TRAM:

The New Numerical Model of Meteo-UIB Suited for All Kinds of Regional Atmospheric Predictions

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RESEARCH ARTICLE

TRAM: A new non-hydrostatic fully compressible numerical model suited for all kinds of regional atmospheric predictions

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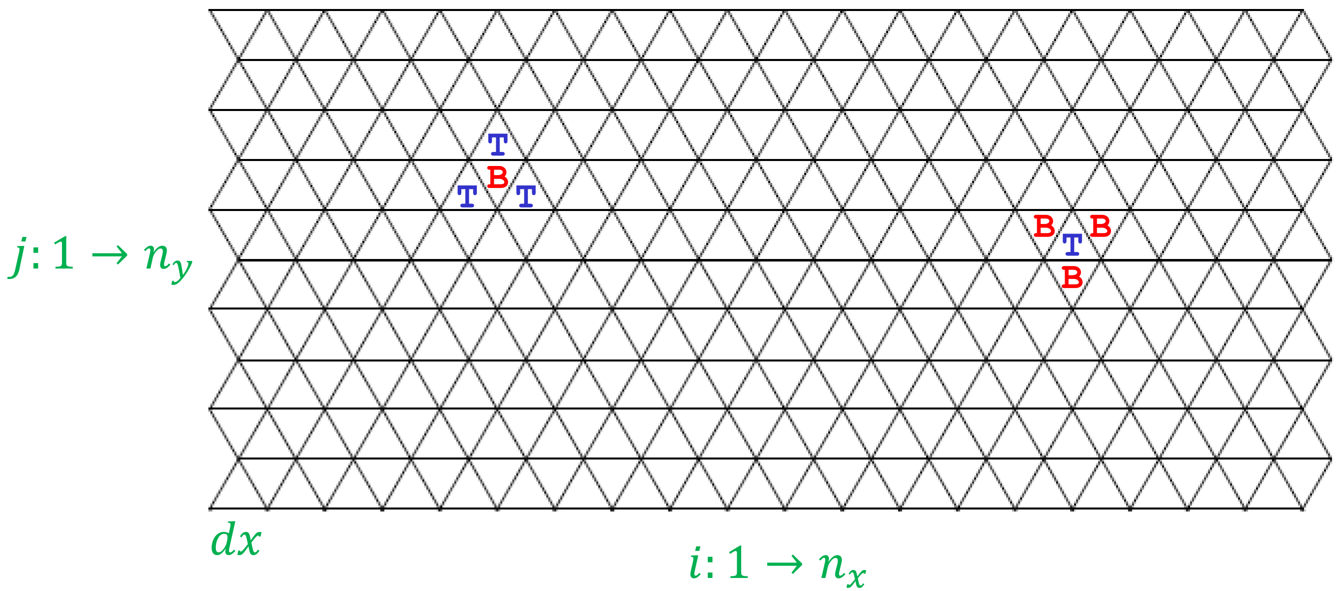
Abstract

A new limited-area numerical model (TRAM, for Triangle-based Regional Atmospheric Model) has been built using a non-hydrostatic and fully compressible version of the Navier–Stokes equations. Advection terms are solved using a Reconstruct–Evolve–Average (REA) strategy over the computational cells. These cells consist of equilateral triangles in the horizontal. The classical *z*-coordinate is used in the vertical, allowing arbitrary stretching (e.g., higher resolution in the Planetary Boundary Layer, PBL). Proper treatment of terrain slopes in the bottom boundary conditions allows for accurately representing the orographic forcing. To gain computational efficiency, time splitting is used to integrate fast and slow terms separately and acoustic modes in the vertical are solved implicitly. For real cases on the globe, the Lambert map projection

> Triangular-based mesh



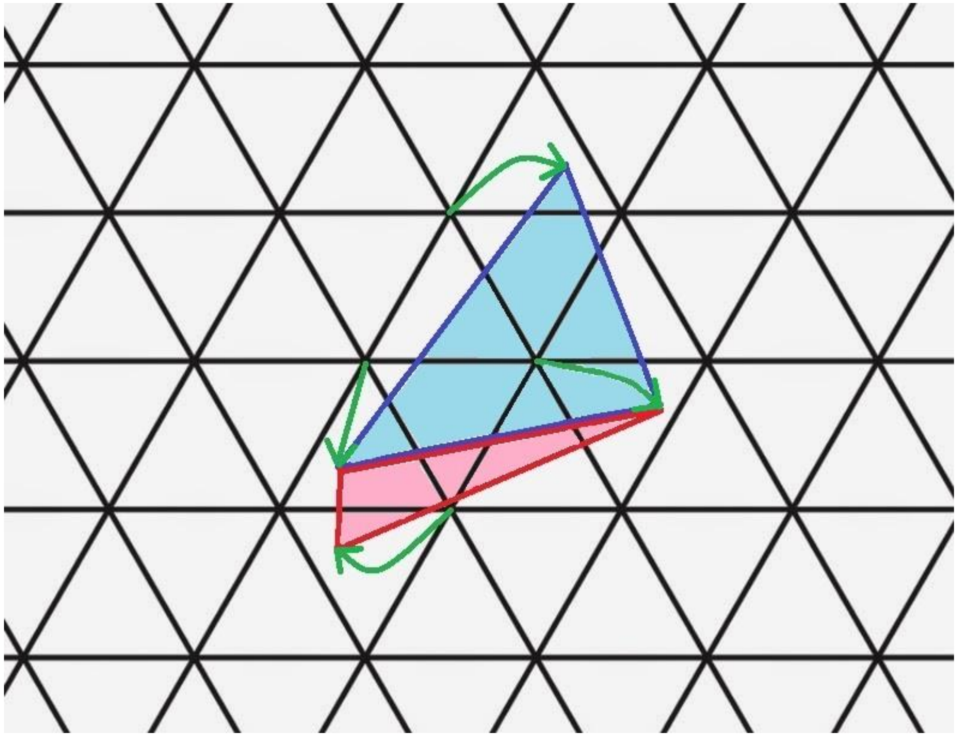
> Actual resolution (square-based domain) is $\approx \frac{2}{3} dx$

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

Non-Hydrostatic Fully-Compressible Equations

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

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

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

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

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

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

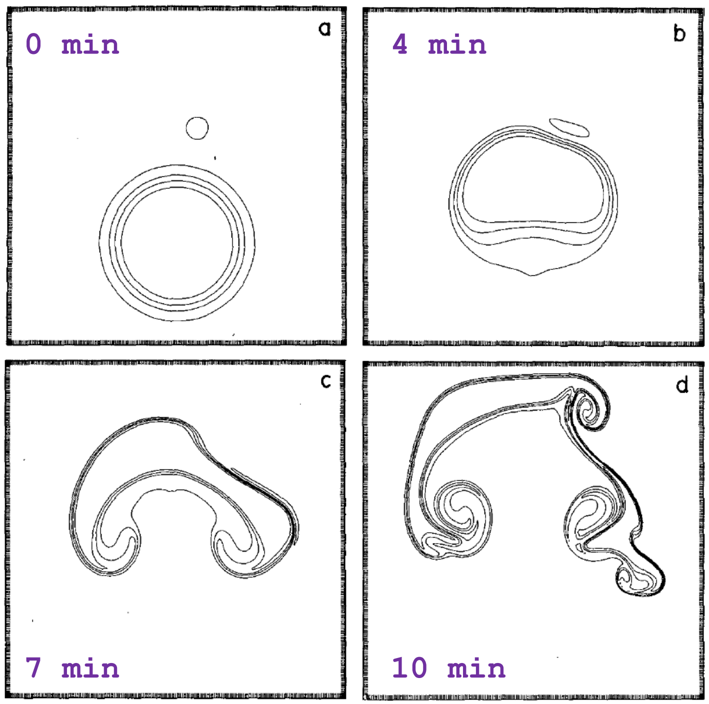
> **Numerical implementation 3D** [CFL $\xrightarrow{c_s > 300\ m/s}$ $\Delta t \approx 2\ \Delta x(\Delta z)$]

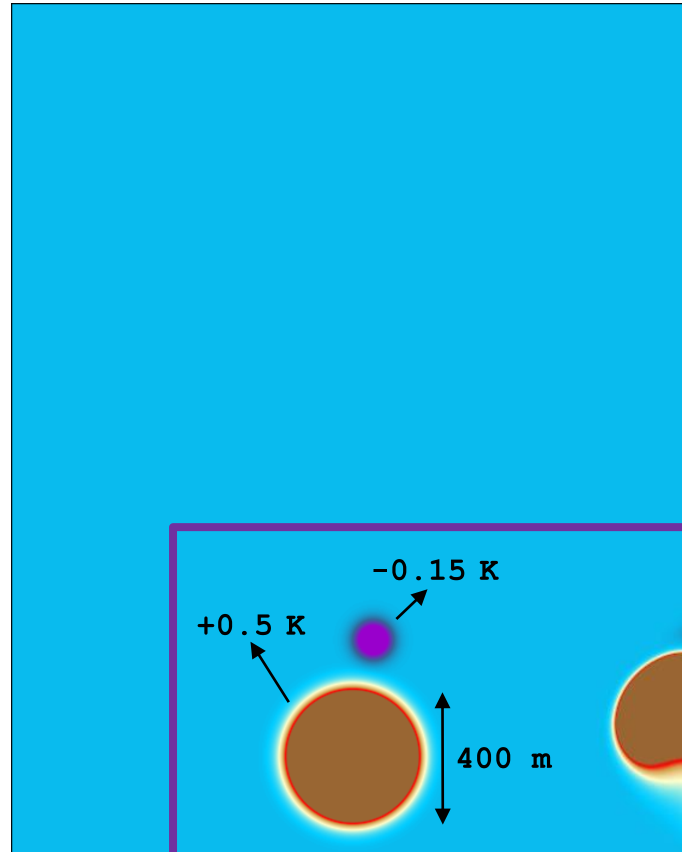
* Forward-Backward integration of "forcings" in RK2 cycle
* REA (V and H) integration of advection every 6-10 Nsteps
* Rigid Wall BCs at W/E S/N B/T boundaries

> Large Warm & Small Cold Bubbles

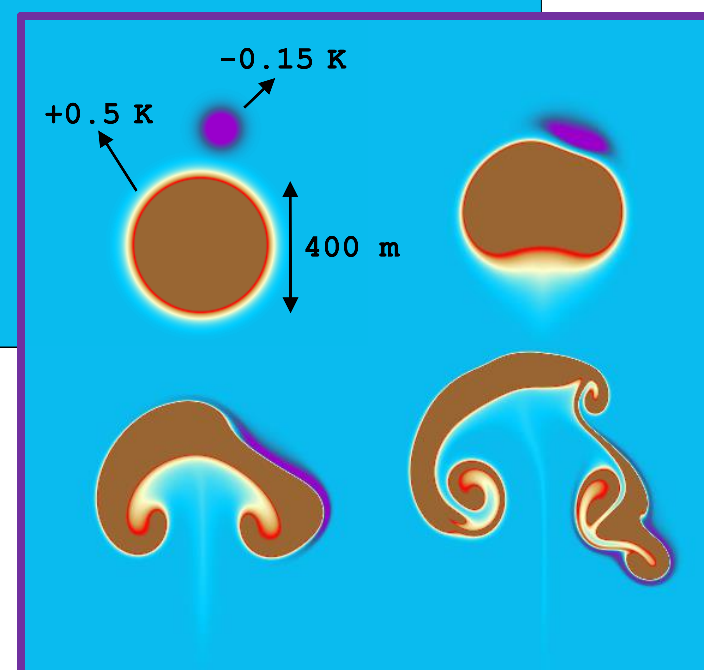
(dx=dz=2.5m,dt=0.00625s,Nstep=10,40min)

Robert (1993)





Initial



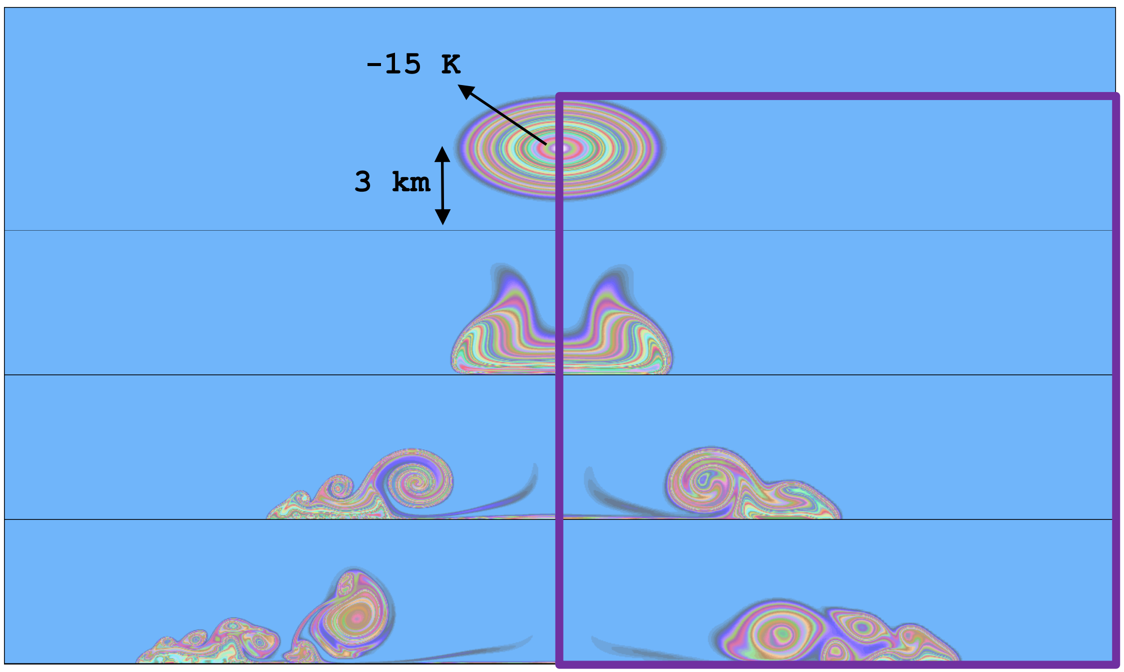
Animation

> Density Current

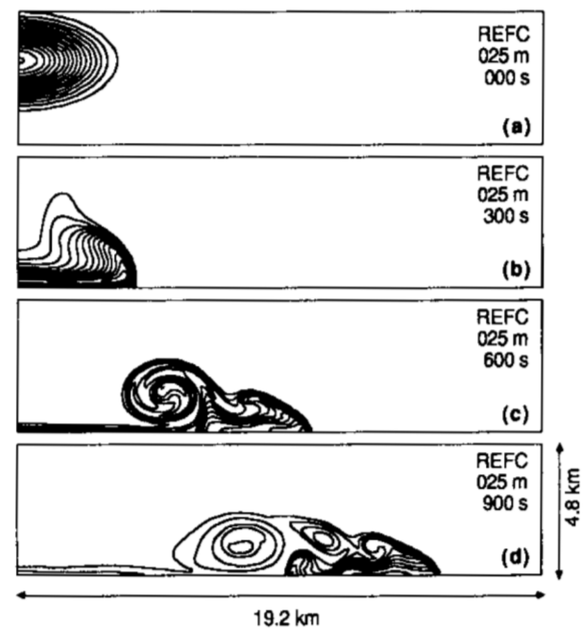
(dx=dz=100m,dt=0.25s,Nstep=10,3h)

Quadruple resolution

Initial

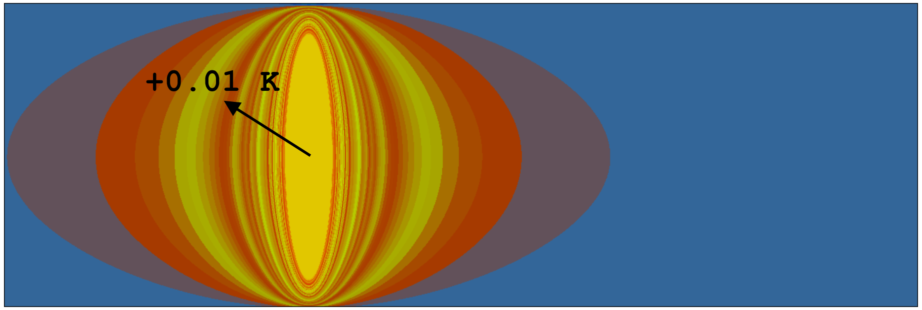


Straka et al. (1993)

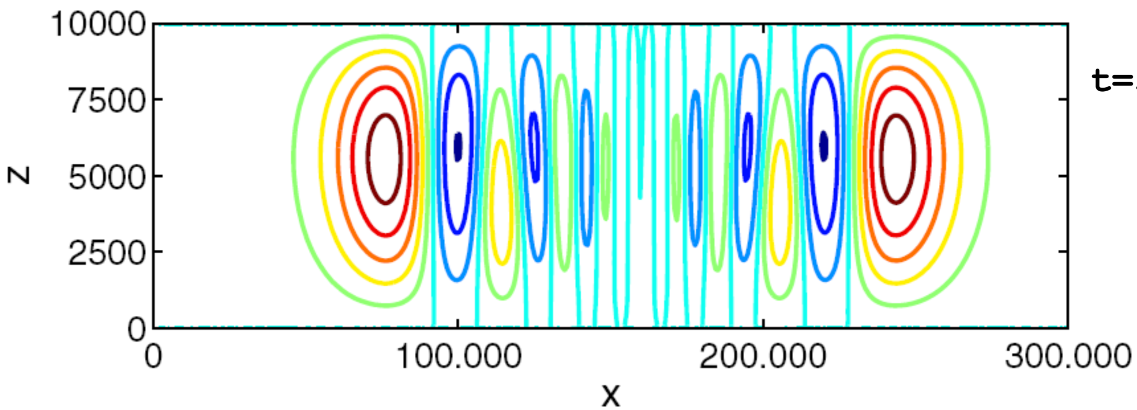


> Inertia-Gravity Waves (uniform wind/stability: $U=20ms^{-1}/N=0.01s^{-1}$)

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

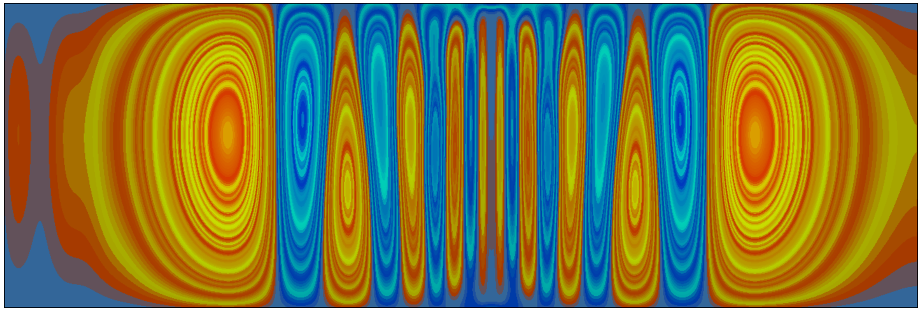


Initial



t=50min

Giraldo & Restelli (2008)



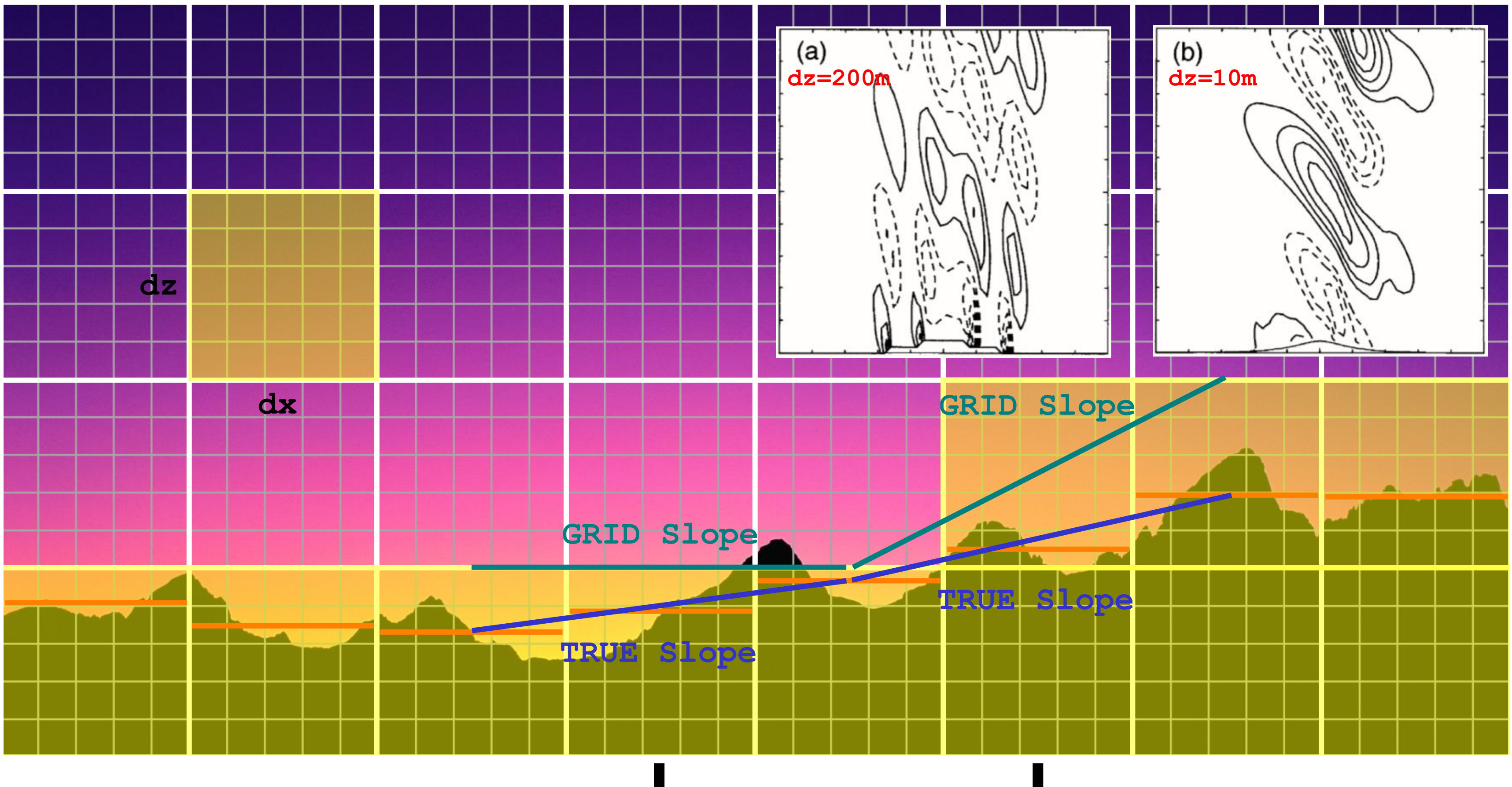
Animation

Inclusion of Orography (+ GW Absorbing Layer)

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

ETA MODEL

Gallus & Klemp (2000)



NO forcing !!!

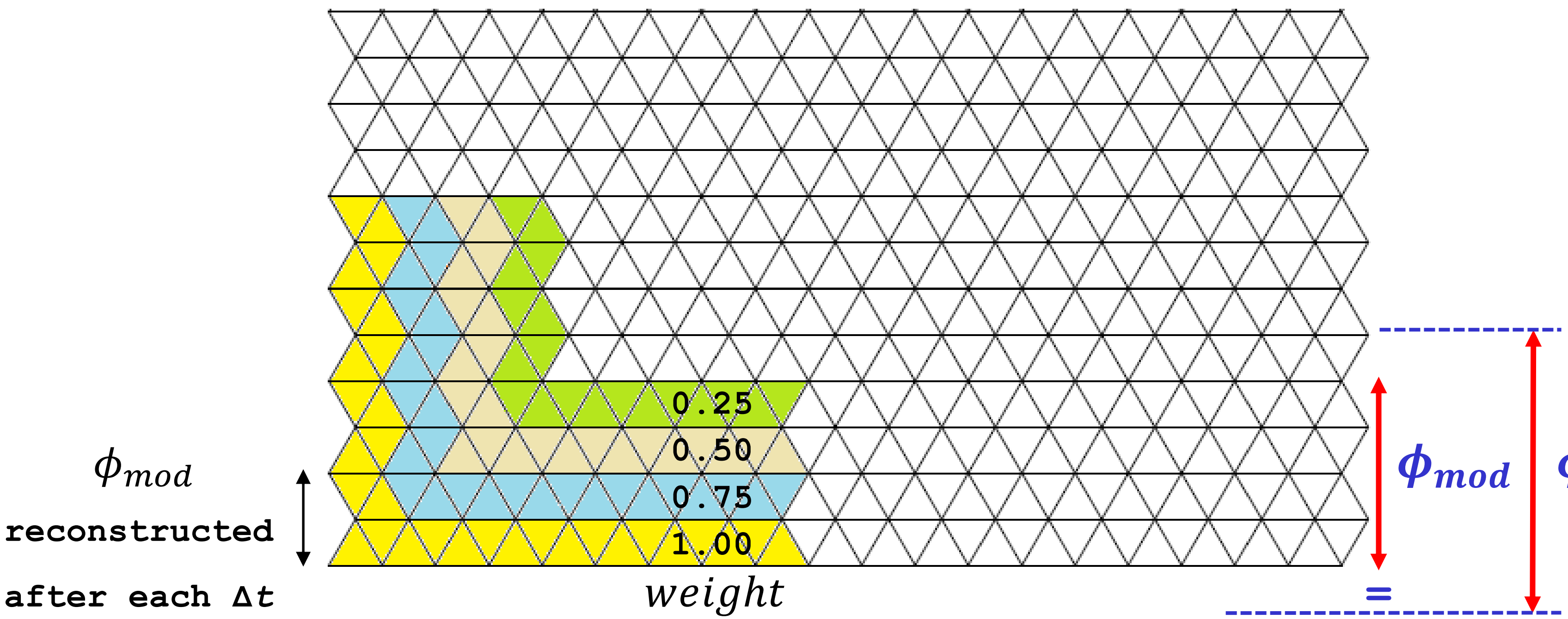
CORRECT forcing

TOO MUCH forcing !!!

CORRECT forcing

Specified Lateral Boundary Conditions

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



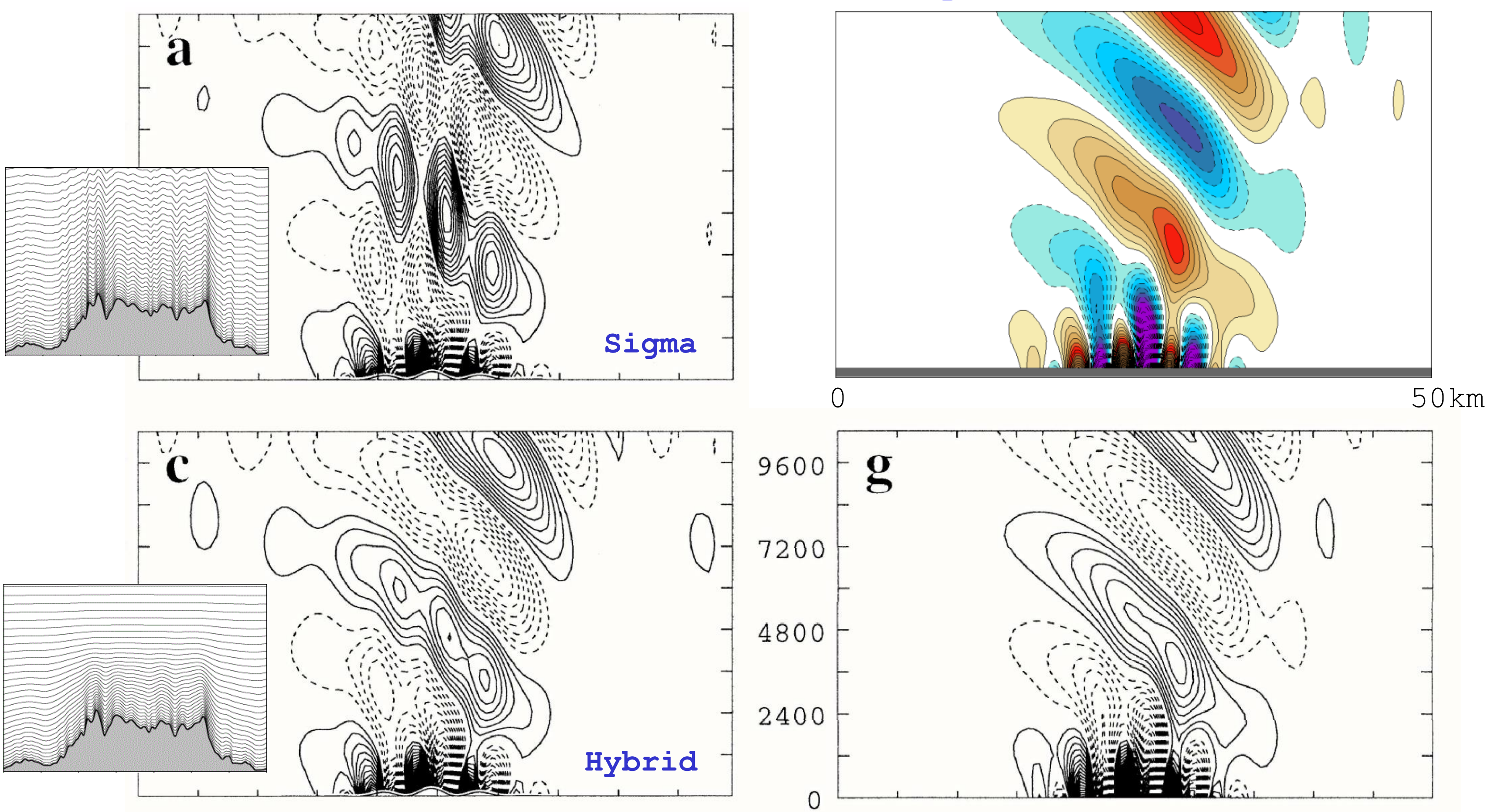
$$\frac{\partial \phi_{mod}}{\partial t} = weight\,[F(\phi_{LS} - \phi_{mod}) - G\Delta^2(\phi_{LS} - \phi_{mod})]$$

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

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

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

Steady-state

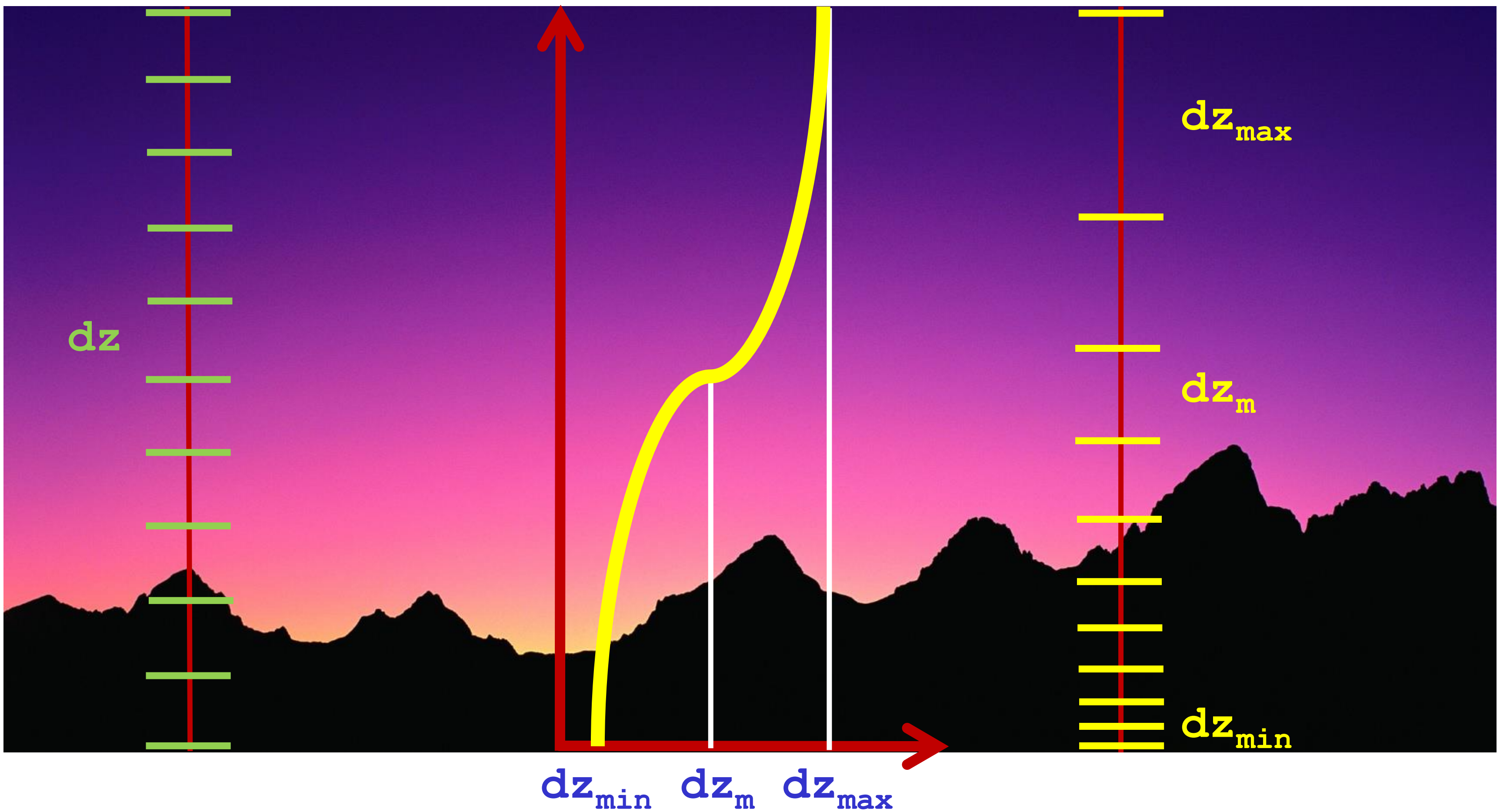


Schär et al.(2002)

Analytical

Vertical Stretching (+ Stabilization Fast Modes)

> **Higher resolution at low levels (cos profile)**



> **Two parameters (stretch, dz_m)**

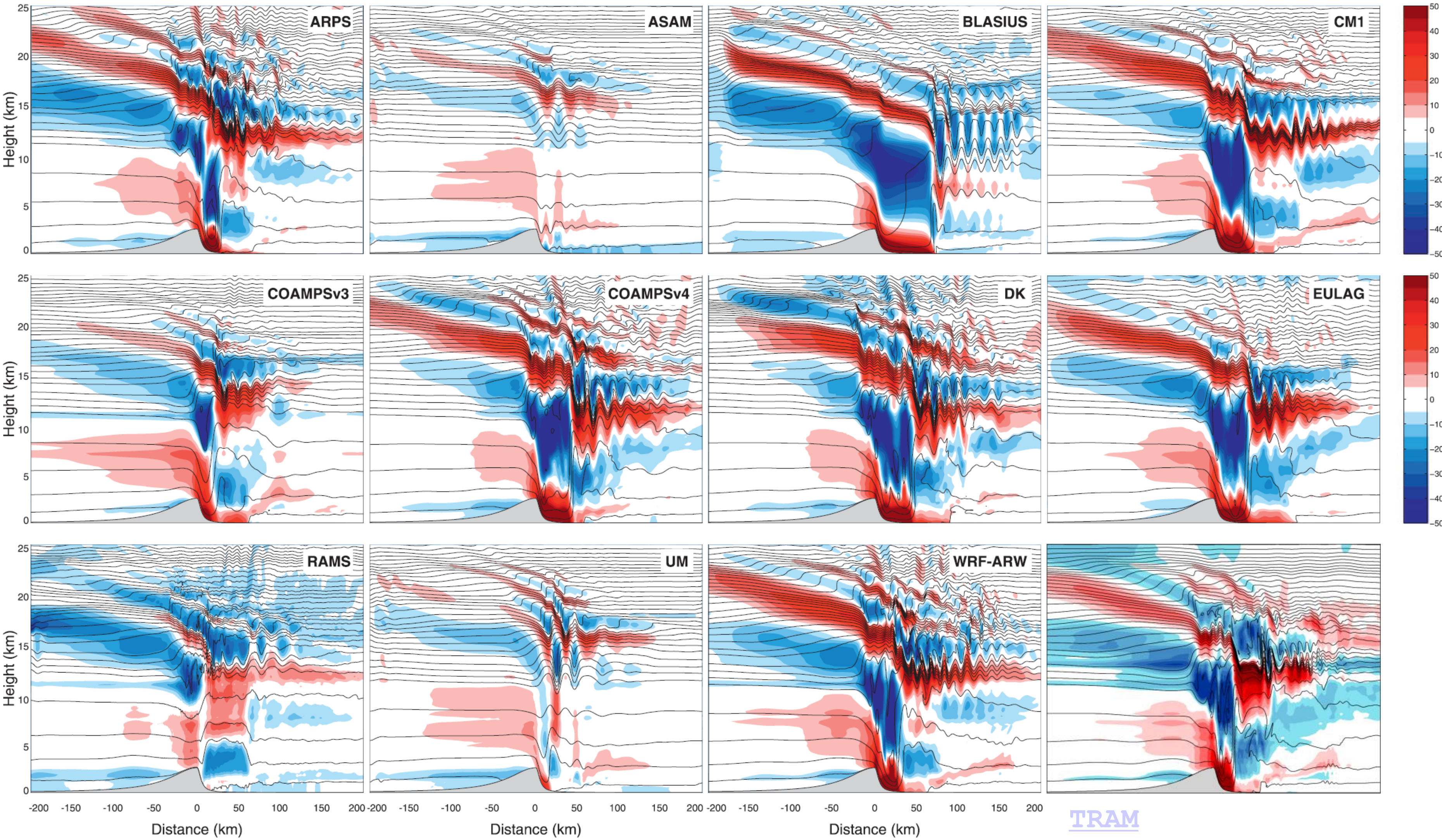
$$\begin{cases} dz_{min} = dz_m / stretch \\ dz_{max} = dz_m + (dz_m - dz_{min}) \end{cases}$$

> T-REX Intense Mountain-Wave

t=4h

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

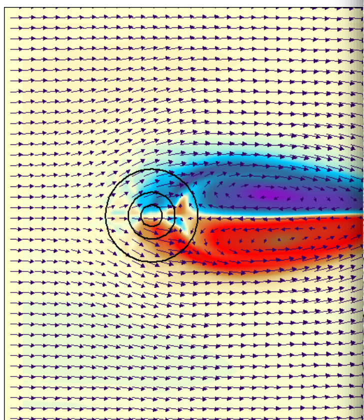
Doyle et al. (2011)



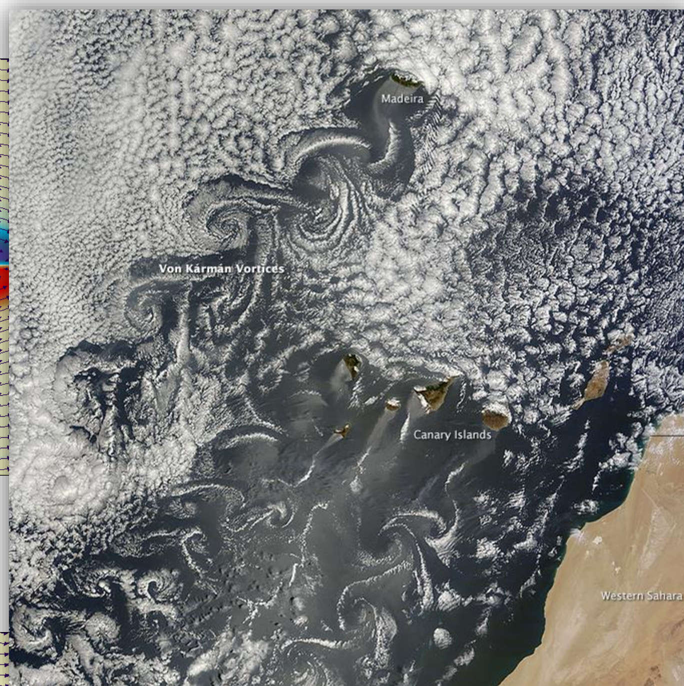
> Von Kármán Vortex Streets (U=10ms^{-1},N=0.01s^{-1})

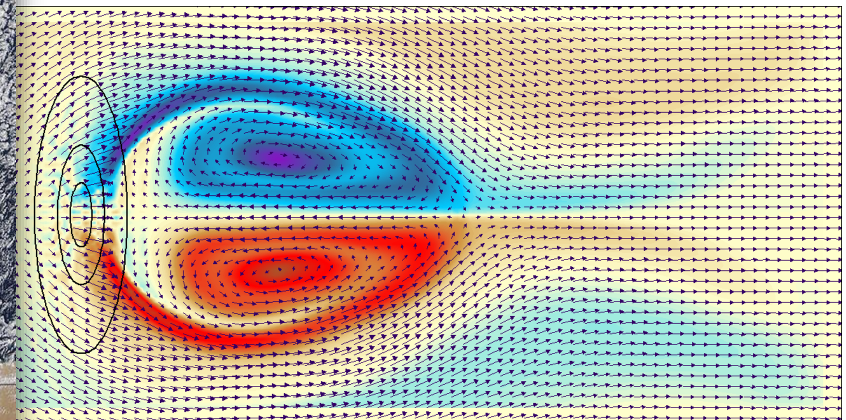
(dx=2km,dzm=500m,stretch=2,dt=4s,Nstep=10,48h)

e.g. Schär and Durran (1997)

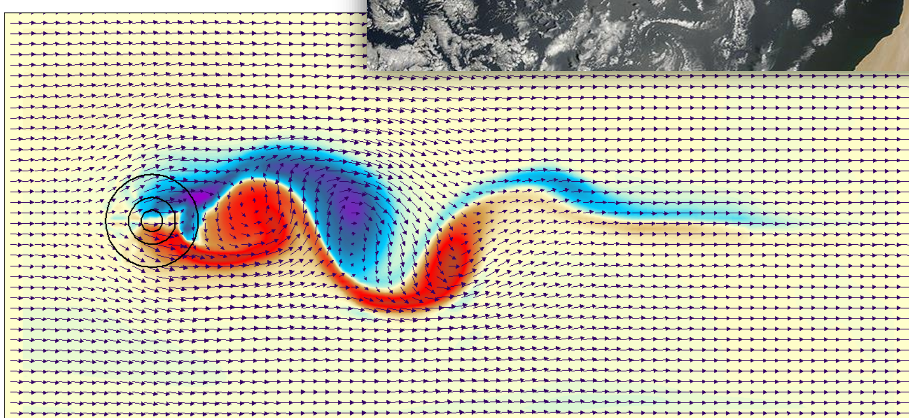


h=3000m

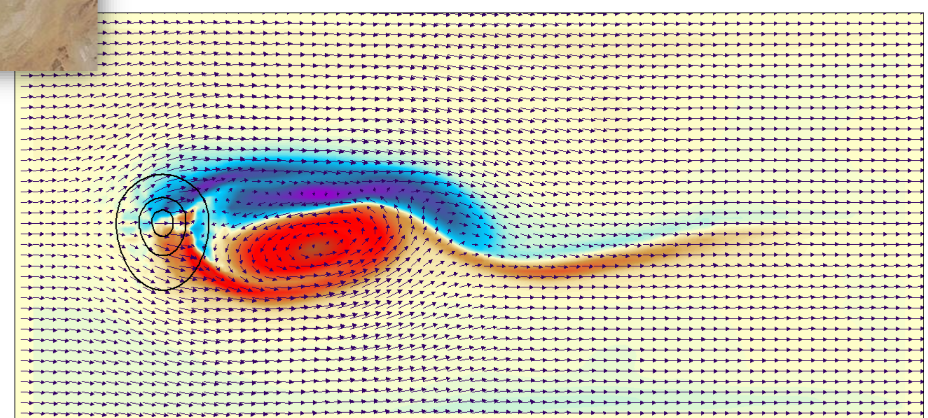




h=3000m



h=3000m (asymmetric I.C)

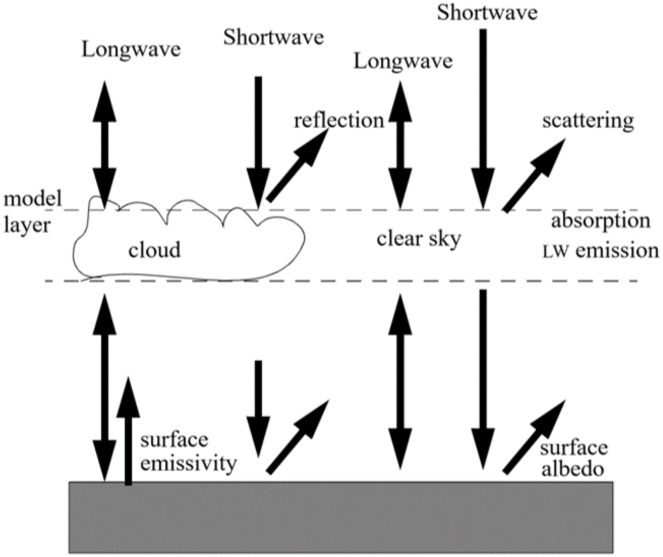


Animation
Tracer

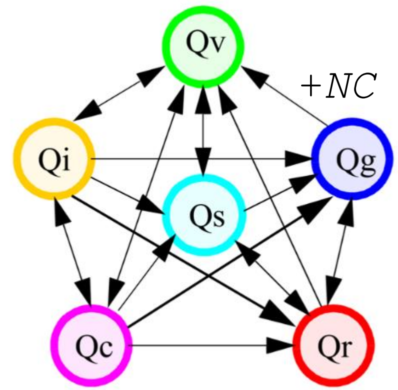
h=3000m

TRAM Physics (MM5-based schemes)

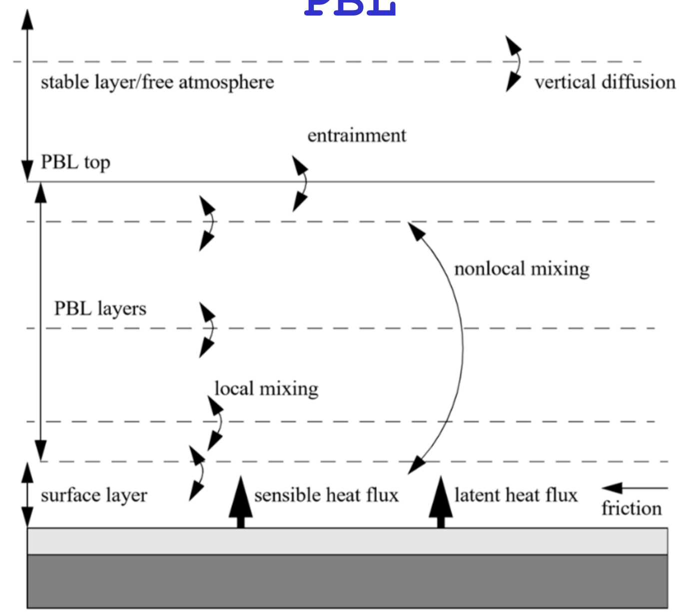
Radiation



Microphysics



PBL



NEW

Prognostic fields

Q_χ

Forcing terms

F_{Q_χ}

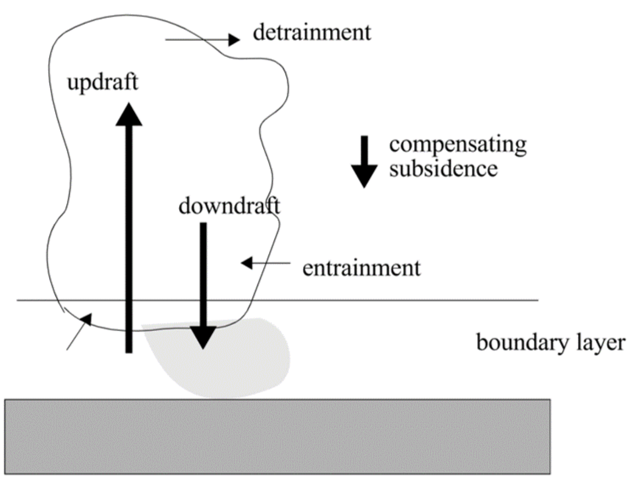
F_T

$F_u \quad F_v$

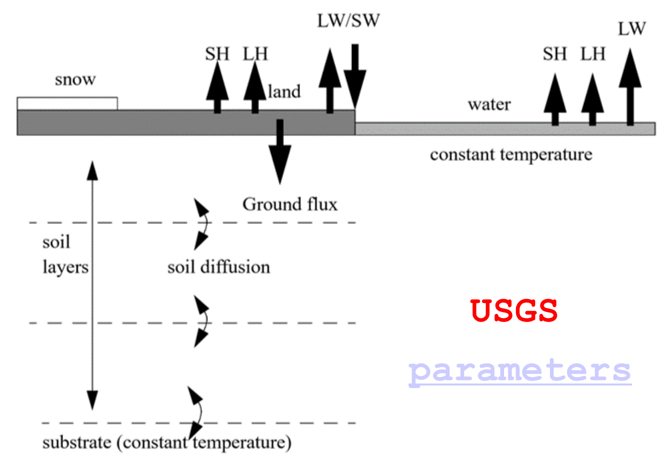
Surface variables

$T_g \quad R_{nc} \quad R_c \quad \ldots$

Cumulus



Surface



NEW Form of Equations: MESOSCALE-IDEALized

$$\frac{\partial \pi'}{\partial t} = -u\frac{\partial \pi'}{\partial x} - v\frac{\partial \pi'}{\partial y} - w\frac{\partial \pi'}{\partial z} - w\frac{\partial \bar{\pi}}{\partial z} - \frac{R_d}{c_p}\frac{c_{pm}}{c_{vm}}(\bar{\pi}+\pi')\left[\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}\right] + \frac{R_d}{c_{vm}}\frac{1}{\bar{\theta}+\theta'}F_T$$

$$+\frac{R_d}{c_p}\frac{R_v}{R_m}\frac{c_{pm}}{c_{vm}}(\bar{\pi}+\pi')F_{Q_v}$$

ALL moist effects on pressure and thermodynamics

$$\frac{\partial \theta'}{\partial t} = -u\frac{\partial \theta'}{\partial x} - v\frac{\partial \theta'}{\partial y} - w\frac{\partial \theta'}{\partial z} - w\frac{\partial \bar{\theta}}{\partial z} - \left(\frac{R_m}{C_{vm}} - \frac{R_d}{C_p}\frac{c_{pm}}{c_{vm}}\right)(\bar{\theta}+\theta')\left[\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}\right]$$

$$+\frac{c_v}{c_{vm}}\frac{1}{\bar{\pi}+\pi'}F_T + \frac{R_v}{c_{vm}}\left(1-\frac{R_d}{c_p}\frac{c_{pm}}{R_m}\right)(\bar{\theta}+\theta')F_{Q_v}$$

Physics computed in NSTEP-cycle

$$\frac{\partial u}{\partial t} = -u\frac{\partial u}{\partial x} - v\frac{\partial u}{\partial y} - w\frac{\partial u}{\partial z} - c_p(\bar{\theta}_\rho+\theta'_\rho)\frac{\partial \pi'}{\partial x} + fv - \hat{f}w + F_u$$

$$\frac{\partial v}{\partial t} = -u\frac{\partial v}{\partial x} - v\frac{\partial v}{\partial y} - w\frac{\partial v}{\partial z} - c_p(\bar{\theta}_\rho+\theta'_\rho)\frac{\partial \pi'}{\partial y} - fu + F_v$$

$$\frac{\partial w}{\partial t} = -u\frac{\partial w}{\partial x} - v\frac{\partial w}{\partial y} - w\frac{\partial w}{\partial z} - c_p(\bar{\theta}_\rho+\theta'_\rho)\frac{\partial \pi'}{\partial z} + g\frac{\theta'_\rho}{\bar{\theta}_\rho} + \hat{f}u - g(Q_{liq}+Q_{ice})$$

$$\frac{\partial Q_\chi}{\partial t} = -u\frac{\partial Q_\chi}{\partial x} - v\frac{\partial Q_\chi}{\partial y} - w\frac{\partial Q_\chi}{\partial z} + F_{Q_\chi}$$

$$\pi = \left(\frac{P}{P_0}\right)^{R_d/c_p} \qquad \theta = \frac{T}{\pi} \qquad P = \rho R_d T\frac{1+Q_v/\varepsilon}{1+Q_v}$$

$$\theta_\rho = \theta\frac{1+Q_v/\varepsilon}{1+Q_v+Q_{liq}+Q_{ice}} \qquad c_p\bar{\theta}_\rho\frac{\partial\bar{\pi}}{\partial z} = -g$$

$$R_m = R_d + R_v\,Q_v \qquad \varepsilon = R_d/R_v$$

$$c_{pm} = c_p + c_{pv}\,Q_v + c_l\,Q_{liq} + c_i\,Q_{ice}$$

$$c_{vm} = c_v + c_{vv}\,Q_v + c_l\,Q_{liq} + c_i Q_{ice}$$

NEW Form of Equations: SYNOPTIC-REALcase

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

$$+\frac{R_d}{c_{vm}}\frac{1}{\bar{\theta}+\theta'}F_T + \frac{R_d}{c_p}\frac{R_v}{R_m}\frac{c_{pm}}{c_{vm}}(\bar{\pi}+\pi')F_{Q_v}$$

ALL Coriolis and curvature terms

$$\frac{\partial \theta'}{\partial t} = -mu\frac{\partial \theta'}{\partial x} - mv\frac{\partial \theta'}{\partial y} - w\frac{\partial \theta'}{\partial z} - w\frac{\partial \bar{\theta}}{\partial z} - \left(\frac{R_m}{C_{vm}} - \frac{R_d}{C_p}\frac{c_{pm}}{c_{vm}}\right)(\bar{\theta}+\theta')\left[m^2\left(\frac{\partial(\frac{u}{m})}{\partial x} + \frac{\partial(\frac{v}{m})}{\partial y}\right) + \frac{\partial w}{\partial z}\right]$$

$$+\frac{c_v}{c_{vm}}\frac{1}{\bar{\pi}+\pi'}F_T + \frac{R_v}{c_{vm}}\left(1 - \frac{R_d}{c_p}\frac{c_{pm}}{R_m}\right)(\bar{\theta}+\theta')F_{Q_v}$$

LAMBERT projection

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

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

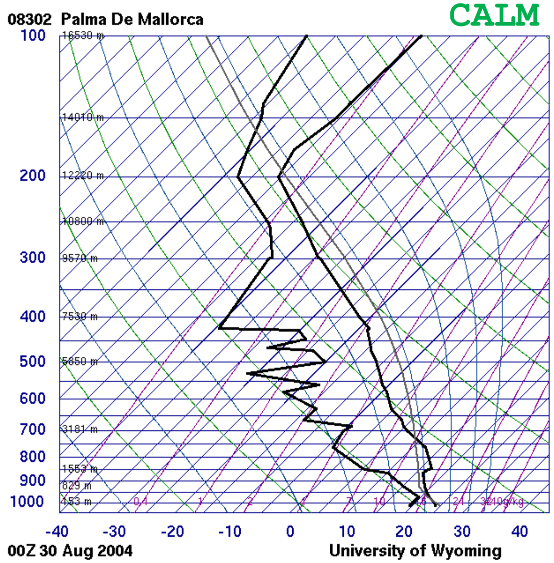
$$\frac{\partial w}{\partial t} = -mu\frac{\partial w}{\partial x} - mv\frac{\partial w}{\partial y} - w\frac{\partial w}{\partial z} - c_p(\bar{\theta}_\rho + \theta'_\rho)\frac{\partial \pi'}{\partial z} + g\frac{\theta'_\rho}{\bar{\theta}_\rho} + \hat{f}(u\cos\alpha - v\sin\alpha) + \frac{u^2+v^2}{a}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

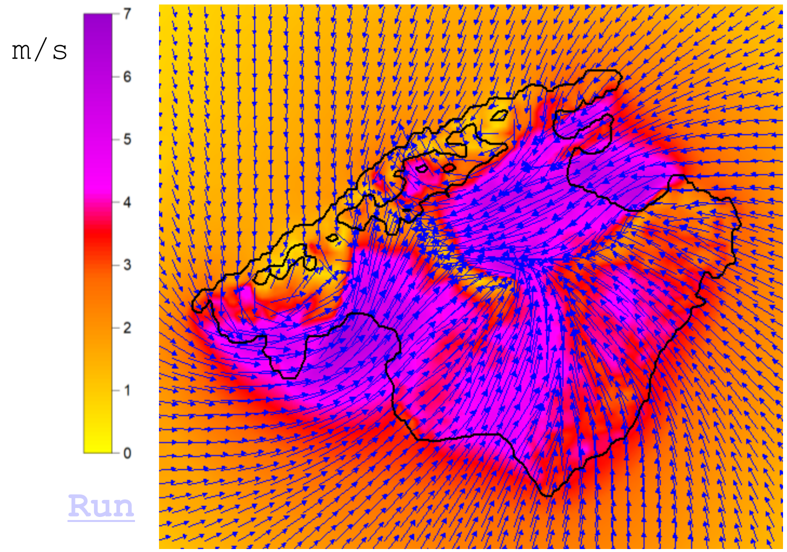
$$\frac{\partial Q_\chi}{\partial t} = -mu\frac{\partial Q_\chi}{\partial x} - mv\frac{\partial Q_\chi}{\partial y} - w\frac{\partial Q_\chi}{\partial z} + F_{Q_\chi}$$

> Breeze Circulation in Mallorca (IC: Sounding 00 UTC 30 Ago 2004)

(dx=1.5km,dzm=400m,stretch=20,dt=3s,Nstep=10,30h)

CALM



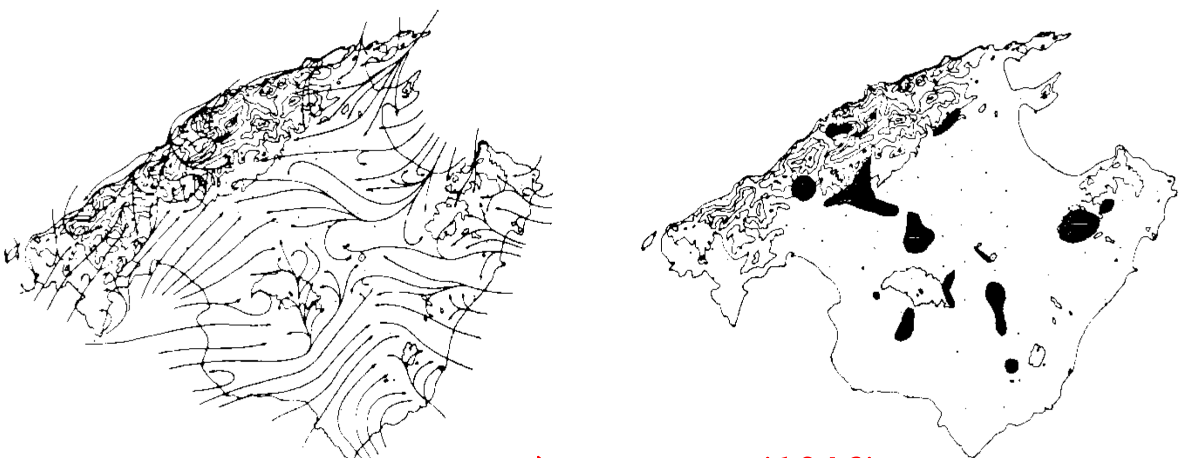


t=13h

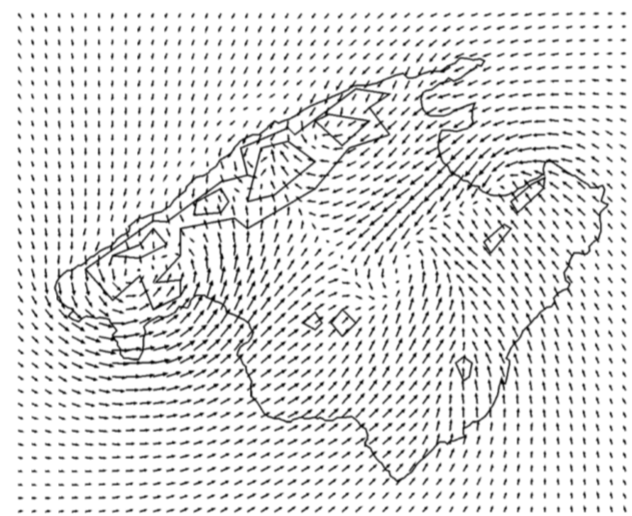
Run

Clouds

Rainfall



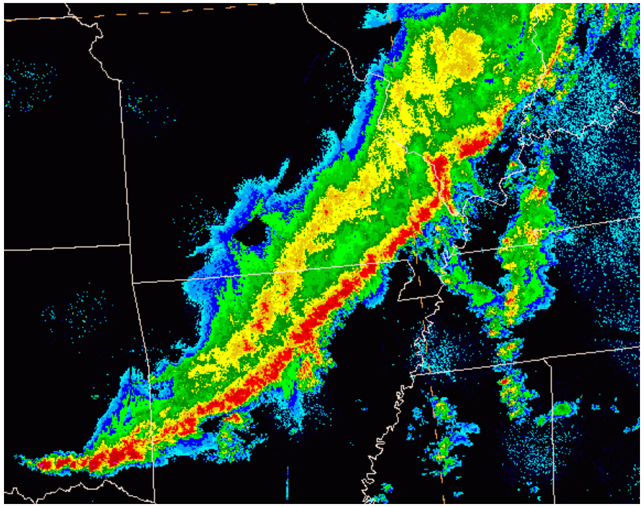
Jansà & Jaume (1946)



Ramis & Romero (1995)

> Squall-Line Simulation (NO Coriolis, Radiation, PBL and Cumulus)

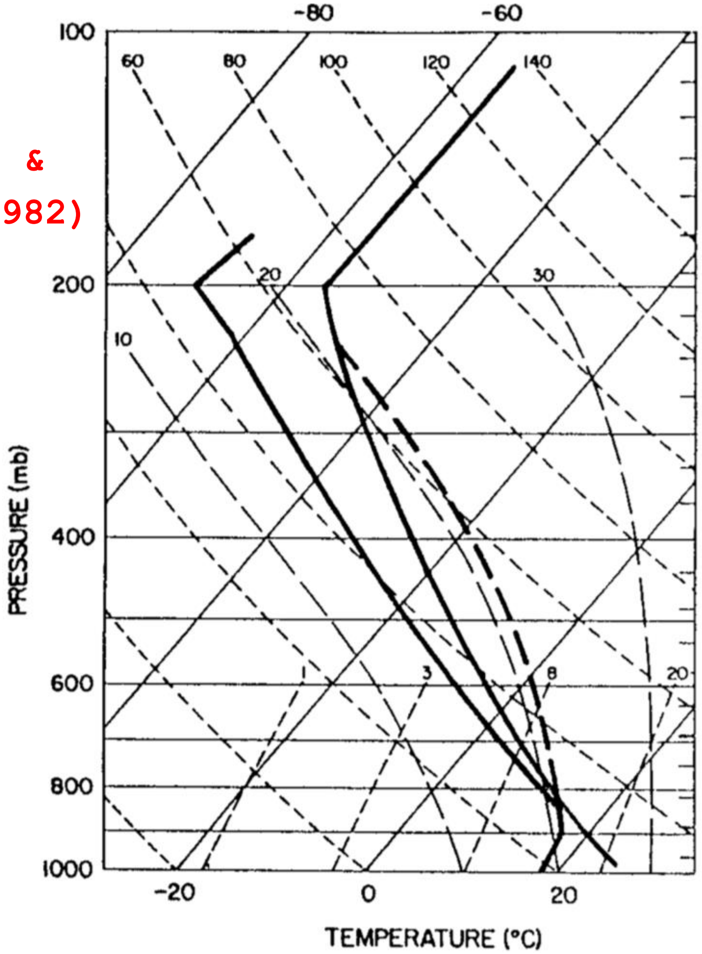
(dx=1.5km,dzm=200m,stretch=10,dt=3s,Nstep=5,10h)



IC: WK82 SOUNDING + 8K Surface Cold Pool

... and 3 different wind profiles

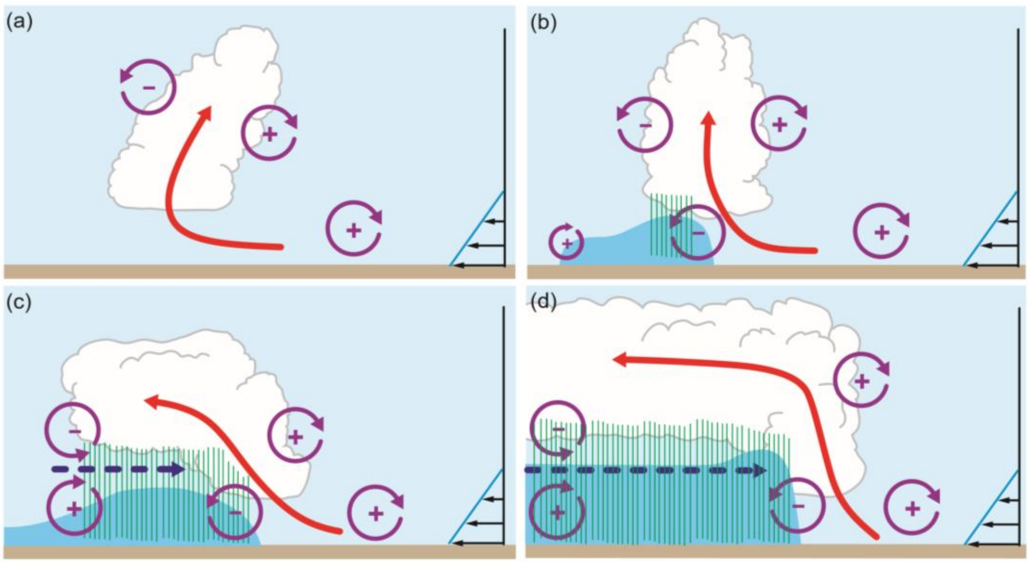
Weisman & Klemp (1982)



TRAM_physics_3D (MESOSCALE-IDEALized)

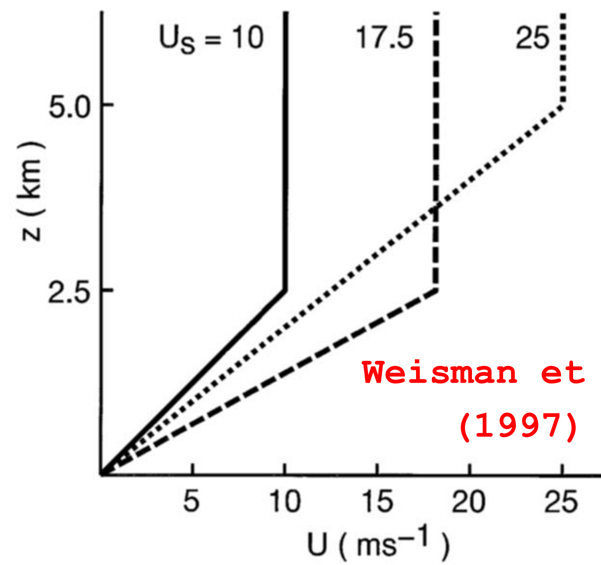
> Squall-Line Simulation (NO Coriolis, Radiation, PBL and Cumulus)

(dx=1.5km,dzm=200m,stretch=10,dt=3s,Nstep=5,10h)

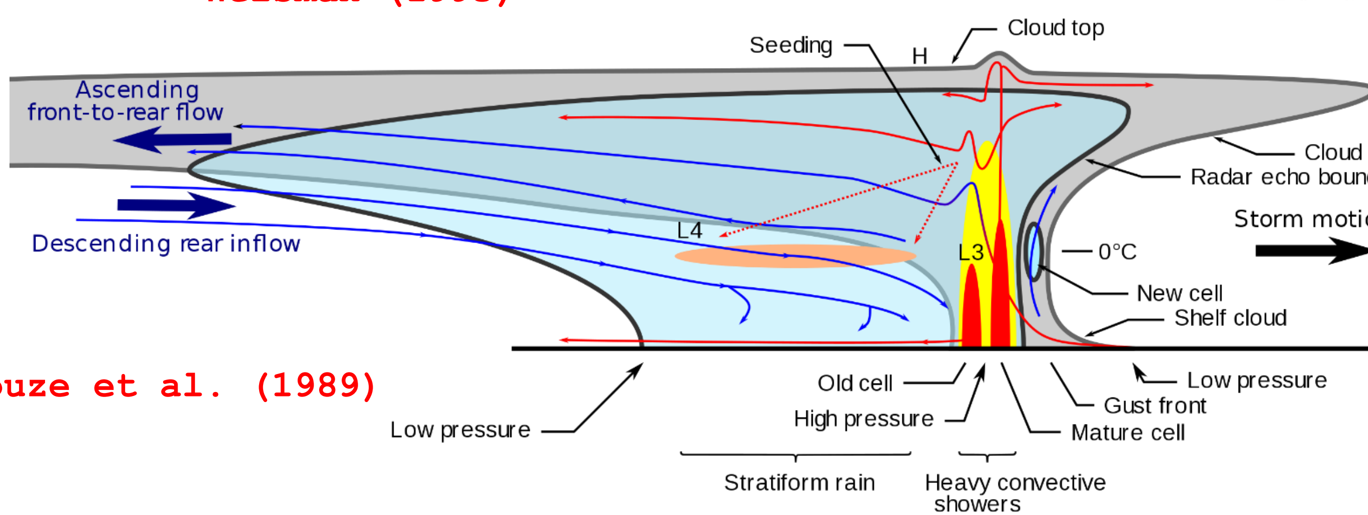


Weisman (1993)

SHEAR: Weak Moderate Deep



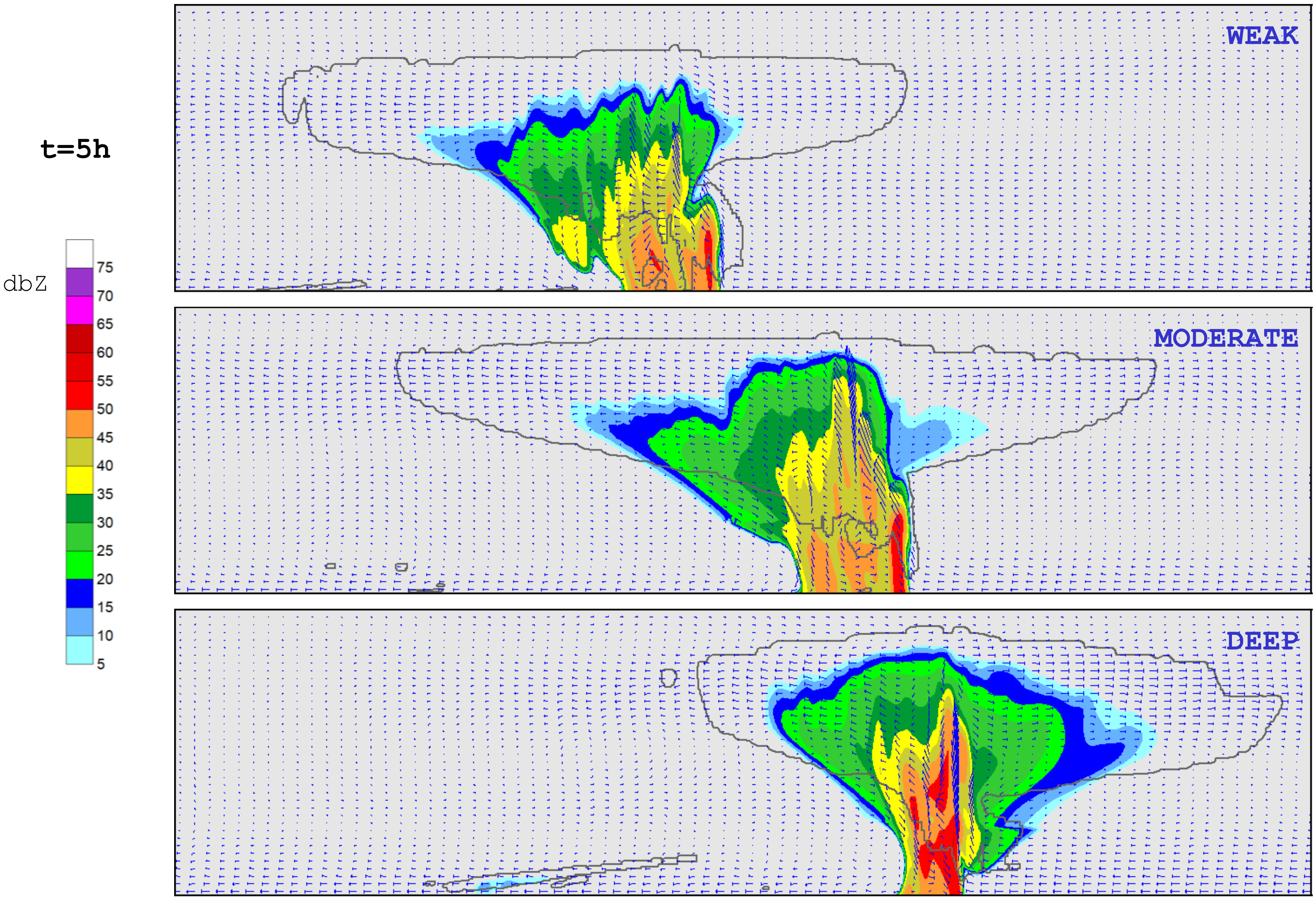
Weisman et al. (1997)



Houze et al. (1989)

> Squall-Line Simulation (NO Coriolis, Radiation, PBL and Cumulus)

(dx=1.5km,dzm=200m,stretch=10,dt=3s,Nstep=5,10h)



Run

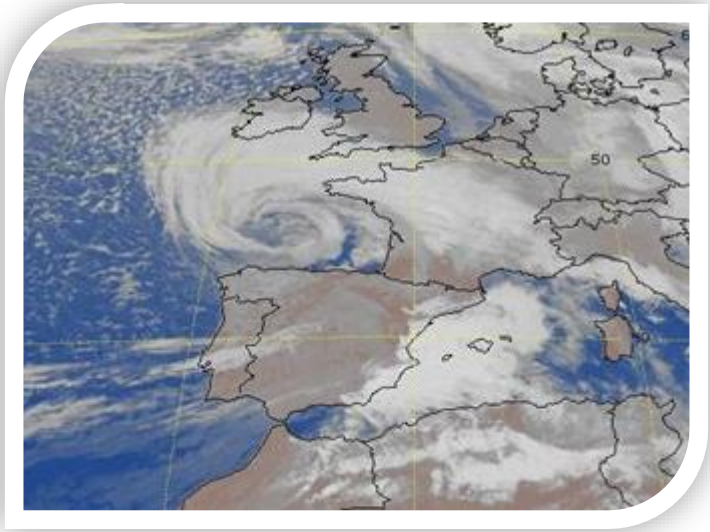
Run +Oro

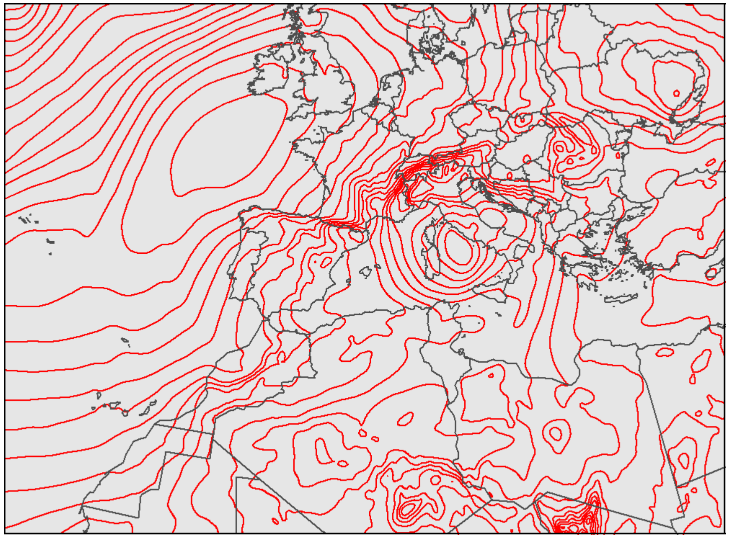
v.2D

Run

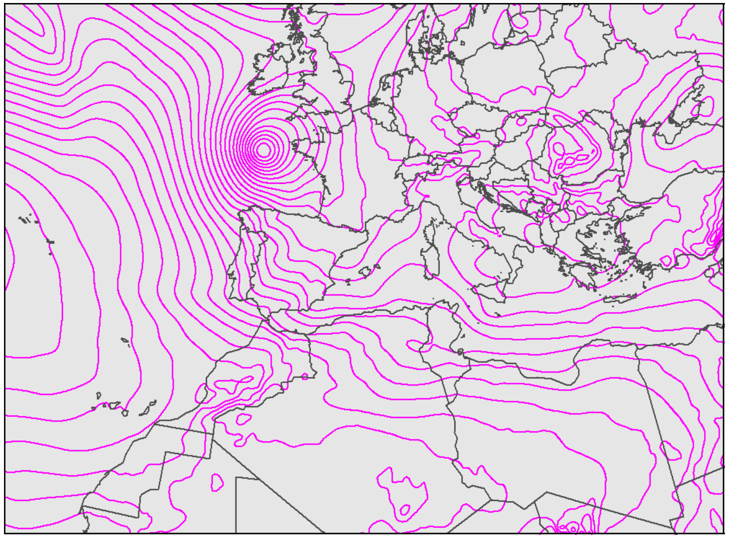
> "HUGO" Intense Cyclonic Storm (IC: 00 UTC 21 Mar 2018)

(MR:dx=25km,dzm=200m,stretch=10,dt=45s,Nstep=5,90h)

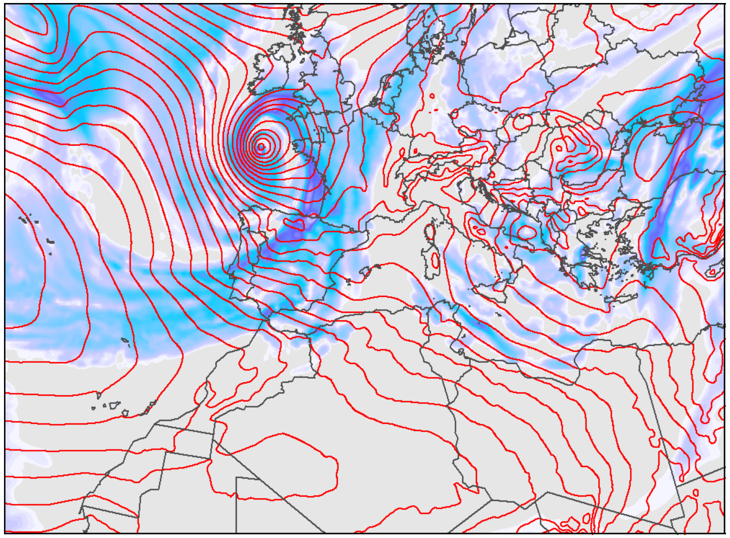


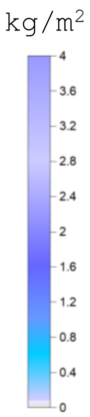


t=0h



t=72h





ERA-5

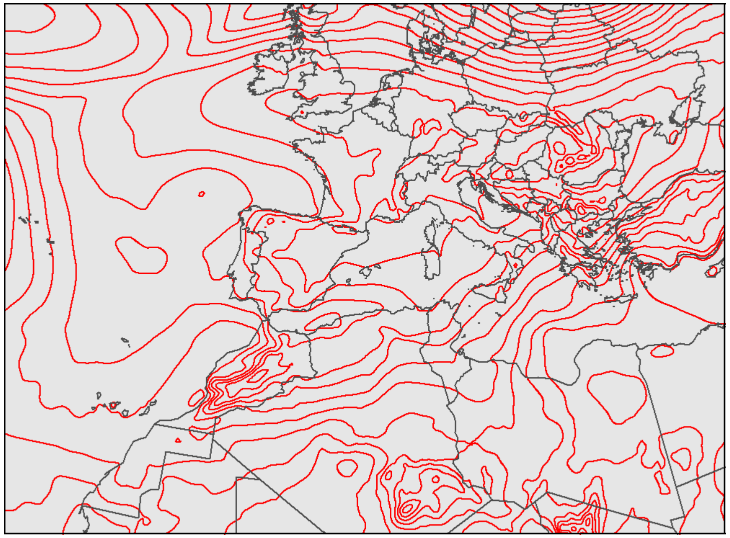
TRAM

Winds Rainfall

TRAM_physics_3D (SYNOPTIC-REALcase)

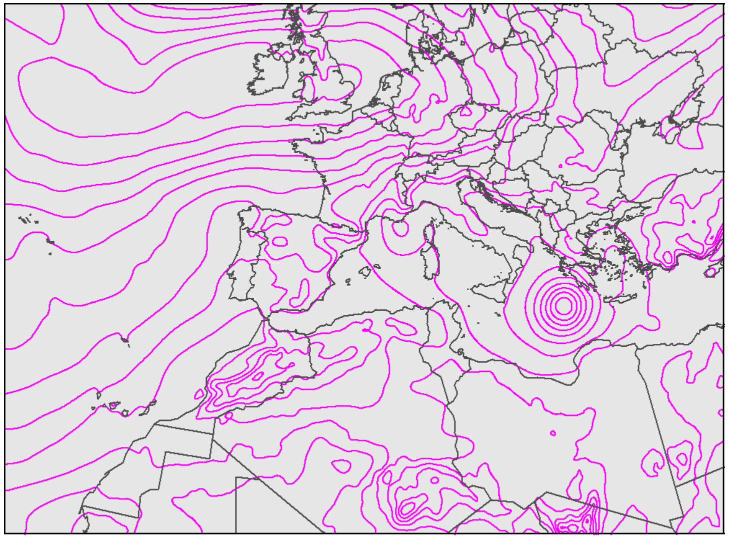
> "ZORBAS" Ionian Sea Medicane (IC: 00 UTC 27 Sept 2018)

(**MR**:dx=25km,dzm=200m,stretch=10,dt=45s,Nstep=5,**90h**)

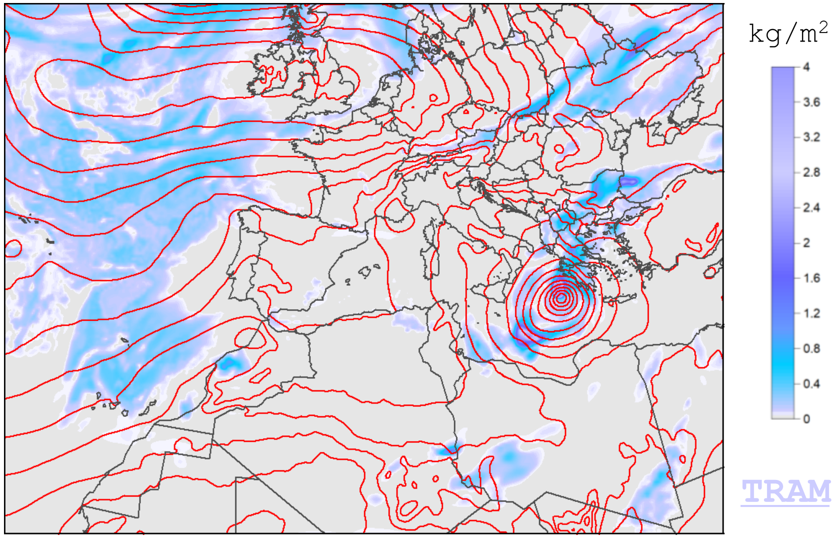


t=0h

ERA-5



t=48h

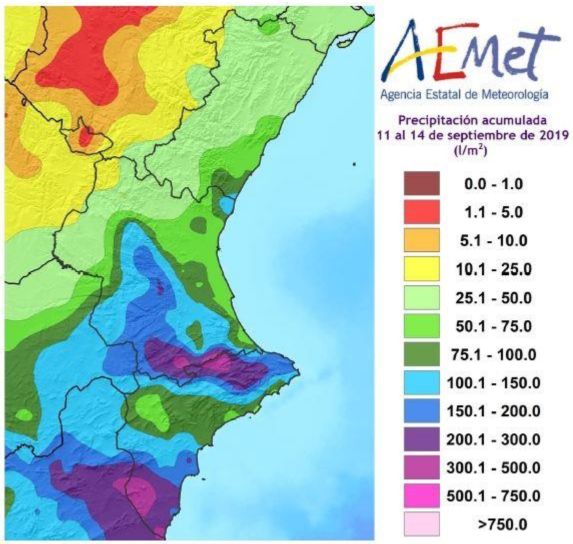


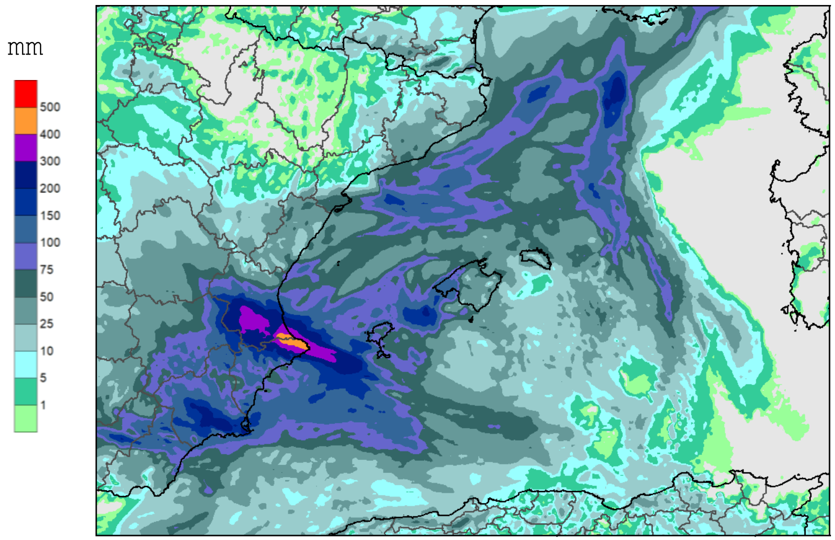
TRAM

Winds Rainfall

> "DANA" Valencia-Murcia Floods (IC: 00 UTC 10 Sept 2019)

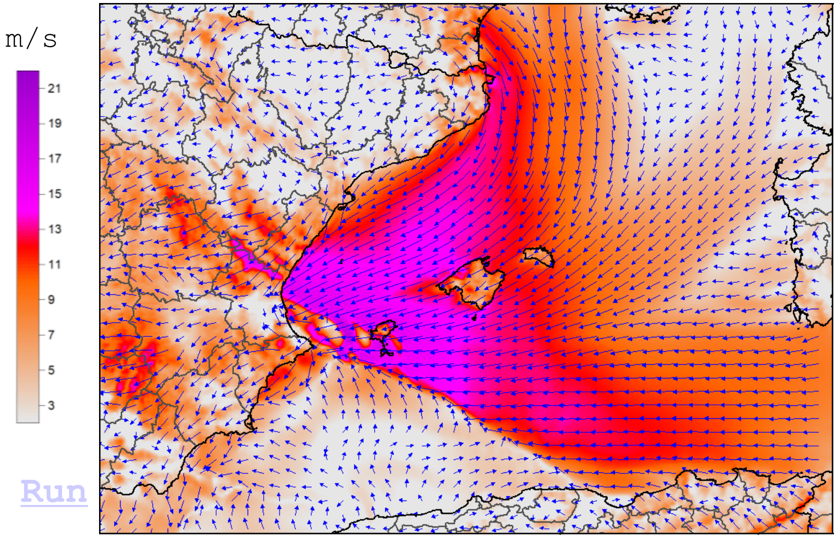
(HR_double:dx=4.5km,dzm=200m,stretch=10,dt=9s,Nstep=5,90h)





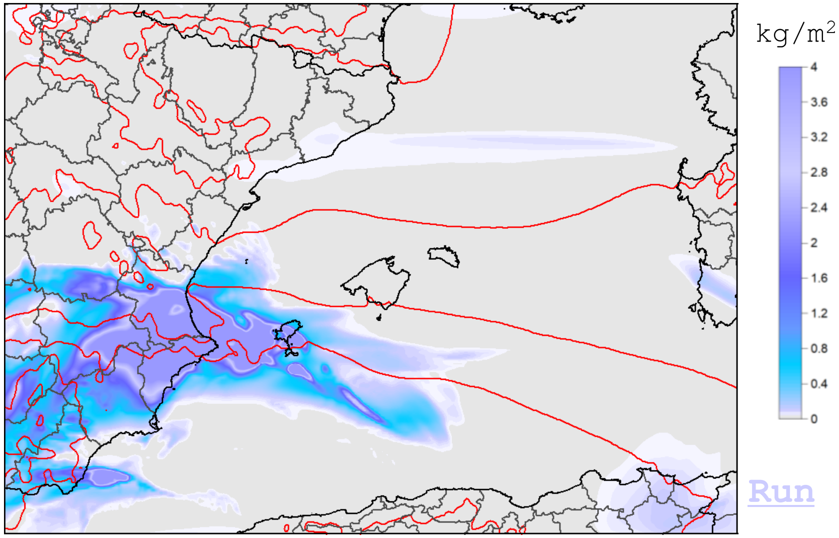
total

Run



Run

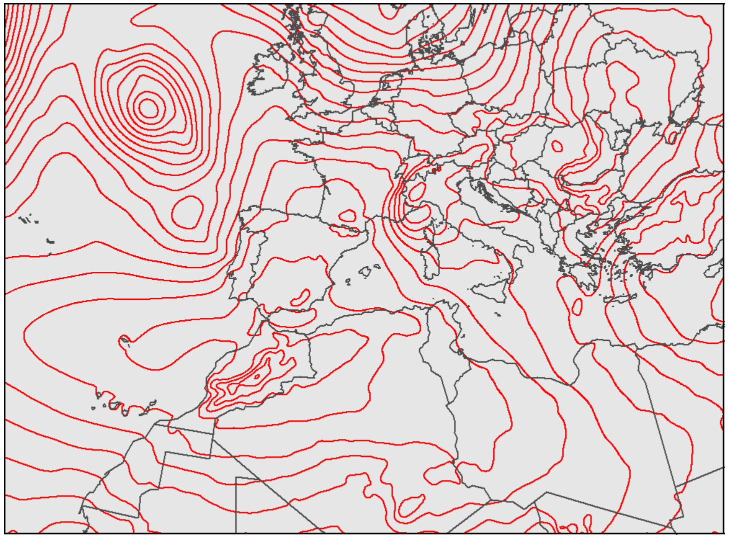
t=54h



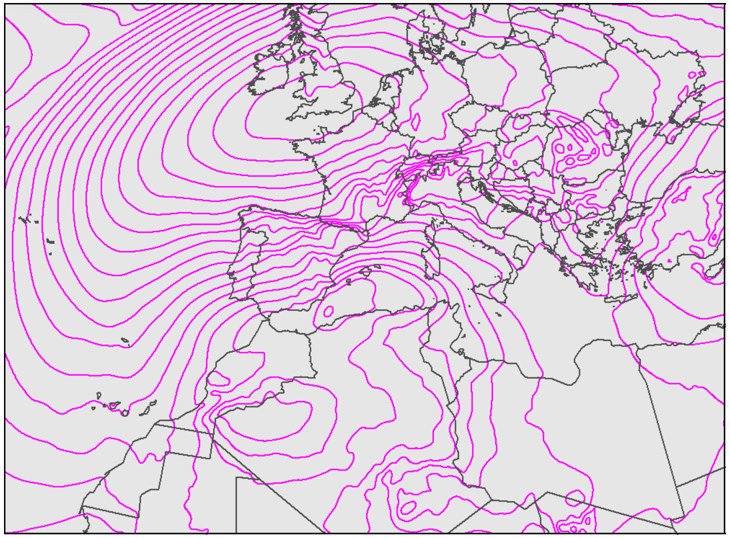
Run

> "GLORIA" Extraordinary Storm (IC: 00 UTC 18 Jan 2020)

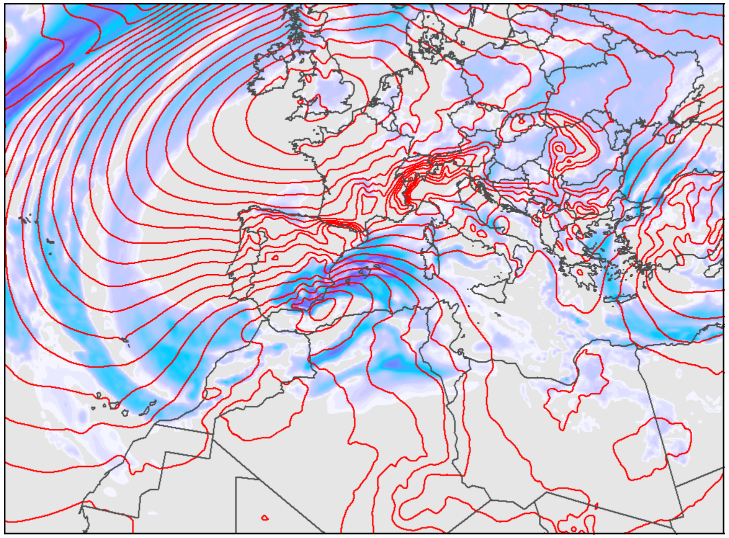
(MR:dx=25km,dzm=200m,stretch=10,dt=45s,Nstep=5,138h)



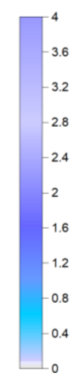
t=0h



t=48h



kg/m^2



ERA-5

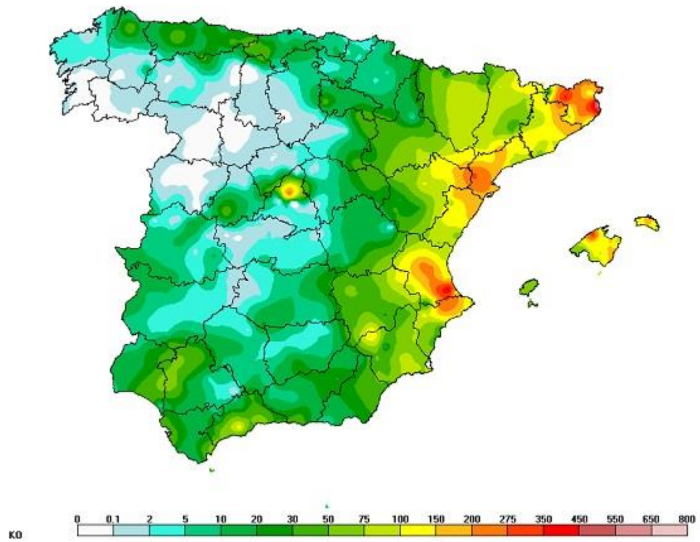
TRAM

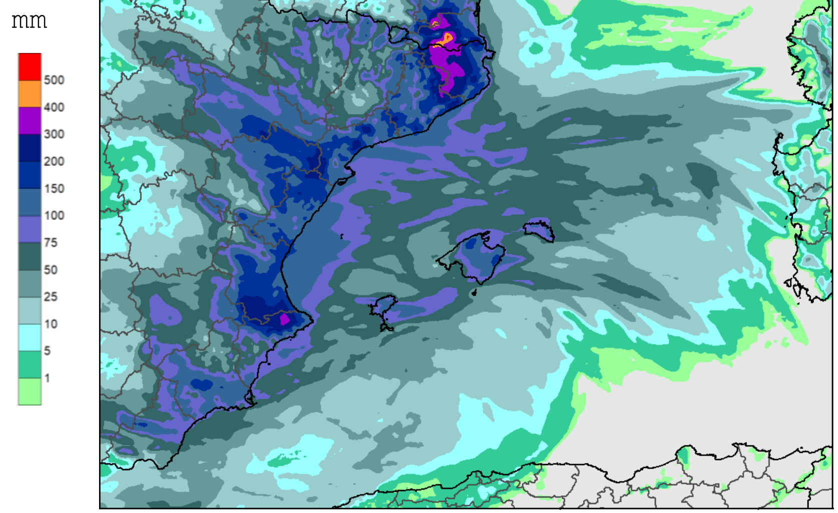
Winds

Rainfall

> "GLORIA" Extraordinary Storm (IC: 00 UTC 18 Jan 2020)

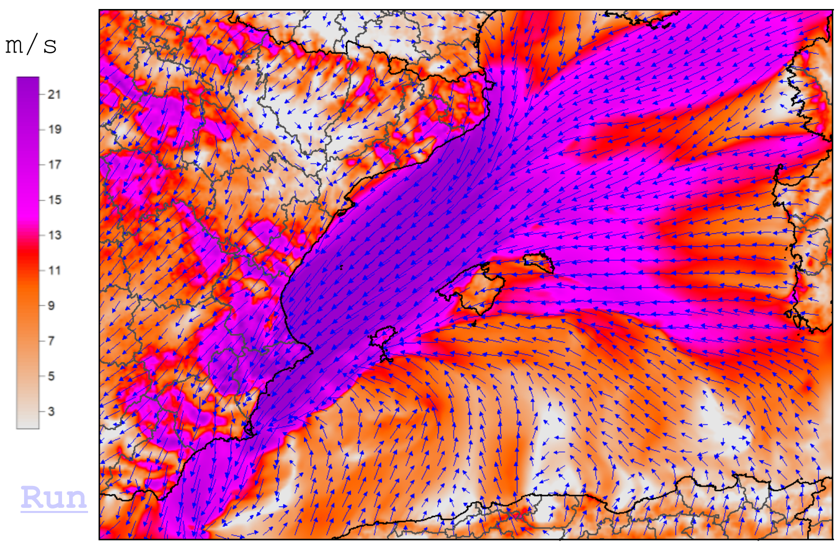
(HR_double:dx=4.5km,dzm=200m,stretch=10,dt=9s,Nstep=6,138h)





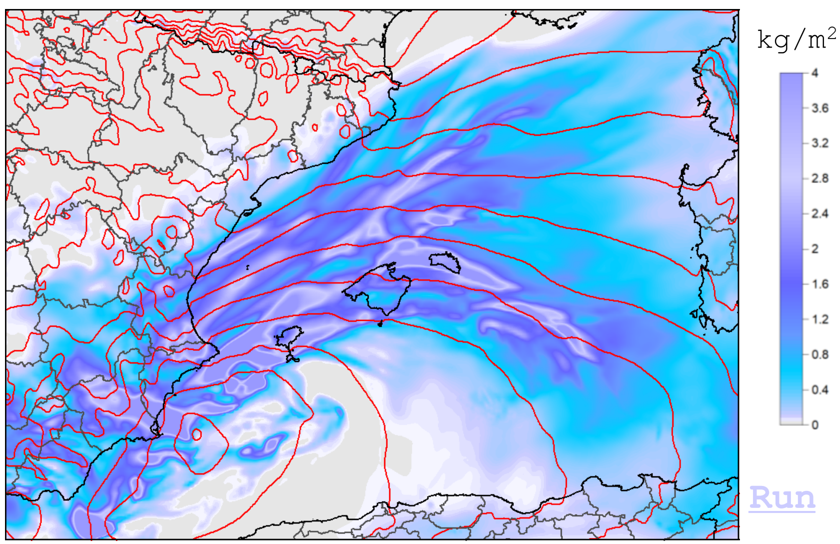
total

Run



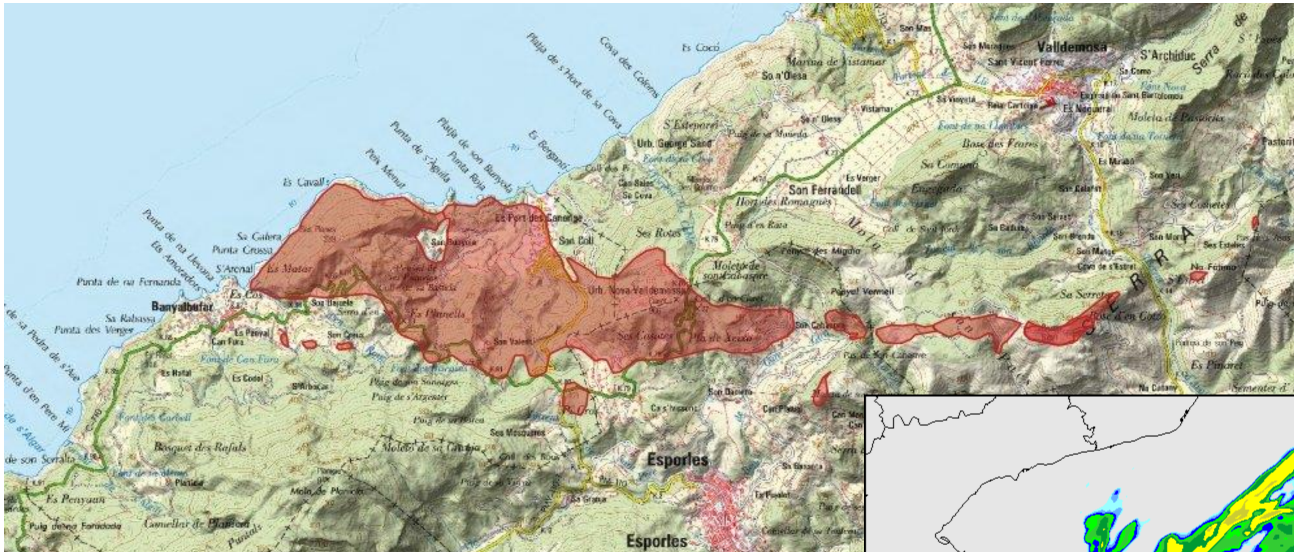
Run

t=48h

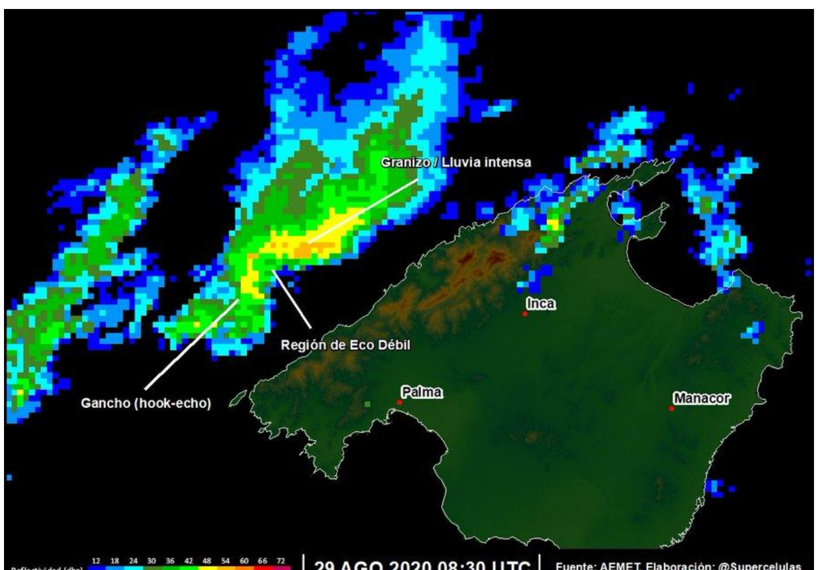


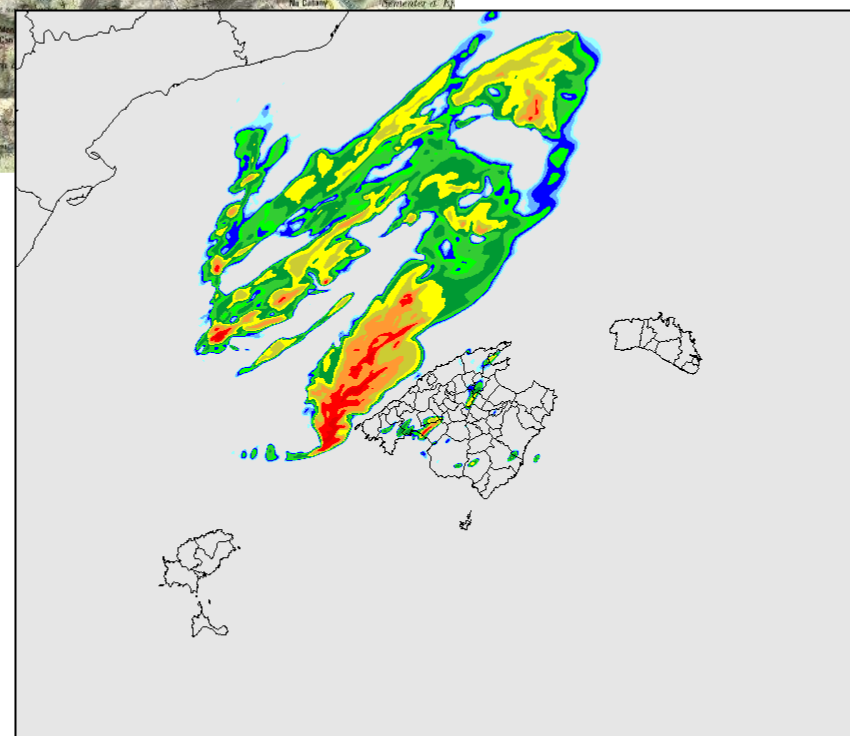
Run

> 29/00-29/18 TRAM Simulation (dx=0.75km, GFS-fcst)



Run



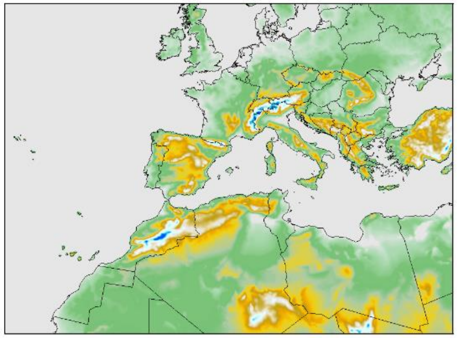


Wind Speed Rainfall Temperature

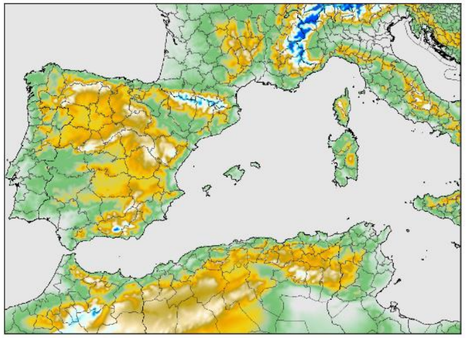
OPERATIONAL at: http://meteo.uib.es/tram

TRAM / MeteoUIB

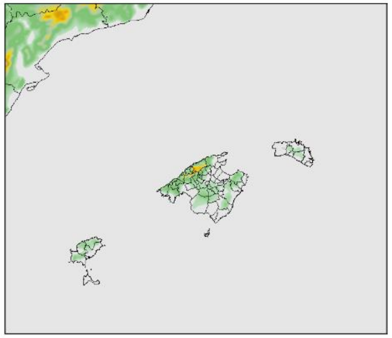
MR (17 km)



HR (6 km)



SR (2 km)



Grup de Meteorologia

UIB Universitat de les Illes Balears

THANK YOU

for

your attention