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METEOROLOGY

Diagnosing forecast error using relaxation experiments
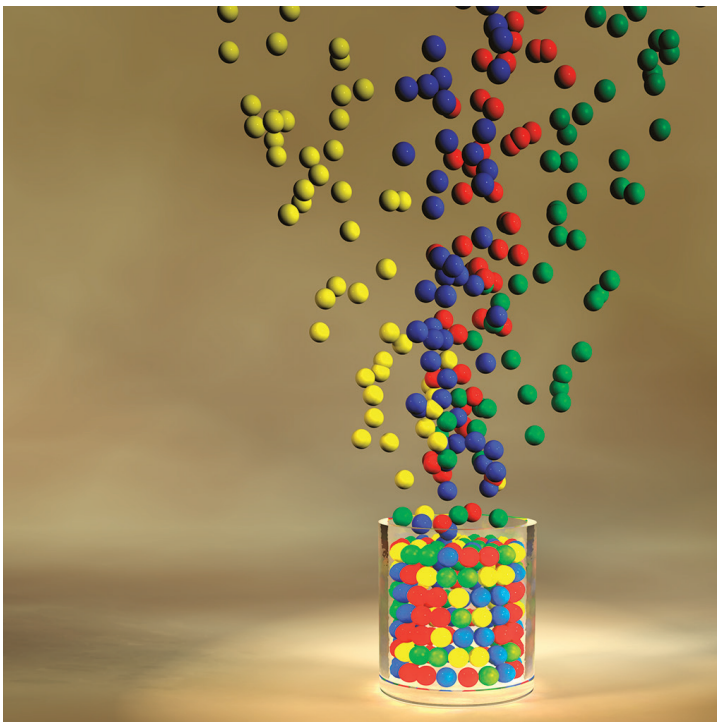
Diagnosing forecast error using relaxation experiments

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Despite substantial improvements in model formulation, data assimilation systems and observing systems, forecasts are still prone to failures. For example, extended-range forecasts (beyond 10 days) of the extratropical flow have moderate skill at the best of times. Apart from being of purely academic interest, understanding the origin of forecast error is the first step towards possible future improvements of the forecasting system. One important piece of information about forecast error is where it originates. If it turns out, for example, that extended-range predictability in the extratropics is primarily limited by model errors in the tropics then future model development should focus on exactly this region.

In this study we apply the so-called relaxation technique (also know as nudging technique), where prognostic fields are relaxed towards ERA-40 reanalyses produced at ECMWF (see Box A for details). The aim is to investigate how much of the extratropical forecast error in 30-day integrations originates in the tropics and how much in the stratosphere. These regions are two parts of the atmosphere with (theoretically) enhanced extended-range predictability. The relaxation technique is also applied in a case study to investigate the potential seasonal predictability of the cold European winter of 2005/06.

Origin of extratropical forecast error in 30-day integrations

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 Cy32r1 at a resolution of T159 (about 125 km) and with 60 vertical levels (T159L60). For each of the experiments a total of 88 30-day forecasts were carried out. Forecasts were started on the 15th of the months: November, December, January and February, for each of the winters from 1980/81 to 2001/02. The initial conditions were taken from ERA-40 reanalysis data and in most experiments initial sea surface temperature (SST) and sea ice fields were persisted throughout the forecast. A control integration with observed SST and sea ice fields was also carried out in order to quantify the influence that knowledge of the lower boundary conditions has on atmospheric forecast skill.

The relaxation experiments can be divided into three groups depending on the region being relaxed: tropics, northern hemisphere troposphere and northern hemisphere stratosphere. Additional experiments were carried out to investigate the relative importance of different tropical regions and to study the sensitivity to the strength of the relaxation. A more detailed description of the relaxation formulation is given in Box A. Also the various 30-day experiments are summarized in Table 1.

Tropical skill scores

Figure 1 shows mean absolute forecast error of 5-day averaged tropical velocity potential (divergent flow) and stream function (rotational flow) fields at the 200 hPa level. The control integration (CNT/PER-SST) shows increasing forecast error throughout the 30-day forecast period. Prescribing SST fields (CNT/OBS-SST) reduces these errors slightly, particularly for the tropical rotational winds. "Moderately" relaxing ($\lambda = 0.1$) the tropics towards ERA-40 during the course of the integration (TROP/0.1) is sufficient to reduce the forecast error of tropical velocity potential and stream function fields substantially throughout the forecast, thereby illustrating the effectiveness of the relaxation formulation.

Also shown in Figure 1 are mean absolute forecast error for an experiment in which the troposphere over the northern hemisphere has been relaxed towards ERA-40 (NH/0.1). Interestingly, "knowledge" of the extratropical circulation is particularly beneficial when it comes to predicting the rotational wind component in the tropics; the influence on the divergent component seems to be less pronounced. These results are in line with the notion that the extratropics affect the tropics on intra-seasonal time scales primarily through equatorward travelling extratropical Rossby wave trains.

Relaxation Formulation   A

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

$$-\lambda\,(\mathbf{x}-\mathbf{x}^{\text{ref}})$$

The model state vector is represented by x and reference field towards which the model should be drawn (here analysis data) by 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 $(\text{time step})^{-1}$. For a time step of one hour, for example, a value of $\lambda = 0.1$ indicates that at each time step the model is "corrected" using 10% of the departure of x from x^{ref}.

In this study the relaxation is carried out in grid point space in order to allow for localization. Parameters being relaxed include u, v, T and $\ln p_s$; the same λ is used for each of these parameters. The reference fields used in this study (i.e. ERA-40 reanalyses and operational analyses) are available at 6-hourly intervals only. Since a time step of 1 hour is used in the integrations linear interpolation is applied to the reference fields.

When applying masks to 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 10° belts, both in longitude and latitude. Boundaries stated in the text refer to the centre of the respective 10° belt. 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.

Experiment	Comment	Relaxation region	Relaxation strength
CNT/PER-SST	Control run with persisted SSTs	–	–
CNT/OBS-SST	Control run with observed SSTs	–	–
TROP	Relaxation in the tropics	20°S–20°N, 180°W–180°E, all levels	$\lambda = 0.1$, $\lambda = 1.0$
NH	Relaxation of the troposphere (northern hemisphere)	20°–90°N, 180°W–180°E, p>300 hPa	$\lambda = 0.1$, $\lambda = 1.0$
STRAT	Relaxation of the stratosphere (northern hemisphere)	20°–90°N, 180°W–180°E, p<70 hPa	$\lambda = 0.1$, $\lambda = 1.0$
MCIN	Relaxation over the tropical Africa, Indian Ocean and Maritime Continent	20°S–20°N, 0°–140°E, all levels	$\lambda = 0.1$
TPAC	Relaxation over the tropical Pacific	20°S–20°N, 140°E–90°W, all levels	$\lambda = 0.1$
SAAT	Relaxation over tropical South America and the tropical Atlantic	20°S–20°N, 90°E–0°, all levels	$\lambda = 0.1$

Table 1 Summary of 30-day forecast experiments. All experiments are based on a resolution of T159 with 60 levels in the vertical using model cycle Cy32r1. Lower boundary conditions were persisted throughout the forecast for all relaxation experiments.
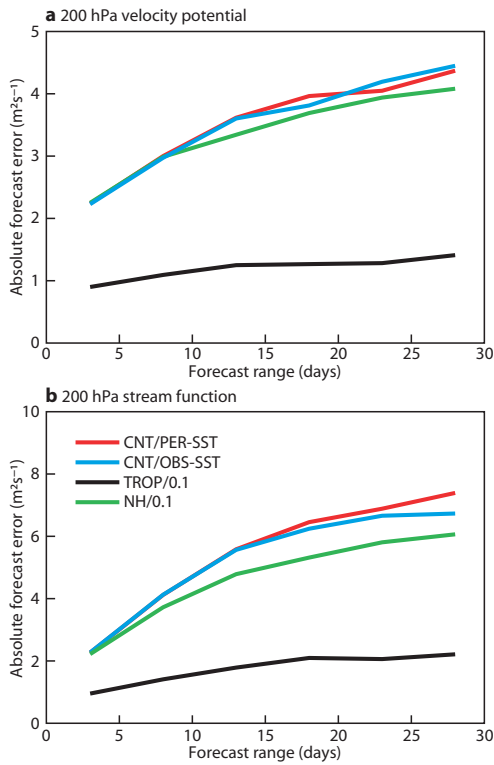
a 200 hPa velocity potential

Figure 1 Mean absolute error of 5-day averaged forecasts of (a) velocity potential and (b) stream function at 200 hPa in the tropics (10°S–10°N) 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, 20°S–20°N) and northern hemisphere extratropics (NH/0.1, 20°N–90°N) relaxed towards ERA-40 reanalysis data.

b 200 hPa stream function

Northern hemisphere Z500 skill scores

Figure 2 shows mean absolute forecast error of 5-day averaged northern hemisphere 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; knowledge of true rather than persisted lower boundary conditions in the short-range and medium-range, on the other hand, provides little, if any, benefit.

Relaxing either the tropics or the stratosphere (TROP and STRAT integrations), leads to a substantial reduction in Z500 forecast error. 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 STAT/1.0. The "delayed" positive impact of the relaxation in the tropics and stratosphere can be explained by the fact that forecasts are still quite successful in the short-range and medium-range (i.e., the relaxation has little work to do) and that it takes some time for the signal (reduced forecast error) to propagate from the tropics and stratosphere, respectively, into the northern hemisphere troposphere (e.g. *Jung & Barkmeijer,* 2006).

Figure 2 also reveals that the magnitude of Z500 forecast error reduction in the northern hemisphere troposphere depends somewhat on the strength of the relaxation coefficient λ . For a value of $\lambda = 1.0$ relaxing the tropics and northern hemisphere stratosphere leads to similar forecast error reductions throughout the 30-day forecast period. For a value of $\lambda = 0.1$ the tropics appear to be more efficient than the stratosphere in reducing Z500 forecast error.
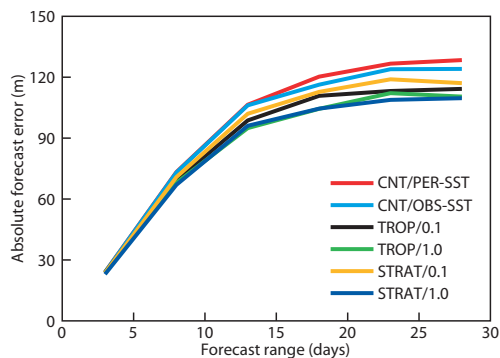

Figure 2 Mean absolute error of 5-day averaged forecasts of northern hemisphere (north of 40°N) 500 hPa geopotential height fields (in metres): control forecast with persisted (CNT/PER-SST) and observed (CNT/OBS-SST) SSTs as well as experiments with the tropics (TROP/0.1 and TROP/1.0) and extratropical stratosphere (STRAT/0.1 and STRAT/1.0) relaxed towards ERA-40 reanalysis data.

Regional impacts of tropical and stratospheric relaxation

So far the focus has been on forecast error of the northern hemisphere as a whole. In order to identify possible regional differences in the relaxation experiments "difference maps" of mean absolute Z500 forecast error between the relaxation integrations for the tropics (TROP/1.0) and stratosphere (STRAT/1.0) and the control integration (CNT/PER-SST) have been produced (Figures 3(b) and 3(c)). For reference, mean absolute forecast errors for the control integration are also shown (Figure 3(a)).

Not too surprisingly, the tropical relaxation experiment (Figure 3(b)) leads to substantial forecast error reduction in the northern hemisphere subtropics, which is adjacent to the region where the model has been relaxed towards ERA-40. The fact that the forecast error reduction with tropical relaxation appears to be largely "confined" to the subtropics might also be explained by the presence of strong subtropical wave guides (e.g. *Branstator,* 2002). In the eastern North Pacific and the central North Atlantic, however, the "signal" appears to be spreading from the tropics into the northern hemisphere mid-latitudes. Western Europe appears to be benefiting in particular from an improved representation of the tropical circulation. This is true from the medium-range well into the extended-range. The Z500 forecast error reduction is largest just west of the British Isles in an area which is known for the frequent occurrence of persistent small-scale ridges ("blocking") and troughs which tend to produce high-impact weather over Western Europe (e.g. UK floods in autumn 2000). North America is the other area in the northern hemisphere mid-latitudes which benefits from improved forecasts in the tropics.

In the medium-range the stratospheric relaxation experiment leads to the largest forecast error reduction in high latitudes (Figure 3(c)). This is consistent with the initial tropospheric response found in the ECMWF model as a result of changes in the strength reduction of forecast error is found over large parts of the northern hemisphere mid and high latitudes. Interestingly, Europe is also one of the key-beneficiaries of a better representation of the stratospheric circulation, both in the medium-range and extended-range.
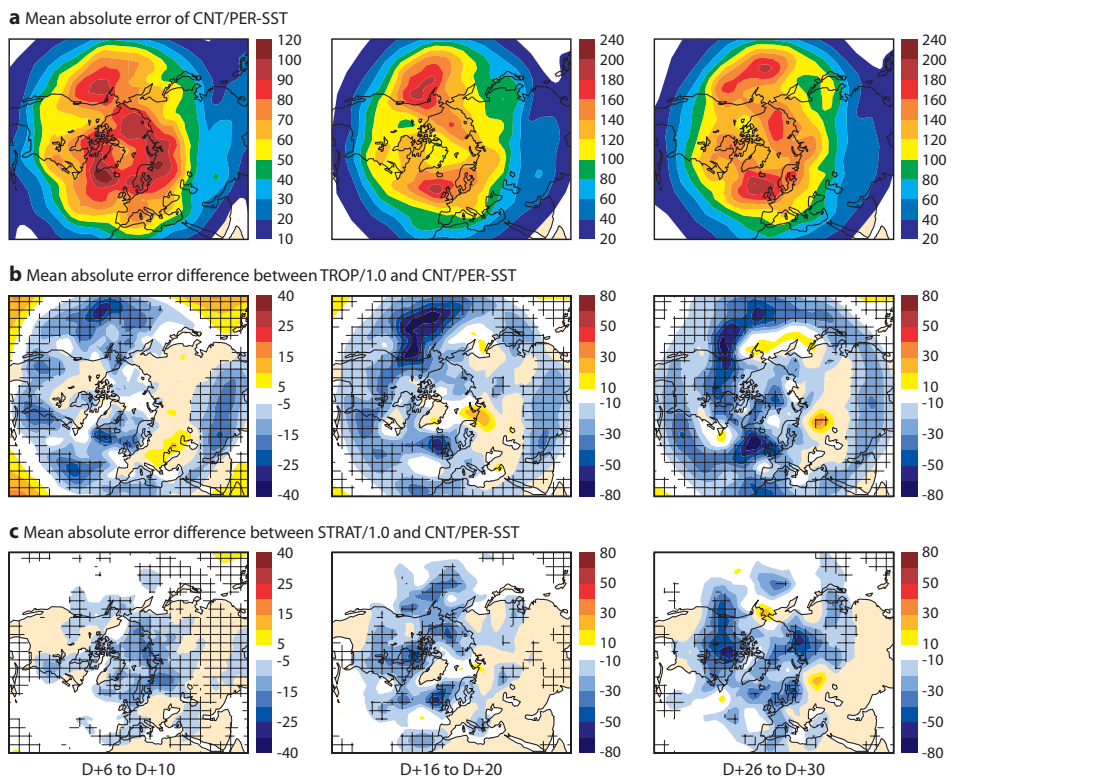

a Mean absolute error of CNT/PER-SST

b Mean absolute error difference between TROP/1.0 and CNT/PER-SST

c Mean absolute error difference between STRAT/1.0 and CNT/PER-SST

D+6 to D+10   D+16 to D+20   D+26 to D+30

Figure 3 (a) Mean absolute forecast error of 500 hPa geopotential height field (in metres) for the control integration with persisted SSTs (CNT/PER-SST). (b) Mean absolute forecast error between the relaxation experiments TROP/1.0 and the control integration. (c) As (b) but for experiment STRAT/1.0. Results are shown for 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.

Further exploring the tropical influence

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

- 0°–140°E: Africa, Indian Ocean and Maritime Continent (MCIN).
- 140°E–90°W: Tropical Pacific (TPAC).
- 90°W–0°: South America and Atlantic (SAAT).

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

Figure 4 shows the impact of the various tropical relaxation experiments (with λ=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 (Figure 4(b)). 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 (Figure 4(a), 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).

A comparison of Figure 3(b) with Figure 4(a) gives a more detailed picture of the sensitivity of the reduction of Z500 forecast error to the exact choice of λ for the tropical relaxation experiment. In general, increasing λ from 0.1 to 1.0 leads to a further reduction of forecast error; this further reduction, however, is small compared to the reduction achieved with λ=0.1, and the spatial structure of forecast error reduction is similar for either of the values.
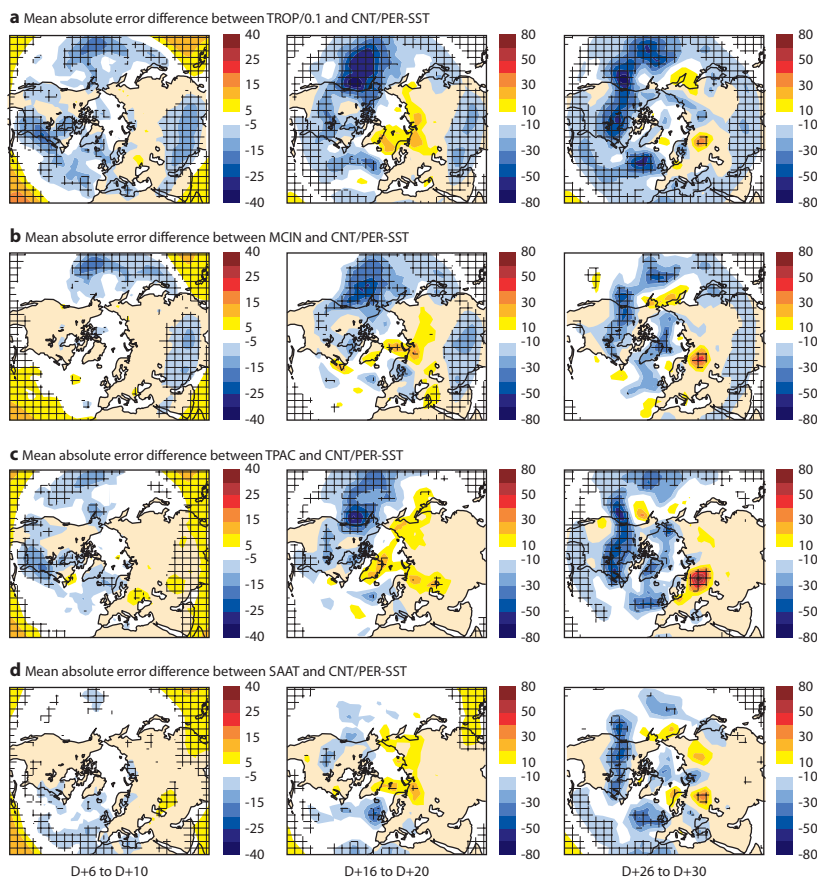

Figure 4 Mean absolute forecast error (in metres) between the relaxation experiments confined to (a) tropics (TROP), (b) Indian Ocean/Maritime Continent (MCIN), (c) central tropical Pacific (TPAC) and (d) tropical South America/tropical Atlantic (SAAT) and the control integration (CNT/PER-SST). All relaxation experiments are based on λ=0.1. Results are shown for 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.

The role of the Madden-Julian Oscillation

Previous studies have highlighted that the Madden-Julian Oscillation (MJO), the dominant atmospheric phenomenon in terms of intra-seasonal tropical variability (e.g. *Zhang,* 2005), gives rise to strong extratropical teleconnections, particularly in the North Pacific region. It seems likely, therefore, that improved prediction of the MJO would lead to improved medium-range and extended-range forecasts in the extratropics (see also *Jones et al.,* 2004), a notion that also features prominently in the THORPEX International Science Plan (*Shapiro & Thorpe,* 2004). Indeed, if extratropical forecast error in the control integration is considered separately for periods with active and non-active MJO then it turns out that forecast error is smaller during active MJO spells (Figure 5(a)). It is tempting to assume that the beneficial impact that relaxing the tropics has on extratropical forecast skill (see previous discussion) is a result of "improved forecasts" of the MJO. This notion is supported by previous studies (e.g., *Ferranti et al.,* 1990; *Jones et al.,* 2004). Here, the classification into active and non-active MJO periods was done subjectively by inspecting individual Hovmöller diagrams of bandpass-filtered (30–60 days) tropical velocity potential anomalies at the 200 hPa level from ERA-40.

If improvements in the prediction of the MJO were the main contributor to the reduction of extratropical forecast errors when relaxing the tropics, then we would expect the relaxation to improve 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 (Figure 5(b)) and active MJO (Figure 5(c)) shows that this is not the case. Forecast error reduction of Z500 in the northern hemisphere extratropics is comparable for active and non-active MJO periods. This shows that there are other aspects of the tropical atmosphere as well that, if simulated more realistically, would lead to more skilful extratropical forecasts. Examples for such tropical aspects include mean systematic error and a wide spectrum of tropical convectively coupled waves.

The fact that it is not just the MJO that leads to extratropical forecast error reduction in the relaxation experiments of this study may be interpreted as indirect evidence for the relatively high quality of the ERA-40 reanalysis in the tropics. Operational analysis fields in the 1980s (based on Optimal Interpolation), as used in the study of *Ferranti et al.* (1990), do capture main features associated with the MJO. There are large differences, however, between these old operational analyses and ERA-40 re-analyses on other spatial and temporal scales (not shown). So, the fact that *Ferranti et al.* found such an important role of the MJO might be explained by the relatively poor representation of the analysis of other aspects of the tropical circulation. Furthermore, improvements in MJO prediction in our control experiments relative to the comparable experiments of Ferranti et al., who used a much older model cycle, may explain the relatively less important role that the MJO plays in our experiments. Indeed, *Vitart et al.* (2007) show that there is useful skill in predicting the MJO up to D+15 to D+20 in a recent model version of the ECMWF model.
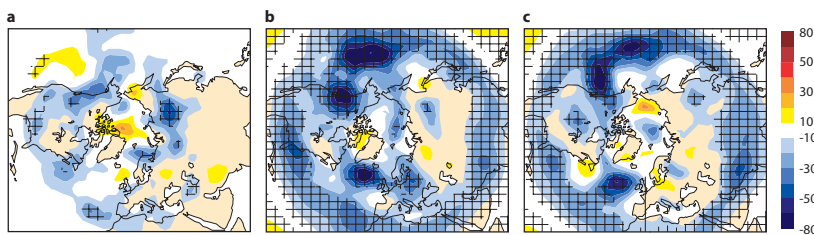

Figure 5 (a) Difference in mean absolute forecast error of 5-day averaged 500 hPa geopotential fields (in metres) between episodes with active and non-active MJO for the control experiment (CNT/ PER-SST). Also shown are differences between tropical relaxation (TROP/1.0) and control experiments for (b) non-active and (c) active MJO episodes. The active (non-active) MJO sample comprises n=22 (n=27) 30-day forecasts for each of the experiments. To increase the sample size forecast errors were computed by aggregating all D+16 to D+20, D+21 to D+25 and D+26 to D+30 forecasts.

The cold European winter of 2005/06 – a case study

The winter of 2005/06 was marked by the frequent occurrence of Euro-Atlantic blocking episodes, which led to anomalously cold conditions over large parts of Europe. The observed seasonal mean Z500 anomaly, shown in Figure 6(a), clearly reflects the anomalous atmospheric condition during December to February 2005/06. Did the operational ECMWF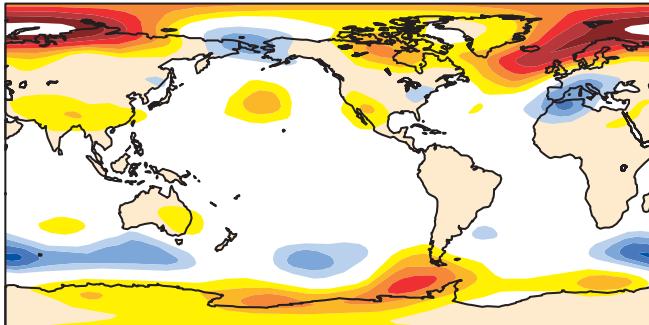 seasonal forecasting system predict the observed anomalies? Figure 6(b), which shows the ensemble mean anomaly based on ECMWF seasonal forecasts started on 1 November 2005, gives some evidence for a reduction of the climatological westerly winds over Europe. The predicted ensemble mean anomaly, however, is rather small (about 6 times smaller than the observed anomaly) and it is not statistically significantly different from climatology (not shown).

To evaluate the forecast performance of the operational ECMWF seasonal forecasting system for the cold European winter of 2005/06 it is necessary to understand the "origin" of the observed anomaly. Was the observed anomaly a result of internal dynamics of the extratropical atmosphere (suggesting weak, if any, predictability on seasonal time scales), or was the anomaly "externally" forced?

Figure 7 shows observed SST anomalies for December to February 2005/06. SST Anomalies were present in all ocean basins, including a moderate La Niña event in the tropical Pacific. The winter of 2005/06 was also marked by the occurrence of a strong stratospheric warming event at the end of January 2006 which lasted for more than four weeks, which might be seen as an alternative explanation for the increased frequency of occurrence of Euro-Atlantic blocking events.

In order to understand the origin of the anomalously cold winter 2005/06, a large number of seasonal forecast experiments with and without relaxation have been carried out using a T95L60 resolution and observed lower boundary conditions. A set of calibration runs covering winters of the period 1990/91 to 2005/06 was carried out in order to obtain the model's climatology. For the winter of 2005/06 a set of seasonal ensemble forecasts was then carried out. The ensembles were generated by starting forecasts in 6-hourly intervals from 12 UTC on 16 November to 12 UTC on 20 November 2005 giving a total of 17 ensemble members. In the relaxation experiments the model was relaxed towards interpolated (T95L60) operational analysis fields. A relaxation coefficient of λ=0.1 has been used in all relaxation experiments. A summary of all forecast experiments is given in Table 2.

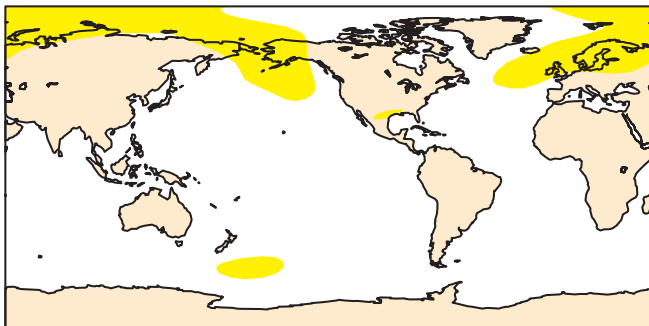**a** Observed anomaly

b Forecast anomaly

Figure 6 500 hPa geopotential height anomaly (in metres) for the winter December to February 2005/06: (a) observed and (b) ensemble mean from the operational ECMWF seasonal forecasting system (starting on 1 November 2005).
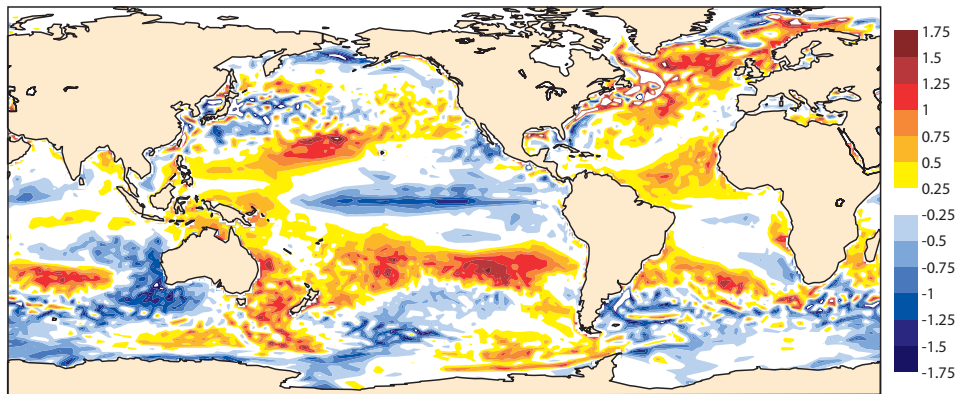
Figure 7 Observed SST anomalies (in K) for December to February 2005/06.

Experiment	Comment	Relaxation region(s)	Relaxation strength
CAL	Calibration run, observed SSTs, 1990/91 to 2005/16	–	–
CNT	Control ensemble without relaxation, observed SSTs, December to February 2005/6	–	–
TROP	Tropical relaxation ensemble, observed SSTs, December to February 2005/06	20°S–20°N, 180°W–180°E, 0°–140°E, 140°E–0°, whole atmosphere, troposphere only	$\lambda = 0.1$
STRAT	Stratospheric relaxation ensemble (NH), observed SSTs, December to February 2005/06	20°–90°N, 180°W–180°E, p<70 hPa	$\lambda = 0.1$

Table 2 Summary of seasonal forecast experiments for the winter 2005/06 case study. All experiments are based on a T95L60 resolution using model cycle Cy32r1. Notice that TROP comprises different tropical regions.

Tropospheric response

Figure 8 shows observed Z500 anomalies for December to February 2005/06 along with those obtained from the various seasonal forecast experiments. Prescribing observed SST anomalies, Figure 8(b), produces rather weak Z500 anomalies. There is some evidence for weakening of the climatological westerly winds over Europe; the anomalies, however, are hardly statistically significant (at the 95% confidence level). Prescribing the tropics (Figure 8(c)), on the other hand, leads to very realistic circulation anomalies over Europe, both in terms of amplitude and spatial structure. Does this mean that the observed anomalies originated from the tropics? Figure 8(d) shows that by prescribing the northern hemisphere stratosphere, similar Z500 anomalies can be produced in the Euro-Atlantic region. This raises the question whether the anomalous cold European winter of 2005/06 originated in the tropics and/or the polar stratosphere.

Stratospheric response

Observed and simulated anomalies of the stratospheric polar vortex, expressed in terms of geopotential height fields at the 50 hPa level (Z50 hereafter), are shown in Figure 9. The control experiment (Figure 9(b)), with observed SSTs, clearly fails in simulating the anomalously weak stratospheric polar vortex. Interestingly, the weak stratospheric polar vortex can be successfully simulated by relaxing the tropics (Figures 9(c) and 9(d)). This suggests that the origin of the observed atmospheric anomalies associated with the cold European winter of 2005/06 as well as the sudden stratospheric warming in January/February 2006 lies in the tropics. It is possible, however, that once established, the stratospheric warming contributed to the persistence of Euro-Atlantic blocking throughout the latter part of December to February 2005/06. Our results highlight the danger of interpreting stratospheric relaxation experiments in terms of "cause and effect". This is particularly true, given that "sudden stratospheric warmings" are believed to be driven by planetary waves of tropospheric origin, which propagate in the stratosphere, where they break and slow down the polar vortex.

The notion that the stratospheric warming originated from the tropics is further supported by the realistic timing of the "ensemble mean" warming in the tropical relaxation experiment (Figure 10). The observational data show that the warming occurred at the end of January 2006. The control integration with observed SSTs, on the other hand, shows a gradual intensification of the stratospheric polar vortex. This "intensification" can largely be understood as a gradual development of a systematic model error. In fact, it is well-known that model cycle Cy32r1, which has been used in this study, produces an erroneously strong stratospheric polar vortex (*Bechtold et al.,* 2008). If considered relative to the control integration (in order to remove the influence of this bias) then it turns out that the timing of the stratospheric warming event in the tropical relaxation experiment is simulated quite realistically (Figure 10(d)). The relatively smooth warming (in contrast to the observed sudden warming) in the relaxation experiment may be explained by the fact that ensemble mean Z50 fields were used in Figures 10(b) to 10(d) which, by nature, are smoother than individual ensemble members (and the observational record).
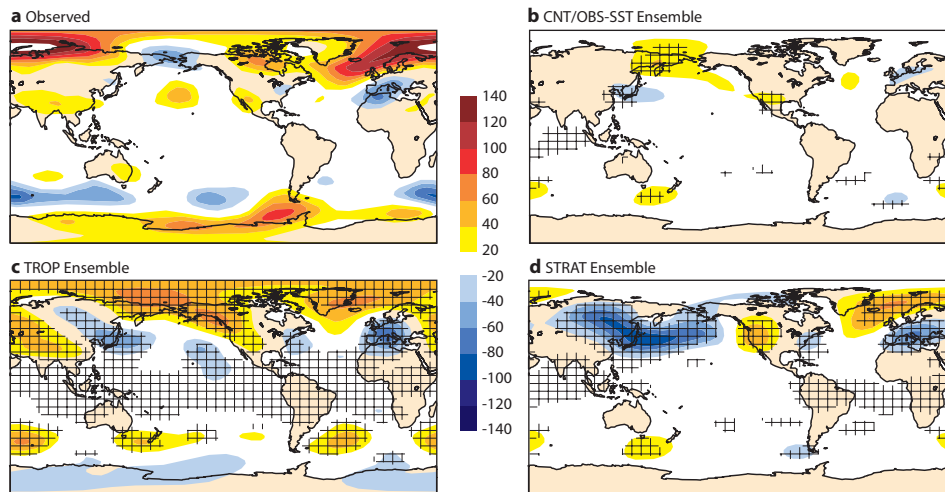

Figure 8 Mean 500 hPa geopotential height anomaly (in metres) for the winter December to February 2005/06: (a) observed, (b) control ensemble (CNT/OBS-SST), (c) tropical relaxation ensemble (TROP) and (d) ensemble with stratospheric relaxation over the northern hemisphere (STRAT). All integrations were carried out using observed SSTs as lower boundary. The anomalies in (b) to (d) are relative to a "calibration" run with observed SST covering winters of the period 1990/91 to 2005/06 and are based on ensemble mean fields (17 members). Statistically significant differences at the 95% confidence level are hatched.
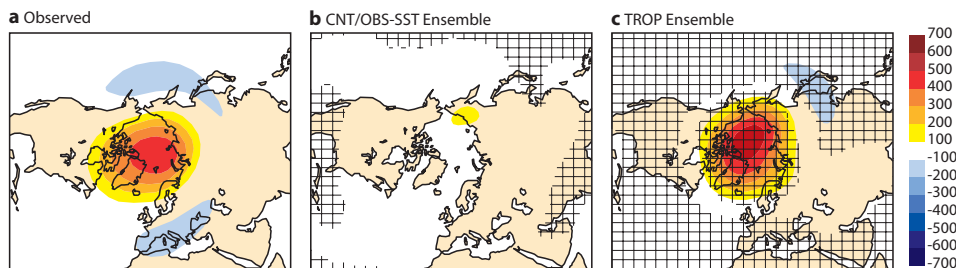

Figure 9 As in Figure 8, but for 50 hPa geopotential height fields: (a) observed, (b) control ensemble (CNT/OBS-SST) and (c) tropical relaxation ensemble (TROP).
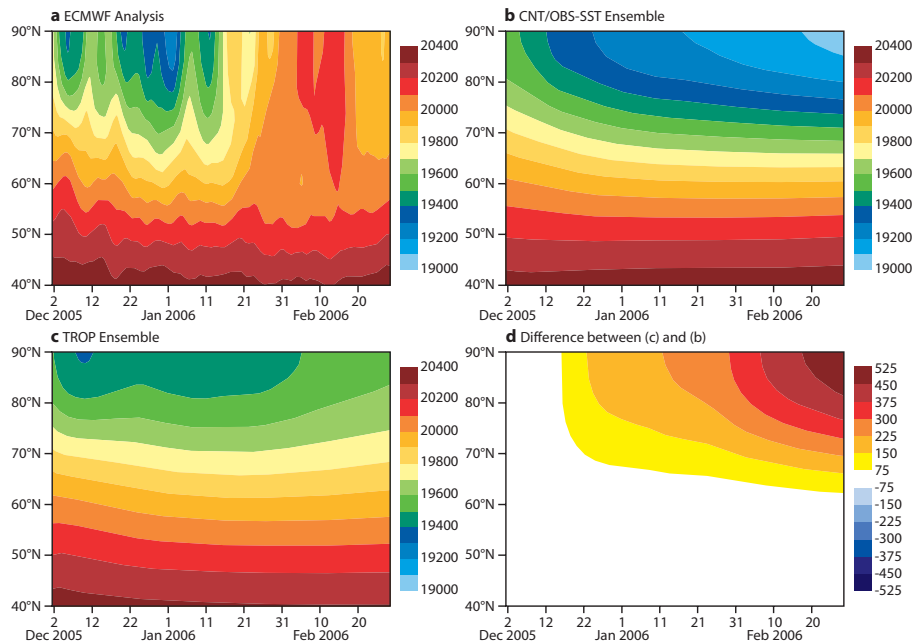
Figure 10 Time-latitude diagrams of zonally averaged daily 50 hPa geopotential height fields (in m) for (a) operational analysis data, (b) the control ensemble (CNT/OBS-SST) and (c) the tropical relaxation ensemble (TROP). (d) Difference between the tropical relaxation and control ensemble. Results in (b) to (d) are based on ensemble mean data (17 members).

Tropical-extratropical teleconnections

After having found evidence for the crucial role of the tropics in setting up the atmospheric circulation anomalies leading to the anomalously cold European winter 2005/06, it is worth briefly discussing the underlying teleconnections. Observed and simulated mean meridional components of the rotational wind (Vrot) in the upper troposphere for December to February 2005/06 are shown in Figure 11. Vrot is chosen here since it is a good parameter to characterise stationary Rossby waves.

Over the northern hemisphere the observations show the presence of a Rossby wave on the Asian Jet Stream, which appears to extend all the way across the North Pacific into the North Atlantic and Europe. The corresponding anomalies for the control ensemble with observed SSTs (Figure 11(b)) do not show the existence of the anomalous Rossby wave on the Asian wave guide. There is evidence, however, for a Rossby wave train propagating from the eastern tropical Pacific, through the Caribbean towards Europe. Although the spatial pattern of this wave appears to agree quite well with the observed anomalies in this region, the magnitude of this wave train, particularly over Europe, is much smaller than observed.

In the following, the relaxation experiments are discussed in terms of their departure from the control ensemble for the winter 2005/06. In this way it is possible to focus on the response which is not captured by prescribing observed SSTs. The first thing to notice is that the effect of relaxing the atmosphere is generally larger than that arising from specifying observed lower boundary conditions (Figure 11). Furthermore, Figure 11(c) shows that the tropical relaxation experiment is capable of reproducing most of the observed anomalous Rossby wave structure in the northern hemisphere extratropics; differences occur primarily in high latitudes. By confining the tropical relaxation to the area 0°–140°E (Africa, Indian Ocean and Maritime Continent) the Rossby wave on the Asian Jet Stream and its extension towards North America can be well simulated (Figure 11(d)).

The response over the North Atlantic and Europe, however, is much weaker than for the case in which the whole tropics are being relaxed. In fact, it turns out that in order to get the observed anomalous circulation over Europe correctly, it is necessary to relax the tropics from 140°E–0° (Pacific, South America and Atlantic, Figure 11(e)). One plausible explanation is that the correct atmospheric response to the La Niña conditions in the tropical Pacific (see Figure 7) was crucial for establishing the Rossby wave response capable of reaching Europe. In fact, this notion is consistent with results from a previous study in which it was shown that the response of the ECMWF model to a La Niña-type diabatic forcing tends to favour the negative phase of the North Atlantic Oscillation (*Greatbatch & Jung,* 2006), that is, anomalously cold European winters. Finally, Figure 11(f) confirms that the origin of the extratropical signal is primarily located in the tropical troposphere.
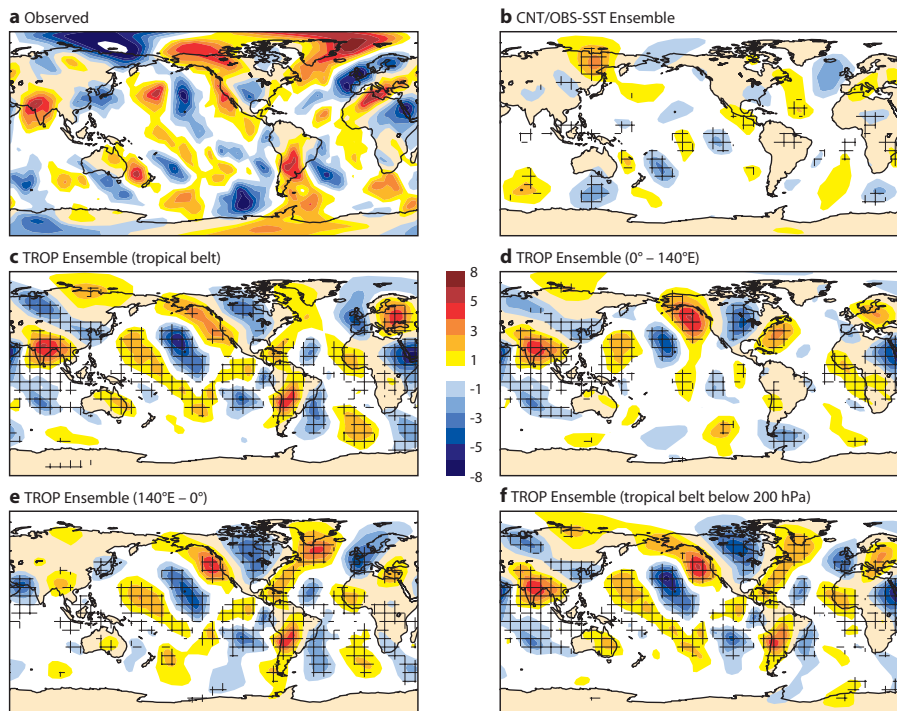

Figure 11 Mean meridional component of the rotational wind anomaly in the upper troposphere (in ms^{-1}) for the winter December to February 2005/06: (a) observed and (b) control ensemble. Also shown is the velocity potential response, which is defined as departure from the control ensemble for the winter of 2005/06, for relaxation (c) in the whole tropical belt, (d) in the tropics from 0°–140°E, (e) in the tropics from 140°E–0° and (f) in the whole tropical troposphere (p>200 hPa). Results in (b) to (f) are based on ensemble mean fields (17 members). Statistically significant differences at the 95% confidence level are hatched. The data have been averaged in the vertical over three pressure levels (300, 250 and 200 hPa).

Using the relaxation technique

First results from using the relaxation technique to understand the origin of extratropical forecast error have been presented. The focus has been on "remote" influences from the tropics and the extratropical stratosphere. Most importantly, our results demonstrate the potential of the relaxation technique for understanding how forecast improvements in certain regions can lead to forecast error reductions in other regions. One question, that the relaxation technique leaves unanswered, however, is what level of predictability in the relaxation areas will actually be achievable by improving the forecasting system.

We feel that there is considerable scope for future forecast improvements in both, the tropics and the stratosphere. In both regions substantial systematic model errors are still present which are likely to hamper successful medium-range and extended-range forecasts. Results from the relaxation technique suggest that certain regions will benefit more from such improvements than others; and it seems that the Euro-Atlantic region will be at the "receiving end". Having said this, it should be kept in mind that possible model improvements will lead to modest improvements in the extended-range. Our results suggest, for example, that it is unlikely that in the future we will obtain the same level of forecast skill beyond D+20 in the Euro-Atlantic region that we presently obtain in the far medium-range (D+5 to D+10, Figure 3).

Furthermore, the relaxation technique is useful for understanding the "origin" of seasonal mean anomalies. Understanding the origin of such anomalies is important when evaluating the performance of ECMWF seasonal forecasts in predicting high impact events. The fact that the cold European winter 2005/06 most likely had its origin in the tropics suggests, for example, that there was some degree of predictability and that improvements of the ECMWF forecasting system would be beneficial when it comes to forecasting such events. By how much seasonal forecasts of the tropical atmosphere could be improved, however, remains unknown at the moment.

Finally, it is perhaps interesting to note that the relaxation technique is not a new diagnostic method. It has already been widely used at ECMWF in the 1980s (*Haseler,* 1982; *Klinker,* 1990; *Ferranti et al.,* 1990) to understand medium-range forecast error in the extratropics. Recently, it has been decided to (re-)implement the relaxation technique in recent model cycles (Cy32r1 and higher). This decision was motivated by different factors.

- It was felt that 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 the production of more forecasts, thereby increasing the robustness of the results.

- The availability of more realistic (re-)analyses (towards which to model is relaxed), particularly in the tropics, makes the relaxation technique much more powerful. This will be especially true with availability of the full ERA-Interim reanalysis in autumn 2008.

For the immediate future it is planned to carry out more case studies. This includes, for example, an investigation of the mechanisms giving rise to anomalously wet Western European summer of 2007. It is also planned to further refine the relaxation code. It would be helpful, for example, to be able to relax the model towards the analysis for specific spatial scales only (scale-dependent relaxation). In this way it would be possible, for example, to prescribe the MJO more directly during the course of the integration. Finally, it is planned to carry out a detailed investigation of the origin of the systematic model error, in particular the systematic underestimation of the frequency of occurrence of Euro-Atlantic blocking events in the extended-range.

Further Reading

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