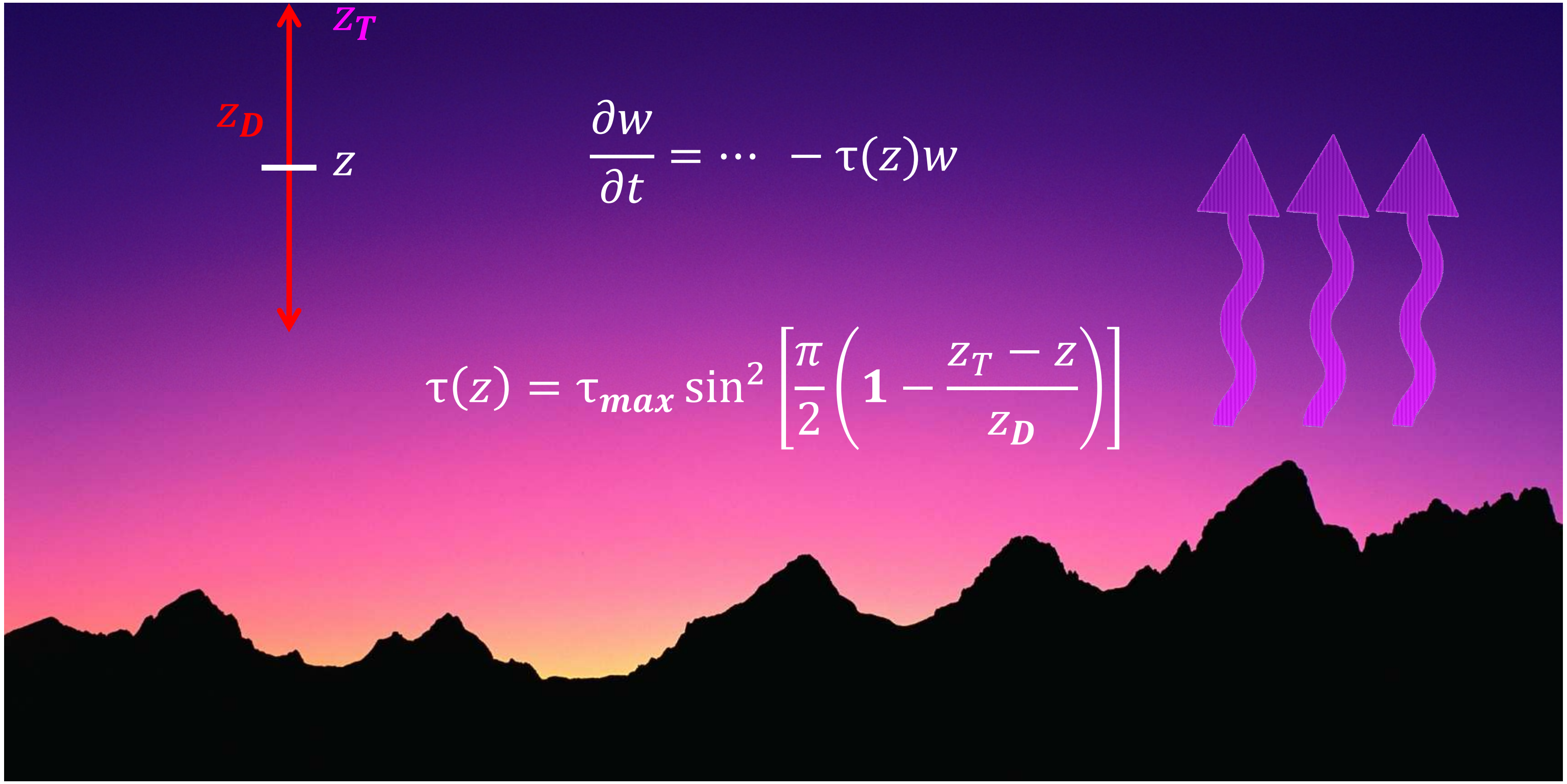
Two mountains

ΔM = +2.26 %

ΔE = +3.12 %

t=21min

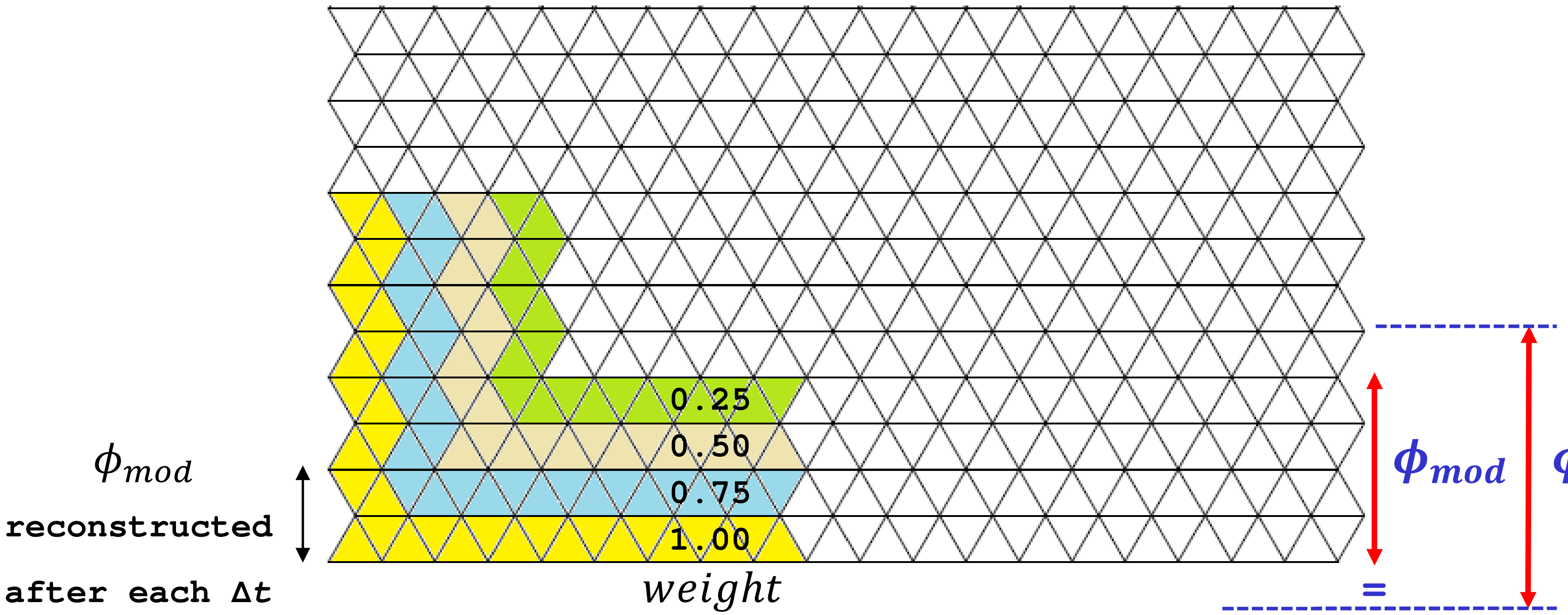
> **Rayleigh damping** term added to $\frac{\partial w}{\partial t}$ equation **within** z_D



> **Typical values** $\begin{cases} z_D = 10\ km \\ \tau_{max} = 0.1\ s^{-1} \end{cases}$ (above 10km only)

Specified Lateral Boundary Conditions

> Interior solution ϕ_{mod} relaxed towards specified ϕ_{LS}



$$\frac{\partial \phi_{mod}}{\partial t} = weight\,[F(\phi_{LS} - \phi_{mod}) - G\Delta^2(\phi_{LS} - \phi_{mod})]$$

> Typical values $\begin{cases} F = 1/10\Delta t \\ G = 1/50\Delta t \end{cases}$ (×5 if using grid analyses)

> Linear Mountain Waves (10m bell-shaped mountain, $U=10ms^{-1}$, $N=0.01s^{-1}$)

(dz=200m, dt=0.6s, Nstep=10)

150h

dx=5km

Rotation

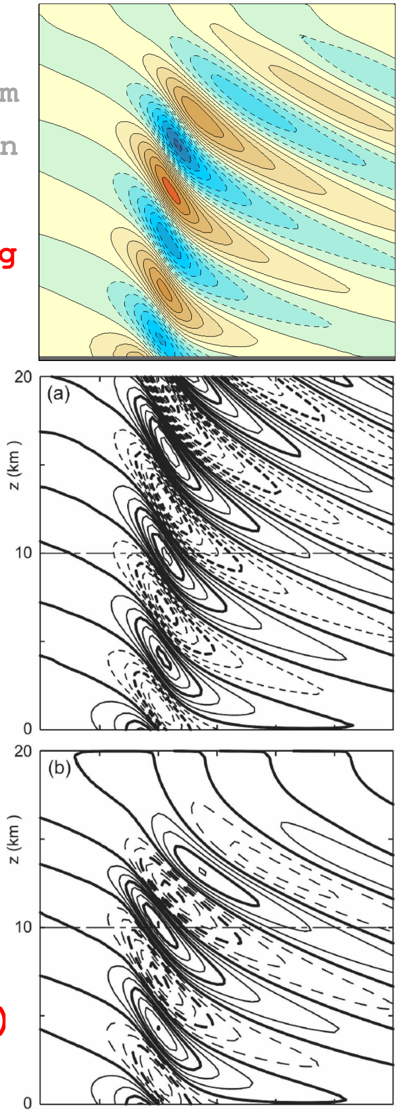
Damping ×4

Analytical

a=50km

L=300km

Klemp et al. (2008)

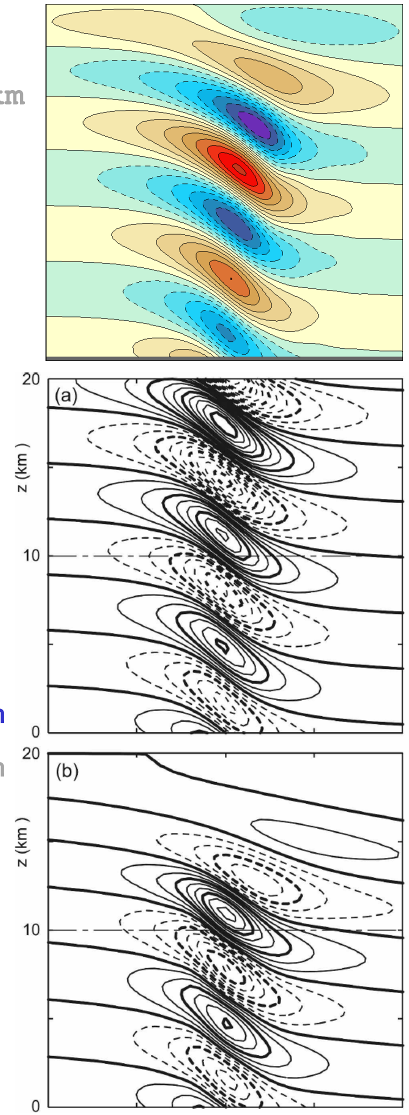


30h

dx=1km

a=10km

L=80km



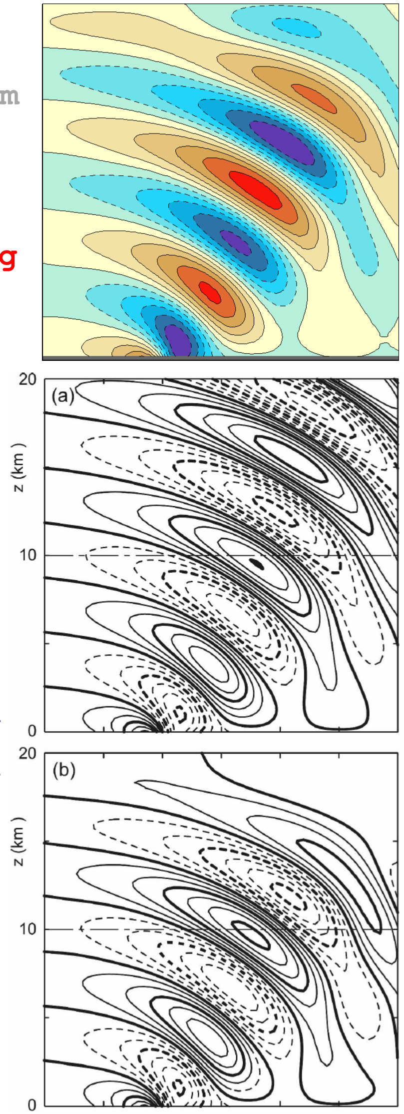
6h

dx=500m

Damping ÷4

a=2km

L=24km

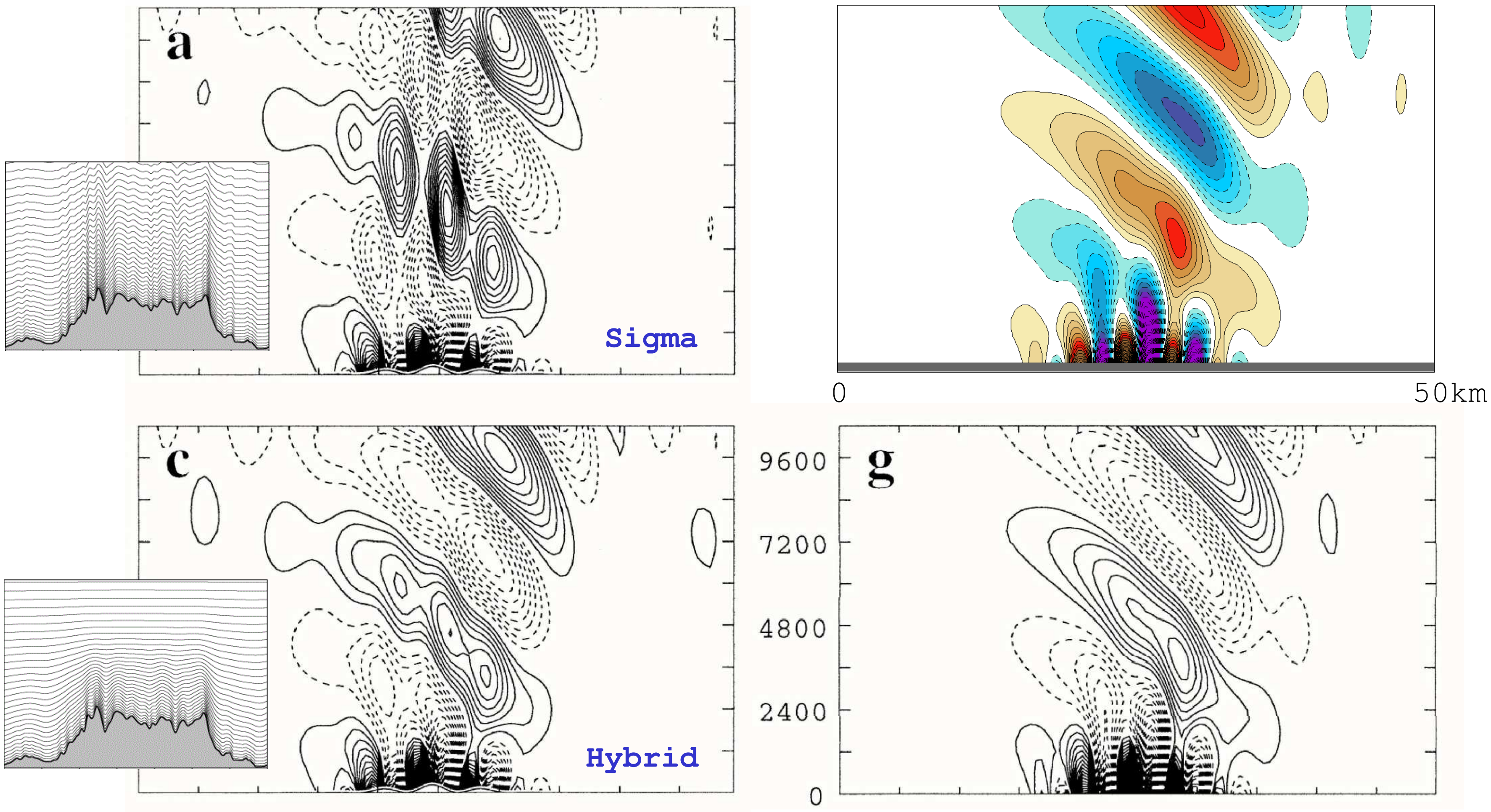


> Schär Mountain (250m bell-shaped + small-scale, $U=10ms^{-1}$, $N=0.01s^{-1}$)

(dx=250m, dz=250m, dt=0.75s, Nstep=10, 10h)

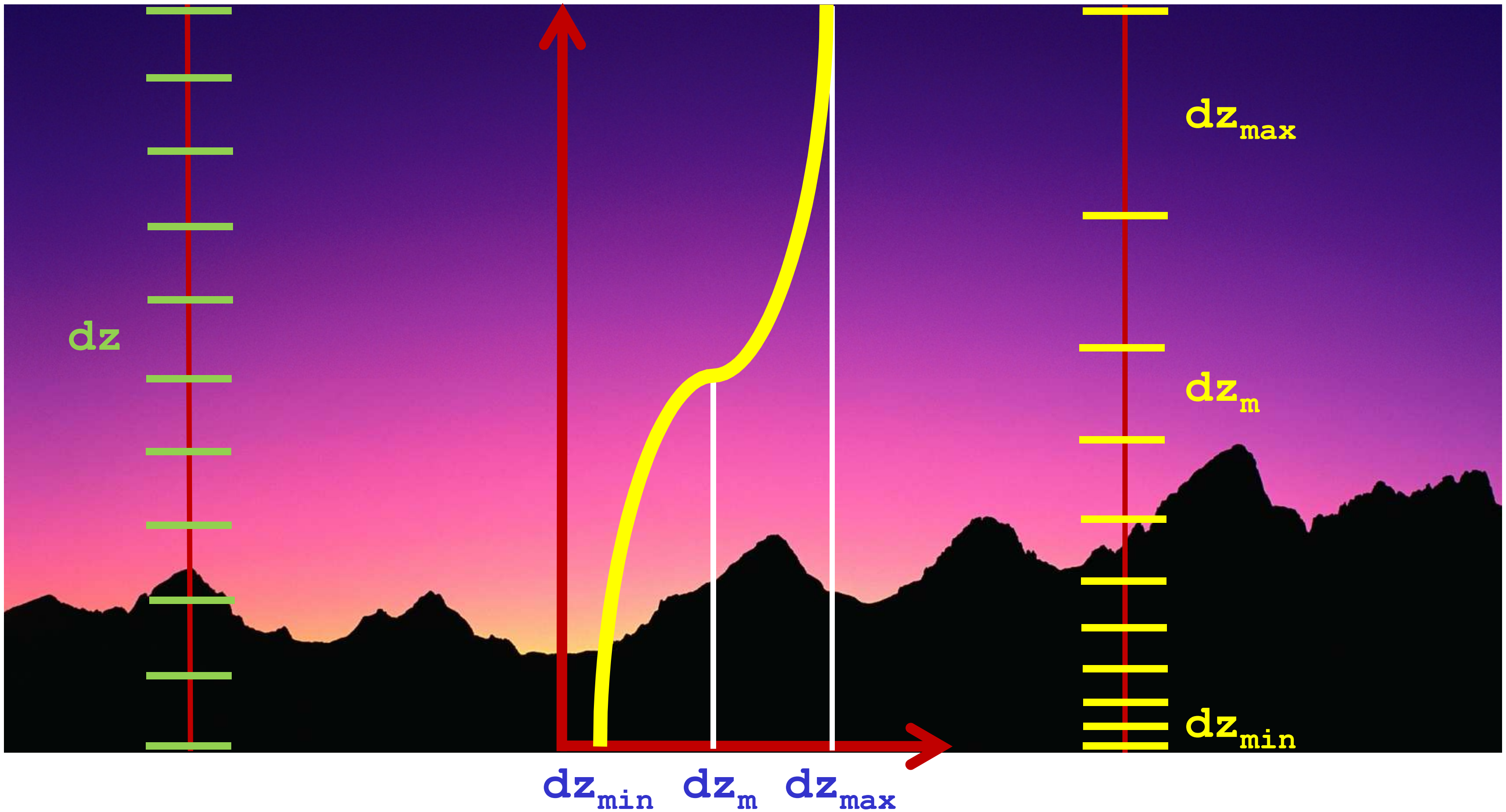
ΔM = −0.0048 %

Steady-state ΔE = −0.0021 %



Schär et al.(2002) Analytical

> Higher resolution at low levels (cos profile)



> Two parameters (stretch, dz_m)

$$\begin{cases} dz_{min} = dz_m / stretch \\ dz_{max} = dz_m + (dz_m - dz_{min}) \end{cases}$$

> Stabilization of acoustic vertical modes (RK2-cycle)

$$\frac{\partial \pi'}{\partial t} = F^n + G^n \left[\alpha \frac{\partial w^n}{\partial z} + \beta \frac{\partial w^{n+1}}{\partial z}\right] \longrightarrow \pi'^{n+1} = A + B\frac{\partial w^{n+1}}{\partial z}$$

$$\frac{\partial w}{\partial t} = R^n + T^n \left[\alpha \frac{\partial \pi'^n}{\partial z} + \beta \frac{\partial \pi'^{n+1}}{\partial z}\right] \longrightarrow w^{n+1} = C + D\frac{\partial \pi'^{n+1}}{\partial z}$$

α=0.3 β=0.7

Off-centered

$$w^{n+1} = C + DA_z + DB_z\frac{\partial w^{n+1}}{\partial z} + DB\frac{\partial^2 w^{n+1}}{\partial z^2}$$

$$a w_{k-1}^{n+1} + b w_k^{n+1} + c w_{k+1}^{n+1} = f \xrightarrow{\text{Tridiagonal solver}} \begin{cases} w^{n+1} \\ \pi'^{n+1} \xrightarrow{\text{F-B}} u^{n+1}, v^{n+1} \end{cases}$$

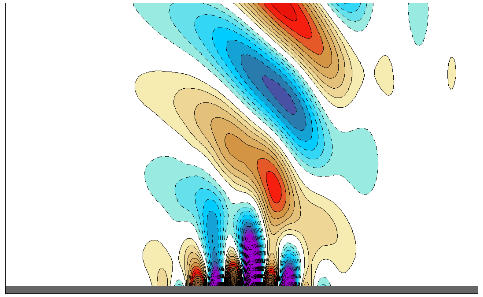
> Additional optimizations [CFL $\xrightarrow{c_s > 300\ m/s}$ $\Delta t \approx 2\ \Delta x$(~~$\Delta z$~~)]

* Vertical diffusion implicit (BTCS/CN)
* Slow terms and θ' in Nsteps-cycle
* Flexible REA-V

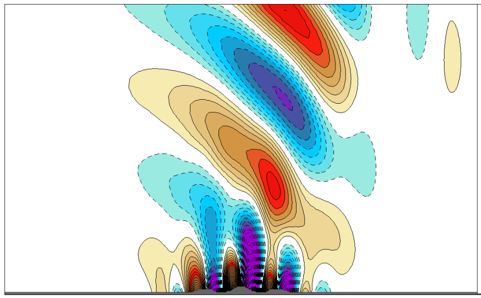
> Schär Mountain Comparison

(dx=250m,dzm=250m,dt=0.75s,Nstep=10,10h)

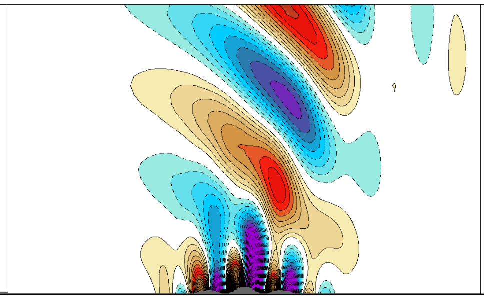
stretch=1



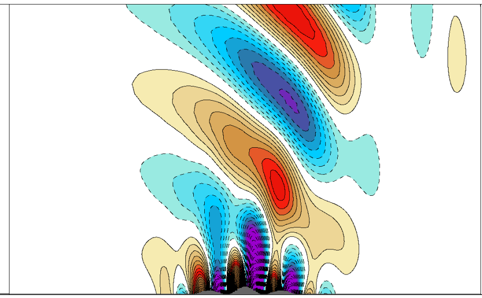
stretch=5



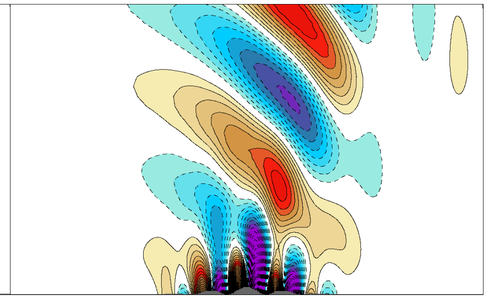
stretch=10



stretch=20

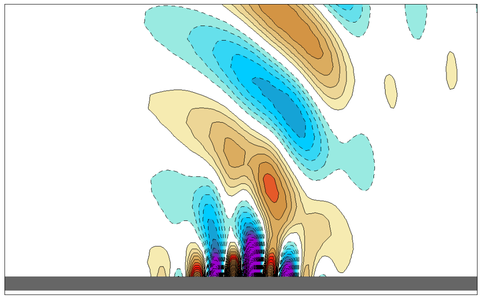


stretch=30

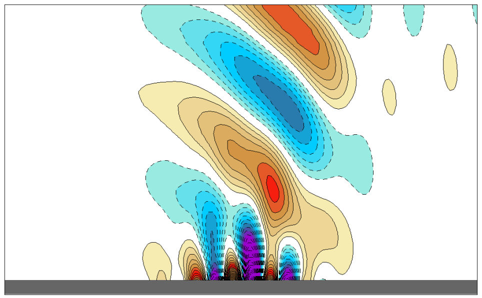


dzm=500m

stretch=1

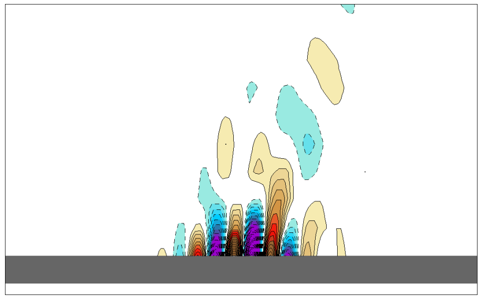


stretch=2

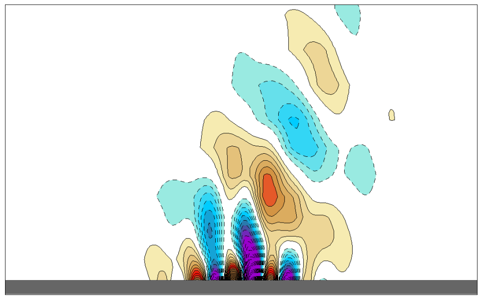


dzm=1000m

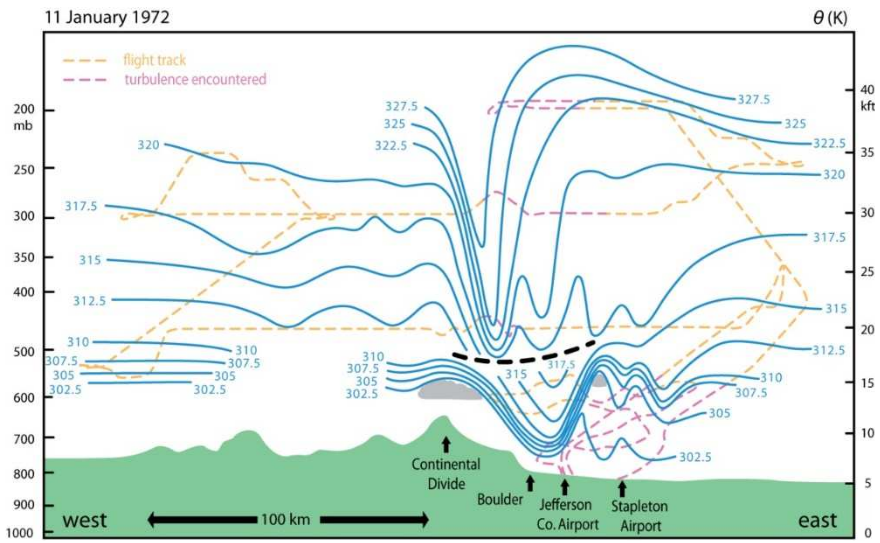
stretch=1



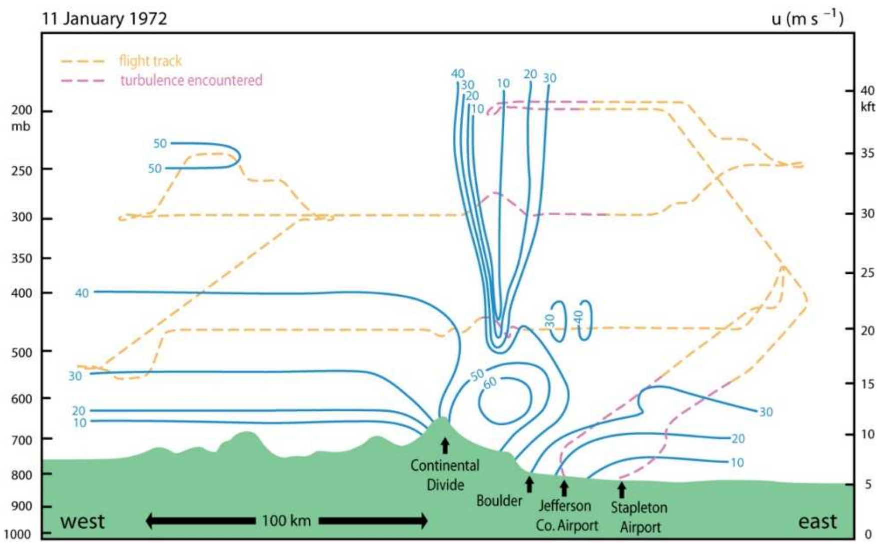
stretch=4



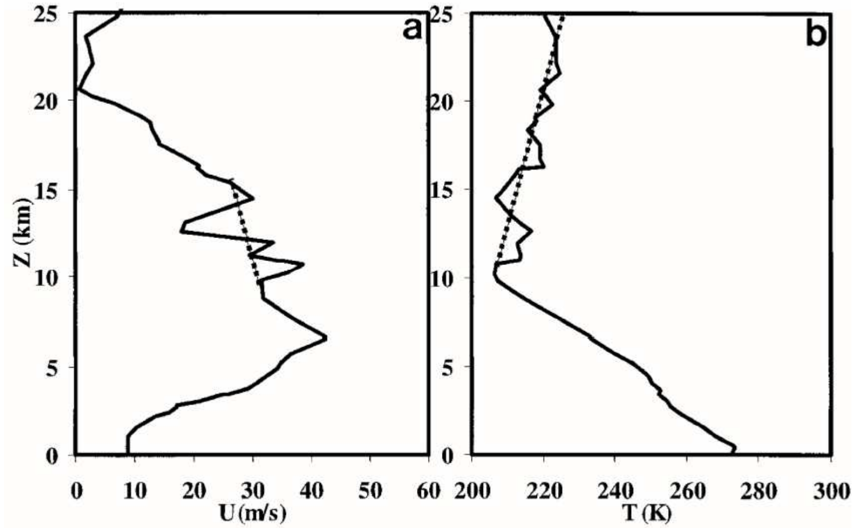
> 11 January 1972 Boulder Windstorm



Klemp and Lilly (1975)

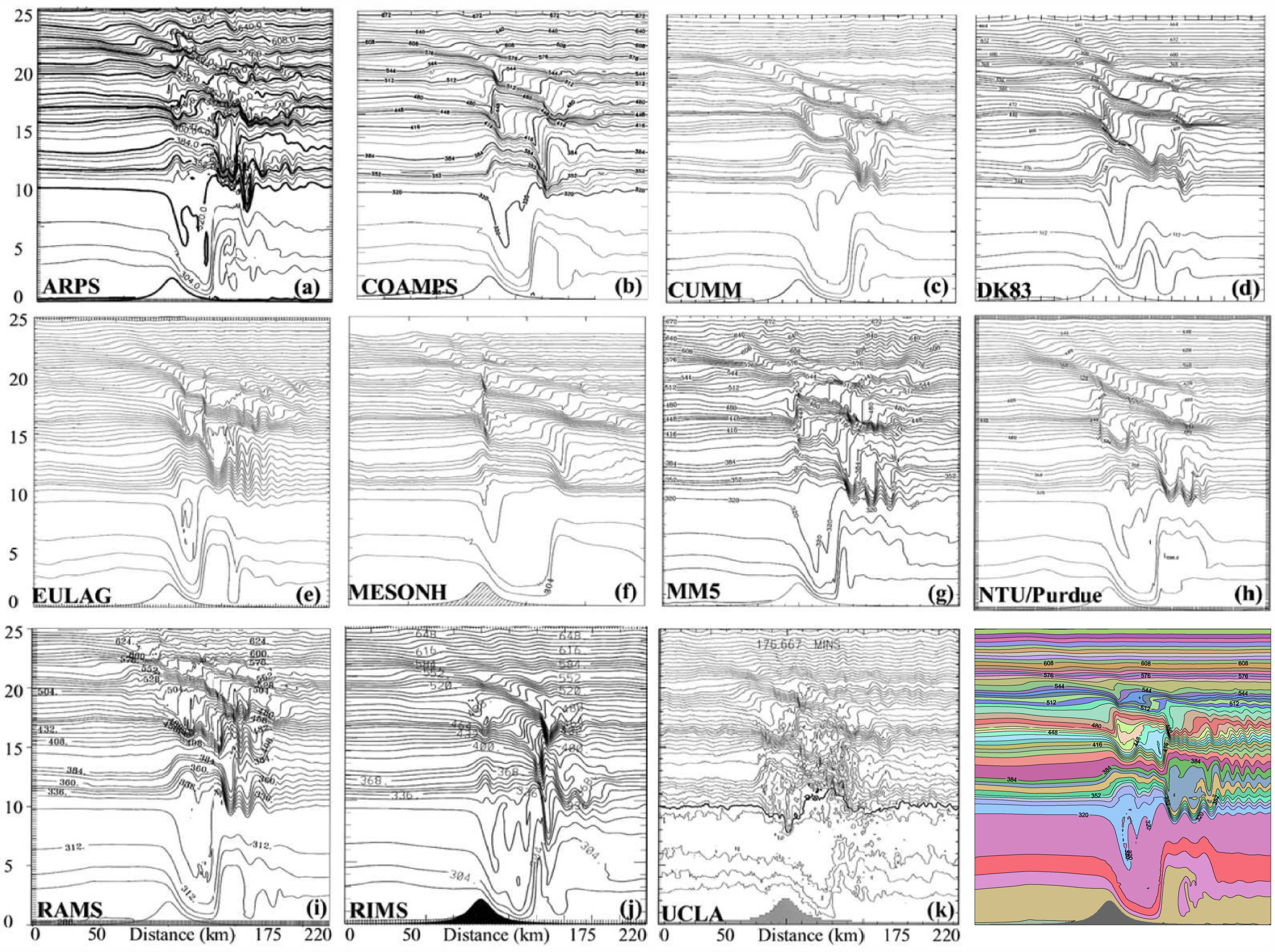


Grand Junction, CO
sounding at 12 UTC



> 11 January 1972 Boulder Windstorm

(dx=500m,dzm=125m,stretch=5,dt=1.5s,Nstep=8,20h)



t=3h

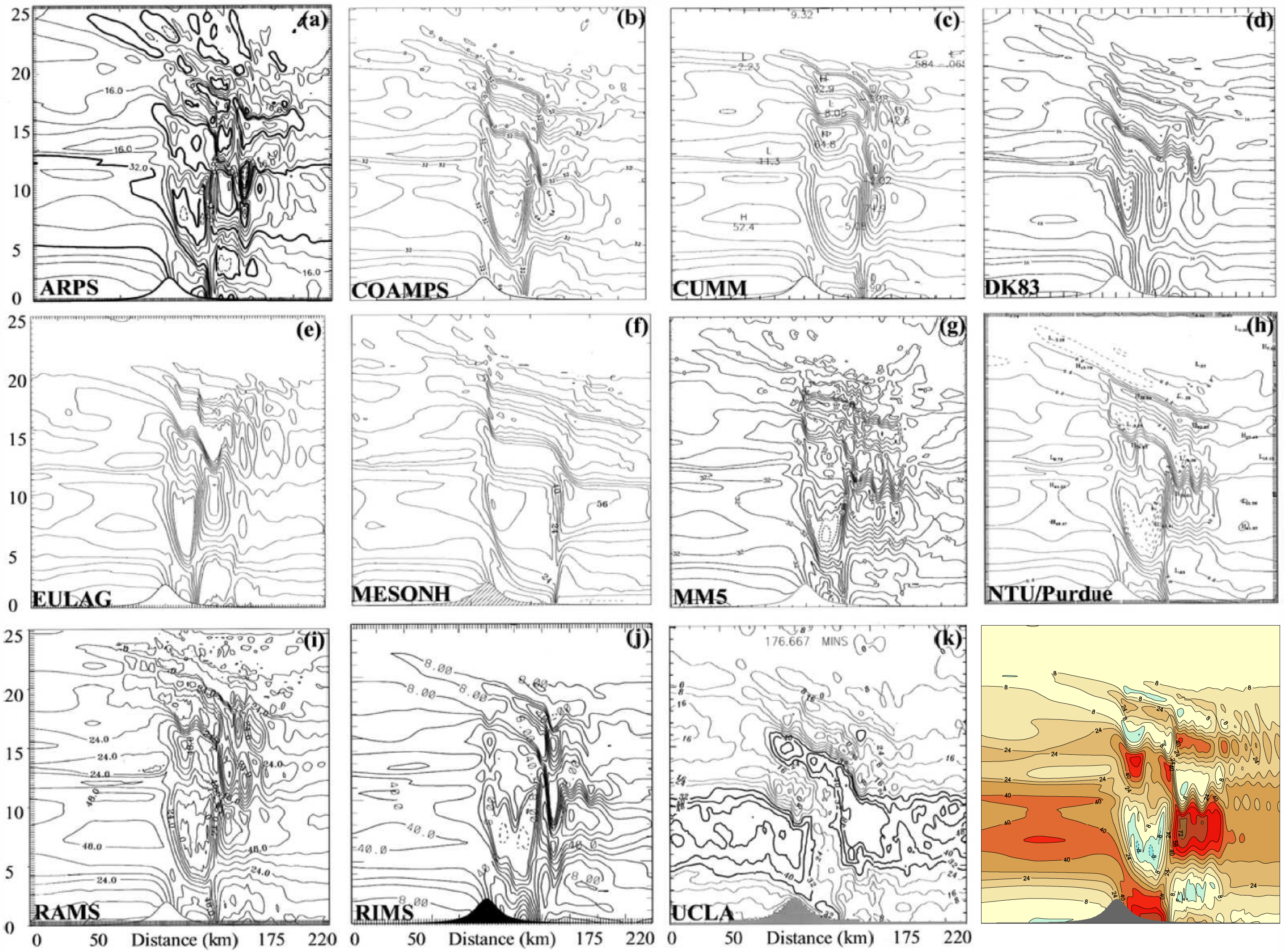
Doyle et al. (2000)

TRAM

ΔM = -0.76 %
ΔE = -0.36 %

> 11 January 1972 Boulder Windstorm

(dx=500m,dzm=125m,stretch=5,dt=1.5s,Nstep=8,20h)



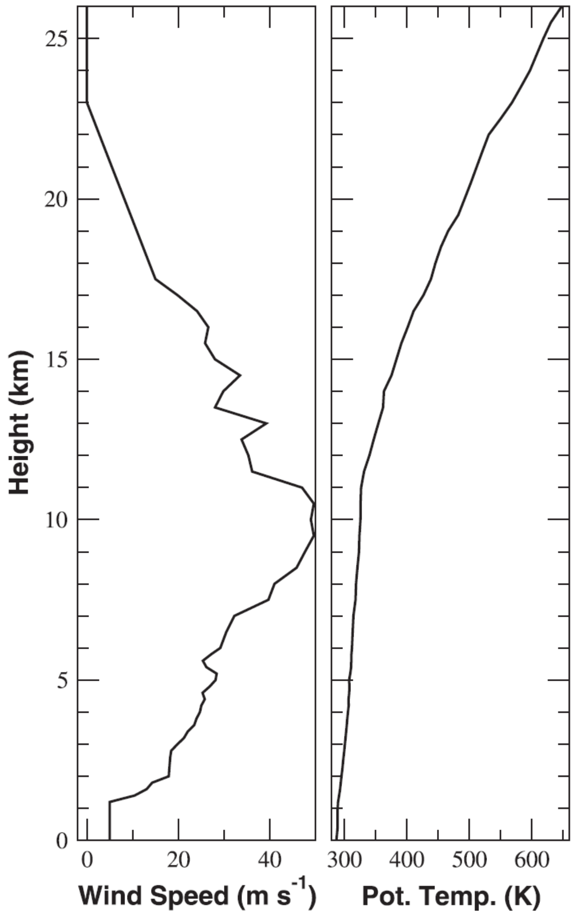
t=3h

Doyle et al. (2000)

TRAM

ΔM = -0.76 %
ΔE = -0.36 %

> T-REX Intense Mountain-Wave



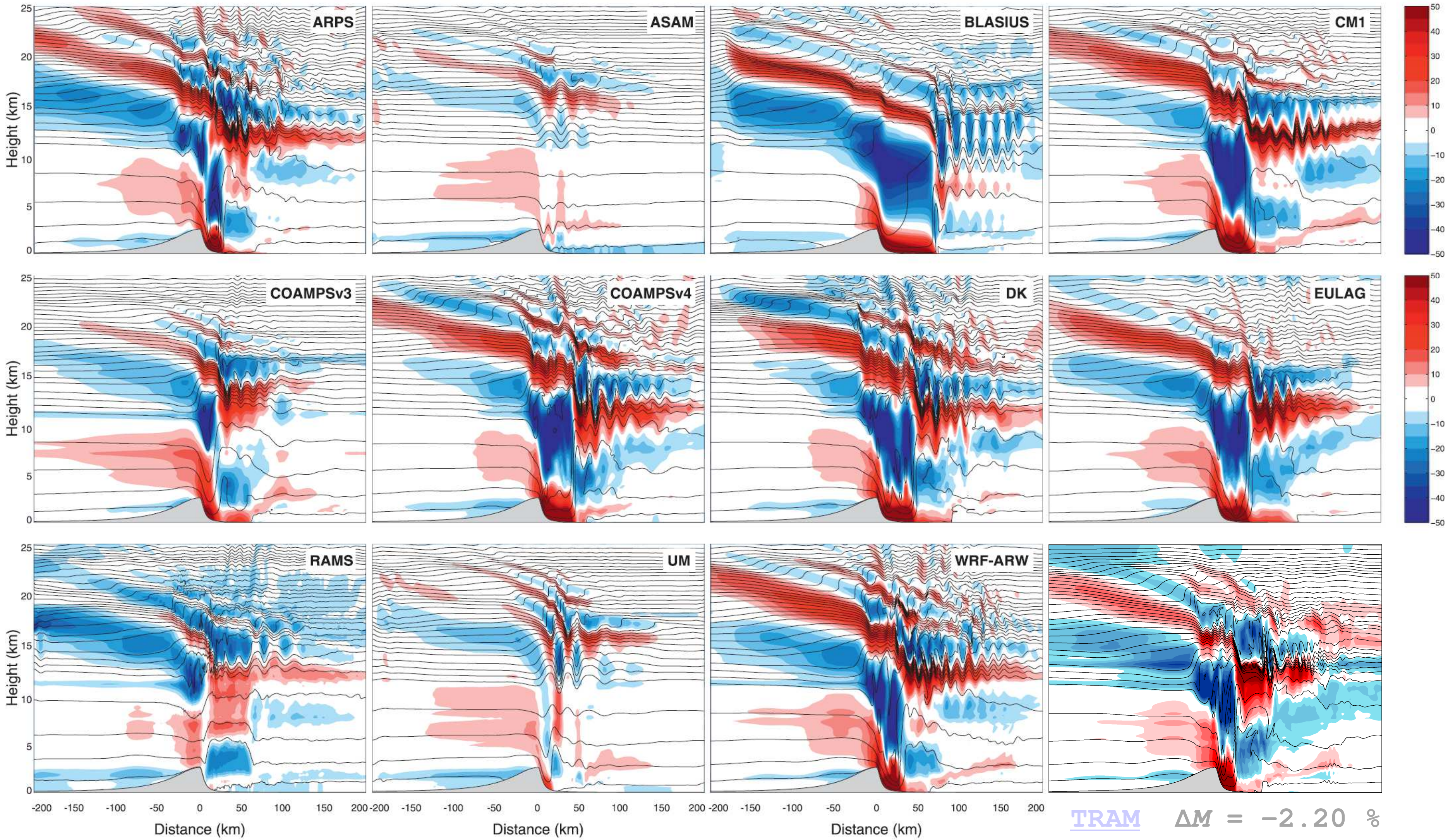
21 UTC 25 Mar 2006
Sounding upstream of the
Sierra Nevada (CA)

> T-REX Intense Mountain-Wave

t=4h

(dx=500m,dzm=100m,stretch=5,dt=1.5s,Nstep=6,20h)

Doyle et al. (2011)



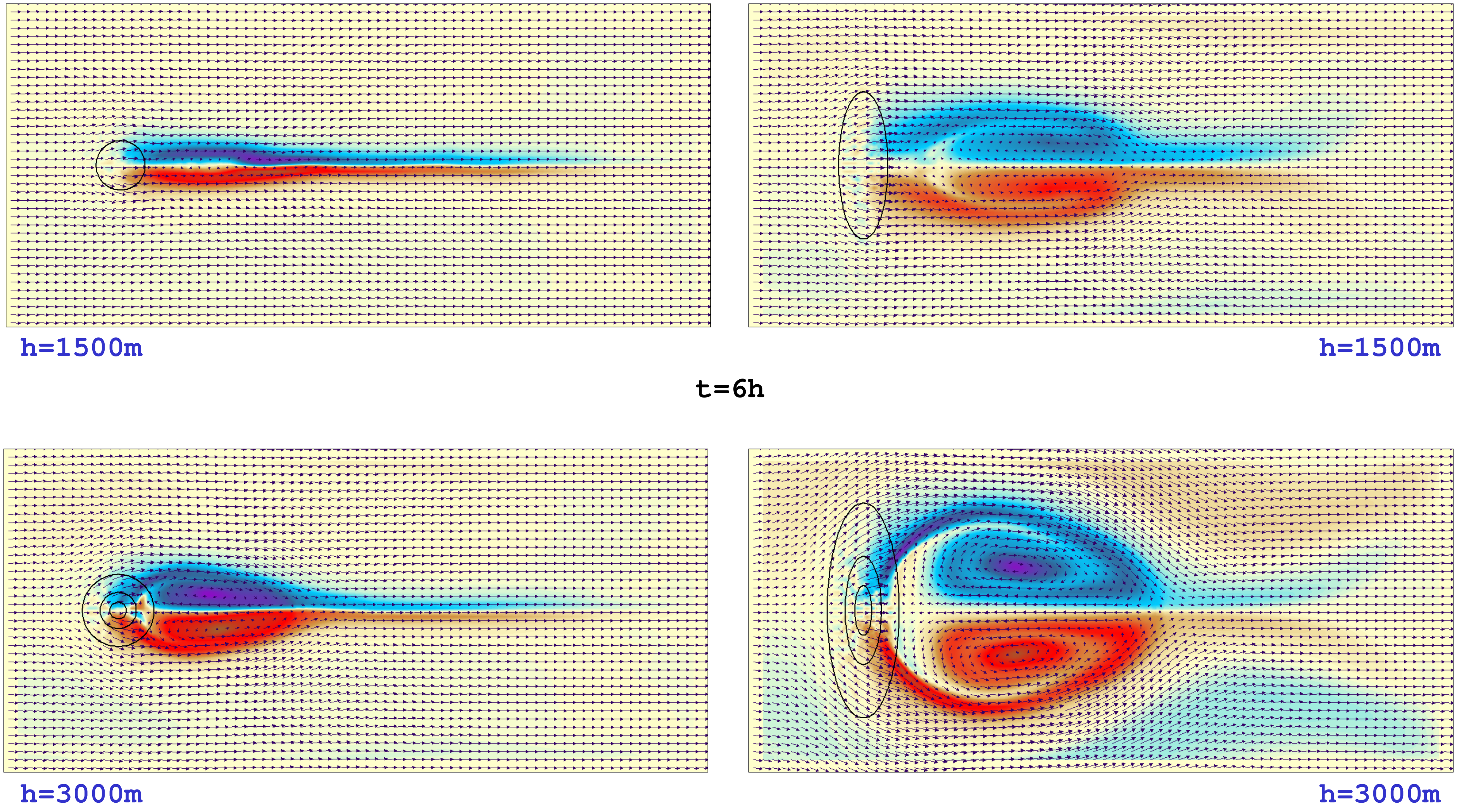
TRAM ΔM = −2.20 %

Anim ΔE = −0.61 %

> Vortices Past Isolated Topography ($U=10ms^{-1}$, $N=0.01s^{-1}$)

(dx=2km, dzm=500m, stretch=2, dt=4s, Nstep=10, 48h)

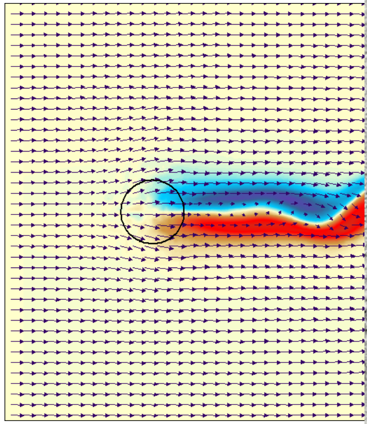
e.g. Schär and Durran (1997)



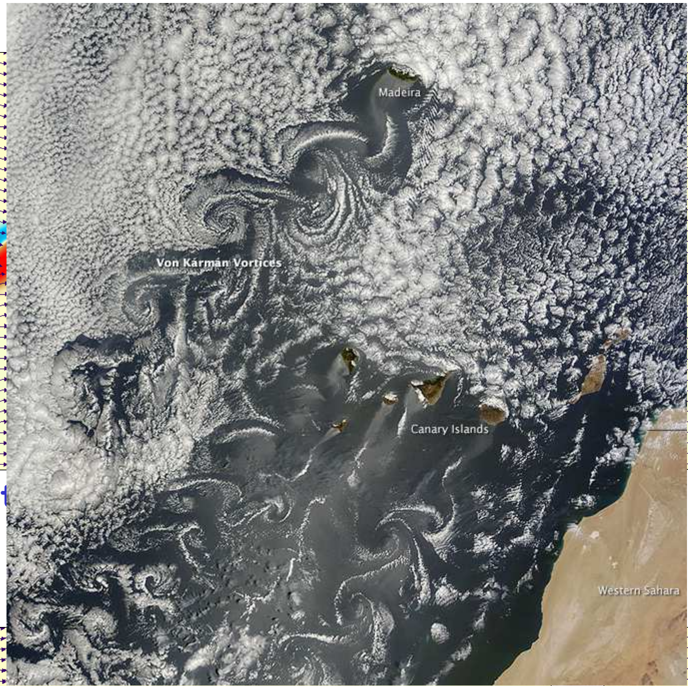
> Von Kármán Vortex Streets ($U=10ms^{-1}, N=0.01s^{-1}$)

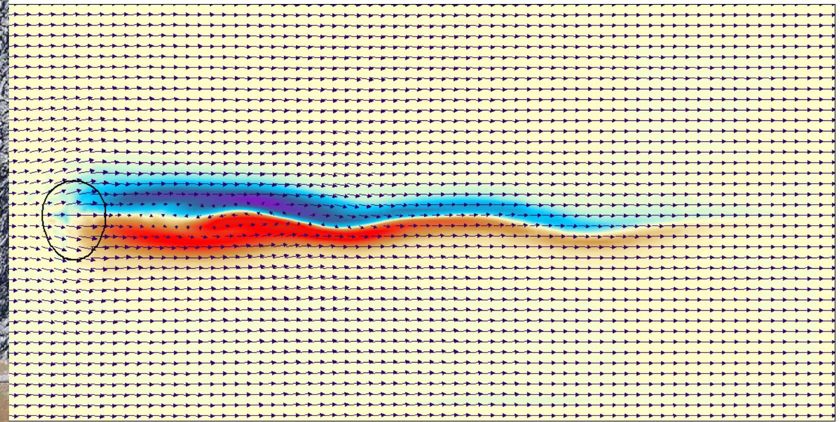
(dx=2km, dzm=500m, stretch=2, dt=4s, Nstep=10, 48h)

e.g. Schär and Durran (1997)

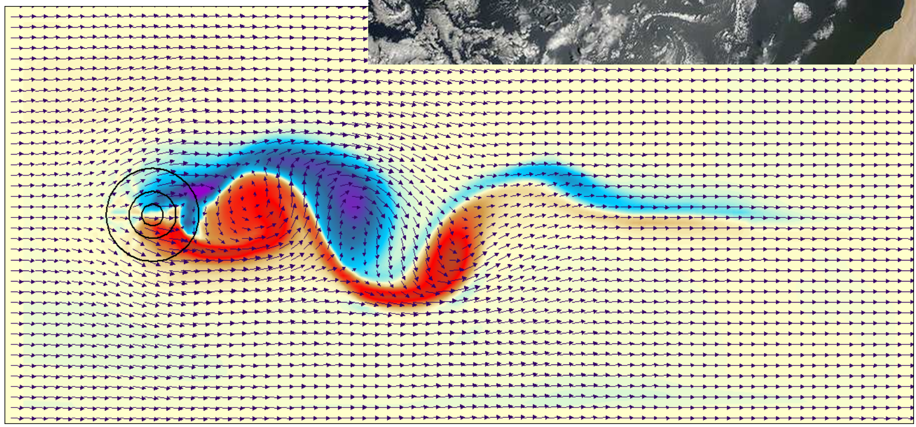


h=1500m (asymmet

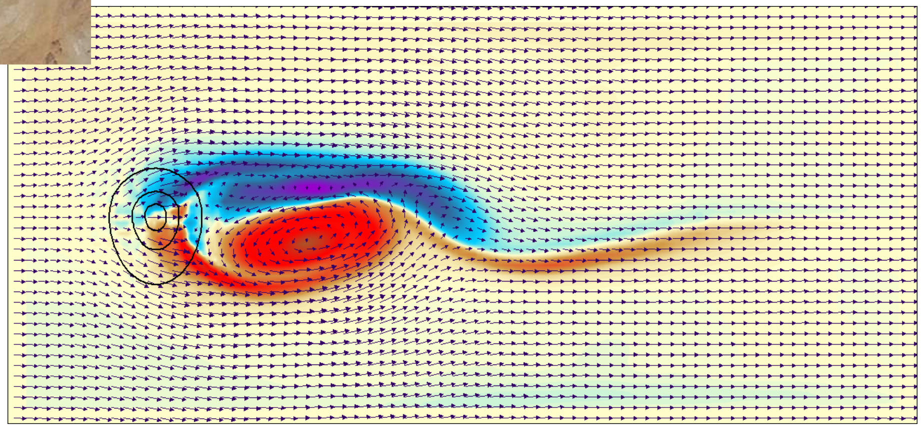




h=1500m



h=3000m (asymmetric I.C)



Animation ΔM = −0.054 %

Tracer ΔE = −0.014 %

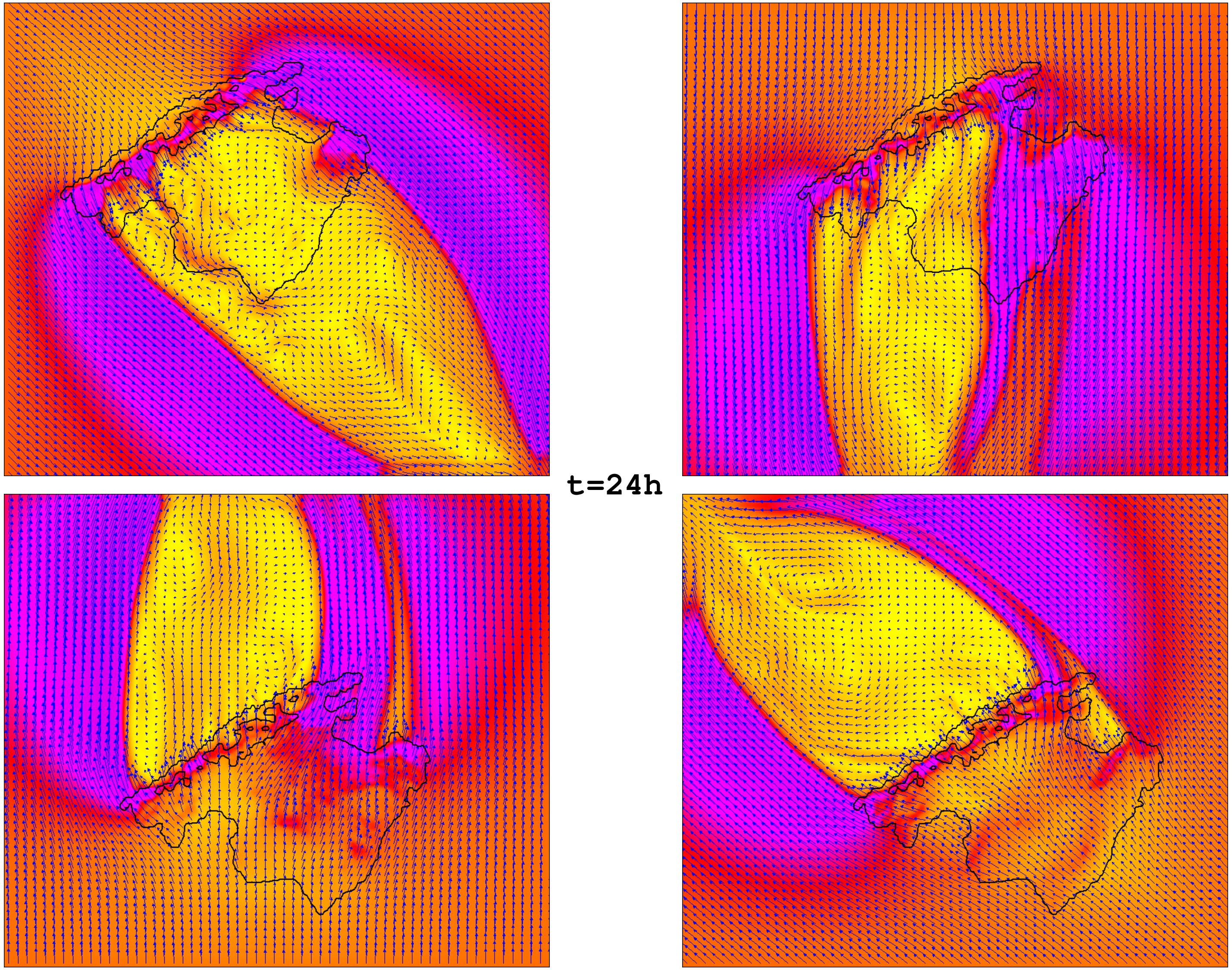
h=3000m

> Idealized Flow over Mallorca ($U=5ms^{-1}$, $N=0.0184s^{-1}$)

(dx=1.5km, dzm=400m, stretch=20, dt=3s, Nstep=10, 24h) ΔM < 0.015 % ΔE < 0.0004 %

Northwest

North



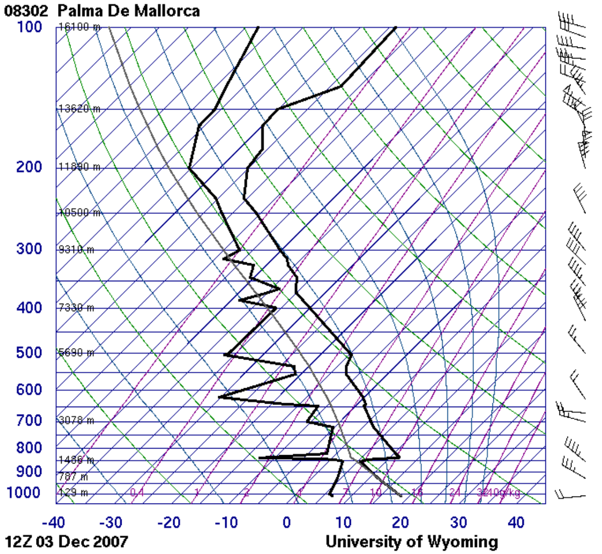
South

Southeast

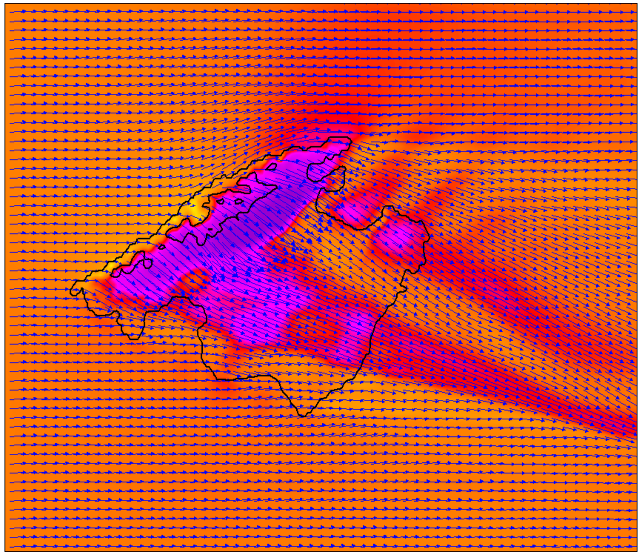
> Sounding-Derived Flow over Mallorca

(dx=1.5km,dzm=400m,stretch=20,dt=3s,Nstep=10,24h)

t=12h

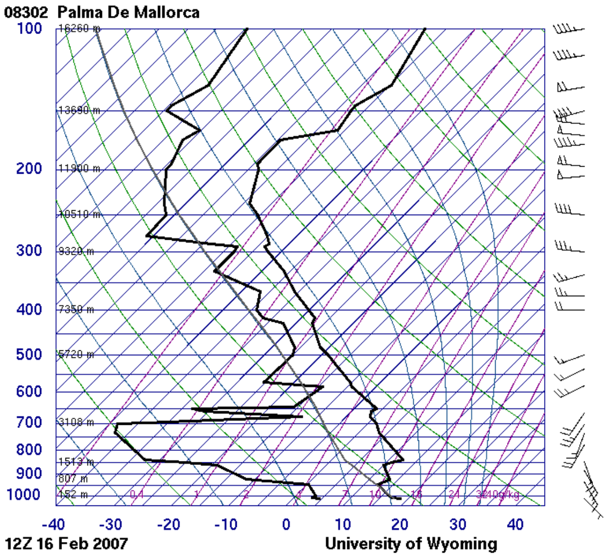


Run

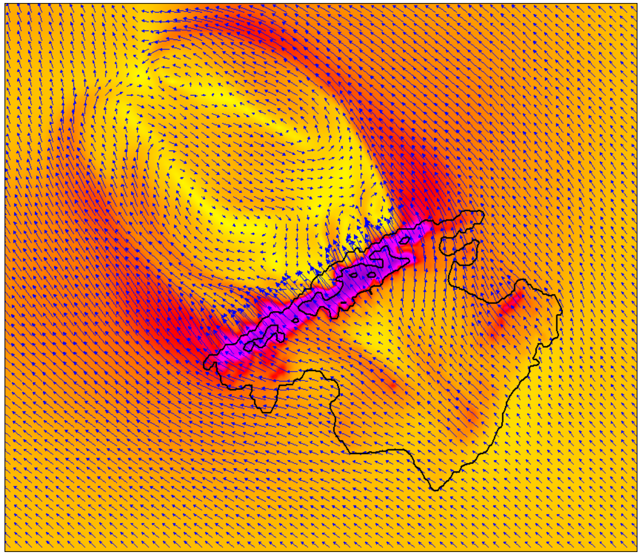


ΔM = −0.059 %

ΔE = +0.0030 %



Run

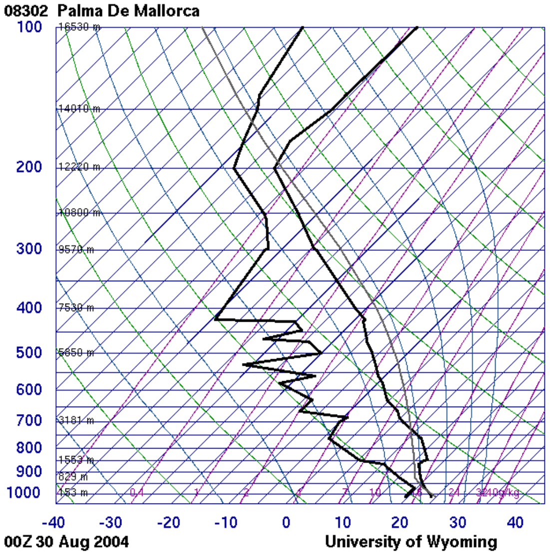


ΔM = −0.027 %

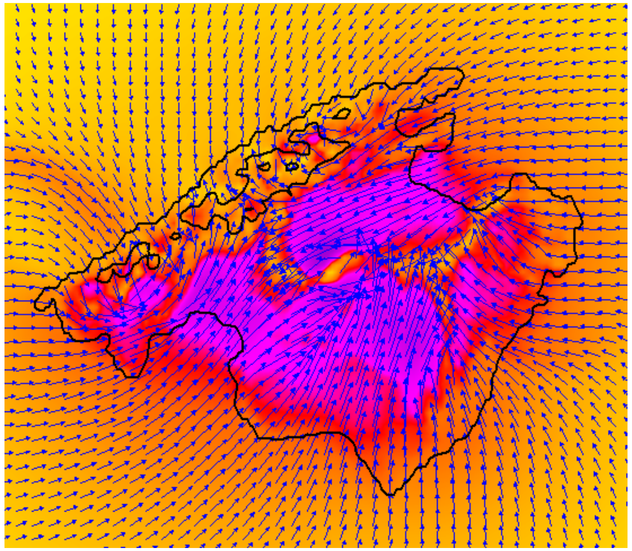
ΔE = +0.0001 %

> Breeze Circulation in Mallorca (θ'_s ,Diffusion θ',Coriolis)

(dx=1.5km,dzm=400m,stretch=20,dt=3s,Nstep=10,24h)



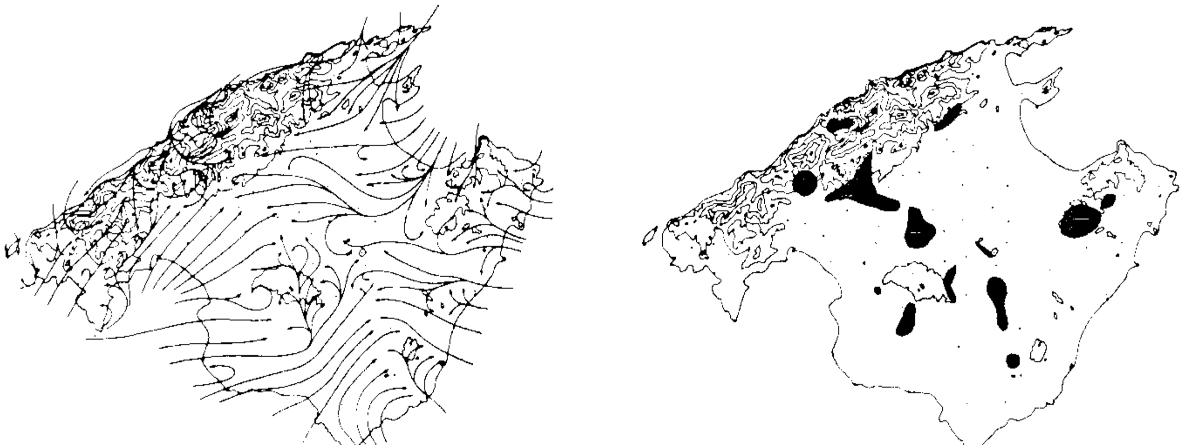
Run



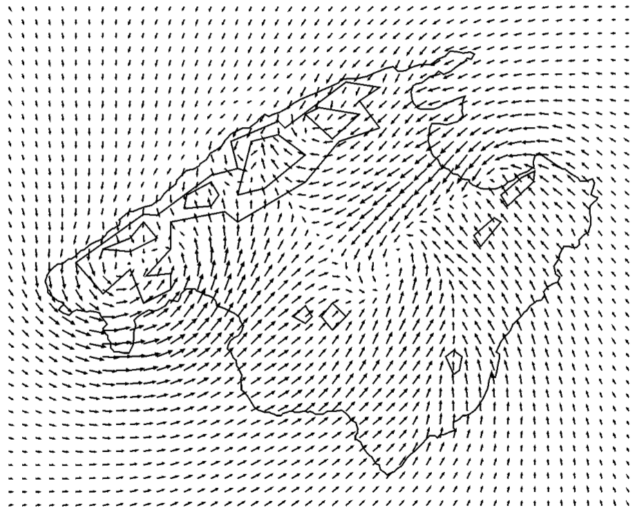
t=13h

ΔM = −0.0013 %

ΔE = +0.00007 %



Jansà & Jaume (1946)

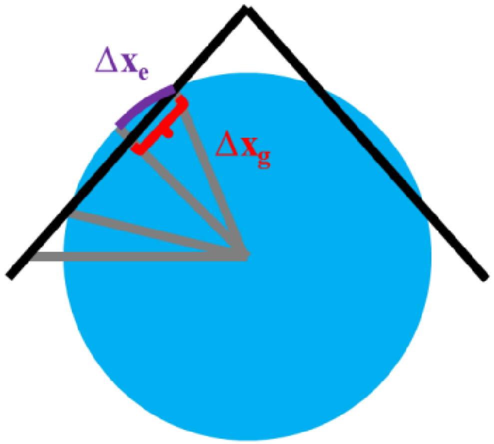


Ramis & Romero (1995)

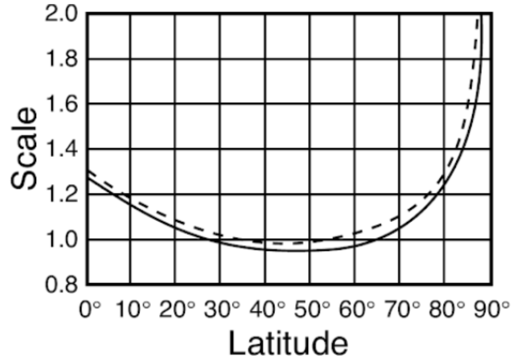
> **Lambert** conformal map projection

  + **Coriolis** terms

  + **Curvature** terms



$$m = \frac{\Delta x_g}{\Delta x_e}$$



> **Modified** equations

$$\frac{\partial \pi'}{\partial t} = -mu\frac{\partial \pi'}{\partial x} - mv\frac{\partial \pi'}{\partial y} - w\frac{\partial \pi'}{\partial z} - w\frac{\partial \bar{\pi}}{\partial z} - \frac{R}{c_v}(\bar{\pi} + \pi')\left[m^2\frac{\partial(\frac{u}{m})}{\partial x} + m^2\frac{\partial(\frac{v}{m})}{\partial y} + \frac{\partial w}{\partial z}\right]$$

$$\frac{\partial \theta'}{\partial t} = -mu\frac{\partial \theta'}{\partial x} - mv\frac{\partial \theta'}{\partial y} - w\frac{\partial \theta'}{\partial z} - w\frac{\partial \bar{\theta}}{\partial z}$$

[Diffusion terms omitted]

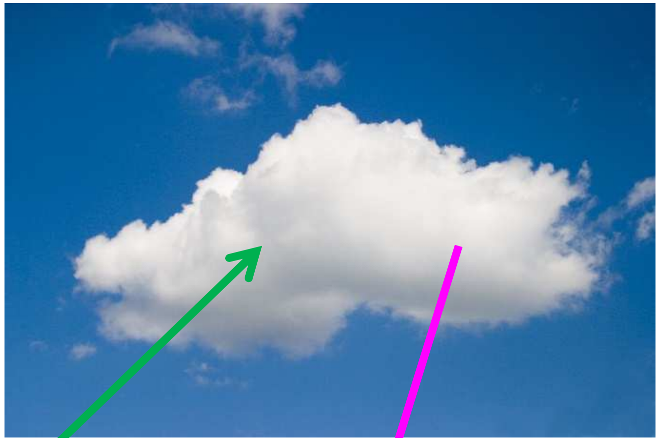
$$\frac{\partial u}{\partial t} = -mu\frac{\partial u}{\partial x} - mv\frac{\partial u}{\partial y} - w\frac{\partial u}{\partial z} - c_p(\bar{\theta} + \theta')m\frac{\partial \pi'}{\partial x} + v\left(f + u\frac{\partial m}{\partial y} - v\frac{\partial m}{\partial y}\right) - \hat{f}w\cos\alpha - \frac{uw}{a}$$

$$\frac{\partial v}{\partial t} = -mu\frac{\partial v}{\partial x} - mv\frac{\partial v}{\partial y} - w\frac{\partial v}{\partial z} - c_p(\bar{\theta} + \theta')m\frac{\partial \pi'}{\partial y} - u\left(f + u\frac{\partial m}{\partial y} - v\frac{\partial m}{\partial y}\right) + \hat{f}w\sin\alpha - \frac{vw}{a}$$

$$\frac{\partial w}{\partial t} = -mu\frac{\partial w}{\partial x} - mv\frac{\partial w}{\partial y} - w\frac{\partial w}{\partial z} - c_p(\bar{\theta} + \theta')\frac{\partial \pi'}{\partial z} + g\frac{\theta'}{\bar{\theta}} + \hat{f}(u\cos\alpha - v\sin\alpha) + \frac{u^2+v^2}{a}$$

Simple Representation of Moist Processes

> **Equations for Water Vapor/Cloud Water Mixing Ratios**



$$\frac{\partial r_v}{\partial t} = -mu\frac{\partial r_v}{\partial x} - mv\frac{\partial r_v}{\partial y} - w\frac{\partial r_v}{\partial z} - \dot{r}_{cond} + \dot{r}_{evap}$$

$$\frac{\partial r_c}{\partial t} = -mu\frac{\partial r_c}{\partial x} - mv\frac{\partial r_c}{\partial y} - w\frac{\partial r_c}{\partial z} + \dot{r}_{cond} - \dot{r}_{evap}$$

> **WV ⇔ CW Parameterization**

$r_v > r_{vsat}$

$r_c > 0$

$r_{vsat} > r_v$

Rutledge & Hobbs (1983):

$$\dot{r}_{cond} \equiv \frac{r_v - r_{vsat}}{\Delta t\left(1 + \frac{L_v^2\, r_{vsat}}{c_p\, R_v\, T^2}\right)} \qquad \dot{r}_{evap} \equiv \frac{r_{vsat} - r_v}{\Delta t\left(1 + \frac{L_v^2\, r_{vsat}}{c_p\, R_v\, T^2}\right)}$$

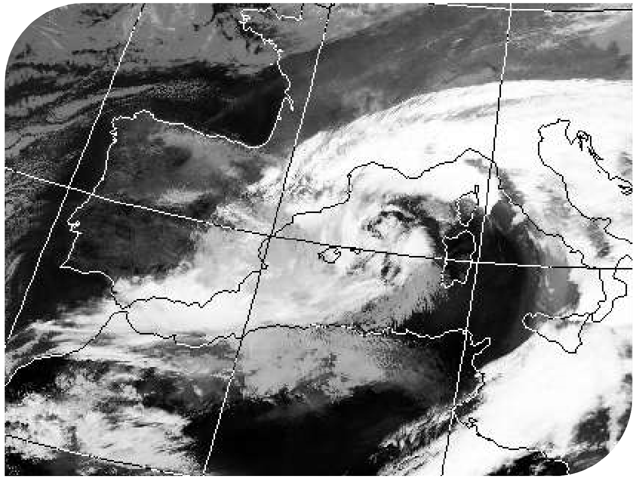
> **NO Precipitation & NO Feedback on Thermodynamics**

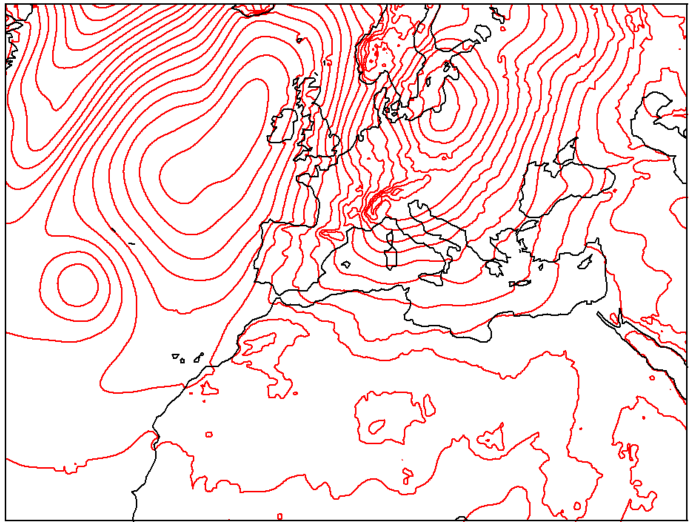
EXAMPLE: **T-REX with RH=90%**

> "SUPERSTORM" Baroclinic Cyclone (IC: 00 UTC 9 Nov 2001)

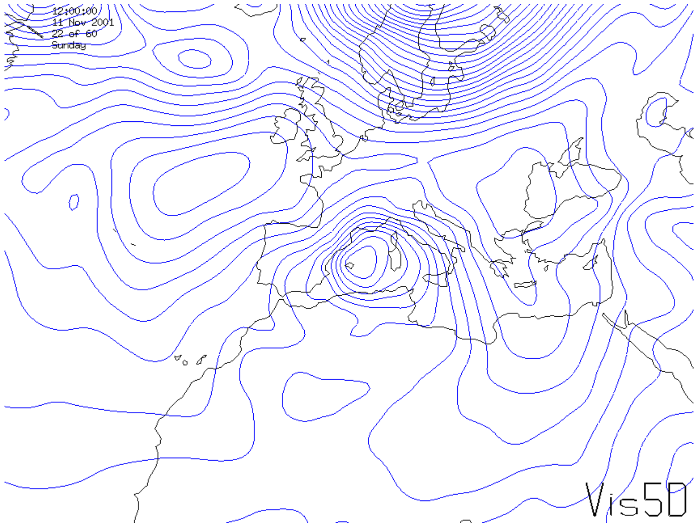
(dx=50km,dzm=200m,stretch=1,dt=75s,Nstep=6,120h)

ΔM = +0.056 % ΔE = +0.071 %

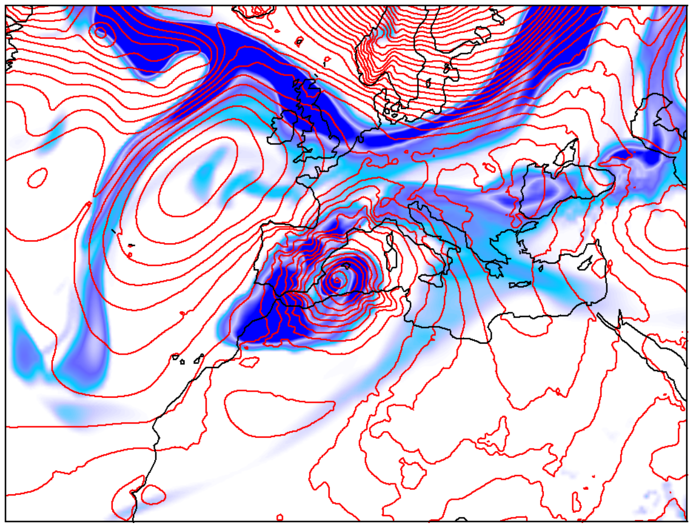




Initial



t=60h



NCEP

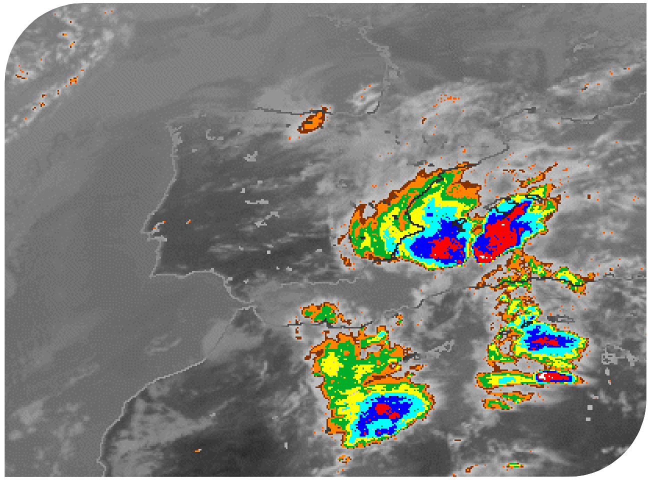
TRAM

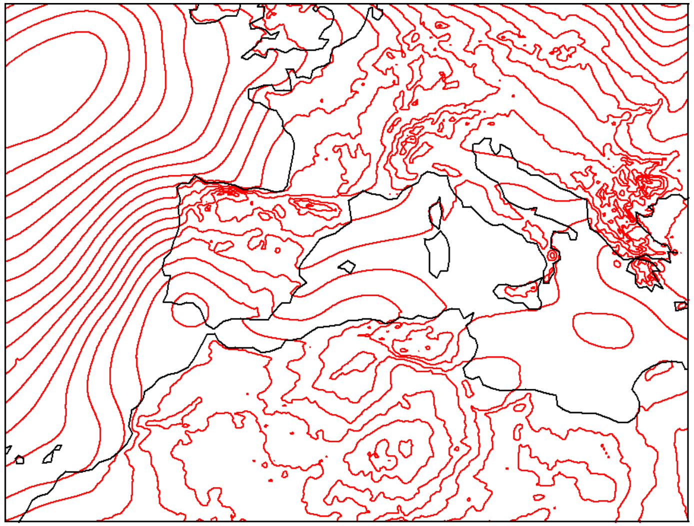
*TRAM_**non_hydro_set1_3D_oroSTRETCH_implicit_MAP***

> "VALENCIA" Flood Episode (IC: 00 UTC 28 Sept 1994)

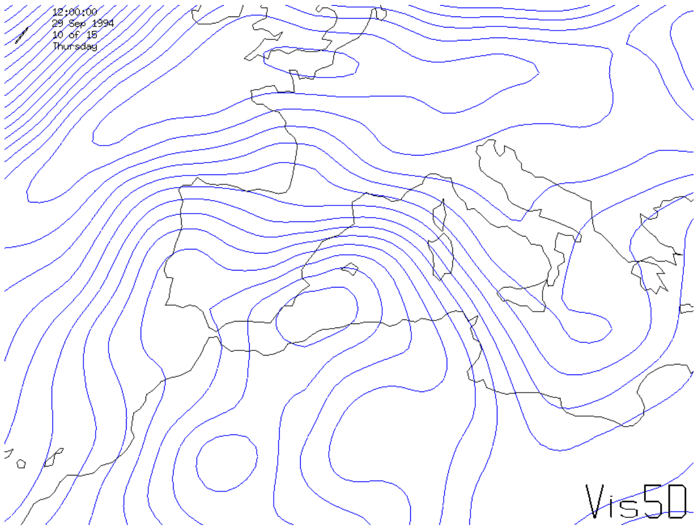
(dx=25km,dzm=200m,stretch=10,dt=40s,Nstep=6,96h)

ΔM = −0.035 % ΔE = +0.200 %

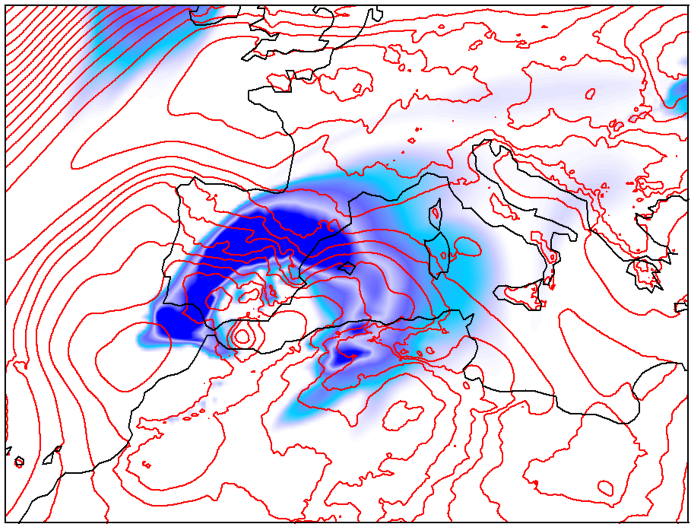




Initial



t=36h



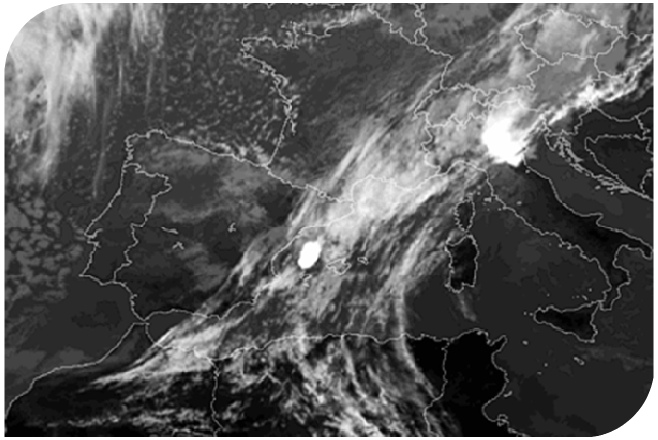
NCEP

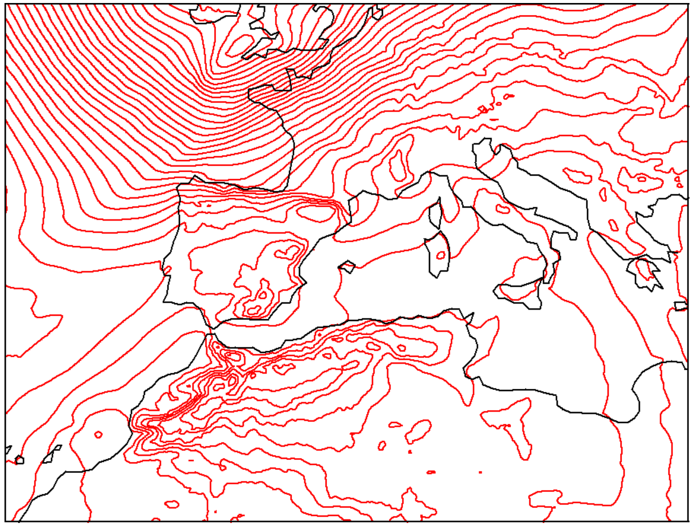
TRAM

> "MALLORCA" Severe Squall Line (IC: 00 UTC 28 Oct 2013)

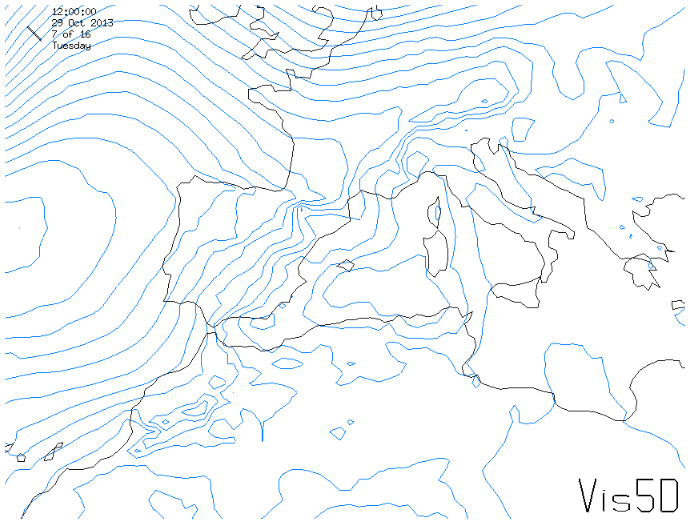
(dx=25km,dzm=200m,stretch=10,dt=40s,Nstep=6,90h)

ΔM = +0.511 % ΔE = +0.075 %



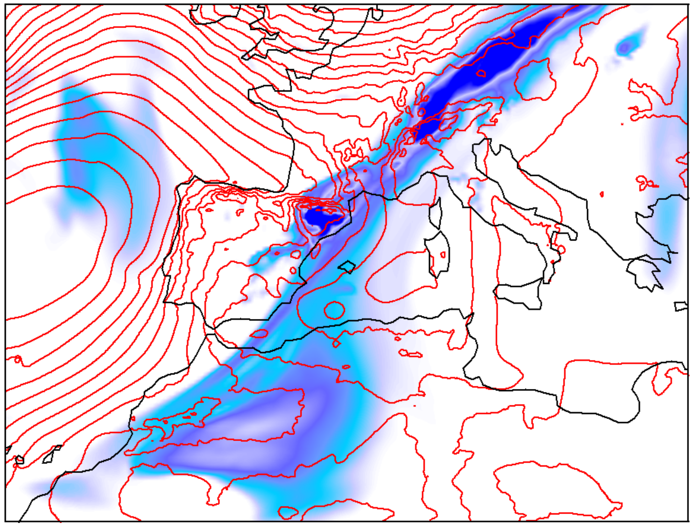


Initial



ECMWF

t=36h



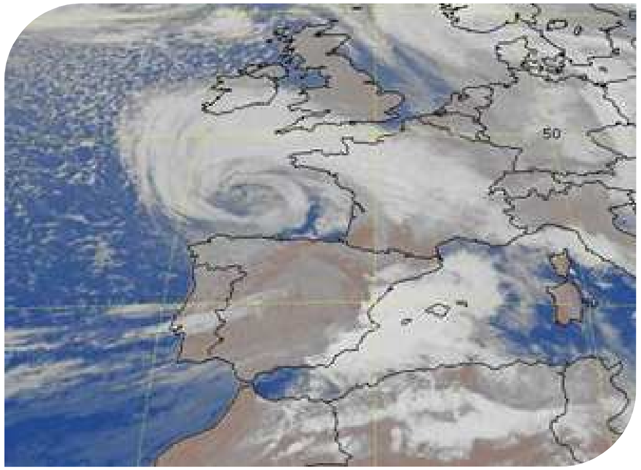
TRAM

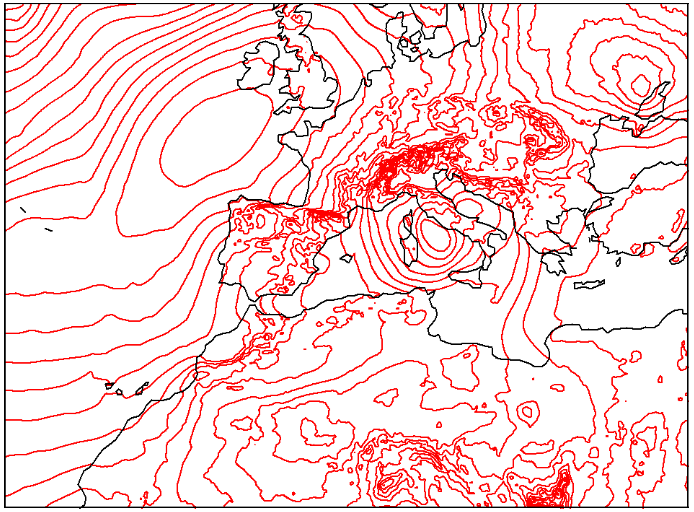
TRAM_non_hydro_set1_3D_oroSTRETCH_implicit_MAP

> "BRUNO" Intense Cyclonic Storm (IC: 00 UTC 21 Mar 2018)

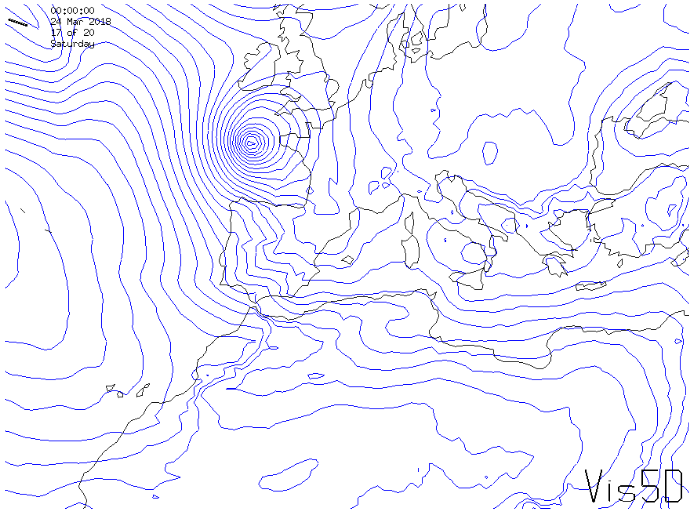
(dx=25km,dzm=200m,stretch=10,dt=40s,Nstep=6,90h)

ΔM = −0.533 % ΔE = −0.285 %

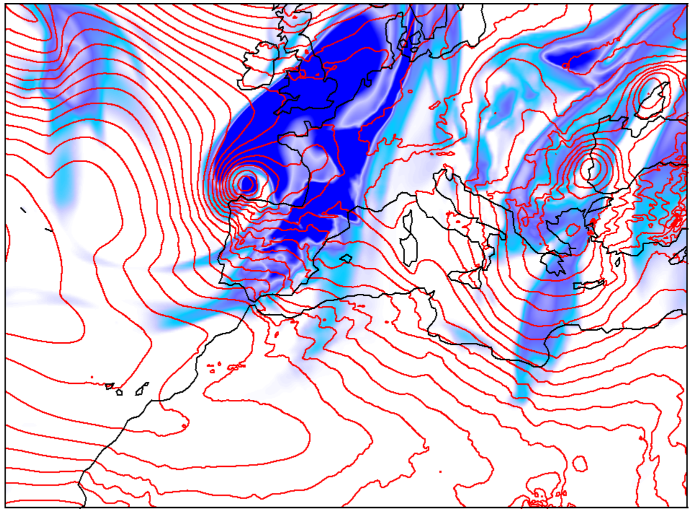




Initial



t=72h



ECMWF

TRAM

CONCLUSIONS

> **NEW MODEL** achieved (at present just dynamical core) **SUITABLE** to simulate processes ranging from small-scale thermal bubbles **(≈ 10 m)** to synoptic-scale baroclinic ciclones **(≈ 1000 km)**, including orographic circulations

> **MAIN CHARACTERISTICS:** Advection form under REA approach (mass & energy not strictly conserved); Fully compressible & Non hydrostatic; Time-splitting strategy; Vertically semi-implicit; Triangle-based horizontal mesh (no staggering); Z-coordinate (no staggeging) allowing arbitrary stretching (proper treatment of slopes and bottom BCs); Lambert projection with all Coriolis and curvature terms retained; No explicit filters needed

> A variety of comparison tests showed that **TRAM PERFORMS AT LEAST AS WELL** as state-of-the-art models

NEXT STEPS

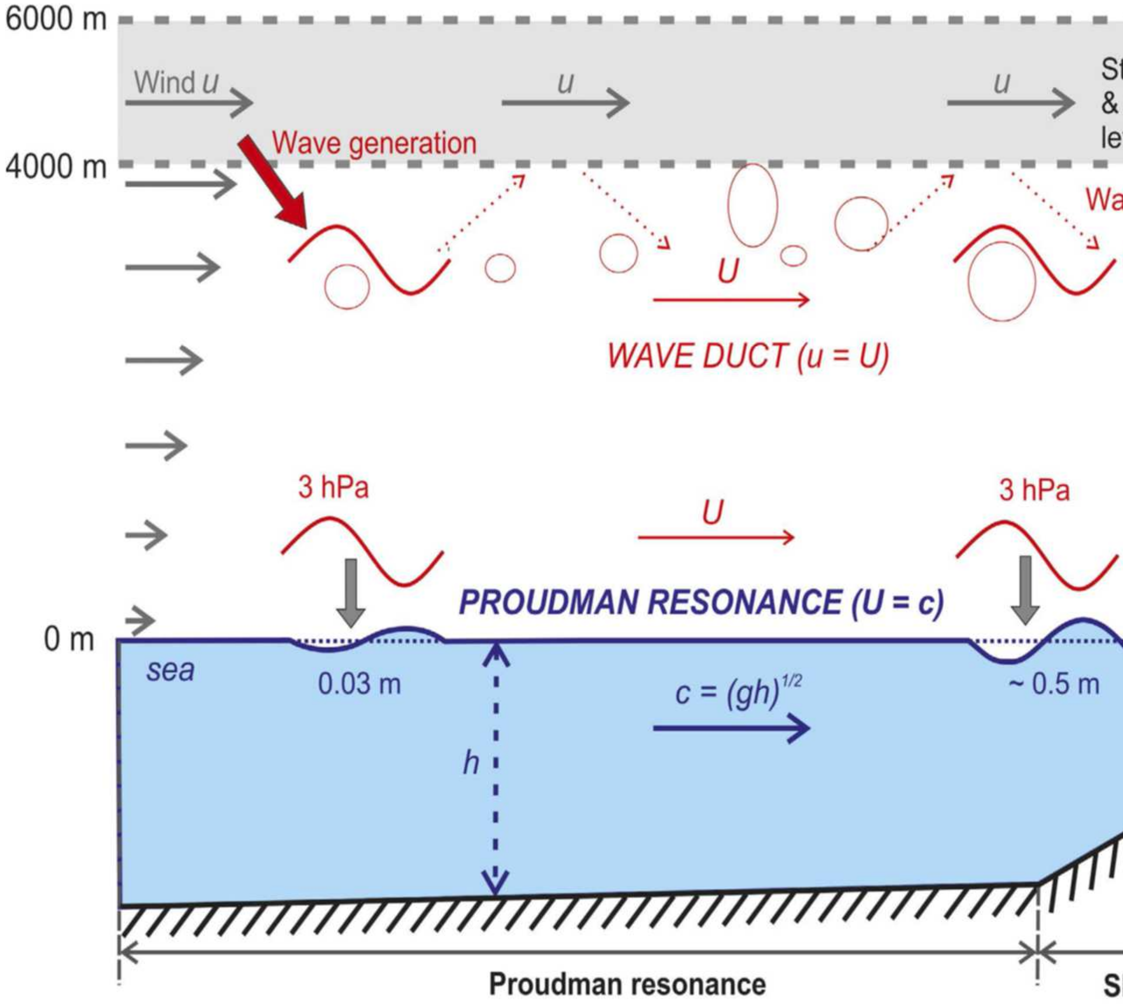
> COMPLETE TRAM with appropriate PHYSICS package (fast approach: WRF-based parameterization schemes); Reexamine the real cases and consider new tests (e.g. simulation of convective & precipitation systems)

> OPTIMIZE THE PERFORMANCE (i.e. reduce running times) of TRAM in our computer platforms, beyond the current adaptation to shared-memory systems using the OpenMP directives

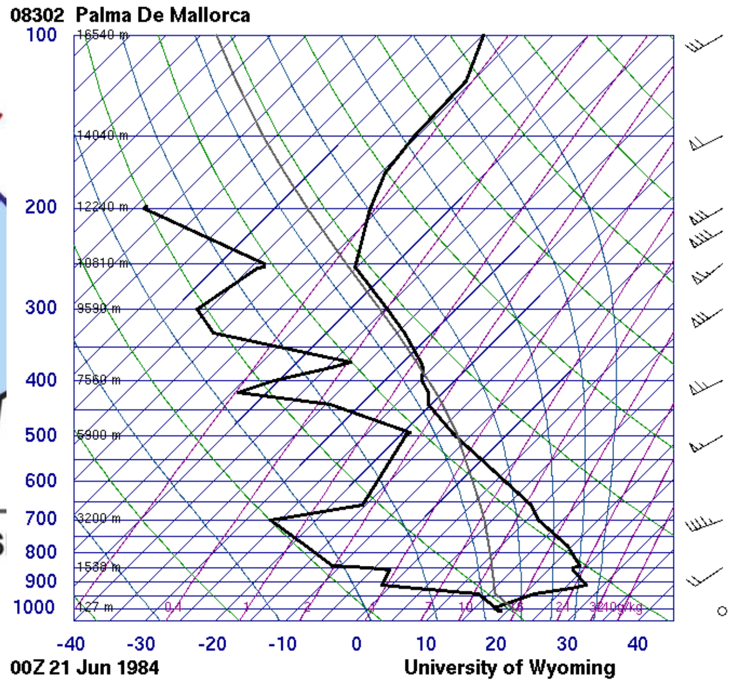
> EXPLOIT THE CAPABILITIES of the new tool in the academic and research arena, with particular focus on regional problems (e.g. "Rissaga Study")

> "Rissaga" Study

(dx=250m,dzm=250m,stretch=5,dt=0.75s,Nstep=10,24h)



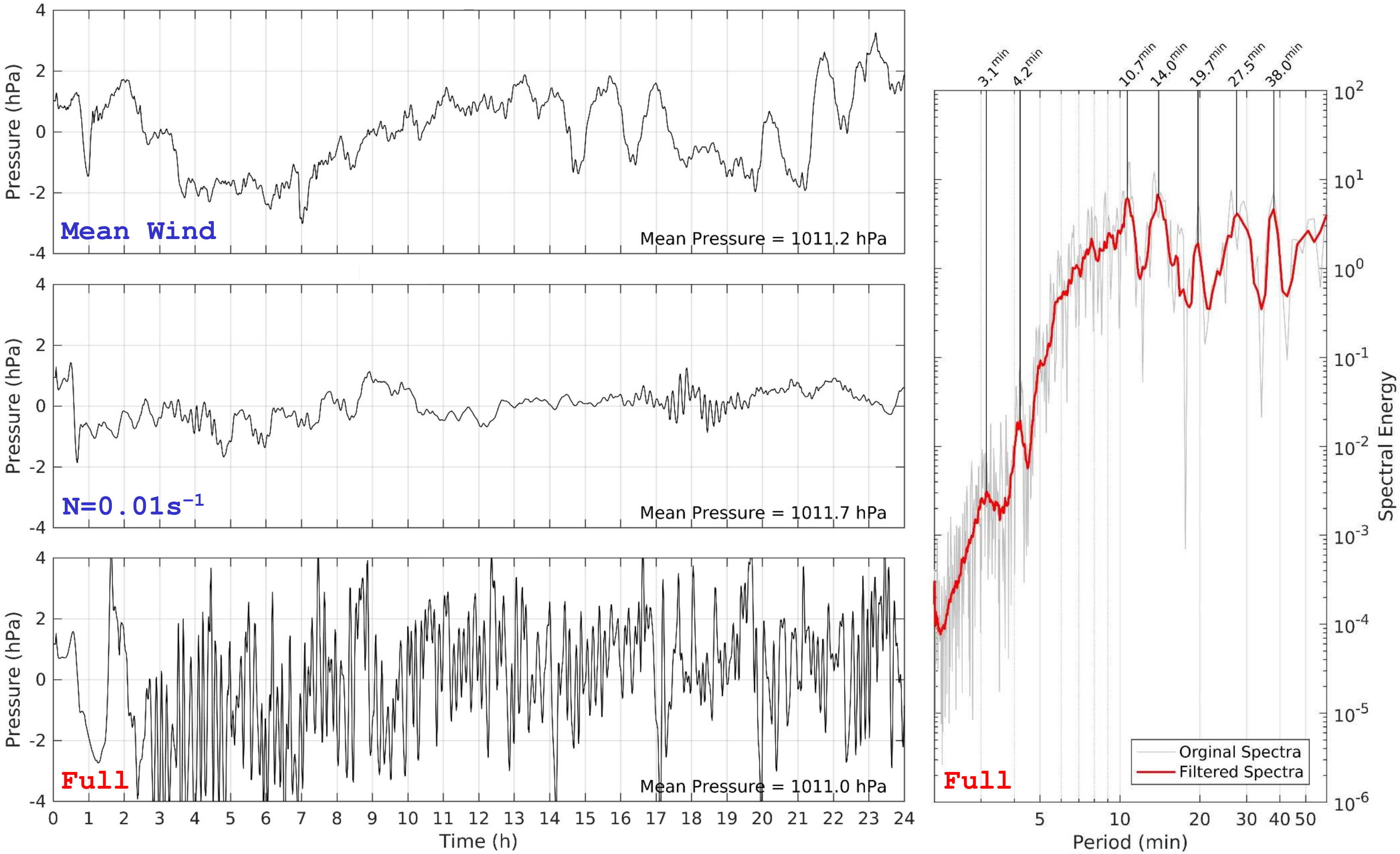
Run



Šepić et al. (2015)

> "Rissaga" Study

(dx=250m,dzm=250m,stretch=5,dt=0.75s,Nstep=10,24h)



THANK YOU

for

your attention