TECHNICAL MEMORANDUM

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Diagnosing the Origin of Extended-Range Forecast Error

T. Jung, M.J. Miller and T.N. Palmer

Research Department

ECMWF, Shinfield Park, Reading RG2 9AX, United Kingdom

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Abstract

Experiments with the ECMWF model are carried out to study the influence that a correct representation of the lower boundary conditions, the tropical atmosphere and the Northern Hemisphere stratosphere would have on extended-range forecast skill of the extratropical Northern Hemisphere troposphere during boreal winter. Generation of forecast error during the course of the integration is artificially reduced by relaxing the ECMWF model towards the ERA-40 reanalysis in certain regions. Prescribing rather than persisting sea surface temperature and sea ice fields leads to a modest forecast error reduction in the extended-range, especially over the North Pacific and North America; no influence is found in the medium-range. Relaxation of the tropical troposphere leads to reduced extended-range forecast errors especially over the North Pacific, North America and the North Atlantic. It is shown that a better representation of the Madden-Julian Oscillation is of secondary importance for explaining the results of the tropical relaxation experiments. The influence from the tropical stratosphere is negligible. Relaxation of the Northern Hemisphere stratosphere leads to forecast error reduction primarily in high latitudes and over Europe. However, given the strong influence from the troposphere onto the Northern Hemisphere stratosphere it is argued that stratospherically forced experiments are very difficult to interpret in terms of their implications for extended-range predictability of the tropospheric flow. The results are discussed in the context of future forecasting system development.

1 Introduction

Despite substantial improvements in model formulation, data assimilation systems and observing systems, forecasts are still prone to failures. This is particularly true for extended-range forecasts (beyond 10 days) of the extratropical flow, which have moderate skill at the best of times. Apart from being of scientific interest, understanding the origin of forecast error is a first step towards future forecasting system improvements. One important piece of information is the origin of forecast error. If extended-range predictability in the extratropics is primarily limited by model error in the tropics then future model development should focus on exactly this region.

The aim of this study is to investigate how much of the extratropical forecast error in extended-range (11–30 days) integrations originates from parts of the climate system with (potentially) enhanced extended-range predictability (e.g. Baldwin et al., 2003; Shukla, 1998): the lower bounday conditions, the tropical atmosphere and the stratosphere. To this end a relaxation technique (also sometimes called nudging) is used in which prognostic fields are relaxed towards reanalysis data during the course of the integration. In this way it is possible to suppress artificially the development of forecast errors in certain regions of the globe (e.g. tropical atmosphere).

The relaxation technique is a well-established technique in the atmospheric sciences. It has been used, for example, in data assimilation (see Kalnay, 2003, for an overview), for determining corrections to empirically reduce model deficiencies (Kaas et al., 1999), for dynamical downscaling (von Storch et al., 2000), for better understanding planetary wave–synoptic wave interactions in the atmosphere (Straus and Yi, 1998), and for validation of a synoptic system in an atmospheric circulation model (Bauer et al., 2008). The approach employed in this study is very similar to the method used at ECMWF in the 1980s in order to understand the origin of *medium-range* forecast error in the northern hemisphere extratropics (Haseler, 1982; Klinker, 1990; Ferranti et al., 1990). It has been decided to revive the relaxation technique at ECMWF as a diagnostic tool for the following reasons:

- The relaxation technique could also be useful to understand forecast error in the extended-range, addressing the monthly and seasonal forecasting problem.

- The availability of larger computer resources allows significant increases in sample size and therefore robustness of the results compared to previous studies.
- The availability of more realistic analysis data, particularly in the tropics, makes the relaxation technique much more effective.

The paper is organized as follows: In the next section details about the monthly forecast experiments and about the model formulation will be given. Subsequently the results will be presented. The impact that relaxing various regions has on forecast skill will be first described first for the tropics and then the extratropics. For the extratropics the focus is on the role of the tropics and stratosphere. For tropical relaxation experiments the role of the Madden-Julian Oscillation will be considered separately. Finally, the results will be summarized and discussed.

2 Methodology

2.1 Monthly forecasts

To investigate the origin of extratropical forecast error during boreal winter a large set of 30-day control and relaxation experiments has been carried out using model cycle 32r1 (used operationally at ECMWF from 5 June–5 November 2007) at a resolution of T_L159 (about 125 km) and with 60 vertical levels ($T_L159L60$). For each of the experiments a total of 88 30-day forecasts were carried out. Forecasts were started on the 15^{th} of the months November, December, January and February, for each of the winters from 1980/81 to 2001/02. Initial conditions were taken from ERA-40 reanalysis data. If not stated otherwise, sea surface temperature (SST) and sea ice fields were persisted throughout the forecast. An additional control integration with observed SST and sea ice fields from ERA-40 was also carried out in order to quantify the influence that 'knowledge' of the lower boundary conditions has on atmospheric forecast skill.

Forecast experiments with relaxation of the following regions have been carried out:

- whole tropical atmosphere,
- tropical stratosphere,
- tropical troposphere,
- Northern Hemisphere stratosphere, and
- Northern Hemisphere troposphere.

Additional sensitivity experiments were carried out to investigate the relative importance of different tropical regions and to study the sensitivity to the strength of the relaxation. The various 30-day experiments are summarized in Table 1. In the following a more detailed description of the relaxation formulation is given.

2.2 Relaxation formulation

In the relaxation experiments the model is drawn towards the ERA40 reanalysis data during the course of the integration. In this way it is possible to reduce forecast error in specific regions, such as the tropics, in some

Table 1: Summary of 30-day forecast experiments. All experiments are based on model cycle 32R1 using a resolution of T_L159 with 60 levels in the vertical. Lower boundary conditions were persisted for all relaxation experiments.

Abbreviation	Comment	Relaxation Region	λ
CNT/PER-SST	Control run, persisted SST	—	—
CNT/OBS-SST	Control run, observed SST	—	—
TROP	Tropical relaxation	20^oS–20^oN, 180^oW–180^oE all levels	0.02, 0.1, 1.0
NH	Relaxation of Northern Hemisphere	20^o–90^oN, 180^oW–180^oE all levels	0.1, 1.0
NH-T	Relaxation of troposphere (Northern Hemisphere)	20^o–90^oN, 180^oW–180^oE p>300 hPa	0.1, 1.0
NH-S	Relaxation of stratosphere (Northern Hemisphere)	20^o–90^oN, 180^oW–180^oE p<70 hPa	0.1, 1.0
MCIN	Relaxation over Africa, Indian Ocean and Maritime Continent	20^oS–20^oN, 0^o–140^oE all levels	0.1
TPAC	Relaxation over tropical Pacific	20^oS–20^oN, 140^oE–90^oW all levels	0.1
SAAT	Relaxation over South America and tropical Atlantic	20^oS–20^oN, 90^oW–0^o all levels	0.1

controlled way. The relaxation experiments are carried out by adding an extra term of the following form to the ECMWF model:

$$-\lambda(\mathbf{x}-\mathbf{x}^{ref}). \tag{1}$$

The model state vector is represented by $\mathbf{x}$ and the reference vector towards which the model should be drawn (here reanalysis data) by $\mathbf{x}^{ref}$. The strength of the relaxation is determined by λ, which generally can be a function of the variable, region (both the horizontal and vertical) and spatial scale (e.g., planetary scales only) considered. The units of λ are in (time step)$^{-1}$. For a time step of one hour employed in this study a value of $\lambda = 0.1$, for example, indicates that at each time step the model is 'corrected' using 10% of the departure of $\mathbf{x}$ from $\mathbf{x}^{ref}$.

In this study the relaxation is carried out in grid point space in order to allow for localization. Parameters being relaxed include the zonal and meridional wind components, temperature and the logarithm of surface pressure; the same λ is used for each of these parameters. The reference fields used in this study are from the ERA-40 reanalysis (Uppala et al., 2005) at 6-hourly intervals (00, 06, 12 and 18UTC). For all model time steps for which no direct analysis is available, neighboring analysis fields are linearly interpolated.

When applying masks to spatially localize the relaxation, care has to be taken in order to reduce adverse effects close to the relaxation boundaries. Here the transition from relaxed to non-relaxed regions is smoothed using the hyperbolic tangent. The smoothing in the horizontal is carried out over 20^o belts, both in longitude and latitude. Boundaries stated in the text refer to the centre of the respective 20^o belt. The latitudinal dependence of λ in TROP/0.1 is illustrated in Figure 1. The transition in the vertical is smoothed over about 8 model levels, which corresponds to a pressure interval of about 200 hPa close to the tropopause in the 60 level model used in this study. The vertical dependence of λ for tropospheric and stratospheric relaxation experiments is illustrated in Figure 2.

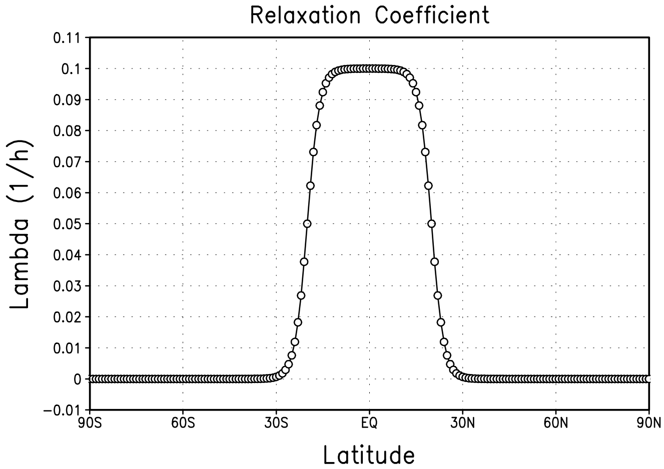

Figure 1: Latitudinal dependence of λ in Eqn. 1 (hrs^{-1}) for the tropical relaxation experiment (TROP/0.1).

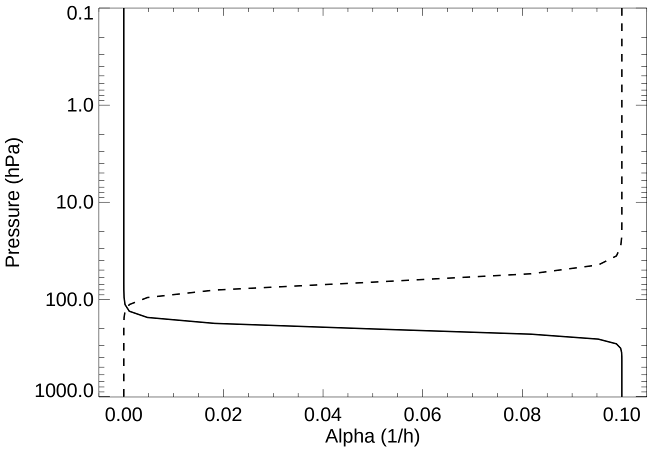

Figure 2: Vertical dependence of λ in Eqn. 1 (hrs^{-1}) for tropospheric (solid) and stratospheric (dashed) relaxation experiments.

3 Results

3.1 Tropical forecast error

Figure 3 shows mean absolute forecast error of 5-day averaged zonal wind at the 250 hPa (tropical troposphere) and 50 hPa level (tropical stratosphere). The control integration (CNT/PER-SST) shows increasing forecast error in the tropical troposphere throughout the 30-day forecast period suggesting that current forecasting systems possess some useful monthly forecast skill (see also Vitart, 2004). In the tropical stratosphere there is no evidence for saturation of forecast error throughout the first 30 days suggesting a relatively high level of extended-range predictive skill.

Prescribing rather than persisting SST fields throughout the integration (CNT/OBS-SST) reduces forecast error of the tropical troposhere slightly in the extended-range; in the medium-range better 'knowledge' of SST has no impact on forecast skill (Fig. 3a). Not too suprisingly, the influence of the lower boundary conditions has a

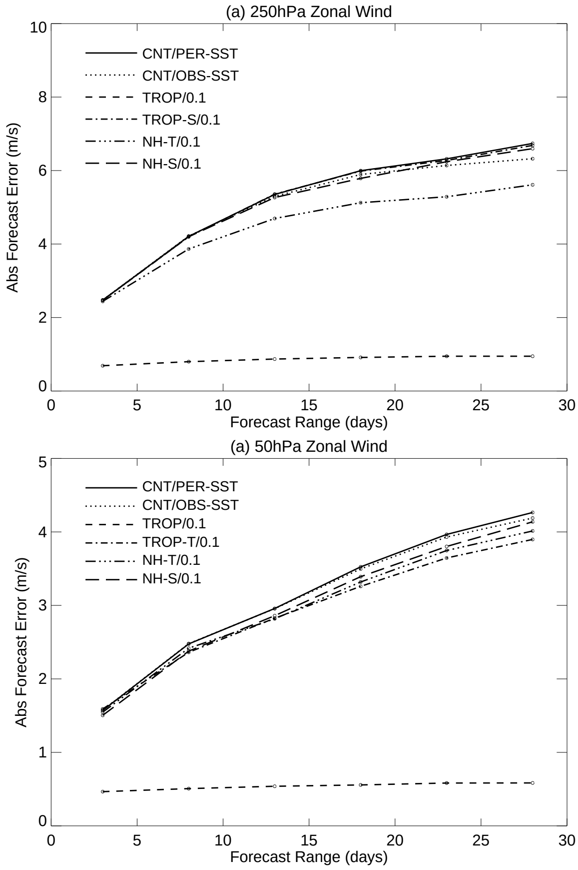

Figure 3: Mean absolute error (ms^{-1}) of 5-day averaged forecasts of zonal wind at (a) 250 hPa and (b) 50 hPa. Results are shown for the control forecast with persisted (solid, stream function at 200 hPa in the tropics (10^oS–10^oN) for control forecast with persisted (CNT/PER-SST) and observed (CNT/OBS-SST) SSTs as well as for experiments with the tropics (TROP/0.1 and TROP/0.02) and northern hemisphere troposphere (NH-T/0.1) relaxed towards ERA-40 reanalysis data.

rather small effect on tropical stratosphere.

The experiment with relaxation of the whole tropical atmosphere (TROP/0.1) shows that the relaxation is efficient in reducing forecast error in both the troposphere and the stratosphere. Throughout the 30-day forecasts, forecast error of zonal wind at 250 and 50 hPa are kept significantly below the level seen in the short-range and early medium-range (5-day average from D+1 to D+5).

The influence of the Northern Hemisphere (NH-S/0.1) and especially the tropical stratosphere (TROP-S/0.1) on tropical zonal winds at 250 hPa is relatively small (Fig. 3a). The largest 'non-local' influence comes from the Northern Hemisphere extratopics, whose impact is felt throughout the whole forecast. This finding is consistent with the notion that extratropical forcing can influence tropical convection and equatorial waves (Kiladis and Weickmann, 1992; Hoskins and Yang, 2000).

Tropical zonal winds at the 50 hPa level (Fig. 3b) are clearly influenced by a better representation of the tropical troposphere. This is expected given that gravity waves and equatoral planetary-scale (Kelvin and Rossby) waves tend to propagate from the trosposhere into the stratosphere (e.g., Baldwin et al., 2001; Ern et al., 2007). The tropical stratosphere is not only influenced from below. Both the extratropical troposphere and stratosphere have some impact on the tropical stratosphere.

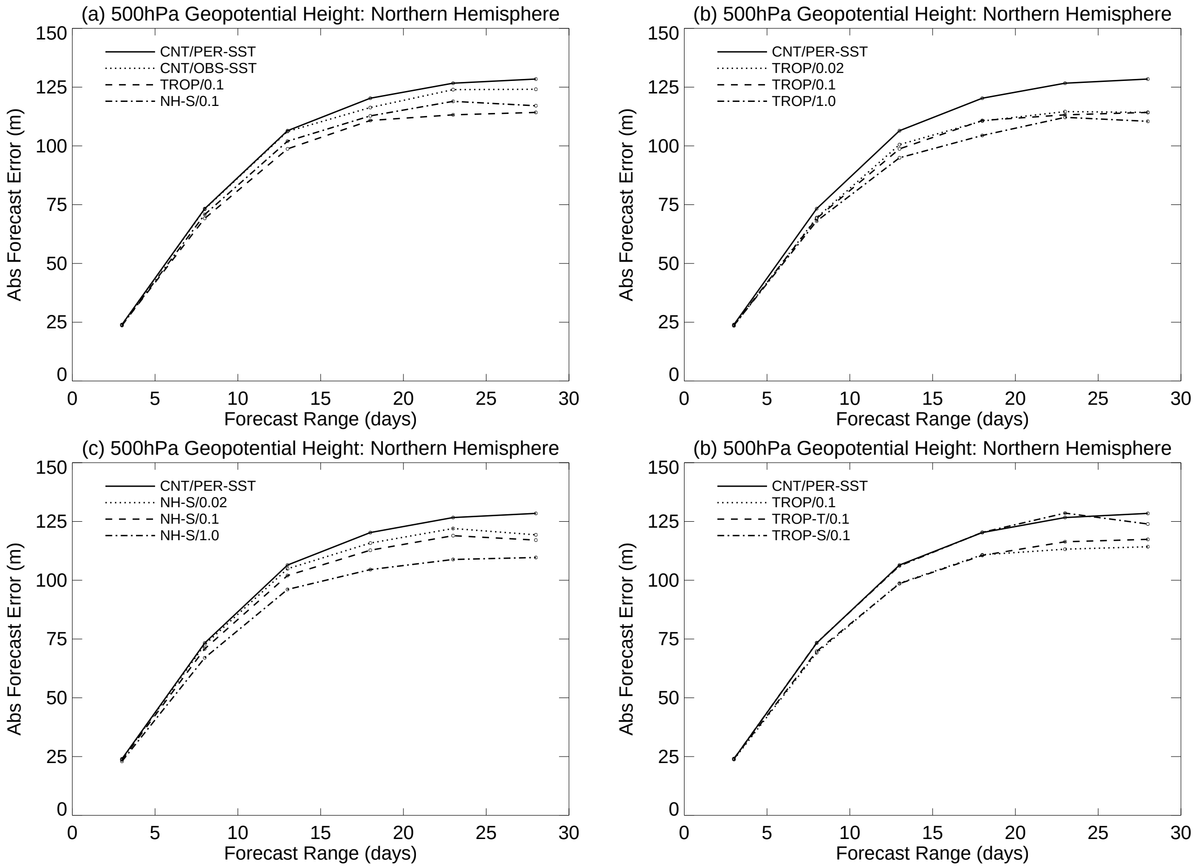

Figure 4: Mean absolute error (m) of 5-day averaged forecasts of 500 hPa geopotential height fields over the Northern Hemisphere (north of 40°N): (a) control forecast with persisted and observed SSTs as well as for experiments with relaxation of the tropics (TROP/0.1) and the Northern Hemisphere stratosphere (NH-S/0.1) towards ERA-40 reanalysis data. (b) as in (a), but for different tropical relaxation experiments (TROP/0.02, TROP/0.1 and TROP/1.0). (c) as in (a), but for different experiments with relaxation of the Northern Hemisphere stratosphere (NH-S/0.02, NH-S/0.1, and NH-S/1.0)

3.2 Northern Hemisphere forecast error

Figure 4 shows mean absolute forecast error of 5-day averaged extratropical Northern Hemisphere[1] geopotential height fields at the 500 hPa level (Z500, hereafter) for various experiments. The control integrations with persisted and observed SST/sea ice fields (CNT/PER-SST and CNT/OBS-SST) show that it takes about 30 days for forecast error to saturate and that knowledge of the lower boundary conditions increases the skill in the extended-range slightly (Figure 4a); in the short-range and medium-range,on the other hand, using observed rather than persisted lower boundary conditions provides little, if any, benefit (see also Jung and Vitart, 2006).

Relaxing the tropics (TROP/0.1) and the Northern Hemisphere stratosphere (NH-S/0.1) both lead to a noteworthy reduction in Z500 forecast error over the Northern Hemisphere (Figure 4a). In relative terms the forecast error reduction is largest in the extended-range (beyond D+10), where it amounts to about 10–20% of the forecast error of the control integration for TROP/1.0 and NH-S/1.0. The 'delayed' positive impact of the tropical and stratospheric relaxation can be explained by the fact that forecasts are still quite successful in the short-range and medium-range (where the relaxation has little work to do). Furthermore, it takes some time for

[1]Here the Northern Hemisphere encompasses only the region north of 40°N in order to stay way clear of the relaxation zone used in experiment TROP/0.1

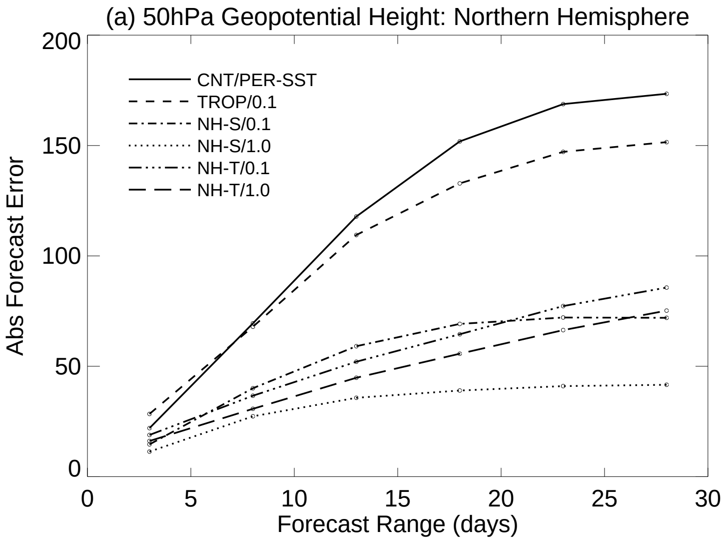

Figure 5: Mean absolute error (m) of 5-day averaged forecasts of 50 hPa geopotential height fields over the Northern Hemisphere (north of 30°N) for control forecast with persisted SSTs (CNT/PER-SST) and experiments with the tropics (TROP/0.1), the northern hemisphere stratosphere (NH-S/0.1 and NH-S/1.0) and the northern hemisphere troposphere (NH-T/0.1 and NH-T/1.0) relaxed towards ERA-40 reanalysis data.

the signal (reduced forecast error) to 'propagate' from the tropics and the stratosphere, respectively, into the northern hemisphere troposphere (e.g. Hoskins and Ambrizzi, 1993; Jung and Barkmeijer, 2006).

The sensitivity of the results to the strength of the relaxation (i.e., the choice of λ in Eqn. 1) for TROP and NH-S can be inferred from Figure 4 b and c, respectively. For the relaxation time scales considered here (1, 10 and 50 hours) the tropical relaxation appears to be less sensitive to the choice of λ. One way to interpret this result is that the reduction of Northern Hemisphere Z500 error is due to relatively persistent and large-scale rather than fast and small-scale tropical features. The Z500 forecast error reduction appears to be more sensitive to λ for NH-S. The fact that a stronger relaxation is required for the stratosphere compared to the tropics could mean that the latter has a larger direct influence on the Northern Hemisphere extratropics (see also below).

As shown above, relaxation of the tropical atmosphere leads to reduced forecast error over the Northern Hemisphere. How much of this improvement originates in the tropical troposphere and how much in the tropical stratosphere? In order to answer this question, additional relaxation experiments have been carried out with relaxation of the tropical troposphere (TROP-T/0.1) and tropical stratosphere (TROP-S/0.1) only. Results from these experiments clearly show that it is primarily the tropical *troposphere* which influences the tropospheric flow over the Northern Hemisphere (Fig. 4d).

How the relaxation towards ERA-40 in different regions influences the predictability of the *stratospheric* circulation (in terms of geopotential height at 50 hPa, Z50 hereafter) over the Northern Hemisphere can be inferred from Fig. 5. The forecast error of the control integration saturates much later at 50 hPa than it does at 500 hPa. This highlights the relatively high level of extended-range predictability of the Northern Hemisphere stratosphere. The tropics have some influence on the stratospheric circulation, especially beyond D+15 or so. Not too surprisingly, relaxing the stratosphere towards ERA-40 reduces Z50 forecast error over the Northern Hemisphere substantially. Interestingly, however, relaxing the extratropical *troposphere* has a similar influence, at least for values of λ much smaller than 1.0. These results are a reminder of the strong troposheric forcing of the Northern Hemisphere stratosphere during boreal winter.

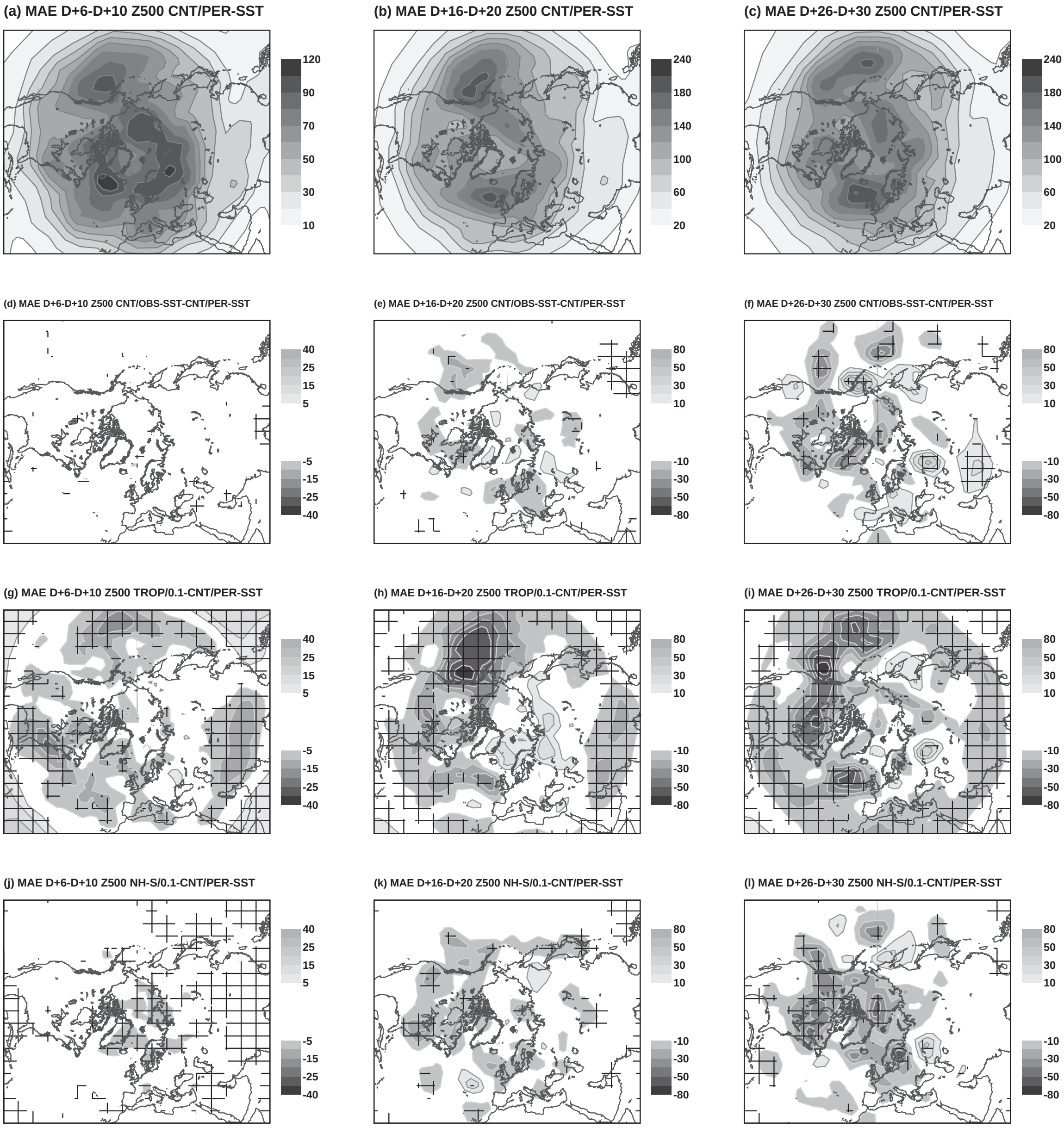

Figure 6: (a)–(c) Mean absolute forecast error of 500 hPa geopotential height field (in metres) for the control integration with persisted SSTs (CNT/PER-SST). (d)–(f) Difference in mean absolute forecast error for Z500 between the control intregration with observed (CNT/OBS-SST) and persisted (CNT/PER-SST) SSTs. (g)–(i) as for (d)–(f), but for the differenced between TROP/0.1 and CNT/PER-SST. (j)–(l) as for (d)–(f), but for the differenced between NH-S/0.1 and CNT/PER-SST. Results are shown for 5-day averaged data: D+6 to D+10 (left), D+16 to D+20 (middle) and D+26 to D+30 (right). Differences significant at the 95% confidence level (two-sided t-test) are hatched.

3.2.1 Regional impacts of tropical and stratospheric relaxation

So far, the focus has been on Z500 forecast error for the extratropical Northern Hemisphere as a whole. It is likely, however, that the Z500 response over the Northern Hemisphere described above shows some interesting spatial structure. The way how Z500 error is influenced over the Northern Hemisphere by prescibing rather than persisting the the lower boundary conditions can be inferred from Figure 6d–f. Perfect knowledge of the observed SST/sea ice fields has a positive impact primarily in the extended-range over the North Pacific and over North America. The impact over the North Atlantic and Europe, on the other hand, is rather small (and non-significant) throughout the first 30 days of the forecast.

Not too surprisingly, the tropical relaxation experiment, TROP/0.1 (Fig. 6g–i), leads to substantial forecast error reduction in the northern hemisphere subtropics, that is, close to the relaxation region. The fact that the forecast error reduction with tropical relaxation appears to be largely ‘confined’ to the subtropics in certain regions such as south-east Asia might be explained by the presence of strong subtropical zonal wave guides (e.g. Branstator, 2002) which propagate the signal in zonal rather than meridional direction. There is also a clear positive impact of a correct representation of the tropics in certain regions of the Northern Hemisphere *mid-latitudes* such as the eastern North Pacific, the North American continent and the central North Atlantic. This is true from the medium-range well into the extended-range. In the Euro-Atlantic region the Z500 forecast error reduction is largest just west of the British Isles. This is an area which is known for the frequent occurrence of persistent ridges (‘blocking’) and troughs, both which tend to produce high-impact weather over Western Europe (e.g. UK floods in autumn 2000). North America is the other populated area in the Northern Hemisphere mid-latitudes which benefits from improved forecasts of the tropical troposphere.

In the medium-range and extended-range, the stratospheric relaxation experiment leads to the largest forecast error reduction in high latitudes (Fig. 6j–l). This is consistent with the tropospheric response found in the ECMWF model as a result of changes in the strength of the stratospheric polar vortex (Jung and Barkmeijer, 2006). Interestingly, Europe and northern parts of North America are also key-beneficiaries of a better representation of the stratospheric circulation, both in the medium-range and extended-range.

It is worth mentioning that the *spatial structure* of the response is much less sensitive to the exact choice of λ than is the *magnitude* (not shown).

The same experiments deascribed above were repeated for the *independent* period 1958–1981 (not shown). In general the conclusions remain unchanged, except for a small reduction of the tropical and stratospheric impact on Z500 forecast error over North America. This may at least partly be explained by the slightly poorer quality of the ERA-40 reanalysis during the pre-satellite era (Uppala et al., 2005).

3.2.2 *Further exploring the tropical influence*

Having demonstrated the beneficial impact of reduced tropical forecast error for Z500 forecasts over Western Europe and North America, it is interesting to understand from which part(s) of the tropics the forecast improvement originates. To this end, three additional relaxation experiments were carried out (see also Tab. 1). The three tropical regions considered are:

- 0^o–140^oE: Africa, Indian Ocean and Maritime Continent (MCIN).
- 140^oE–90^oW: Tropical Pacific (TPAC).
- 90^oW–0^o: South America and Atlantic (SAAT).

The choice is motiviated by the fact that (i) MCIN represents a region in which the MJO is strongly associated with moist processes (Madden and Julian, 1994) leading to strong anomalies of the large-scale divergent flow and, hence, the potential for pronounced extratropical teleconnections (e.g. Matthews et al., 2004), (ii) TPAC is associated with ENSO-type variability (including ‘moist’ MJO event during El Nino years), and (iii) SAAT reflects atmospheric conditions in a region which, although generally less affected by strong intraseasonal and

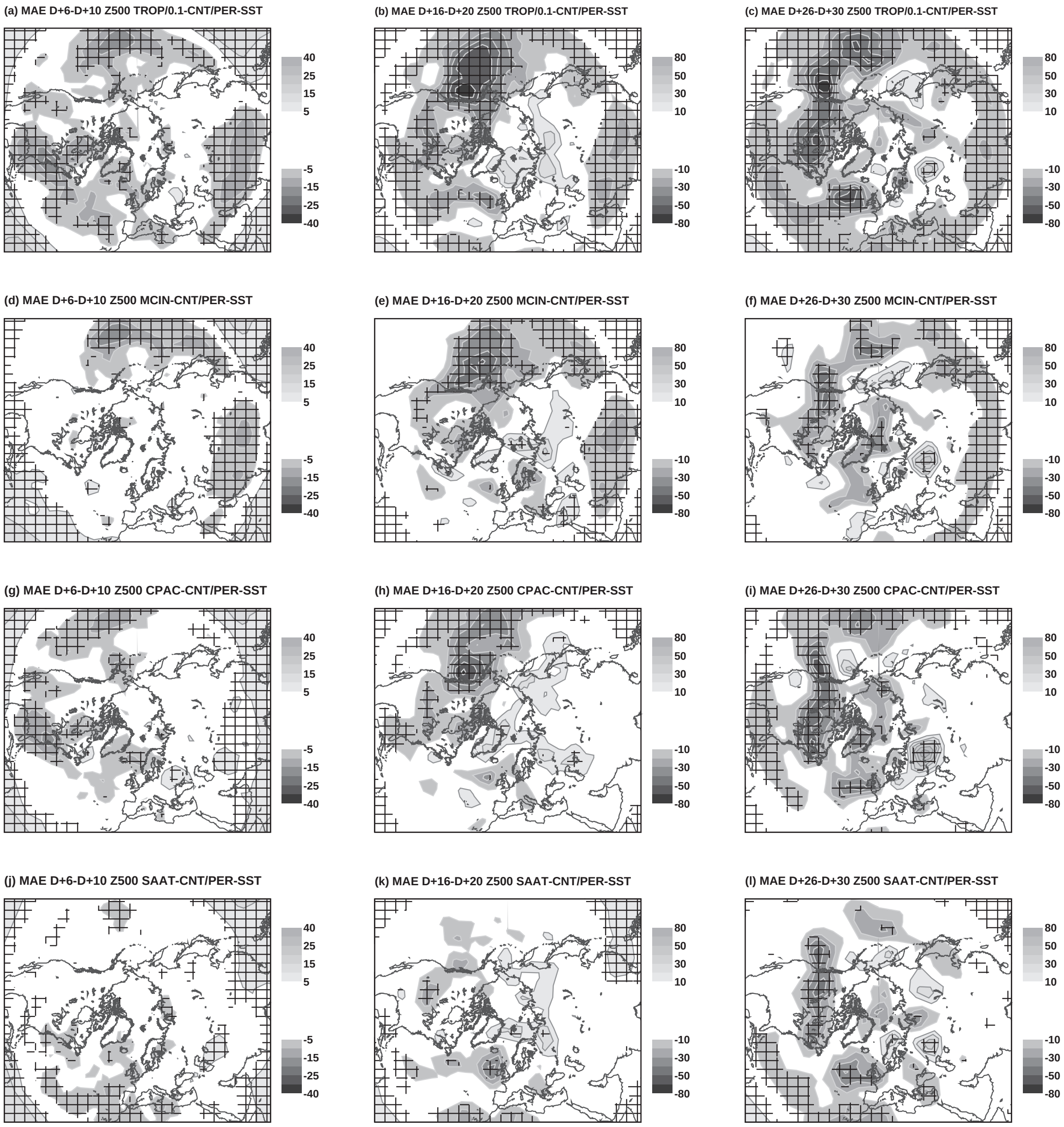

Figure 7: Mean absolute forecast error (in metres) between the experiments with relaxation confined to (a)–(c) tropics (TROP/0.1), (d)–(f) the Indian Ocean/Maritime Continent (MCIN), (g)–(i) the central tropical Pacific (TPAC) and (j)–(l) the tropical South America/tropical Atlantic (SAAT) and the control integration (CNT/PER-SST). All relaxation experiments are based on $\lambda = 0.1$. Results are shown for 5-day averaged data: D+6 to D+10 (left), D+16 to D+20 (middle) and D+26 to D+30 (right). Differences significant at the 95% confidence level (two-sided t-test) are hatched.

interannual atmospheric variations, has the potential to affect weather over Europe (e.g. Hoskins and Ambrizzi, 1993).

An investigation of the forecast error for these experiments in the tropics suggests that the forecast 'improvement' is largely confined to the relaxation regions (not shown). This suggests that it is possible to trace extratropical forecast error reduction back to different tropical regions.

Table 2: Forecast start dates (format: year-month) for various types of composites. Notice that all forecasts were started on the 15th of the respective month.

Type	Forecast start dates
Active MJO	1981-12, 1983-11, 1985-01, 1985-02, 1985-12, 1986-01, 1987-02, 1987-11, 1987-12, 1988-01, 1988-02, 1988-12, 1989-01, 1989-02, 1990-01, 1990-02, 1990-11, 1991-12, 1992-01, 1992-12, 1993-01, 1994-02, 1994-11, 1994-12, 1996-11, 1996-12, 1997-02, 2000-11
Non-active MJO	1980-12, 1982-01, 1982-02, 1982-11, 1983-01, 1983-02, 1984-01, 1984-02 1984-12, 1987-01, 1991-01, 1993-11, 1995-01, 1997-01, 1998-02, 1998-12 2000-01, 2001-11, 2001-12

Figure 7 shows the impact of the various tropical relaxation experiments (with $\lambda = 0.1$) on mean absolute Z500 forecast error over the northern hemisphere. Forecast improvement for MCIN is largely confined to the Asian subtropical Jet Stream and the North Pacific region throughout the 30-day forecast (Fig. 7b). Although there appears to be some influence in the North Atlantic by D+26 to D+30, forecast error reduction is relatively small compared to the experiment in which the whole tropical belt has been relaxed (Fig. 7a, right panel). Relaxing the tropical Pacific, TPAC, leads to forecast improvements from the eastern North Pacific, over North America into the North Atlantic region. A similar forecast error reduction is found for SAAT. In both experiments TPAC and SAAT, Z500 forecast in the North Atlantic region are already improved in the medium-range; the largest signal, however, is found in the extended-range (both, in absolute and relative terms).

3.2.3 *The role of the Madden-Julian Oscillation*

Previous studies have highlighted the importance of the Madden-Julian Oscillation (MJO, Madden and Julian, 1972) in generating extratropical teleconnections, especially in the North Pacific region (Matthews et al., 2004). Given that the representation of the MJO in most atmospheric models is rather poor (e.g. Moncrieff et al., 2007) it seems plausible that improved prediction of the MJO will lead to improved extended-range forecasts of the extratropical circulation (Ferranti et al., 1990; Jones et al., 2004)—a notion that also features prominently in the THORPEX International Science Plan (Shapiro and Thorpe, 2004). In the light of the earlier study by Ferranti et al. (1990), it is tempting to explain the beneficial impact of tropical relaxing on extended-range extratropical forecast skill, illustrated in previous sections, by more skilful ‘forecasts’ of the MJO.

In order to better understand the role of the MJO in the tropical relaxation experiments, diagnosis of the experiments was carried out separately for active and non-active MJO episodes. Here, the classification into active and non-active MJO episodes was carried out subjectively[2] by inspecting individual Hovmöller diagrams of bandpass-filtered (30–60 days) tropical velocity potential anomalies at the 200 hPa level using ERA-40 reanalysis data. A summary of the forecast start dates for active and non-active MJO periods is summarized in Table 2. Notice, for example, that the two strong MJO events during the TOGA/COARE Intensive Observing Period (Yanai et al., 2000) are captured by the active MJO subset.

If extratropical forecast error in the control integration is considered separately for periods with active and non-active MJO then it turns out that Z500 forecast error over the Northern Hemisphere is smaller during active compared to non-active MJO episodes (solid lines in Fig. 8a and b). These results, which are consistent with the study of Jones et al. (2004), suggest that extended-range forecasts of the Northern Hemisphere circulation

[2]Using an objective technique with various threshold did not change the conclusions.

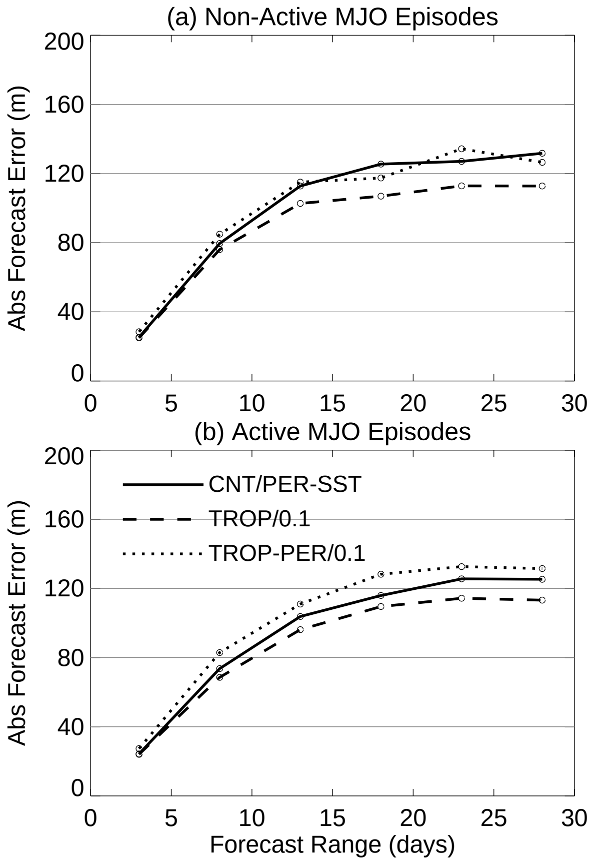

Figure 8: Mean absolute error (m) of 5-day averaged 500 hPa geopotential height forecast error over the Northern Hemisphere (north of 40°N) for (a) active and (b) non-active MJO episodes. Results are shown for the control integration CNT/PER-SST (solid) and TROP/0.1 (dashed) and TROP-PER/0.1 (dotted).

with present-day versions of the ECMWF draw some of their skill from successful prediction of the MJO.

If improvements in the 'prediction' of the MJO were the main contributor to the reduction of extratropical forecast errors in the tropical relaxation experiments, then we would expect the tropical relaxation to yield improvements primarily during active MJO periods. Comparing the differences in mean absolute errors between the tropical relaxation (TROP/1.0) and control experiment for non-active MJO (Fig. 8a) and active MJO (Fig. 8b) shows that this is not the case. In fact, if anything, then the reduction of Z500 forecast error over the Northern Hemisphere is larger during non-active compared to active MJO episodes.

This conclusion is in stark contrast to the results by Ferranti et al. (1990). How can this discrepancy be explained? Firstly, it should be mentioned that the analysis towards which the model is drawn in this study is much of much higher quality compared to that used by Ferranti et al. (1990). This can be inferred from Fig. 9, which shows how the squared coherency spectrum[3] between operational analyses and ERA-40 (re-)analyses of equatorial velocity potential anomalies at the 200 hPa level depends on zonal wave number for two different periods. For the 1985–1988 period, which represents approximately the period investigated by Ferranti et al. (1990), correspondence between the two analyses is confined to very low wave numbers. This suggests that in the late 1980s only the largest spatial scales—including the MJO—were realistically represented by the-then

[3]The (squared) coherency is formally similar to the (squared) correlation coefficient and, therefore, gives a measure for the similarity of two fields as a function of zonal wavenumber (e.g. von Storch and Zwiers, 1999).

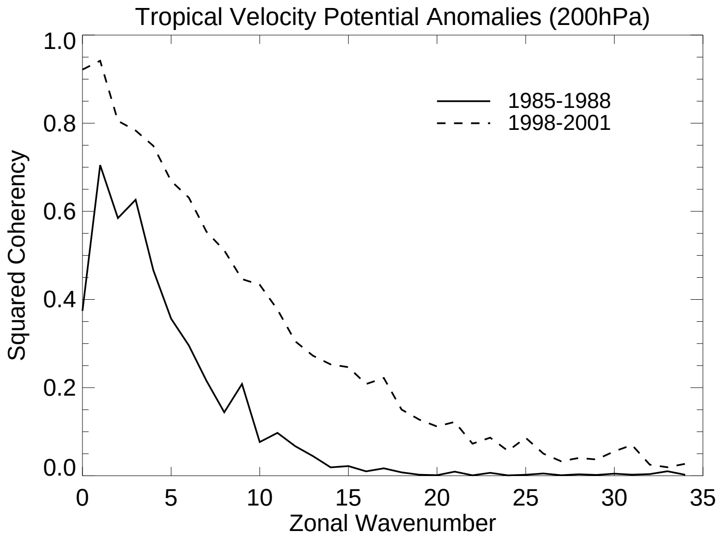

Figure 9: Mean squared coherency of equatorial velocity potential anomalies at the 200hPa level as a function of zonal wavenumber between operational analysis and ERA-40 reanalysis data: 1985–1988 (solid) and 1998–2001 (dashed). The 'chunk method' (see von Storch and Zwiers, 1999, for details) has been used for smoothing.

operational analysis (i.e. constrained by the observations). For the 1998–2001 period, however, the agreement between the the-then operational analysis and ERA-40 reanalysis is much better for all zonal wavenumbers. Secondly, differences in the predictive skill of the MJO in the 1980s compared to today may explain discrepancies regarding the role of the MJO in this study compared to that of Ferranti et al. (1990). Figure 10 shows that today's forecasts of MJO-type atmospheric variability at D+10 show the same skill as D+3 forecasts used to show in the late 1980s. In fact,Boer (1995) finds "a comparatively rapid decrease of skill in the tropical region" for ECMWF forecasts during the period 1986–91. Vitart et al. (2007), on the other hand, point out that in a recent version of the ECMWF model there is useful skill in predicting the MJO up to D+15 to D+20 in advance.

In order to further elucidate the influence that changes in tropical forecast error have on extratropical predictive skill a set of experiments has been carried out in which the the model is relaxed towards the initial conditions in the tropics using $\lambda = 0.1\,hrs^{-1}$ (TROP-PER/0.1 hereafter). In this way it is possible to artificially *deteriorate* forecasts of the tropical atmosphere (Ferranti et al., 1990). For non-active MJO episodes it is found that increasing forecast error in the tropics leads to slightly larger extratropical forecast error in the medium-range; in the extended-range, however, deteriorating tropical forecasts has no impact compared to the control forecast (Fig. 8a). For non-active MJO episodes this suggests that present-day extended-range forecasts of the extratropical atmosphere with the ECMWF model do not draw any predictive skill from the tropics. For active MJO episodes (Fig. 8b), on the other hand, the control forecast shows much lower forecast error compared to TROP-PER, suggesting that part of the present level of medium-range and extended-range extratropical forecast skill actually originates in the tropics and is associated with the MJO.

4 Discussion

The origin of extended-range forecast error has been studied with the ECMWF model by carrying out relaxation experiments. By spatially confining the relaxation it is possible to study the *remote* impact that forecast error

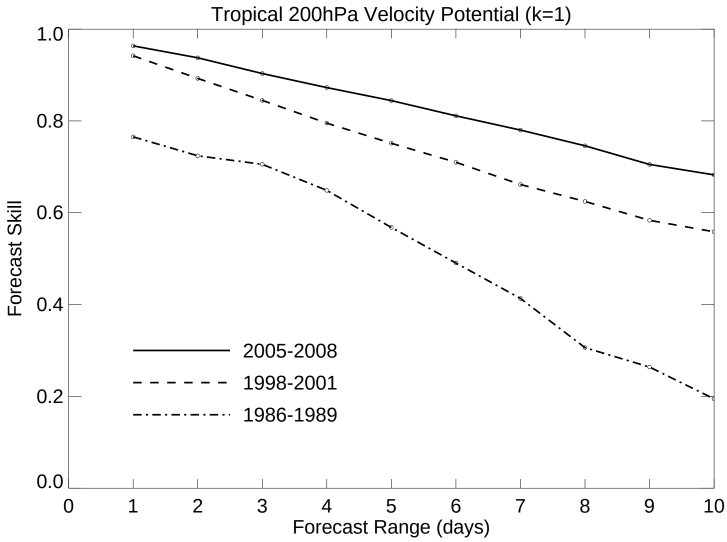

Figure 10: Predicted variance fraction of operational ECMWF forecasts of equatorial, large-scale (only zonal wavenumbers one has been retained) velocity potential at 200hPa level for the periods 1986–1989 (dash-dotted), 1998–2001 (dashed) and 2005–2008 (solid) (see text and Boer, 1994, for further details).

reduction in certain regions has. A schematic of the interactions considered along with estimates of their strength is shown in Figure 11.

The focus of this study has been on the influence that the tropics and the Northern Hemisphere stratosphere have on extended-range forecast skill of the Northern Hemisphere circulation. Emphasis has been put on the role of the tropics since it is widely believed that extended-range predictions of the extratopical atmosphere benefit from better forecasts of the MJO (e.g. Ferranti et al., 1990; Jones et al., 2004; Moncrieff et al., 2007); the influence of the Northern Hemisphere stratosphere has been studied in more detail in order to understand the role that anomalies in the strength of the stratospheric polar vortex and their 'downward propagation' into the the troposphere (Baldwin and Dunkerton, 2001; Baldwin et al., 2003) have on extended-range forecast skill.

Our results show that a reduction of forecast error in the tropical troposphere has a beneficial impact on extended-range forecast skill over the Northern Hemisphere. In terms of populated areas this is especially true for North America and Western Europe. Perhaps somewhat surprisingly, the MJO plays a secondary role for explaining these results. Here, it is argued that this is due to a relatively high level of predictive skill in the current versions of the ECMWF forecasting system, both in the medium-range and extended-range; leaving the relaxation relatively little work to do to suppress MJO-related forecast error.

As mentioned in the Introduction the relaxation experiments were carried out in order guide future forecasting system development. The tropical relaxation experiments were carried out, for example, to see how much forecast skill, if any, could be gained by reducing forecast error in tropics (e.g., by a better representation of physical processes). Our results suggest, for example, that reduced tropical forecast error is unlikely to increase extended-range skill in predicting the Northern Hemisphere tropospheric circulation beyond the current skill in the range from D+11–D+15 (Fig. 4a). Notice, however, that there a large regional variations. These estimates have to be seen as very *optimistic* given that in these experiments tropical forecast error is reduced to levels unlikely to in the future.

Stratospheric relaxation experiments show that reduced forecast error in the Northern Hemisphere stratosphere leads to reduced forecast error in the troposphere below. These results are consistent with previous modeling

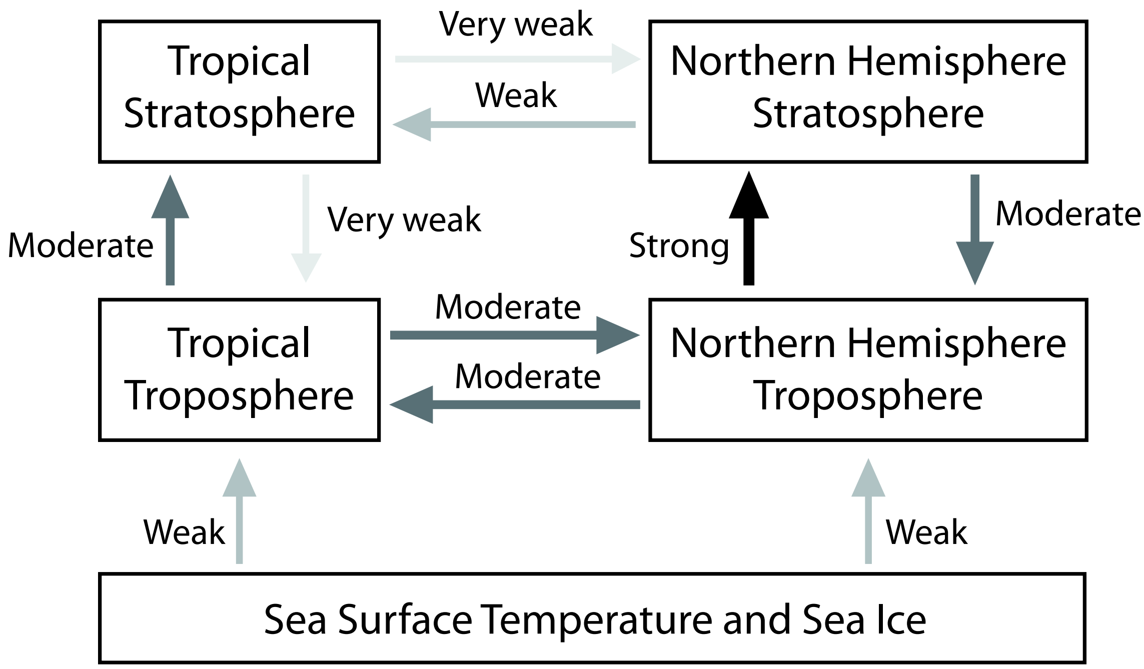

Figure 11: Schematic of the estimated strength of the interactions during boreal winter. Notice that the arrows to not necessarily imply predictability (see text for details).

studies in which a relatively strong tropospheric response has been found to imposed stratospheric perturbations (e.g. Boville, 1984; Charlton et al., 2004; Jung and Barkmeijer, 2006). Moreover, the stratospheric relaxation experiments are very difficult to interpret in terms of the implied gain in tropospheric predictability. This is because tropospheric relaxation is as efficient in reducing stratospheric forecast error as is direct stratospheric relaxation, highlighting the strong influence of the troposphere on the Northern Hemisphere stratospheric during boreal winter (see also, e.g., Martius et al., 2009). A very illuminative discussion of difficulties in interpreting numerical experiments, in which a strongly forced component of the coupled system is artificially prescribed, is given by Bretherton and Battisti (2000) for the atmosphere-ocean system[4].

Our conclusions are very similar to that from the study by Newman and Sardeshmukh (2008) using a completely different approach by diagnosing linear inverse models fitted to observational data. They find that tropical influences are generally larger than stratospheric influences in terms of predictability of the extratropical troposphere during boreal winter.

One of the potential weaknesses of the tropical relaxation experiments is the presence of the transition zone around 20^{o}N, where the relaxaton coefficient changes in latitudinal direction (see Fig. 1). It could be argued, for example, that the presence of the transition zone leads to spurious reflection of extratropical Rossby waves. While it cannot be exluded that spurious reflection does occur, it is worth pointing out that the tropical relaxation is doing something *realistic* since, otherwise, extratropical forecast skill would not be reduced compared to the experiment without tropical relaxation. One way to reduce adverse effects is to relax divergence and vorticity rather than the horizontal wind components (Greatbatch et al., 2003). Another way would be to carry out experiments with the ECMWF 4D-Var data assimilation system in which all observations outside the tropics are blacklisted. Given the computational cost of 4D-Var data assimilation experiments it would only be possible to look at a limited number of cases. Preliminary results for a limited number of cases show that the two

[4]The atmosphere and ocean in their study correspond to the troposphere and stratosphere, respectively, discussed here.

approaches yield very similar results thereby suggesting that the relaxation methos employed in this study is very effective (T. jung, manuscript in preparation).

Summarizing, the relaxation technique appears to be a very powerful diagnostic technique in order to localize possible 'remote' origins of forecast error. We applied the same technique (i) focussing more on medium-range rather than extended-range predictions, (ii) to study the origin of seasonal mean circulation anomalies such as the cold European winter of 2005/06 (Jung et al., 2009) and (iii) to understand the tropical origin of extrattropical systematic error. Results of these studies will be reported in forthcoming papers.

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