Summary of the ARM activities at ECMWF from 2007-2009

(Grant No. DE-FG02-07ER64400)

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1. Introduction

The European Centre for Medium-Range Weather Forecasts (ECMWF), as one of the leading centres in numerical weather prediction, has been an active user of observations for model evaluation for many years (e.g. Betts et al. 1996). Many examples exist where detailed experimental studies have inspired model improvement (e.g. Hogan and Illingworth, 2000). To establish a link between the Atmospheric Radiation Measurement (ARM) research and our model development, funding was provided for an "ARM fellow" at ECMWF. Furthermore, ECMWF has been working closely with ARM related projects for many years. ECMWF provides operational analysis data for the ARM stations (permanent and mobile) as background meteorological information and ECMWF has implemented the Rapid Radiative Transport Model long wave and short wave schemes as radiation codes in the operational system (Morcrette et al. 2008). These codes were developed at Atmospheric and Environmental Research Inc. with ARM support and were extensively evaluated using detailed ARM observations. This short report describes the history of the ARM-fellowship at ECMWF and summarizes the achievements over the last 3 years.

2. The ARM-fellowship at ECMWF

The ARM-fellowship at ECMWF has been occupied by three persons, namely by Sylvain Cheinet from 03-Nov-2003 to 02-Nov-2004, by Roel Neggers from 01-Jan-2005 to 31-Aug-2007 and by Maike Ahlgrimm from 01-Jan-2008 until present.

The first study by Cheinet et al. (2005) was of a diagnostic nature. Extensive verification of short range forecasts was carried out using data from the ARM Southern Great Plains (SGP) site. It clearly indicated deficiencies in the representation of shallow convection in the ECMWF system. Cloud cover was too low and the air was too dry over the SGP site in summer. After that a more extensive evaluation of the planetary boundary layer scheme was made using the single column version of the model (SCM). To this purpose observational datasets of the ARM program and the European CloudNet project (Illingworth et al. 2007) were used, as well as large-eddy simulations of idealized case studies. The emphasis was on the diurnal cycles of shallow cumulus convection over land, as this regime is frequently observed at the ARM Southern Great Plains (SGP) site. The results suggested that some systematic biases existed in the representation of both marine steady state convection and continental transient convection.

The next step was to develop a new boundary layer and shallow convection scheme that treats boundary layer turbulence and shallow convection in a unified framework: the Dual Mass Flux (DualM) parameterization (Neggers et al. 2009 and Neggers 2009). The scheme has been developed and optimized using a wide range of single column cases, covering different climate regimes. Preparations for implementation in ECMWF's operational system for numerical weather prediction and seasonal forecasting (referred to as Integrated Forecasting System, IFS) are still ongoing.

In support of the implementation work, further diagnostic studies of the global atmospheric model have been performed using cloud lidar from space (Ahlgrimm et al. 2009 and Ahlgrimm and Köhler 2010). It could be concluded that the new DualM scheme generates better cumulus structures, with the maximum cloud cover at cloud base as observed and not at cloud top as in the operational system. However, also deficiencies are seen particularly in the cloud radiative effects over land. A number of improvements were tested but the land problem still needs further improvement.

3. Summary of the work over the last three years

3.1. The DualM boundary layer/shallow convection scheme

The DualM boundary layer/shallow convection scheme is an extension to the currently used Eddy Diffusivity Mass Flux parameterization (EDMF, Köhler et al., 2010). In this scheme, the strongest updrafts in the convective boundary layer are directly modelled as a mass flux, while smaller scale turbulence is treated diffusively. Moist conserved variables are used to keep track of the boundary layer's humidity, temperature and saturation state. Since only one updraft is explicitly modelled in the mass flux component of the scheme, this updraft can either saturate (cloudy boundary layer, such as stratocumulus) or remain unsaturated (clear boundary layer), but a partially cloudy case cannot be described. The DualM extends this parameterization such that the updraft is flexibly partitioned into a dry and a moist updraft. Depending on the partitioning, boundary layers ranging from completely clear to overcast can in principle be modelled.

The DualM scheme has been evaluated for a broad range of scenarios, and in various stages of interactivity with the larger-scale circulation. Single column evaluation is performed for a range of prototype boundary layer cases, supported by large-eddy simulation results. These include both equilibrium and transitional scenarios. The equilibrium set covers various stages in the low-level trade wind flow, while the transitional set includes a diurnal cycle of shallow cumulus, a stratocumulus to shallow cumulus transition, and a shallow to deep convection transition. Results from the equilibrium cases are summarized in Fig. 1. The first 4 cases are subtropical cases sorted according to their cloud regime in the trade wind flow, with RICO in the purely shallow convection regime (and low cloud cover) and DYCOMS2 representing the stratocumulus regime (with nearly 100% cloud cover). M-PACE is an Arctic cold air outflow stratocumulus case. Transitional cases include the GCSS ASTEX Lagrangian case and the ARM SGP diurnal cycle case. From the SCM experimentation it is concluded that the scheme has indeed sufficient flexibility to cope with a wide range of climatological conditions, which is an obvious requirement for a parameterization scheme in a global atmospheric model.

Further evaluation has taken place in the 3-dimensional modelling environment, by considering the model climate and by looking at short range forecasts. To be able to use the scheme in the full IFS a considerable amount of technical work had to be carried out and the interaction of the scheme with other parameterizations had to be considered. Fig. 2 shows the impact of the DualM scheme on the short wave cloud forcing of the IFS. A clear beneficial impact can be seen particularly in the subtropics, as one would hope from a better representation of shallow cumulus.

As explained in the introduction, the development of the DualM scheme was inspired by deficiencies in the IFS that were exposed by comparison of short range forecasts with ARM-SGP data. Therefore daily short range forecasts have been run for the same period using the new DualM scheme. The composite of these forecasts is shown in Fig. 3 together with a 2 week composite of the ARM-SGP cloud occurrence observations. Three different model versions are shown. It is clear that the DualM version maintains the best cloud structure even in the day 2 to 3 range.

3.2. Stratocumulus evaluation study

In her previous job at Colorado State University, Maike Ahlgrimm worked on the evaluation of stratocumulus in the ECMWF model using data from the GLAS lidar. This work was finalized at ECMWF and resulted in the Ahlgrimm et al. (2009) paper. The paper shows that the frequency of occurrence of stratocumulus clouds in the model compares favourably with the observations (Fig. 4), and that the model cloud tops are lower than observed. It is demonstrated that improvement can be obtained by increasing the temperature excess in the parcel lifting algorithm that is used for the boundary layer depth computation.

3.3. Trade cumulus evaluation and further development of the DualM scheme

To further evaluate the DualM scheme, advantage was taken of ECMWF's collaboration with the CloudSat/CALIPSO science teams. A comprehensive comparison was made of the modelled cumulus clouds in the trade regime. A clear result from this work is the marked improvement in cloud top height distributions of trade cumulus clouds in the IFS when the DualM parameterization is introduced (Fig. 5). This is consistent with the improved vertical structure of shallow convective clouds which was seen in the single column model tests performed with DualM (Neggers 2009). The results from this study have been accepted for publication (Ahlgrimm and Köhler 2010).

Objective evaluation showed several areas where the DualM performed worse than the operational model:

- A lack of moisture, momentum and temperature transport through the boundary layer and lower troposphere.
- The overestimation of cloudiness over the tropical oceans, and a lack of daytime cloudiness over land.

To improve model transport, the original formulation of the DualM parameterization (Neggers et al. 2009) was adjusted as follows: Convective pre-moistening was implemented. As shown by Derbyshire et al. (2004), convection favours a moist environment, possibly preconditioned by earlier convective events. The mean and variance of total water are described by prognostic variables in the DualM scheme, assuming a simple Gaussian probability distribution function (PDF). This allows a choice of the properties for the entrained air from the range of total water values in the PDF. To parameterize preconditioning, the air entrained in updrafts has properties of the upper (moist) tail of the PDF, rather than mean environmental properties. This change leads to enhanced transport by the updrafts.
Further improvement of the momentum transport could be achieved by including the cloud pressure gradient term (Gregory et al. 1997) in the momentum transport equations. Lastly, a diagnostic buoyancy sorting scheme was employed to determine the mass flux profile. Together, these modifications improved the DualM's transport to be comparable with the standard model.

The DualM parameterization is only active when the surface buoyancy flux is positive with the implication that the model fails to produce clouds in cases where convection is not surface-driven. The multi-level triggering of the Tiedtke scheme closes this gap, allowing shallow convection to form when the DualM scheme is not active. Objective scores show that due to the enhanced transport together with this modification, the DualM scheme outperforms the operational model over the extra-tropical oceans.

The one area where the DualM scheme still performs worse than the operational model, despite numerous attempts for improvement, is over the summertime continents. The lack of cloudiness in the DualM run compared to the control run is easy to spot in the mid-level model cloud cover, with the maximum differences lagging local noon by approximately three hours (Figs. 6). However it is more difficult to determine under what circumstances the cloud cover is lacking, and how this is tied to the DualM scheme. For a “typical” day with shallow convection at SGP, the DualM parameterization appears to perform well, consistent with earlier offline simulations. This is illustrated in Fig. 7 with a single case. However, it seems that neither the “golden day” case investigated and modelled with LES and SCM, nor the month-long investigation by Cheinet (ARM Report 1) are sufficiently representative of summertime conditions at SGP to address this problem. Fig. 8 shows monthly average July cloud cover profiles from the Active Remotely-Sensed Cloud Locations VAP. The amount of low and mid-level cloud cover is highly variable from year to year.
Upgrades trying to address the land problem include: The introduction of separate CCN concentrations for land and ocean conditions to enhance the cloud lifetime over land before precipitation onset; re-formulation of precipitation re-evaporation to occur in the convective updrafts; adding a diagnostic cloud anvil formulation similar to the Tiedtke scheme to the DualM parameterization; and changing the total water variance used in the DualM scheme from a diagnostic to a prognostic variable. To date, none of these modifications have managed to substantially improve scores over summertime land.

3.4. Comparison of data from the ARM mobile station in Niamey with the ECMWF model

The ARM mobile facility was deployed to Niamey, Niger during the summer of 2006 and contributed to the African Monsoon Multidisciplinary Analysis (AMMA) project (Redelsperger et al. 2006). The impact of the additional observations on the analysis was investigated by running a special analysis experiment (the AMMA re-analysis) with all the additional observations included (Agusti-Panareda et al. 2010). The AMMA re-analysis was run from May through September. To study the model behaviour, short range forecasts from this re-analysis were compared to radiosonde observations, and turbulent/radiative surface fluxes were compared to measurements from the ARM site.

Fig. 9 shows a 7-day composite of sonde profiles of moisture at Niamey for the four synoptic times of the day. It clearly indicates that the model has a tendency of mixing the boundary layer too much during day time. The result is that the model's boundary layer quickly becomes too deep and well-mixed. The question is whether biases in surface fluxes contribute to this problem.

Observations of incoming and outgoing short wave radiation from the ARM mobile facility show brief periods of decreased shortwave radiation during the dry phase (January through April), which are lacking in the model (Fig. 10). While some of these events may correspond to occasions with cloudy conditions, periods with heavy aerosol loading also contribute to the observed drop in shortwave radiation. In the model, most of these episodes are missing or underestimated, resulting in an overestimation of net shortwave radiation absorbed by the ground (Fig. 11 upper panel). Similarly, precipitation events, which decrease the shortwave radiation reaching the surface, are missing in the model during the pre-onset and monsoon phases (May through mid-September). This is true for the operational model, as well as the forecasts initialized from the AMMA analysis, though precipitation events occur a bit more frequently in the AMMA forecasts. Both outgoing and incoming longwave radiation are overestimated in the model during the dry season, but are in reasonable agreement with the observations during the pre-onset and monsoon phases. However, compensation of the two longwave fluxes leads to a realistic estimation of the net longwave flux at the surface, while the net shortwave flux is overestimated (Fig. 11 upper panel). As a consequence, the surface absorbs up to 50 W/m^2 more solar radiation than observed. When released into the atmosphere through the latent and sensible heat fluxes, this extra energy likely contributes to the deep, well-mixed boundary layers found in the model.

In the ECMWF surface analysis, corrections to the 2 m temperature and humidity can be effected by adjusting the amount of available soil moisture, and thus influencing the Bowen ratio. The well-mixed boundary layer in the model results in a drier 2 m humidity value than the observed profiles, where moisture is concentrated near the surface. The surface analysis increments performed in order to correct this departure from observations lead to an increase in soil moisture (Balsamo et al. 2009). Consequently, the sensible and latent heat fluxes in the model have similar magnitude during the dry phase, despite observations that show that the latent heat flux is very small during this season (Fig. 12). During the monsoon, the observed Bowen ratio is close to one, while the model continues to overestimate the latent heat flux.

4. Concluding remarks

It is clear that the ARM data have been extremely valuable in diagnosing model problems related to clouds and radiation. Systematic errors related to the shallow cumulus parameterization have been identified and a completely new scheme has been developed. The verification has been extended to marine stratocumulus and cumulus clouds, making use of CALIPSO data. The new scheme improves the boundary layer cloud structures substantially, but has not been able to completely rectify the short wave errors associated with convection over land. Much of the evaluation effort has been focussed on cloud amount and vertical distribution, but the link between short wave errors and cloud microphysical properties has yet to be fully established. The ARM observations offer a rich opportunity to further pursue this problem.

The observations of the mobile facility in Niamey (Sahel) have also been exploited to look at the thermodynamic profile and the surface energy balance in the ECMWF model. Because the observation network is so sparse in Africa, these additional observations through the AMMA project were extremely valuable. It turns out that the errors in the ECMWF model are large in West Africa, and that more emphasis is needed on the energy and radiation budgets. The errors in the energy budget are probably related to aerosols, clouds, moisture and land surface processes.

5. Literature

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6. Figures

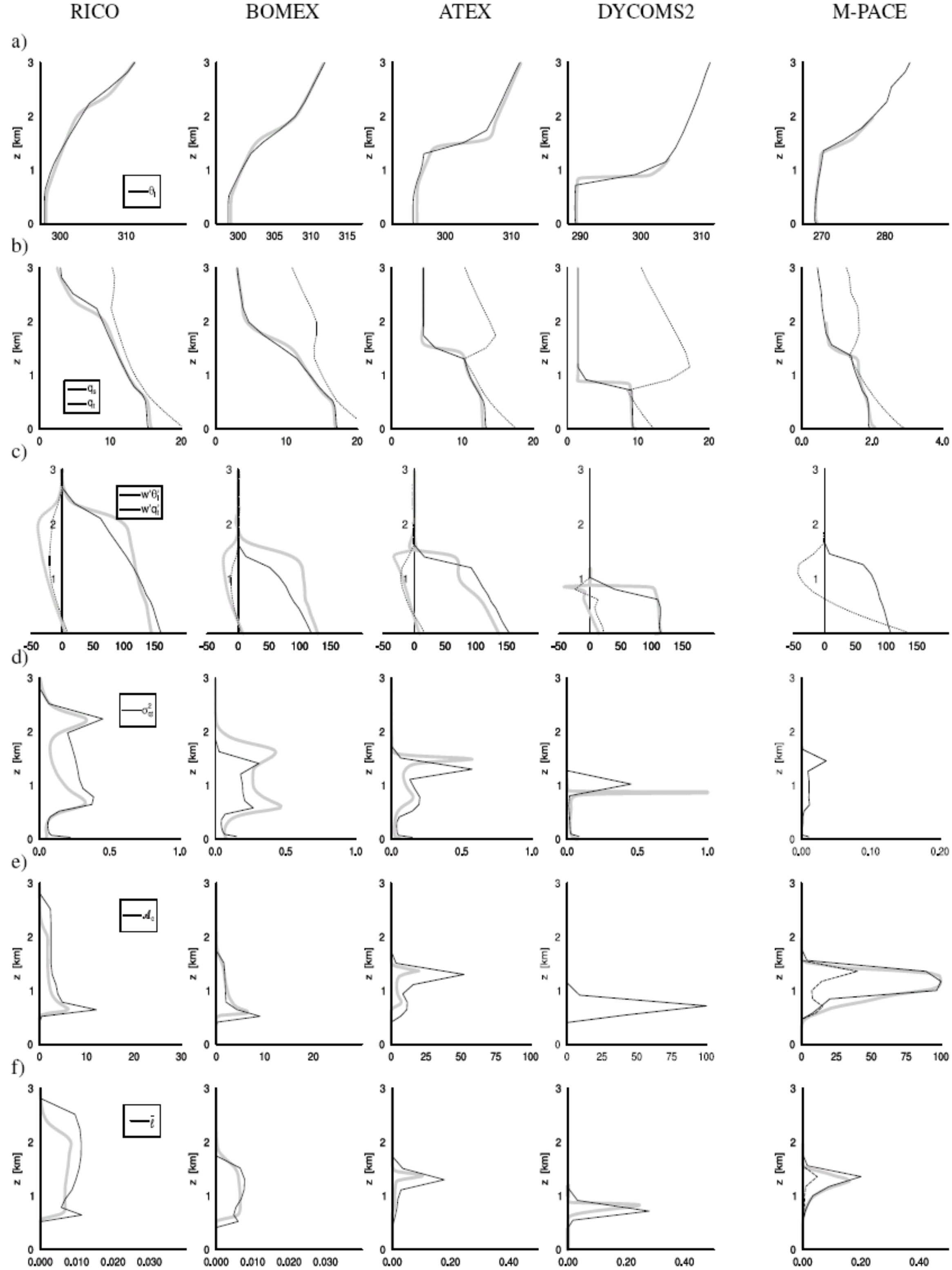

Fig. 1 DualM results on the vertical structure of the mean, turbulent and cloudy state of various idealized steady-state marine cases. Each column represents a different case; from left to right: RICO, BOMEX, ATEX, DYCOMS2, MPACE. Each row shows a different variable; from top to bottom: a) Θ_l (K), b) q_t and q_s (g/kg), c) turbulent latent and sensible heat flux (W/m^2), d) q_t variance (g^2/kg^2), e) cloud fraction (%), and f) total condensate (g/kg). LES results are plotted in grey, SCM results in black.

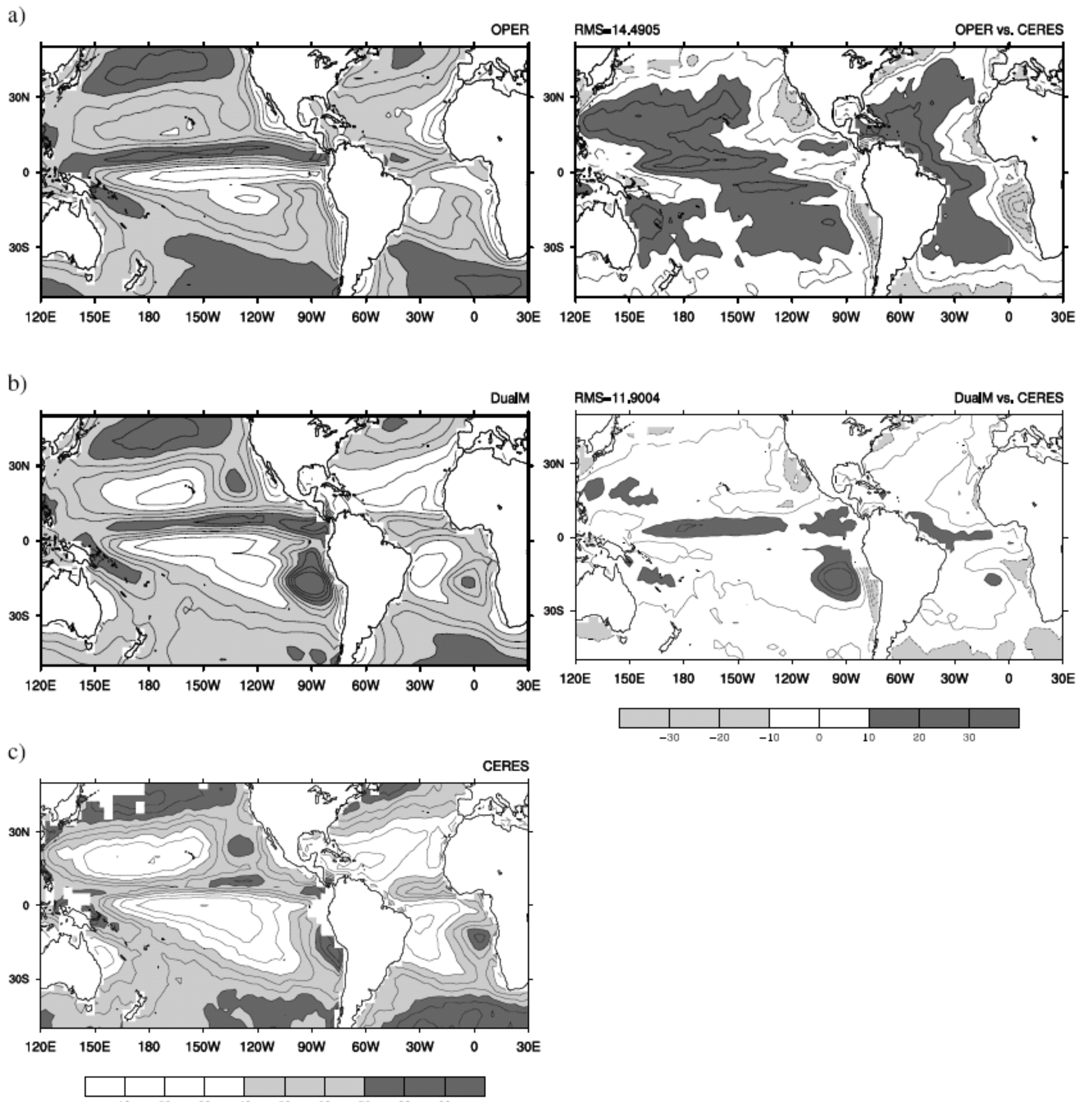

Fig. 2 Climatology of the short wave cloud forcing at the top of the atmosphere (W/m²). The left hand column shows the climate of the operational model with model cycle 32R1 (a), the model climate using the DualM scheme (b), and observations from CERES (c). The right hand column shows the difference between model climate and CERES.

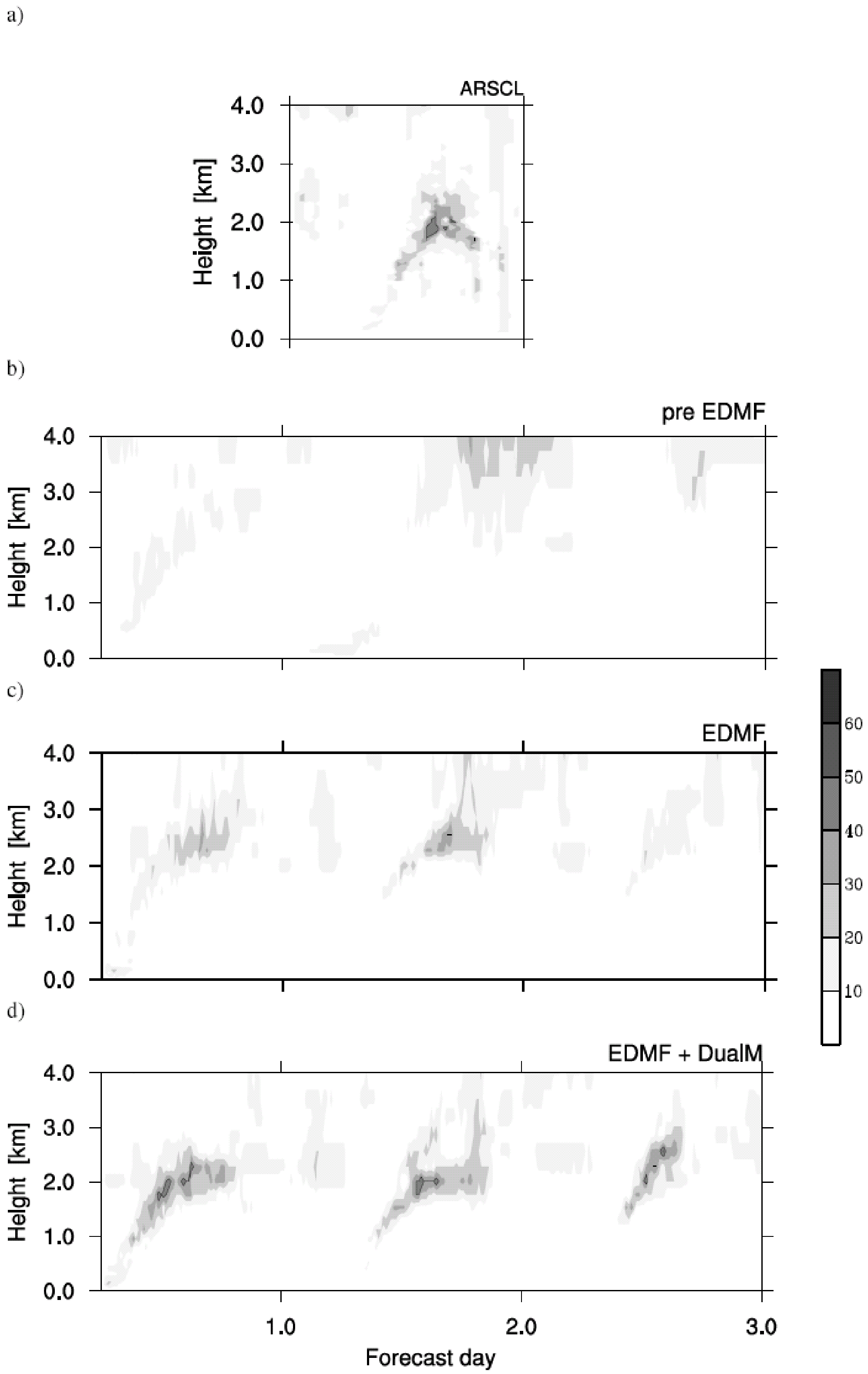

Fig. 3 Composites of cloud frequency of occurrence at ARM-SGP for the first half of July 2003. Panel a) shows the cloud radar observations (ARSCL), while b), c) and d) show the composite of daily short range forecasts with 3 different model versions (pre-EDMF, EDMF and EDMF+DualM respectively). The short range forecasts go out to day 3 which is indicated on the horizontal axis.

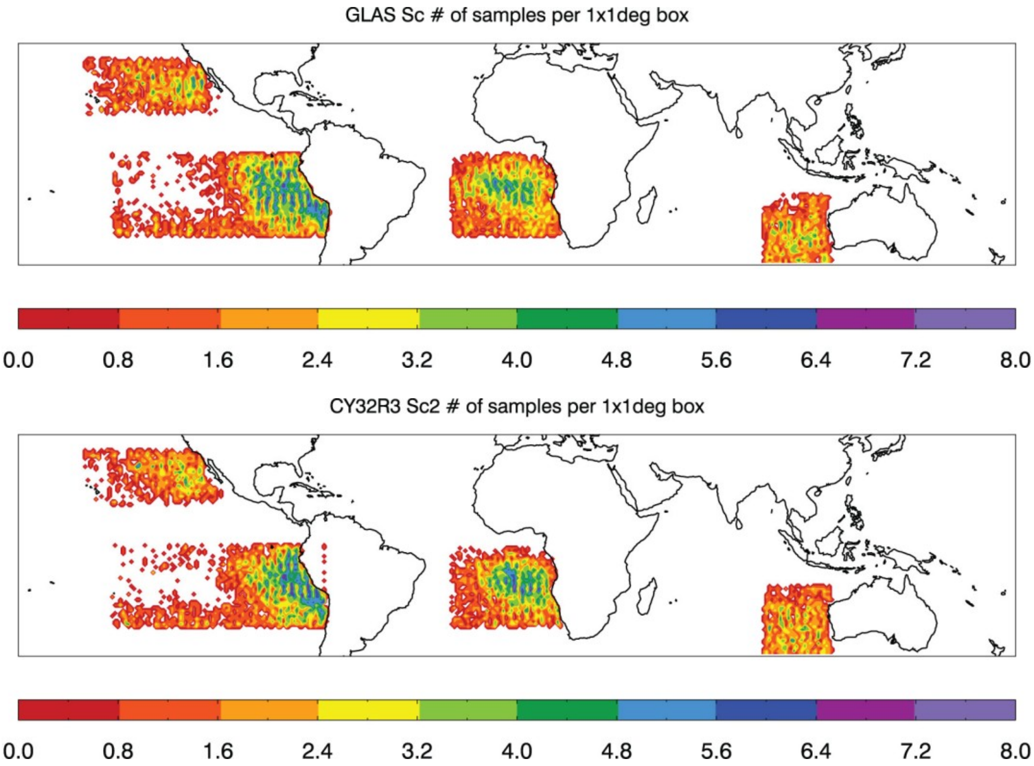

Fig. 4 Frequency of occurrence of marine stratocumulus samples during the GLAS Laser 2A period (Sept 26th through Nov 18th 2003). For comparison, model data (24 to 72 hour forecasts every 2 days with model version 32R3) was extracted along the GLAS orbits. The GLAS observations were then averaged onto the model grid. A 1x1 degree column is classified as stratocumulus when the low cloud fraction is at least 80%, and the cloud top height does not exceed 2 km. Only samples over ocean, and in four specified regions are taken into consideration.

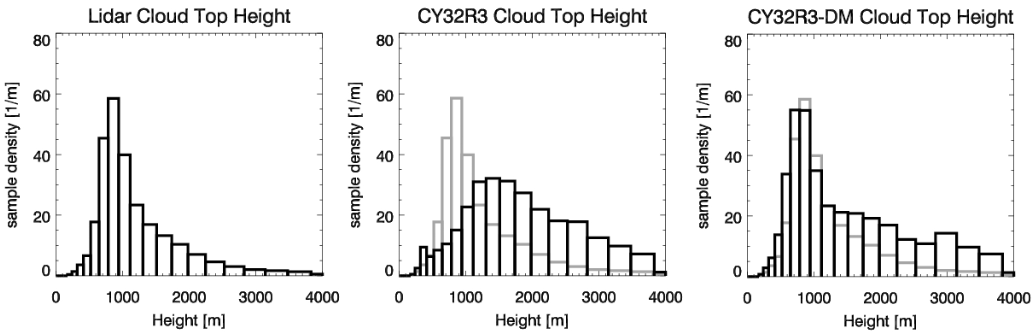

Fig.5 Cloud top height distributions from the standard model (left), from CALIPSO observations (middle) and from the DualM run (right). Trade cumulus samples were determined by identifying model columns along the satellite track with 50% or less low cloud cover, and cloud tops not exceeding 4 km. The results shown are for July 2008. Cloud tops are placed too high in the standard model, but are in very good agreement with the DualM parameterization. How ever, sample frequency of occurrence is overestimated in both model versions compared to observations.

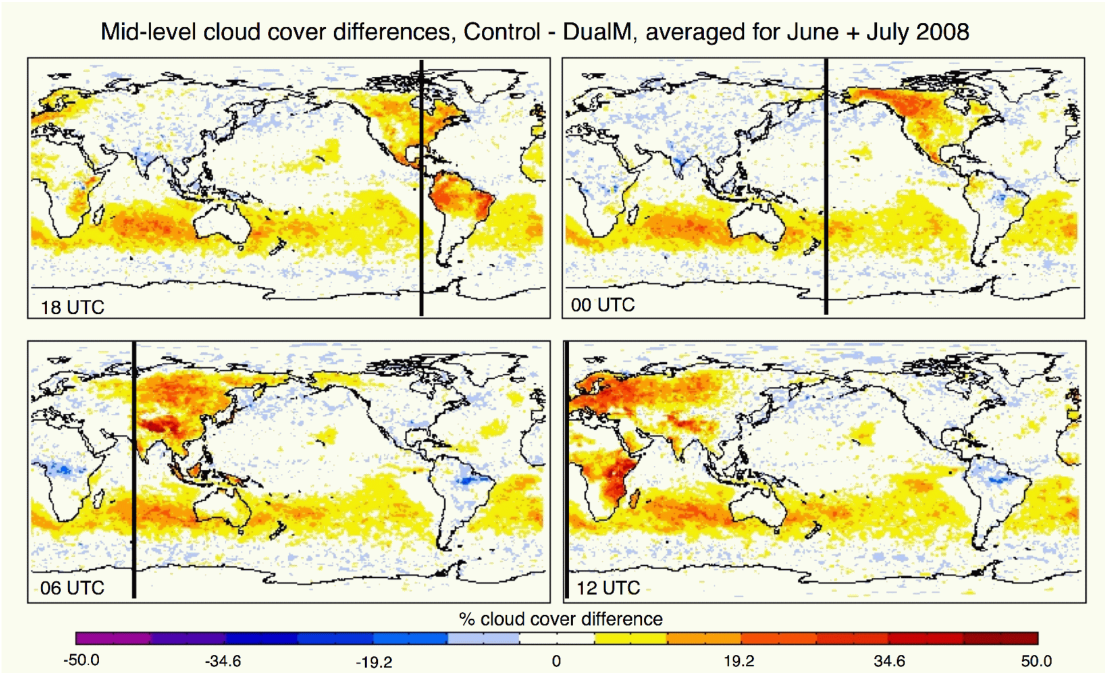

Fig. 6 Difference in mid-level cloud cover between control model and DualM version, averaged for four times a day over two months June-July 2008. Red values indicate that the DualM version of the model produces less mid-level cloud cover. The black bar marks the approximate position of local noon.

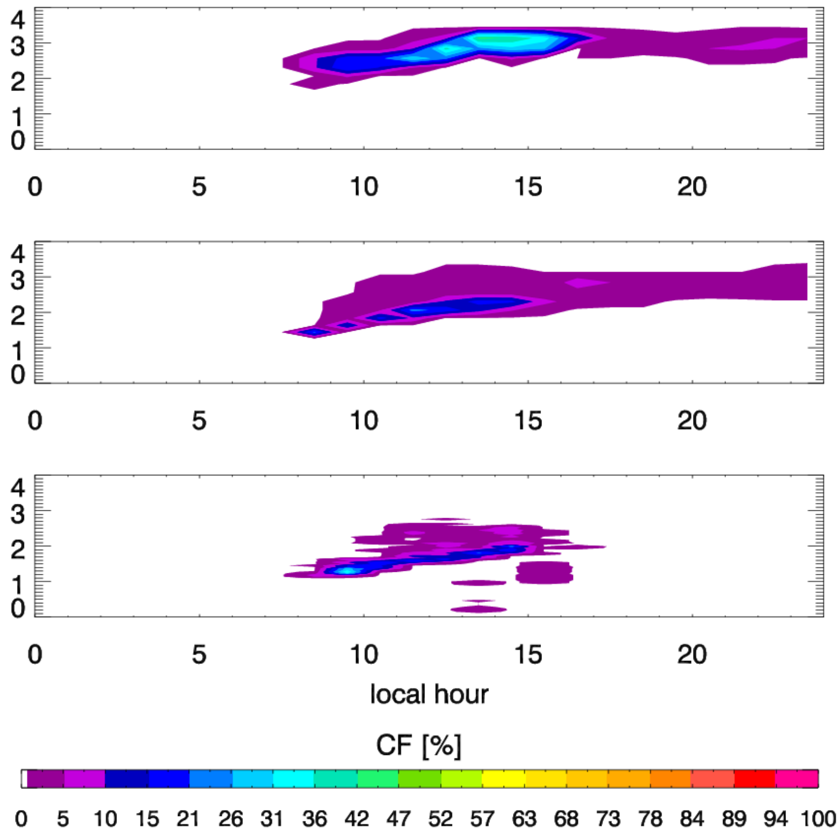

Fig. 7 Cloud cover at ARM SGP site on August 5th 2007. Top: standard model; middle: DualM, bottom: Climate Modelling Best Estimate cloud fraction (ARM observationally based product).

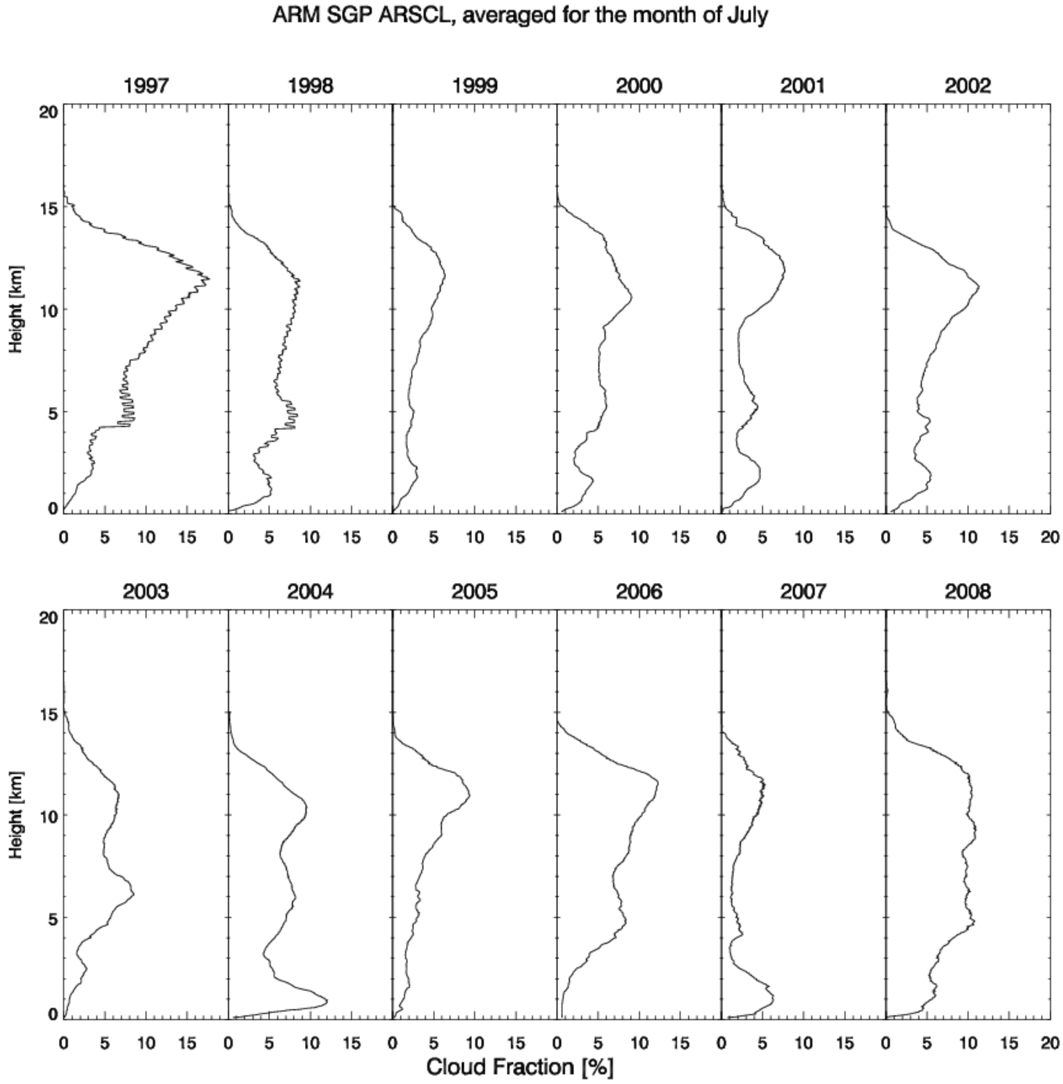

Fig. 8 Monthly average cloud fraction profiles for July from the Active Remotely-Sensed Cloud Locations VAP at Southern Great Plains. Low and midlevel cloud amounts are highly variable from year to year.

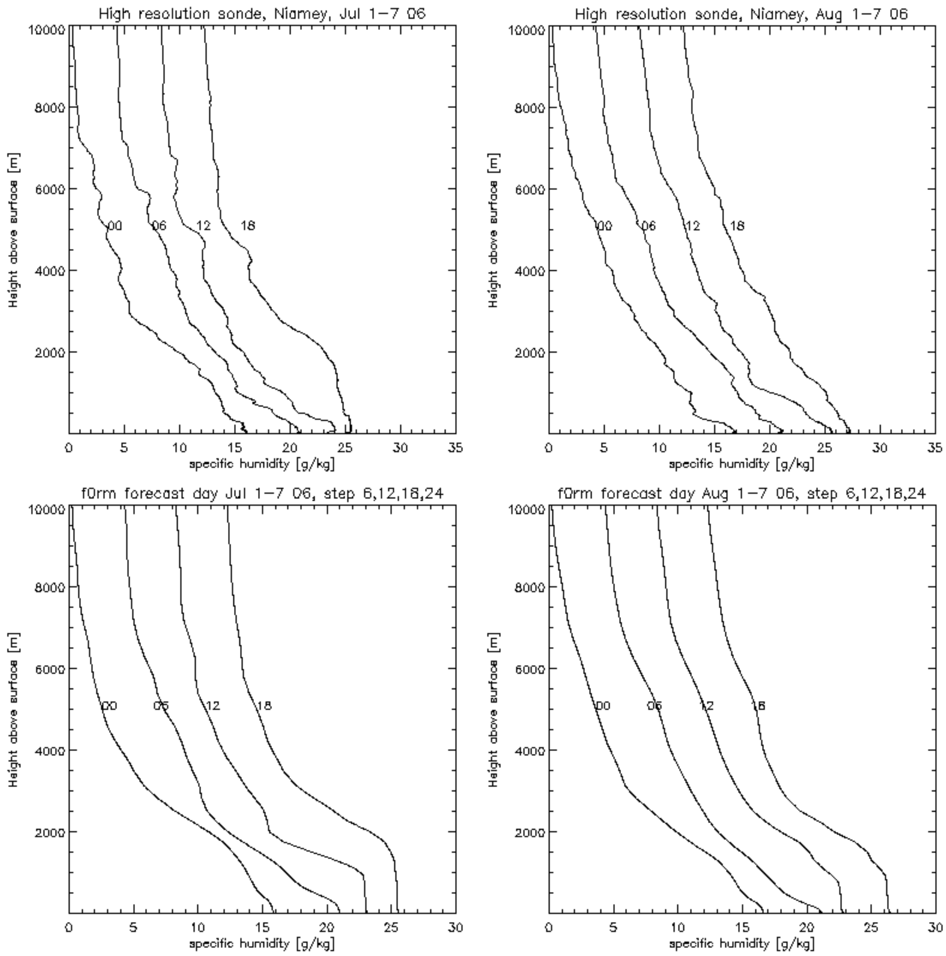

Fig. 9 The top row shows composite profiles of specific humidity averaged from bias-corrected radio sonde observations at Niamey for the first week of the months of July and August 2006 at 00, 06, 12 and 18 UTC. Note the strong near-surface moisture gradient. The bottom row shows equivalent composite profiles from the IFS forecast initialized at 00 UTC from the AMMA reanalysis. Forecast steps 6, 12, 18 and 24 were composited, i.e. the profile labelled 00 UTC is in fact the composite profile from forecast step 24. By noon each day, the profiles indicate that moisture is well mixed throughout the boundary layer in both forecasting periods.

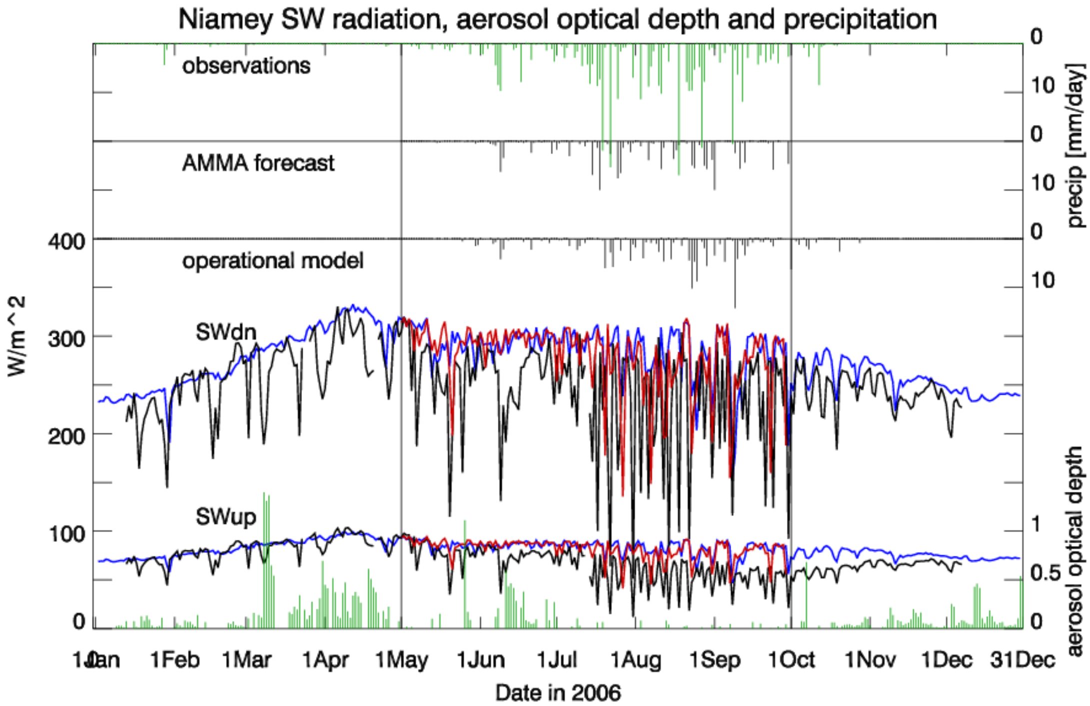

Fig. 10 Surface radiation, aerosol optical depth and precipitation at the ARM mobile facility, Niamey. Lower panel: upward and downward shortwave radiation at the surface with observations in black, operational 1-day forecast in blue and forecast initialised from AMMA analysis in red; the green bars indicate daily average aerosol optical depth, multiplied by a factor 100. Two upper panels: precipitation derived from satellite (FEWS RFEv2 dataset, courtesy of Climate Data Centre, NOAA) and the AMMA 1-day forecast [mm/day]. The black vertical lines delimit the period of the AMMA re-analysis.

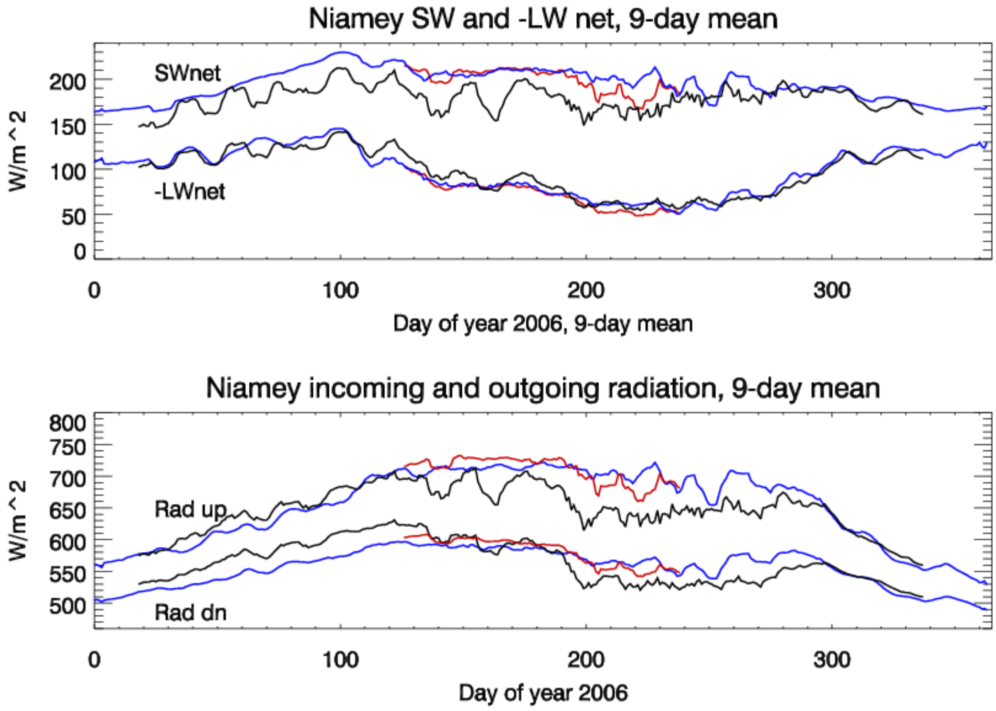

Fig. 11 Surface radiation at the ARM mobile facility, Niamey. Upper panel: 9-point running mean of net shortwave and net longwave radiation at the surface. Lower panel shows combined short-and longwave upward and downward radiation at the surface. Observations are in black, operational forecast in blue and forecast initialized from AMMA analysis in red.

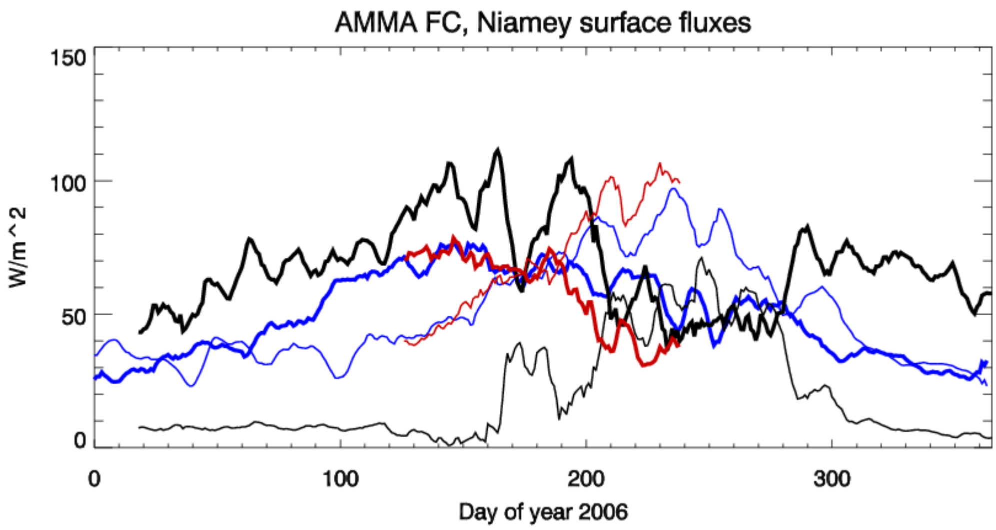

Fig. 12 Surface latent and sensible heat fluxes at the ARM mobile facility, Niamey. The sensible heat flux is shown in thick lines, the latent heat flux in thin lines. Observations are in black, operational forecast in blue and forecast initialized from AMMA analysis in red.