Global Climatic Change
Its Implications for Crop Protection

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Preface

Whether the climate of the world is different now to that enjoyed fifty years ago and whether climate is different to that which it will be in fifty years time, tends not to be in dispute. Depending upon how climate is defined, the answer tends to be that it is, and it will be. The important questions are: how will it differ, and will it be different enough to matter? The first of these questions is being defined by current measurement, the second, although the subject of a number of current research programmes, is the subject for dispute within the general public and within most professional and industrial groups. The crop protection industry is no different in this respect to other groups.

The activity of herbicides depend upon the conditions for their activity within the soil. Changes in soil temperature and soil water content, both through direct effects, on e.g. soil binding properties, chemical movement within soil, uptake by crops, and indirect effects, e.g. on the activities of degrading soil bacteria, the distribution of crop and weed root systems will influence the fate of herbicides. Similarly, change in air temperature will influence the rate of development of foliar fungal pathogens and the activity of pesticides. In addition to direct effects on the working of crop protection materials and on the systems developed around them, global change may also influence some of the fundamental factors controlling agricultural production. The soils developed in different parts of the world, and even those developed in different parts of the UK, vary as a consequence of climate. The carbon content of soils is greatly influenced by temperature and in its turn has a major effect upon the ability of the soil to retain water. These factors, and major climatic factors such as temperature, thus influence the crops which can or cannot be grown in a particular area of the world or of an individual country.

The potential effects of global change are thus important for us all, both as private individuals who enjoy (or don't enjoy) particular average weather conditions, and as professionals who wish to manage or to improve agricultural production and the rural environment. Despite its obvious potential importance, it is clear that the "what" and "how much" questions are not yet the subject of definitive answers. To improve upon this situation for all of those with an interest in crop production and the maintenance of crop health, BCPC has convened a symposium on the probable implications of global change for the wider crop protection industry. Global change is much more than merely global warming. It includes factors such as increased levels of CO_2, O_3 and other gases, linked and consequential effects on crop production and its distribution and the environmental consequences of these changes in addition to simple changes in temperature.

The papers presented here thus aim to:

- identify the issues related to global change, i.e. to spell out those factors which are likely to change and the consequences of this alteration;
- detail the best current thinking derived from models of the probable effects of global changes on climate in the foreseeable future;
- assess the probable effects of these changes on food supply;
- estimate the likely effects of global change on one of the major components of the global carbon budget, the soil and upon the, at times, poorly understood physical, chemical and biological process which occur within it;

- illustrate some of the possible effects of global change by detailing effects on the activity of one specific crop protection material (phenmedipham) that can be produced as a consequence of the alteration of a single environmental factor (ozone concentration) which is likely to change as part of a general shift in climatic conditions.

The basis of much of our scientific understanding is dependent upon experimentation and measurement. While effects of individual factors, such as CO_2 on temperature can be assessed in laboratory, glasshouse or field trials with varying degrees of difficulty, to assess the direct effect of the complete catalogue of factors are more difficult. However, some attempt can be made to assess implications by consulting the fosil and evolutionary record and by assessing the impact of previous climate changes.

Information from all these approaches are contained in this volume in an attempt to suggest answers to the questions raised above. This is not however a volume for the specialist in climate change, it is unashamedly an attempt to identify and quantify the main global change issues for those involved with one agriculture-related industry, crop protection. It is hoped that it will be of value as much to those involved with chemical related research as to those who seek to maintain crop health by genetic selection or cultural management. If it helps in the definition of questions, it will have served its purpose.

D Atkinson

Symposium Chairman

Abbreviations

acid equivalent	a.e.
active ingredient	AI
boiling point	b.p.
British Standards Institution	BSI
centimetre(s)	cm
concentration x time product	ct
concentration required to kill 50% of test organisms	LC50
correlation coefficient	*r*
cultivar	cv.
cultivars	cvs.
day(s)	d
days after treatment	DAT
degrees Celsius (centigrade)	^{o}C
dose required to kill 50% of test organisums	LD50
dry matter	d.m.
Edition	Edn
Editor	Ed
Editors	Eds
emulsifiable concentrate	EC
freezing point	f.p.
gas chromatography-mass spectrometry	gcms
gas-liquid chromatography	glc
gram(s)	g
growth stage	GS
hectare(s)	ha
high performance (or pressure) liquid chromatography	hplc
hour	h
infrared	i.r.
International Standardisation Organisation	ISO
Kelvin	K
kilogram(s)	kg
least significant difference	LSD
litre(s)	Litre
litres per hectare	l/ha
mass	*m*
mass per mass	*m/m*
mass per volume	*m/V*
mass spectrometry	m.s.
maximum	max.
melting point	m.p.
metre(s)	m
milligram(s)	mg
millilitre(s)	ml
millimetre(s)	mm
minimum	min.
minute (time unit)	min
molar concentration	M

nuclear magnetic resonance	nmr
number average diameter	n.a.d.
number median diameter	n.m.d.
organic matter	o.m.
page	p.
pages	pp.
parts per million by volume	mg/l
parts per million by weight	mg/kg
pascal	Pa
percentage	%
post-emergence	post-em.
power take off	p.t.o.
pre-emergence	pre-em.
probability (statistical)	*P*
relative humidity	r.h.
revolutions per minute	rev./min
second (time unit)	s
standard error	SE
standard error of means	SEM
soluble powder	SP
species (singular)	sp.
species (plural)	spp.
square metre	m^2
subspecies	ssp.
surface mean diameter	s.m.d.
suspension concentrate	SC
temperature	temp.
thin-layer chromatography	tlc
tonne(s)	t
ultraviolet	u.v.
vapour pressure	v.p.
variety (wild plant use)	var.
volume	*V*
weight	*W*
weight by volume (mass by volume is more correct)	*W/V* (m/*V*)
weight by weight (mass by mass is more correct)	*W/W* *(m/m)*
wettable powder	WP

approximately	c.
less than	<
more than	>
not less than	<
not more than	>

Multiplying symbols-		Prefixes
mega	(x 10^{6})	M
kilo	(x 10^{3})	k
milli	(x 10^{-3})	m
micro	(x 10^{-6})	µ
nano	(x 10^{-9})	n
pico	(x 10^{-12})	p

CLIMATE CHANGE AND ITS IMPLICATIONS

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ABSTRACT

The driving forces for climatic and global change are briefly reviewed. It is concluded that some form of climatic change is very likely, but prediction of detailed changes is still very difficult. The practical consequences for the agricultural and forest industries may be severe, especially if there is interaction with land-use change caused by socioeconomic forces.

INTRODUCTION

The title given here is 'climate change', but it is important to distinguish what we mean by the term. The more all-embracing concept is 'global change', and it is best to start by considering this. The International Geosphere-Biosphere Programme (IGBP, 1992) usually takes there to be three separate but linked driving forces for terrestrial change on a global scale. These are

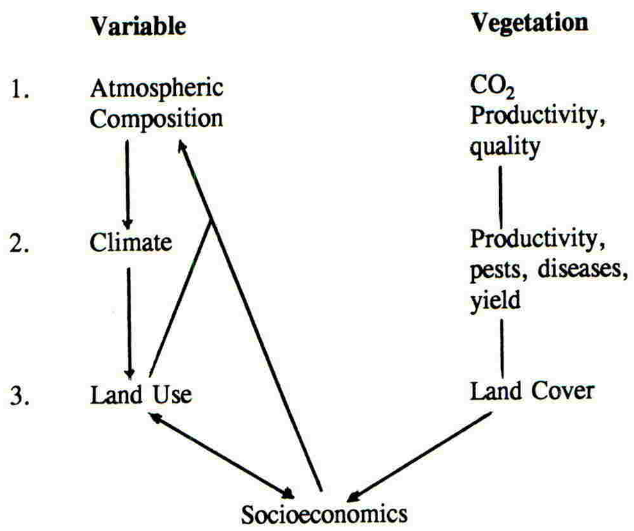
a) atmospheric composition change
b) change in climate
c) change in land use

These will be described in turn, together with their interactions (Fig. 1).

Most of us have tended to assume that we live on a planet which is highly stable. With a few fluctuations such as the 'Little Ice Age' of the 16th Century, and more or less local droughts or floods, the climate has seemed rock-steady throughout recorded history. We are of course aware that before this there were major Ice Ages, both in the relatively recent past of the last 100,000 years, and in earlier epochs. Gradually we have become aware that we are living in a relatively brief interglacial period, and that a recurrence of the Ice Ages was likely, but this has always seemed a distant prospect. In the 1970s there was indeed a short flurry of alarm that we were headed for an imminent Ice Age, but this was then swallowed up in the concern over an imminent rise in temperatures.

The idea behind climate change is however quite different to earlier concerns. The basic concept has been known for around a century. It states that human action (as opposed to natural forces) is altering the composition of the atmosphere such that more of the incoming radiant energy tends to be trapped within the atmosphere, and that this must ultimately alter the climate. The idea that human action can alter the fundamental processes of the earth was quite new, as it had been assumed that the earths systems were massively buffered against any human activity. It now appears that some of them are quite delicately balanced.

Figure 1. Driving variables in global change, and some of their interactions.



As the possibility of global change has gained support, a large infrastructure of organizations and programmes has grown up to research into global change, or to monitor or control it (da Cunha, 1991). This mass of organisations gives cause for some concern, because the funding support is not commensurate with the need of such a complex system. This structure has also developed into the socio-economic sciences (Berk, 1991).

Global problems have given a great impetus to the development of large multidisciplinary, coordinated research programmes. In the terrestrial sciences, it is becoming clear that the single researcher working on a limited and detailed problem can make little impact on the scale of the research needed, though the programmes themselves always need individuals with the unexpected insight or approach.

ATMOSPHERIC CHANGE

The main perturbing mechanism causing climate change is the production of 'greenhouse gases', of which the principal one is carbon dioxide, that contributes a little over half the total effect. Economic development during the 19th Century led to a huge increase in its output. So long as wood was the primary fuel, this caused no problem, since it was cycled back into vegetation by photosynthesis. The use of fossil fuels however produced a net injection of new CO_2 into the atmosphere. At first this was exceeded by other sources, caused by cutting down of large areas of forest, and the ploughing up of large parts of the temperate grasslands of America and Russia. During this century the use of fossil fuels has rapidly outgrown other sources, even though the felling of tropical forests has now become a major source.

Table 1. The annual global CO_2 balance sheet in 1990 (from Jarvis and Dewar, 1993)

Sources	Gt/a	Sinks	Gt/a
Fossil fuels	5.7	Atmosphere	3.2
Tropical deforestation	2.1	Oceans	1.0
CO & CH_4 from burning vegetation and soil changes	0.7	Temperate & boreal forests	1.8
		Tropical forests & grasslands	2.5
Total sources	8.5	Total sinks	8.5

The total current carbon balance of the earth is in Table 1 (Jarvis and Dewar, 1993), that shows the importance of fossil fuel use. Of the net total input of additional CO_2 to the atmosphere, roughly half remains there, and causes the problems described below. The other half is absorbed by the ocean or by the terrestrial land surface. The resultant net change is that CO_2 in the atmosphere is increasing by about 0.5% per year, though with quite marked differences from year to year, and has risen from about 280 ppm in the preindustrial period to about 350 ppm now.

The other greenhouse gases are methane, which has a wide variety of sources and sinks, and nitrous oxide. Unexpectedly, it appeared that the chlorofluorocarbon chemicals, produced as refrigerants and for many other uses, are extremely potent greenhouse gases. This is in addition to their better known effect in breaking down stratospheric ozone and thereby increasing UV-B irradiation in some parts of the world, that can also be regarded as one aspect of global change. Mainly because of this latter effect, action has been taken to ban them under the Montreal Convention, though they are still increasing in the atmosphere. Ozone itself also has a greenhouse effect, but this will be due to pollutant tropospheric rather than the protective stratospheric ozone.

The production of the three major greenhouse gases are all bound up with agriculture and land use. A substantial part of the carbon dioxide flux, both in and out of the atmosphere, depends upon loss or gain of forests, with a net flux of 1-2 Gt per year. Current estimates of the total loss of tropical forests range around 10-12 M ha per year, though the data are open to many errors (Table 2). Goudriaan (1992) concluded that deforestation was responsible for 12-17% of the total CO_2 emission rate in the decade 1980-1990, but that increased uptake of CO_2 by vegetation caused an uptake equivalent to 20-25%. It is now usually agreed that there is a large terrestrial sink, mainly due to uptake by the large northern forests. The sources and sinks have been identified from small anomalies in CO_2 concentrations (Enting and Mansbridge, 1991). The equatorial source is probably from tropical deforestation and associated loss of soil organic matter, and the southern sink is believed to be photosynthesis in the ocean. It has been suggested that massive programmes of reafforestation should be carried out to sequester significant amounts of carbon dioxide now in the atmosphere. However, the land areas required for storage of all fossil fuel carbon dioxide output would be huge for even a few years, and all possible storage capacity would soon be used up, so such a project could only provide temporary and partial relief.

Table 2. Summary of Global Annual Deforestation Estimates (10^6 ha) (IPCC 1992 - see original for references).

Reference	Myers 1980	FAO/UNEP 1981	Myers 1989	FAO 1991	WRI 1990
Year of Deforestation	1979	1976-80	1989	1981-90	late 1980s
Closed Canopy Forest Only	7.3	7.3	13.9	14.0	16.5
Closed and Open Canopy Forests	-	11.3	-	17.0	20.4

Table 3. Estimated Sources and Sinks of Methane (Tg CH_4 per year) (IPCC 1992)

Sources		
Natural		
Wetlands	115	(100-200)
Termites*	20	(10-50)
Ocean	10	(5-20)
Freshwater	5	(1-25)
CH_4 Hydrate	5	(0-5)
Anthropogenic		
Coal Mining, Natural Gas and Pet. Industry*	100	(70-120)
Rice Paddies*	60	(20-150)
Enteric Fermentation	80	(65-100)
Animal Wastes*	25	(20-30)
Domestic Sewage Treatment*	25	?
Landfills*	30	(20-70)
Biomass burning	40	(20-80)
Sinks		
Atmospheric (tropospheric + stratospheric) removal*	470	(420-520)
Removal by soils	30	(15-45)
Atmospheric Increase	32	(28-37)

*indicates revised estimates since IPCC 1990

Methane is produced from many sources (Table 3), of which paddy farming and animal wastes are agricultural. From this Table, the very large uncertainties attaching to almost all these sources is obvious, so it is difficult to determine which are the most important issues to address. The uncertainties are even larger for nitrous oxide (Table 4), but it appears that emissions from soils dominate (Bouwman, 1990). The effect of nitrogen fertilizer use is a particularly important issue which has still not been properly resolved.

There is one further important consequence of these changes in atmospheric composition. Carbon dioxide forms most of the dry matter of plants, by photosynthesis, and the present mean concentration is not sufficient to allow this to proceed at the maximum rate. An increase may therefore cause vegetation to grow faster, unless it is limited by some other factor. Increasing CO_2 has other profound effects, in improving the water use efficiency of plants, altering their chemical composition and root growth. These impacts on plant growth, which may well be beneficial, are expected to be very important to agriculture and forestry.

Table 4. Estimated Sources and Sinks of Nitrous Oxide (Tg N per year) (IPCC 1992)

Sources	
Natural	
Oceans	1.4-2.6
Tropical Soils	
Wet forests	2.2-3.7
Dry savannas	0.5-2.0
Temperate Soils	
Forests	0.05-2.0
Grasslands	?
Anthropogenic	
Cultivated Soils	0.03-3.0
Biomass Burning	0.2-1.0
Stationary Combustion	0.1-0.3
Mobile Sources	0.2-0.6
Adipic Acid Production	0.4-0.6
Nitric Acid Production	0.1-0.3
Sinks	
Removal by soils	?
Photolysis in the Stratosphere	7-13
Atmospheric Increase	3-4.5

CLIMATIC CHANGE

The greenhouse effect noted above results from the atmosphere being fairly transparent to the relatively short-wavelength radiation from the sun. This is absorbed by the surface, and partly re-emitted as longer wavelength infra-red radiation. Greenhouse gases are opaque to this, hence this radiation is trapped within the atmosphere to an extent depending upon the concentration and the type of gases. The various gases have different trapping power, so the total effect is usually expressed as an equivalent carbon dioxide effect. Predictions of future climates are often given in terms of an effective doubling of the CO_2 level, which is expected to occur sometime around the middle of next century. There are however very large uncertainties in this, as it depends upon the policy response of countries, and the effectiveness of the Montreal Convention in controlling some greenhouse gas emissions. The various scenarios in IPCC (1992) show outputs varying from 5 to 35 Gt CO_2 per year in 2100.

The step from establishing the amount of greenhouse gas in the atmosphere to predicting the consequent climate change is an extremely difficult one, which will be described in detail in a subsequent paper at this conference. The latest update of the studies of the Intergovernmental Panel on Climate Change (IPCC 1992) confirms the earlier prediction (IPCC 1990) that the global mean temperature will increase by between 1.5 and 4.5 °C for a doubling of CO_2 concentration. Temperature rise is expected to be greatest near the poles, and quite small at the equator, which is fortunate for the tropics of the world. However, there is still much doubt about the local or even regional effects, and it is of course these that are needed to estimate impacts on crops, grasslands and forests. Goodess and Palutikof (1992) have assessed the possibility of producing climate scenarios for impact assessment, and Viner and Hulme (1992) have produced scenarios for the UK based on coupled ocean-atmosphere Global Circulation Models.

The ability to predict changes in precipitation, including its distribution and intensity is poorer. This causes very serious difficulties for estimating impacts, because a major change in rainfall can have more devastating effects than a change in temperature. For example, some predictions suggest that the Mediterranean basin will be much drier, especially in summer. The consequences of this for areas that are already semi-arid do not need to be elaborated. At the present time the unreliability and variability of rainfall is a particular problem in many areas, for example the Sahel. On average it is believed that in a warmer world there will be somewhat more rainfall, because evaporation will be larger. However, this generalization is of little use to those areas which will receive even less rain than now, or where its distribution forces a complete change in cropping system.

At present the increase in greenhouse gases is fully documented and beyond dispute. There has been a global warming of approximately 0.5 °C over the last century, and this is very roughly in line with what would be expected from the predictions of the greenhouse effect. However, the effect is similar in size to previously occurring natural fluctuations in temperature, and it is as yet not possible to state categorically that climate change is occurring.

Because of these uncertainties, there is a point of view that dismisses climate change as an unproven hypothesis. Despite the problems of prediction, this seems too facile. We know that greenhouse gases are increasing sharply, to levels well above any that we have ever experienced. The basic physics of the greenhouse effect are fully established, and satisfactorily explain the wide differences in the surface temperatures of the planets. In addition, we have good records from the past, that establish, firstly, that temperature has fluctuated sharply over the last 100,000 years at least, and secondly, that these fluctuations were closely correlated with changes in the concentrations of carbon dioxide and other greenhouse gases in the atmosphere. It is very difficult to consider this evidence, without concluding that our climate will be perturbed, but in ways and at rates that at present are still uncertain.

Very recent work (Dansgaard *et al.*, 1993; White, 1993) has used analyses of Greenland icecores to show that temperature fluctuated sharply and frequently throughout the last Ice Age and the last interglacial period. Indeed the most stable period is precisely the last 10,000 years, since the last retreat of the ice fronts, which therefore appears anomalous. This clearly raises the question of whether anthropogenic disturbance of the present climate will make it more unstable. In brief, it appears sensible to proceed in the belief that a climate change will occur, and that we should follow the precautionary principle in making forward plans to deal with it.

SEA LEVEL RISE

A consequence of any rise in temperature is that the global sea level will change. This results from the expansion of seawater as it warms up, and from changes in the Antarctic and Greenland ice caps. Initially it was expected that the ice caps would shrink, perhaps drastically, and this gave rise to the extreme predictions of seas level rise of several meters. It is now believed that increased snowfall may compensate for more rapid melting, and current predictions are for a rise of around 20 cm for a doubling of CO_2. This may cause problems in some low-lying areas, but is not likely to be catastrophic.

LAND USE CHANGE

Land use is a particularly complex factor, because it may be driven by climate change, but there are also very powerful socioeconomic forces causing change. These are basically of two types. In the developed world, there is overproduction of food and a surplus of agricultural land. There is consequently a strong movement to return land to other uses, such as forestry, leisure or conservation. In the underdeveloped world, the pressure is reversed, with rapidly growing populations, threatening shortages of food, which is leading to felling of forests, misuse of agricultural land and soil degradation. These processes are considered as a separate set of forces causing a major global change, because of the widespread and pervasive nature of their consequences. However, the socioeconomic forces that underlie this form of land use change cannot be dealt with here. It is very relevant that when climate change occurs it will itself cause land use change, as land cover and farming systems change. The detailed analysis of this set of complex interlocking processes is far beyond the scope of this paper, but some of the simpler interactions are outlined in Fig. 1. Many of these processes and effects are outlined in a general way in Agenda 21, the result of the UNCED Conference in Rio de Janeiro in 1992. More scientific detail is in a large number of publications over the last few years, in particular IPCC (1990; 1992), and in the Operational Plans from the International Geosphere-Biosphere Programme (IGBP, 1992). The Human Dimensions of Environmental Change Programme (HDP) is also particularly relevant to this topic. Here I will focus on those factors that seem most likely to have implications for plants.

GLOBAL AND SITE-SPECIFIC EFFECTS

The term 'global change' is used in several different senses, that can cause confusion. In its true sense, it applies to changes in a totally global system, such as the atmosphere or the oceans. In both these fluid media, a change will be propagated around the globe relatively soon. Such a change is, for example, a variation in the nitrous oxide concentration of the atmosphere resulting from a major new emission source. Terrestrial changes are different, in that each incident remains local. Cases of soil erosion or soil salinization following upon land use or climate change may extend over a large area, but each is essentially independent of other similar cases of the same process. The reason for calling them global is that we expect there to be so many occurrences that the total impact has global significance. It is more difficult to deal with this type of global change in a coherent and general way than it is for the first type, because each case is inevitably to some degree different from any other.

IMPACT ON AGRICULTURE AND FORESTRY

In terms of agricultural effects, it seems unlikely that either pests or soils will be affected directly by the increase in greenhouse gases, since the increase in CO_2 is of the order of a few hundred ppm, whereas soil air often contains over 1% CO_2. However, plants will be changed both in growth rate, habit and chemical composition (Woodward, 1992). There is a surprising diversity in the responses of different species. Partly this can be explained on the basis of general principles - e.g. C3 plants tend to respond in growth rate much more than do C4 plants (Kimball, 1983). This is expected, since the C4 effect is due to a mechanism that concentrates CO_2 in the chloroplasts, hence the photosynthetic mechanism is easily saturated. However, in addition to this different species vary in unpredictable ways, particularly in wild species. The subject is still confusing, because short-term experiments do not give the same results as long-term ones, field experiments do not necessarily agree with laboratory work and differences in other environmental factors interact with the CO_2 effects.

There is evidence that some, but probably not all, plants have an increased root/shoot ratio when grown under elevated CO_2 levels. This can be important for the input of carbon into soil organic matter, as discussed in a subsequent paper. It may also affect the ability of plants to absorb water and nutrients relative to other species, and hence alter the competitive situation. In addition to direct effects on growth, it is now well established that water is used more efficiently under high CO_2 concentrations, in terms of dry matter production, because of changes in stomatal aperture.

The important question for agriculturalists is whether these differential effects will result in a different species balance in competitive situations. This could be in mixed vegetation, as in grass-clover mixtures. Much more relevant here is the question of whether they will benefit particular weed species, so that they become more damaging. Major field effects are particularly difficult to predict from single species laboratory experiments (Woodward, 1992) so there appears to be no substitute for field experimentation. To do this with gas concentrations is notoriously difficult, and it really calls for the expensive Free Air CO_2 Enrichment experiments (FACE). Only one large facility of this type has been in use for a significant period, in Arizona, USA. The major finding so far is that the yield of cotton was increased by 40% when CO_2 was elevated to 550 ppm, and that there was no increase in water use (Kimball, private communication).

So far there is no evidence that the increase in CO_2 which has already happened has caused any significant changes in the agricultural industry. It is however questionable whether these could be detected during the continual change in the methods of developed agriculture which have taken place over the last half-century. So far it has not been possible to show that this increase in CO_2 has increased productivity in agriculture or forestry, though experiments under controlled conditions suggest it should be happening, and the evidence for major CO_2 sinks in terrestrial vegetation supports the idea (Goudriaan, 1992).

The prediction of the effects of climate change on wild or semi-wild vegetation is more difficult than for monoculture agriculture. Quite complex models are needed to simulate the dynamics of forests (Smith, Shugart, Bonan and Smith, 1992). The modelling of the long-term macroscopic behaviour of natural ecosystems must be even more difficult, because the component species may not remain together during migration under climate change (Huntley, 1992).

Farmers always have to face some degree of risk from the weather. They do however expect that the climate will remain constant, so that variations over a few years tend to average out. During climate change, there will be a continuing trend, on which annual or cyclical variations will be superimposed. The assessment of risk in such circumstances will be very much more difficult, because cultivars, crops and agronomic practices may need to be changed. Decisions on when such changes should be introduced will be critical.

In this situation the IGBP response has been to develop work over a wide range, largely based upon developing or proving models of ecological change or of crop development and growth (IGBP, 1992). In regard to agriculture, it clearly cannot undertake the massive location-specific and adaptive research that will be necessary if climate change becomes a serious problem. It is therefore working to ensure that there are appropriate crop models for major crops, that have been tested under a wide range of climatic conditions, and in presence of elevated CO_2 concentrations.

CONCLUSION

There seems no doubt that there will be major changes in the earth system over the next century, and perhaps more. This will be so even if land use alone remains as the main driving force for change. The particular problem with climate change is that it is so pervasive. It has been considered here mainly in the context of agriculture, forestry and land use, but there will be many other effects, such as in the energy, insurance, transport, construction and other industries. However, of all these, there is little doubt that the potential impact may fall most sharply upon agriculture.

REFERENCES

Berk, R.A. (1991) Research priorities for the Human Dimensions Global Environmental Change. In: *Global Environmental Change*, R.W. Correll and P.A. Anderson (Eds), NATO ASI series, Springer-Verlag, Berlin, 83-96.

Bouwman, A.F. (1990) *Soils and the greenhouse effect*. John Wiley, Chichester.

da Cunha, L.V. (1991) International activity related to global environmental change. In: *Global Environmental Change*, R.W. Correll and P.A. Anderson (Eds), NATO ASI series, Springer-Verlag, Berlin.

Dansgaard, W.; Johnson, S.J.; Clausen, H.B.; Dahl-Jensen, D.; Gundestrup, N.S.; Hammer, C.U.; Huidberg, C.S.; Steffensen, J.P.; Sveinbjornsdottir, A.E.; Jouzel, J.; Bond, G. (1993) Evidence for general instability of past climate from a 250 kyr ice-core record. *Nature*, **364**, 218-219.

Enting, I.G.; Mansbridge, J.V. (1991) Latitudinal distribution of sources and sinks of CO_2: results of an inversion study. *Tellus*, **43B**, 156-170.

Goodess, C.M. and Palutikof, J.P. (1992) The development of regional climate scenarios and the ecological impact of greenhouse gas warming. *Advances in Ecological Research*, **22**, 33-62.

Goudriaan, J. (1992) Biosphere structure, carbon sequestering potential and the atmospheric ^{14}C Carbon record. *Journal of Experimental Botany*, **34**, 1111-1119.

IPCC (1990) *Climate Change: the IPCC Scientific Assessment*, J.T. Houghton, G.J. Jenkins and J.J. Ephraums (Eds), Cambridge University Press, Cambridge.

IPCC (1992) *Climate Change 1992 - The Supplementary Report to the IPCC Scientific Assessment*, J.T. Houghton, B.A. Callander and S.K. Varney (Eds), Cambridge University Press, Cambridge.

Huntley, B. (1992) How ecosystems respond to environmental change: evidence from late-Quaternary paleoecological records. In: *Responses of forest ecosystems to environmental changes*, A. Teller, P. Mathy and J.N.R. Jeffers (Eds), Elsevier Applied Science, London, 45-54.

IGBP (1992) *Global Change and Terrestrial Ecosystems - the Operational Plan*. International Geosphere-Biosphere Programme Report no. 21, Stockholm.

Jarvis, P.G.; Dewar, R.C. (1993) Forests in the global carbon balance: from stand to region. In: *Scaling Physiological Processes: Leaf to Globe*, J.R. Ehleringer and C.B. Field (Eds), Academic Press Inc., San Diego, 191-221.

Kimball, B.A. (1983) Carbon dioxide and agricultural yield. An assemblage and analysis of 430 prior observations. *Agronomy Journal*, **75**, 779-788.

Smith, T.M.; Shugart, H.H.; Bonan, G.B.; Smith, J.B. (1992) Modelling the potential response of vegetation to global climate change. *Advances in Ecological Research*, **22**, 93-116.

Viner, D.; Hulme, M. (1992) *Climate change scenarios for impact studies in the UK*. Report prepared for the UK Department of the Environment, Climatic Research Unit, Norwich.

White, J.W.C. (1993) Don't touch that dial. *Nature*, **364**, 186.

Woodward, F.I. (1992) Predicting plant responses to global environmental change. *New Phytologist*, **122**, 239-251.

CLIMATIC MODELS - CHANGES IN PHYSICAL ENVIRONMENTAL CONDITIONS

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ABSTRACT

The models used to estimate equilibrium and evolving changes in climate due to increases in greenhouse gas concentrations are described, with the main focus on results from a 75 year experiment with carbon dioxide increasing at 1% per year. The models suggest that temperatures will increase generally, but with large spatial variations which differ considerably between models. Precipitation is increased in amount globally but there are substantial areas of decrease particularly in summer. For a given mean fall, it tends to decrease in frequency. Because of increases in evaporation, soil moisture is decreased in many areas especially in summer but increases through most of the year in high latitudes. Changes in circulation significantly modify these general statements on a regional scale.

There are important uncertainties concerning the future (and also past) changes in radiative forcing including the effects of sulphate aerosols. Uncertainties with the model include the ocean simulation and the representations of clouds and land surface evaporation. However, evidence from observations encourages some credence in the predictions, at least on the larger scales.

THE GREENHOUSE EFFECT

The greenhouse effect is not new. It has been keeping the Earth warm since its formation. In geologically recent times the most important greenhouse gases have been water vapour and carbon dioxide (CO_2). In the absence of greenhouse gases, the heating by incoming solar radiation must be balanced by longwave radiation emitted from the earth's surface. If we know the reflectivity of the earth for solar radiation - it is about 30% at present - we can calculate the temperature of the Earth's surface needed to give this balance to be about -18^{o}C or 255K. With greenhouse gases present, the longwave radiation from the surface is partly absorbed and then re-emitted by the gases at the temperature of the air at their level. This has the effect of raising the level from which radiation is effectively emitted to space to several kilometres above the surface, where the temperature is about 30K lower than that near the surface. Consequently, the surface temperature can be higher by about this amount and the Earth will emit the same amount of radiation to space as in the absence of greenhouse gases.

The concentrations of several greenhouse gases are observed to be increasing. CO_2, methane, nitrous oxide and several chlorofluorocarbons (CFCs) have all increased since the start of the industrial era. However, it is also believed that the amount of sulphate aerosols in the atmosphere has increased so increasing its reflectivity for solar radiation - though this is difficult to measure. Also, stratospheric ozone, a greenhouse gas, has been depleted over the last 20 years or so due to the increases in CFCs. Its effect is thought to be perhaps as large as that due to the CFCs and of opposite sign (Isaksen et al., 1992). Measurements of air in ice cores, supported by late 19th century observations, suggest that since the start of the industrial era in about 1750, the largest contribution, about 1.5 W m^{-2} so far in terms of its effect on longwave radiation at the top of the troposphere, has come from CO_2. Methane and nitrous oxide have together contributed another 0.5 W m^{-2}, whilst a "best estimate" of the opposite effect of aerosols is also about 0.5 W m^{-2}. Volcanic eruptions, such as that of Mt. Pinatubo in 1991, are thought to have significant shortterm effects on global mean temperature; however, they are not expected to induce longterm change unless there is a major change in their frequency or intensity.

MODELLING CLIMATE CHANGE DUE TO THE GREENHOUSE EFFECT

Climate models

To predict the effects of increasing CO_2 and other trace gases on climate, it is necessary to use a climate model based on the relevant physical equations. In "finite difference" models, such as that used at the Meteorological Office (MO), the temperatures, winds or currents and other variables in the atmosphere and ocean are represented for a three-dimensional array of boxes. In the horizontal, the gridbox array follows lines of constant latitude and longitude, while in the vertical there are typically 10 to 20 layers in both atmosphere and ocean. Because of the large computing requirements, the horizontal grid length used in CO_2 experiments to date has been limited to about 2.5 degrees of latitude; Gates et al. (1990) found that, with this resolution, quite a realistic simulation of the atmospheric circulation was obtained. With coarser resolution, major errors were evident in the simulated circulation patterns (see Fig. 4.1 in Gates et al.). However, the ocean simulation at 2.5 degrees latitude is quite poor, typical horizontal scales being less in the ocean than in the atmosphere; it is clear that in future the ocean model will need to be on a finer mesh.

Climate predictions

To make a climate simulation, the procedure is much as in a numerical forecast, the equations representing the atmospheric physics being integrated forwards in time. After 5 days the accuracy of prediction of individual events is deteriorating; however if the model is run further, its anticyclones and depressions should continue to develop and move in a realistic fashion, and by running the model on for many years a simulation of climate can be obtained. To estimate the effect of a change in forcing, the relevant parameter (e.g. the amount of CO_2) is changed and the simulation is repeated with this change.

Equilibrium and transient response experiments

Results obtained from climate models over the last decade have been from two types of experiment, commonly called equilibrium experiments and transient response experiments. The equilibrium experiments are intended to estimate the equilibrium response to an increase (usually a doubling) of CO_2. Because of the large amount of computing that would be needed to take a model with a deep ocean to equilibrium, they usually use a "slab" ocean model consisting of a mixed layer 50m thick with no currents but sufficient thermal inertia to represent the seasonal variation. The advection of heat in this slab model is represented by a prescribed seasonally varying "flux correction" by which energy is input to the ocean so as to maintain realistic temperatures and sea-ice distributions in a longterm climatological sense. In any perturbation experiment, for example with CO_2 doubled, the same flux correction as calculated for the control experiment is applied.

The "transient response" experiments use a model with a deep ocean to predict the evolving response to gradually increasing greenhouse gases. Thus ocean currents are represented including vertical motion on the gridscale and subgridscale convective and diffusive mixing which disperse the effects of surface fluxes of heat, water and momentum throughout the ocean.

MODELS

As discussed by Gates et al. (1992) in the 1992 IPCC (Intergovernmental Panel for Climate Change) Report, four coupled models of the atmosphere and deep ocean have been used to study the transient response to increasing greenhouse gases. These are from the Geophysical Fluid Dynamics Laboratory (GFDL) at Princeton, USA (Manabe et al., 1992), the National Center for Atmospheric Research (NCAR) at Boulder, USA (Meehl et al, 1993), the Max Planck institute (MPI) at Hamburg, Germany (Cubasch et al., 1992) and the Meteorological Office (MO) at Bracknell, UK (Murphy, 1992).

TABLE 1: Structure of four models used for transient response experiments (see text for explanation)

Model	GFDL	NCAR	MPI	MO
Atmosphere				
Horizontal resolution[1]	R15	R15	T21	$2.5^{o}*3.75^{o}$
Layers	9	9	19	11
Ocean				
Horizontal resolution[1]	$4.5^{o}*3.75^{o}$	5^{o}	4^{o}	$2.5^{o}*3.75^{o}$
Layers	12	4	11	17
Greenhouse gas scenario				
CO_2 increase (/year)[2]	1%	1%	IPCCA	1%
CO_2 doubling time (yr)	70	100	60	70

Notes: [1]: R15 and T21 indicate spectral resolutions (see text) (R = Rhomboidal and T = Triangular). For the non-spectral representations, the first figure is the latitudinal, the second the longitudinal resolution - only one figure is given if both are the same.

[2]: For GFDL and MO 1% compound, for NCAR 1% simple. "IPCCA" refers to the Scenario A (also called "Business as usual") used in the 1990 IPCC Report (Houghton et al., 1990)

The structure of these models is indicated in Table 1. Note that three of the models use a spherical harmonic (or "spectral") representation of the atmosphere for advection. The atmospheric physics is computed on a 4.5^{O} by 7.5^{O} grid for the R15 models, and a 5.6^{O} by 5.6^{O} grid for the T21 spectral resolution. The models were run both with constant CO_2 (the control experiments) and with gradually increasing CO_2. Except for the NCAR model all were run to the time of doubling of CO_2 or beyond. Meehl et al. (1993) report results for the NCAR model to Year 60.

An increase of 1%/year is faster than the observed past rate of increase for CO_2 which has risen from about 0.3%/year in the 1960s to nearly 0.5%/year in the 1980s; thus the accumulated increase over the 1960-90 period is equivalent to about 12 years at 1%/year. Earlier increases starting from about 1750 were slower though not negligible. As discussed earlier, the globally averaged changes in radiative forcing due to other trace gases and aerosols may have been roughly in balance over recent decades, though their regional effects probably have not, due to the uneven distribution of sulphate aerosols.

Most of the results discussed here will be from the MO model, which is described in more detail below, with comparisons to results from other coupled models where available either from published work or through the IPCC. This is a significant limitation; in particular, the effects on pressure at mean sea level (PMSL) are only available for the MO model. However, as noted earlier, the relatively low horizontal resolution provided by R15 or T21 spectral model does not allow as realistic simulations of the circulation as can be obtained with the grids of the resolution used in the MO model, especially in high latitudes, so the MO model may provide the best guidance on circulation changes.

The Meteorological Office (MO) model

The MO atmospheric model used in the experiments discussed here is a development of that assessed in the 1990 IPCC Report by Gates et al. (1990); they found that the model simulated climate in a generally realistic manner for the features they considered - sea level pressure and zonal wind, precipitation patterns, top of atmosphere radiation, and soil moisture and snowcover for limited regions. As indicated in Table 1, it represents the surface pressure, and the temperature, humidity and wind components on 11 layers on a 2.5 by 3.75 degree latitude-longitude mesh. The deep ocean model has temperature, salinity and currents on 17 layers and the same horizontal mesh as the atmospheric model. A flux correction is still needed to maintain a realistic climate, though the temperature errors without it are smaller than in the equilibrium experiment with the slab model. There is an assumption implicit in the use of the flux correction technique that the errors in the simulations of the control and perturbed climates are similar. This is a useful first approximation to estimation of the errors, though it is likely to become increasingly invalid as the differences between the ocean and atmosphere circulations in the control experiment and the perturbation experiment increase.

The land surface is represented by a model with the same horizontal mesh as the atmosphere. Fourteen surface and subsurface characteristics are defined as a function of the soil and vegetation types for each gridbox which are specified from the 1o data sets constructed by Wilson and Henderson-Sellers (1985). The soil is represented by four layers for thermal processes and one layer plus a canopy water store for hydrological processes.

RESULTS

Temperature changes

The annually averaged temperature changes in transient response experiments have been shown by Gates et al. (1992). The responses obtained from these experiments at the time of doubling of CO_2 are similar in many ways to those from equilibrium experiments (Mitchell et al, 1990) but there are important differences, in part due to the inclusion of the deep ocean and ocean currents; this allows representation of the vertical mixing which slows the response of the ocean, so that by the time of doubling at 1%/year (typical of the rates to be expected in the next few decades) the global mean warming is only 60-70% of that at equilibrium, and the warming of the oceans is generally less than that of the land, particularly in the MO model. Parts of the ocean with deep mixing in winter, notably the Antarctic Ocean and the North Atlantic Ocean, are particularly slow to warm. In the Hadley Centre experiment (Fig. 1), some small regions of cooling in both areas still persist at Years 66-75 (when CO_2 is doubled) when the mean land surface warming is about 3K (or degree C) compared with 1.5K for the ocean. In contrast, in equilibrium experiments, the high latitude oceans could display some of the largest temperature rises (e.g. Bretherton et al (1990), Fig 6.5(b)).

The typical magnitudes of warming for different surfaces in the MO experiment for middle and high latitudes may be ordered from large to small in each season as shown in Table 2. In summer the greatest warming occurs over those land areas which have less snow (e.g. the Canadian Archipelago) as a result of the climate change, and almost as large over land which is drier as a result of the increase in CO_2 and is sufficiently dry as to limit evaporation (and so evaporative cooling). In winter, the warming over land is again greatest in regions with reduced snow cover. Throughout the year, warming over land is least where the winds blow from ocean or sea-ice regions with relatively small warming.

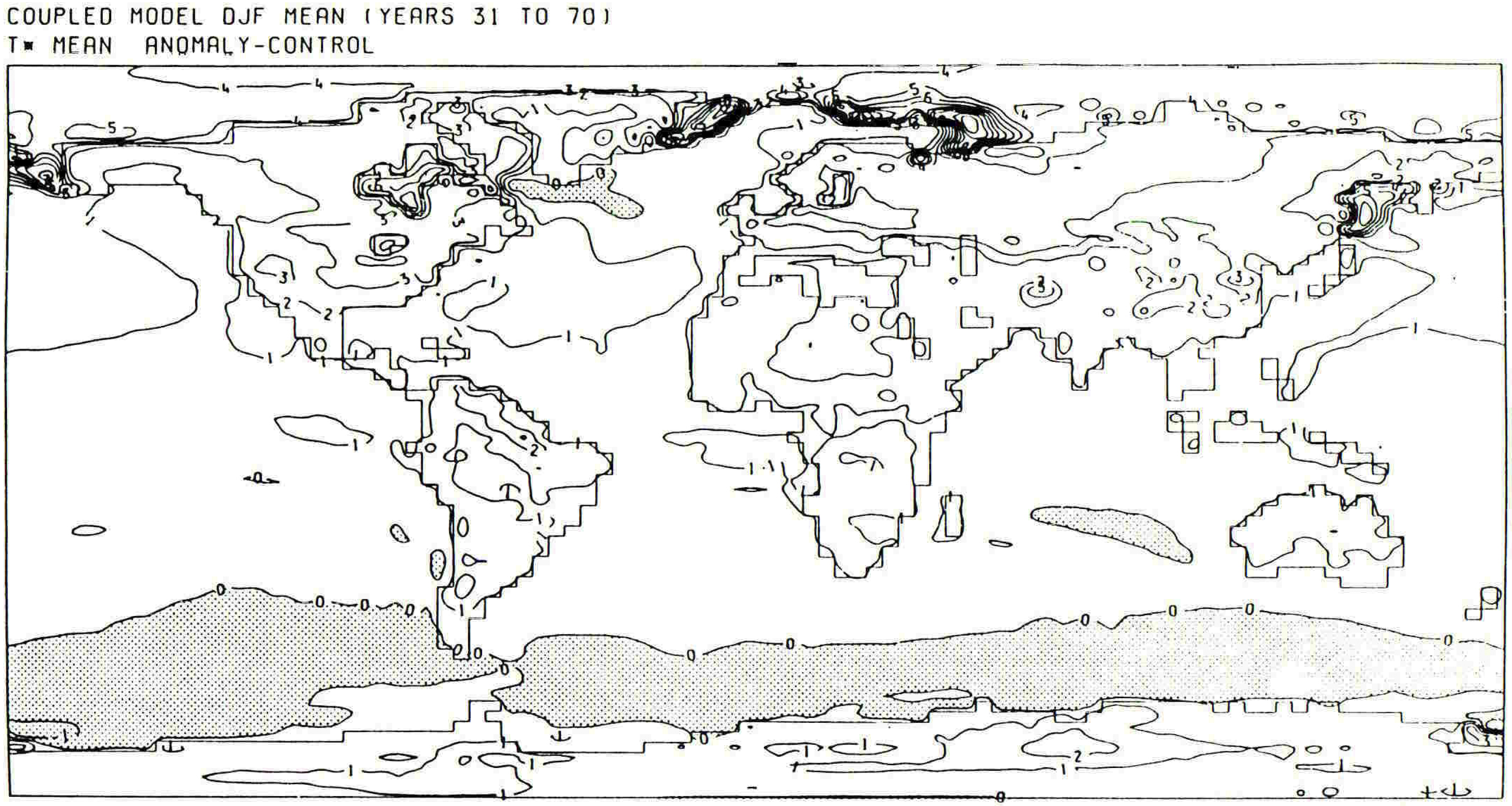

Fig.1: Surface temperature differences (Contours every 1K) (Shaded area negative)
(a) December-February

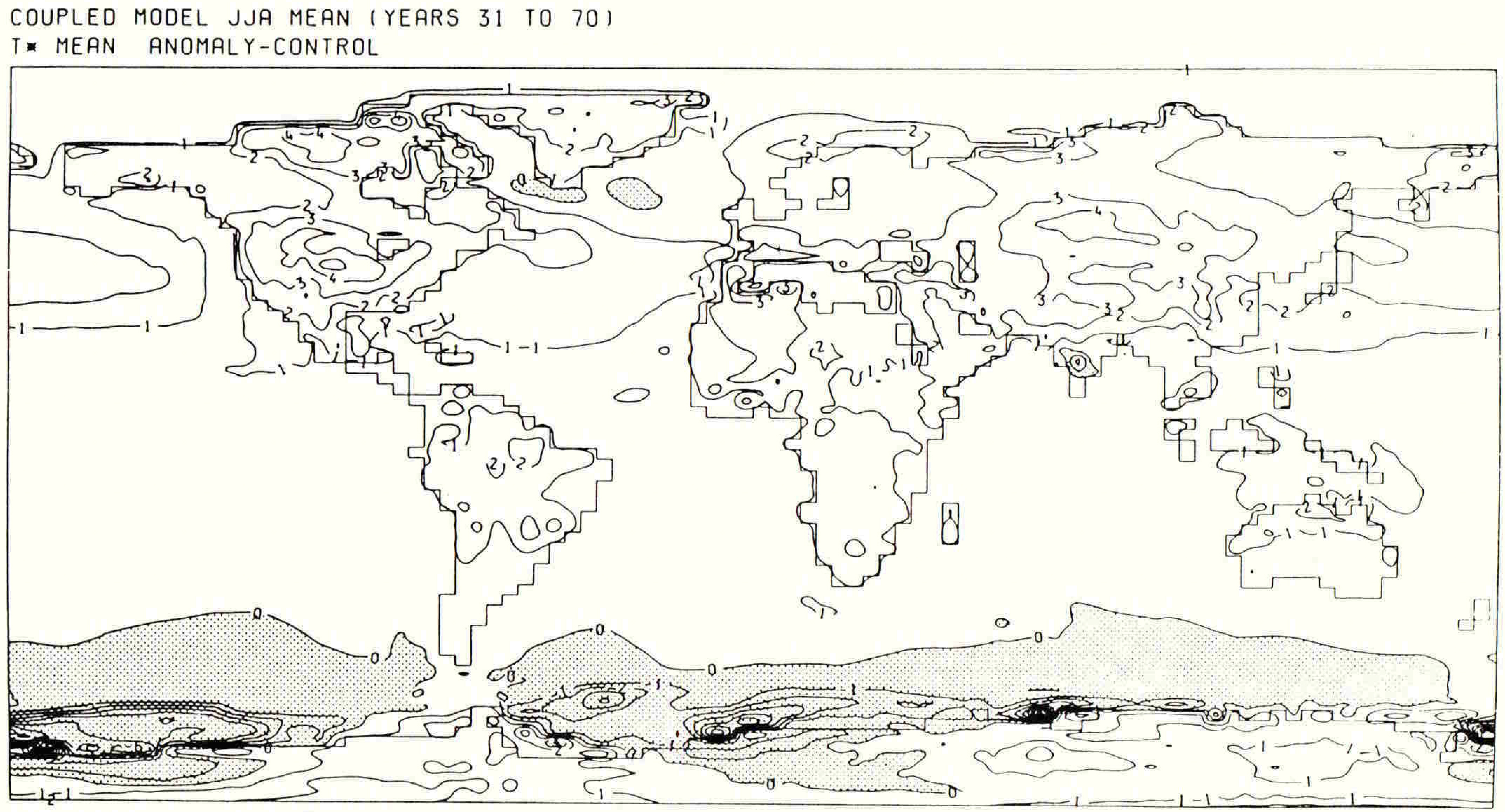

Fig.1(b): June-August

TABLE 2: Ordering of temperature changes from highest to lowest with typical changes (K) at Year 66-75 of the MO experiment for middle and high northern latitudes

	Typical change
For winter:	
melted sea-ice	about 10
other sea-ice	+4 - +8
melted snow	+4 - +8
most land	+3 - +6
land with ocean/ice to windward	-1 - +4
most ocean	+1 - +2
ocean with deep mixing	-1 - 0
For summer:	
melted snow	+4 - +7
dried land (see text)	+3 - +6
most land	+2 - +4
land with ocean/ice to windward	+1 - +3
most ocean	+1 - +3
sea-ice	+0 - +1
ocean with deep mixing	-1 - +1

Interactions between temperature and circulation changes

The atmospheric circulation can be substantially modified by spatial variations of the warming (Fig. 2). One example is a general reduction of pressure over the summer continents; this corresponds to the greater warming of the continents than of the oceans and can be thought of as an intensification of the continental lows associated with the summer monsoon. A less obvious example pointed out by Hall et al. (1993) is that the reduced baroclinic gradient over the west Atlantic associated with the large winter warming over eastern Canada weakens the storm track in this region, while the cooling near southern Greenland enhances baroclinicity further east. This, together with the effects of a moister atmosphere increasing the potential for latent heat release in storms, leads to a downstream intensification of the storm tracks and associated westerly winds. In the MO model, this generates an increased westerly flow in autumn and winter over the North Atlantic sector and northern Eurasia south of a fall of pressure over the Arctic. Consequently some aspects of the climate change are of a regional nature and can be attributed to changes in wind direction etc. For example, increased northwesterlies generate a warming of over 3K over Scandinavia because the water in that direction is warmer than the land to the southeast. On the other hand, over the Pacific coasts of eastern Alaska and western Canada, where a reduction of northward flow weakens warm air advection, there is cooling or only slight warming, though the small warming of the ocean to windward (southwest) may also contribute. These circulation changes and the associated temperature changes, while not likely to be correct in detail, are indicative of the type of regional effects to be expected with greenhouse warming.

Precipitation changes

With enhanced CO_2, precipitation is increased generally in winter

COUPLED MODEL DJF MEAN (YEARS 31 TO 70)
PMSL ANOMALY-CONTROL

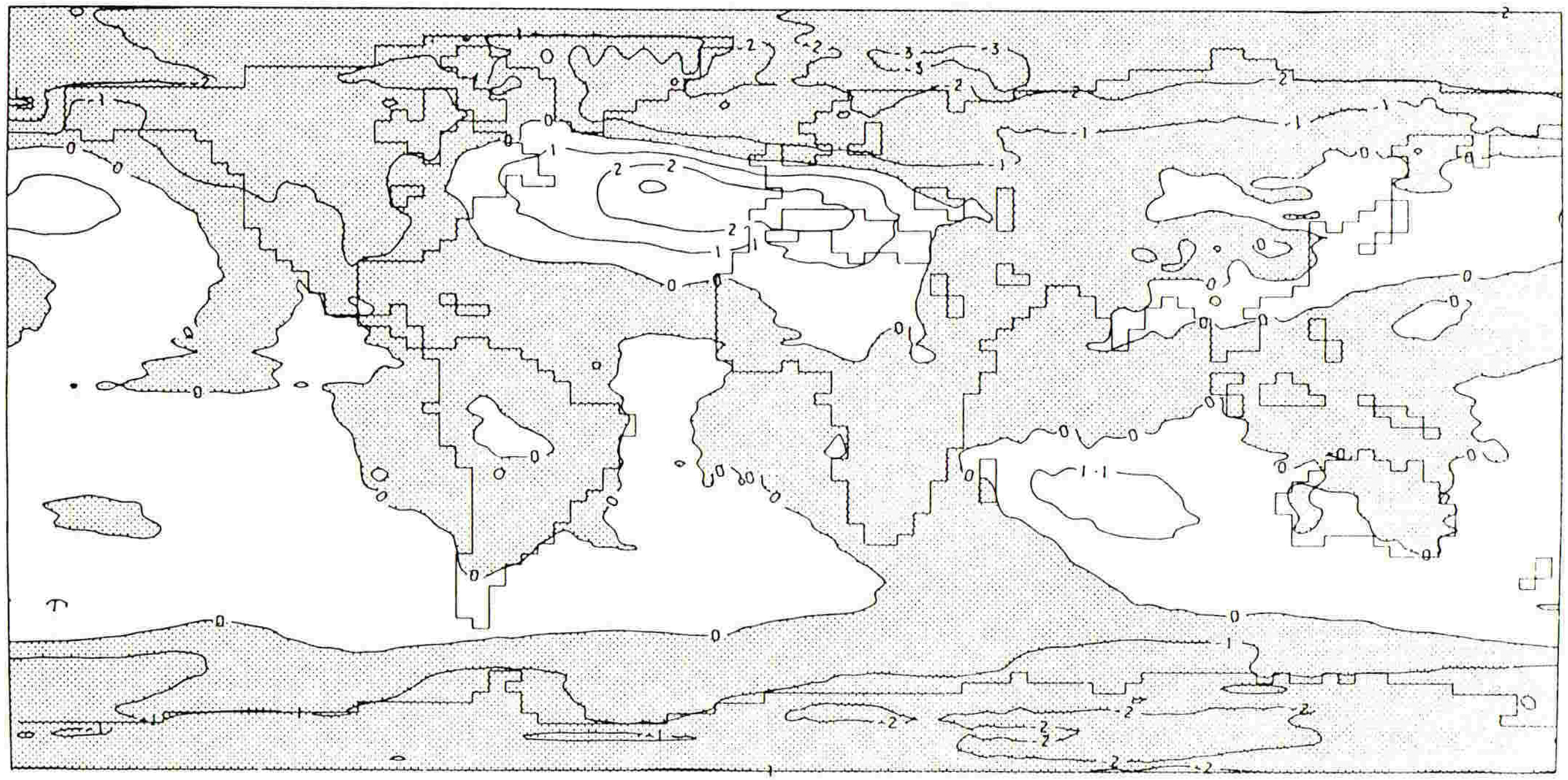

Fig.2: Sea Level pressure differences (Contours every 1 hPa)(Shaded areas negative)
(a) December-February

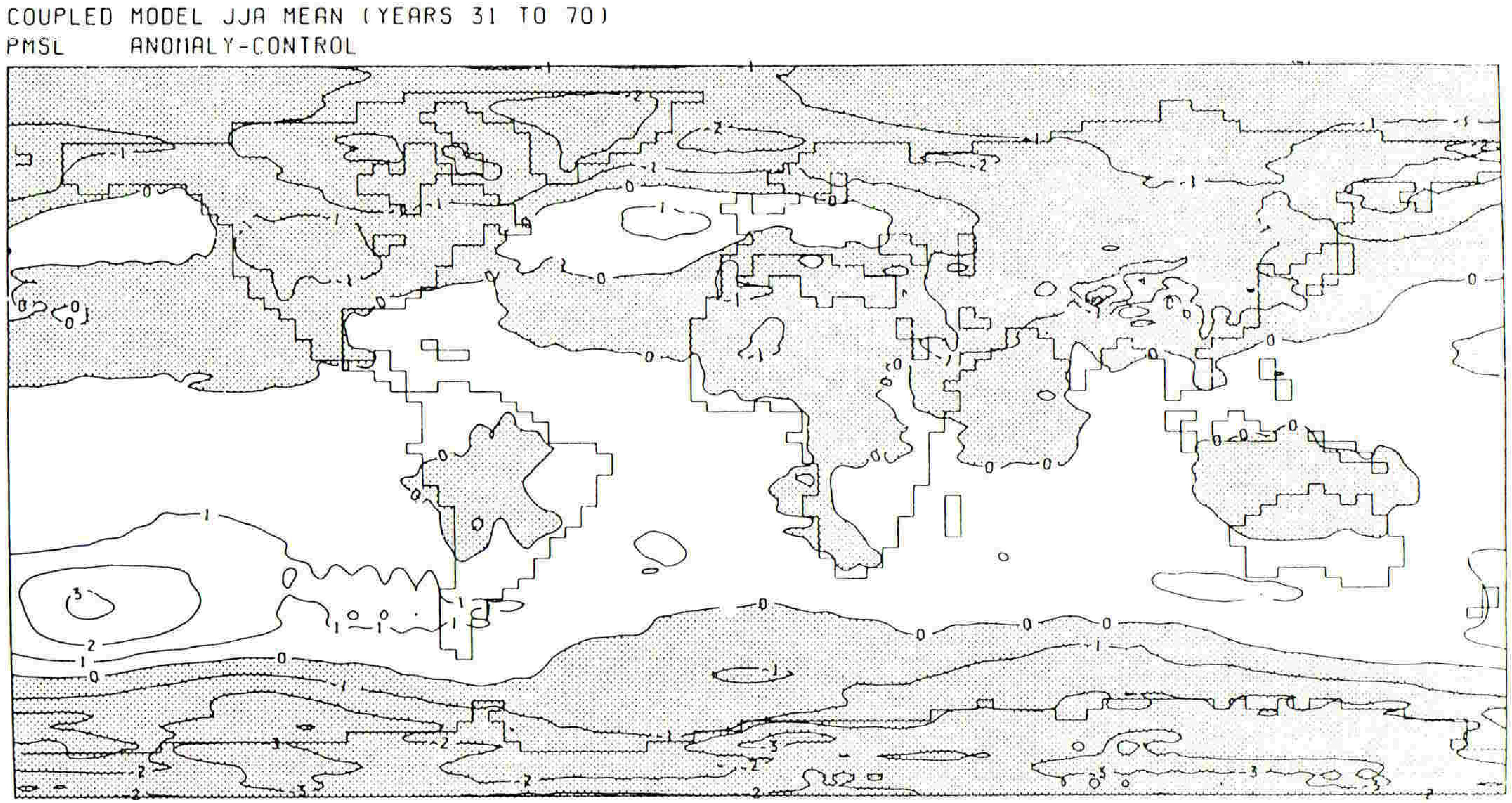

Fig.2(b) June-August

over land north of 45N (e.g. Fig. 3) and over most of the Arctic land areas in summer. The MO model shows large areas of decreases in middle latitudes which extend furthest north in summer, reaching about 55N over western Europe and 45N over N America. The corresponding latitudes in winter are about 45N and 35N. Mostly, these changes do not exceed 0.5 mm/day in the Year 31-70 mean. Exceptions to these general statements can be attributed to circulation changes, falls of pressure being associated with the larger increases in precipitation, or to land being downwind of areas with small ocean warming where the increase in moisture content of the air responsible for many of the increases is small or absent.

Soil Moisture changes

Increases in soil moisture are generally less widespread than increases in precipitation. The main reason for this is that evaporation is predicted to increase from spring onwards due to earlier snowmelt and to the effect of higher temperatures on the evaporation through the Clausius-Clapeyron relation (e.g. see Rowntree, 1991). In the MO transient response experiment, summer soil moisture (Fig. 4), even in high latitudes, is increased only where rainfall is increased by more than about 0.25 mm/day. This is consistent with the changes in evaporation (not shown) which are typically an increase of about 0.25 mm/day in the June-August mean. Most regions have decreases; these reach 2 cm locally over western Europe, central Asia and the eastern USA in the Year 31-70 mean. There is little consistent increase in the soil moisture differences after Years 31-40; the same applies to the changes in precipitation and sea level pressure; the explanation is believed to be the similarity of the land-ocean temperature contrasts through this period. This is discussed further in the section on "Comparison of transient experiment results".

Changes in intensity of precipitation

Analysis of the results over Europe (J Gregory, personal communication; see also Rowntree et al., 1993) from the equilibrium experiment UKHI used in Mitchell et al. (1990) has shown that in the warmed (doubled CO_2) climate, for a given average rainfall, the rainfall tends to be more intense, with the rainfall on the wettest day of the season generally increasing more (or decreasing less) than the mean rainfall. This is presumably because of the greater water content of warmer air. Consistently with this, the percentage of dry days commonly increases relative to the mean rainfall. The year to year variability (standard deviation of seasonal precipitation) also generally increases more than the mean. The original analysis was confined to mid-latitude regions of Europe, but an analysis of dry day frequency for summer data north of 45N for Years 66 to 75 of the MO transient response experiment shows a similar result.

Snowfall and snowmass changes

The increase in CO_2 reduces winter snow mass (not shown) over most regions south of 60N, and also over regions of Scandinavia and southern Alaska north of this latitude. Most of the rest of the Arctic land has increased snow mass in this season, with increases exceeding 20 kg/m^2 northwest of Hudson's Bay and in the northern parts of the Ob and Yenisei basins. In these regions of increased snowmass the increase in snowfall associated with the general increase in precipitation has more effect on the snow budget than does the later start to the snow season. The

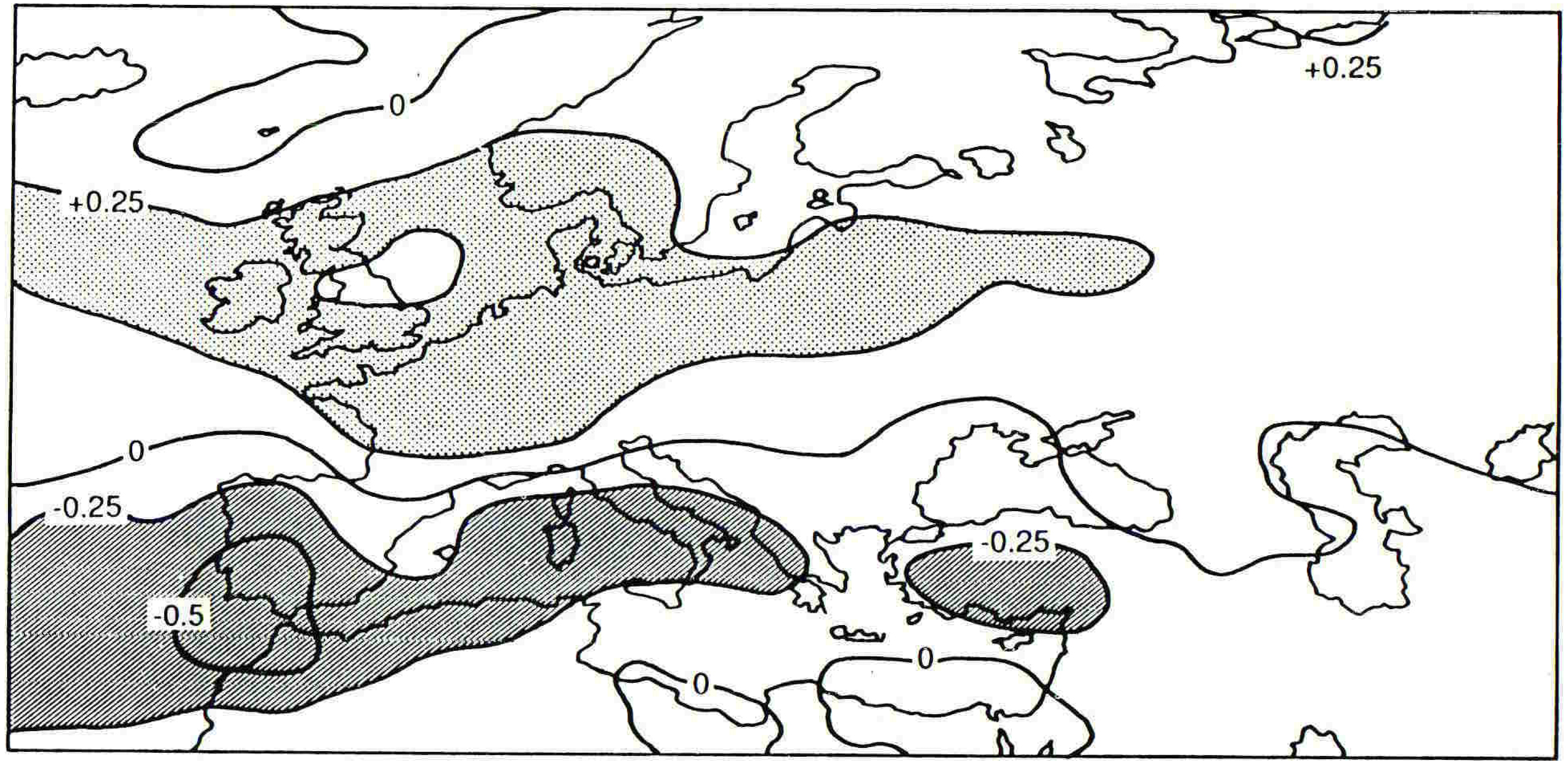

Fig.3: Precipition differences (Anomaly-Control) Years 31-70 (mm/day)
(a) December-February

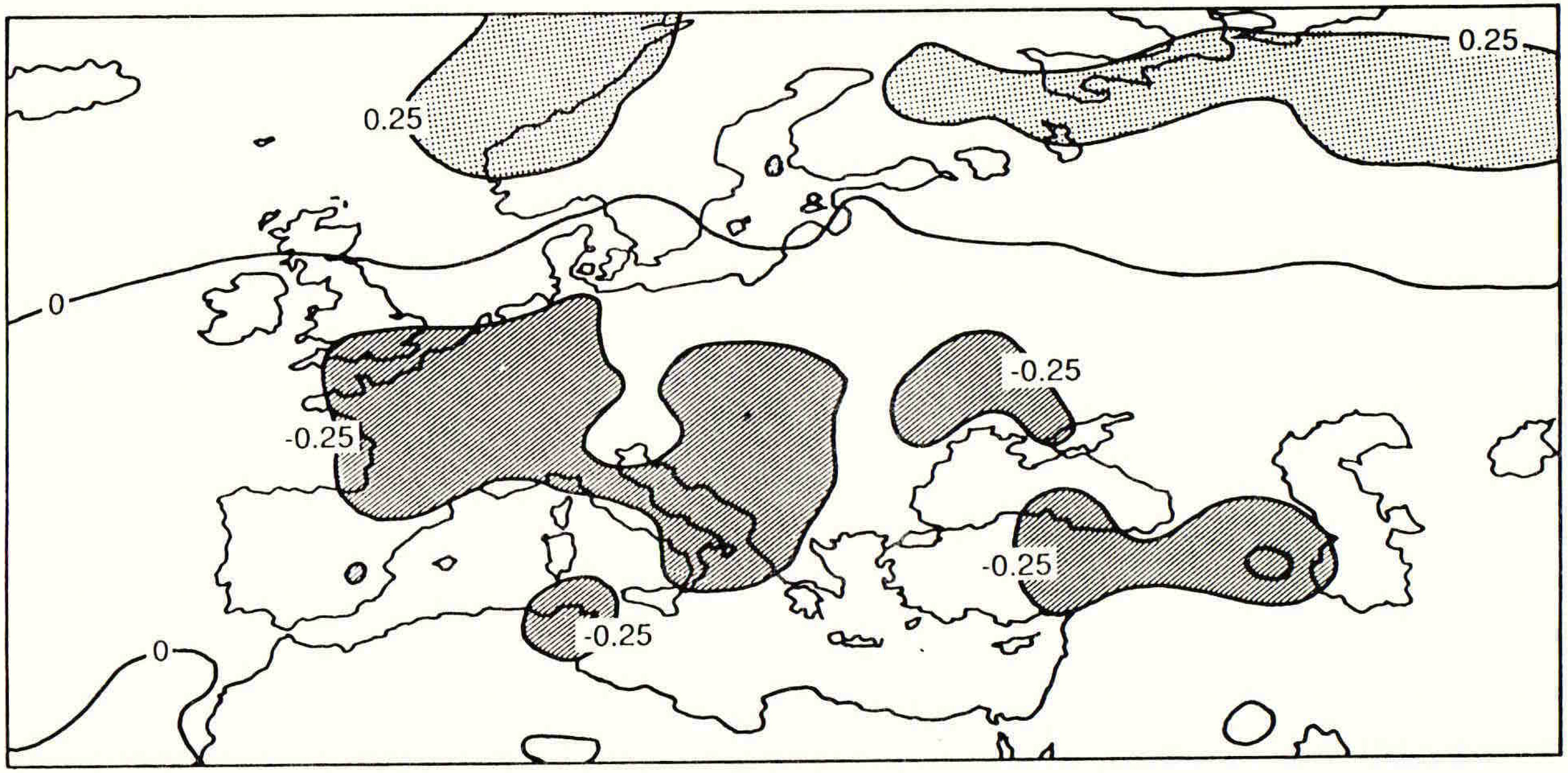

Fig.3(b): June-August

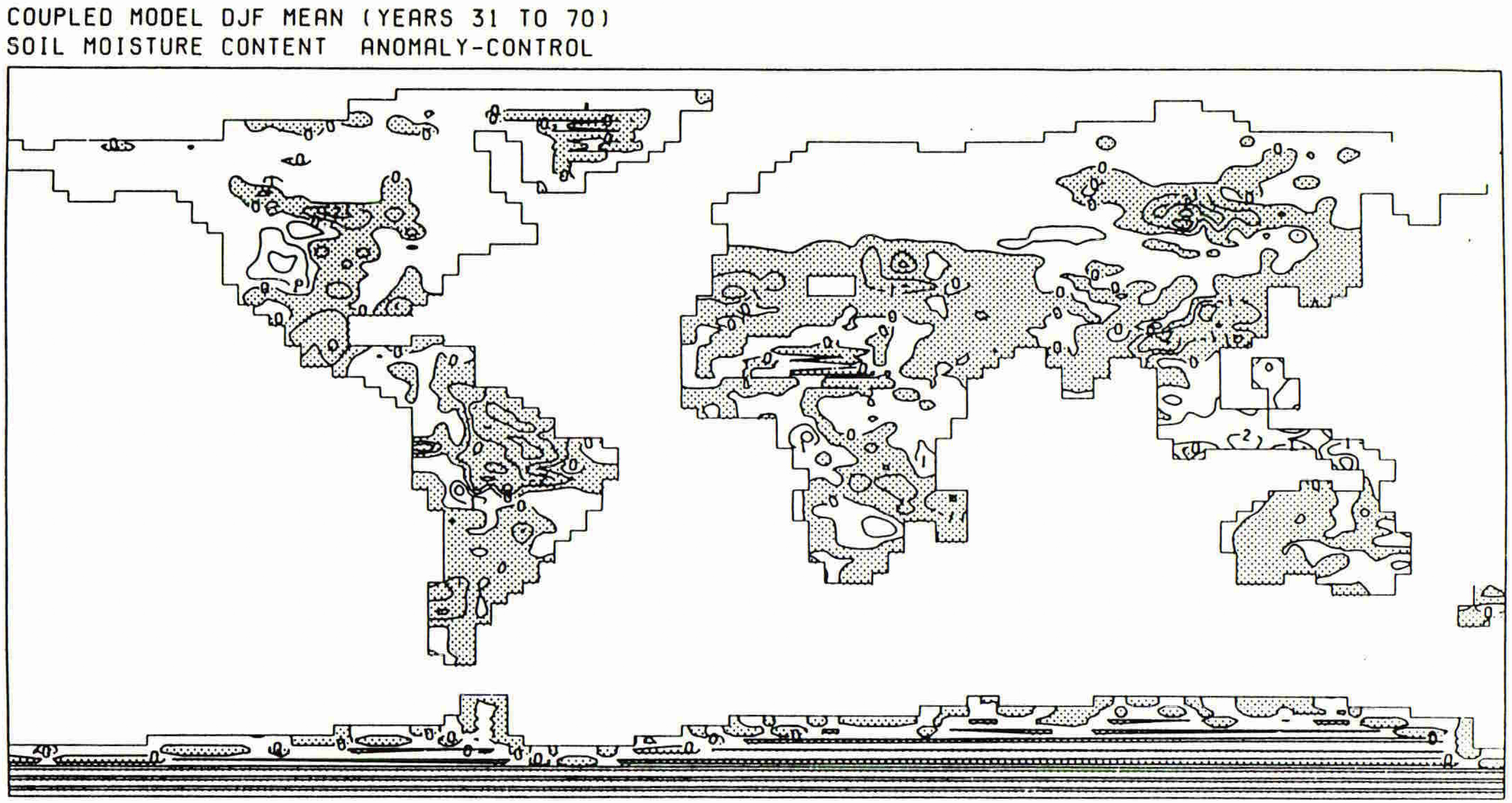

Fig.4: Soil moisture differences (Contours every 1cm) (Shaded areas negative)
(a) December-February

COUPLED MODEL JJA MEAN (YEARS 31 TO 70)
SOIL MOISTURE CONTENT ANOMALY-CONTROL

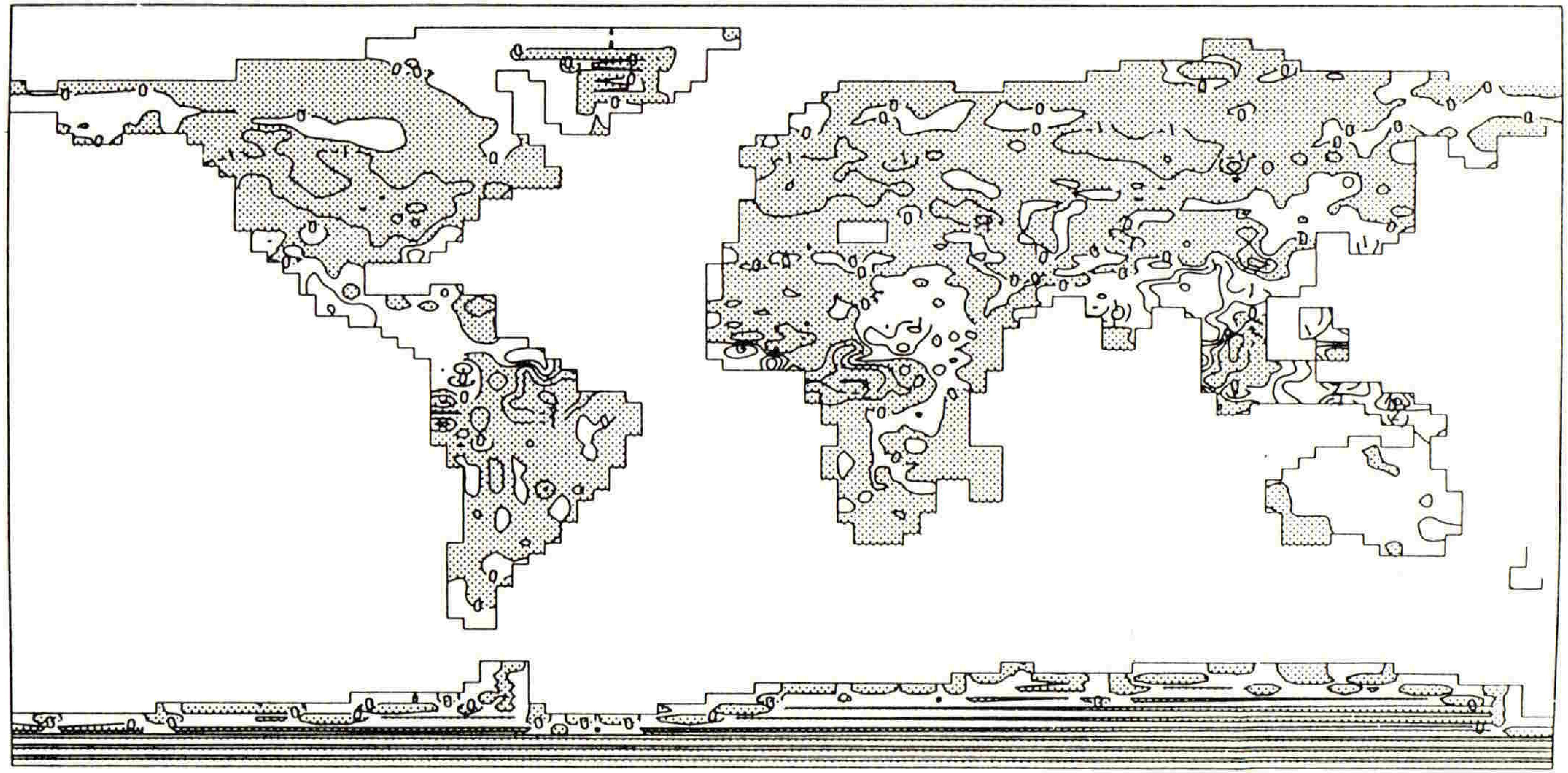

Fig.4b: June-August

differences in snowfall rate in winter (not shown) indicate a large area (much greater than that with increased snow cover) with increased rate of snowfall. This area includes most of the land areas with a persistent winter snowcover.

In summer, snowfall and snow mass are decreased over virtually all northern hemisphere land except parts of Greenland where there is more precipitation and little or no summer melting. This result suggests that, even where the winter snowpack is greater, the snow melts earlier in spring.

COMPARISON OF TRANSIENT EXPERIMENT RESULTS

As discussed earlier, four experiments were compared by Gates et al. (1992), run with the NCAR, GFDL, MPI and MO models. Averages were shown for about the time of doubling, except that the NCAR run was for about a 45% increase, when the equilibrium warming would be just over half that at the time of doubling.

Only annual mean temperature changes were shown for all four experiments, but there is additional information available, mostly in the papers on the results referenced earlier.

TABLE 3: Range (Rnge) and estimated average (Avge) of annual mean temperature (K) differences for a range of latitudes (based on Gates et al. (1992) but NCAR values doubled - see text)

	GFDL		MPI		NCAR		UKMO	
	Rnge	Avge	Rnge	Avge	Rnge	Avge	Rnge	Avge
Arctic Oc	4-6	5	4-8	6	1-5	3	3-7	5
Land 60N	2-5	3.7	1-3	1.9	1-4	2.4	1-5	3.9
Ocean 60N	1-4	3.2	0-2	1.2	1-4	3.1	-1-4	1.2
Land 30N		3.1		1.9		1.1		2.7
Ocean 30N		2.3		1.1		1.3		2.0
Ocean 0N		1.9		1.6		1.2		1.3
Differences in averages between regions								
AOc-Land 60N		1		4		0.6		1
AOc-Ocn 60N		2		5		0		4
Land-Ocn 60N		0.5		0.7		-0.7		2.7
Land-Ocn 30N		0.8		0.8		-0.2		0.7

Table 3 shows estimated annual mean temperature changes for selected regions and differences between the regions. The NCAR differences have been doubled to allow for the smaller CO_2 increase. There are large differences between the patterns of warming in the different experiments. The NCAR model is quite distinct with little difference between the warming over the Arctic Ocean and that at 60N. However, although the other models have a similar overall gradient between the Arctic Ocean and the equator

(3.2-4.7K), they differ markedly in its distribution. For example, comparing the MO and GFDL models, they have similar gradients between the Arctic Ocean and 60N over land, but the MO model has a much smaller warming over the ocean at this latitude, and so a larger north-south gradient between there and the Arctic Ocean. The MPI model has a gradient of this size or greater over both ocean and land.

The ocean-land contrast at 60N is much larger in the MO model than in the others; however this is not evident at 30N. The contrast near 60N is likely to be important in generating ocean-land contrasts in atmospheric variables. An interesting feature of the MO results is that after the first 30 years clear patterns of precipitation and circulation change have developed in the MO model which then persist with little further amplification through the next 40 years. These features appear to be associated with the development of the ocean-land contrasts which show a similar temporal evolution. The weakness of these ocean-land contrasts in the other models may explain the fact that similar temporal behaviour is not obvious in them for example, the GFDL soil moisture differences shown by Gates et al (1992) and Manabe et al. (1992) increase rather steadily from years 40-60 to 80-100. The reasons for the large ocean-land contrast in the MO model are not fully known, though Murphy (1992) has suggested a role for cloud feedbacks over land, with the warming reducing the cloudiness there and so intensifying the warming.

The soil moisture differences at about the time of doubling of CO_2 can also be compared. These are similar in the GFDL model to those already discussed for the MO model, with decreases predominant in summer and increases in winter over most land north of about 40N. The MPI model has a similar but smaller seasonal variation in the effects of CO_2 on soil moisture; the land is generally wetter in winter north of 45-50N, but summer drying is less widespread than with the MO and GFDL models. All the models tend to have more precipitation north of 45N in winter with rather patchy changes at lower latitudes; in summer, patterns are patchy with the MO model showing more consistent increases at high latitudes than the other models.

UNCERTAINTIES

There are important uncertainties in these results. Major ones include:

(a) Radiative forcing - as discussed earlier, the forcing of the climate system by changes in the environment is imperfectly known. This problem is not confined to predicting future greenhouse gas concentrations; sulphate aerosols are thought to be important in compensating the warming due to greenhouse gases but they are only just being included in the climate models and their past as well as their future concentrations and distributions are uncertain. Evidence so far indicates that the predictions of warming omitting aerosol effects may be too large particularly in the regions of large emissions and immediately downwind. Interestingly, just as the effects are being recognised, they are decreasing in two of the most important areas, Europe and N America, as fuel use turns increasingly to less sulphurous forms. If such a decrease becomes of global scale, one may expect an acceleration of warming in the immediate future as the braking effect of aerosols is reduced.

(b) The ocean model - the flux corrections applied to keep the ocean temperatures and salinities near to reality are of similar order of magnitude to the actual fluxes, suggesting that the modelled changes in temperature and salinity due to the ocean currents are too small.

(c) the representation of cloud-radiation interactions - sensitivity to this was highlighted by a series of experiments in which global mean warming ranged from 1.9 to 5.2K for doubled CO_2, depending on which of three cloud representations was used (Senior and Mitchell, 1993).

(d) the representation of the land surface hydrology - one improvement needed is to make the resistances imposed by plant stomata dependent on atmospheric variables such as temperature, vapour pressure deficit below saturation and solar radiation, as well as increased CO_2. An increase in evaporation as the climate warms is likely to be reduced by these dependences; they are now being included in the MO model.

VALIDATION

Validation of the model's global mean temperature predictions is difficult because of the wide range of model sensitivities (e.g. the sensitivity to different cloud representations discussed above), the uncertainty in the total changes in greenhouse forcing to date and the influence of natural variations of the climate. If only the enhancements of the greenhouse effect are considered, the observed warming of about 0.5K over the last century (Folland et al., 1990) fits best with the least sensitive of Senior and Mitchell (1993)'s experiments, which gave a 1.9K response of global mean temperature for a doubling of CO_2. However, if the contributions of decreased ozone and increased sulphate aerosol have been as important as suggested in the 1992 IPCC Supplement (Isaksen et al., 1992), a greater sensitivity is needed to fit the observed record. Natural variations introduce a similar uncertainty: in their absence, the observed warming might have been either larger or smaller, implying a larger or smaller sensitivity.

Validation of regional effects is at an early stage. Comparison of the spatial pattern of warming in the 1980s relative to the preceding 30 years with model predictions (Gates et al., 1992 (Fig B4), Folland et al., 1992 (Fig C5)) shows some marked similarities, notably in the strong warming over the northern continents, and the cooling near southern Greenland. On a more local scale, Mayes (1991) analysed the summer rainfall of the British Isles for 1981-90 relative to the preceding 30 years. The pattern has some of the modelled character, with increases over western Scotland and decreases over eastern and southern Britain. However, only the decreases in the extreme southeast were statistically significant and these were from a level which was relatively high compared with the first half of the century.

SUMMARY AND CONCLUSIONS

The conclusions of this paper may be summarised as below.

1. The predictions of climate change over land in the MO model show the following effects of increasing CO_2:

a. Temperatures increase generally, but with a wide range of magnitudes - most over melted snow and some seasonally semi-arid regions, least over land with ocean to windward, especially where the ocean warming is small.
b. Precipitation increases generally throughout the year in high latitudes. There are substantial areas of decreases in middle latitudes, which extend further north in summer. For a given mean rainfall, the intensity, at least in summer, tends to increase, and frequency to decrease. Soil moisture patterns are similar to those for precipitation; however, because evaporation tends to increase for moist soil, decreases in soil moisture are more extensive than those in precipitation
c. Snowfall increases in winter over most of the Arctic; snowmass increases over a smaller area; snowfall decreases in summer.
d. Circulation changes forced by spatial variations in warming are responsible for regional features including relatively weak warming and other exceptions to the above general statements.

2. Comparison of the four available transient response experiments reveals large differences in the gradients between the Arctic Ocean and 60N and the ocean-land contrast at 60N.

3. There are important uncertainties associated with the radiative forcing including the effects of sulphate aerosols, with ocean simulation, with cloud representations and with land surface hydrology. However, evidence from observations encourages some credence in the predictions, at least on the larger scales.

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REFERENCES

Bretherton, F.P.; Bryan, K.; Woods, J.D. (1990) Time-dependent greenhouse-gas-induced climate change. In: Climate change: the IPCC scientific assessment, (Houghton J.T., Jenkins G.J. and Ephraums, J.J., Ed.), Cambridge University Press, 173-193.

Cubasch, U.; Hasselmann, K.; Hock, H.; Maier-Reimer, E.; Santer, B.D.; Sausen. R. (1992) Time-dependent greenhouse warming computations with a coupled ocean-atmosphere model. Climate dynamics, 8, 55-69.

Folland, C.K.; Karl, T.R.; Nicholls, N.; Nyenzi, B.S.; Parker, D.E.; Vinnikov, K.Ya. (1992) Observed climate variability and change. In: Climate change 1992: the supplementary report to the IPCC scientific assessment (Houghton, J.. T., Callander, B.A. and Varney, S.K., Ed.). Cambridge University Press, 135-170.

Folland, C.K.; Karl, T.R.; Vinnikov, K.Ya. (1990) Observed climate variations and change. In: Climate change: the IPCC scientific assessment, (Houghton J.T.., Jenkins G.J. and Ephraums, J.J., Ed.), Cambridge University Press, 195-238.

Gates, W.L.; Mitchell, J.F.B.; Boer, G.J.; Cubasch, U.; Meleshko, V.P. (1992) Climate modelling, climate prediction and model validation. In:

Climate change 1992: the supplementary report to the IPCC scientific assessment (Houghton, J.T., Callander, B.A. and Varney, S.K., Ed.). Cambridge University Press, 97-134.

Gates, W.L.; Rowntree, P.R.; Zeng, Q.-C., (1990) Validation of climate models. In: Climate change: the IPCC scientific assessment, (Houghton J.T., Jenkins G.J. and Ephraums, J.J., Ed.), Cambridge University Press, 93-130.

Hall, N.M.J.; Hoskins, B.J.; Valdes, P.J. and Senior, C.A. (1993) Storm tracks in a high resolution GCM with doubled CO2. Accepted for publication in Q. J. R. Meteorol. Soc.

Houghton, J.T.; Jenkins, G.J.; Ephraums, J.J. (Editors) (1990) Climate Change. The IPCC scientific assessment, Cambridge University Press, 365 pp.

Isaksen, I.S.A.; Ramaswamy, V.; Rodhe, H.; Wigley, T.M.L. (1992) Radiative forcing of climate. In: Climate change 1992: the supplementary report to the IPCC scientific assessment (Houghton, J.T., Callander, B.A. and Varney, S.K., Ed.). Cambridge University Press, 47-67.

Manabe, S.; Spelman, M.J.; Stouffer, R.J. (1992) Transient responses of a coupled ocean-atmosphere model to gradual changes of atmosphereic CO2. Part II: seasonal response. J. Climate, 5, 105-126.

Mayes J.C. (1991) Recent trends in summer rainfall in the United Kingdom. Weather, 46, 190-196.

Meehl, G.A.; Washington, W.M.; Karl, T.R. (1993) Low-frequency variability and CO2 transient climate change. Part 1. Time-averaged differences. Climate Dynamics, 8, 117-133.

Mitchell, J.F.B.; Manabe, S.; Tokioka, T.; Meleshko, V. (1990) Equilibrium climate change. In: Climate change: the IPCC scientific assessment, (Houghton J.T., Jenkins G.J. and Ephraums, J.J., Ed.), Cambridge University Press, 131-164.

Murphy, J.M. (1992) A prediction of the transient response of climate, Climate Research Technical Note 32, Meteorological Office, Bracknell, UK.

Rowntree, P.R. (1991) Atmospheric parametrization schemes for evaporation over land: basic concepts and climate modelling aspects. In: Land surface evaporation: measurement and parametrization (Schmugge, T.J. and Andre, J-C., Ed.), Springer-Verlag, New York, 5-29.

Rowntree, P.R.; Murphy, J.M.; Mitchelll, J.F.B. (1993) Overview of climate change and future rainfall predictions. Journal of the Institute of Water and Environmental Management (in press).

Senior, C. A.; Mitchell, J.F.B. (1993) CO2 and climate; the impact of cloud parametrizations. Journal of Climate, 6, 393-418.

Wilson, M.; Henderson-Sellers, A. (1985) A global archive of land cover and soil data for use in general circulation climate models. J. Climatology, 5, 119-143.