Impacts of Assimilating AMMA Soundings on ECMWF Analyses and Forecasts

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ABSTRACT

The field experiment of the African Monsoon Multidisciplinary Analysis (AMMA) project during the 2006 wet monsoon season provided an unprecedented amount of radiosonde/dropsonde data over the West African region. This paper explores the usage and impacts of this invaluable dataset in the European Centre for Medium-Range Weather Forecasts analyses and forecasts. These soundings are the only source of data that can provide 3D information on the thermodynamic and dynamic structures of the lower troposphere over continental West Africa. They are particularly important for the Sahel region located between 12° and 20°N, which is characterized by large gradients in temperature and moisture in the lower troposphere. An assimilation experiment comparison between the pre-AMMA and AMMA radiosonde networks shows that the extra AMMA soundings have a significant analysis impact on the low-level temperature over the Sahel and on the structure of the African easterly jet. However, the impacts of the extra AMMA data on the forecast disappear after 24 h. The soundings reveal large model biases in boundary layer temperature over the northern and eastern Sahel, which are consistent with the well-known model biases in cloud, rainfall, and radiation. Large analysis increments in temperature lead to increments in divergence and subsidence, which act to suppress convection. Thus, the analysis increments appear to have an undesirable feedback on the cloud and temperature model biases. The impact of the AMMA soundings on the African easterly jet is to enhance and extend the jet streak to 15°E, that is, toward the eastern part of the Sahel. No observations are assimilated east of 15°E at the level of the African easterly jet to support the jet enhancement farther east. Comparisons with independent atmospheric cloud motion vectors indicate that the African easterly jet in the analysis is too weak over this data-sparse region. This could have implications for the development of African easterly waves in the model forecast. Further experimentation by assimilating atmospheric motion vectors—currently not used—could address this problem.

1. Introduction

The West African monsoon provides most of the annual precipitation over the drought-prone Sahel. However, numerical weather prediction (NWP) precipitation forecasts are generally poor during the wet West African monsoon season from June to September, partly because of the lack of observations available. Before the African Monsoon Multidisciplinary Analysis (AMMA) field experiment in 2006, the radiosonde network was quite sparse and only a small amount of data was received via the Global Telecommunication System (GTS). Therefore, few radiosonde observations were assimilated into NWP analyses. The AMMA project made a large effort toward restoring and enhancing the radiosonde network (Parker et al. 2008), which is the only data source that gives comprehensive 3D thermodynamic and dynamic information of the atmosphere over continental West Africa. Indeed, an earlier study by Tompkins et al. (2005b) showed that the thermodynamic observations from the operational radiosonde network in August 2000 provided the most important source of information for an accurate representation of the African easterly jet (AEJ) in the European Centre for Medium-Range Weather Forecasts (ECMWF) analysis.

The aim of this paper is to assess the impacts of the enhanced AMMA radiosonde network on the ECMWF
During August 2006 (i.e., within the peak of the monsoon season). To do this, observational system experiments (OSEs) were performed by comparing two scenarios: the AMMA scenario with the enhanced radiosonde network versus the pre-AMMA scenario with a degraded radiosonde network comprising only those stations that reliably distributed the data through GTS in 2005.

During the AMMA field experiment the radiosonde humidity data were found to have large biases, creating dry pockets in the analysis and degrading the precipitation field in the forecast. Agustí-Panareda et al. (2009c) developed a new bias correction scheme for the AMMA radiosondes that led to an improved precipitation forecast in the ECMWF Integrated Forecasting System (IFS). A validation of the corrected AMMA radiosondes shows good agreement with independent ground-based total column water vapor (TCWV) measurements at several AMMA sites. Faccani et al. (2009) tested the impacts of this bias correction scheme on the AMMA soundings in the French Action de Recherche Petite Echelle Grande Echelle (ARPEGE) assimilation system (Gauthier and Thépaut 2001; Janisková et al. 1999) during the period between 15 July and 15 September 2006. They also found positive impacts on precipitation forecasts, as well as conventional forecast scores in the medium range. The use of the radiosonde humidity bias correction is therefore crucial when assessing the benefits of the AMMA observations on the NWP analyses and forecasts.

The structure of the paper is as follows. Section 2 describes the pre-AMMA and AMMA radiosonde networks. A summary of the data assimilation system used for the experiments is also provided. Sections 3 and 4 show the data impact results and comparisons with independent observations. A discussion of the results is presented in section 5. The main conclusions and suggestions for future work are given in section 6.

2. The AMMA and pre-AMMA observation system experiments

To assess the impacts of the enhanced radiosonde network during the AMMA special observing period (SOP), two analysis experiments were performed. The first experiment uses all the sounding data from the AMMA database (available online at http://amma-international.org/data/), as well as all the GTS data received during August 2006 (see Table 1) and it is referred to as AMMA. Many stations have high-resolution datasets with approximately 3000 levels in the vertical. Because the analysis vertical resolution is 91 levels, before assimilating the

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<th>WMO station ID</th>
<th>Lat (°N)</th>
<th>Lon (°E)</th>
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Table 2. Pre-AMMA radiosonde network.

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<th>Lat (°N)</th>
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High-resolution observations, it was necessary to apply some thinning in order to avoid oversampling. This was performed by taking a maximum of four vertical measurements between two model levels. Namely, if the pressure difference between consecutive sounding levels was less than one-fourth of the model vertical resolution, then that sounding level was discarded. The thinned data profile was checked for consistency with the high-resolution vertical profile. The second experiment is the control experiment, which uses only data received via GTS from stations that were reliably reporting to the GTS in 2005, that is, before the AMMA SOP (see Table 2). Thus, it is referred to as pre-AMMA. The total number of soundings available for the two experiments is shown in Tables 1 and 2. The station names and the daily frequencies are shown in Fig. 1.

Both experiments are based on the ECMWF IFS cycle CY32R3. This cycle was operational from 6 November 2007 to 3 June 2008. It includes improved physics compared to the previous model cycle. Namely, the improvements include a new formulation of the convective entrainment and adjustment, vertical diffusion reduction in the free atmosphere, new soil hydrology, and new operational radiosonde temperature and humidity bias correction. Bechtold et al. (2008) showed that the changes in the model physical parameterizations led to an improved precipitation forecast in the short range over the tropics and in particular over West Africa, where the ITCZ shifts northward by approximately 1° (Agusti-Panareda and Beljaars 2008).

The AMMA radiosonde humidity bias correction of Agusti-Panareda et al. (2009c) is also used in both experiments. Almost half of the AMMA radiosondes in 2006 were Vaisala RS80-A, which are known to have large dry biases in relative humidity (RH) (Wang et al. 2002). The other main types of radiosondes were MODEM and Vaisala RS92. The RH biases were estimated as a function of sonde type, solar elevation, pressure level, and observed RH, using the cumulative distribution function (CDF) matching technique, and Vaisala RS92 at nighttime as a reference. The bias correction ranges from 10% to 28% at low levels within the boundary layer and 8% to 20% from 800 to 300 hPa. The validation of the bias correction was done by comparing the corrected radiosonde data with independent ground-based GPS TCWV at six sites in the Sahel. The comparison shows that the mean difference between the two datasets ranges between −1 and 1.5 kg m⁻², which is close to the uncertainty of the GPS TCWV data (±1 kg m⁻²). Clearly, the use of corrected humidity profiles in the analysis also reduces the TCWV bias with respect to GPS at all sites. The impacts on the analyzed TCWV and short-range precipitation forecast are significant. TCWV increases between 2 and 6 kg m⁻² around the corrected radiosonde stations and there is an increase of approximately 2 mm day⁻¹ in the 1-day precipitation forecast within the latitude band from 8° to 15°N.

The IFS data assimilation system is a four-dimensional variational data assimilation scheme (4DVAR; Rabier et al. 2000) with a full representation of the linearized physical processes (Janisková et al. 2002; Tompkins and Janisková 2004; Lopez and Moreau 2005). The 4DVAR assimilation system provides an estimate of the atmospheric state by combining meteorological observations and prior model information or background. The solution is a weighted mean of the two datasets (observations and model) and the weights are given by the so-called background error covariance matrix (B matrix) and by an estimate of the observation error variances (R matrix). The observations are assimilated within a 12-h window at the correct time. The background error covariance matrix plays a key role in spreading the information on different pressure levels and away from the observing stations. Furthermore, balance among the model parameters is imposed mainly in the extratropics (Derber and Bouttier 1999).

Figure 2 displays the distribution of the conventional observations assimilated in August 2006 only below 500 hPa, that is, the layer that comprises the monsoon flow and the African easterly jet. In this layer, aircraft provide information of wind and temperature in the ascending and descending phases close to the airports. Surface pressure and daytime 2-m humidity observations are assimilated from synoptic observations (SYNOPs) over land,
ships, and buoys. Over the ocean, the 10-m wind and 2-m nighttime humidity are also assimilated from buoys. Observed temperature, wind, and humidity profiles from radiosondes and dropsondes are also provided to 4DVAR, and wind profiles from sonde pilot balloons are available as well. However, a significant number of the pilot balloon winds are not used because of their inconsistent quality.

Meteosat atmospheric motion vectors (AMVs) from cloud and water vapor feature tracking processed by the European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT) are assimilated over the AMMA region with stringent restrictions in the lower and mid troposphere. This is due to some known issues with AMV height assignments (e.g., Velden et al. 2005; Velden and Bedka 2009) and the resulting large discrepancy (departure) with the model values at the observation locations, which can have negative impacts on the forecasts (von Bremen 2005). Because of these issues, only high-level AMVs (above 400 hPa) are assimilated in the AMMA domain over land. AMVs from visible channels are used below 400 hPa only over the ocean. Despite these restrictions, monthly statistics for the tropics from EUMETSAT show that AMV and radiosonde profiles are in good agreement for the $U$ and $V$ wind components (information online at http://cimss.ssec.wisc.edu/iwwg/iwwg_monitoring_amv.html). Thus, it is believed that over the AMMA region, the large discrepancies between the model and the AMVs are mainly due to model biases.

Scatterometer data and brightness temperatures from satellites were also assimilated over the ocean, providing information about the surface wind, temperature, and specific humidity. Unfortunately, due to the difficulty in the specification of emissivity over land, satellite radiances are not assimilated in the lower troposphere. In summary, the main source of information on the three-dimensional atmospheric state over the African continent is provided by radiosonde observations.

3. Impacts of the AMMA radiosonde network on the analysis

In this section the impacts on the analysis of the radiosonde observations from the AMMA campaign are shown. The impacts of these data are assessed for the temperature, wind, and humidity, as well as for cloud
coverage. The analysis increments are examined first, followed by a comparison of the mean analysis fields. Finally, independent observations are used to evaluate the results.

a. Analysis increments

The temperature, wind, and humidity analysis increments (differences between the analysis and 12-h forecast or background) in the AMMA and pre-AMMA experiments are consistent. Namely, the analysis increments in AMMA reinforce the mean increment pattern already present in pre-AMMA. Moreover, the analysis increments at 0000 UTC are mostly in agreement with those at 1200 UTC for all parameters. For this reason, the mean increments are computed together for 0000 and 1200 UTC. The largest analysis increments are in the boundary layer and in the midtroposphere. Thus, pressure levels at 925 and 700 hPa are chosen as the representative standard levels to show results.

Figure 3a shows the mean analysis increments for the temperature and wind at 925 hPa in AMMA. The largest temperature increments are negative and are located in the Sahel (12°–22°N) around the observing radiosonde stations. This indicates a temperature reduction in the analysis over the Sahel. The temperature reduction is largest at 1200 UTC, and less pronounced at 0000 UTC (not shown). Over the coast (5°–7°N), over the Soudanian region (7°–12°N), and over the Sahara (22°–35°N), the temperature analysis increments are mainly positive. This brings an increase in temperature in the analysis, notably at nighttime. Overall, the wind analysis increments are against the prevalent southwesterly monsoon flow (Fig. 3b), particularly in the Sahel. This is consistent with a reduction in the north–south temperature gradient seen here and the associated reduction in the north–south pressure gradient (not shown).

It is also worth noting that around several stations in the Sahel (e.g., Timbuktu, Mali; N’Djamen, Chad; and Agadez, Niger) the horizontal wind vector analysis increments are divergent and the vertical wind analysis increments are subsiding (solid black contours in Fig. 3a), providing an unrealistic circulation.

The analysis increments for temperature (Fig. 3a) are similar throughout the pressure layer between the surface and 850 hPa over the Sahel and from the surface to 925 hPa in the regions near the coast, over the Soudanian region, and over the Sahara. At 700 hPa the mean temperature analysis increments are very small in magnitude (not shown).

Figure 4 shows the mean analysis increments for the zonal wind at 700 hPa. A dipole of negative and positive increments north and south of 15°N implies that the African easterly jet (AEJ) is displaced northward in the analysis. The jet is also strengthened by around 1.5 m s$^{-1}$ at the entrance region near 15°N, 15°E, surrounding the radiosonde station at N’Djamen. This increase of the wind speed around 15°N is enhanced during the daytime. Another region where there is an increase in the speed of the AEJ is around Timbuktu (16.43°N, 3.00°W). Note that data from neither N’Djamen nor Timbuktu are available in pre-AMMA.
The analysis increments for the meridional winds (not shown) reduce the northerly wind in the eastern Sahel (east of 15°E) and increase the northerly wind west of 5°E, mainly during the daytime. This results in a more zonal jet. During the nighttime, the analysis increments at the latitude of the jet are small in magnitude and in areal coverage.

Figure 5a shows the vertical profile of the mean observation departures for specific humidity in the whole West African region (5°–30°N, 20°W–20°E). Below 850 hPa, the model background is drier than the observations. The dry bias is of the same order of magnitude as the standard deviation of the departures (not shown). The analysis increments—equal to the difference between the dashed and solid lines in Fig. 5—are very small or negligible at 925 hPa (see also Fig. 6a). As a result, the specific humidity analysis at low levels over the whole region is also drier than the bias-corrected radiosonde measurements. It is likely that the observational influence for specific humidity is low due to the high background error correlations in the $B$ matrix close to the surface (Cardinali et al. 2004).

Although the overall specific humidity analysis increments are very small near the surface, the relative humidity increments (not shown) are large, reflecting the large temperature increments described above. It is also worth noting that the bias-corrected radiosonde humidity was found to have a moist bias in TCWV with respect to
ground-based GPS observations (Agustí-Panareda et al. 2009c).

Over the Sahel, the model background has a moist bias close to the boundary layer top—around 850 hPa—depicted by a small kink in the observation departures in Fig. 5b. The analysis is able to reduce this bias effectively by reducing the moisture bias that develops in the background (Fig. 6b). In the midtroposphere (between 700 and 400 hPa), the dry bias in the model background is reduced in the analysis for the whole West African region (Fig. 5a).

b. Mean analysis

The mean low-level temperature for the AMMA analysis is shown in Fig. 7a. The strong positive thermal gradient is responsible for the presence of the AEJ, which dominates the West African region during the summer months (Thorncroft et al. 2003). The mean 925-hPa temperature in AMMA is about 2 K cooler than in pre-AMMA in the vicinity of Agadez (16.97°N, 7.98°E) and extending over the region 10°–25°N, 5°W–15°E (Fig. 7b). The fact that the main reduction in temperature occurs

![Fig. 4. Mean zonal wind analysis increments at 700 hPa for August 2006 based on both the 0000 and 1200 UTC analyses from the AMMA experiment (shaded). The arrows depict the mean wind vector analysis at the same level and time. The black dots depict the locations of the AMMA radiosonde stations.](image-url)

![Fig. 5. Mean vertical profile of radiosonde observation–background departures (OB–BG, solid line) and radiosonde observation–analysis departures (OB–AN, dashed line) of the specific humidity (g kg⁻¹) for the AMMA analysis over (a) the whole West African region (5°–30°N, 20°W–20°E) and (b) the Sahel region (12°–22°N, 20°W–20°E). Numbers on the left indicate the number of observations available around a given level.](image-url)
between 15° and 22°N means that the gradient between the southern (12°–15°N) and northern (15°–22°N) Sahel becomes weaker. Conversely, the temperature gradient between the northern Sahel and the Sahara becomes stronger, suggesting a northward shift of the gradient.

The mean sea level pressure (MSLP) is characterized by a center or belt of minimum pressure associated with the heat low in the latitude band centered around 22°N (not shown). The mean MSLP difference between AMMA and pre-AMMA shows an increase mainly in the region around Agadez (not shown), which is consistent with the decrease in the mean temperature described above.

The monsoon flow at low levels plays a key role in the moisture advection over the Sahel. This flow expands throughout the layer from the surface to 850 hPa over the central (10°W–10°E) and eastern Sahel, but only up to 925 hPa in the western Sahel (west of 10°W). The 925-hPa wind field is used here to depict the low-level monsoon flow. The overall impact of the AMMA data on the low-level monsoon flow is shown in Fig. 7c by comparing the AMMA mean analysis with pre-AMMA. The southwesterly flow at 925 hPa is stronger near the coast in the region of 0°–10°N, 5°W–10°E. Between Tamanrasset, Algeria, and Agadez (in the region of 17°–21°N, 0°–10°E), the southwesterly monsoon flow is also much stronger. However, the largest impact is on the southern flank of the heat low. This is the region where the MSLP gradient (not shown) is strongest and the 925-hPa wind within the southwesterly monsoon flow is fastest (4–8 m s⁻¹; see Fig. 3b). The monsoon flow is between 1 and 3 m s⁻¹ slower in AMMA, particularly west of N'Djamena and Timbuktu (Fig. 7c). The reason why the difference is mainly upstream of these two stations can be explained by
Fig. 7. (a) Mean temperature (K) at 925 hPa for August 2006 based on 0000 and 1200 UTC analyses from the AMMA experiment. The difference between the AMMA and pre-AMMA experiments for the (b) mean temperature at 925 hPa (K) and (c) mean wind from the 0000 and 1200 UTC analyses. The gray shading in (c) indicates the difference in mean wind speed and the arrows depict the mean difference in wind vectors. The black dots show the locations of the AMMA radiosonde stations.
the divergent analysis increments located over Timbuktu, Agadez, and N’Djamena in the AMMA experiment (see Fig. 3a). The difference in mean vertical velocity also reveals an increase in subsidence over these three stations (not shown), with up to a 0.1 Pa s\(^{-1}\) increase in the downward mean vertical velocity over N’Djamena.

In the midtroposphere, the AEJ dominates the flow from 750 to 500 hPa. It is one of the most characteristic components of the West African monsoon. It is particularly well known for its key role in the North Atlantic tropical cyclogenesis through the development of African easterly waves (e.g., Berry and Thorncroft 2005). The mean zonal wind analysis difference at 700 hPa between the two experiments shows that there is a large impact from the extra AMMA observations on the structure of the AEJ (Fig. 8). The jet streak associated with the AEJ extends east of 10\(^{\circ}\)E in the AMMA experiment whereas in pre-AMMA the easterly winds in the jet entrance region (5\(^{\circ}\)–15\(^{\circ}\)E) are weaker by approximately 2 m s\(^{-1}\).

There is a small impact from the enhanced AMMA radiosonde network on the African tropical easterly jet at 150 and 200 hPa over the Gulf of Guinea (not shown). In AMMA the tropical easterly jet is stronger by approximately 1 m s\(^{-1}\). However, observation departures (not shown) indicate that the strength of the tropical easterly jet over western Africa is overestimated at the core by ~1 m s\(^{-1}\). This is probably a consequence of the enhanced convection over the Soudanian and southern Sahel regions, associated with an overestimation of the low-level humidity from the corrected AMMA radiosonde observations (Agustí-Panareda et al. 2009c).

Humidity is one of the key parameters for forecasting precipitation. The impacts of the AMMA observations on the analyzed TCWV will help us to interpret the
radiosonde impacts on the precipitation forecast presented in section 4. Comparison of mean TCWV analyses for the two experiments (Fig. 9) shows an increase between 1 and 3 kg m$^{-2}$ in the region 5°–11°N and 1°W–7°E (i.e., in the vicinity of Parakou, Benin) as well as in the regions between Agadez, Tamanrasset (16°–25°N, 3°–13°E), and Tambacounda, Senegal (13.77°N, 13.68°W). On the other hand, the areas around Timbuktu and N’Djamena show a significant decrease in TCWV of around 2 kg m$^{-2}$. The regions with decreased TCWV correspond to regions with enhanced negative humidity analysis increments in the vicinity of the boundary layer top and downward vertical velocity increments within the boundary layer in the AMMA versus pre-AMMA experiments (described in the previous section). Similarly, regions with increased TCWV are associated with larger positive humidity analysis increments in the AMMA experiment.

c. Evaluation using independent observations

The impacts of the observations on the analysis are also evaluated by comparing the analyses from the two experiments with independent observations. Since Meteosat-8 AMVs are not assimilated in the analysis below 400 hPa over land (see section 2), they are used to evaluate the analyzed structure of the AEJ. The presence of cold cloud tops is assessed using Meteosat-8 infrared images, which are also not assimilated.

The AMV data were gridded at 2° resolution from 750 to 500 hPa to cover the vertical layer of the AEJ. The mean zonal winds from the AMVs and from the two analysis experiments during August 2006 for the same layer are plotted in Fig. 10. In general, there are large differences in the structure of the AEJ between the AMVs and the experiments. In the jet exit (around 15°W)
the easterly wind speeds are stronger in both AMMA and pre-AMMA compared to the AMVs. It is worth noting that most of the radiosonde observations used in the analysis experiments are on the gradient of the zonal wind, not on the core of the AEJ itself. Between 10° and 17°E, AMMA has a much stronger jet than pre-AMMA, which does not contain radiosonde observations. This indicates that the model tends to produce a weaker jet than
is observed. The AMVs extend the jet core farther with wind speeds faster than 8 m s$^{-1}$ up to the Red Sea (around 40°E). It is also clear that the location and spread of the jet from the AMVs in Fig. 10a are influenced by the orography (Fig. 10a), as well as the surface temperature gradient (Fig. 7a). In fact, the jet slows down and is displaced southward by the Darfur mountain range, which peaks at 3088 m (equivalent to approximately 720 hPa). This curvature in the jet is not present in the analysis experiments (Figs. 10b and 10c) because the height of the model orography is only 1000 m over Darfur. Another clear difference can be found in the representation of the Southern Hemispheric AEJ (AEJ-S). Although the AEJ-S is weaker than its northern counterpart, Mari et al. (2008) found that it played an important role in the interhemispheric transport of biomass-burning plumes during the 2006 wet season. AMVs display a much stronger AEJ-S, with maximum wind speed of 9 m s$^{-1}$ around the equator, whereas the analyses show a weaker jet (approximately 5 m s$^{-1}$) located farther south, at around 5°S.

Despite the differences between the AMVs and AMMA, a bulk comparison of the AMVs with individual radiosonde stations indicates that in the vicinity of the jet core the mean difference is less than 1.5 m s$^{-1}$ (see Table 3). The AMVs’ median and standard deviation are within 2 m s$^{-1}$ of the radiosonde data. Note that the individual collocation approach was not used because it would significantly reduce the data volume for the comparison. Moreover, the bulk comparison shows results that are very similar to the statistics derived during EUMETSAT operational Meteosat-9 AMV quality monitoring (see section 2).

The TCWV from the AMMA experiment during August 2006 was assessed with independent GPS ground-based data by Agusti-Panareda et al. (2009c). TCWV time series from GPS and the AMMA analysis show correlations between 0.7 and 0.9. Results comparing TCWV at six GPS stations indicate that the AMMA analysis is too dry in Timbuktu and too moist in Dakar and Tamale, Ghana [see Fig. 13 in Agusti-Panareda et al. (2009c)], suggesting that the analysis dry bias at low levels found in Fig. 5 is not widespread over the whole AMMA region.

Figure 11 shows the simulated infrared brightness temperatures (IR Tb) from AMMA and pre-AMMA, as well as those from Meteosat-8. Cold cloud tops less than 285 K are used to detect deep convection. Within the latitude band 10°–15°N, it is clear that both analysis experiments produce less cold cloud tops than are observed. However, west of 10°E, AMMA shows a large improvement compared to pre-AMMA, with colder mean brightness temperatures. While east of 10°E and particularly around N’Djamena (15°E), the brightness temperatures in AMMA are warmer than in the pre-AMMA experiment. This indicates an undesirable reduction in convective clouds in areas where there was already a deficit compared to the observations. Similarly, in the region north of 15°N the mean analyses for both experiments lack deep convective clouds whereas the observations show some convective clouds at 0000 UTC. In summary, the AMMA analysis of deep convective cloud is better than that of pre-AMMA in the denser radiosonde region (5°–15°N, 20°W–10°E).

4. Impacts of the AMMA radiosonde network on the forecasts

Forecast skill from the AMMA and pre-AMMA experiments is compared in this section. Figure 12 shows the root-mean-square error,

$$\text{RMSE} = \sqrt{(\text{FC} - \text{OB})^2},$$

of the temperature, RH, and wind for different forecast (FC) ranges (up to 48 h) and different pressure levels (925 and 700 hPa) verified against radiosonde observations (OBs) for AMMA and pre-AMMA. The evolution of the RMSE is remarkably similar for all parameters. There is a positive impact of the extra AMMA observations in the first 12–24 h, which becomes neutral afterward. The impact is significant, with an 80% confidence interval up to 12 h. For some fields (e.g., RH at 925 hPa and zonal wind at 925 hPa), the impact is lost before 12 h. The reason for this short-lived impact lies in the systematic error associated with the model physics, the processes of which can act on time scales of the order of half a day. This is discussed further in section 5.

One of the most important parameters to forecast during the West African monsoon season is the precipitation.
FIG. 11. Mean brightness temperatures (K) (10.8-μm channel) at 0000 and 1200 UTC during August 2006 from (a),(e) observations (Meteosat), (b),(f) pre-AMMA analysis, (c),(g) AMMA analysis, and (d),(h) the difference between the analysis experiments (AMMA − pre-AMMA). The contour lines in (a)–(c) and (e)–(g) represent the orography with contours at 700, 1000, and 2000 m, and every 500 m thereafter. The black dots depict the locations of the AMMA radiosonde stations.
Overall, there is an improvement in the mean 1-day precipitation forecast over the central Sahel, with a precipitation increase of around 2 mm day$^{-1}$ with respect to pre-AMMA. The overestimation of precipitation in the area around Parakou (9.35$^\circ$N, 2.62$^\circ$E) is induced by an overestimation of the observed RH, which can be traced back to ground-check problems in the soundings at that station (M. Nuret 2009, personal communication). In contrast, east of 10$^\circ$E, the reduced precipitation amount (Fig. 13) collocated with increased subsidence makes the forecast worse in that region. The contrast in the impact on the precipitation between the central and eastern Sahel is consistent with the impact on the cold brightness temperatures associated with convective clouds in the analysis (see section 3c).

5. Discussion

The results from the two experiments with and without the enhanced AMMA radiosonde network demonstrate that the impacts of the observations on the analysis are significant, in particular in the region of the low-level monsoon flow and the AEJ. However, the effects of the observations on the forecast disappear after only 24 h. This is believed to be related to the presence of biases in the model. Therefore, the observation impacts are limited mainly to the analysis fields. For precipitation, the forecast initialized with the analysis containing the AMMA observations is worsened in some regions. AMMA shows an improvement in the precipitation pattern over the central Sahel, but a degradation over the eastern Sahel. In this section, the discussion will focus on three important issues: (i) the presence of biases in the model, (ii) the analysis increments and their role in the degradation of the forecast, and (iii) the lack of observations in the eastern part of the Sahel.

a. The model bias

The mean analysis increments presented in the previous section indicate that there is a very large warm temperature bias at low levels over the Sahel. The variability of the temperature analysis increments reflects the diurnal cycle of the model temperature bias. Boundary layer temperature is modulated by the net radiation, the
Bowen ratio, and the advection by the monsoon flow. Guichard (2009) and Agustí-Panareda et al. (2009b) presented evidence of a large model bias in the incoming solar radiation, resulting in the net radiation being overestimated in the Sahel, which could easily explain the bias in temperature.

Possible reasons for this net radiation bias were pointed out by Guichard et al. (2009) and include model deficiencies in cloud cover, precipitation, and aerosol, as well as the need to improve the surface scheme, in particular the representation of vegetation. It is well known that the ECMWF model has problems with the cloud and precipitation over West Africa, with the ITCZ being shifted to the south and an overall lack of precipitation over the Sahel (Agustí-Panareda and Beljaars 2008; Agustí-Panareda et al. 2009c). Agustí-Panareda et al. (2009b) and Meynadier et al. (2010, manuscript submitted to J. Geophys. Res.) have shown that the cloud and precipitation bias is linked to an overestimation of the moisture flux divergence associated with an overintensification of the heat low circulation in the model forecast. The lack of precipitation and cloud feeds back on the soil moisture, which has a large deficit over the Sahel (Boone et al. 2009; Agustí-Panareda et al. 2009a) and also on the overestimation of incoming solar radiation.

The Saharan dust aerosols have also been proven to play an important role in the West African monsoon. Tompkins et al. (2005a) and Rodwell and Jung (2008) presented some of the large impacts on the AEJ and the precipitation over West Africa from changes in the aerosol climatology. In the future, the coupling of aerosol forecasts with radiation is expected to improve the bias in the net radiation and precipitation through the physical and dynamical feedbacks in the Saharan heat low system during the wet monsoon season. The main model biases linked to the different physical aspects over West Africa have been further documented in the AMMA reanalysis by Agustí-Panareda et al. (2009b) using independent observations.

b. Analysis increments and their impacts on the forecast

The temperature bias in the model (see section 5a) results in large low-level temperature analysis increments, which in turn produce unrealistic divergent wind increments with sinking motion below 700 hPa. There are three ways in which these divergent wind increments could be created. First, they could be induced by the balance or empirical correlations between the temperature and wind imposed on the background error covariance $B$ matrix (see section 2). Second, they could be produced by the assimilation of wind observations. Third, they could be associated with the model response to the localized large cooling analysis increments in an environment with a warm temperature bias.
The first hypothesis is tested by performing an analysis experiment with univariate divergence. That is, the divergent wind increments can only come from the assimilation of wind observations. The results from this experiment showed no significant change in the divergent wind increments. This is in accordance with the changes made by Derber and Bouttier (1999), which effectively reduced the balance in the B matrix for the tropics.

The second hypothesis can be tested by monitoring the wind departures between the analysis and the observations in the region where these divergent winds are located. If the divergent wind analysis increments are induced by the assimilation of wind observations, then the analyzed winds should be closer to the observed winds. This is not the case, as the background winds are in many cases closer to observations than the analyzed winds. Thus, this leads to the conclusion that the divergent wind in the analysis increments is not produced by the wind observations themselves. Therefore, the only explanation for the divergent and subsiding analysis increments around several stations in the data-sparse areas of the Sahel (e.g., N’Djamena, Agadez, and Timbuktu) is the response of the warm-biased model to the very large and localized cooling analysis increments around the point-wise radiosonde observations. Namely, it appears that the reduction in temperature is producing cool temperature anomalies around the radiosonde stations, which result in thermally driven circulations. These subsiding and diverging circulations constitute a deterrent for the triggering of convection, which also explains why the precipitation forecasts did not improve over the data-sparse regions. Whereas in regions where the radiosonde network is denser (e.g., the southern Sahel region), the analysis increments around each station can cohere, thereby resulting in a more consistent temperature and wind structure in the analysis.

In summary, the use of more observations can generate larger model forecast errors in specific regions due to the combination of two main factors: (i) large systematic errors in the model and (ii) a very sparse observational network. The issue of the observation scarcity in the analysis is further discussed in the next section.

c. The African easterly jet over the data-sparse eastern Sahel

It is clear that the wind observations at 700 hPa contribute to the change of the AEJ structure in the ECMWF analysis, particularly at the jet entrance and the northern flank of the AEJ. AMVs show that the jet streak indeed appears to extend all the way to the Red Sea. Thus, the winds in the eastern part of tropical North Africa are likely to be too weak in the model analyses. This could have important consequences for the prediction of African easterly wave (AEW) activity in the region on daily to medium-range time scales. First, since some AEWs clearly develop in this eastern region, it is possible that the current observing system fails to pick up AEWs in their early stages of development. Capturing them sooner in the analysis would likely have significant benefits for downstream prediction. Also, recent analyses of AEWs suggest that they are triggered by finite-amplitude diabatic forcing (Berry and Thornicroft 2005) that is most commonly linked to topography (see Mekonnen et al. 2006). Thornicroft et al. (2008) showed, using an idealized dry-adiabatic model, that imposed transient diabatic heating can trigger an AEW downstream as well as increase the overall AEW activity for several days thereafter. This is due to a projection of the perturbation on the most unstable mode for the zonally varying basic state (Hall et al. 2006). The amplitude of the downstream AEW response depends on the location of the heating with respect to the AEJ (Thornicroft et al. 2008) and the nature of the AEJ itself (Leroux and Hall 2009). Hence, these observational and modeling studies motivate the need to represent the AEJ in NWP models as accurately as possible. If the AEJ was strengthened in the east, this would likely mean that AEWs could develop sooner, in association with convection in the Ethiopian Highlands for example.

6. Conclusions and future work

Radiosondes are the only observing system that provides a full description of the atmospheric profile in the lower and mid troposphere in ECMWF analyses. It is therefore not surprising that the AMMA radiosonde observations have a significant impact on the ECMWF analyses. On the other hand, the influence on the forecast is very short lived due to large model biases. The AMMA radiosonde observations are crucial to detecting these model biases. Mean analysis increments indicate that there is a very large model bias in low-level temperature over the Sahel consistent with a bias in net radiation, as well as a lack of cloud cover and precipitation. These model biases make the 4DVAR data assimilation nonoptimal, as the 4DVAR scheme used here assumes a perfect model in the 12-h assimilation window.

The mean analysis differences between the AMMA and pre-AMMA experiments show a large impact from the radiosonde observations on the low-level temperature over the Sahel and the AEJ. This impact is particularly pronounced in the northern and eastern Sahel. Comparison with AMVs leads to the conclusion that over the eastern Sahel the AEJ is too weak in the ECMWF model. There are important implications of having a weaker AEJ in the model forecast for the
development of African easterly waves. As future work, experiments could be performed to test the impacts of assimilating AMVs in the region of the AEJ, in particular over the eastern Sahel where there are no other observations available.

There is an overall improvement in the cloud and precipitation in the AMMA experiment with an increase in the deep cloud in the analysis and a precipitation increase in the 1-day forecast between 10°W and 10°E. However, there is a decrease in both the cloud and precipitation east of 15°E over the Sahel, where there is a deficit in the model. Thus, although the mean analysis–forecast is improved over the central Sahel, it is actually degraded over the eastern Sahel. The degradation is caused by unrealistic analysis increments of winds that are the result of very localized large temperature increments in regions where the model is highly biased and the sounding network is very sparse. These unrealistic wind increments are divergent and lead to enhanced subsidence in the analysis, which has an unfavorable feedback on the cloud and temperature biases. They can also explain the negative impacts of the extra observations in the data-sparse region north of 15°N and east of 15°E. In order to make good use of the observations, further work needs to be done to reduce the bias in the cloud and surface temperature over the region of the Sahel (e.g., by including aerosol coupling with radiation).

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