An investigation into the mechanisms of changes in mid-latitude storm tracks as greenhouse gases are increased.

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Ruth E. Carnell and Catherine A. Senior

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Ruth E. Carnell and Catherine A. Senior

Met Office

Hadley Centre for Climate Prediction and Research

London Road

Bracknell

Berkshire

RG12 2SY

United Kingdom

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Correspondence should be addressed to Ruth McDonald (nee Carnell)

Met Office Hadley Centre for Climate Prediction and Research

London Road Bracknell Berkshire RG12 2SY United Kingdom

Email: ruth.mcdonald@metoffice.com

Tel: (44) (0) 1344 856947

Fax: (44) (0) 1344 854898

Abstract

When greenhouse gases are increased in coupled GCM experiments there is both a direct effect and an indirect effect due to changes in the surface conditions. In this study we carry out experiments with a perpetual winter atmosphere only model in order to investigate the influence of changes to the surface conditions (sea surface temperatures, sea-ice and snow amount) on the Northern Hemisphere winter mid-latitude mean sea level pressure response. The surface conditions for the perpetual winter model experiments are prescribed from time averages of the HadCM2 control and greenhouse gas experiments.

Forcing the perpetual winter model with the HadCM2 greenhouse gas surface conditions produces a negative mean sea level pressure (MSLP) response across both Northern Hemisphere ocean basins, as was found in the coupled model HadCM2 experiment. Additional PW model experiments show that the sea surface temperature forcing from the HadCM2 greenhouse gas experiment dominates the snow and soil moisture content forcings. The sea-ice forcing from the HadCM2 greenhouse gas experiment reduces MSLP at high latitudes.

In the north Pacific region MSLP decreases when the global mean warming is applied to the sea surface temperature forcing field at all open sea points. In the north Atlantic region the increased tropics to mid-latitude meridional sea surface temperature gradient is required for MSLP to decrease.

These experiments show that the MSLP response in the Northern Hemisphere mid-latitude storm track regions is sensitive to the non-local sea surface temperature anomaly pattern.

1 Introduction

The atmospheric response to increased greenhouse gases consists of a direct effect due to changes in the radiative forcing and an indirect effect due to the changes in surface conditions, such as sea surface temperature, snow depth and sea-ice concentrations, which occur as the troposphere warms. The tropospheric response to increased greenhouse gases in coupled ocean-atmosphere models is usually a decrease in pressure across mid-latitudes with a deepening of the Icelandic and Aleutian lows (e.g. Carnell and Senior (1998); Boer et al. (2000); Voss and Mikolajewicz (2001)). In this study we investigate which of the changes to the surface conditions has the largest influence on the tropospheric response.

The HadCM2 model (Johns et al., 1997) gives a decrease in pressure in the region of the Aleutian low as greenhouse gases are increased (Carnell and Senior, 1998). However, in the more recent version of this model, HadCM3, there is an increase in MSLP in the north Pacific region as greenhouse gases are increased (Williams et al., 2001). The pattern of sea surface temperature (SST) response in HadCM3 is also different to that in HadCM2 with less warming occurring in the tropics in HadCM3 (Williams et al., 2001).

Some studies have looked at the role played by the surface forcing on changes in mid-latitude variability. Stephenson and Held (1993) were able to reproduce a coupled model's response to increased greenhouse gases by prescribing a perpetual winter model with sea surface temperatures, soil moisture and sea-ice from the coupled model experiments. They found that a weakening of the north Atlantic storm track was due to reduced baroclinicity associated with a change to the stationary waves.

Experiments in which the Arctic sea-ice is removed tend to produce low-level warming in the Arctic and a weakening of the mid-latitude westerly wind (e.g. Herman and Johnson (1978); Royer et al. (1990); Murray and Simmonds (1995)). Changes in MSLP are less consistent. For example in the perpetual January experiments carried out by (Murray and Simmonds, 1995) the pressure tended to decrease at high latitudes where the temperature rise was greatest and increase elsewhere. At mid-latitudes there were some decreases in MSLP which they attributed to barotropic rather than thermal effects. In the experiments carried out by Herman and Johnson (1978) there were increases and decreases in pressure in the regions where sea-ice was reduced. In the Southern Hemisphere the MSLP response to the removal of Antarctic sea-ice is also ambiguous with both increases and decreases in regions where sea-ice was removed (e.g. Mitchell and Hills (1986); Mitchell and Senior (1989); Simmonds and Wu (1993); Menendez et al. (1999)). Walland and Simmonds (1997) found that increased snow cover in a perpetual winter model increased the mean sea level pressure over land and weakened the north Atlantic storm track. The weaker storm track was linked to changes in the baroclinicity over the ocean basin.

Perpetual winter models (henceforth referred to as PW model) have been used by other authors to study the effects of changed SST and sea-ice (Stephenson and Held, 1993), snow (Walland and Simmonds, 1997), Arctic sea-ice (Murray and Simmonds, 1995) and Antarctic sea-ice (Simmonds and Wu, 1993). In this study we carry out PW model experiments similar to those performed by Stephenson and Held (1993). The aim of our study is to investigate the effects of changing surface conditions on the mid-latitude tropospheric response of the HadCM2 model. This will continue the work of Carnell and Senior (1998) and help to explain the mechanisms of the changes which occur in mid-latitudes as greenhouse gases are increased in coupled models. As an extension of this we will test whether we can reproduce the different MSLP response which occurs as greenhouse gases are increased in HadCM3, by forcing the PW model with the HadCM3 sea surface temperature response pattern.

We will begin with a brief description of HadCM2 and the PW model. We will then compare the PW model's control simulation with the HadCM2 control and the PW model's climate change response with that of HadCM2. In section 4 we will study the effects of changing the sea surface temperature, snow amount, soil moisture content and sea-ice surface forcing fields and in section 5 we will investigate the effects of changing the gradients of the SST forcing pattern. Finally in section 6, we will study the sensitivity of the MSLP response to the SST surface forcing pattern by applying the HadCM3 greenhouse gas SST response pattern to the SST forcing field.

2 Models and experiments

In this study we use data from experiments carried out with the second Hadley Centre coupled ocean-atmosphere model (HadCM2, Johns et al. (1997)). The atmosphere component of HadCM2 is known as HadAM2 and has a horizontal grid spacing of 2.5° latitude by 3.75° longitude and 19 levels in the vertical. The HadCM2 control (CON; see Johns et al. (1997)) has present day CO_2 forcing and we average the data over 120 winters (December, January, February, (DJF)). The greenhouse gas experiment (GHG; see Mitchell and Johns (1997)) has historical CO_2 forcing to 1990 and then CO_2 increases at 1% per year (Mitchell and

Johns, 1997). We average the GHG data over 30 winters from 2006 to 2036. The level of CO_2 is approximately twice preindustrial levels during this period. A correction to account for the loss of mass that occurs in HadCM2 (Osborn et al., 1999) is applied to the HadCM2 MSLP fields prior to averaging.

We also use data from experiments carried out with the third Hadley Centre coupled ocean-atmosphere model (HadCM3, Pope et al. (2000); Gordon et al. (2000)). The control experiment (CON3) has CO_2 fixed at 1860 levels and GHG3 (see Williams et al. (2001)) has historic CO_2 forcing and then scenario IS95a (Houghton et al., 1996) from 1990, which includes changes in CO_2 and other trace gases. The MSLP data from the HadCM3 experiments is corrected for loss of mass, as for HadCM2.

Our PW model is based on the HadAM2 atmosphere only model and has insolation fixed at 15th January and the surface boundary forcing fields (SST; sea-ice depth and grid box fractional area; snow depth; soil moisture content and deep soil temperatures on 3 levels) are prescribed from the time averages (DJF) of the CON and GHG coupled model experiments. The PW model MSLP fields are also corrected for loss of mass.

3 Validation of the PW model

The PW model control experiment (PWCON) has present day CO_2 forcing, surface forcing fields from CON and initial conditions from the 1/1/1991 of CON. The run length is 380 months with time averages being made over the final 360 months. As PWCON is parallel to CON a comparison of these experiments provides a means of validating the PW model. The surface fields for the PW model experiments are derived from DJF means of the coupled model experiments so the PW model results will be compared to DJF means of the coupled model experiments even though the solar forcing for the PW model is fixed at 15th January which is the mid point of the season. The MSLP pattern in PWCON compares well to that in CON (Fig. 1) with the positions of both the Icelandic and Aleutian lows being well reproduced, although they are both deeper in PWCON than in CON. These differences are within the unforced variability (i.e. within one standard deviation on CON) of the north Atlantic and north Pacific regions.

In the PW model greenhouse gas experiment (PWGHG) the CO_2 concentrations are fixed at twice that in PWCON and all surface boundary forcing (SBF) fields are taken from GHG. In PWGHG the SST at points which are sea-ice in CON but open sea in GHG is set to the SST in GHG. The SST changes in GHG, compared to CON are shown in (Fig. 2a), the reduction in sea-ice fraction are shown in (Fig. 2b) and the changes in snow amount are shown in (Fig. 2c). The run length of PWGHG is 140 months from initial conditions taken from 1/1/1991 of CON and the time averages are performed over the final 120 months.

The 1.5 m temperature changes in GHG (Fig. 3b) are captured well by PWGHG (Fig. 3a). The enhanced warming over the Northern Hemisphere land which occurs in GHG also occurs in PWGHG. The MSLP response in GHG (Fig. 3d) is negative across both the north Atlantic and north Pacific storm track regions and over the Arctic and positive over Europe. There is an overall decrease of atmospheric mass in the Northern Hemisphere in GHG which is consistent with the warming being larger in the Northern Hemisphere than in the Southern Hemisphere, particularly in the boreal winter (Mitchell and Johns, 1997). MSLP also decreases across both storm track regions in PWGHG (Fig.

3c) and whilst both the pattern and magnitude of the change in GHG is well reproduced in the north Pacific region, in the north Atlantic region the decrease in MSLP is too large and extends too far into western Europe. The changes in the north Pacific compare well with the changes in the coupled model because in this region the difference between PHGHG and GHG (not shown) is similar to the difference between PWCON and CON (Fig. 1). This is not the case in the north Atlantic region where the difference between PWGHG and GHG is considerably greater than the difference between PWCON and CON leading to an enhanced response in the PW model compared to HadCM2. The different response in the PW model is likely to be mainly due to the lack of ocean feedbacks in the PW model, which might be expected to be more substantial in the north Atlantic region than in the north Pacific region. Other possible causes are the fixed solar variability or the short length of the PW model experiments, but tests have shown that these are not the main cause of the differences. As we are using a solar forcing of 15th January rather than a DJF mean forcing we have also tested whether the PW model response is more similar to the coupled model January response. Whilst the coupled model's MSLP response is greater in JAN (-2hPa) than in DJF (-1hPa) in the north Atlantic region, this does not fully explain the difference between the PW model and the coupled model response in this region.

Despite the differences in the MSLP response between the PW model and the coupled model we believe that physical explanations for the mechanisms of changes in MSLP in the PW model are likely to also be valid for the coupled model.

4 Response to surface boundary forcings

We will now use the PW model to study the changes in MSLP due to increased greenhouse gases and to show the contribution of the changes to each component of the surface forcing to the net change in MSLP. The first question we pose is: 'What is the contribution of each surface boundary forcing field to the causes of decreases in MSLP in the storm track regions which occur in PWGHG (Fig. 3c)?' To answer this question we run a group of anomaly experiments in which CO_2 is kept fixed at 1xCO_2 but the SBF fields are changed (Table 1, experiments: dSBF, NOSST, dSST, dSI, dSMC and dSNOW). In dSBF and NOSST the SST at points which are sea-ice in CON but open sea in GHG is set to the SST in GHG. Each experiment is run for 140 months from initial conditions taken from 1/1/1991 of CON and with the time averages performed over the final 120 months.

When all of the GHG surface forcing conditions are applied (dSBF) the MSLP response (Fig. 4a) is very similar to that in PWGHG (Fig. 3c). This confirms that the direct effect of CO_2 forcing on the PW model's MSLP response is small compared to the effects of the surface boundary forcings in these experiments. The change in MSLP in dSBF is significant at the 95% level across the storm track regions (using a 2-sided t-test). The degrees of freedom of the t-test are calculated at each grid point and allow for consecutive months not being independent in the PW model experiments. The mean degrees of freedom is 295. When the SST forcing is removed (NOSST, Fig. 4b) the MSLP response shows significant increases in the north Pacific region and northeast Canada and significant decreases over the Arctic and central north America. When the SST forcing is applied on its own (dSST, Fig. 4c) there are significant decreases in MSLP across both of the storm track regions. A comparison of the MSLP responses in dSST and dNOSST with the response in dSBF shows that the SST forcing is dominating the other surface forcings in dSBF. However, the MSLP response in dSBF is close to a linear combination of the response in dSST and NOSST, so whilst the SST forcing is dominant the other surface forcings are also having an effect. This is particularly true in the north Pacific region where the increase in MSLP in NOSST acts to reduce the magnitude of the decrease in MSLP in dSBF compared to that in dSST and in polar regions where the decrease in MSLP in dSBF amplifies the decrease in MSLP seen in dSST.

As the MSLP response in dSBF is close to the coupled model's response it is clear that as well as the SST forcing the other surface forcings are also required to reproduce the coupled model's MSLP response pattern. This is similar to the results of Stephenson and Held (1993) who found that their perpetual winter model had to be forced with both the SST and sea-ice forcings in order to reproduce their coupled model's response. These results show that although the SST forcing is dominant the other forcings also have a role, in producing the MSLP response seen in PWGHG. We will now investigate the roles of the sea-ice, snow and soil moisture forcings and in the next section we will investigate the mechanism of the SST forcing.

First, we consider the response due to the reduction of sea-ice. To do this we run dSI in which the sea-ice is from GHG and the other fields are from CON. The SST is set to 271.35 K at points which are sea-ice in CON but open sea in GHG. The reduced sea-ice in dSI decreases MSLP over the Arctic and the surrounding seas such as the Bering Sea and the Sea of Okhotsk and also over Hudson Bay (Fig. 4d). These changes are similar to the changes that Murray and Simmonds (1995) found when they reduced Arctic sea-ice in their model. We also get a similar increase in MSLP over Siberia to the one which occurred in their experiments. The reduction in sea-ice in climate change experiments has been linked to decreased MSLP by enhanced sensible heating (Knippertz et al., 2000) and changes in the surface roughness (Mitchell and Senior, 1989). The decrease in MSLP due to reduced sea-ice can also be seen in NOSST (Fig. 4b) and in the northward shift of the reduction in MSLP in the north Pacific in dSBF compared to dSST (compare Fig. 4a and Fig. 4c).

To consider the response due to changes in soil moisture content and snow amount we run experiments dSMC and dSNOW (see Table 1). However, to see the changes in MSLP due to both the snow and soil moisture forcings we can consider the changes in NOSST (Fig. 4b) as this is an approximately linear combination of the changes in dSNOW (not shown), dSMC (not shown) and dSI (Fig. 4d). So the changes due to the snow and soil moisture forcings are the changes which occur in NOSST, which has all 3 forcings, but do not occur in dSI, which has just the sea ice forcing. We have already seen that there is almost no change in MSLP in NOSST (Fig. 4b) compared to PWCON across the north Atlantic and over western and southern Europe. This is because the MSLP response due to reductions in soil moisture and snow amount are small and of opposite sign in this region so they approximately cancel. Over the north American and Asian continents MSLP decreases, this is because as the lower atmosphere warms the cold stable condition high pressure weakens over these regions and pressure is reduced. In the north Pacific region there is a downstream response to the reductions in snow and soil moisture over Asia with MSLP increasing across mid-latitudes. The increase in MSLP in the north Pacific region due to reduced snow is consistent with Walland and Simmonds (1997) who found that an increase in surface snow decreased MSLP in the north Pacific because of a strengthening of the pole to equator temperature gradient across Asia as the snow line shifted south. This increased the baroclinicity downstream in the storm track region and decreased the MSLP. In NOSST the effect is reversed, with a weaker meridional temperature gradient across Asia weakening the baroclinicity and increasing the MSLP across the storm track region.

In summary, the decreased MSLP over the north Atlantic and north Pacific storm track regions in PWGHG (Fig. 3c) is due to the SST forcing and the reduction in MSLP over high latitudes is mainly a response to the sea-ice forcing. In the north Pacific region the snow and soil moisture forcings act to increase MSLP and so the magnitude of the net decrease in MSLP is less than the magnitude of the decrease in MSLP caused by the SST forcing alone.

5 Mechanism of response to sea surface temperature forcings

As the SST forcing is the dominant forcing, the next question we pose is: 'How sensitive is the MSLP response to the SST forcing pattern?' To answer this question we perform two additional PW model anomaly experiments, parallel to dSBF, but with simplified SST forcing patterns (Table 1, experiments: GMSST and

ZMSST). In GMSST the SST warming pattern is removed completely so that there are no changes to the SST gradients. This is done by applying the global mean SST difference between GHG and CON (1.278 K) at all open sea points. In this experiment MSLP increases in the north Atlantic region and decreases in the north Pacific region (Fig. 5) with a much weaker decrease in the Northern Hemispheric mass than in dSBF. This is expected as in GMSST the southern oceans are warmed by the same amount as the northern oceans where as in dSBF the northern oceans are warmed more than the southern oceans, which decreases the Northern Hemisphere mass. As there are no changes to the SST gradients the only surface temperature gradient that is changed is the land / sea temperature gradient, which is increased. This increase in land / sea temperature gradient might be expected to decrease MSLP over the oceans due to a simple monsoon type mechanism.

The different behaviour in the two ocean basins can also be seen in the Eady parameter (Lindzen and Farrell (1980); Hoskins and Valdes (1990)). The Eady parameter is the maximum Eady growth rate and quantifies baroclinic instability. It is defined as $\sigma_{BI} = 0.31(f/N)|\delta \mathbf{v}/\delta z|$, where f is the Coriolis parameter, N is the static stability, z is the vertical coordinate and $\mathbf{v}$ is the horizontal wind vector. In the north Atlantic, baroclinicity decreases at mid-latitudes, whereas in the north Pacific region baroclinicity increases at mid-latitudes (Fig. 6a). These differences between the north Pacific and north Atlantic regions extends upwards to 200 hPa where the increase in temperature gradient over the east of the north Pacific is much larger than the increase over the east north Atlantic (Fig. 6b). The temperature gradient is larger in the north Pacific region because there is more warming in the tropical troposphere in the north Pacific region. This is because the climatological region of ascent over Asia is enhanced by the SST warming and so the upper atmosphere is warmed by increased amounts of latent heat release. The upper troposphere meridional temperature gradient is also influenced by the storm tracks themselves so in these experiments it is not possible to identify the causality of the changes.

The tropics to mid-latitude meridional temperature gradient is an important energy source for extra tropical cyclones and more or deeper cyclones tend to make the MSLP deeper across the storm track regions. In GHG warming is enhanced at high-latitudes near the surface and so the low level mid-latitude to pole temperature gradient is reduced (Fig. 7). However, the tropics warm more than mid-latitudes so the equator to mid-latitude temperature gradient is increased which increases baroclinicity and may give rise to more storms, lowering the MSLP. To test the effects of changing the meridional temperature gradient we run ZMSST in which the zonal mean SST difference between GHG and CON is applied at all of the open sea points. In ZMSST the pattern of changes in MSLP (Fig. 8a) are similar to the response due to the full SST pattern in dSBF (Fig. 4a) with decreases in both of the storm track regions. In the north Pacific region the decrease in MSLP which occurred in GMSST (Fig. 5) is enhanced in ZMSST (Fig. 8a) and is now deeper than in dSBF (Fig. 4a). In the north Atlantic region MSLP now decreases as in the north Pacific and is approximately the same magnitude as in dSBF. At 500 hPa the baroclinicity is shifted south and increased in both the north Pacific and north Atlantic storm track regions (Fig. 8b).

In summary, changing the land / sea temperature gradient by applying just the global mean warming to the SST forcing field decreases MSLP in the north Pacific region but not in the north Atlantic region. In the north Atlantic region MSLP decreases when the tropics to mid-latitude SST gradient is increased. In both regions, decreased MSLP is associated with increased baroclinicity at 500 hPa and increased upper tropospheric meridional temperature gradients between the tropics and mid latitudes.

6 Response to a warming pattern from another coupled model

So far we have shown that the SST forcing is the dominant surface forcing field and that the MSLP response is sensitive to the meridional temperature gradient of the SST forcing applied. Williams et al. (2001) shows that the MSLP response in a HadCM3 greenhouse gas experiment, GHG3, is opposite to the response in GHG in both the north Pacific storm track region and the north Atlantic storm track region (compare Fig. 9a to Fig. 3d). The secondary maximum in SST warming in the tropics which occurs in GHG does not occur in GHG3 (Fig. 7 and compare Fig. 9b to Fig. 2a) and is related to different cloud feedback effects arising from differences in the physical parameterisations (Williams et al., 2001). In this section we investigate if we can reproduce the HadCM3 MSLP response by forcing our PW model with the HadCM3 SST response. We pose the question: 'Does the change in SST response in the HadCM3 greenhouse gas experiment compared to the SST response in the HadCM2 greenhouse gas experiment force changes in the mid-latitude MSLP response?'

To answer this question we force the PW model with SST forcing fields made up of the HadCM3 SST response added to the HadCM2 CON SST field. All other boundary conditions are taken from the HadCM2 GHG experiment so as to isolate the changes due to the SST anomaly pattern. As the only difference between these experiments and their parallel HadCM2 experiments is the SST forcing field we also compare these experiments to PWCON. We use data from a 30 DJF (2010-2040) period of GHG3 and 100 DJF of CON3. The period of GHG3 was chosen to give a forcing change approximately equivalent to that in the HadCM2 experiments. We run two experiments with the HadCM3 SST response (Table 1, experiments CM3SST and ZM3SST).

When the full SST anomaly (GHG3-CON3) pattern is added to the CON SST (CM3SST) the MSLP response (Fig. 10a) is of the same sign as the MSLP response in GHG3 (Fig. 9a) in both the north Atlantic and north Pacific storm track regions. The main differences between the MSLP response in GHG3 and CM3SST occur at western end of the north Pacific storm track and over central Asia.

Experiment ZM3SST is designed to test whether the differences in the storm track regions is due to just the change to the meridional SST gradient. So the zonal mean of the anomaly (GHG3-CON3) SST field is added to the CON SST field. A comparison of the MSLP response in ZM3SST (Fig. 10b) with that in ZMSST (Fig. 8a) shows that the reduced meridional SST gradient between the tropics and mid-latitudes in ZM3SST compared to ZMSST gives a much weaker MSLP response. A comparison of ZM3SST and CM3SST shows that the full SST anomaly pattern is required to produce the full coupled model response.

In summary, the PW model is able to reproduce the different sign of the MSLP response to increased greenhouse gases seen in HadCM3 from the HadCM3 SST forcing fields. The enhanced meridional temperature gradient between the tropics and mid-latitudes in HadCM2 produces an enhanced MSLP response in the mid-latitude storm track regions. Therefore, the mid-latitude MSLP response is sensitive to the non-local SSTs in the tropics.

7 Concluding remarks

When greenhouse gases are increased in HadCM2 MSLP decreases across both the north Atlantic and north Pacific storm track regions (Carnell and Senior, 1998). In this paper we have investigated the mechanisms which cause these changes in MSLP by carrying out a series of perpetual winter atmosphere only experiments which have surface forcing fields derived from winter means of the HadCM2 control and greenhouse gas experiments. This technique enabled us to test the contribution of changes to each of the surface forcing components to the overall mechanism of change in MSLP in the coupled model.

Comparison of the PW model control experiment with the HadCM2 control experiment show that there are some differences between the two models. These differences are increased, particularly in the north Atlantic region, in the comparison of the greenhouse gas experiments. However, despite these differences the PW model is able to qualitatively reproduce the coupled model's response to increased greenhouse gases and we believe that the PW model is still a useful tool in determining the mechanisms of changes in MSLP in the coupled model.

Experiments carried out with the PW model show that the decreases in MSLP over the north Atlantic and north Pacific storm track regions which occur in both the coupled model and PW model greenhouse gas experiments are due to the changes to the sea surface temperatures which occur as greenhouse gases are increased. The reduction in sea-ice makes the polar vortex less shallow and acts to decrease MSLP in regions where there is less sea-ice particularly over north America, around Greenland and Iceland and over the Bering Sea and Sea of Okhotsk in the north Pacific. The changes in snow amount and soil moisture which occur as greenhouse gases are increased act to increase MSLP across the north Pacific storm track region. When all of the greenhouse gas surface forcings are applied together the SST forcing dominates and MSLP decreases across the north Pacific region, although the magnitude is less than when just the SST forcing is applied. The SST forcing has been shown to dominate the other forcings in other models (e.g. Stephenson and Held (1993)).

In the north Pacific region MSLP also decreases when only the global mean SST change is applied to the SST forcing field, showing that this change in MSLP is partly due to local changes in the land / sea temperature gradient. However, the decrease in MSLP is enhanced when the sea surface temperature gradient between the tropics and mid-latitudes is increased. Therefore, this temperature gradient is also an important part of the mechanism of MSLP changes in the north Pacific region.

In the north Atlantic storm track region the MSLP does not decrease when just the global mean SST change is applied to the SST forcing field. In this region the increase to the tropics to mid-latitude meridional temperature gradient of SSTs is required for MSLP to decrease. Therefore, the increase in this temperature gradient is the most important component of the mechanism that produces the reduction in MSLP in the north Atlantic storm track region.

In HadCM3, MSLP increases in the north Pacific region when greenhouse gases are increased and this different MSLP response can be recreated by forcing the PW model with HadCM3 SST responses. From these PW model experiments the largest factor in the different MSLP responses in mid-latitudes between HadCM3 and HadCM2 appears to be the different tropics to mid-latitude meridional SST gradient response.

These results are important for understanding climate change because they show that any changes in the mid-latitude MSLP, particularly in the north Pacific storm track region may partly depend on non local changes to the SSTs. The changes in the large scale flow may then feedback onto the tropical SSTs however the difference between the tropical SST responses in the HadCM2 and HadCM3 experiments is due to local cloud feedback effects Williams et al. (2001).

Experiments such as these can help to unravel complex coupled model experiments as they enable the mechanisms which control how mid-latitude variability changes with increased greenhouse gases to be studied. An increased knowledge of the mechanisms involved in climate change will help to improve confidence in model predictions.

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Table 1:

Summary of the surface boundary forcings (SBF) and CO_2 forcing used in each of the experiments carried out with the perpetual winter model.

		Surface Boundary Forcings				
Experiment name	CO_2 level	SST (sea surface temperature)	SI (sea-ice fraction and depth)	SMC (soil moisture content)	SNOW (snow amount)	SLT (soil temp. on 3 levels)
PWCON	1	CON	CON	CON	CON	CON
PWGHG	2	GHG	GHG	GHG	GHG	GHG
dSBF	1	GHG	GHG	GHG	GHG	GHG
NOSST	1	CON	GHG	GHG	GHG	GHG
dSST	1	GHG	CON	CON	CON	CON
dSI	1	CON	GHG	CON	CON	CON
dSMC	1	CON	CON	GHG	CON	CON
dSNOW	1	CON	CON	CON	GHG	CON
GMSST	1	[GHG-CON]+CON	GHG	GHG	GHG	GHG
ZMSST	1	<GHG-CON>+CON	GHG	GHG	GHG	GHG
CM3SST	1	GHG3-CON3+CON	GHG	GHG	GHG	GHG
ZM3SST	1	<GHG3-CON3>+CON	GHG	GHG	GHG	GHG

The CON surface forcing fields are from 120 DJF means of the HadCM2 control experiment and the GHG surface forcing fields are from 30 (2006-2036) DJF means of the HadCM2 greenhouse gas experiment. In CM3SST and ZM3SST sea surface temperature fields have been used from a 100 DJF mean of the HadCM3 control experiment (CON3) and a 30 (2010-2040) DJF mean of a HadCM3 greenhouse gas experiment (GHG3). [] is the global mean of the HadCM3 SST anomaly and <> is the zonal mean of the HadCM3 SST anomaly. In experiments which used both the GHG sea-ice forcing field and the GHG SST forcing field the SST at points which are sea-ice in CON but open sea in GHG is set to the SST in GHG. In dSI the SST is set to 271.35 K at points which are sea-ice in CON but open sea in GHG.

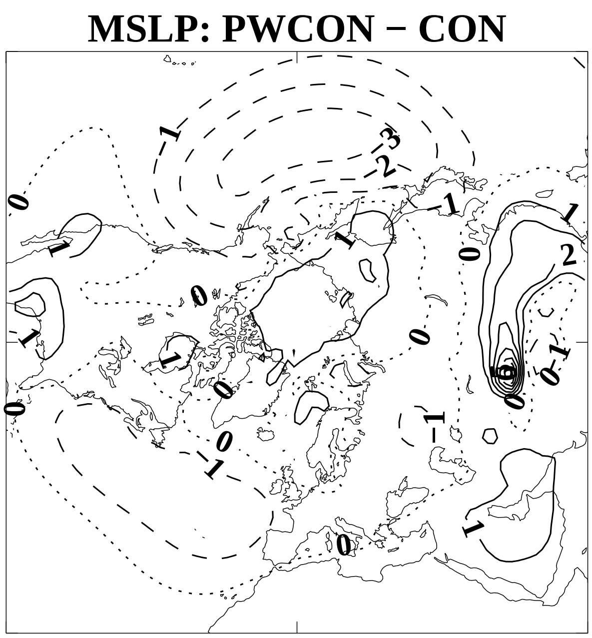


Figure 1: Mean sea level pressure difference of PWCON (360 m average of monthly mean data) minus CON (120 y average of monthly mean data for December, January, February). Isobars are at 1 hPa intervals. Positive contours are solid, the zero contour is dotted and negative contours are dashed.

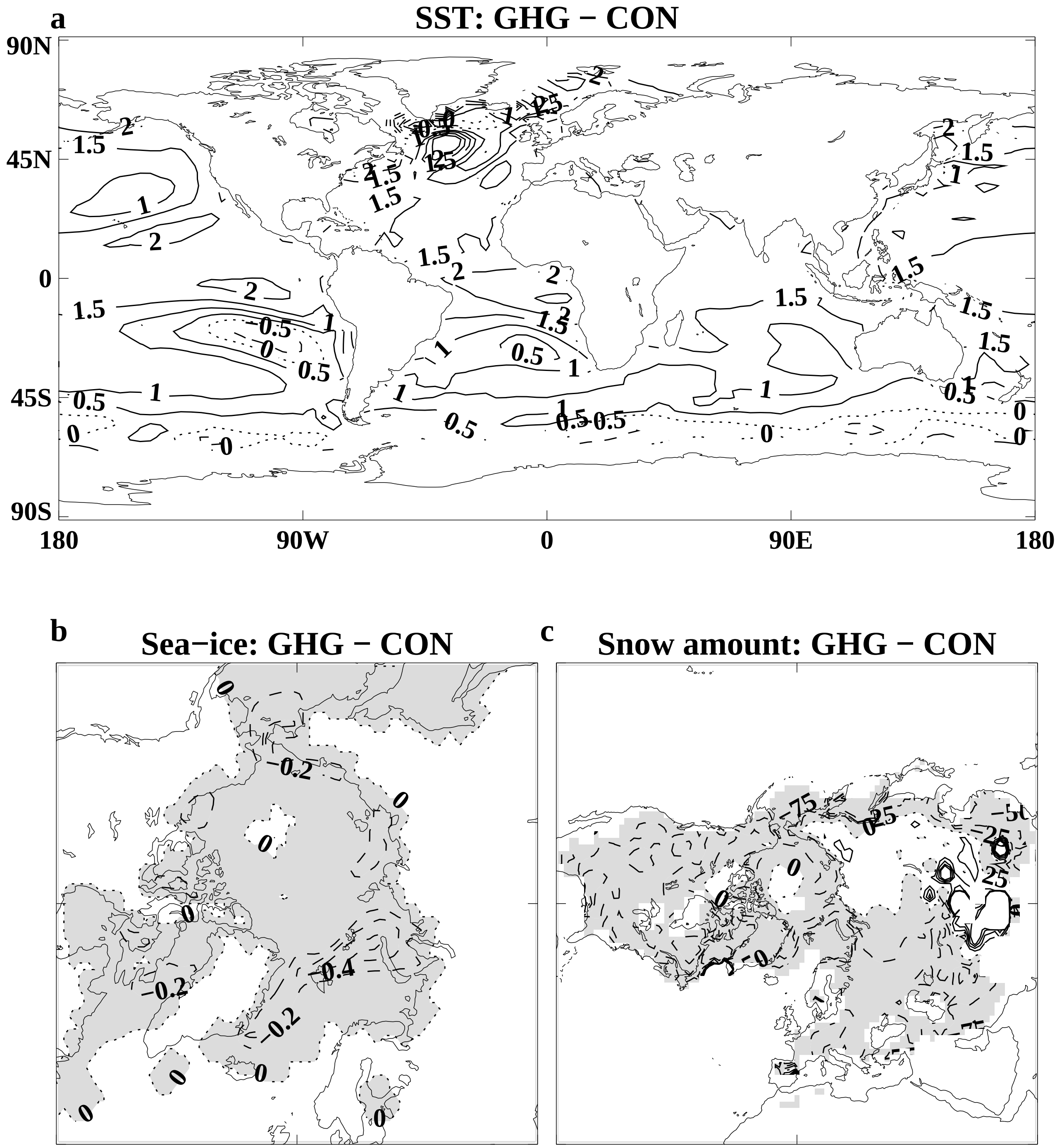


Figure 2: Difference of the GHG (30 y (2006-2036) average of DJF seasonal mean data) minus CON (120 y average of DJF seasonal mean data). **a** Sea surface temperature with contours at 0.5 K intervals. **b** Sea-ice fraction with contours at 0.2 intervals, negative changes are shaded. **c** Percentage change in snow amount with contours at 25% intervals, negative changes are shaded.

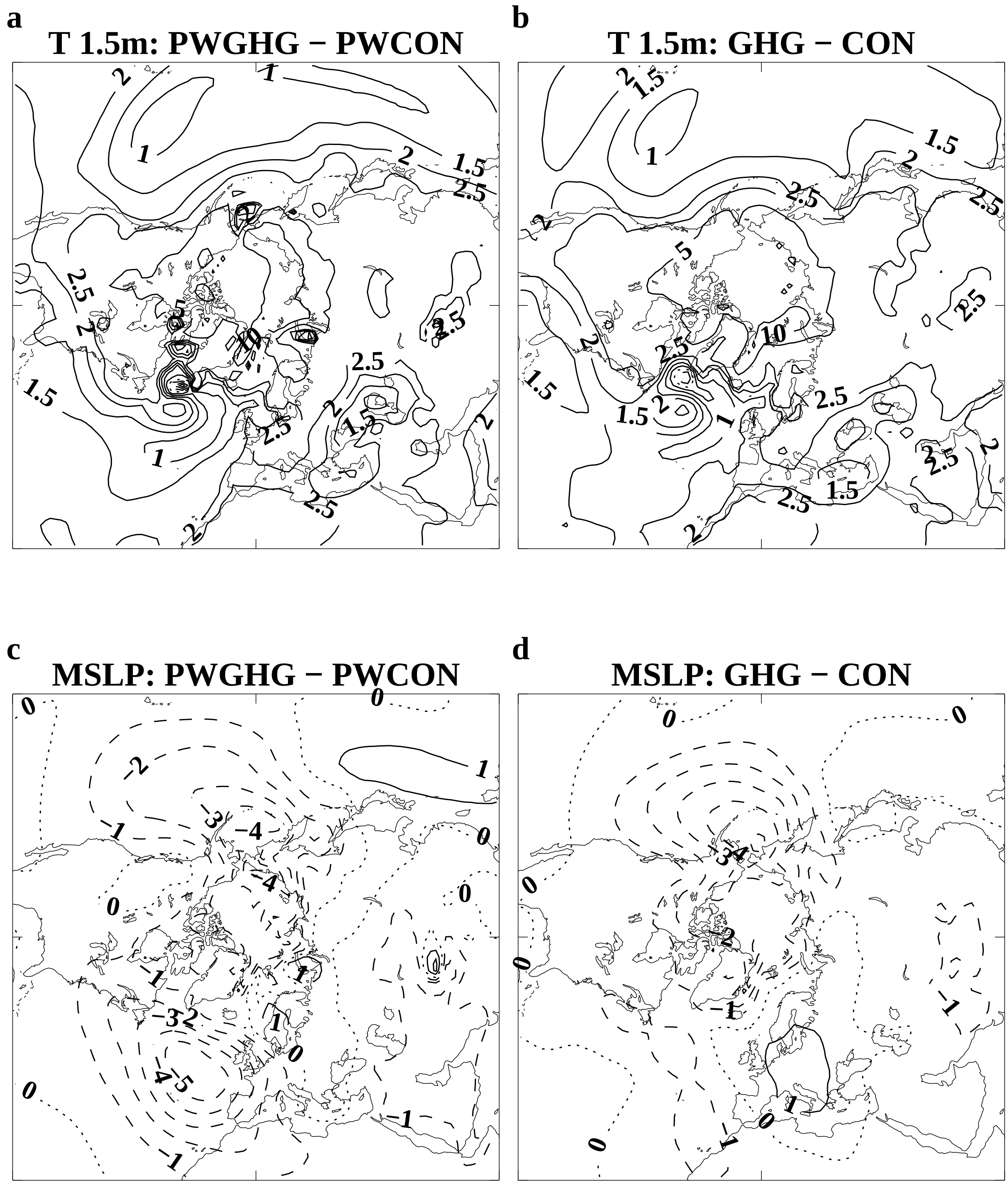


Figure 3: **a** and **b** 1.5 m temperature with contours at 0.5 K intervals to 2.5 K then at 5 K and 10 K. **c** and **d** mean sea level pressure differences with isobars at 1 hPa intervals. **a** and **c** PWGHG (120 m average of monthly mean data) minus PWCON (as for Fig. 1). **b** and **d** GHG (30 y (2006-2036) average of monthly mean data for December, January, February) minus CON (as for Fig. 1).

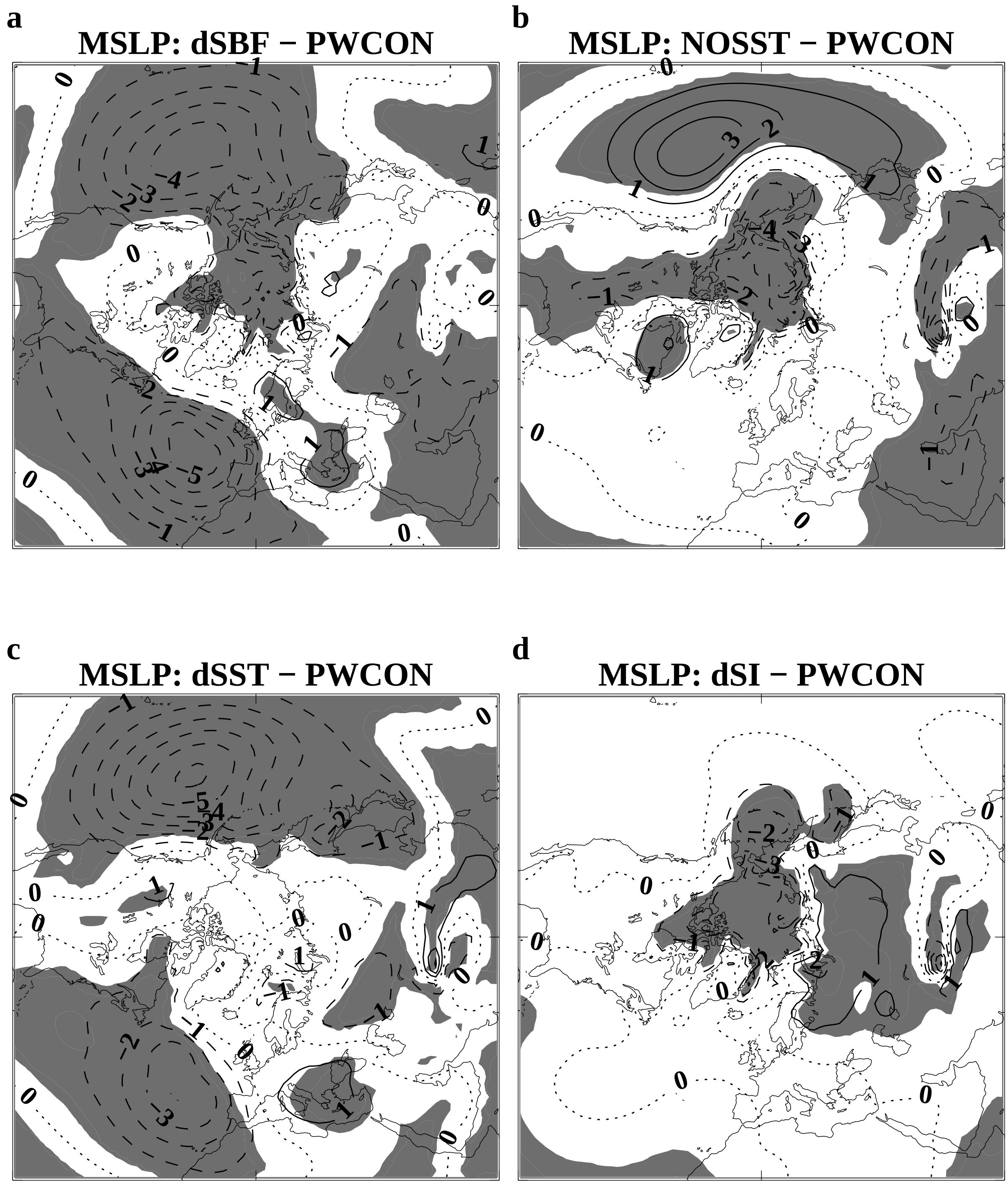


Figure 4: Mean sea level pressure differences with isobars at 1 hPa intervals. Regions where the changes are 95% significant using a 2-tailed t-test are shaded. Anomaly experiments are 120 m averages of monthly mean data and PWCON is as for Fig. 1. **a** dSBF minus PWCON; **b** NOSST minus PWCON; **c** dSST minus PWCON; and **d** dSI minus PWCON.

MSLP: GMSST − PWCON

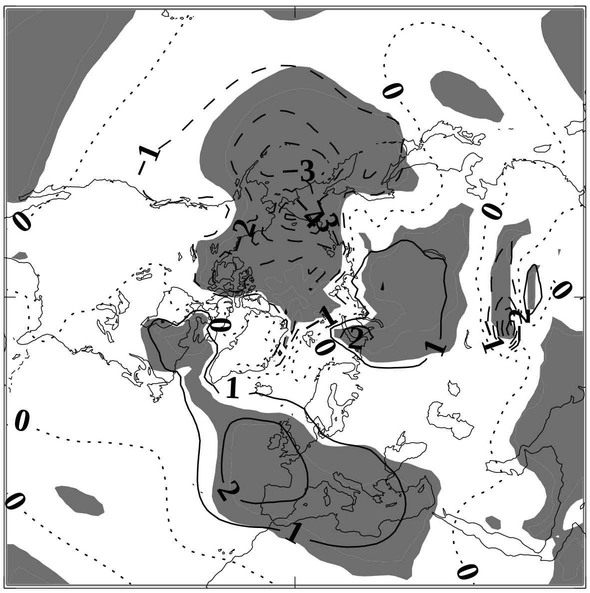


Figure 5: Mean sea level pressure differences for GMSST minus PWCON with isobars at 1 hPa intervals. Regions where the changes are 95% significant using a 2-tailed t-test are shaded. GMSST is a 120 m average of monthly mean data and PWCON is as for Fig. 1.

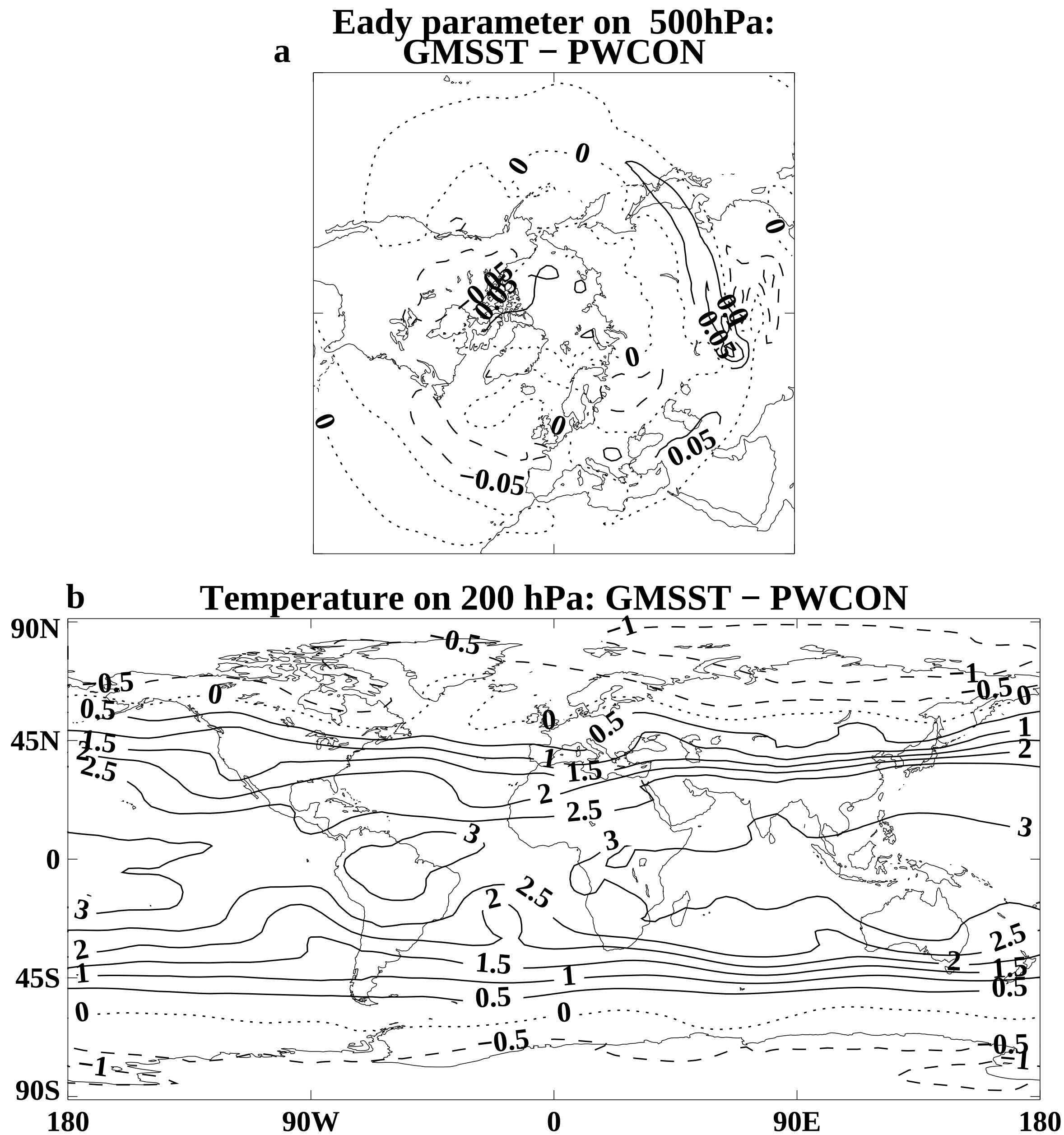


Figure 6: Differences of GMSST minus PWCON. GMSST is a 120 m average of monthly mean data and PWCON is as for Fig. 1. **a** Eady parameter on 500 hPa calculated using data on 600 hPa, 500 hPa and 400 hPa with contours at 0.05 day^{-1} intervals. **b** Temperature on 200 hPa with contours at 0.5 K intervals.

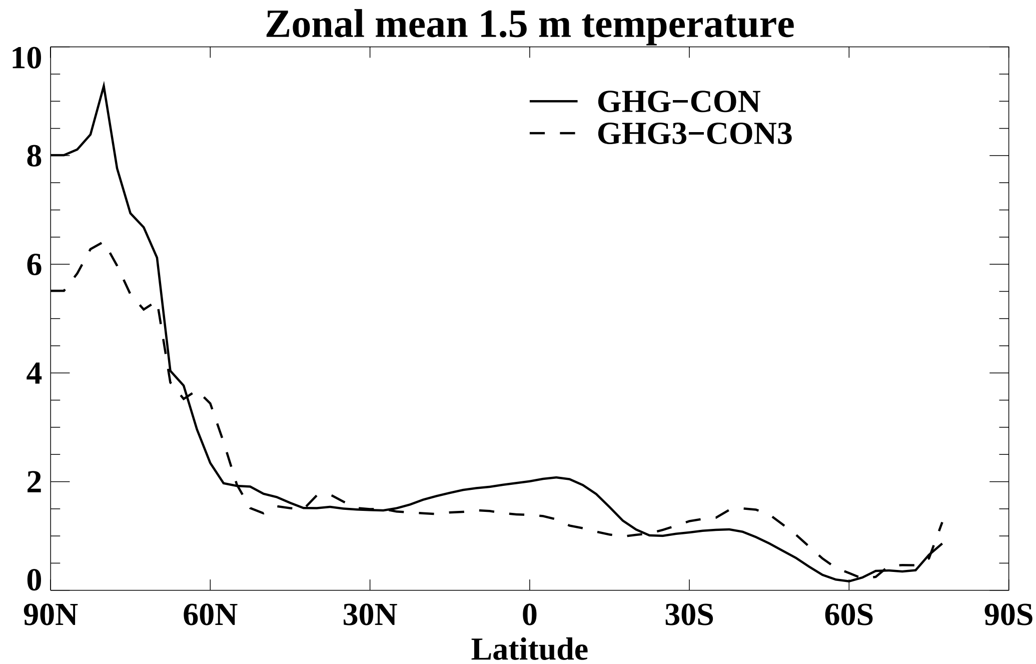


Figure 7: Zonal mean of 1.5 m temperature changes over open sea and sea-ice points for: GHG (30 y (2006-2036) average) minus CON (120 y average) (solid line); and GHG3 (30 y (2010-2040) average) minus CON3 (100 y average) (dashed line). Calculated using long term means of monthly mean data for December, January, February.

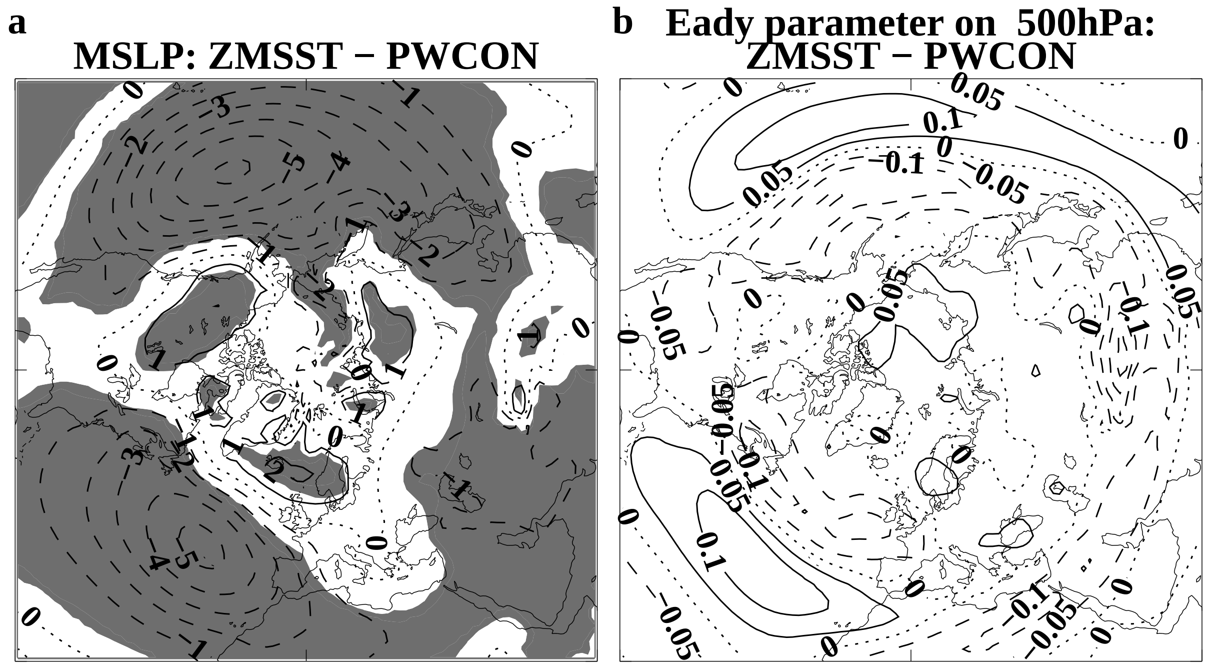


Figure 8: Differences of ZMSST minus PWCON. ZMSST is a 120 m average of monthly mean data and PWCON is as for Fig. 1. **a** Mean sea level pressure differences for ZMSST minus PWCON with isobars at 1 hPa intervals. Regions where the changes are 95% significant using a 2-tailed t-test are shaded. **b** Eady parameter on 500 hPa calculated using data on 600 hPa, 500 hPa and 400 hPa with contours at 0.05 day^{-1} intervals.

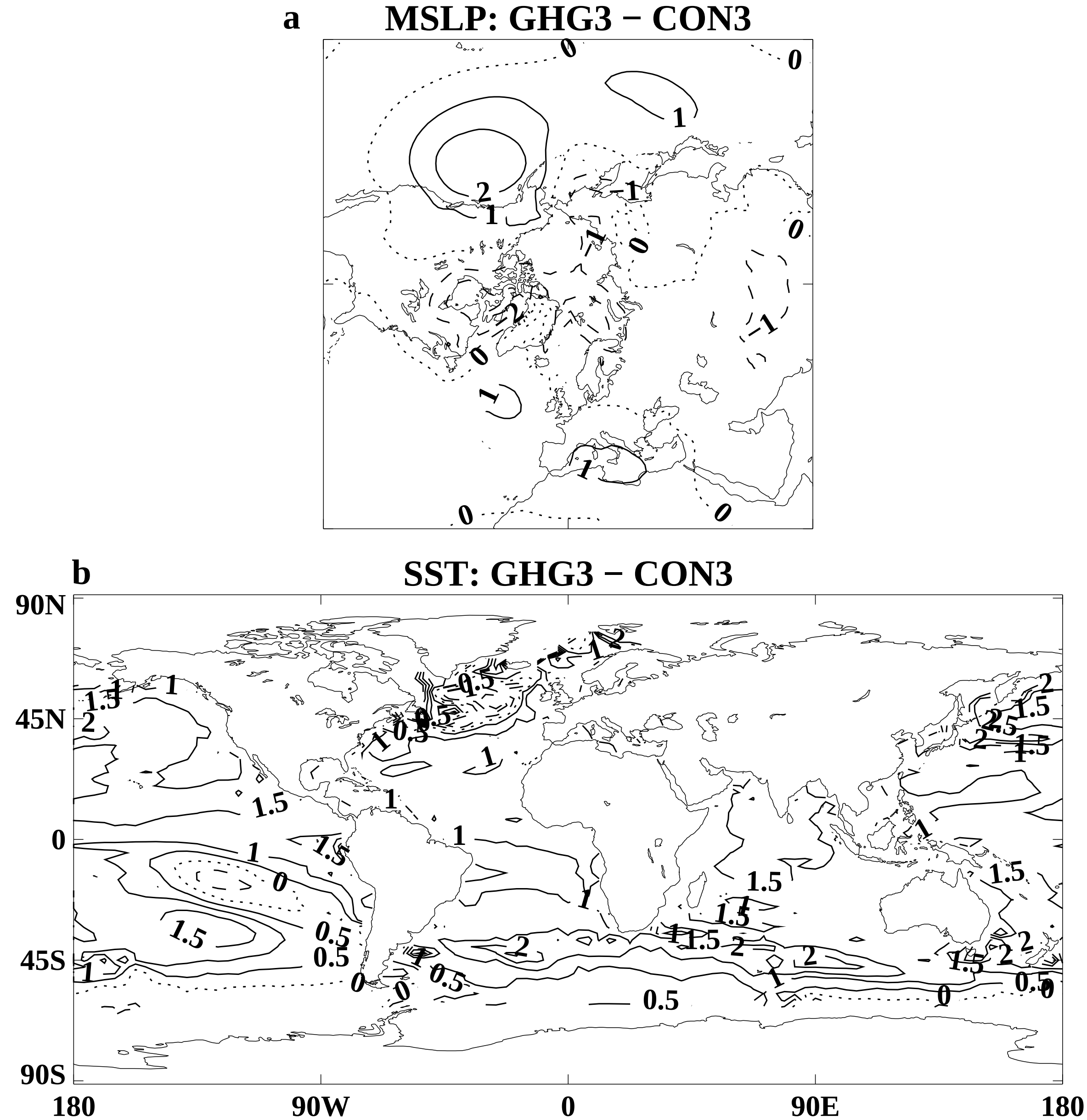
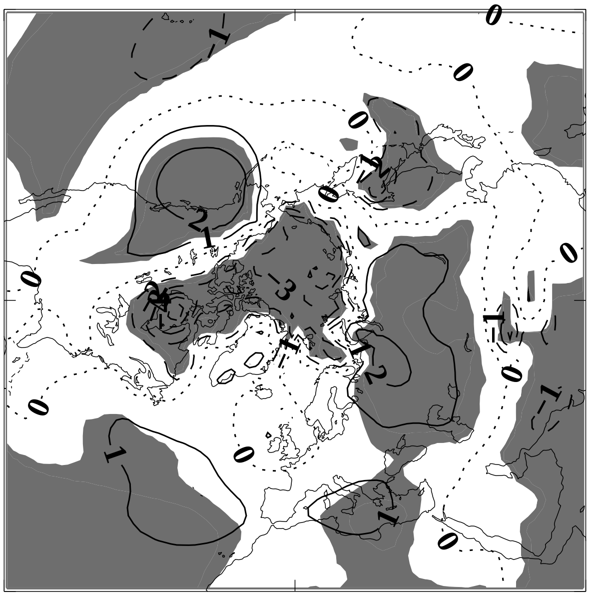


Figure 9: Difference of GHG3 (30 y (2010-2040) average of monthly mean data for December, January, February) minus CON3 (100 y average of monthly mean data for December, January, February). **a** Mean sea level pressure with isobars at 1 hPa intervals. **b** Sea surface temperature with contours at 0.5 K intervals.

a



b

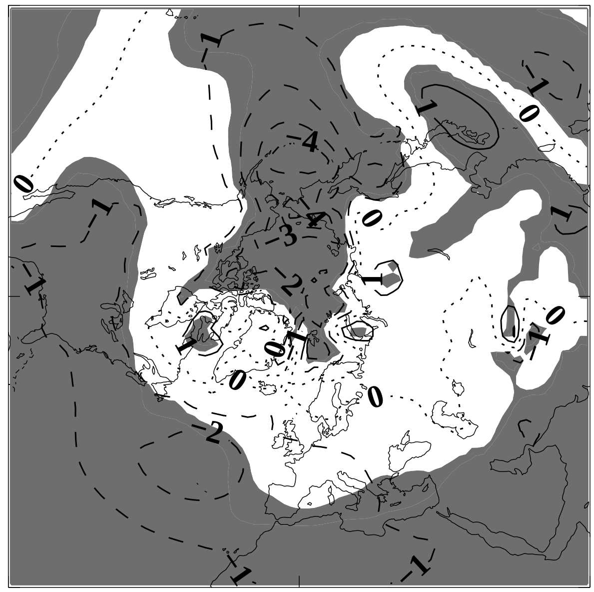


Figure 10: Mean sea level pressure differences with isobars at 1 hPa intervals. Regions where the changes are 95% significant using a 2-tailed t-test are shaded. Anomaly experiments are 120 m averages of monthly mean data and PWCON is as for Fig. 1. **a** CM3SST minus PWCON and **b** ZM3SST minus PWCON.