Why Do Global Climate Models Struggle to Represent Low-Level Clouds in the West African Summer Monsoon?

SUPPLEMENTARY MATERIAL

Lisa Hannak *, Peter Knippertz †, Andreas H. Fink, Anke Kniffka, and Gregor Pante

Institute of Meteorology and Climate Research, Karlsruhe Institute of Technology, Karlsruhe, Germany

*Current affiliation: German Weather Service, Frankfurter Str. 135, 63067 Offenbach, Germany.
†Corresponding author address: Prof. Dr. Peter Knippertz, Institute of Meteorology and Climate Research, Karlsruhe Institute of Technology, Wolfgang-Gaede-Str. 1, 76131 Karlsruhe, Germany.
E-mail: peter.knippertz@kit.edu
ABSTRACT

In this supplementary material detailed information on the surface radiation measurements in West Africa and details on the cloud schemes of the YoTC models are provided. In addition, the plots shown for MRI-AGCM3 in the main paper (Figs. 6–8) are provided here for the other seven YoTC models discussed in the main paper as well as their precipitation climatologies relative to ERA-I and a satellite product.
1. Ground-based solar surface radiation measurements in southern West Africa

The table below lists all stations used for the comparison of surface downwelling shortwave radiation. The observational stations are identified by their names and locations (see als Fig. 1). The temporal coverage of the measurements, the climatological average over the available period in W m$^{-2}$, and the data source are provided. For the stations Cotonou (Benin) and Ilorin (Nigeria) the same observational periods as in Knippertz et al. (2011) were taken. The station at Ilorin used to be operated by the Baseline Surface Radiation Network (BSRN, http://bsrn.awi.de) (Aro 2007). The data for Parakou (Benin) were updated and now cover the period 2002–2015. Measurements from Parakou and Cotonou were obtained in the framework of the IMPETUS project (Pohle et al. 2010). These data are available from Andreas H. Fink (andreas.fink@kit.edu). Details of instrumentations are described in the Supporting Material of Knippertz et al. (2011).

New shortwave radiation data from a Gunn-Bellani radiometer operated at the Lamto Geophysical Observatory in Ivory Coast have been acquired for the period 2001–2014. Furthermore, historic monthly radiation data from the Global Energy Balance Archive (GEBA) (Gilgen and Ohmura 1999) provided by the World Radiation Data Centre (WRDC, http://wrdc.mgo.rssi.ru) were taken to calculate mean JAS global irradiance for eleven Ghanaian stations with varying averaging periods between the 1950s and 1990s.

2. Cloud schemes used in YoTC models

A key process for the model performances evaluated here is subgrid-scale cloud cover. The eight YoTC models analyzed in the main paper use a range of different approaches to this problem. Short summaries for each model with some key references are given below.
a. GEOS5 (Molod et al. 2012)

The prognostic cloud cover and cloud water scheme is from Bacmeister et al. (2006). It assumes that the probability distribution function of total water is top-hat shaped with the width of the distribution associated with the grid box critical relative humidity ($RH_{crit}$), the RH at which condensation takes place. The vertical profile of $RH_{crit}$ includes an Atmospheric Infrared Sounder (AIRS)-based profile and a dependence on model horizontal resolution after Molod (2012). Typical $RH_{crit}$ profiles show high values in the PBL and then a sharp drop around 900 hPa (see Fig. 2 in Molod et al. 2012).

b. NavGEM1 (Hogan et al. 2014)

For stratiform clouds, cloud fraction is computed based on RH, vertical motion, and lapse rate (Teixeira and Hogan 2002), when cloud water is present. The diagnostic scheme for stratocumulus uses a simple parameterization of turbulent diffusion, leading to a dependence of cloud fraction on inversion strength. For strong inversions, an increased variance in the PBL leads to considerable cloud cover, even for moderate RH, while for weak inversions, significant cloud fractions are only diagnosed close to saturation. According to Jiang et al. (2015) the model version used for YoTC lacks prognostic cloud water in contrast to that described in Hogan et al. (2014).

c. CAM5 (Neale et al. 2012) & CAM5-ZM (Song and Zhang 2011)

Following Smith (1990), liquid stratus fraction in CAM5 is derived from an assumed triangular distribution of total liquid RH, $v_l = q_{l,l}/q_{s,w}$ where $q_{l,l}$ is the total liquid specific humidity and $q_{s,w}$ is grid-mean saturation specific humidity. Then liquid stratus fraction becomes a unique function of grid-mean RH (see Park et al. 2014, for more details). CAM5-ZM uses a different convection scheme, but to the best of our knowledge, the subgrid-cloud scheme is the same.
d. CNRM-AM (Voldoire et al. 2013)

Stratiform cloud fraction and stratiform liquid water content are computed from Ricard and Royer (1993). The scheme takes into account interactions between cloud fraction coverage, liquid water content, and turbulence. It has been developed on the basis of a statistical cloud scheme and a level-2 subgrid scale turbulence scheme (Mellor and Yamada 1974).

e. FGOALS-s2 (Bao et al. 2013)

The cloud scheme is described in Bao et al. (2010). It is a diagnostic method based on vertical motion and RH. The threshold for low cloud is modified to take account of the differences between land, sea, and regions of snow/ice cover.

f. GISS-E2 (Schmidt et al. 2014)

Stratiform clouds are based on a Sundqvist-type prognostic cloud water approach with diagnostic cloud fraction (Del Genio et al. 1996). Improvements for CMIP5 are given in detail in Kim et al. (2012). The use of threshold RH for liquid and ice clouds distinguishes between free-tropospheric and boundary-layer clouds. The latter is based on an assumed Gaussian distribution of saturation deficit as suggested by Siebesma et al. (2003) with a scaling parameter, while for the free troposphere (above 850 hPa in the absence of moist convection) it assumes that clouds form at lower humidity when strong rising motion is present, with a scale-aware correction for layer thickness.

g. MRI-AGCM3 (Yukimoto et al. 2012)

This model uses a new cloud scheme MRI-TMBC, which is based on the Tiedtke (1993) cloud scheme, which treats cloud water and fraction as prognostic variables. The time evolution of
clouds is derived from large-scale budget equations for cloud water content and cloud air, considering cloud formation through large-scale ascent, diabatic cooling, and PBL turbulence.

3. Additional plots for YoTC model analysis

In the main paper, a detailed discussion for the MRI-AGCM3 model is provided mainly based on Figs. 6–8. Here we provide corresponding plots for the other seven YoTC models. Figures 2 and 3 show results analogous to Fig. 6 in the main paper. Since no low-cloud data are available for FGOALS-s2, this model is not shown. Figs. 4 and 5 are analogous to Fig. 7 in the main paper, and Figs. 6 and 7 for Fig. 8.

With regard to the surface radiation plots, enormous differences in patterns are found. For 06–12 UTC, area averages over our study region vary from 235 to 394 W m\(^{-2}\). For 12–18 UTC, the range remains similarly large but values shift to slightly higher values (269 to 421 W m\(^{-2}\)). Generally speaking, biases persist for most models through the day. It is interesting to note that for two models (CNRM-AM, NavGEM1) radiation decreases into the afternoon as in ERA-I (see main paper), while for all others it increases, probably due to dissolving low-level clouds. For the morning hours, only three models show a clear reflection of the stratus belt across SWA (CAM5, CAM5-ZM, and FGOALS-s2), while the other five do not. Patterns in the afternoon differ very strongly, both over our study region but also over the Sahel to the north, where we would expect cloudiness from afternoon convective systems.

In addition, Fig. 8 shows the climatological diurnal cycle of precipitation from the YoTC models, ERA-I, and TRMM. As with many other fields, the spread between the different datasets in terms of absolute values and diurnal cycle is enormous. There is a general tendency for less precipitation during the night and more during the day, but details differ substantially. The minimum between 06 and 12 UTC evident from TRMM is only reproduced by NavGEM1, while many of the models...
and particularly ERA-I shows substantial rainfall during this period, most likely related to too early triggering of convective rainfalls by the parameterizations employed in the models. Many YoTC models are generally too dry compared to TRMM. ERA-I overestimates rainfall, although it should be kept in mind that uncertainties in quantitative satellite-based rainfall estimates are large. However, TRMM is known to capture the climatological phasing of the diurnal cycle well (Pfeifroth et al. 2016), suggesting substantial errors in this regard in ERA-I. Inspection of the horizontal distribution of rainfall in ERA-I (not shown) indicates early triggering over mountains (e.g., the Jos Plateau in Nigeria) and then unrealistic precipitation in the afternoon along the coast of Ghana and Ivory Coast, possibly related to a too strong land-sea-breeze circulation. This short discussion casts some doubt on the ability of ERA-I to realistically reproduce the precipitation dynamics over the SWA region.

A south–north transect of precipitation averaged from 8°W–8°E (Fig. 9) shows a clear south–north increase across the study region in ERA-I and TRMM but some large deviations from this in some of the YoTC models. A moderate increase is only reproduced by MRI-AGCM3 but at a lower overall level. This model is in good agreement with ERA-I in other parameters as well (Fig. 10 of the main paper). CAM5-ZM and CNRM-AM show a much too steep increase. The much larger difference in latent heating associated with that is consistent with the too large north–south difference in Z925 in these models (Fig. 10 of the main paper). GEOS5 and GISS-E2 show a peak in the middle of the box and a moderate decrease towards 10°N. Nevertheless the Z925 gradient is not too dissimilar from ERA-I (Fig. 10 of the main paper). NavGEM1 also shows a peak at 7.5°N but then a much stronger decrease towards 10°N, consistent with a too small north–south difference in Z925 (Fig. 10 of the main paper). Finally, FGOALS reveals a very awkward behavior with a decrease in precipitation towards the north but then a too large Z925 gradient. This indicates a fundamentally different monsoon circulation to the other models.
References


Table 1. List of surface stations in southern West Africa with measurements of downwelling solar radiation. Stations are listed by country. In addition to the station name, the location, the available time period, and the source of the data are provided. The last column gives the climatological average over the period for which data are available. More details are provided in the text. . . . . . . 13
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<table>
<thead>
<tr>
<th>Station name</th>
<th>Location (lat/lon)</th>
<th>Time period</th>
<th>Source</th>
<th>Average [W m$^{-2}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nigeria</td>
<td></td>
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<tr>
<td>Ilorin</td>
<td>8.53° N, 4.57° E</td>
<td>10 1992 – 8 2005</td>
<td>BSRN</td>
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<td>Ghana</td>
<td></td>
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<td></td>
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<td>Accra</td>
<td>5.60° N, 0.17° W</td>
<td>01 1954 – 09 1979</td>
<td>WRDC/GEBA</td>
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<tr>
<td>Akuse</td>
<td>6.10° N, 0.12° E</td>
<td>01 1980 – 08 1993</td>
<td>WRDC/GEBA</td>
<td>189.5</td>
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<tr>
<td>Axim</td>
<td>4.87° N, 2.23° W</td>
<td>02 1995 – 02 2000</td>
<td>WRDC/GEBA</td>
<td>173.0</td>
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<tr>
<td>Bole</td>
<td>9.02° N, 2.42° W</td>
<td>02 1964 – 02 1994</td>
<td>WRDC/GEBA</td>
<td>190.0</td>
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<tr>
<td>Ho</td>
<td>6.67° N, 0.50° W</td>
<td>08 1964 – 01 1973</td>
<td>WRDC/GEBA</td>
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<td>Kumasi</td>
<td>6.72° N, 1.60° W</td>
<td>03 1964 – 03 1989</td>
<td>WRDC/GEBA</td>
<td>152.2</td>
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<td>Navrongo</td>
<td>10.88° N, 1.08° W</td>
<td>01 1965 – 11 1973</td>
<td>WRDC/GEBA</td>
<td>226.5</td>
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<td>Tafo</td>
<td>6.25° N, 0.38° E</td>
<td>03 1972 – 03 1979</td>
<td>WRDC/GEBA</td>
<td>146.8</td>
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<td>Takoradi</td>
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<td>01 1965 – 10 1983</td>
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<td>Tamale</td>
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<td>07 1966 – 10 1980</td>
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<td>Wenchi</td>
<td>7.75° N, 2.10° W</td>
<td>10 1989 – 12 1997</td>
<td>WRDC/GEBA</td>
<td>143.8</td>
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<td>Benin</td>
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<td>Cotonou</td>
<td>6.35° N, 2.43° E</td>
<td>06 2001 – 10 2008</td>
<td>IMPETUS</td>
<td>197.8</td>
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<td>Parakou</td>
<td>9.33° N, 2.62° E</td>
<td>10 2001 – 10 2015</td>
<td>IMPETUS</td>
<td>171.8</td>
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<td>Ivory Coast</td>
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<tr>
<td>Lamto</td>
<td>6.22° N, 5.03° W</td>
<td>01 2001 – 12 2014</td>
<td>Lamto Geophysical Research Observatory</td>
<td>127.9</td>
</tr>
</tbody>
</table>
LIST OF FIGURES

Fig. 1. Location of the 15 stations with long-term radiation observations. . . . . . . . . . 15

Fig. 2. As Fig. 6 in the main article but for the YoTC models CAM5, CAM5-ZM, and CNRM-AM. . 16

Fig. 3. As Fig. 6 in the main article but for the YoTC models GEOS5, GISS-E2, and NavGEM1. . . 17

Fig. 4. As Fig. 7 in the main article but for the YoTC models CAM5, CAM5-ZM, CNRM-AM, and FGOALS-s2. Note that for CAM5 no advection terms are available but that additionally temperature tendencies due to gravity wave drag ($\Delta T$ gravwave) are plotted. . . . . . . . . . 18

Fig. 5. As Fig. 7 in the main article but for the YoTC models GEOS5, GISS-E2, and NavGEM1. . . 19

Fig. 6. As Fig. 8 in the main article but for the YoTC models CAM5, CAM5-ZM, CNRM-AM, and FGOALS-s2. For FGOALS-s2 no data along 2.5°W are available. . . . . . . . . . 20

Fig. 7. As Fig. 8 in the main article but for the YoTC models GEOS5, GISS-E2, and NavGEM1. . . 21

Fig. 8. Diurnal cycle of precipitation rates averaged over the red box shown in Fig. 1 of the main paper and temporally over JAS 1991–2010. The lines show 6-hourly averages from ERA-I (black line) and seven YoTC models (colored lines; no precipitation available for CAM5). Note that the averaging periods in CAM5-ZM and GISS-E2 are shifted by 3 hours relative to the other models. As an observational reference the satellite-based TRMM 3B42 V7 product (Huffman et al. 2007) is included as 3-hourly averages (gray line; 1998–2010 only). . . . . . 22

Fig. 9. Zonal distribution of precipitation rates averaged between 8°W and 8°E and temporally over JAS 1991–2010. The lines show values from ERA-I (black line) and seven YoTC models (colored lines; no precipitation available for CAM5). As an observational reference the satellite-based TRMM 3B42 V7 product (Huffman et al. 2007) is included, too (gray line; 1998–2010 only). . . . . . . . . . . . . . . . . . . . . . 23
FIG. 1. Location of the 15 stations with long-term radiation observations.
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Fig. 3. As Fig. 6 in the main article but for the YoTC models GEOS5, GISS-E2, and NavGEM1.
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