The New TRAM MODEL:

Achievements at Meteo-UIB Towards Numerical Modelling Capabilities Aimed at a Wide Range of Time-Space Scales

Romu Romero

9th METMED Conference

Genoa (Italy), 22-24 May 2023

...in previous Mediterranean Meetings

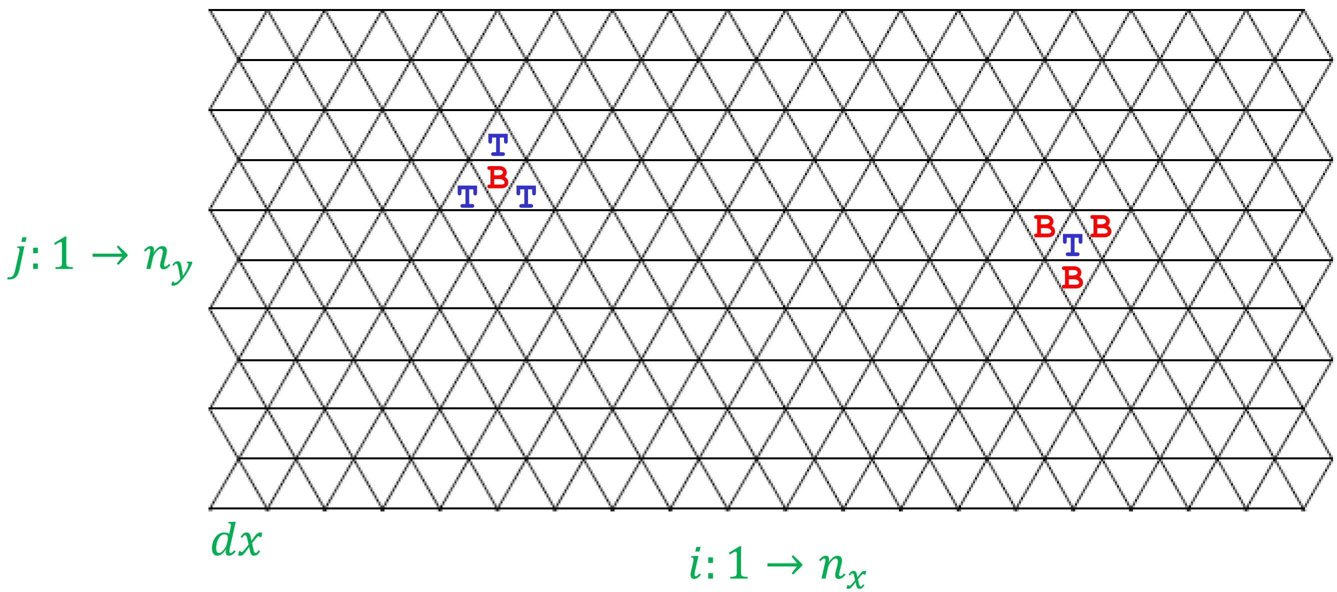
TRAM: **T**riangle-based **R**egional **A**tmospheric **M**odel

> 16th EGU PLINIUS Conference (Montpellier, 2018):
"TRAM: A new nonhydrostatic fully compressible numerical model"

> 7th METMED Conference (Palma de Mallorca, 2019):
"A computationally cheap atmosphere-ocean modelling system aimed at anticipating meteotsunami occurrence in Ciutadella"

> 8th METMED Conference (Online, 2021):
"TRAM with physics: A new numerical model suited for all kinds of atmospheric applications"

> Triangular-based mesh



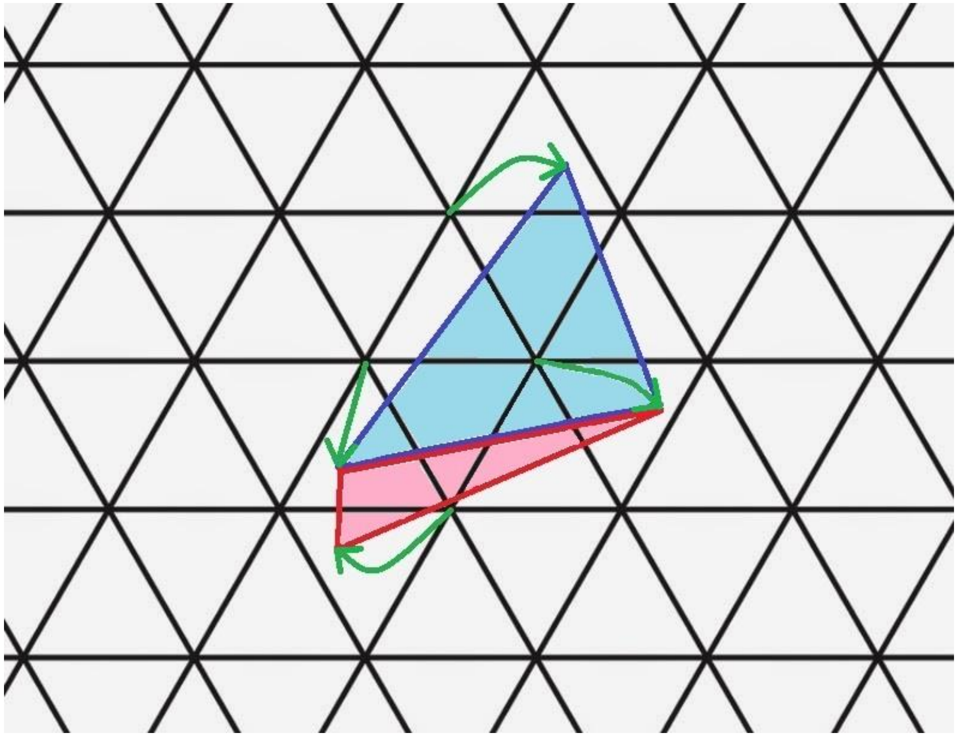
> Actual resolution (square-based domain) is $\approx \frac{2}{3} dx$

> 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 $\overline{U}_{ij}^{n}$ $\overline{V}_{ij}^{n}$

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

Non-Hydrostatic Fully-Compressible Equations

> FINAL version of Euler (Navier-Stokes) equations

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

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

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

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

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

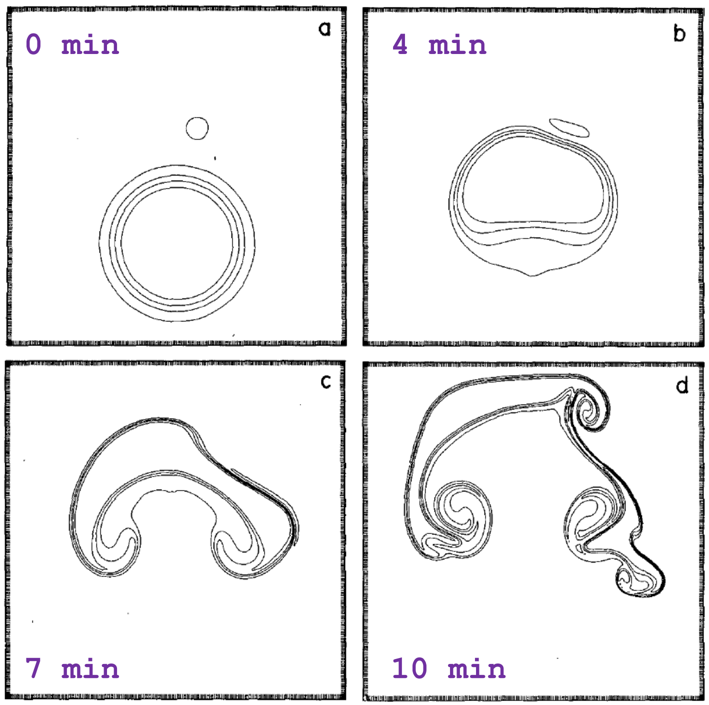
> Numerical implementation 3D [CFL $\xrightarrow{c_s > 300\ m/s}$ $\Delta t \approx 2\ \Delta x(\Delta z)$]

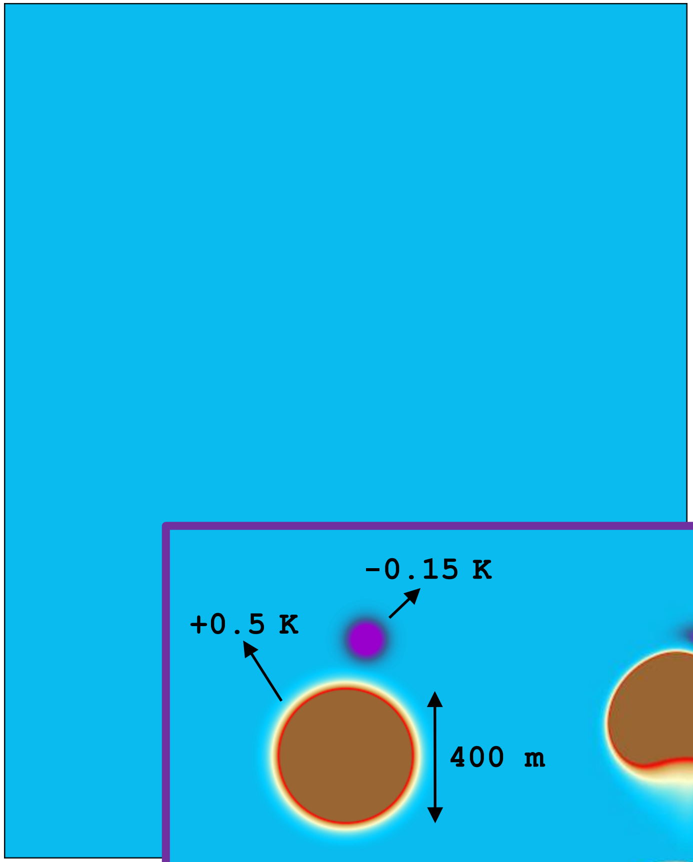
* Forward-Backward integration of "forcings" in RK2 cycle
* REA (V and H) integration of advection every 6-10 Nsteps
* Rigid Wall BCs at W/E S/N B/T boundaries

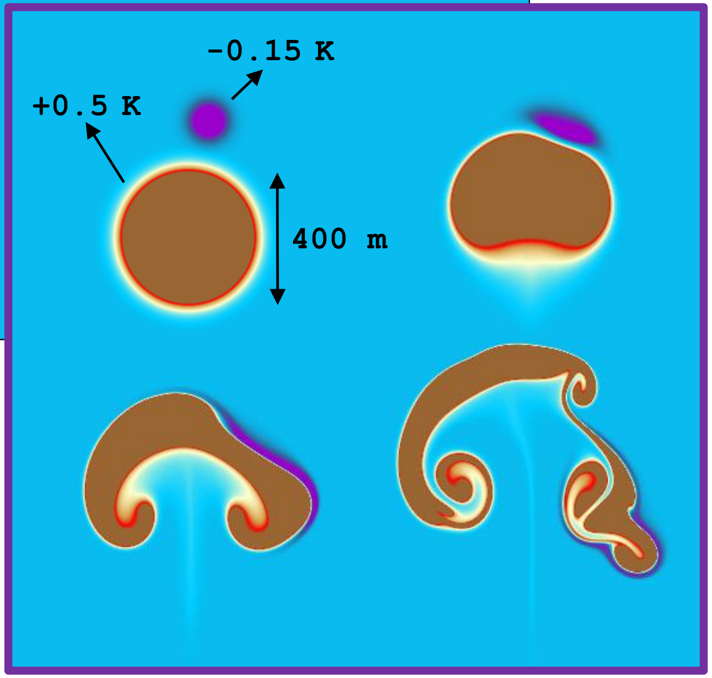
> Large Warm & Small Cold Bubbles

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

Robert (1993)







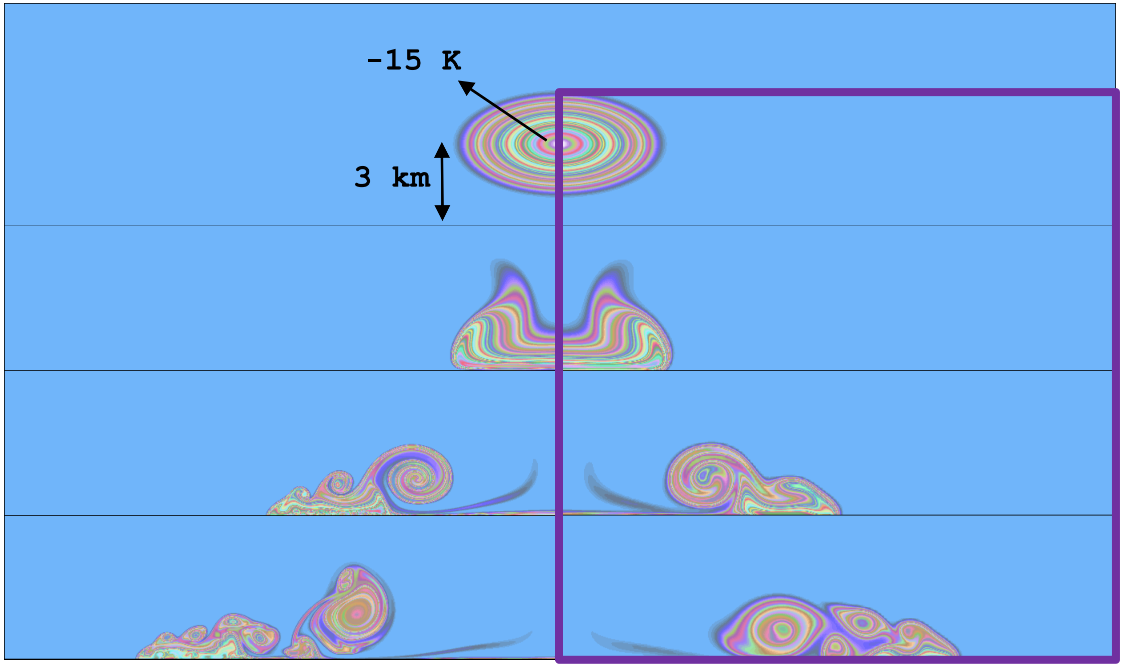
Animation

> Density Current

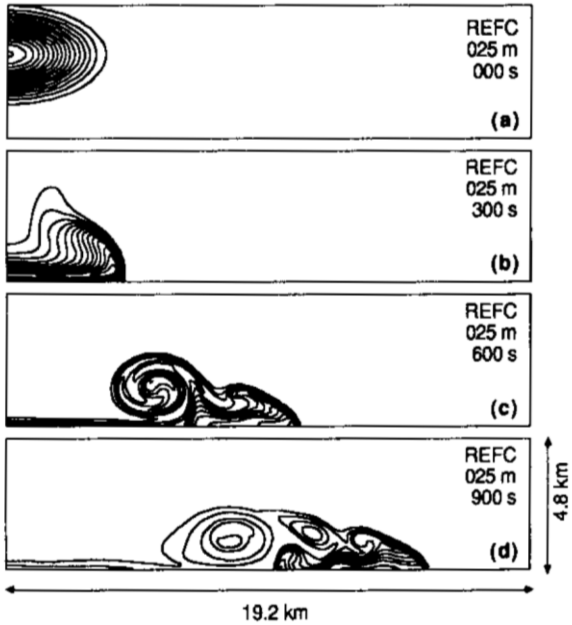
(dx=dz=100m,dt=0.25s,Nstep=10,3h)

Quadruple resolution

Initial

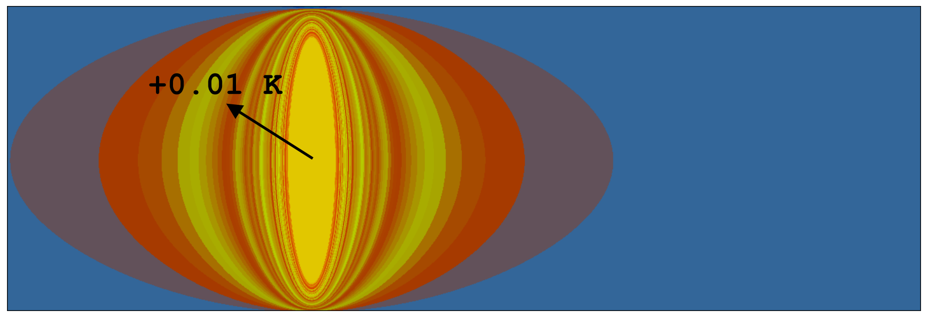


Straka et al. (1993)



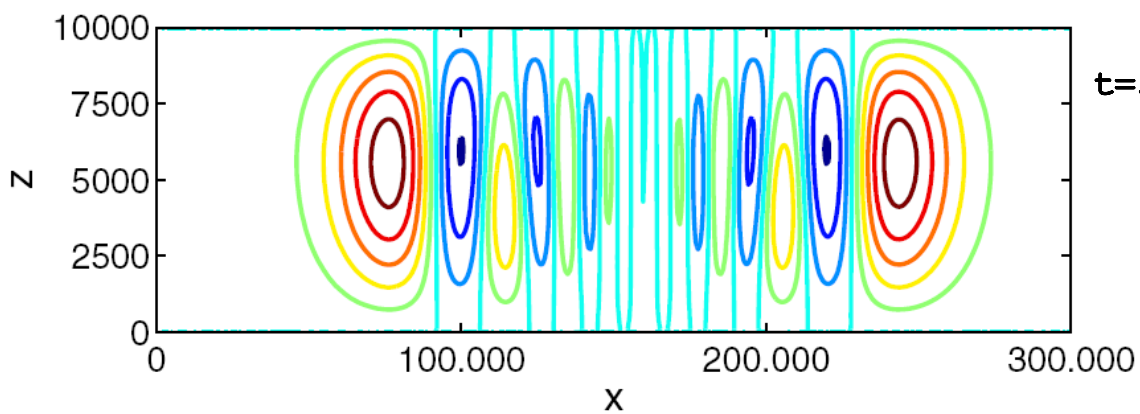
> Inertia-Gravity Waves (uniform wind/stability: $U=20ms^{-1}/N=0.01s^{-1}$)

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

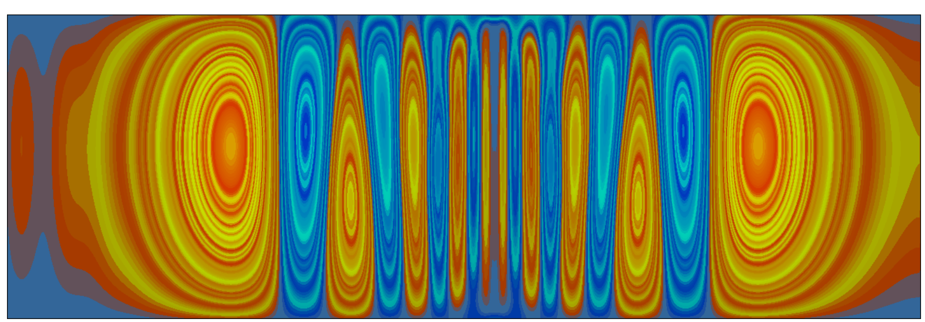


Initial

Giraldo & Restelli (2008)



t=50min



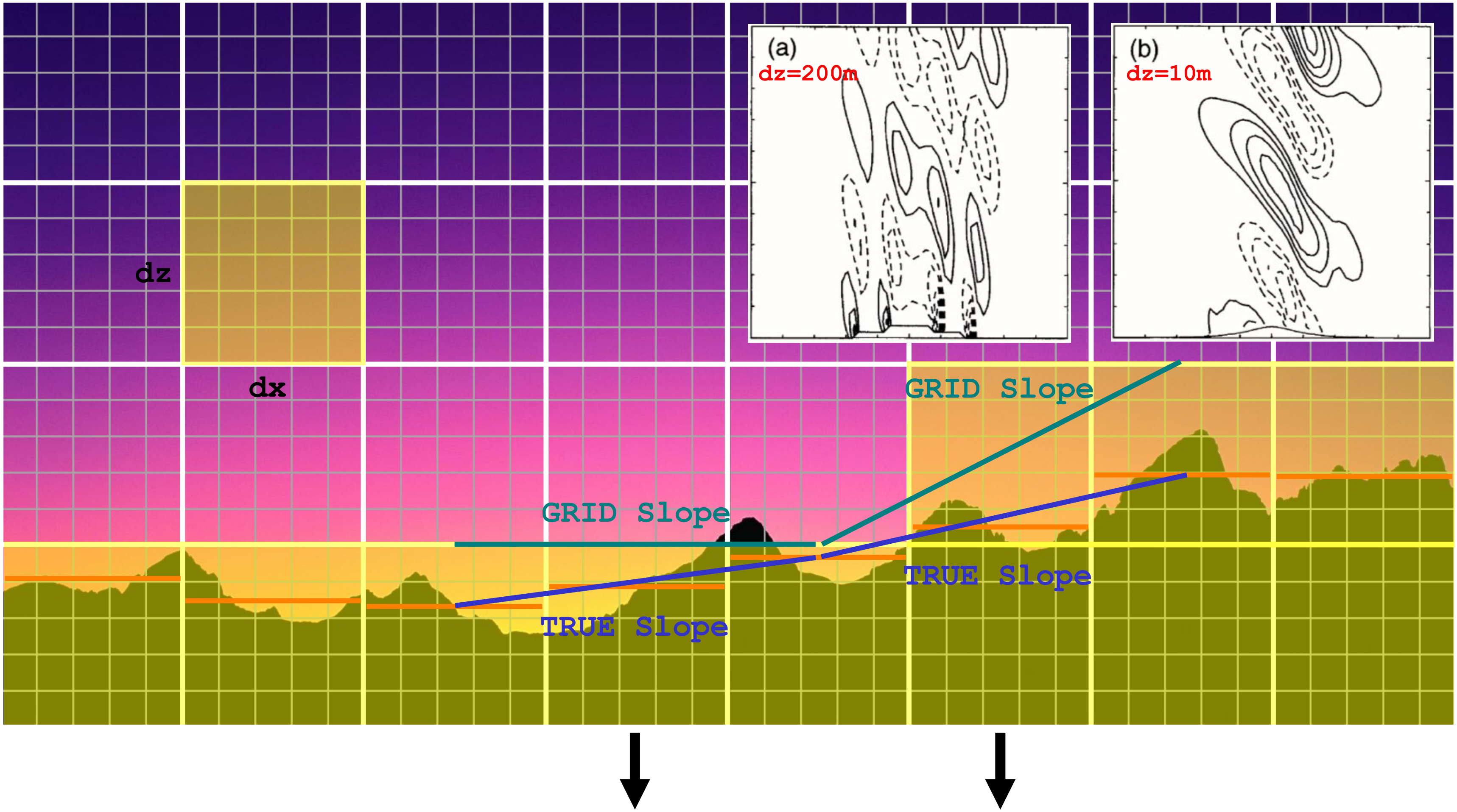
Animation

Inclusion of Orography (+ GW Absorbing Layer)

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

ETA MODEL

Gallus & Klemp (2000)



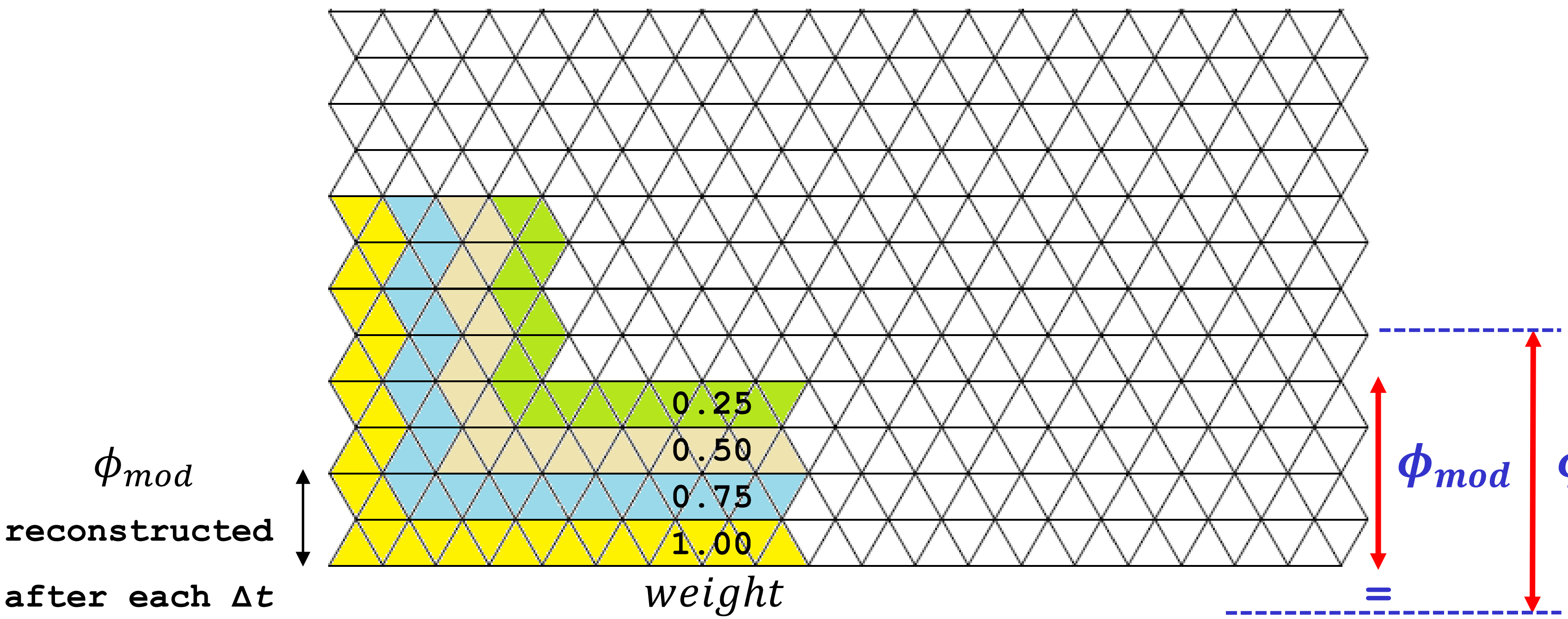
NO forcing !!!

CORRECT forcing

TOO MUCH forcing !!!

CORRECT forcing

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



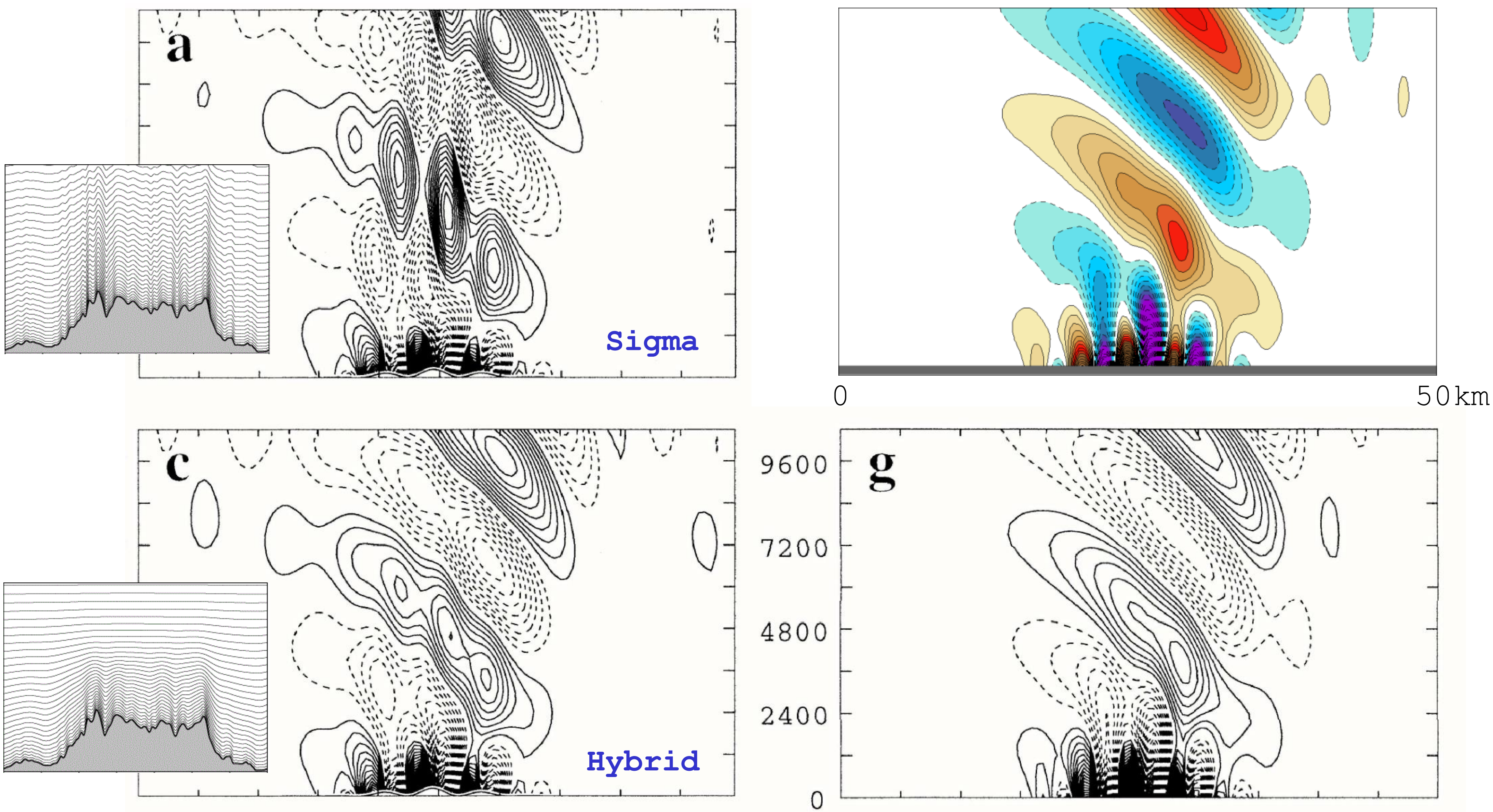
$$\frac{\partial \phi_{mod}}{\partial t} = weight\,[F(\phi_{LS} - \phi_{mod}) - G\Delta^2(\phi_{LS} - \phi_{mod})]$$

> **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

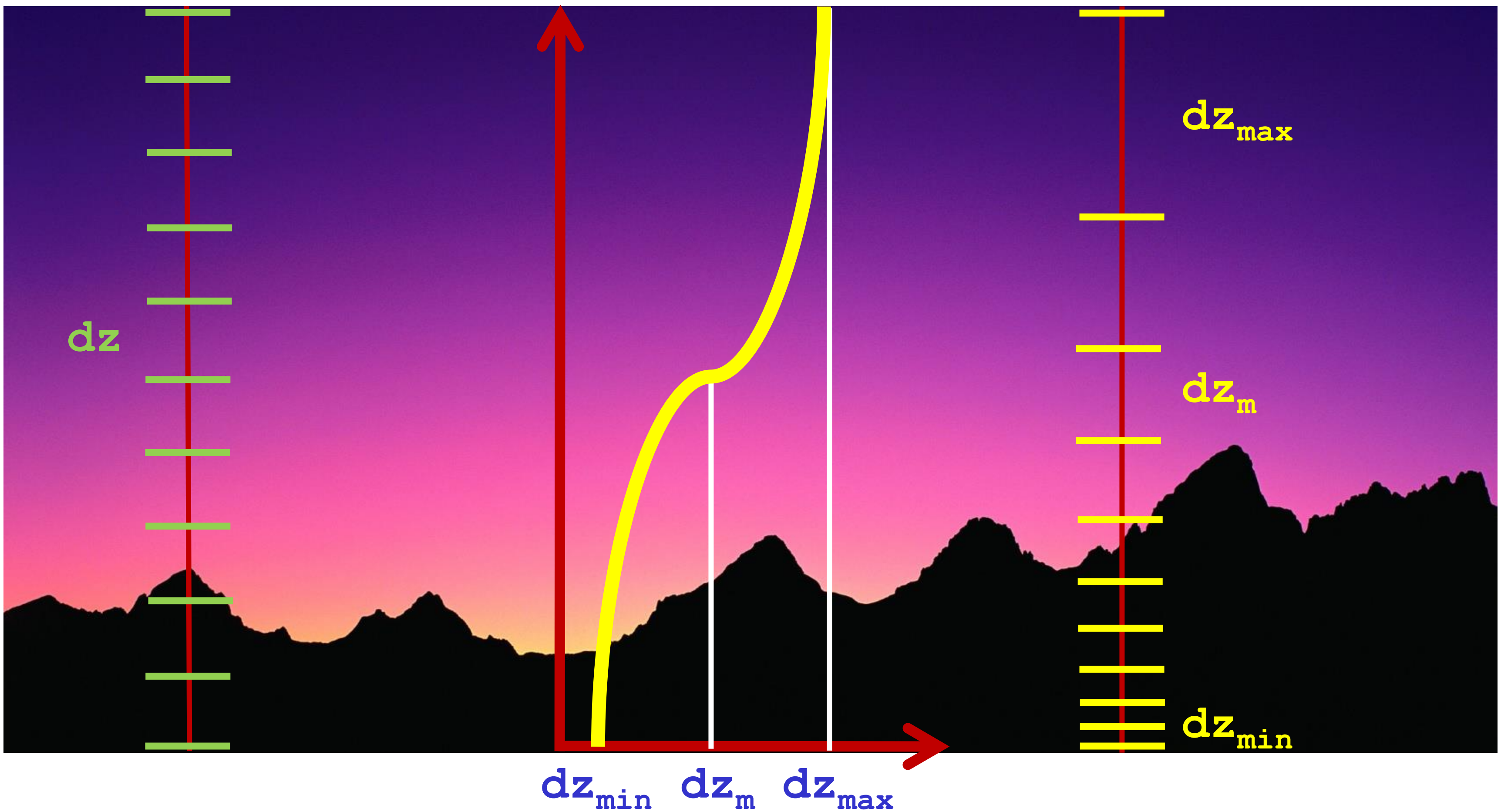


Schär et al.(2002)

Analytical

Vertical Stretching (+ Stabilization Fast Modes)

> Higher resolution at low levels (cos profile)



> Two parameters (stretch, dz_m)

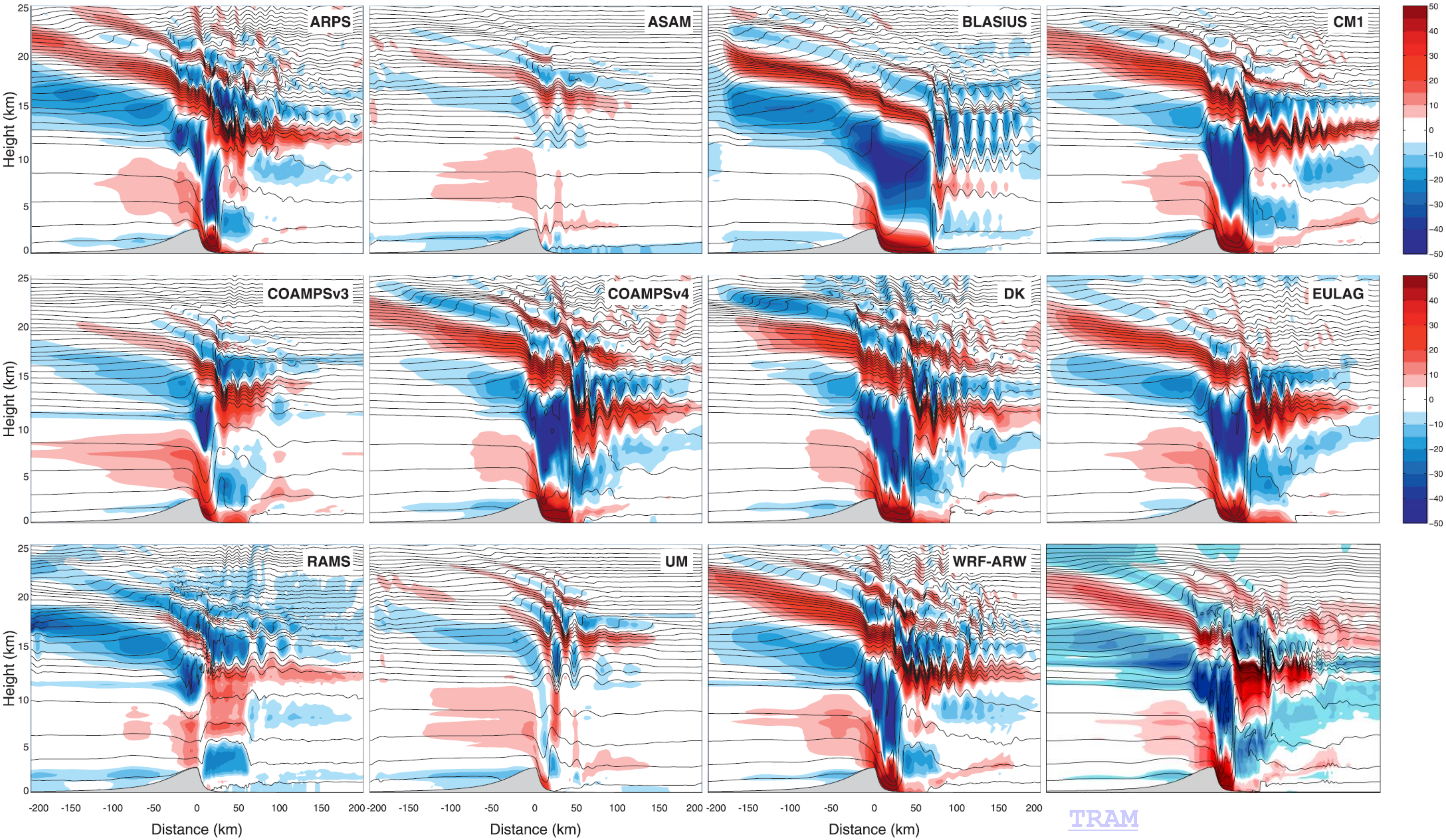
$$\begin{cases} dz_{min} = dz_m/stretch \\ dz_{max} = dz_m + (dz_m - dz_{min}) \end{cases}$$

> T-REX Intense Mountain-Wave

t=4h

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

Doyle et al. (2011)

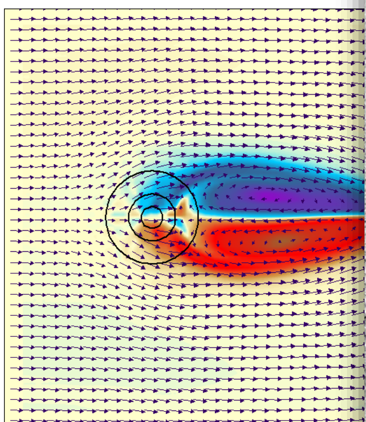


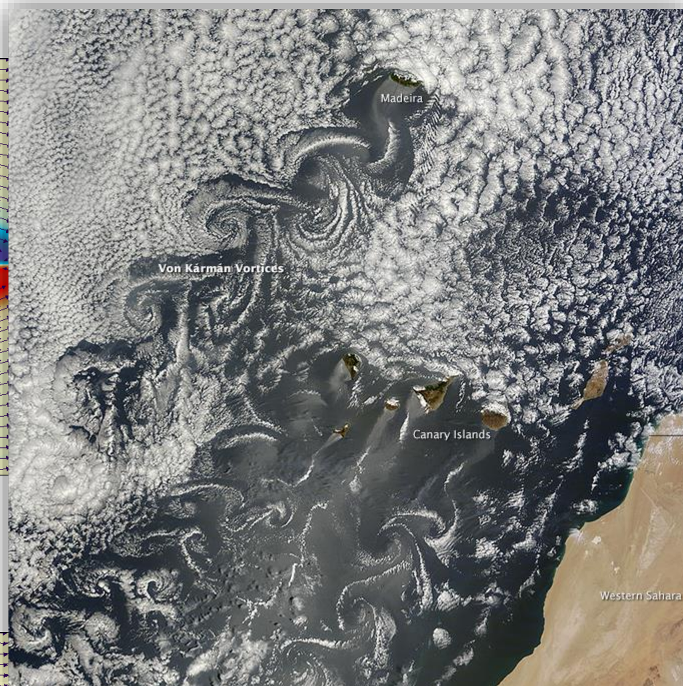
TRAM
Anim

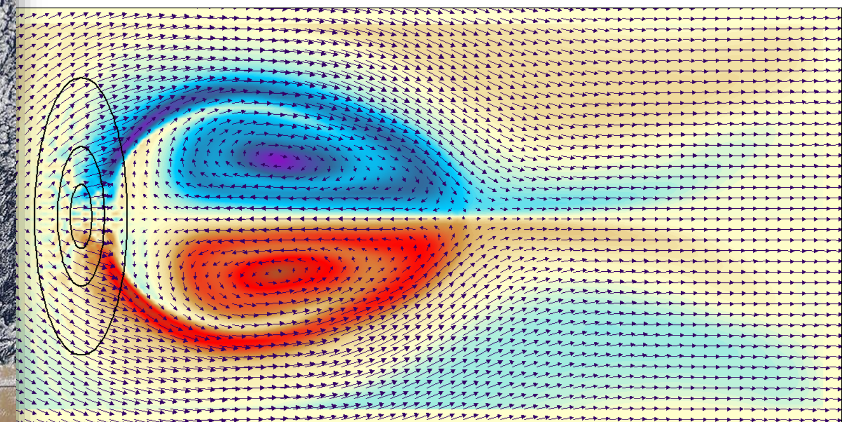
> Von Kármán Vortex Streets ($U=10ms^{-1}$, $N=0.01s^{-1}$)

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

e.g. Schär and Durran (1997)

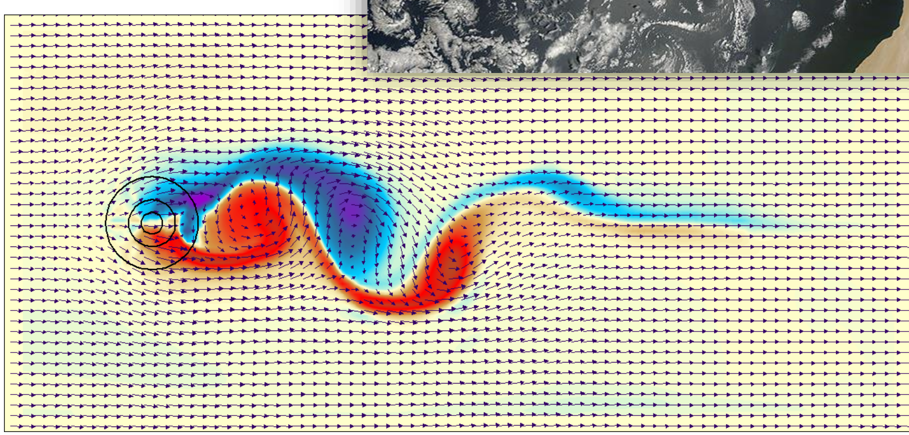


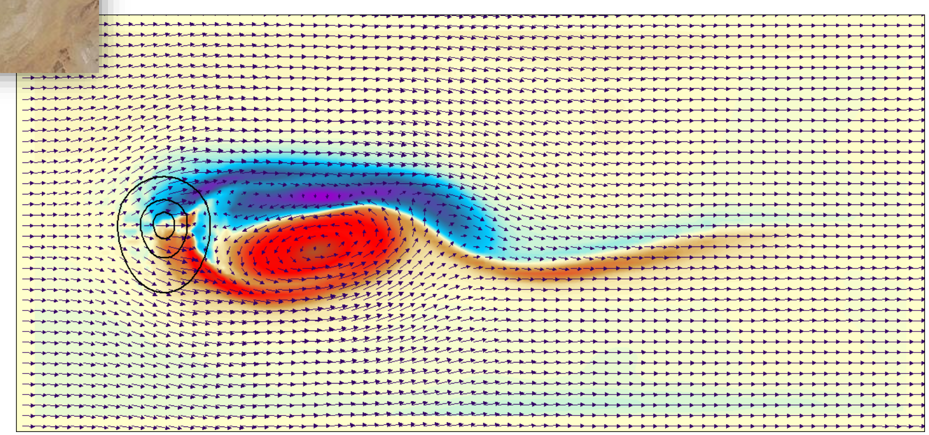




h=3000m

h=3000m





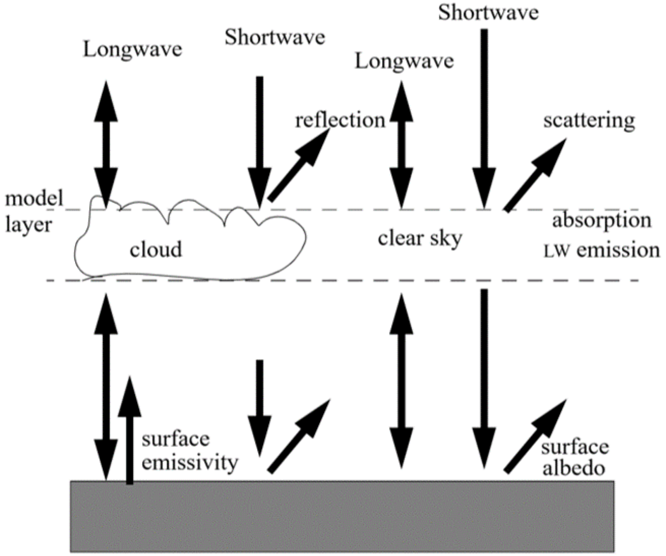
h=3000m (asymmetric I.C)

Animation
Tracer

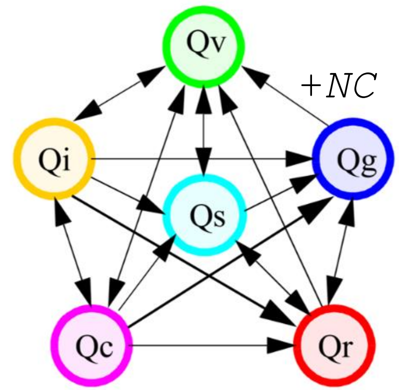
h=3000m

TRAM Physics (MM5-based schemes)

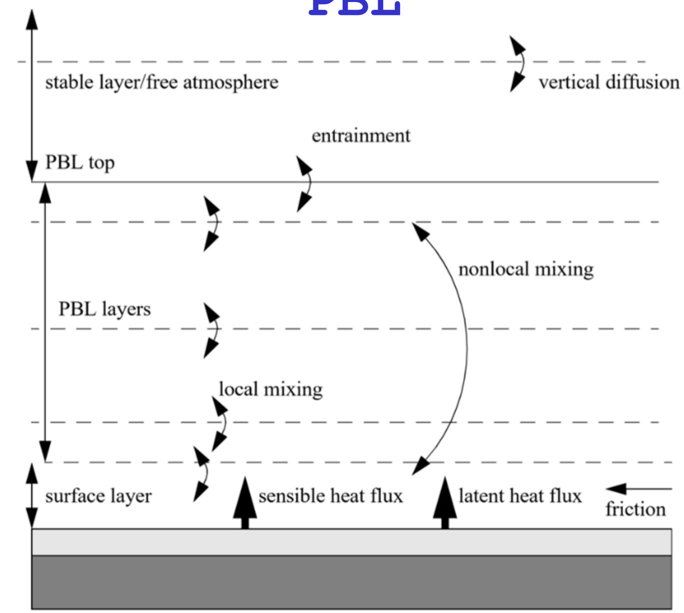
Radiation



Microphysics



PBL



NEW

Prognostic fields

Q_χ

Forcing terms

F_{Q_χ}

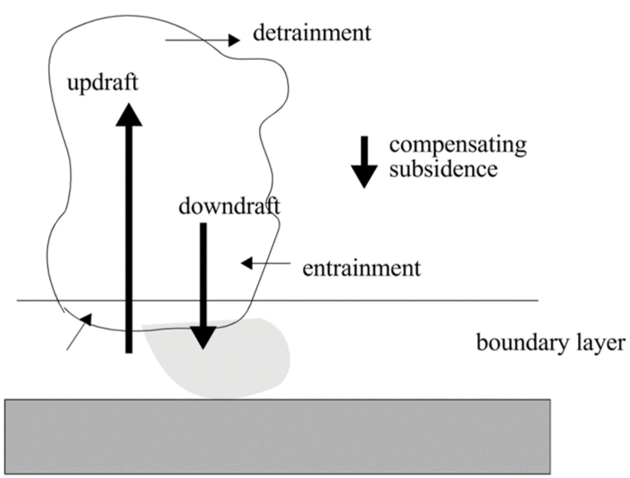
F_T

$F_u \quad F_v$

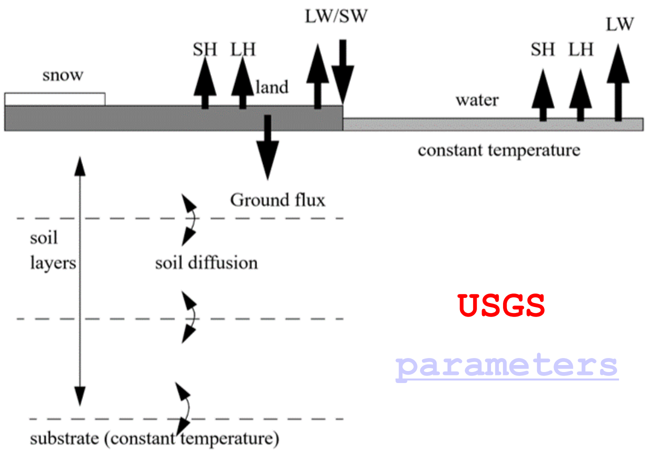
Surface variables

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

Cumulus



Surface



USGS

parameters

NEW Form of Equations: MESOSCALE-IDEALized

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

ALL moist effects on pressure and thermodynamics

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

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

Physics computed in NSTEP-cycle

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

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

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

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

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

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

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

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

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

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

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

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

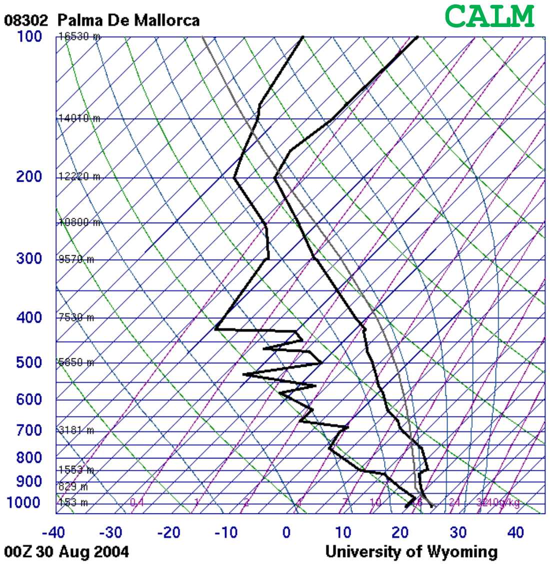
$$\frac{\partial v}{\partial t} = -mu\frac{\partial v}{\partial x} - mv\frac{\partial v}{\partial y} - w\frac{\partial v}{\partial z} - c_p(\bar{\theta}_\rho + \theta'_\rho)m\frac{\partial \pi'}{\partial y} - u\left(f + u\frac{\partial m}{\partial y} - v\frac{\partial m}{\partial x}\right) + \hat{f}w\sin\alpha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

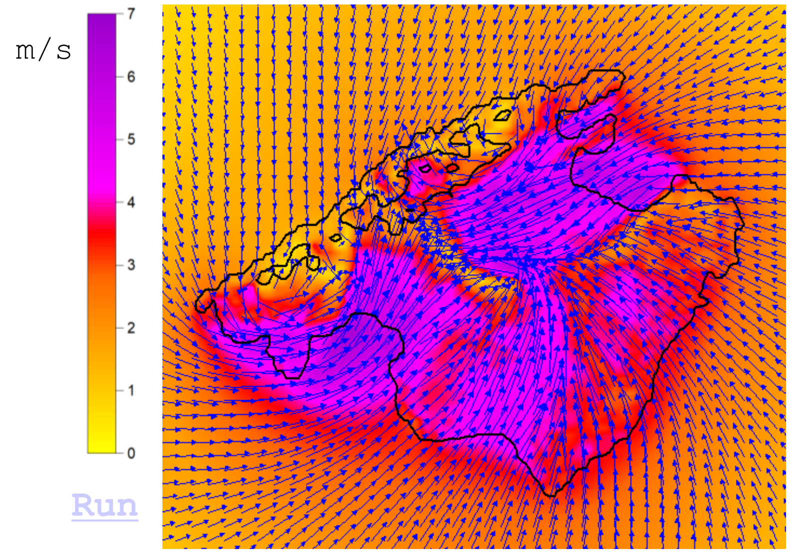
$$\frac{\partial w}{\partial t} = -mu\frac{\partial w}{\partial x} - mv\frac{\partial w}{\partial y} - w\frac{\partial w}{\partial z} - c_p(\bar{\theta}_\rho + \theta'_\rho)\frac{\partial \pi'}{\partial z} + g\frac{\theta'_\rho}{\bar{\theta}_\rho} + \hat{f}(u\cos\alpha - v\sin\alpha) + \frac{u^2+v^2}{a}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

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

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

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

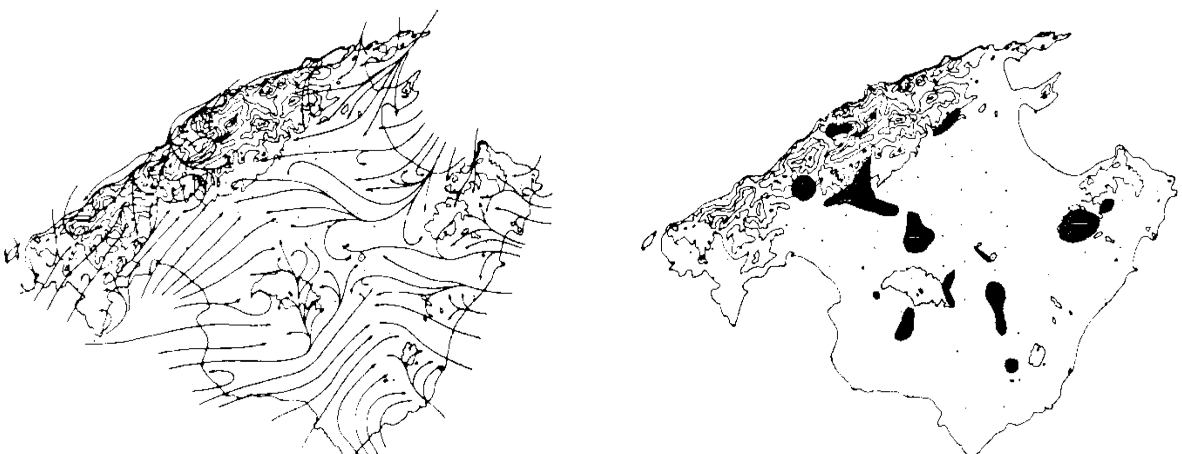




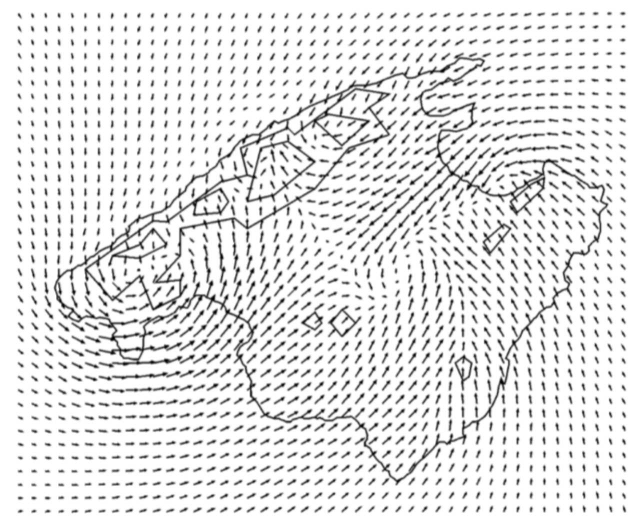
t=13h

Clouds

Rainfall



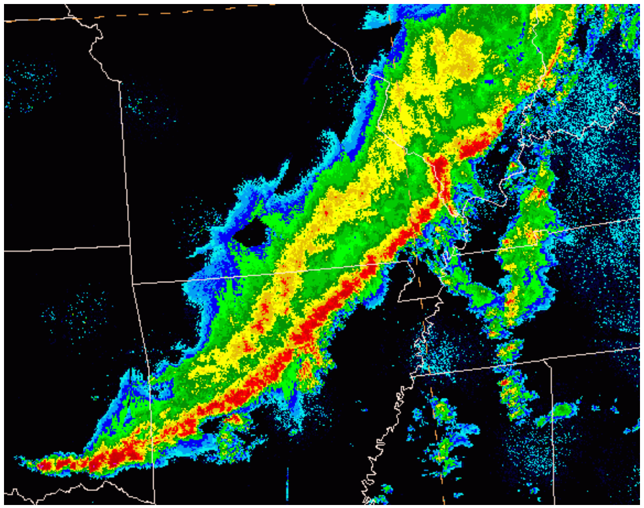
Jansà & Jaume (1946)



Ramis & Romero (1995)

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

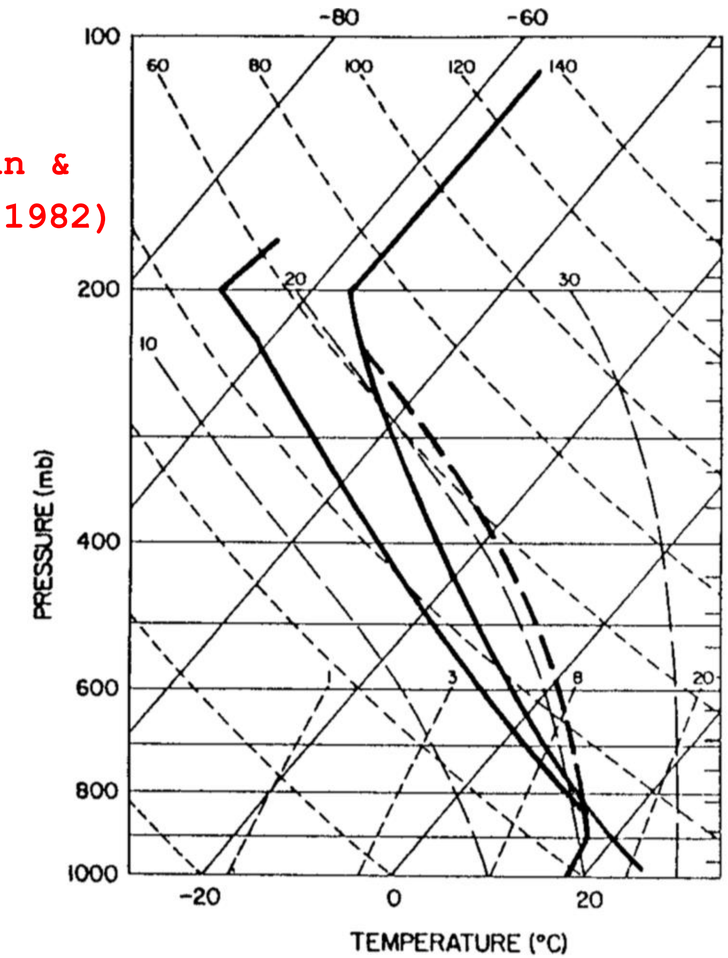
(dx=1.5km,dzm=200m,stretch=10,dt=3s,Nstep=5,10h)



IC: WK82 SOUNDING + 8K Surface Cold Pool

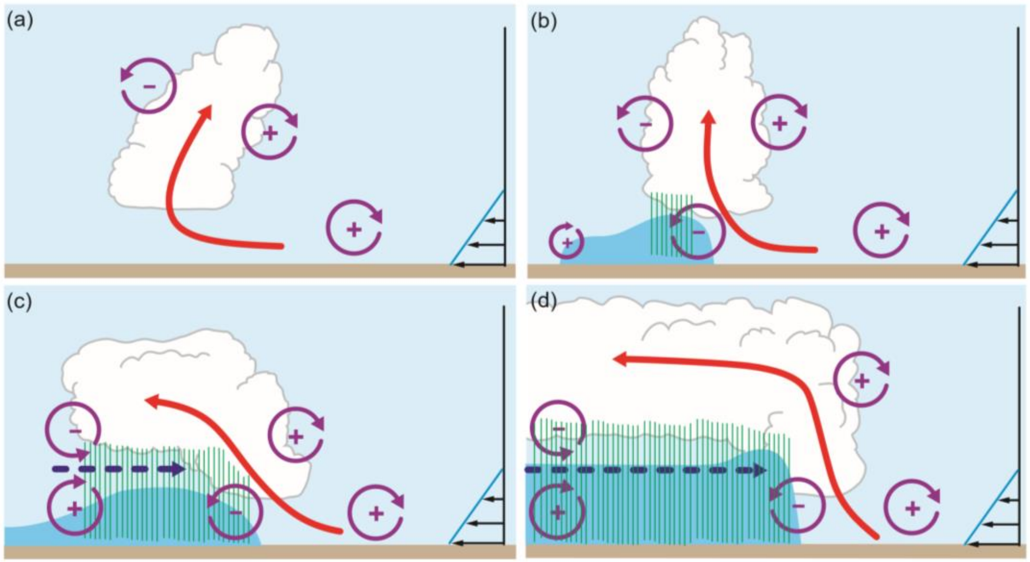
... and 3 different wind profiles

Weisman & Klemp (1982)



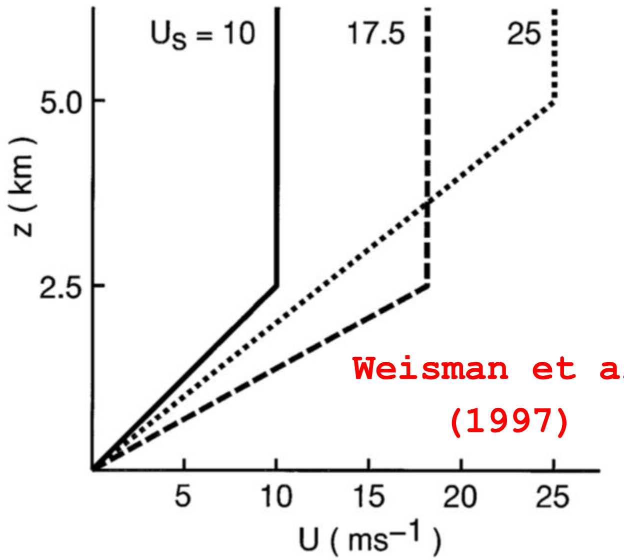
> Squall-Line Simulation (NO Coriolis, Radiation, PBL and Cumulus)

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

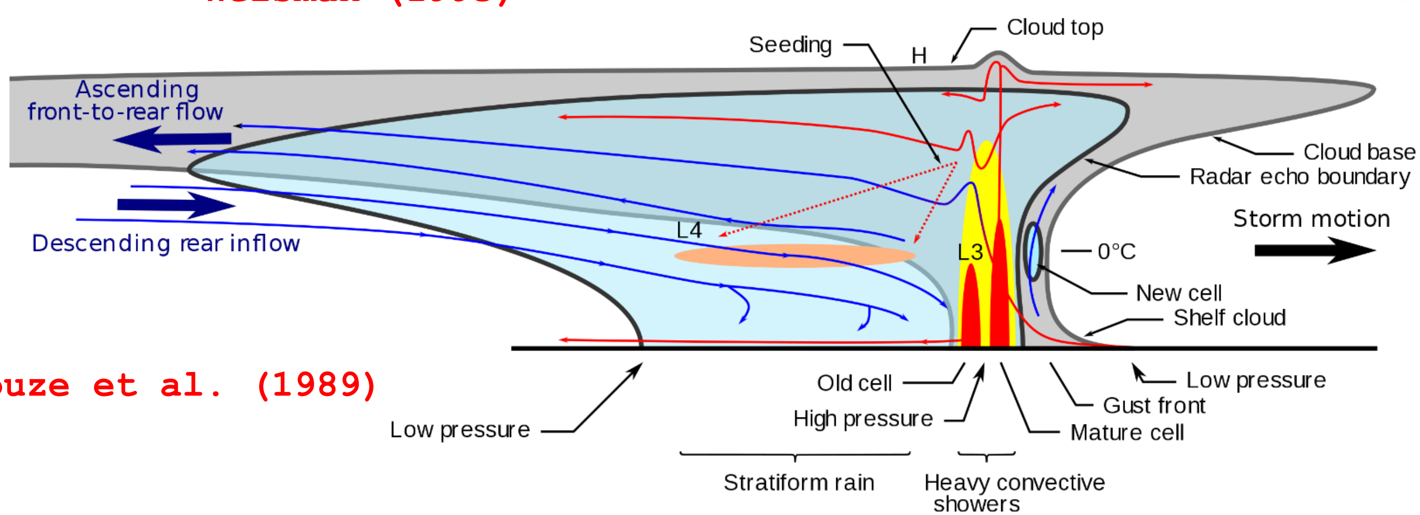


Weisman (1993)

SHEAR: Weak Moderate Deep



Weisman et al. (1997)

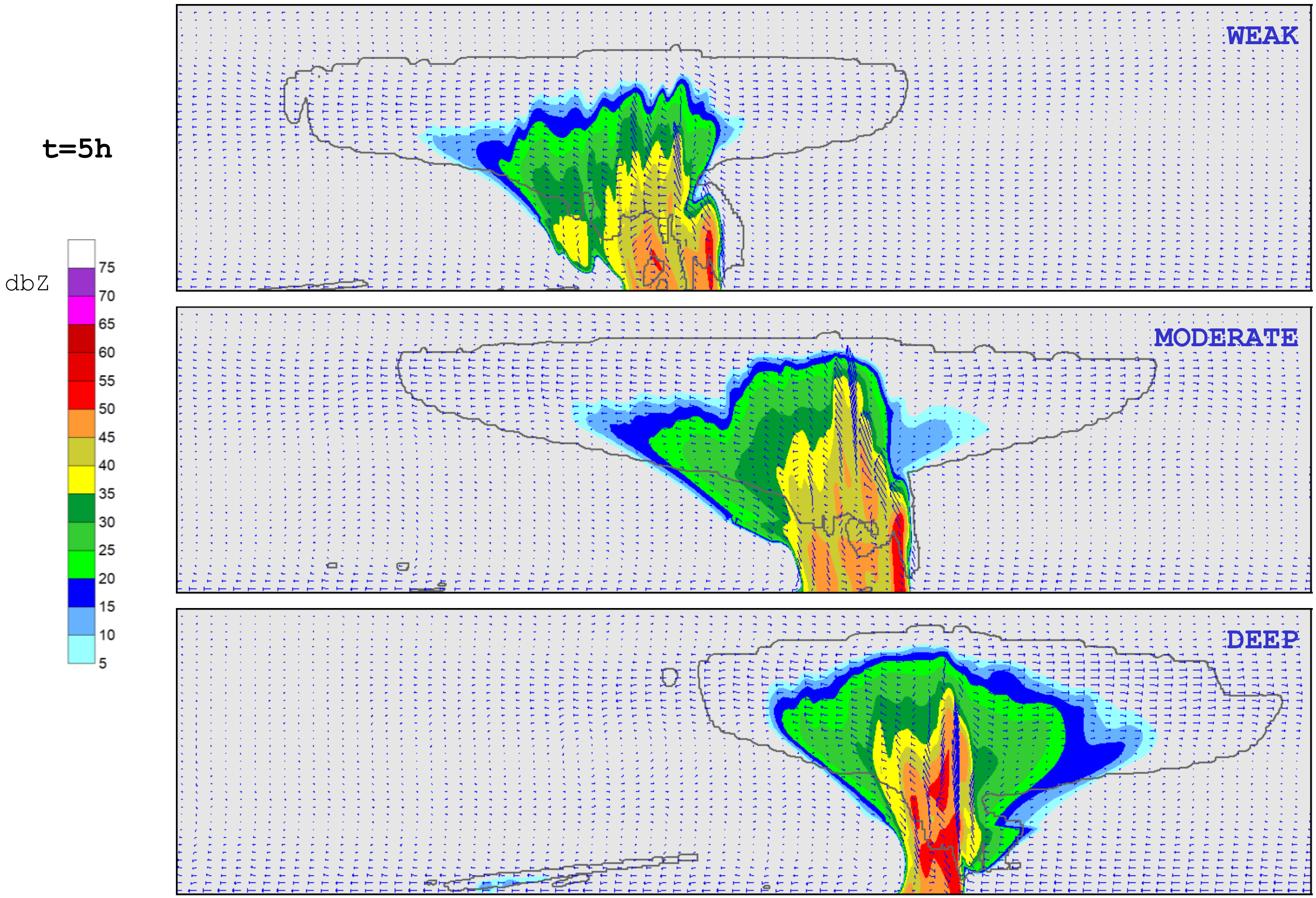


Houze et al. (1989)

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

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

t=5h



Run

Run +Oro

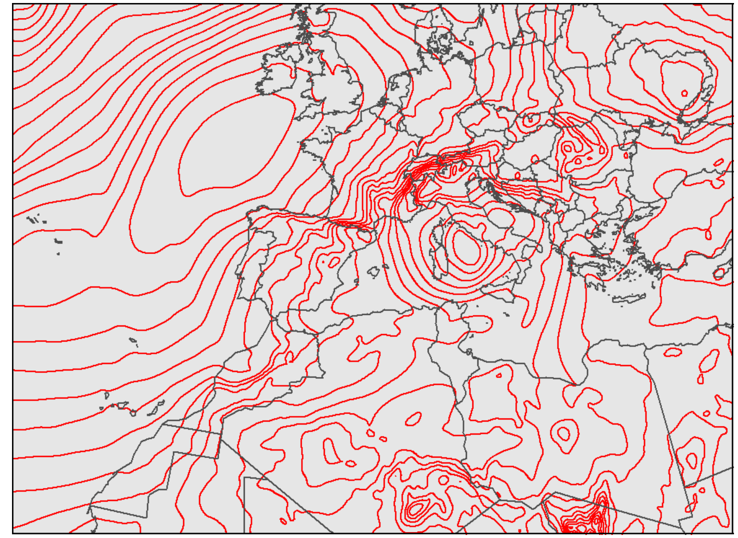
v.2D

Run

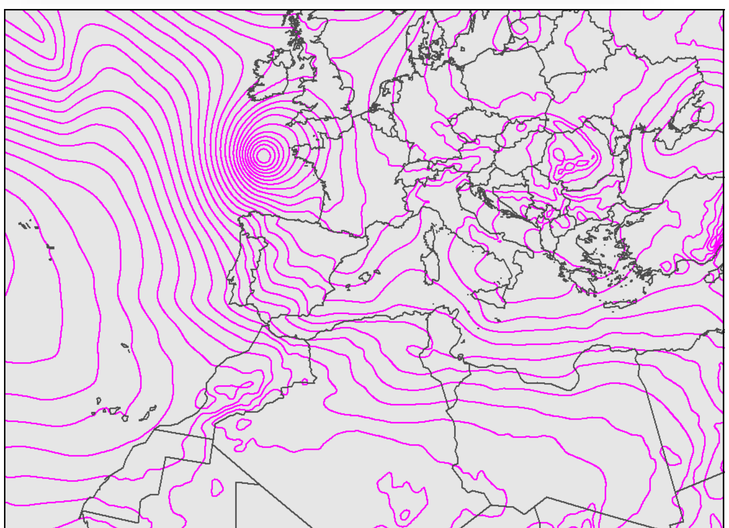
TRAM_physics_3D (SYNOPTIC-REALcase)

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

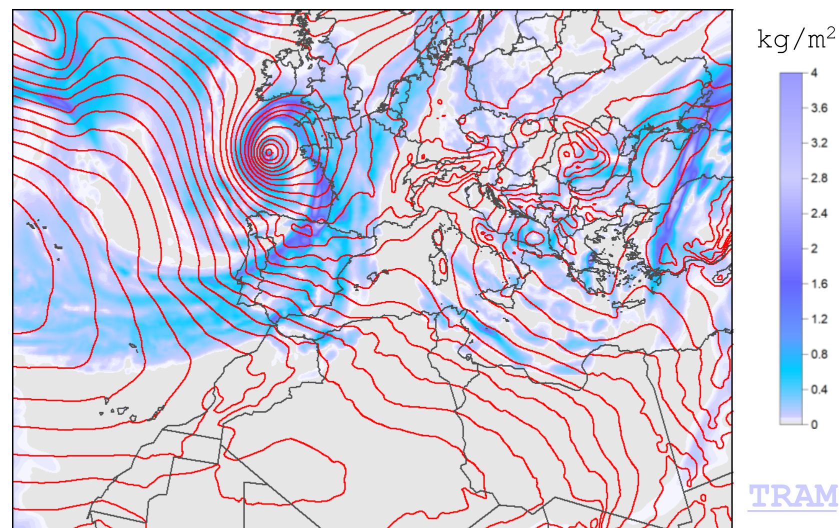
(MR:dx=25km,dzm=200m,stretch=10,dt=45s,Nstep=5,90h)



t=0h



t=72h



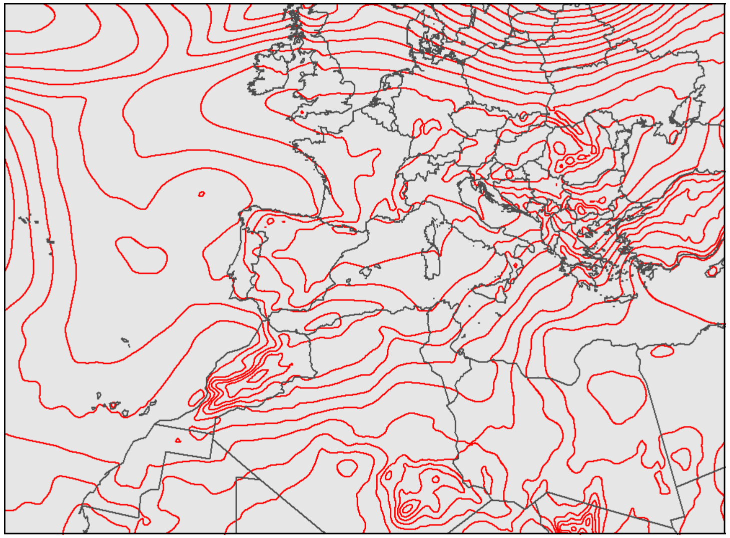
ERA-5

TRAM

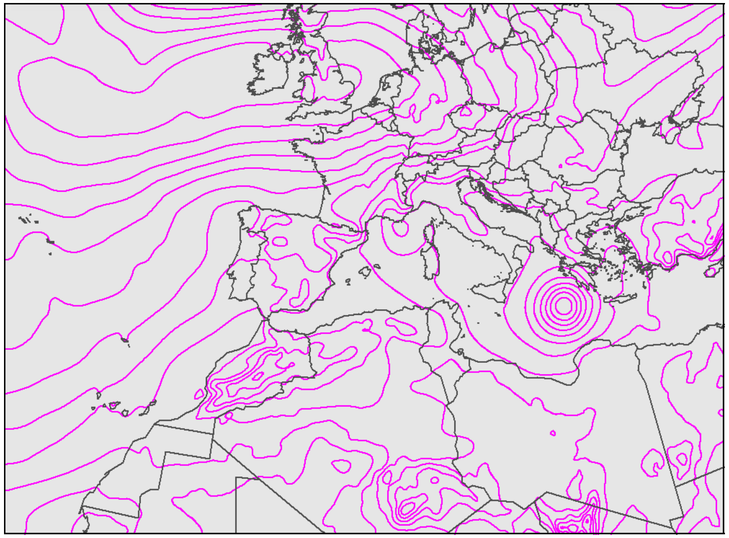
Winds   Rainfall

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

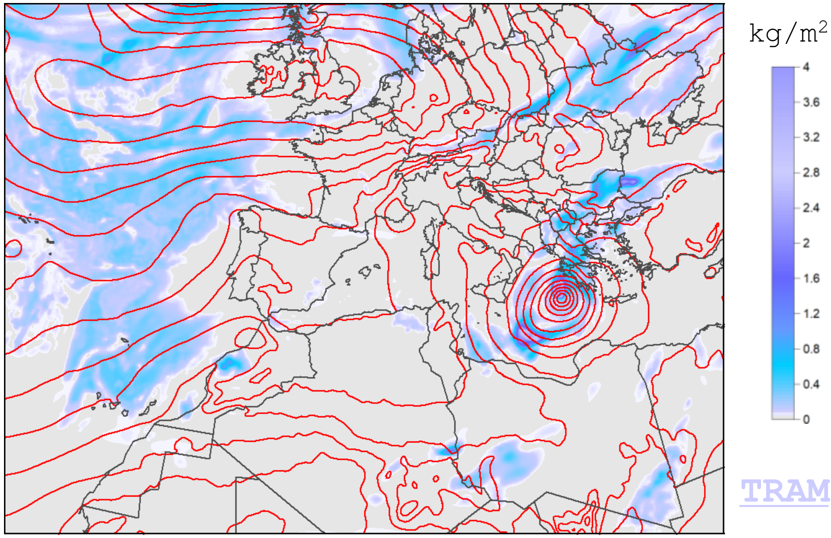
(MR:dx=25km,dzm=200m,stretch=10,dt=45s,Nstep=5,90h)



t=0h



t=48h



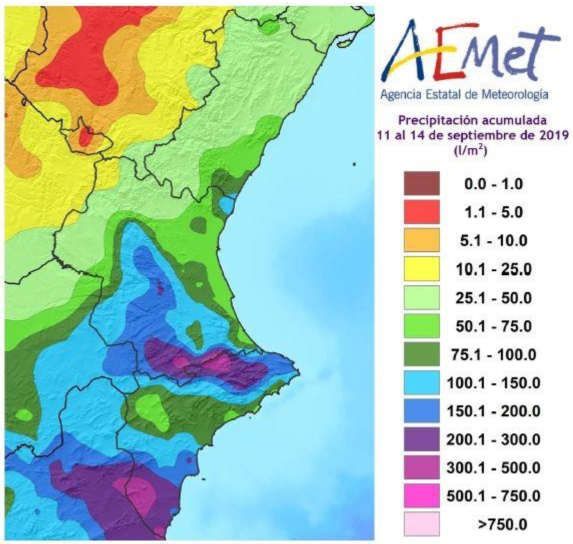
ERA-5

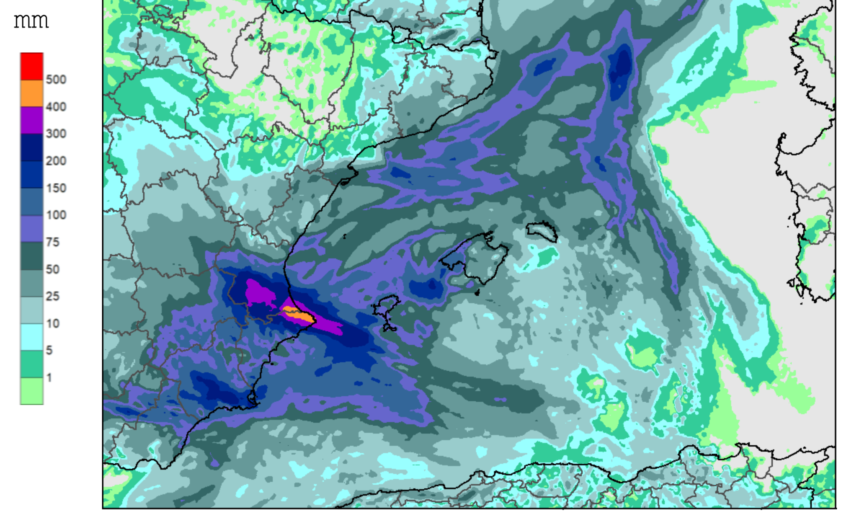
TRAM

Winds Rainfall

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

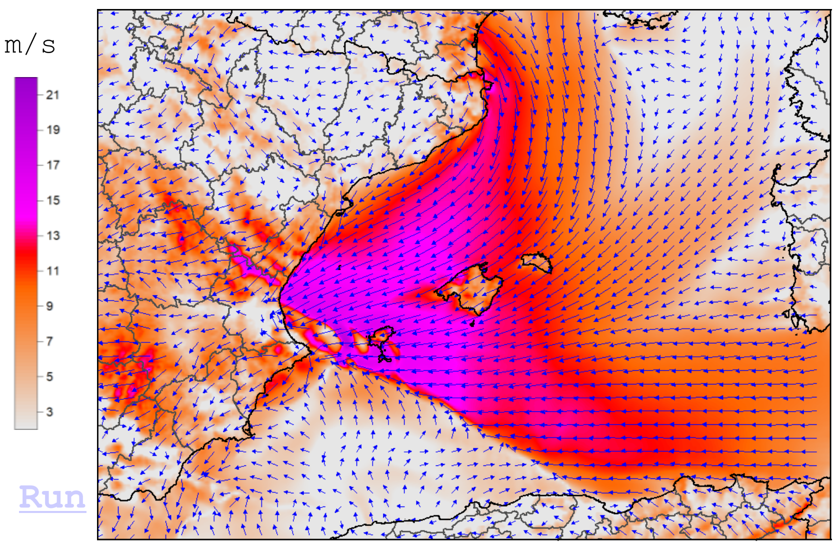
(HR_double:dx=4.5km,dzm=200m,stretch=10,dt=9s,Nstep=5,90h)





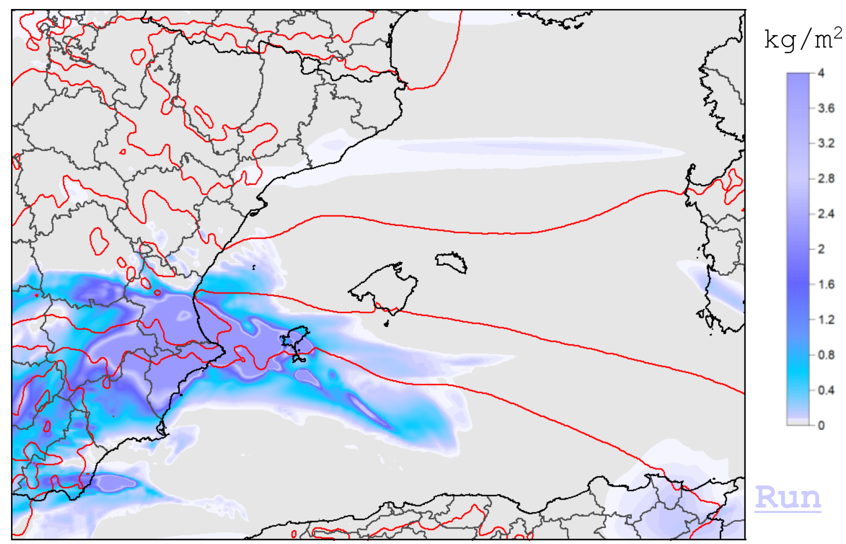
total

Run



Run

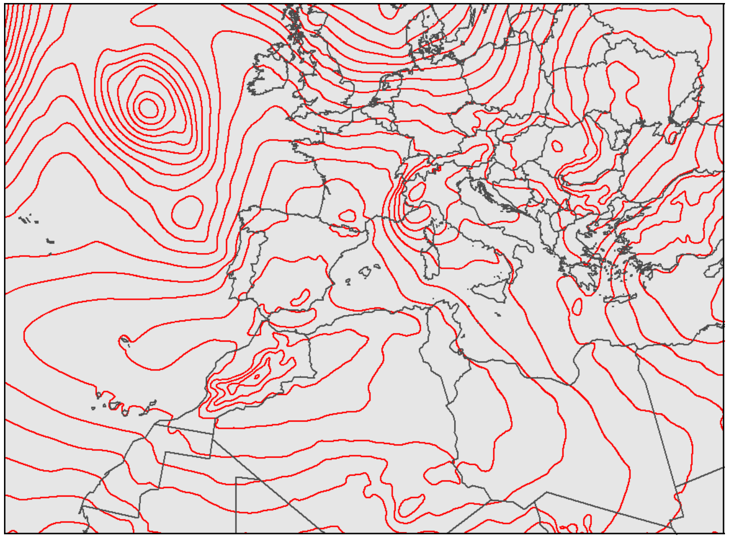
t=54h



Run

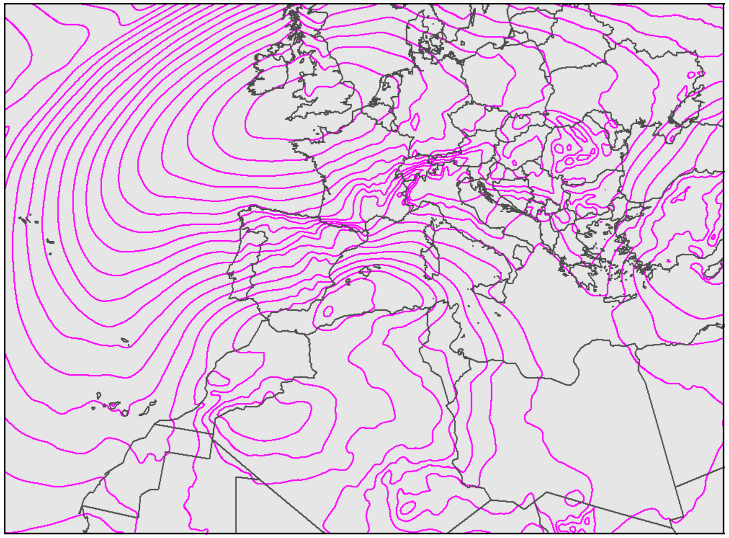
> "GLORIA" Extraordinary Storm (IC: 00 UTC 18 Jan 2020)

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

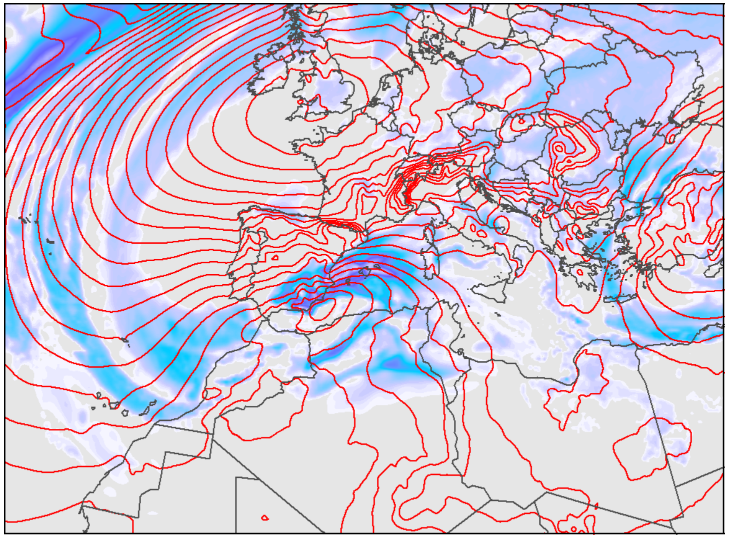


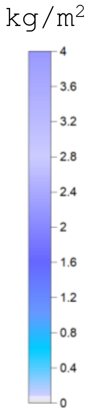
t=0h

ERA-5



t=48h



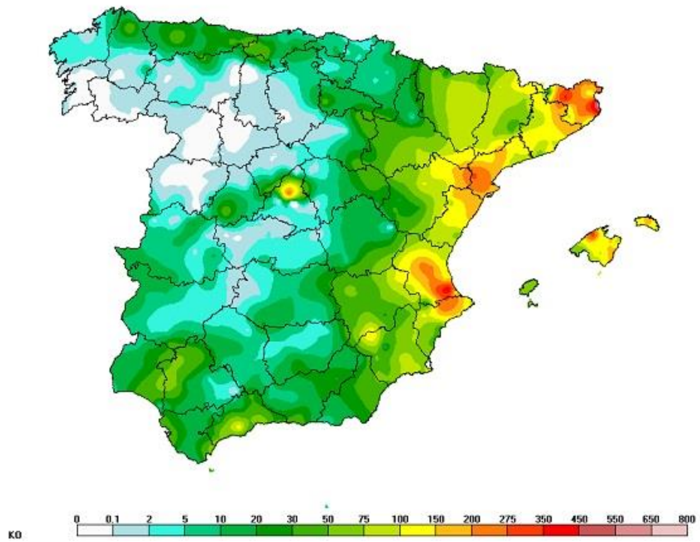


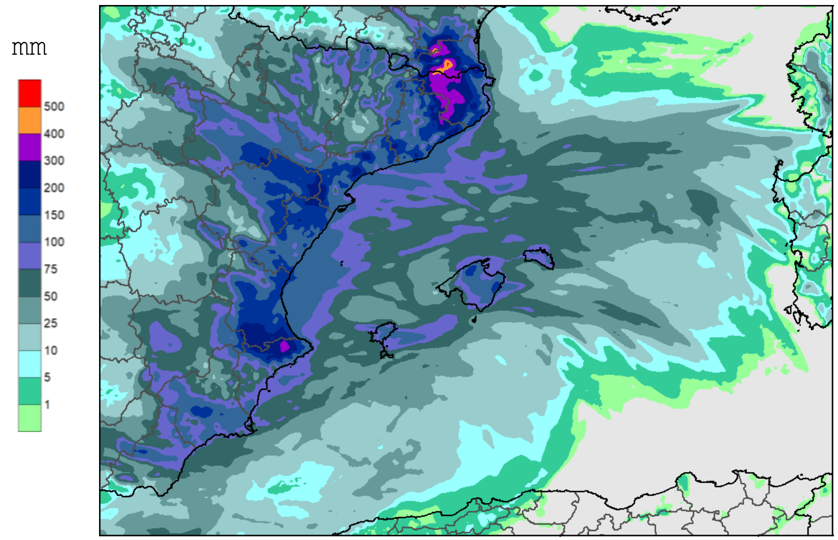
TRAM

Winds Rainfall

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

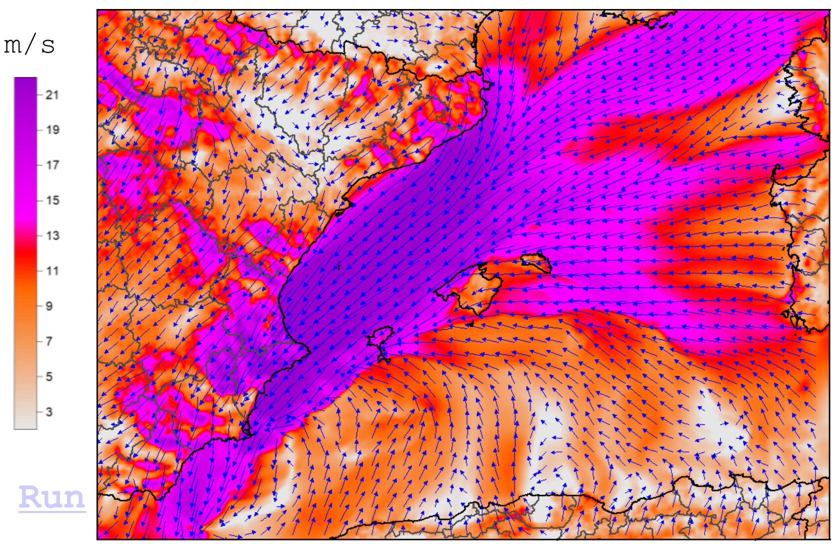
(HR_double:dx=4.5km,dzm=200m,stretch=10,dt=9s,Nstep=6,138h)





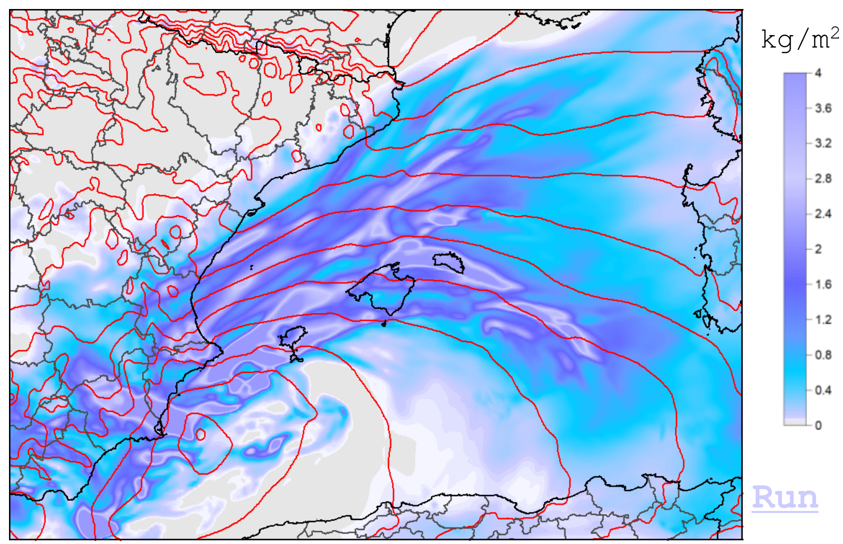
total

Run



Run

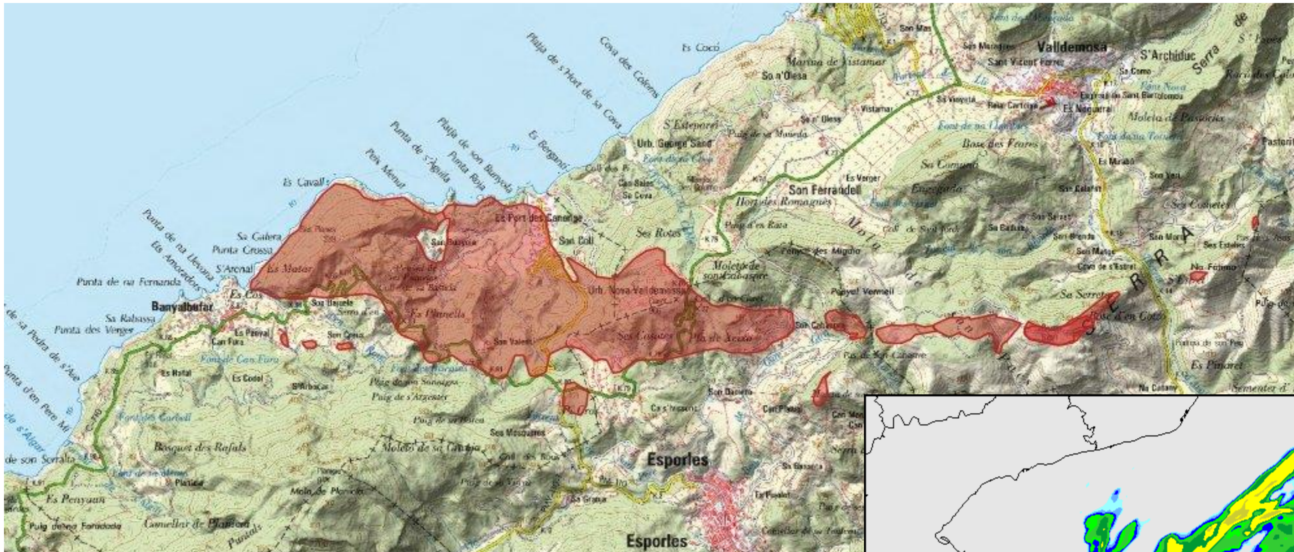
t=48h



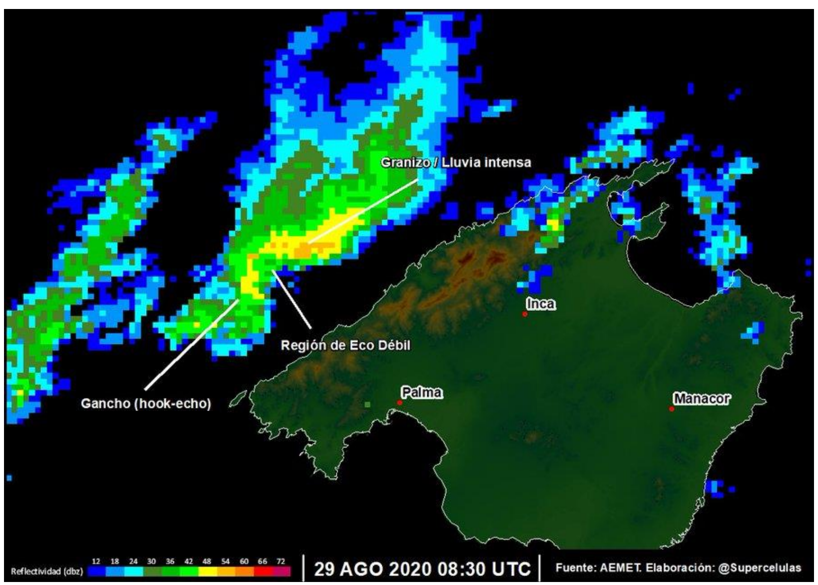
Run

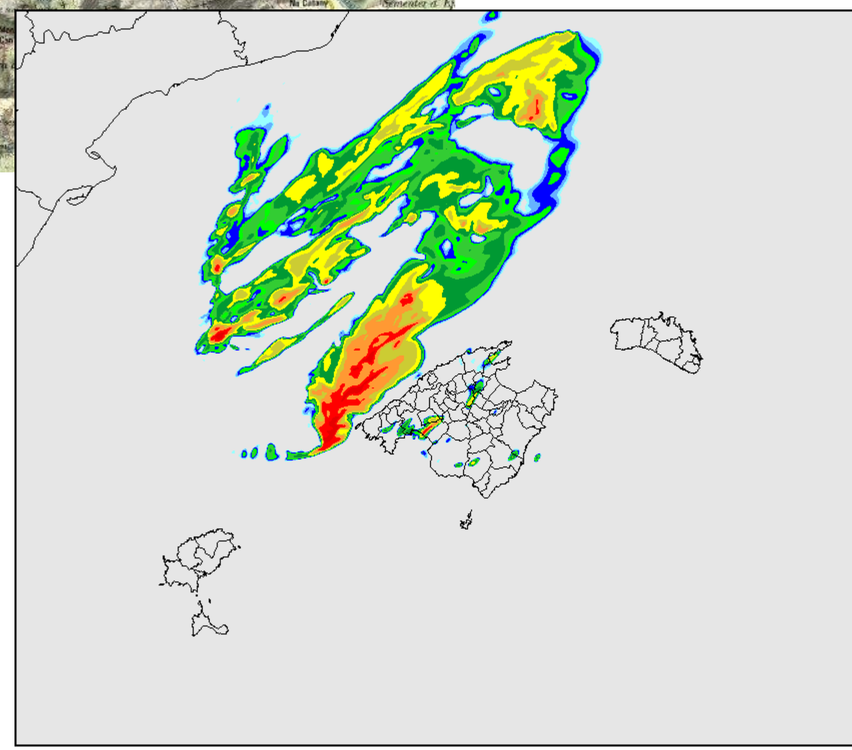
BANYALBUFAR-ESPORLES *Severe Supercell (29 August 2020)*

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



Run



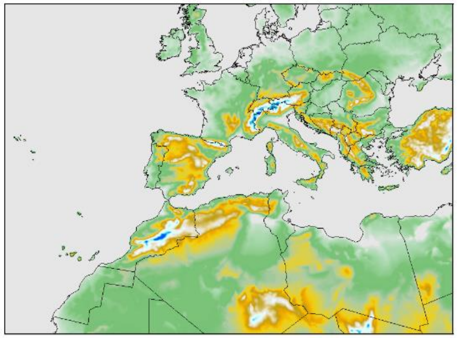


Wind Speed Rainfall Temperature

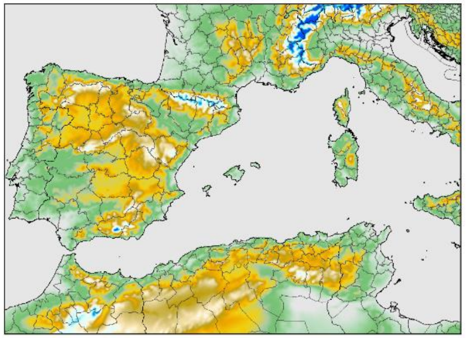
OPERATIONAL at: http://meteo.uib.es/tram

TRAM / MeteoUIB

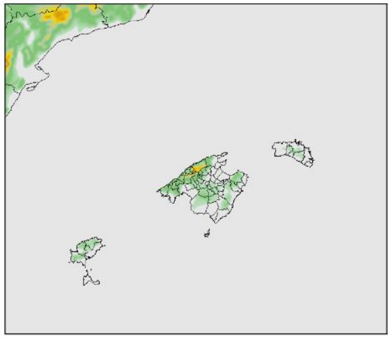
MR (17 km)



HR (6 km)



SR (2 km)

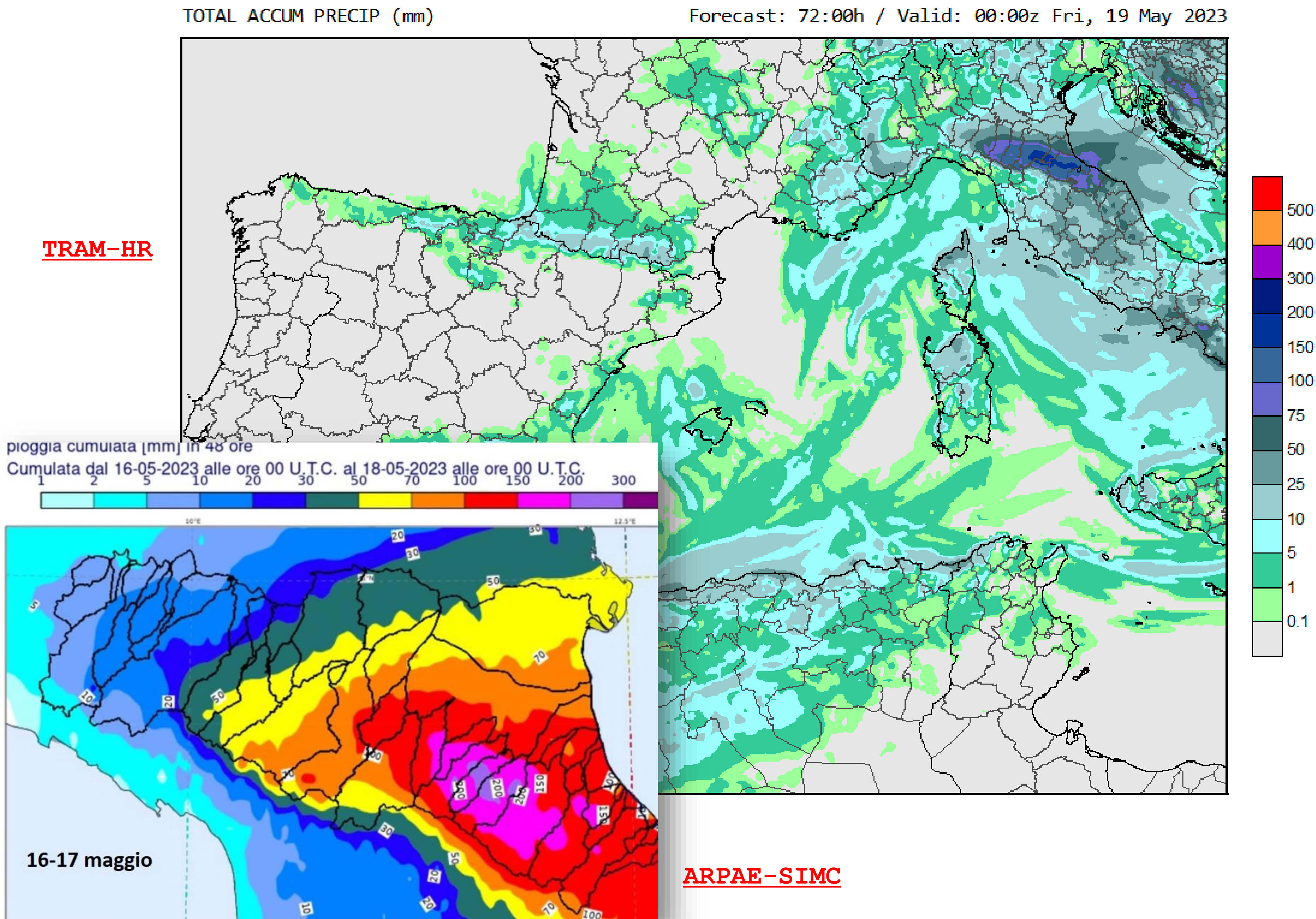


Grup de Meteorologia

UIB Universitat de les Illes Balears

EMILIA-ROMAGNA Catastrophic Floods (16-17 May 2023)

TRAM-HR



ARPAE-SIMC

THANK YOU

for

your attention