Short-Range and Medium-Range Weather Forecasting in the Extratropics during Wintertime with and without an Interactive Ocean

THOMAS JUNG AND FREDERIC VITART

ECMWF, Reading, United Kingdom

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ABSTRACT

The ECMWF monthly forecasting system is used to investigate the impact that an interactive ocean has on short-range and 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. The authors’ conclusions apply equally for a number of cases of rapidly intensifying extratropical cyclones in the North Atlantic region. Further experimentation with different atmospheric model versions, different horizontal atmospheric resolutions, and different ocean model formulation reveals the robustness of the findings. The 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 1–10-day 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 analyzed sea surface temperatures (SSTs) throughout the forecast. The assumptions inherent to this procedure are 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,” which 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 $180 \text{ W m}^{-2}$ 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 $1000 \text{ W m}^{-2}$ (e.g., Neiman and Shapiro 1993). Extratropical low pressure systems are accompanied by anomalously strong (weak) heat fluxes out of the ocean

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We shall use the abbreviation $D + n$ for $n$-day forecasts.

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Corresponding author address: Dr. Thomas Jung, ECMWF, Shinfield Park, Reading RG2 9AX, United Kingdom. E-mail: thomas.jung@ecmwf.int

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upstream (downstream) of the cyclone’s center (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 winter time. In the past this has been exploited by the NWP community by persisting analyzed SST field throughout the forecast. The success of this method can be inferred from the relatively high predictive 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 windstorms), 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 1998; Hagedorn et al. 2000).

Here we use the European Centre for Medium-Range Weather Forecasts (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 forecasts 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 versions are considered), horizontal resolution of the atmospheric model used (T159 versus T1255), and the complexity of the oceanic mixed layer?

By addressing the above items we aim to clarify the question whether 1–10-day 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 formulation, horizontal resolution, and ocean model used is investigated.

Finally, the main conclusions of this study are summarized and discussed in section 4.

2. Methods

2.1. Model description

In this study we use the ECMWF monthly forecasting system (Vitart 2004), which is basically a coupled atmosphere–ocean model. The atmospheric component used here is based on model version 25r3, which has been used operationally at ECMWF from 14 January to 28 April 2003. The horizontal resolution is T159 (=1.125° × 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 atmospheric model includes an interactive wave model (Janssen 2004). The monthly forecasting system can be run either by persisting analyzed 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 \(-1.73^\circ\text{C}\).

In the monthly forecasting system, atmospheric singular vectors are used to generate initial perturbation for the perturbed ensemble members. 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. 2005). A set of SST perturbations has been constructed by taking the difference between two weekly mean SST analyses from the National Centers for Environmental Prediction [NCEP; Reynolds OIv2 and Reynolds two-dimensional variational data assimilation (2DVAR) both described in Reynolds et al. (2002)] from 1985 to 1999. A second set of SST perturbations has been constructed by taking the difference between Reynolds 2DVAR SSTs and its 1-week persistence. Combinations from these two different sets of perturbations are randomly selected and are added to the SST initial conditions. To have a 3D structure, the SST perturbations are linearly interpolated from the full value at the surface to zero at an oceanic depth of 40 m. The wind stress has also been randomly perturbed during the oceanic data assimilation, in order to produce five different ocean analyses (see Vialard et al. 2005 for more details). The wind stress and SST perturbations have been combined to produce the perturbed oceanic initial conditions. The ensembles encompass one control forecast (deterministic forecast started from the analysis) and eight perturbed forecasts.

The ocean is also perturbed in the same way as is done in operational seasonal forecasts (Vialard et al. 2005). The ensembles encompass one control forecast (deterministic forecast started from the analysis) and nine perturbed forecasts.

b. Case selection

One might expect the use of an interactive ocean to be most beneficial for cases of strong cyclonic development over oceanic regions, for which air–sea interaction is at its strongest. Therefore, we decided to rerun the ECMWF monthly forecasting system for 12 cases of rapidly intensifying cyclones in the North Atlantic region. The dates of these events are summarized in Table 1 along with a description where the cyclogenesis took place. The cases have been selected more or less randomly from a catalog of cases of rapid cyclogenesis in the North Atlantic region (S. Gulev 2004, personal communication). For each of these events control and ensemble integrations were started 3, 5, and 7 days prior to cyclogenesis. The total number of forecasts considered, therefore, amounts to 36, both for the uncoupled and the coupled system. All forecast were started using ECMWF 40-yr Re-Analysis (ERA-40) data as initial conditions.

c. 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. Broadly speaking, we use two different classes of measures, the first one describing differences on a hemispheric basis [Eqs. (1)–(3)] and the second class describing differences on a gridpoint basis [Eqs. (4)–(5)].

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

\[
\tilde{x}_{\text{det}} = \frac{1}{K} \sum_{k=1}^{K} \text{rms}_s(x^k, y^k), \tag{1}
\]

where \(x^k\) and \(y^k\) represent the verifying analysis and the (uncoupled or coupled) deterministic forecast, respectively, for the \(k\)th forecast; \(\text{rms}_s\) denotes the (spatial) root-mean-square distance between \(x^k\) and \(y^k\) (here we focus on the Northern Hemisphere taking area weighting into account). Note that \(\tilde{x}_{\text{det}}\) is a scalar and represents the mean \(\text{rms}_s\) over all \(K = 36\) forecasts.

To quantify the impact of coupling we use a similar scheme, that is,

\[
\tilde{x}_{\text{coup}} = \frac{1}{K} \sum_{k=1}^{K} \left[ \frac{1}{N} \sum_{i=1}^{N} \sigma(x_{ui}^k - x_{ui}^k) \right], \tag{2}
\]

\begin{table}
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<th>Date</th>
<th>Note</th>
</tr>
</thead>
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<td>19871017</td>
<td>October storm (France and United Kingdom)</td>
</tr>
<tr>
<td>19890105</td>
<td>Gulf Stream</td>
</tr>
<tr>
<td>19900109</td>
<td>Central North Atlantic</td>
</tr>
<tr>
<td>19900126</td>
<td>Eastern North Atlantic</td>
</tr>
<tr>
<td>19911031</td>
<td>Nova Scotia/Gulf Stream</td>
</tr>
<tr>
<td>19921207</td>
<td>Gulf Stream</td>
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<tr>
<td>19940330</td>
<td>Central North Atlantic</td>
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<td>19960107</td>
<td>Eastern North Atlantic</td>
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<tr>
<td>19970217</td>
<td>Central North Atlantic</td>
</tr>
<tr>
<td>19990104</td>
<td>Eastern North Atlantic and Labrador</td>
</tr>
<tr>
<td>19991227</td>
<td>Christmas storm (France and Germany)</td>
</tr>
<tr>
<td>20000121</td>
<td>Gulf Stream and Labrador</td>
</tr>
</tbody>
</table>

Table 1. Target dates (format yyyy-mm-dd) of major, rapidly deepening Northern Hemisphere extratropical cyclones considered in this study. For every target date three 10-day ensembles were produced (one control forecast and nine perturbed forecasts) starting 3, 5, and 7 days before the major event. Therefore, the total number of forecasts amounts to 36.
where $x^{i,k}_{ur}$ and $x^{i,k}_{coup}$ represent the uncoupled and coupled forecasts, respectively; $\sigma_i$ denotes the spatial standard deviation. The ensemble members are given by $i = 1, \ldots, N (N = 10)$ ($i = 1$ represents the control forecast). Notice that members $i$ are based on the same atmospheric 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:

$$\bar{S}_{init} = \frac{1}{K} \sum_{k=1}^{K} \left[ \frac{1}{N(N-1)/2} \sum_{i=1}^{N} \sum_{j=1}^{i} \sigma_i(x^{i,k}_{ur} - x^{j,k}_{coup}) \right].$$

where $x^{i,k}_{ur}$ represents the $i$th member of the $k$th forecast (either uncoupled or coupled). Note that every ensemble member is compared with all the other members. Here $\bar{S}_{init}$ effectively describes forecast uncertainties due to initial perturbations 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 local diagnostics. The impact of coupling is quantified at every grid point $l = 1, \ldots, L$ by computing the standard deviation of the difference between coupled and uncoupled ensemble members, which use the same atmospheric initial conditions, that is,

$$\bar{S}_{coup} = \frac{1}{K} \sum_{k=1}^{K} \sigma_l(x^{i,k}_{coup} - x^{i,k}_{ur}),$$

where $\sigma_l(z) = [(1/N)\sum_{i=1}^{N}(z_i - z)^2]^{1/2}$.

A related diagnostic is used to quantify the impact of analysis uncertainties for every grid point:

$$\bar{S}_{init} = \frac{1}{K} \sum_{k=1}^{K} \sigma_l(x^{i,k}_{init} - x^{i,k}_{coup}),$$

where $\sigma_l(z) = [(1/N(N-1)/2)\sum_{i=1}^{N} \sum_{j=1}^{i} (z_i^j - z^j)^2]^{1/2}$.

3. Results

a. Performance on a hemispheric scale

We start by investigating the impact that coupling has on deterministic skill scores. Northern Hemisphere deterministic skill scores for the uncoupled (solid) and coupled (dashed) model and mean sea level pressure (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. Figure 1 clearly reveals that the use of a coupled model does not improve the Northern Hemispheric deterministic forecast skill during the first 10 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. To test this conjecture we have computed root-mean-square errors at every grid point. The difference field shows values up to ±0.2–0.3 hPa (±0.6–0.8 hPa) at $D + 2$ ($D + 5$) and is rather noisy, suggesting that a sample size of 36 forecasts is too small to detect any noteworthy local differences—if existent (not shown).

The fact that differences of Northern Hemisphere MSLP fields between the uncoupled and coupled integrations are relatively small throughout the forecast can partly be inferred from Fig. 2a. 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 hemispheric-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. 2a is that the ensemble spread of the coupled and uncoupled integration is virtually the same for MSLP throughout the whole forecast. (The dashed and dash–dot–dotted curves are practically indistinguishable.)

By $D + 10$ the impact of coupling amounts to about 25% of the evolved initial perturbations (Fig. 2a) and one might argue that by then the impact of coupling is important. However, it should be pointed out that fore-
cast differences due to coupling do not project onto deterministic forecast errors (deterministic forecast errors for the uncoupled and coupled control integrations are the same; Fig. 1). Moreover, as noted above coupling does not add any additional spread to the ensemble. The most likely explanation is that in the medium-range perturbations due to coupling affect levels above the boundary layer and start to project onto fast-growing baroclinically unstable modes in a way similar to evolved initial perturbations.

The relative impact of initial perturbations and coupling on precipitation forecasts can be inferred from Fig. 2b. The motivation to investigate precipitation along with MSLP comes from the fact that the former is more directly affected by sensible and, especially, latent heat fluxes. The conclusion for precipitation is essentially the same as that for MSLP, that is, the initial perturbation effect is much larger than the effect of coupling, particularly in the short range and early medium range. Furthermore, the ensemble spreads for precipitation in the uncoupled and coupled system are very much alike.

Geographical differences of the impact of two-way atmosphere–ocean coupling on $D + 1$, $D + 3$, $D + 5$, and $D + 10$ MSLP forecasts can be inferred from Fig. 3. 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 largely 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 persisted in the atmosphere-only runs. In the coupled version, on the other hand, the sea ice is deduced from SSTs and atmospheric fluxes. Since the errors of sea ice in the ocean analysis are not consistent with the atmospheric fluxes and SSTs, the coupled model quickly corrects those errors.

The other two areas standing out in Fig. 3a are the Kuroshio and Gulf Stream extensions, where the MSLP standard deviation amounts to about 0.2 hPa. There are two likely (and related) explanations why these areas stand out. 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. 2).

The effect of analysis uncertainties on MSLP forecasts is shown in Fig. 4 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 outweighs that of coupling. The ensemble spread at $D + 3$ in the Gulf Stream extension, for example, amounts to 6–8 hPa compared to 0.5–0.6 hPa due to the impact of coupling; that is, the impact of analysis uncertainties is one order of magnitude larger than that of coupling (using MSLP as a metric).

To help understanding the above results it is useful to
quantify how different SST fields in the coupled and uncoupled integrations actually are. The average standard deviation of the difference between coupled and uncoupled SST are shown in Fig. 5 at \( D + 1 \), \( D + 3 \), \( D + 5 \), and \( D + 10 \). Note 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 extensions amounting to about 1 K at \( D + 10 \), which seems 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 and their extensions). This can be explained by the fact that substantial atmospheric differences have developed, both over land and over sea, by \( D + 10 \) (Fig. 3), which have a bigger impact over land due to 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, both in the coupled and uncoupled integrations.)

b. 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 rela-
tively 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 intense extratropical cyclones are rarely found in particular areas of the Northern Hemisphere, 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 Table 1).

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 h 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 W m$^{-2}$ (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. 6) and the coupled ensembles (Fig. 7). 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 (0000 UTC on 5 January 1989) a

![Image](https://example.com/image.png)

**FIG. 4.** As in Fig. 3, except for standard deviation of the MSLP difference (hPa) between individual members of the uncoupled ensemble.
very intensive cyclone is located over Newfoundland, Canada. The major shortcoming of the coupled and uncoupled control forecasts is that the cyclone is located too far to the south. Neither coupling nor initial perturbations seem to affect the location of the developing storm, while both affect its intensity. The initial perturbation, however, has a much larger effect on intensity than does coupling with an ocean 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 Figs. 8 and 9, respectively. For the models used in this study it is clear that the forecast of intensive cyclogenesis that took place from 4 to 6 January 1989 over the Gulf Stream is relatively insensitive to coupling (Fig. 8). Uncertainties associated with analysis errors, on the other hand, lead to relatively large differences of the intensity of the cyclone (about 15 hPa; Fig. 9).

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 h. The control forecast of MSLP of the uncoupled ensemble (contours) at $D + 1, D + 2, D + 3$, and $D + 4$ is shown in Fig. 10 together with the standard deviation 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 hPa at $D + 3$ (Fig. 11). The spread for the coupled and uncoupled ensemble is virtually the same (not shown). Therefore, as for the first case of intense North Atlantic cyclogenesis, the impact of coupling is much smaller than that due to the growth of analysis errors.

3) Other Cases of Rapid Intensifying North Atlantic Cyclones

We have investigated also the relative importance of coupling for the other cases summarized in Table 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.

c. Sensitivity to model version, resolution, and ocean formulation

So far, the results of this study are based on one atmospheric model version only (25r3). One might ask whether our conclusions are sensitive to the model version used. To address this question the two cases of rapid cyclogenesis in the North Atlantic described above have been rerun at the same resolution using a more recent model version (29r1) that has been used operationally at ECMWF from 5 April to 27 June 2005. Differences between version 25r3 and 29r1 encompass almost all components of the ECWMF model (for a detailed list of model changes see http://www.ecmwf.int/products/data/technical/model_id/index.html). For clarity the impact of coupling using model version 25r3 is redrawn in Figs. 12a and 13a for $D + 4$ MSLP forecasts started on 2 January 1989 and 27 March 1994.
respectively. Corresponding results for version 29r1 are shown in Figs. 12b and 13b, respectively. The first thing to notice is that in both cases the impact of coupling is more pronounced for model version 29r1: the difference between coupled and uncoupled ensemble members is about twice that in the runs based on model version 25r3. However, even for version 29r1, the perturbation growth due to analysis uncertainties by far outweighs the impact of coupling.

Next, the sensitivity of our results to changes in horizontal resolution is investigated (T\textsubscript{L}159 versus T\textsubscript{L}255), keeping the model version (29r1) and ocean model (HOPE) unchanged. A comparison of Figs. 12b and 12c as well as Figs. 13b and 13c 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 modeling 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 that changes on short time scales (1–10 days). Moreover, the use of ocean mixed-layer models allows us to carry out the integrations at a higher vertical and horizontal resolution. We have rerun coupled forecasts for the two cases using model version 29r1 at T\textsubscript{L}159 coupled to a relatively high resolution ocean mixed-layer model (Woolnough et al. 2003). (Here we use the same horizontal resolution as in the operational monthly forecasting system. In the vertical, however, the resolution is increased to 1 m.) By comparing Figs. 12b and 12d as well as Figs. 13b and 13d 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.

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 achieved 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

**Fig. 8.** MSLP control forecasts of uncoupled system (contour interval is 5 hPa) and standard deviation of the MSLP 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 0000 UTC on 2 Jan 1989.

**Fig. 9.** Control forecasts of MSLP (contour interval is 5 hPa) and standard deviation of the MSLP 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 0000 UTC on 2 Jan 1989.
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 short range and 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 (precipitation) 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 version used (two versions have been considered), (ii) changes in horizontal resolution (T159 compared to T255), 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

Fig. 10. As in Fig. 8, except for forecasts started at 0000 UTC on 27 Mar 1994.

Fig. 11. As in Fig. 9, except for forecasts started at 0000 UTC on 27 Mar 1994.
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 project onto baroclinically unstable modes unlike singular-vector-based initial perturbations used in

![Fig. 12. D + 4 MSLP control forecasts of the uncoupled system (contour interval is 5 hPa) and standard deviation of the MSLP difference at D + 4 between coupled and uncoupled ensemble members (shading in hPa): (a) version 25r3 and T L 159, (b) version 29r1 and T L 159, (c) version 29r1 and T L 255, and (d) version 29r1, T L 159, and a vertically high resolution ocean mixed-layer model in the coupled integration. Forecasts have been started at 0000 UTC on 2 Jan 1989.](image)

![Fig. 13. As in Fig. 12, except for D + 4 forecasts started at 0000 UTC on 27 Mar 1994.](image)
the ECMWF ensemble prediction system (e.g., Palmer et al. 1993). Our results show that on synoptic time scales the atmosphere is relatively insensitive to perturbations of the surface sensible and latent heat fluxes (second-order effect). This interpretation is also 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, at levels well above sea surface (e.g., Buizza and Palmer 1995; Rabier et al. 1996; Klinker et al. 1998). One might also argue that coupling has a relatively small impact on rapidly intensifying extratropical cyclones since the largest impact happens to occur in the wake of the low pressure system. In fact, it has been found that storm systems are sensitive to surface heat fluxes only in the particular area relative to the storm, that is, in areas ahead of the developing storm (e.g., Gyakum and Danielson 2000) and in the warm sector of the low pressure system (Langland et al. 1995). We have determined the impact of coupling in terms of turbulent surface heat fluxes for the case of rapid cyclogenesis in the central North Atlantic that took place at the end of March 1993. Just before the most intense deepening of the storm off the coast of Newfoundland coupling has a substantial impact on the surface heat fluxes amounting to more than 20 W m\(^{-2}\) (Fig. 14). For this particular case coupling has an impact on surface heat fluxes in sensitive regions, even though the influence on the subsequent MSLP forecast is rather small. However, it is also true that large surface heat flux perturbations trail the storm, as can be seen at D + 4 (Fig. 14d). Similar results have been found for the case of rapid cyclogenesis in early January 1989 (not shown).

So far, the discussion has focused 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 might well be important (e.g., Emanuel 2003), with 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 downstream. 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 that 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 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.

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REFERENCES


