ON THE ONSET AND EVOLUTION OF DEEP MOIST CONVECTION OVER AREAS CHARACTERIZED BY COMPLEX OROGRAPHY: THE CASE OF FRIULI VENEZIA GIULIA

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On the onset and evolution of deep moist convection over areas characterized by complex orography: the case of Friuli Venezia Giulia

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1 Introduction

Deep moist convection (hereafter DMC) is one of the main sources of water during the warm season over the alpine area, but at the same time represents one of the major threats for people and property because of the large rain rates it can produce as well as for the related phenomena it can host (severe gusts, hail, lightning). For this reason it is extremely important to discriminate in advance the potentially dangerous situations, to ensure both a suitable risk management and a wise use of the water resources.

Apart from the nowcasting activity, which can be carried out essentially through in situ observations and remote sensing, a fundamental tool to gain awareness of potentially dangerous rain events is represented by the output of operational numerical models. Numerical models, in fact, can supply useful information to risk managers and local authorities nearly one or two days in advance, then increasing the effectiveness and efficiency of their actions. Nevertheless the use of high resolution numerical models (hereafter HRNM) for these purposes is threatened at its base by two major questions: a physical and a technical one.

The physical question arises from the observation that the "embryos" of DMC, that is the anomalies in the atmospheric fields (temperature, moisture, divergence, etc.) that might represent the forcing for the onset of self sustaining vertical motions (and then of DMC), live in spatial scales which are of the order of a few km only. These are well beyond the resolution of the analyses and global numerical models currently available for the initialization of the operational HRNM. In other words, even if in principle a state-of-the-art HRNM can reproduce correctly deep moist convection, it might not have enough accurate initial conditions to forecast DMC correctly.

Small scale data assimilation does not represent the best solution to this problem. In fact, even if assimilation has proven to be effective for the prognostic description of the onset and evolution of DMC (Schumacher and Johnson, 2005; 2006), it reduces dramatically the lead-time of the prognostic products. In other words, data assimilation can satisfy our physical requirements, but only if we accept the structural operational constraints it represents in the timing of the products.

An alternative solution, satisfactory both under the point of view of physical requirements and of operational needs, can be proposed in a frame of reference which includes orography. Orography, in fact, represents a stationary perturbation for the synoptic and mesoscale flows and its effects at small and microscale can, in principle, be recognized and modelled well in advance, once a satisfactory knowledge of the flow at larger scales is provided. Under this interpretation, far from representing an additional source of indetermination, orography might become the major trigger which forces the atmospheric system toward a more predictable behaviour.

The technical question arises from the fact that, operationally, the highest resolutions reached so far by operational models are in the range from 5 to 10 km. This spatial scale is larger than that occupied by the single convective cells, but not large enough to encompass enough convective cells to be properly described by convective parametrizations (Gallai et al., 2008; Appendix A). For this reason, the scale at which current HRNM work is defined as the "no men’s land" of convection (Klemp, 2007).
This technical trouble can be overcome only adopting numerical models with a resolution enough high to permit the explicit resolution of convection, even if this approach requires large computational power and probably a more sophisticated treatment of cloud and precipitation.

To face both the physical and technical questions, the WRF non-hydrostatic numerical model has been used to perform sensitive studies of archetypical cases of convection in the southern side of the Alps, in particular over the Friuli Venezia Giulia region. Sensitivity studies were thought to increase the understanding of convective phenomena related to complex orography, looking for possible precursors that might, hopefully, be recognized well in advance even by numerical models running with a coarse resolution. If identified, these precursors might enter into the operational prognostic procedures carried out by human forecasters improving the final quality of the forecasts themselves.

Sensitivity runs of the WRF numerical model were devoted to the analysis of two classical DMC situations for the southern part of the Alps: i) the onset and evolution of stationary DMC over the inner part of the mountain ridge; ii) the onset and evolution of orographically triggered DMC over flat-land. These two archetypical situations have been chosen for the potential threat they represent for people and property and because they are often poorly figured out by the currently available numerical models.

2 Stationary DMC over the inner mountain ridge of Friuli Venezia Giulia

2.1 Phenomenology

The flash flood of 29th August 2003 occurred in Valcanale (North eastern Italy, nearly on the border between Italy, Austria and Slovenia) represents quite well the main features that can occur when the onset of stationary DMC takes place in the inner part of the Alpine ridge, although in extreme form. These events are characterized by the fact that DMC is not triggered above the Prealpine area of the southern Alps, i.e., on the first ridge encountered by the southerly flows, but in the inner part of the Friulian Alps.

The main atmospheric features of these events are: 1) a moist southerly flow (i.e., large amounts of water vapour) in the lowest atmospheric layer near the ground; 2) an intense south-westerly flow aloft; 3) a layer characterized by convective instability near to the ground (Morgan, 1992). The onset of DMC in the inner part of the Alpine ridge represents itself a major degree of threat; in fact, the inner areas of the Alps are not prone to receive the usually large amounts of rain produced by DMC. The hydro-geological response of the system might therefore be critical if compared to the expected response of the Prealpine areas, even with similar rain rates. Moreover, in these cases, DMC often becomes stationary, i.e. convective cells develop and evolve along the same path, then iterating the hydro-geological solicitation on the same area for relatively long periods of time.

In detail, during the 29th August 2003 flash flood, roughly 380 mm of rain were observed in four hours at Pontebba, but even higher values might be retrieved in the same area through radar
estimates. The flash flood was originated by stationary thunderstorms and caused severe damages to the villages of Ugovizza and Pietratagliata because of land slides and extreme run-off caused by the high rain rates. Two casualties occurred during the event and the state of the roads in the area was severely compromised for several years due to the damaged roads. This event was poorly foreseen by operational numerical models (both global and local): all the available runs pointed out the pre-alpine area as the most interested by precipitations, while the inner alpine zone should have been only partially interested by rain. The vice-versa occurred. Moreover, the foreseen amounts of rain were not only misplaced but even barely comparable to the observed ones.

2.2 Sensitivity runs with a high resolution numerical model

The AR-WRF numerical model (version 2.2.1 and later, Skamarock and Klemp, 2007; www.wrf-model.org) is initialized with simulations from the ECMWF global model, with a resolution of 0.5 deg. The adopted resolution for the AR-WRF numerical model is of nearly 2 km. This is obtained through a two-ways nesting sequence which encompasses domains with 50 km and 10 km resolutions.

Several model runs, where different model configurations were tested, allowed us to realize that events like the 2003 flash floods are best simulated using a non-hydrostatic model formulation with an explicit DMC. A six components microphysics (Thomson et al., 2004) in place of a simpler scheme is also important to reproduce correctly the positioning of rain maxima. This behaviour is ascribed to an improved representation of the advective effects which, indeed, produce a better description of precipitation distribution. An even better description of the rain amounts and positioning is obtained increasing the orographic height by a factor 1.2, bringing the relieves profile closer to the real one. The obtained "best description" of the spatial distribution of
total rain amount results in pretty good agreement with that obtained through the RADAR estimates (see figures 1a and 1b), even if slight displacements still remain.

However, even if correctly represented in terms of spatial distribution, the exact amounts of rainfall observed at the ground could not be correctly reproduced, being the simulated rain amounts lower than those observed nearly by a factor four. So far there are no answers for such a behaviour of the numerical model. The only attempt made during the FORALPS project to improve the rain amount representation was that of modifying the parameters of the microphysical scheme, increasing the graupel density from 400 to 600 kg m$^{-3}$ (Gilmore, 2004a; 2004b). The effects of the modified graupel density are, however, essentially null both on the rain positioning and intensity aspects. This probably happens because the forcing exerted by the increased graupel

![Figure 2](image-url)

**Figure 2.** Propagation of rainfall with observed (panel b) and increased (panel a) relative humidity in the lowest levels. Circled numbers represent UTC hours, and correspond to the location of the rain centroid at that time.
description do not have enough time to affect such a rapidly evolving convection. It is not clear so far if the adopted microphysical parametrization has in itself the capability of reproducing what was observed in the Valcanale flash flood, or if new schemes has to be introduced to reach that goal.

Once the "best description" of the Valcanale event was achieved, sensitivity runs were carried out modifying the atmospheric state and looking for the reasons of the onset and stationarity of DMC. These sensitivity runs show that a fundamental ingredient to explain the Valcanale event is the presence of a relatively dry layer (low relative humidity) near to the ground contemporary to the event itself. Because of this dry layer, in fact, the DMC onset can take place only if triggered by the relieves through their interaction with the south-westerly flow. The low relative humidity is in fact associated to a high lifting condensation level and to a high level of free convection. In other words, if the relative humidity close to the ground is low, the onset of DMC can take place only in the upwind side of the largest and tallest mountains; then it can be advected along the same direction because of the stationarity of the upper air flow.

When relative humidity is increased, instead, even if the onset of DMC still occurs above the inner part of the relieves, DMC is not merely advected by the mean upper level flow but also shifted eastward interesting a wider area and diluting the hydro-geological solicitation (see figure 2). This propagation takes place through the so called "mother-daughter" mechanism (Ogura and Liou, 1980; Rotunno et al., 1988), i.e., the downdraught outflow favours the low level convergence, then the lifting, of the moist southerly flow near to the ground. The effectiveness of the mother-daughter mechanism is increased with high relative humidity close to the surface, because the level of free convection is relatively low in these conditions. Therefore the mechanical lifting of the moist air-mass exerted by the cold outflow, often magnified by the presence of orography, is enough to reach that level and trigger conditional instability. The eastward propagation of the cells is the result of the vector superposition of the northeastward component due to the southwest synoptic flow with the southward component due to the "mother-daughter" component (we recall

![Figure 3. Vectorial representation of the mother-daughter propagation scheme.](image-url)
that the "mother-daughter" propagation of convective cells takes place against the low-level wind direction, in this case blowing from south and/or southeast, see figure 3).

Sensitivity runs have also been carried out trying to obtain information on the reasons for the partial failure of the operational HRNM available to the human forecasters and decision-makers before of the event occurrence. To mimic the behaviour of operational HRNM, AR-WRF is used keeping the same microphysical parametrization (Thomson et al., 2004) and ECMWF initialization conditions, but adopting a coarser resolution (e.g., 5 km) and a cumulus parametrization (in this case the Kain-Fritsh scheme). These sensitivity runs misplace the positioning of the precipitation maxima producing the largest amounts of rain on the Prealpine area, almost with the same results of the operational HRNM. In particular it has been noticed that the production of large amounts of rain in the Prealpine area dries "too early" the air-mass near to the ground, then reducing the amounts of precipitation on the inner Alpine ridge. From this point of view the coarse-resolution, parameterized-convection runs produce a double fault because they indicate a possible threat on the pre-alpine area (false alarm), and consider the inner Alpine ridge as relatively protected (missed warning). This detrimental effect is due to the convolution of cumulus parametrization and coarse resolution, although it seems that the major role is played by the parametrization scheme, not suited to represent real convection in this intermediate range. The worst results are obtained with a resolution between 5 and 10 km (figure 4).

Before concluding, it is worth to mention that, in the case of the Valcanale flash flood, the relatively low values of relative humidity near the ground were quite well foreseen even by the operational runs of the numerical models available at that time (see figure 5). In other words, even if the available operational numerical models could not forecast the event well (because of their resolution and cumulus parametrization), they were able to identify the main feature of the air-masses that originated the flash flood itself.

**Figure 4.** Observed (a) and virtual (b) skew-T plots of the vertical atmospheric profile at 12:00 UTC of 29th August 2003. Low relative humidity close to the ground is well reproduced by a coarse resolution numerical model, since it is related to air-mass properties at relatively large scale.
Figure 5. Rain amount of the numerical simulation with a 5 km resolution.

3 Orographically triggered DMC over the Friuli Venezia Giulia flat-land

3.1 Phenomenology

Quite often, during the interaction between cold fronts and orography, in the so called "warm sector", DMC develops on flat areas (plain and/or coast) of Friuli Venezia Giulia. In particular a cold front moving from Northwest to Southeast and interacting with the Alpine chain, relatively often, favours the onset of DMC on the western part of the plain and coast of Friuli Venezia Giulia. The convective cells usually travel eastward, sometimes so slowly to be considered quasi-stationary. These convective cells quite often produce large amounts of rain and sometimes large hail. Since the rain-rate maxima interest areas climatically not prone to receive large amounts of precipitation (this is specially true for the coast), these episodes often represent a threat for people and property. Moreover, these events are poorly foreseen by the currently available operational numerical models, then reducing the lead-time for the issuing of warnings and for the emergency management. Episodes that might enter into this class of events are the flash floods of 9th September 2005 in Pordenone (stationary class, figure 6), of 27th May 2007 in Latisana (UD) (slowly moving class, figure 7) and 9th July 2007 in the northern plain of Friuli (large hail, figure 8). But even the 29th August 2003 Valcanale flash flood episode, as shown in the below paragraphs, presents some interesting features that can be used to increase the awareness and understanding of this class of events. Even if the source of the thermodynamic instability at the base of the above events is quite well understood (Morgan, 1973) and explained by the
**Figure 6.** Flash flood of 09 September 2005 produced by stationary DMC.

**Figure 7.** Large rain amounts produced by slow moving DMC.

**Figure 8.** Large rain (and large hail) produced by travelling DMC
contemporary cold air advection aloft and by the warm advection near to the ground due to the lee-
side low, the reasons for the DMC onset on flat lands are not so far clear and are the object of the
present work.

3.2  Sensitivity runs with a high resolution numerical model

During the sensitivity runs of the Valcanale flash-flood it was serendipitously noted that, with
certain choices of the parameters, the numerical model caused the onset of DMC even on the plain
and coast of Friuli Venezia Giulia. In the virtual reality represented by simulations, this onset takes
place in the morning of 29th August and its causes can be found in the wind convergence observed
in the lowest levels near the ground, produced by the southerly and southeasterly flow that turns
westward impinging into the orography. This convergence mechanism is similar to that described
by Rotunno and Ferretti (2001) but it takes place at a smaller scale (meso-beta).

The latitude of the wind "turning point" which is fundamental for the correct positioning of the
convergence area and then of the DMC onset, is a function of the wind speed near to the ground.
The latter is ultimately a function of the pressure deepening in the southern side of the Alps,
related in turn to the blocking exerted by the relieves on the cold front motion (from Northwest to
Southeast).

Two more ingredients are considered important for the onset and evolution of DMC in this class of
events: i) high values of relative humidity on a significant amount of troposphere (e.g., more than
half of the whole air column); ii) direction and intensity of the winds aloft.

High values of relative humidity near the ground lower the lifting condensation level (altitude at
which condensation occurs) and the level of free convection (altitude at which a lifted parcel starts
to buoy), favouring the onset of DMC. Moreover, high values of relative humidity in the upper
levels (substantially above the boundary layer), for a fixed temperature, are an evidence of the high
values of precipitable water available in the atmosphere.

Wind direction and intensity aloft also play an important role for the evolution of DMC. In fact, if
wind direction aloft has a negligible component orthogonal to orography (e.g., wind blows form
southwest toward northeast over Friulian plain) and is nearly equiverse with the wind in the
lowest levels, then convective cells will propagate eastward (e.g., case of 27th May 2007, figure
7). If instead the wind direction has a significant component orthogonal to the orography (e.g.,
wind blows from south toward north over Friuli Venezia Giulia), then convective cells move
slowly or remain stationary (e.g., case of 9th September 2005, figure 6).

This happens because propagation takes place through the mother-daughter mechanism and the
overall DMC displacement (sequence of cells) is the result of the vectorial sum of the mother
“updraft displacement” (triggered by upper level wind) and of the daughter “onset displacement”
(opposite to the wind in the lowest levels near to the ground, see figure 3). The wind speed
intensity aloft plays an important role for the updraft intensity. In particular, large wind speed aloft
favour the significant tilting of the updraft, then reducing the hydrometeors loading (Giaiotti et al.,
2007), which counteracts buoyancy. In other words large winds aloft permit large updraft
velocities, then increasing its capability to sustain even large hailstones (e.g., case of 9th July
2007, figure 8).

4 Conclusions

Figure 9. Flow chart developed to help human forecasters in taking their decisions concerning the onset and evolution of DMC on the lee side of the Alps (Friuli Venezia Giulia).

The AR-WRF sensitivity runs on the onset of DMC in the southern lee side of the Alps (Friuli Venezia Giulia) finally led us to the preparation of a look-up table (figure 9), intended as a flow chart devoted to human forecasters for their operational activities. This chart is meant to be used to retrieve information from the current available operational HRNM, and benefits from the know-how matured through the sensitivity runs.
The flow chart starts by checking the presence of convective instability (Morgan, 1992). If convective instability is expected to be a significant feature of the forecast, then the presence/absence of southerly flow in the medium-to-high atmospheric levels (e.g., from 600 hPa up to 200 hPa) needs to be evaluated. If southerly flow is probable, then convective instability can be released through orographic lifting, but the presence/absence of dry layers near to the ground has to be checked. If dry layers are expected to occur from the ground up to 600 hPa, then DMC will most probably be generated on the inner alpine ridge, and might remain stationary. If, on the contrary, the atmospheric sounding shows an atmosphere relatively moist at all the levels (high values of relative humidity), DMC might develop even in the pre-alpine area, and should propagate according to the mother-daughter mechanism.

If the probability of high values of relative humidity is high all along the vertical, then another scenario has to be evaluated, i.e. the possible occurrence of a low-level mesoscale convergence on the plain and coast (figure 10).

If this convergence zone is recognized, then the onset of DMC can occur even in the flat land. Its behaviour would then be a function of the wind speed and direction aloft. If the wind aloft (say at 500 hPa) is nearly equiverse to the wind level near to the ground, then DMC might be almost stationary or slowly moving. On the contrary, if the wind near the ground is not parallel to upper levels motions, then DMC propagation following the mean wind aloft might take place. If, moreover, the vertical profile of the atmosphere is everywhere near to saturation and the high-level wind is particularly intense (e.g. presence of a jet stream), then the effects of hydrometeors loading on the updraught could be reduced enough to permit the sustain of large hailstones.

Figure 10. Examples of real wind patterns which favour the convergence of flow in the low levels.
5 Appendix: The Kain-Fritsh convective parametrization

5.1 *Introduction to cumulus parameterization*

Because of the scale at which convective processes take place, current operational models cannot predict them explicitly and must reproduce their effects through parameterizations. Cumulus Parametrization (CP) schemes operate reducing thermodynamic instability by rearranging temperature and moisture in a grid column using information averaged over entire grid boxes. It is worth noting that, even if one of the primary tasks of CP schemes is to estimate the rate of subgrid scale convective precipitation, this result is merely an incidental by-product, and the scheme can not be expected to correctly predict it. Other tasks of the CP schemes are the estimate of the latent heat release and of the vertical redistribution of heat, moisture and momentum. The way in which these parameters can be linked to the resolvable scales of the model depends from the horizontal resolution of the numerical model itself. For example, observations suggest that for scales smaller than 50 km these parameters strongly correlate with CAPE whereas for larger scales they are mainly related to the moisture convergence and rate of destabilization. Furthermore, since the parameters used in the scheme assumptions are adjusted to optimize the overall scheme performance, they may work well for some situations but not for others. Typically they are tuned to perform well on the average base and not for extreme events.

5.2 *Kain-Fritsch parameterization scheme*

The Kain-Fritsch scheme (hereafter KF; Kain and Fritsh, 1990; Kain 2003) is a mass flux parameterization, i.e. it uses a simple cloud representation to simulate rearrangements of mass in a vertical column. In particular, it uses the Lagrangian parcel representation, including even vertical momentum dynamics, to estimate whether instability exist, whether any existing instability will become available for cloud growth and what might be the properties of the convective clouds. For simplicity it is possible to distinguish three elements in the conceptual design of the scheme:

1. the trigger function
2. the mass flux formulation
3. the closure assumptions

5.2.1 *The trigger function*

The first step of the KF scheme is to identify the layers that might host the initiation of convective clouds. These layers are called updraft source layers (USL). Starting from the surface, vertically adjacent layers in the model are grouped until the depth in pressure of the resultant layer is of at least 60 hPa. This is the first potential USL; the mean thermodynamic parameters of this layer are computed and a parcel with these characteristics is lifted up to its LCL, where its temperature and height are calculated. The LCL temperature is then summed up with a temperature perturbation term, function of the vertical motion. This perturbation typically has a magnitude of 1-2 K for vertical velocities ranging from 1 to 10 cm/s. The resulting temperature is then compared with that of the environment to estimate the likelihood of convective initiation: if the former is less than the
latter the parcel is not considered for a possible source of convection. Another USL is therefore retrieved with the same procedure adopted above, and the process is iterated.

If, on the contrary, the parcel obtained from the USL is warmer than the surroundings, it becomes a candidate for deep moist convection. Solving the “parcel buoyancy equation”, which also considers the effects of entrainment, detrainment and water loading, the parcel vertical velocity is computed at each model level above the LCL. The cloud top is reached when the vertical velocity becomes negative. If the cloud depth reaches a minimum value (a function of the temperature at LCL), deep convection is activated. If not, this layer will be remembered as a possible source for shallow convection and the search is moved up to the next potential source layer, repeating all the above steps.

The process continues until a candidate is found within the lowest 300 hPa of the atmosphere. If there are no parcels candidate for deep convection, shallow convection is activated using the deepest shallow candidate encountered during the test. If convection is initiated, the stabilizing mechanisms described in the next section can start.

5.2.2 Mass flux formulation

The KF scheme, being a bulk-cloud model, assumes that only one cloud exists in each air column, and that this cloud entrains and detrains at many levels. In the scheme, entrainment is assumed to produce many different mixtures which have different buoyancy properties and thus detrain at different levels, instead of a single mixture of cloud and environment. This allows the scheme to be more responsive and sensitive to different soundings. Moreover it allows a more realistic detraining of hydrometeors, which can be passed to complex microphysical schemes at different levels, if the model is set up for the purpose.

The updrafts in the KF scheme are represented using a one-dimensional entraining/detraining plume model (ODEDP), where potential temperature and water vapor are both entrained and detrained. In this frame, entrainment is favored by positive buoyancy and moist environments, whereas the vice-versa is true for detrainment (negative buoyancy and dry environments). The main role of updrafts in the cumulus scheme is to remove volumes of air with high potential temperature from the lower troposphere, to transport them aloft, and to generate condensation. This condensate, then, is used to feed, by evaporation, convective downdrafts that drag mass from the 150-200 hPa layer above the cloud base, depositing air with low potential temperature in the sub-cloud layers. These downdrafts are assumed to be saturated above the cloud base, whereas below relative humidity is assumed to decrease at a rate of 10 % per km. The downdraft stops if it becomes warmer than the environment or if it reaches the surface.

A return flow is necessary to compensate for any mass surplus or deficit eventually created by updrafts and downdrafts. Typically the updraft creates a mass surplus aloft and a deficit below, so that the return flow is directed downward. Kain-Fritsch precipitation amounts depends on the quantity of condensate generated and dumped into the environment by updrafts as well as on the rate of his evaporation caused by downdrafts: any leftover condensate accumulates at the ground as precipitation.

5.2.3 Closure assumptions

The KF scheme rearranges the mass in a column, using updrafts, downdrafts and environmental mass fluxes, until at least the 90 % of CAPE is removed. The CAPE in other layers may be used in
triggering another round of convection after this cycle ends, if the changes in the sounding have not incidentally eliminated it. The convection time scale typically ranges from 30 to 60 min. The changes in the vertical profile produced at the end of the CP cycle are the sum of the effects of compensating subsidence, cloud sources at detrainment levels and downdrafts. Generally these effects compensate each other. Sometimes, however, the model response to CP heating can result in a vigorous overturning of the atmospheric column over a period of time, resulting in a vertical profile which is far different from the initial conditions. Finally, differently from other CP schemes, the KF scheme does not converge to a characteristic sounding; indeed, the final vertical profile produced by the KF CP scheme varies case by case. However, if convection is active for some time in the same region, the model tends to develop a deep saturated layer with its base at low levels.

5.2.4 Strengths
1. Suitable for mesoscale models and for the coupling with microphysical schemes that use a wide variety of hydrometeors
   i. The assumption about consuming CAPE is appropriate for short time and space scales.
   ii. Accounts for microphysical processes in convection and can be set up to feed hydrometeors to the microphysical scheme.
   iii. May perform better in cases of severe convection.
2. Physically realistic in many ways:
   i. Has the most realistic treatment of trigger and cap (although it still fails if the model boundary-layer forecast is bad).
   ii. Accounts for entrainment and detrainment more realistically than other schemes.
   iii. Handles elevated convection.
   iv. Can vary its response to different forecast scenarios.

5.2.5 Limitations
1. Has a tendency to leave unrealistically deep saturated layers in post-convective soundings. This could lead the microphysical scheme to simulate post-convective stratiform precipitation, which may be overdone.
2. Takes longer to run than simpler schemes.
3. The assumption about the rapid consumption of CAPE is not appropriate for coarse-resolution models.
4. Model fields may look “spotted like” if convection triggered in scattered grid boxes, making the interpretation of model fields more difficult.

5.3 Relationship between resolution and average amount of rain produced by numerical simulations

Part of the sensitivity runs carried out through AR-WRF have been devoted to test the WRF efficiency in producing rain during convective events as a function of resolution. Results are summarized in figure 11. It is clear that the efficiency in producing rain is a non-linear function of
resolution. In particular, at least in the case of 29th August 2003, the maximum efficiency has been reached for resolutions encompassed between 5 and 10 km, even if at this resolution the simulations were not satisfactory regarding the correct positioning of the rain maxima.

Figure 11. Average and standard deviation of rain amount produced by the WRF numerical model as a function of spatial resolution. The numerical simulation is that of 29th August 2003.

6 References


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<td><strong>ZAMG-K</strong></td>
<td>Central Institute for Meteorology and Geodynamics: Regional Office for Carinthia</td>
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<td><strong>ZAMG-S</strong></td>
<td>Central Institute for Meteorology and Geodynamics: Regional Office for Salzburg and Oberösterreich</td>
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<tr>
<td><strong>ZAMG-W</strong></td>
<td>Central Institute for Meteorology and Geodynamics: Regional Office for Wien, Niederösterreich and Burgenland</td>
<td><a href="http://www.zamg.ac.at">www.zamg.ac.at</a></td>
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The project FORALPS pursued improvements in the knowledge of weather and climate processes in the Alps, required for a more sustainable management of their water resources. The FORALPS Technical Reports series presents the original achievements of the project, and provides an accessible introduction to selected topics in hydro-meteorological monitoring and analysis.