TECHNICAL MEMORANDUM

534

Influence of the quasi-biennial oscillation on the ECMWF model short-range forecast errors in the tropical stratosphere

Nedjeljka Žagar[1], Erik Andersson, Michael Fisher and Agathe Untch

Research Department

[1]National Center for Atmospheric Research, P.O. Box 3000, Boulder, CO 80307-3000

To appear in Q. J. R. Meteorol. Soc.

August 2007

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

Series: ECMWF Technical Memoranda

A full list of ECMWF Publications can be found on our web site under:
http://www.ecmwf.int/publications/

Contact: library@ecmwf.int

Abstract

This paper addresses the impact of the quasi-biennial oscillation (QBO) on the background-error covariances in the tropical atmosphere of the ECMWF model. The tropical short-range forecast error covariances are represented in terms of equatorial waves coupled to convection.

By comparing the forecast-error proxy data from two different phases of QBO, it is shown that the phase of the QBO has an effect on the distribution of tropical forecast-error variances between various equatorial waves. The influence of the QBO is limited to the stratospheric levels between 50 hPa and 5 hPa. In the easterly QBO phase, the percentage of error variance in Kelvin waves is significantly increased in comparison with the westerly phase. In the westerly phase, westward-propagating inertio-gravity waves become more important at the expense of Kelvin modes, eastward-propagating mixed Rossby-gravity waves and inertio-gravity modes. Comparison of datasets from two easterly phases shows that the maxima of stratospheric error variance in various equatorial modes follow the theory of the interaction of waves with descending shear zones of the horizontal wind.

Single-observation experiments illustrate an impact of the phase of the QBO on stratospheric analysis increments, which is mostly seen in the balanced geopotential field. Idealized 3D-Var assimilation experiments suggest that background-error statistics from the easterly QBO period are on average more useful for the multivariate variational assimilation, as a consequence of a stronger mass-wind coupling due to increased impact of Kelvin waves in the easterly phase.

By comparing the tropical forecast errors in two operational versions of the model a few years apart, it is shown here that recent model improvements, primarily in the model physics, have substantially reduced the errors in both wind and geopotential throughout the tropical atmosphere. In particular, increased wind-field errors associated with the intertropical convergence zone have been removed. Consequently, the ability of the applied background-error model to represent the error fields has improved.

Contents

1 Introduction

Information about forecast uncertainty is an important input to data assimilation for Numerical Weather Prediction (NWP). It is required in order to optimally combine *a priori* information (in the form of a short-range forecast) with new observations. However, forecast-error statistics can be estimated only approximately, and assumptions need to be made to define the background-error covariance matrix (Rabier 2005). In the operational four-dimensional variational (4D-Var) application at the European Centre for Medium-Range Weather Forecasts (ECMWF), the covariance statistics are represented by a stationary model valid at the beginning of the assimilation time window. This model is defined in spectral space. The implied correlations spread the observation impact quite uniformly in terms of vorticity and the un-balanced variables while the non-linear balance equation imposes the appropriate correlations between mass and wind variables (Fisher 2003). The background-error covariance model thus controls both the adjustment of background information to observations and the mass/wind balance (Lorenc 2003).

In variational assimilation the error covariances are recomputed when significant changes in the model or observing system take place; otherwise, the statistics are assumed independent of the background flow[1]. The assumption of stationarity is often inadequate as various modes of variability in time and space are present throughout the atmosphere. In the tropics, an important mode of temporal variability is the stratospheric quasi-biennial oscillation (QBO) (Baldwin *et al.* 2001).

A review of the challenges involved with analyzing middle atmosphere variability was presented by Polaravapu *et al.* (2005). Gaspari *et al.* (2006) used multi-level, multi-variate covariance functions to improve the QBO representation in the Goddard Earth Observing System. In this paper, the impact of the QBO on tropical background-error covariances is studied, based on the ECMWF short-range forecast errors.

The present paper closely follows Žagar *et al.* (2005, hereafter ŽAF) which studied multivariate tropical data assimilation, and applied equatorial wave theory in modelling the background-error covariances. It was concluded that on average about 60% of the tropical large-scale variability in wind and geopotential field errors of the ECMWF model can be represented by equatorial Rossby (ER), equatorial inertio-gravity (EIG), Kelvin and mixed Rossby-gravity (MRG) waves. Of most relevance for the present study was the distribution of the error variance in the stratosphere; it was found that the westward-propagating waves were significantly less pronounced than the eastward-propagating modes. It was speculated that this result was related to the easterly phase of QBO during the study period (October 2000).

As new datasets representing the forecast errors in two different phases of the QBO became available, we were able to test the hypothesis about the QBO impact on stratospheric correlations. New datasets were prepared using a more recent model version. The time periods for which the errors were simulated were September 2003 (easterly phase) and August 2004 (westerly phase).

In the following section, we summarize developments of the ECMWF data assimilation system in the last few years since the generation of the forecast errors studied in ŽAF. Subsequently we present related changes in the structure of the wind-field errors. As a result of model advancements, the applied methodology is capable of explaining a greater portion of the background-error fields in the present system than in the old dataset, at all model levels. In order to allow comparison with the previous study, the same methodology is applied and the reader is referred to ŽAF and references therein for details.

Our main results are presented in section 3. They confirm our hypothesis on the impact of the QBO on the distribution of the background-error variance among various equatorial modes in the stratosphere. We present

[1] In the operational ECMWF application, the background-error correlations are constant but standard deviations can change from cycle to cycle based on data density in the preceding analyses.

the consequences of this impact for horizontal correlations in single-observation experiments. In addition, we discuss the potential impact on wind and geopotential analysis increments in the tropical stratosphere, through the use of idealized assimilation experiments. Conclusions are presented in Section 4.

2 Datasets and the background-error modelling

2.1 Data

Tropical background-error covariances are obtained from data-assimilation ensembles used for the background-error representation in the operational 4D-Var system of ECMWF. Details of the ensemble method are discussed in ŽAF and Fisher (2003). The ensembles of analyses are produced by independent data assimilations that each use different sets of randomly perturbed observations. The ten-member analysis ensemble is available twice per day (at 06 and 18 UTC) and forecasts are run from each analysis. Differences between 12-hour forecasts of ensemble members started at 18 UTC are used as a proxy for background errors. The two wind components and geopotential height at 60 model levels are extracted for the tropical belt $20^{\circ}\mathrm{S}-20^{\circ}\mathrm{N}$ at one-degree resolution.

The first dataset is from September 2003 when the QBO was in the same (easterly) phase as in the dataset analyzed in ŽAF. In August 2004, the time of the second set, the QBO was in the westerly phase. These two datasets form the basis for this study and they will be referred to as ESTAT and WSTAT, corresponding to the easterly (negative) and westerly (positive) phases of QBO, respectively. The old dataset from October 2000 will be referred to as OSTAT.

The WSTAT ensemble is shorter than ESTAT (135 as compared to 270 samples). By taking additional forecasts from 6 UTC analysis time and comparing the results for the same sample length it was verified that the length difference of the ensembles in this case has no significant influence on the results. In each case, the first 6 days of the ensemble were discarded to allow time for the ensemble to “spin up” (initial background fields were not perturbed).

The model version used to generate the two new ensembles was cy28r4, operational from October 2004 to April 2005. As summarized below, intervening model changes since cy23r4 (used to generate OSTAT, and operational between June 2001 and January 2002) are numerous. Another difference between ESTAT/WSTAT and OSTAT is the perturbation of observations used to create the ensembles; in the new ensembles SATOB winds were perturbed with spatially correlated, rotational wind observation errors.

Since the different datasets originate from roughly the same time of year (October, September and August for OSTAT, ESTAT and WSTAT, respectively) we shall interpret the differences between OSTAT and ESTAT/WSTAT as due to the model changes and (interannual) changes in the background flow.

2.2 Impact of recent model changes on the tropical short-range forecast errors

The analysis and forecast system used to create the ESTAT and WSTAT data sets is improved with respect to OSTAT, reflecting the development of ECMWF’s operational system between January 2002 and October 2004[2]. There have been improvements to the analysis algorithms (Andersson *et al.* 2004), more extensive use of geostationary radiances (Köpken *et al.* 2004) and direct assimilation of SSMI radiances was introduced (Bauer *et al.* 2002). In terms of the tropical wind field, the most significant model improvement was a change to the initiation of convection (Bechtold *et al.* 2004); the new model version removes convective potential

[2] See http://www.ecmwf.int/products/data/operational_system for full details

instability more effectively and realistically, without creating local intense divergent features in the wind field.

The effect of the changes is illustrated in Fig. 1, which compares 12-hour zonal wind errors, as estimated from the spread of ensemble, at two model levels in OSTAT and ESTAT. This figure makes evident a major change in the horizontal structure of wind-field errors in the troposphere. The most striking difference is over the intertropical convergence zone (ITCZ) region, where ESTAT does not show any pronounced error maxima in the troposphere. Although the eastern Pacific remains the region with the largest errors, the error maximum at the South American coast, present in OSTAT, has disappeared. On average, the errors have significantly decreased, especially in the lower troposphere. (Note, however, that ensemble spread significantly underestimates the true errors due to inadequacies in the representation of model error and errors of representativity.)

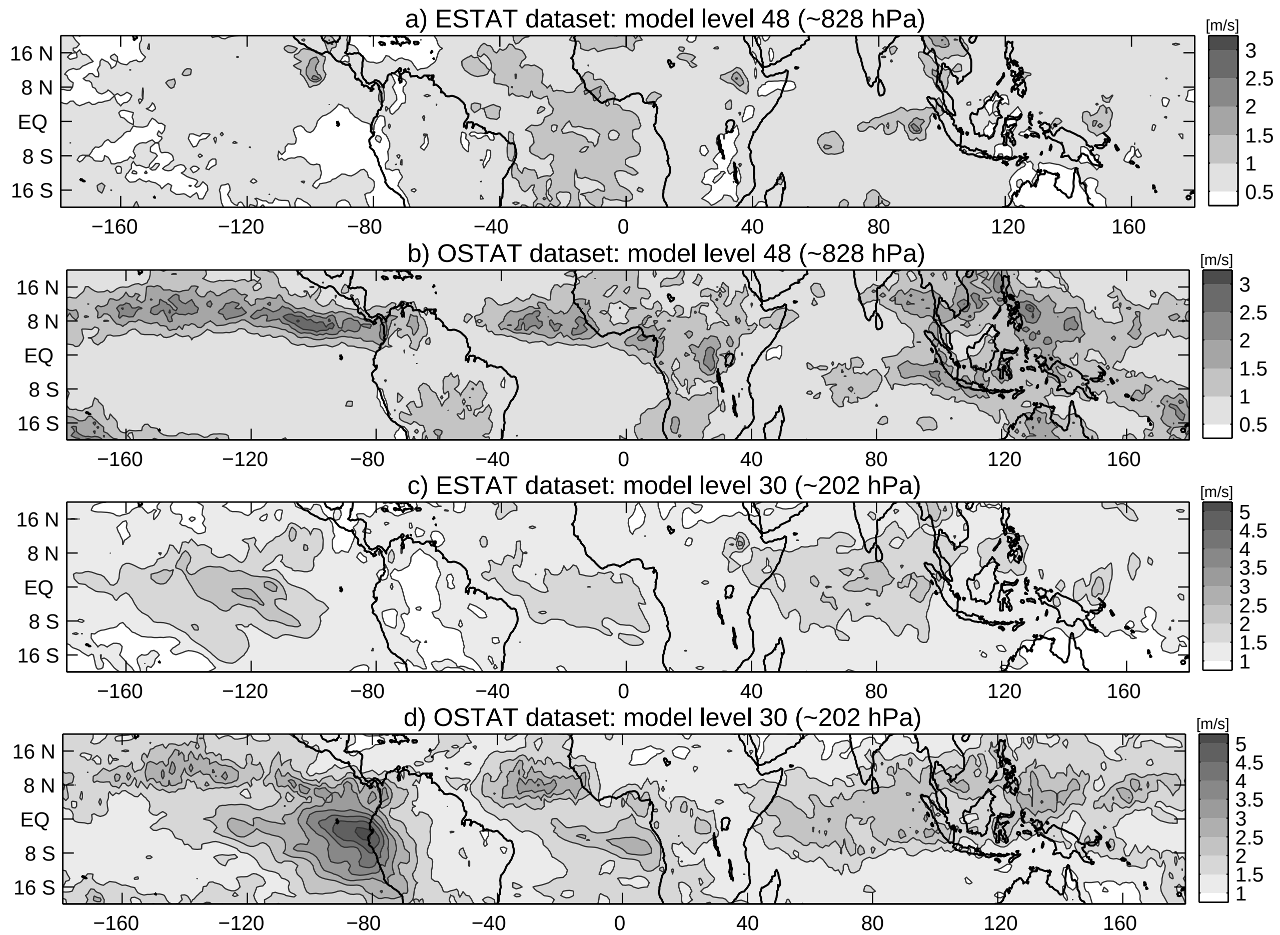

Figure 1: Standard deviations of 12-hour forecasts errors in the zonal wind field (in m s^{-1}) of the ECMWF model in the tropics, as estimated with data-assimilation ensembles (a,c) ESTAT and (b,d) OSTAT based on model versions cy28r4 and cy23r4, respectively. Shown are model levels (a,b) 48 (approximately 828 hPa) and (c,d) 30 (approximately 202 hPa). Panels (b,d) correspond to panels (a,b), respectively, in Fig. 1 in ŽAF.

The impact of the reduction of errors in the ITCZ is additionally presented in Fig. 2, which shows the meridional profiles of wind errors averaged across the tropics at two model levels. The new statistics (ESTAT) display only a very small zonal wind maximum over the ITCZ in the lower troposphere, of about the same amplitude as another maximum centred just south of the equator. The main error maximum is in the zonal wind field in the upper troposphere and the maximum is centred at the equator (Fig. 2b).

Average vertical error profiles (not presented) show the maxima of wind-field errors just below the tropical

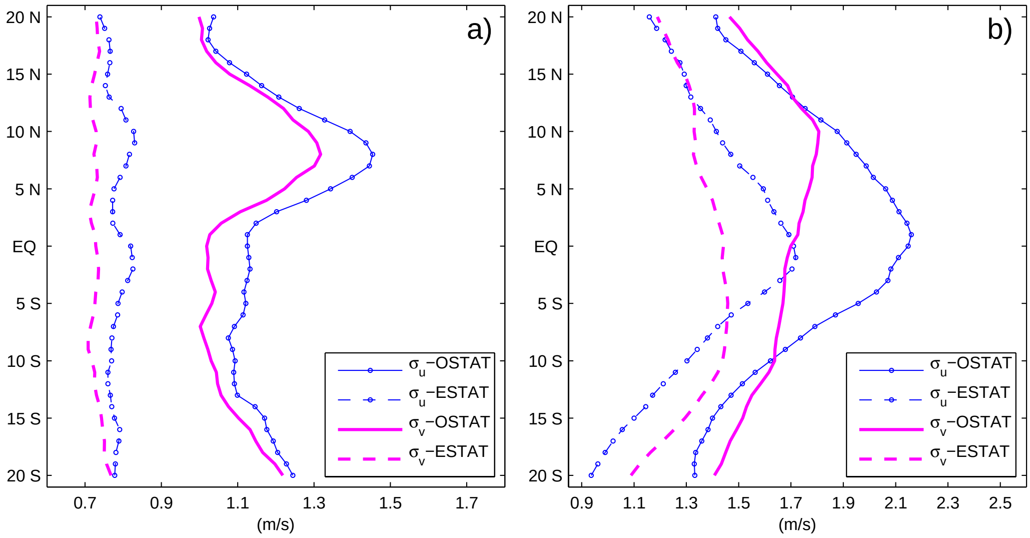

Figure 2: Meridional profiles of 12-hour forecasts errors in the zonal and meridional wind in OSTAT (full lines) and ESTAT (dashed lines). (a) model level 43 (approximately 654 hPa), (b) model level 27 (approximately 133 hPa).

tropopause (model level 27, at about 133 hPa) while a minimum is located in the stratosphere close to 36 hPa (level 20). A comparison with OSTAT confirms that the error decrease in the upper stratosphere and in particular at model levels close to 4 hPa (just below the stratopause) is especially large. The geopotential errors in the stratosphere are reduced by about 50% with respect to OSTAT. Stratospheric wind errors are nearly homogeneous across the tropics except for somewhat larger errors over Indonesia and south-eastern Asia. On the other hand, the geopotential stratospheric errors between 35-20 hPa in ESTAT peak over the ITCZ region. Above these levels, the error minimum is located at the equator and the maximum is shifted northward (not shown).

In WSTAT (not shown) the structure of wind-field errors in grid-point space is similar to that shown in Figs. 1-2 for ESTAT. Average errors between 500 and 800 hPa are somewhat larger in WSTAT than in ESTAT. The main difference between ESTAT and WSTAT is in the stratospheric height-field errors; the average height error is 10% smaller in WSTAT than in ESTAT and the meridional profile has a minimum over the ITCZ while a maximum is found south of the equator (not shown).

2.3 Representativity of the covariance model

ŽAF found that the asymmetry around the equator was the main impediment for a methodology based on equatorial wave theory, especially below 500 hPa. The error profiles modelled by equatorial waves have maxima at the equator. In contrast, OSTAT contained maximal errors over the ITCZ, related to the above-mentioned shortcomings in the convection scheme.

As a consequence of the reduction of asymmetry with respect to the equator, the ability of the applied background-error model to represent the error fields has improved. In the new datasets, the unexplained part of the background-error variance is reduced by an additional 10% with respect to OSTAT. The reduction is larger in the lower troposphere and is larger for wind than for the mass field (not shown). As before, the method becomes useless below model level 50 (i.e. within the planetary boundary layer). In conclusion, our background-error variance model is on average representative of 70-80% of the tropical error variance in the ECMWF model at a single horizontal level in the free atmosphere. The following discussion related to the impact of the QBO applies only to this “explained” variance.

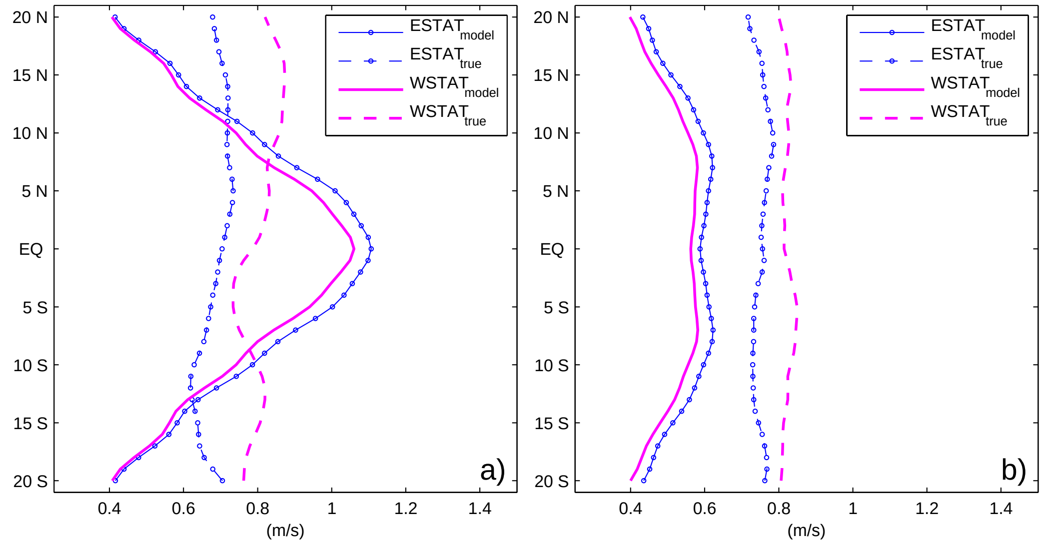

Figure 3: Meridional profiles of 12-hour forecast errors in the (a) zonal wind and (b) meridional wind fields in ESTAT (thin black lines) and WSTAT (thick gray lines). Dashed lines apply to the ’truth’ whereas full lines apply to the covariance model output at model level 19 (approximately 29 hPa) (see text for further details).

For the same reason of model improvements, we found that the assumed covariance model can represent the meridional variation of errors at the tropospheric levels better in ESTAT than in OSTAT. In the stratosphere, however, ECMWF model forecast errors in the wind field are largely homogeneous, as shown in Fig. 3. In contrast, the covariance model has the zonal wind maximum at the equator due to the strong impact of Kelvin waves in the stratosphere, as discussed in the next section.

The meridional structure of errors in grid-point space presented in Fig. 3 is obtained by transforming an ensemble of random vectors in spectral space, drawn from $N(0,1)$, to grid-point space using our tropical spectral mode-based covariance model (details in ŽAF and Fisher 1996). The resulting grid-point errors are homogeneous in the zonal direction and they represent the part of the error fields which was projected onto the equatorial modes (around 80% of the zonal wind error variance at 30 hPa). Averaged original grid-point errors serve as verifying “truth”.

Figure 3 also shows that the average zonal wind error in the two datasets is about 15% smaller in ESTAT than in the WSTAT dataset, while for the meridional component this difference is about 50%. For the modelled profiles the average difference between the two phases is smaller by about 4% for the zonal wind and 6% for the meridional component. Furthermore, the modelled difference has the opposite sign from the “truth” error data, as a consequence of the stronger Kelvin wave impact in the easterly QBO phase. Implications for the assimilation are discussed in the following section. In both datasets, modelled geopotential profiles are very similar; simulated forecast errors are underestimated and the profiles display a small minimum at the equator. As noticed earlier, proxy error data have their maxima north and south of the equator in ESTAT and WSTAT datasets, respectively.

3 Structure of the errors in the stratosphere

3.1 Variances and vertical correlations

The impetus for the present study was the particular distribution of the stratospheric error variance found in the previously studied dataset (OSTAT). In that study, stratospheric variances presented broad minima between 5 hPa and 35 hPa levels for all westward-propagating modes, especially WEIG waves. On the other hand, eastward-propagating EIG, MRG and Kelvin waves had maxima in the same level range. This feature was assumed to be attributable to the eastward phase of the QBO in the study period (October 2000).

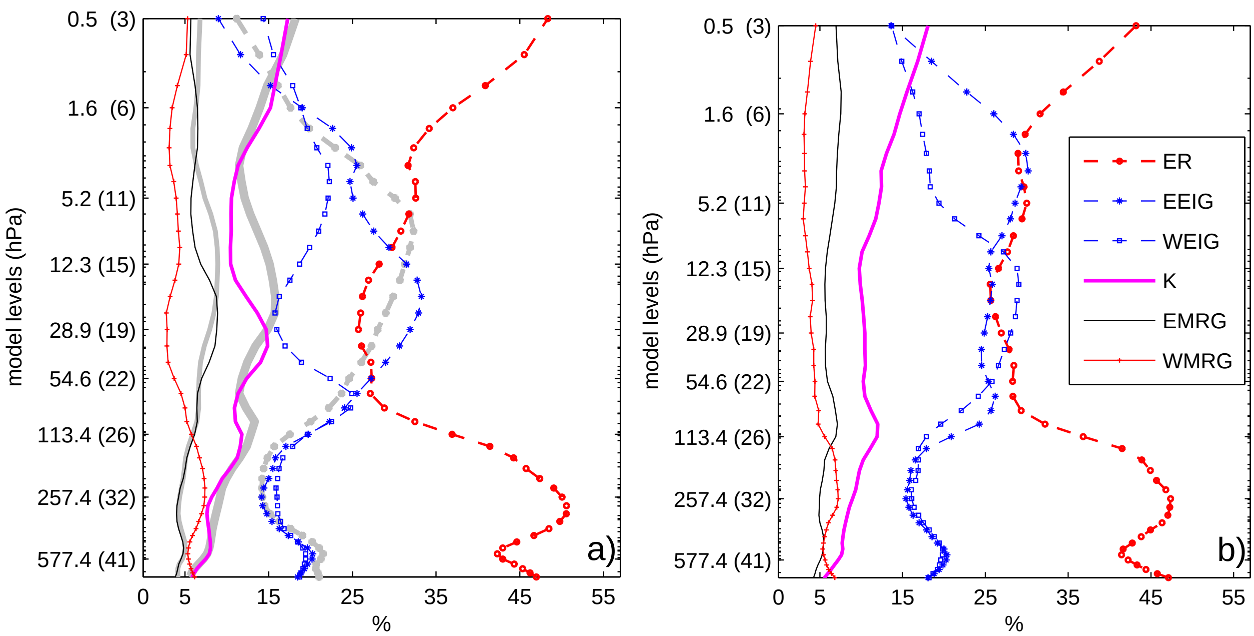

Figure 4: Vertical distribution of the variance among various equatorial eigenmodes: equatorial Rossby (ER) modes, eastward-propagating (EEIG) and westward-propagating (WEIG) equatorial inertio-gravity modes, (K) Kelvin modes, eastward- (EMRG) and westward-propagating (WMRG) mixed Rossby-gravity waves. (a) ESTAT, (b) WSTAT. Three thick gray lines in a) correspond to OSTAT curves for EEIG, Kelvin and EMRG modes. The x-axis notation applies to the percentage of the total explained variance. Numbers within parenthesis on the y-axis are model level indices. Lowest 15 model levels (levels 46-60) are not shown.

Figure 4 confirms our assumption: the difference between the vertical distributions of error variance in the two phases is significant only in the stratosphere, and the difference extends all the way up to the stratopause. In the positive QBO phase (WSTAT, Fig. 4b) there is no marked minimum for the westward-propagating EIG and MRG modes. Instead, the variance for these waves increases above the tropopause and the profile for WEIG modes follows that of ER waves up to the stratopause.

In the same QBO phase (ESTAT and OSTAT, Fig. 4a) some differences in the stratosphere are likely related to the period of the descending wind shear zones in the easterly phase from which the data come. Based on the zonal wind anomaly at 30 hPa level, the easterly phase of ESTAT (September 2003) lasted between December 2002 and January 2004 with a peak in August 2003, whereas the OSTAT (October 2000) dataset is from the first part of the easterly phase which lasted between May 2000 and November 2001, peaking in July 2001. Consequently, maxima of variance in Kelvin, EMRG and EEIG modes in ESTAT are located at lower levels than in OSTAT.

Lower down in the troposphere, the relative percentage of EIG is smaller in ESTAT than in OSTAT, while there is relatively more variance in the ER waves in ESTAT (not shown). In the layer between 885 hPa and 130 hPa, the average percentage of errors associated with EIG has decreased from 40% in OSTAT to 35% in ESTAT dataset. This suggests that more recent tropical analysis increments in the ECMWF system (ESTAT) include less divergence, in agreement with the use of non-divergent perturbations for SATOB winds observations, and with the removal of the problem with the convection initiation, mentioned in Section 2.

Different behaviour of the westward and eastward-propagating modes in the two phases is more clearly illustrated in Fig. 5 by the stratospheric variance spectra at model level 19 (around 29 hPa). Except at the smallest wavenumbers, spectra at this level in the two phases are different for all modes except for ER waves. The total variance represented by EIG modes is the same in ESTAT and WSTAT, but for the negative QBO case westward EIG make up one-third of that sum while in the positive phase both propagation directions are equally important. Similarly, the total variance in westward MRG modes is the same in the two phases, but eastward modes are less important in WSTAT. The percentage of the variance represented by Kelvin modes reduces to 60% in the westerly phase. In summary, the relative increase of variance in WEIG modes in the positive phase of QBO, seen in Fig. 4, occurs at the expense of Kelvin, eastward MRG and eastward EIG waves.

These results concerning both the differences in the same phase as well as the differences between the two phases are consistent with observations, theory and numerical modelling of the QBO (e.g. Dunkerton 1997, Hamilton 1998, Horinouchi and Yoden 1998, Randel and Wu 2005). For example, the reduction of Kelvin-wave variance in the westerly phase is, according to the theory, a consequence of their slower vertical group speed and consequently more active dissipation along critical lines. Variability of the error variance between the two phases is consistent with the analyzed variability in the outgoing longwave radiation observations and the ECMWF reanalysis fields (G. Kiladis 2007, pers. communication). Phillips (1986) hypothesized that forecast errors are dominated by structures resembling the structures of growing (quasi-geostrophic) perturbations in a model atmosphere. Here Phillips' ideas can be seen as valid for the large-scale tropical flows.

Vertical correlations in ESTAT are not significantly altered with respect to OSTAT (figures 6-8 inŽAF). Stratospheric vertical correlations are narrow. For example, correlations of the zonal wave number 4 Kelvin wave at 12 hPa drop to 0.4 within 4 model levels apart (6 hPa and 20 hPa). The wings of negative correlations in WSTAT are more intense than in ESTAT for the zonal wave numbers greater than 10 (not shown). ER modes with odd n (fields symmetric with respect to the equator) are characterized by deeper correlations than ER modes of even n (asymmetric fields).

3.2 Sensitivity of the horizontal analysis increments on the QBO phase

In this section we investigate by idealized assimilation experiments how the observed difference in the stratospheric variance distribution due to the QBO affects the horizontal structure of balanced analysis increments in 3D-Var. The applied variational data assimilation model is the same as was used inŽAF. The model solves shallow-water equations in spectral space and the error-covariance model uses the spectra of equatorial modes just presented. Details of the model and its background-error term are presented inŽagar *et al.* (2004a,b).

Figure 6 shows analysis increments due to single observations of height, zonal and meridional wind located at the equator in cases when the background-error variance spectrum is taken from easterly phase and westerly phase at model level 19 (approximately 29 hPa) (spectra shown in Fig. 5). This figure suggests that the impact of QBO is most significant for the balanced geopotential field.

For a height observation higher than the background and using the westerly phase error spectra, height-field increments are smaller and a little more zonally elongated than in the easterly phase. Balanced westerly winds are weaker than with error spectra based on ESTAT; the maximal zonal wind increment is about four times

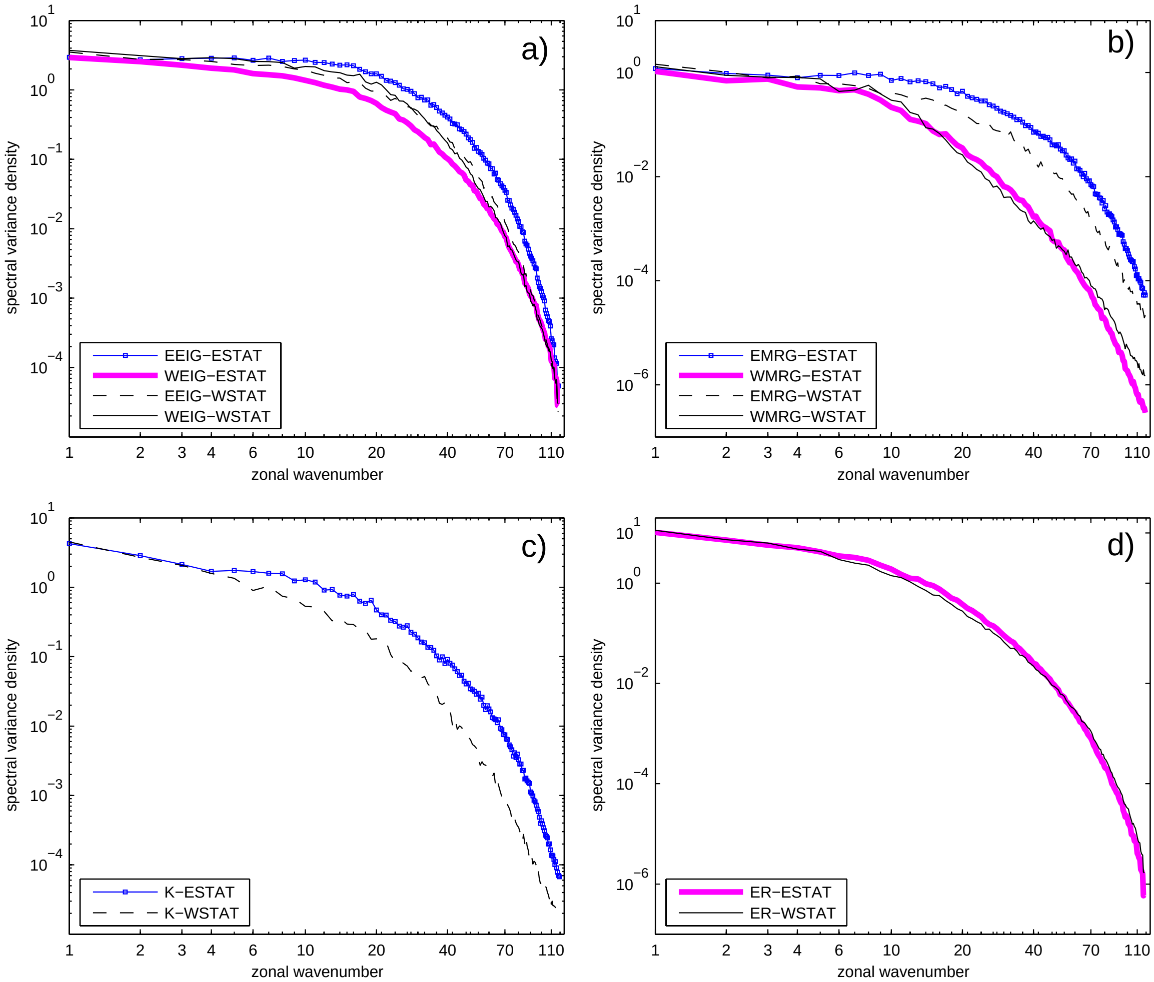

Figure 5: Spectral variance density at model level 19 (approximately 29 hPa) in various modes in ESTAT and WSTAT. (a) EIG modes, (b) MRG modes, (c) Kelvin modes, (d) ER modes.

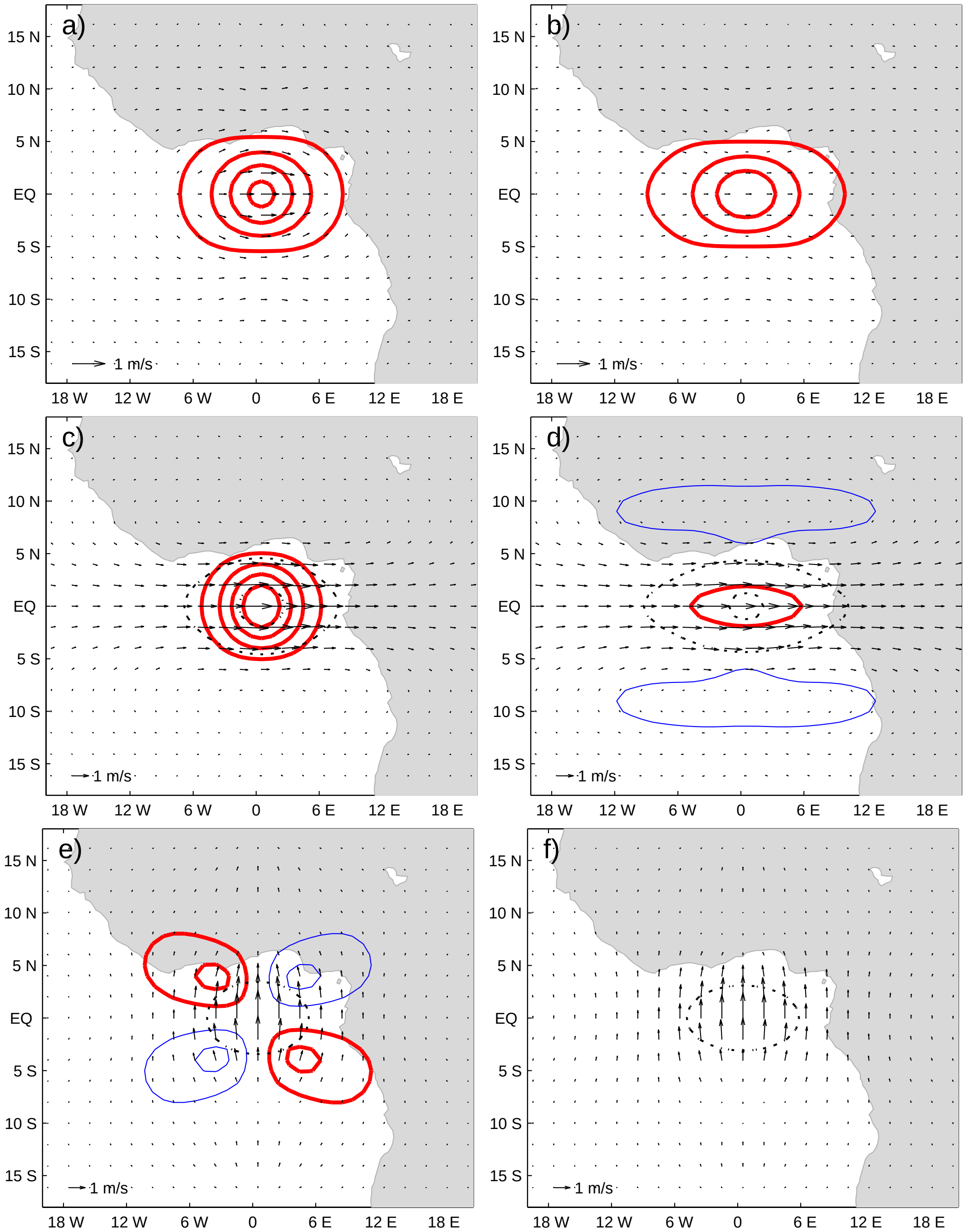

Figure 6: Horizontal structure of the analysis increments due to (a,b) a single height, (c,d) a single zonal wind and (e,f) a single meridional wind observation located at the equator. Left-hand panels (a,c,e) apply the error variance from the easterly phase while right-hand panels (b,d,f) use the error spectra from the westerly phase. The background-error variances corresponds to the ECMWF model levels 19 (approximately 29 hPa). The height observation is 5 m higher than the background and the observation error is 1 m. Zonal and meridional wind observations have magnitudes 5 m s^{-1} and the observation error is 1 m s^{-1}. The background state is a motionless fluid of depth h_0. Isoline spacing for the height field increment is ±0.5 m (height observation), ±0.25 m for the zonal wind observation and ±0.15 m for the meridional wind observation. Thick lines correspond to positive values, while thin lines are used for negative values and the zero contour is omitted. Dashed lines denote wind speed, with spacing 1 m s^{-1}.

smaller with the westerly than with the easterly phase errors (Fig. 6a,b).

The difference between the two sets of statistics is larger in the case of wind observations and balanced geopotential increments. Again, the mass-wind coupling close to the equator is significantly stronger in ESTAT than in WSTAT as a consequence of a greater contribution from Kelvin waves in the easterly phase. This impact is felt also in the subtropics, up to around ten degrees latitude (not shown). The increase of the variance in WEIG modes at the expense of the reduction of Kelvin-wave variance in the westerly phase has a significant influence on horizontal correlations in case of a zonal wind observation; at the equator correlations are weaker by a factor 4 and small negative correlations appear off the equator. Length scales are longer in the westerly phase (Fig. 6c,d). In the case of meridional wind observation, the relative reduction of eastward-propagating MRG and EIG modes in the westerly phase results in almost negligible balanced mass-field increments in WSTAT in comparison with ESTAT. The potential energy of the increment is in this case smaller by a factor 20 in WSTAT than in ESTAT (Fig. 6e,f).

In both phases, the wind-field increments produced by height observation are small, illustrating the fact that an average mixture of mass-wind relationships built into the background-error covariance matrix results in a nearly univariate mass-field analysis dominated by mass observations in the tropics, just as is the case in the full-scale assimilation system (Derber and Bouttier 1999) This is reflected also by the 3D-Var analysis scores based on idealized experiments presented in Fig. 7.

In order to test the impact of the background-error statistics, simulated observations were obtained from the background-error covariance model using error variances from different phases, as inŽagar *et al.* (2004a). For each simulated "truth", the assimilation was performed using background-error variances from both phases. The idea is to check whether using the background-error spectra from the wrong phase has a significant impact on analysis fields. Simulated observations are homogeneously distributed within the tropical belt 20°S-20°N, although the model domain was defined larger, between 33°S and 33°N. For each observation type, 1000 homogeneously distributed observations were assimilated and observations were assigned errors equal to the background error at the same point, $N(0,\sigma_b)$, as obtained from the randomization experiment (average meridional profiles of grid-point errors are shown in Fig. 3). Results from one hundred 3D-Var assimilation experiments are summarized in Fig. 7.

This figure shows that the consequence of using the background-error statistics from the "wrong" phase in an ideal 3D-Var system is between zero and 5% of the reduction of the first-guess error. This range of magnitudes is in agreement with the average difference of the variance model in the two phases, presented in Fig. 3. The difference is larger for the "truth" fields representative of the easterly phase; in this case using the westerly phase errors systematically deteriorates the analysis scores for all variables and all observation types (Fig.7a). For the flows characterizing the westerly phase (Fig. 7b), the assimilation using easterly-phase errors (ESTAT) produces average scores almost identical to those from the westerly phase (WSTAT), except for the zonal wind score and height-field observations. Verification in this case was carried out within 10°S-10°N, but the results for the belt 20°S-20°N and different amount of observations are similar.

In another sensitivity experiment, observations were prepared from the differences between ensemble members at analysis times. For each dataset, an analysis member was selected as a control and its scaled differences from other members served as "truth". Another ensemble member, left out from the "truth" preparation, was used as a control to construct the first-guess fields. In this case the background-error variance model was representative only for the "explained" part of simulated observations and the impact of using statistics from different QBO phases was almost negligible (not shown).

Based on the statistics results and the single observation experiments, we had expected a more significant difference in the analysis scores. The numbers presented in Fig. 7 apply to the idealized model, which is assumed good, and reliable background-error covariances. We do not know whether the impact in NWP applications

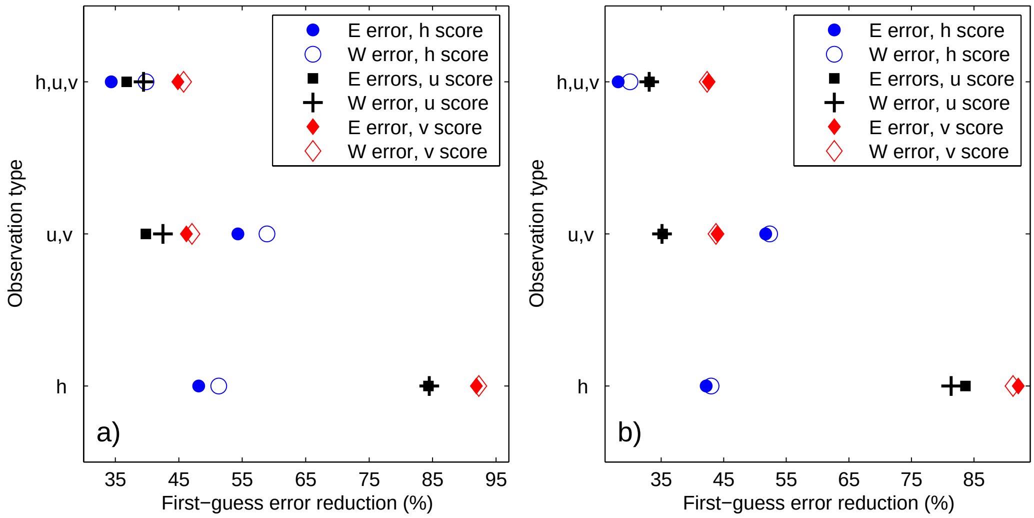

Figure 7: Average reduction of the root mean square error of the first-guess field in the 3D-Var analysis by using various observation types and background-error statistics. (a) "Truth" is based on the variance from the eastward QBO phase, (b) "Truth" is based on the westward QBO phase. Circles denote scores for the height field, squares and pluses denote the zonal wind field scores while diamonds belong to the scores for the meridional wind component. Filled markers are for the assimilation using the background-error variances from ESTAT while empty markers belong to the experiments with the error spectra from the WSTAT dataset. Verification is carried out within 10°S−10°N.

(e.g. the ECMWF model) using the proposed background-error covariance representation would be negligible. Because of the way our experiments are constructed, simulated observations from ESTAT contain on average somewhat more energy in the zonal than in the meridional wind component (around 58% of kinetic energy in the zonal wind). Since realistic stratospheric flows are characterized by far more zonal wind component than in these experiments, it is likely that the background-error spectra from the easterly QBO phase are more valuable in comparison with the westerly phase than suggested by Fig. 7. It is worth mentioning that the 40-year reanalysis project at ECMWF (Uppala *et al.* 2005) used the background-error covariances from the easterly phase and reconstructed QBO reasonably well.

Comparison of the height scores obtained by the assimilation of wind data and wind-field scores produced by assimilating height observations illustrates that wind observations are far more efficient in restoring the height field than height observations are in recovering the wind-field structure, in accordance with previous results in Žagar *et al.* (2004a). When mass and wind data are analyzed together, scores for the height-field variable improve further. This points out a need for direct wind observations in the tropics and for more efficient data assimilation procedures. Among the three variables, the variable least sensitive to the error statistics is the meridional wind, in agreement with balanced increments shown in Fig. 6.

4 Discussion and Conclusions

The QBO is an important mode of tropical variability on interannual scales. While the ECMWF model (re)analysis fields capture the QBO and stratospheric zonal winds reasonably well (Randel *et al.* 2004, Baldwin and Gray 2005), the present study addressed the impact of the QBO phase on the background-error statistics for variational data assimilation. In the absence of direct wind observations in the tropics, the possibility for improvements of stratospheric wind analyses and related transport of constituents in the middle atmosphere through the improved assimilation procedure involving equatorial waves is challenging.

In a previous study (Žagar *et al.* 2005) we speculated about the potential impact of QBO on background-error covariances in the tropical stratosphere; this and the fact that a major part of tropospheric forecast errors was associated with the ITCZ region were reasons to discuss the possibility of significant variations of the tropical background-error statistics on seasonal and interannual scales. We showed in this study that

1. increased errors in the wind field over the ITCZ region, present in the earlier ECMWF model version, were removed by the recent model improvements,

2. the phase of the QBO has an impact on the background-error variances represented by the various equatorial modes in the tropical stratosphere.

Although it is not impossible that QBO variations modulate deep convection in the tropics, and consequently the model errors (e.g. Collimore *et al.* 1998, Collimore *et al.* 2003), the present study suggests that the influence of the QBO phase on forecast errors is limited to the stratosphere. The difference between the vertical distributions of the error variance in the two phases is seen in the relative increase of variance in WEIG modes in the westerly phase. On the other hand, there is relatively more Kelvin, EMRG and EEIG wave variance in the easterly phase. The difference in the vertical profiles of variances in datasets from two easterly phases is consistent with the theory of the interaction of waves with the descending wind shear zones during the easterly QBO.

Idealized assimilation experiments, used to test whether using the background-error covariances from the phase different from the one for which the observations were simulated deteriorates the analysis scores, suggest that this impact is marginal. On average, the easterly phase statistics appear to be more efficient in the assimilation, related to a stronger mass-wind coupling close to the equator in the easterly phase and a prevalance of zonal winds in the stratosphere.

Acknowledgements

This study was partly funded by the EUMETSAT Contract EUM/CO/05/1447/PS. We thank Joan Alexander, Jeff Anderson, George Kiladis, Adrian Simmons and Joe Tribbia for discussions and comments on the manuscript.

References

Andersson, E., Fisher, M., Munro. R. and McNally, A., 2000: Diagnosis of background errors for observed quantities in a variational data assimilation scheme, and the explanation of a case of poor convergence. *Q. J. R. Meteorol. Soc.*, **126,** 1455–1472

Andersson, E., Cardinali, C., Fisher, M., Holm, E., Isaksen, L., Trémolet, Y. and Hollingsworth, A., 2004: ‘Developments in ECMWF’s 4D-Var system‘. Proceedings of the AMS Symposium on Forecasting the Weather and Climate of the Atmosphere and Ocean, Seattle, Washington State, 11–15 Jan. 2004. Available from the American Meteorological Society, http://ams.confex.com/ams/84Annual/20WAF16NW/program.htm

Baldwin, M. P., Gray, L. J., Dunkerton, T. J., Hamilton, K., Haynes, P. H., Randel, W. J., Holton, J. R., Alexander, M. J., Hirota, I., Horinouchi, T., Jones, D. B. A., Kinnersley, J. S., Marquardt, C., Sato, K. and Takahashi, M., 2001: The quasi-biennial oscillation. *Rev. Geophys.* **39,** 179–229

Baldwin, M. P. and Gray, L. J., 2005: Tropical stratospheric zonal winds in ERA-40 reanalysis, rocketsonde data, and rawinsonde data. *Geophys. Res. Lett.* **32,** doi:10.1029/2004GL022328

Bauer, P., Kelly, G. and Andersson E., 2002: ‘SSM/I radiance assimilation at ECMWF‘. Pp. 167–175 in Proceedings of the ECMWF/GEWEX workshop on Humidity Analysis, 8–11 July 2002, Reading, U.K.

Bechtold, P., Chaboureau, J.-P., Beljaars, A., Betts, A. K., Köhler, M., Miller, M. and Redelsperger, J. L., 2004: The simulation of the diurnal cycle of convective precipitation over land in global models. *Q. J. R. Meteorol. Soc.,* **130,** 3119–3137

Collimore, C. C., Hitchman, M. H. and Martin, D. W., 1998: Is there a quasi-biennial oscillation in tropical deep convection? *Geophys. Res. Lett.* **25,** 333–336

Collimore, C. C., Martin, D. W., Hitchman, M. H., Huesmann, A. and Waliser, D. E., 2003: On the relationship between the QBO and tropical deep convection. *J. Climate* **16,** 2552–2568

Derber, J. C. and Bouttier, F., 1999: Formulation of the background error covariances in the ECMWF global data assimilation system. *Tellus*, **51A,** 195–221

Dunkerton, T. J., 1997: The role of gravity waves in the quasi-biennial oscillation. *J. Geophys. Res.,* **102,** 26053–26076

Hamilton, K., 1998: Dynamics of the tropical middle atmosphere: a tutorial review. *ATMOSPHERE-OCEAN,* **36,** 319–354

Horinouchi, T. and Yoden, S., 1998: Wave-mean flow interaction associated with a QBO-like oscillation simulated in a simplified GCM. *J. Atmos. Sci.,* **55,** 502–526

Fisher, M., 1996: ‘The specification of background error variances in the ECMWF variational analysis system‘. Pp. 645–652 in Proceedings of the ECMWF Workshop on Non-linear aspects of data assimilation, 9–11 September 1996, Reading, U.K.

Fisher, M., 2003: ‘Background error covariance modelling‘. Pp. 45–64 in Proceedings of the ECMWF Workshop on Recent developments in data assimilation for atmosphere and ocean, 8–12 September 2003, Reading, U.K.

Gaspari, G., Cohn, S. E., Guo, J. and Pawson, S., 2006: Construction and application of covariance functions with variable length-fields. *Q. J. R. Meteorol. Soc.,* **132,** 1815–1838

Köpken, C., Kelly, G. and Thépaut, J.-N., 2004: Assimilation of Meteosat radiance data within the 4D-Var system at ECMWF: Assimilation experiments and forecast impact. *Q. J. R. Meteorol. Soc.,* **130,** 2277–2292

Lorenc, A. C., 2003: Modelling of error covariances by 4D-Var data assimilation. *Q. J. R. Meteorol. Soc.,* **129,** 3167–3182

Phillips, N., 1986: The spatial statistics of random geostrophic modes and first-guess errors. *Tellus,* **38A,** 314–322

Polavarapu, S., Shepherd, T. G., Rochon, Y. and Ren, S., 2005: Some challenges of middle atmosphere data assimilation. *Q. J. R. Meteorol. Soc.,* **131,** 3513–3527

Rabier, F., 2005: Overview of global data assimilation developments in numerical weather-prediction centres. *Q. J. R. Meteorol. Soc.,* **131,** 3215–3233

Randel, W., Udelhofen, P., Fleming, E., Geller, M., Gelman, M., Hamilton, K., Karoly, D., Ortland, D., Pawson, S., Swinbank, R., Wu, F., Baldwin, M., Chanin, M-L., Keckhut, P., Labitzke, K., Ramsberg, E., Simmons, A. and Wu, D., 2004: The SPARC Intercomparison of Middle-Atmosphere Climatologies. *J. Climate*, **17,** 986–1003

Randel, W. J. and Wu, F., 2005: Kelvin wave variability near the equatorial tropopause observed in GPS radio occultation measurements. *J. Geophys. Res.*, **110,** D03102, doi:10.1029/2004JD005006

Uppala, S. M., Kållberg, P. W., Simmons, A. J., Andrae, U., Da Costa Bechtold, V., Fiorino, M., Gibson, J. K., Haseler, J., Hernandez, A., Kelly, G. A., Li, X., Onogi, K., Saarinen, S., Sokka, N., Allan, R. P., Andersson, E., Arpe, K., Balmaseda, M. A., Beljaars, A. C. M., Van De Berg, L., Bidlot, J., Bormann, N., Caires, S., Chevallier, F., Dethof, A., Dragosavac, M., Fisher, M., Fuentes, M., Hagemann, S., Hólm, E., Hoskins, B. J., Isaksen, L., Janssen, P. A. E. M., Jenne, R., McNally, A. P., Mahfouf, J. F., Morcrette, J. J., Rayner, N. A., Saunders, R. W., Simon, P., Sterl, A., Trenberth, K. E., Untch, A., Vasiljević, D., Viterbo, P. and Woollen, J., 2005: The ERA-40 re-analysis. *Q. J. R. Meteorol. Soc.*, **131,** 2961–3012

Žagar, N., Gustafsson, N. and Källén, E., 2004a: Variational data assimilation in the tropics: the impact of a background error constraint. *Q. J. R. Meteorol. Soc.*, **130,** 103–125

Žagar, N., Gustafsson, N. and Källén, E., 2004b: Dynamical response of equatorial waves in four-dimensional variational data assimilation. *Tellus*, **56A,** 29–46

Žagar, N., Andersson, E. and Fisher, M., 2005: Balanced tropical data assimilation based on a study of equatorial waves in ECMWF short-range forecast errors. *Q. J. R. Meteorol. Soc.*, **131,** 987–1011