AGU PUBLICATIONS

JGR

Journal of Geophysical Research: Atmospheres

RESEARCH ARTICLE

10.1002/2016JD025068

Key Points:

- The GFDL high-resolution climate model hydroclimatology was assessed over African river basins
- The model mostly overestimated precipitation and evapotranspiration compared to observational reference
- The model showed consistent net radiation, higher latent heat, and lower sensible heat relative to observational reference

Correspondence to:

D. Tian,
dtian@princeton.edu

Citation:

Tian, D., M. Pan, L. Jia, G. Vecchi, and E. F. Wood (2016), Assessing GFDL high-resolution climate model water and energy budgets from AMIP simulations over Africa, *J. Geophys. Res. Atmos.*, *121*, 8444–8459, doi:10.1002/2016JD025068.

Received 9 MAR 2016
Accepted 14 JUL 2016
Accepted article online 16 JUL 2016
Published online 29 JUL 2016

Assessing GFDL high-resolution climate model water and energy budgets from AMIP simulations over Africa

Di Tian[1], Ming Pan[1], Liwei Jia[2], Gabriel Vecchi[2], and Eric F. Wood[1]

[1]Department of Civil and Environmental Engineering, Princeton University, Princeton, New Jersey, USA, [2]Princeton University/NOAA Geophysical Fluid Dynamics Laboratory, Princeton, New Jersey, USA

Abstract This study assessed surface water and energy budgets in Atmospheric Model Intercomparison Project (AMIP) simulations of a coupled atmosphere-land model developed by Geophysical Fluid Dynamics Laboratory (Atmospheric General Circulation Model (AM2.5)). The AM2.5 water and energy budget variables were compared with four reanalyses data sets and an observational-based reference, the Variable Infiltration Capacity model simulations forced by Princeton Global Meteorological Forcing (PGF/VIC) over 20 year period during 1991–2010 in nine African river basins. Results showed that AM2.5 has closed water and energy budgets. However, the discrepancies between AM2.5 and other data sets were notable in terms of their long-term averages. For the water budget, the AM2.5 mostly overestimated precipitation, evapotranspiration, and runoff compared to PGF/VIC and reanalyses. The AM2.5, reanalyses, and PGF/VIC showed similar seasonal cycles but discrepant amplitudes. For the energy budget, while the AM2.5 has relatively consistent net radiation with other data sets, it generally showed higher latent heat, lower sensible heat, and lower Bowen ratio than reanalyses and PGF/VIC. In addition, the AM2.5 water and energy budgets terms mostly had the smallest interannual variability compared to both reanalyses and PGF/VIC. The spatial differences of long-term mean precipitation, runoff, evapotranspiration, and latent heat between AM2.5 and other data sets were reasonably small in dry regions. On average, AM2.5 is closer to PGF/VIC than R2 and 20CR are to PGF/VIC but is not as close as Modern-Era Retrospective analysis for Research and Applications and Climate Forecast System Reanalysis to PGF/VIC. The bias in AM2.5 water and energy budget terms may be associated with the excessive wet surface and parameterization of moisture advection from ocean to land.

1. Introduction

Assessing numerical models' ability to estimate water and energy budgets on river basin scales has been a key objective of the past Global Energy and Water Experiment. A number of studies have been conducted to assess models' water and energy budgets for major river basins, such as Missisipi River basin [e.g., *Betts et al.*, 1998, 2003b; *R. Yang et al.*, 2015], Mackenzie River basin [e.g., *Betts et al.*, 2003a], and Amazon River basin [e.g., *Fernandes et al.*, 2008] using data from different sources. A variety of data sets produced by global forecast and analysis systems were evaluated against observations [e.g., *Betts et al.,* 1998, 2003a, 2009; *Fernandes et al.*, 2008; *R. Yang et al.*, 2015] or intercompared with reanalyses and global model outputs [e.g., *Betts et al.,* 2003b].

Assessment of model water and energy budgets can produce credible hypothesis for model deficies in representing land surface processes and provide useful information for improving model physics and prediction capacity. Climate models, such as North American Multi-Model Ensemble [*Kirtman et al.*, 2014], typically used 1.0 × 1.0° (approximately 100 × 100 km) horizontal resolution in climate research and seasonal forecasting. In this study, those climate models higher than 1.0 × 1.0° horizontal resolution are referred to as high-resolution climate models. Those high-resolution climate models, developed by various modeling centers, have the ability to better represent small scale processes and showed advantages in simulating key climate events and variables [e.g., *Delworth et al.,* 2012; *Jia et al.,* 2015; *Jung et al.,* 2012; *Kapnick and Delworth*, 2013]. The Geophysical Fluid Dynamics Laboratory (GFDL) has recently developed a forecast-oriented climate model (FLOR) based on the fully coupled high-resolution CM2.5 [*Delworth et al.,* 2012], which is the first high-resolution climate model used for operational seasonal forecast in the United States [*Jia et al.,* 2015]. FLOR has showed relatively skillful seasonal predictions on El Niño–Southern Oscillation, precipitation, and 2 m temperature over land [*Jia et al.,* 2015], tropical cyclones [*Vecchi et al.,* 2014], hurricanes [*Murakami et al.,* 2015], and storm tracks [*X. Yang et al.*, 2015]. The initial conditions for the FLOR atmosphere and land components were taken from the GFDL atmospheric model (AM2.5) simulations forced by observed sea surface temperature (SST) and sea ice concentration. The AM2.5 simulations can be used for model diagnosis, validation, and intercomparison, which provide us an opportunity to look into its water and energy budgets representations. Assessing AM2.5 water and energy budgets would be helpful to understand the error sources and uncertainties of representing land and atmosphere components in FLOR initial conditions.

Reanalyses were developed through merging available observations with numerical models and have been increasingly used as a surrogate of observations, especially in data sparse regions. There are several global reanalyses with high spatial and temporal resolution developed over the past few years. Some of the examples include National Centers for Environmental Prediction (NCEP) Climate Forecast System Reanalysis [*Saha et al.,* 2010], NOAA-CIRES 20th Century Reanalysis [*Compo et al.,* 2011], Modern-Era Retrospective Analysis for Research and Application [*Rienecker et al.,* 2011], and NCEP reanalysis II [*Kanamitsu et al.,* 2002]. However, reanalyses contain uncertainties from the forecast model, input data, and data assimilation [*Hodges et al.,* 2011]. With those newly released reanalyses available, it is desirable to conduct an intercomparison for the AM2.5, reanalyses, and observation-based reference to better understand the depiction of the AM2.5 and reanalyses water and energy budgets and to point out the limitations and issues before real applications.

Africa is a data sparse region and the most vulnerable continent to impacts of climate change and variability [*Intergovernmental Panel on Climate Change*, 2013]. Africa needs full-coverage, high-resolution, and reliable climate data and forecast models at basin or higher scale to fight climate risks in agricultural production, water supply, public health, and so forth. High-resolution climate forecast models and reanalyses can provide potentially accurate climate data and forecast services to Africa, even at basin scale. However, to our knowledge, systematic evaluation of the surface water and energy budgets at basin scale over Africa is hardly available in the literature. Therefore, it is very important to assess the surface water and energy budgets of the AM2.5 and the latest reanalyses in Africa. Such assessments will have direct significance for evaluating the quality and efficiency of climate models and reanalyses and may help improve physics of land surface processes in climate models and reanalyses over Africa and elsewhere.

The objective of this study is to conduct a preliminary investigation on how well the AM2.5 can simulate the seasonal and interannual variation of surface water and energy budgets in major African river basins, including Zhua, Chad, Congo, Limpopo, Niger, Nile, Okavango, Orange, and Zambezi for a 20 year period from 1991 to 2010. We look at the long-term average, monthly and interannual variability, and spatial differences of precipitation, evapotranspiration, and runoff in the AM2.5, reanalyses, and observation-based reference as well as energy budgets. We compared surface water and energy budget variables as well as skin temperature and 2 m air temperature from Atmospheric Model Intercomparison Project (AMIP) simulations of AM2.5 with four reanalysis (Climate Forecast System Reanalysis (CFSR), 20CR, R2, and Modern-Era Retrospective analysis for Research and Applications (MERRA)) and observational reference. The observational reference used for comparison with the AM2.5 and reanalyses is Princeton Global Meteorological Forcing data set [*Sheffield et al.,* 2006] and its forced Variable Infiltration Capacity model simulations (PGF/VIC) [*Pan et al.,* 2012]. It is believed that the PGF/VIC provides the most reliable information about climatology and variability of water and energy budgets over Africa given the lack of availability for high-quality observations in this region. This comparison will help us understand how well does AM2.5 simulate surface water and energy budgets related to the four reanalysis products.

2. Model and Data Sets

2.1. Model Description

The GFDL AM2.5 model coupled atmosphere and land components of the CM2.5 model [*Delworth et al.,* 2012] and forced by observed SST and sea ice concentration. The CM2.5 model is considered as a high-resolution climate model developed by the GFDL. The AM2.5 has archived AMIP simulations over 1981 to 2010. The AM2.5 AMIP simulations have archived 12-member ensembles at a spatial resolution of $0.5 \times 0.5°$ (approximately 50×50 km). The 12-member ensembles from the AM2.5 were averaged into ensemble mean. The monthly mean of daily water and energy budget variables over the 20 year period from 1991 to 2010 was then evaluated, including precipitation (P), evapotranspiration (ET), runoff (RO), net radiation (R_n), latent heat (LH), and sensible heat (SH), 2 m air temperature (T_a), and skin temperature (T_s). For the basin-wide evaluation,

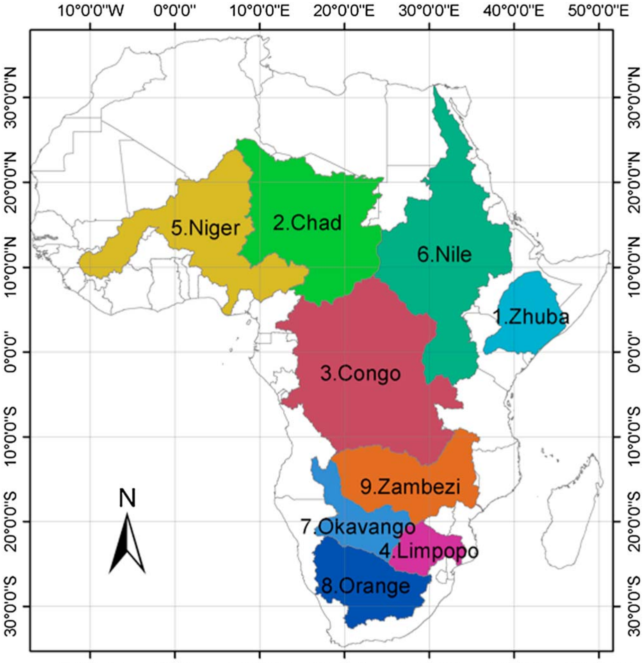

Figure 1. Locations of major river basins in Africa.

the gridded data were averaged over each of the catchment areas, including Zhua, Chad, Congo, Limpopo, Niger, Nile, Okavango, Orange, and Zambezi, as shown in Figure 1.

2.2. PGF/VIC and Reanalysis Data Sets

It is difficult to assess model simulations of surface hydroclimatology due to lack of high-quality observed data sets in Africa. The evaluation of AM2.5 will have to rely on model-driven estimates of land surface variables. Thus, we compared AM2.5 water and energy budgets with four reanalyses (CFSR, R2, 20CR, and MERRA) and observation-based PGF/VIC for. The PGF/VIC was used as observational reference. Monthly mean of daily data from these reanalyses and VIC simulations over 20 year period from 1991 to 2010 was used for water and energy budget assessment.

The temporal coverage for R2, MERRA, and CFSR data were from 1979 to present, and for 20CR was from 1871 to 2012, all with monthly mean of daily data available. The spatial resolution for those data sets varies from approximately 0.5° × 0.5° to 2.5° × 2.5°. All data sets were bilinearly interpolated to a same spatial resolution 0.5° × 0.5° for comparing with AM2.5 as well as with each other. The CFSR is the first global reanalysis product to apply a coupled land-atmosphere-ocean-sea ice system [*Saha et al.,* 2010]. The CFSR land analysis assimilates satellite radiances and hydrological quantities from the four-layered Noah land surface model [*Ek et al.,* 2003] forced by the Climate Prediction Center (CPC) merged analysis of precipitation [*Xie and Arkin*, 1997] and the CPC unified daily gauge analysis [*Xie et al.,* 2010]. MERRA is a recent reanalysis developed by National Aeronautics and Space Administration (NASA). It includes a catchment hydrological model [*Koster et al.,* 2000] and the NASA's Goddard Earth Observing System version 5 global climate model and assimilates satellite rainfall estimates from the Special Sensor Microwave Imager and the Tropical Rainfall Measuring Mission Microwave Imager. It has showed improved hydrological cycles in global assessments [*Rienecker et al.,* 2011]. R2 includes updated NCEP Global Spectral Model (1999 version of NCEP GSM), data assimilation system. It improved convective parameterization and used Xie-Arkin precipitation estimates [*Xie and Arkin*, 1997] to compute soil moisture within a Global Land Data Assimilation System. 20CR is a multidecadal long reanalysis product, which is developed for examining long time scale climate processes as well as looking at the

Table 1. Long-Term Mean of Monthly Change in Surface Water Storage (mm d^{-1}) and Energy Budget Residuals (W m^{-2} d^{-1}) Over the 20 Year Period From 1991 to 2010

	Changes in Water Storage						Energy Budget Residuals					
Basins	AM2.5	VIC	20CR	CFSR	MERRA	R2	AM2.5	VIC	20CR	CFSR	MERRA	R2
Zhua	0.02	0.00	−0.25	0.48	0.00	−0.89	0.30	0.01	6.06	5.39	−0.08	3.80
Chad	−0.01	0.00	0.26	0.44	0.00	−0.38	0.18	0.49	3.80	1.27	0.03	5.66
Congo	0.00	−0.01	0.52	1.90	−0.01	−0.57	0.39	−0.31	2.28	3.16	0.11	4.82
Limpopo	−0.02	0.00	0.11	0.07	0.00	−0.60	0.26	0.08	2.24	4.08	−0.04	3.83
Niger	−0.03	0.00	0.83	0.78	0.00	−0.69	0.35	−0.04	3.56	0.05	0.02	6.51
Nile	0.12	0.00	0.28	0.91	0.03	−0.44	0.21	0.06	6.44	5.68	−0.01	7.57
Okavango	0.00	0.01	0.29	0.18	0.00	−0.40	0.22	−0.15	4.63	2.50	−0.04	8.16
Orange	0.00	0.00	0.38	−0.02	0.00	−0.35	0.26	0.33	1.69	3.61	−0.02	5.33
Zambezi	−0.02	0.00	0.81	0.89	0.00	−0.35	0.15	0.16	4.00	4.53	−0.03	6.89

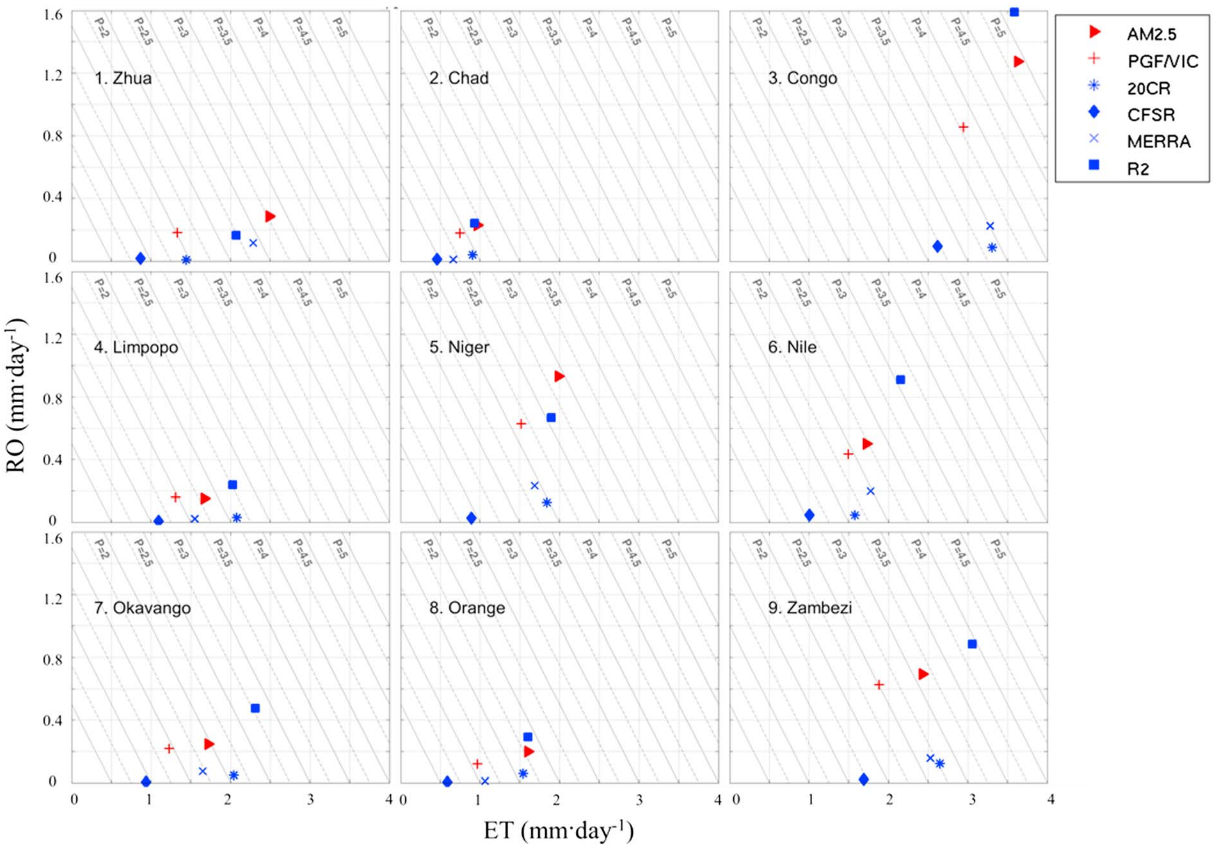

Figure 2. Scatterplot of 20 year mean of monthly runoff (RO, mm d^{-1}) against monthly evapotranspiration (ET, mm d^{-1}) over each of the nine African river basins. Labeled lines are constant monthly precipitation (*P*, mm d^{-1}).

dynamics of historical climate and weather events. It combines surface and sea level pressure observations with a short-term forecast from a coupled atmosphere-land model (April 2008 experimental version of the NCEP Global Forecast System (GFS)) using an Ensemble Kalman Filter data assimilation method.

The observational reference is from the VIC model simulations of *Pan et al.* [2012] and *Sheffield and Wood* [2007]. This simulation is forced with surface meteorological data from the PGF [*Sheffield et al.,* 2006], which is a merged data set from reanalysis, satellite remote sensing, and gridded observation. VIC is calibrated against streamflow data for 25 large river basins globally and thus gives a reasonable depiction of the terrestrial water cycle at least at monthly time scale. Given a lack of high-quality observations for Africa, PGF/VIC is considered as providing the most reliable water and energy budget information over Africa under current conditions.

3. Evaluation of AM2.5 Surface Water and Energy Budgets

3.1. Surface Water Budget on Monthly Time Scale

The surface water budget is given by

$$\Delta S = P - \mathrm{ET} - \mathrm{RO} \quad (1)$$

where ΔS is the change in surface water storage, *P* is precipitation, ET is evapotranspiration, and RO is total runoff (on surface and base flow in the soil). We first compare overall mean monthly water budget over each of the nine river basins in Africa. On an interannual time scale, the mean ΔS is approximately equal to zero. At such time scale a large deviation of $\mathit{\Delta S}$ from zero may be interpreted as nonconservation of water in the land surface due to parameterization or initialization problems. Table 1 shows that AM2.5, PGF/VIC, and MERRA fully close the water budget within 0.15 mm d^{-1} over all nine African river basins. By contrast, neither 20CR nor R2 closes the surface water budget to within 0.15 mm d^{-1} in any basin; CFSR only closes the water budget in Limpopo and Orange basins. These water budget nonclosures may due to the nudging

Table 2. Euclidean Distances Between PGF/VIC and AM2.5/Reanalyses for Water and Energy Budgets Indicated in Figures 2 and 5[a]

	Water Budget (mm d^{-1})					Energy Budget (W m^{-2} d^{-1})				
Basins	AM2.5	20CR	CFSR	MERRA	R2	AM2.5	20CR	CFSR	MERRA	R2
Zhua	1.16	**0.21**	0.49	0.96	0.74	33.00	14.71	**11.68**	21.63	28.68
Chad	0.22	0.21	0.34	**0.19**	**0.19**	33.01	**6.11**	9.30	24.05	42.08
Congo	0.80	0.85	0.83	**0.71**	0.97	17.71	40.48	27.81	26.15	**17.46**
Limpopo	0.36	0.78	**0.26**	0.28	0.72	14.54	19.07	**13.49**	26.05	17.55
Niger	0.56	0.60	0.87	0.43	**0.38**	17.96	**12.80**	17.02	16.25	22.63
Nile	**0.24**	0.40	0.63	0.36	0.81	17.92	16.89	10.24	**5.80**	35.62
Okavango	0.49	0.83	**0.36**	0.44	1.11	**13.29**	28.50	16.91	21.22	27.82
Orange	0.64	0.58	0.40	**0.14**	0.66	22.08	13.20	6.98	**12.16**	22.73
Zambezi	**0.55**	0.92	0.64	0.80	1.20	**12.23**	34.45	27.96	30.60	28.69
Mean	0.56	0.60	0.53	**0.48**	0.76	20.19	20.69	**15.71**	20.43	27.03

[a] The closest distances are highlighted in bold.

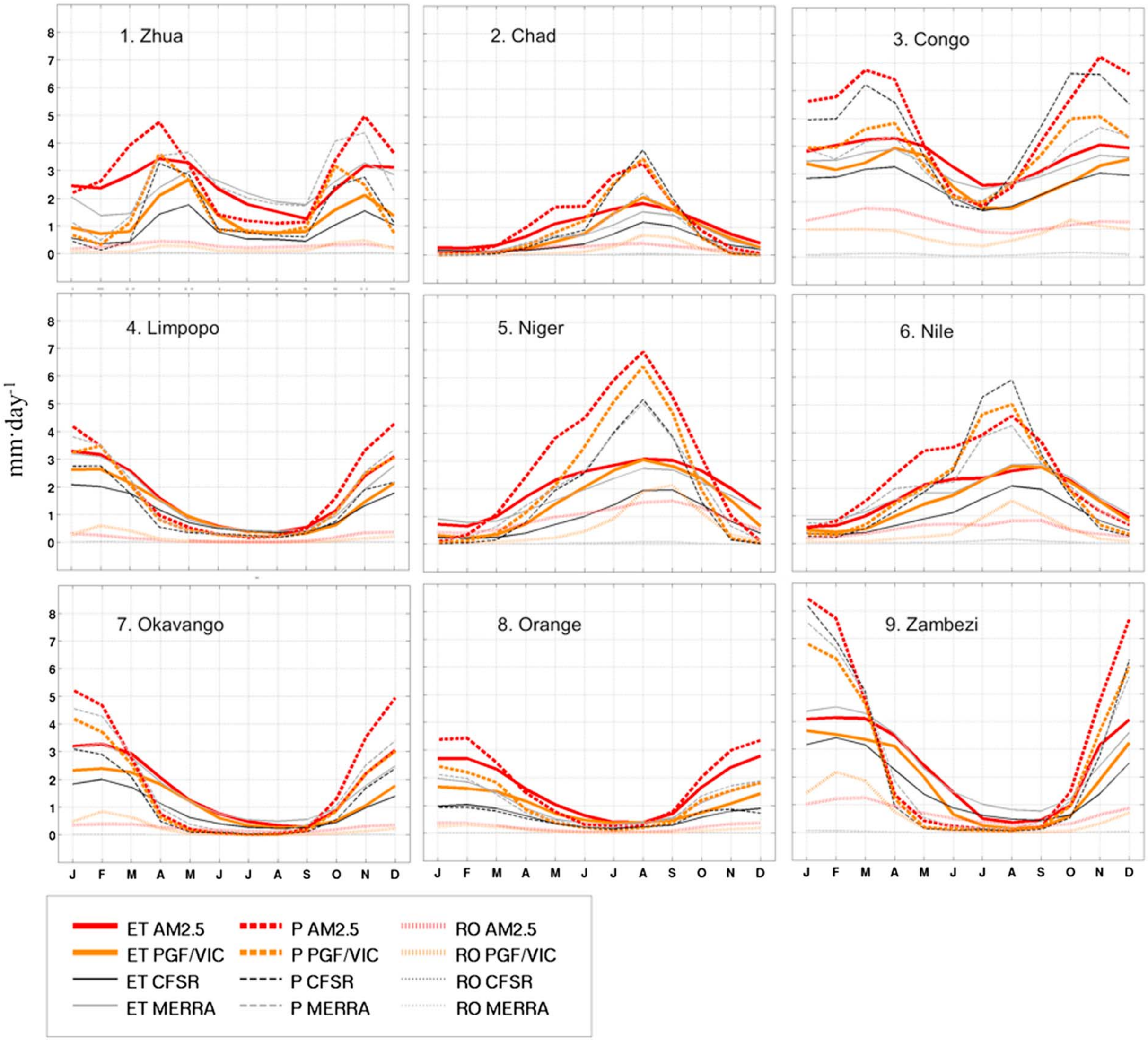

Figure 3. Comparison of monthly ET (mm d^{-1}), *P* (mm d^{-1}), and RO (mm d^{-1}) climatology in AM2.5, PGF/VIC, CFSR, and MERRA over nine African river basins.

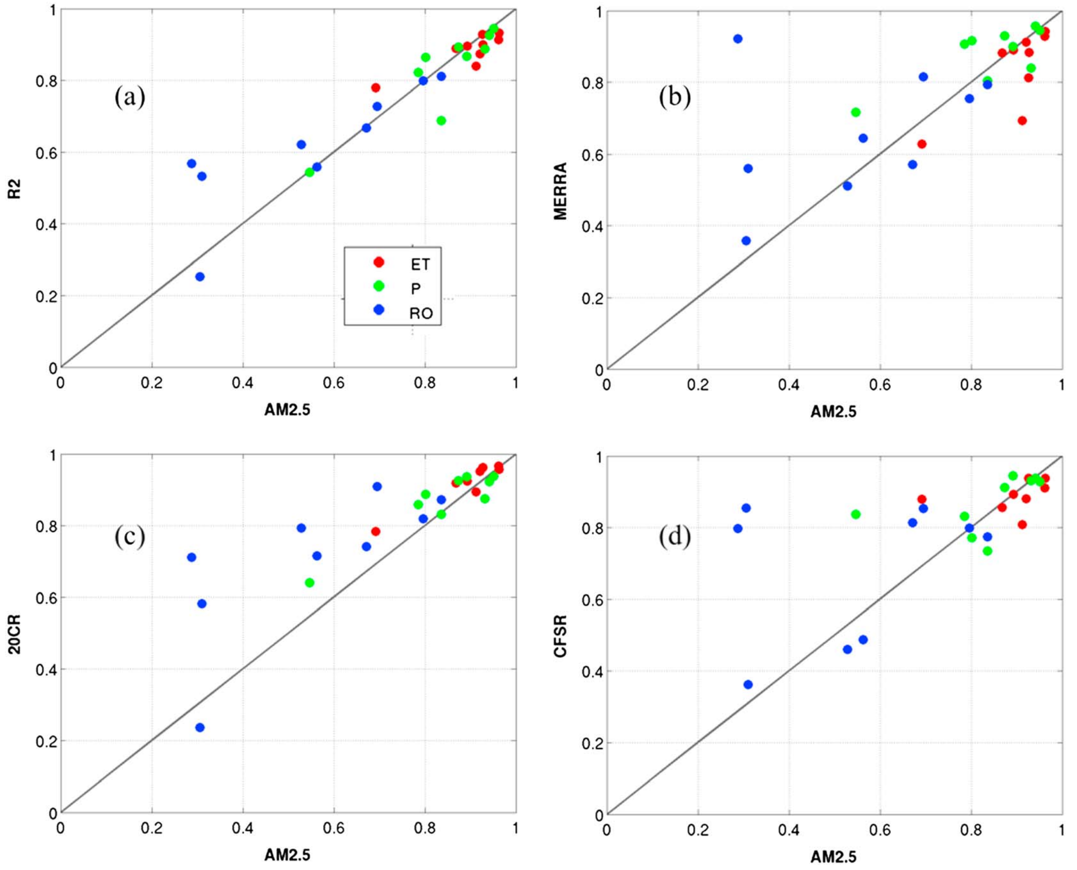

Figure 4. Scatterplot of (a) correlation between PGF/VIC and R2 versus correlation between PGF/VIC and AM2.5, (b) correlation between PGF/VIC and MERRA versus correlation between PGF/VIC and AM2.5, (c) correlation between PGF/VIC and 20CR versus correlation between PGF/VIC and AM2.5, and (d) correlation between PGF/VIC and CFSR versus correlation between PGF/VIC and AM2.5. The point in the plot indicates correlations for monthly ET, *P*, and RO series in each of the nine river basins. The 1–1 line indicates that AM2.5 and reanalyses have the same similarity to PGF/VIC.

of selected variables in those reanalyses to prevent drifting of the analysis toward its own climatology [*Roads and Betts*, 2000].

Figure 2 shows the scatterplot of 20 year mean of monthly runoff against monthly ET over each of the nine African river basins. Labeled lines are theoretical monthly precipitation, which is equal to runoff plus evapotranspiration. In most of the basins, we can see that AM2.5 has overestimated precipitation, evapotranspiration, and runoff relative to the other data sets. Only in a few basins, R2, or 20CR showed high bias than AM2.5, which may due to the unclosed water budget for R2 and 20CR. The large bias of AM2.5 in precipitation, evapotranspiration, and runoff may be associated with the excessive wet surface and parameterization of moisture advection from ocean to land. Table 2 summarized the distances between AM2.5/reanalyses and PGF/VIC. It shows that, on average, for water budget variables, the distance between AM2.5 and PGF/VIC is smaller than the distances between R2 and PGF/VIC and between 20CR and PGF/VIC, but greater than the distances between CFSR and PGF/VIC and between MERRA and PGF/VIC. In other words, AM2.5 is closer to PGF/VIC than R2 and 20CR are to PGF/VIC, but is not as close as MERRA and CFSR to PGF/VIC.

Since MERRA and CFSR are two of the newest reanalysis data sets and shown relatively good performance on representing land surface water budgets, it is worthwhile to compare the AM2.5 climatology of water budget variables with MERRA and CFSR. Figure 3 shows the AM2.5, PGF/VIC, CFSR, and MERRA monthly climatology of the water budget for the 20 years (1991–2010) in nine African river basins. While the amplitudes have great discrepancies, AM2.5 accurately described the mean seasonal cycle of precipitation, runoff, and evapotranspiration. The river basins in the north (Zhua, Chad, Niger, and Nile river basins) showed wet conditions from June to August and dry conditions from November to February; river basins in the south including Congo,

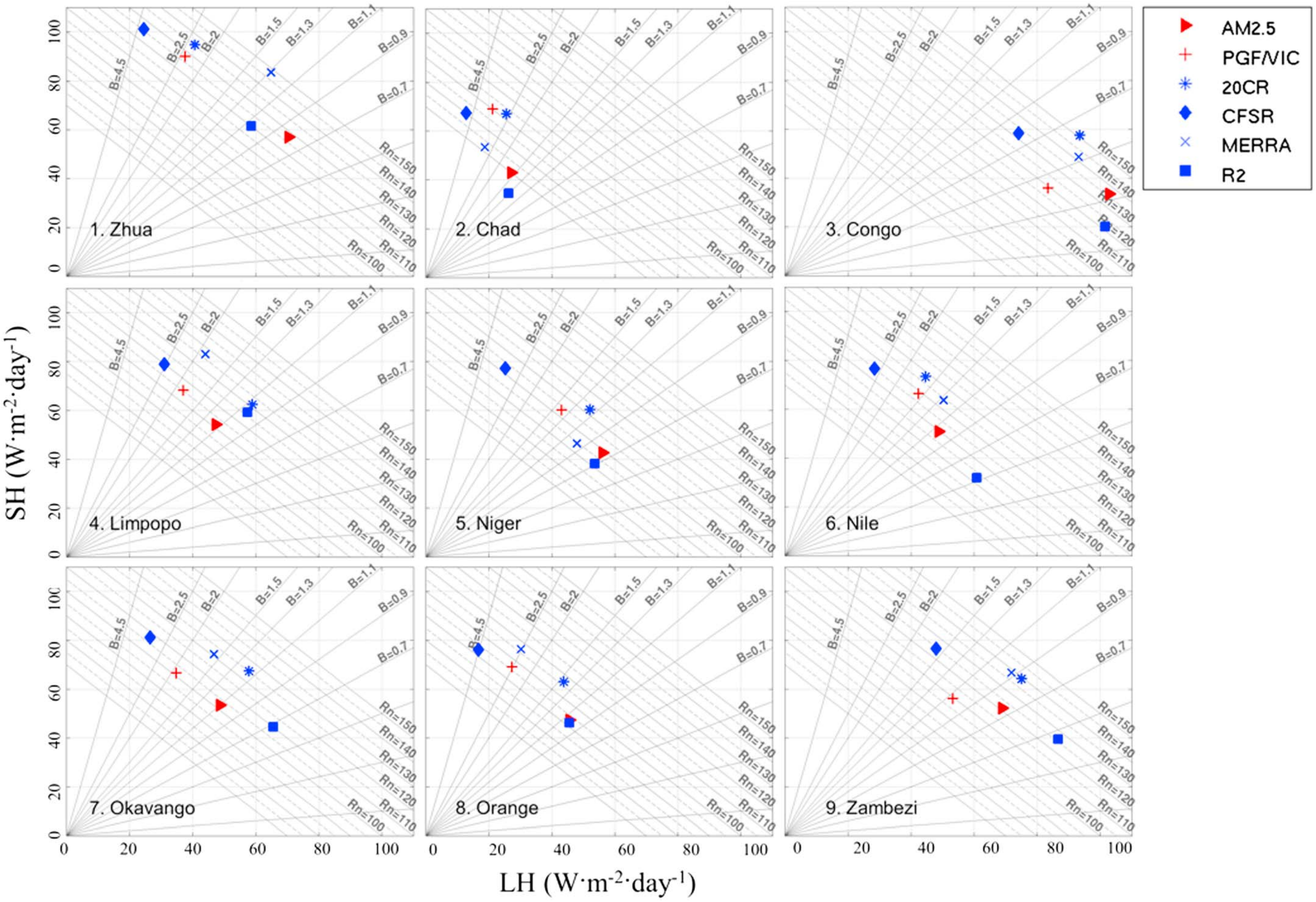

Figure 5. Scatterplot of 20 year mean of monthly latent heat (LH) against monthly sensible heat (SH) over each of the nine African river basins. Labeled lines are constant monthly net radiation (R_n), which is equal to LH plus SH. Radial lines are constant Bowen ratio (SH/LH).

Limpopo, Okavango, Orange, and Zambezi showed wet conditions during November to February and dry conditions during June to August. Compared to the PGF/VIC, the precipitation and evapotranspiration in AM2.5 showed high bias during warm seasons and slightly low bias during cool seasons in most river basins. This may due to the model representation of soil moisture and vegetation covers related to land surface-precipitation feedbacks, since the atmosphere is more sensitive to evaporation from bare soil and vegetation interception and transpiration from plant during warm seasons than during cool seasons. In AM2.5, high (low) runoff is corresponding to high (low) precipitation, which suggests a realistic response of runoff to precipitation. Note that the CFSR and MERRA runoff are persistently low and showed very small annual cycle despite the realistic variation of precipitation, which may due to the absence of lateral flow representations and simplistic treatment of groundwater hydrology in their land models.

Figure 4 shows the correlation of monthly precipitation, evapotranspiration, and runoff series between reanalyses and PGF/VIC versus correlation between AM2.5 and PGF/VIC. The points below the 1–1 line indicate that PGF/VIC is closer to reanalyses than to AM2.5. We can see that in many cases, AM2.5 is closer to PGF/VIC than reanalysis data sets are to PGF/VIC, particularly for evapotranspiration and precipitation.

3.2. Surface Energy Budget at Monthly Time Scale

The surface energy budget is given by

$$0 = R_n - \mathrm{LH} - \mathrm{SH} - \mathrm{G} \tag{2}$$

The surface energy budget is maintained by the net radiation R_n, the latent heat LH, the sensible heat SH, and soil heat flux G. Since the soil heat flux G is positive when the soil is warming and negative when the soil is

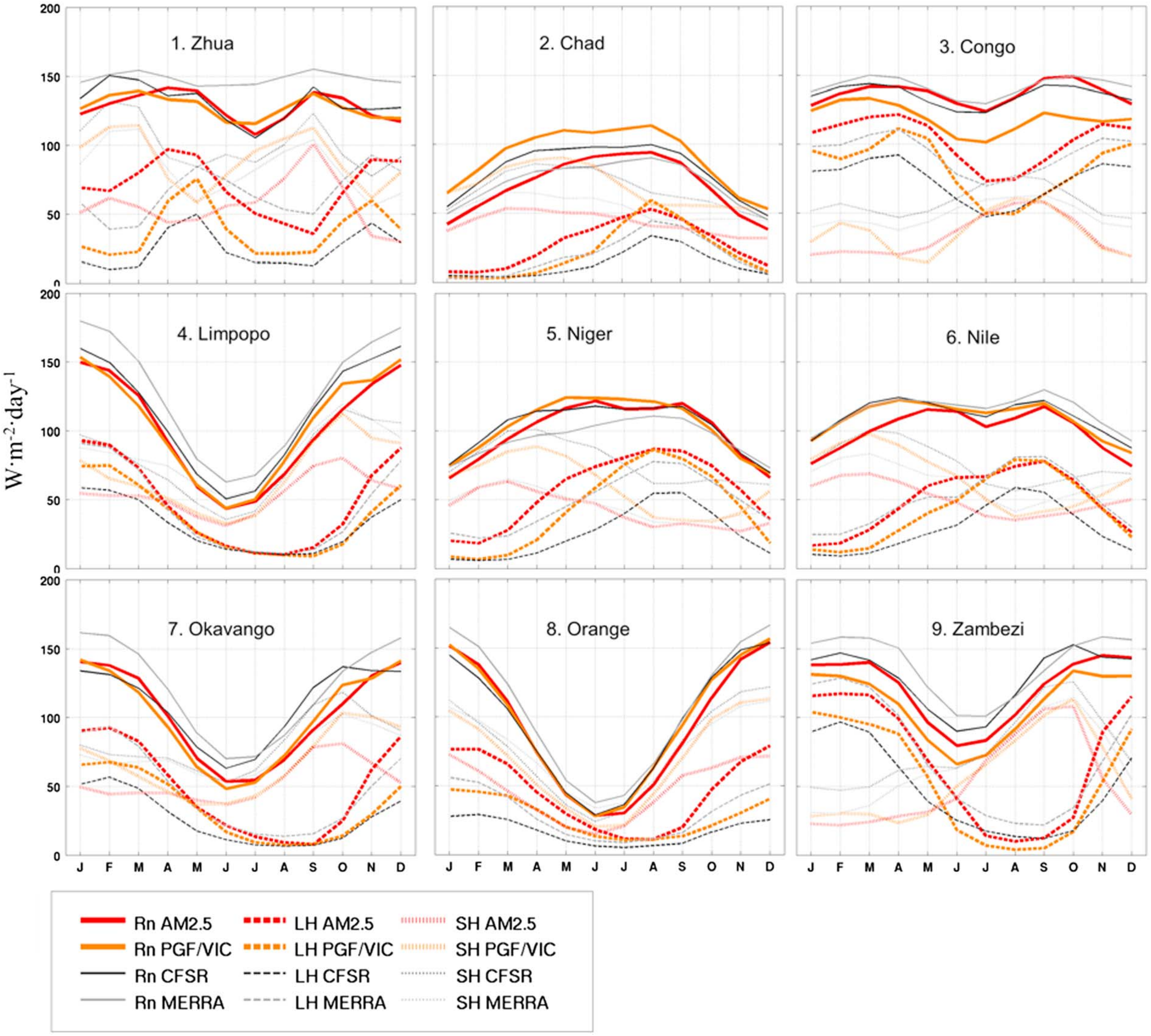

Figure 6. Comparison of monthly R_n (W m^{-2} d^{-1}), LH (W m^{-2} d^{-1}), and SH (W m^{-2} d^{-1}) climatology in AM2.5, PGF/VIC, CFSR, and MERRA over nine African river basins.

cooling, the effect of G can be ignored for daily calculations. Table 1 shows the 20 year mean residuals of the energy budget for nine African river basins from 1991 to 2010. Since this energy budget calculation is at averaged daily time step, G is small enough to be ignored, and the residuals should be approximately equal to zero. Table 1 shows that neither 20CR nor R2 closes the surface energy budget in any basin; CFSR only close the energy budget in Chad and Niger basins. Similar to the water budget, these energy budget nonclosures may due to the nudging of selected variables in those reanalyses to prevent drifting of the analysis toward its own climatology [*Roads and Betts*, 2000]. By contrast, AM2.5, PGF/VIC, and MERRA fully close the energy budget within 0.5 W m^{-2} d^{-1} over all nine African river basins. The ranges of the energy budget residuals for those three data sets are small, given that they also fully closed the water budget within this small range.

Figure 5 is the scatterplot of 20 year mean of monthly sensible heat versus latent heat over each African river basin. The labeled parallel lines indicate isonet radiation (approximately equal to LH + SH) and the radial lines indicate iso-Bowen ratio (B, equal to SH/LH). Net radiation provides energy input, which is balanced in part by sensible heat and latent heat to cool the surface. Note that the AM2.5 has higher latent heat and lower sensible heat, which is consistent with the relatively larger evapotranspiration in the AM2.5. The high latent heat and low sensible heat in AM2.5 also cause it to have the lowest Bowen ratio compared to the other data sets. In spite of those differences in the energy terms, net radiation in AM2.5, PGF/VIC, and four reanalyses are

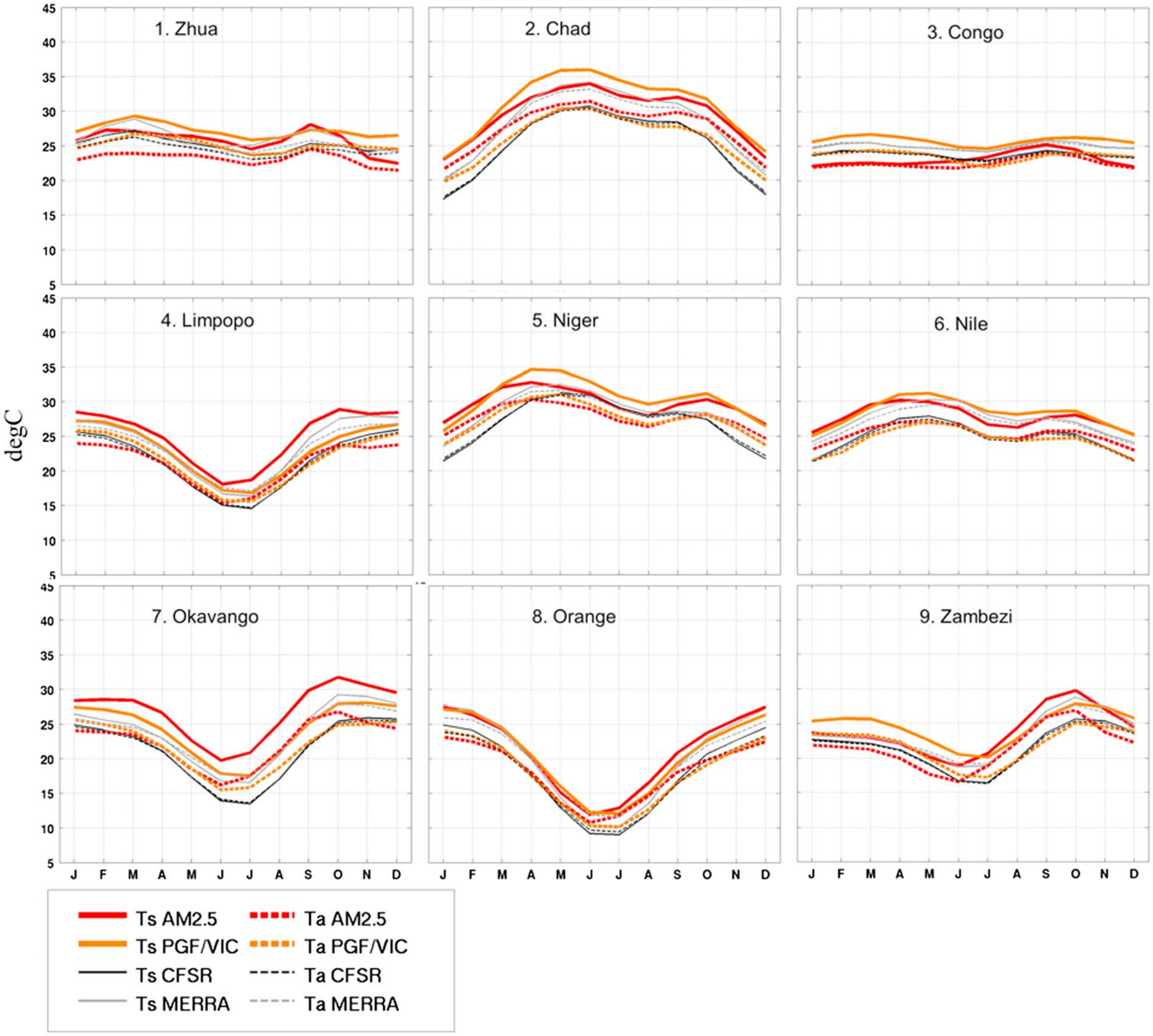

Figure 7. Comparison of monthly skin temperature (T_s, degree Celsius) and 2 m air temperature (T_a, degree Celsius) climatology in AM2.5, PGF/VIC, CFSR, and MERRA over nine African river basins.

remarkably consistent with each other. Again, the summary distances in Table 2 shows that for the energy budget variables, AM2.5 is closer to PGF/VIC than R2 and 20CR are to PGF/VIC, but similar to CFSR and MERRA in terms of their average distances to PGF/VIC.

Since MERRA and CFSR are two of the newest reanalysis data sets and have shown relatively good performance on representing land surface energy budgets, it is worthwhile to compare the AM2.5 climatology of energy budget variables with MERRA and CFSR. Figures 6 and 7 show the seasonal cycle of the energy terms and temperatures, respectively, in AM2.5, PGF/VIC, CFSR, and MERRA over nine African river basins. While the variations of the AM2.5 energy budget terms closely mirror the other data sets, there are discrepancies between AM2.5 and other data sets in terms of the amptitudes. The AM2.5 net radiation is less different with other data sets than latent heat and sensible heat, with the latent heat mostly having large bias and the sensible heat expectedly having low bias. This again may due to the model representation of soil moisture, which controls sensible and latent heat fluxes between the surface and atmosphere. Despite the differences in energy terms, AM2.5 temperatures are close to the other data sets and the variations of skin temperature closely follows 2 m air temperature in all data sets, with skin temperature consistently showing a few degrees higher than 2 m air temperature, suggesting a reasonable representation of the vertical temperature gradient.

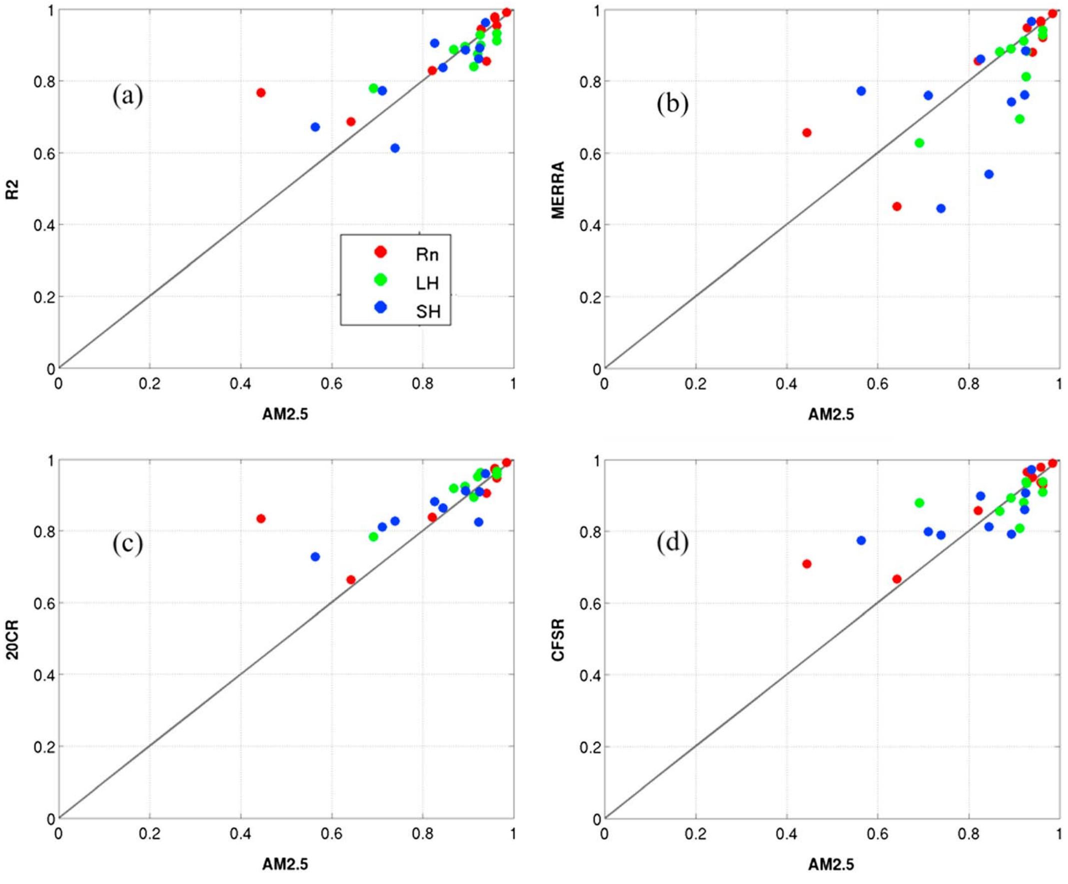

Figure 8. As in Figure 4 but for R_n, LH, and SH.

Figure 8 shows the correlation of monthly R_n, LH, and SH series between reanalyses and PGF/VIC versus correlation between AM2.5 and PGF/VIC. The points below the 1–1 line indicate that PGF/VIC is closer to reanalyses than to AM2.5. Similar to water budget variables, we find that in many cases, AM2.5 is closer to PGF/VIC than reanalyses data sets are to PGF/VIC.

3.3. Interannual Variability and Patterns of Spatial Differences in Water and Energy Budgets

Figure 9 shows the interannual variability of all water and energy budget variables for nine river basins over Africa based on the coefficient of variation (CV). For most of the water and energy budgets terms, including evapotranspiration, precipitation, runoff, latent heat, and sensible heat in those nine river basins, AM2.5 showed much lower interannual variability relative to the other data sets. The net radiation, skin temperature, and 2 m air temperature had the lowest interannual variability and the other terms in AM2.5 had similar interannual variability with the other data sets.

Since CFSR and MERRA are two of the newest developed reanalysis data sets and have mostly shown relatively good performance on representing water and energy budgets, we further compare the spatial differences between AM2.5, PGF/VIC, and those two reanalysis data sets. Figures 10 and 11 show the spatial differences between the 30 year mean of monthly water budget terms of AM2.5 and PGF/VIC, CFSR and PGF/VIC, and MERRA and PGF/VIC and the spatial differences between the 30 year mean of monthly energy budget terms of AM2.5 and PGF/VIC, CFSR and PGF/VIC, and MERRA and PGF/VIC, respectively. In general, AM2.5 mostly showed positive difference, and CFSR and MERRA mostly showed negative difference relative to PGF/VIC in space; those differences are relatively small in arid regions (e.g., northern Africa) due to the small water flux between the land surface from soil moisture and plants and the atmosphere in those region. Over most regions of sub-Saharan Africa, in particularly near the central Africa, AM2.5 showed high precipitation, runoff, and evapotranspiration biases compared to the other data sets. In Figure 11, as expected, the patterns of spatial differences between AM2.5 or reanalysis data sets and PGF/VIC in latent heat are similar

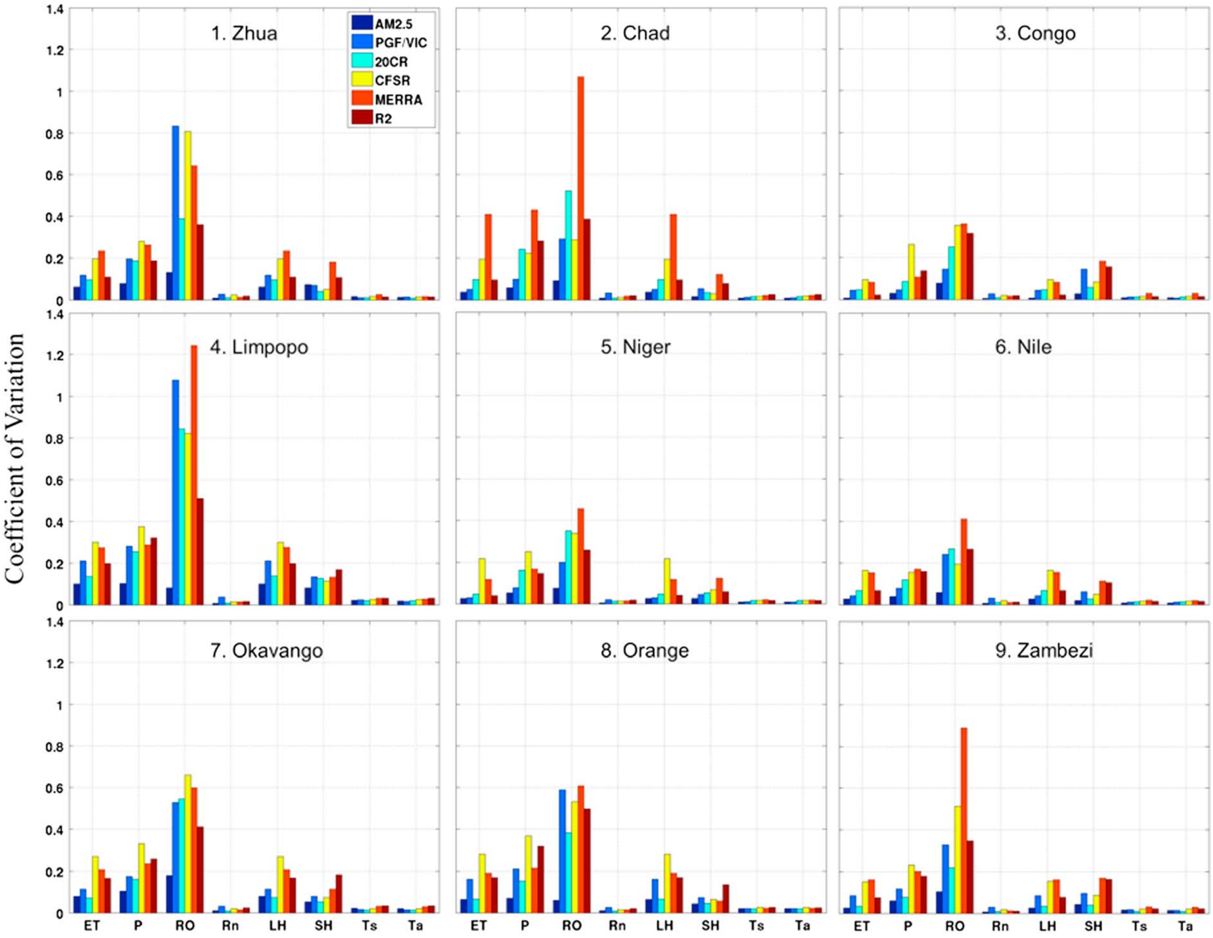

Figure 9. Coefficient of variation (CV) of annual series of water and energy budget terms in AM2.5, PGF/VIC, 20CR, CFSR, MERRA, and R2 over nine major basins over Africa.

to evapotranspiration. Spatially, the AM2.5 showed higher net radiation than PGF/VIC over central Africa, and lower net radiation over other regions in Africa; the sensible heat was lower than PGF/VIC over most regions in Africa. CFSR and MERRA showed higher net radiation and sensible heat than PGF/VIC over most areas of sub-Saharan Africa. By comparing AM2.5, MERRA, CFSR, and PGF/VIC water and energy budgets in Figures 10 and 11, we can see that the PGF/VIC differs from MERRA or CFSR as much as the PGF/VIC differ from the AM2.5, while the spatial patterns are different.

Table 3 shows the summary statistics of spatial root-mean-square error (RMSE), bias, and R between 30 year mean of monthly water and energy budget terms of AM2.5 and PGF/VIC, MERRA and PGF/VIC, CFSR and PGF/VIC, 20CR and PGF/VIC, and R2 and PGF/VIC. In many cases, AM2.5 showed smaller RMSE and bias and higher R the reanalysis data sets; the difference between the PGF/VIC and the four reanalysis data sets is no more than the difference between the PGF/VIC and the AM2.5. Among all of the variables, RO and SH showed the lowest R and the largest RMSE and bias.

3.4. Discussing Causes of Model Biases

The atmospheric water balance equation can be written as

$$\Delta W = \mathrm{ET} - P - \nabla\cdot\vec{\mathrm{Q}} \tag{3}$$

where W is the amount of water vapor stored in the atmospheric column, ET is evapotranspiration, P is precipitation, and $\nabla\cdot\vec{Q}$ is the divergence or net outflow of water vapor across the sides of the atmospheric column. Combining equations (1) and (3) yields the expression

$$-\Delta W - \nabla\cdot\rightarrow Q = \Delta S + \mathrm{RO} = P - \mathrm{ET} \tag{4}$$

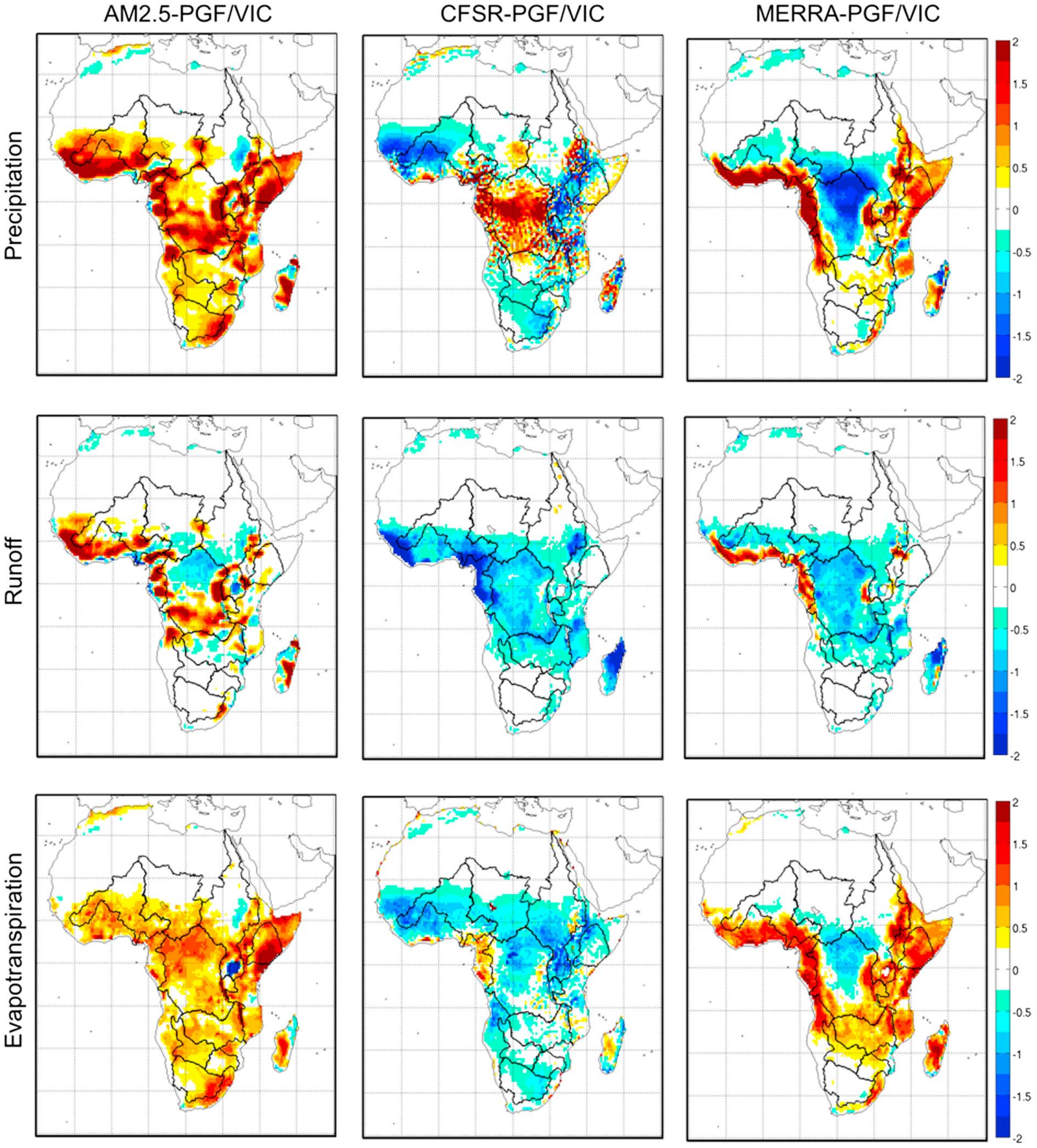

Figure 10. Spatial differences of water budget terms (mm d^{-1}) between AM2.5 and PGF/VIC, CFSR and PGF/VIC, and MERRA and PGF/VIC.

In mean annual water balance computations, the change in atmospheric storage (ΔW) and surface water storage (ΔS) are often assumed to be negligible so that runoff is approximately equal to the negative of the divergence or convergence:

$$-\nabla\cdot\vec{Q} = \mathrm{RO} = P - \mathrm{ET} \quad (5)$$

With this assumption, we can then take a further look at the causes of the wet bias in the AM2.5 model. Is it due to moisture recycling within a basin or atmospheric moisture convergence? To investigate this, in Table 4, we calculated the difference between the AM2.5 and the PGF/VIC (ΔP, ΔET, and ΔRO).

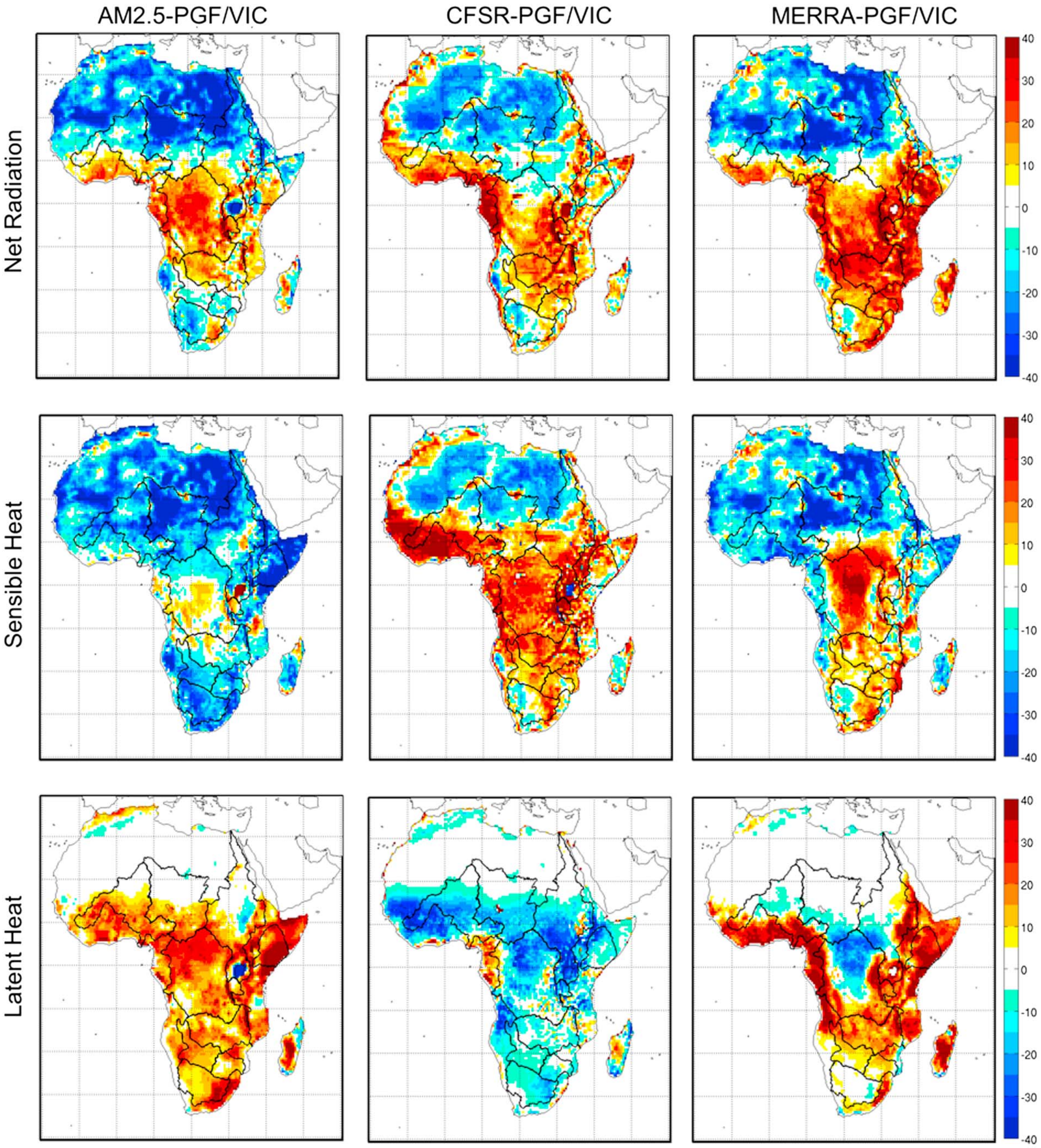

Figure 11. Spatial differences of energy budget terms (W m^{-2} d^{-1}) between AM2.5 and PGF/VIC, CFSR and PGF/VIC, and MERRA and PGF/VIC.

We can see that the AM2.5 showed much greater *P* and ET but relatively similar RO compared to the PGF/VIC in seven of nine river basins (Zhua, Chad, Limpopo, Nile, Okavango, Orange, and Zambezi). According to the equation (5), RO is equal to the atmospheric convergence. Therefore, the small difference between the AM2.5 RO and the PGF/VIC RO indicates that the AM2.5 simulated the atmospheric convergence relatively well. In those seven river basins, since the AM2.5 over estimated both *P* and ET but well simulated the convergence, the model bias is mostly likely due to the excessive moisture recycling within a basin (i.e., too much *P* and ET within the basin instead of moisture convergence from the outside). Those excessive moisture recycling could be caused by the AM2.5 model representation of soil moisture and vegetation covers. For Niger and Congo river basins, ΔRO is relatively large, indicating an over estimation of atmospheric convergence. This

Table 3. Spatial Root-Mean-Square Error (RMSE), Bias, and Correlation (R) of Surface Water and Energy Budget Terms Between AM2.5 and PGF/VIC, 20CR and PGF/VIC, CFSR and PGF/VIC, MERRA and PGF/VIC, and R2 and PGF/VIC

Data Set	RMSE	Bias	R	RMSE	Bias	R	RMSE	Bias	R
		ET (mm d^{-1})			*P* (mm d^{-1})			*RO* (mm d^{-1})	
AM2.5 versus PGF/VIC	0.73	0.36	0.91	1.05	0.56	0.94	0.75	0.18	0.76
20CR versus PGF/VIC	0.58	0.28	0.90	0.78	0.18	0.89	0.56	−0.33	0.65
CFSR versus PGF/VIC	0.52	−0.28	0.86	0.93	0.03	0.87	0.65	−0.38	0.56
MERRA versus PGF/VIC	0.64	0.29	0.90	0.83	0.10	0.92	0.51	−0.19	0.73
R2 versus PGF/VIC	0.79	0.55	0.89	0.79	0.27	0.90	0.53	0.22	0.67
		R_n (W m^{-2} d^{-1})			*LH* (W m^{-2} d^{-1})			*SH* (W m^{-2} d^{-1})	
AM2.5 versus PGF/VIC	21.21	−6.39	0.88	20.50	10.26	0.91	24.09	−16.61	0.56
20CR versus PGF/VIC	24.70	16.17	0.92	16.38	7.83	0.90	18.76	3.91	0.52
CFSR versus PGF/VIC	18.89	2.51	0.89	14.65	−8.03	0.86	21.49	8.03	0.49
MERRA versus PGF/VIC	23.10	2.83	0.94	18.19	8.20	0.90	19.81	−5.11	0.63
R2 versus PGF/VIC	29.25	−6.31	0.87	22.34	15.61	0.89	34.83	−27.07	0.53

might be due to the process representation of the West African monsoon such that it is not well simulated in the AM2.5 model. The AM2.5 model simulation at basin scales could be further improved by reducing moisture recycling within a basin and reducing moisture convergence from Atlantic Ocean to western Africa.

4. Concluding Remarks

In this study, AMIP simulations of AM2.5 were compared with four reanalyses and with VIC simulations forced by PGF for the period from 1991 to 2010 for the nine African river basins. The AM2.5 water and energy budget showed a number of differences and similarities with the other data sets. While AM2.5 fully closed the water budget within 0.15 mm d^{-1} over all nine African river basins, it mostly overestimated precipitation, evapotranspiration, and runoff relative to other data sets. Despite the AM2.5 accurately described the mean seasonal cycle of precipitation, runoff, and evapotranspiration, its amptitudes over different seasons had great discrepancies with other data sets. Compared to the PGF/VIC, the precipitation and evapotranspiration in AM2.5 showed high bias during warm seasons and slightly low bias during cool seasons in most river basins. However, the AM2.5 showed a realistic response of runoff to precipitation. Similar to the water budget, the AM2.5 fully close the energy budget within a small range over all nine African river basins. Despite the net radiation in AM2.5 being remarkably consistent with other data sets, AM2.5 had a low bias in sensible heat and a high bias in latent heat, which also led to the low bias in the Bowen ratio. Also, despite the differences in energy terms, the temperature differences between AM2.5 and other data sets are small, and the variations of skin temperature closely follows 2 m air temperature in all data sets. While most of the water and energy budget terms from the AM2.5 showed much lower interannual variability relative to the other data sets, the interannual variability of net radiation, skin temperature, and 2 m air temperature in the AM2.5 was relatively consistent with the other data sets. In space, the AM2.5 water budget terms and latent heat showed small differences in arid regions (e.g., northern Africa) but high bias over other regions compared to MERRA, CFSR, and PGF/VIC. The AM2.5 showed higher net radiation than MERRA, CFSR, and PGF/VIC over central

Table 4. Difference Between the AM2.5 and the PGF/VIC (ΔP, ΔET, and ΔRO: mm d^{-1})

	AM2.5-PGF/VIC		
Basins	ΔET	ΔP	ΔRO
Zhua	1.16	1.28	0.10
Chad	0.22	0.26	0.05
Congo	0.69	1.12	0.42
Limpopo	0.36	0.33	−0.01
Niger	0.47	0.75	0.30
Nile	0.23	0.41	0.07
Okavango	0.49	0.51	0.03
Orange	0.64	0.71	0.08
Zambezi	0.55	0.59	0.07

Africa and lower sensible heat than MERRA, CFSR, and PGF/VIC over most regions in Africa. On average, AM2.5 is closer to PGF/VIC than R2 and 20CR are to PGF/VIC, but not as close as MERRA and CFSR to PGF/VIC.

The reasons for the discrepancies in water and energy budgets were likely due to the biases from the physical parameterizations in the land model and the coupling between atmosphere-ocean-land components. The high bias of AM2.5 in precipitation, evapotranspiration, and runoff may be associated with the excessive wet surface and parameterization of moisture advection from ocean to land. The high bias during warm seasons and slightly low bias during cool seasons for AM2.5 precipitation and evapotranspiration are likely due to the model representation of soil moisture and vegetation covers related to land surface-precipitation feedbacks, since the atmosphere is more sensitive to evaporation from bare soil and vegetation interception and transpiration from plant during warm seasons than during cool seasons. The high bias of latent heat in the AM2.5 is consistent with its relatively larger evapotranspiration, which again may be due to the model representation of soil moisture that controls sensible and latent heat fluxes between the surface and atmosphere. The AM2.5 skin temperature consistently showed a few degrees higher than 2 m air temperature, suggesting a reasonable representation of vertical temperature gradient. The small spatial differences between AM2.5 and MERRA, CFSR, and PGF/VIC in arid regions (e.g., northern Africa) were likely due to the little water flux between the land surface from soil moisture and plants and the atmosphere in those regions.

A well-represented land surface condition is very important for seasonal climate forecast. Since the initial conditions for the FLOR atmosphere and land components were taken from the AM2.5 simulations, this assessment of AM2.5 water and energy budgets would be useful to improve FLOR initial conditions and further enhance its forecasting capacity.

Acknowledgments
This work was supported by NOAA Geophysical Fluid Dynamics Laboratory through the Princeton University Cooperative Institute for Climate Science (CICS). The authors acknowledge PICSciE/OIT at Princeton University for the supercomputing support. CFSR and R2 data sets were obtained from the NOAA National Centers for Environmental Information at http://nomads.ncdc.noaa.gov/data/. MERRA data set was obtained from the NASA/GES/DISC at http://disc.sci.gsfc.nasa.gov/daac-bin/FTPSubset.pl. The 20CR was obtained from the NOAA/ESRL/PSD at http://www.esrl.noaa.gov/psd/data/20thC_Rean/. The PGF/VIC and AM2.5 simulation results and figures are available from the authors upon request (dtian@princeton.edu).

References

Betts, A. K., P. Viterbo, and E. Wood (1998), Surface energy and water balance for the Arkansas–Red River Basin from the ECMWF reanalysis, *J. Clim.*, *11*(11), 2881–2897.

Betts, A. K., J. H. Ball, and P. Viterbo (2003a), Evaluation of the ERA-40 surface water budget and surface temperature for the Mackenzie River Basin, *J. Hydrometeorol.*, *4*(6), 1194–1211.

Betts, A. K., J. H. Ball, M. Bosilovich, P. Viterbo, Y. Zhang, and W. B. Rossow (2003b), Intercomparison of water and energy budgets for five Mississippi subbasins between ECMWF reanalysis (ERA-40) and NASA Data Assimilation Office fvGCM for 1990–1999, *J. Geophys. Res.*, *108*(D16), 8618, doi:10.1029/2002JD003127.

Betts, A. K., M. Köhler, and Y. Zhang (2009), Comparison of river basin hydrometeorology in ERA-Interim and ERA-40 reanalyses with observations, *J. Geophys. Res.*, *114*, D02101, doi:10.1029/2008JD010761.

Compo, G. P., et al. (2011), The twentieth century reanalysis project, *Q. J. R. Meteorol. Soc.*, *137*(654), 1–28.

Delworth, T. L., et al. (2012), Simulated climate and climate change in the GFDL CM2.5 high-resolution coupled climate model, *J. Clim.*, *25*(8), 2755–2781.

Ek, M. B., K. E. Mitchell, Y. Lin, E. Rogers, P. Grunmann, V. Koren, G. Gayno, and J. D. Tarpley (2003), Implementation of Noah land surface model advances in the National Centers for Environmental Prediction operational mesoscale Eta model, *J. Geophys. Res.*, *108*(D22), 8851, doi:10.1029/2002JD003296.

Fernandes, K., R. Fu, and A. K. Betts (2008), How well does the ERA40 surface water budget compare to observations in the Amazon River basin?, *J. Geophys. Res.*, *113*, D11117, doi:10.1029/2007JD009220.

Hodges, K. I., R. W. Lee, and L. Bengtsson (2011), A comparison of extratropical cyclones in recent reanalyses ERA-Interim, NASA MERRA, NCEP CFSR, and JRA-25, *J. Clim.*, *24*(18), 4888–4906.

Intergovernmental Panel on Climate Change (2013), *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, 1535 pp., Cambridge Univ. Press, Cambridge, U. K., doi:10.1017/CBO9781107415324.

Jia, L., et al. (2015), Improved seasonal prediction of temperature and precipitation over land in a high-resolution GFDL climate model, *J. Clim.*, *28*(5), 2044–2062.

Jung, T., et al. (2012), High-resolution global climate simulations with the ECMWF model in project Athena: Experimental design, model climate, and seasonal forecast skill, *J. Clim.*, *25*(9), 3155–3172.

Kanamitsu, M., W. Ebisuzaki, J. Woollen, S.-K. Yang, J. J. Hnilo, M. Fiorino, and G. L. Potter (2002), NCEP–DOE AMIP-II Reanalysis (R-2), *Bull. Am. Meteorol. Soc.*, *83*(11), 1631–1643.

Kapnick, S. B., and T. L. Delworth (2013), Controls of global snow under a changed climate, *J. Clim.*, *26*(15), 5537–5562.

Kirtman, B., et al. (2014), The North American multimodel ensemble: Phase-1 seasonal-to-interannual prediction; phase-2 toward developing intraseasonal prediction, *Bull. Am. Meteorol. Soc.*, *95*(4), 585–601.

Koster, R. D., M. J. Suarez, A. Ducharne, M. Stieglitz, and P. Kumar (2000), A catchment-based approach to modeling land surface processes in a general circulation model: 1. Model structure, *J. Geophys. Res.*, *105*, 24,809–24,822, doi:10.1029/2000JD900327.

Murakami, H., et al. (2015), Simulation and prediction of category 4 and 5 hurricanes in the high-resolution GFDL HiFLOR coupled climate model, *J. Clim.*, *28*(23), 9058–9079.

Pan, M., A. K. Sahoo, T. J. Troy, R. K. Vinukollu, J. Sheffield, and E. F. Wood (2012), Multisource estimation of long-term terrestrial water budget for major global river basins, *J. Clim.*, *25*(9), 3191–3206.

Rienecker, M. M., et al. (2011), MERRA: NASA's modern-era retrospective analysis for research and applications, *J. Clim.*, *24*(14), 3624–3648.

Roads, J., and A. Betts (2000), NCEP–NCAR and ECMWF reanalysis surface water and energy budgets for the Mississippi River Basin, *J. Hydrometeorol.*, *1*(1), 88–94.

Saha, S., et al. (2010), The NCEP Climate Forecast System Reanalysis, *Bull. Am. Meteorol. Soc.*, *91*(8), 1015–1057.

Sheffield, J., and E. F. Wood (2007), Characteristics of global and regional drought, 1950–2000: Analysis of soil moisture data from off-line simulation of the terrestrial hydrologic cycle, *J. Geophys. Res.*, *112*, D17115, doi:10.1029/2006JD008288.

Sheffield, J., G. Goteti, and E. F. Wood (2006), Development of a 50-year high-resolution global dataset of meteorological forcings for land surface modeling, *J. Clim.*, *19*(13), 3088–3111.

Vecchi, G. A., et al. (2014), On the seasonal forecasting of regional tropical cyclone activity, *J. Clim.*, *27*(21), 7994–8016.

Xie, P., and P. A. Arkin (1997), Global precipitation: A 17-year monthly analysis based on gauge observations, satellite estimates, and numerical model outputs, *Bull. Am. Meteorol. Soc.*, *78*(11), 2539–2558.

Xie, P., M. Chen, and W. Shi (2010), CPC unified gauge-based analysis of global daily precipitation, paper presented at 24th Conference on Hydrology, Am. Meteorol. Soc., Atlanta, Ga.

Yang, R., M. Ek, and J. Meng (2015), Surface water and energy budgets for the Mississippi river basin in three NCEP reanalyses, *J. Hydrometeorol.*, *16*(2), 857–873.

Yang, X., et al. (2015), Seasonal predictability of extratropical storm tracks in GFDL's high-resolution climate prediction model, *J. Clim.*, *28*(9), 3592–3611.