Simulation of present-day climate in RACMO2: first results and model developments.

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1. Introduction

In the last two years a new, second version of the KNMI regional atmospheric climate model (RACMO) has been developed. This version 2 of RACMO (hereafter RACMO2) uses the ECMWF cycle 23r4 physics embedded in HIRLAM semi-Lagrangian dynamics (5.0.6). The ECMWF CY23r4 physics package has been used in the ERA40 re-analysis project; a detailed description of this physics package can be found online at http://www.ecmwf.int/research/ifsdocs/. Details about the model setup can be found in the Appendix.

To investigate the quality of the model under present climate conditions, a 15-year run was driven by realistic boundary conditions given by the ECMWF ERA15 re-analysis. This ERA15 run has been completed at the end of summer 2002. Analysis of the output of the ERA15 run revealed serious shortcomings of the model. In summer, the temperature bias of the model is 4–8 degrees in central and south Europe. In Fig. 1 we plotted the mean temperature at 12 UTC at the lowest model level (30m) in RACMO2 compared to the driving analysis field in June 1983 – a year in which the temperature bias is very pronounced. It shows that RACMO2 is excessively warm. Associated are a strong reduction of the hydrological cycle, a strong reduction of the cloud cover, and a drying of the soil. At that time it was decided that the model was not suited yet to perform climate scenario runs.

The purpose of this Technical Report is i) to assess the quality of the control simulation of RACMO2 for the present climate and ii) to document the changes we have made to the standard version of RACMO2 in order to improve the simulation of present-day climate. These changes include changes in the physics parameterizations, changes in the orography, and changes in the lateral boundary relaxation of the model. It should be noted that the number of changes is deliberately kept as small as possible, keeping the model as close as possible to the reference ECMWF 23r4 cycle and the HIRLAM dynamics. Some remaining, more complex deficiencies of the model (for example with summer time convective precipitation) are subject to future investigations.

2. Changes in the orography

In a rather early stage it turned out that the model produced rather excessive precipitation over mountains, in particular during spring when the air is relatively warm and has not yet completely dried out. One cause of this defect appeared to be related to small-scale disturbances triggered by the small (grid) scale variability of the orography. The HIRLAM Semi-Lagrangian (SL) dynamics does not cope well with the grid-scale disturbances; they might be amplified within the domain causing high levels of noise. (Note that this is not only typical of a SL advection scheme, but does also occur in Eulerian schemes.) For that reason the orography was treated with a Raymond filter, which takes out the variance of the orography on the grid scale (de Bruijn 1998). In addition, the filter reduces the height of the peaks of the orography, which reduces the rainfall amounts. The filtered and unfiltered orography is shown in Fig. 2. It appears a rather general problem in regional climate models (e.g., the UK Hadley centre model HadRM3, the Rossby climate centre model RCA) that rain falls mainly on top of the mountains instead

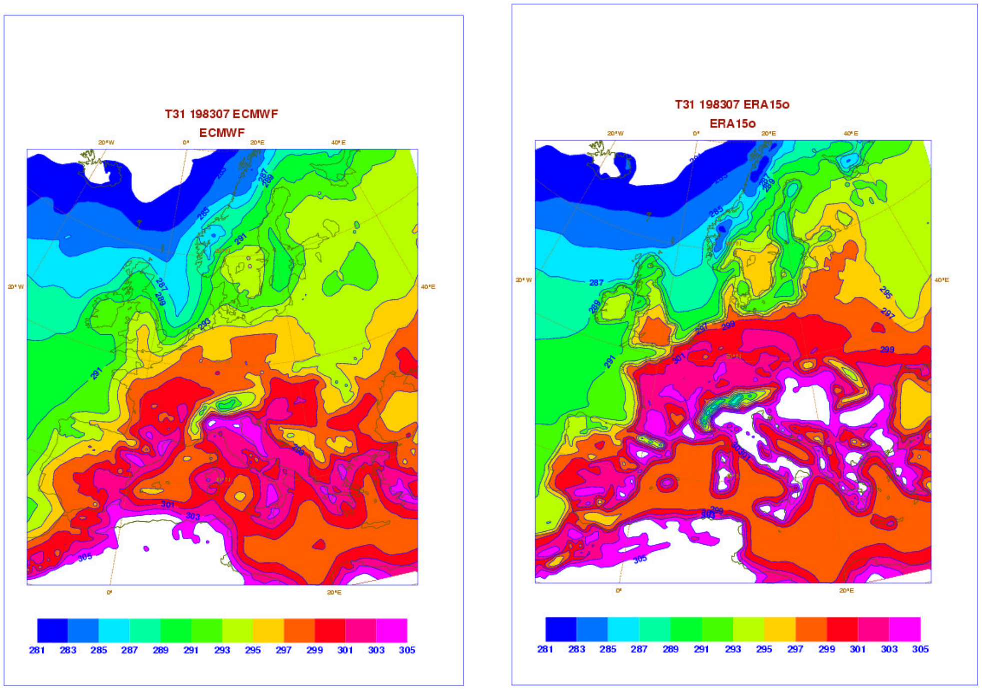

Fig. 1. *Temperature at lowest model level (30m), mean 12 UTC in July 1983 (left-hand side ECMWF analysis; right-hand side RACMO2 ERA15 run)(contour interval 2K).*

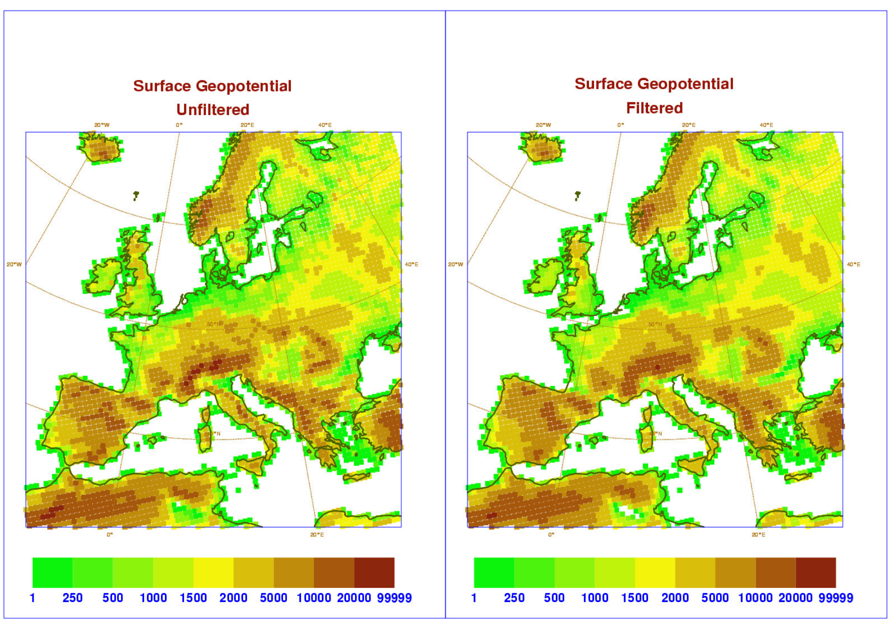

Fig. 2. *Surface geopotential of the orography (left-hand side: unfiltered orography; right-hand side: filtered orography).*

of at the slopes of the mountains. This results in a stronger height dependence of precipitation in the models than is observed.

Results of the mean precipitation in the period 1-3-1981 to 1-5-1981 are shown in Fig. 3. With the unfiltered orography unrealistically high mean values of average precipitation of more than 20 mm/day are simulated over the Pyrenees and the Alps. With the filtered orography, precipitation amounts over mountains decrease with 6-10 mm/day.

At a later stage, and running RACMO2 with a revised physics package, it turned out that rainfall amounts over the mountains were still rather high. One cause is related to artificial moisture transport due to horizontal diffusion. This will be discussed in section 5.

3. Changes in the physical parameterizations

a. Initial experiments

Initially, we focussed the changes in the ECMWF physics package on two different aspects:

1. Changes in the surface (sensible) heat budget of the model. These include changes in cloud parameterizations to increase cloud cover, and reduce the incoming solar radiation at the surface.
2. Changes in the strength of the hydrological cycle. One major aspect was to increase the water holding capacity of the soil. Also changes in the cloud microphysics have been attempted to increase formation of precipitation, and thereby enhancing the local re-circulation of moisture.

Of course, these two aspects do not stand alone, but are strongly connected. Too much radiation at the surface in spring could lead to too much evaporation, leading to too dry soils in summer and a reduction of the hydrological cycle. At the same time, a too small water holding capacity of the soil might lead to a too dry soil in summer, thereby reducing the cloud cover and increasing incoming surface radiation. Beforehand it is not clear what is cause and what is effect.

We performed a series of experiments focussing on the surface sensible heat budget of the model. Initially these included many one- and three months long integrations starting first of June or first of April 1979 running until end of June 1979. These have led to a quite clear idea which changes are essential (that is, determining the feedback loop leading to the dry and warm bias). At a later stage, we performed a series of more structured, longer experiments for the year 1981. Results of those experiments are discussed in the last part of this section.

We have made several changes in the prognostic cloud scheme, which combines several source and sink terms into a prognostic equation for the cloud fraction and cloud liquid water (see equations 6.9 and 6.10 of the IFS CY23r4 documentation). The source term due to the generation of stratiform clouds has been increased by a factor two, whereas the sink term due to cloud dissipation has been decreased to 10% of its original value. This turned out to have a marginal effect on the model results only, and resulted in summer to increases of the cloud cover of only a few percents. The weak sensitivity to these modifications is due to internal feedbacks in the cloud scheme and the strong control of the dry conditions in the model, keeping cloud fractions low. Also more fundamental

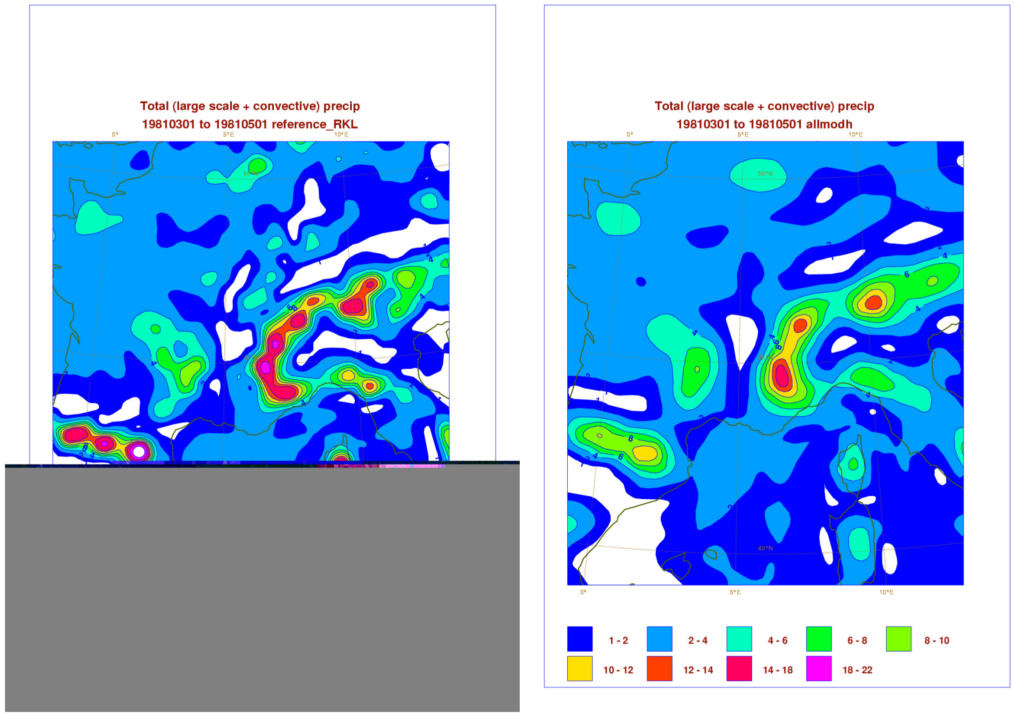

Fig.3. *Mean precipitation (mm/day) 1-3-1981 to 1-5-1981. Left-hand side standard orography, right-hand side filtered orography.*

shortcomings of the cloud scheme result in an underestimation of the low-level cloud cover (see discussion).

In a second series of experiments we have attempted to modify the ratio between the heat flux penetrating into the soil and the sensible heat flux into the atmosphere. It was observed that in early summer the atmospheric temperature in the boundary layer in RACMO2 was below the ERA15 reanalysis. The hypothesis was that in early summer too much energy was penetrating into the soil, giving rise to a too strong warming trend of the soil. (Note that a heat flux of only a few Watts per square meter gives rise to a soil warming of several degrees over a seasonal time scale.). This could explain the high soil temperatures in summer that were observed in the model. We have attempted to i) increase the surface sensible heat flux by increasing the exchange coefficient between the surface skin temperature and the first model level, and ii) to decrease the soil heat flux by decreasing the exchange coefficient between the skin temperature and the first soil layer. These experiments were not very successful either, and had only a marginal effect. This suggests that the warm bias of the model is not controlled by a bias in the sensible heat budget directly, but that the latent heat budget (moisture budget) controls the bias. Therefore we focussed on the role of the hydrological cycle in the next experiments.

We have made the three following changes in the formulation of the soil scheme:

- Compared to many other climate models, the ECMWF physics package has a rather shallow soil layer. The soil depth in ECMWF is only 2.89 m total, and the vegetation extracts most of its water from the first three layers, which extend to about one meter depth. The water holding capacity (accessible to the vegetation) might therefore be too small for the purpose of performing climate integrations (in the absence of a soil water assimilation scheme used in the weather prediction mode). In addition the thickness of the soil might be too small to represent temperature variations on longer time scales. For these reasons, we increased the soil depth of the deeper layers significantly, leading to a **total** soil depth of nearly 5 meters. More precisely we changed from (0.07, 0.21, 0.72, and 1.89 m) to (0.07, 0.33, 1.27, and 3.32 m). The first two layers are only slightly modified in order to retain a similar temperature response of the soil to the diurnal cycle. It should be noted that the increase in the thickness of the first three layers is about 67 %; that is, from 1 m to 1.67 m.

  In addition, a corresponding change in the root fraction formulation has been made. In ECMWF the amount of water that can be extracted by vegetation from the soil is governed by the roots of the vegetation, which are a function of depth and vegetation type. This means that one can increase the thickness of the soil layers without a corresponding increase in evapotranspiration, because the vegetation cannot extract the water from the soil if there are no roots. Therefore we increased the depth of the roots of the vegetation by 67 %, similar to the increase in depth of the interface between the third and the fourth model layer (note that the plants extract most water out of the first three layers). This is perhaps physically debatable since root fractions are to some extent measured quantities. However, considering the uncertainty how the root fraction translates into evapotranspiration, it might be still defendable.
- The second change concerns the way vegetation responds to soil drying. In the reference version this is a linear function between 1 (when the soil is at field capacity) and 0 when the soil is at wilting point. The evaporation is parameterised by:

  $$E = \frac{\rho_a}{r_a + r_c}\left(q_{sat}(T_{sk}) - q_l\right)$$
  $$r_c^{-1} = f(w_s)G(R, LAI, ...),$$

  where T_{sk} is the skin temperature, ρ_a is the density of air, and q_l is the atmospheric specific humidity at the lowest model level. Furthermore, r_a is the atmospheric resistance, and r_c is the resistance due to the vegetation, which is a function f of available soil water w_s. In addition, the vegetation resistance is modified by a function G of radiation R, the leaf area index LAI, etc. (see ECMWF IFS documentation equations 7.7 to 7.14).

  In the following we will loosely call this function $f(w_s)$ the stress function. We have changed the stress function from a linear relation into a non-linear one. The new stress function is shown in Fig.4. The function is such that evaporation is reduced for soil moisture values near field capacity, but a higher evaporation is supported for intermediate values of soil moisture. This functional dependency makes evaporation less sensitive to changes in soil moisture content in a large range of intermediate soil moisture values.

- The third change concerns the percolation of soil water to deeper layers. In the reference system the percolation is based on the average properties of the soil. However, percolation is a strongly non-linear function, and the average percolation of the different soil types is much lower that the percolation based on the average soil properties. Therefore, to mimic this effect we reduced the percolation to 10 % of its original value. (This might seem a rather big change, but because percolation is highly non-linear it is a rather small change even.) The impact of the first two changes turned out to be largest; the impact of the change in percolation is more moderate. In the near future we plan to include a soil type map in the climate system.

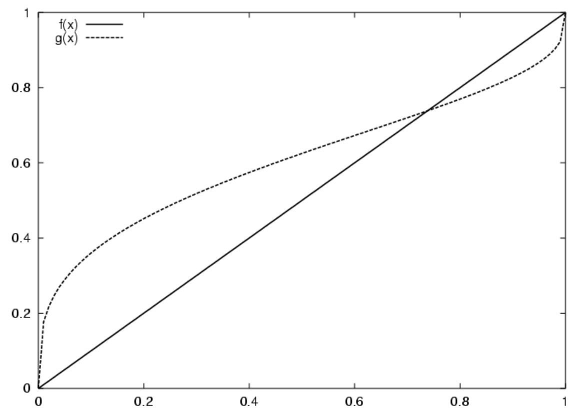

Fig.4. *Response of the evaporation to soil moisture (normalized to1 field capacity; 0 is wilting point). The solid line corresponds to the formulation in the reference model; the dashed line to the new non-linear formulation.*

b. Results

In this section we will illustrate and quantify our findings further. The initial experiments indicated that a change in the soil thickness (in order to increase the buffer) is quite essential to prevent a drying out of the soil in summer. Because it takes some to time to adjust to the thicker soil layers, we spun our model with the thicker soil up from 1 Dec. 1978 to 1 Jan. 1981. Then we started a series of one-year experiments with changes in the physics. In this report we discuss the results of three packages of modifications:

1. *Modified-soil physics:* All changes in the soil physics; that is, thicker soil layer, non-linear vegetation stress function, and 10 % percolation.
2. *Thick-soil physics:* All changes in the soil (as 1.), but with the linear stress function used in ECMWF CY23r4.
3. *Full-modified physics:* All changes in the soil and the following additional changes:
    - Lower threshold convective precipitation (0.5 to 0.25 g/kg).

- Evaporation of precipitation reduced to 50 %
  (5.44 10^{-4} to 2.72 10^{-4} in Eq. 6.54 of the IFS documentation).
- Prescribed entrainment flux of dry convective boundary layer reduced from 20 % to 10 %

The first two changes are an attempt to increase precipitation amounts, and enhance the local re-circulation of water, in particular in summer time where the precipitation bias is most pronounced. The entrainment flux is reduced because at the present low vertical resolution 20 % gives an overestimation of the entrainment flux due to resolution effects. If the grid spacing equals the thickness of the entrainment layer, the prescribed entrainment flux should be about half the value of 20 %. This modification also enhances the humidity in the boundary layer, thereby increasing the potential for cumulus convection.

In the following we will denote the ERA15 run with standard physics and unfiltered orography the reference run, whereas the new runs are shortly denoted the modified-soil physics (package 1), the thick-soil physics (package 2), and the full-modified physics (package 3). The latter runs all use the filtered orography. (Some short integrations of RACMO2 showed that filtering the orography has only a marginal effect on the summer temperature bias. Decreasing the precipitation over mountains is not accompanied by a corresponding increase in precipitation at lower altitudes.) As a rough indication of the impact of the changes, we show in Fig. 5 the JJA mean temperature at lowest model level (30 m) at 12 UTC. The reference run is clearly too warm (compared to the ERA15 analysis) by approximately 4 K in central Europe, the Balkan and Spain. (Note that the comparison should be considered as a rough indication of the bias only, since the ECMWF ERA15 re-analysis is based on an interpolation between measurements and model. The temperature field shown is corrected for the difference in orography between the ECMWF ERA15 re-analysis and the orography used in RACMO2. Differences between filtered and unfiltered orography are not very significant, except for places with steep orography like the Alps and the Pyrenees.) Figure 5 also shows results of the run with the modified-soil physics and the full-modified physics. Both show a vast improvement compared to the reference run. In most areas the temperature bias reduces by 2 to 3 K. In Spain, the Balkan and the southern part of France a positive bias remains. Part of this bias, in particular over France, can be explained by differences in the synoptic patterns between (internally generated in) RACMO2 and the ERA15 re-analysis. This will be discussed in the next section. The results with the thick-soil physics are in-between the results of the reference run and the other two revised physics packages. The results show that the main improvement is due to the changes in the soil physics, both due to the increase in water holding capacity and in the weaker dependency of evapotranspiration on soil water content (the vegetation stress.).

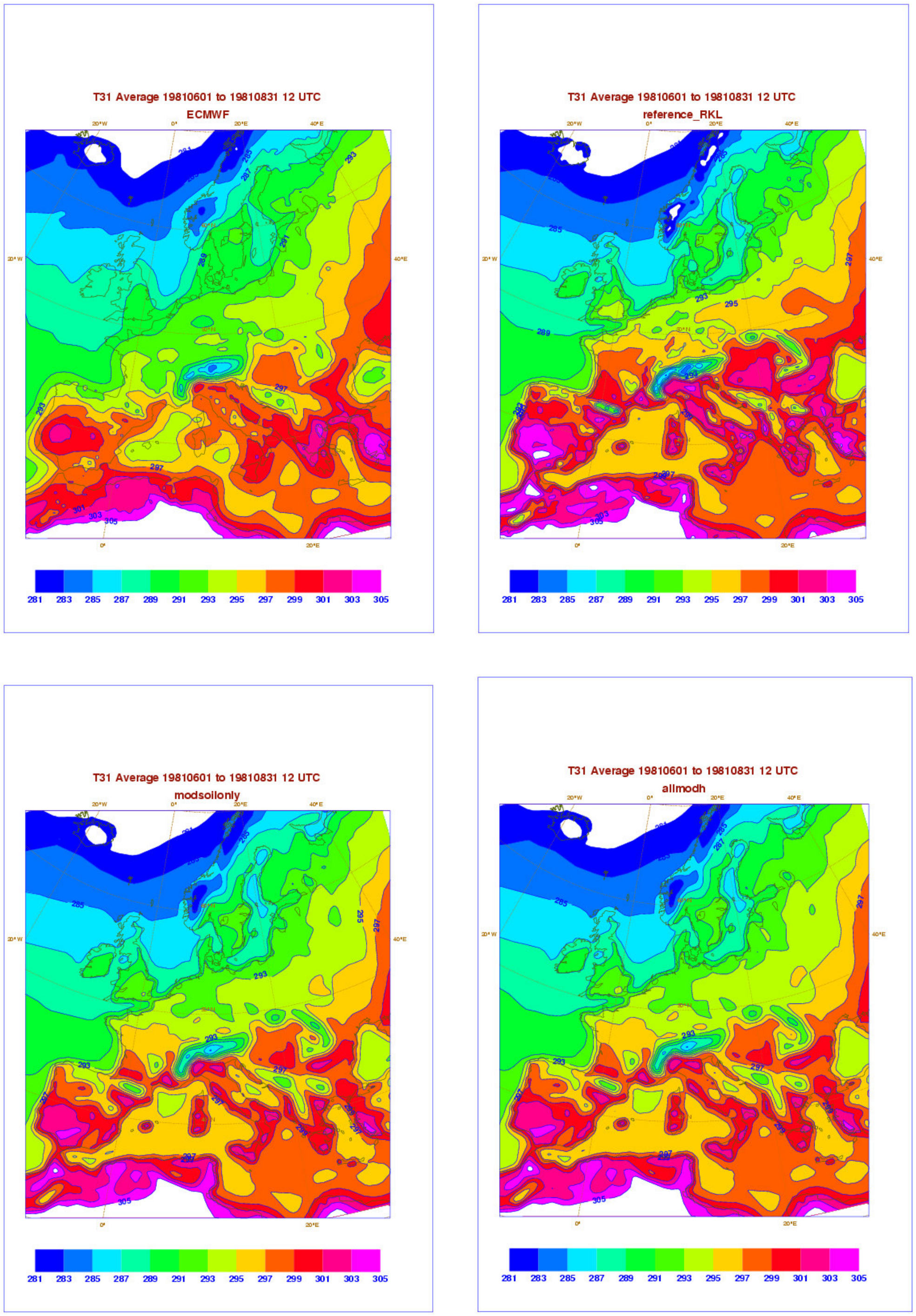

Fig.5. *Mean JJA 30 m (lowest model level) at 12 UTC in 1981. Upper panels: left ECMWF driving analysis; right: RACMO2 ERA15 run; lower panels: left: RACMO2 modified-soil physics (phys package 1); right: RACMO2 full-modified physics (phys package 3).*

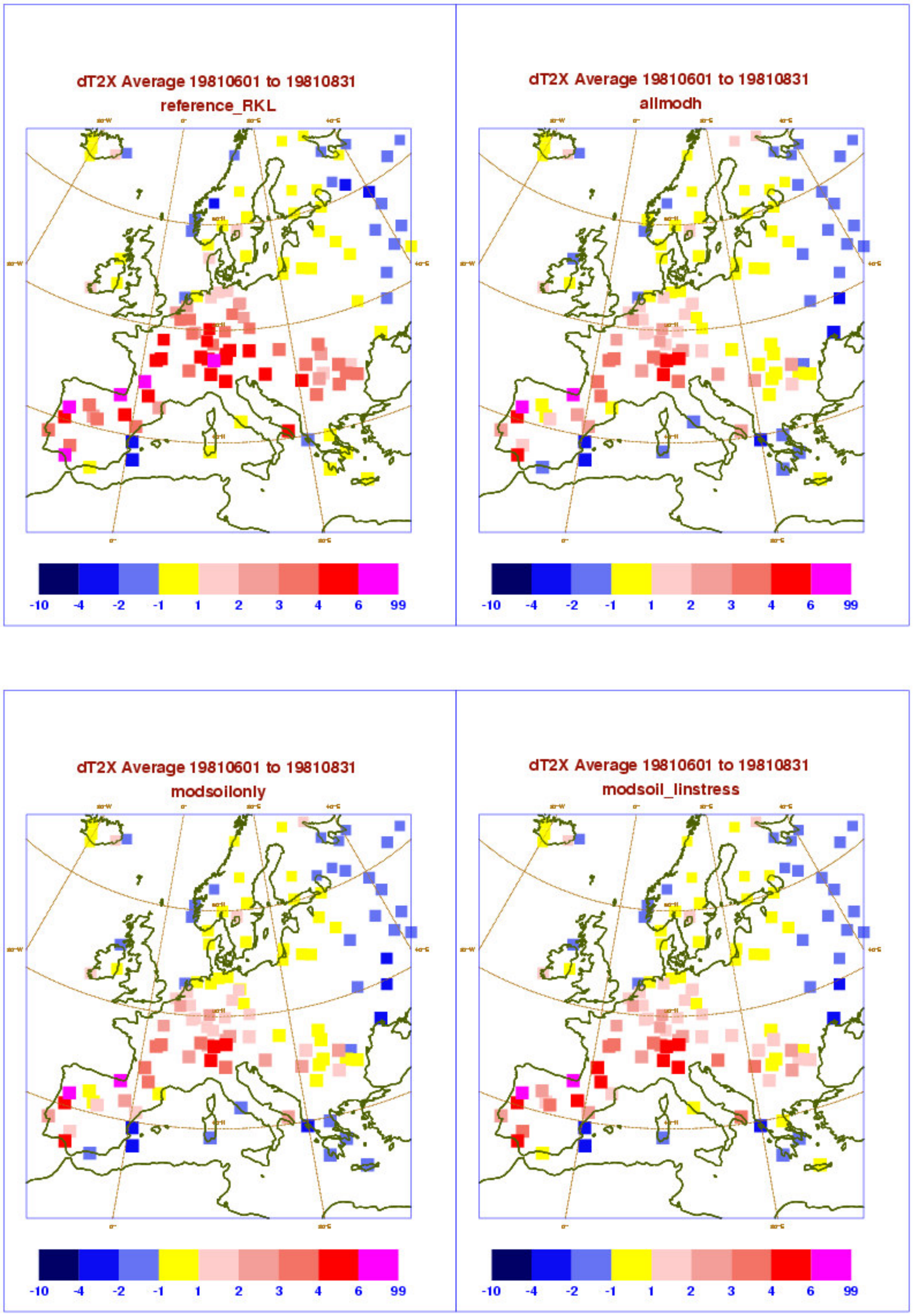

Fig.6 *Bias of the model compared to ECA stations. Mean maximum temperature over June, July and August 1981.Upper panels: Left-hand side: reference model; right-hand side: full-modified physics. Lower panels: left-hand side: modified-soil physics; right-hand side: thick-soil physics.*

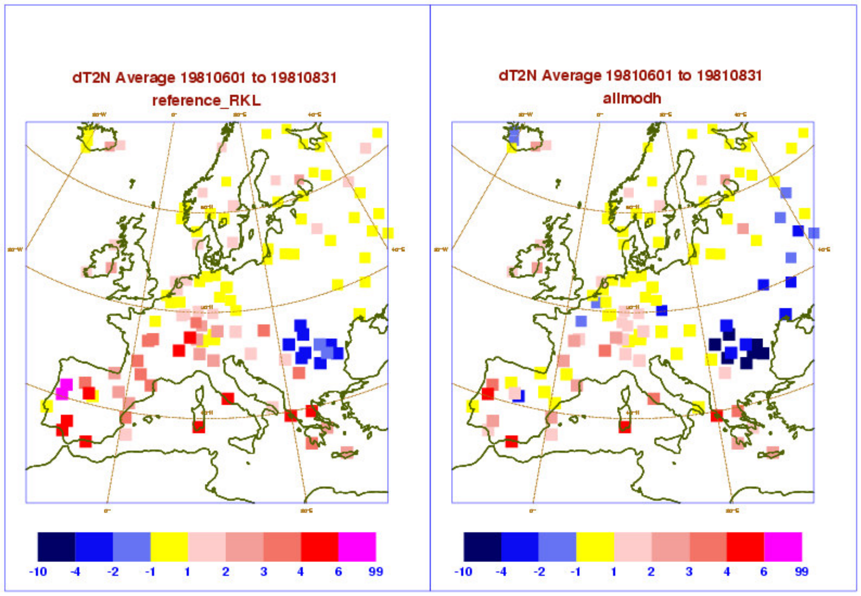

Fig.7 *Bias of the model compared to ECA stations. Mean minimum temperature over June, July and August 1981. Left-hand side: reference model; right-hand side: full-modified physics.*

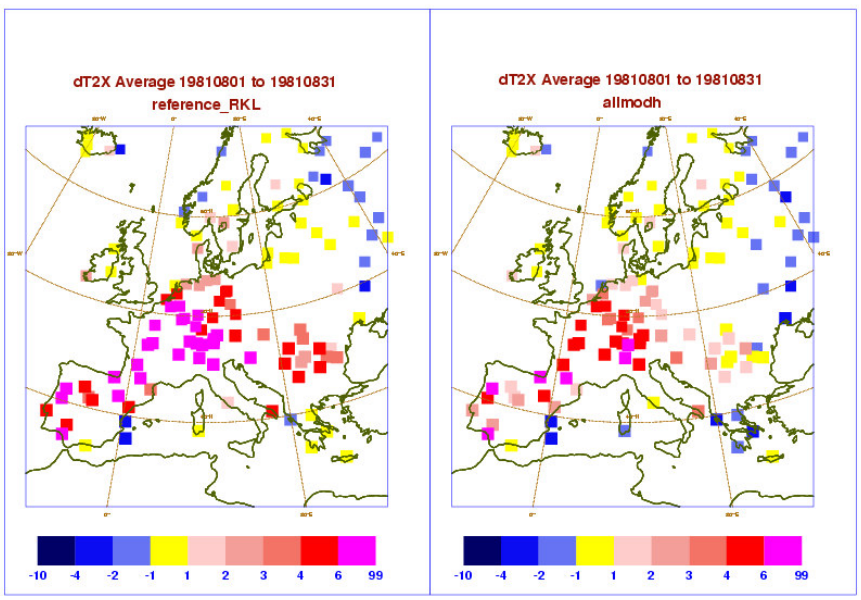

Fig.8 *Bias of the model compared to ECA stations. Mean maximum temperature of August 1981. Left-hand side: reference model physics; right-hand side: full modified physics.*

In Fig. 6 a comparison of the mean JJA maximum temperature in RACMO2 with the ECA station data (Klein-Tank et al. 2002) is shown. The reference run is clearly much too warm over central Europe, in accordance with the comparison with the ERA15 re-analysis. Note also that the north-eastern part of the domain is too cold. This appeared to be related to spurious effects at the boundary relaxation zone of the domain (to be discussed later). The run with modified soil and the full-modified physics are again rather similar. They improve significantly over most areas of central and south Europe; over France, however, a significant bias of 2-4 K remains. The thick soil physics run is somewhat worse, in particular over the central part of Spain and over France. The average minimum temperature in Fig. 7 also shows an improvement for the revised physics package. Again the modified soil and the full-modified physics are very similar. Note that there is a cold area near the Black-sea with temperature biases of –4 to -6 K. This bias gets worse with the revised physics. The cause of this bias is yet unclear. Also the HadRM3 model appears to experience a similar bias in this region when compared to ECA data (Moberg and Jones, 2003).

In the following, we will focus on August 1981. Late summer the soil is dry, and consequently the temperature bias is particularly strong. The reference run has a bias of over 6 K over large parts of France and Spain (see Fig. 8). In the run with the full-modified physics the bias has decreased, but it is still rather large (approximately 4 K over France). The run with modified-soil physics is again very close to the latter. Because the soil is dried out in August and there is still a large short-wave radiation flux at the surface, this month is optimal to illustrate the impact of the change in the vegetation stress function. Figure 9 shows the temperature response (compared to the reference run) in the run with the modified-soil physics, and the difference between the run with thick-soil physics and the modified soil physics to show the impact of the non-linear vegetation stress function. The run with modified-soil physics is about 3-5 K colder at noon than the reference run. In central and south Europe the impact of the non-linear stress function is about 2 K. However, in Spain, where soil moisture amounts are very small, the difference is larger and most of the temperature reduction in the run with modified-soil physics is explained by the non-linear vegetation stress function.

4. Lateral boundary relaxation

Further analysis revealed that the situation in Aug 1981 with a warm bias in France is not exceptional; similar situations occurred in June 1979 and 1981. In addition, it appears that the temperature bias over France in August 1981 is not only related to the physics. Other warm summer months did not seem to suffer from this bias pattern. For example, a short 6-month integration starting 1-3-1983 made in an earlier stage (with a physics package close to the full modified physics) revealed that the bias for July 1983 (see Fig. 1) had practically disappeared. In this run the bias at the lowest model level compared to the ERA15 re-analysis was almost everywhere between –2 and 2 K. (Unfortunately, this run also included some additional changes to the cloud scheme, which might blur the comparison somewhat. At this time, we do not have precise quantification of the additional impact of these changes, but based on previous experiments we estimate this effect to be small. In short integrations, the increase in cloud cover due to these changes turned out to be rather small, with systematic differences of only a few percent in total cloud cover.)

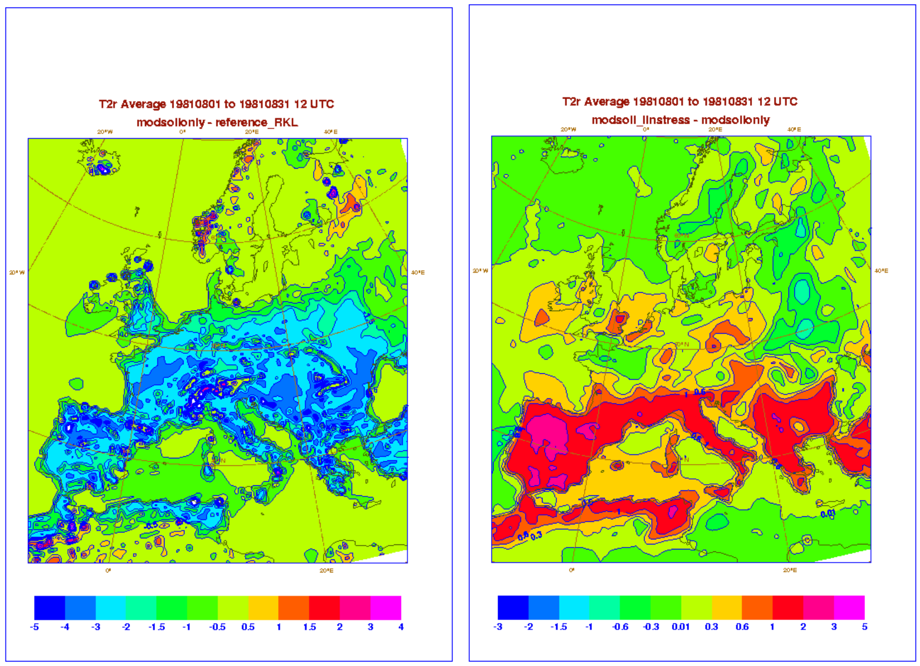

Fig.9 *Temperature response of the model to changes in the physics. Shown is temperature at 12 UTC mean over Aug. 1981. Left-hand panel: difference between modified-soil physic and reference run. Right-hand panel: difference plot thick-soil minus modified-soil physics to show impact non-linear stress function.*

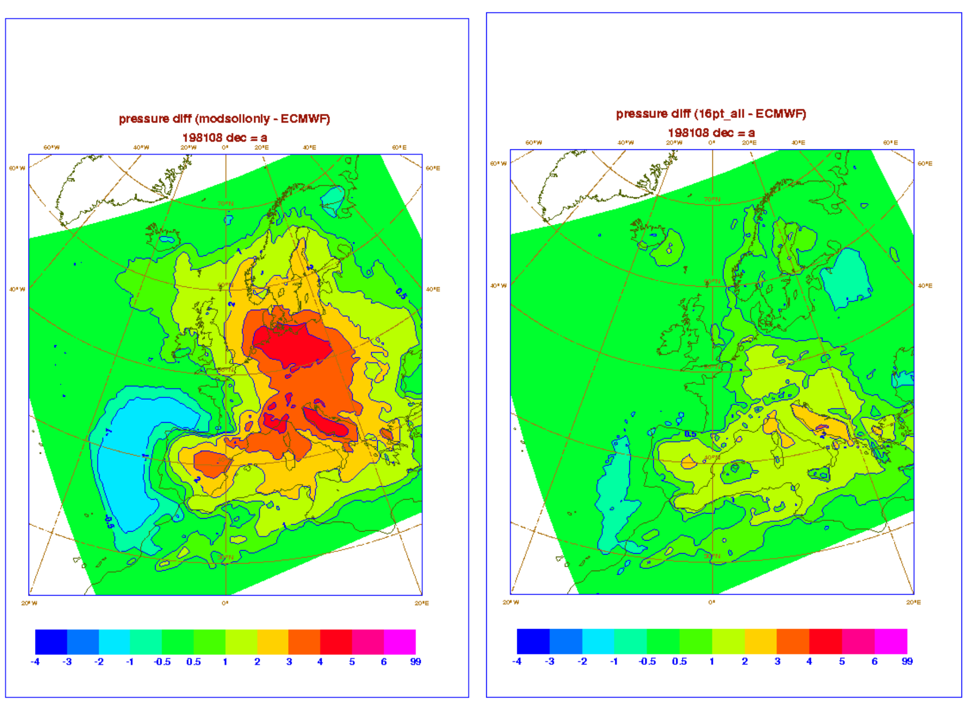

Fig.10. *Mean sea level pressure bias(compared to driving analysis fields). Left-hand side: standard boundary relaxation field; right-hand side: new relaxation field.*

To illustrate what is causing the anomalous temperature in France, we plotted in Fig. 10 the mean pressure bias in the RACMO2 simulation, compared to the driving re-analysis data. A large positive pressure anomaly is causing anomalous south-easterly winds over the western part of the continent, bringing warm air to France and Benelux. Similar anomalous pressure patterns occurred in June 1979 and June 1981. Other seasons, however, did not experience such large deviations from the driving analysis fields. All experiment with modifications in physics (as presented in the previous section) had a marginal impact on the mean pressure bias only, though they had quite some effect on the temperature bias. It is therefore not likely that the pressure bias shown in Fig. 10 is a response to the temperature response due to the different physics. (Some experiments with the stable length scale for the mixing of momentum by the turbulence scheme did seem to have some effect, giving a response pattern similar to the observed anomaly pattern. But this is not sorted out very systematically at the moment.) Another potential explanation of the pressure bias problem is that it is caused by a mismatch of the pressure systems in the domain and the boundaries. In particular at the eastern boundary relaxation zone of the domain, a mismatch in timing may lead to the production of noise and reflections. (The boundaries are not "transparent" to disturbances.) This hypothesis is to some extent consistent with the sensitivity to the turbulence scheme. The mixing of momentum impacts on the timing and development of the pressure systems, which might influence the mismatch at the eastern boundary.

An analysis of the day-to-day development of the synoptic systems learned that in some events the model deviates strongly from the driving analysis fields. These events typically last a few days to a week. In particular this may occur when the circulation is weak. In Fig. 11 such a case is shown. RACMO2 (right-hand side figures) does not reproduce the pronounced blocking pattern with a separated low just south of the Alps as shown in the re-analysis data (figures in the middle). Instead it produces a ridge over western Europe and a through over eastern Europe. Surface pressure anomalies that remain locked-in at the eastern boundary of the domain are present. In some periods these anomalies show to have a tendency to move anti-clockwise along the eastern boundary.

The lateral boundary relaxation scheme turned out to play a significant role. The scheme describes the fields at the boundary by:

$$\phi^{n+1} = (1 - f(i))(\phi^n + \Delta\phi^n) + f(i)\phi^{n+1}_{bound},$$

where ϕ is *{u,v,q,T,ps}*; *$\Delta\phi$ is the* tendency of physics and dynamics; *n+1* is the new time step, and *n* the old time step; ϕ_{bound} is the boundary field given by the forcing fields. The relaxation function *f(i)* is a function of the grid point distance to the outer boundary zone; it is 1 at the outer boundary (hard reset to the forcing field) and small at the innermost point that is relaxed. In Fig. 12 the relaxation functions are shown. The standard scheme uses 8 points, with the same function for all variables.

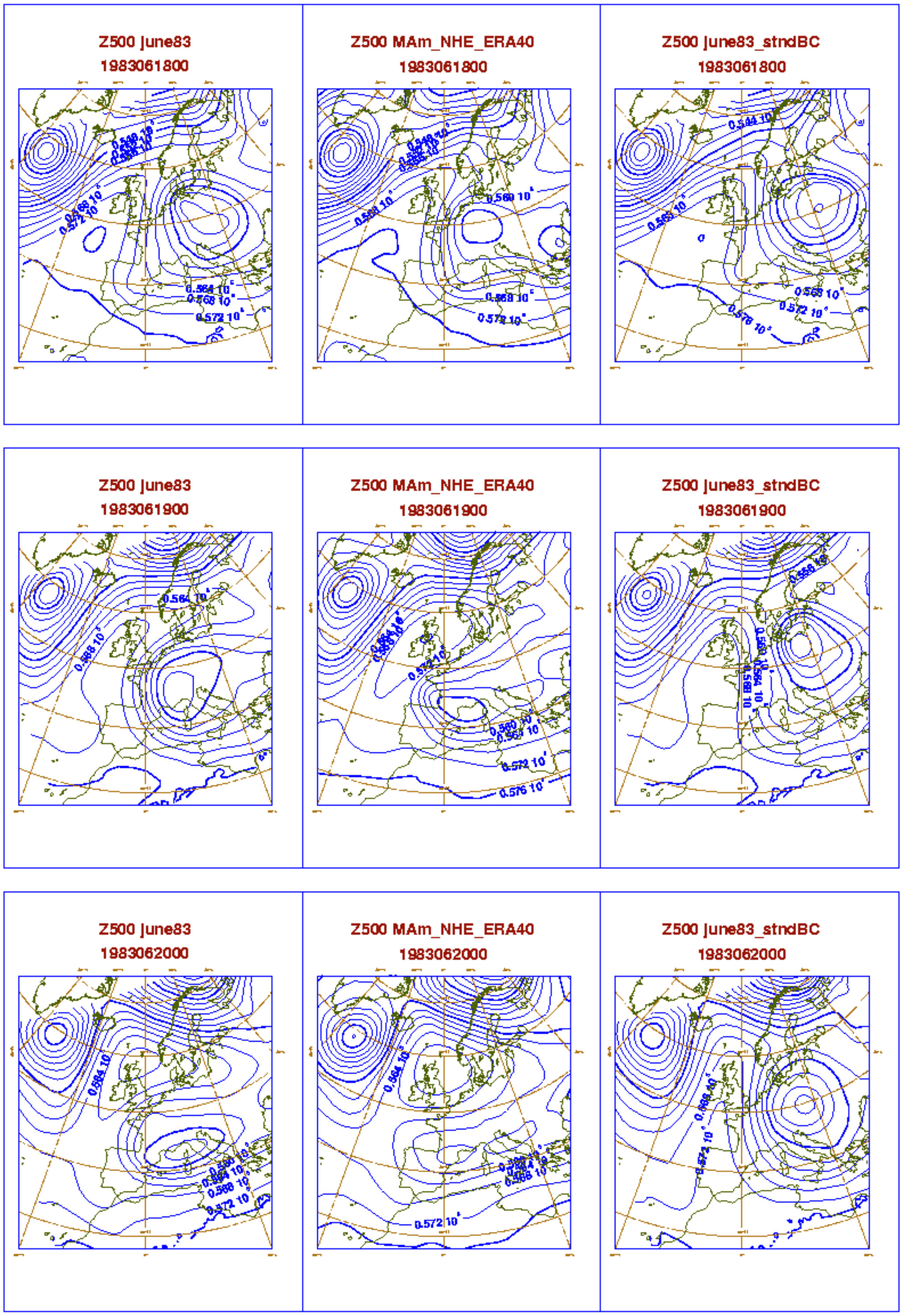

Fig.11. *500 hPa height fields for 00 UTC on 18 (upper panel), 19(middle panel) and 20 (lower panel) June 1981. Left: RACMO2 with new boundary relaxation scheme; middle: ECMWF re-analysis; right: RACMO2 with standard boundary relaxation scheme.*

The new scheme extends the boundary relaxation zone to 16 points. With a grid spacing of approximately 50 km in the RACMO2 model set-up, the boundary relaxation scheme extends 800 km. For temperature, moisture and the surface pressure, the new relaxation function adds a longer tail (with low values), keeping the value for the outermost 8 points the same. For wind the relaxation function falls off two times slower; at point 16 the value is the same as point 8 in the reference scheme. Two reasons for making this adjustment are:

- The broader boundary layer zone for wind exerts a stronger control of synoptic systems in the model domain.
- The different relaxation for heat, moisture and pressure on the one hand and horizontal velocity on the other has additional advantages. The weaker relaxation of temperature and humidity (compared to wind) allows more freedom of the temperature and humidity fields, and it reduces the areas of spurious, intense precipitation close to the boundary layer. These areas of intense precipitation may occur because the relaxation term for water vapour may act as a source term, which compensates for the sink term driven by anomalous vertical motions producing precipitation. In the new scheme anomalous vertical motions (coupled to anomalous horizontal winds) are already strongly damped before the relaxation of humidity may start to act as a source term of moisture.

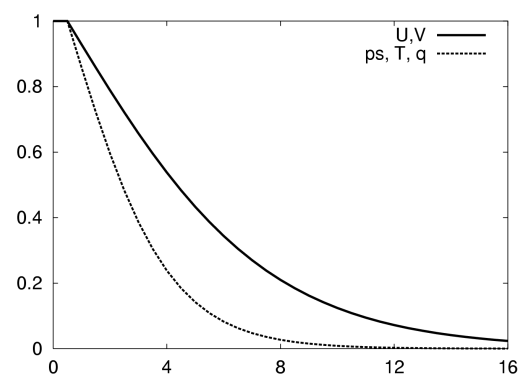

Fig.12. *Relaxation function of the revised boundary layer scheme. The boundary layer zone extends 16 grid-points. The standard scheme equals the dashed line until 8 points (for all variables) and is zero further away.*

Figure 10 shows the mean surface pressure anomaly (compared to ECWMF re-analysis) with the standard relaxation scheme and with the new scheme. The persistent pressure anomaly is reduced significantly with the new relaxation scheme. The time series of the surface pressure anomaly still show fairly strong patterns, but the lifetime of these anomalies is strongly reduced. The same holds for anomalies in the 500-hPa height. Figure 11 (left-hand side panels) shows that the synoptic development of the 500-hPa height remains much closer to the driving analysis fields. Still there is a tendency to produce different synoptic systems with the new scheme (see the situation at the 18th of June), the new scheme produces a much stronger damping of these anomalous pressure systems; two days later (the 20th of June) the Z500 height is again rather close the driving re-analysis.

The response of the daily mean maximum temperature is shown in Fig. 13. A large improvement of the bias compared to ECA stations is clearly visible; the temperature bias in France decreases from more than 4 K to almost zero with the new boundary relaxation scheme. The impact on the mean summer time precipitation is shown in Fig. 14. The spurious, intense precipitation in the north-eastern part of the domain is much less pronounced with the new relaxation scheme.

Also in a longer time integration the new relaxation scheme turned out to perform better than the standard relaxation scheme. A run from Jan 81 to Sep 82 with the new scheme, including the full-modified physics package, showed that in almost every month (except one in which both runs were similar) the pressure bias improved. The pressure patterns in June and August 81 were significantly better simulated with the new scheme. A short integration of June 79 showed similar improvements. At the same time no negative side effects were discovered.

To summarize the results of the different runs we show in Fig. 15 the mean bias in maximum temperature and precipitation over all ECA stations. The run with revised physics and new boundary relaxation scheme has a bias between 0 and –1 K during almost the whole year, and the vast improvement compared to the other runs is evident. The two peaks in June and August, corresponding to the anomalous circulations in RACMO2, have disappeared. For the precipitation the signal is not as clear. Until September the new boundary relaxation scheme does not lead to systematic differences. However, the period from September to December is systematically dryer with the new lateral relaxation scheme. Part of this decrease in precipitation can be explained by the decrease in spurious precipitation at the eastern boundary. In addition, the standard boundary relaxation scheme produces a persistent anomalous low-pressure system in autumn over central Europe, causing higher – though unrealistically forced – precipitation amounts. The amplitude of this anomalous pressure pattern is reduced to about 30 % with the new relaxation scheme, with a corresponding decrease in precipitation. It should also be noted that the number of ECA stations is rather small which limits the statistical significance of this results.

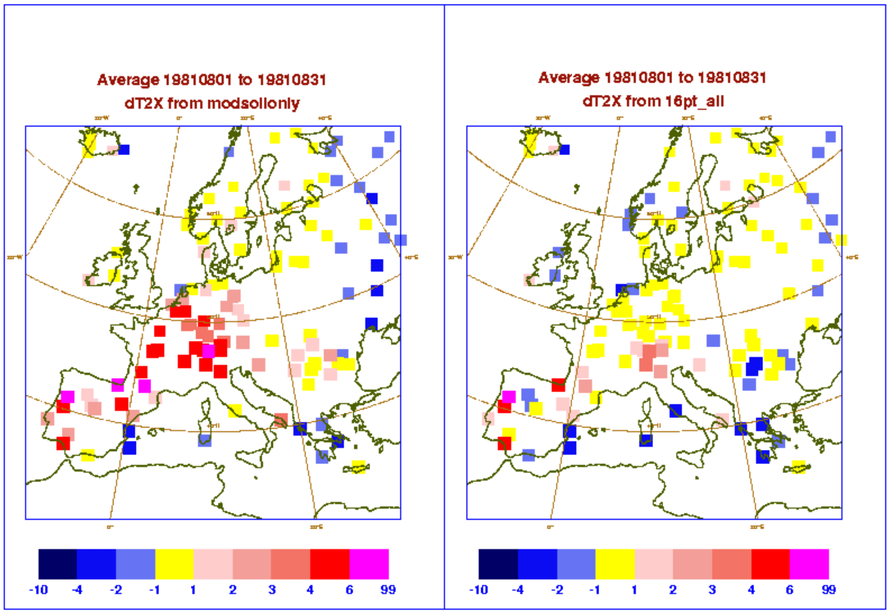

Fig.13. *Temperature response to boundary relaxation scheme. Left-hand side: temperature bias compared to ECA with standard boundary relaxation scheme; right-hand side: with new relaxation scheme.*

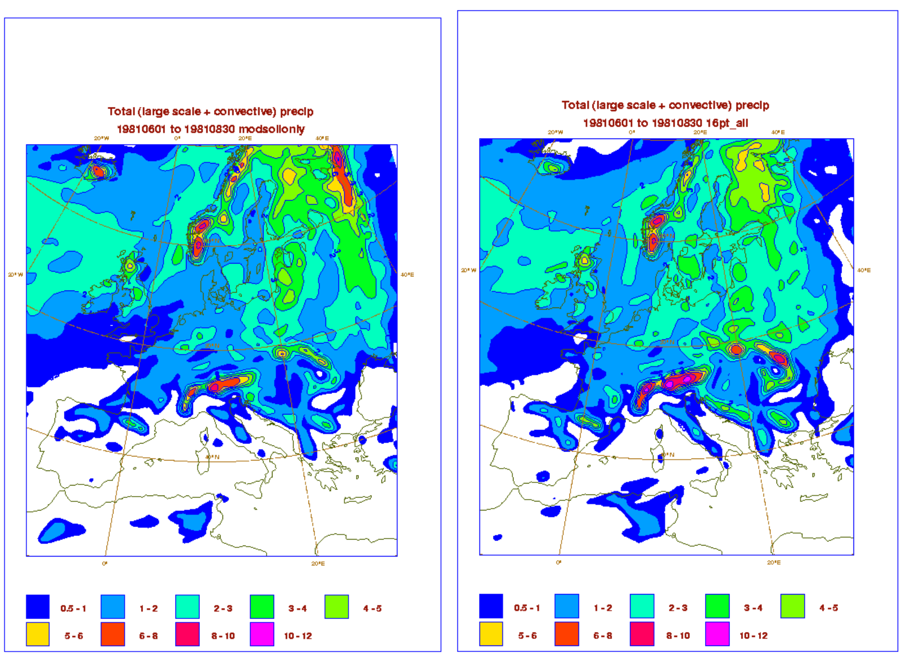

Fig.14. *Total precipitation with standard boundary relaxation scheme (left-hand side) and with new boundary relaxation scheme (right-hand side).*

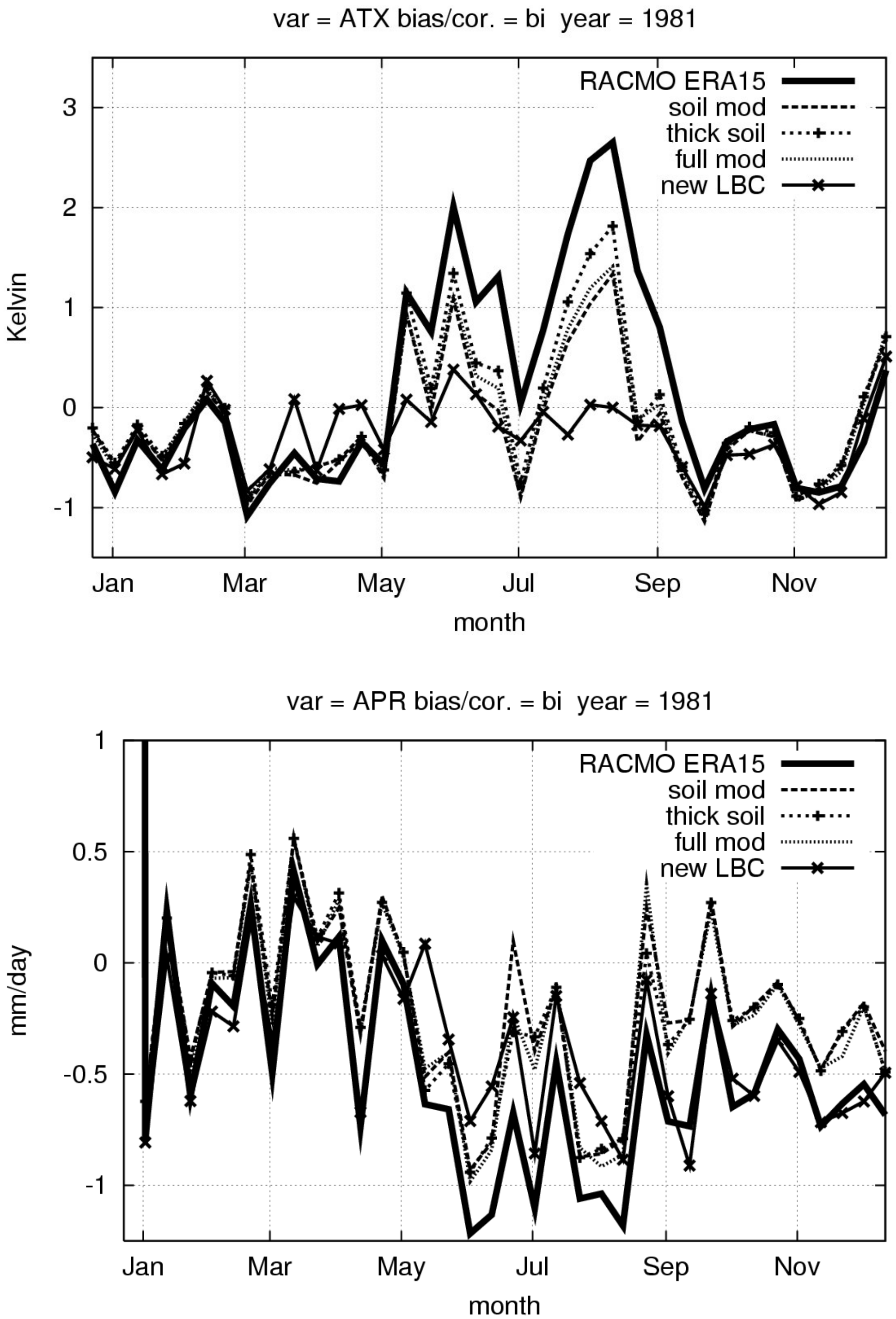

Fig. 15. *Bias maximum temperature and precipitation (mean over the domain) compared to ECA station data.*

5. Horizontal diffusion

The horizontal diffusion of moisture may enhance rainfall over mountains. The standard option in the HIRLAM semi-Lagrangian dynamics is to diffuse moisture along model levels. (A. McDonald who is responsible for the SL dynamics is not aware of the existence of a semi-implicit diffusion solver for moisture that can be used to diffuse along pressure levels.) The diffusion along model levels causes transport up the mountains, since a gradient in water vapour content between the valleys and the mountains tops related to the temperature gradient is nearly always present. This causes an enhancement of the precipitation on the tops of the mountains. Though there might be a physical basis for some uphill transport due to diffusive processes, the amount of diffusive transport in RACMO2 is certainly unrealistically high.

Fig. 16 shows the JJA rainfall in the model run (revised full-modified physics and filtered orography) with the standard diffusion coefficient and with diffusion coefficient reduced to 10 % of its original value. The reduction of the diffusion leads to a decrease in precipitation amounts over the top of 1-3 mm/day, bringing it closer to realistic values. Reducing the diffusion constant even more has a small impact only.

6. Summary and discussion.

We have described changes to the standard configuration of RACMO2 to improve the simulation of present-day climate. The standard configuration of RACMO2 consists of the ECMWF cycle 23r4 physics and the HIRLAM 5.0.6 semi-Lagrangian dynamics. We have discussed the following changes:

- *ECMWF physics package:*
  The increase in soil depth to enhance the soil water holding capacity and the implementation of a non-linear vegetation stress function, which determines the response of evapotranspiration to soil drying, are most important to decrease the sensitivity of the model to summer time warming. In addition, the percolation of water to the deeper layers has been reduced.
- *Orography:*
  The orography of the model has been filtered. This reduces artificial rainfall over the tops of the mountains. At the same time, however, spatial information is lost.
- *Lateral boundary relaxation:*
  A new boundary relaxation scheme has been developed to improve the development of the synoptic systems in the model. In the new scheme the horizontal winds are forced in broader zone (16 points extending 800 km) than the other variables. It improves the statistics of blocking patterns in the model significantly. Also spurious rainfall along (in particular) the eastern boundary is reduced.
- *Horizontal diffusion of moisture:*
  The horizontal diffusion of moisture causes additional uphill transport of moisture, causing increases in rainfall on the top of the mountains. The

diffusion constant for moisture has been reduced to 10 % of the original value.

The combination of these changes has resulted in a significant improvement of the summer temperature bias. Additional changes in the physics package, for example in the cloud scheme, did not have a large impact on the summer temperature bias. The experiments point at the strong control of the surface scheme on the summer time simulation, in particular over central and southern Europe.

The model is still found to underestimate summer precipitation. This appears to be related to the underestimation of convective rain events. With the revisions proposed in this report we were not able to improve significantly on this aspect. (It should be noted that the representation of convective summertime precipitation is rather poor in many regional climate models.) This might be due to the triggering mechanism of deep convection over land. Note that in a simulation of the Hadley circulation performed over the Pacific Ocean in the EUROCS project, the standard physics package did give reasonable cloud amounts (except for the stratocumulus area) as well as realistic convective precipitation amounts connected to the deep convection over sea near the Equator (http://www.knmi.nl/samenw/eurocs/). This suggests that, if the activity of the convection scheme is about right, the precipitation amounts are also. Also RACMO2 seems to produce much more convective precipitation over sea than over land.

Another worrying aspect of RACMO2 concerns the vertical structure of the clouds. The low-level cloud fraction is (very) low, whereas the middle level cloud cover seems overestimated. This might be related to the fact that i) there is no separate formulation for low level stratiform clouds, such as Stratocumulus and Stratus, in the ECMWF physics (it is part of the convective clouds), and ii) the cloud cover is highly connected to the massive detrainment by the mass flux scheme in the inversion. A EUROCS inter-comparison showed that the ECMWF model tends to have the maximum cloud cover and cloud liquid water at a (much too) high level. This characteristic has been confirmed by comparison with observations in the CLIWA-NET project as can been seen from Fig. 34 of Crewel (2003) The representation of boundary layer clouds, and in particular the representation of convective precipitation, deserve further attention since these weaknesses may limit the applicability of the model.

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APPENDIX

RACMO2 runs at a resolution of 0.44 degrees, both in latitudinal and longitudinal direction. This corresponds to approximately 49 km. The domain, which has 114 points in longitudinal direction and 100 in latitudinal direction, is shown in Fig. 17. The boundary relaxation scheme is 8 points wide in the standard model setup.

The model uses 31 vertical levels, corresponding to the ECMWF 31 Level resolution. The lowest model level is at 30 m. A time step of 12 min is taken. Though with the SL dynamics longer time steps should be possible, the model does not run stably at the moment with longer time steps than 12 min.

The boundary layer update interval is 6 h. The model integration is split up in short runs of one day, taking about 10 min on 4 CPU's at the SUNFIRE 15K.

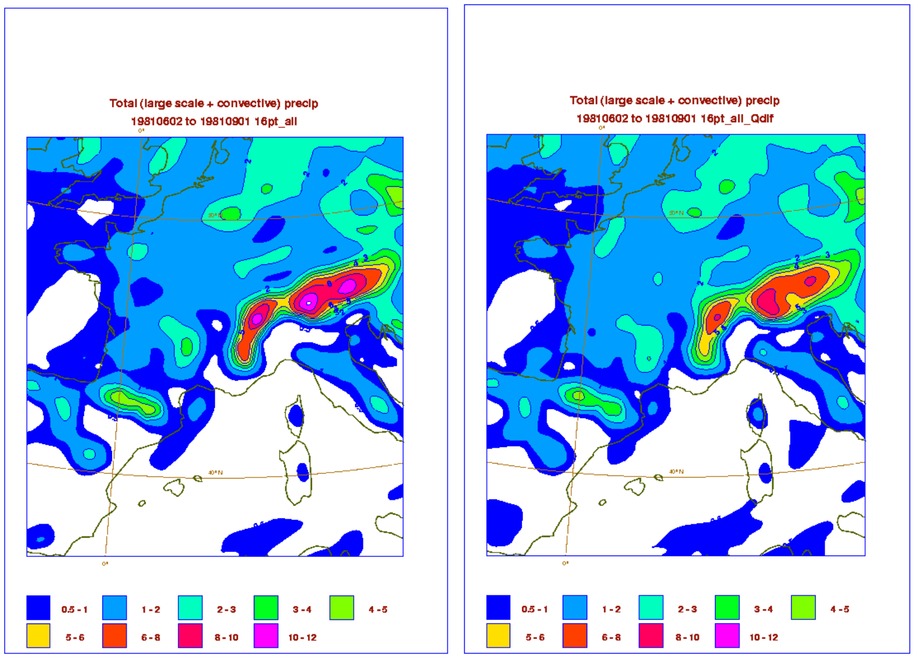

Fig. 16. Precipitation over the Alps with standard coefficient horizontal diffusion of moisture (left) and with reduced (to 10 %) coefficient for horizontal diffusion (right).

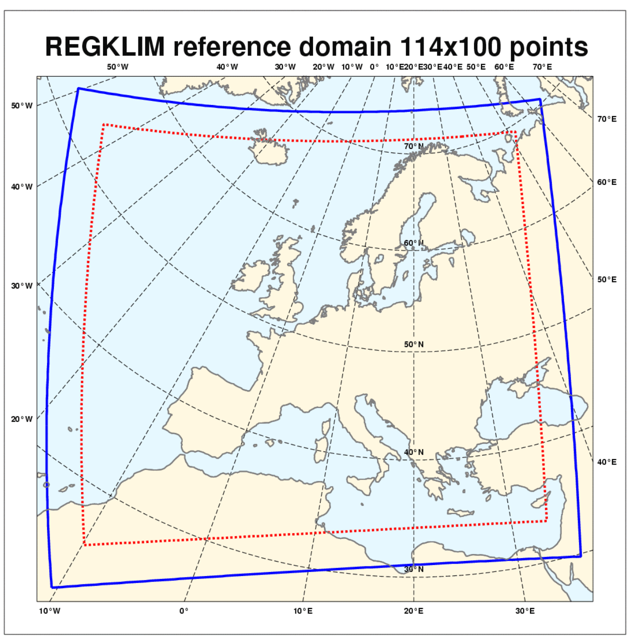

Fig. 17. Model domain of RACMO2. The area between the red and the blue line is the boundary relaxation zone, which extends 8 points in the standard model set-up. With the new relaxation scheme the boundary relaxation zone extended 8 points more into the inner domain.

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