8th ICTP Workshop on the Theory and Use of Regional Climate Models

Nonhydrostatic vs. hydrostatic dynamics: testing new capabilities in RegCM

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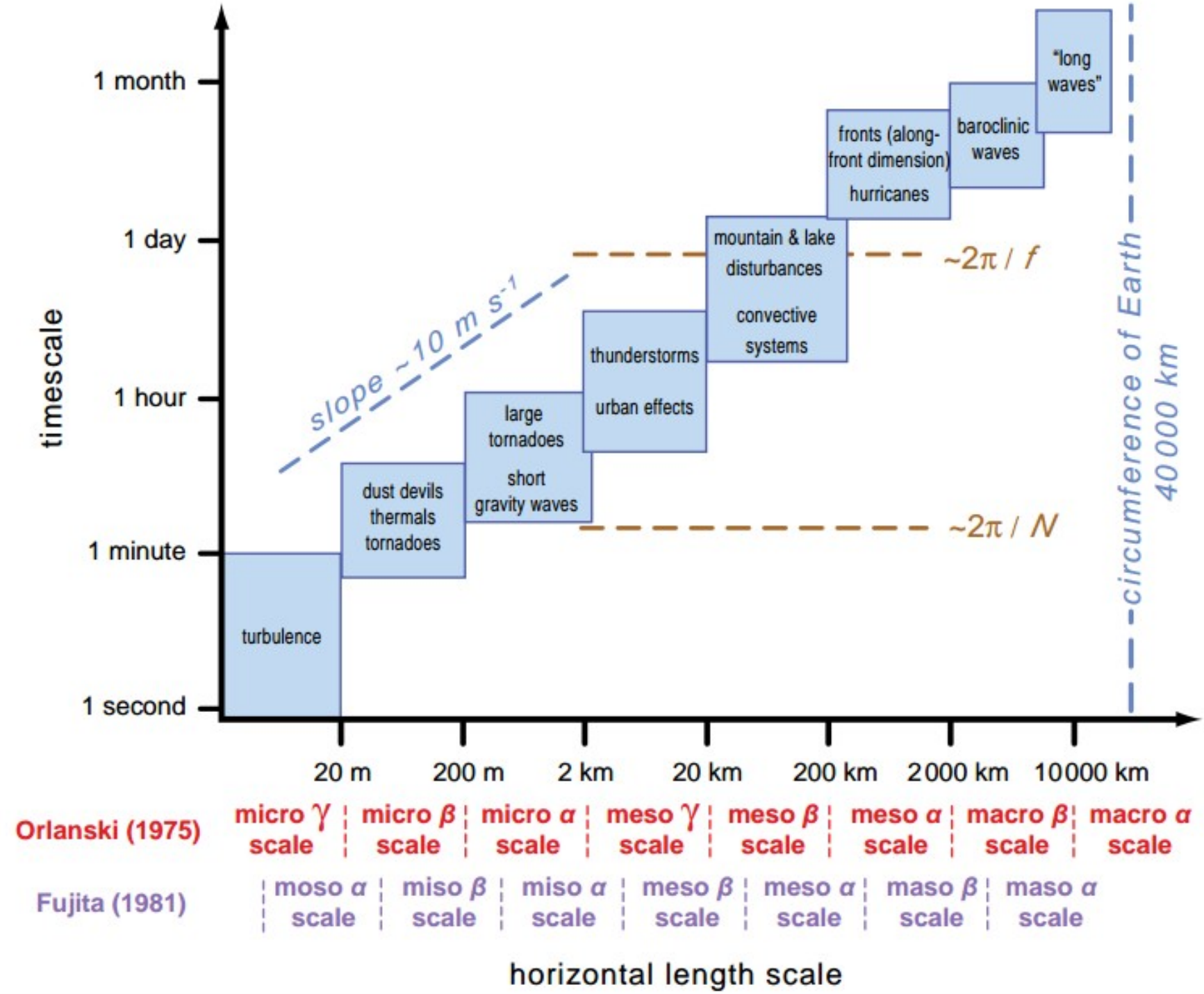
26th May 2016, Trieste, Italy



Markowski and Richardson (2010, *Mesoscale Meteorology in Midlatitudes*)

$$\frac{\mathrm{d}w}{\mathrm{d}t} = -\frac{1}{\rho}\frac{\partial p}{\partial z} + 2\Omega u\cos\phi - g + F_u$$

$$\frac{\mathrm{d}w}{\mathrm{d}t} = -\frac{1}{\rho}\frac{\partial p}{\partial z} - g$$

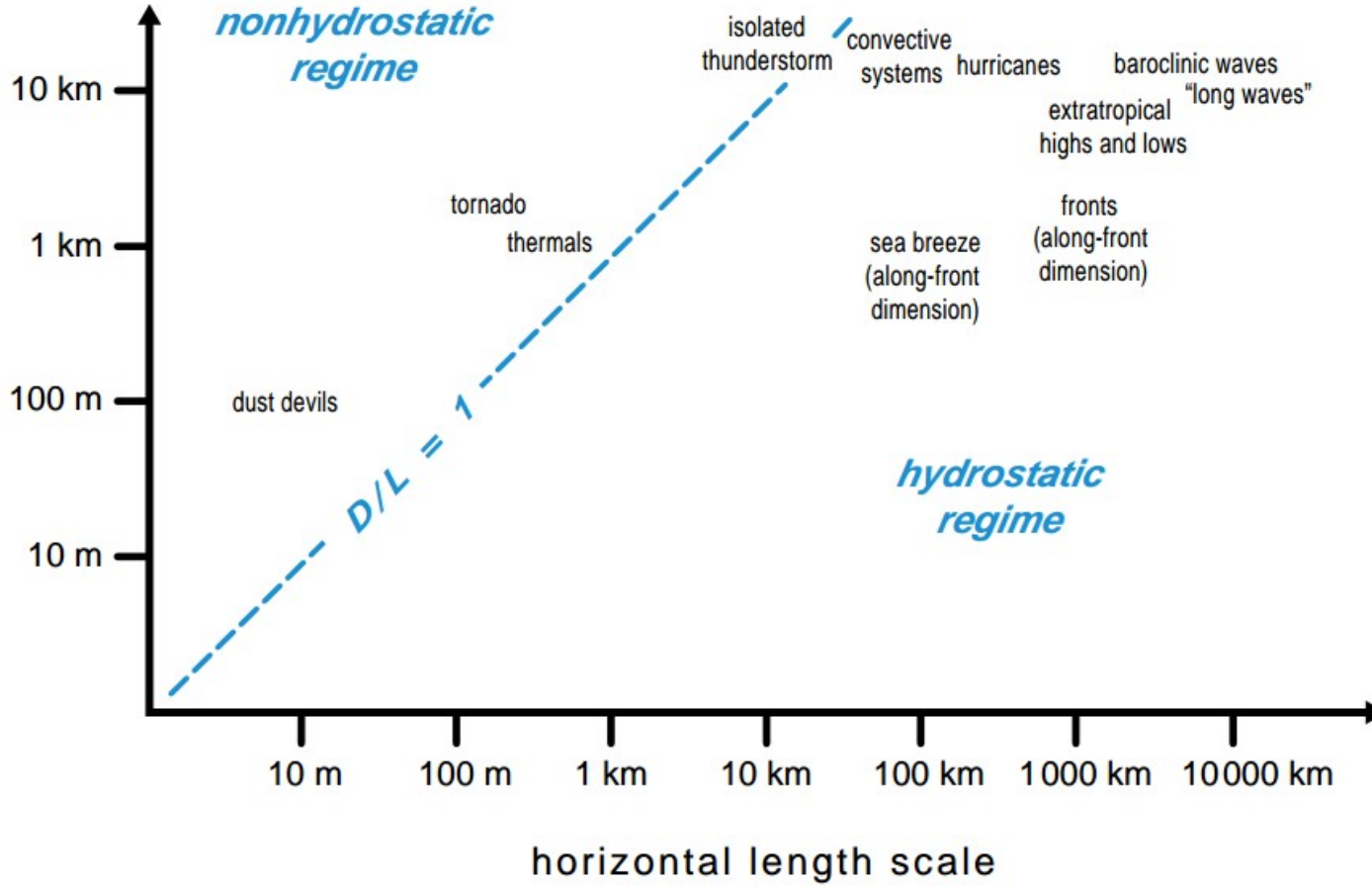
$$p = \overline{p}\,(z) + p'\,(x, y, z, t)$$

$$\rho = \overline{\rho}\,(z) + \rho'\,(x, y, z, t)$$

$$0 = -\frac{\partial \overline{p}}{\partial z} - \overline{\rho} g$$

$$\frac{\mathrm{d}w}{\mathrm{d}t} = -\frac{1}{\rho}\frac{\partial p'}{\partial z} - \frac{\rho' g}{\rho}$$

$$\frac{O\left(\frac{\mathrm{d}w}{\mathrm{d}t}\right)}{O\left(-\frac{1}{\rho}\frac{\partial p'}{\partial z}\right)} \sim \left(\frac{D}{L}\right)^2$$



Markowski and Richardson (2010, *Mesoscale Meteorology in Midlatitudes*)

RegCM hydrostatic dynamical core

$$\underbrace{\frac{\partial p^* u}{\partial t}}_{\text{u tendency}} = \underbrace{-m^2\left(\frac{\partial}{\partial x}\frac{p^* uu}{m}+\frac{\partial}{\partial y}\frac{p^* uv}{m}\right)}_{\text{horizontal advection}} \underbrace{-\frac{\partial p^* u\dot{\sigma}}{\partial \sigma}}_{\text{vertical advection}} \underbrace{-mp^*\left(\frac{\sigma}{\rho}\frac{\partial p^*}{\partial x}+\frac{\partial \phi}{\partial x}\right)}_{\text{pressure gradient}} \underbrace{+p^* fv}_{\text{horizontal Coriolis}} \underbrace{+D_u}_{\text{diffusion and mixing}}$$

$$\underbrace{\frac{\partial p^* v}{\partial t}}_{\text{v tendency}} = \underbrace{-m^2\left(\frac{\partial}{\partial x}\frac{p^* vu}{m}+\frac{\partial}{\partial y}\frac{p^* vv}{m}\right)}_{\text{horizontal advection}} \underbrace{-\frac{\partial p^* v\dot{\sigma}}{\partial \sigma}}_{\text{vertical advection}} \underbrace{-mp^*\left(\frac{\sigma}{\rho}\frac{\partial p^*}{\partial y}+\frac{\partial \phi}{\partial y}\right)}_{\text{pressure gradient}} \underbrace{-p^* fu}_{\text{horizontal Coriolis}} \underbrace{+D_v}_{\text{diffusion and mixing}}$$

$$\underbrace{\frac{\partial p^* T}{\partial t}}_{\text{T tendency}} = \underbrace{-m^2\left(\frac{\partial}{\partial x}\frac{p^* Tu}{m}+\frac{\partial}{\partial y}\frac{p^* Tv}{m}\right)}_{\text{horizontal advection}} \underbrace{-\frac{\partial p^* T\dot{\sigma}}{\partial \sigma}}_{\text{vertical advection}} \underbrace{+p^*\frac{\omega}{\rho c_p}}_{\text{adiabatic heating}} \underbrace{+p^*\frac{\dot{Q}}{c_p}}_{\text{diabatic heating}} \underbrace{+D_T}_{\text{diffusion and mixing}}$$

$$\underbrace{\frac{\partial p^*}{\partial t}}_{\text{p* tendency}} = -m^2\int_0^1 \underbrace{\left(\frac{\partial}{\partial x}\frac{p^* u}{m}+\frac{\partial}{\partial y}\frac{p^* v}{m}\right)}_{\textit{mass divergence}} d\sigma$$

$$\dot{\sigma} = -\frac{1}{p^*}\int_0^\sigma \left[\frac{\partial p^*}{\partial t}+m^2\left(\frac{\partial}{\partial x}\frac{p^* u}{m}+\frac{\partial}{\partial y}\frac{p^* v}{m}\right)\right] d\sigma'$$

$$\omega = p^*\dot{\sigma}+\sigma\left[\frac{\partial p^*}{\partial t}+m\left(u\frac{\partial p^*}{\partial x}+v\frac{\partial p^*}{\partial y}\right)\right]$$

$$\frac{\partial \phi}{\partial ln(\sigma+p_t/p^*)} = -RT_v\left(1+\frac{q_c+q_r}{1+q_v}\right)^{-1}$$

RegCM non-hydrostatic dynamical core

- MM5-based
- to be superseded by Tumolo's dynamical core

$$\underbrace{\frac{\partial p^* u}{\partial t}}_{\text{u tendency}} = \underbrace{-m^2\left(\frac{\partial}{\partial x}\frac{p^* uu}{m}+\frac{\partial}{\partial y}\frac{p^* uv}{m}\right)}_{\text{horizontal advection}} \underbrace{-\frac{\partial p^* u\dot{\sigma}}{\partial \sigma}}_{\text{vertical advection}} + uDIV \underbrace{-\frac{mp^*}{\rho}\left(\frac{\partial p'}{\partial x}-\frac{\sigma}{p^*}\frac{\partial p^*}{\partial x}\frac{\partial p'}{\partial \sigma}\right)}_{\text{pressure gradient}} \underbrace{+p^* fv - p^* ewcos(\theta)}_{\text{horizontalCoriolis}} \underbrace{+D_u}_{\text{diffusion and mixing}} \underbrace{+p^* v\left(u\frac{\partial m}{\partial y}-v\frac{\partial m}{\partial x}\right)-\frac{p^* wu}{r_{Earth}}}_{\text{curvature}}$$

$$\underbrace{\frac{\partial p^* v}{\partial t}}_{\text{v tendency}} = \underbrace{-m^2\left(\frac{\partial}{\partial x}\frac{p^* vu}{m}+\frac{\partial}{\partial y}\frac{p^* vv}{m}\right)}_{\text{horizontal advection}} \underbrace{-\frac{\partial p^* v\dot{\sigma}}{\partial \sigma}}_{\text{vertical advection}} + vDIV \underbrace{-\frac{mp^*}{\rho}\left(\frac{\partial p'}{\partial y}-\frac{\sigma}{p^*}\frac{\partial p^*}{\partial y}\frac{\partial p'}{\partial \sigma}\right)}_{\text{pressure gradient}} \underbrace{-p^* fu + p^* ewsin(\theta)}_{\text{horizontal Coriolis}} \underbrace{+D_v}_{\text{diffusion and mixing}} \underbrace{-p^* u\left(u\frac{\partial m}{\partial y}-v\frac{\partial m}{\partial x}\right)-\frac{p^* wv}{r_{Earth}}}_{\text{curvature}}$$

$$\underbrace{\frac{\partial p^* w}{\partial t}}_{\text{w tendency}} = \underbrace{-m^2\left(\frac{\partial}{\partial x}\frac{p^* wu}{m}+\frac{\partial}{\partial y}\frac{p^* wv}{m}\right)}_{\text{horizontal advection}} \underbrace{-\frac{\partial p^* w\dot{\sigma}}{\partial \sigma}}_{\text{vertical advection}} + wDIV \underbrace{+p^* g\frac{\rho_0}{\rho}\left(\frac{1}{p^*}\frac{\partial p'}{\partial \sigma}+\frac{T'_v}{T}-\frac{T_0 p'}{Tp_0}\right)}_{\text{bouyancy [?]}} \underbrace{+p^* e\left[ucos(\theta)-vsin(\theta)\right]}_{\text{vertical Coriolis}} \underbrace{+D_w}_{\text{diffusion and mixing}} \underbrace{+\frac{p^*\left(u^2+v^2\right)}{r_{Earth}}}_{\text{curvature}} \underbrace{-p^* g\left(q_c+q_r\right)}_{\text{liquid water loading}}$$

$$\underbrace{\frac{\partial p^* p'}{\partial t}}_{\text{p' tendency}} = \underbrace{-m^2\left(\frac{\partial}{\partial x}\frac{p^* p'u}{m}+\frac{\partial}{\partial y}\frac{p^* p'v}{m}\right)}_{\text{horizontal advection}} \underbrace{-\frac{\partial p^* p'\dot{\sigma}}{\partial \sigma}}_{\text{vertical advection}} + p'DIV - m^2 p^* \gamma p\left(\frac{\partial}{\partial x}\frac{u}{m}-\frac{\sigma}{mp^*}\frac{\partial p^*}{\partial x}\frac{\partial u}{\partial \sigma}+\frac{\partial}{\partial y}\frac{v}{m}-\frac{\sigma}{mp^*}\frac{\partial p^*}{\partial y}\frac{\partial v}{\partial \sigma}\right)+\rho_0 g\gamma p\frac{\partial w}{\partial \sigma}+p^*\rho_0 gw$$

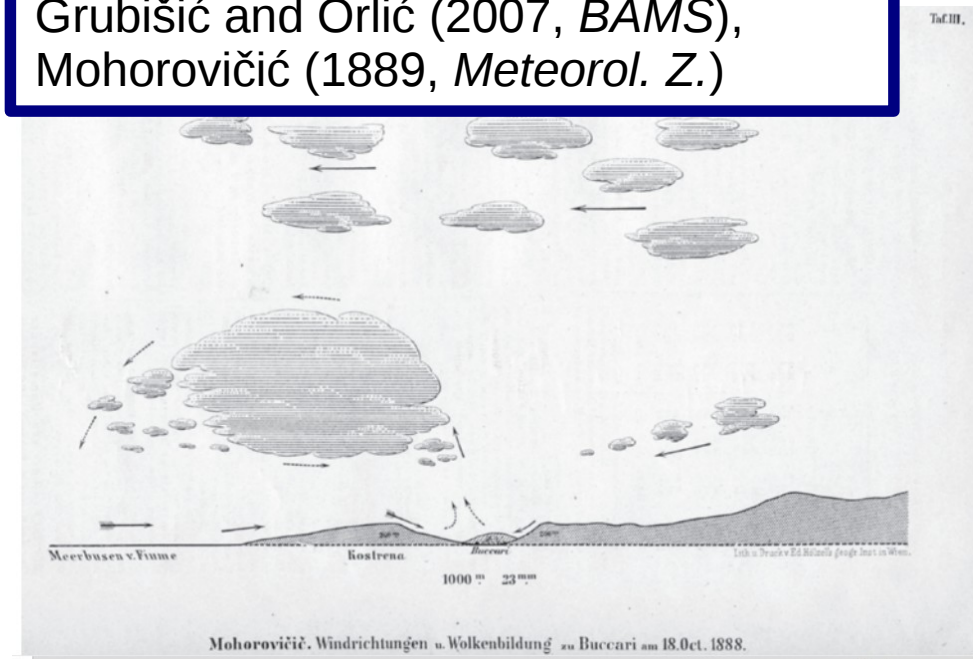
$$\underbrace{\frac{\partial p^* T}{\partial t}}_{\text{T tendency}} = \underbrace{-m^2\left(\frac{\partial}{\partial x}\frac{p^* Tu}{m}+\frac{\partial}{\partial y}\frac{p^* Tv}{m}\right)}_{\text{horizontal advection}} \underbrace{-\frac{\partial p^* T\dot{\sigma}}{\partial \sigma}}_{\text{vertical advection}} + TDIV \underbrace{+\frac{1}{\rho c_p}\left(p^*\frac{Dp'}{Dt}-p^*\rho_0 gw-D_{p'}\right)}_{\text{adiabatic term[?]}} \underbrace{+p^*\frac{\dot{Q}}{c_p}}_{\text{diabatic heating}} \underbrace{+D_T}_{\text{diffusion and mixing}}$$

$$DIV = m^2\left(\frac{\partial}{\partial x}\frac{p^* u}{m}+\frac{\partial}{\partial y}\frac{p^* v}{m}\right)+\frac{\partial p^*\dot{\sigma}}{\partial \sigma}$$

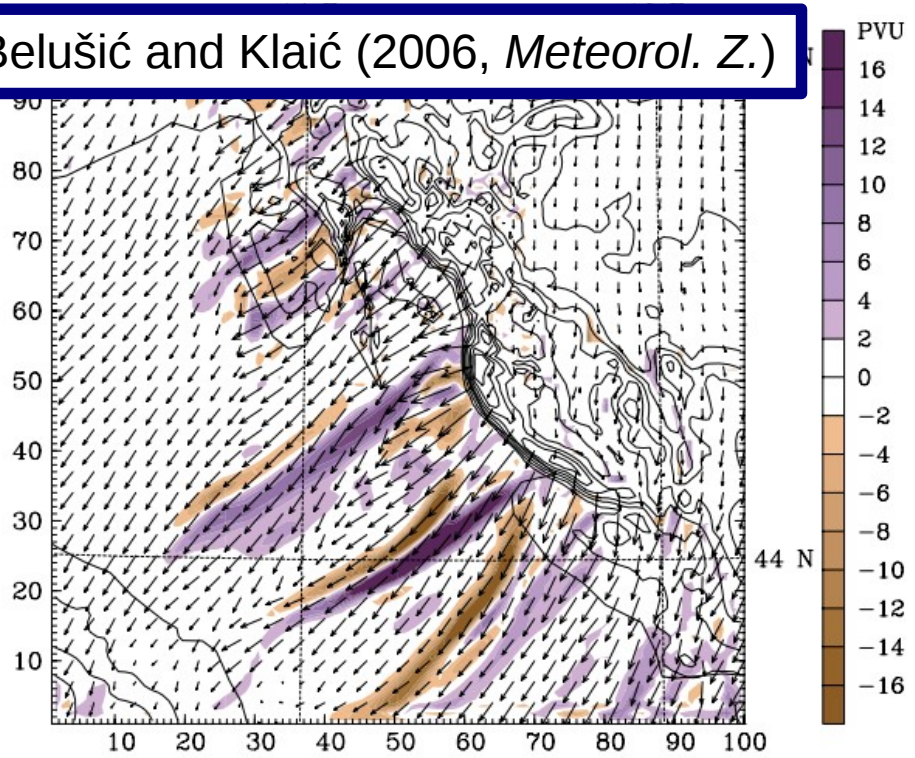
$$\dot{\sigma} = -\frac{\rho_0 g}{p^*}w-\frac{m\sigma}{p^*}\frac{\partial p^*}{\partial x}u-\frac{m\sigma}{p^*}\frac{\partial p^*}{\partial y}v$$

New prognostic equations for vertical velocity and pressure perturbations

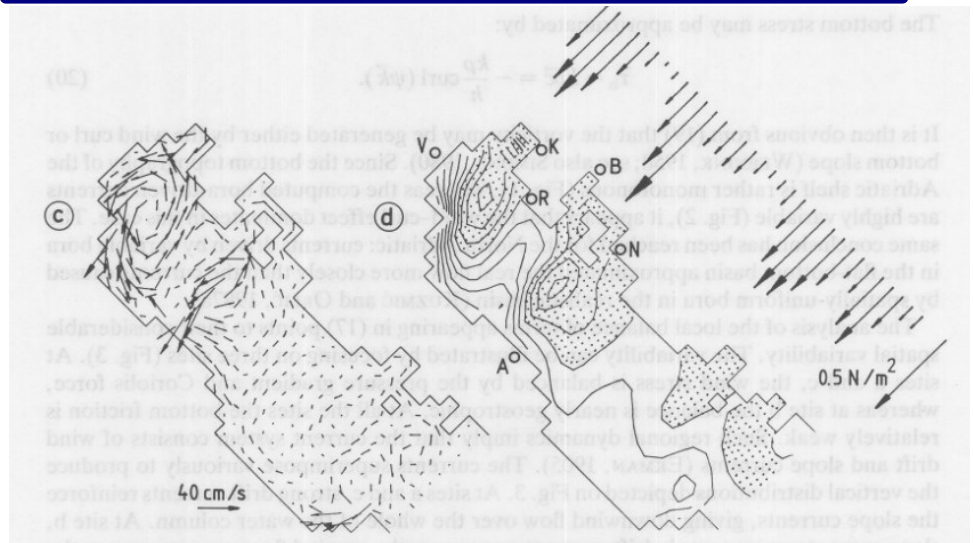
Grubišić and Orlić (2007, *BAMS*), Mohorovičić (1889, *Meteorol. Z.*)



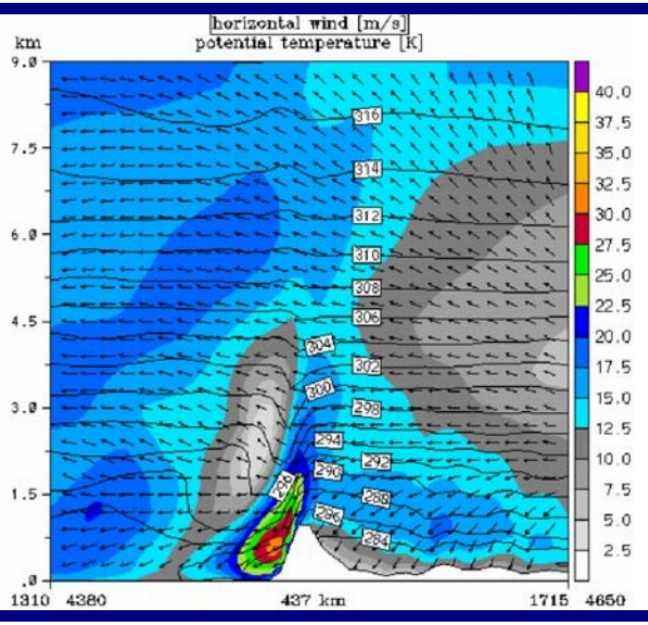
Belušić and Klaić (2006, *Meteorol. Z.*)



Orlić et al. (1994, *Continent. Shelf Res.*)

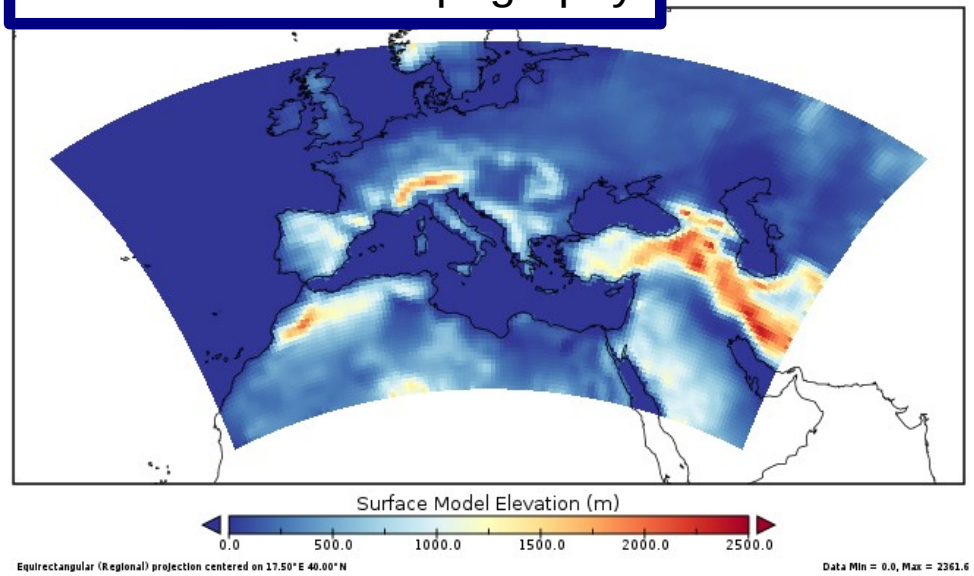


Horvath et al. (2009, *Wea. Forecasting*)

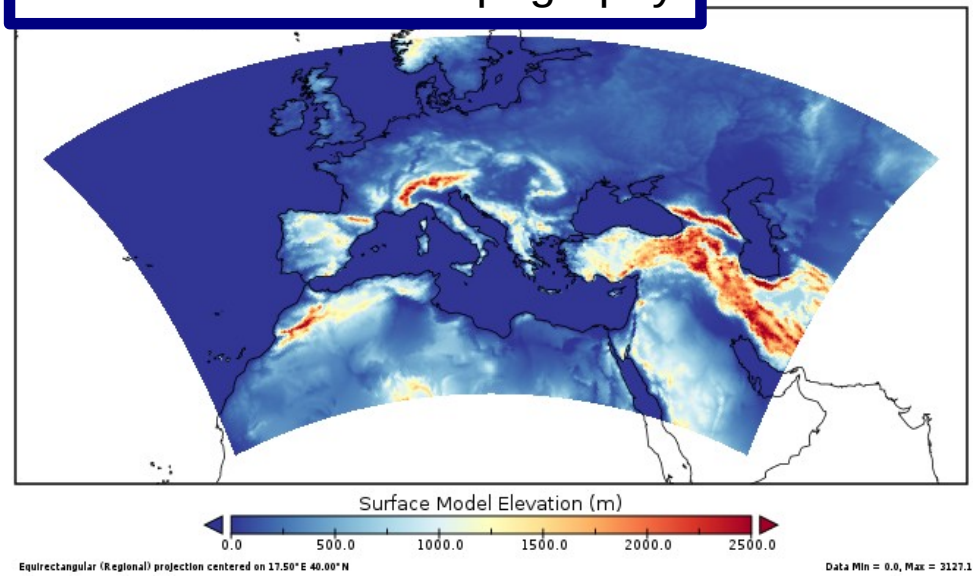


For a review paper about the strong *bura* winds see Grisogono and Belušić (2009, *Tellus*)

50-km domain & topography



12.5-km domain & topography



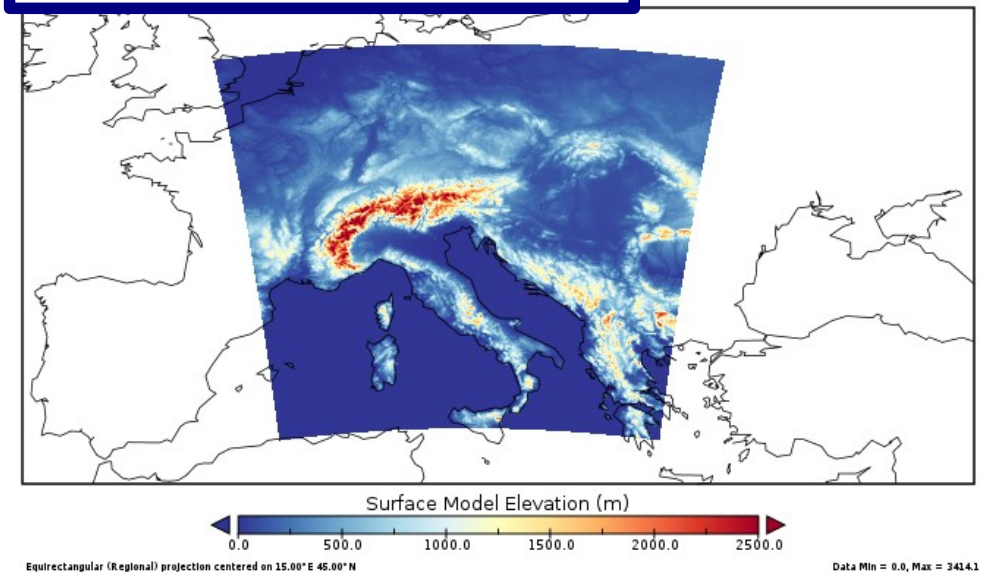
Hydro. 50-km: 82x144x23 (← ERAInterim)
Hydro. 12.5-km: 328x576x23 (← ERAInterim)

Hydro. 3-km: 576x576x23 (← Hydro. 12.5-km)
Nonhydro. 3-km: 576x576x23 (← Hydro. 12.5-km)

Schemes.: BATS, Holtslag, CCM3, SUBEX, MIT
Convection scheme active only in 50-km and 12.5-km experiments.

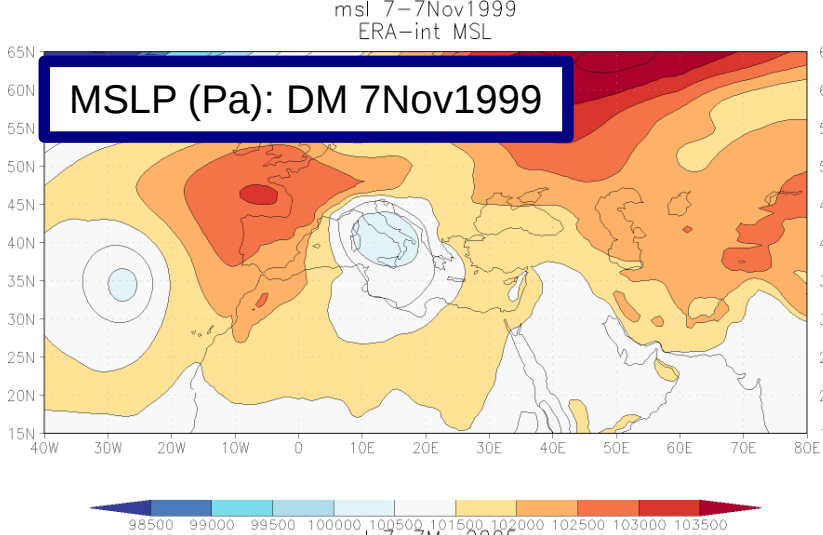
Model version: regcm-core / **r5549**

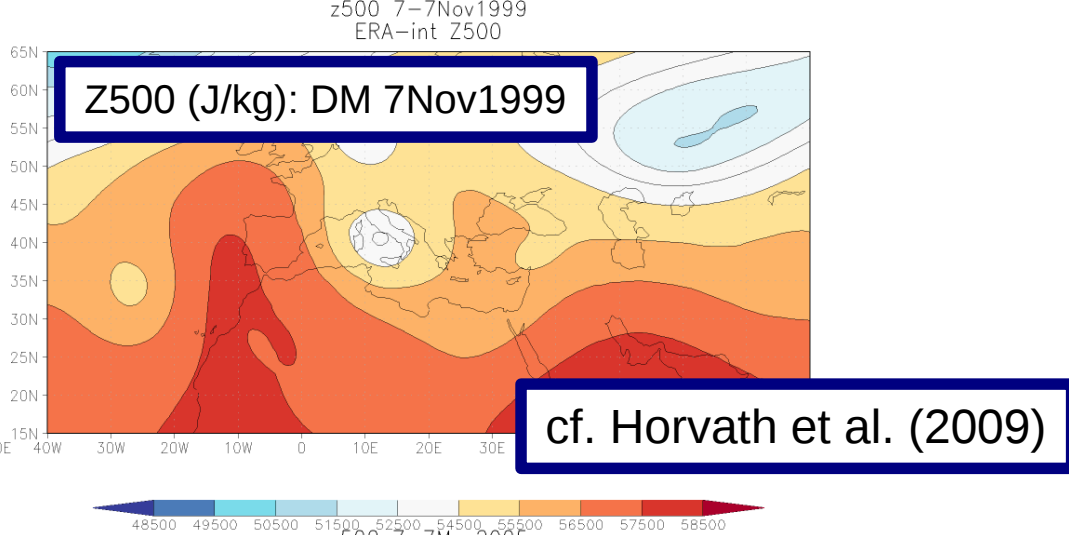
3-km domain & topography



Three periods simulated:
A: Oct.-Nov. 1999 (Nov. 1999 in 3-km runs)
B: Apr.-May 2005 (May 2005 in 3-km runs)
C: Jan.-Feb. 2012 (Feb 2012 in 3-km runs)

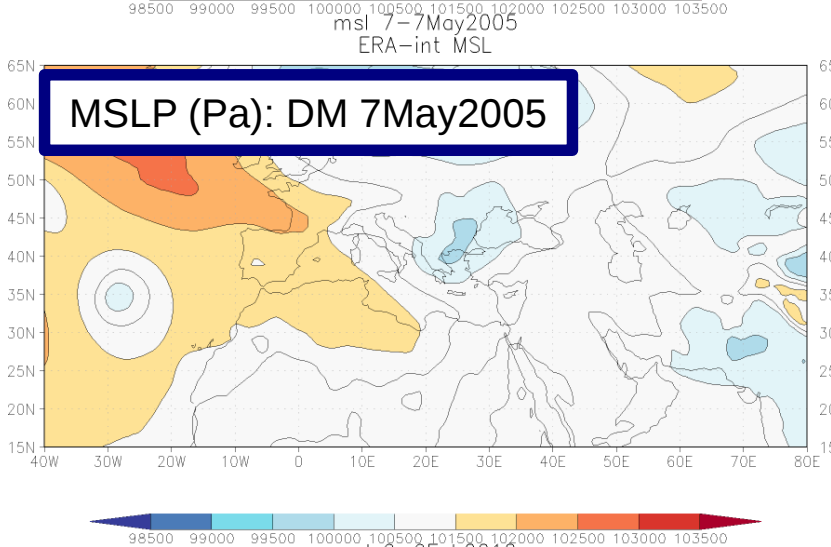
A

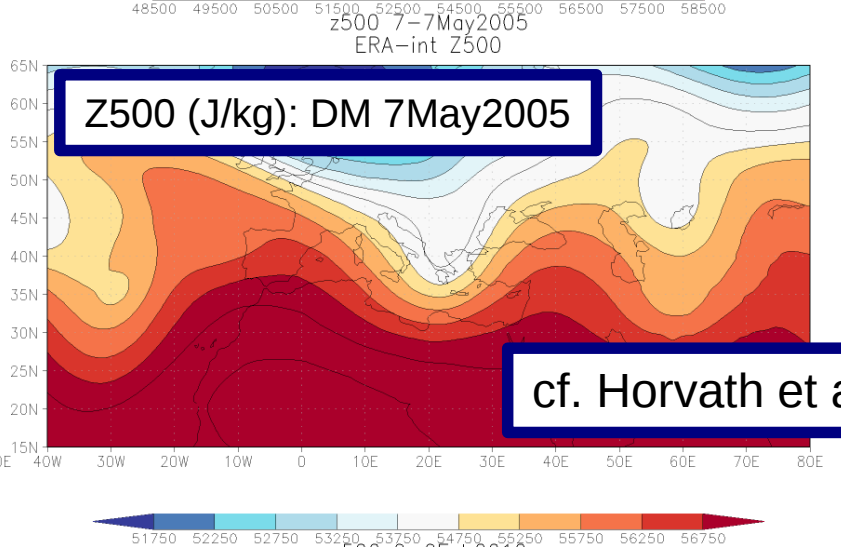




cf. Horvath et al. (2009)

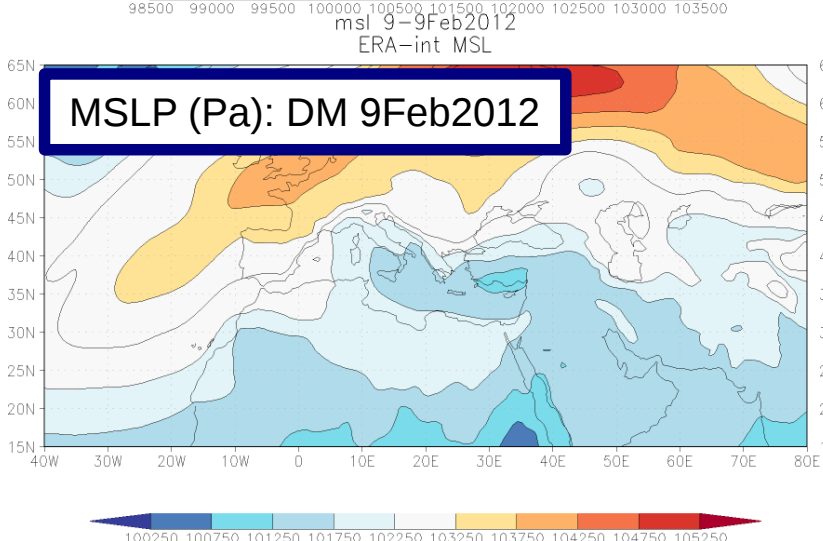
B

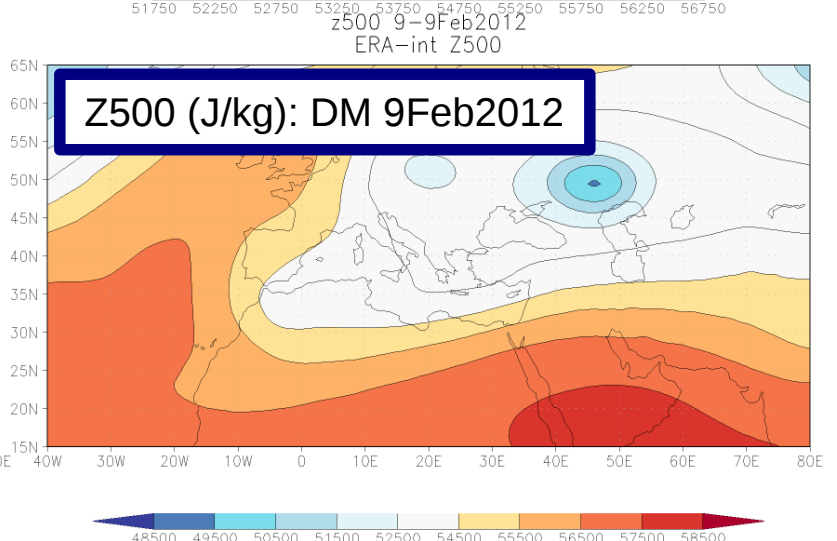




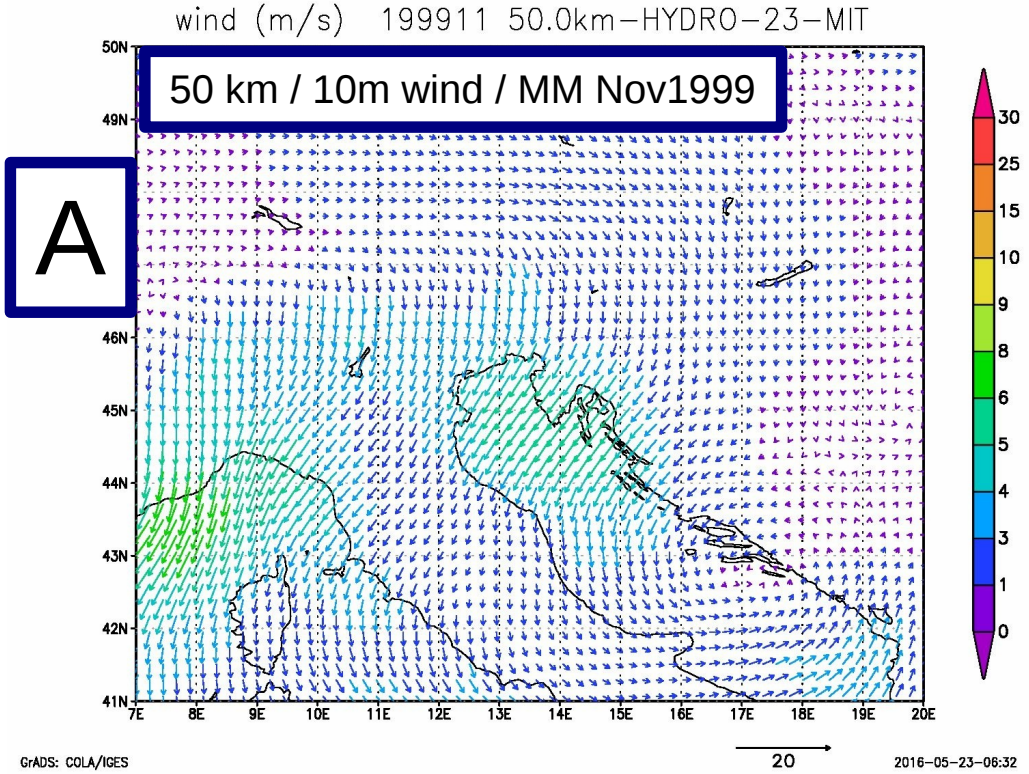
cf. Horvath et al. (2009)

C





A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50 km / 10m wind / MM Nov1999
GrADS: COLA/IGES
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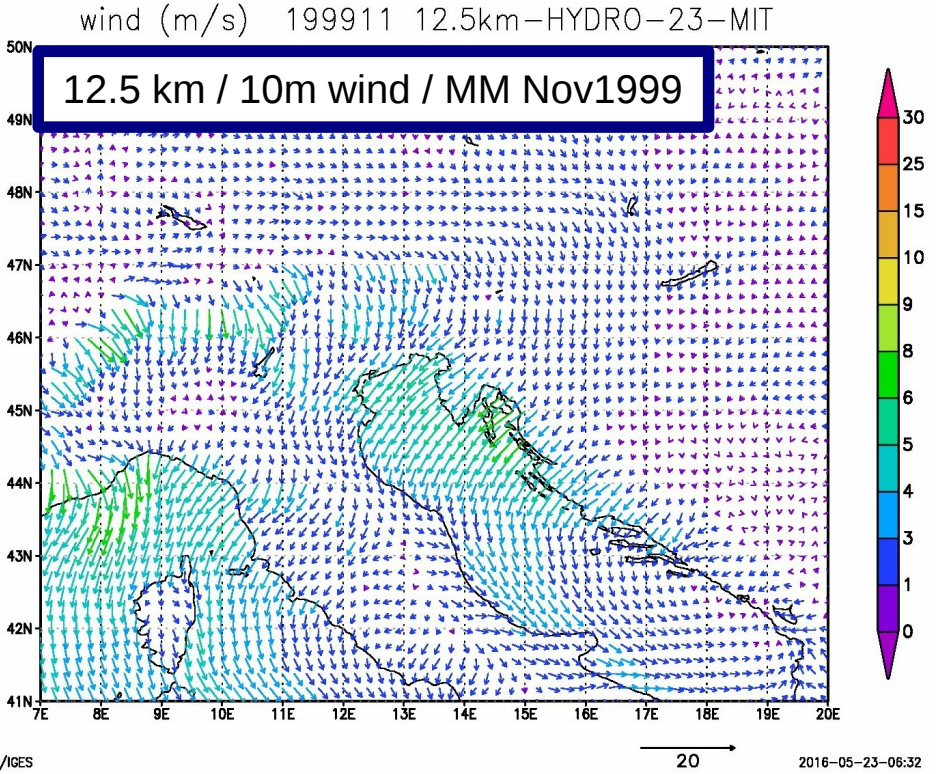
2016-05-23-06:32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12.5 km / 10m wind / MM Nov1999
GrADS: COLA/IGES
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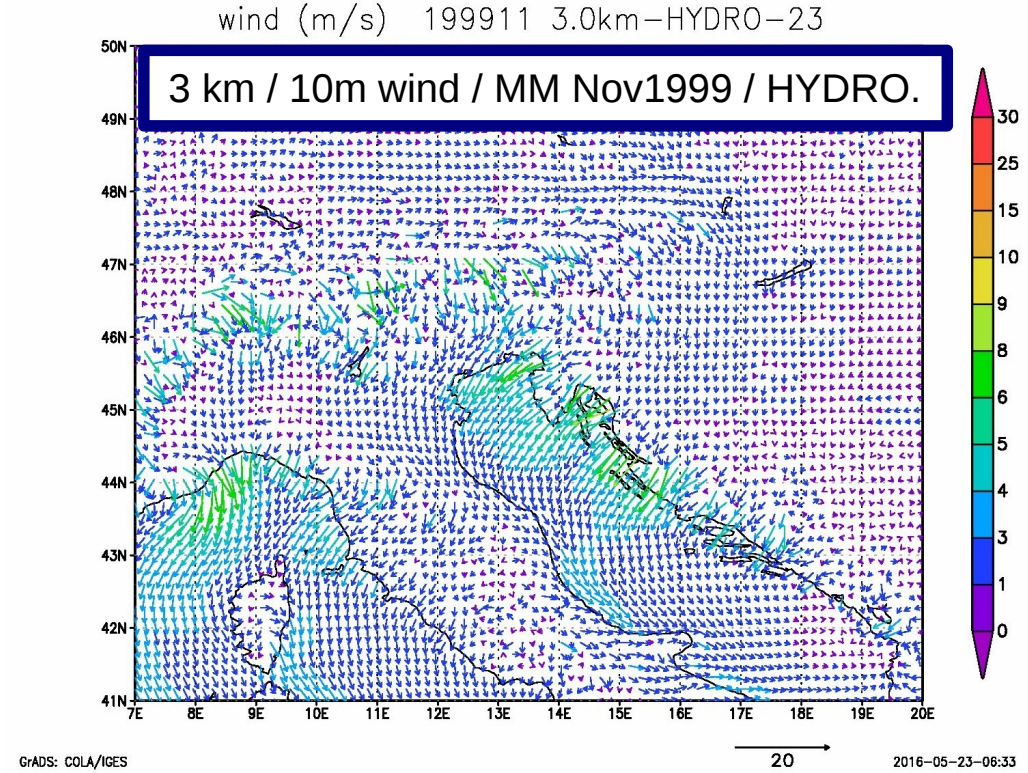
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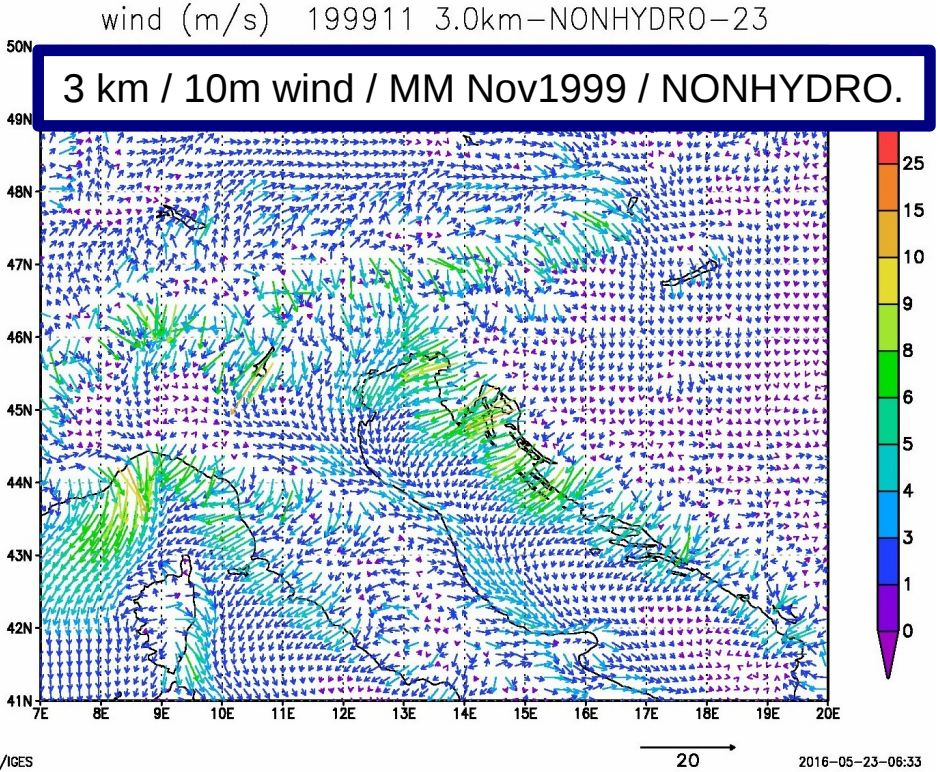
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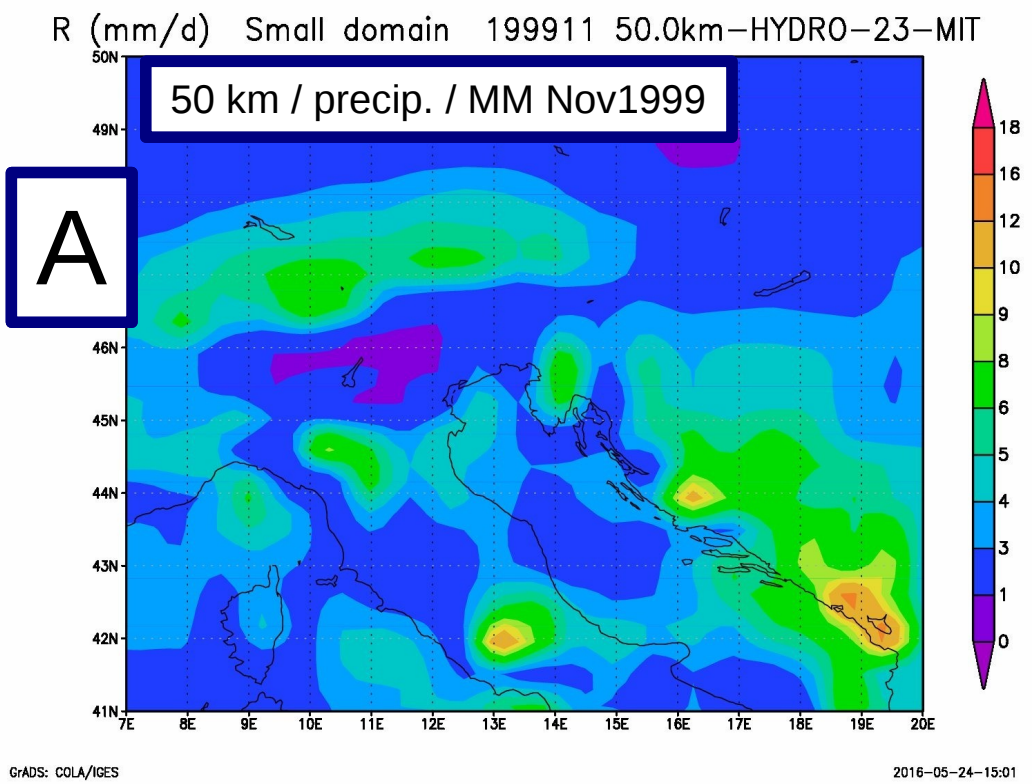
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50 km / precip. / MM Nov1999
A
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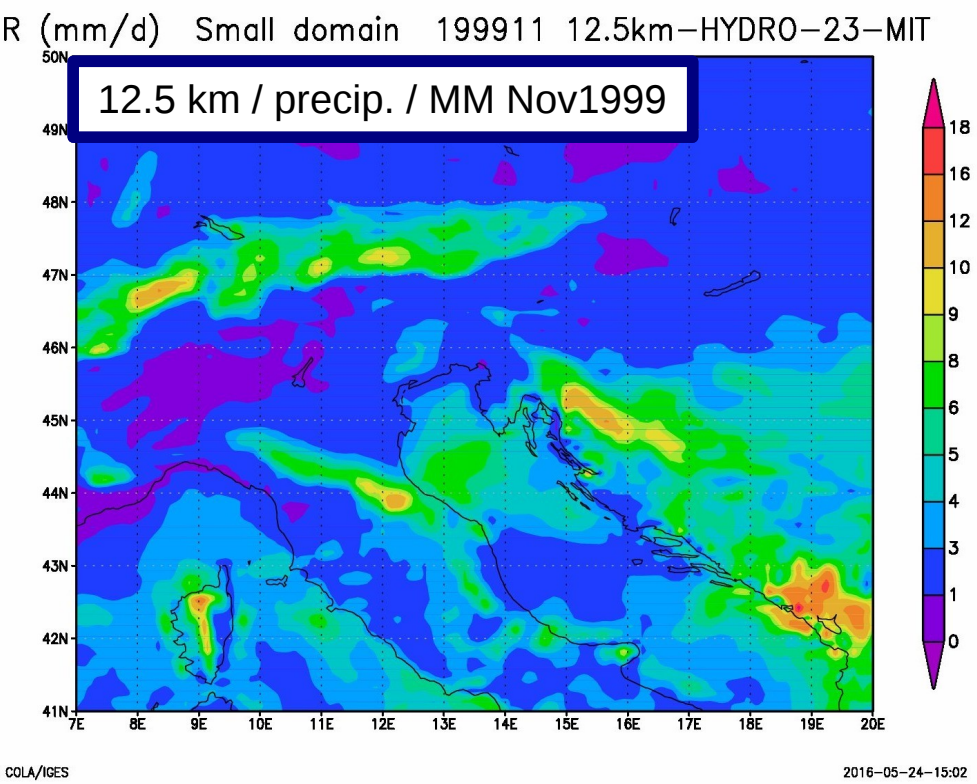
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12.5 km / precip. / MM Nov1999
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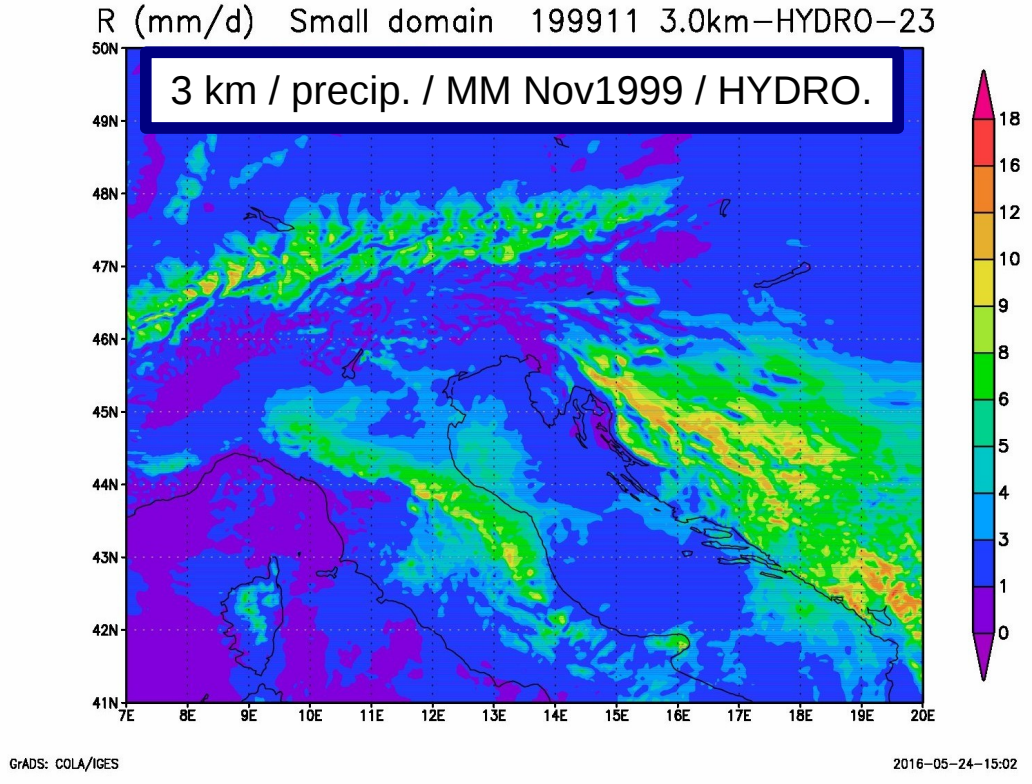
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3 km / precip. / MM Nov1999 / HYDRO.
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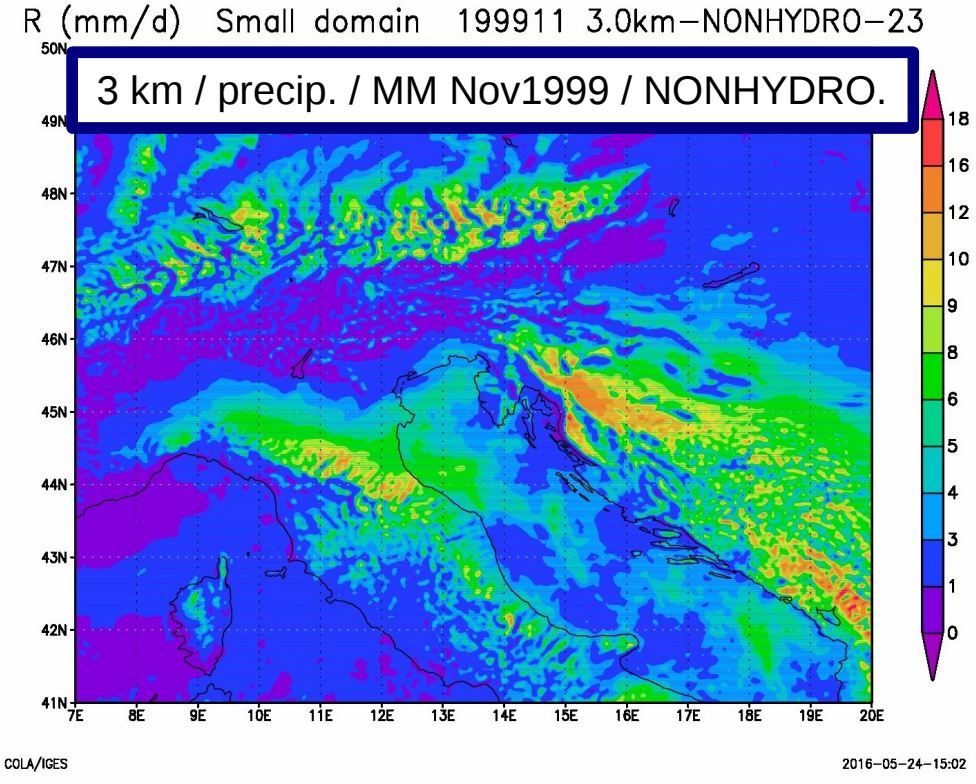
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3 km / precip. / MM Nov1999 / NONHYDRO.
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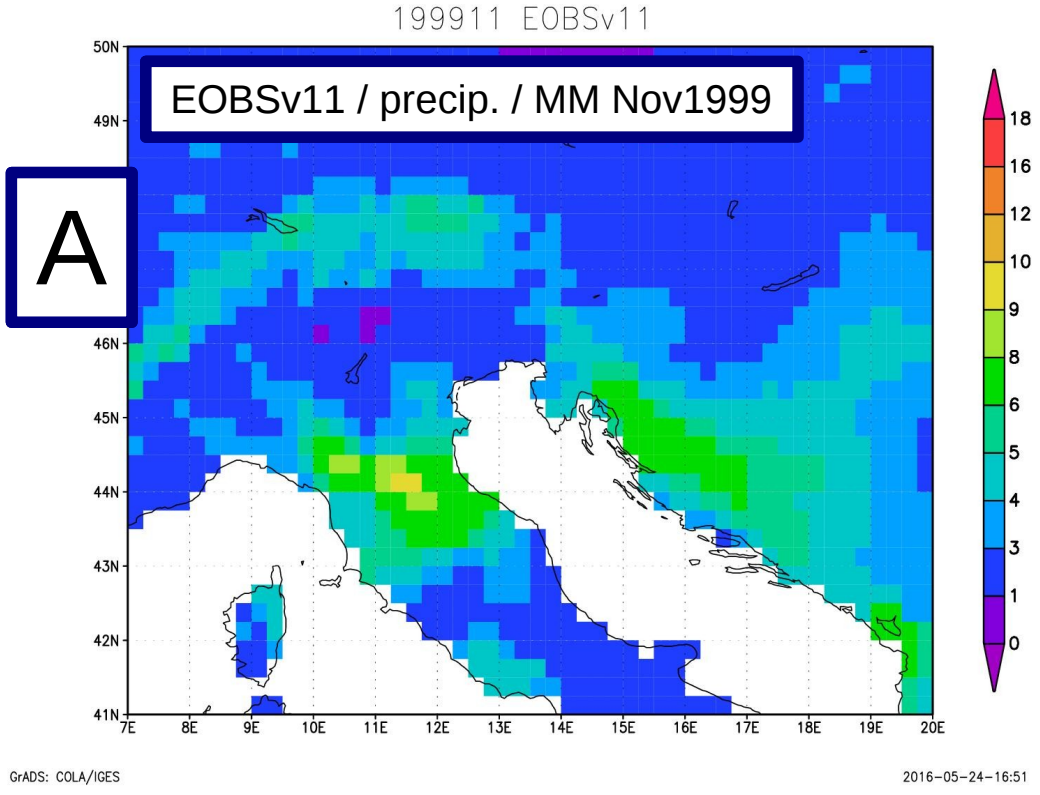
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EOBSv11 / precip. / MM Nov1999
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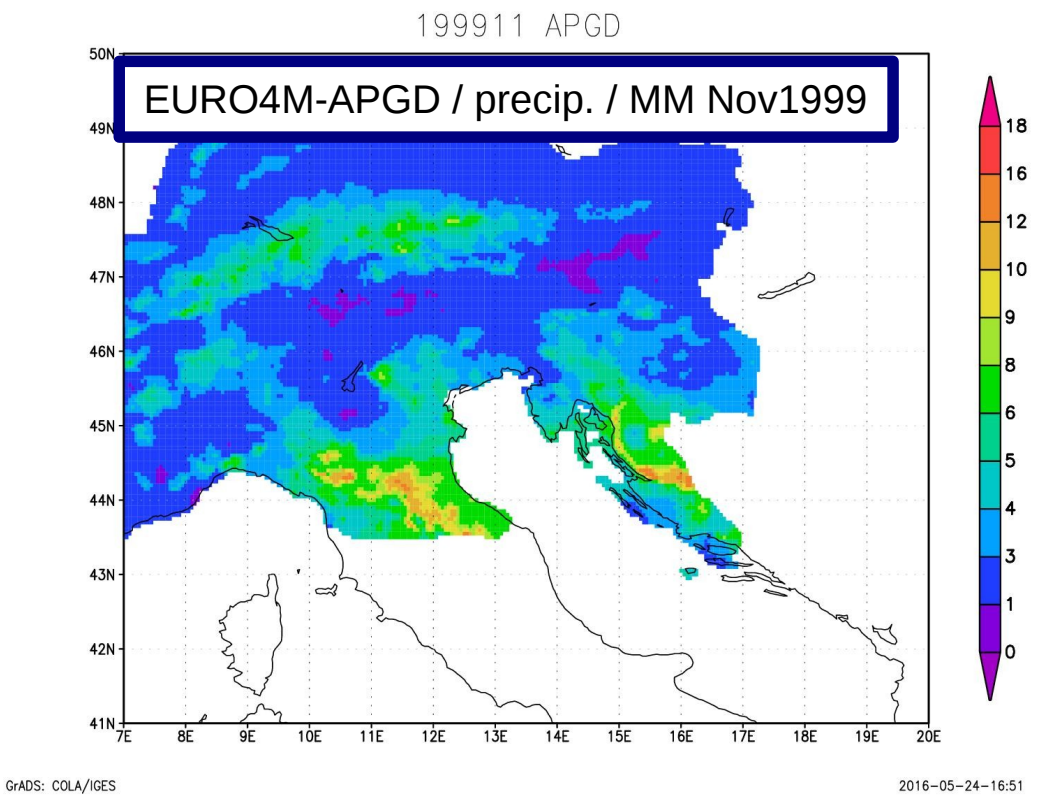
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EURO4M-APGD / precip. / MM Nov1999
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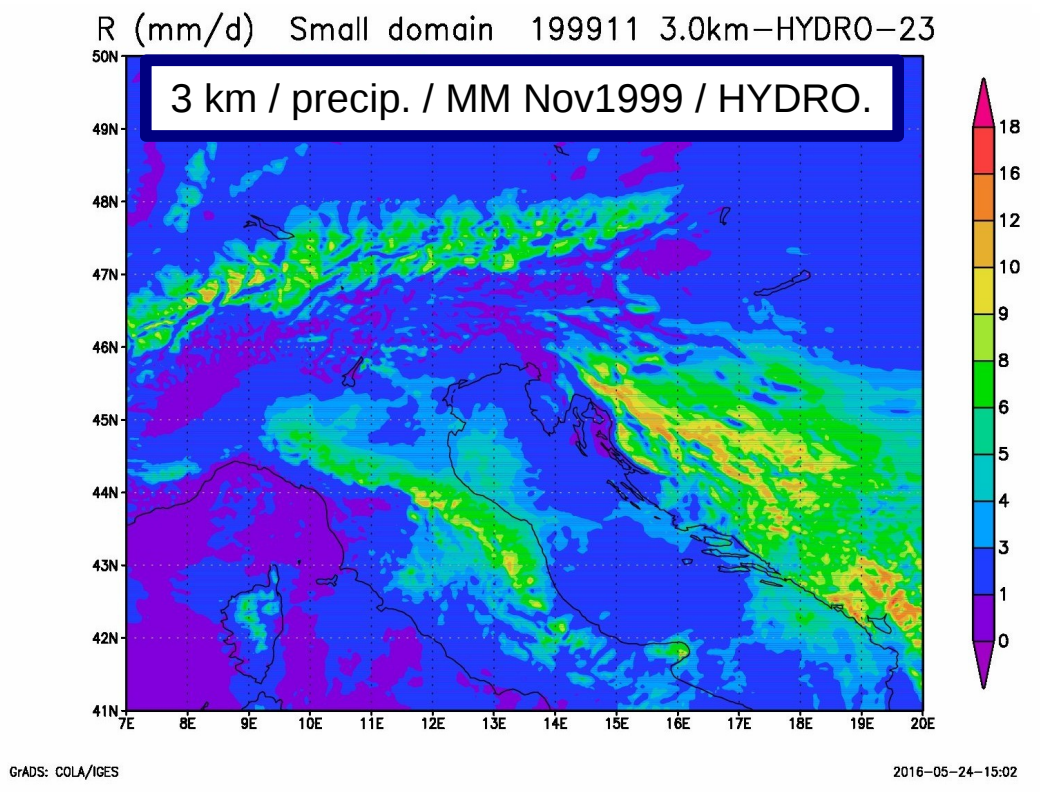
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3 km / precip. / MM Nov1999 / HYDRO.
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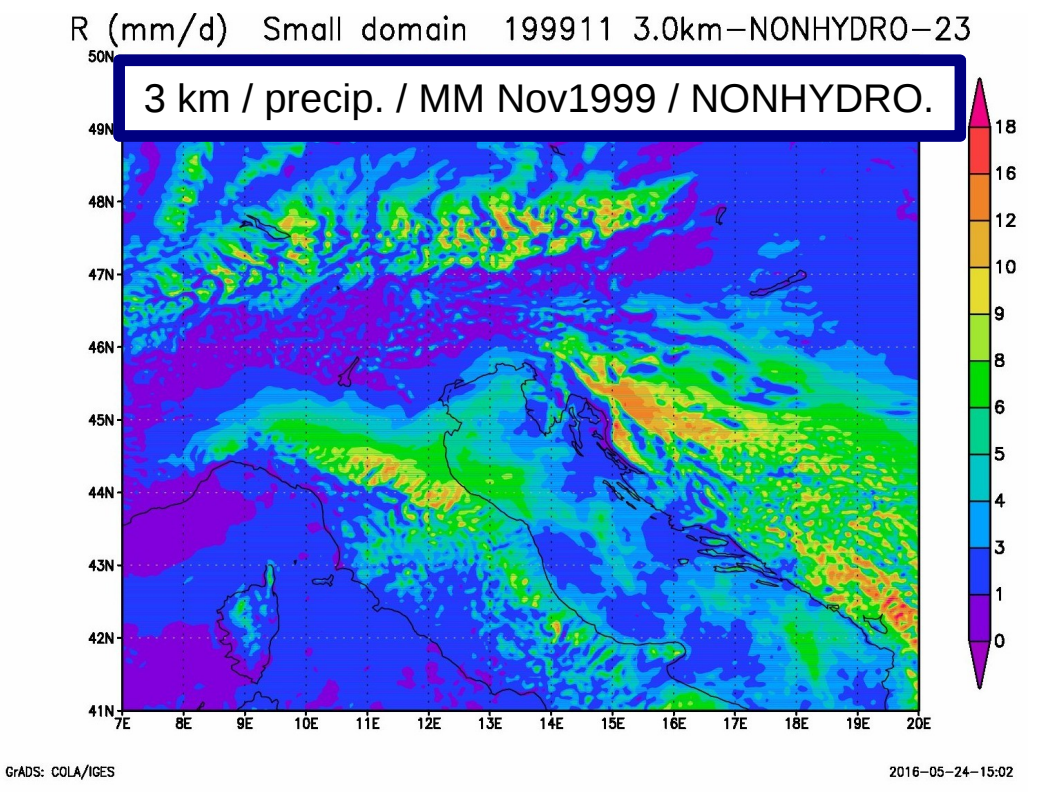
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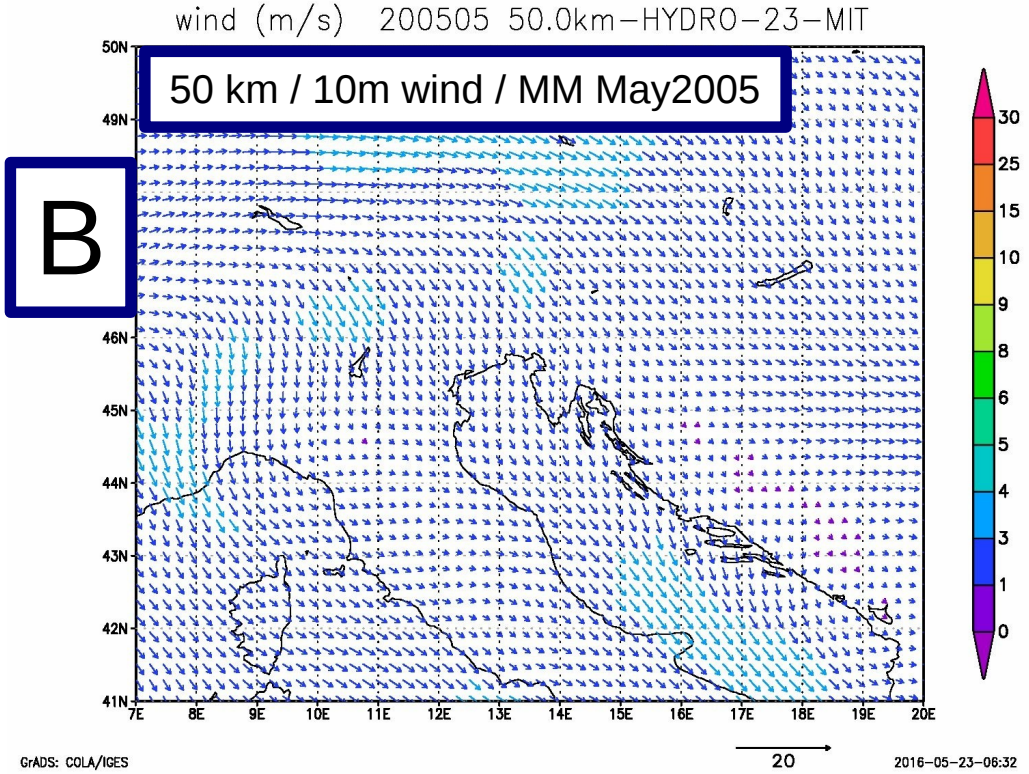
B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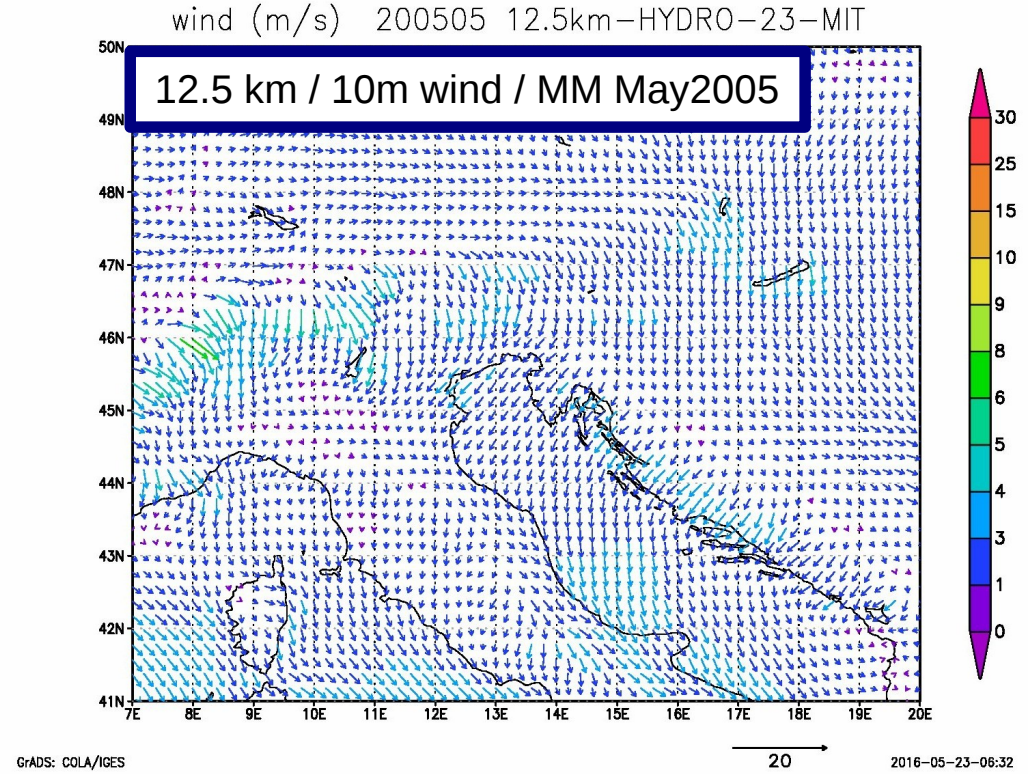
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12.5 km / 10m wind / MM May2005
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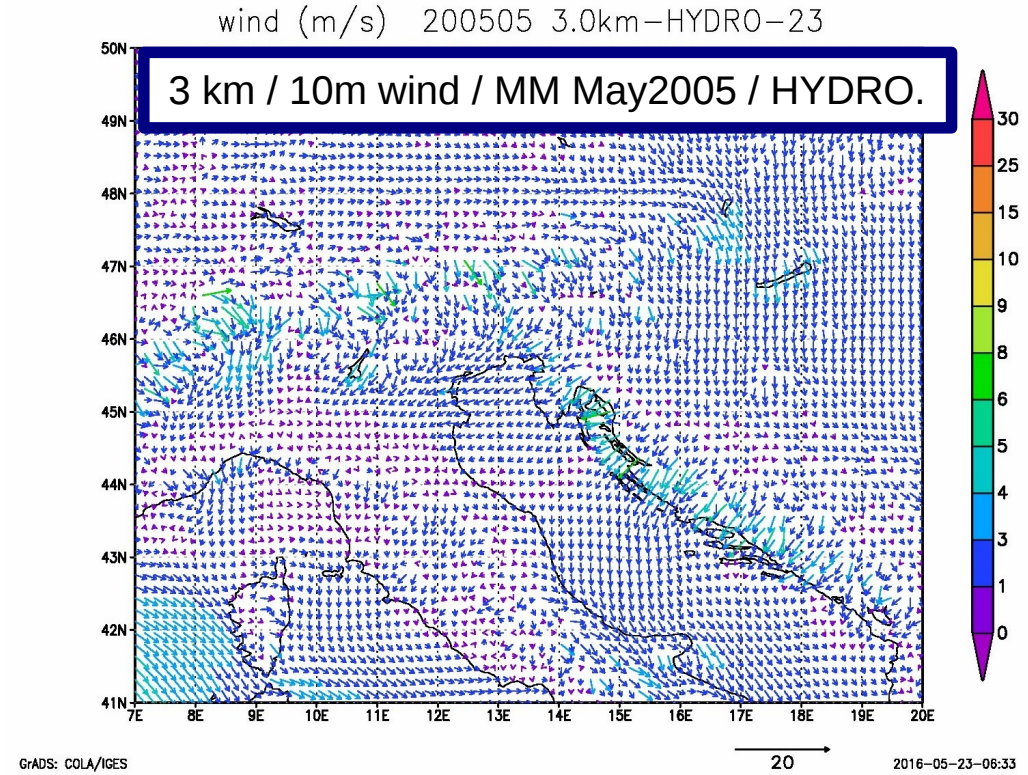
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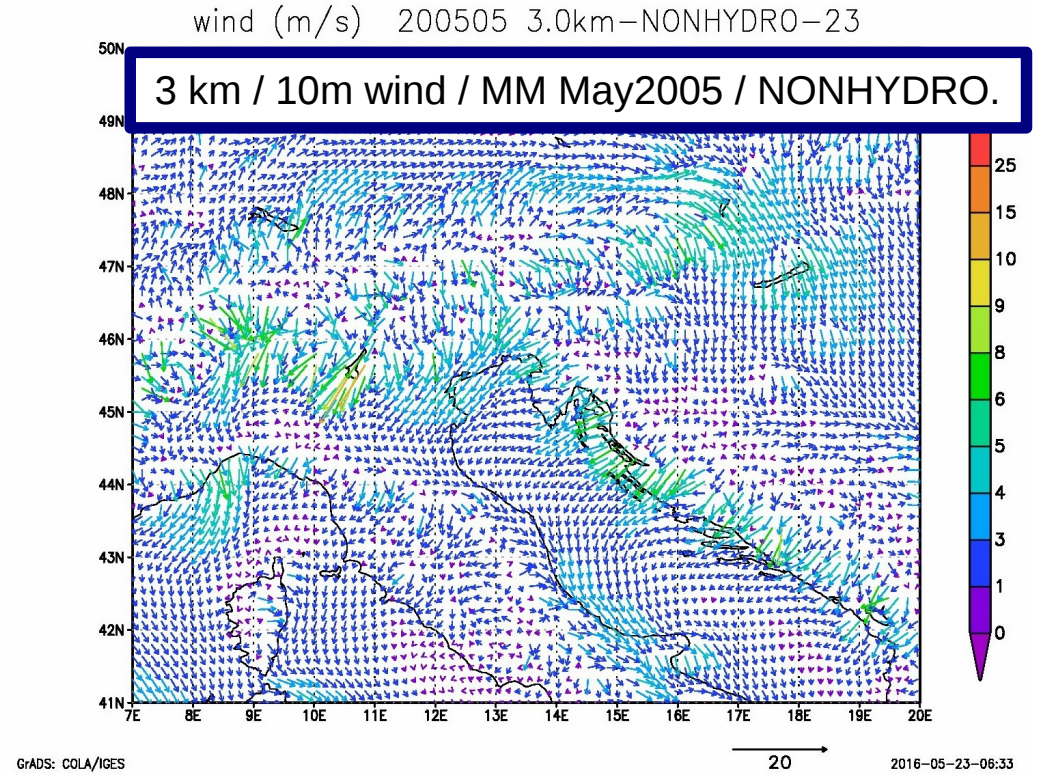
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3 km / 10m wind / MM May2005 / NONHYDRO.
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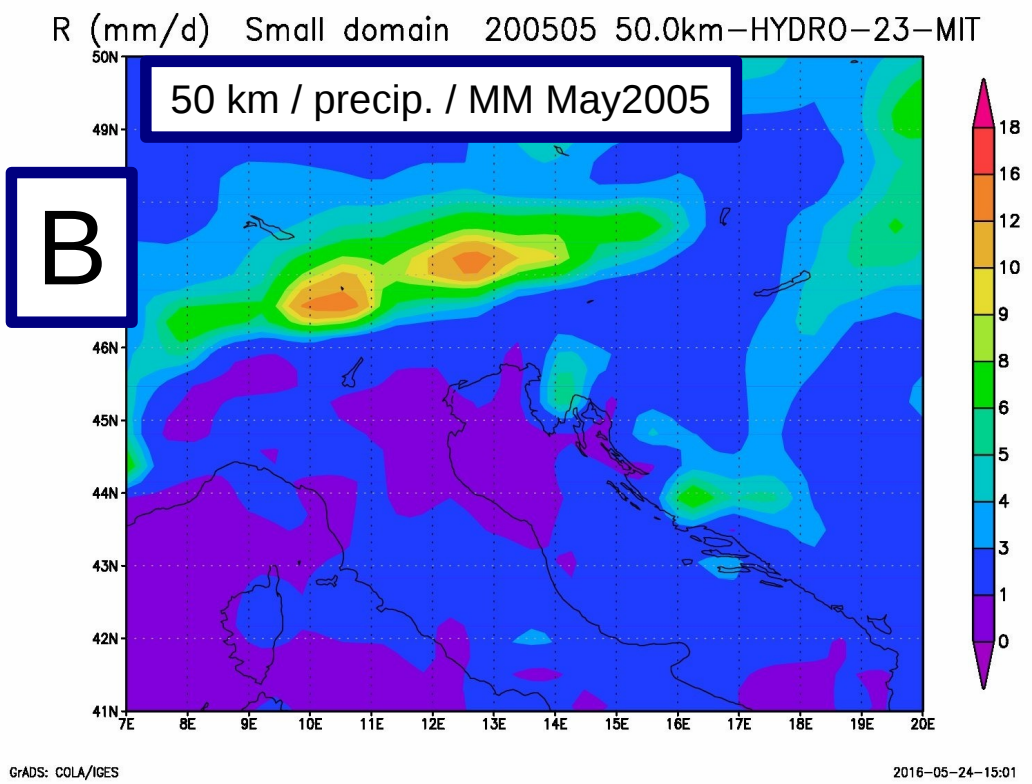
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50 km / precip. / MM May2005
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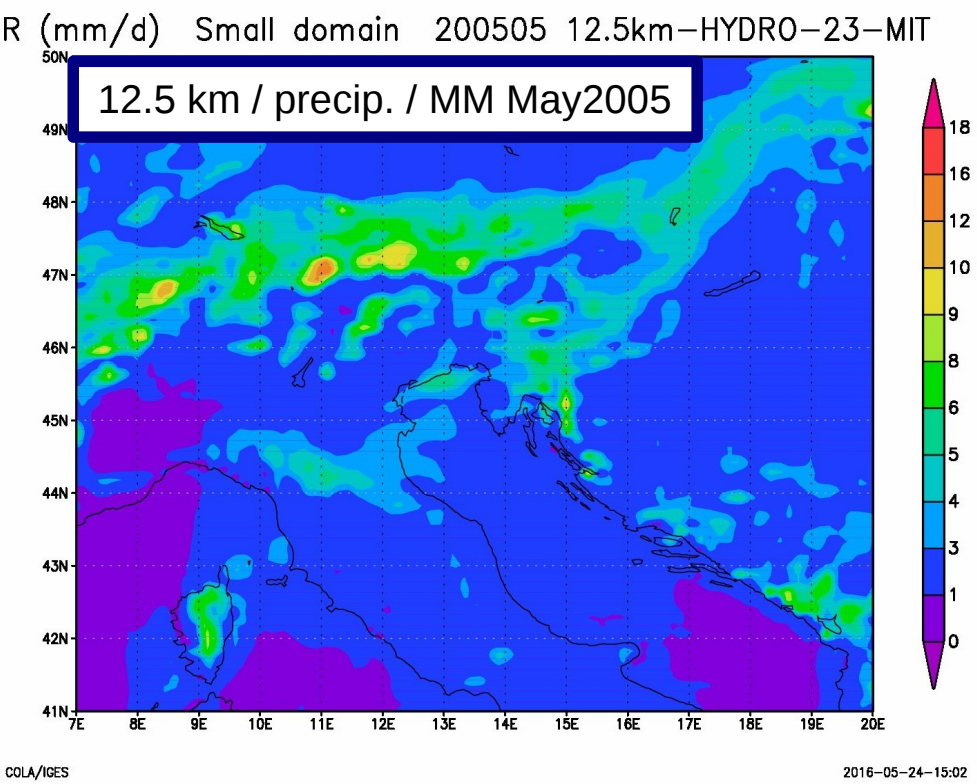
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12.5 km / precip. / MM May2005
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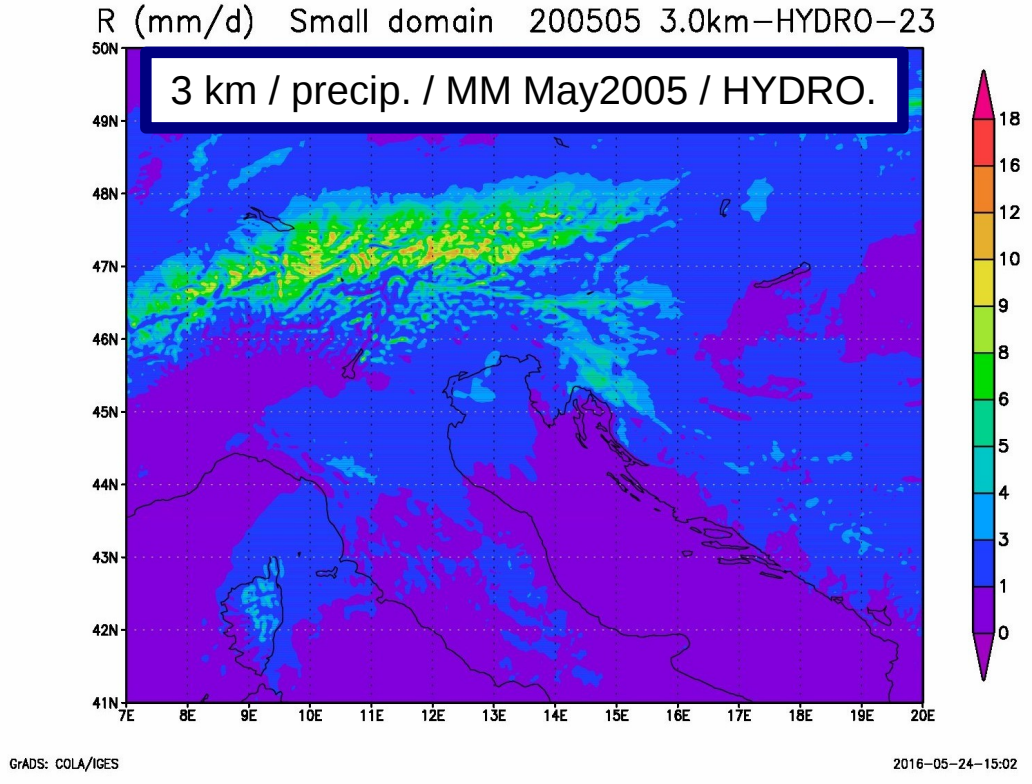
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3 km / precip. / MM May2005 / HYDRO.
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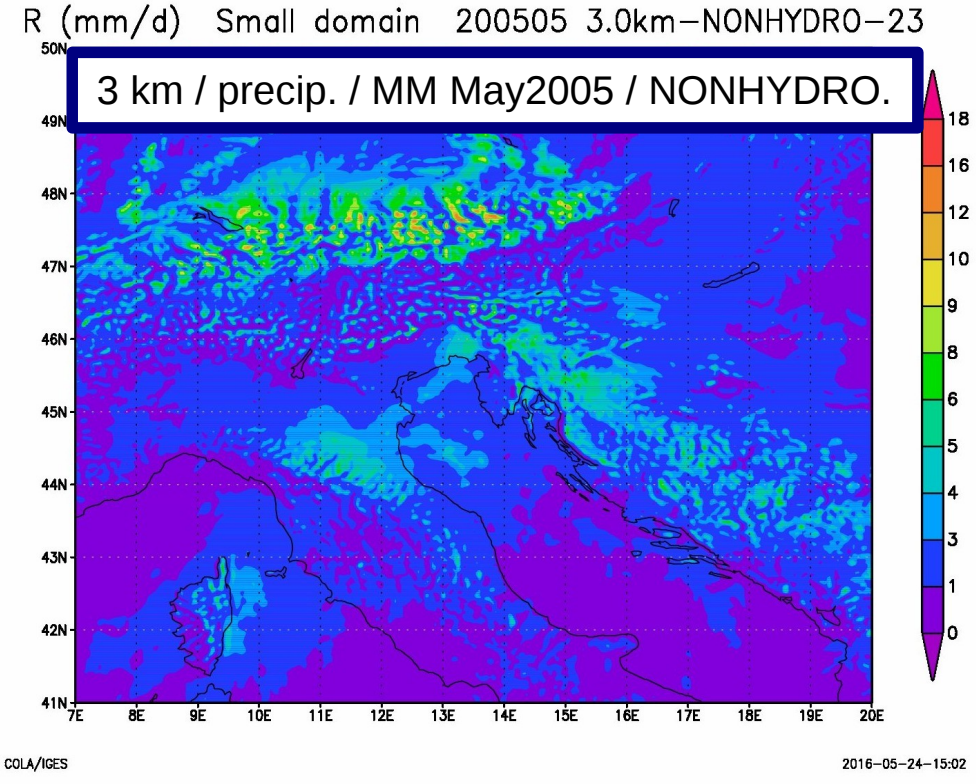
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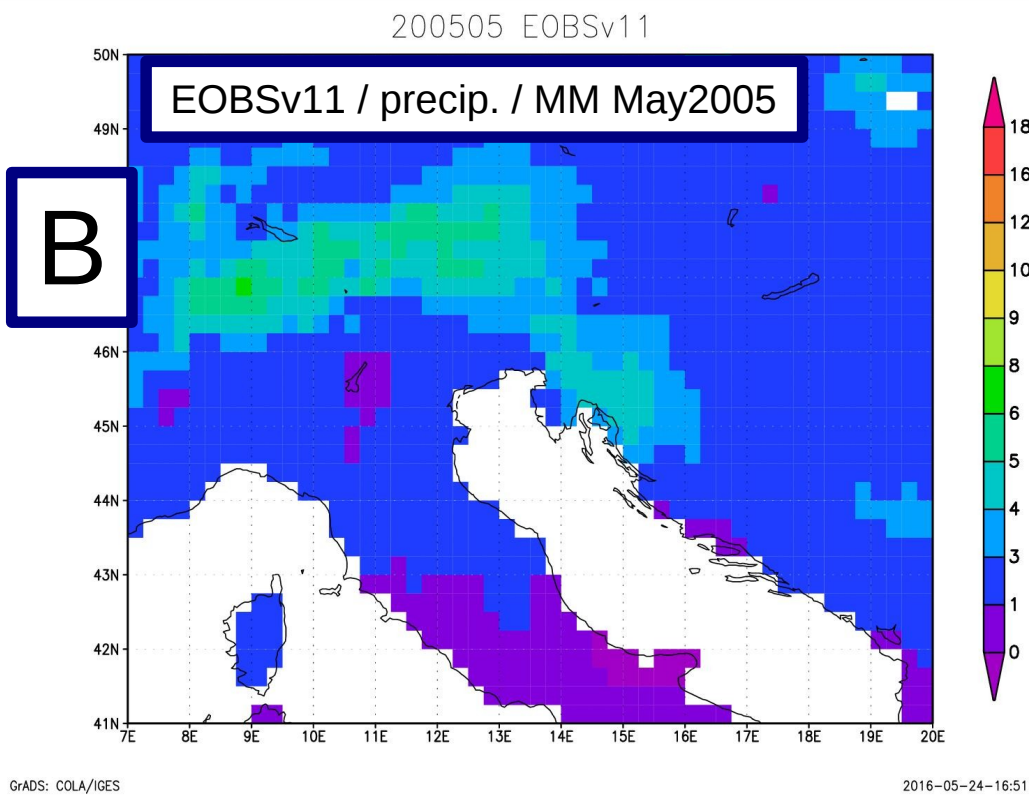
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EOBSv11 / precip. / MM May2005
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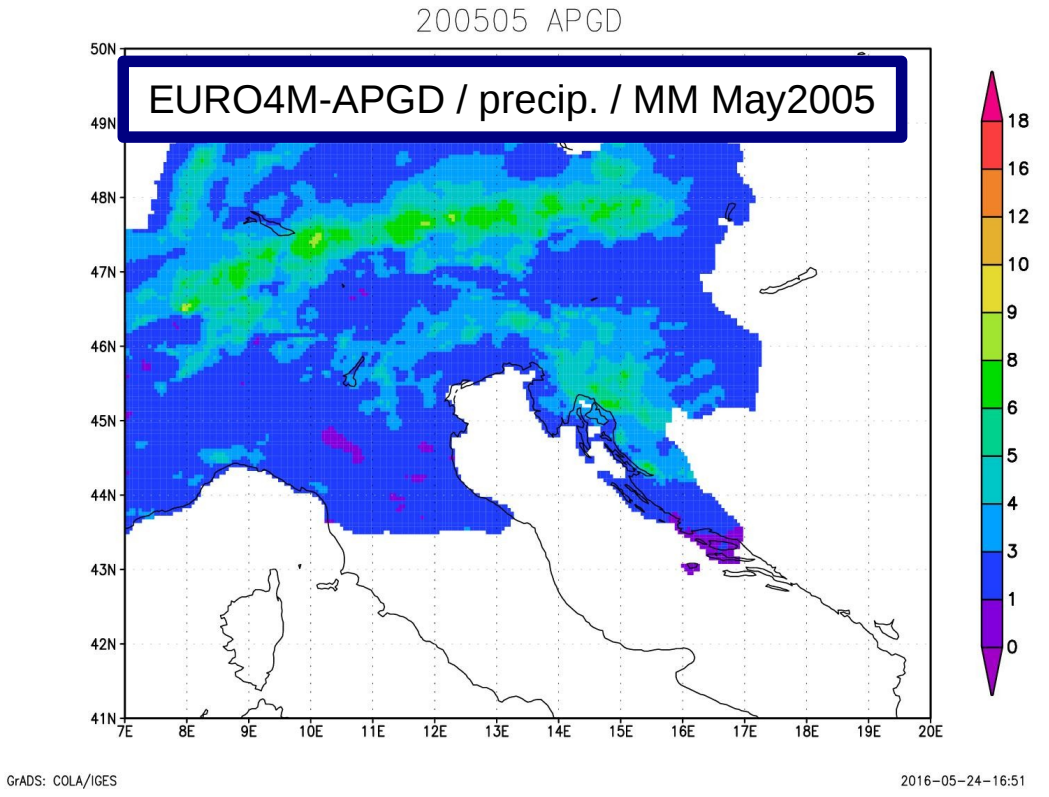
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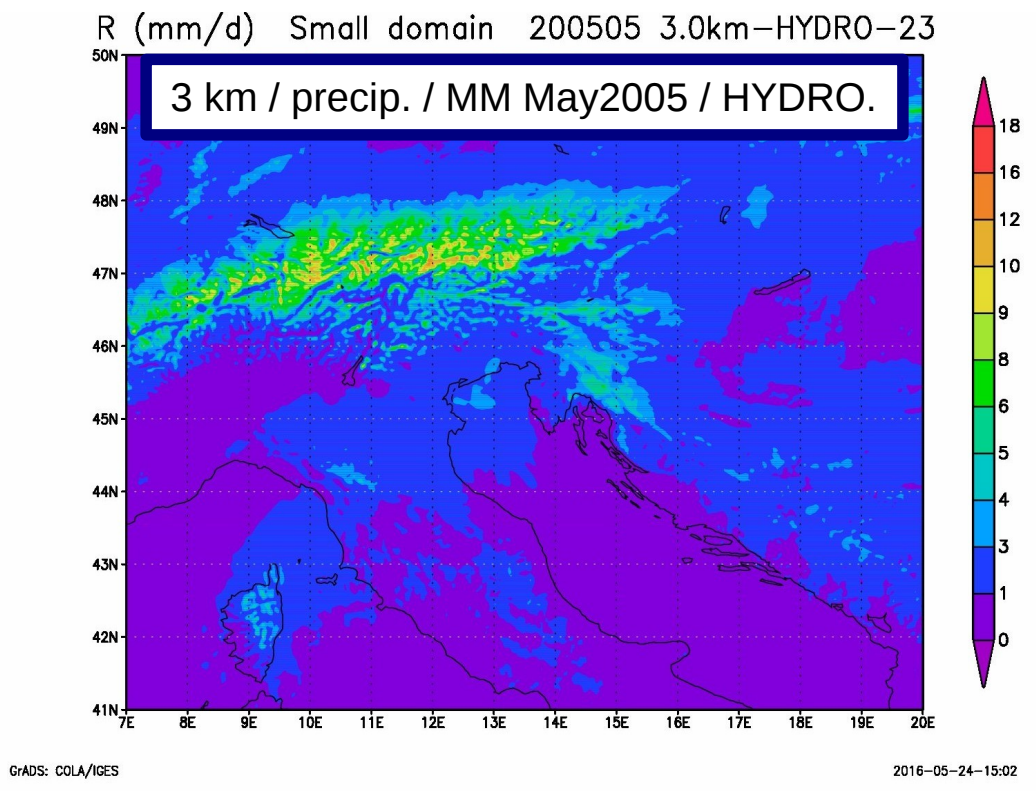
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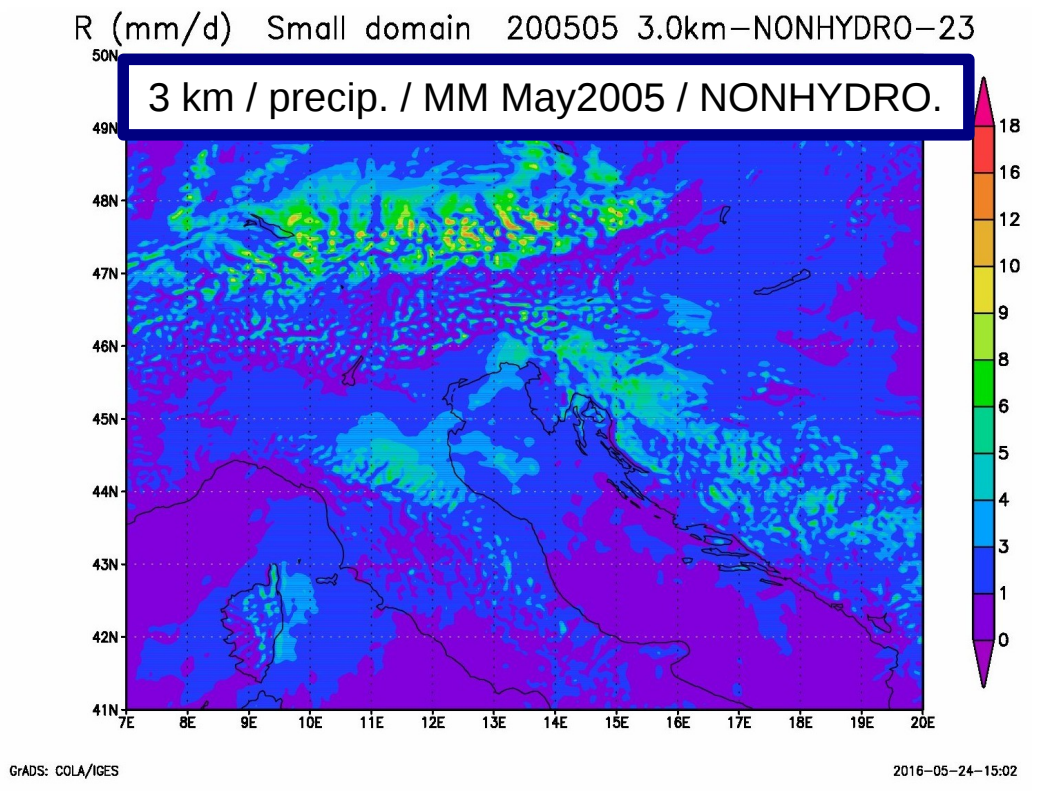
R (mm/d) Small domain 200505 3.0km-NONHYDRO-23
3 km / precip. / MM May2005 / NONHYDRO.
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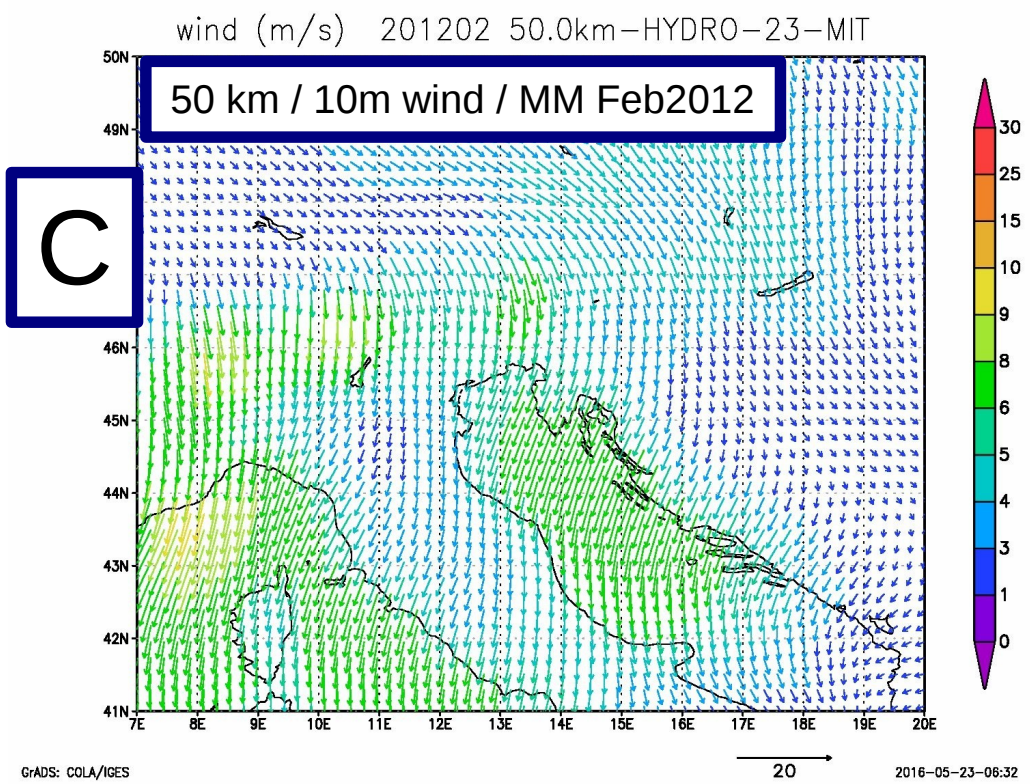
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50 km / 10m wind / MM Feb2012
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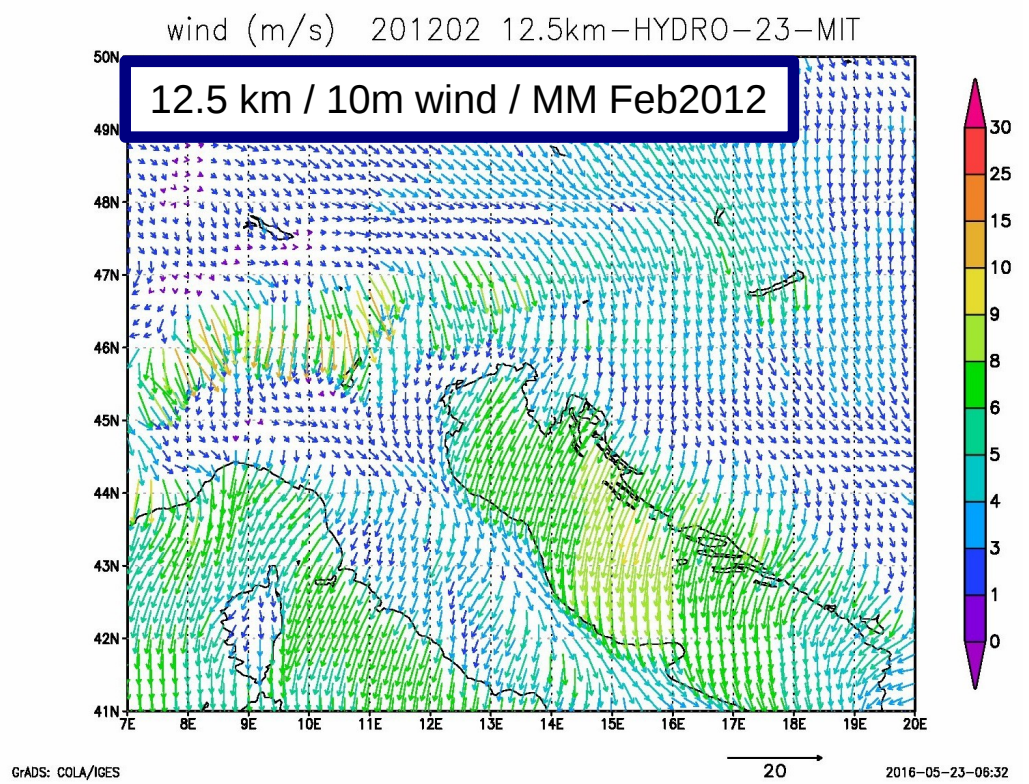
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12.5 km / 10m wind / MM Feb2012
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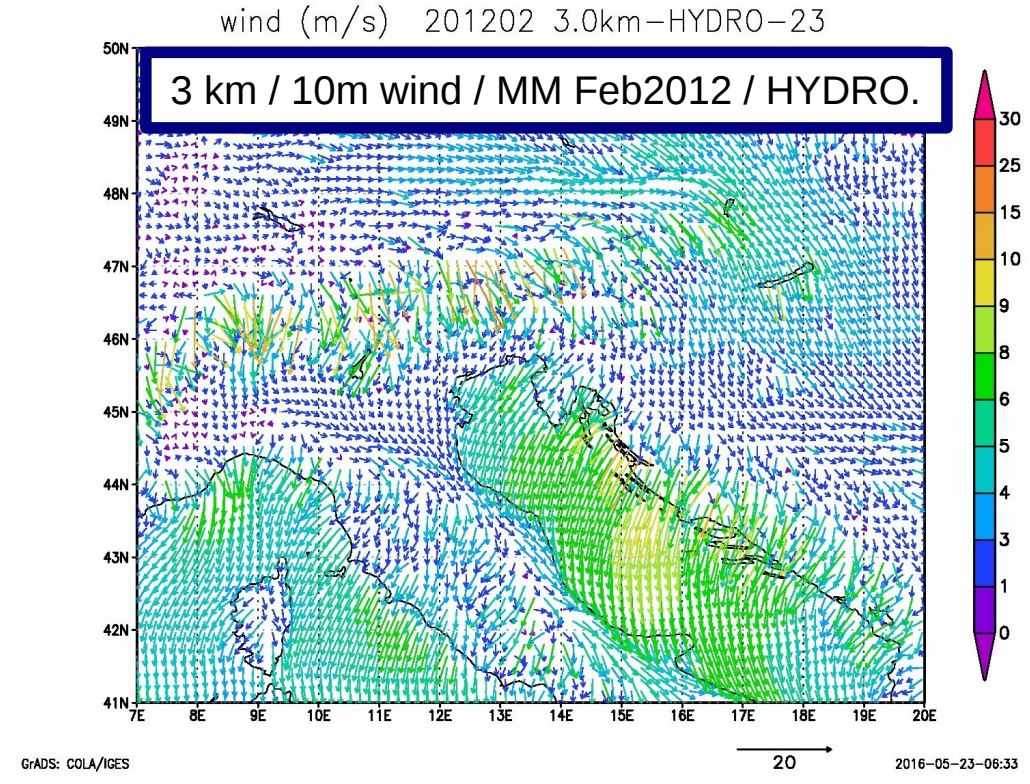
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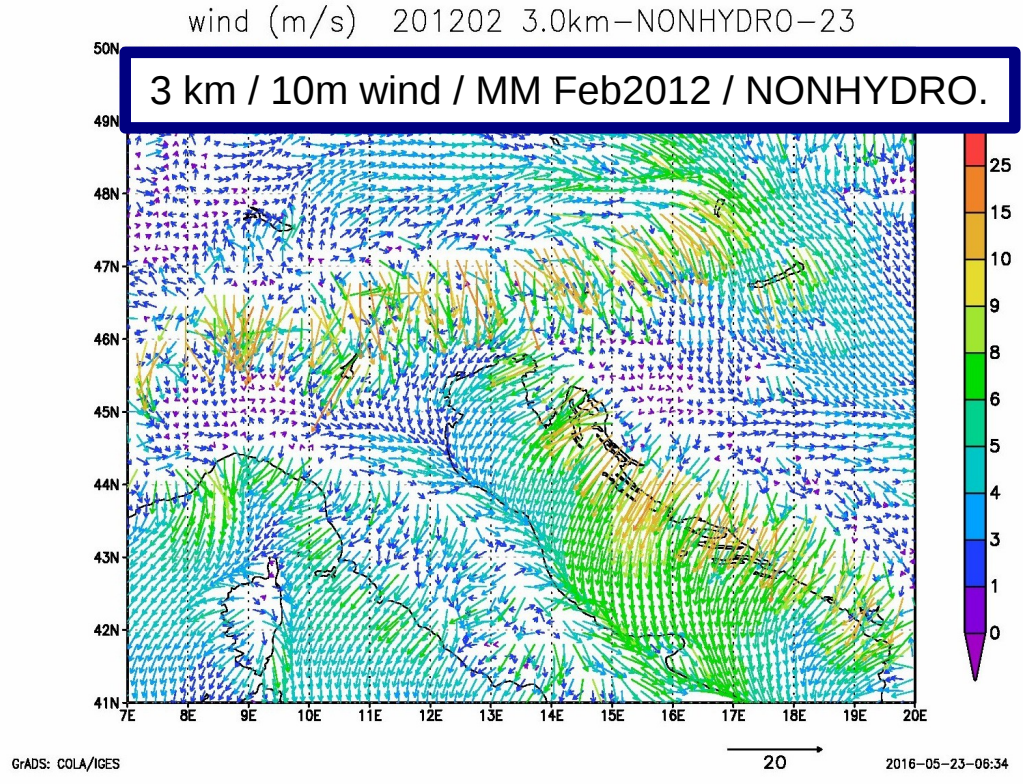
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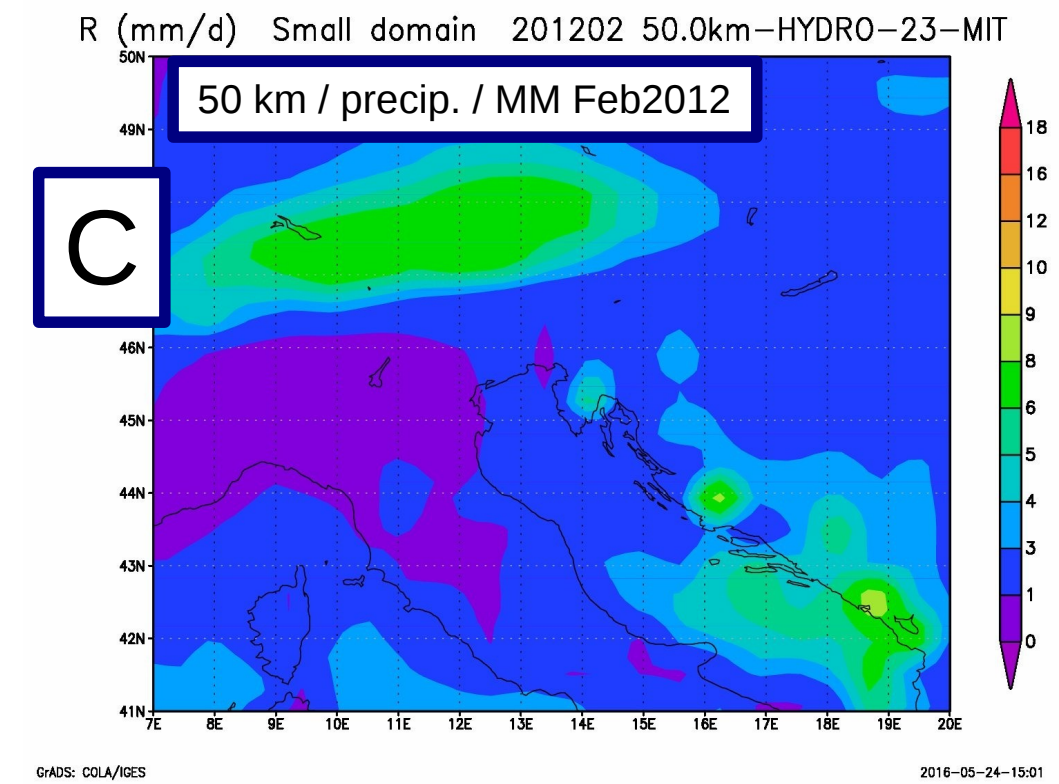
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50 km / precip. / MM Feb2012
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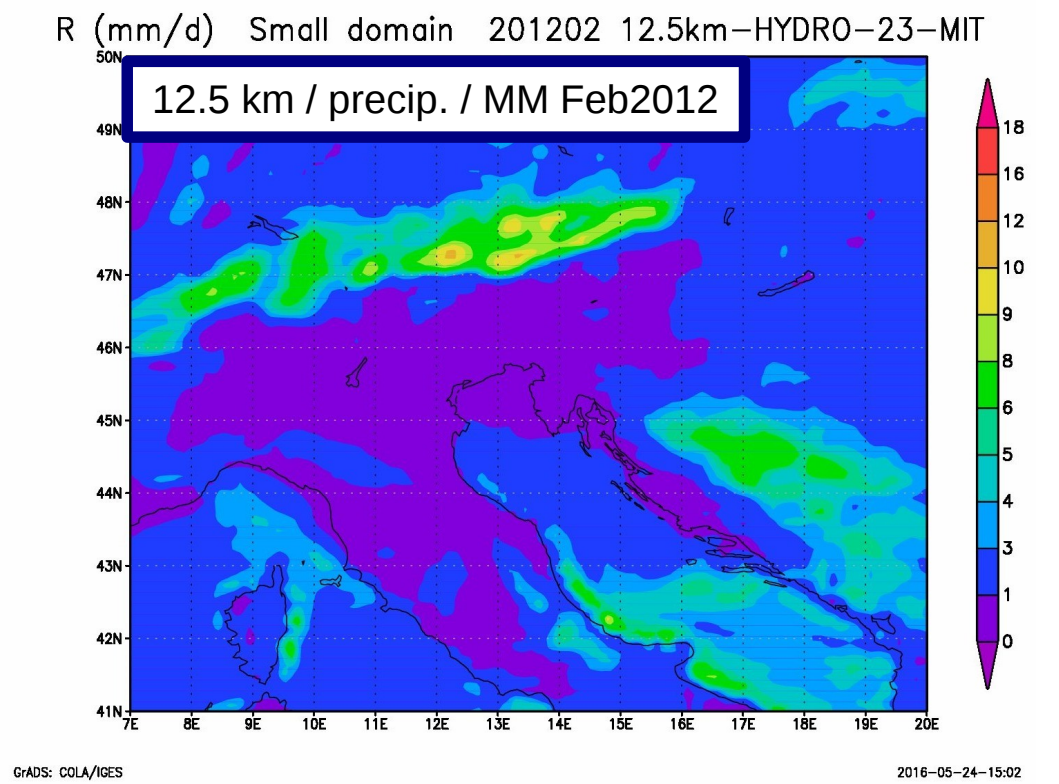
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12.5 km / precip. / MM Feb2012
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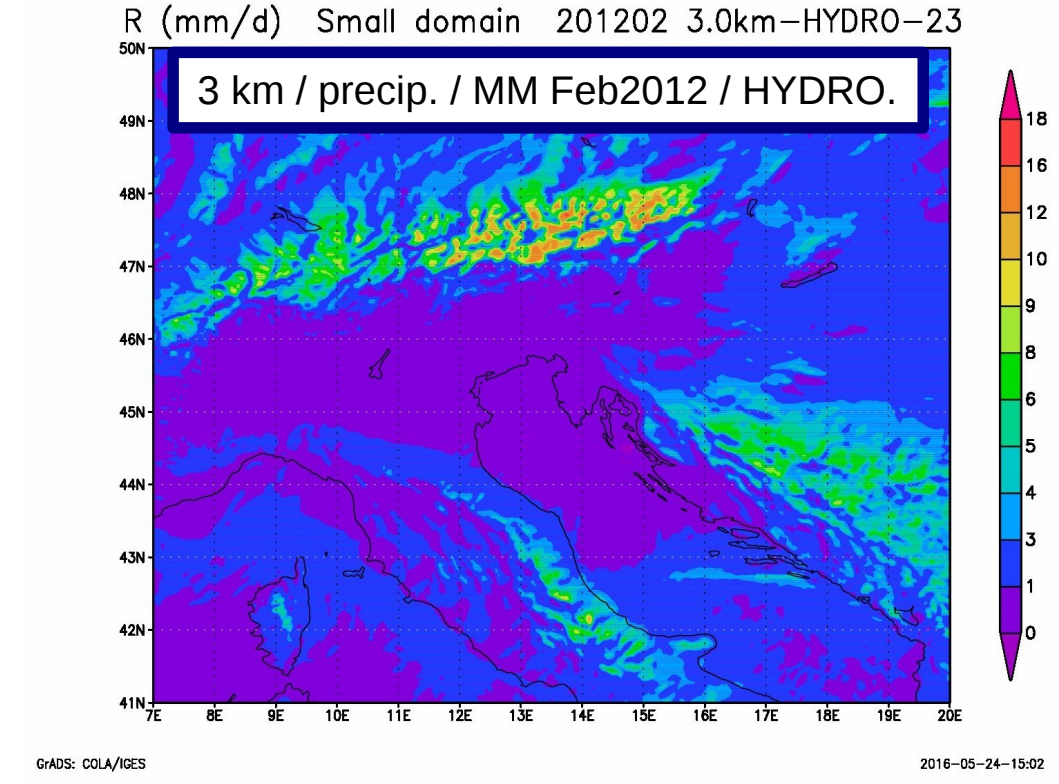
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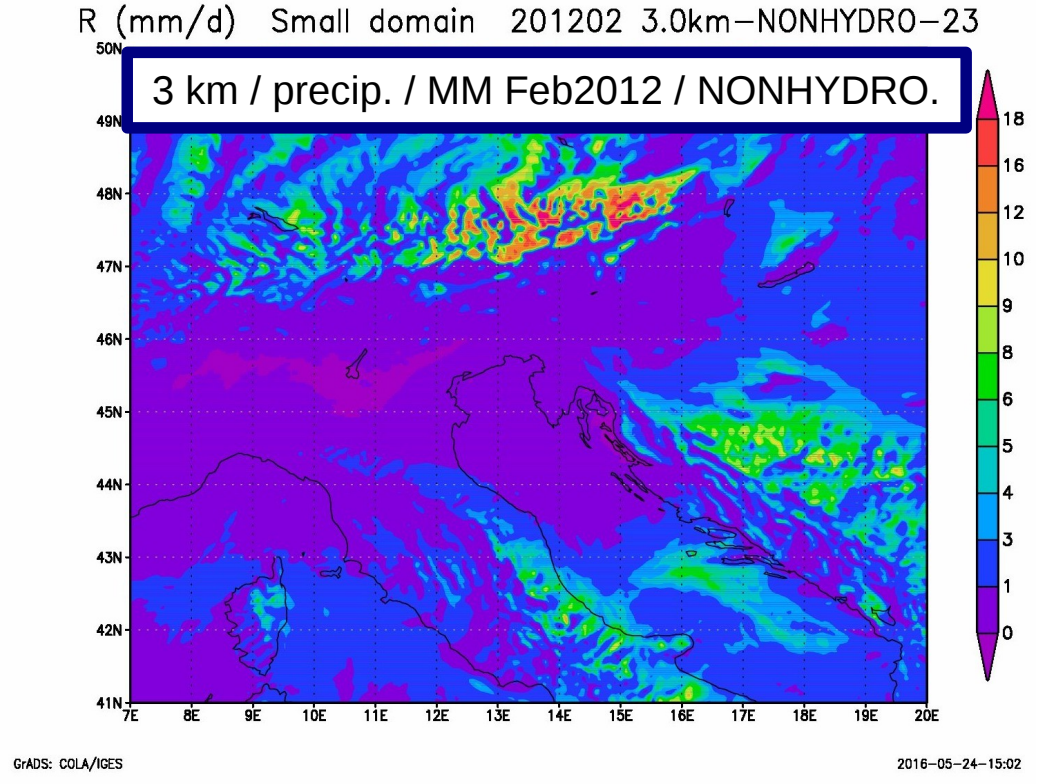
R (mm/d) Small domain 201202 3.0km−NONHYDRO−23
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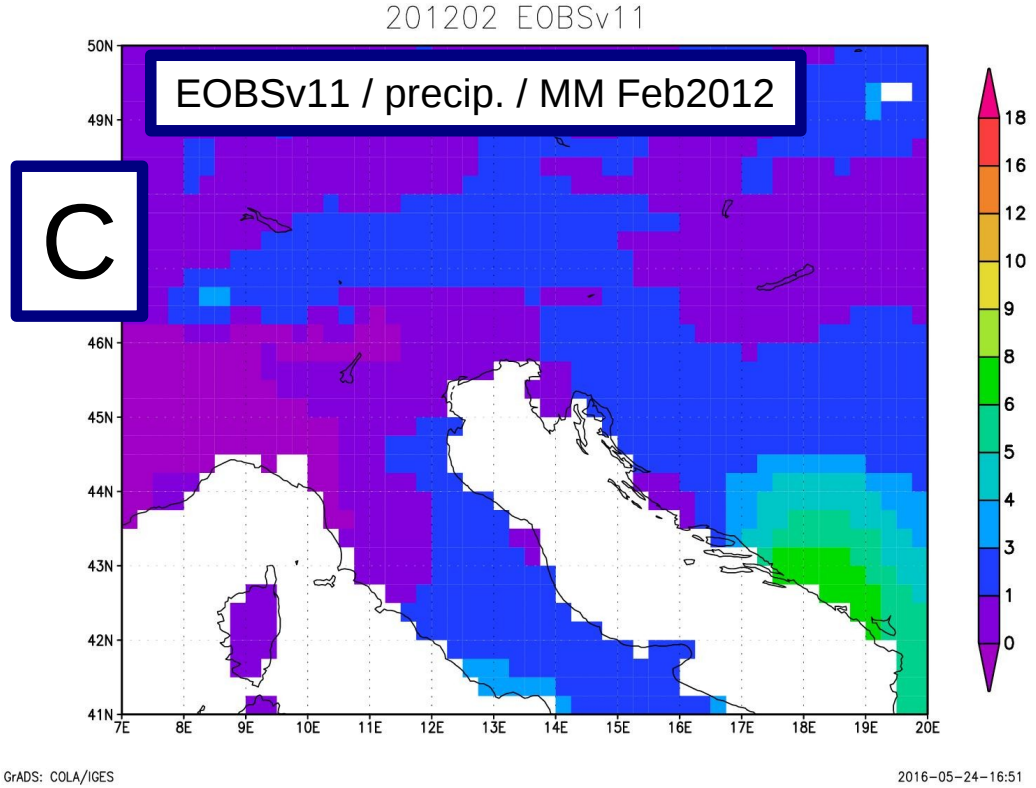
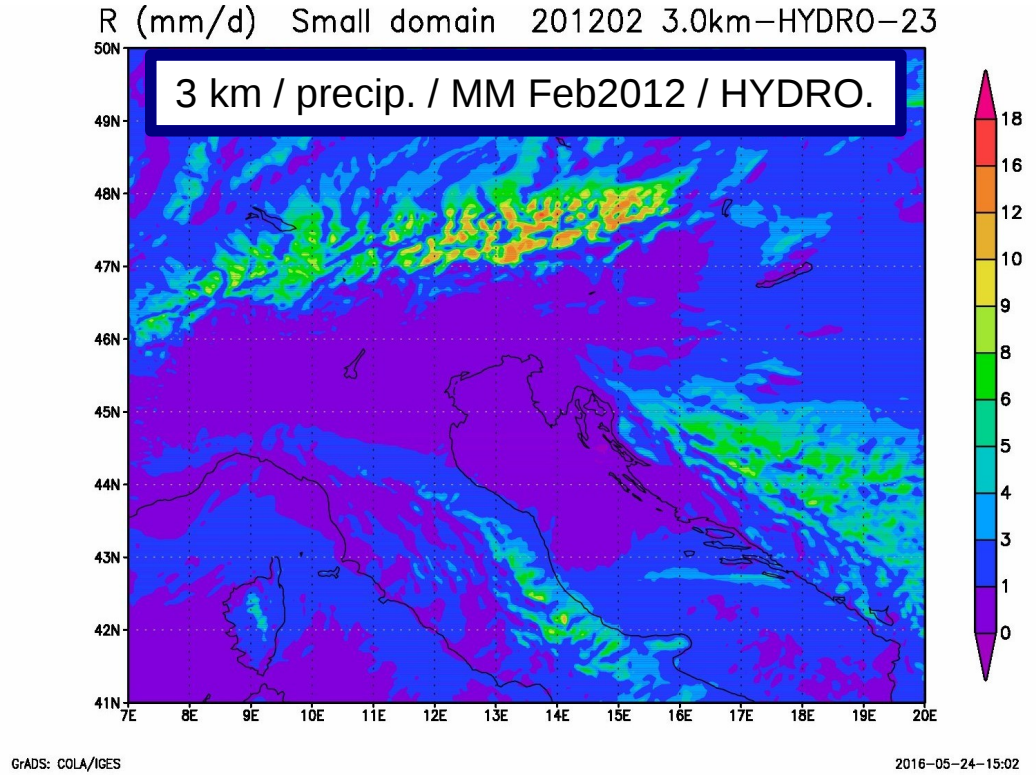
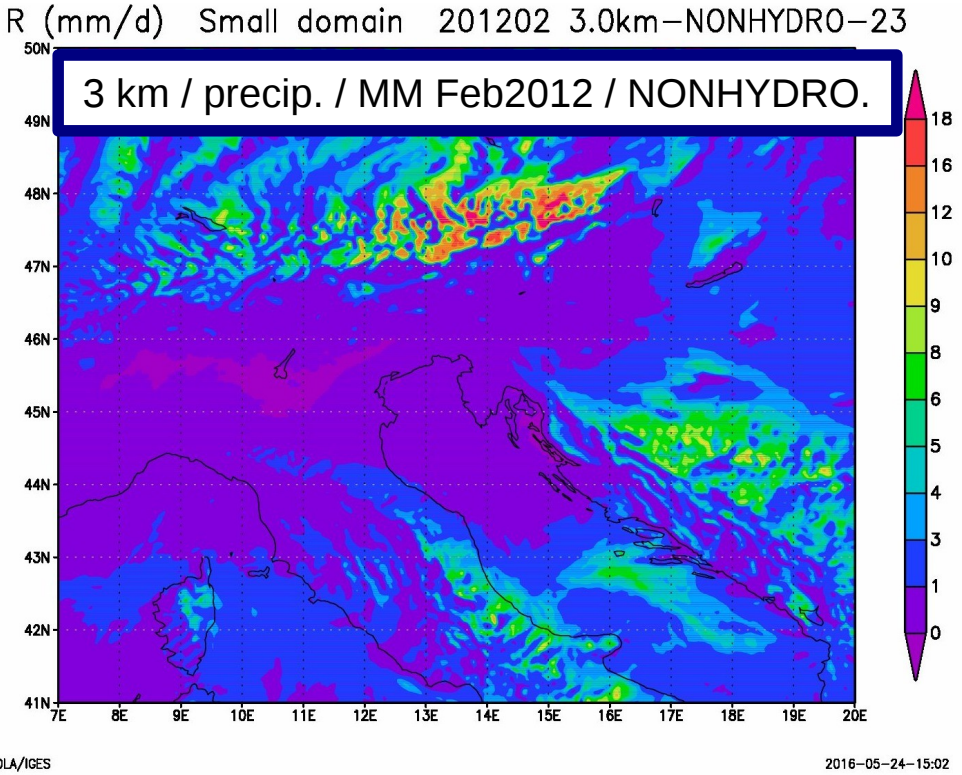
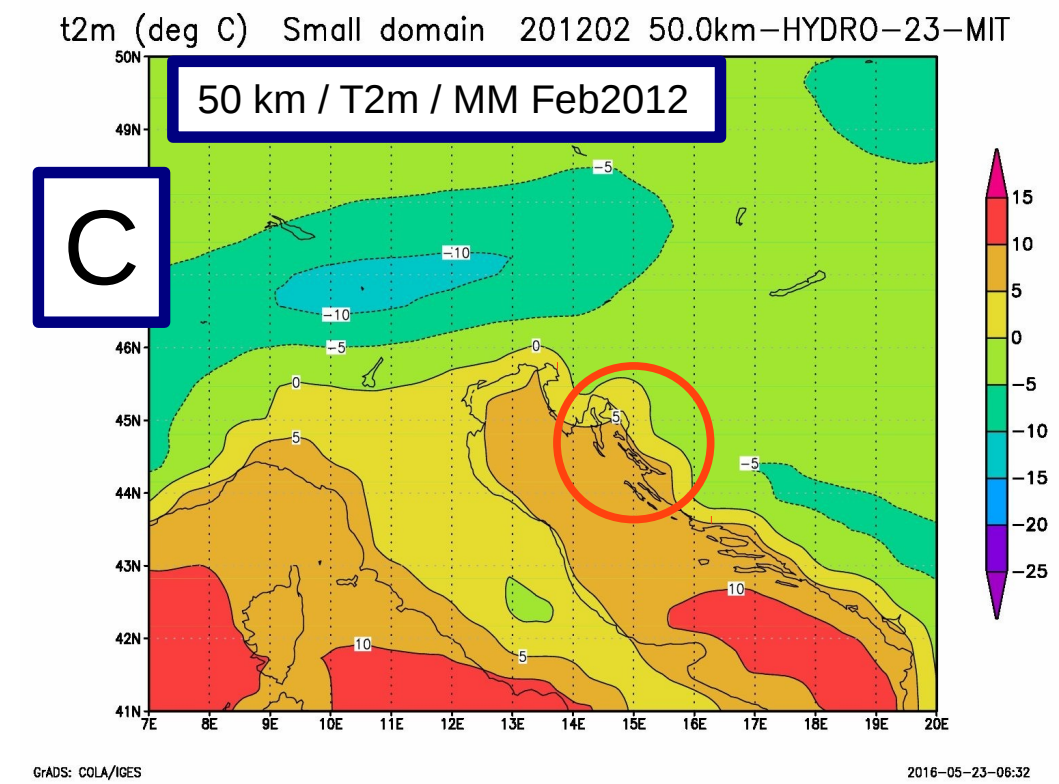


EURO4M-APGD not available for this period.



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50 km / T2m / MM Feb2012
C
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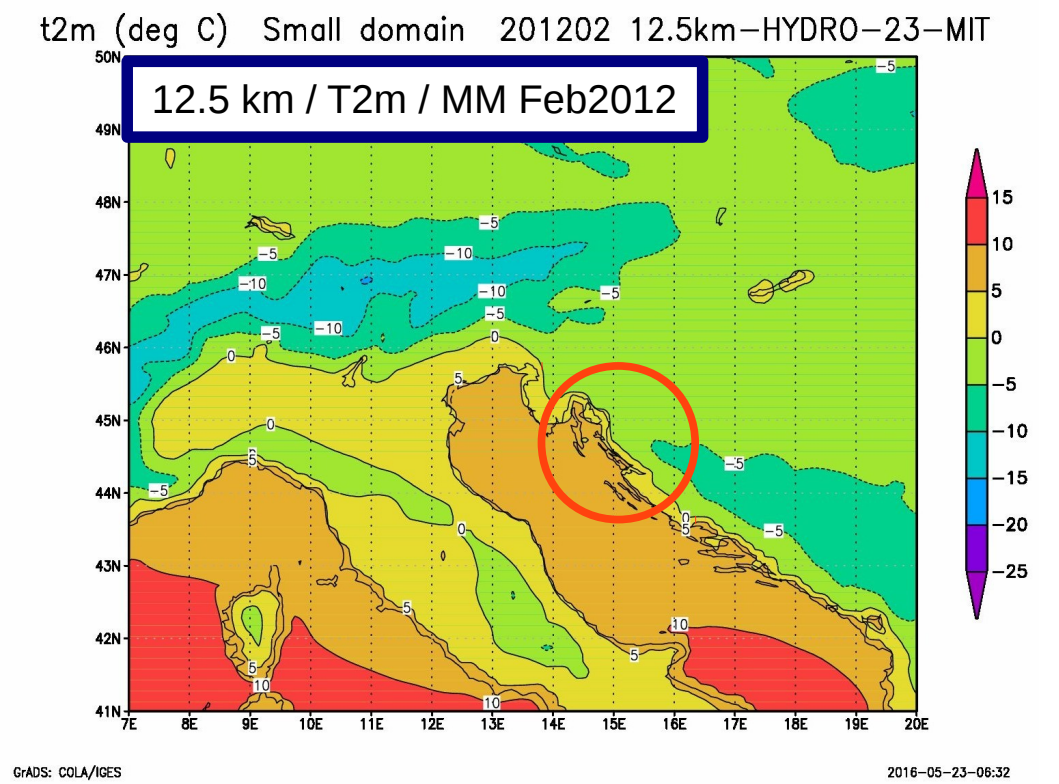
t2m (deg C) Small domain 201202 12.5km−HYDRO−23−MIT
12.5 km / T2m / MM Feb2012
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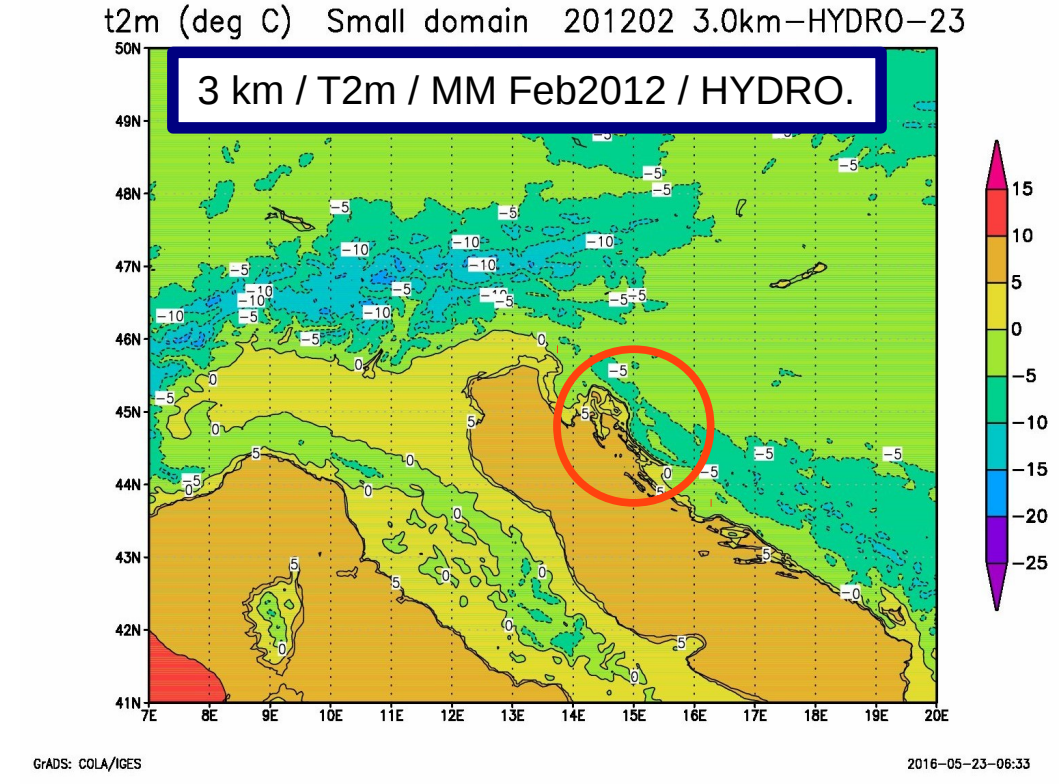
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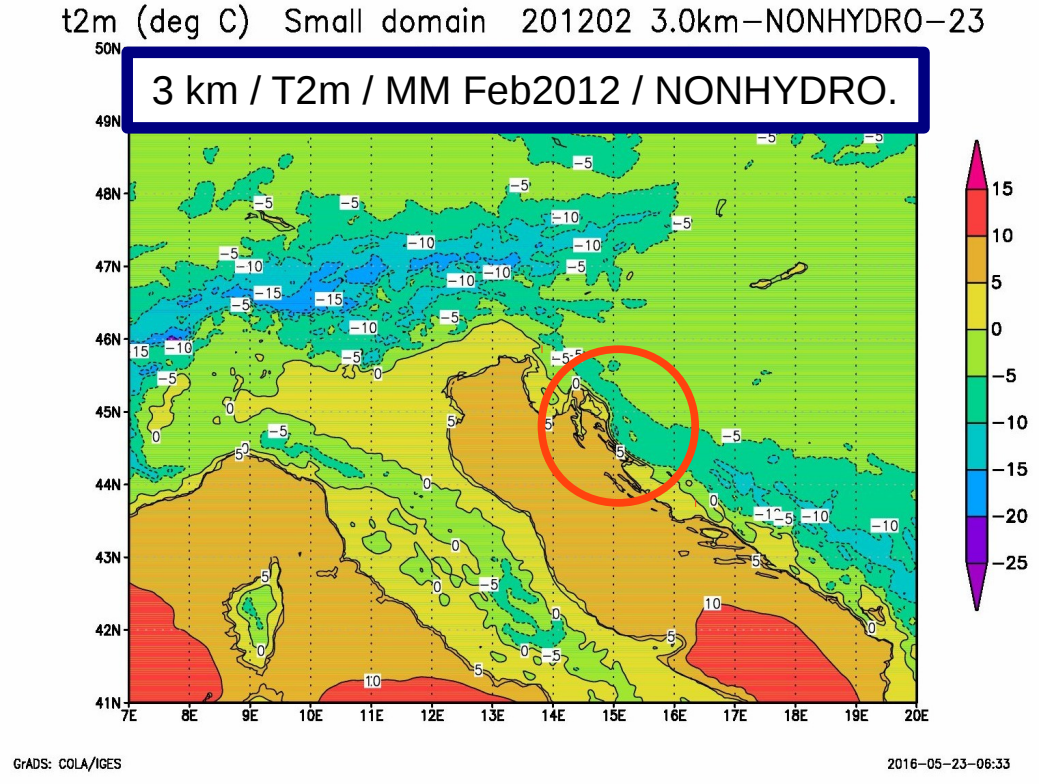
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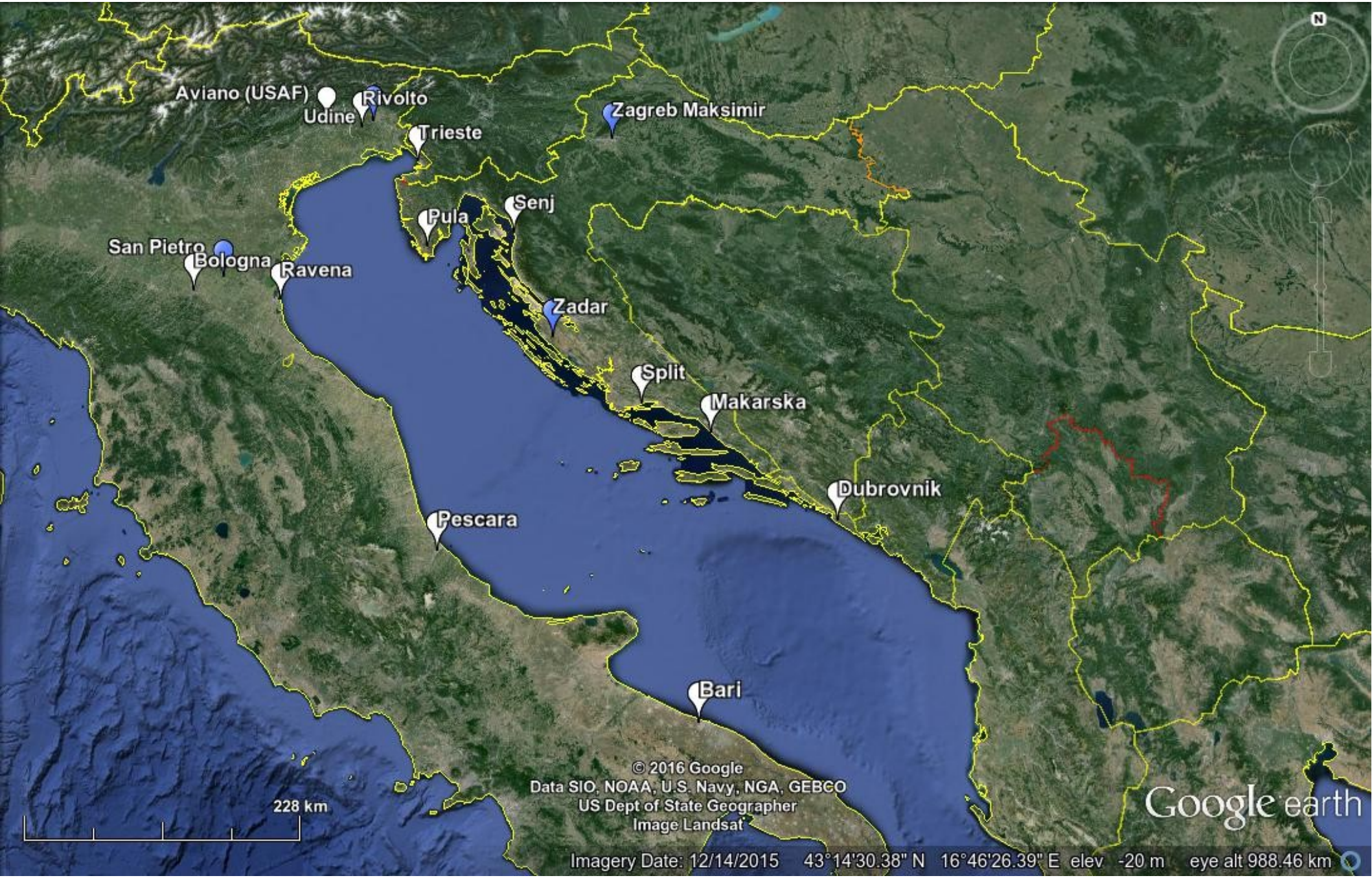
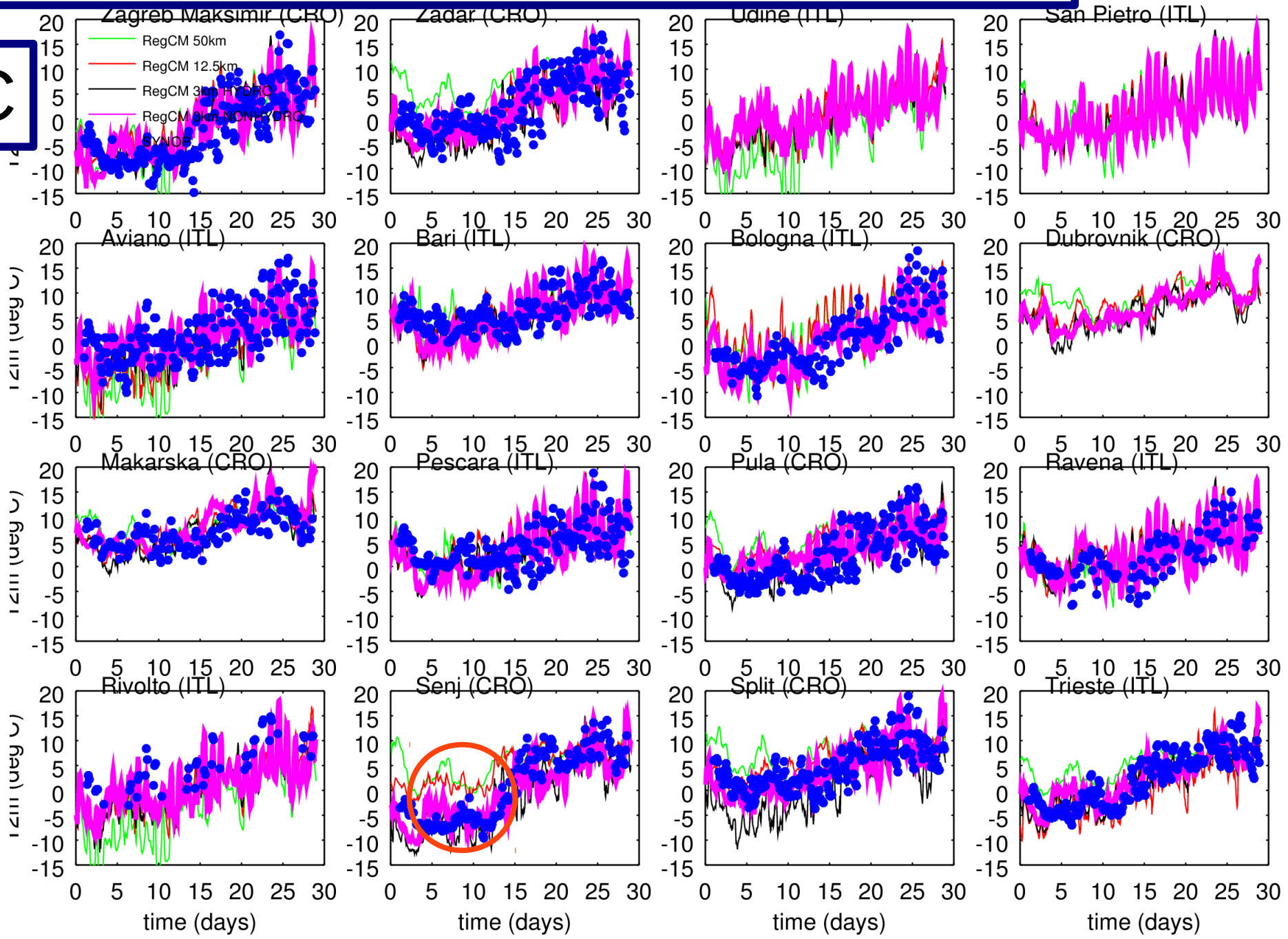
Vertical soundings (blue locations) and station observations (white locations) are used for evaluating C case



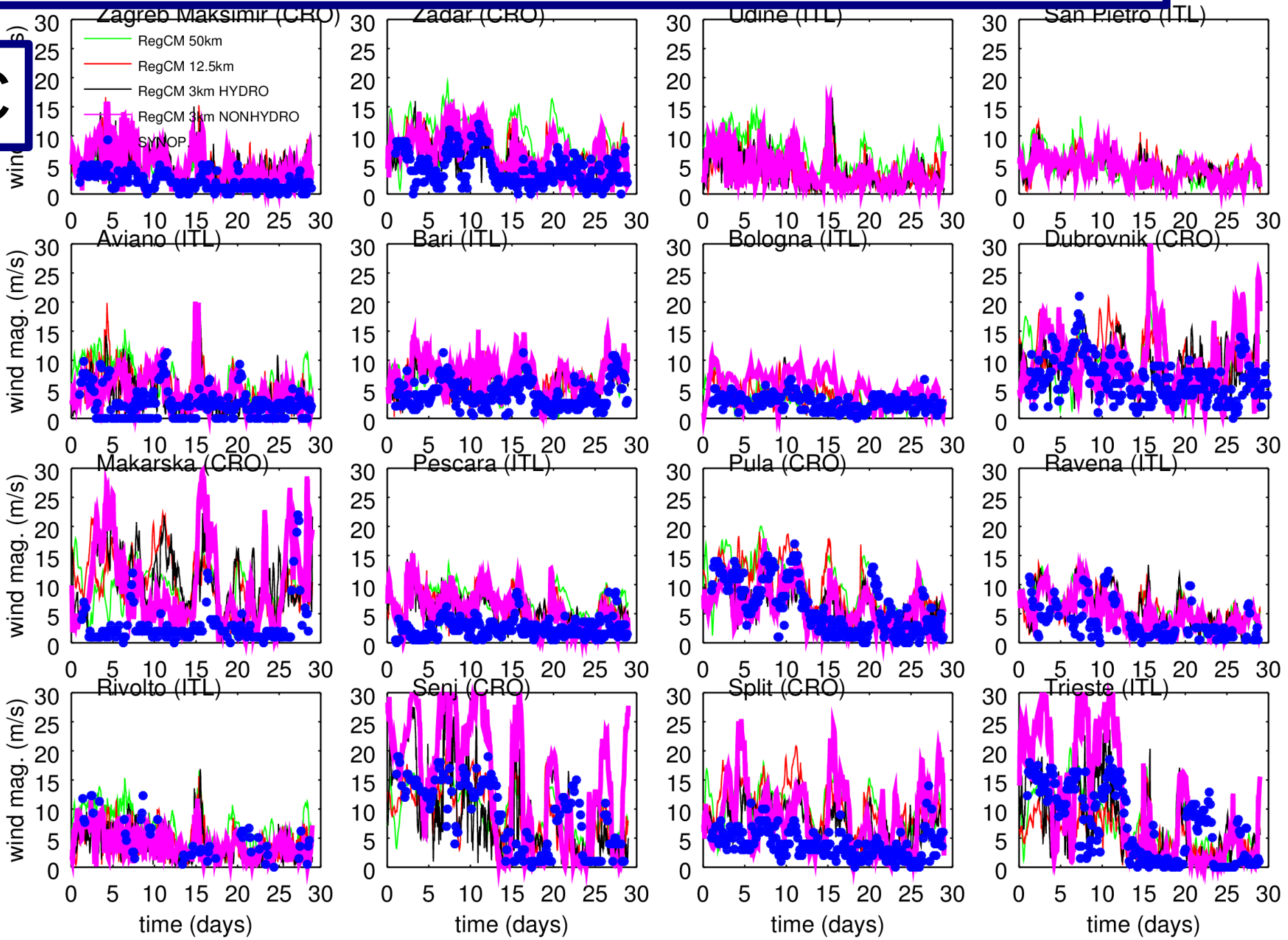
T2m time-series Feb2012: RegCM vs. SYNOP observations

C

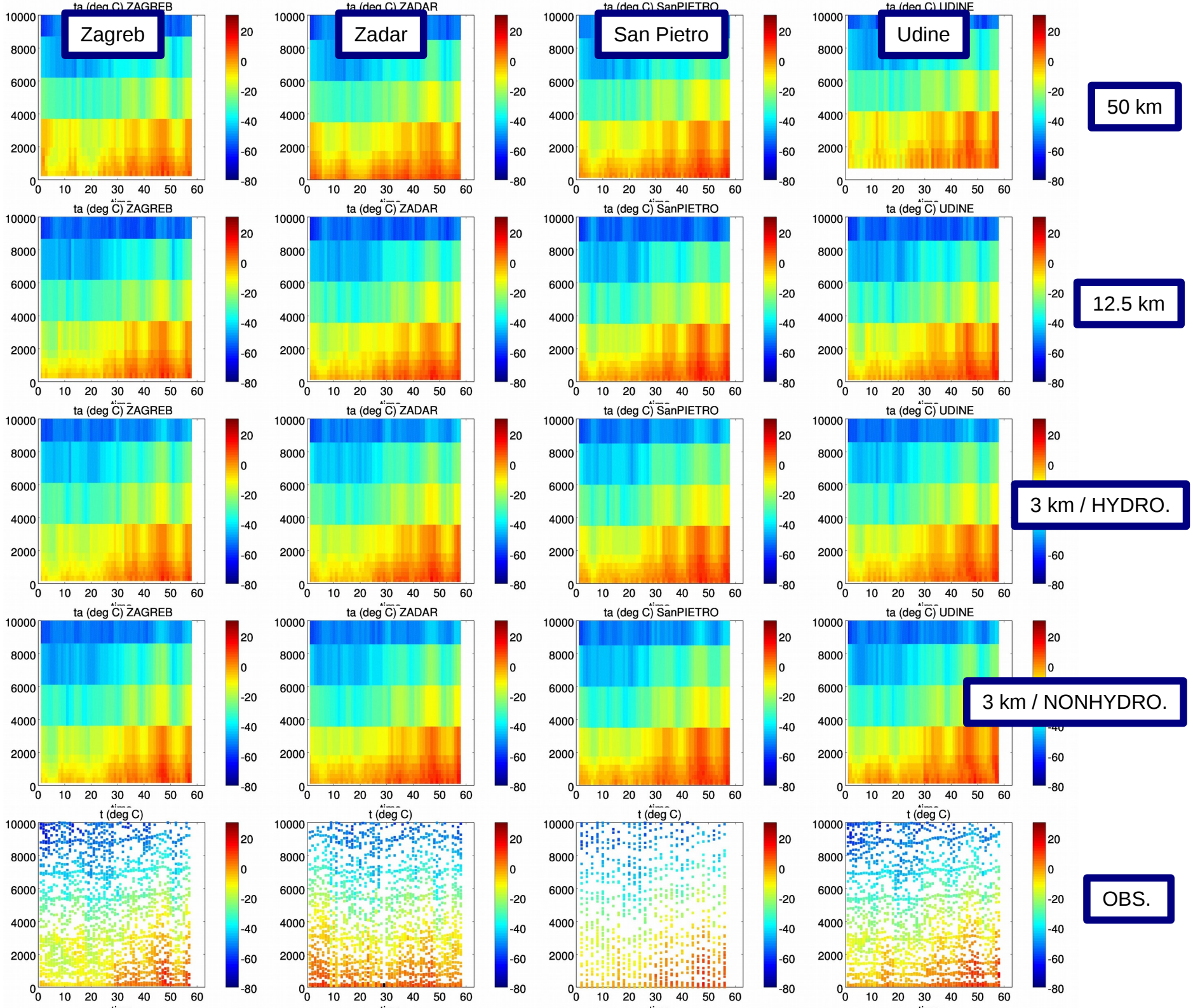


10m wind time-series Feb2012: RegCM vs. SYNOP observations

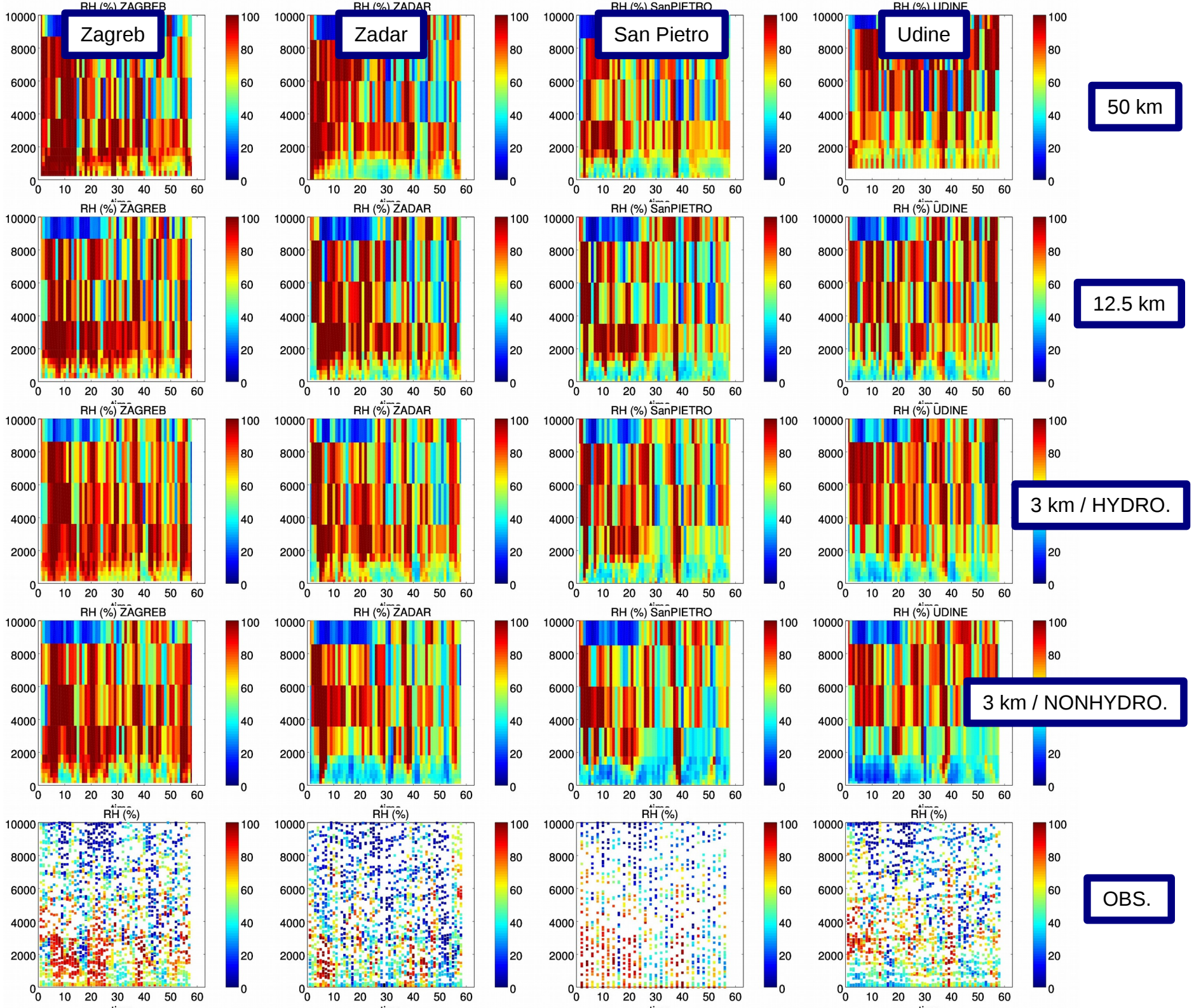
C



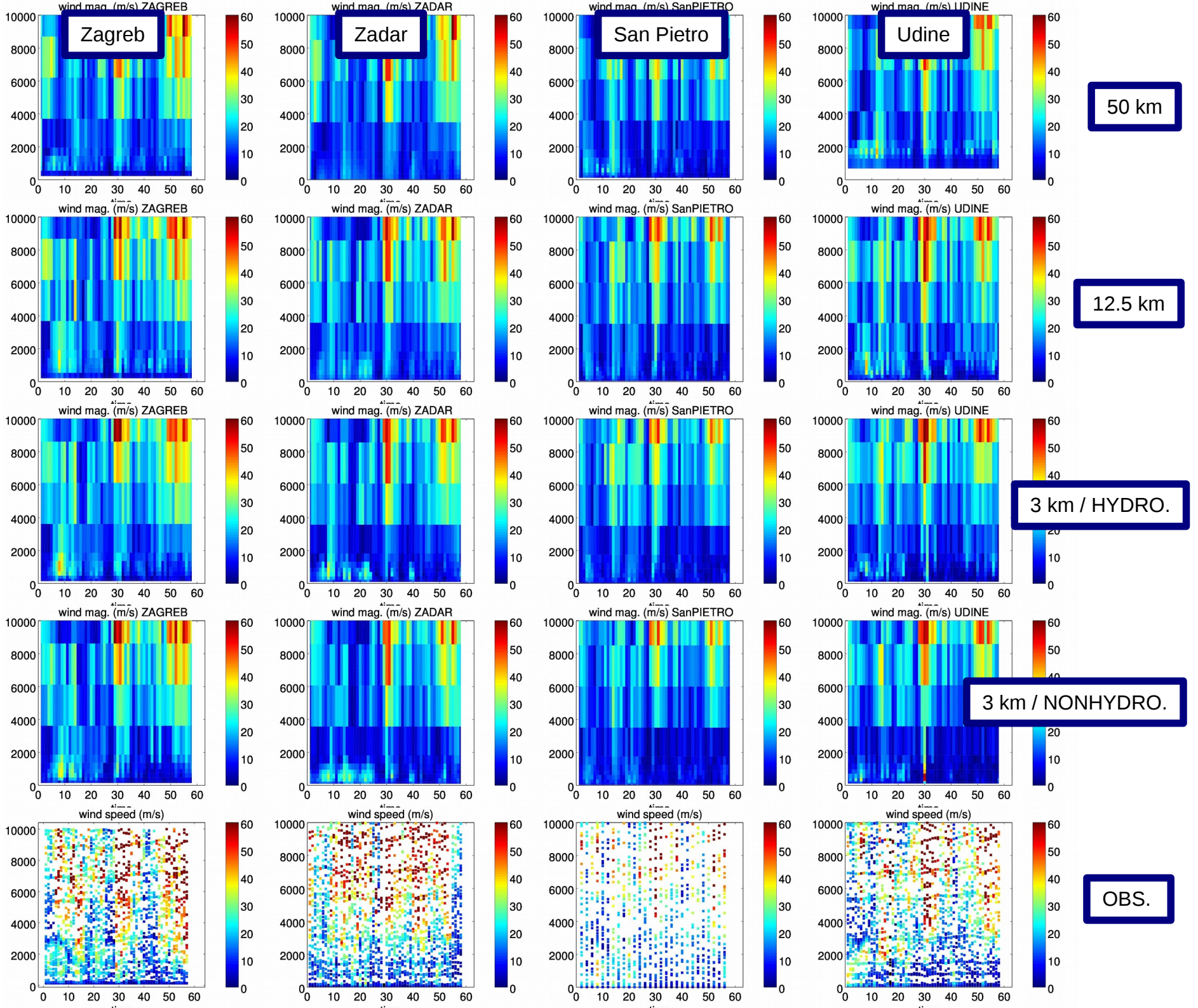
Temperature (z,t) Feb2012: RegCM vs. soundings



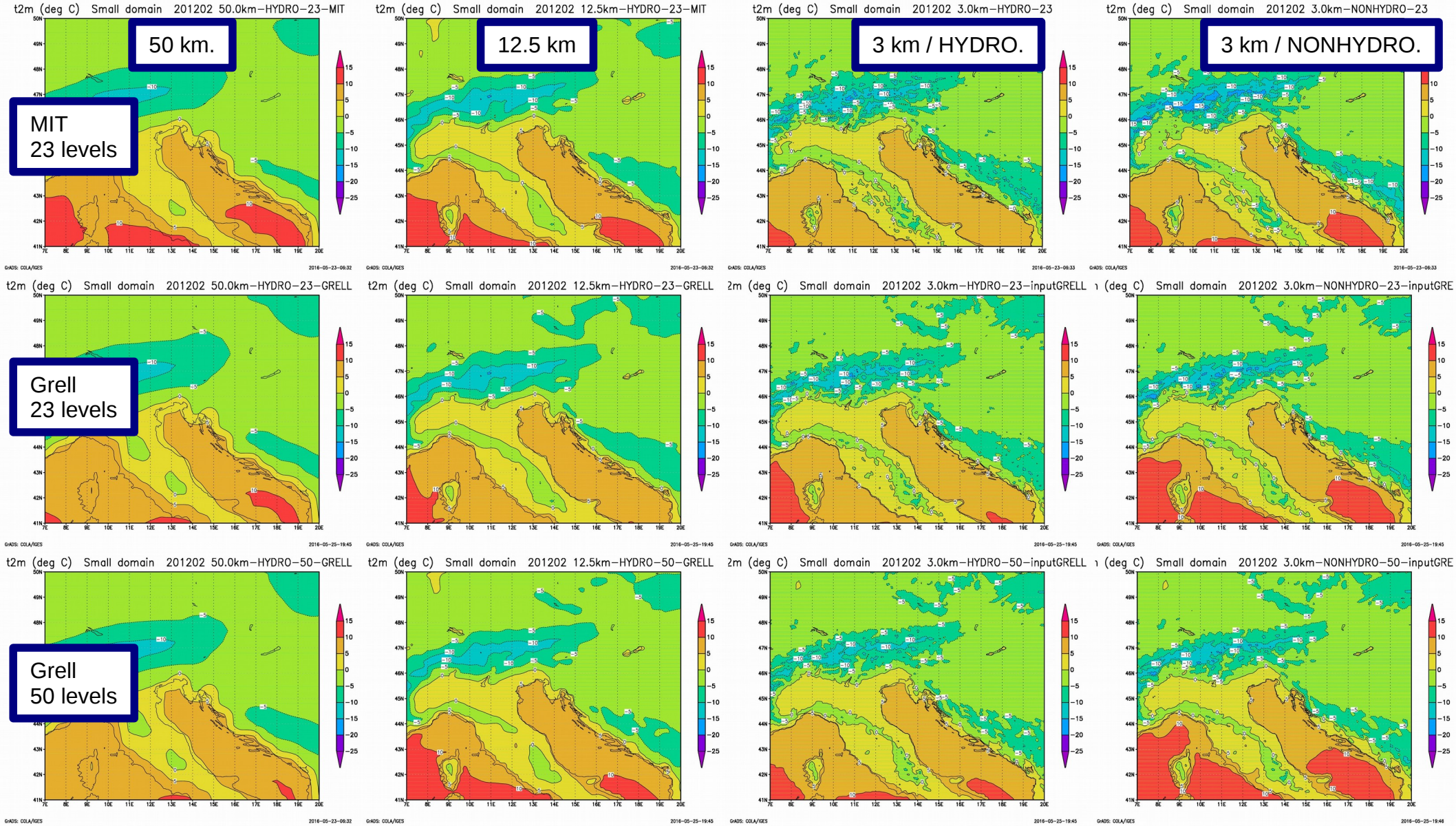
Relative humidity (z,t) Feb2012: RegCM vs. soundings



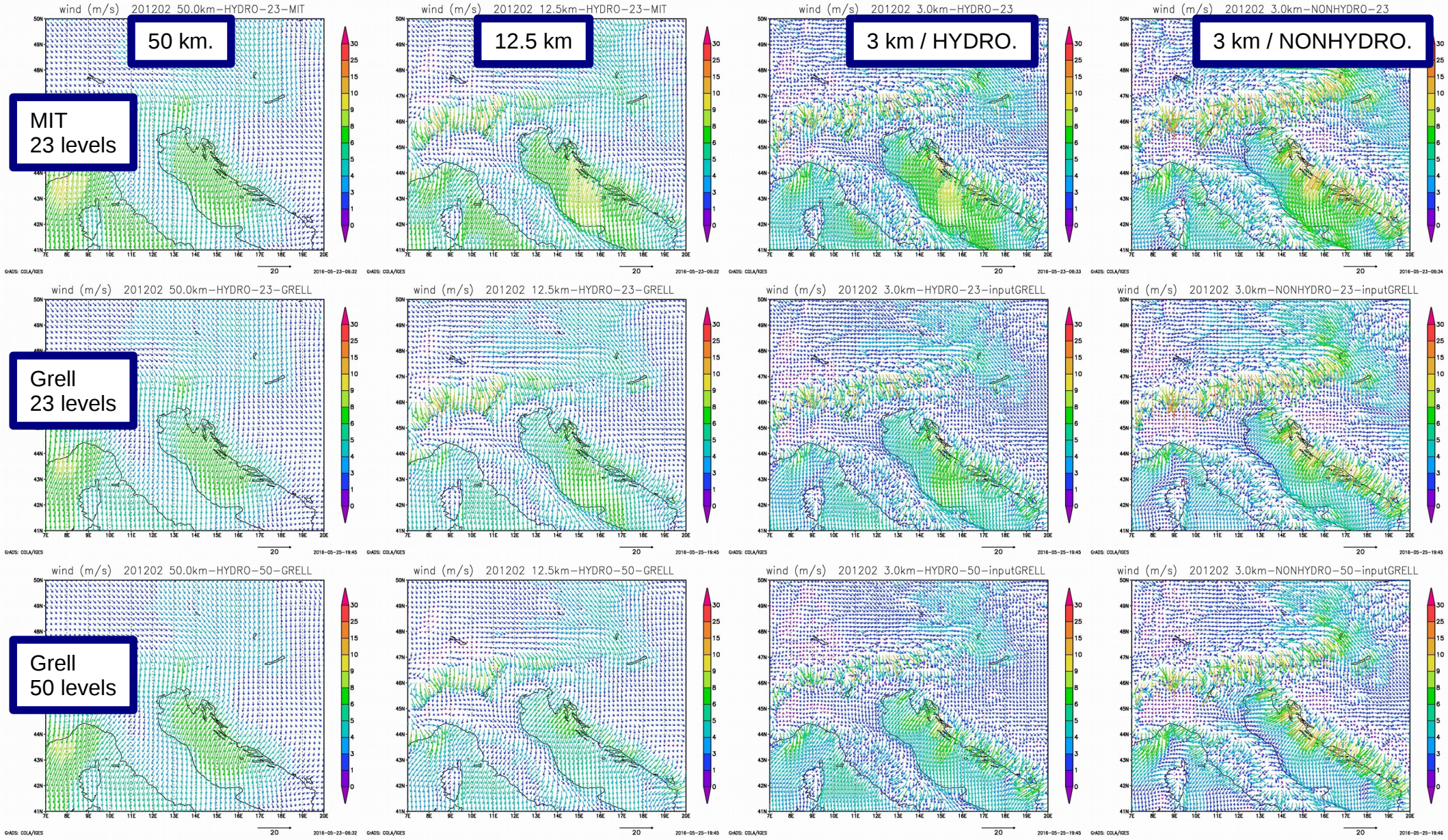
Wind magnitude (z,t) Feb2012: RegCM vs. soundings



Additional experiments: (1) MIT(23)>Grell(23) and (2) Grell(23)>Grell(50)
T2m / MM / Feb2012

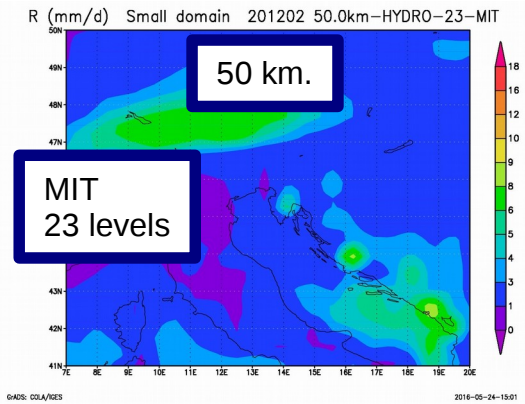


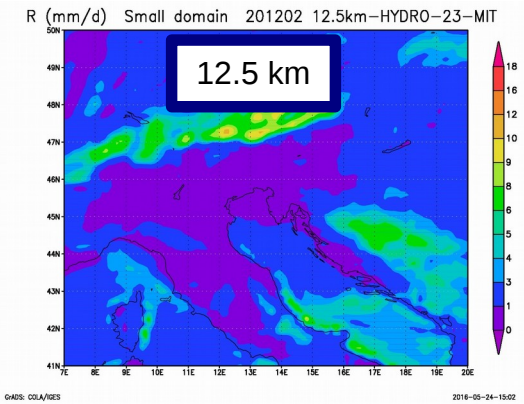
Additional experiments: (1) MIT(23)>Grell(23) and (2) Grell(23)>Grell(50)
10m wind / MM / Feb2012

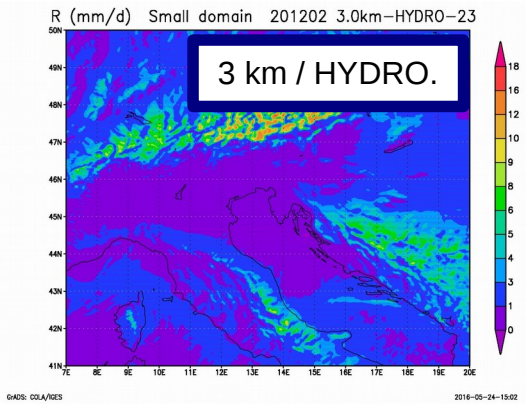


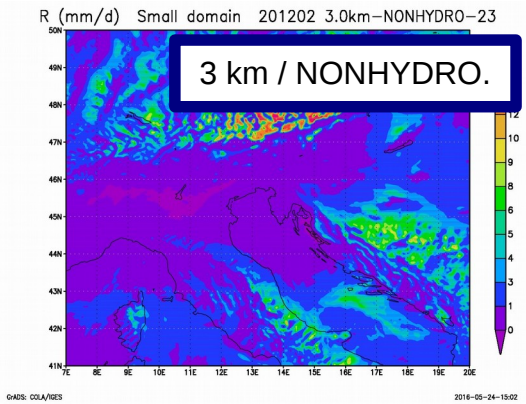
Additional experiments: (1) MIT(23)>Grell(23) and (2) Grell(23)>Grell(50)

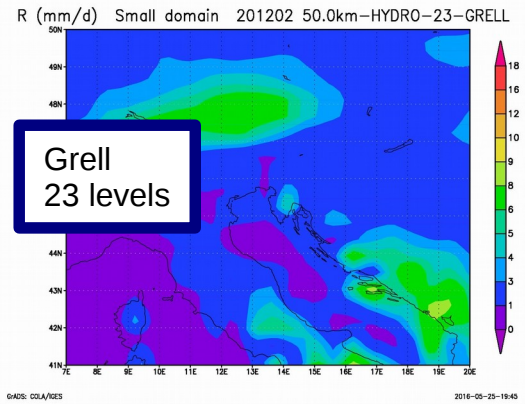
Total precipitation amount / MM / Feb2012

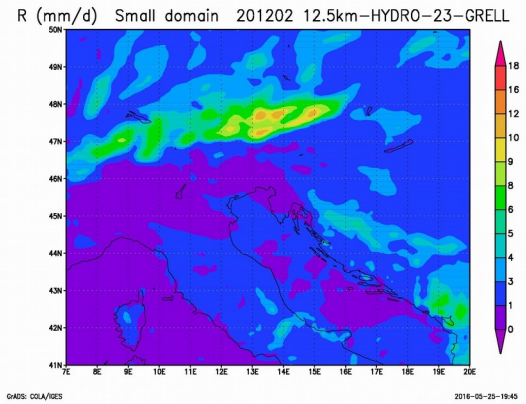


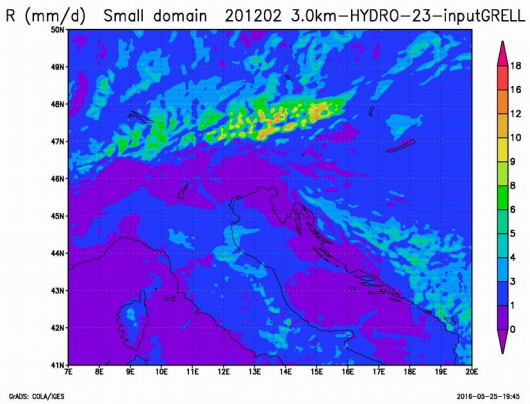


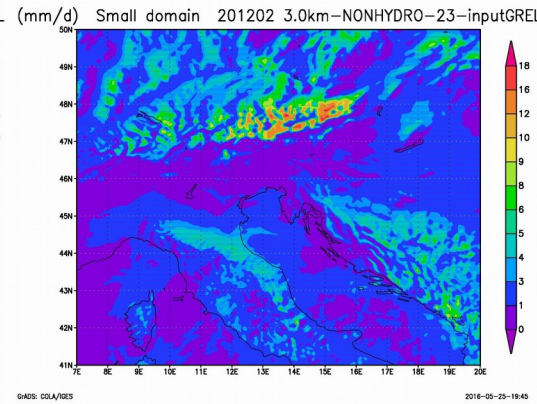


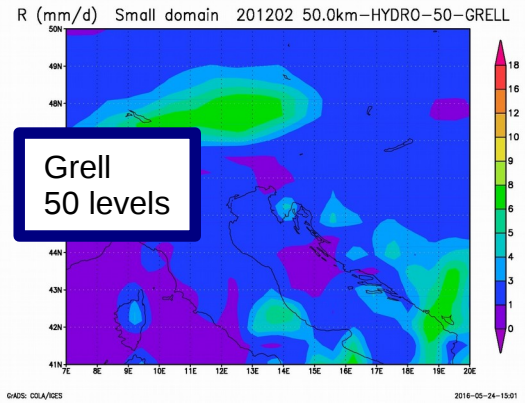


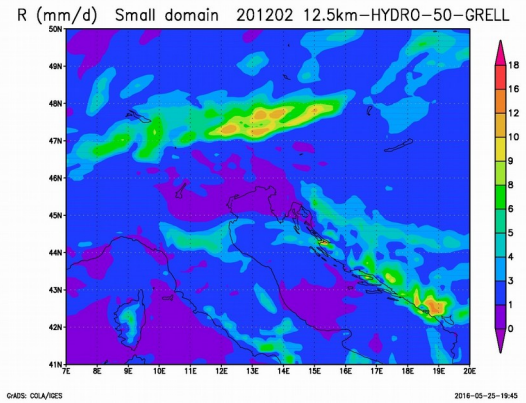


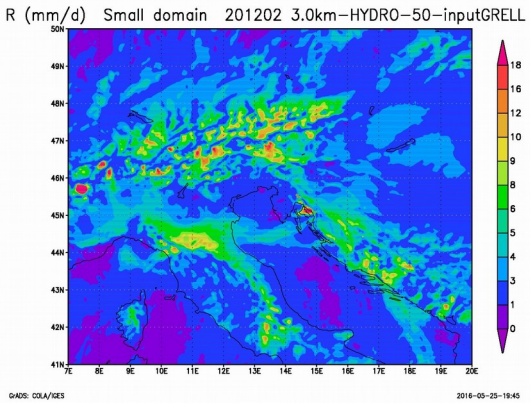


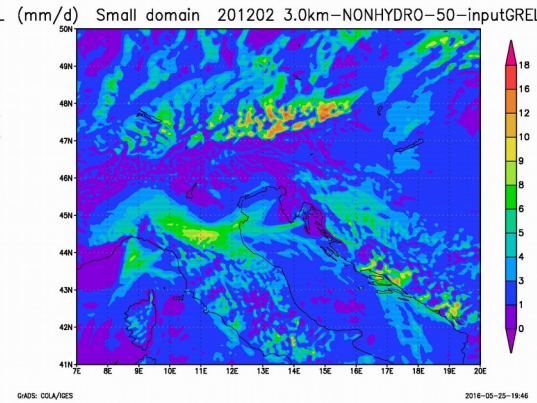












Summary and some suggestions for *early RegCM users*

[1] both hydrostatic and nonhydrostatic dynamical cores are functional in 3 km experiments discussed here. Test this options in your lab session over your domains, and in combination with other physical parametrizations.

[2] hydrostatic/nonhydrostatic assumption can be justified based on problem at hand. Test these options for your problem (e.g., there are many bora-type flows all over the world, and there are many other processes where nonhydrostatic effects are active).

[3] As usual, there will be always code errors, but the important thing is to reduce their number. Be sure RegCM performs well before starting long (>10 yrs.) runs. For example, it takes ~18 h (~37 h) for 3 km hydrostatic simulation with 23 (50) levels, and ~29 h (~48 h) for 3 km nonhydrostatic simulation with 23 (50) levels using 360 cores (on ECMWF Cray machine).

[4] Use all available observations, and experience from the NWP community over your domain. With RegCM able to work in the 1km-10km range, we can revisit NWP test cases (except those where data assimilation is important). As soon as you have confidence model is able to reproduce e.g. main flow types over your domain, long climate runs can be sent to queue.

DHMZ

This work was partly supported by the Croatian Science Foundation under the project 2831 (CARE).

Take-home message:

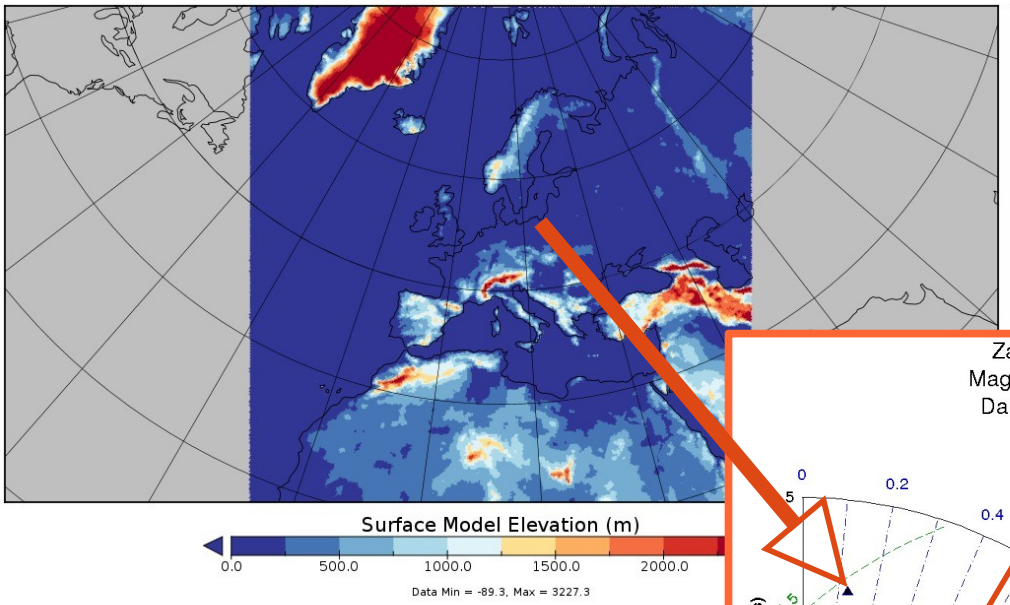
What is the impact of the change from the hydrostatic to nonhydrostatic core in RegCM4?

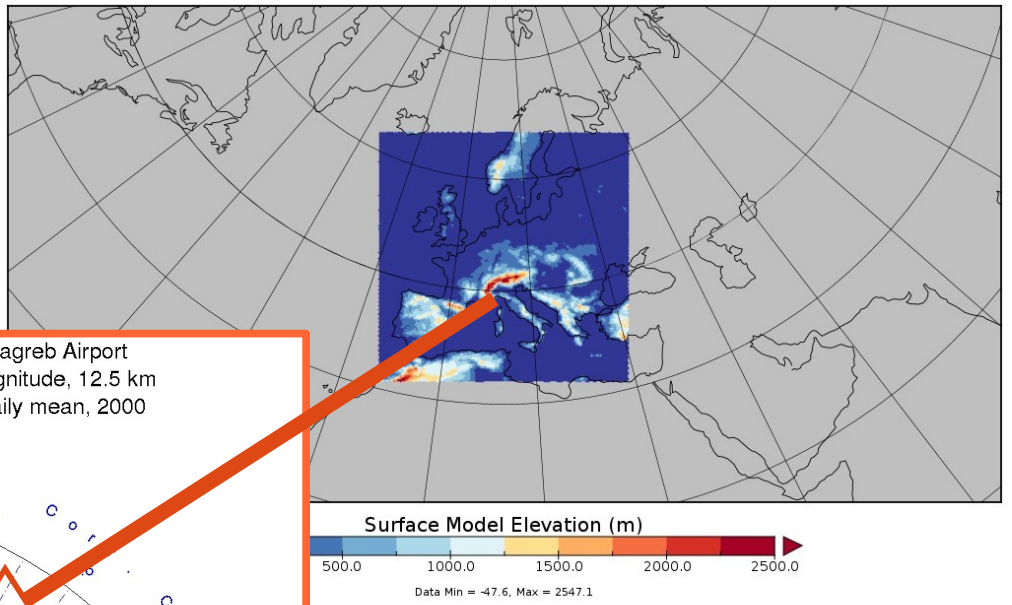
Optimist: it gets better
Pessimist: it gets worse
Realist: it is what it is
Academic: it depends

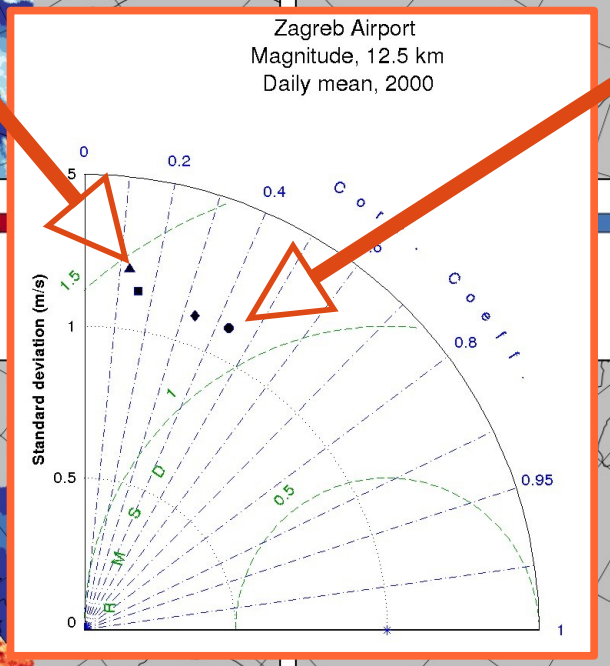
Thank you for your attention!

https://en.wikipedia.org/wiki/Bora_(wind)#/media/File:Winter_bora_in_Senj.jpg

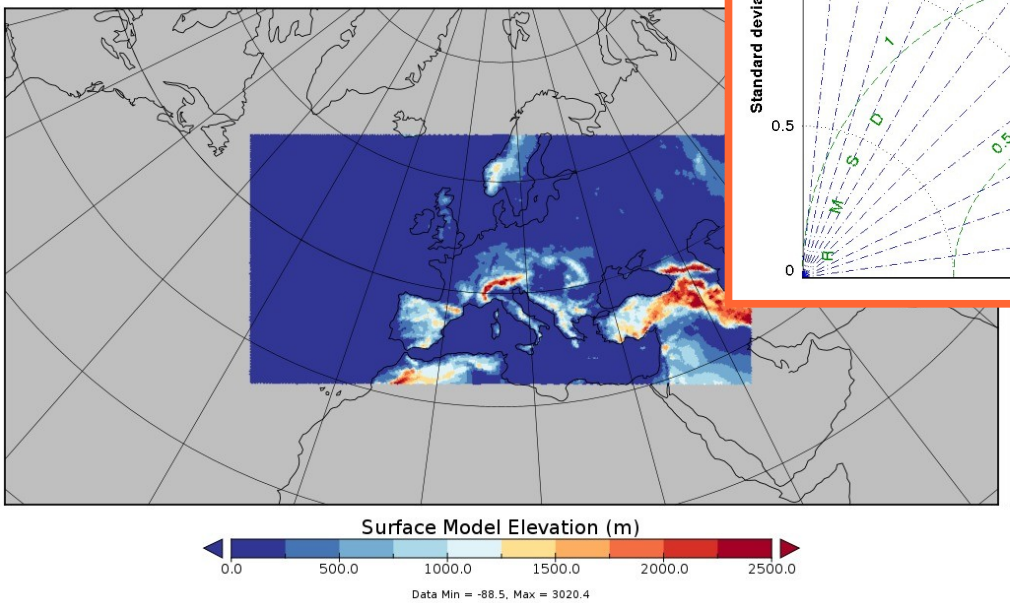
Bonus slide 1: sensitivity to the domain size (RegCM4.2+ERAInterim, 12.5km)

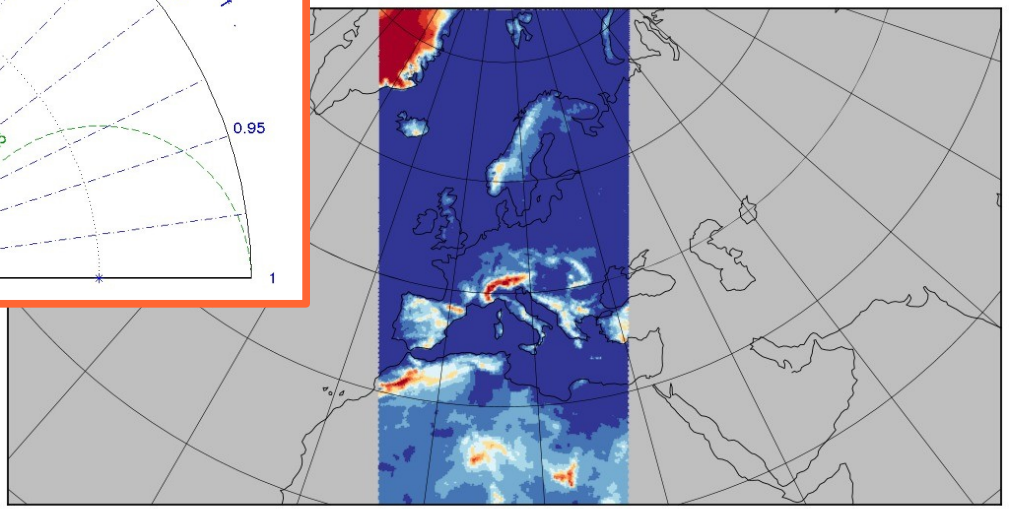






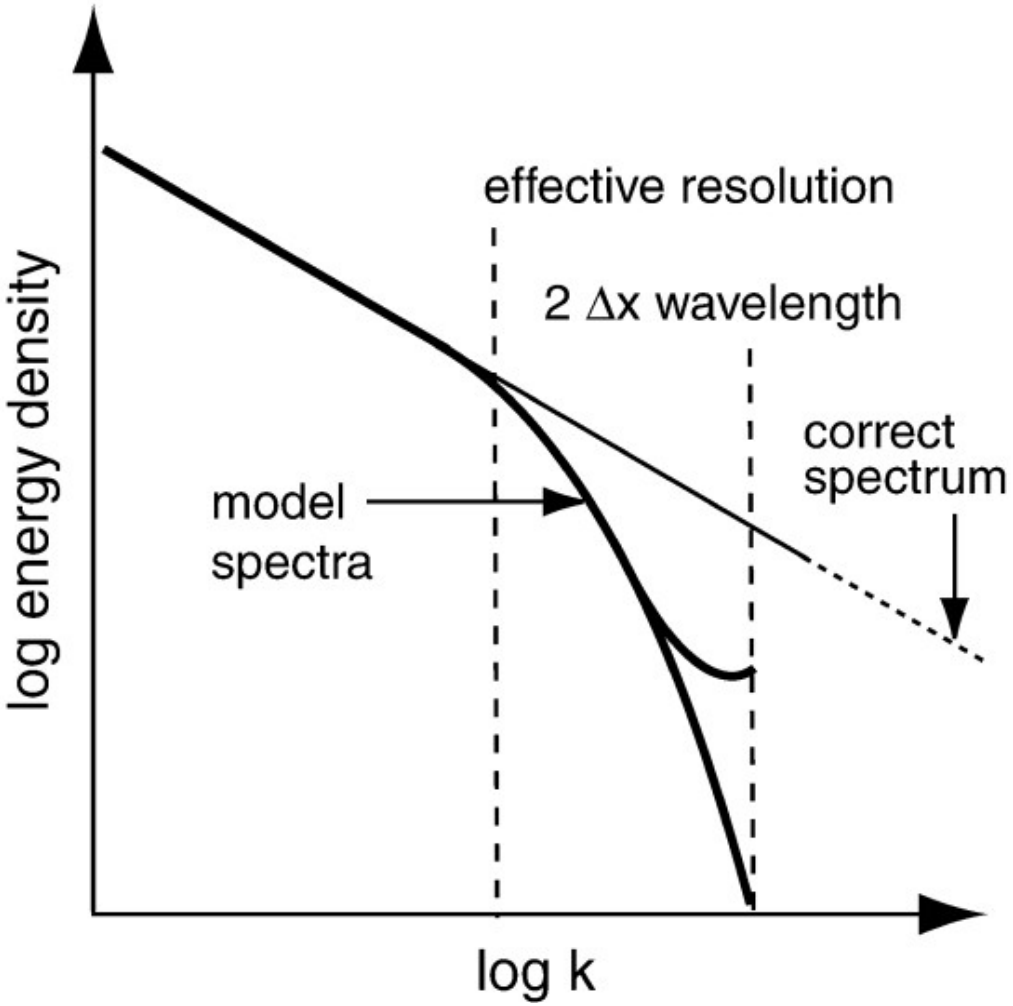
Surface Model Elevation

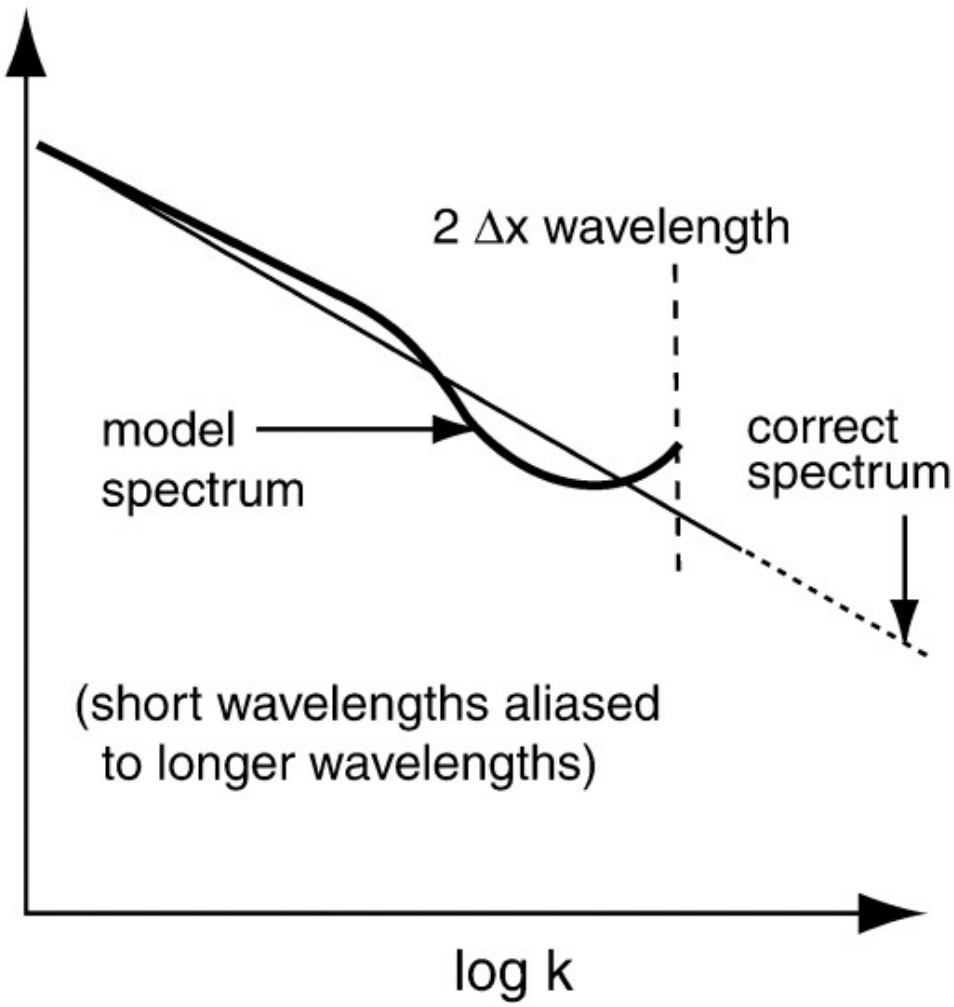




Belušić et al. (*in preparation*)

Bonus slide 2: effective resolution ≠ 2 dx





Skamarock (2004, *MWR*)

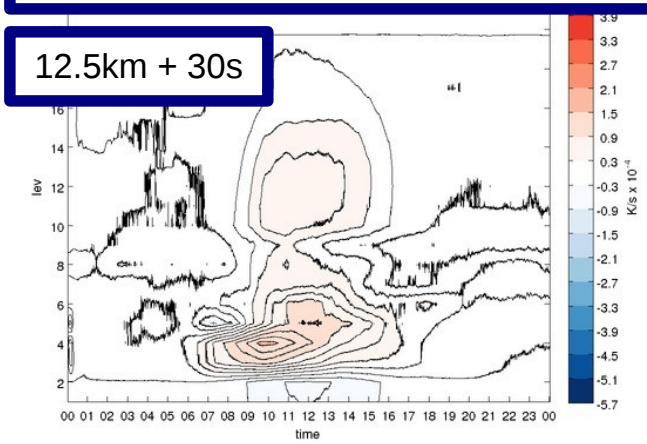
Bonus slide 3: MIT sensitive to *dt*

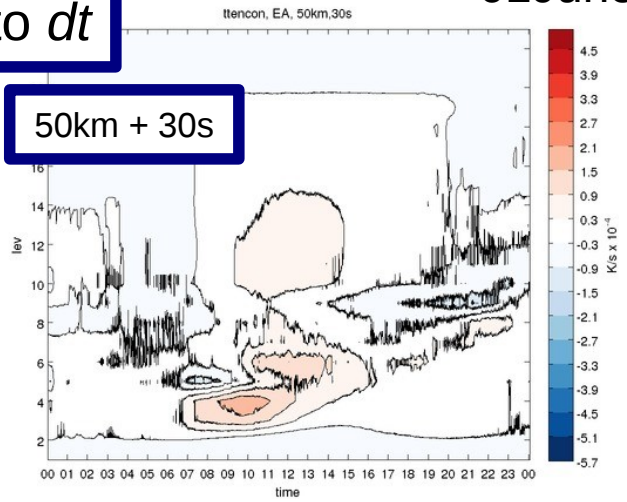
01June1989: RegCM4(MIT)+ERAInterim

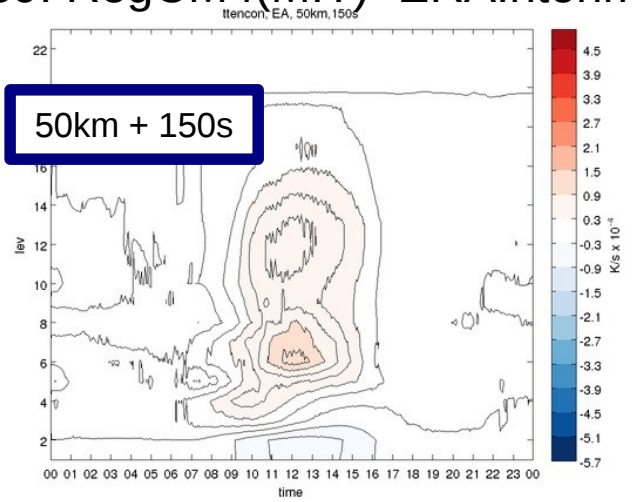
12.5km + 30s

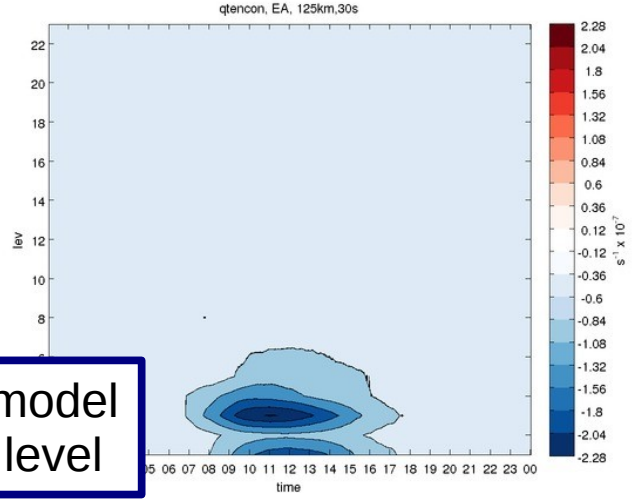
50km + 30s

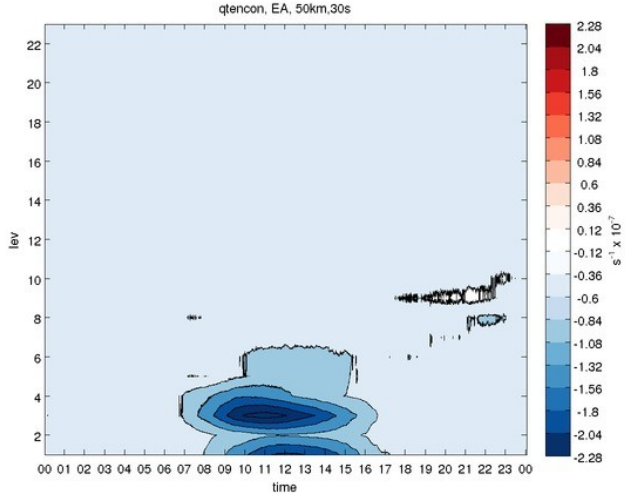
50km + 150s

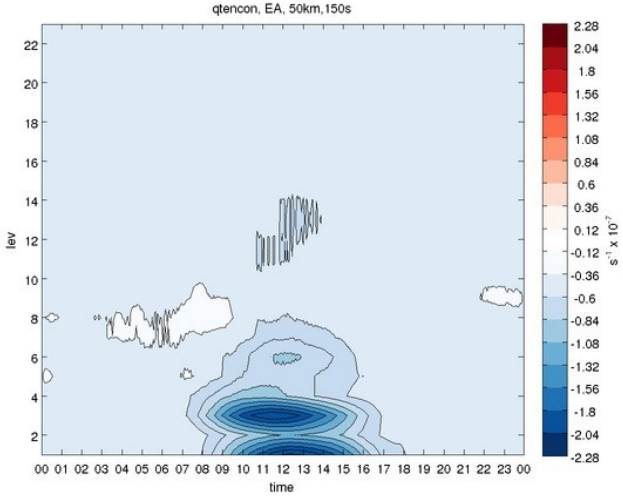




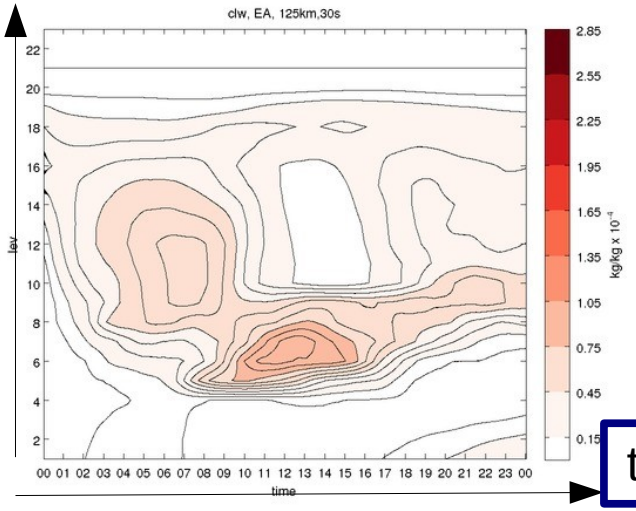


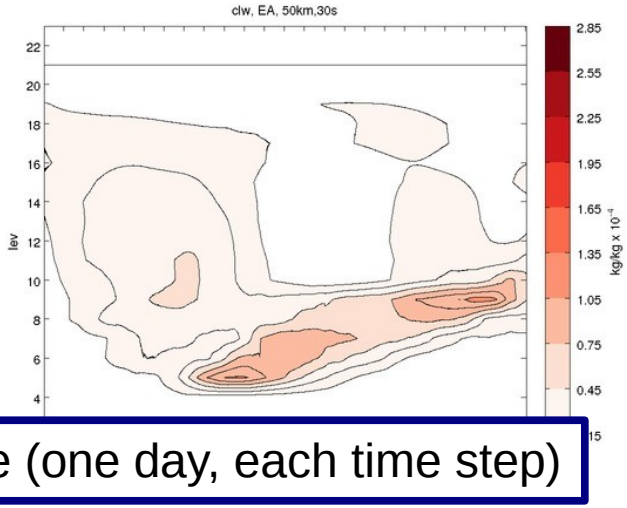


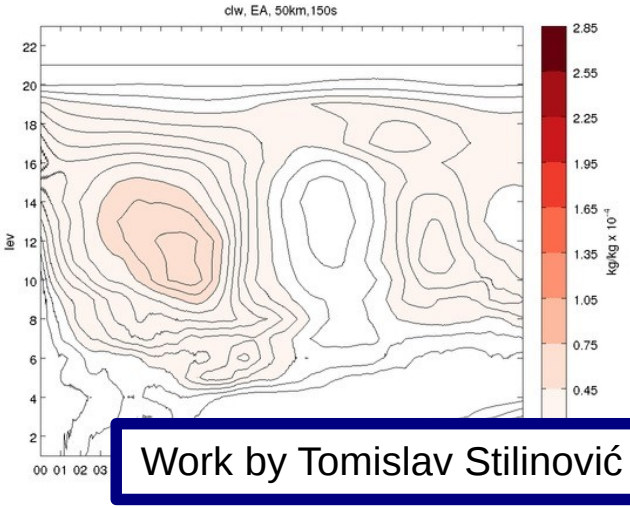




model level







time (one day, each time step)

Work by Tomislav Stilinović

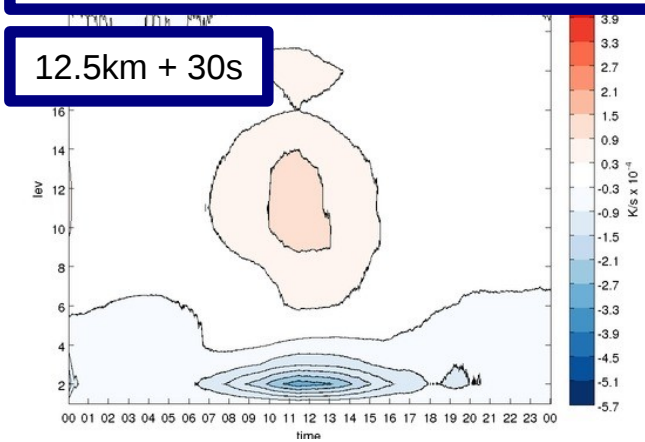
Bonus slide 3: MIT sensitive to *dt*

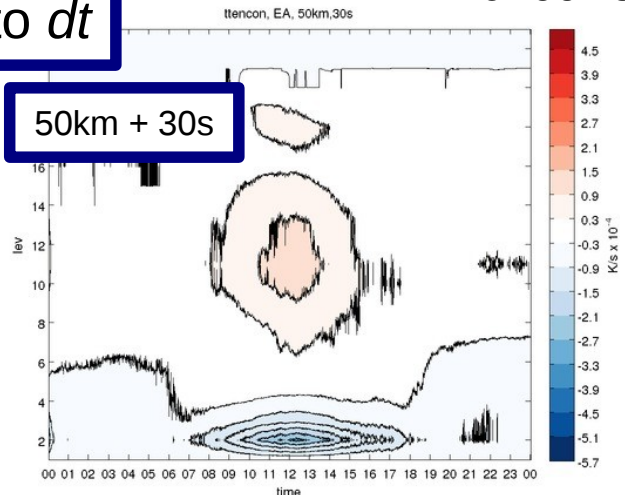
01June1989: RegCM4(Grell)+ERAInterim

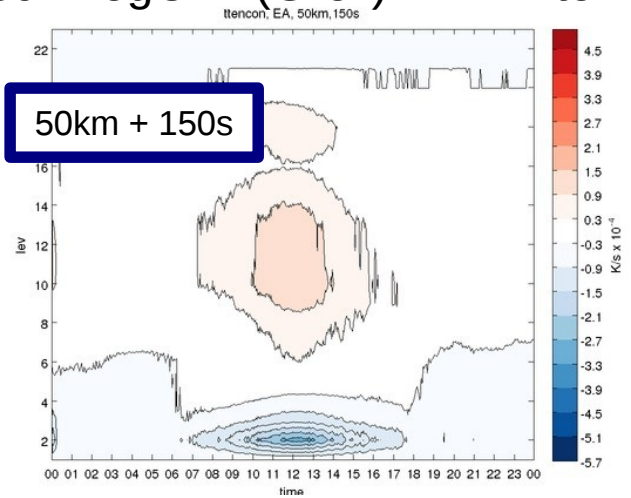
12.5km + 30s

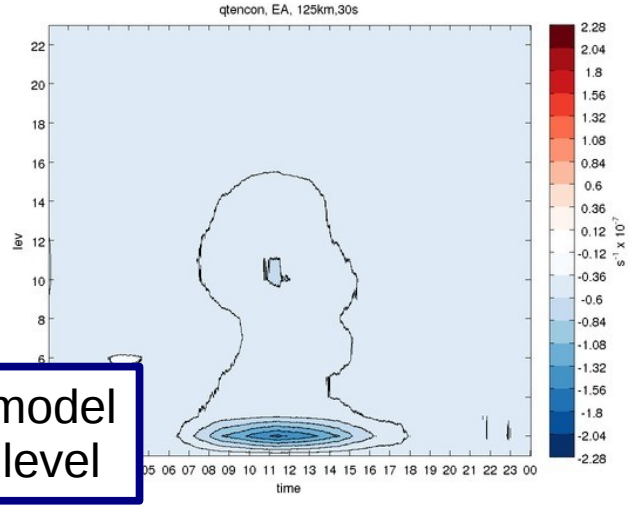
50km + 30s

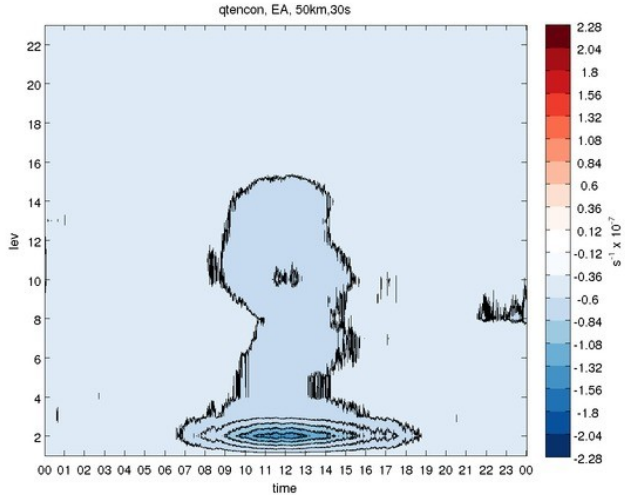
50km + 150s

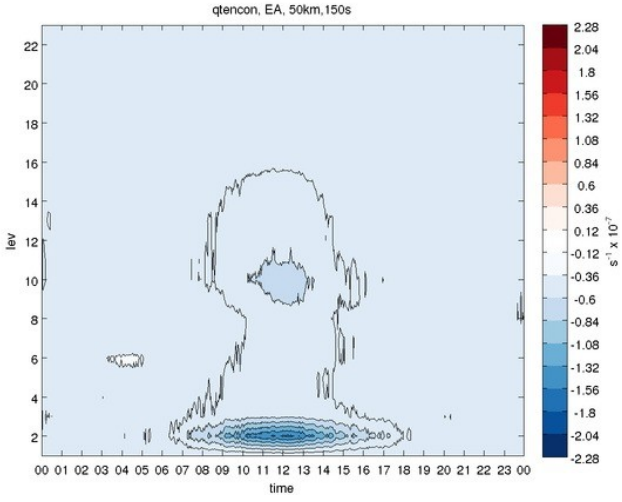




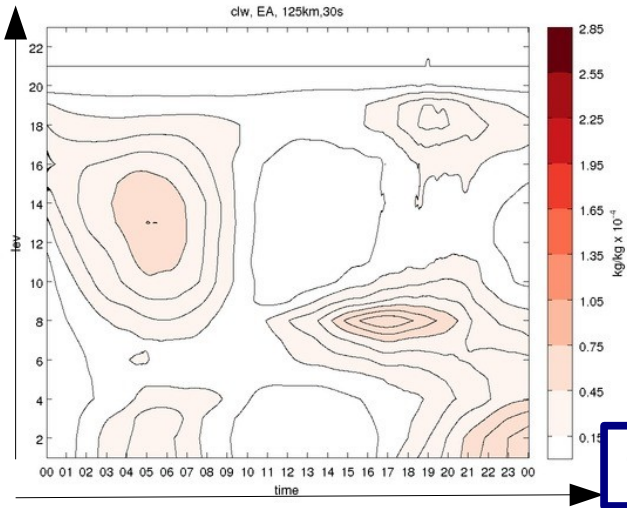


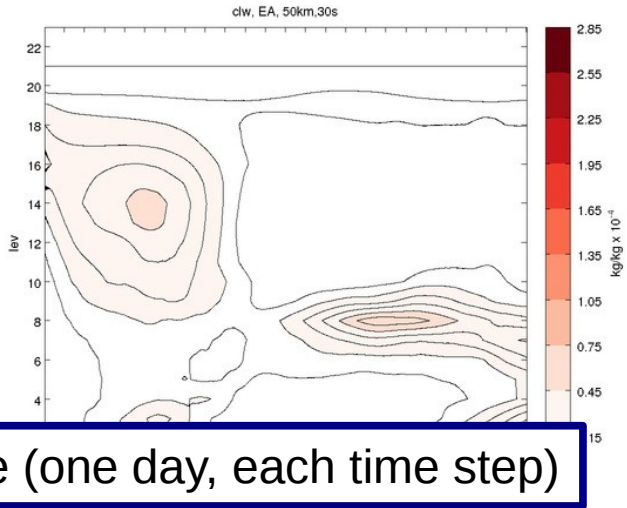


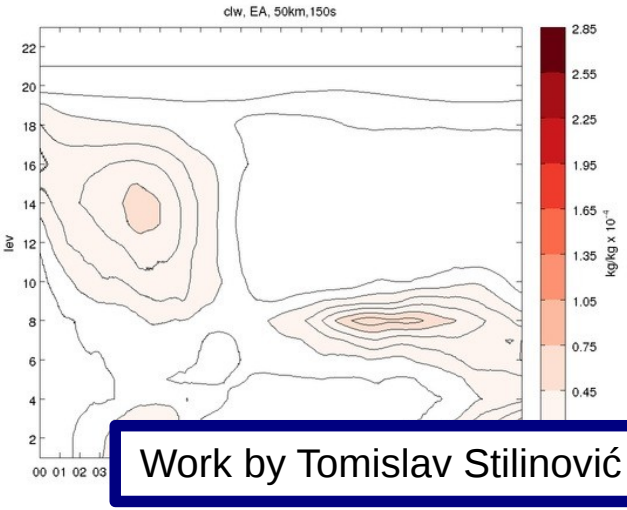




model level







time (one day, each time step)

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