Assessment of satellite surface radiation budget radiation products in highland regions with Tibet instrumental data

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Abstract: This study presents results of comparisons between instrumental radiation data in the elevated Tibetan Plateau and two global satellite products: the Global Energy and Water Cycle Experiment - Surface Radiation Budget (GEWEX-SRB) and International Satellite Cloud Climatology Project - Flux Data (ISCCP-FD). In general, shortwave radiation (SW) is estimated better by ISCCP-FD while longwave radiation (LW) is estimated better by GEWEX-SRB, but all the radiation components in both products are under-estimated. Severe and systematic errors were found in monthly-mean SRB SW (on plateau-average, -48 W m^{-2} for downward SW and -18 W m^{-2} for upward SW) and FD LW (on plateau-average, -37 W m^{-2} for downward LW and -62 W m^{-2} for upward LW) for radiation. Errors in monthly-mean diurnal variations are even larger than the monthly mean errors. Though the LW errors can be reduced about 10 W m^{-2} after a correction for altitude difference between the site and SRB and FD grids, these errors are still higher than that for other regions. The large errors in SRB SW was mainly due to a processing mistake for elevation effect, but the errors in SRB LW was mainly due to significant errors in input data. We suggest reprocessing satellite surface radiation budget data, at least for highland areas like Tibet.

1. Introduction

Remote sensing satellite algorithms and products for surface radiation have been developed since 1970s (Pinker et al., 1995). These satellite products can be applied to analyses of global climate change and large-scale hydro-meteorological studies. Two representative satellite products of surface radiation budget are the Global Energy and Water Cycle Experiment — Surface Radiation Budget (GEWEX-SRB) (Stackhouse et al., 2004) and the International Satellite Cloud Climatology Project — Flux Data (ISCCP-FD) (Zhang et al., 2004). Both products have a global cover and high temporal resolution. Surface radiation budget or radiation components estimated from the two products were widely assessed by the data developers (Stackhouse et al., 2004; Cox et al. 2006; Zhang et al., 2004) and other researchers (Li et al., 1995; Liu et al., 2005; Xia et al. 2006; Raschke et al. 2006), but observational data used in these studies were generally collected in lowland areas, and the errors of these satellite products for highlands are virtually unknown.

In this study, we presented the results of comparisons between the two satellite products and instrumental data in the elevated Tibetan Plateau. The plateau has small air mass (nearly half of the sea level) and low aerosol concentration (almost the lowest) that results in high solar radiation and low longwave radiation. Because radiation algorithms are usually developed, calibrated and validated with data collected in lowland areas, systematic errors associated with elevation and elevation-relevant atmospheric environment can be too small to be detected in lowland areas. However, these errors can be amplified and become identifiable in highland areas. Therefore, Tibet is an ideal region for validating radiation schemes and satellite products. This evaluation is also helpful for data users to be aware of satellite data quality for highland areas, where observations of radiation and sunshine in these areas are usually too sparse to satisfy hydro-meteorological studies, and the satellite products are almost the only sources of radiation data.

2. Data

Surface radiation budget data in the Tibetan Plateau were collected through GEWEX Asian Monsoon Experiments - Tibet (GAME-Tibet) IOP during May~September 1998. The GAME-Tibet project is an international field experiment that collected a variety of data for studying the land-atmosphere interactions and their effects on the Asian monsoon. The field campaign was summarized in Koike et al. (1999) and all the data are accessible through its website (http://monsoon.t.u-tokyo.ac.jp/tibet/). Figure 1 shows the observing network, which comprises of experiments in a plateau-scale region and a meso-scale area. Table 1 shows basic information of surface radiation measurements at PBL Tower, Flux-PAM and some AWS sites. There were a total of ten downward shortwave radiation (SWD) sites, six upward SW (SWU) sites, and five downward and upward longwave radiation (LWD and LWU) sites. Half of the sites were deployed in the 150 km × 250 km meso-scale area in East Tibet. These sites cover a wide region of the plateau (31 ~35.5°N, 80~93.8°E), and all their elevation is above 4000 m MSL. For MS3608, the measured SWD in many hours are much higher than the clear-sky SWD estimated by a high-accuracy model developed by Yang et al. (2006), and even frequently higher than the solar constant. Though solar radiation exceeding the solar constant was also measured at other sites and through other experiments in Tibet, but its occurrence was never so frequent as that at MS3608. Therefore, this site was excluded from the following comparisons.

GEWEX-SRB makes use of two sets of algorithms: primary and quality-check. In this study, we assessed the surface radiation budget from the primary algorithm, which is adapted from Pinker and Laszlo (1992) for SW and from Fu et al. (1997) for LW. A pre-release version (v2.5) was used in this study. ISCCP-FD calculates surface radiation budget using a radiatve transfer model (Zhang et al. 1995; Zhang et al. 2004). The two projects use the same ISCCP cloud information (Rossow and Schiffer, 1999) but different ancillary data sources. See Cox et al. (2006) for GEWEX-SRB input and Zhang et al. (2004) for ISCCP-FD input. Both products have a temporal resolution of 3 hours. The former has a spatial resolution of 1 degree, and the latter is 2.5 degree. The correspondence between observational sites and SRB and FD grids was also shown in Table 1. Some grids cover more than one site, and the altitudes between the sites and the grids are usually different.

3. Results

Table 2 shows the mean bias error (MBE) and root mean square error (RMSE) in monthly-mean radiation for each site and their average. In general, FD estimates SWD better than SRB; by contrast, SRB gives LW better than FD. For SRB, SWD is severely underestimated at all the sites. Biases for the individual sites range over -39~-55 W m^{-2} with an average of -48 W m^{-2} or -18%. Accordingly, SWU is underestimated about 30% except at SQH (Shiquanhe) in the West Tibet, where SWU is overestimated due to very high albedo. LWD is slightly underestimated, with an average bias of -11 W m^{-2} or -4%, but LWU has large biases at West Tibet sites: -50 W m^{-2} at SQH and -34 W m^{-2} at Gerze. RMSE values for monthly-mean SWD (50 Wm^{-2} on average) are much large than LWD (13 Wm^{-2} on average). For FD data, SWD is estimated well and its biases are about -4~-18 W m^{-2} with an average of -10 W m^{-2} (-4%), but SWU is underestimated about 15 W m^{-2} or 25% averagely. Compared to SWD, LWD and LWU have much larger negative biases: -37 W m^{-2} or -13% for LWD and –62 or -16% for LWU. RMSE values for monthly-mean LWD (40 Wm^{-2} on average) are much large than SWD (17 Wm^{-2} on average).

Figure 2 shows the monthly-mean diurnal variations in the meso-scale area of East Tibet, where two (three) sites correspond to one SRB (FD) grid. It shows that significant errors exist throughout the observing period, so the errors are systematic rather than random. Errors in diurnal variations can reach more than 100 W m^{-2}, such as SRB SWD and FD LWD and LWU. It also shows that the spatial variability is smaller than the difference between satellite products and the observations, suggesting that the under-estimation cannot be explained by spatial heterogeneity of radiation.

Table 3 shows the errors in monthly–mean satellite SWD and LWD in the literature, compared with this study. It is clear that the errors in SRB SWD and FD LWD are much higher in Tibet than in other regions.

4. Discussions

This section explores major factors that cause large errors in the elevated Tibet region.

4.1 Elevation differences. The altitudes at observational sites are usually lower than corresponding SRB and FD grids, as shown in Table 1. Because air temperature decreases with elevation, LWD is sensitive to these differences in altitude. Following Wild et al. (2001), a height correction of 2.8 W m^{-2} per 100 m was applied to satellite LW. As shown in Table 3, this correction reduces MBE of 7-10 W m^{-2}, and errors in the corrected SRB LW are comparable to early studies, but errors in FD LW are still much larger. There is no correction for SW because it is affected by many factors (e.g. ozone thickness, aerosol), which are determined regardless of the altitude.

4.2 Input data accuracy. The estimated LW is sensitive to air temperature and humidity profiles, and very sensitive to their near-surface and surface values (Zhang et al., 2006). In Table 5, we compared observed (or estimated from observations) and ISCCP surface skin temperature (T_{sfc}), surface air temperature (T_{air}), and precipitable water (PW). It shows observed T_{sfc} and T_{air} are significantly higher than ISCCP data except at one site. The differences can be partially accounted for by aforementioned altitude differences, but most of the differences are errors in ISCCP data. In addition, observed PW is also higher than ISCCP except at two sites. All this leads to significant under-estimations of FD LW. The large errors in the ISCCP data are expected, because very sparse or even no operational observations in Tibet were used for its analysis, and thus the ISCCP data are virtually simulation output or satellite algorithm applications without validation in this region. This recalls the importance of in situ observations in the highland remote regions.

4.3 Algorithm error. As addressed in Yang et al. (2005), elevation has a significant effect on solar radiation transfer. Observations show that SW in the elevated Tibet can be 10%~30% higher than in lowland areas. The SRB adopted Pinker and Laszlo (1992) algorithm for SW calculation. Its calculation is based on reflection/transmission look-up tables produced by a radiative transfer code. However, current lookup tables were all normalized relative to mean sea level without a further elevation effect on Rayleigh scatter taken into account. Reflection/transmission tables are used to compute a surface albedo from the clear-sky radiance values. Thus, the Rayleigh scatter overestimate will darken the surface albedo. Then, the clear-sky "aerosol optical depth" and cloudy-sky "cloud optical depth" are tuned to match the TOA estimate of planetary albedo with that errant surface albedo. Thus, the faulty assumption propagates all aspects of the code wrongly trying to compensate for the imbalances. Our estimation is that the effect accounts for clear-sky bias errors between 40 and 60 W m^-2 in the Tibetan summer depending upon the elevation of the site. We certainly see these sorts of errors over the South Pole (any reference). Beside this version of SRB (v2.5), previous version (v2.0) and the following release version (v2.6) also contain the algorithm error.

4.4 Surface properties. Surface albedo is very important for calculation of SWU. As shown in Figure 3, SRB gives much higher SWU values than FD and observations, perhaps because a snow-free surface in West Tibet was wrongly recognized as a snow-covered surface by SRB. On the other hand, FD SWU was under-estimated mainly due to too small surface albedo. The observed albedo averaged over all the sites is 0.22, but SRB gives 0.19 and FD gives 0.17.

5. Conclusions and comments

This study assessed accuracy of surface radiation budget of two satellite products with Tibet instrumental data. It was found that GEWEX-SRB SW and ISCCP-FD LW were severely under-estimated for Tibet. This leads to the total of SWD and LWD being under-estimated 50-60 W m^{-2} or 10%. Because SWD and LWD are important input of many hydro-meteorological studies, their values should be corrected when the two satellite products are applied for the highland region.

Because these errors for Tibet (perhaps also for other highland regions) are much larger than in other regions, we recommend reprocessing the two satellite products, at least for highland regions like Tibet. With the help of GEWEX-SRB team, it was recognized that the elevation effect were not effectively activated in the processing (Laszlo and Masuda, 2006). This team is now reprocessing the solar radiation data again, with activation of the elevation effect. On the other hand, we found with Tibet data that the under-estimation of ISCCP-FD LW was due to large errors in input humidity and temperature profile as well as surface skin temperature.

The results in this study also address the role of the Tibet data as a benchmark for verifying other radiation schemes and satellite products. Atmospheric conditions in the elevated Tibetan Plateau (small air mass and low aerosol concentration) are contrast to lowland areas for where radiation schemes are developed and validated, and therefore Tibet instrumental data could be a good test bed to verify the universality and applicability of a radiation scheme or product.

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Table 1 Site information and geographical correspondence between GAME－Tibet radiation sites and GEWEX-SRB and ISCCP-FD grids. SWD was measured at all the sites; SWU were measured at six sites (gray); LWD and LWU were measured at five sites (bold). ISCC-FD altitude is not available and thus converted from mean surface pressure.

No	Station	In situ					GEWEX-SRB			ISCCP-FD		
		Alt (m)	Lat (°N)	Lon (°E)	Data-length (day)		Alt (m)	Lat (°N)	Lon (°E)	Alt (m)	Lat (°N)	Lon (°E)
					SWD	LWD						
1	**SQH**	**4282**	**32.5**	**80.08**	**133**	**133**	**4978**	**32.5**	**80.5**	**5181**	**33.75**	**81.25**
2	**Gerze**	**4420**	**32.3**	**84.05**	**146**	**44**	**5012**	**32.5**	**84.5**	**4978**	**31.25**	**83.75**
3	**Naqu**	**4496**	**31.38**	**91.54**	**92**	**92**	**4816**	**31.5**	**91.5**	**4997**	**31.25**	**91.25**
4	D66	4600	35.52	93.78	146	0	4708	35.5	93.5	3686	36.25	93.75
5	MS3608	4610	31.23	91.78	118	0	4816	31.5	91.5	5257	31.25	91.25
6	MS3637	4820	31.02	91.66	74	0	4816	31.5	91.5	4997	31.25	91.25
7	**Anduo**	**4700**	**32.24**	**91.64**	**98**	**98**	**5141**	**32.5**	**91.5**	**5010**	**31.25**	**91.25**
8	TTH	4535	34.22	92.44	144	0	4982	34.5	92.5	**5236**	33.75	91.25
9	**MS3478**	**5063**	**31.93**	**91.72**	**116**	**116**	**4816**	**31.5**	**91.5**	5007	**31.25**	**91.25**
10	D110	5070	32.69	91.88	98	0	5141	32.5	91.5	5320	33.75	91.25

Table 2 Errors in SRB and FD monthly-mean surface radiation at all the sites listed according to ascendance of altitude. Bold: Largest errors; Unit: W m^{-2}.

	Station	Mean Obs	GEWEX-SRB		ISCCP-FD	
			MBE	RMSE	MBE	RMSE
SWD	SQH	318	-46	51	**-18**	22
	Gerze	297	-51	54	-16	20
	Naqu	249	-41	45	-14	20
	D66	268	-54	**55**	-4	10
	MS3637	233	-40	39	-6	12
	Anduo	255	-39	39	-15	19
	TTH	259	**-55**	57	6	16
	MS3478	264	-51	**55**	-16	29
	D110	286	-54	54	-9	10
	Average	270	-48	50	-10	17
SWU	SQH	77	7	**43**	-18	20
	Gerze	80	-30	31	-21	22
	Naqu	42	-13	13	-5	7
	MS3637	56	**-34**	33	**-26**	**27**
	Amdo	49	-16	14	-12	13
	MS3478	56	-20	20	-8	9
	Average	60	-18	26	-15	16
LWD	SQH	259	-1	8	-29	31
	Gerze	229	0	0	-8	21
	Naqu	311	**-27**	**28**	**-62**	**62**
	Anduo	287	-11	12	-39	42
	MS3478	290	-15	15	-46	45
	Average	275	-11	13	-37	40
LWU	SQH	422	**-50**	**52**	**-82**	**83**
	Gerze	407	-34	36	-71	72
	Naqu	374	-15	15	-56	60
	Anduo	374	-19	21	-55	62
	MS3478	368	-9	10	-48	49
	Average	389	-25	27	-62	65

Table 3 Comparison of errors in monthly-mean satellite surface radiation data between Tibet and other regions. Reference: L95 - Li et al., 1995; C06 - Cox et al. 2006; S04 – Stackhouse et al., 2004; X06 - Xia et al., 2006; L05 - Liu et al., 2005; Z04 - Zhang et al., 2004. A-O: Arctic ocean.

	GEWEX-SRB					ISCCP-FD		
Ref.	L95	C06	S06	X06	Tibet	L05	Z04	Tibet
SWD MBE	10	-5~-15	-3	-9~	**-48**	-2	-20~21	-10
SWD RMS	25	15~25	23	22~	**50**	-	12~22	17
SWU MBE	-	-5~5	-5	-	-11	5	-3~19	**-37**
SWU RMS	-	12~17	13	-	13	-	-	**40**

Table 4 Site-mean errors of SRB and FD LWD and LWU before and after the altitudinal correction in Tibet.

Errors	GEWEX-SRB		ISCCP-FD	
	Before	After	Before	After
LWD MBE	-11	-4	-37	-27
LWD RMSE	13	15	40	31
LWU MBE	-25	-18	-62	-54
LWU RMSE	27	20	65	57

Table 5 Observed ("Obs") and ISCCP surface skin temperature (T_{sfc}, K), air temperature (T_{air}, K), and precipitable water (PW, cm) for the Tibet sites. "Observed" PW is estimated by $PW = 0.00493\, rh\, T_{air}{}^{-1} \exp[26.23 - 5416 T_{air}{}^{-1}]$ with T_{air} (K) and rh (%). The formula was validated with 366 data of precipitable water from sonde sounding data.

Site	Tsfc(K)		Tair (K)		PW (cm)	
	Obs	ISCCP	Obs	ISCCP	Obs	ISCCP
SQH	295.4	279.4	286.1	270.8	0.73	0.46
Gerze	291.9	278.3	284.6	276.0	0.83	1.09
Naqu	287.5	274.6	283.0	269.1	1.73	0.92
D66	283.6	283.4	275.1	276.7	0.60	0.66
MS3637	292.6	270.2	281.3	269.1	1.45	0.86
Anduo	285.0	274.6	280.3	269.3	1.01	0.70
TTH	284.6	275.6	279.8	268.9	1.04	0.56
MS3478	282.9	275.3	280.3	269.3	1.08	0.69
D110	280.0	275.0	278.3	268.9	0.94	0.53

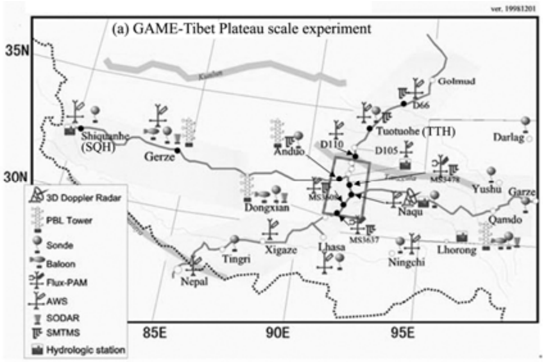

Figure 1 GAME-Tibet experimental map, IOP 1998. Radiation was measured at sites marked by solid dots (see Details in Table 1), half of them were deployed in a mesoscale region (91-92.5°E, 30.5-33°N).

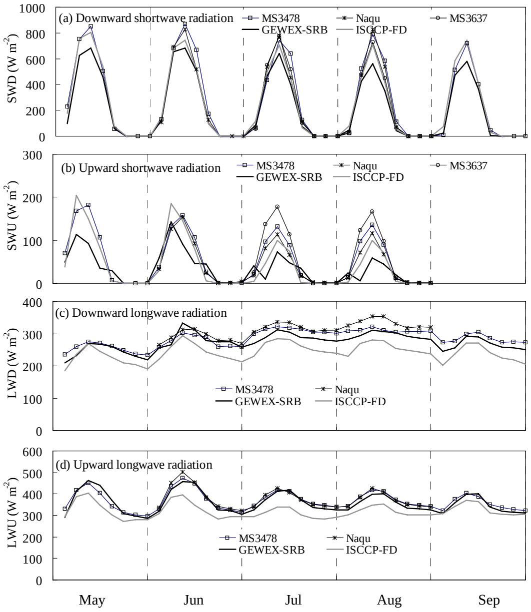

Figure 2 Seasonal and diurnal variations of surface radiation budget at three Eastern Tibet sites (Naqu, MS3478, MS3637), compared with corresponding GEWEX-SRB and ISCCP-FD data

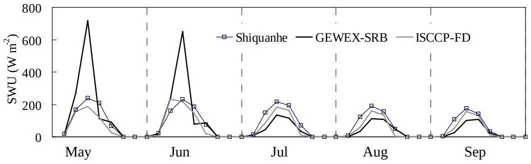

Figure 3 Similar to Figure 2, but for SWU at Shiquanhe (SQH) of West Tibet