TECHNICAL MEMORANDUM

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Medium-Range Weather Forecasting in the Extratropics During Wintertime With and Without an Interactive Ocean

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Submitted to Monthly Weather Review

July 2005

European Centre for Medium-Range Weather Forecasts
Europäisches Zentrum für mittelfristige Wettervorhersage
Centre européen pour les prévisions météorologiques à moyen terme

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Abstract

The ECMWF monthly forecasting system is used to investigate the impact an interactive ocean has on medium-range weather predictions in the Northern Hemisphere extratropics during wintertime. On a hemispheric scale the predictive skill for mean sea level pressure (MSLP) with and without an interactive ocean is comparable. This can be explained by the relatively small impact that coupling has on MSLP forecasts. In fact, deterministic and ensemble integrations reveal that the magnitude of forecast error and the perturbation growth due to analysis uncertainties, respectively, by far outweigh MSLP differences between coupled and uncoupled integrations. Furthermore, no significant difference of the ensemble spread between the uncoupled and coupled system is found. Our conclusions apply equally for a number of cases of rapidly intensifying extratropical cyclones in the North Atlantic region. Further experimentation with different atmospheric model cycles, different horizontal atmospheric resolutions and different ocean model formulation reveals the robustness of our findings. Our results suggest that (for the cases, resolutions and model complexities considered in this study) the benefit of using coupled atmosphere-ocean models to carry out medium-range MSLP forecasts is relatively small, at least in the Northern Hemisphere extratropics during wintertime.

1 Introduction

Medium-range weather forecasts out to D+10[1] are commonly carried out with atmosphere-only models persisting analysed sea surface temperatures (SSTs) throughout the forecast. The assumptions inherent to this procedure is that SST changes occur on time scales well beyond 10 days and that two-way air-sea interaction is negligible for short-range and medium-range weather forecasting.

In the wintertime extratropics, turbulent surface sensible and latent heat fluxes (turbulent heat fluxes hereafter) represent the most important surface flux components in terms of the influence they have on the atmosphere. The former provide a direct temperature forcing in lower model levels and the latter provide the source of moisture for the diabatic temperature forcing due to the release of latent heat during condensation. The importance of turbulent surface heat fluxes on the western sides of the North Atlantic and North Pacific basin for the existence of the storm tracks, for example, has been pointed out by Hoskins and Valdes (1990). Moreover, the low-level diabatic potential vorticity forcing associated with turbulent surface heat fluxes may be crucial in the development of rapidly intensifying cyclones, as has been pointed out by Wernli et al. (2002) for the Christmas storm 'Lothar' that hit France on 26 December 1999 with devastating consequences.

Turbulent surface heat fluxes undergo considerable day-to-day variations particularly in the Gulf Stream and Kuroshio area, where climatological SST gradients are at their largest. The standard deviation of 6-hourly turbulent surface heat fluxes on synoptic time scales (2–6 days) amounts to as much as 180 Wm^{-2} along the Gulf Stream (Zolina and Gulev, 2003). Moreover, turbulent surface heat fluxes associated with the passage of very intense low pressure systems can locally exceed 1000 Wm^{-2} (e.g. Neiman and Shapiro, 1993). Extratropical low-pressure systems are accompanied by anomalously strong (weak) heat fluxes out of the ocean upstream (downstream) of the cyclone's centre (Zolina and Gulev, 2003). The former (latter) is due to the advection of cold and dry (warm and moist) air. This effect is particularly pronounced in the vicinity of sharp SST gradients (western boundary currents).

Medium-range weather forecasts based on fixed underlying SST fields capture large parts of day-to-day variations of turbulent surface heat fluxes. This is because on synoptic time scales variations of near-surface temperature and specific humidity dominate turbulent surface heat flux anomalies due to the thermal inertia of the ocean's mixed-layer, particularly during wintertime. In the past this has been exploited by the NWP community in the sense that forecasts with global atmospheric models were carried out by persisting analyzed SST field throughout the forecast. The success of this method can be inferred from the relatively high predictive

[1] We shall use the abbreviation D+n for n-day forecasts.

skill of current operational forecasting systems (e.g. Simmons and Hollingsworth, 2002). However, given the increasing interest of the public in reliable forecasts, particularly of severe weather events (severe wind storms), it seems timely to investigate whether numerical short-range and medium-range weather forecasts could further benefit from the use of coupled ocean-atmosphere models. The use of coupled models is motivated by the fact that surface heat flux anomalies do alter SSTs, which in turn affect the heat fluxes. It is the aim of this study to investigate whether this effect is large enough to be of any practical significance for weather forecasts with state-of-the-art, global numerical forecasting systems.

It should be mentioned that in the past work has been done to investigate some aspects of the impact of the use of an interactive ocean on synoptic time scales. These studies, however, focus either on single cases (e.g. Josse et al., 1999) or are based on regional models (e.g. Gustafsson et al., 1998; Hagedorn et al., 2000). Here we use the ECMWF monthly forecasting system (Vitart, 2004), which can be run, both uncoupled and coupled, to carry out 10-day forecasts. The focus is on the winter season. Based on a relatively large sample size (a total of 36 cases is considered) the following questions are addressed:

- Does coupling improve deterministic skill scores?
- How large is the impact of coupling compared to the forecast uncertainties due to analysis errors?
- Does coupling have an impact on ensemble spread?
- Do forecasts of rapidly intensifying extratropical cyclones benefit from the use of coupled atmosphere-ocean models?
- How sensitive are the results to model formulation (two model cycles are considered), horizontal resolution of the atmospheric model used (T_L159 versus T_L255) and the complexity of the oceanic mixed-layer?

By addressing the above items we aim to clarify the question whether medium-range weather forecasts in the extratropics could benefit from the use of coupled atmosphere-ocean models.

The structure of the paper is as follows. The ECMWF monthly forecasting system used in this study is described in the following section. This section also gives an overview of the cases selected. Thereafter, the results are given. We start with a description of the relative importance of two-way atmosphere-ocean coupling on a hemispheric scale. This is followed by a more in-depth discussion of selected cases of rapidly intensifying North Atlantic cyclones. Then, the sensitivity of the results to changes of the model cycle, horizontal resolution and ocean model used is investigated. Finally, the main conclusions of this study are summarized and discussed Section 4.

2 Methods

2.1 Model description

In this study we use the ECMWF monthly forecasting system (Vitart, 2004). The atmospheric component is based on model cycle 25r3, which has been used operationally at ECMWF from 14 January to 28 April 2003. The horizontal resolution is T_L159 ($\approx 1.125 \times 1.125$) and 40 levels in the vertical are employed. The vertical resolution in the troposphere is roughly the same as that of the 60 level model used operationally for the medium-range during the time of writing. The monthly forecasting system can be run either by persisting analysed SST fields (uncoupled model), as is done for operational medium-range forecasts, or by coupling the atmospheric model to an ocean general circulation model (coupled model), as used to carry out operational monthly forecasts.

The oceanic component, that is, the Hamburg Ocean Primitive Equation (HOPE) model (Wolff et al., 1997), is the same as used operationally in the ECMWF seasonal forecasting system. The ocean model has lower resolution in the extratropics but higher resolution in the equatorial region. The ocean model has 29 levels in the vertical. The atmosphere and ocean communicate with each other through the Ocean Atmosphere Sea Ice Soil (OASIS) coupler (Terray et al., 1995). The atmospheric fluxes of momentum, heat, and freshwater are passed to the ocean every hour. In this coupled system, the sea ice cover is deduced from the SSTs predicted by the ocean model. There is sea ice if the SST predicted by the ocean model is below than -1.73 degC.

In the monthly forecasting system, atmospheric singular vectors are used to generated initial perturbation to generated ensemble forecasts. The singular vector methodology is the same as that used to carry out ensemble forecasts for the medium-range (Molteni et al., 1996; Buizza and Palmer, 1995). The ocean is also perturbed in the same way as is done in operational seasonal forecasts (Vialard et al., 2003). The ensembles encompass one control forecast (deterministic forecast started from the analysis) and nine perturbed forecasts.

2.2 Case selection

One might expect any beneficial impact of the use of an interactive ocean to be most pronounced for cases of strong cyclonic development over oceanic regions, for which air-sea interaction is at its strongest. Therefore, we decided to select twelve cases of rapidly intensifying cyclones the North Atlantic region. The dates of these events are summarized in Tab. 1 along with a description where the cyclo-genesis took place. For each of these events control and ensemble integrations were started 3, 5, and 7 days prior to cyclo-genesis. The total number of forecasts considered, therefore, amounts to 36, both for the uncoupled and the coupled system.

Table 1: Target dates of major rapidly deepening Northern Hemisphere extratopical cyclones considered in this study. For every target date three 10-day ensembles were produced (1 control forecast and 9 perturbed forecasts) starting 3, 5, and 7 days before the major event. Therefore, the total number of forecasts amounts to 36.

Date	Note
19871017	October Storm (France and UK)
19890105	Gulf Stream
19900109	Central North Atlantic
19900126	Eastern North Atlantic
19911031	Nova Scotia/Gulf Stream
19921207	Gulf Stream
19940330	Central North Atlantic
19960107	Eastern North Atlantic
19970217	Central North Atlantic
19990104	Eastern North Atlantic and Labrador
19991227	Christmas Storm (France and Germany)
20000121	Gulf Stream and Labrador Sea

2.3 Measures for quantifying of forecast differences

Before starting to discuss the results it is worthwhile to introduce some diagnostics, which are used in this study to quantify deterministic forecast errors, the impact of coupling, and the ensemble spread in more detail. Broadly speaking, we use two different classes of measures, the first one describing differences on a hemispheric basis (Eqn. 1–3) and the second class describing differences on a grid point basis (Eqn.4–5).

Deterministic forecast errors for one particular forecast step (e.g., D+1) are determined as follows:

$$\bar{s}_{det} = \frac{1}{K}\sum_{k=1}^{K} rms_s(\mathbf{x}^k - \mathbf{y}^k), \tag{1}$$

where $\mathbf{x}^k$ and $\mathbf{y}^k$ represent the verifying analysis and the (uncoupled or coupled) deterministic forecast, respectively, for the k-th forecast. rms_s denotes a function that computes the spatial root mean square distance of vector fields (here for the Northern Hemisphere taking area weighting into account). Note, that $\bar{s}_{det}$ is a scalar and represents the mean over all $K = 36$ cases.

In order to quantify the impact of coupling we use a very similar scheme, that is,

$$\bar{s}_{coup} = \frac{1}{K}\sum_{k=1}^{K}\left[\frac{1}{N}\sum_{i=1}^{N} rms_s(\mathbf{x}^{i,k} - \mathbf{y}^{i,k})\right], \tag{2}$$

where $\mathbf{x}^{i,k}$ and $\mathbf{y}^{i,k}$ represent the uncoupled and coupled forecast, respectively, and $i = 1,\ldots,N$ ($N = 10$) denotes the i-th ensemble member ($i = 1$ is the control forecast). Notice, that members i are based on the same initial conditions, so that $\bar{s}_{coup}$ yields a measure of the average impact of coupling.

Finally, the ensemble spread is evaluated separately for the coupled and uncoupled ensembles based on the following equation:

$$\bar{s}_{init} = \frac{1}{K}\sum_{k=1}^{K}\left[\frac{1}{N(N-1)/2}\sum_{i=1}^{N}\sum_{j=1}^{i} rms_s(\mathbf{x}^{i,k} - \mathbf{x}^{j,k})\right], \tag{3}$$

where $\mathbf{x}^{i,k}$ represents the i-th member of the k-th forecast. For the coupled system $\mathbf{x}^{i,k} \equiv \mathbf{y}^{i,k}$. Note, that every ensemble member is compared with all the other members. $\bar{s}_{init}$ effectively describes forecast uncertainities associated with the growth of analysis errors and, like $\bar{s}_{coup}$ and $\bar{s}_{det}$, is a scalar.

The above measures give a picture of the sensitivity on a hemispheric scale. These measures are augmented by two diagnostics operation on a local scale. The impact of coupling is quantified at every grid point $l = 1,\ldots,L$ by taking the average of rms difference between coupled and uncoupled ensemble members, which use the same initial conditions, that is,

$$\bar{s}_{l,coup} = \frac{1}{K}\sum_{k=1}^{K}\left[\frac{1}{N}\sum_{i=1}^{N}\left(x_l^{i,k} - y_l^{i,k}\right)^2\right]^{1/2} \tag{4}$$

A related diagnostic is used to quantifying the impact of analysis uncertainites for every grid point:

$$\bar{s}_{l,init} = \frac{1}{K}\sum_{k=1}^{K}\left[\frac{1}{N(N-1)/2}\sum_{i=1}^{N}\sum_{j=1}^{i}\left(x_l^{i,k} - x_l^{j,k}\right)^2\right]^{1/2} \tag{5}$$

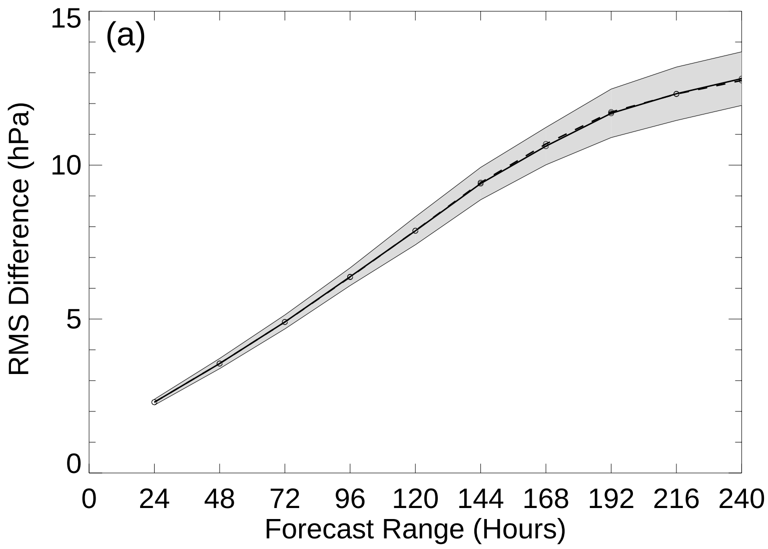

Figure 1: Average spatial rms errors of Northern Hemisphere (north of 30^{o}N) MSLP control forecasts (hPa) for the uncoupled (solid) and coupled (dashed) model. Also shown is the 95% confidence interval for the uncoupled run. Results are based on 36 individual forecasts. Area weighting has been taken into account.

3 Results

3.1 Performance on a hemispheric scale

We start by investigating the impact which the use of coupled model has on deterministic skill scores. Northern Hemisphere deterministic skill scores for the uncoupled (solid) and coupled (dashed) model and MSLP are shown in Fig. 1. We use MSLP instead of 500 hPa geopotential height fields, which are traditionally used to evaluate forecast skill, since the former is likely to be more sensitive to surface perturbations, at least during first few days of the integrations. Fig. 1 clearly reveals that the use of a coupled model does not improve the northern hemispheric deterministic forecast skill during the first ten days of the forecast.

One might argue that MSLP forecasts for some regions might benefit more than others from atmosphere-ocean coupling, an effect that might be masked by hemispheric-scale diagnostics. In order to test this conjecture we have evaluted Eqn. 1 at every grid point, the results which are shown in Fig. 2 in terms of the difference between coupled and uncoupled deterministic forecast errors at D+2 and D+5. The difference field is rather noisy suggesting that a sample size of 36 forecasts is too small to detect any noteworthy local differences—if existent.

The fact that differences of Northern Hemisphere MSLP fields between the uncoupled and coupled integrations are relatively small throughout the forecast can be inferred from Fig. 3 (solid line with 95% confidence intervals). The average spatial standard deviation ($\bar{s}_{coup}$) at D+3 amounts to 1 hPa for example, whereas the ensemble spread takes values around 4 hPa. As will be discussed in more detail below, the impact of the coupling during the early stages of the integrations as reflected by hemisperic-scale diagnostics is likely to be exaggerated due to problems associated with the initialization of sea ice in some regions.

Another interesting feature highlighted by Fig. 3 is that the ensemble spread of the coupled and uncoupled integration is virtually the same throughout the whole forecast. (Notice, that the dashed and dash-dot-dotted curves are practically indistinguishable.)

Geographical differences of the impact of two-way atmosphere-ocean coupling on D+1, D+3, D+5, and D+10

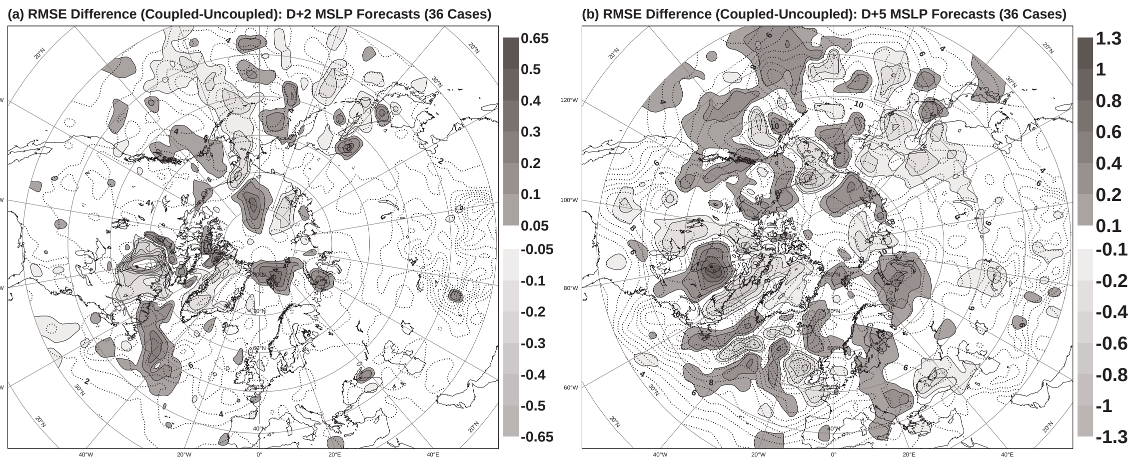

Figure 2: Difference of rms errors between coupled and uncoupled MSLP control forecasts (hPa, shading): (a) D+2 and (b) D+5. Also shown are the rms errors for the uncoupled experiment (dotted line). Results are based on a total of 36 cases.

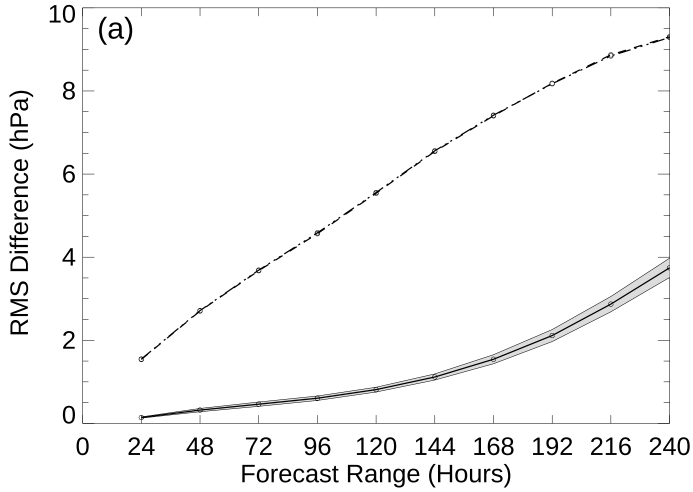

Figure 3: Average spatial rms difference (hPa) of Northern Hemisphere (north of 30°N) MSLP forecasts: coupled minus uncoupled integrations (solid, Eqn. 2) along with 95% confidence levels. Also shown are average spatial rms differences between individual members from the uncoupled (dashed) and coupled (dash dot dot) emsemble (Eqn. 3). Results are based on 36 cases and 11 ensemble members.

MSLP forecasts can be inferred from Fig. 4. At D+1, the largest impact (0.5–1 hPa) can be found in the Hudson Bay, the Labrador Sea, the Bering Strait, and in the Sea of Ochotsk. In these regions differences between the coupled and uncoupled forecasts can partly be explained by problems with the sea ice analysis. In the Hudson Bay, for example, the sea ice in the ocean analysis is incorrect (there is almost no sea-ice in this analysis when there should be) and this error is persisted in the atmosphere-only runs. In the coupled version, on the other hand, the sea ice is deduced from SSTs and the error gets reduced.

The other two areas standing out in Fig. 4a are the Kuroshio and the Gulf Stream area, where the MSLP standard deviation amounts to about 0.2 hPa. There are two likely (and related) explanations why these areas stand out.

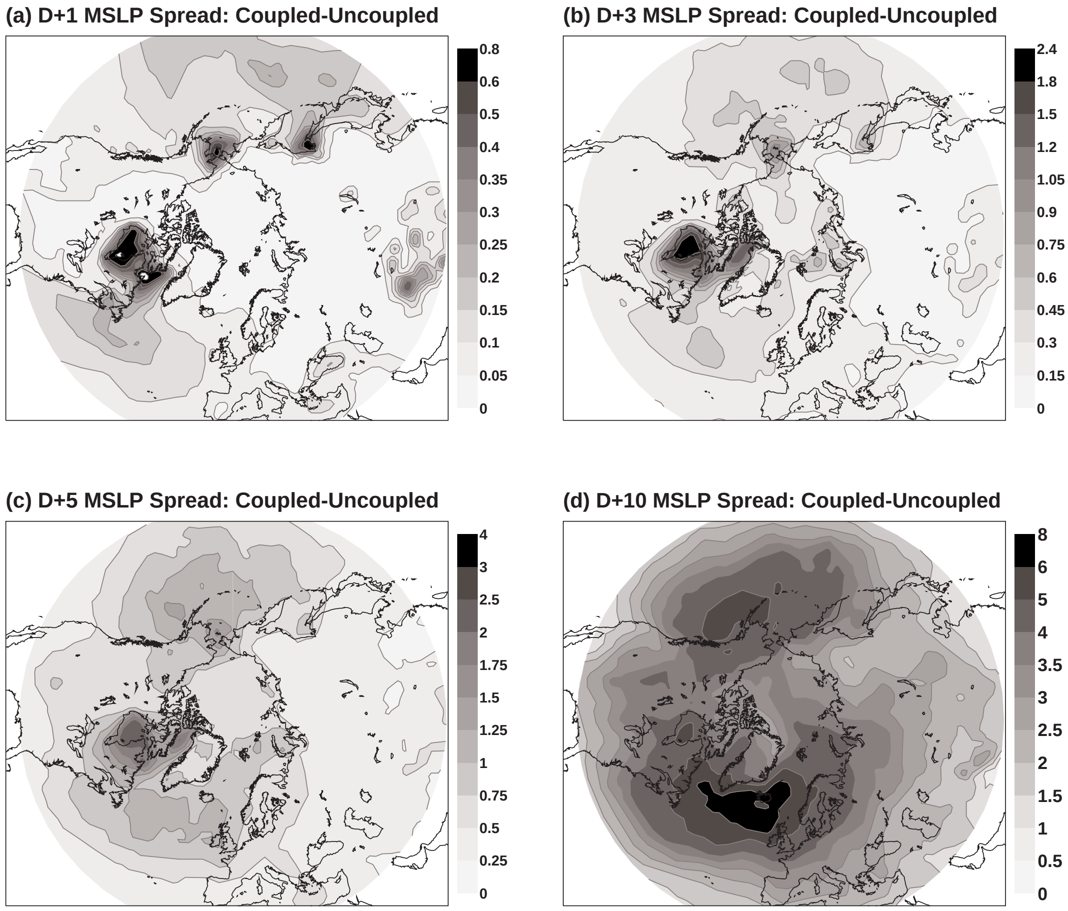

Figure 4: Average MSLP rms difference (hPa) between coupled and uncoupled ensemble members (Eqn. 4): (a) D+1, (b) D+3, (c) D+5, and (d) D+10. Notice that the contour interval changes linearly with lead time. Results are based on a total of 36 cases.

First, predictability studies show that the growth of perturbations is the largest in western parts of the North Atlantic and North Pacific ocean (e.g. Toth and Kalnay, 1993; Buizza and Palmer, 1995). Second, both areas are marked by large SST gradients so that any atmospheric response has a relatively large impact on SST due to changes in turbulent surface heat fluxes (through advection). During the first 5 days of the integrations the MSLP perturbation growth is relatively small compared to the growth during the last 5 days (see also Fig.3).

The effect of analysis uncertainties on MSLP forecasts is shown in Fig. 5 for the uncoupled ensembles. The results are virtually the same for the coupled ensembles (not shown). The most important thing to notice is that the impact of analysis uncertainties clearly outweights that of coupling. The ensemble spread at D+3 in the Gulf Stream area, for example, amounts to 2–3 hPa compared to 0.2–0.3 hPa due to coupling, that is, the impact of analysis uncertainties is one order of magnitude larger than that of coupling (using the MSLP rms difference as metric).

In order to help understanding the above results it is useful to quantify how different SST fields in the coupled and uncoupled integrations actually are. Average rms differences of SSTs between the coupled and uncoupled integrations are shown in Fig. 6 at D+1, D+3, D+5 and D+10. Notice, that over land the soil temperature of the first level (above 3 cm) of the land surface scheme is shown. The first thing to notice is that SST (soil temperature) differences between the coupled and uncoupled run increase throughout the forecast. The largest SST differences are found in the Kuroshio and Gulf Stream area amounting to about 1 K at D+10, which seems

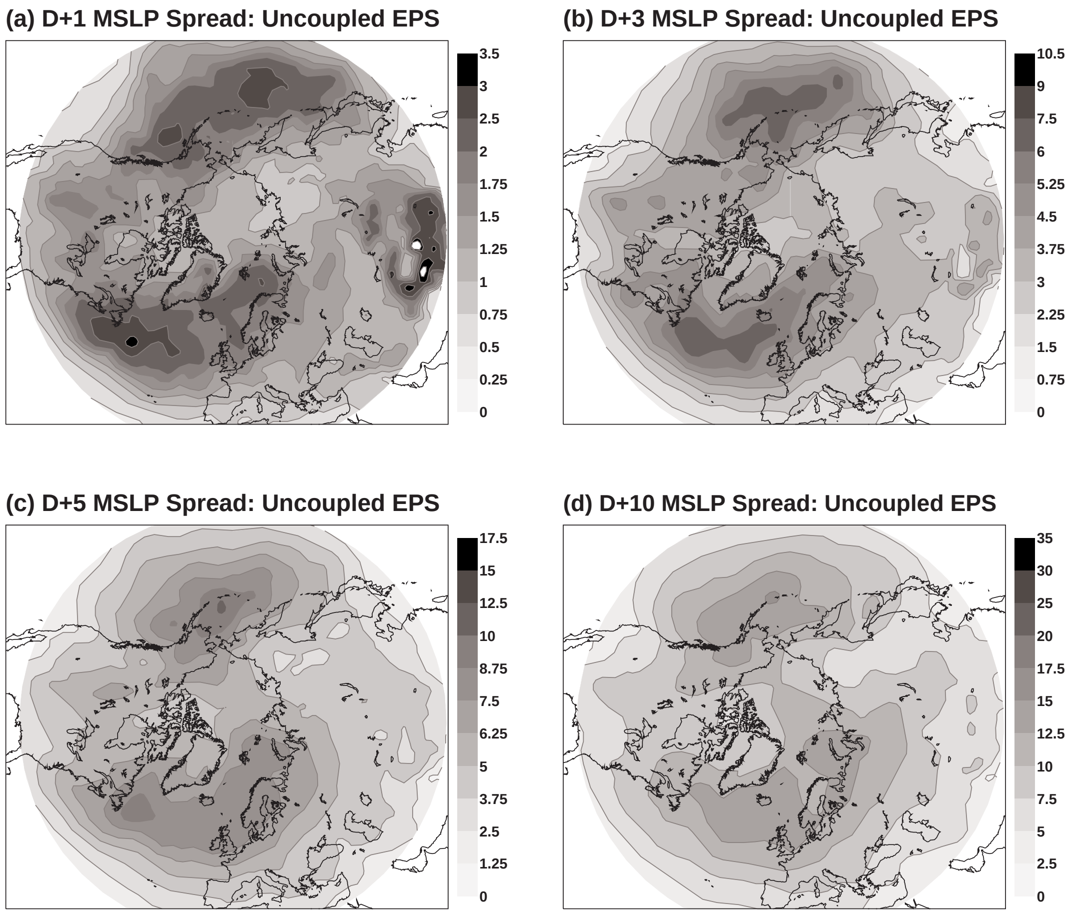

Figure 5: Average MSLP difference (hPa) between individual members of the uncoupled ensemble (Eqn. 5): (a) D+1, (b) D+3, (c) D+5, and (d) D+10 forecasts. Notice that the contour interval changes linearly with lead time. Results are based on a total of 36 cases.

reasonable given that relatively large SST gradients are present. Large differences are also found along the sea ice margins. This is in line with the fact that even small changes of the sea ice edge lead to relatively large changes of surface temperatures. Finally, it is interesting to note that by D+10 land surface temperature differences are larger than SST differences (except for the Kuroshio and Gulf Stream region), which can be explained by the smaller thermal inertia of the land surface compared to the ocean mixed layer. (It should be mentioned that an interactive land surface scheme is used in, *both* the coupled and uncoupled integrations.)

3.2 Case studies of rapidly intensifying extratropical cyclones

The previous section has revealed that on a hemispheric scale and in terms of an average over a relatively large number of cases (36 forecasts) the impact of coupling is relatively small. One might argue that this could have been expected *a priori* given that intensive extratropical cyclones are rarely found in particular areas, and it is for intensive cyclones that air-sea interaction is most pronounced. In the following we shall investigate the impact of coupling for some of the most rapidly intensifying cyclones that occurred in the period 1958–2000 (see Tab. 1).

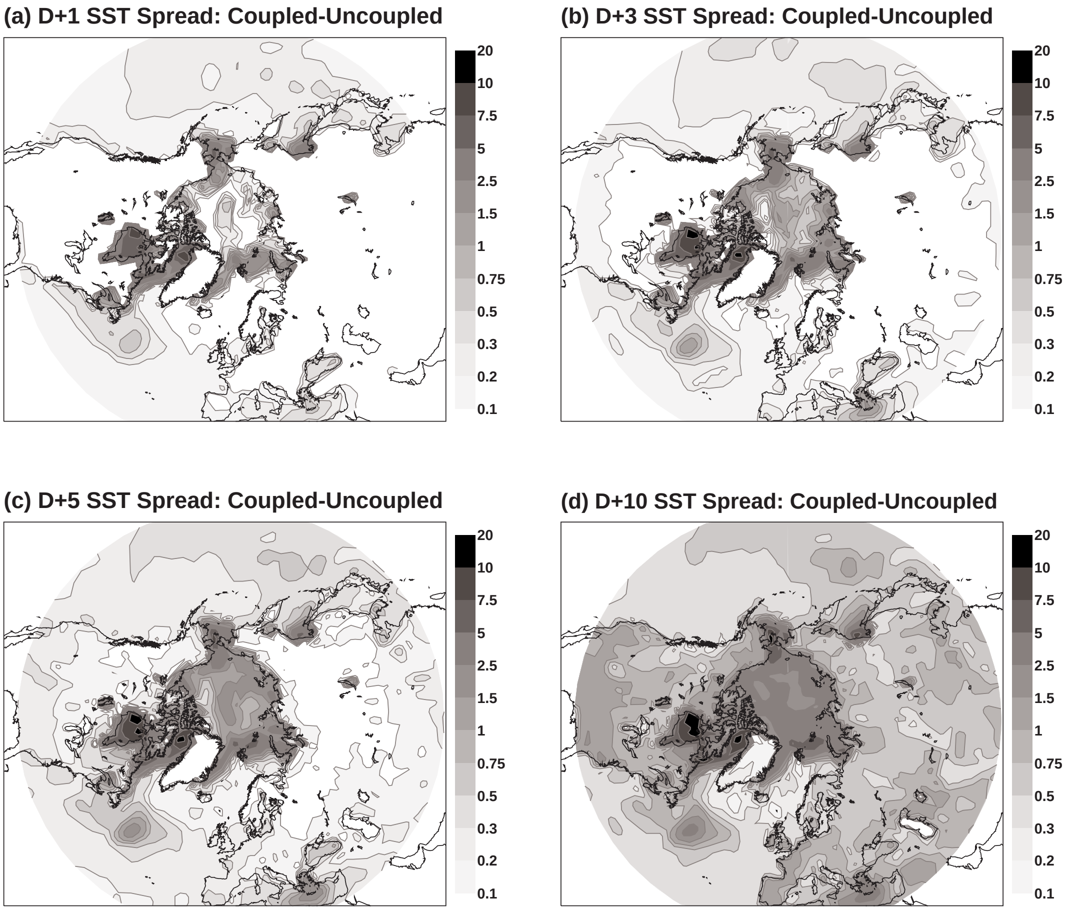

Figure 6: As in Fig. 4, except for surface temperature differences (K) of the surface. Note, that this parameter reflects SSTs over the oceans and the soil temperature at level one of the land-surface scheme over the continents. Notice also that the shading is the same for all forecast steps.

3.2.1 Case 1: Rapid Intensification in the Gulf Stream Area

The first case considered in more detail involves the development of an intense cyclone in the western North Atlantic, which has been described in more detail by Neiman and Shapiro (1993). The most intense cyclogenesis occurred during the period 4–5 January 1989 over the Gulf Stream. Within 24 hours the cyclone's central pressure decreased by more than 60 hPa from 996 to 936 hPa. It has been estimated that turbulent surface heat fluxes during the mature state of the cyclone have been in excess of 2000 Wm^{-2} (for details, see Neiman and Shapiro, 1993) making it a prime candidate for a more detailed investigation of the impact of two-way atmosphere-ocean coupling.

We start by investigating so-called "stamp maps" for the uncoupled (Fig.7) and the coupled ensembles (Fig. 8). The stamp maps used here show the verifying MSLP analysis along with the control forecasts and all perturbed forecasts. The focus is on D+3 forecasts. At verification time (00UTC on 5 January 1989) a very intensive cyclone is located over Newfoundland. The major short-coming of the coupled and uncoupled control forecasts is that the cyclone is located too far to the south. None of the the perturbed forecasts, neither coupled nor uncoupled, captures the right locating. The largest difference between the ensemble members are found for the intensity. Differences in the location are relatively small. By comparing individual members of the coupled and uncoupled ensemble, which are based on the same initial perturbations, it becomes evident that for this particular cyclone the impact of initial uncertainties is much larger than that of coupling.

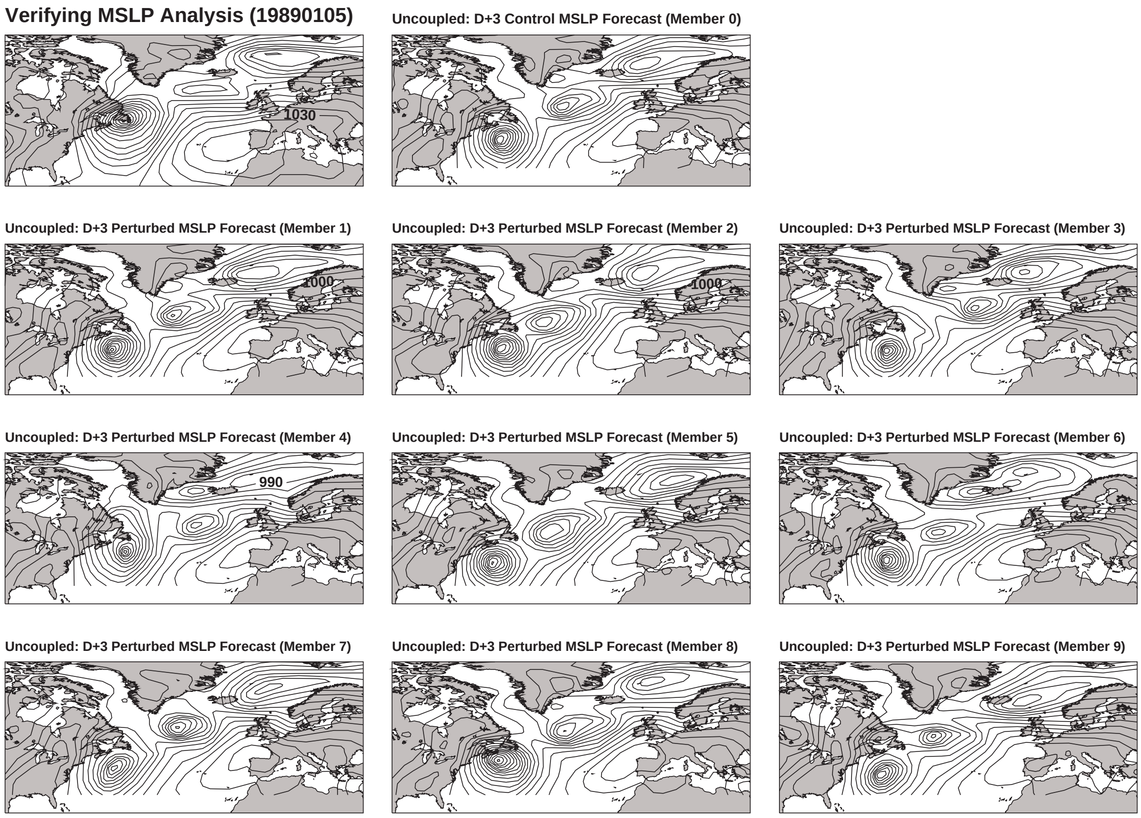

Figure 7: Verifying MSLP analysis (contour interval is 5 hPa) along with corresponding D+3 forecasts valid for 00UTC on 5 January 1989: unperturbed control forecast (upper row, middle panel) and perturbed ensemble forecasts (lower 3 rows) with the uncoupled model.

Instead of producing stamp maps for all cases and forecast steps it is convenient to summarize the impact of coupling and analysis uncertainties for particular cases in a more compact form as done in Fig.9 and Fig. 10, respectively. For the models used in this study it is clear that the forecast of intensive cyclo-genesis that took place from 4–6 January 1989 over the Gulf Stream is relatively insensitive to coupling (Fig.9). Uncertainties associated with analysis errors, on the other hand, lead to relatively large differences of the intensity of the cyclone (rms difference of about 15 hPa).

3.2.2 Case 2: Rapid Intensification in the Central North Atlantic

The next extratropical cyclone investigated in more detail rapidly deepened in a strongly baroclinic and confluent environment east off Newfoundland (not shown) during the period 29 March to 1 April 1994. The maximum deepening amounted to 50 hPa during 24 hours.

The control forecast of MSLP of the uncoupled ensemble (contours) at D+1, D+2, D+3 and D+4 is shown in Fig. 11 together with rms differences between the coupled and uncoupled ensemble members (impact of coupling, shaded). The main impact of coupling at D+3 and D+4 is to change the intensity of the cyclone. As for the case discussed above, however, the impact is relatively small amounting to just 0.5 hPa.

The impact of analysis uncertainties as reflected by the ensemble spread is much larger amounting to about 10

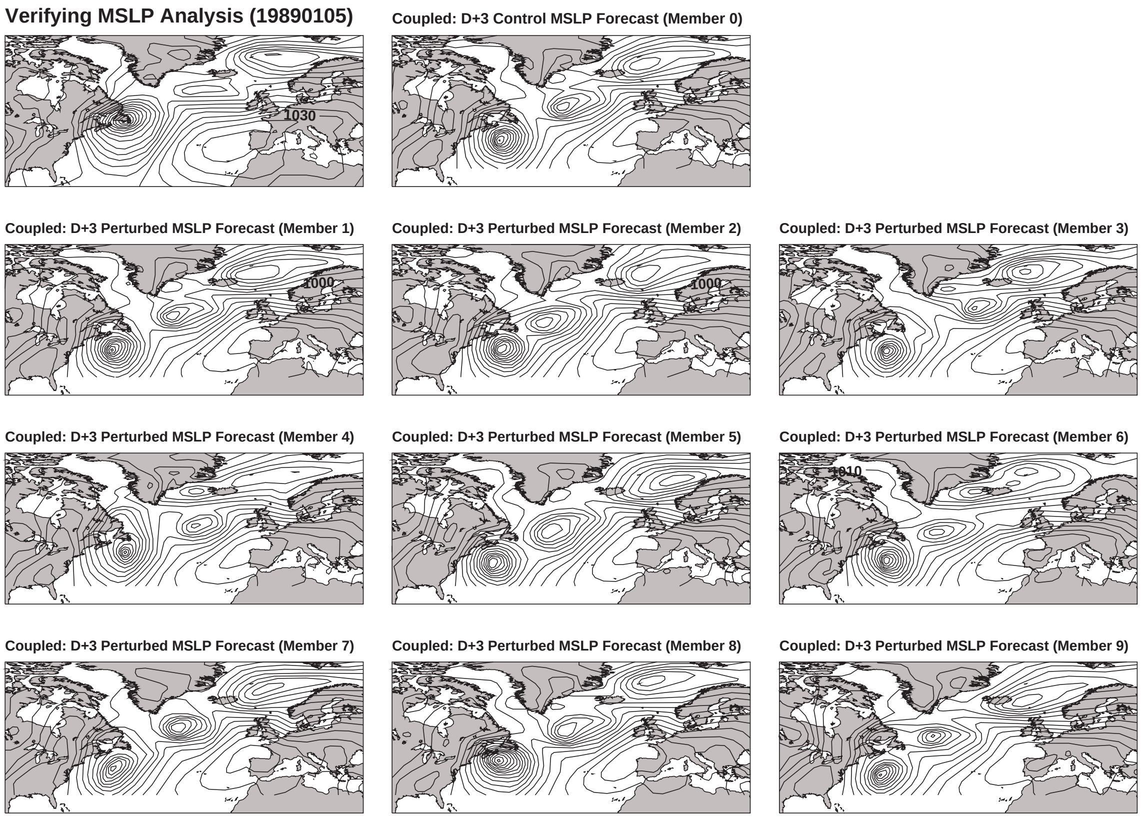

Figure 8: As in Fig. 7, except for the coupled model.

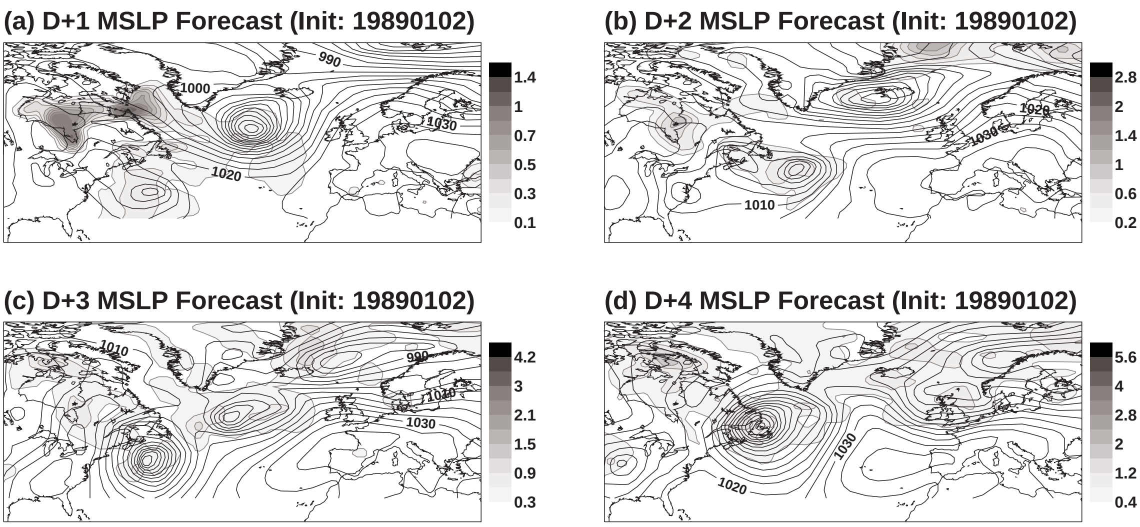

Figure 9: Control forecasts of MSLP (contour interval is 5 hPa) and mean MSLP rms difference between coupled and uncoupled ensemble members (shading in hPa): (a) D+1, (b) D+2, (c) D+3, and (d) D+4 forecasts started at 00UTC on 2 January 1989.

hPa at D+3 (Fig. 12. The spread for the coupled and uncoupled ensemble is virtually the same (not shown). Therefore, as for the first case of intense North Atlantic cyclo-genesis, the impact of coupling is much smaller than that due to the growth of analysis errors.

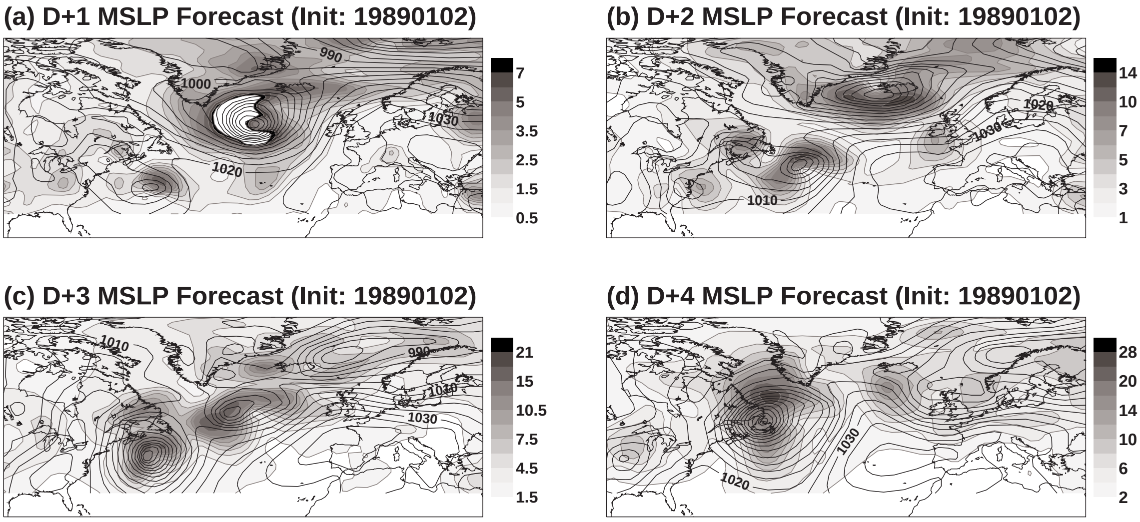

Figure 10: Control forecasts of MSLP (contour interval is 5 hPa) and mean MSLP rms difference between all individual ensemble members of the uncoupled system: (a) D+1, (b) D+2, (c) D+3, and (d) D+4 forecasts started at 00UTC on 2 January 1989.

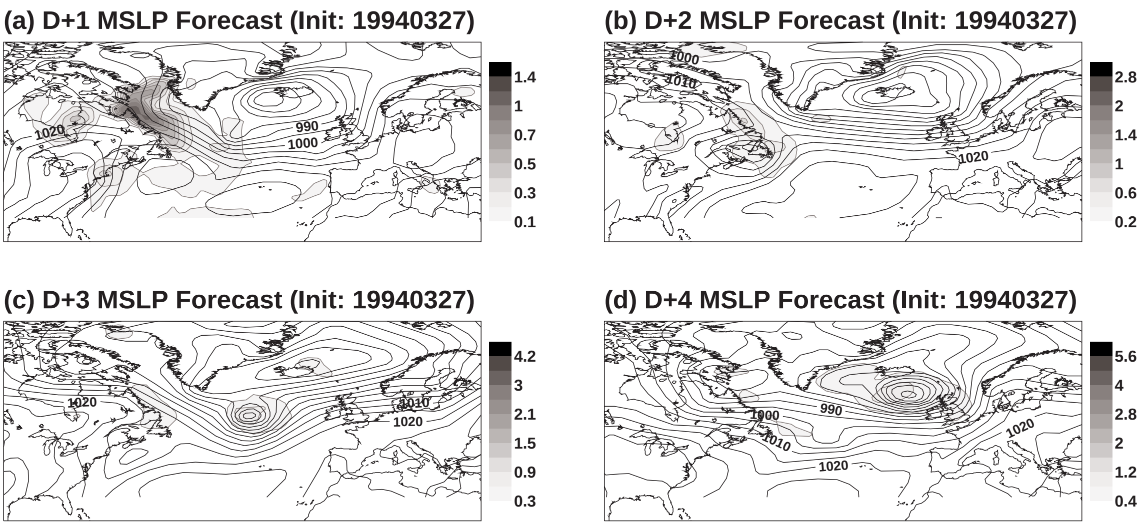

Figure 11: As in Fig. 9, except for forecasts started at 00 UTC on 27 March 1994.

3.2.3 Other Cases of Rapidly Intensifying North Atlantic Cyclones

We have investigated also the relatively importance of coupling for the other cases summarized in Tab.1; the conclusions are basically the same as for the cases discussed in more detail above. This shows that the impact of coupling on medium-range forecasts of rapidly intensifying cyclones is relatively small when the ECMWF monthly forecasting system is used, at least in the Northern Hemisphere during boreal winter.

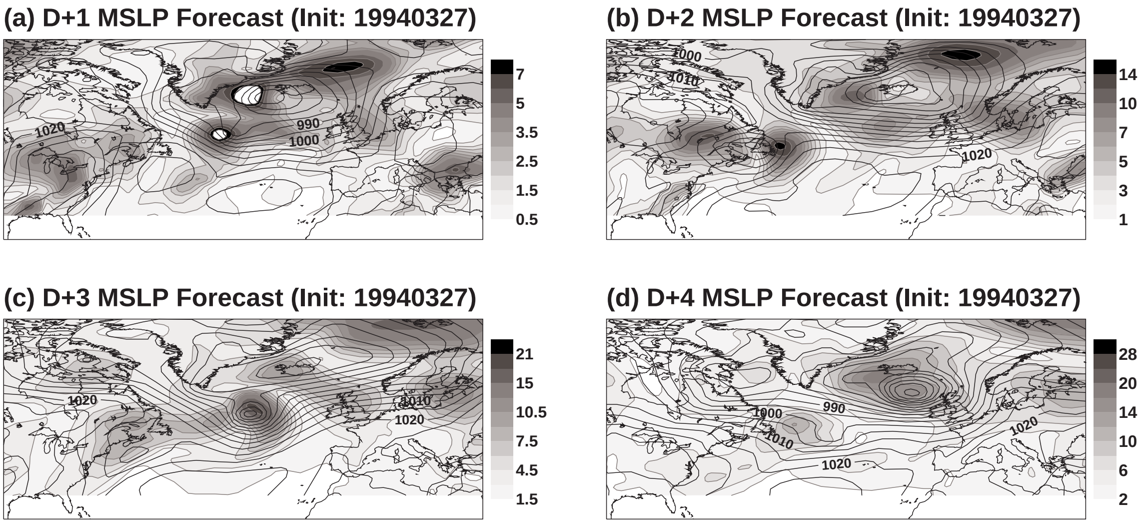

Figure 12: As in Fig. 10, except for forecasts started at 00 UTC on 27 March 1994.

3.3 Sensitivity to model cycle, resolution and ocean formulation

So far, the results of this study are based on one atmospheric model cycle only (25r3). One might ask whether our conclusions are sensitive to the model cycle used. To address this question the two cases of rapid cyclogenesis in the North Atlantic described above have been re-run at the same resolution using a more recent model verison, cycle 29r1, which is used operationally at ECMWF since 5 April 2005. For clarity the impact of coupling using model cycle 25r3 is redrawn in Figs. 13a and 14a for D+4 MSLP forecasts started on 2 January 1989 and 27 March 1994, respectively. Corresponding results for cycle 29r1 are shown in Figs.13b and 14b, respectively. The first thing to notice is that in both cases the impact of coupling is more pronounced for model cycle 29r1; the difference between coupled and uncoupled ensemble members is about twice that in the runs based on model cycle 25r3. However, even for cycle 29r1 the perturbation growth due to analysis uncertainties by far outweights perturbation growth due to coupling.

Next, the sensitivity of our results to changes in horizontal resolution are is investigated (T_L159 vs. T_L255), keeping the model cycle (29r1) and ocean model (HOPE) unchanged. A comparison of Fig. 13 b and c as well as Fig. 14 b and c reveals that increasing the horizontal resolution of the atmospheric component from about 125 km to about 80 km does not increase the impact that coupled atmosphere-ocean modelling has on subsequent forecasts, at least for the two cases considered in this study.

Finally, one might argue that it is not really necessary to use a full ocean general circulation model (HOPE in this study) for coupled medium-range weather forecasting, because it is primarily the ocean's mixed-layer which changes on short time scales (about 1–10 days). Moreover, the use of ocean mixed-layer models allows to carry out the integrations at a higher vertical and horizontal resolution. We have rerun coupled forecasts for the two cases using model cycle 29r1 at T_L159 coupled to a relatively high-resolution ocean mixed-layer model (Woolnough et al., 2003). By comparing Fig. 13 b and d as well as Fig. 14 b and d it becomes evident that the use of an ocean mixed-layer model instead of a full ocean general circulation model does not change the conclusion that the impact of coupling is relatively small for these two cases.

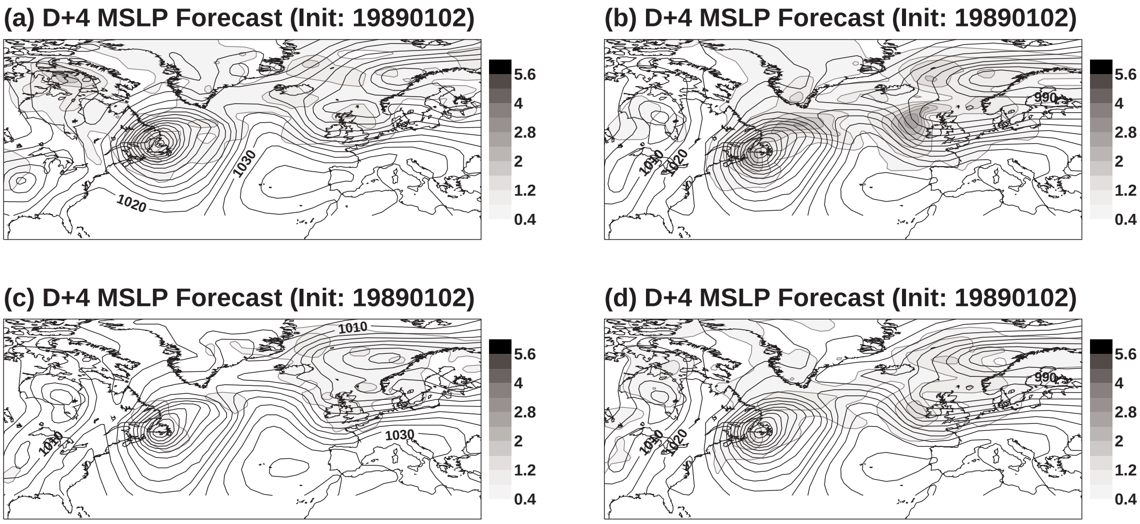

Figure 13: D+4 control forecasts of MSLP (contour interval is 5 hPa) and mean MSLP rms difference at D+4 between coupled and uncoupled ensemble members (shading in hPa): (a) cycle 25r3 and T_L159, (b) cycle 29r1 and T_L159, (c) cycle 29r1 and T_L255, and (d) cycle 29r1, T_L159 and a vertically high-resolution ocean mixed-layer model in the coupled integration. Forecasts have been started at 00 UTC on 2 January 1989.

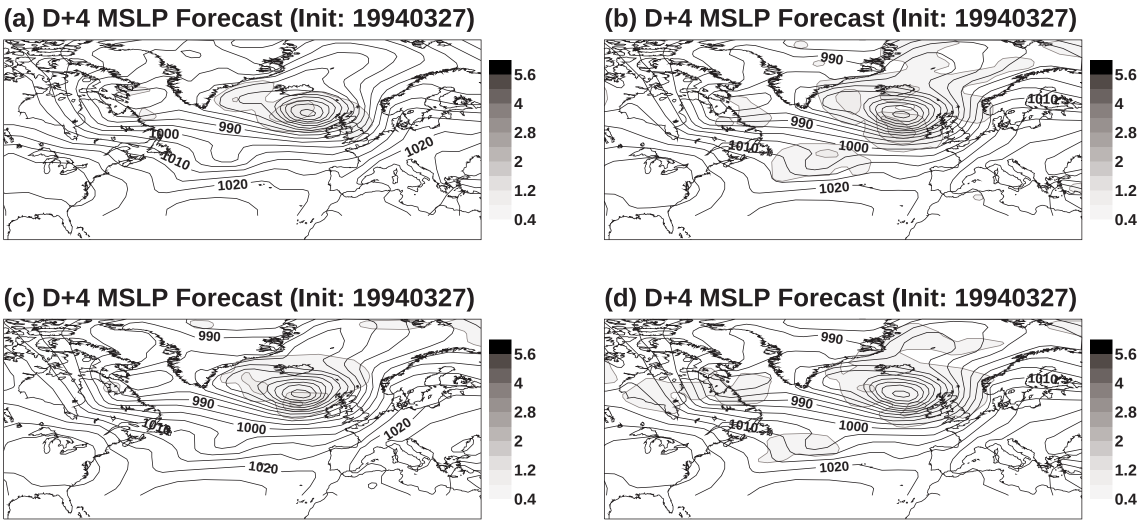

Figure 14: As in Fig. 13, except for D+4 forecasts started at 00 UTC on 27 March 1994.

4 Discussion

Fueled by ever increasing computer resources atmospheric models have become more and more realistic in recent decades. These improvements are reflected by a considerable decrease of short-range and medium-range forecast errors since numerical weather prediction became operational in the 1960s (Kalnay, 2003). These improvements can be explained by the fact that much effort has been put in the development of more sophisticated numerical schemes and analysis procedures, higher resolutions employed, an increasing number of observations in less well-sampled regions (satellites) and more realistic parameterizations of physical processes (e.g. Simmons and Hollingsworth, 2002; Kalnay, 2003; Jung, 2005). The remarkably high forecast skill of current numerical forecasting systems has been achived by using atmosphere-only models using persisted SSTs during the course of the integration.

With the operational implementation of a monthly forecasting system at ECMWF (Vitart, 2004) in autumn of 2004, which is based on a coupled atmosphere-ocean model and meant to close the gap between medium-range and seasonal forecasting, we have a tool allowing us to test whether the use of coupled atmosphere-ocean models can further increase the forecast skill in the medium-range, including intense extratropical cyclones developing over the oceans.

Using the ECMWF monthly forecasting system it has been shown for relatively large sample of rapidly intensifying cyclones in the North Atlantic region that short-range and medium-range MSLP forecasts are relatively insensitive to the effect of two-way atmosphere-ocean coupling. The effect of coupling, although present, is clearly overshadowed by the growth of analysis uncertainties, at least in the Northern Hemisphere extratropics during boreal winter. It has been found that this conclusion is not sensitive to (i) the ECMWF model cycle used (two cycles have been considered), (ii) changes in horizontal resolution (T_L159 compared to T_L255), and (iii) details of the representation of the ocean (full OGCM versus 1D ocean mixed-layer model).

In our opinion this finding is important and might well be seen as a positive outcome in the sense that it justifies the method currently being used (persisting analyzed SSTs during the course of the integration), at least for the complexity of atmosphere and ocean models that are affordable to be used operationally at the time of writing.

It is natural to ask why the impact of SST anomalies (difference between coupled and uncoupled SSTs) on the atmospheric circulation is so small in the short-range and medium-range. It has been shown that SST changes during the course of the integration are not necessarily small (1–1.5 K east of Newfoundland). Actually their magnitude is comparable to atmospheric temperature perturbations used to generate ensemble forecasts (Molteni et al., 1996). One possible way to explain these differences is that the SST perturbations do not necessarily project onto growing directions unlike initial perturbation generated by the ECMWF ensemble prediction system, which are based atmospheric singular vectors (e.g. Palmer et al., 1993). In fact, one might argue that on synoptic time scales the atmosphere is relatively insensitive to perturbations of the lower boundary conditions. This interpretation is in line with the outcome of adjoint sensitivity studies, which suggest that short-range forecasts are most sensitive to perturbations between 400 and 700 hPa for temperature and 500 and 850 hPa for vorticity, that is, in levels well above sea surface (e.g. Buizza and Palmer, 1995; Rabier et al., 1996; Klinker et al., 1998).

So far, the discussion has focussed on the *extratropics* only. One might argue, however, that extratropical forecasts could benefit indirectly from the use of coupled atmosphere-ocean models through improved forecasts in the Tropics. In this context, the prediction of tropical cyclones and hurricanes, for which two-way air sea interaction seems to be important (e.g. Emanuel, 2003), using coupled atmosphere-ocean models provides some potential. In fact, it is conceivable that if tropical cyclone forecasts could be improved by using coupled models, then this might have beneficial impacts in the extratropics later throughout the forecast. This can be explained, for example, by the fact that errors in forecasting the transition of tropical into extratropical cyclones usually grow rapidly while propagating downtream. Since this study has only investigated the impact of coupling for boreal winter months—during which no hurricanes are present in the tropical Atlantic—the potential benefit of coupling from improved hurricane forecasts has not been incorporated in this study. It would clearly be worthwhile investigating this aspect in more detail in a separate study.

Another aspect which has not been addressed in this study is the impact that coupling has on forecasts of polar lows. In fact, there is evidence suggesting that turbulent surface heat fluxes are crucial for the development and maintenance of polar lows (presumably even more than for "regular" extratropical cyclones) (e.g. Rasmussen and Turner, 2003). Unfortunately, the horizontal and vertical resolutions used in this study for the atmosphere are too low in order to properly resolve the dynamics and thermodynamics of polar lows. Therefore, any detailed investigation of coupling on polar low forecasts has to await further substantial increases in resolution of the ECMWF model or, alternatively, should be carried out with high-resolution regional models.

Acknowledgements We thank Dr. Richard Greatbatch, whose interest in this subject was influential in summarizing and publishing the results of this study. Dr. Sergey Gulev kindly provided the data set used to identify rapidly intensifying extratropical cyclones.

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