Non-Hydrostatic RegCM4 (RegCM4-NH): Model description and case studies over multiple domains.

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Abstract

We describe the development of a non-hydrostatic version of the regional climate model RegCM4, called RegCM4-NH, for use at convection-permitting resolutions. The non-hydrostatic dynamical core of the Mesoscale Model MM5 is introduced in the RegCM4, with some modifications to increase stability and applicability of the model to long-term climate simulations. Newly available explicit microphysics schemes are also described, and three case studies of intense convection events are carried out in order to illustrate the performance of the model. They are all run at convection-permitting grid spacing of 3 km over domains in northern California, Texas and the Lake Victoria region, without the use of parameterized cumulus convection. A substantial improvement is found in several aspects of the simulations compared to corresponding coarser resolution (12 km) runs completed with the hydrostatic version of the model employing parameterized convection. RegCM4-NH is currently being used in different projects for regional climate simulations at convection-permitting resolutions, and is intended to be a resource for users of the RegCM modeling system.

Keywords:

Regional climate models; RegCM4; km-scale resolution; climate change

Introduction

Since the pioneering work of Dickinson et al. (1989) and Giorgi and Bates (1989), documenting the first regional climate modeling system (RegCM, version 1) in literature, the dynamical downscaling technique based on limited area Regional Climate Models (RCMs) has been widely used worldwide, and a number of RCM systems have been

developed (Giorgi 2019). RegCM1 (Dickinson et al., 1989, Giorgi and Bates, 1989) was originally developed at the National Center for Atmospheric Research (NCAR) based on the Mesoscale Model version 4 (MM4) (Anthes et al, 1987). Then, further model versions followed: RegCM2 (Giorgi et al. 1993a,b), RegCM2.5, (Giorgi and Mearns 1999), RegCM3 (Pal et al. 2007), and lastly RegCM4 (Giorgi et al 2012). Except for the transition from RegCM1 to RegCM2, in which the model dynamical core was updated from that of the MM4 to that of the MM5 (Grell et al. 1995), these model evolutions were mostly based on additions of new and more advanced physics packages. RegCM4 is today used by a large community for numerous projects and applications, from process studies to paleo and future climate projections, including participation in the Coordinated Regional Downscaling EXperiment (CORDEX, Giorgi et al. 2009; Gutowski et al. 2016). The model can also be coupled with ocean, land and chemistry/aerosol modules in a fully interactive way (Sitz et al. 2017).

The dynamical core of the standard version of RegCM4 is hydrostatic, with sigma-p vertical coordinates. As a result, the model can be effectively run for grid spacings of ~10 km or larger, for which the hydrostatic assumption is valid. However, the RCM community is rapidly moving to higher resolutions of a few km, i.e. "convection-permitting" (Prein et al. 2015; Coppola et al. 2020) and therefore the dynamical core of RegCM4 has been upgraded to include a non-hydrostatic dynamics representation usable for very high resolution applications. This upgrade, which we name RegCM4-NH, is essentially based on the implementation of the MM5 non-hydrostatic dynamical core within the RegCM4 framework, which has an entirely different set of model physics compared to MM5.

RegCM4-NH is already being used in some international projects focusing on climate simulations at convection-permitting km-scales, namely the European Climate Prediction System (EUCP, Hewitt and Lowe 2018) and the CORDEX Flagship Pilot Study dedicated to convection (CORDEX-FPSCONV, Coppola et al. 2020), and it is starting to be used more broadly by the RegCM modeling community. For example, the recent papers by Ban et al. (2021) and Pichelli et al. (2021) document results of the first multi-model experiment of 10-year simulations at the convection-permitting scales over the so-called greater Alpine region. Two different simulations with RegCM4-NH for present day conditions have contributed to the evaluation analysis of Ban et al. (2021). They were carried out at the International Centre for Theoretical Physics (ICTP) and the Croatian Meteorological and Hydrological Service (DHMZ) using two different physics configurations. The results show that RegCM4-NH largely improves the precipitation simulation as compared to available fine scale observations when going from coarse to high resolution, in particular for higher order statistics, such as precipitation extremes and hourly intensity. Pichelli et al. (2021) then analyse multi-model ensemble simulations driven by selected CMIP5 GCM projections for the decades 1996–2005 and 2090–2099 under the RCP8.5 scenario. ICTP contributed to the experiment with

simulations using RegCM4-NH driven by the MOCH-HadGEM GCM (r1i1p1) in a two level nest configuration (respectively at 12 and 3 km grid). The paper shows new insights into future changes, for example an enhancement of summer and autumn hourly rainfall intensification compared to coarser resolution model experiments, as well as an increase of frequency and intensity of high-impact weather events.

In this paper we describe the structure of RegCM4-NH and provide some illustrative examples of its performance, so that model users can have a basic reference providing them with background information on the model. In the next section we first describe the new model dynamical core, while the illustrative applications are presented in section 4. Section 5 finally provides some discussion of future developments planned for the RegCM system.

Model description

In the development of RegCM4-NH, the RegCM4 as described by Giorgi et al. (2012) was modified to include the non-hydrostatic dynamical core (*idynamic* = 2 namelist option as described in RegCM-4.7.1/Doc/README.namelist of the source code) of the mesoscale model MM5 (Grell et al. 1995). This dynamical core was selected because RegCM4 already has the same grid and variable structure as MM5 in its hydrostatic core, which substantially facilitated its implementation (Elguindi et al. 2017).

The model equations with complete description of the Coriolis force and a top radiative boundary condition, along with the finite differencing scheme, are given in Grell et al. (1995). Pressure, p, temperature, T, and density, ϱ, are first decomposed into a prescribed reference vertical profile plus a time varying perturbation. The prognostic equations are then calculated using the pressure perturbation values. Compared to the original MM5 dynamical core, the following modifications were implemented in order to achieve increased stability for long term climate simulations (Elguindi et al. 2017 document any modifications which follow the choice of the non-hydrostatic dynamical core through the namelist parameter *idynamic* = 2; further available user-dependant options, and the corresponding section in the namelist, are explicitly indicated):

i) The reference state temperature profile is computed using a latitude dependent climatological temperature distribution and thus is a function of the specific domain coordinates (*base_state_pressure*, *logp_lrate* parameters in *&referenceatm*) (Elguindi et al. 2017). These two parameters were hard-coded in the original MM5 while for the RegCM are user configurable;

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234 ii) The lateral time dependent boundary conditions (*iboudy* in *&physicsparam*) for each
235 prognostic variable use the same exponential relaxation technique (*iboudy* = 5) described
236 in Giorgi et al. (1993). The linear MM5 relaxation scheme is also kept as an option (*iboudy*
237 = 1);

238

239 iii) The advection term in the model equations, which in the MM5 code is implemented
240 using a centered finite difference approach, was changed to include a greater upstream
241 weight factor as a function of the local Courant number (Elguindi et al. 2017). The
242 maximum value of the weight factor is user configurable (*uoffc* in *&dynparam*). As detailed
243 in the MM5 model description (Grell et al, 1995), the horizontal advection term for a scalar
244 variable X contributes to the total tendency as:

245

$$\Delta_{adv}\left(p^*X\right)_G = -m^2|_G\left[\frac{\left(p^*X|_b\frac{u}{m}|_b - p^*X|_a\frac{u}{m}|_a\right)}{dx} + \frac{\left(p^*X|_d\frac{v}{m}|_d - p^*X|_c\frac{v}{m}|_c\right)}{dy}\right]$$

246

247

248 where the m is the projection mapping factor and, with respect to Figure 1, assuming that
249 the computation is to be performed for the gold cross point G, the averages are performed
250 in the points a, b, c, d. For the u/m and v/m terms, the average value is computed using
251 respectively the values in points AC, BD, CD, AB.

252 In RegCM4 for the term p^*X, the model computes a weighted average value of the field
253 using the value in gold+cyan and gold+green cross points with weights increasing the
254 relative contribution of the upstream point up as a function of the local courant number:

255

256 $p^*X|_a = 0.5((1-f_1)p^*X|_G + (1+f_1)p^*X|_{c_1})$
257 $p^*X|_b = 0.5((1-f_1)p^*X|_{c_2} + (1+f_1)p^*X|_G)$
258 $p^*X|_c = 0.5((1-f_2)p^*X|_G + (1+f_2)p^*X|_{g_1})$
259 $p^*X|_d = 0.5((1-f_2)p^*X|_{g_2} + (1+f_2)p^*X|_G)$
260 where f_1, f_2 are defined as the local Courant number for the 1D advection equations
261 multiplied for a control factor:

262

263 $f_1 = \mu_{fc}dt\dfrac{(u|_a + u|_b)}{2dx}$

264 $f_2 = \mu_{fc}dt\dfrac{(v|_c + v|_d)}{2dy}$;

265

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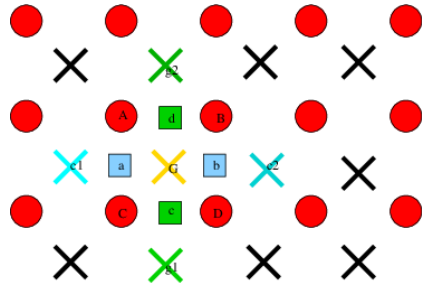
267
268 **Figure 1 Schematic representation showing the horizontal advection scheme**
269 **staggering. Circles are U,V points. X are scalar variable points.**
270
271
272
273 iv) The water species (cloud, ice,rain, snow) term uses the same advection scheme as

274 the other variables (Elguindi et al. 2017) and not a complete upstream scheme as in the
275 MM5 code (Grell et al. 1995);
276
277 v) A local flux limiter reduces the advection terms in order to remove unrealistic strong
278 gradients and its limits are user configurable (in the *&dynparam* section the maximum
279 gradient fraction for advection; temperature, *t_extrema*, specific humidity, *q_rel_extrema*,

280 liquid cloud content, *c_rel_extrema* and for tracers, *t_rel_extrema*). This was hardcoded
281 in the MM5 code and the limits were not user configurable;
282
283 vi) The diffusion stencil of the Laplace equation uses a nine point approach as in LeVeque
284 (2006) and a topography dependent environmental diffusion coefficient is added to

285 reduce spurious diffusion along pressure coordinate slopes (Elguindi et al. 2017) as in
286 the hydrostatic version of the code (Giorgi et al. 1993b). The change in stencil does not
287 affect the overall fourth order precision of the model, but reduces the computational
288 stencil size, thus reducing the communication overhead;
289
290 vii) The top boundary radiative condition (*ifupr* = 1 in *&nonhydroparam*) adopted in the
291 semi-implicit vertical differencing scheme to reduce the reflection of energy waves uses
292 coefficients on a 13x13 matrix which are re-computed every simulation day and not kept
293 constant throughout the whole simulation as in the MM5 code. This allows the model to
294 be run for longer simulation times while not being strongly tied to the intial atmospheric
295 conditions;
296

300   viii) The dynamical control parameter β in the semi-implicit vertical differencing scheme
301   (*nhbet* in *&nonhydroparam*) used for acoustic wave damping (Elguindi et al. 2017) is user
302   configurable (Klemp and Dudhia, 2008), while it is hard-coded in the MM5;
303
304   ix) A Rayleigh damping (*ifrayd* = 1 in *&nonhydroparam*) of the status variables towards
305   the input GCM boundary conditions can be activated in the top layers (*rayndamp*
306   configuring the number of top levels to apply) with a configurable relaxation time
307   (*rayalpha0*, Klemp and Lilly, 1978, Durran and Klemp, 1983. This is consistent to what is
308   implemented in the WRF model);
309
310   x) The water species time filtering uses the Williams (2009) modified filter with α = 0.53
311   instead of the RA filter used by all the other variables. The ν factor in the RA filter is user
312   configurable (*gnu1* and *gnu2* in *&dynparam*). This reduces the damping introduced by the
313   Robert-Asselin filter and the computational diffusion introduced by the horizontal
314   advection scheme.
315
316   With these modifications, the model basic equations, under leap-frog integration scheme,
317   are (Elguindi et al. 2017) :
318
319

$$\frac{\partial p^* u}{\partial t} = -m^2 \left[\frac{\partial p^* uu/m}{\partial x} + \frac{\partial p^* vu/m}{\partial y} \right] - \frac{\partial p^* u\dot{\sigma}}{\partial \sigma} + uDIV -$$
$$\frac{mp^*}{\rho} \left[\frac{\partial p'}{\partial x} - \frac{\sigma}{p^*} \frac{\partial p^*}{\partial x} \frac{\partial p'}{\partial \sigma} \right] + p^* fv - p^* ew \cos\theta + D_u \qquad (1)$$

320
321

$$\frac{\partial p^* v}{\partial t} = -m^2 \left[\frac{\partial p^* uv/m}{\partial x} + \frac{\partial p^* vv/m}{\partial y} \right] - \frac{\partial p^* v\dot{\sigma}}{\partial \sigma} + vDIV -$$
$$\frac{mp^*}{\rho} \left[\frac{\partial p'}{\partial y} - \frac{\sigma}{p^*} \frac{\partial p^*}{\partial y} \frac{\partial p'}{\partial \sigma} \right] - p^* fu + p^* ew \sin\theta + D_v \qquad (2)$$

322
323

$$\frac{\partial p^* w}{\partial t} = -m^2 \left[\frac{\partial p^* uw/m}{\partial x} + \frac{\partial p^* vw/m}{\partial y} \right] - \frac{\partial p^* w\dot{\sigma}}{\partial \sigma} + wDIV +$$
$$p^* g \frac{\rho_0}{\rho} \left[\frac{1}{p^*} \frac{\partial p'}{\partial \sigma} + \frac{T'_v}{T} - \frac{T_0 p'}{T p_0} \right] - p^* g \left[(q_c + q_r) \right] + p^* e (u\cos\theta - v\sin\theta) + D_w \quad (3)$$

324
325

$$\frac{\partial p^* p'}{\partial t} = -m^2 \left[\frac{\partial p^* up'/m}{\partial x} + \frac{\partial p^* vp'/m}{\partial y} \right] - \frac{\partial p^* p'\dot{\sigma}}{\partial \sigma} + p'DIV -$$
$$m^2 p^* \gamma p \left[\frac{\partial u/m}{\partial x} - \frac{\sigma}{mp^*} \frac{\partial p^*}{\partial x} \frac{\partial u}{\partial \sigma} + \frac{\partial v/m}{\partial y} - \frac{\sigma}{mp^*} \frac{\partial p^*}{\partial y} \frac{\partial v}{\partial \sigma} \right] + \rho_0 g \gamma p \frac{\partial w}{\partial \sigma} + p^* \rho_0 g \quad (4)$$

326

332

$$\frac{\partial p^* T}{\partial t} = -m^2 \left[\frac{\partial p^* u T/m}{\partial x} + \frac{\partial p^* v T/m}{\partial y} \right] - \frac{\partial p^* T \dot{\sigma}}{\partial \sigma} + TDIV +$$

$$\frac{1}{\rho c_p} \left[p^* \frac{Dp'}{Dt} - \rho_0 g p^* w - D_{p'} \right] + p^* \frac{\dot{Q}}{c_p} + D_T \qquad (5)$$

333
334
335   Where:

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

336

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

337

$$\tan \theta = -\cos \phi \frac{\partial \lambda/\partial y}{\partial \phi/\partial x}$$

338

$$p(x,y,z,t) = p_0(z) + p'(x,y,z,t)$$
$$T(x,y,z,t) = T_0(z) + T'(x,y,z,t)$$
$$\rho(x,y,z,t) = \rho_0(z) + \rho'(x,y,z,t)$$

339
340
341   with the vertical sigma coordinate defined as:
342

$$\sigma = \frac{(p_0 - p_t)}{(p_s - p_t)}$$

343
344
345   where p_s is the surface pressure and p_0 is the reference pressure profile. The total
346   pressure
347   at each grid point is thus given as:
348
349    $$p(x,y,z,t) = p^* \sigma(k) + p_t + p'(x,y,z,t)$$
350
351   With p_t being the top model pressure assuming a fixed rigid lid.

The model physics schemes for boundary layer, radiative transfer, land and ocean surface processes, cloud and precipitation processes are extensively described in Giorgi et al. (2012) and summarized in Table 1. For each physics component a number of parameterization options are available (Table 1), and can be selected using a switch selected by the user. As mentioned, the use of non-hydrostatic dynamics is especially important when going to convection-permitting resolutions of a few km (Prein et al. 2015). At these resolutions the scale separation assumption underlying the use of cumulus convection schemes is not valid any more, and explicit cloud microphysics representations are necessary. The RegCM4 currently includes two newly implemented microphysics schemes, the Nogherotto-Tompkins (Nogherotto et al. 2016) and the WSM5 scheme from the Weather Research Forecast (WRF, Skamarok et al. 2008) model, which are briefly described in the next sections for information to model users.

Model physics (Namelist flag)	Options	n. option	Reference
Dynamical core (idynamic)	Hydrostatic	1	Giorgi et al. 1993a,b Giorgi et al. 2012
	Non-Hydrostatic (*)	2	present paper
Radiation (irrtm)	CCSM	0	Kiehl et al. 1996
	RRTM (*)	1	Mlawer et al. 1997
Microphysics (ipptls)	Subex	1	Pal et al 2000
	Nogherotto Thompkins	2	Nogherotto et al. 2016
	WSM5 (*)	3	Hong et al 2004
Cumulus (icup)	Kuo	1	Anthes et al. 1987
	Grell	2	Grell 1993
	Emanuel	4	Emanuel 1991
	Tiedtke	5	Tiedtke 1989, 1993

	Kain-Fritsch	6	Kain and Fritsch, 1990; Kain 2004
	MM5 Shallow cumulus (only mixing) (*)	-1	Grell et al. 1994
Planetary Boundary Layer (ibltyp)	Modified-Holtslag	1	Holtslag et al., 1990
	UW	2	Bretherton et al. 2004
Land Surface (code compiling option)	BATS	/	Dickinson et al. 1993; Giorgi et al. 2003
	CLM4.5	/	Oleson et al. 2013
Ocean Fluxes (iocnflx)	BATS	1	Dickinson et al. 1993
	Zeng	2	Zeng et al. 1998
	COARE	3	Fairall et al. 1996a,b
Interactive lake (lakemod)	1D diffusion/convection	1	Hostetler et al. 1993
Tropical band (i_band)	RegT-Band	1	Coppola et al. 2012
Coupled ocean (iocncpl)	RegCM-ES	1	Sitz et al. 2017

370 **Table 1 Core and sub-grid physics scheme available in RegCM-NH. New schemes**
371 **available with this release are starred (*).**

372

373

374 **Explicit microphysics schemes:**

375

376 *Nogherotto-Tompkins Scheme:*

377 A new parameterization for explicit cloud microphysics and precipitation built upon the
378 European Centre for Medium Weather Forecast's Integrated Forecast System (IFS)
379 module (Tiedtke, 1993, Tompkins, 2007), was introduced in RegCM4 (*ipptls* = 2 in
380 *µparam*) by Nogherotto et al. (2016). In the present configuration, the scheme
381 implicitly solves 5 prognostic equations for water vapor, q_v, cloud liquid water, q_l, rain, q_r,
382 cloud ice, q_i, and snow, q_s, but it is also easily extendable to a larger number of variables.
383 Water vapor, cloud liquid water, rain, cloud ice and snow are all expressed in terms of the
384 grid-mean mixing ratio.

385 Cloud liquid and ice water content are independent, allowing the existence of supercooled
386 liquid water and mixed-phase clouds. Rain and snow precipitate with a fixed terminal fall
387 speed and can then be advected by the three dimensional winds. A check for the
388 conservation of enthalpy and of total moisture is ensured at the end of each timestep. The
389 governing   equation   for   each   variable   is:
390

$$\frac{\partial q_x}{\partial t} = S_x + \frac{1}{\rho}\frac{\partial}{\partial z}(\rho V_x q_x)$$

391
392

393 The local variation of the mixing ratio q_x of the variable x is given by the sum of S_x,
394 containing the net sources and sinks of q_x through microphysical processes (i.e.
395 condensation, evaporation, auto-conversion, melting, etc.), and the sedimentation term,
396 which is a function of the fall speed V_x . An upstream approach is employed to solve the
397 equations. The sources and sinks contributors are divided in two groups according to the
398 duration of the process they describe: processes that are considered to be fast relative to
399 the model time step are treated implicitly while slow processes are treated explicitly. The
400 processes taken into account (shown in Figure 2) are the microphysical pathways across
401 the 5 water variables: condensation, autoconversion, evaporation, cloud water collection
402 (accretion), and autoconversion for warm clouds, and freezing, melting, deposition,
403 sublimation for cold clouds.

404

412
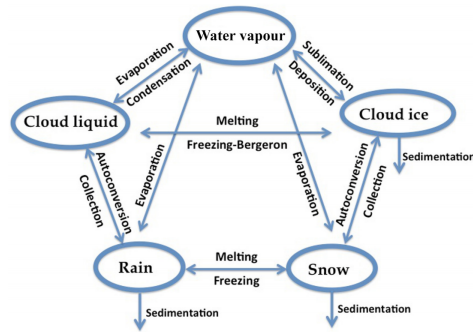
Figure 2: Depiction of the new scheme, showing the five prognostic variables and how they are related to each other through microphysical processes

415 For each microphysical pathway, phase changes are associated with the release or
416 absorption of latent heat, which then impacts the temperature budget. The impact is
417 calculated using the conservation of liquid water temperature TL defined as:
418

$$T_L = T - \frac{L_v}{C_p}(q_l + q_r) - \frac{L_s}{C_p}(q_i + q_s).$$

419

420 Given that dTL =0, the rate of change of the temperature is given by the following
421 equation:
422

$$\frac{\partial T}{\partial t} = \sum_{x=1}^{m} \frac{L(x)}{C_p}\left(\frac{dq_x}{dt} - D_{q_x} - \frac{1}{\rho}\frac{\partial}{\partial z}(\rho V_x q_x)\right)$$

423
424

425 where $L(x)$ is the latent heat of fusion or evaporation, depending on the process
426 considered, Dqx is the convective detrainment and the third term in brackets is the
427 sedimentation term.

428 At the end of each time step a check is carried out of the conservation of total water and
429 moist static energy: $h = C_P T + gz + Lq_x.$

430 The scheme is tunable through parameters in the *µparam* section of the namelist
431 (RegCM-4.7.1/Doc/README.namelist; Elguindi et al. 2017).

WSM5 Scheme:

433

434 RegCM4-NH also employs the Single-Moment 5-class microphysics scheme of the WRF
435 model (Skamarock et al., 2008). This scheme (*ipptls* = 3 in *µparam*) follows Hong
436 et al. (2004) and, similarly to Nogherotto et al. (2016), includes vapor, rain, snow, cloud
437 ice, and cloud water hydrometeors. The scheme separately treats ice and water
438 saturation processes, assuming water hydrometeors for temperatures above freezing,
439 and cloud ice and snow below the freezing level (Dudhia, 1989, Hong et al., 1998). It
440 accounts for supercooled water and a gradual melting of snow below the melting layer
441 (Hong et al., 2004, and Hong and Lim, 2006). Therefore, the WSM5 and Nogherotto-
442 Tompkins schemes have similar structures (Figure 2), but also important differences.

443 Differently from the Nogherotto-Tompkins scheme, the WSM5 (as well as the other WSM
444 schemes in WRF) prescribes an inverse exponential continuous distribution of particle
445 size (ex. Marshall and Palmer (1948) for rain, Gunn and Marshall (1958) for snow). It also
446 includes the size distribution of ice particles and, as a major novelty, the definition of the
447 number of ice crystals based on ice mass content rather than temperature. Both the
448 Nogherotto-Tompkins and WSM5 schemes include autoconversion, i.e. sub-time step
449 processes of conversion of cloud water to rain and cloud ice to snow. For rain, Hong et
450 al. (2004) use a Kessler (1969) type algorithm in WSM5, but with a stronger physical basis
451 following Tripoli and Cotton (1980). The Nogherotto-Tompkins scheme also includes the
452 original Kessler (1969) formula as an option, but it makes available other three
453 exponential approaches following Sundqvist et al. (1989), Beheng (1994), and
454 Khairoutdinov and Kogan (2000). For ice autoconversion the Nogherotto-Tompkins
455 scheme uses an exponential approach (Sundqvist, 1989) with a specific coefficient for ice
456 particles (following Lin et al., 1983) depending on temperature, while the WSM5 uses a
457 critical value of ice mixing ratio (depending on air density) and a maximum allowed ice
458 crystal mass (following Rutledge and Hobbs, 1983) that suppresses the process at low
459 temperatures because of the effect of air density. Finally, the WSM5 has no dependency
460 on cloud cover for condensation processes while the Nogherotto-Tompkins scheme uses
461 cloud cover to regulate the condensation rate in the formation of stratiform clouds.

462

Illustrative case studies

464

465 Three case studies (Table 2) of Heavy Precipitation Events (HPE) have been identified in

466 order to test and illustrate the behavior of the non-hydrostatic core of the RegCM4-NH,

467 with focus on the explicit simulation of convection over different regions of the world. In

468 two test cases, California and Lake Victoria, data from the ERA-Interim reanalysis (Dee

471 et al. 2011) are used to provide initial and lateral meteorological boundary conditions for

472 an intermediate resolution run (grid spacing of 12 km, with use of convection

473 parameterizations) (Figure 3), which then provides driving boundary conditions for the

474 convection-permitting experiments. In the Texas case study, however, we nested the

475 model directly in the ERA-Interim reanalysis with boundary conditions provided every 6

476 hours, given that such configuration was able to reproduce accurately the HPE intensity.

477 In this case the model uses a large LBC relaxation zone which allows the description of

478 realistic fine-scale features driving this weather event (even if not fully consistent with the

479 Matte et al. (2017) criteria). All simulations start 24-48 hours before the HPE. The analysis

480 focuses on the total accumulated precipitation over the entire model domain at 3 km

481 resolution (Fig. 3) for the periods defined in Table 2. In the cases of California and Texas

482 the evaluation also includes the time series of 6 hourly accumulated precipitation

483 averaged on the region of maximum precipitation (black rectangles in Figs. 3) against

484 available high temporal resolution observations (NCEP/CPC) (Table 3). The discussion

485 of the case studies is presented in the next sections; the configuration files (namelists)

486 with full settings for the three test cases are available at

487 https://zenodo.org/record/5106399.

488

489 A key issue concerning the use of CP-RCMs is the availability of very high resolution,

490 high quality observed datasets for the assessment and evaluation of the models, which

491 is not there for most of the world regions. Precipitation measurements come from

492 essentially three distinct sources: in-situ rain-gauges, ground radar and satellite. In the

493 present study we use 7 observational datasets depending on the case study and the area

494 covered, as described in Table 2. We have used: Precipitation Estimation from Remotely

495 Sensed Information using Artificial Neural Networks - Climate Data Record (PERSIAN-

496 CDR), Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS), the

497 Climate Prediction Center morphing method (CMORPH), Tropical Rainfall Measuring

498 Mission (TRMM), NCEP/CPC-Four Kilometer Precipitation Set Gauge and Radar

499 (NCEP/CPC), CPC-Unified daily gauge based precipitation estimates (CPC) and

500 Parameter-elevation Regressions on Independent Slopes Model (PRISM) (Table 3).

501 NCEP/CPC is a precipitation analysis which merges a rain gauge dataset with radar

502 estimates. CMORPH and PERSIAN-CDR are based on satellite measurements, CHIRPS

503 incorporates satellite imagery with in-situ station data. CPC is a gauge-based analysis of

504 daily precipitation and the PRISM dataset gathers climate observations from a wide range

520 of monitoring networks, applies sophisticated quality control measures, and develops
521 spatial climate datasets incorporating a variety of modeling techniques at multiple spatial
522 and temporal resolutions.

523

524

Case	ACRONYM	Region of The event	Domains size lon x lat x vertical levels	Simulation Time Window
1	CAL	California	480 x 440 x 41	15 Feb 2004 00:00 19 Feb 2004 00:00
2	TEX	Texas	480 x 440 x 41	9 June 2010 00:00 12 June 2010 00:00
3	LKV	Lake Victoria	550 x 530 x 41	25 Nov 1999 00:00 1 Dec 1999 00:00

525 **Table 2: List of acronyms and description of the test cases with corresponding 3km**

526 **domain sizes and simulation period.**

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Dataset name	Region	Spatial Resolution	Temporal Resolution	Data Source	Reference
TRMM	World	0.5°	Daily	Satellite	Huffman et al. (2007)
CHIRPS	World	0.05°	Daily	Station data+Satellite	Funk et al. (2015)
CMORPH	World	0.25°	Daily	Satellite	Joyce et al.

					(2004)
NCEP/CPC	USA	0.04°	Hourly	Gauge and Radar	https://doi.org/10.5065/D69Z93M3. Accessed: 27/06/2018
CPC	World	0.5°	Daily	Station data	Chen and Xie (2008)
PRISM	USA	0.04°	Daily	Station data	PRISM Climate Group. 2016.
PERSIAN-CDR	World	0.25°	Daily	Satellite	Ashouri et al. (2015)

529 **Table 3: List of observed precipitation datasets used for comparison.**

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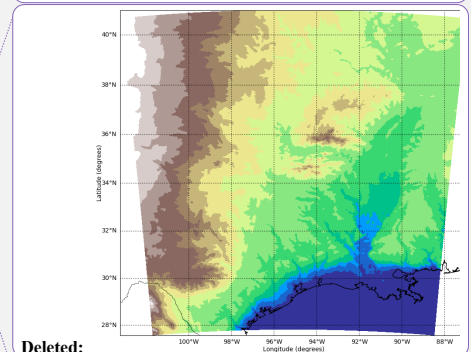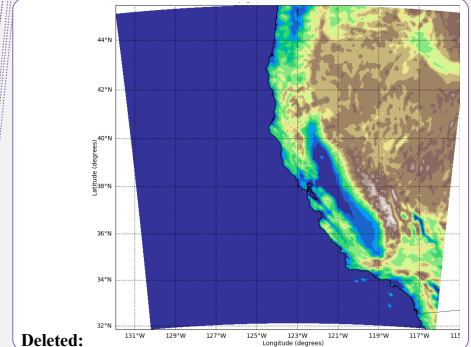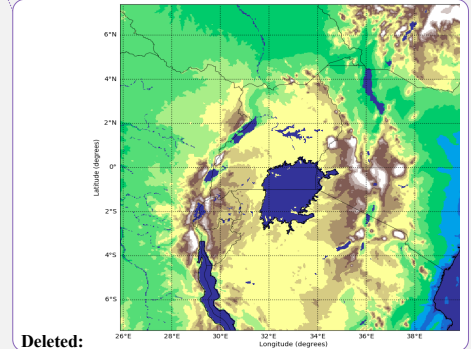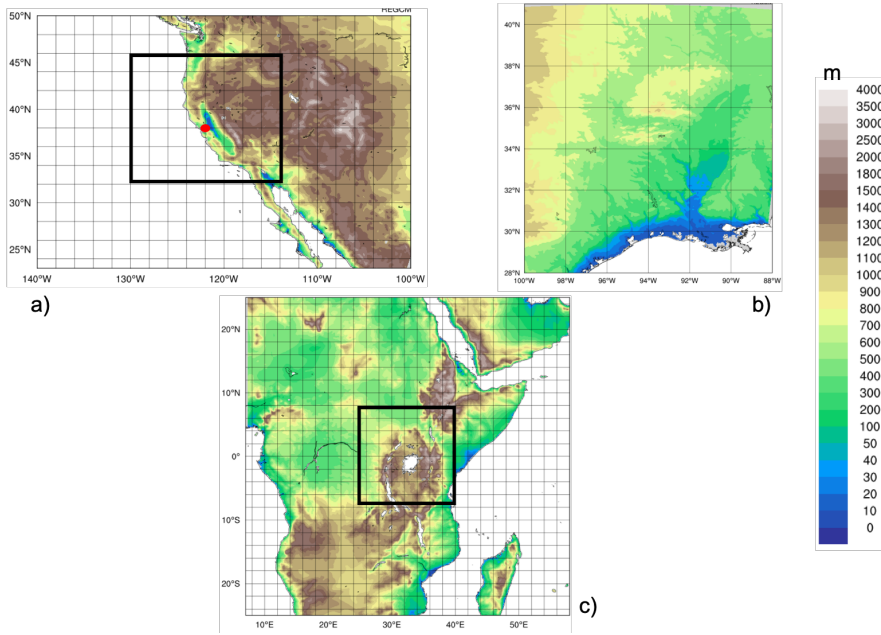
Figure 3: Simulation domains tested , a) California (CAL) , b) Texas (TEX), c) Lake Victoria (LKV) . For CAL (a) and LKV (b) the black square shows the 3 km simulation domains nested in the 12 km domain in figure. For TEX the 3 km domain simulation (c) is fed directly with the ERA-Interim reanalysis fields.

California

The first case, referred to as CAL (California) in Table 2, is a HPE which occurred on 16– 18 February 2004, producing flooding conditions for the Russian River, a southward-flowing river in the Sonoma and Mendocino counties of northern California (red-dot) (Figure 3). The event is documented in detail by Ralph et al. (2006), who focused their

556 attention on the impact of narrow filament-shaped structures of strong horizontal water

557 vapor transport over the eastern Pacific Ocean and the western U.S. coast, called

558 Atmospheric Rivers (ARs). ARs are typically associated with a low-level jet stream ahead

559 of the cold front of extratropical cyclones (Zhu and Newell 1998; Dacre et al. 2015; Ralph

560 et al. 2018), and can induce heavy precipitation where they make landfall and are forced

561 to rise over mountain chains (Gimeno et al. 2014). The CAL event consists of a slow

562 propagating surface front arching southeastward towards Oregon and then

563 southwestward offshore of California (Fig.3a,c). Rain began over the coastal mountains

564 of the Russian River watershed at 0700 UTC, 16 February, as a warm front descended

565 southward, and also coincided with the development of orographically favoured low-level

566 upslope flow Ralph et al. (2006).

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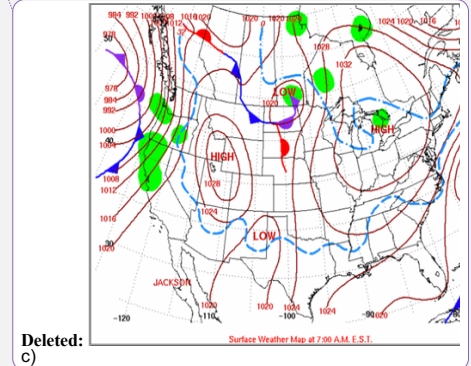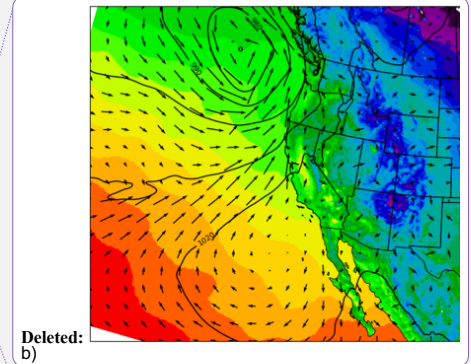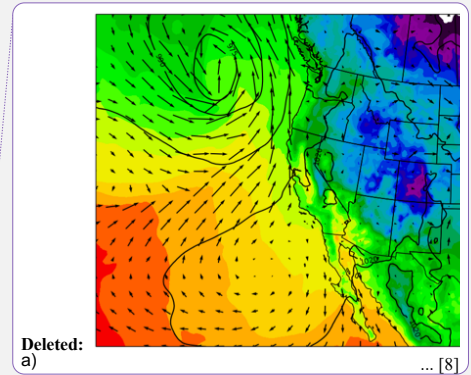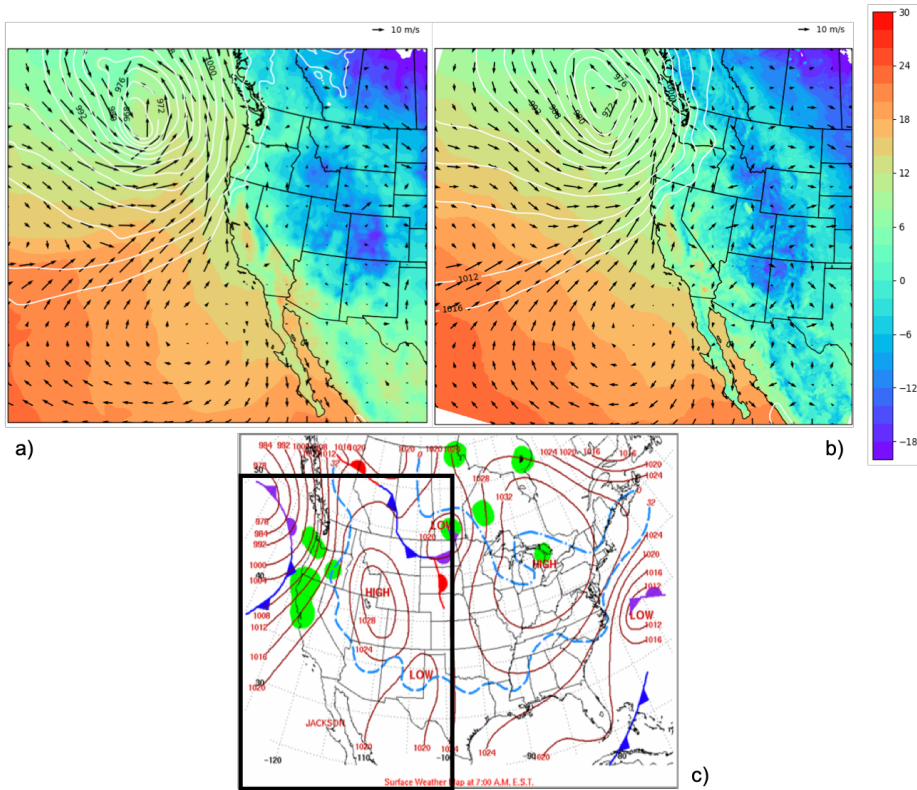
Figure 4: Mean sea level pressure (mslp) (white contour lines), surface temperature

(color shading) and 100-m wind direction (black arrows) at 7:00 UTC, 16 Feb. 2004

of ERA5 reanalysis (a) and RegCM 12km (b) respectively. (c) NCEP-NOA Surface

Analysis of pressure and fronts . The black box in (c) bounded the area represented

in (a) and (b)

The intermediate resolution (12 km) domain (Figure 3a) covers a wide area

encompassing California and a large portion of the coastal Pacific Ocean, with 23 vertical

589 levels and a parameterization for deep convection based on the Kain–Fritsch scheme

590 (Kain, 2004). The ERA-Interim driven simulation is initialized at 0000 UTC, 15 February

591 2004 (Table 2) and lasts until 0000 UTC 19 February 2004. This simulation drives a

592 corresponding RegCM4-NH run using a smaller domain centered over northern California

593 (Fig. 3a) at 3 km horizontal grid spacing and 41 vertical levels, with boundary conditions

594 updated at 6 hour intervals. In RegCM4-NH only the shallow convection component of

595 the Tiedtke scheme (Tiedtke, 1996) is activated. Simulated precipitation is compared with

596 the CHIRPS, CMORPH, TRMM, PRISM, NCEP/CPC observations described in Table 3.

597 First, we notice that the synoptic conditions characteristic of this case study, which are

598 fed into the RegCM4-NH model, are well reproduced by RegCM4 at 12 km, as shown in

599 Figure 4, where we compare the mean sea level pressure (mslp), surface temperature

600 and wind direction on 14 Feb at 7:00 am, as simulated by RegCM at 12 km (Fig.3b) with

601 corresponding fields from the ERA5 reanalysis (Fig.4a). The surface analysis of pressure

602 and fronts derived from the operational weather maps prepared at the National Centers

603 for Environmental Prediction, Hydrometeorological Prediction Center, National Weather

604 Service (https://www.wpc.ncep.noaa.gov/dailywxmap/index_20040216.html) is also

605 reported in Figure 4c.

606 The observed precipitation datasets show similar patterns for the total accumulated
607 precipitation (Figure 5), in particular CHIRPS, PRISM and NCEP exhibit similar spatial
608 details and magnitudes of extremes. CHIRPS places a maximum around 42°N which is
609 not found in the other datasets. CMORPH and TRMM show lower precipitation maxima
610 and lesser spatial details due to their lower resolution, indicating that the performance of
611 satellite-based products may be insufficient as a stand alone product to validate the model
612 for this case.

613

640 In general, the observed precipitation datasets place the highest maxima on the terrain

641 peaks, with extreme rainfall greater than 250 mm in 60 hours over the coastal mountains

642 and greater than 100 – 175 mm elsewhere (Fig. 5a). The black box in Fig 5 shows the

643 area of the Russian River watershed, highlighting the locations of the observing systems,

644 including Cazadero (CZD) and Bodega Bay (BBY) where the largest rainfall rates were

645 detected, 269 mm and 124 mm in 60-h accumulated rainfall between 0000 UTC 16

646 February and 1200 UTC 18 February 2004, respectively (Ralph et al., 2006).

647 The convection-permitting simulation captures the basic features of the observed

648 precipitation, as shown for example in Fig.5, both in terms of spatial distribution and

649 temporal evolution of rainfall (Fig.6a). However, it shows higher precipitation rates than

650 observed over the sea and over the mountain chains, with lower intensities than observed

651 in the south-east part of the mountain chain (Fig.5). By contrast, the 12-km simulation

652 severely underestimates the magnitude of the precipitation event (Fig.5).

653 Concerning the timing and intensity of the event in the CZD subregion, 6-hourly

654 accumulated precipitation (Fig.6a) averaged over the black box of Figure 5, shows that

655 both the 3 km and 12 km simulations capture the onset of the event, but the peak intensity

656 is strongly underestimated by the 12 km run, while it is well simulated by the 3 km run,

657 although the secondary maximum is overestimated. Therefore, our results demonstrate

658 that only the high resolution convection-permitting model captures this extreme event,

659 and that parameterized convection has severe limits in this regard (Done et al. 2004; Lean

660 et al. 2008; Weisman et al. 2008; Weusthoff et al. 2010; Schwartz 2014; Clark et al. 2016).

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Total accumulated precipitation during the events (mm)

CAL   TEX   LKV

a)   b)   c)

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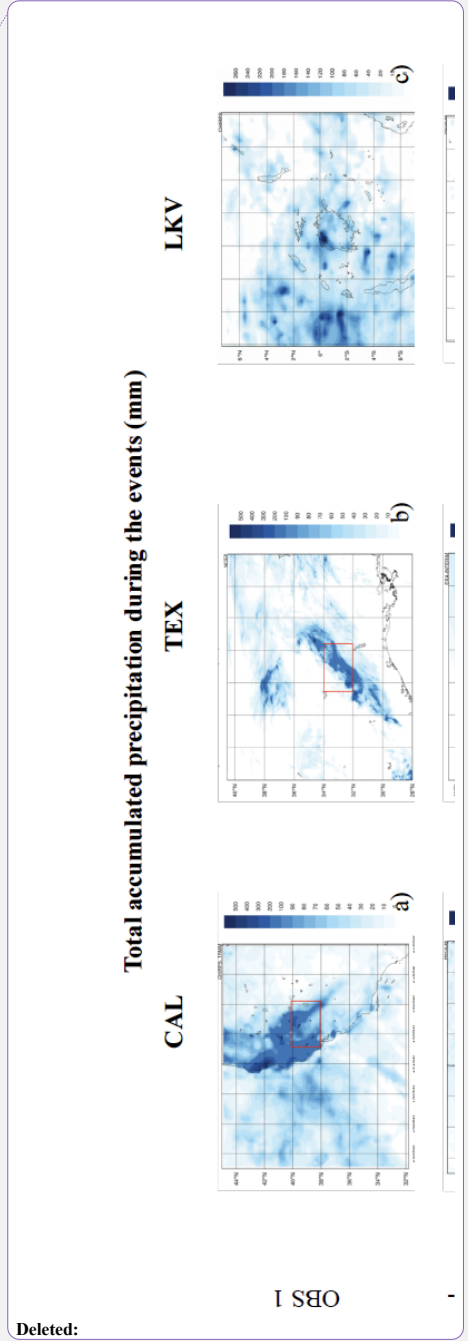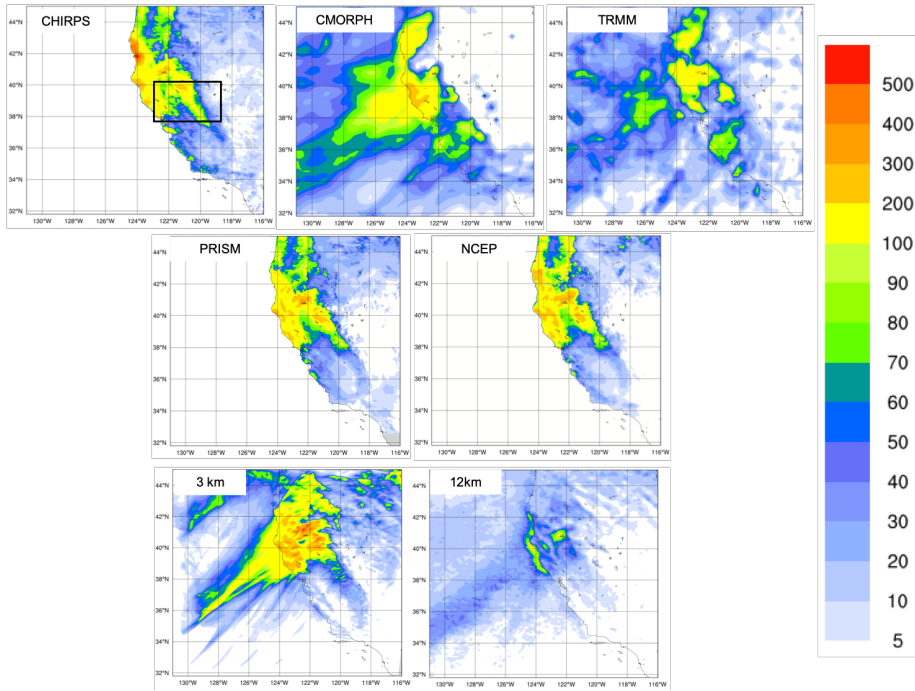
Figure 5 : Total accumulated precipitation (mm) during the California case: CHIRPS, CMORPH, TRMM observations (top line), PRISM and NCEP Reanalysis (middle line) and convection-permitting simulation with RegCM4-NH at 3km and RegCM4 at 12km (bottom line) .The black box denotes the area where the spatial average of 6-hourly accumulated precipitation is calculated and reported in Fig. 6.

CAL (a)	TEX (b)
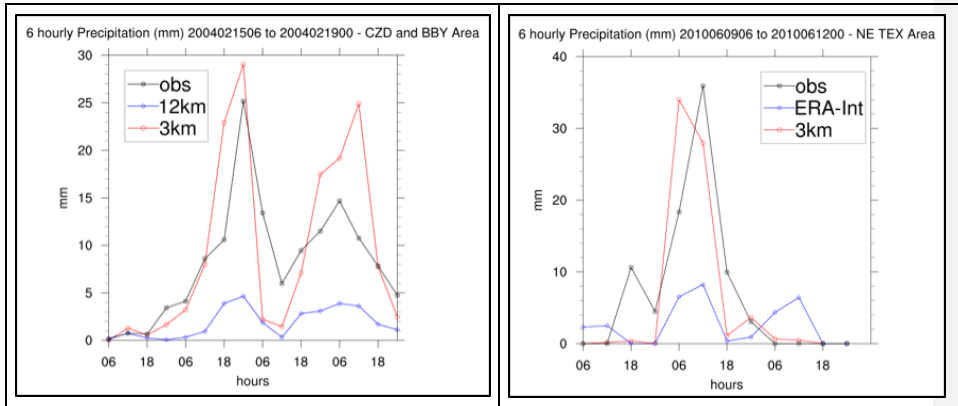
Figure 6: Time series of the 6 hourly accumulated precipitation (in mm on the y-axis) during the CAL event (a) and during the TEX event (b). The blue lines show RegCM4 12 Km and ERA interim 6 hourly accumulated precipitation averaged over the areas indicated by the red square in Figure 3 (a,b) while the red line shows the 6 hourly accumulated precipitation simulated by RegCM4-NH. The observations are shown with a black line.

Texas

Case 2, hereafter referred to as TEX (Table 2), is a convective precipitation episode exhibiting characteristics of the "Maya Express" flood events, linking tropical moisture plumes from the Caribbean and Gulf of Mexico to midlatitude flooding over the central United States (Higgins 2011). During the TEX event, an upper-level cutoff low over northeastern Texas, embedded within a synoptic-scale ridge, moved slowly northeastward. Strong low-level flow and moisture transport from the western Gulf of Mexico progressed northward across eastern Texas. The event was characterized by low-level moisture convergence, weak upper-level flow, weak vertical wind shear, and

721 relatively cold air (center of cutoff low), which favored the slow-moving convective storms

722 and nearly stationary thunderstorm outflow boundaries. The main flooding event in

723 eastern Texas occurred on June 10, 2010, with a daily maximum rainfall of 216.4 mm of

724 the region in the black box of Figure 7 (Higgins 2011).

725

726 **Figure 7: Total accumulated precipitation (mm) during the Texas case: CHIRPS,**
727 **CMORPH, TRMM observations (top line), PRISM and NCEP Reanalysis (central**
728 **line) and convection-permitting simulation with RegCM4-NH at 3 km grid spacing**
729 **and Era-Int (bottom line).The black box shows the area where the spatial average**
730 **of 6-hourly accumulated precipitation was calculated and reported in Figure 6.**

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740 As for the California case, the observed precipitation datasets show coherent patterns for

741 the total accumulated precipitation (Fig. 6), with the highest values related to the

742 mesoscale convective system in eastern Texas (~ 200 mm), and another smaller area of

743 high precipitation more to the north, approximately over Oklahoma. PRISM and NCEP

744 capture similar spatial details and magnitudes of extremes, CHIRPS has lower

745 precipitation extremes in the north compared to the other datasets, while CMORPH and

746 TRMM show the lowest precipitation extremes and reduced spatial details as already

747 noted for the California case.

748 The bottom panels in Figure 7 present precipitation as produced by the RegCM4-NH and

749 the ERA-Interim reanalysis (driving data), respectively. ERA-Interim reproduces some of

750 the observed features of precipitation, but with a substantial underestimation over the

751 areas of maximum precipitation because of its coarse resolution. By comparison, the

752 RegCM4-NH simulation (Fig. 7) shows an improvement in both pattern and intensity of

753 precipitation, and is substantially closer to observations over eastern Texas. However,

754 the precipitation area is slightly overestimated and the model is not capable of

755 reproducing the small region of maximum precipitation in the north.

756

757 The time series of precipitation over eastern Texas from 9 to 12 June 2010 for

758 observations (black line), ERA-Interim (blue line) and RegCM4-NH (red line) are reported

759 in Figure 6b. Precipitation increases over this region from 00:00, 10 June, until it reaches

810   the observed maximum at 12:00, 10 June (~35 mm), gradually decreasing afterwards

811   until 6:00, 11 June. The RegCM4-NH simulation shows a more realistic temporal

812   evolution than the ERA-Interim, which exhibits an overall underestimation of precipitation.

813   In general, the non-hydrostatic model produces precipitation values close to the

814   observations, however, the simulated maximum is reached 6 hours earlier than observed.

815

816

817   **Lake Victoria**

818   Case 3 focuses on Lake Victoria (LKV), with the purpose of testing RegCM4-NH on a

819   complex and challenging region in terms of convective rainfall. It is estimated that each

820   year 3,000-5,000 fishermen perish on the lake due to nightly storms (Red Cross, 2014).

821   In the Lake Victoria basin, the diurnal cycle of convection is strongly influenced by

822   lake/land breezes driven by the thermal gradient between the lake surface and the

823   surrounding land. As the land warms during the course of the day, a lake breeze is

824   generated which flows from the relatively cooler water towards the warmer land surface.

825   The circulation is effectively reversed at night, when the land surface becomes cooler

826   than the lake surface, leading to convergence over the lake and associated thermal

827   instability.

828   In the LKV region, prevailing winds are generally easterly most of the year with some

829   variability due to the movement of the ITCZ. The local diurnal circulation created by the

830   presence of the lake within the larger scale easterly wind field creates two diurnal rainfall

831   maxima. During daylight hours, when the lake breeze begins to advance inland,

832   convergence is maximized on the eastern coast of the lake as the lake breeze interacts

833   with the prevailing easterlies. Studies have also noted the importance of downslope

834   katabatic winds along the mountains to the east of the lake in facilitating convergence

835   along the eastern coastal regions (Anyah et al. 2006). This creates a maximum in rainfall

836   and convection on the eastern coast of LKV. Conversely, during nighttime hours, when

837   the local lake circulation switches to flow from the land towards the lake, the prevailing

838   easterlies create locally strong easterly flow across the lake and an associated maximum

839   in convergence and rainfall on the western side of LKV.

840   The LKV simulation starts on 25 November 1999 and extends to the beginning of

841   December 1999 (Table 2), covering a 5-day period which falls within the short-rain season

842   of East Africa. The choice of 1999, an ENSO neutral year, was made in order to focus the

843   analysis on local effects, such as the diurnal convection cycle in response to the lake/land

844   breeze, with no influence of anomalous large scale conditions. A 1-dimensional lake

845   model (Hostetler et al. 1993; Bennington et al. 2014) interactively coupled to RegCM4-

846   NH was utilized to calculate the lake surface temperature (LST), since lake-atmosphere

847   coupling has been shown to be important for the LKV (Sun et al. 2015; Song et al. 2004).

848   This coupled lake model has been already used for other lakes, including Lake Malawi in

849   southern Africa (Diallo et al. 2018). As with the other experiments, the boundary

850   conditions are provided by a corresponding 12 km RegCM4 simulation employing the

851   convection scheme of Tiedtke (1996).

852   At the beginning of the simulation, the LST over the lake is uniformly set to 26C, and is

853   then allowed to evolve according to the lake-atmosphere coupling. This initial LST value

854   is based on previous studies. For example, Talling (1969) finds Lake Victoria surface

855   temperatures ranging from 24.5-26°C during the course of the year. Several studies have

856   used RCMs to investigate the Lake Victoria climate (Anya et al., 2006; Anyah and

858 Semazzi 2009, Sun et al. 2015), and found a significant relationship between lake

859 temperature and rainfall depending on season. The value of 26°C is typical of the winter

860 season and was chosen based on preliminary sensitivity tests using different values of

861 initial temperature ranging from 24°C to 26°C.

862 The synoptic feature favorable for the production of precipitation over the LKV in this

863 period corresponds to a large area of southeasterly flow from the Indian Ocean (Fig. 8a),

864 which brings low-level warm moist air into the LKV region facilitating the production of

865 convective instability and precipitation. This synoptic situation, with a low-level

866 southeasterly jet off the Indian Ocean, is a common feature associated with high

867 precipitation in the area (Anyah et al. 2006) is found in ERA5 (Figure 7a).

868

a)	b)

Deleted: is initial LST value was chosen based on preliminary simulations and was shown to produce the most realistic precipitation for the period compared with CMORPH (Joyce et al, 2004)

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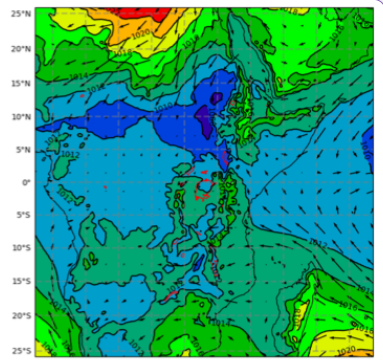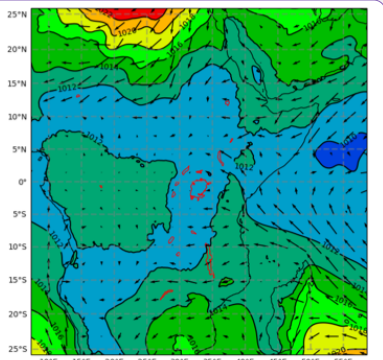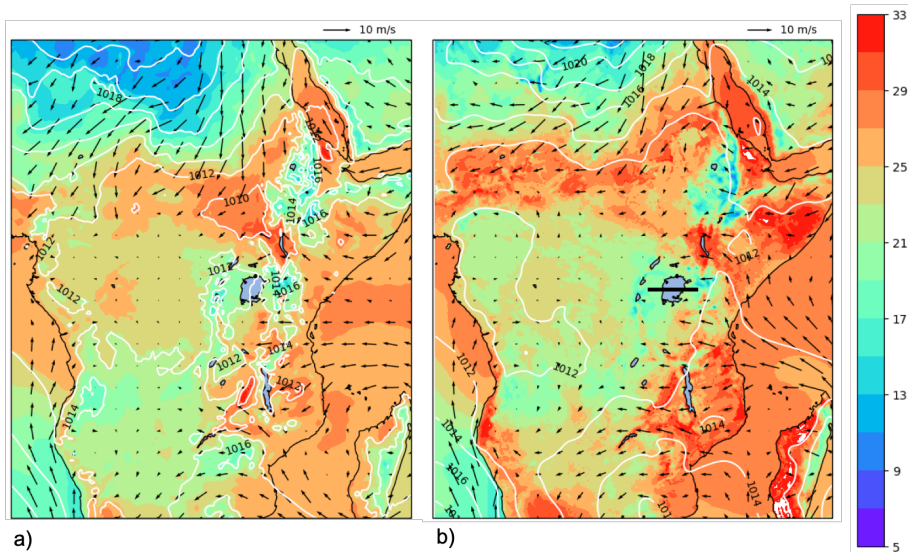
Figure 8: Mean sea level pressure (mslp) (white black contour lines), surface temperature (color shading) and 100-m wind direction (black arrows) averaged over the period 25 November 00:00 - 1 December 00:00, of ERA5 reanalysis (a) and RegCM 12km (b). The black line (b) shows the cross-section position represented in Fig. 9

891

The LKV region dynamics are quite distinct between nighttime and daytime and the rainfall in and around the lake has a pronounced diurnal cycle. To understand this strong diurnal cycle, Figure 9 shows a cross-section through the lake (32E to 34E, black line in right panel of Fig. 8) along 1S latitude at a period during strong nighttime (Fig. 9b,d; 6Z 30 November) and daytime convection (Fig. 9a,c; 12Z 29 November). During the day,

surface heating around the lake leads to a temperature differential between the land and lake sufficient to generate a lake breeze, which causes divergence over the lake, while over the surrounding highlands the environment is more cnducive to convection (9a,c). Conversely, during the night, a land breeze circulation is generated, which induces convergence and convection over the lake (Figure 9b,d).

Comparing the 3 km simulation to the 12 km forcing run, we find that the localized circulations created by local forcings (i.e. convection) are much stronger in the high resolution experiment. We also find stronger and more localized areas of convective updrafts as seen in the vertical velocities (9a,b) compared to the 12 km simulation (8c,d; omega is shown instead of vertical velocity here because of the difference in model output). The stronger convection simulated in the 3 km experiment is also tied to the stronger temperature gradients between lake and land and between day and night (Figure 10).

This demonstrates that the 3km simulation is better equipped to simulate the localized circulations associated with this complex land-lake system.

a)

Figure 7: Cross-section through 1oS of zonal-wind [1]

979   15 ms⁻¹

980   **Figure 9. Cross-section through 1S (red line in bottom right panel of Fig. 9) of the**

981   **mean (0-2N) zonal-wind anomaly (30E-36E) vectors and contoured vertical velocity**

982   **(m/s) at a) 12Z 29 November and b) 6Z 30 November from the 3km simulation.**

983   **Purple dashed contours indicate -0.1 m/s, light blue contours indicate 0.1 m/s,**

984   **yellow contours indicate 0.3 m/s, and red contours indicate 0.5 m/s. Lake Victoria**

985   **encompasses about 32E to 34E. The bottom 2 panels show the cross-section also**

986   **through 1S and mean zonal-wind anomaly vectors as in a) and b) but from the 12km**

987   **simulation at c) 12Z 29 November and d) 6Z 30 November. Purple dashed contours**

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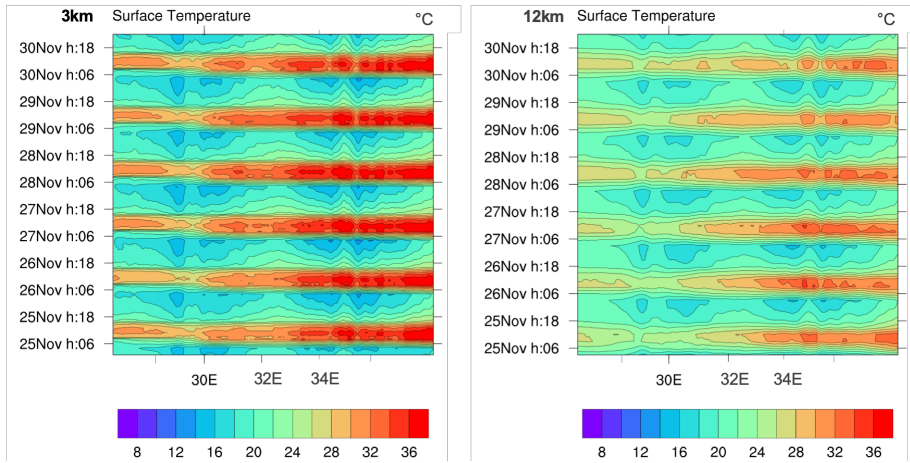
990 **indicate -0.01 hPa/s, light blue dashed contours indicate -0.005 hPa/s, and yellow**

991 **dashed contours indicate 0.005 hPa/s.**

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993 **Figure 10 : Longitude-time (hourly) Hovmöller diagram of LKV domain surface**
994 **temperature (shading, in °C). Panels correspond to the 3km simulation (left) and**
995 **12km simulation (right). The lake Victoria is between 32E and 34E longitude**

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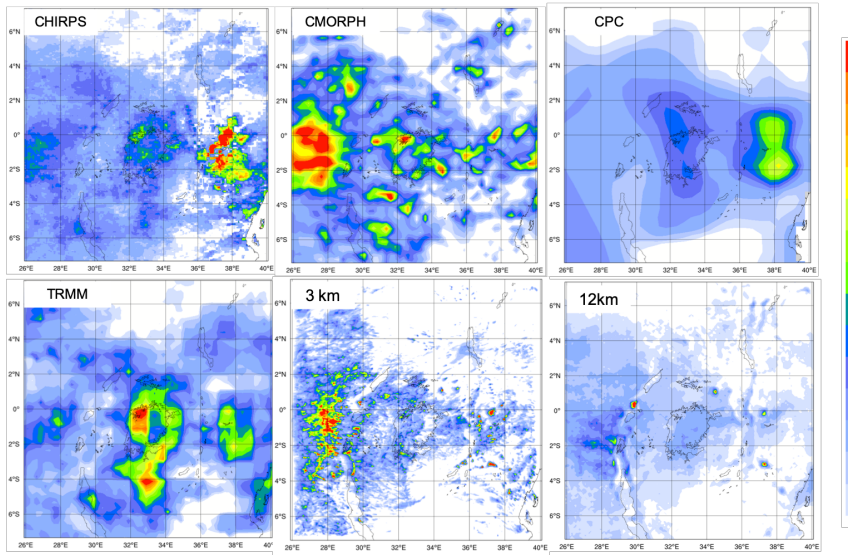
Figure 11: Total accumulated precipitation during the LKV case measured by CHIRPS (top left), CMORPH (top center), CPC (top right) TRMM (bottom left) and calculated by RegCM4 at 3 km (bottom center) and 12 km (bottom right) .

Figure 11 finally reports the total accumulated precipitation observed and simulated for the LKV case. TRMM and CPC show a similar pattern, with two-rainfall maxima of different intensities over the southeastern and northwestern lake areas. CMORPH shows a western rainfall maximum similar to TRMM and one large rainfall area almost entirely centered over the highlands to the west of the lake. Conversely in CHIRPS a maximum is found to the east of the lake while several localized maxima occur over the lake. The differences between the observed datasets highlight the issue of observational uncertainty and the need to take into consideration shortcomings associated with the types of observational datasets considered. Different datasets can have significantly

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different climatology, especially in areas of low data availability. For example, Prein and Gobiet (2017) analyzed two gauge-based European-wide datasets, and seven global low-resolution datasets, and found large differences across the observation products, often of similar magnitude as the difference between model simulations. In this case and for this area the observation uncertainty plays a big role especially at high resolution, and highlights the need for an adequate observational network for model validation.

However, even taking into account the elevated uncertainty existing in the observations datasets, we find a significant underestimation of rain amounts in the 12 km run (Fig 11), with a wide area of rainfall around 80mm over the whole of LKV. In contrast, the 3 km simulation shows substantially greater detail, with rainfall patterns more in agreement with the CMORPH observations. In particular, the 3 km simulation reproduces well the local rainfall maxima on the western side of the lake, although these appear more localized and with a multi-cell structure compared to CMORPH and TRMM. Additionally, the 12 km simulation underestimates the observed heavy rainfall totals in the highlands to the west of the lake region, which are instead reproduced by the 3 km simulation.

This last test case demonstrates the ability of RegCM4-NH in simulating realistic convective activity over a morphologically complex region, which is a significant improvement compared to the hydrostatic-coarse resolution model configuration.

Conclusions and future outlook

In this paper we have described the development of RegCM4-NH, a non hydrostatic version of the regional model system RegCM4, which was completed in response to the

need of moving to simulations at convection-permitting resolutions of a few km. The dynamical core of the non-hydrostatic version of MM5 has been thus incorporated into the RegCM4 system, an approach facilitated by the fact that the this last is essentially an evolution of the MM5. Some modifications to the MM5 dynamical core were also implemented to increase the model stability for long term runs. RegCM4-NH also includes two explicit cloud microphysics schemes needed to explicitly describe convection and cloud processes in the absence of the use of cumulus convection schemes. Finally, we presented a few case studies of explosive convection to illustrate how the model provides realistic results in different settings and general improvements compared to the coarser resolution hydrostatic version of RegCM4 for such types of events.

As already mentioned, RegCM4-NH is currently being used for different projects, and within these contests, is being run at grid spacings of a few km for continuous decadal simulations, driven by reanalyses of observations or GCM boundary conditions (with the use of an intermediate resolution domains) over different regions, such as the Alps, the Eastern Mediterranean, Central-Eastern Europe and the Caribbeans. These projects, involving multi-model intercomparisons, indicate that the performance of RegCM4-NH is generally in line with that of other convection permitting models, and exhibits similar improvements compared to coarser resolution models, such as a better simulation of the precipitation diurnal cycle and of extremes at hourly to daily time scales. The results obtained within the multi-model context confirm previous results from single-model studies (Kendon et al. 2012, 2017, Ban et al. 2014, 2015; Prein et al. 2015, 2017), but also strengthen the robustness of the findings through reduced uncertainty compared to coarse resolution counterpart (Ban et al., 2021, Pichelli et al., 2021). The convection-permitting scale can thus open the perspective of more robust projections of future changes of precipitation, especially over short time scales.

One of the problems of the RegCM4-NH dynamical core is that, especially for long runs with varied meteorological conditions, a relatively short time step needs to be used for stability reasons. This makes the model rather computationally demanding, although not

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more than other convection-permitting modeling systems such as the Weather Research and Forecast model (WRF, Skamarok et al. 2008). For this reason, we are currently incorporating within the RegCM system a very different and more computationally efficient non-hydrostatic dynamical core, which will provide the basis for the next version of the model, RegCM5, to be released in the future.

Following the philosophy of the RegCM modeling system, RegCM4-NH is intended to be a public, free, open source community resource for external model users. The non-hydrostatic dynamical core has been implemented in a way that it can be activated in place of the hydrostatic dynamics through a user-set switch, which makes the use of RegCM4-NH particularly simple and flexible. We therefore envision that the model will be increasingly used by a broad community so that a better understanding can be achieved of its behavior, advantages and limitations.

Code availability: https://zenodo.org/record/4603556

Cases study configuration files: https://zenodo.org/record/5106399

Author contribution: CE prepared the manuscript with contributions from all co-authors and coordinated research, SP, TA, GR carried out and analysed the simulations, PE investigated solutions to stabilize/adapt the model at the km-scale and performed preliminary validation tests, GG developed/adapted the model code, FDS contributed to develop the coupled version of the model, NR developed one of the microphysics scheme, GF supervised and coordinated all activities.

Competing interests: The authors declare that they have no conflict of interest.

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