

Regional climate simulation with a mosaic of RCMs

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Abstract

The aim of the present study is to explore the possibility of getting high horizontal resolution over Europe by using a cluster of low computational cost atmospheric general circulation models (AGCM). The approach is based on global models with stretched grid, driven by a medium-resolution model serving as a “conductor” to maintain time consistency of the synoptic events and avoid climate degradation in the low resolution part of the grids. Thus the global models behave as regional climate models (RCM). A perfect model approach is used with a high resolution AGCM serving as a reference. The results show that when the different models are merged on a high resolution grid, the mean climate is similar to what is obtained with an equivalent high resolution AGCM with an unstretched grid. A climate change numerical experiment shows that this is also valid for the climate response to increased greenhouse gas concentration.

1. Introduction

The expectation in the forthcoming decades of a warming of the planet by a couple of degrees and the fear that the frequency of extreme events will increase are commonly mentioned by the mass media, but are not sufficient for decision makers at a regional level. In the 4th IPCC Assessment Report (IPCC, 2007), some results at regional-scale were given through statistical downscaling of large-scale (200 to 400 km) general circulation models (GCM), and some regional climate models (RCM) simulations at higher resolution (30 to 100 km). At European level the FP5-PRUDENCE coordinated experiment (CHRISTENSEN et al. 2002, JACOB et al. 2007) proposed an ensemble of RCM simulations at 50 km resolution.

The next IPCC exercise (AR5) will include contributions of regional models on areas of the globe that have not been covered recently by international multimodel projects like NARCCAP over North America (<http://www.narccap.ucar.edu/>) or ENSEMBLES over Europe (HEWITT AND GRIGGS, 2004). This project, endorsed by the World Climate Research Program (WCRP), is named CORDEX (COordinated Regional Downscaling EXperiment). The target resolution will be 50 km. Ideally, the best exercise would be to run global models at 50 km resolution (or higher, e.g. MATSUEDA et al., 2009 used a 20 km resolution) driven by sea surface temperatures (SST) from lower resolution coupled model (between 100 and 200 km in AR5). But such an exercise is not affordable for many modeling groups, and very heavy for other groups. Since one key issue of regional response to climate change is the evaluation of uncertainties (DÉQUÉ et al., 2007), the number of available independent numerical experiments is as important as the horizontal resolution of the model outputs.

Another approach is to use several models focusing on various regions. The traditional approach is based on limited area modeling (GIORGI, 1990). But global modeling is also feasible, as long as horizontal resolution is not constant (FOX-RABINOWITZ et al., 2008). The total computation cost of many regional models over the globe is larger than the cost with a single high resolution model, but:

- one is not obliged, in practice, to cover the whole globe, because there are areas of interest
- the present generation of computers favors the distribution of computations over several nodes, and the elapsed time with parallel independent models may be less than running a single high resolution model
- the computations can be shared between different centers having different areas of interest (this is the principle of CORDEX)

Recent results presented in the Lund 2009 workshop and available from the author upon request as a technical report (DÉQUÉ, 2009) show that covering the globe with 20 variable resolution models produce a seamless global mean climate comparable to the climate generated by a single high resolution version of the same model. Introducing lateral boundary conditions to maintain a time consistency between the 20 variable resolution AGCMs introduces a minor degradation in boreal winter temperature.

The aim of the present study is to explore the above approach with a focus on Europe. In section 2 the model characteristics are presented and in section 3 the method to get high resolution over a part of the globe is developed. The cost and benefits of the approach, in terms of computation are examined in section 4. In section 5, the mean climate of a cluster of global variable resolution AGCMs is compared with the mean climate of a single high resolution AGCM. In section 6, the response of this cluster to a climate change scenario is compared with the response of the high resolution AGCM. A conclusion and two perspectives are given in section 7.

2. ARPEGE-Climate AGCM

ARPEGE-IFS is the numerical model used for operational forecasting at Météo-France and European Centre for Medium-range Weather Forecasts (ECMWF) since the 1990s. It is also used as a climate model (DÉQUÉ et al., 1994). This model has been natively built to allow having the pole of longitude-latitude coordinates everywhere on the globe (not necessarily in the Arctic Ocean). In addition, the latitudes circles can be distributed in a non-uniform way, with a homothetic transform on the polar stereographic projection plan. This is the only transformation family which enables isotropy everywhere over the sphere (COURTIER and GELEYN, 1988). The principle of the transformation is:

- 1.project the globe onto a plan by a stereographic projection centered on the pole of stretching
- 2.multiply all distances to this pole by a constant factor c , named the stretching factor
- 3.go back to the sphere by an inverse stereographic projection

At a given location, the mesh size in any direction is multiplied by a map factor m which depends only on the angular distance θ to the pole of stretching:

$$m = \frac{2c}{(c^2+1) - (c^2-1) \sin \theta} \quad (1)$$

Isotropy of the horizontal discretization (made possible with a spectral decomposition based on a triangular truncation) is a useful property because the atmosphere equations (except the Coriolis term) are independent of the direction of the axes. So, introducing anisotropy in the numerics introduces artifacts in the solutions, e.g. by filtering more efficiently waves coming from the West than waves coming from the North. The drawback of the ARPEGE-IFS technique, named polar stretching, is that there is less flexibility in designing the area of high resolution than when playing independently with latitude and longitude discretizations (STANFORTH and MITCHELL, 1978, LI, 2006). This approach, primarily designed for Numerical Weather Prediction, has been validated in climate mode by DÉQUÉ and PIEDELIEVRE (1995).

The climate model used here is version 5.1 of ARPEGE climate. This version is an adaptation of the version described in GIBELIN and DÉQUÉ (2003) to a more recent cycle of ARPEGE-IFS (cycle 32 instead of cycle 18). The characteristics of its dynamical core as well as the physical parameterizations are very similar. One can find a detailed description at <http://www.cnrm.meteo.fr/gmgec/arpege-climat/ARPCLI-V5.1/index.html>. This spectral model has 31 levels on the vertical and a time step of 20 min whatever the spectral truncation used in the present study, thanks to its semi-implicit and semi-Lagrangian dynamics.

As far as the physical parameterizations are concerned, the convection scheme is a mass-flux scheme with convergence of humidity closure described by BOUGEAULT (1985) in its original formulation. The cloud-diffusion-precipitation scheme is presented in RICARD and ROYER (1993). The radiative scheme is derived from MORCRETTE (1990). The orographic gravity wave scheme is based on LOTT (1999) developments. The soil-vegetation-snow scheme is ISBA (DOUVILLE et al., 2000). The Sea Surface Temperatures (SST) are prescribed with monthly means coming from FP6-ENSEMBLES stream 2 coupled simulation (1950-2100). This scenario was run with a TL63 version of ARPEGE coupled with OPA.8 ocean model (MADEC et al., 1998). Beyond year 2000 (see section 6), the A1B scenario was used for the radiative forcing. The SST are corrected by subtracting the calendar monthly mean bias calculated with the 1961-2000 period. In the present study, only two time slices (1961-1990 and 2071-2100) have been considered.

3. An AGCM used as an RCM

With the polar stretching technique, the area of maximum resolution is a spherical cap. The higher the stretching factor, the smaller the area of high resolution (e.g. the area with more than 80% of the maximum resolution). An alternative to the use of a low stretching factor to cover a large area is the use of several models. If one wants to cover the globe with a uniform distribution of poles, the maximum number is 20, due to the limited series of platonic solids. However, one can cheat a little, by considering the 20 faces of an icosahedron: they are equilateral triangles and can be easily divided into equal-area equilateral triangles. For example, if each triangle is divided into 9 triangles, the total number of triangles is 180. The 92 triangle vertices are almost uniformly distributed on the sphere. Getting more vertices is easy to obtain by using a finer discretization of the primary triangles. Here 9 poles, located in and around Europe, are considered amongst those 92 vertices. Their coordinates are given in Table 1. For each model a TL63 spectral truncation (312 km resolution) has been used. This resolution has been typically used in IPCC-AR4 and can be run at a speed of a few simulated years per real day on a standard personal computer. This is a cheap but reasonable truncation in 2009 computer standards. With a stretching factor c of 5, the maximum resolution at the pole is 62 km and the minimum resolution, at the antipodes is 1560 km. If we merge the 9 stretched grids, retaining at each location the model which has the highest resolution, we get a composite grid. Figure 1 shows the resolution of this grid over Europe. Its minimum resolution between two poles is 83 km and the mean resolution over the display area is 70 km.

Contrary to DÉQUÉ (2009) such models cannot be run in standalone mode (or GCM mode) because their too coarse resolution outside Europe is detrimental to the simulation everywhere. These models need a driver, like standard limited area models (LAM). Here the driver is a non-stretched version of the same model with a TL127 truncation (156 km) which is enough to represent the synoptic circulation. The stretched models are relaxed each time step over the globe towards the TL127 simulation, which acts also as a “conductor” by enabling the nine simulations to remain in agreement at their boundaries. Otherwise, each model would have an independent chronology. The lowest vertical level is let free, as well as the soil variables, with a linear transition of the relaxation coefficient in the lowest 5 levels. The e-folding time of the relaxation is one time step (20 min) for wind, temperature and surface pressure, whereas it is 3 hours for moisture. Indeed the driving (TL127) and driven (stretched) models have the same physics and the same vertical discretization: if they use the same prognostic variables as an input, they calculate the same fluxes. But the driving and driven models have a different surface elevation, which introduces differences in the planetary boundary layer. It is therefore traditional to let some freedom at the time step scale to the diabatic processes in the driven model for numerical adjustments (e.g. GULDBERG et al., 2005). Such differences are harmless because they are little advected from far areas inside the high resolution part of the stretched grid.

These nine stretched models are RCMs, so they must have a relaxation-free area. To this purpose, a spatial mask is applied to the relaxation coefficients. For model i ($i=1 \dots 9$) at location x , this mask is :

$$M_i(x) = Z(d_i(x) \leq d_0, d_i(x) \leq d_1(x), \dots, d_i(x) \leq d_9(x)) T(d_i(x)/d_0) \quad (2)$$

where $d_i(x)$ is local mesh size of model i , calculated with Eq. (1); d_0 is the constant mesh size of the TL127 driver. Z is zero when the condition of its argument is met, i.e. when model i has the maximum resolution, and is one otherwise. Z cannot be zero for two models at the same location. T is a piecewise linear function built as:

- $T=0$ below 0.4
- $T=1/24$ for $d_i(x)/d_0=0.6$

- $T=1/4$ for $d_i(x)/d_0=0.8$
- $T=1$ for $d_i(x)/d_0=1$
- $T=10$ beyond 2

The base idea is that the lower the RCM resolution, the higher the constraint. According to Eq. (2), an RCM is let free ($M_i(x)=0$) at any grid point where its resolution is the maximum out of all stretched models and driver. As a consequence, the composite grid (Figure 1) is built by collecting out of each stretched model the grid points for which $Z=0$. Figure 2 shows this mask for the model with pole 4.

In order to check the reliability of the composite grid, a single situation is displayed as an example: January 1st, 12 UTC, year 30 of the control simulation (year 1990 in the chronology of the SST from the coupled scenario). This map is not the result of a selection: no other daily map has been plotted. Figure 3 shows mean sea level pressure for the driver (TL127) and the driven (composite) models. When looking carefully at the lower panel, one can see some seams south of Iceland, north of Gotland ... but from a synoptic point of view, the two maps are identical. However inside each contributing sub-domain a different model has been run with a progressive constraint outside its boundary.

A static situation is not enough to convince that transient phenomena translate nicely through the domain. Figure 4 shows a Hovmoeller diagram along the 40°N parallel during the last winter of the simulation. This trajectory does not correspond to a storm track, but enables to cross equivalently 4 sub-domains (see caption). In the western half, trough are moving rapidly eastwards, whereas in the eastern half, quasi-stationary high pressure (above 1030 hPa) appear from time to time. The composite is close to the driver, and no seam appear at 32°W, 0°E and 32°E, whereas different simulations are put side-by-side. In order to get a more systematic evaluation of the day-to-day variability, Figure 5 shows the daily standard deviation of January mean sea level pressure. Here again, the 9 different models match in a satisfactory way. In particular, the undulations over Atlas mountain or South of Iceland are not a lateral boundary effect, because they are also present in the driver simulation.

4. Computation costs and benefits

If the aim were to run 92 models in order to cover the whole globe, the approach would be much more expensive than running a single global model at equivalent high resolution. On the other hand, if the aim is to focus on a small region, a single stretched model is sufficient, and the approach has been already discussed in FOX-RABINOWITZ et al. (2008). Here the region we want to downscale covers North Atlantic and Europe at 60 km resolution. A global version of the model at such resolution corresponds to a TL319 spectral truncation and involves 144004 grid points. In the multi-model approach used here, we need a driver model at TL127 truncation, involving 24572 grid points, and 9 stretched models involving 6232 grid points. We use thus 80660 grid points, so 56% of the cost of a global model.

However, counting the grid points gives only a partial view of the real cost, because there are overheads due to input/output, memory distribution, etc. Another evaluation, closer to the actual need of a scientist performing a simulation, is the elapsed time for a 30-year simulation. This time is of course machine dependent. The experiments presented here have been run on a 32-core node of the mainframe IBM computer available at ECMWF in 2009. The TL319 run lasted 25 days, the TL127 run lasted 7 days, and the 9 stretched model runs lasted 8 days. The ratio is 60%, close to what we get when counting the grid points.

The choice of nine models here has been dictated by the need to have enough seams to prove that

the "mozaic" is not a "patchwork". If we want just a downscaling over Europe, four stretched models are enough and the benefit is higher (ratio 34% in grid point and 44% in elapse time). Another advantage of the multi-stretched approach is that a TL319 version of the models requires a big computer, because of the memory. A TL127 version can be run on a big personal computer with 12 GB memory, and a stretched TL63 needs 15 days for a 30-year run on a standard desktop personal computer. When the constraint is not only real time for experiment, but access to a mainframe computer, we have here another benefit. But we must keep in mind that this provides a downscaling approach, which is not as reliable as an original global high-resolution free simulation. In the following, we will examine how close the "copy" is from the "original".

5. Perfect model validation

At this stage, we shall examine the climate of the composite model. We will not compare model data with observations, but use a perfect model approach. Indeed, the scope of the technique used here is not to compensate some errors of ARPEGE-IFS climate model by other errors coming from this odd composite approach. The aim of the composite is to mimic at a lower computation cost the behavior of a high resolution model over a given region. The reference here is therefore a 30 year simulation of the same model, used at TL319 truncation, which corresponds to 62km, the maximum resolution of the composite map.

Figure 6 shows the 2m temperature differences. In winter, the only region where the RCM behaves in a different way from the high resolution AGCM is Greenland and North Canada. In summer, Europe is 0.5 K warmer with the RCM, and this warming reaches 1 K in south-eastern Europe. All these features are significant at 95% level (simple Gaussian test on the average of 30 independent values). A t-test is not applicable here because the simulations are driven by the same SST and are not completely independent. These features are a response of the model to the lateral conditions, which means they are not a result of the sampling variability (coming from the driving run) or from the model internal variability. This behavior has been observed in perfect model experiments with a LAM (RADU et al., 2008). The warm spot near the Red Sea in summer is outside the domain and is an extrapolation artifact.

Figure 7 show the precipitation systematic error. The amplitude is between -0.6 and 0.6 mm/day and the error pattern does not exhibit any strong structure, except a 0.3 mm/day dry bias over Europe in summer, consistent with the warm bias and statistically significant.

6. Response to a climate change scenario

One of the major applications of GCM/RCM is the response to greenhouse gas increase. Here we will consider the A1B scenario for the period 2071-2100. The reference period is 1961-1990, examined in section 5.

In winter, the temperature response of the high resolution model (not shown) is about 2 K in southern and western Europe and 2.5 K in north-eastern Europe (up to 4 K in northern Finland). The difference between the composite and the high resolution response (Figure 8a) show that the composite is 0.5 K warmer in north-eastern Europe. In summer, the warming reaches 5 K in southern Europe and is between 2 and 4 K in the northern part (not shown) . The composite is colder by 0.5 K over the northern part (Figure 8b). One can remark that in both seasons, the RCM approach increases the spatial contrasts.

As far as the precipitation response is concerned, we get a decrease in winter (-0.3 to -0.6 mm/day) over the Mediterranean area, with an extension to the Azores area. North of the 45° parallel, precipitation increases with a maximum of 1 mm/day South of Iceland and along the Norwegian coast. The composite model (Figure 9a) does not modify this pattern but reduces the dry response in

the western part of the Mediterranean and amplifies it in the western part. In summer, the precipitation decrease depicted by the high resolution AGCM (not shown) is generalized over Europe, with a maximum of -0.9 mm/day over Germany. Here, the composite reduces the response with a positive difference of 0.3 mm/day over northern Europe.

Given the strong uncertainties which are attached to climate change over Europe, one can consider that the differences we observe in Figures 8 and 9 do not express a real disagreement between the high resolution AGCM and the composite RCM.

7. Conclusion and perspectives

It has been shown that the grid stretching technique with a high factor, associated with a progressive driving in the low resolution part of the grid offers an interesting alternative to the traditional limited area modeling constrained by Davies lateral relaxation. One can easily build non-rectangular domains (even non-connected domains like Europe and North America). The fact that the constraint is rather loose at the limit between two neighbors makes the seams quasi-invisible and avoids the adjustments problems at the lateral boundaries. With an appropriate adaptation, this technique could also be applied to a mosaic of limited area models.

This series of nine simulations is preliminary, because the equivalent resolution is not different from a single 120-km-grid model run with a stretching factor of 2. We got positive results in terms of time consistency between neighbor AGCMs, as well as in terms of similarity of the mean climates and mean climate responses with a global 60-km-grid model. This suggests that the resolution of the stretched AGCMs could be increased (e.g. going to 100 km). One could also increase the stretching factor c which was 5 in this experiment. A factor $c=8$ seems feasible from preliminary tests. A factor $c=12$ yields to numerical instabilities with ARPEGE-IFS, due to the divergence term in the semi-implicit scheme. With an increased stretching factor the number of poles should increase, in order to avoid large spatial variations in resolution. This is not a technical problem: an equilateral triangle is easy to divide into equal areas. The approach used here can be extended to reach a mesh size of 10-15 km over a flexible domain.

A second perspective is to pass the high resolution information (e.g. a deep cyclone) from one domain to its neighbor by a two way nesting technique (Lorenz and Jacob, 2005). This will mimic what occurs in a true high resolution model. The counterpart of this is that all simulations (the driver and the driven ones) must be synchronous, which makes the computation less flexible. But on a distributed computer, the exchange of information between the neighbors will occur every 2-3 hours instead of every time step in a high resolution model (20 min), which makes the approach potentially fruitful.

The validation approach used in this study gives a framework to experiment the feasibility of the above mentioned two perspectives.

Acknowledgments

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Pole number	1	2	3	4	5	6	7	8	9
longitude	0.	45.	-45.	0.	0.	-38.97	38.97	-15.45	15.45
latitude	20.91	35.26	35.26	58.28	78.36	58.73	58.73	40.76	40.76

Table 1: Longitudes and latitudes of the nine poles used in this study.

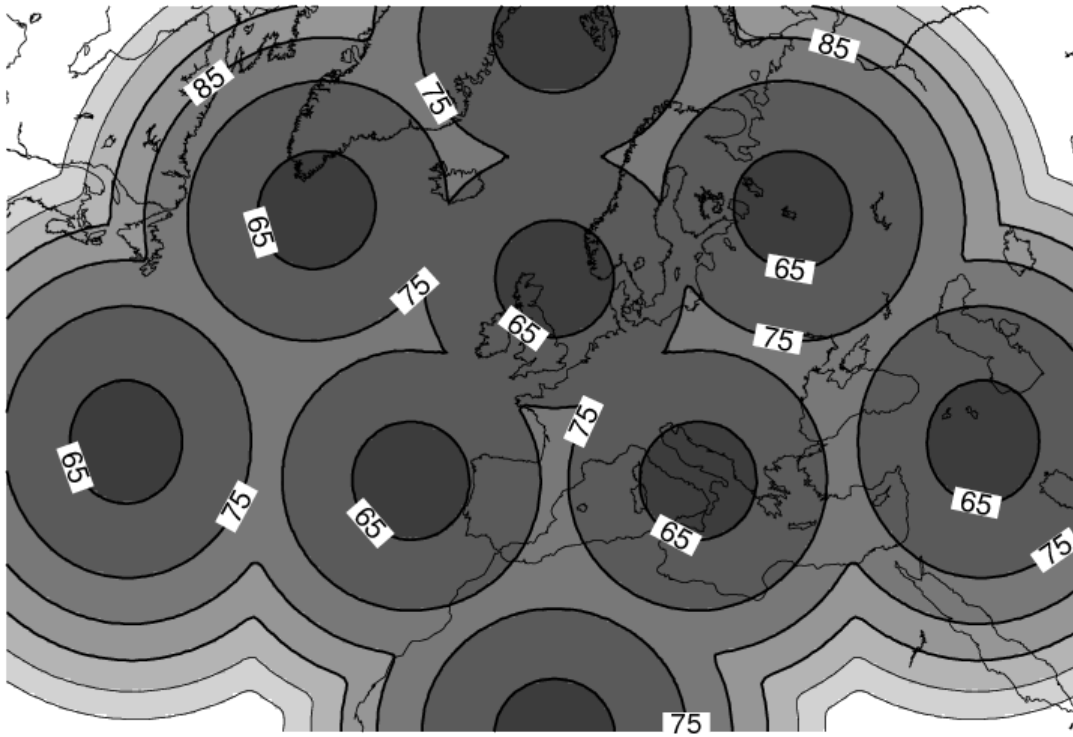


Figure 1: Horizontal resolution of the composite grid based on the 9 stretched grids. Contour interval 10 km.

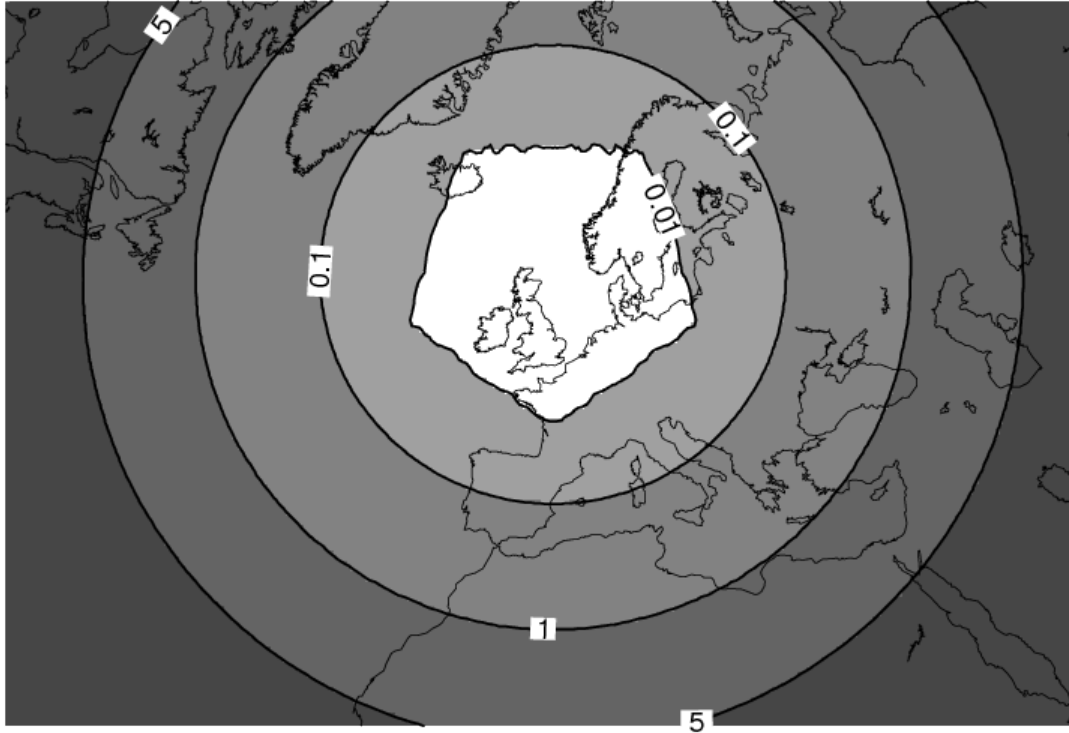


Figure 2: Mask applied to the relaxation coefficient for the stretched model with pole 4. Contours 0.01, 0.1, 1 and 5.

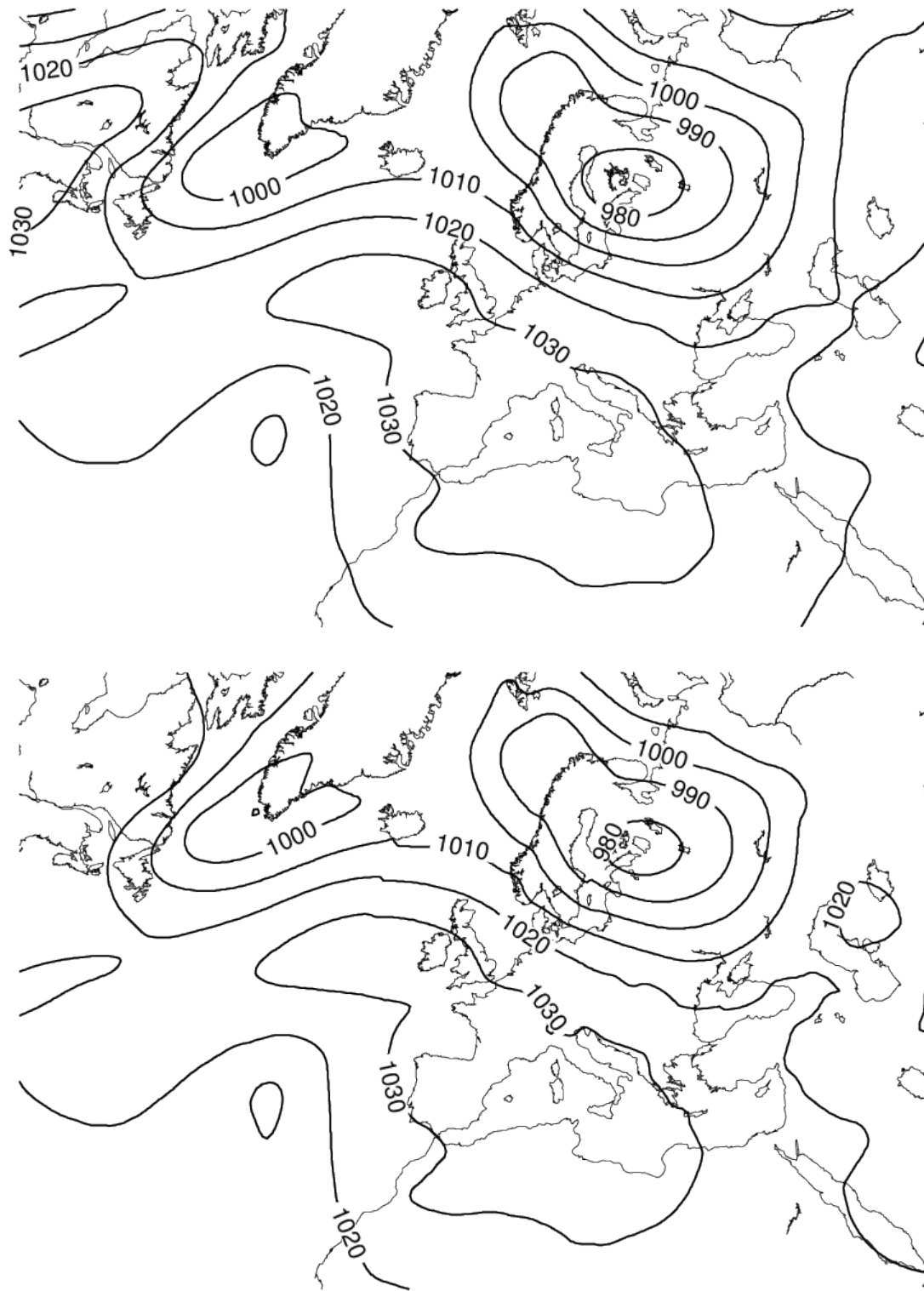


Figure 3: Mean sea level pressure of January 1, year 30 of the control simulation for driving model (top) and composite model (bottom). Contour interval 10 hPa

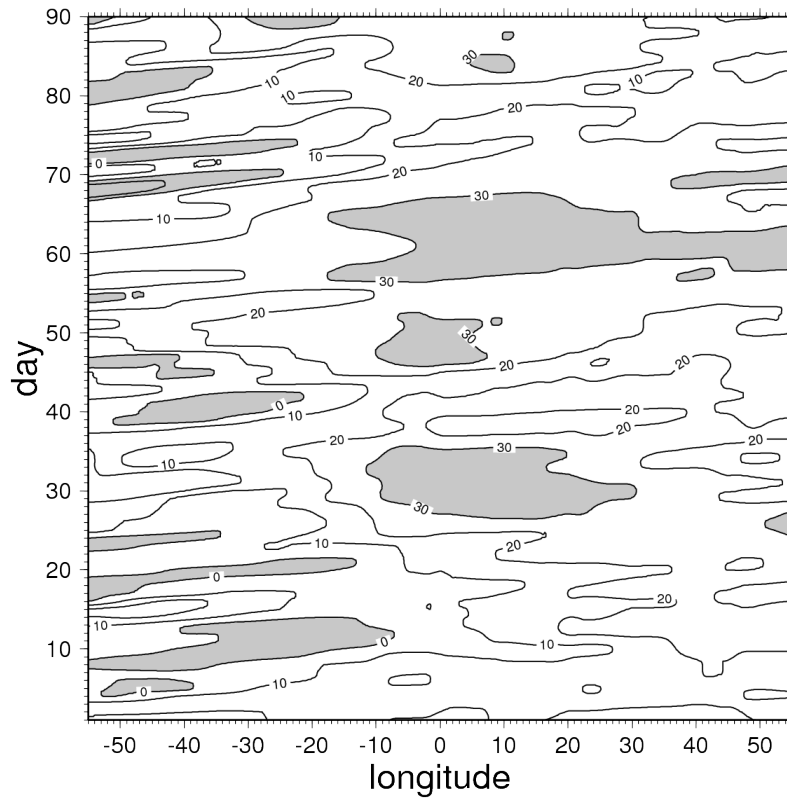
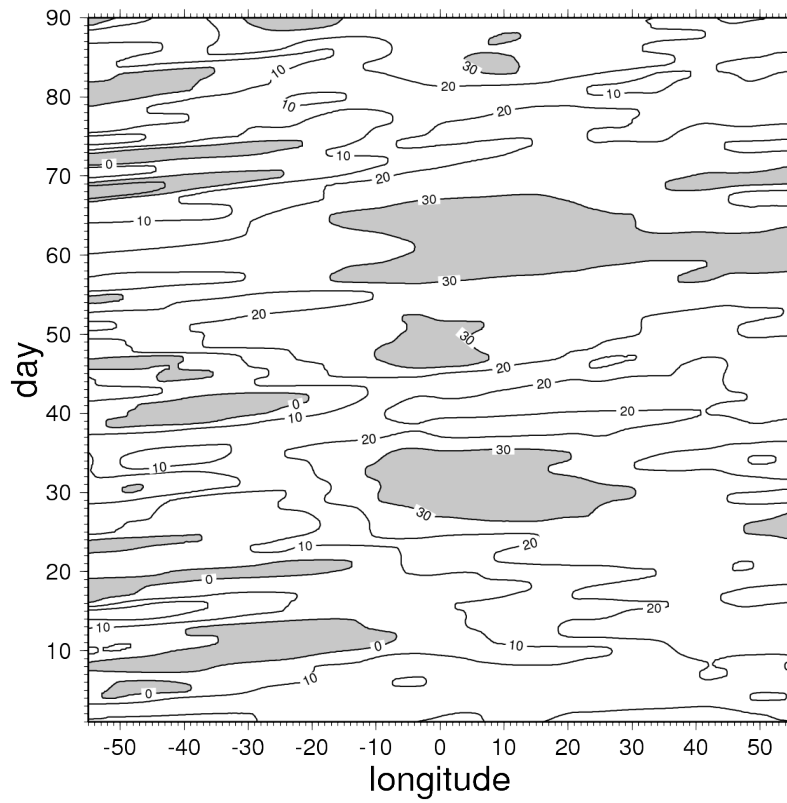


Figure 4: Hovmoeller diagram of mean sea level pressure of the last winter (DJF) along 40°N parallel for driving model (top) and composite (bottom). The composite corresponds to pole 2 (55W- 32W), pole 3 (32W-0E), pole 4 (0E-32E) an pole 1 (32E-55E). Unit is difference to 1000hPa, contour interval is 10 hPa, data above 30 or below 0 are shaded.

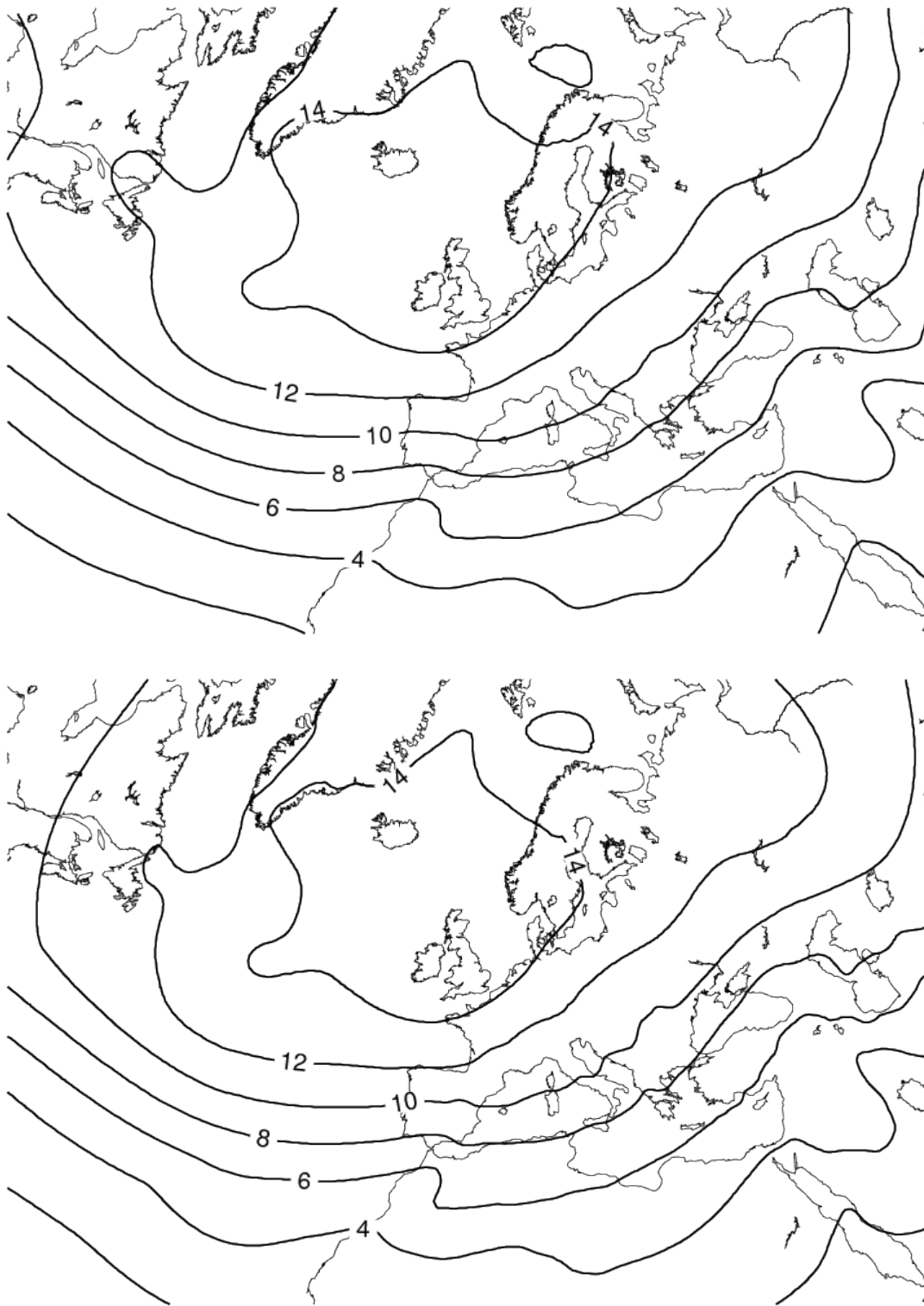


Figure 5: Daily standard deviation of January mean sea level pressure for driving model (top) and composite (bottom); contour interval 2 hPa.

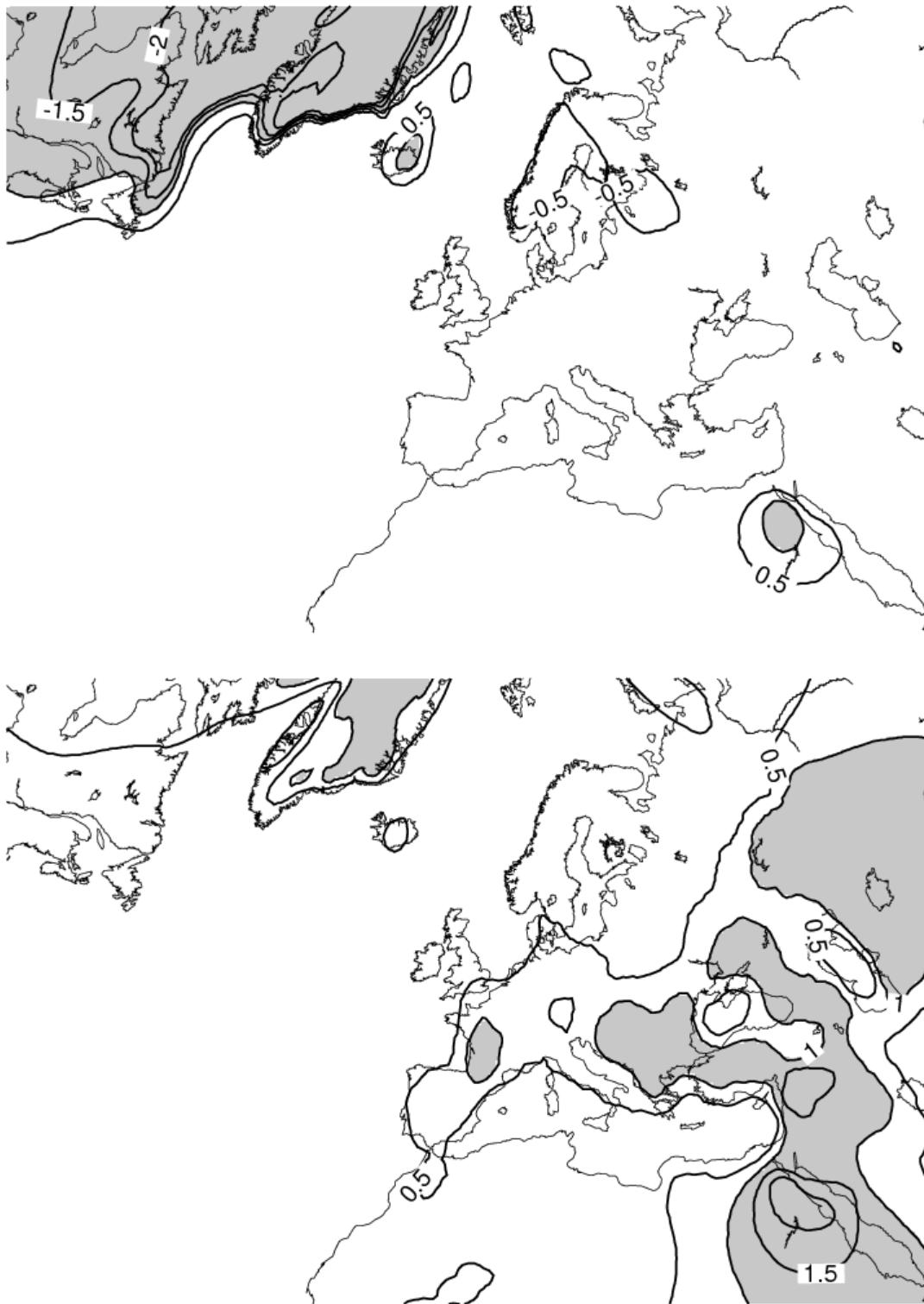


Figure 6: 2m temperature systematic error in the control run in DJF (top) and JJA (bottom). Contour interval 0.5 K, 0-contour omitted, shading above 1 K and below 1 K

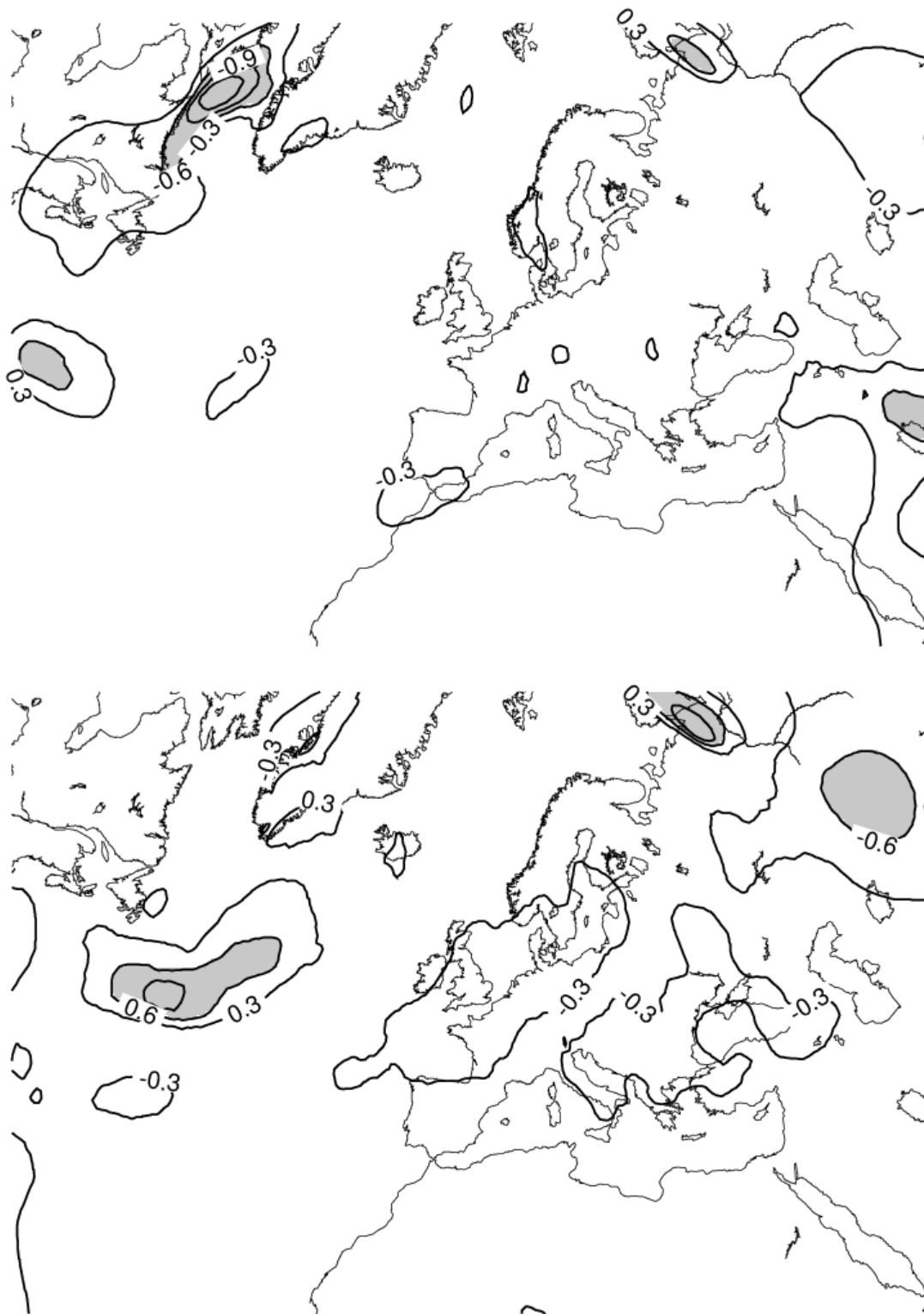


Figure 7: As figure 6 for precipitation. Contour interval 0.3 mm/day, shading above 0.6 and below -0.6



Figure 8: Difference in 2m temperature climate change response for DJF (top) and JJA (bottom). Contour interval 0.5 K, 0-contour omitted, shading above 1 K and below 1 K

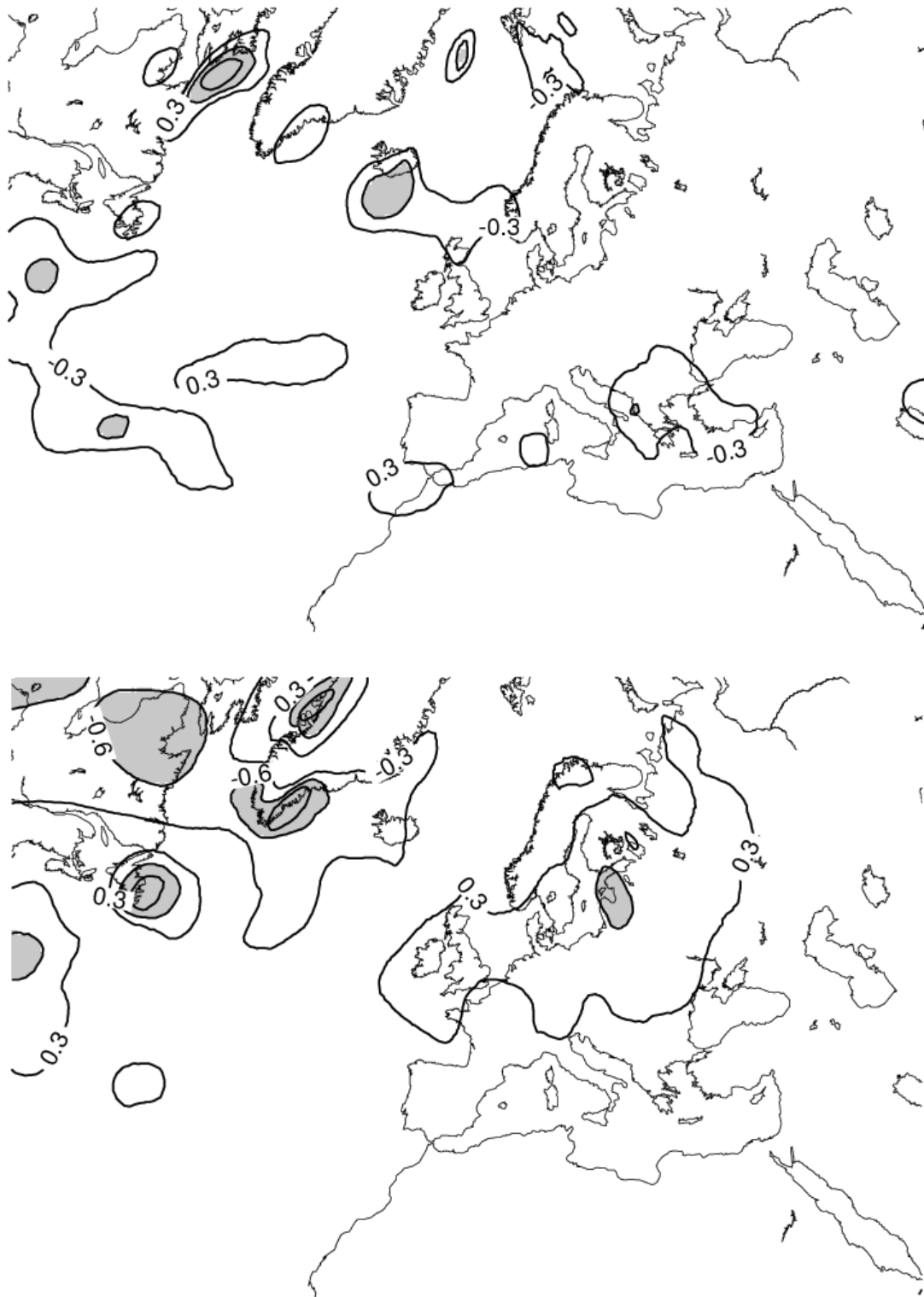


Figure 9: As figure 8 for precipitation. Contour interval 0.3 mm/day, shading above 0.6 and below -0.6