TRAM
(Triangle-based Regional Atmospheric Model)

A New Nonhydrostatic Fully Compressible Numerical Model

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MOTIVATION

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

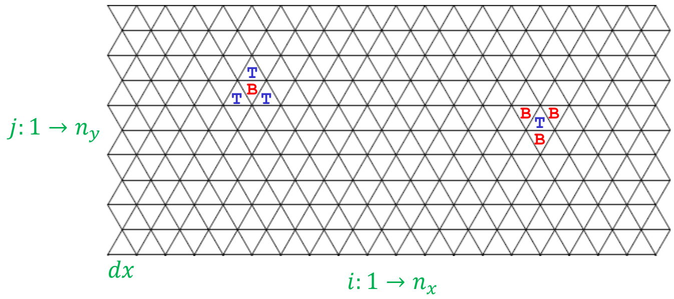
> Mostly for RESEARCH and ACADEMIC purposes, but potentially for "FORECASTING" as well

> 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

Advection 2D

> **Triangular-based** mesh



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

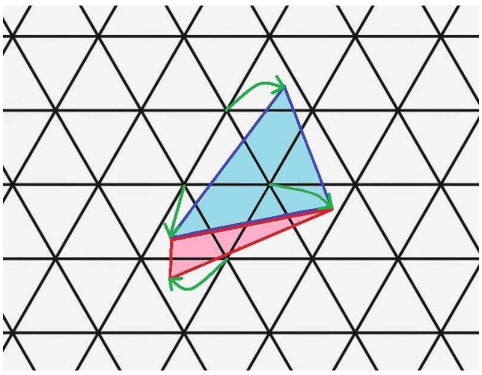
> All **variables** defined at triangle barycenters: T_{ij} B_{ij}

> 1^{st} **derivatives** (slopes) at T/B from neighbor B/T

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

Advection 2D

> **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 $\xrightarrow{c_s > 300\ m/s}$ $\Delta t \approx 2\ \Delta x(\Delta z)$]

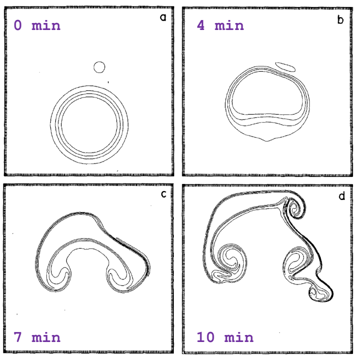
* Forward-Backward integration of "forcings" in RK2 cycle
* REA (V and H) integration of advection every 6-10 Nsteps
* Rigid Wall BCs at W/E S/N B/T boundaries

TRAM_non_hydro_set1_2D

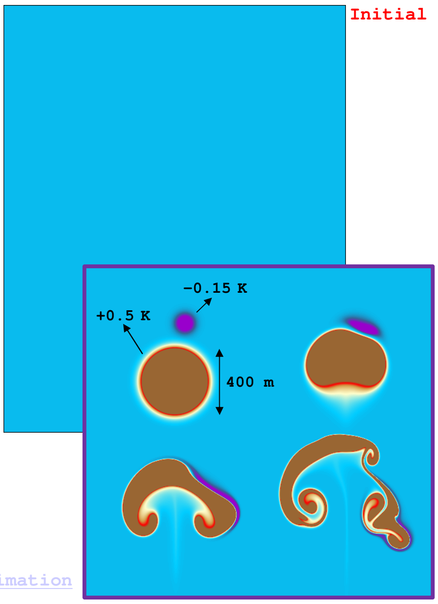
> **Large Warm & Small Cold Bubbles**

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

Robert (1993)



Initial



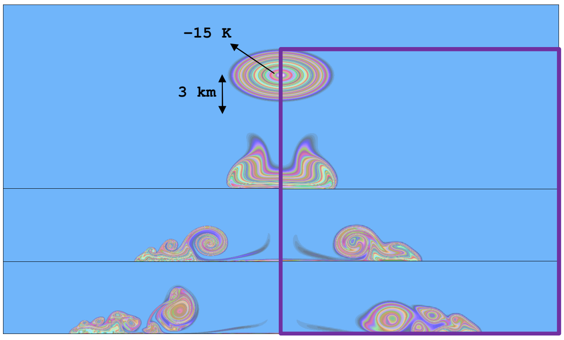
Animation

> Density Current

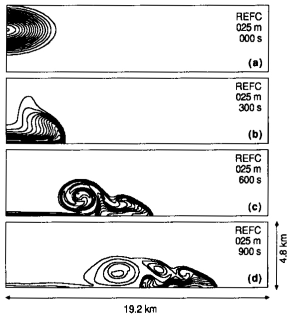
(dx=dz=100m,dt=0.25s,Nstep=10,3h)

Quadruple resolution

Initial



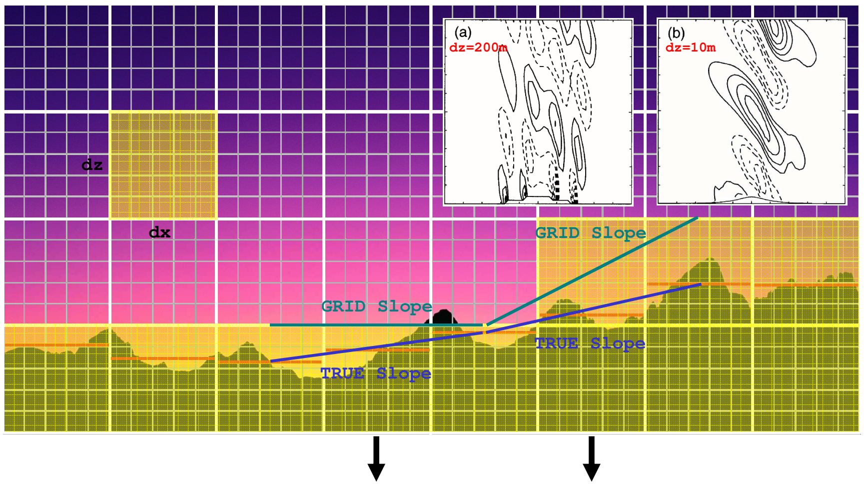
Straka et al. (1993)



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

ETA MODEL

Gallus & Klemp (2000)



NO forcing !!!

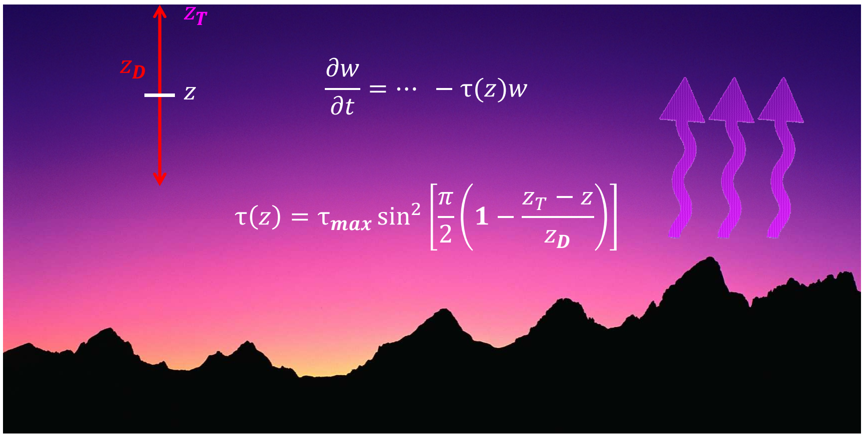
CORRECT forcing

TOO MUCH forcing !!!

CORRECT forcing

Gravity Wave Absorbing Layer

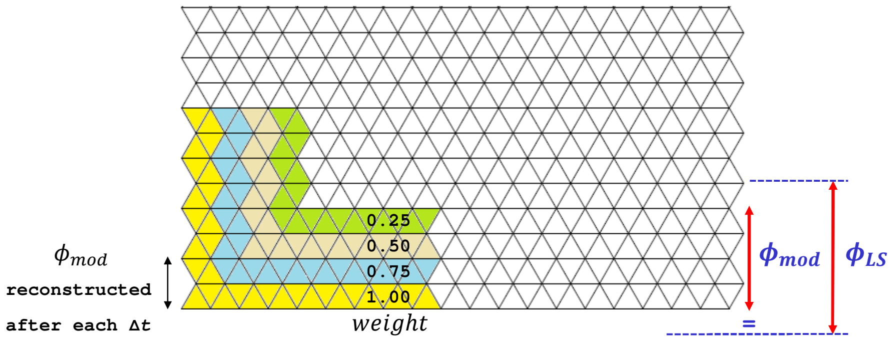
> Rayleigh damping term added to $\frac{\partial w}{\partial t}$ equation within z_D



> 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}

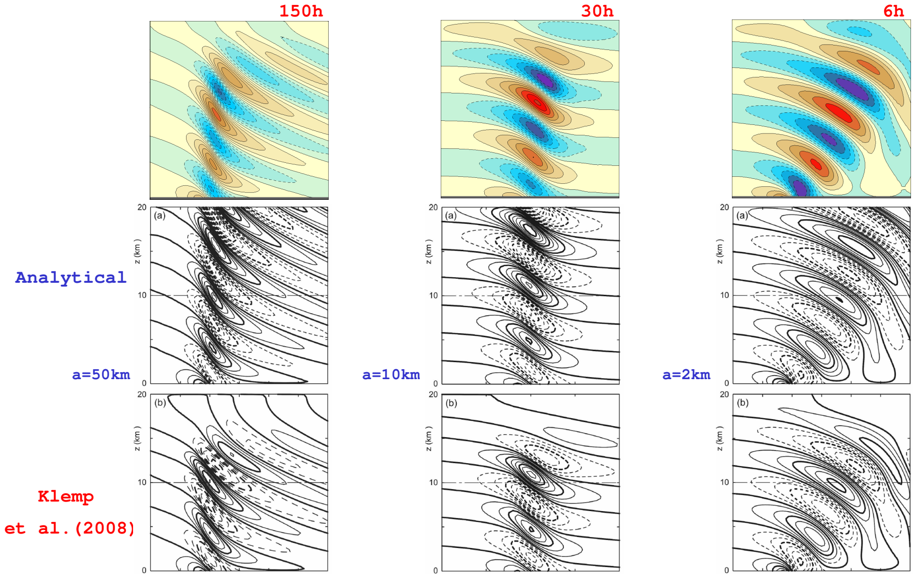


$$\frac{\partial \phi_{mod}}{\partial t} = weight\ [F(\phi_{LS} - \phi_{mod}) - G\Delta^2(\phi_{LS} - \phi_{mod})]$$

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

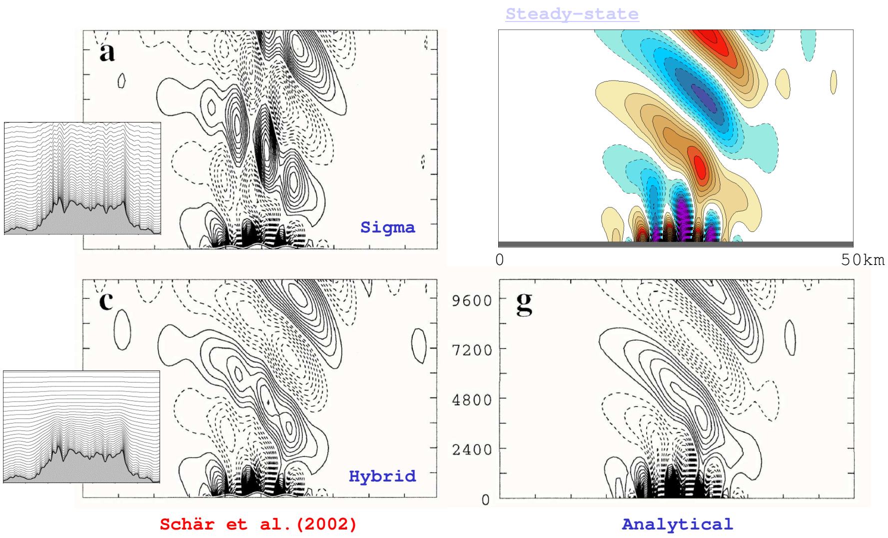
> Linear Mountain Waves (10m bell-shaped mountain, $U=10ms^{-1}$, $N=0.01s^{-1}$)

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



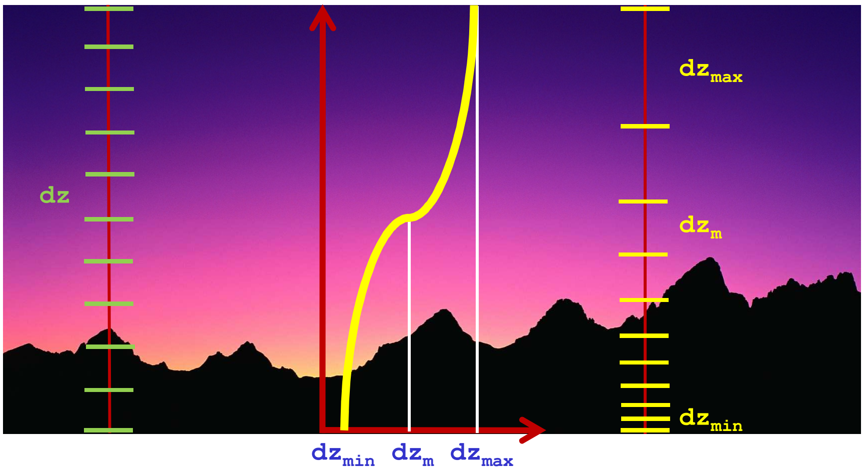
> Schär Mountain (250m bell-shaped + small-scale, $U=10ms^{-1}$, $N=0.01s^{-1}$)

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



Vertical Stretching

> Higher resolution at low levels (cos profile)



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

Semi-Implicit Scheme

> 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

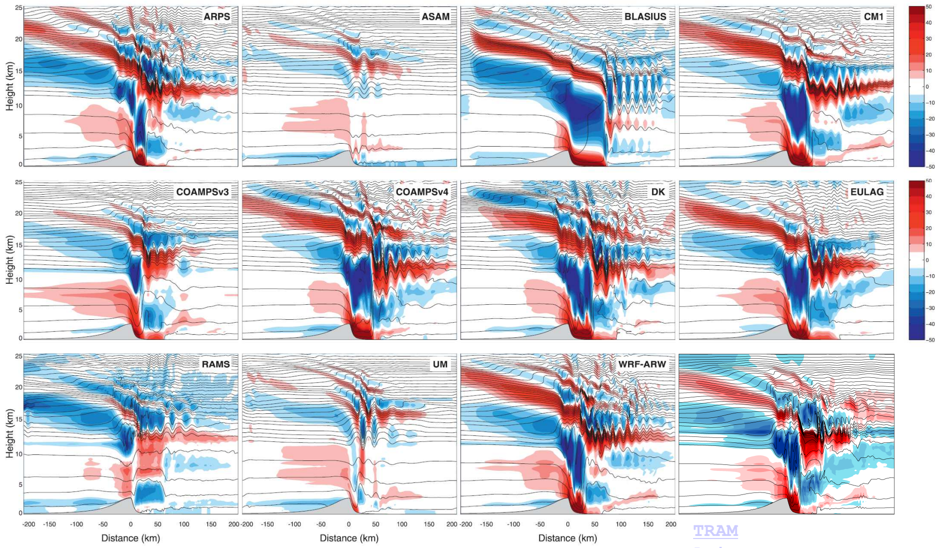
TRAM_non_hydro_set1_2D_oroSTRETCH_implicit

> T-REX Intense Mountain-Wave

t=4h

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

Doyle et al. (2011)



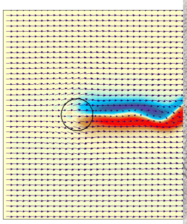
TRAM
Anim

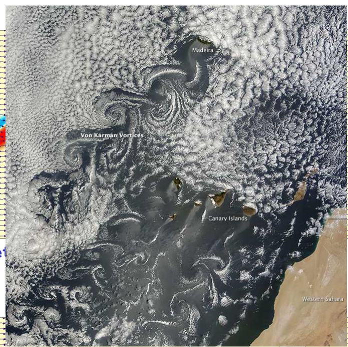
TRAM_non_hydro_set1_3D_oroSTRETCH_implicit

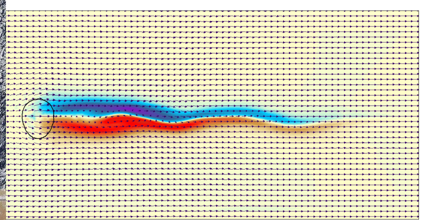
> Von Kármán Vortex Streets ($U=10ms^{-1}$, $N=0.01s^{-1}$)

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

e.g. Schär and Durran (1997)

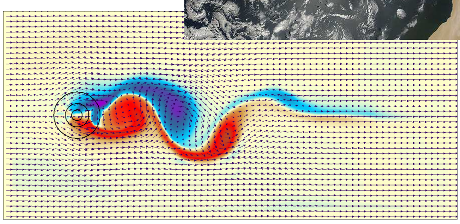


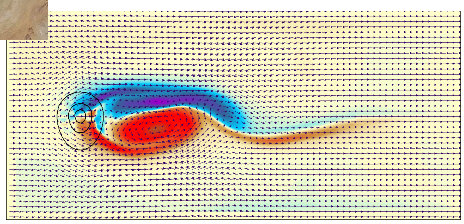




h=1500m (asymmet

h=1500m





h=3000m (asymmetric I.C)

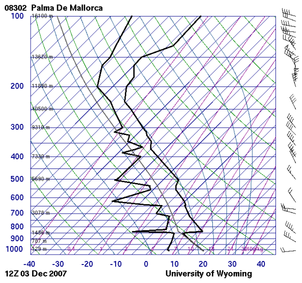
Animation
Tracer

h=3000m

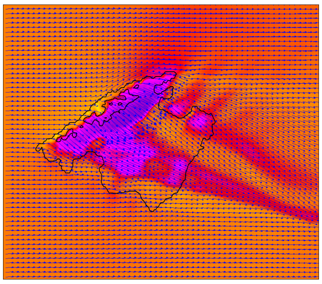
> Sounding-Derived Flow over Mallorca

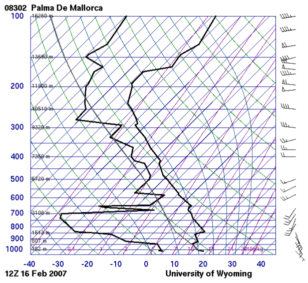
(dx=1.5km,dzm=400m,stretch=20,dt=3s,Nstep=10,24h)

t=12h

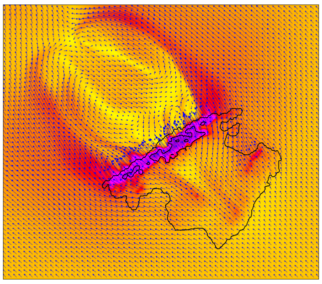


Run





Run

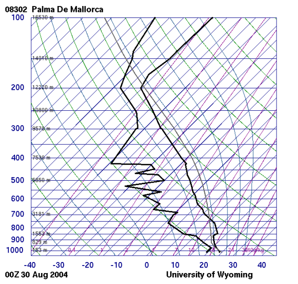


TRAM_non_hydro_set1_3D_oroSTRETCH_implicit

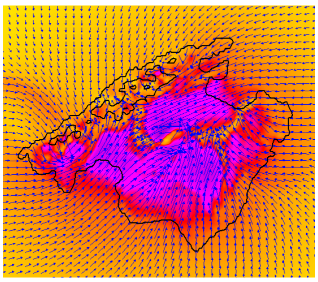
> Breeze Circulation in Mallorca (θ'_s ,Diffusion θ',Coriolis)

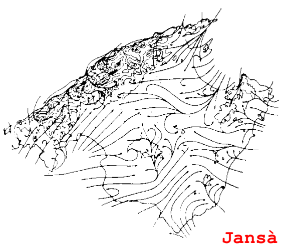
(dx=1.5km,dzm=400m,stretch=20,dt=3s,Nstep=10,24h)

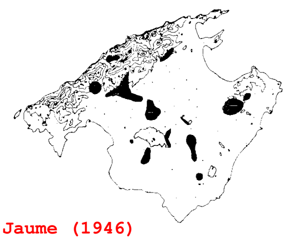
t=13h



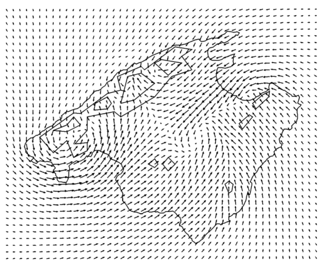
Run







Jansà & Jaume (1946)

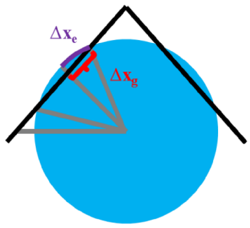


Ramis & Romero (1995)

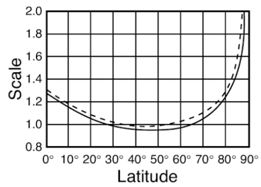
Real Case Applications

> **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]

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

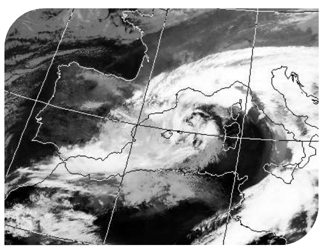
$$\frac{\partial v}{\partial t} = -mu\frac{\partial v}{\partial x} - mv\frac{\partial v}{\partial y} - w\frac{\partial v}{\partial z} - c_p(\bar{\theta}+\theta')m\frac{\partial \pi'}{\partial y} - u\left(f + u\frac{\partial m}{\partial y} - v\frac{\partial m}{\partial y}\right) + \hat{f}w\sin\alpha -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

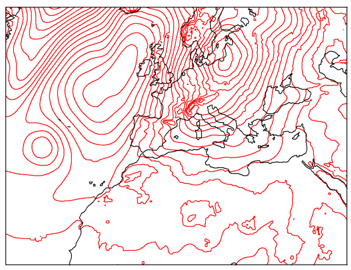
$$\frac{\partial w}{\partial t} = -mu\frac{\partial w}{\partial x} - mv\frac{\partial w}{\partial y} - w\frac{\partial w}{\partial z} - c_p(\bar{\theta}+\theta')\frac{\partial \pi'}{\partial z} + g\frac{\theta'}{\bar{\theta}} + \hat{f}(u\cos\alpha - v\sin\alpha) + \frac{u^2+v^2}{a}$$

TRAM_non_hydro_set1_3D_oroSTRETCH_implicit_MAP

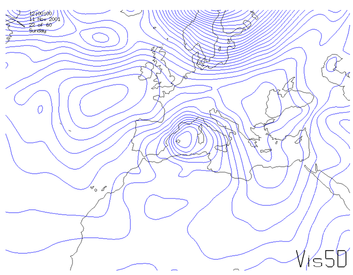
> **"SUPERSTORM" Baroclinic Cyclone** (IC: 00 UTC 9 Nov 2001)

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

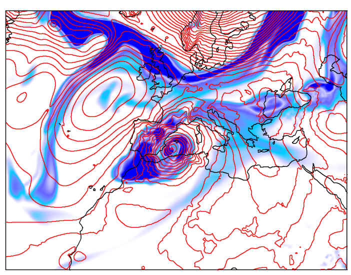




Initial



t=60h



NCEP

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

THANK YOU
for
your attention