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Tropical influence on boreal summer mid-latitude stationary waves

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Abstract While organized tropical convection is a well-known source of extratropical planetary waves, state-of-the-art climate models still show serious deficiencies in simulating accurately the atmospheric response to tropical sea surface temperature (SST) anomalies and the associated teleconnections. In the present study, the remote influence of the tropical atmospheric circulation is evaluated in ensembles of global boreal summer simulations in which the Arpege-Climat atmospheric General Circulation Model (GCM) is nudged towards 6-h reanalyses. The nudging is applied either in the whole tropical band or in a regional summer monsoon domain. Sensitivity tests to the experimental design are first conducted using prescribed climatological SST. They show that the tropical relaxation does not improve the zonal mean extratropical climatology but does lead to a significantly improved representation of the mid-latitude stationary waves in both hemispheres. Low-pass filtering of the relaxation fields has no major effect on the model response, suggesting that high-frequency tropical variability is not responsible for extratropical biases. Dividing the nudging strength by a factor 10 only decreases the magnitude of the response. Model errors in each monsoon domain contribute to deficiencies in the model's mid-latitude climatology, although an exaggerated large-scale subsidence in the central equatorial Pacific appears as the main source of errors for the representation of stationary waves in the Arpege-Climat model. Case studies are then conducted using either climatological or observed SST. The focus is first on summer 2003 characterized by a strong and persistent anticyclonic anomaly over western Europe. This pattern is more realistic in nudging experiments than in simulations only driven by observed SST, especially when the nudging domain is centred over Central America. Other case studies also show a significant tropical forcing of the summer mid-latitude stationary waves and suggest a weak influence of prescribed observed SST in the northern extratropics. Results therefore indicate that improving the tropical divergent circulation and its response to tropical SST anomalies remains a key issue for increasing the skill of extratropical seasonal predictions, not only in the winter hemisphere but also in the boreal summer hemisphere where the prediction of heatwave and drought likelihood is expected to become an important challenge with increasing concentrations of greenhouse gases.

Keywords Stationary waves · Climatology · Interannual variability · Tropical forcing · Boreal summer · Seasonal predictability

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1 Introduction

Despite significant improvements in observing and data assimilation systems as well as in model formulation, long-

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range forecasting with coupled ocean–atmosphere General Circulation Models (GCM) remains a challenge for the global climate modelling community. The modern age of long-range forecasting is considered to have been born in the late 1990s when several meteorological centres successfully predicted the major 1997–1998 El Niño event in the equatorial Pacific. The El Niño Southern Oscillation (ENSO) is indeed the main mode of interannual variability in the tropics. Theoretical studies suggest that the associated shift in equatorial convection is likely to trigger stationary barotropic Rossby waves that can sustain seasonal climate anomalies in the extratropics (Hoskins and Karoly 1981; Webster and Chang 1997). Such remote effects are generally referred to as teleconnections and have been confirmed by observational studies showing a significant statistical link between the tropical Pacific variability and mid-latitude anomalies of sea level pressure, surface temperature and precipitation in both hemispheres (e.g. Trenberth and Caron 2000).

Our ability to predict seasonal climate fluctuations has however reached a plateau with little subsequent improvement in quality (Kirtman and Pirani 2009). Dynamical seasonal forecasting systems have been implemented in several operational centres, but do not always outperform empirical statistical prediction schemes both at mid-latitudes and in the tropics. The skill of seasonal forecasting systems is particularly poor in the boreal summer extratropics. This is true for the North American continent where ENSO is much less influential in summer than in winter (Wallace and Gutzler 1981). This is also clear over Europe where the principal pattern of interannual variability is the North Atlantic Oscillation whose summer expression is only weakly influenced by ENSO (Folland et al. 2009).

This lack of summer skill in the northern extratropics can be related to at least three factors. First, the ENSO phenomenon generally peaks in boreal winter and exhibits a seasonal dependence in persistence known as the “spring barrier” or “predictability barrier” (e.g. Weiss and Weiss 1999). Second, ENSO teleconnections are stronger in the winter hemisphere where the subtropical jet is closer to the tropics and is thereby more sensitive to the diabatic forcing induced by moist convection (e.g. Hoskins and Ambrizzi 1993). Third, land–atmosphere coupling can be relatively strong in summer compared to remote SST forcings (e.g. Conil et al. 2009; Douville 2009a) and is not necessarily well represented in dynamical seasonal predictions given model uncertainties (Koster et al. 2004) and the limitations of the current-generation data assimilation systems.

The severe socio-economic impacts of the summer 2003 European heat wave (Schär et al. 2004) and the emerging picture of an increased frequency of mid-latitude droughts and heat waves in a warmer climate (Meehl and Tebaldi 2004) emphasize the need to develop efficient long-range forecasting techniques in the boreal summer extratropics. Given the limited success of operational systems, it is probably useful to come back to more idealized studies in order to identify the main deficiencies of GCMs and the most promising sources of potential predictability. While increasing efforts are devoted to the evaluation of extratropical sources of predictability at the land surface (e.g. Douville 2009a) and/or in the stratosphere (e.g. Douville 2009b), the fact remains that tropical SSTs exert a major influence on atmospheric variability at the seasonal timescale and that model errors in the tropics and/or associated teleconnections continue to hamper seasonal prediction skill (Kirtman and Pirani 2009).

The present study, conducted in the framework of the French IRCAAM (Influence Réciproque des Climats d’Afrique de l’Ouest, du sud de l’Asie et du bassin Méditerranéen) project, is aimed at a better understanding of the tropical influence on summer mean climate and interannual variability in the boreal extratropics. Former studies have been mainly based on either simple atmospheric models driven by tropical heating anomalies (e.g. Hoskins and Karoly 1981) or atmospheric GCM simulations driven by observed SSTs (e.g. Hoerling and Kumar 2002). The focus was mainly on the boreal winter hemisphere. Yet, boreal summer monsoon climates show strong diabatic heating with considerable year-to-year variability. Moreover, simple model experiments suggest that tropical–extratropical teleconnections are not confined to the winter hemisphere. The summer hemisphere can also support stationary Rossby waves if the heating occurs in the vicinity of the subtropical jet (Lee et al. 2009).

Here the emphasis is on the influence of boreal summer monsoons on the northern extratropical climatology and variability. A set of global atmospheric simulations has been performed in which the Arpege-Climat atmospheric GCM is nudged towards the European Centre for Medium-range Weather Forecasts (ECMWF) analyses. Such an experimental design is not really new and was tested at ECMWF in the early 1990s (Klinker 1990). It was however penalized by the lack of observations in the tropics and the limitations of data assimilation systems. Substantial improvements have been made in these fields over the last two decades and this strategy appears again as a promising approach to diagnosing the origin of systematic and long-range prediction errors in atmospheric GCMs. Indeed, this technique has been re-implemented in recent cycles of the ECMWF model (Jung et al. 2008, 2009). In this paper, a relaxation is applied either in the whole tropical band or in a selected monsoon domain.

The model and experimental design are described in Sect. 2. Section 3 shows sensitivity tests to nudging strength, low-pass filtering of ECMWF data as well as nudging domain, and describes the systematic impact on the model climatology with a focus on the Northern Hemisphere stationary waves. Section 4 presents additional ensembles of summer simulations designed to evaluate the role of different tropical forcings on the 2003 European heat wave. Other case studies are briefly discussed in Sect. 5, as well as the role of the mid-latitude SST forcing. Section 6 summarizes the main conclusions and outlines some prospects.

2 Experimental design

Two main techniques can be used to control the tropical circulation in global atmospheric simulations: the introduction of a 3D diabatic forcing in the prognostic equation for temperature (e.g. Cassou et al. 2005) or the implementation of a regional nudging towards atmospheric analyses (e.g. Klinker 1990; Bielli et al. 2009). The main difficulty with the first method is the definition of an accurate diabatic forcing (Chan and Nigam 2009) and the possibility that the tropical circulation may not respond to this forcing in a realistic way. The nudging technique that is used in the present study enables a stronger control of the tropical atmosphere and a potentially more direct comparison of the model response with observations.

All simulations are based on version 4 of the Arpege-Climat model derived from the Arpege/IFS numerical weather prediction model developed jointly by ECMWF and Météo-France. It is a spectral model with a progressive hybrid σ-pressure vertical coordinate. The model is used in its standard configuration (linear T63 truncation, reduced 128 by 64 Gaussian grid, 31 vertical levels). The dynamical core is close to the one used at ECMWF with a semi-implicit, semi-Lagrangian, two time level discretization scheme. The physical package is partly inherited from the Météo-France operational weather forecast model and is very similar to the one used by Salas-Mélia et al. (2005) in CMIP3 simulations. In particular, it includes a mass flux convective scheme with a Kuo-type closure (Bougeault 1985) that has a strong impact on the vertical profile of diabatic heating in the tropical troposphere.

The nudging is applied at each time step (every $\Delta t = 30$ min) to the horizontal wind, temperature, specific humidity and the logarithm of surface pressure in order to simulate a "quasi-perfect" tropical atmosphere. This is done by adding a $-\lambda(y - y_{\mathrm{ref}})/\Delta t$ extra term in the model tendency equations where y is the model state vector, y_{ref} is the reference field towards which the model is relaxed and λ is the strength of the relaxation. In the present study, the reference fields are the 6-h ERA40 reanalyses (Uppala et al. 2005) or ECMWF operational analyses (for the summer 2003 case study) which are interpolated linearly at the model time step. Horizontal and vertical interpolation onto the model grid are also necessary and have been done as accurately as possible using a particular configuration of the Arpege/IFS system. Given the limited vertical resolution of our experiments, the main difficulty for the interpolation scheme is the representation of strong inversions in the subtropical planetary boundary layer. This is presumably not a major issue since our main objective is rather to improve the simulation of wind and temperature profiles in deep convective areas.

Generally speaking, the dimensionless λ coefficient in Arpege-Climat can be a function of the variable, the location (longitude, latitude and vertical level) and the scale. Here the relaxation is applied within a limited domain and is therefore carried out in grid point space so that no scale selection is done. Within the nudging domain λ is horizontally uniform, but has a vertical profile (i.e. the relaxation vanishes in the three lowest and five top model levels) in order to let the divergent tropical circulation adjust to the relaxation, especially in the lower troposphere due to the different orography between the Arpege-Climat and ECMWF models. By default, the maximum nudging is fixed at a 5-h e-folding time for the wind components (i.e. $\lambda = 1/5 = 0.1$), against 12 h (i.e. $\lambda = 1/12 = 0.04$) for other variables. These values are derived from former sensitivity tests (Guldberg et al. 2005) and allow the model to capture not only the ERA40 large-scale dynamics, but also the large-scale fraction of the observed precipitation (without a strong perturbation of the diurnal cycle since the nudging only accounts for a small fraction of the right-hand term of the prognostic equations at each time step).

The control experiment, CtCl, is a 30-year simulation (after a 2-year spin-up) with specified ERA40 monthly mean climatological SST averaged over the 1971–2000 period. All nudging experiments and case studies consist in ensembles of 30 boreal summer integrations initialized on May 15th from each individual year of CtCl. Daily and monthly outputs have been archived from June 1st to September 30th, i.e. after a 15-day spin-up allowing the Arpege-Climat model to adjust to the tropical nudging and/or the perturbed SST forcing (for case studies). Four domains of nudging have been considered: the whole tropical band (Tr), West Africa and the surrounding tropical Atlantic (Af), South Asia and the northern Indian Ocean (As) and Central America and the surrounding eastern tropical Pacific and Caribbean basins (Am). This latter domain is not a canonical monsoon region, but it is a source of strong diabatic heating that might have played a role in favoring the summer 2003 European heat wave (Cassou et al. 2005). All domains are specified between 5°S and 20°N and are therefore centered on the boreal summer Inter-Tropical Convergence Zone (ITCZ). They are all surrounded by a buffer zone of about 900 km wide in which the

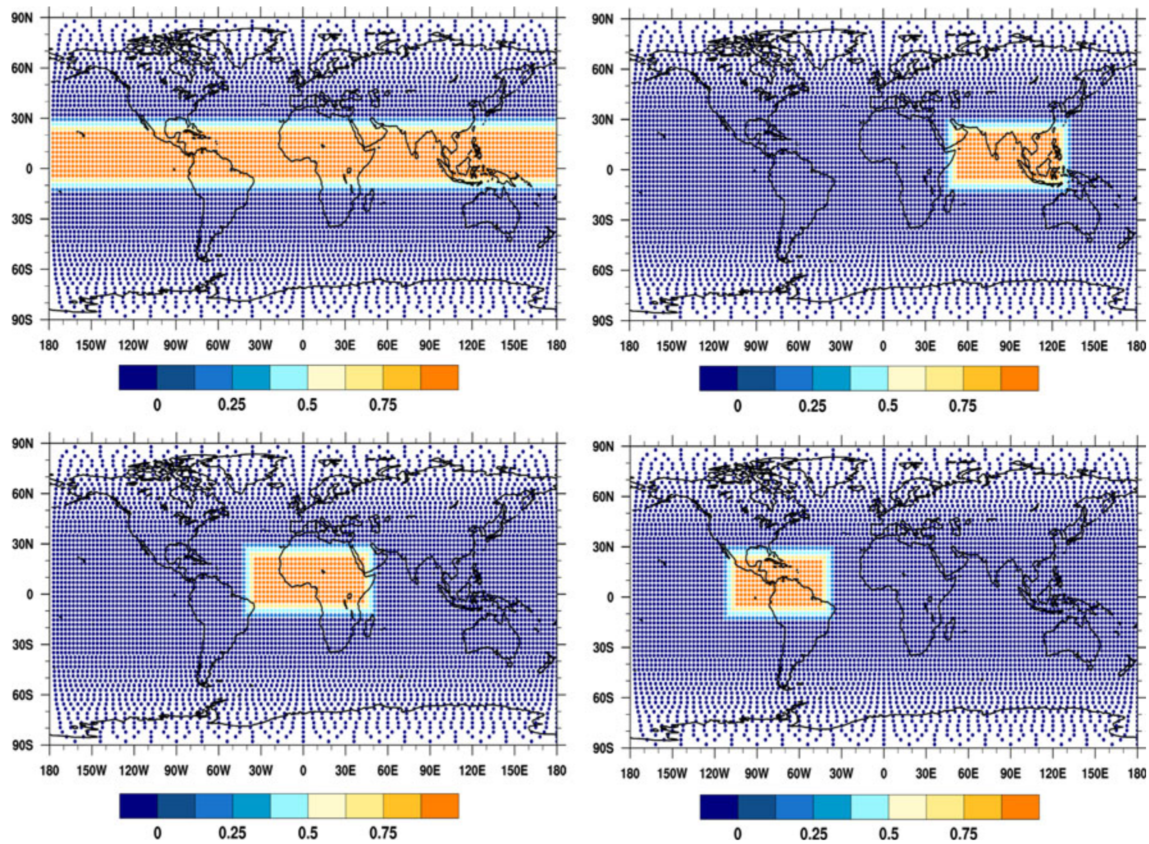

Fig. 1 The four nudging masks used in the Tr, As, Af, and Am experiments respectively. Each pixel is a grid cell of the Arpege-Climat reduced gaussian grid. The nudging strength is maximum in the *dark orange box* and the relaxation vanishes in the *dark blue* domain where the model is completely free

nudging vanishes progressively to ensure a smooth transition between the nudged and free atmosphere (Fig. 1). In the Northern Hemisphere, the southward boundary of the "fully free" atmosphere is therefore at 30°N.

A first set of nudging experiments is summarized in Table 1. For each nudging domain, the systematic effect of tropical relaxation has been assessed over the 1971–2000 period using prescribed monthly mean climatological SSTs. Preliminary tests have been conducted with nudging in the whole tropical band to assess the sensitivity to λ and to low-pass filtering of relaxation fields. Three options have been considered: strong nudging (λ default values) towards the raw ERA40 data (N1); strong nudging towards low-pass filtered ERA40 data using a 25-day cut-off period (N2) and weak nudging (λ divided by a factor 10) towards low-pass filtered ERA40 data (N3). Options N2 and N3 have been tested to check that option N1 does not lead to numerical instabilities given the limited ability of the model to adjust to the tropical relaxation. Option N2 could also be useful to study timescale interactions and can be compared with N1 to assess the possible extratropical influence of the high-frequency tropical variability. Note that this point will be only briefly discussed in Sect. 3. Note also that the question of optimizing the λ coefficient is beyond the scope of the present study. This is indeed a difficult issue given the flexibility of the nudging technique and the fact that the nudging strength here varies not only

Table 1 Matrix of climatological experiments

Type of nudging			Name of experiment
Domain	Strength	ERA40 data	
None			CtCl
Tropics	Strong	6-h	TrN1Cl/TrNuCl
	Strong	Filtered	TrN2Cl
	Weak	Filtered	TrN3Cl
American monsoon	Strong	6-h	AmNuCl
African monsoon	Strong	6-h	AfNuCl
Asian monsoon	Strong	6-h	AsNuCl

Each experiment (except the CtCl control experiment which is a continuous 30-year simulation and provides the initial conditions for the other experiments) is an ensemble of 30 integrations from May 15 to September 30 driven by climatological monthly mean SST. In the nudging experiments, the model is relaxed towards ERA40 from summer 1971 to summer 2000. Note that experiment TrN1Cl is also referred to as TrNuCl from one variable to the other, but also both vertically and horizontally.

3 Model JJAS climatology

Figure 2 shows latitude-pressure zonal mean cross sections of zonal wind and temperature averaged over 30 summer (June–September, JJAS hereafter) seasons. It illustrates both the principle of the nudging technique and its limited impact on the zonal mean model climatology. Note that here and in all subsequent figures in Sect. 3 we have decided to show the reverse of the model errors in order to ease the comparison with the impact of nudging, and to assess whether or not nudging leads to an improved climatology.

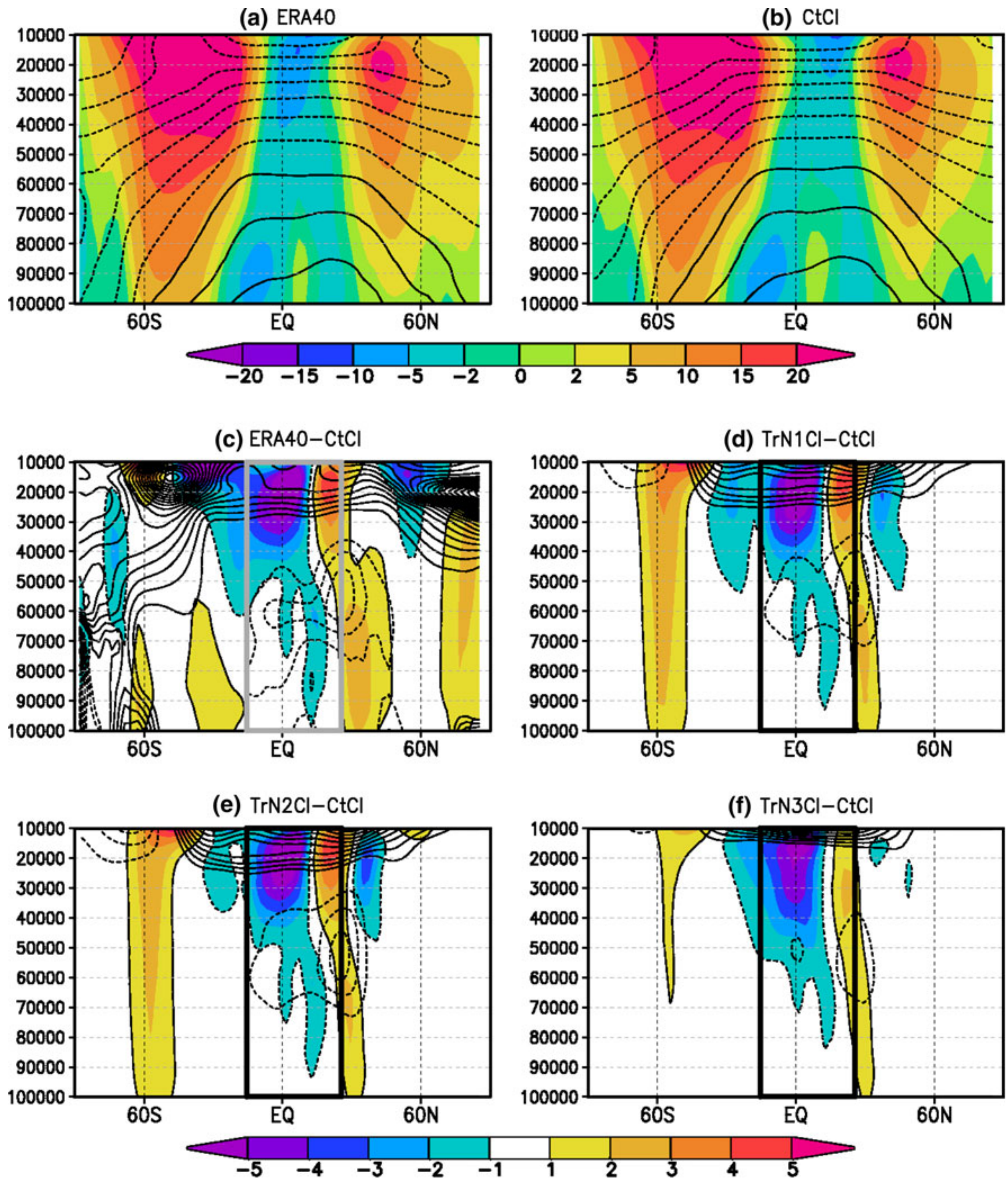

Fig. 2 JJAS climatological zonal mean latitude-pressure cross section of zonal wind (m/s, *shaded*) and temperature (K, *contours*): **a** ERA40, **b** control experiment, **c** reverse of model errors, **d–f** impact of *tropical* nudging (see text for the experiment details). *Black rectangles* represent the nudging domain. *Grey rectangle* in **c** is drawn for an easier comparison with (**d–f**). Contour interval for temperature is 10 K in (**a–b**) and 0.5 K in (**c–f**)

All simulations in Sect. 3 share the same climatological SST forcing and differ only by the tropical relaxation. Compared to ERA40, the control simulation (CtCl) shows a reasonable climatology, but the model is too warm in the mid-troposphere on both sides of the ITCZ, and is too cold in the upper troposphere. These recurrent tropical biases are partly due to deficiencies of the mass-flux moist convection scheme in the Arpege-Climat model (J.-F. Guérémy, personal communication). Deficiencies in the radiative scheme and the limited vertical resolution can also contribute to the cold bias around the tropopause. Consistent with thermal wind balance, the control simulation shows an underestimation and a poleward shift of the tropical easterly jet (TEJ) despite a reasonable signature of the monsoon wind reversal in the lower troposphere. The subtropical westerly jet is also too weak in the mid-troposphere and expands too far poleward, which can influence the propagation of planetary waves and the simulation of tropical–extratropical teleconnections (Hoskins and Ambrizzi 1993). Note that similar results are found when the model is driven by observed monthly mean SST (not shown) so that the use of climatological SST boundary conditions is not responsible for the model biases.

Figure 2d–f shows the impact of the various nudging options applied in the tropical band and can be compared to Fig. 2c in order to assess the possible benefit of the relaxation on the model climatology. When the model is strongly relaxed towards the raw ERA40 re-analyses (N1), the tropical errors are eliminated but the extratropical climatology is only slightly modified in the Northern (i.e. summer) Hemisphere. The artificial meridional gradient of temperature introduced between the nudged and free upper troposphere in the Southern (i.e. winter) Hemisphere leads to increased westerlies that become stronger than observed. The low-pass filtering of the ERA40 data (N2) does not change the response of the model much, suggesting a weak interaction between the high frequency variability in the tropics and the mean climate in the extratropics. Not surprisingly, a weaker nudging (N3) leads to a weaker impact on the model climatology, but the response is qualitatively the same as in the other experiments.

Figure 3 shows the JJAS climatology of the eddy component (after removal of zonal mean values) of velocity potential (contours) and stream function (shading) at 200 hPa. The main feature of the velocity potential distribution is the Walker circulation over the Indo-Pacific basin, with rising vertical motion and associated upper troposphere divergence (i.e. velocity potential minimum) over the West Pacific warm pool and subsiding branches over the Eastern Pacific and Atlantic oceans. The control experiment (Fig. 3b) shows reasonable agreement with ERA40 (Fig. 3a). The reverse of model errors (Fig. 3c) however indicates that this asymmetric zonal circulation is generally too strong and slightly shifted. There is erroneously large-scale upper-level convergence over the central equatorial Pacific and, to lesser extent, the West African continent, and a tongue of increased divergence from East Africa to the West Pacific warm pool. This might be related to an equatorial shift of the Asian monsoon and the associated diabatic heating in the Arpege-Climat model.

Due to the removal of the zonal mean values, the eddy 200 hPa stream function in ERA40 does not show the dominant signature of the westerlies in both hemispheres but emphasizes a pair of upper troposphere anticyclones associated with the TEJ over the Asian sector. While this feature is reasonably captured by Arpege-Climat, the model shows upper troposphere cyclonic biases on each side of the central equatorial Pacific (Fig. 3c). This pattern can be understood, to a first approximation, as a Gill (1980) response of the tropical atmosphere to the underestimated diabatic heating and associated upper-level divergence along the climatological ITCZ in Arpege-Climat. According to Gill's analytic model, a cyclonic low-level flow and an anticyclonic upper-level flow form on the western margins of an equatorial heating zone. This is broadly what is seen in Fig. 3c. This dipole pattern could be responsible for some systematic errors found in the mid-latitude circulation, especially in the Southern Hemisphere where the errors form a planetary wave train originating from the central Pacific. This hypothesis is confirmed by Fig. 3d, showing a remarkable positive impact of tropical nudging on the 200 hPa eddy stream function. The global Anomaly Correlation Coefficient (ACC, simple Pearson correlation without latitude weighting) with the reverse of model errors is 0.83. ACC here only tests the position and not the amplitude of the simulated patterns (yet also improved by the nudging). Note that the correction to the model's stationary waves is not limited to the nudging domain, since the correlation is close to 0.6 and 0.7 in the northern and southern extratropics respectively. The stronger model improvement in the winter hemisphere is consistent with the Rossby wave theory (Hoskins and Ambrizzi 1993). A significant improvement is also found over North Pacific, but not over North Atlantic.

The low-pass filtering of the ERA40 reference fields has no major impact on the simulated extratropical stationary waves (Fig. 3e vs. 3d). The mid-latitude seasonal mean errors are therefore dominated by the low-frequency component of the tropical errors. Note also that the nudging has a limited impact on the mid-latitude transient eddies (not shown) whose seasonal mean activity is underestimated in all experiments, partly due to the limited horizontal resolution of the Arpege-Climat GCM. Finally, dividing the nudging strength by 10 (Fig. 3f vs. 3e) leads to a less efficient correction of the large-scale upper-level divergence errors in the tropics, and thereby to a weaker

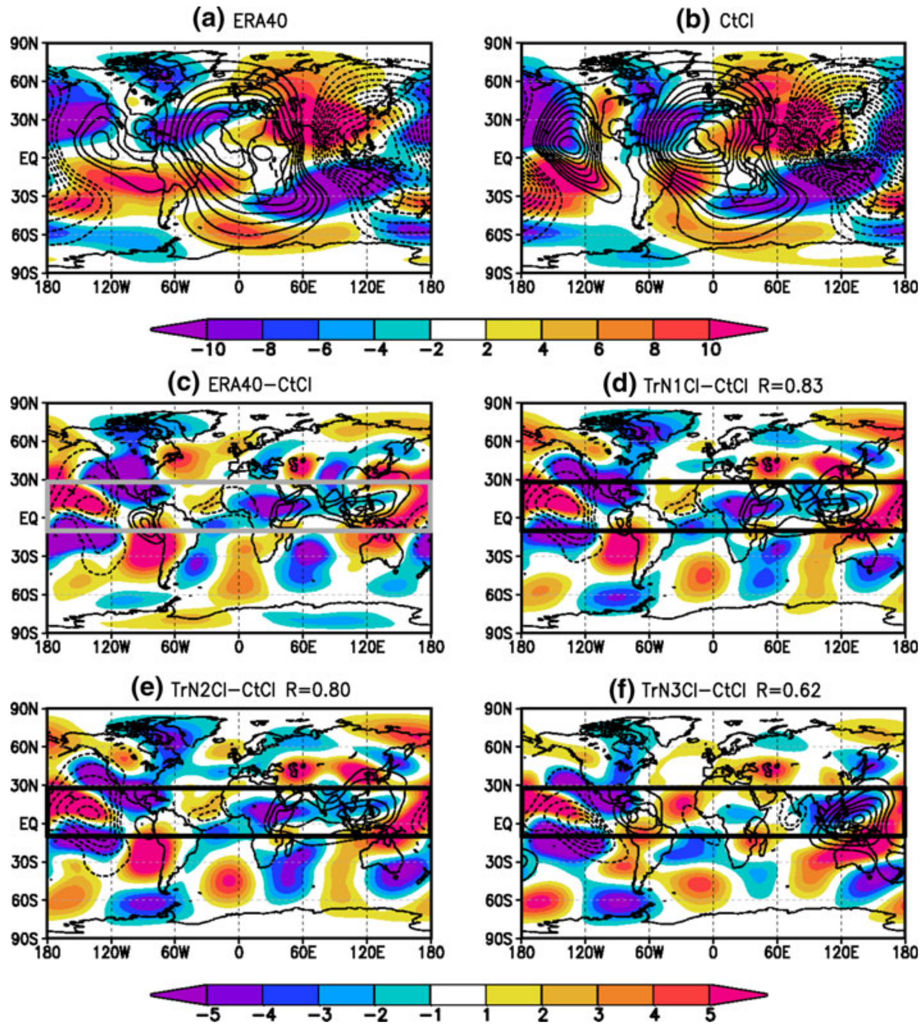

Fig. 3 JJAS climatological eddy component of velocity potential (*contours* in 10^6 m^2/s) and stream function (*shading* in 10^6 m^2/s) at 200 hPa: **a** ERA40, **b** control experiment, **c** reverse of model errors, **d–f** impact of *tropical* nudging. *R* is the ACC with the negative of model errors for stream function. *Black rectangles* represent the nudging domains. *Grey rectangle* in (**c**) is drawn for an easier comparison with (**d–f**)

response and improvement of the mid-latitude stationary waves.

In line with the motivation of the IRCAAM project, Fig. 4 focuses on the Northern Hemisphere stationary waves, as described by the JJAS climatology of the 500 hPa eddy geopotential height (hereafter Z500). In reasonable agreement with ERA40, the control experiment shows minimum values over the Aleutian Low and over the Labrador Sea, and maximum values over North America and Scandinavia. Looking at the reverse of model errors (Fig. 4c) however reveals both a shift and a lack of amplitude in the simulated climatology. Such model errors are consistent with difficulties commonly encountered by GCMs in simulating the northern mid-latitude planetary waves (e.g. Lucarini et al. 2007). The impact of the tropical nudging is clearly positive, as found in Fig. 3 and further illustrated here by the spatial correlation between Fig. 4c and Fig. 4d–f. This is more obvious over North America than over Europe, where the dipole error found in Fig. 4c is only partly rectified through the tropical relaxation, especially when the nudging strength is divided by 10. Once again, the low-pass filtering of the ERA40 reference fields has no major impact on the model extratropical response to tropical nudging.

In summary, option N1 globally shows the strongest improvement of the JJAS model climatology and will be used for the rest of this study. (Note that N1 will be hereafter referred to as Nu in the name of the nudging experiments, cf. Tables 1 and 2.) A different decision might have been taken if reducing the nudging strength and letting the model build its own tropical high-frequency variability (N3) had not lead to a weaker improvement of the mid-latitude stationary waves. We do not claim that option N1 is an optimal implementation of the nudging technique, but that our results are not strongly sensitive to the nudging strength. Additional sensitivity tests with a stronger nudging (not shown) confirm this hypothesis and do not show significant differences compared to option N1, at least on monthly to seasonal timescales.

Coming back to the 200 hPa eddy velocity potential and stream function, Fig. 5 shows the nudging impact not only when the relaxation is applied in the whole tropical band,

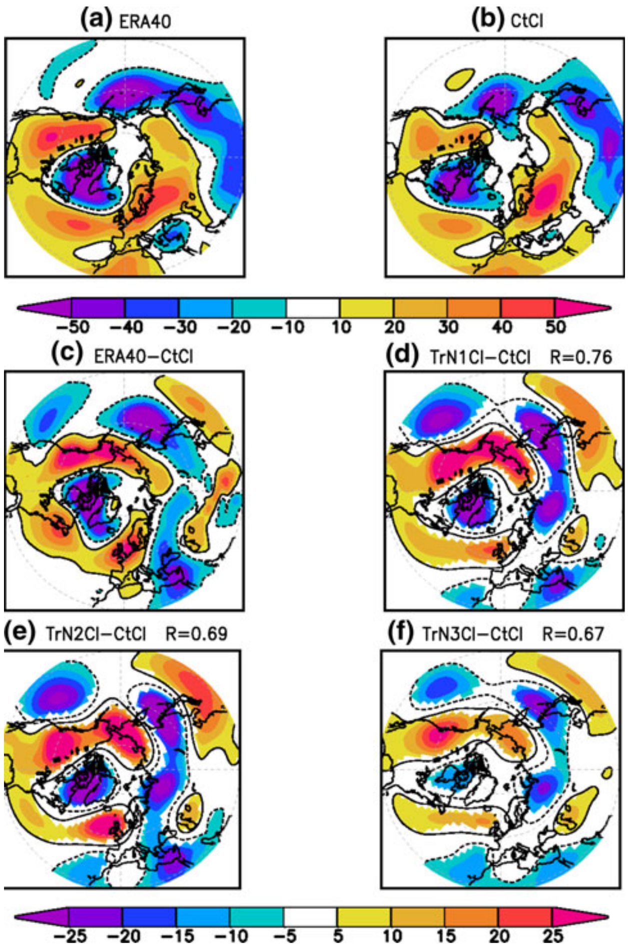

Fig. 4 Same as Fig. 3, but for the JJAS climatological eddy component of geopotential height (m) at 500 hPa in the northern extratropics. *Shaded differences* in (**d–f**) are statistically significant at a 5% level

Table 2 Matrix of case studies

Nudging domain	Monthly SST	
	Climatology	Year YY
None		CtYY
Tropics	TrNuYYCl	TrNuYYYY
American monsoon	AmNuYYCl	AmNuYYYY
African monsoon	AfNuYYCl	AfNuYYYY

Each experiment (except the CtCl control experiment which is a continuous 30-year simulation and provides the initial conditions for the other experiments) is an ensemble of 30 integrations from May 15 to September 30 of year YY. The prescribed monthly mean SST forcing is either climatological (Cl suffix) or observed (YY suffix). Each nudging experiment uses a strong nudging towards 6-h ECMWF data and must be compared with the corresponding climatological experiment in Table 1. No case study has been conducted with nudging only over the As domain

but also for the three selected monsoon domains (Am, Af, As, cf. Fig. 1). Each monsoon region appears to contribute to some model errors in the extratropics. Note however that additivity of the regional forcings cannot be tested given the lack of a Pacific nudging domain. Note also that the extratropical response found in Fig. 5b–d is the consequence of an adjustment of the whole tropical circulation. For example, increasing the large-scale subsidence over the eastern Pacific in AmNuCl (Fig. 5b) leads to changes in the upper troposphere circulation over the Indo-Pacific. The large velocity potential anomalies close to the relaxation boundaries in AfNuCl (Fig. 5c) also illustrate this remark and highlight the numerical difficulties of the nudging technique and the need for a buffer zone around the nudging domain. The lack of systematic improvement of the tropical circulation in the Am, Af and As experiments suggests that the model biases in the tropics are not dominated by remote dynamical mechanisms, but are rather due to poorly parametrized regional diabatic processes. Such a hypothesis is at least consistent with a recent study in which the Arpege-Climat model has been nudged everywhere outside Africa without a clear improvement of the West African monsoon climatology (Pohl and Douville 2010).

Therefore, Fig. 5 only shows that a poor simulation of the Asian or African monsoon is not the main reason for the model errors in the extratropics. None of the regional nudging experiments leads to a model rectification that is comparable with the results of TrNuCl. Whether this relies to the global versus regional scale of the tropical nudging or indicates a dominant influence of systematic errors in the central tropical Pacific, only accounted for in TrNuCL, cannot be tested without Pacific domain in our experimental design. The second hypothesis is however supported by Fig. 6 showing the eddy Z500 response in the northern extratropics. Both the Asian and African nudging experiments have a significant impact over Eurasia, but they show a limited influence over North Pacific and North America compared to AmNuCl. This latter experiment shows a significant improvement of the stationary wave climatology in the western hemisphere and explains a substantial fraction of the signals found in TrNuCl. While this result suggests some additivity of the regional forcings, a perfect additivity would be surprising given the nonlinearities of the atmospheric dynamics. Again, this hypothesis cannot be tested without a Pacific nudging domain in our experimental design. Additivity will be discussed in a forthcoming study using a linear version of a dry primitive equation model where a fixed basic state responds to time independent forcing anomalies.

4 Summer 2003 case study

A record-breaking heatwave affected western Europe in summer 2003 (Schär et al. 2004), where mean summer

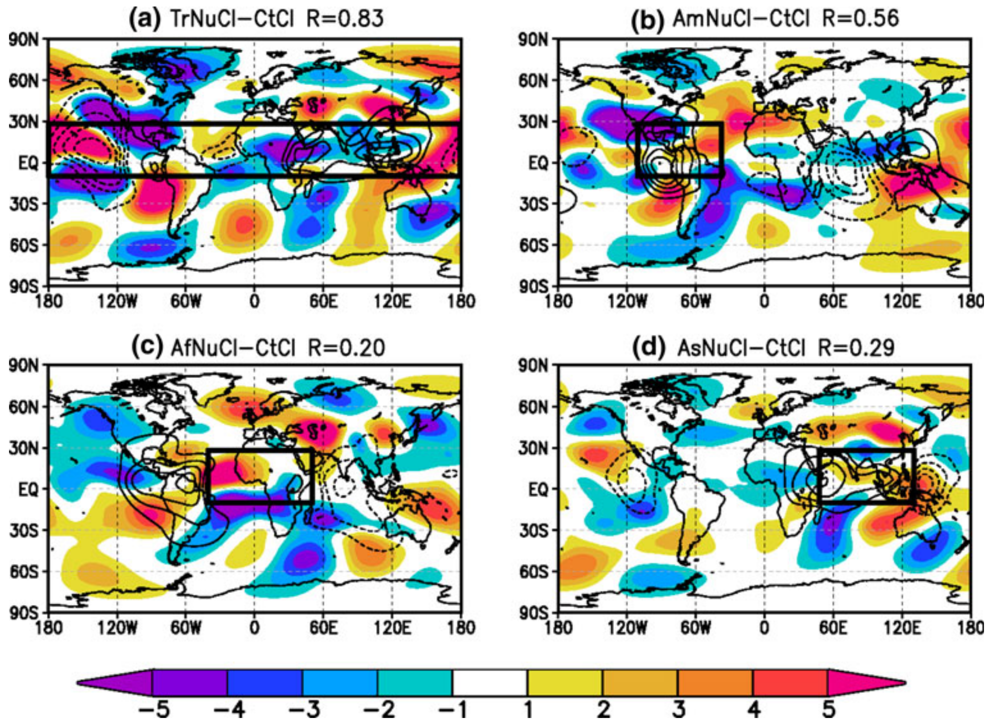

Fig. 5 Impact of *regional* nudging on the JJAS climatological eddy component of velocity potential (*contours* in 10^6 m^2/s) and stream function (*shading* in 10^6 m^2/s) at 200 hPa. Four domains of nudging are compared: **a** tropics, **b** Central America, **c** Africa, **d** South Asia. *R* is the ACC with the negative of model errors for stream function. *Black rectangles* represent the nudging domains

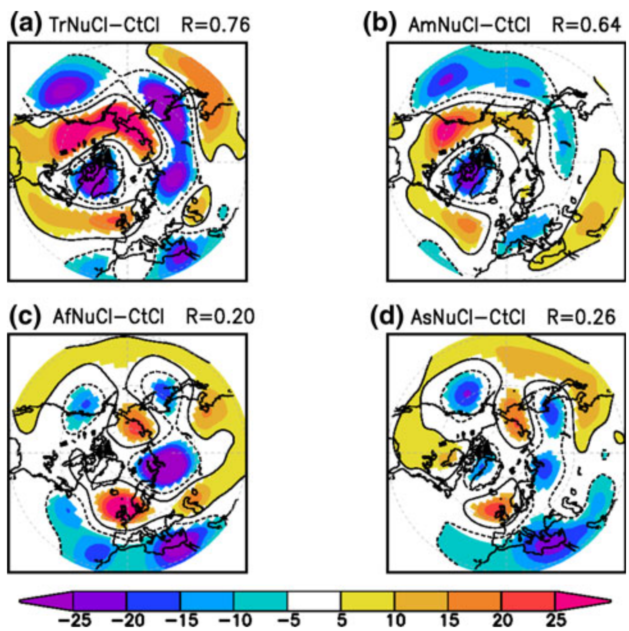

Fig. 6 Same as Fig. 5, but for the JJAS climatological eddy component of geopotential height (m) at 500 hPa in the northern extratropics. *Shaded differences* are statistically significant at a 5% level

temperature (especially June and August) exceeded locally the 1961–1990 climatology by five standard deviations, leading to massive overmortality and socioeconomic impacts. While increasing atmospheric greenhouse-gas concentrations and their impact on daily temperature variability are probably relevant to account for the magnitude of this extreme event (Schär et al. 2004), the dynamics of the summer 2003 heatwave remains a matter of debate (Cassou et al. 2005; Black and Sutton 2006; Jung et al. 2006). Our objective here is not so much to enter into this debate, but rather to illustrate how the nudging technique can be useful to disentangle the contribution of different tropical forcings.

Figure 7c shows the global distribution of the JJAS 2003 SST anomalies compared to the 1971–2000 HadSST-2 (http://badc.nerc.ac.uk/data/hadsst2) climatology (Fig. 7a). Warm anomalies exceeding 1 K (with local values as high as +4 K) are found along the coasts of western Europe, as well as in the northeast Atlantic and the Mediterranean sea. Such anomalies are not directly responsible for the continental heatwave but are rather the consequence of a persistent positive geopotential height anomaly over Europe (Jung et al. 2006). In the IRCAAM project, twin atmospheric simulations coupled to a one-dimensional ocean model however suggest that mid-latitude SSTs in the northeast Atlantic basin can amplify the heatwave through a positive feedback on both surface heat budget and large-scale circulation (Bielli et al. 2010, in preparation). In contrast with the strong surface warming in North Atlantic, Fig. 7c shows relatively weak SST anomalies in the tropics. Using ensembles of atmospheric simulations driven by global observed SST with the Indian Ocean set or not to climatology, Black and Sutton (2006) however suggested a mechanism by which the Indian Ocean tropical warming may have contributed to the persistence of the temperature anomalies over Europe.

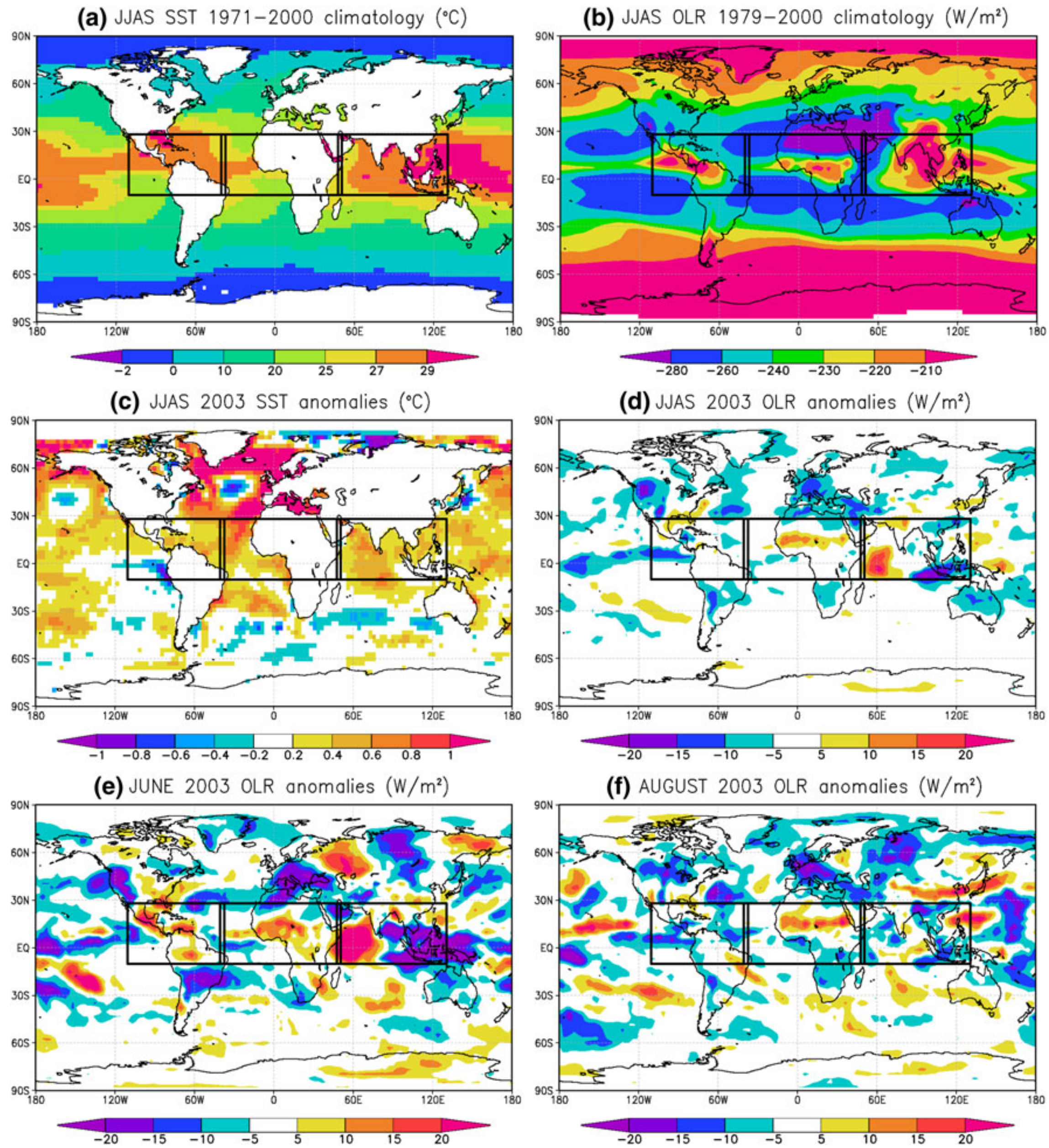

Fig. 7 **a** HadSST JJAS SST (°C) climatology (1971–2000), **b** NOAA JJAS OLR (W/m^2) climatology (1979–2000), **c** HadSST 2003 SST anomalies (°C) in JJAS, **d–f** NOAA 2003 OLR anomalies (W/m^2) in JJAS, June and August respectively

In this section, the focus is on the Carribean and West African regions, in line with the possible tropical Atlantic influence proposed by Cassou et al. (2005). The exceptional heat of summer 2003 occurred during two successive periods: the first one in June and the second one in early August. At the same time, the Atlantic ITCZ showed a northward shift compared to its summer climatology. This is illustrated by Fig. 7d–f based on the NOAA (http://www.esrl.noaa.gov/psd/data/gridded/data.interp_OLR.html) outgoing longwave radiation (OLR) satellite data available since the late 1970s. In the tropics, the OLR climatology (Fig. 7b) shows maximum values over deep convective regions, i.e. over the three monsoon domains where the regional nudging has been tested in the IRCAAM project. During summer 2003 enhanced convection is not only found over the equatorial Indian Ocean, but also over the Sahel and Carribean though with intraseasonal changes. The Carribean anomalous heating is more obvious in June (Fig. 7e), while the enhanced rainy season over the Sahel is found in both June and August (Fig. 7f). Such observations motivated a numerical sensitivity experiment by Cassou et al. (2005) who suggested a different mechanism for enhancing heatwave probability in June and August respectively. The first event could be related to a Rossby wave train pattern triggered by the Caribbean convective heating, while the second event could reveal a direct meridional atmospheric cell triggered by the enhanced West African monsoon flow.

The summer 2003 case study is therefore a good candidate to illustrate the potential of the grid point nudging technique. It allows us to revisit the study by Cassou et al. (2005) where the National Center for Atmospheric Research (NCAR) atmospheric GCM was perturbed by diabatic heating anomalies derived from observed OLR over the tropical Atlantic and West African domains. Grid point nudging represents an alternative and possibly more direct technique to drive the tropical divergent circulation. Table 2 summarizes the experimental design of a prototype case study. Three ensembles of 30 JJAS 2003 simulations, corresponding to the Tr, Am and Af nudging domains, have been first performed using prescribed climatological SST and will be compared with their respective 30-year nudged experimental means (i.e. TrNuCl, AmNuCl and AfNuCl). We are thus comparing a 30-member ensemble mean for 2003 with a 1971–2000 climatology. This strategy allows us to isolate the impact of interannual variability on model response over and above the general effect of nudging over the 30-year period. It also provides a test for the statistical significance of the simulated JJAS 2003 anomalies. Note that the nudging has not been tested over South Asia, which could be the focus of another study.

Figure 8 shows the JJAS response of the 200 hPa eddy component of the global atmospheric circulation. The hypothesis of a North Atlantic Rossby wave train, originating from the Carribean and leading to a persistent anticyclonic anomaly over western Europe, is compatible with the stream function anomalies found in the operational ECMWF analyses (Fig. 8a). However, no clear signal appears in the eddy velocity potential field over the Carribean that could signal strong anomalous diabatic heating in this region. As discussed in Cassou et al. (2005), such a signal appears more clearly in the ECMWF data when focusing on the month of June (not shown) and does not necessarily persist during the whole summer season. A stronger seasonal mean increase in upper divergence is found over the Indian Ocean, in line with the possible interaction with the warm SST anomalies in this basin (Black and Sutton 2006)

When the nudging is implemented over the whole tropical band (Fig. 8b), the main anomalies of eddy velocity potential are well captured by the Arpege-Climat model, thereby suggesting a significant control on the divergent tropical circulation. Eddy stream function anomalies however only show limited similarity with the ECMWF data (as indicated by a global anomaly correlation coefficient of 0.38) and the North Atlantic wave train pattern is hardly discernible. When the nudging is centred over Central America, the eddy velocity potential shows increased large-scale divergence over this region, with eddy stream function anomalies that can be understood as a Gill response to the regional heating anomaly. The anticyclonic cell that appears northwest of the upper divergence anomaly favors a Rossby wave train over North Atlantic with a weak but significant positive anomaly over

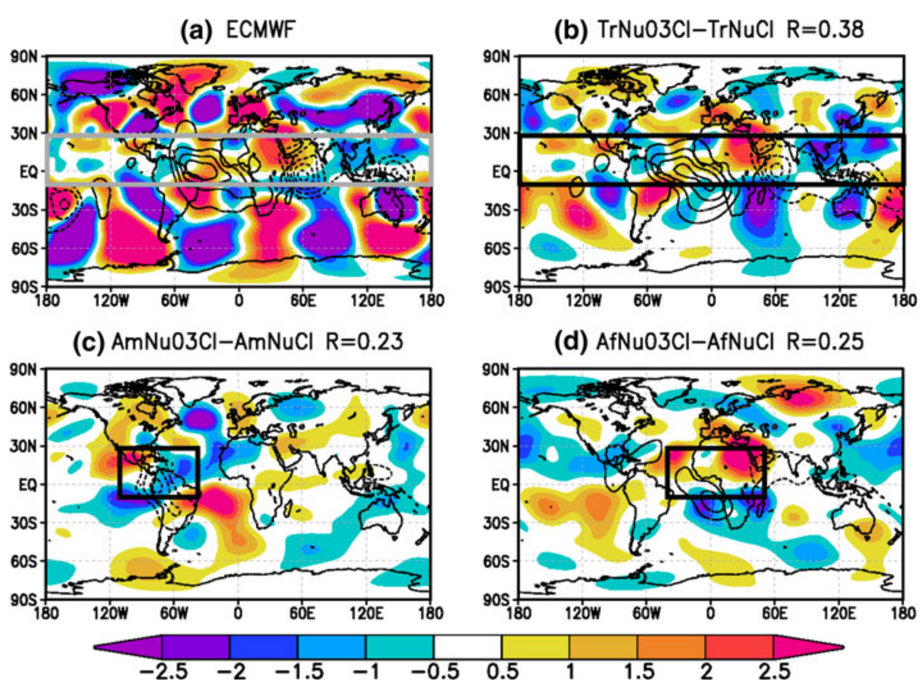

Fig. 8 JJAS 2003 eddy component anomalies of velocity potential (*contours* in 10^6 m^2/s) and stream function (*shading* in 10^6 m^2/s) at 200 hPa. **a** ECMWF operational analyses relative to the 1971–2000 ERA40 climatology, **b–d** Nudging experiments driven by climatological SST. R is the ACC with ECMWF data for stream function. *Black rectangles* represent the nudging domains. *Grey rectangle* in (**a**) is drawn for an easier comparison with (**b–d**)

western Europe. Nudging the model only over West Africa also leads to positive anomalies, but it is unclear whether this response is or not associated with a modulation of the regional Hadley cell.

Figure 9 shows the eddy Z500 response and confirms the relevance of the divergent circulation anomalies around Central America for simulating the positive Z500 signal over western Europe. The strong consistency with the 200 hPa eddy stream function response and the barotropic nature of the low-level geopotential response (not shown) support the Rossby wave hypothesis of Cassou et al. (2005). In line with Fig. 8, significant positive eddy Z500 anomalies are also found when the nudging is applied over Africa and both Am and Af domains contribute to the response found in the Tr nudging experiment. Focusing on June rather than on the whole summer season gives a different perspective with a dominant contribution of the Am domain (Fig. 10). Moving to August (Fig. 11) suggests that the tropical Atlantic heating anomalies also played a significant role in the second peak of the 2003 heatwave, although the simulated wave train pattern is slightly shifted compared to the ECMWF data. The Af domain also shows a significant eddy Z500 response over southern Europe and the Mediterranean, which is even more pronounced in September (not shown). These results are not perfectly consistent with the study of Cassou et al. (2005), which might be explained by a different climatology between the Arpege-Climat and NCAR atmospheric GCMs. This issue will be the focus of a forthcoming study based on a simplified atmospheric model

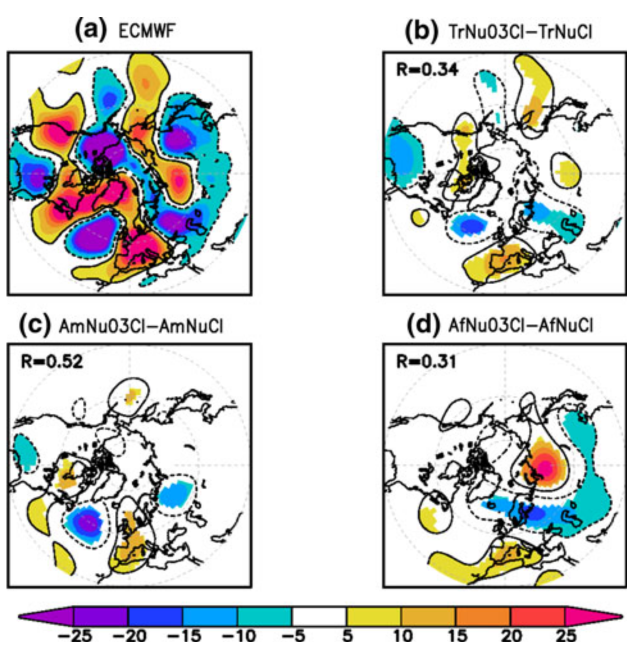

Fig. 9 Same as Fig. 8, but for the JJAS 2003 eddy component anomalies of geopotential height (m) at 500 hPa in the northern extratropics. *Shaded anomalies* in **b–f** are statistically significant at a 5% level

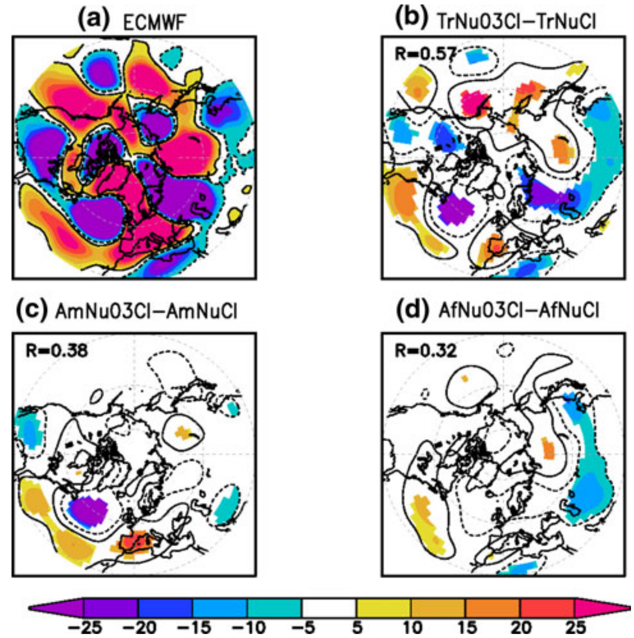

Fig. 10 Same as Fig. 9, but for June 2003 only

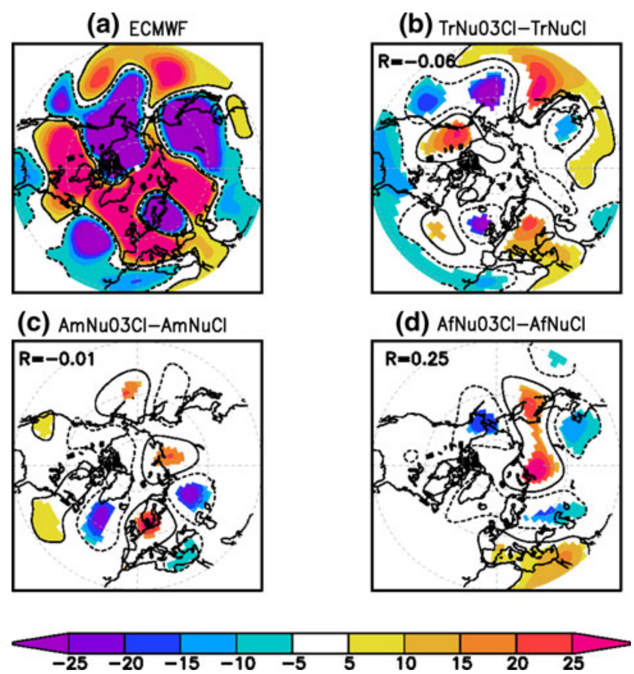

Fig. 11 Same as Fig. 9, but for August 2003 only

whose basic state can be prescribed either from reanalyses or from the GCM climatology.

5 Global SST forcing versus tropical nudging

While Sect. 4 suggests that boreal summer extratropical stationary waves can be triggered by anomalous divergent flow in the tropics, the mid-latitude signals simulated in the nudging experiments are much weaker than observed. Apart from the ensemble mean smoothing effect (i.e. the internal variability of the extratropical atmosphere), a possible reason for the weak model response is the use of prescribed climatological SST. Using another atmospheric GCM, Feudale and Shukla (2010) found that the global SST anomalies can explain many major features of the European heat wave during the summer 2003. While their experiment design allowed them to quantify the specific contribution of the Mediterranean SST, the relative contribution of tropical versus extratropical SST was not discussed. The role of North Atlantic SST will be the focus of a forthcoming IRCAAM study by Cassou et al. (in preparation) where the Arpege-Climat model has been coupled with an ocean mixed layer model. The results suggest that an interactive SST is indeed necessary to tackle this question. In the present study, additional ensemble experiments have been conducted with observed rather than climatological prescribed monthly mean SST. Unlike Feudale and Shukla (2010), we use monthly rather than daily SST since the intra-seasonal variability of North Atlantic SST is probably dominated by atmospheric processes. Even with monthly SST, such AMIP-type experiments remain a matter of debate (Bretherton and Battisti 2000). The purpose is here to provide a preliminary assessment of the additional forcing of the summer 2003 stationary waves by interannual SST variability. The experimental design is summarized in the last column of Table 2. A first ensemble, Ct03, has been conducted without nudging and can be compared with CtCl. A second ensemble, TrNu0303, has been conducted with both tropical nudging and observed SSTs, and can be compared with TrNuCl. Note that the tropical SST forcing can only alter the simulated surface fluxes in the nudging domain, where the strong relaxation used in the present study prevents any response of the underlying tropical atmospheric circulation. Therefore, the value of TrNu0303 compared to TrNU03Cl is to assess the possible impact of the mid-latitude SST anomalies on the simulated 2003 stationary waves.

Figure 12 shows the JJAS mean eddy Z500 response simulated in the Northern Hemisphere. Prescribing observed SST (Fig. 12b) at the lower boundary conditions of the Arpege-Climat model is not sufficient to capture the ECMWF anomalies (Fig. 12a). A wave train pattern does appear over North Atlantic, but is not in phase with its ECMWF counterpart as indicated by the low anomaly correlation coefficient estimated over the northern extratropics. Such a poor result is consistent with the limited skill of dynamical prediction systems in the summer extratropics, even in seasonal hindcasts with perfect SST (e.g. Guérémy et al. 2005). The North Atlantic response obtained by Feudale and Shukla (2010) with another

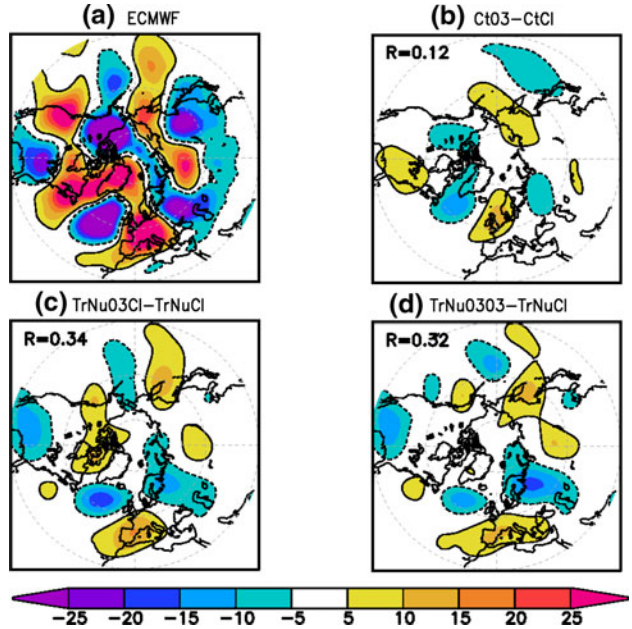

Fig. 12 JJAS 2003 eddy component anomalies of geopotential height (m) at 500 hPa in the northern extratropics: **a** operational ECMWF analyses relative to the 1971–2000 ERA40 climatology, **b** control experiment driven by observed SST, **c, d** nudging experiments driven by climatological and observed SST respectively. *R* is the ACC with ECMWF data

atmospheric GCM is somewhat more realistic, but is difficult to interpret without additional experiments. One hypothesis is that their model response is also more realistic in the tropics. In our Tr nudging experiment, prescribing observed (Fig. 12d) rather than climatological (Fig. 12c) SST does not change the model response much. This result therefore suggests that the mid-latitude SST variability has a weak influence on the boreal summer stationary waves compared to tropical moist convection.

While other case studies have been conducted within the IRCAAM project, a systematic assessment of the boreal summer mid-latitude stationary wave response to tropical circulation anomalies is beyond the scope of the present study. Nevertheless, two additional summer seasons have been selected to strengthen our conclusions. Summer 1994 is another neutral ENSO year (Fig. 13a) with a strong West African monsoon (Fig. 13b) and warm surface temperatures over Europe (not shown). Summer 1997 corresponds to a strong El Niño event developing in the equatorial Pacific (Fig. 13c) and mainly shows enhanced convection over the central and eastern equatorial Pacific (Fig. 13d) and wet conditions over western US and Europe (not shown).

Figure 14 shows the JJAS 1994 eddy Z500 response in the northern extratropics. The ERA40 distribution across North America, North Atlantic and Europe is fairly similar

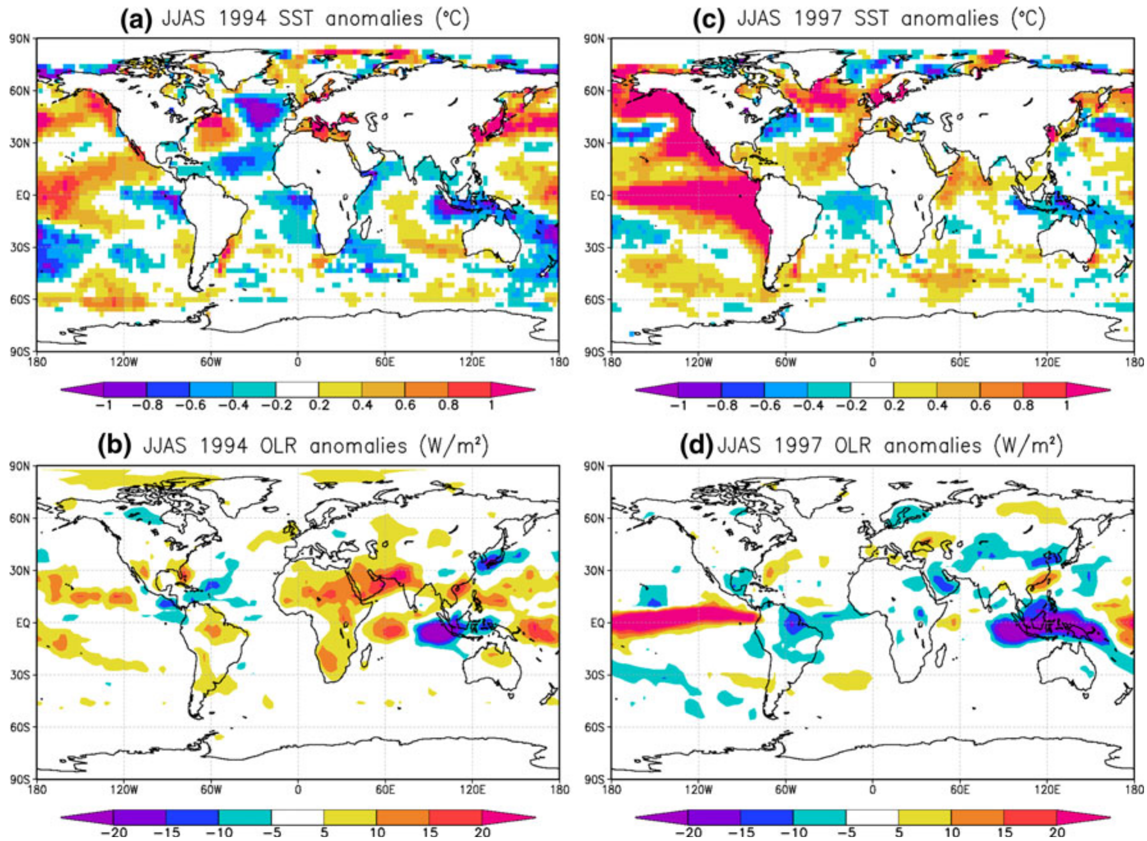

Fig. 13 Observed JJAS SST (°C) and OLR (W/m^2) anomalies in JJAS 1994 (*left panels*) and JJAS 1997 (*right panels*)

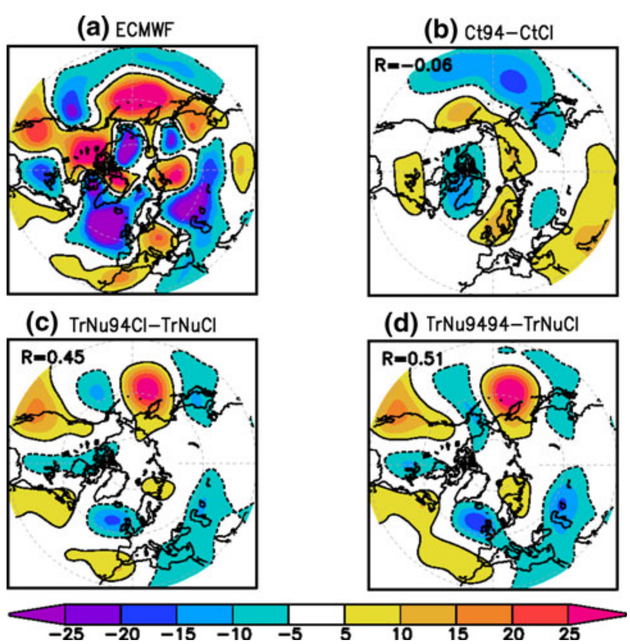

Fig. 14 Same as Fig. 12, but for JJAS 1994

to the 2003 anomalies, although the anomalous anticyclone over western Europe is weaker, in line with a less extreme surface warming. As in 2003, the control experiment driven by observed SST shows a wave train originating from the Caribbean basin but the European anomalous anticyclone is centred over Scandinavia, i.e. north of the 1994 observed signal. As in 2003, the tropical nudging experiment is more realistic, but the signal is much weaker than observed and the improvement is more evident over North Pacific and North America than over Europe. Again, prescribing observed rather than climatological SST has almost no impact on the nudging simulations, thereby suggesting a minor contribution of the mid-latitude SST anomalies to the eddy Z500 response. The important role of the tropical atmospheric divergent circulation as a pathway between the SST forcing and the extratropical climate variability therefore seems to be robust.

Finally, moving to summer 1997 (Fig. 15) with a completely different tropical forcing suggests that the monsoon regions are not the only drivers of the boreal summer stationary waves and that ENSO is likely to trigger strong extratropical signals over North America, not only during the winter season but also in summer. Once again, the Arpege-Climat model driven by observed SST anomalies fails to capture such signals and the tropical nudging is necessary to simulate a more realistic, albeit weak eddy Z500 response.

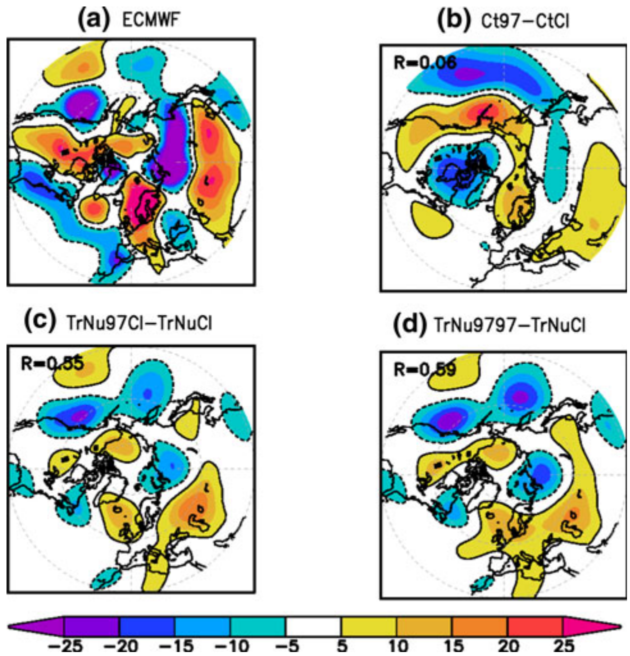

Fig. 15 Same as Fig. 12, but for JJAS 1997

6 Conclusion and prospects

The present study was aimed at quantifying the contribution of systematic and long-range prediction errors in the tropics on the climatology and interannual variability of boreal summer mid-latitude stationary waves. For this purpose, a grid point nudging technique towards ERA40 or operational ECMWF 6-h data was implemented in the Arpege-Climat atmospheric GCM. Each experiment consists in an ensemble of 30 boreal summer integrations starting from May 15 initial conditions derived from the control experiment.

Different flavours of the nudging technique were first tested with prescribed climatological SST: weak versus strong nudging, low-pass filtered versus 6-h ECMWF analyses, regional monsoon versus tropical band relaxation domain. Results show that the stationary wave model climatology is in all cases significantly improved by the nudging, thereby highlighting the contribution of systematic errors in the tropics to the extratropical model climatology in both hemispheres. The beneficial impact of nudging on the stationary wave climatology is still found if the relaxation fields are low-pass filtered, thereby suggesting a generally weak contribution of the tropical high-frequency variability to the seasonal mean errors in the extratropics. Weaker nudging leads to a weaker but still significant improvement of the stationary wave climatology, which makes us relatively confident in the robustness of the nudging technique (i.e. no strong numerical artifact) and in its suitability for the study of tropical–extratropical teleconnections. However, it should be noted that the nudging does not have such a beneficial effect on the zonal mean extratropical circulation. Finally, we have seen that in the Arpege-Climat model systematic errors in the monsoon regions have less impact on the extratropical circulation than the over-estimated subsidence over the equatorial central Pacific.

Case studies focusing on particular boreal summer seasons were also conducted. Each ensemble was compared to the climatology of the corresponding nudging experiment over the 1971–2000 period. In line with the results of Cassou et al. (2005), the summer 2003 nudging experiments suggested a significant contribution of the anomalous heating over the Caribbean basin on the observed heatwaves over western Europe. They also highlighted a possible contribution of the enhanced rainy season over West Africa, but this effect was mainly found at the end of the summer season. The potential role of the Indian Ocean warming (Black and Sutton 2006) was not tested and therefore cannot be excluded.

Additional sensitivity experiments using different atmospheric GCMs and different nudging domains would be necessary to assess the robustness of our results. Note however that, in the framework of the IRCAAM project, parallel nudging experiments have been performed with the LMDZ atmospheric GCM (Hourdin et al. 2006) using the same Tr nudging domain and with the Arpege-Climat model using a smaller tropical nudging domain. Both ensembles also showed an improved simulation of the JJAS 2003 Z500 anomalies over Europe thereby strengthening our conclusions about the important role of the tropical divergent circulation as a pathway between SST forcing and extratropical climate variability. Moreover, the positive impact of the tropical nudging on the eddy Z500 anomalies simulated in the northern extratropics was also found in the JJAS 1994 and JJAS 1997 case studies. Finally, our conclusion is also consistent with the wintertime case study conducted with the ECMWF atmospheric GCM by Jung et al. (2009).

In the continuation of the IRCAAM project, further analyses will be conducted to improve our understanding of the dynamical and physical mechanisms of the mid-latitude response. Parallel nudging experiments with a simple dry atmospheric model (Hall 2000) and with the LMDZ atmospheric GCM will be compared to the Arpege-Climat simulations. Moreover, Arpege-Climat has been recently coupled to a mixed layer ocean model and additional 2003 sensitivity experiments have been designed to explore the limitations of the prescribed-SST experiment design and the role of the mid-latitude SST feedbacks in the tropical–extratropical atmospheric teleconnections (Cassou et al., in preparation).

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