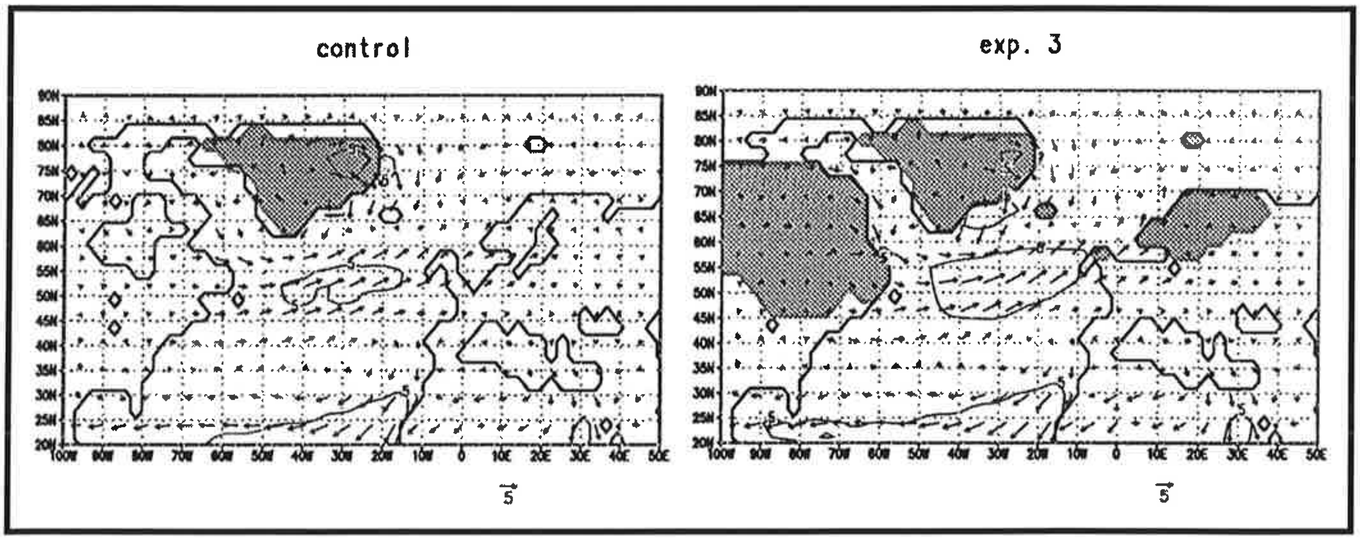
Max-Planck-Institut für Meteorologie

REPORT No. 173



AGCM experiments on the Younger Dryas climate

by

H. Renssen • M. Lautenschlager • L. Bengtsson • U. Schulzweida

HAMBURG, September 1995

AUTHORS:

H. Renssen	Netherlands Centre for Geo-ecological Research (ICG), Department of Physical Geography, Utrecht University Utrecht, The Netherlands
M. Lautenschlager	Deutsches Klimarechenzentrum (DKRZ) Hamburg, Germany
L. Bengtsson	Max-Planck-Institut für Meteorologie Hamburg, Germany
U. Schulzweida	Max-Planck-Institut für Meteorologie Hamburg, Germany

MAX-PLANCK-INSTITUT
FÜR METEOROLOGIE
BUNDESSTRASSE 55
D-20146 HAMBURG
F.R. GERMANY

Tel.:	+49 - (0)40 - 411 73 - 0
Telefax:	+49 - (0)40 - 411 73 - 298
E-Mail:	<name>@dkrz.d400.de

ISSN 0937 – 1060

AGCM experiments on the Younger Dryas climate

H. Renssen[1], M. Lautenschlager[2], L. Bengtsson[3] and U. Schulzweida[3]

[1] Netherlands Centre for Geo-ecological Research (ICG), Department of Physical Geography, Utrecht University

[2] Deutsches Klimarechenzentrum (DKRZ), Hamburg

[3] Max-Planck-Institut für Meteorologie, Hamburg

ISSN 0937-1060

Abstract

The Younger Dryas (YD) cooling (~12.5-11.5 thousand years before present) signified an interruption of the warming during the transition from the last glacial to the present interglacial. Since the mechanism responsible for this cooling is still uncertain, a numerical simulation of the YD climate has been undertaken to obtain some additional insight into this event.

Three experiments with the ECHAM3 atmospheric general circulation model at T42 resolution were carried out to study the YD climate. In a first experiment only the North Atlantic surface conditions were altered according to geological evidence. In a second and third experiment additional boundary conditions were altered, as ice-sheets were introduced in North America and Scandinavia and the insolation and CO_2 concentration were changed. The third simulation was identical to the second, except for an additional North Pacific cooling. The experimental outcomes were compared with that of a control simulation of present climate.

The main deviations in the results were found around the North Atlantic Ocean. In the YD experiments the mean annual temperature was a few degrees lower over the continents, although the difference was larger in the vicinity of newly defined ice-sheets. An intensified atmospheric circulation was simulated.

Deviations from the control climate were compared with climate reconstructions based on geological evidence. The reconstructed cooling in Europe during YD was larger than in the simulations, especially during the northern hemisphere (NH) winter. During the NH summer the reconstructions showed a large temperature gradient going inland which was consistent with the experiments. Improvements in the N-Atlantic sea surface conditions were proposed, since they were the most important factor controlling deviations.

1 Introduction

The transition of the last glacial to the present interglacial was rather irregular. During the Weichselian Late Glacial (approx. 14.5-11.5 ky BP) the climate in Northern Europe was characterised by several rapid shifts. A sudden warming around 14.5 ky BP marked the onset of the Bölling-Alleröd interstadial. This relatively warm period lasted until 12.5 ky BP, when a sharp drop in temperature indicated the beginning of the Younger Dryas (YD) stadial. The cool conditions of the Younger Dryas ended with an abrupt warming at the start of the Holocene (~11.5 ky BP). The mechanisms responsible for the sudden cooling at the beginning of the Younger Dryas and the quick warming afterwards are still debated. Moreover, there is no clear answer to the question whether the Younger Dryas was a global or a regional (North Atlantic) phenomenon. Hence, valuable information concerning climate sensitivity can be obtained by studying the Younger Dryas climate. One way to study this climate is by making use of Atmospheric General Circulation Models (AGCMs). One interesting application of AGCMs is to simulate a climate from the geological past and subsequently to compare the results with climate reconstructions based on geological records. Additional important objectives are to validate the AGCM for another climate and to obtain more insight into climate sensitivity.

In order to perform paleoclimate simulations with AGCMs, the boundary conditions must be altered according to the situation of the period of interest, e.g. the extent of ice-sheets, sea surface temperatures (SSTs), land-sea distribution, the composition of the atmosphere, such as the concentration of greenhouse gasses, and incoming solar radiation. The CLIMAP project members (1981) composed a global set of boundary conditions for the last glacial maximum (LGM, approx. 21 ky BP). This enabled simulation of the climate during the LGM (e.g. Kutzbach and Wright, 1985, Lautenschlager and Herterich, 1990). However, for the Weichselian Late Glacial such a set does not exist and consequently few simulation studies focus on this period. These studies are mostly sensitivity analyses, which deal with the role of a cooled North Atlantic Ocean on climate (Rind et al., 1986, Overpeck et al., 1989, Maasch and Oglesby, 1990). Therefore, this study is the first attempt to simulate the climate during the Younger Dryas period.

In this study three experiments were carried out with the ECHAM3 model at T42 resolution. The objectives of these experiments were firstly to analyze the effect of a North Atlantic Ocean cooled to Younger Dryas temperatures on the atmosphere under present conditions and secondly to simulate a Younger Dryas climate to improve the insight into mechanisms responsible for cooling during the Younger Dryas and moreover to find out if the Younger Dryas was a global or a regional event. In the second section of this report the experimental design will be discussed. Section 3 deals with the simulation results and in section 4 these results will be discussed and compared with reconstructions based on geological evidence. Finally, the main conclusions are summarized in section 5.

2 Experimental design

The experiments were carried out with the ECHAM3 Atmospheric General Circulation Model. The T42 version of this spectral model was used with triangular truncation at zonal wave-number 42, which corresponds to a Gaussian grid of approximately 2.8° latitude-longitude. The vertical resolution is 19 levels in hybrid σ-p coordinates. A time-step of 24 minutes was used. The write-up interval was set to 12 hours. The ECHAM3/T42 model adequately simulates most aspects of the observed time-mean circulation and its intraseasonal variabilities (Roeckner et al., 1992). For more information concerning the ECHAM3 model reference is made to DKRZ report no. 6 (1994).

experiments	SSTs	ice sheets	insolation	CO_2
control	present	present	present	345 ppm
1	YD in N-Atlantic	present	present	345 ppm
2	YD in N-Atlantic	12 ky BP	12 ky BP	230 ppm
3	YD in N-Atlantic + -2°C in N-Pacific	12 ky BP	12 ky BP	230 ppm

The experimental design is summarized in Table 1.

In the **control experiment** a set of boundary conditions is prescribed which agrees with present climate. This control case is used as a standard.

Experiment 1 is designed as a sensitivity analysis, in which the effect of a cold North Atlantic Ocean with Younger Dryas sea surface temperatures (SSTs) is studied. The used set of SSTs is derived from Sarnthein et al. (1995), who reconstructed Younger Dryas sea surface temperatures for several marine cores in the Northern Atlantic Ocean. These reconstructions are based on the relation between the present distribution of planktonic foraminiferal species and the surface conditions in the ocean. A sinus function was fitted through the provided winter and summer SST estimates, in order to obtain an annual cycle. In all experiments a climatological annual cycle of SSTs was used. It was assumed that the surface conditions in the tropical Atlantic Ocean were not significantly different from today. The sea-ice limits in the Greenland-Iceland-Norway (GIN) seas were based on Koç et al. (1993). From the western North Atlantic Ocean less data were available and the chosen sea-ice limit is more speculative (see Figure 1).

One mechanism to explain the Younger Dryas cooling is based on a shut-down of the thermohaline circulation in the northern Atlantic Ocean under influence of meltwater influxes (Broecker, 1992). In such a situation the formation of North Atlantic Deep Water (NADW) could cease. A weakening of the thermohaline circulation would decrease the amount of heat released to the atmosphere over the northern Atlantic Ocean.

Consequently, this would cause an atmospheric cooling over Europe. Nevertheless, there is conflicting evidence from marine cores, indicating that the thermohaline circulation in the Atlantic Ocean was in operation during the Younger Dryas (Veum et al., 1992, Charles and Fairbanks, 1992, Sarnthein et al., 1994). The set of SSTs used in this study implies a considerable surface cooling of the northern Atlantic Ocean. However, since the sea-ice margins in the GIN seas area were defined at around 65°N, relatively temperate waters were present at rather northern latitudes. The used SSTs are therefore consistent with a weakening, but not with a shut-down, of the thermohaline circulation.

Experiment 1 is potentially interesting for model development. The model's sensitivity to a realistic regional SST change can be obtained. Especially the changes in the hydrological cycle under clearly defined boundary conditions may be inferred (Cubasch et al., 1992).

Additional to the set of SSTs described above, other essential boundary conditions were changed in the **experiments 2** and **3**. The purpose of these experiments was to simulate a Younger Dryas type of climate. Ice-sheets were introduced in North America and Scandinavia (see Fig. 1) according to Peltier (1994), who calculated the extent and altitude of Late Quaternary ice-sheets with a geophysical model. The surface albedo of these newly defined ice-sheets was set to 0.8, a value also used for the ice-sheets of Greenland and Antarctica. Additional land points were introduced in the Bering Strait and North Sea areas, in agreement with sea level curves. To these new land points the surface albedo of adjacent land points was assigned. The present surface albedo was used for the remaining points. The solar insolation was calculated for 12 ky BP according to Berger (1978). If one compares the incoming solar radiation on the northern hemisphere at the time of the Younger Dryas event with the present situation, insolation was 6% higher during NH summer and with a similar reduction in winter. The atmospheric CO_2 concentration was reduced from 345 to 230 ppm on the basis of measurements in Antarctic ice cores (Jouzel at al., 1992).

The design of experiments 2 and 3 differs only in the prescribed SSTs in the north Pacific Ocean. There are indications that the North Pacific Ocean was cooled during the Younger Dryas (Kallel et al., 1988), however, no set of reconstructed SSTs exists for this region. Therefore, an arbitrary additional cooling of 2°C is specified in the North Pacific north of 40°N in experiment 3.

The total simulation time per experiment was set to 12 model years. The first two years were taken as 'spin-up' time. The results from the last ten years are considered here.

3 Results

The discussion in this report is focused on surface variables, since it is possible to compare these results directly with reconstructions based on geological evidence. The following variables will be reviewed:

a) surface (2 m) temperature
b) mean sea level pressure (MSLP)
c) precipitation
d) P-E flux
e) snow depth and coverage
f) surface (10 m) winds
g) 850 hPa temperature
h) 500 hPa geopotential height

The data are annually averaged as well as provided for winter (December-January February, DJF) and summer (June-July-August, JJA). The discussion in the forthcoming sections is focused on the middle latitudes in the Northern Hemisphere, with emphasis on the circum North Atlantic region. The reason for this is that the YD signal in the experiments is most clearly found is this area.

Surface temperature

The main difference in the mean annual surface (2 m) temperature between the YD experiments and the control case is found around the northern Atlantic Ocean (Figure 2a). It should be noted that the differences in surface temperature between the first experiment and the second and third experiment are small. This implies that the deviation in surface temperature from the control experiment is mainly forced by the prescribed SSTs. The second important factor regulating the difference are the prescribed ice-sheets in North America and Europe. The mean annual surface temperatures are only a few degrees lower over the NH continents in the YD experiments (Fig. 2d). Only where new ice-sheets are defined, the difference is larger, up to -8°C.

In DJF all continents in the northern hemisphere are cooled in the 2nd and 3rd experiment (Figs. 2b and 2e), a difference of -2 to -4°C with the control experiment. Together with the slight warming in JJA months this suggests a considerable increase in continentality. The cooling in NH winter is most severe above newly prescribed sea-ice, the difference is more than -16°C in the North Atlantic area. The effect of a cooled North Pacific Ocean in experiment 3 is clearly visible. The deviation in temperature reaches -8°C, which partly can be attributed to the effect of extended sea-ice (Fig. 2e). In the southern hemisphere the surface temperature in the DJF season is 2-4 degrees higher over land at middle latitude in the second and third experiment, when compared with the control situation (Fig. 2h). This is probably caused by the prescribed insolation, which increases in the southern hemisphere in DJF.

In NH summer (Fig. 2c) large gradients in temperature exist in experiments 2 and 3 between areas covered with ice and the land surfaces situated south of them. Above the ice-sheets the surface temperature is below 0°C, whereas south of the Laurentide ice-sheet the temperature reaches 30°C and south of the Scandinavian ice-sheet 15°C. Remarkable is also the temperature gradient going inland in NW-Europe with less than 5°C over the North Sea and 20°C over central Europe. It is important to note that in JJA the temperatures over the continents are higher in the YD experiments when compared to the control case, up to 4°C (Fig. 2f). This warming could partly be attributed to the increased summer insolation. However, it is not unlikely that this effect is too strong due to an insufficient soil moisture content which is a deficiency in the ECHAM3 model. This is leading to weaker latent heat fluxes over land and too high surface temperatures.

Mean sea level pressure

The sea level pressures are presented as deviations from the global mean, since these means are not identical in the various experiments. In the control case and in experiment 1 the global mean sea level pressure is 1011.2 hPa, whereas this value is higher in the experiments 2 and 3 due to the introduction of ice-sheets, viz. 1012.6 hPa.

The mean annual MSLP pattern is not very different in the experiments 1-3 when compared to the control simulation (Fig. 3a). More differences are visible in the DJF and JJA plots.

Comparison of the DJF sea level pressure charts shows that the atmospheric circulation is intensified above the Northern Atlantic Ocean in the YD experiments (Fig. 3b). A larger pressure gradient is present in experiment 2 and 3 and consequently the westerlies are stronger. A contributing factor to this is the prescribed set of SSTs, in which the Atlantic Ocean is cooled in the northern part and is left unchanged at the lower latitudes, thus creating an enlarged meridional temperature gradient. However, comparison with experiment 1 shows that the orographic effect of the new ice-sheets is most important. In experiment 2 and 3 the Icelandic Low has clearly deepened, whereas this is not visible in experiment 1. Moreover, the Icelandic Low seems to have been shifted a few degrees to the east. Nevertheless, the pressure pattern is similar, resulting in a westerly flow from the North Atlantic Ocean towards Europe. In the second experiment the Aleutian Low has deepened as well.

During JJA the Azores high pressure system has expanded slightly towards the northwest (Fig. 3c). This supports a more northerly flow over Europe in the YD experiments. The effect of the Laurentide and Scandinavian ice-sheets is visible as an increase in MSLP in the second and third experiment.

Precipitation

The overall pattern in the mean annual charts is very similar in all four experiments (Fig. 4a), the differences are only at a few places larger than 1 mm/day. The seasonal figures show some more variation.

In the DJF plots (Fig. 4b) of the experiment 2 and 3 a slight increase in precipitation up to 5 mm/day is apparent along the European coast at middle latitudes. This is consistent with the observed deepening of the Icelandic Low. More to the north the opposite seems valid, since precipitation decreased in southern Greenland, northern Scandinavia and the GIN seas area. In the control experiment more than 2 mm/day is evident in these places, whereas in the YD experiments the value is 1 mm/day. It is likely that this decrease in precipitation has been caused by the more southerly positioning of the sea-ice margin, thus depriving the area of a major moisture source.

During NH summer the most important deviation in the YD experiments is a decrease in precipitation over central Europe. In the experiments 2 and 3 the precipitation is less than

1 mm/day, while in the control case this figure is 2 mm/day. Presumably, cyclones were forced to take a more northerly route under influence of the changed orography, consequently leading to a reduction of precipitation over central Europe.

P-E flux

Above unglaciated land surfaces no clear deviation in the P-E fluxes is found (Figs 5a-c). In the GIN-seas area the P-E flux increases with more than 1 mm/day during DJF (Fig. 5b). Apparently, the evaporation decreased more than the precipitation, producing a positive difference when compared with the control experiment. This reduction in evaporation in the YD experiments is caused by the extended sea-ice in this region, which is represented in the model as an uniform cover. However, it is doubtful if such a sea-ice distribution is realistic, since one would expect a non-uniform cover in this situation with strong surface winds. Another noteworthy variation is the increase in P-E flux over the southwest flanks of the Laurentide and Scandinavian ice-sheets. Probably this is caused by a combined effect of an increase in precipitation as a result of orographic uplift and a decrease of evaporation above the cold surface. In southern Greenland a small decrease (<1 mm/day) in P-E flux is present. This is probably induced by the reduction in precipitation.

Snow depth and coverage

The mean annual snow coverage expands slightly on the northern hemisphere continents in the YD experiments. In Europe it spreads westwards and reaches the Atlantic coast, while in North America the snow coverage moves southwards. However, when the snow depth charts are examined, it is obvious that this snow cover is very thin (Figure 6). The snow depth in experiment 1 increases only slightly in Scandinavia and N-America when compared with the control case. However, the temperature deviations in the YD experiments are too small in areal coverage to cause a substantial expansion of the snow-cover.

Surface winds

Since the pattern of the mean sea level pressure is rather similar in all four experiments, it is not surprising that the wind directions are also comparable. In Figures 7a-c it is clear that the surface (10 m) wind speed increases above the Northern Atlantic Ocean in the YD experiments, in agreement with an enlarged pressure gradient. As discussed above, this is due to the changed orography and to the cooling of the North Atlantic Ocean.

More local effects of the new ice-sheets are also evident. Strong northwesterly winds are present north of the Laurentide ice-sheet in the experiment 2 and 3. Furthermore, the discussed more northerly track of depression systems in NH summer is visible (Fig. 7c), as the surface winds are southwesterly between Iceland and Scandinavia in the experiments 2 and 3, whereas these winds are westerly in the control experiment.

850 hPa temperature

The temperatures at 850 hPa show the same pattern as the surface temperatures (Figs. 8a-c). When the results of the YD experiments are compared with the control case, a cooling is visible in the North Atlantic region. Cold polar air masses expand southwards, causing a cooling of several degrees over Europe.

500 hPa geopotential height

In agreement with the above discussed changes in the wind fields, the 500 hPa geopotential height profiles show a considerable deepening of the polar vortex in the YD experiments compared with the control run (Figs. 9a-c). This is especially visible during NH winter, as in the control experiment the minimum geopotential height is above 5040 m, while in experiment 2 and 3 a height of 4960 m is apparent. In experiment 1 the value is intermediate between these situations, showing again the effect of the Laurentide and Scandinavian ice-sheets. In summary, the 500 hPa geopotential height fields in the YD experiments are evidence of an intensified atmospheric circulation with strong zonal flow.

4 Comparison with geological evidence

July temperature
Recently NASP members (1994) have published an overview of terrestrial geological evidence for climate change during the Late Glacial in the circum Atlantic region. Their main result are reconstructions of mean July temperatures based on beetle remains and plant fossils. The mean July temperature during the Younger Dryas is estimated at around 10°C in England, the Netherlands, Denmark, south Sweden and northwest Germany. Ireland appears to have been cooler with 7°C as the reconstructed mean July temperature. The present mean July temperature is 15 to 17°C in this region, indicating a temperature reduction by 5-7°C during the summer months in the Younger Dryas. A difference of the same order is found in northern Europe. A YD mean July temperature of about 5°C is estimated for north Norway, whereas today this value is about 10°C. Further north, in Svalbard, a mean July temperature of 4°C is reconstructed, which is close to the present value of 5°C. The reconstructed mean July temperature in central Europe is also not very different from today, with 15°C in lowland Switzerland. Thus, the reconstructions published by NASP (1994) suggest a maximum cooling in July in Europe close to the Atlantic Ocean. The difference with today decreases going away from the oceanic influence, for example inland (Switzerland) or far beyond the YD sea-ice limit (Svalbard). On the North American east coast the reconstructed mean July temperatures range from 15°C in southern New England to 10°C in New Brunswick and about 7°C in northeast Quebec. These values indicate a difference with today of more than 5°C, with increasing cooling closer to the Laurentide Ice-sheet.

January temperature
The Younger Dryas conditions during the NH winter appear to have been close to the full glacial situation in Europe. For the British Isles a mean January temperature as low as -15 to -20°C is reconstructed (Walker et al., 1993), whereas for the Netherlands an estimate of -15°C is given (Bohncke, 1993). These estimates are based on beetle remains and on permafrost relics. Taking into account that the present mean January temperature in this region is about +3°C, a temperature reduction by more than 15°C is indicated.

Mean annual temperature
In most studies the mean annual temperature in NW-Europe is estimated at below 0°C during the Younger Dryas. All through NW-Europe relics of permafrost features have been found, indicating average sub-freezing conditions. For example, Bohncke (1993) considers a mean annual temperature of -2 to -5°C for the Netherlands, while Atkinson et al. (1987) reconstructed a value of -7°C for the British Isles. The difference in mean annual temperature with the situation of today seems to be at least -10°C for NW-Europe, since the present mean annual temperature is 9 to 10°C.

Evidence for cooling outside Europe during YD time have been reported from various places. For Greenland the annual temperature depression during the Younger Dryas is estimated at -10°C (Grootes et al., 1993). In the northeastern USA the mean annual temperatures appear to have been 3 to 4°C lower during the Younger Dryas (Peteet et al., 1993). In the Columbian Andes a cooling equivalent to the Younger Dryas seems to have taken place, as Kuhry et al. (1993) reconstructed a small temperature reduction of 2 to 3°C. At the Pacific coast of North America Mathewes (1993) and Engstrom et al. (1990) have found evidence for a cooling during Younger Dryas time. From Japan an oscillation equivalent to the Younger Dryas was reported (Fuji et al., 1981). In these studies no actual temperatures were reconstructed. Indications of cooling during Younger Dryas time have also been found at high latitudes in the Southern hemisphere, for instance in Chili (Heusser and Rabassa, 1987), New Zealand (Denton and Hendy, 1994) and Antarctica (Jouzel et al., 1992). However, the actual timing of a Late Glacial cooling in the Southern Hemisphere is still debated. This is due to uncertainties in ^{14}C dates (Markgraf, 1991) or in the time-scale in Antarctic ice-cores (Jouzel et al., 1992). Therefore, it is possible that the observed cooling in the Southern Hemisphere was a regional event rather than a global Younger Dryas cooling.

Comparison

In the results of experiments 2 and 3 a strong gradient in the surface temperature was observed for JJA, going from the Atlantic coast inland to central Europe. This pattern is consistent with reconstructions of the July temperature, with a larger temperature reduction in coastal areas than in regions more remote from oceanic influence (Switzerland). In the YD experiments a more northerly flow is present over Europe during NH summer. Such an air flow would bring cool air to the coastal areas in NW-Europe. Nevertheless, the calculated JJA temperature seems to be too high. The difference with the control experiment is about 0°C along the European coast, which seems incompatible with the reconstructed reduction of 5°C. The temperature gradient found near the margins of the Laurentide Ice-sheet in the experiments 2 and 3 is consistent with the reconstructed trend.

In the experiments 2 and 3 a deviation of -2 to -4 °C in the surface temperature is calculated for Europe during DJF. This result is not in agreement with the difference of about -15°C as estimated with geological evidence. Since the surface temperatures over Europe in experiment 1, in which only SSTs were altered, are comparable to those in the experiments 2 and 3, the misfit seems to be caused by the defined surface conditions in the North Atlantic Ocean. Comparison with glacial simulations (e.g. Lautenschlager and Herterich, 1990) suggests that a cooler ocean surface closer to LGM conditions is more realistic for the Younger Dryas. As the atmospheric circulation in the YD experiments is similar to the present one with dominant westerly flow over the North Atlantic Ocean, lowering of the SSTs would result in temperatures closer to YD values over Europe. The finding of ice rafted sediments of Younger Dryas age in cores in the North Atlantic Ocean (Bond et al., 1993), indicating cool surface flow with icebergs, supports a further lowering of SSTs.

The geological evidence for a YD cooling in the Pacific region is more consistent with the outcome of experiment 3 than that of the second experiment. This implies that the outcome of experiment 3 is closest to a Younger Dryas climate.

The outcome of the simulations show no significant cooling in the Southern Hemisphere. Such a result would confirm the indications derived from some geological data. However, the geological evidence for a cooling of Younger Dryas age in the Southern Hemisphere is still not convincing, mostly due to uncertainties in ^{14}C dates (e.g. Markgraf, 1991).

Humidity, P-E
Fluvial and lake level studies indicate a significant change in humidity in Europe during the Younger Dryas. Evidence for high lake levels and large scale flooding was found for the first part of the Younger Dryas. Around 11 ky BP the river activity declined and lake levels lowered (Bohncke, 1993). Hence, the amount of effective precipitation seems to have decreased considerably during Younger Dryas time. On the other side of the Atlantic Ocean, in Nova Scotia (Mott, 1994), an increase of humidity is reported during Younger Dryas time. In addition to this, a remarkable low snow accumulation is reported from Greenland during the Younger Dryas (Alley et al., 1993).

comparison
The plots of the mean annual P-E flux (Fig. 5a) show no significant difference above the European continent. However, it is not possible to resolve the temporal resolution with the YD experiments as found in the geological evidence. Therefore, it is not clear if the results are in agreement or not. On the east coast of N-America no clear deviation in P-E flux from the control experiment is found. In southern Greenland a small reduction in the precipitation is apparent in the simulation results. Such a variation is compatible with evidence for reduced snow fall during Younger Dryas time.

Winds
Wind directions from the past are indicated by fossil dunes. According to many studies in NW-Europe, dunes from the Younger Dryas indicate a westerly wind direction (e.g. Bohncke, 1993). This reconstruction is in agreement with the simulation results (see Fig. 7a-c). However, it is not clear if dunes indicate the mean wind direction or intense winds in association with occasional storm depressions. A westerly wind seems in conflict with the extreme conditions of permafrost, as indicated by geological evidence.

5 Conclusions

Three experiments were carried out with the ECHAM3 AGCM at T42 resolution to study the Younger Dryas climate. Boundary conditions were altered according to geological evidence. The specified SSTs assume a weakening, but not a shut-down, of the modern thermohaline circulation. The experimental results were compared with reconstructions of temperature, humidity and wind direction based on geological evidence. A misfit between model results and these reconstructions could be inferred for Europe. Especially in NH winter the simulated temperatures are too high, the difference between model results and data is approximately 10°C. In NH summer the simulated trend of large temperature gradients going inland is consistent with the reconstructions, although the cooling seems to be too small (a difference of approx. 5°C). Nevertheless the experimental results suggest an increase of the continentality during Younger Dryas time in agreement with the reconstructions. The model simulates an intensified atmospheric circulation, which is clearly visible in the mean sea level pressure and wind charts. The results suggest also that precipitation in Europe increased during NH winter and decreased during NH summer.

Since it is unlikely that the used AGCM is completely wrong, in particular with respect to the circulation pattern, and that the various geological data are totally misinterpreted, the misfit between the simulated and reconstructed temperatures imply a reconsideration of the YD boundary conditions. As the simulated temperature differences in experiment 1, in which only the SSTs were altered, are comparable to those in experiments 2 and 3, it is probable that the defined surface conditions in the North Atlantic Ocean are incorrect. Comparison with glacial simulations (e.g. Lautenschlager and Herterich, 1990) suggests a redefinition of the Younger Dryas NH winter SSTs and sea-ice margins closer to LGM conditions. This could imply inter-annually varying deep water formation in the Labrador Sea during Younger Dryas. It would indicate a weak, but still active formation during summer and no deep water formation during winter. In this case the contribution in the GIN seas to the North Atlantic deep water should practically be absent. Since the reconstructions of SSTs by means of planktonic foraminiferal have large error margins in the low temperature range (<3°C, Sarnthein 1995, personal communication), this new SST set could be consistent with geological evidence.

Due to the conflict between simulation results and geological data, the question whether the Younger Dryas was a regional or global event seems impossible to answer from this study. However, it seems quite unlikely that changing the boundary conditions in the North Atlantic and North Pacific regions will have an impact on conditions in the southern hemisphere.

Geological evidence for a cooling in the North Pacific region suggests that experiment 3 is closer to the Younger Dryas situation than the second experiment.

Acknowledgements
We would like to thank M. Sarnthein, Geologisch-Paläontologisch Institut, Universität Kiel, for providing SST estimates. The first author is supported by the Netherlands Organization for Scientific Research (NWO).

References

Alley, R.B., Meese, D.A., Shuman, C.A., Gow, A.J., Taylor, K.C., Grootes, P.M., White, J.W.C., Ram, M., Waddington, E.D., Mayewski, P.A. and Zielinski, G.A., 1993. Abrupt increase in Greenland snow accumulation at the end of the Younger Dryas event. Nature 362:527-529.

Atkinson, T.C., K.R. Briffa and G.R. Coope, 1987. Seasonal temperatures in Britain during the past 22,000 years, reconstructed using beetle remains. Nature 325:587-591.

Berger, A.L., 1978. Long-term variations of caloric insolation resulting from the earth's orbital elements. Quaternary Research 9:139-167.

Bohncke, S.J.P., 1993. Lateglacial environmental changes in the Netherlands: spatial and temporal patterns. Quaternary Science Reviews 12:707-717.

Bond, G., W. Broecker, S. Johnsen, J. McManus, L. Labeyrie, J. Jouzel and G. Bonani, 1993. Correlations between climate records from North Atlantic sediments and Greenland ice. Nature 365:143-147.

Broecker, W.S., 1992. The strength of the nordic heat pump. In: E. Bard and W.S. Broecker (Eds.), The last deglaciation: absolute and radiocarbon chronologies, NATO ASI Series, Vol. I 2, Springer-Verlag, Berlin, 173-180.

Charles, C.D. and R.G. Fairbanks, 1992. Evidence from Southern Ocean sediments for the effect of North Atlantic deep-water flux on climate. Nature 355:416-419.

CLIMAP project members, 1981. Seasonal reconstructions of the earth's surface at the Last Glacial Maximum. Geological Society of America Map and Chart Series MC-36.

Cubasch, U., K. Hasselmann, H. Höck, E. Maier-Reimer, U. Mikolajewicz, B.D. Santer and R. Sausen, 1992. Time-dependent greenhouse warming computations with a coupled ocean-atmosphere model. Climate Dynamics 8, 55-69.

Denton, G.H. and C.H. Hendy, 1994. Younger Dryas age advance of Franz Josef Glacier in the Southern Alps of New Zealand. Science 264:1434-1437.

DKRZ, Modellbetreuungsgruppe, 1994. The ECHAM 3 Atmospheric General Circulation Model. Deutsches Klimarechenzentrum, Hamburg, Technical Report No. 6, 184 p.

Engstrom, D.R., B.C.S. Hansen, and H.E. Wright Jr., 1990. A possible Younger Dryas record in Southeastern Alaska. Science 250:1383-1385.

Fuji, N., H. Kano and M. Miyamatsu, 1981. Palaeoenvironmental change around lagoon Kahoku-Gata Central Japan during the last ca. 20,000 years. In: S. Horie (Ed.), Quaternary glaciations in the Northern Hemisphere, Report No. 8, International Geological Correlation Program, Kyoto, 67-88.

Grootes, P.M., M. Stuiver, J.W.C. White, S. Johnsen and J. Jouzel, 1993. Comparison of oxygen isotope records from the GISP2 and GRIP Greenland ice cores. Nature 366:552-554.

Heusser, C.J. and J. Rabassa, 1987. Cold climatic episode of Younger Dryas age in Tierra del Fuego. Nature 328:609-611.

Jouzel, J., J.R. Petit, N.I. Barkov, J.M. Barnola, J. Chappellaz, P. Ciais, V.M. Kotlyakov, C. Lorius, V.N. Petrov, D. Raynaud and C. Ritz, 1992. The deglaciation in Antarctica: further evidence of a "Younger Dryas" type climatic event. In: E. Bard and W.S. Broecker (Eds.), The Last deglaciation: absolute and radiocarbon chronologies, NATO ASI Series I2, Springer Berlin, p. 229-266.

Kallel, N., L.D. Labeyrie, M. Arnold, H. Okada, W.C. Dudleyn and J.C. Duplessy, 1988. Evidence of cooling during the Younger Dryas in the western North Pacific. Oceanologica Acta 11:369-375.

Koç, N., E. Jansen and H. Haflidason, 1993. Paleoceanographic reconstructions of surface ocean conditions in the Greenland, Iceland and Norwegian Seas through the last 14 ka based on diatoms. Quaternary Science Reviews 12:115-140.

Kuhry, P., H. Hooghiemstra, B. van Geel and T. van der Hammen, 1993. The El Abra stadial in the Eastern Cordillera of Columbia (South America). Quaternary Science Reviews 12:333-343.

Kutzbach, J.E. and H.E. Wright Jr., 1985. Simulation of the climate of 18,000 years BP: results for North American/North Atlantic/European sector and comparison with the geologic record of North America. Quaternary Science Reviews 4:147-187.

Lautenschlager, M. and K. Herterich, 1990. Atmospheric response to ice age conditions: climatology near earth's surface. Journal of Geophysical Research 95:22547-22557.

Maasch, K.A. and R.J. Oglesby, 1990. Meltwater cooling of the Gulf of Mexico: a GCM simulation of climatic conditions at 12 ka. Paleoceanography 5:977-996.

Markgraf, V., 1991. Younger Dryas in South America? Boreas 20:63-69.

Mathewes, R.W., 1993. Evidence for Younger Dryas-age cooling on the North Pacific coast of America. Quaternary Science Reviews 12:321-331.

Mott, R.J., 1994. Wisconsinan Late-glacial environmental change in Nova Scotia: a regional synthesis. Journal of Quaternary Science 9:155-160.

NASP Members: Executive Group (Lowe, J.J., B. Ammann, H.H. Birks, S. Björck, G.R. Coope, L. Cwynar, J.-L. de Beaulieu, R.J. Mott, D.M. Peteet and M.J.C. Walker), 1994. Climatic changes in areas adjacent to the North Atlantic during the last glacial-interglacial transition (14-9 ka BP): a contribution to IGCP-253. Journal of Quaternary Science 9:185-198.

Overpeck, J.T., L.C. Peterson, N. Kipp, J. Imbrie and D. Rind, 1989. Climate change in the circum-North Atlantic region during the last deglaciation. Nature 338:553-557.

Peltier, W.R., 1994. Ice age paleotopography. Science 265:195-201.

Peteet, D., R.A. Daniels, L.E. Heusser, J.S. Vogel, J.R. Southon and D.E. Nelson, 1993. Late-Glacial pollen, macrofossiles and fish remains in Northeastern U.S.A. - the Younger Dryas oscillation. Quaternary Science Reviews 12:597-612.

Rind, D., D. Peteet, W. Broecker, A. McIntyre and W. Ruddiman, 1986. The impact of cold North Atlantic sea surface temperatures on climate: implications for the Younger Dryas cooling (11-10k). Climate Dynamics 1, 3-33.

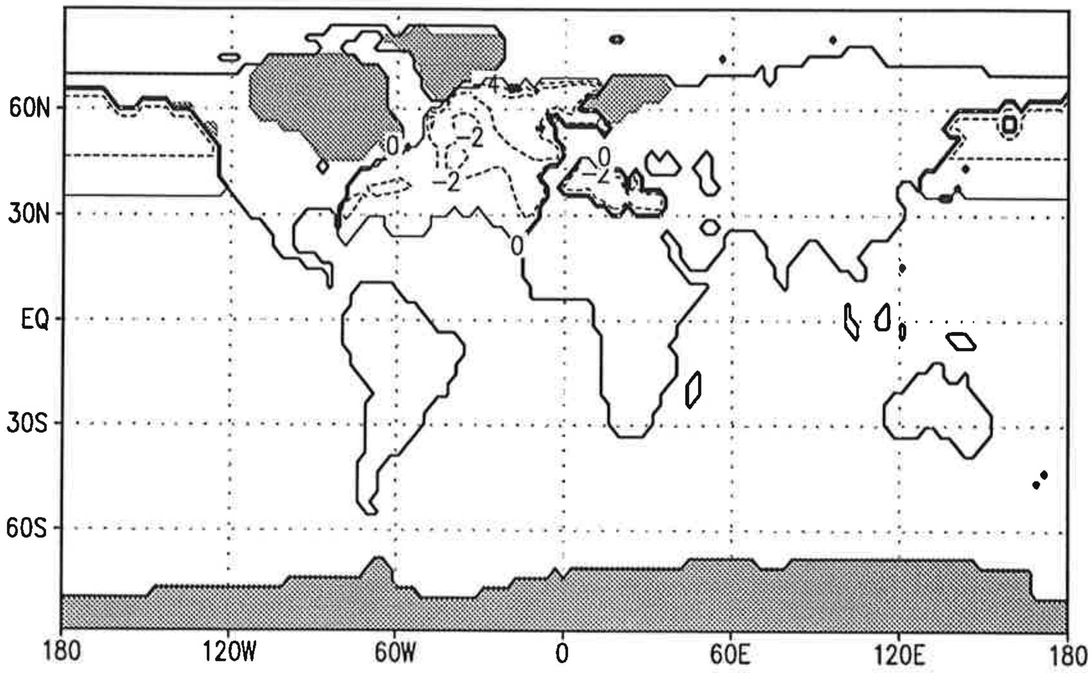
Roeckner, E., K. Arpe, L. Bengtsson, S. Brinkop, L Dümenil, M. Esch, E. Kirk, F. Lunkeit, M. Ponater, B. Rockel, R. Sausen, U. Schlese, S. Schubert and M. Windelband, 1992. Simulation of the present-day climate with the ECHAM model: impact of model physics and resolution. Max Planck Institut für Meteorologie report no. 93, Hamburg, 172 p.

Sarnthein, M., K. Winn, S.J.A. Jung, J.-C. Duplessy, L. Labeyrie, H. Erlenkeuser and G. Ganssen, 1994. Changes in east Atlantic deepwater circulation over the last 30,000 years: Eight time slice reconstructions. Palaeoceanography 9, 209-267.

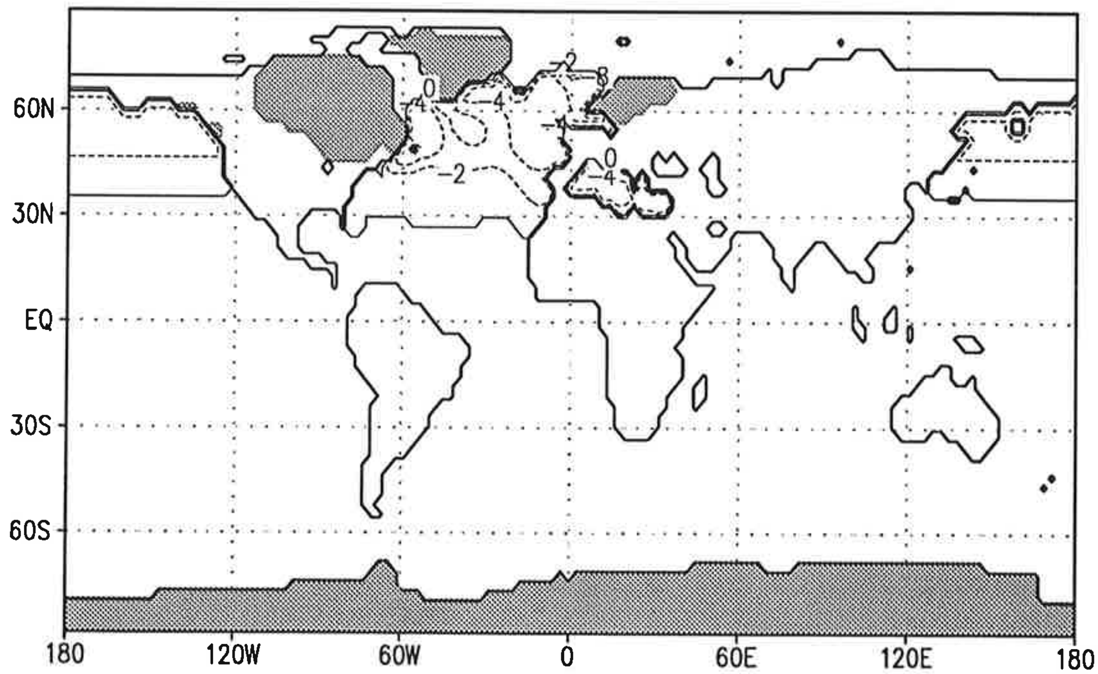
Sarnthein, M., E. Jansen, M. Weinelt, M. Arnold, J.-C. Duplessy, H. Erlenkeuser, A. Flatøy, G. Johannessen, T. Johannessen, S. Jung, N. Koç, M. Maslin, U. Pflaumann and H. Schulz, 1995. Variations in Atlantic surface ocean paleoceanography, 50°-85°N: a time-slice record of the last 30,000 years. In press.

Veum, T., E. Jansen, M. Arnold, I. Beyer, and J-.C. Duplessy, 1992. Water mass exchange between the North Atlantic and the Norwegian Sea during the past 28,000 years. Nature 356:783-785.

Walker, M.J.C., G.R. Coope and J.J. Lowe, 1993. The Devensian (Weichselian) Lateglacial palaeoenvironmental record from Gransmoor, East Yorkshire, England. Quaternary Science Reviews 12:659-680.



GrADS: COLA/UMCP



GrADS: COLA/UMCP

Figure 1. Summary of most important boundary conditions used in experiment 2 and 3: Land-sea mask, extent of ice-sheets (hatched) and sea surface temperature deviations (°C) from present January (above) and July (below) sets (contour interval 2°C). Cooling in N-Pacific only in experiment 3. Forced sea-ice margin in N-Atlantic is indicated by northern limit of SST anomaly. Note additional land points in Bering-strait and North Sea areas.

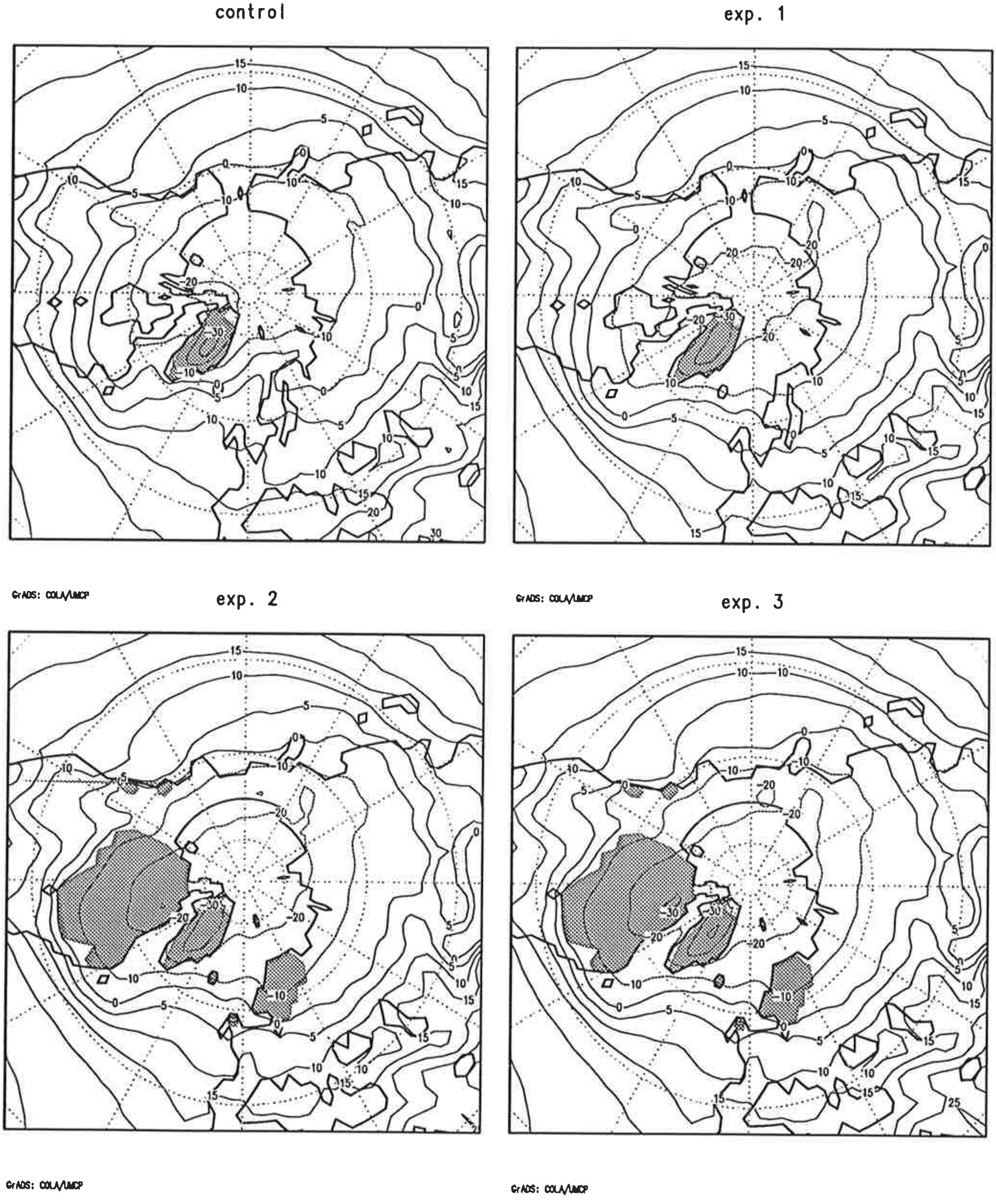


Figure 2a. Annual mean surface (2 m) temperature (°C) in northern hemisphere (10 year average). Contour interval: 5°C.

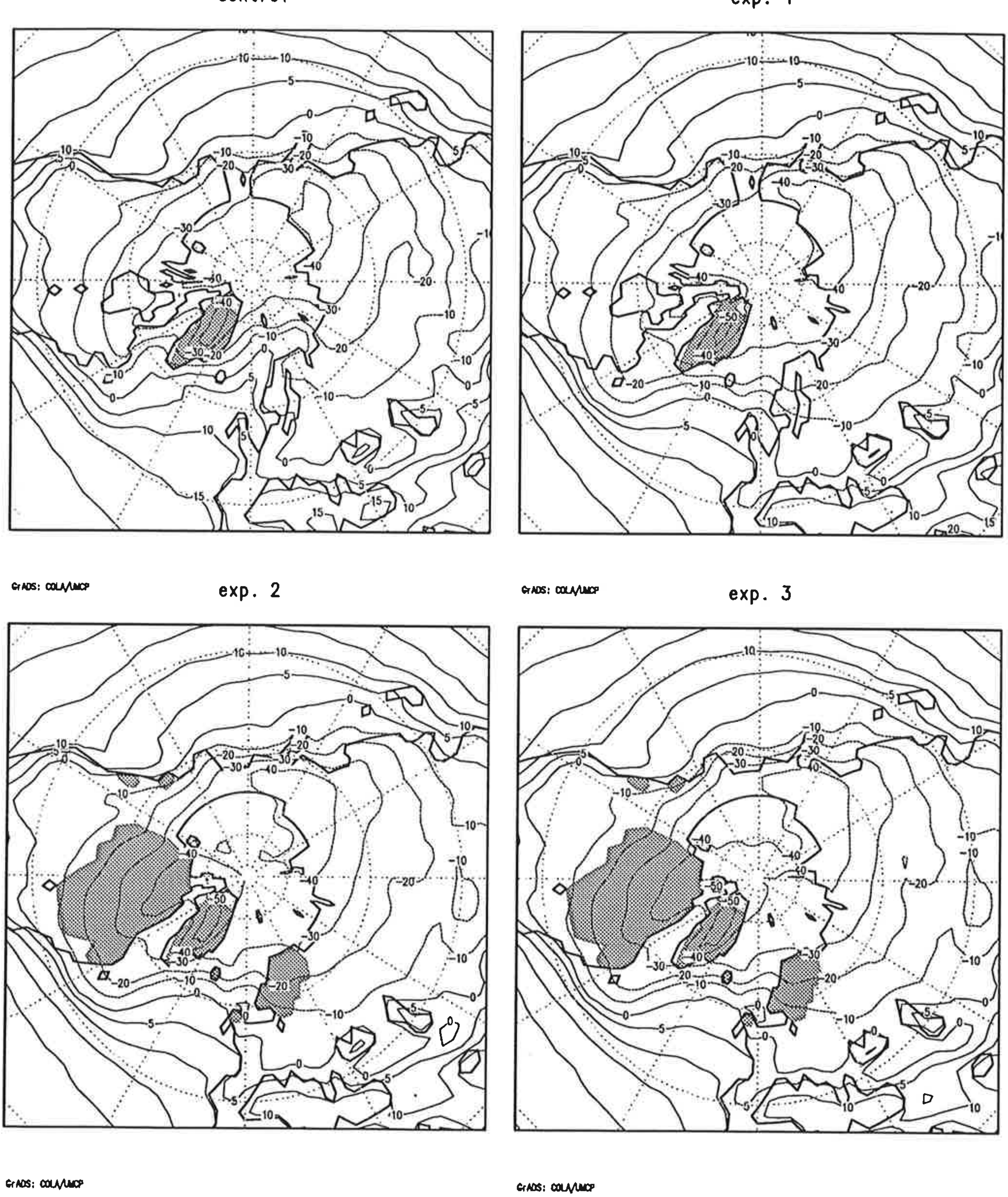


Figure 2b. As in Figure 2a except for the DJF season

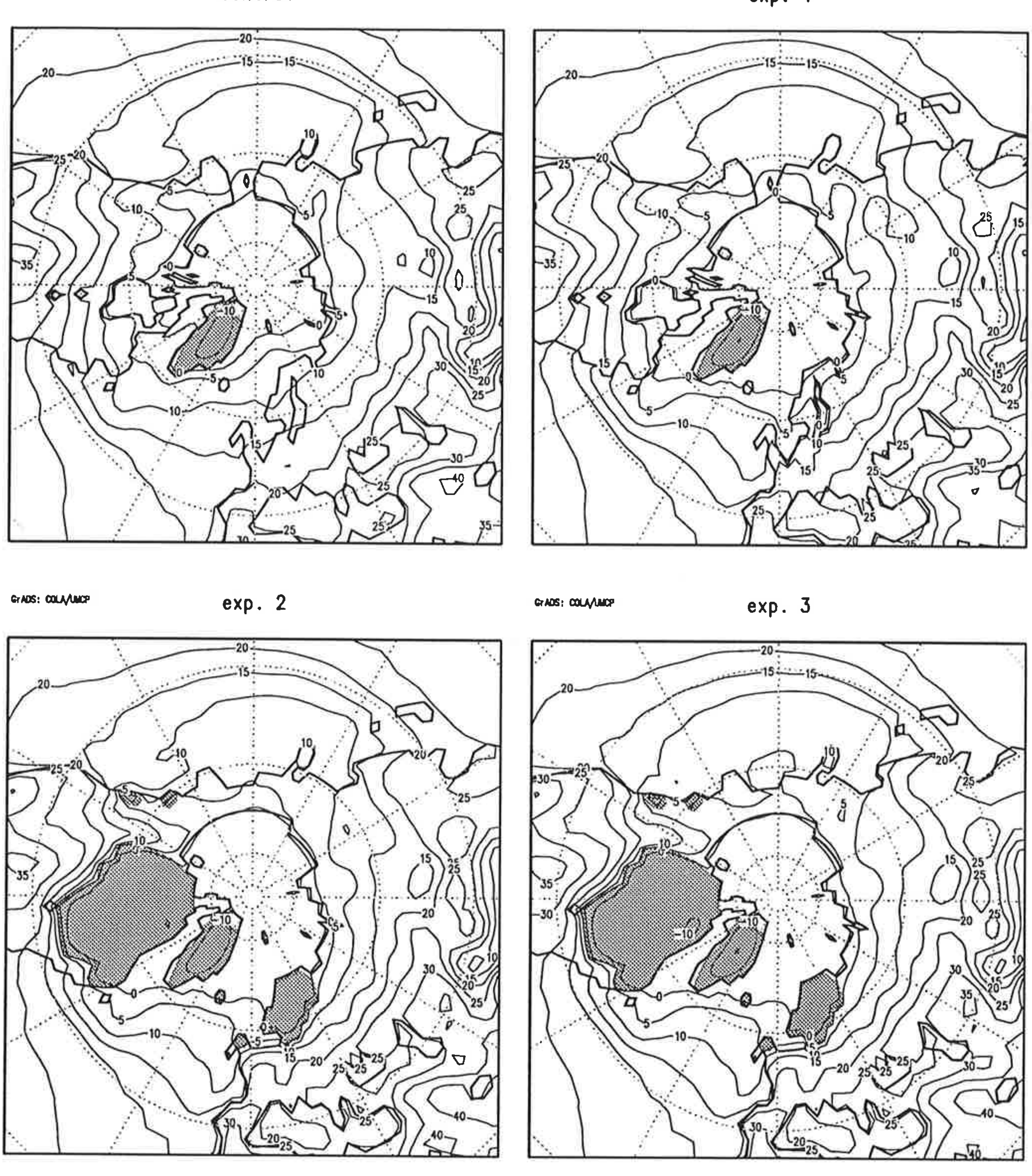


Figure 2c. As in Figure 2a except for the JJA season

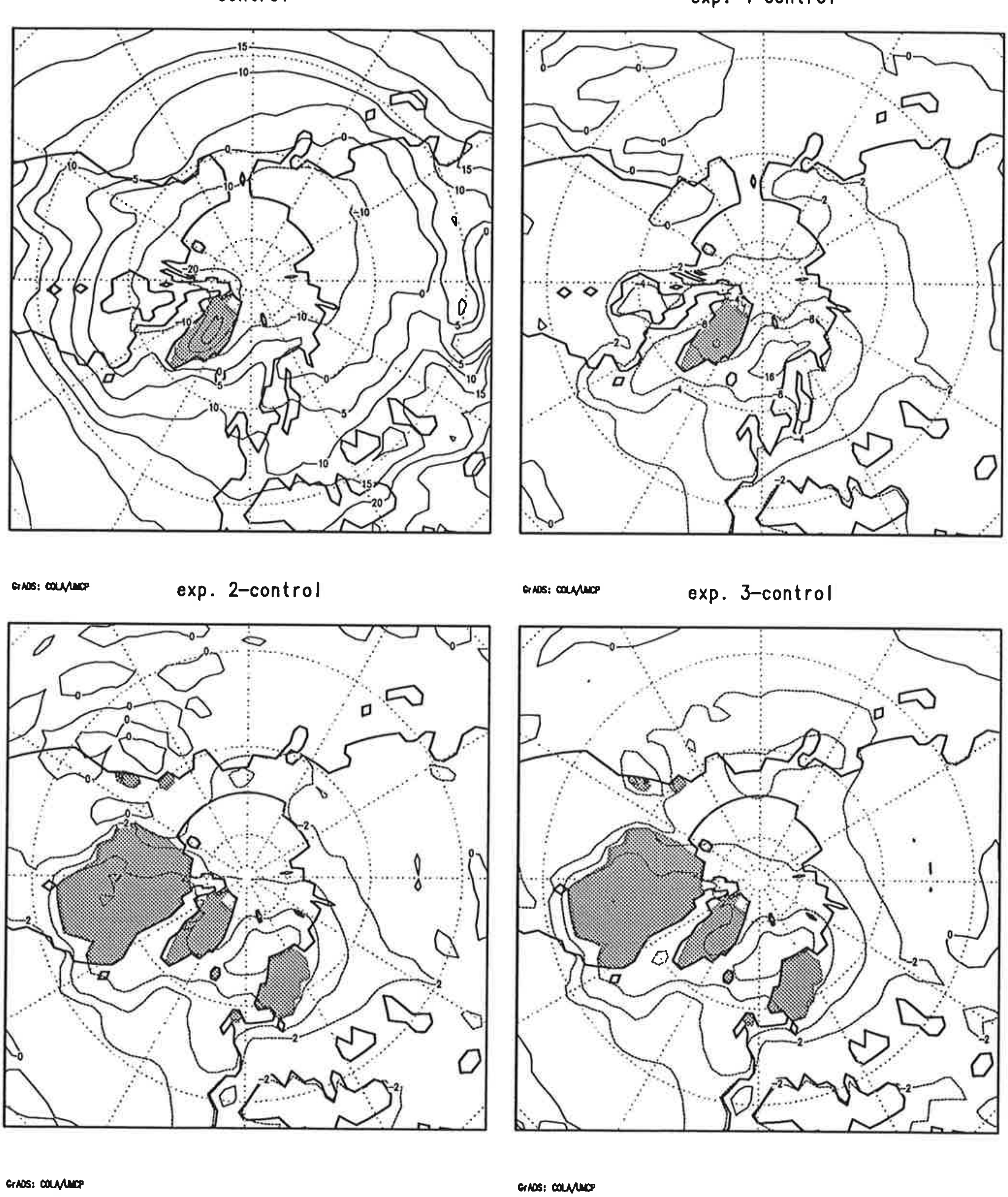


Figure 2d. Annual mean surface (2 m) temperature deviations (C°) from control simulation in northern hemisphere. Contours at 4°C, 2°C, 0°C, -2°C, -4°C, -8°C, and -16°C.

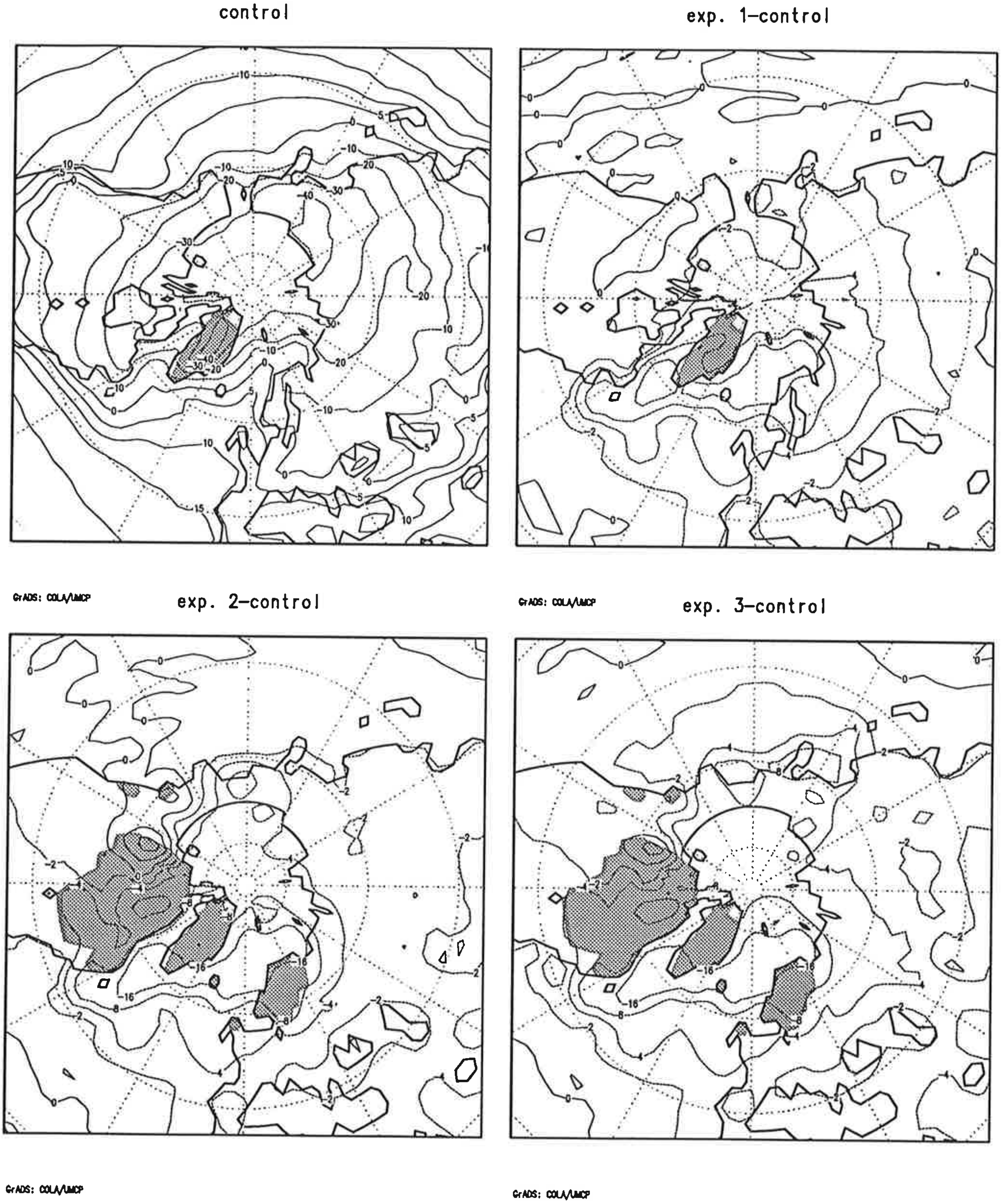


Figure 2e. As in Figure 2d except for the DJF season

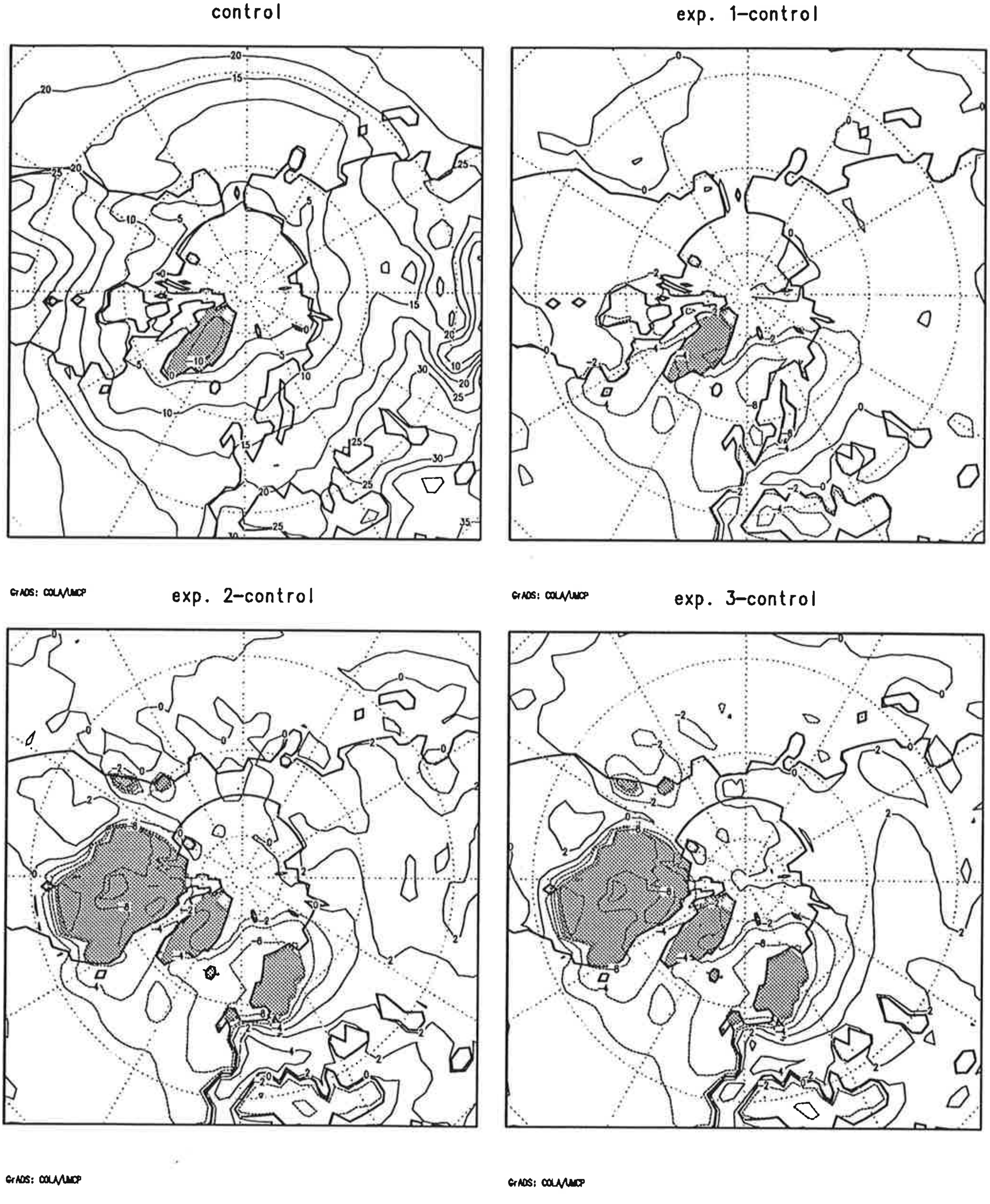


Figure 2f. As in Figure 2d except for the JJA season

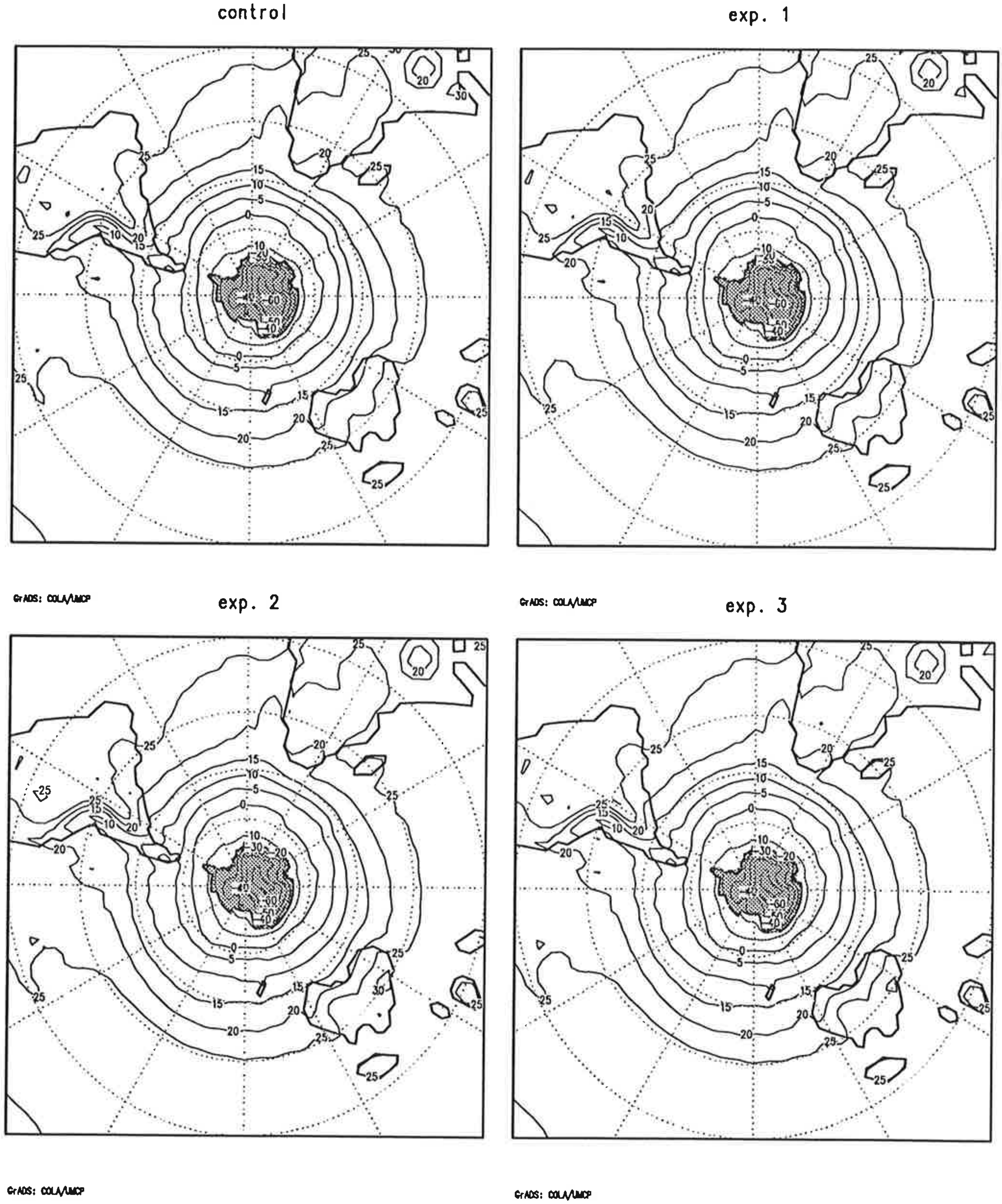


Figure 2g. Annual mean surface (2 m) temperature (°C) in southern hemisphere (10 year average). Contour interval: 5°C.

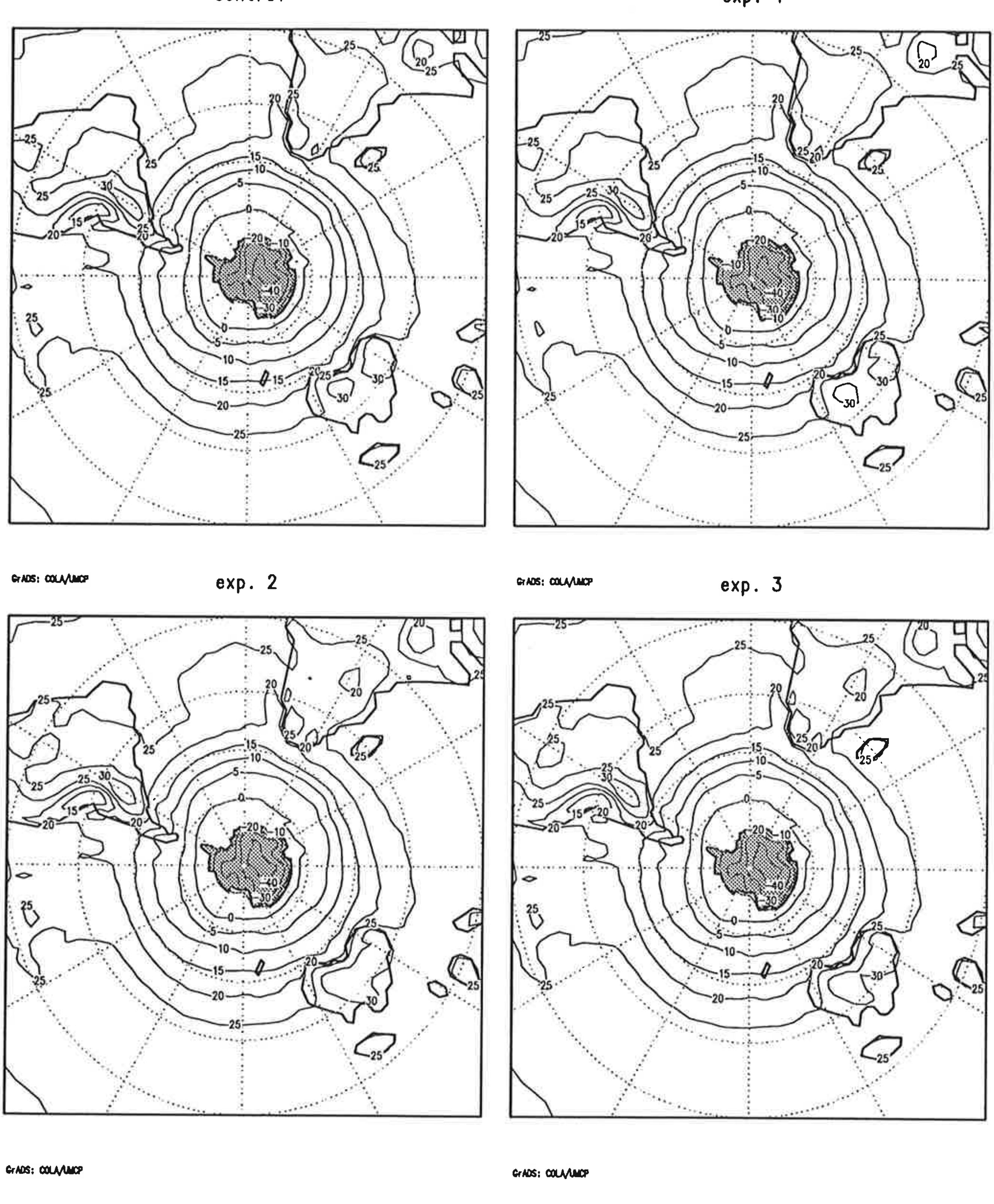


Figure 2h. As in Figure 2g except for the DJF season

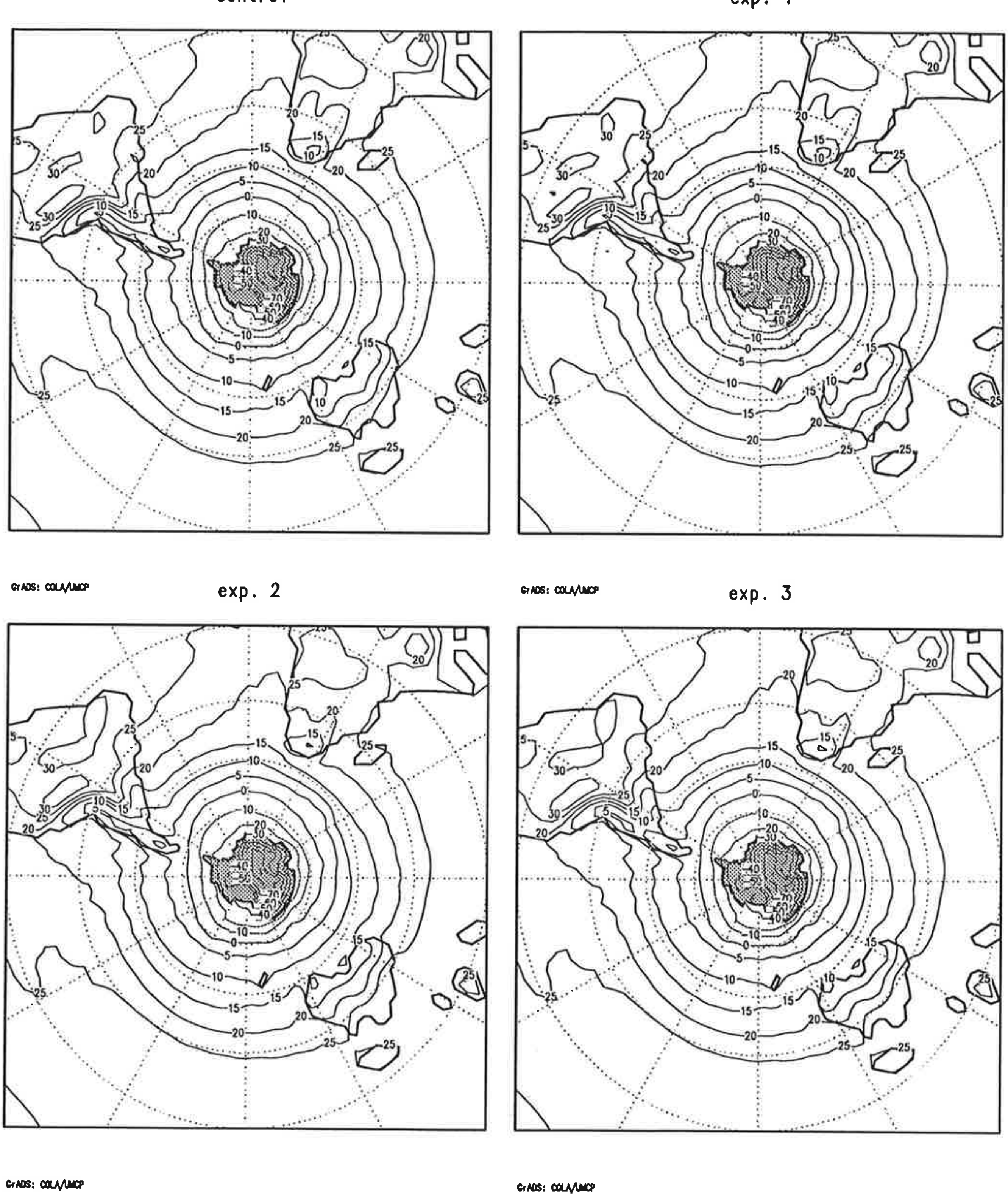


Figure 2i. As in Figure 2g except for the JJA season

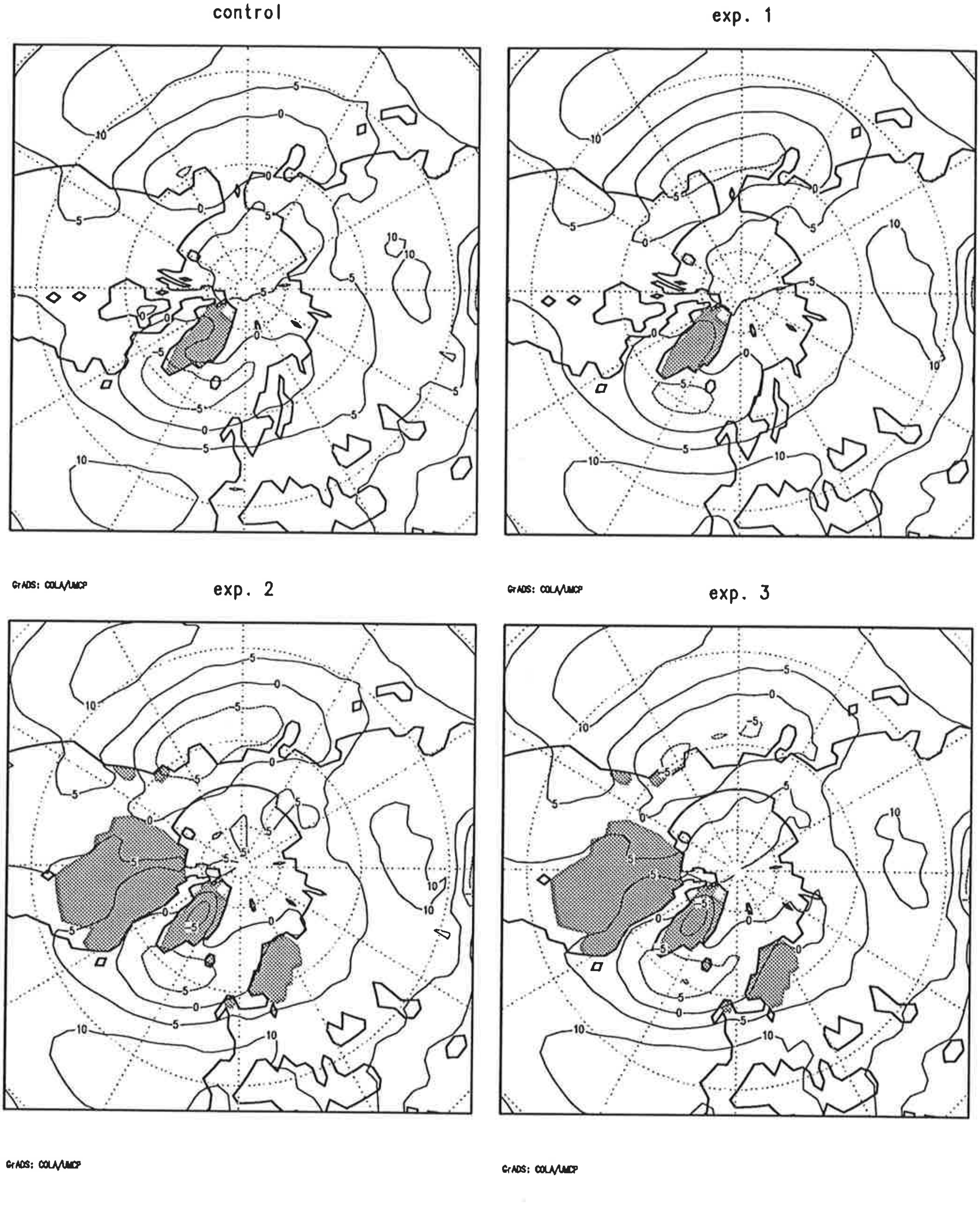


Figure 3a. Annual mean sea level pressure (hPa) as deviation from global mean (1011.2 hPa in control experiment and experiment 1 and 1012.6 hPa in experiments 2 and 3). Northern hemisphere, 10 year average. Contour interval: 5 hPa.

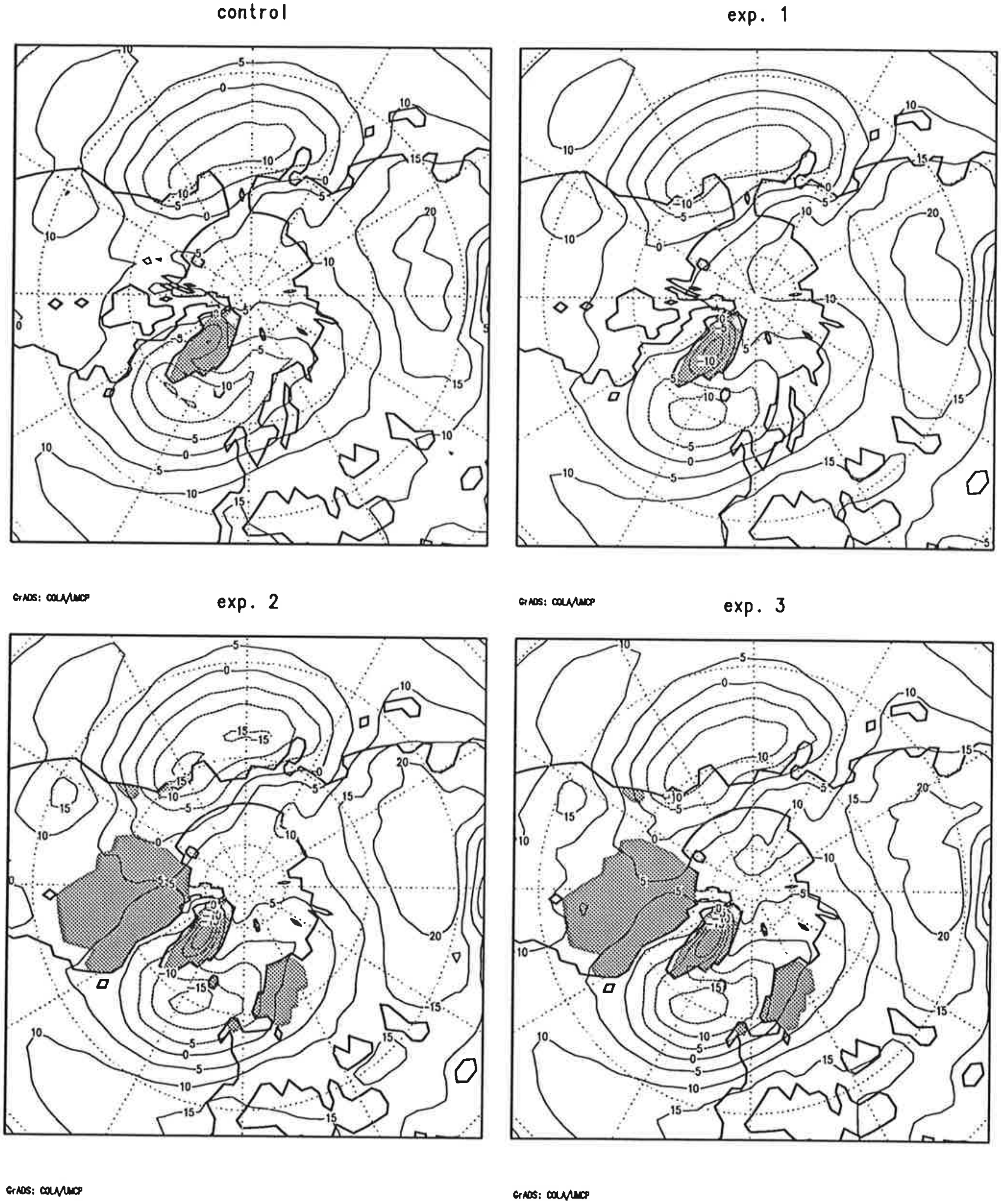


Figure 3b. As in Figure 3a except for the DJF season.

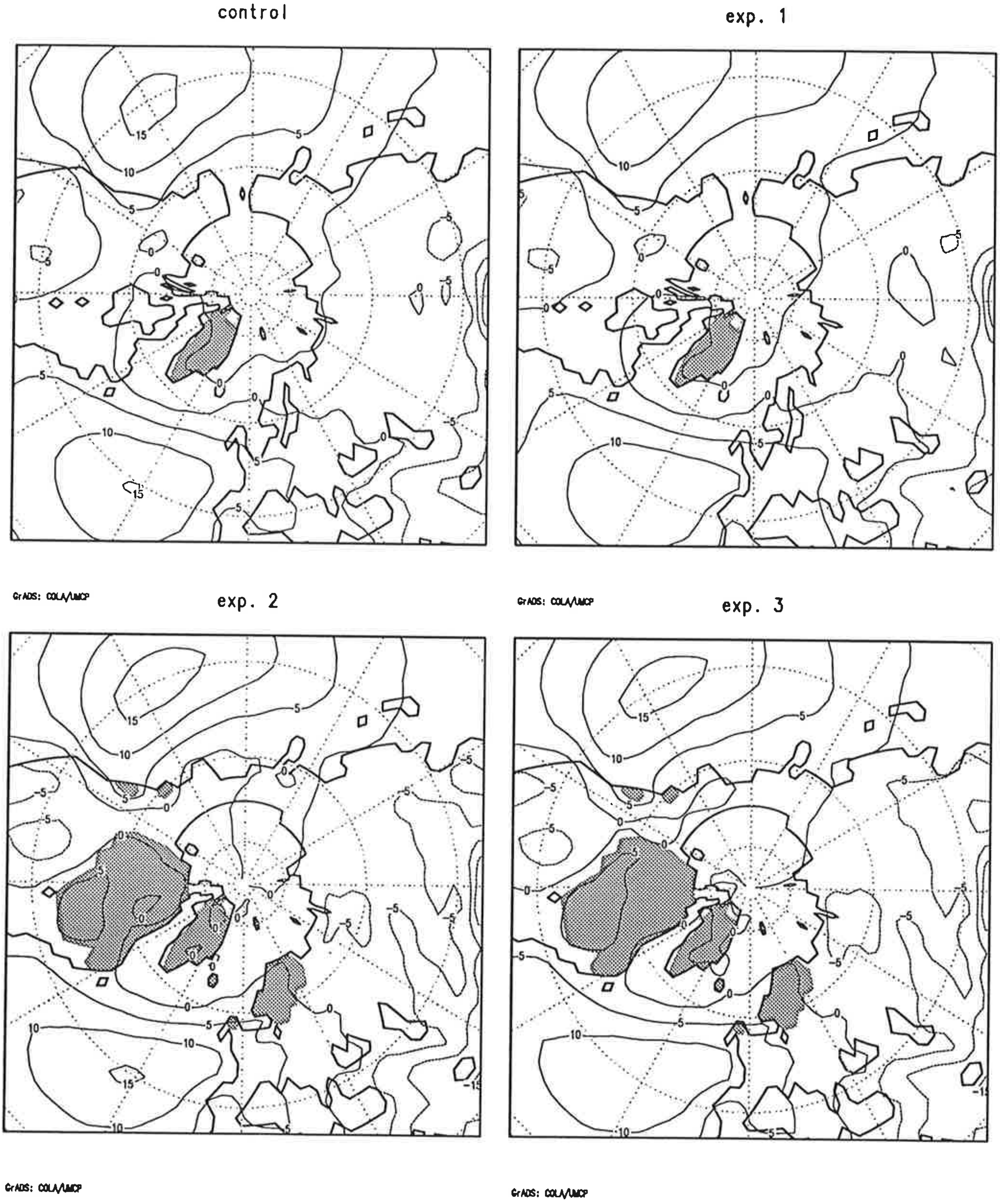


Figure 3c. As in Figure 3a except for the JJA season.

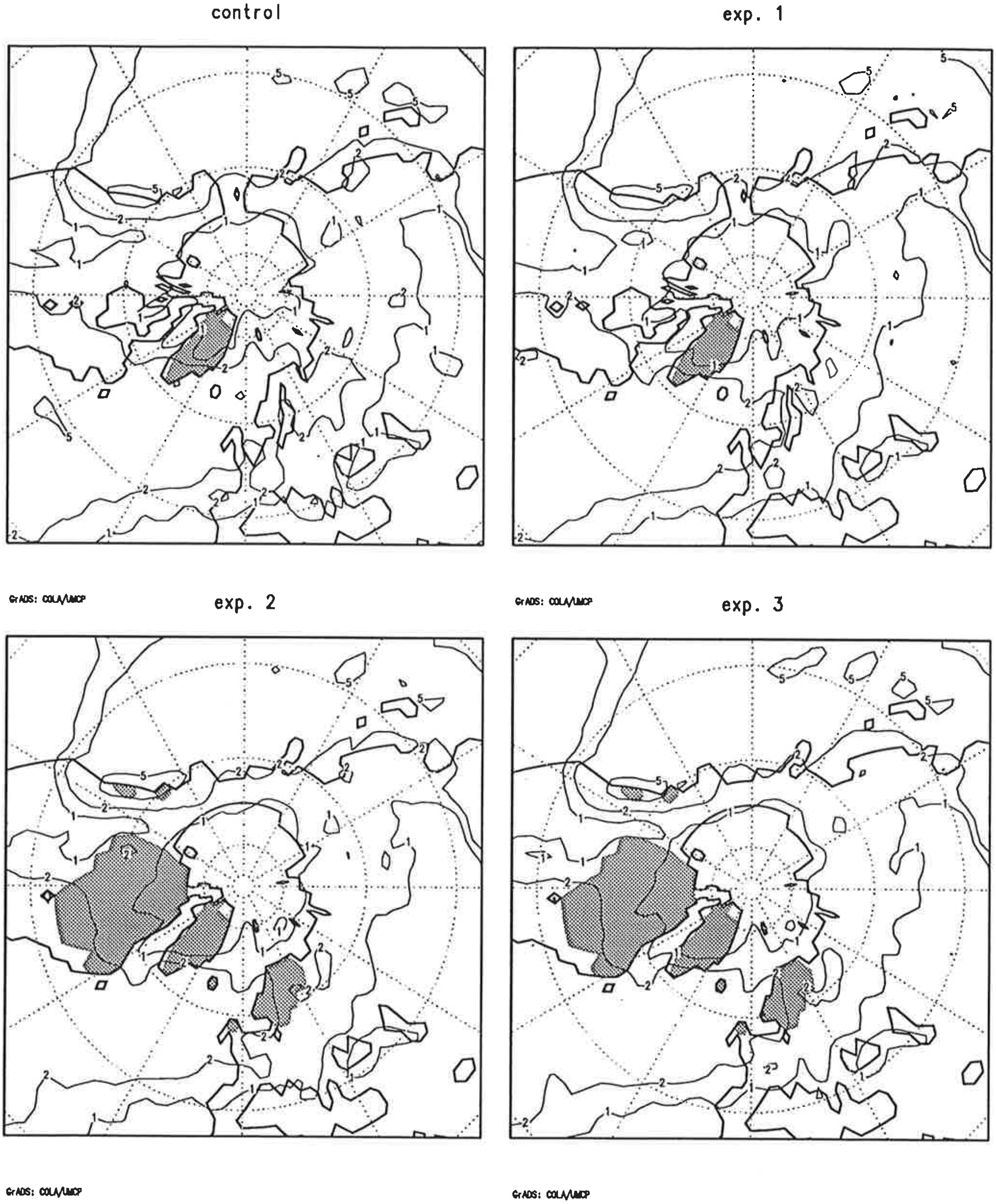


Figure 4a. Annual mean total precipitation (mm/d) in northern hemisphere (10 year average). Contours at 1, 2, 5 and 10 mm/d.

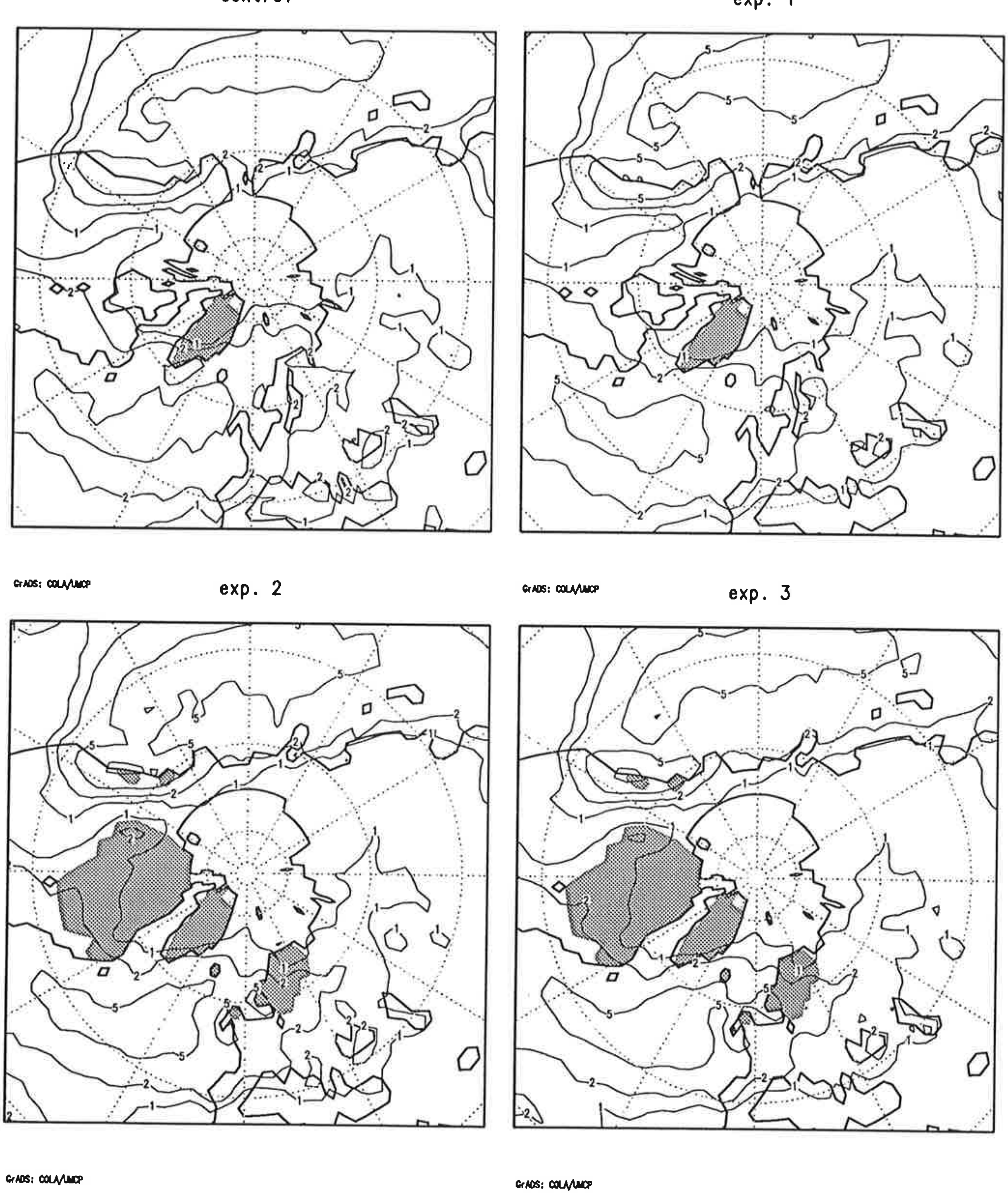


Figure 4b. As in Figure 4a except for the DJF season.

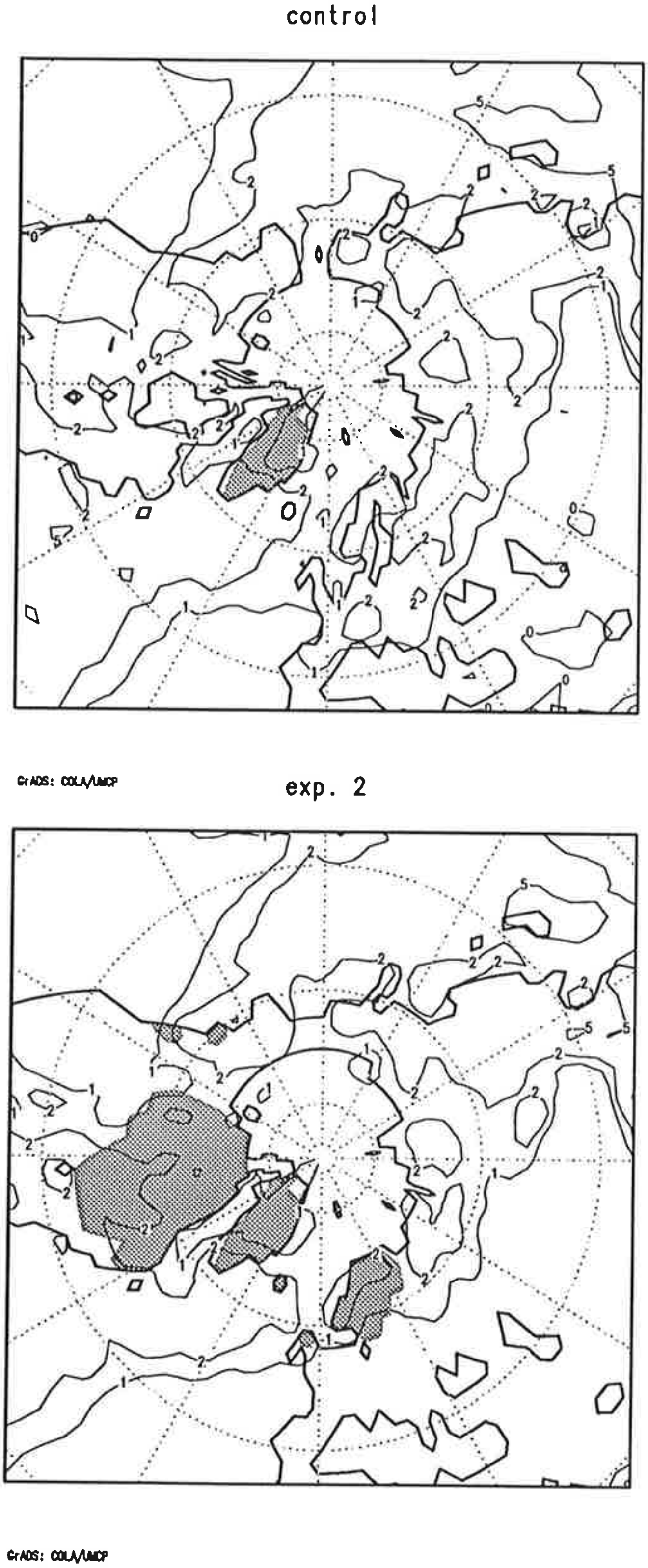


Figure 4c. As in Figure 4a except for the JJA season.

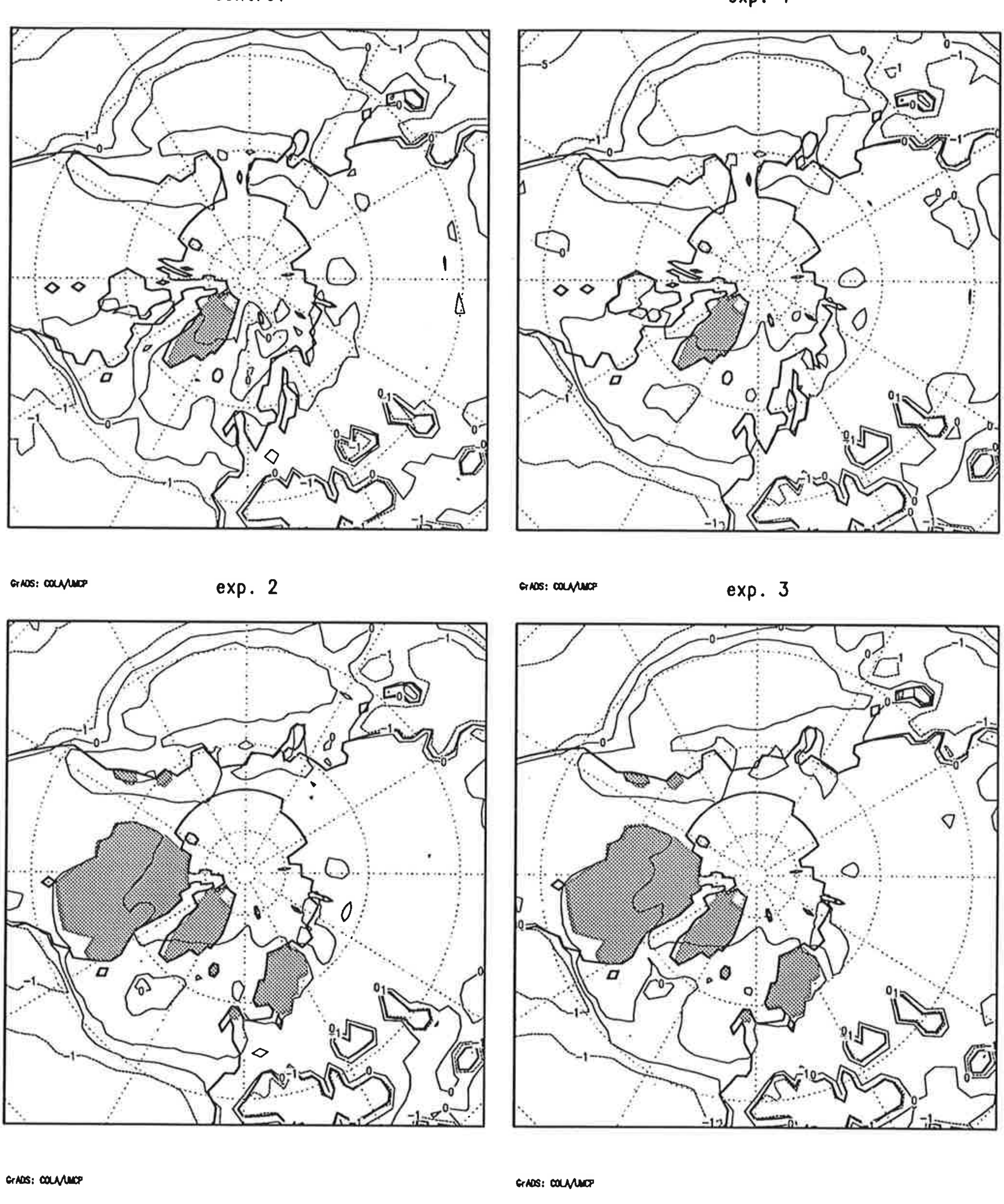


Figure 5a. Annual mean Precipitation-Evaporation flux (mm/d) in the northern hemisphere (10 year average). Contours at -10, -5, -1, 0, 1, 5 and 10 mm/d.

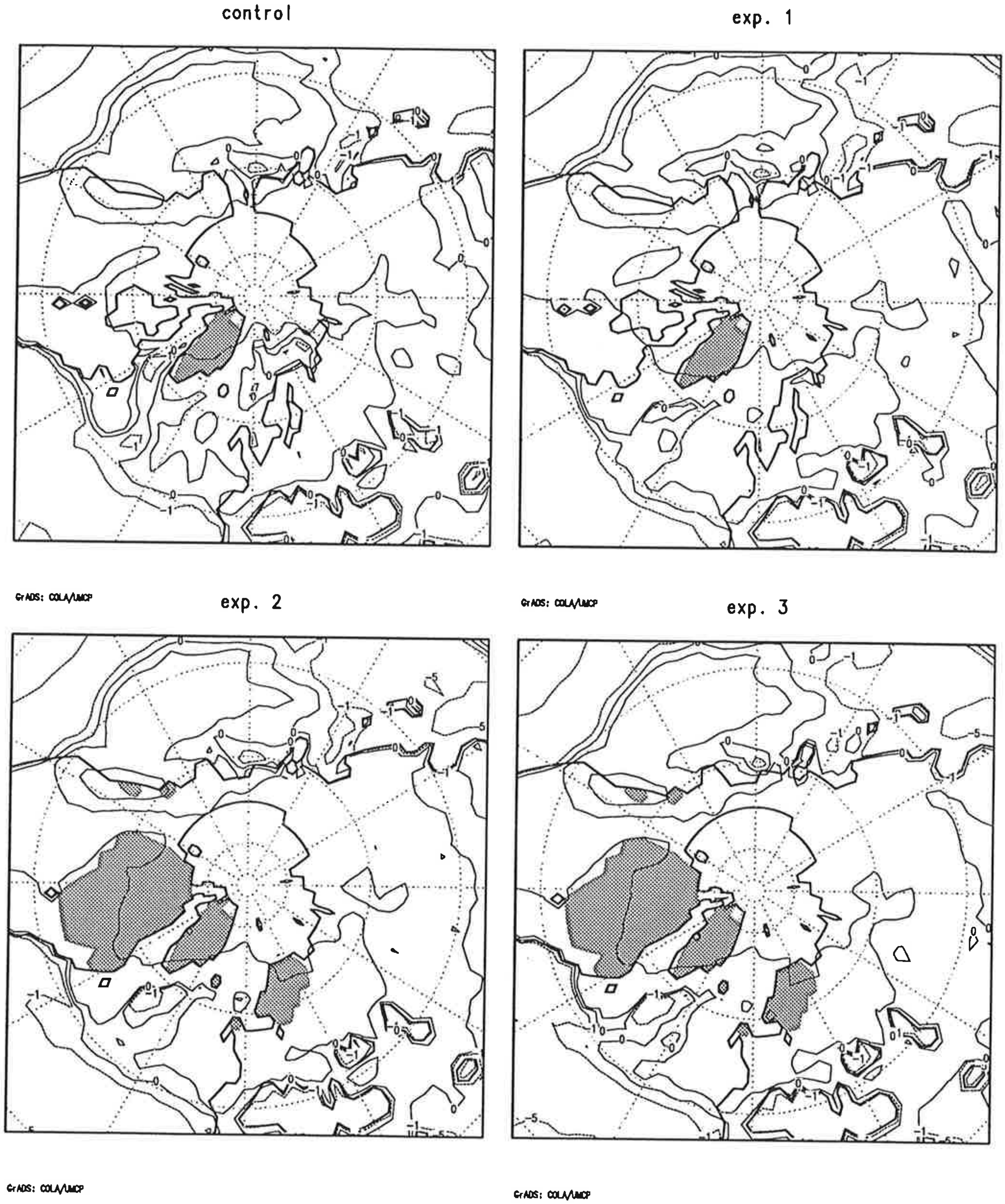


Figure 5b. As in Figure 5a except for the DJF season.

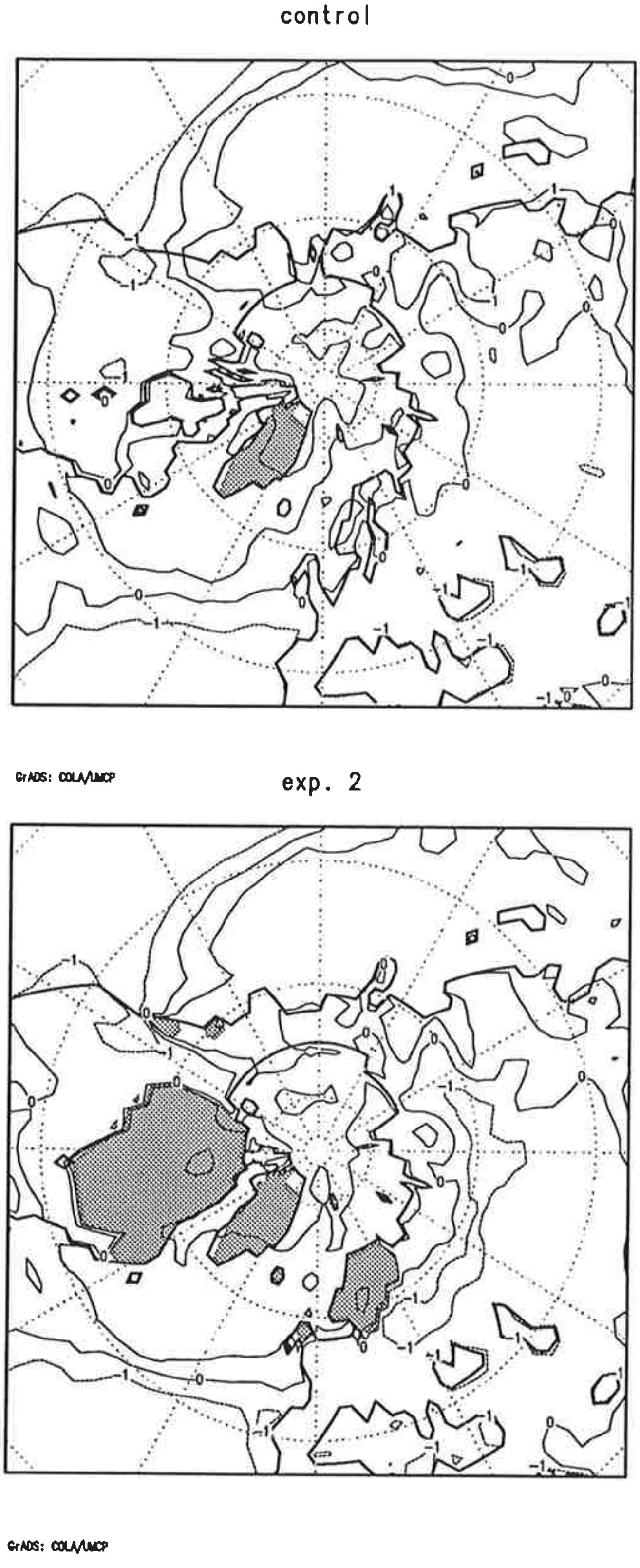


Figure 5c. As in Figure 5a except for the JJA season.

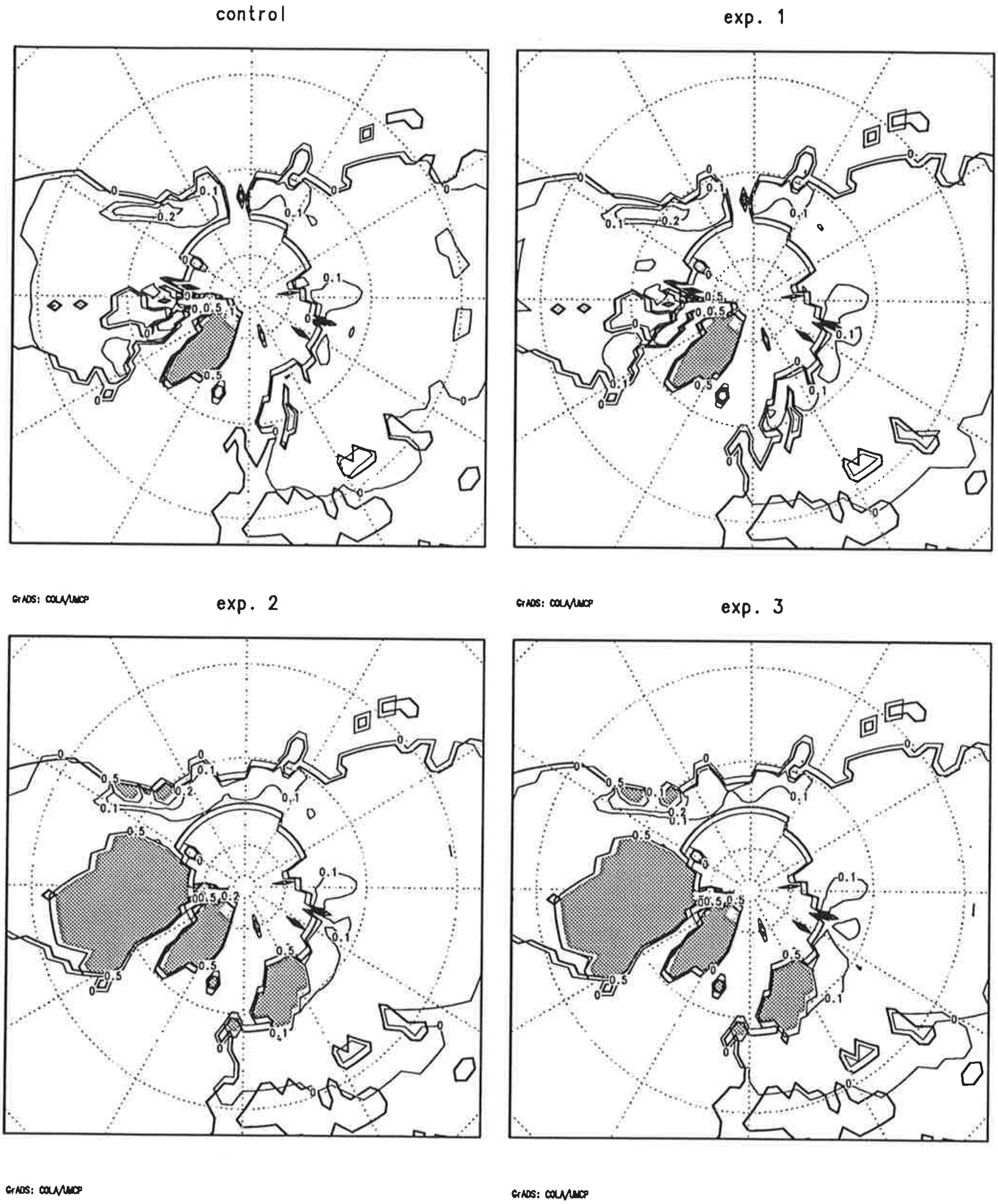


Figure 6. Annual mean snow depth (cm). 10 year average. Contours at 0, 1, 5, 10 and 50 cm.

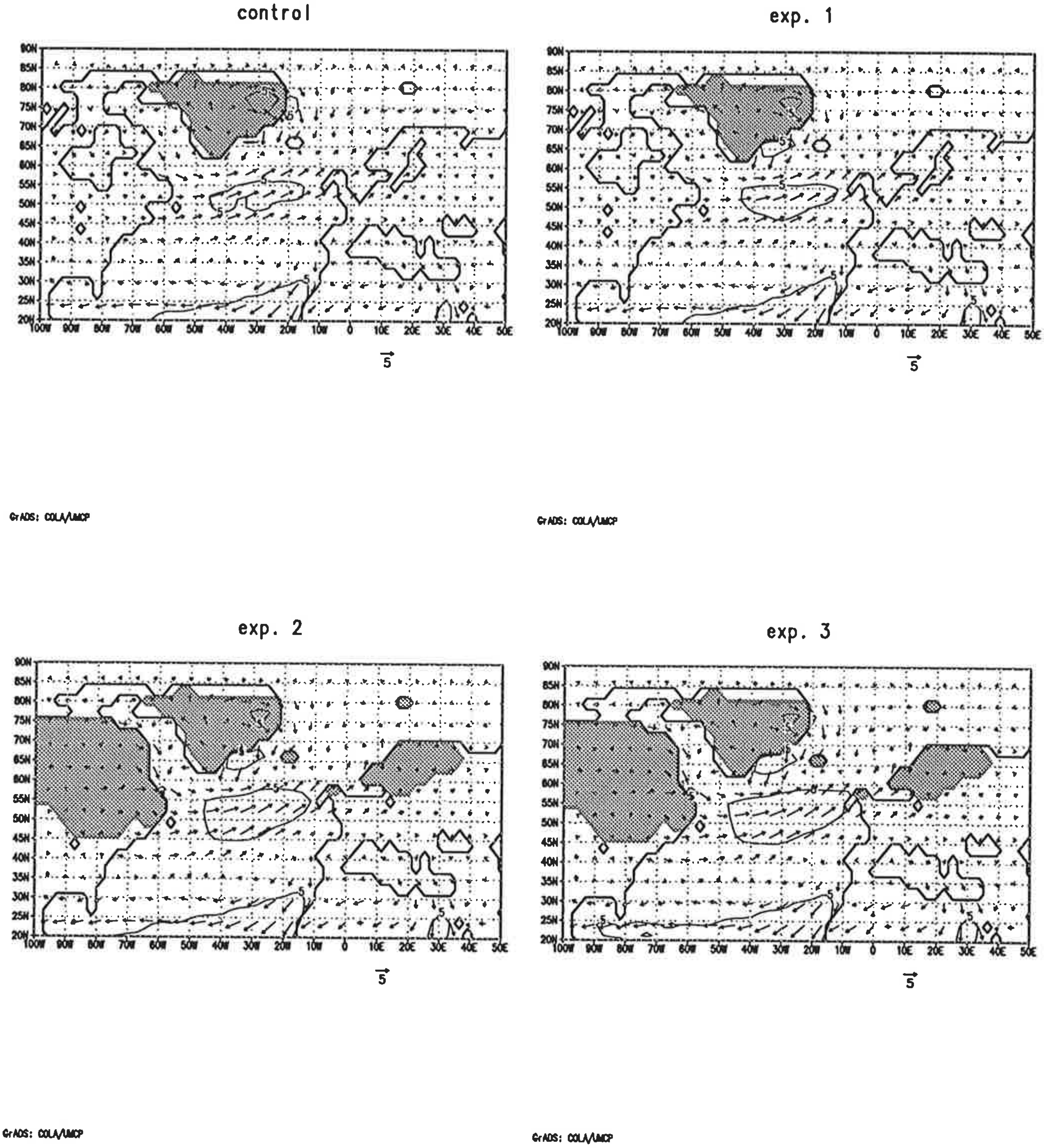


Figure 7a. Global distribution of the annual mean winds (m/s) at 10 m (10 year average). Contour interval: 5 m/s.

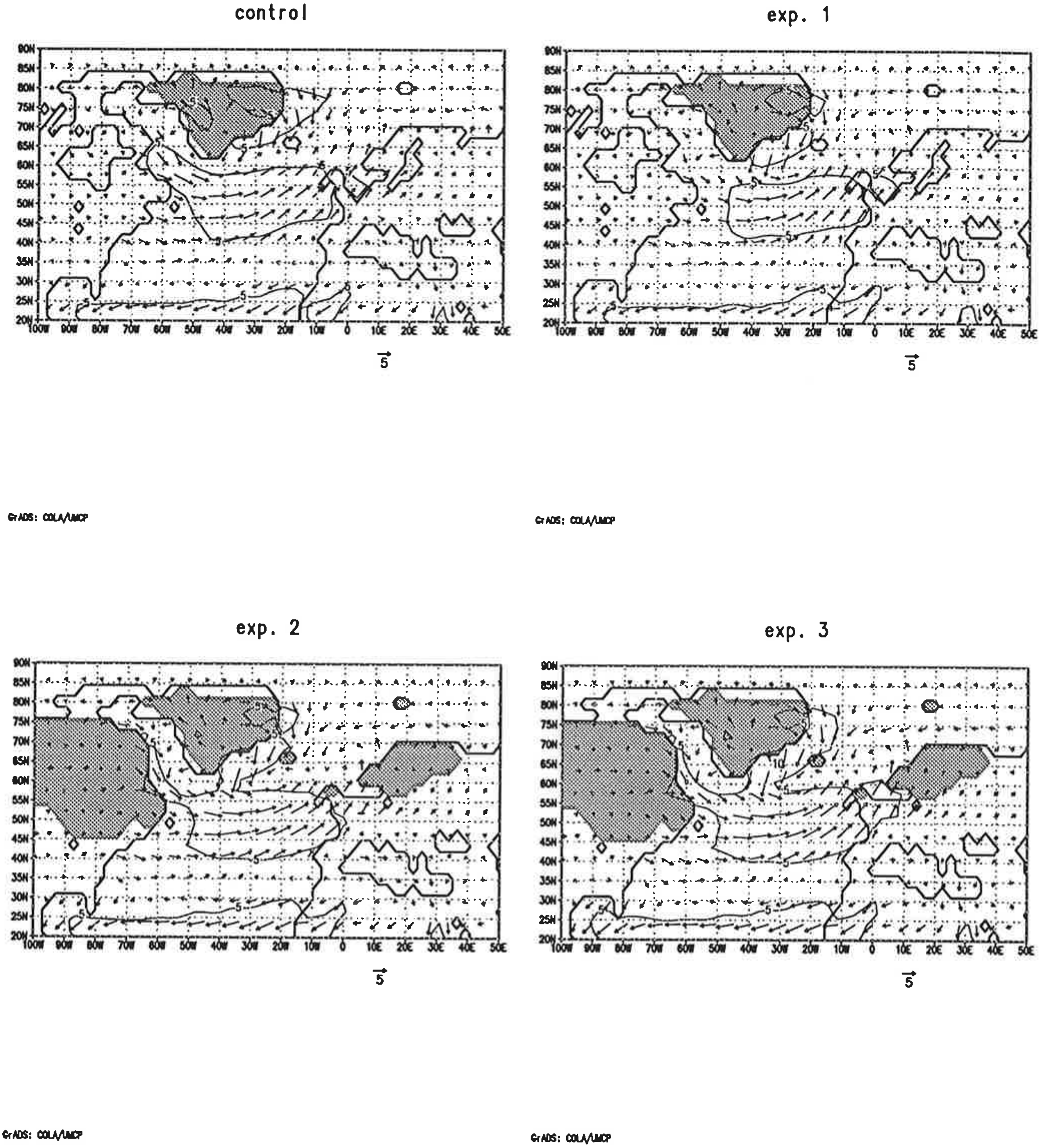


Figure 7b. As in Figure 7a except for the DJF season.

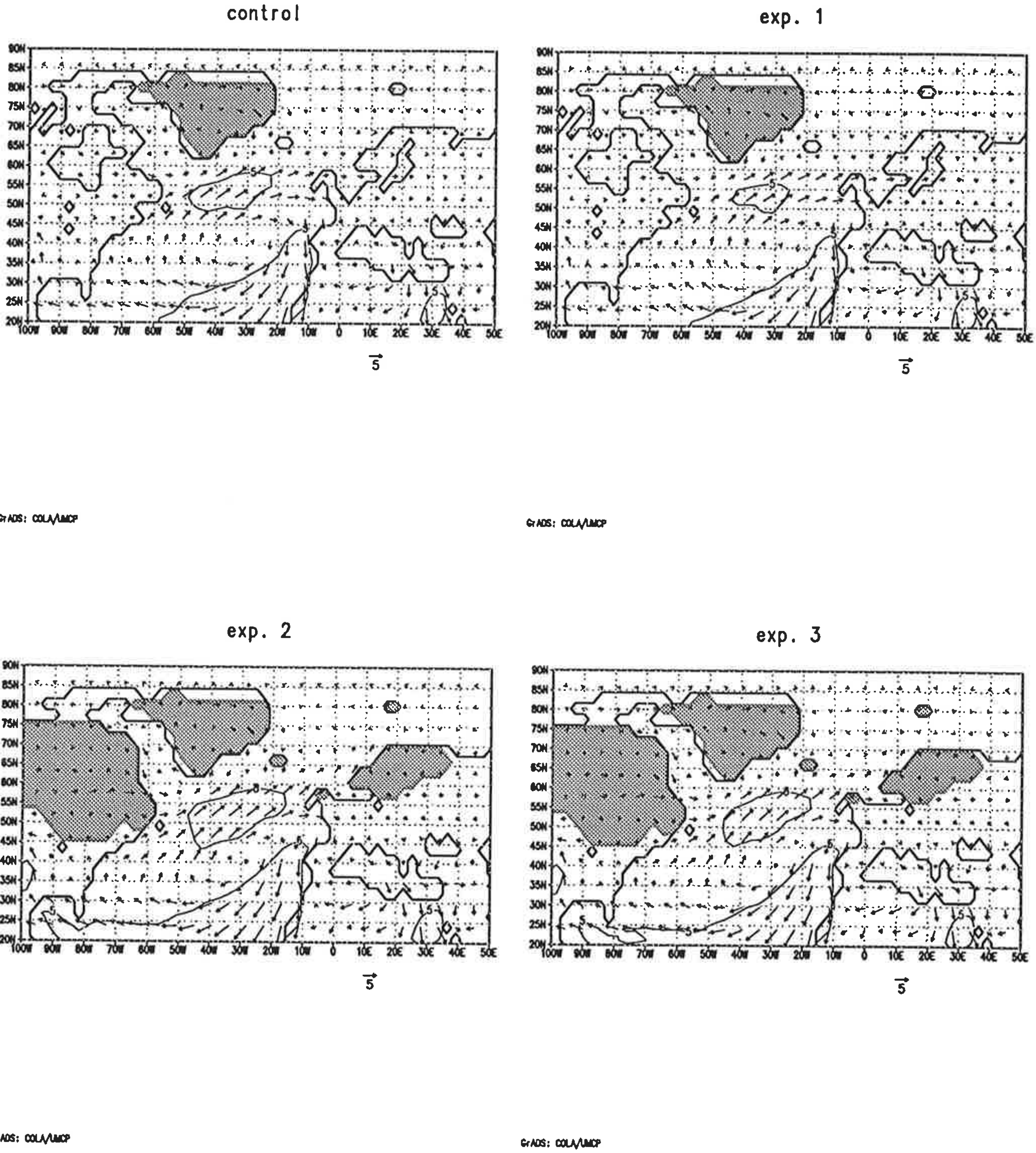


Figure 7c. As in Figure 7a except for the JJA season.

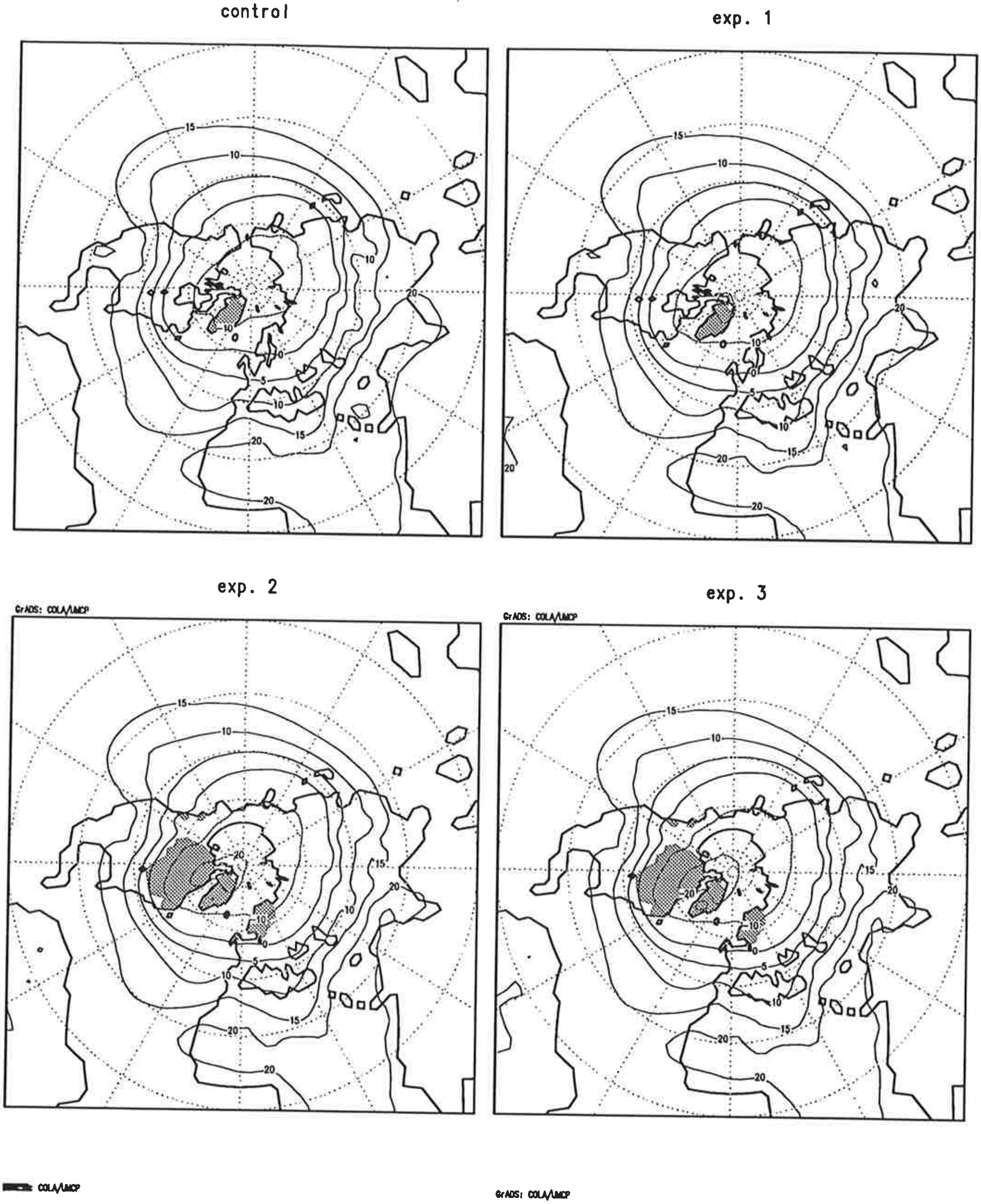


Figure 8a. Annual mean temperature (°C) at 850 hPa for the northern hemisphere (10 year average). Contours at -30, -20, -10, 0, 5, 10, 15, 20, 25 and 30 °C.

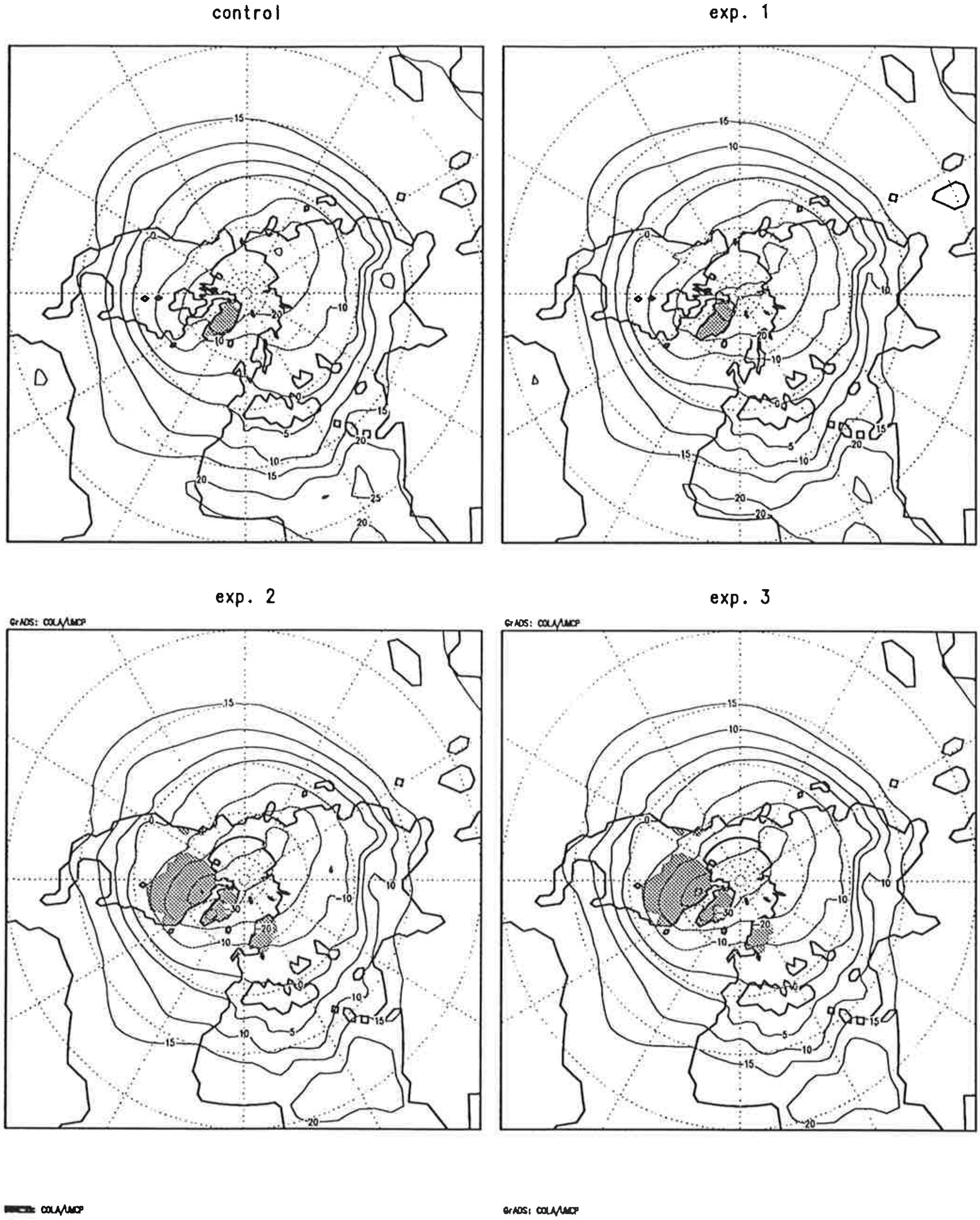


Figure 8b. As in Figure 8a except for the DJF season.

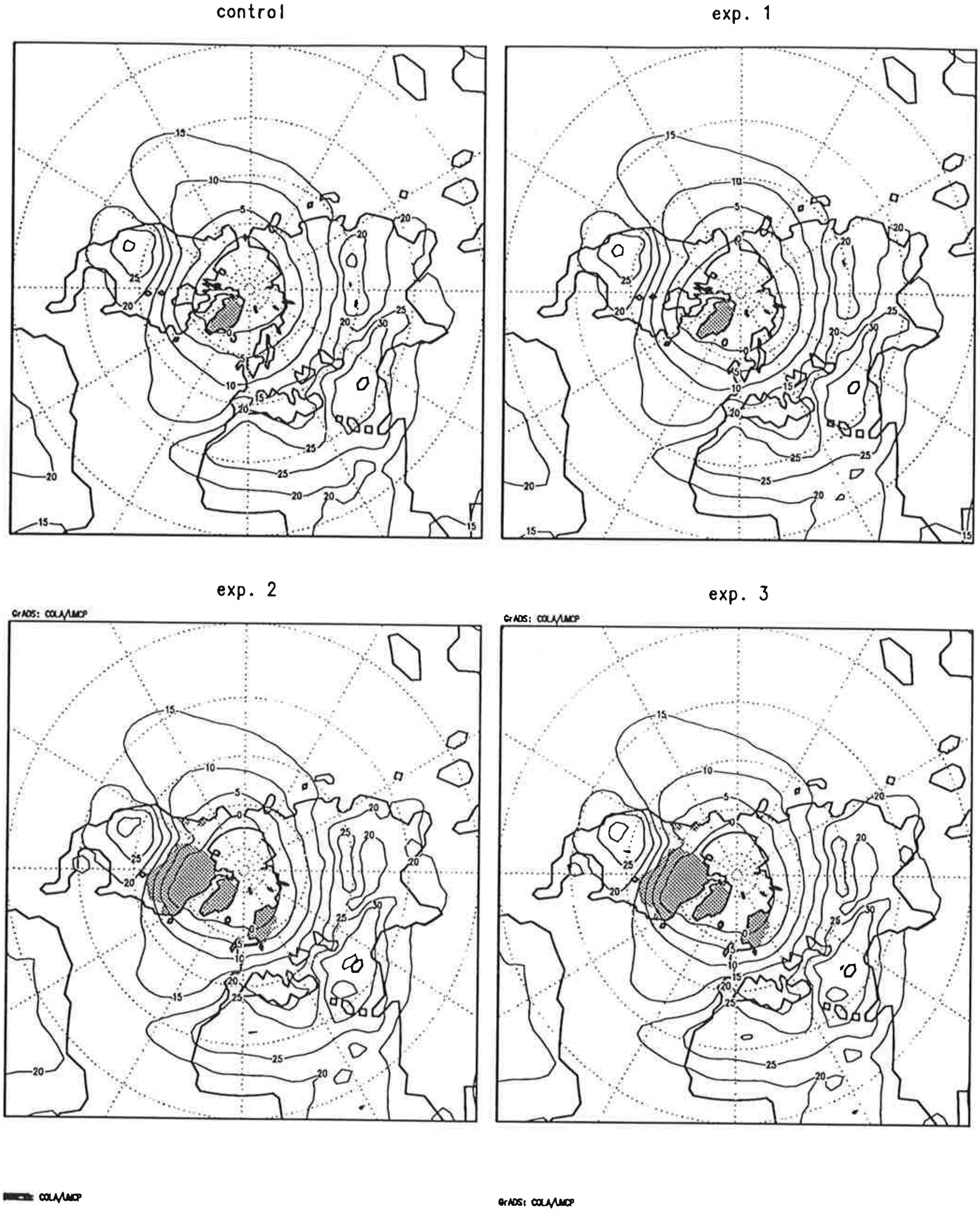


Figure 8c. As in Figure 8a except for the JJA season.

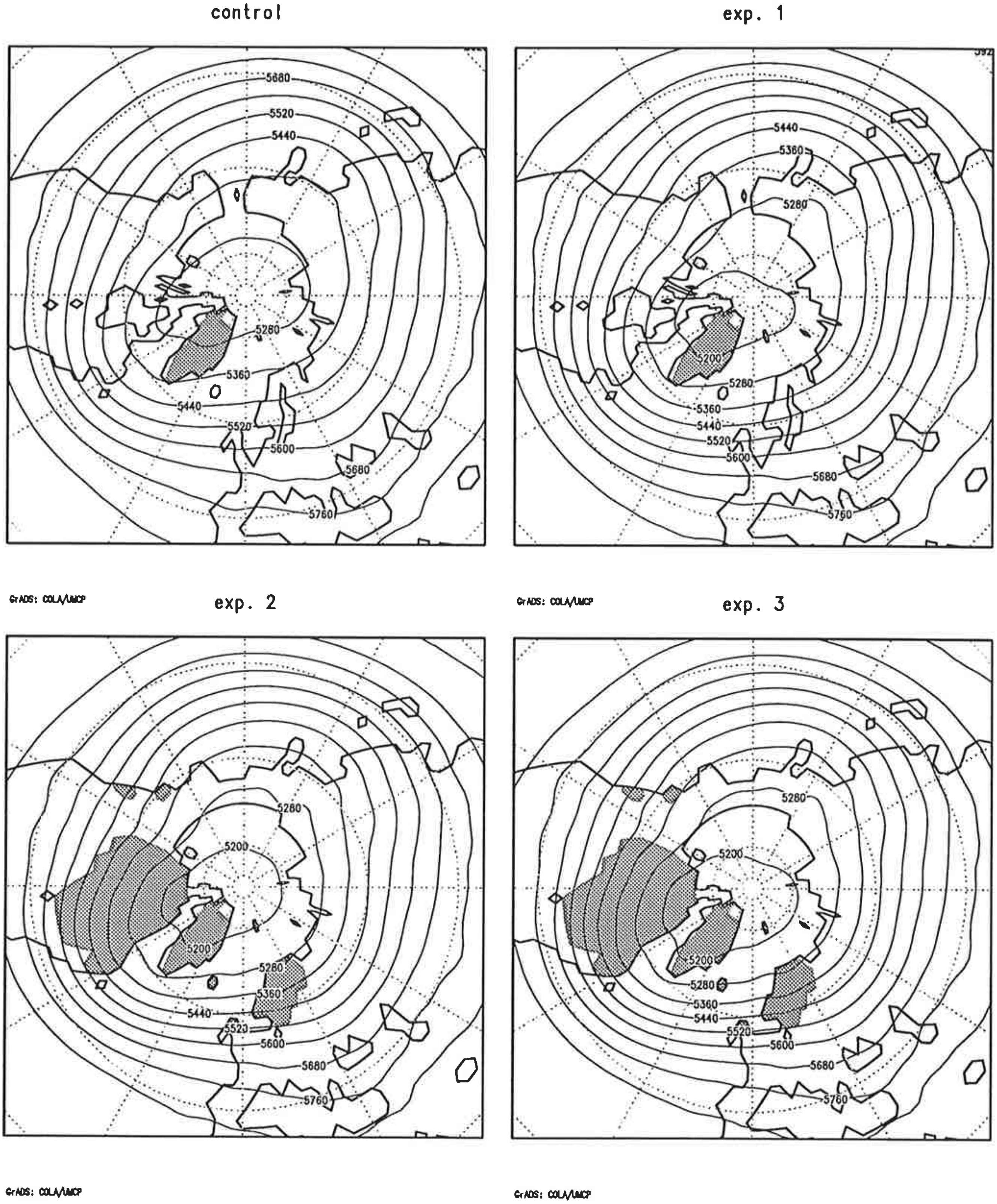


Figure 9a. Geopotential height (m) at 500 hPa for the northern hemisphere (10 year average). Contour interval: 80 m.

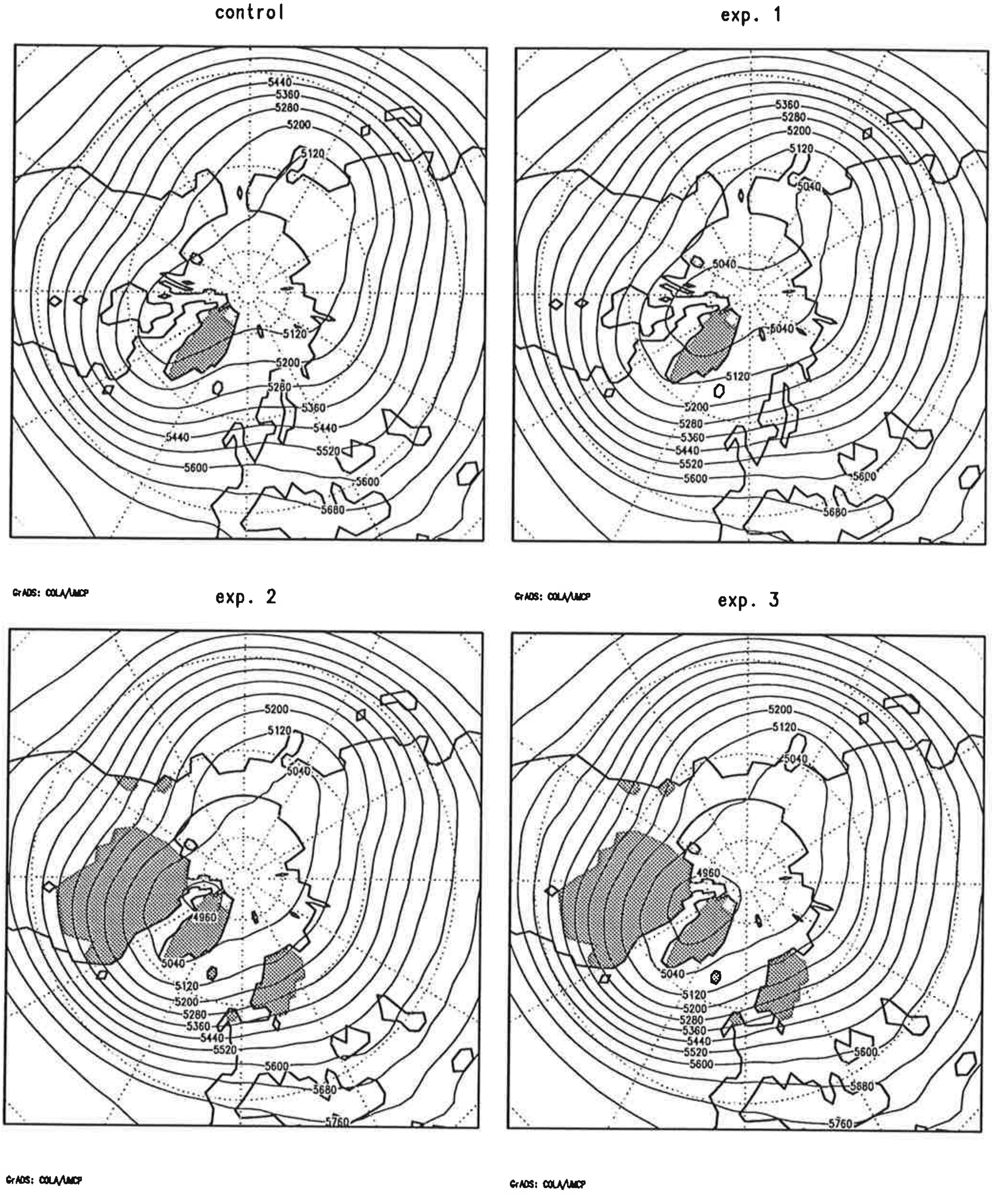


Figure 9b. As in Figure 9a except for the DJF season.

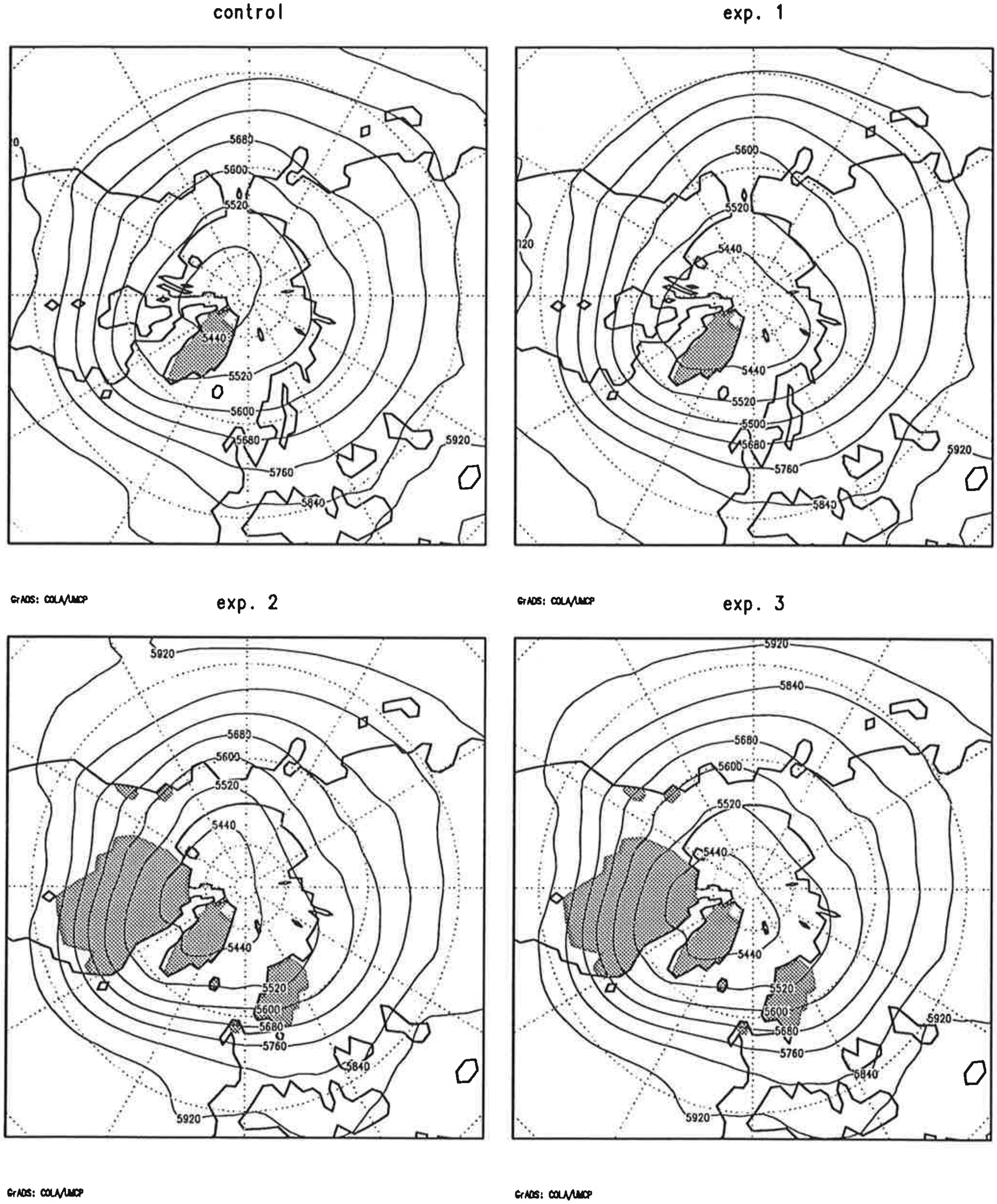


Figure 9c. As in Figure 9a except for the JJA season.