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Short Paper

Wind Speed and Latent Heat Flux Retrieved by Simultaneous Observation of Multiple Geophysical Parameters by AMSR-E

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Abstract

Wind speed and Latent heat flux derived by Advanced Microwave Scanning Radiometer (AMSR) for Earth Observing System (AMSR-E) on Aqua are validated using the tropical and the mid-latitude Pacific surface buoys. Obtaining the wind speed and reducing the Relative Wind Direction effect (RWD effect) according to Konda et al. (2006), the root mean square of the error of the wind speed at the mid-latitude buoys is reduced to 1.6 ms^{-1}, which is slightly worse than that validated by using Tropical Atmosphere Ocean project (TAO) data in the tropics. The validation shows that the mean error and its tendency are almost same as that of AMSR-E standard product. The combined use of the wind speed and the other AMSR-E products provides the instantaneous latent heat flux at every observation cells. We show that ambiguity of the estimation of the latent heat flux is caused by traditional way of computation from the boundary layer parameters, each of which is measured by different sun-synchronized satellites. The ambiguity caused by the time-lagged measurement of them is found to amount to -1.3 ± 44.3 Wm^{-2}. The simultaneous measurement of boundary layer parameters can avoid it and make it possible to directly evaluate the satellite-derived latent heat flux by in situ observation.

Keywords : AMSR-E, Latent heat flux, wind speed, relative wind direction, microwave radiometer

1. Introduction

The satellite measurement technique enables us to monitor the climate conditions over the wide area of the earth surface in a very short time. In addition to the direct measurement of physical parameters, we can obtain indirect estimation of the other parameters such as turbulent heat flux by combining several satellite-derived physical parameters. In particular, monitoring the latent heat flux is very important, as the variation of the amount of water vapor affects the large scale climate change through the cloud genesis and the evaporative cooling at the ocean surface. Usually, the latent heat flux can be obtained from the measurement of sea surface temperature (SST), sea surface wind speed (SSWS), and specific humidity near the sea surface by the bulk formula,

$$Q = L\rho C_e (q_s - q_a) U_{10}, \qquad (1)$$

where L indicates the latent heat of evaporation, ρ, the density of the atmosphere, C_e, the bulk coefficient, and U_{10}, wind speed at height of 10 m. q_a and q_s respectively show the specific humidity at height of 10 m and that saturated at the SST, multiplied by 0.98, which is a typical value of the water vapor reduction at the sea surface with 35‰1).

Advanced Microwave Scanning Radiometer (AMSR) on Advanced Earth Observing Satellite II (ADEOS-II) and AMSR on Earth Observing System (AMSR-E) on Aqua simultaneously measure the SSWS, SST, and integrated water vapor (IWV), and therefore the surface humidity2). The instantaneous value of the latent heat flux, which should physically consistent in its meaning, can be obtained by these parameters. The local sun time of observation is about 10 : 30 (AM/PM) with ADEOS-II, and about 1 : 30 with Aqua.

Contrastively, combined use of the several sun-synchronized satellite sensors can cause a time lag of observations of the individual parameters, caused by the orbital difference of satellites. Some studies point out the climatic importance of the large variation of the diurnal cycle of parameters in eq. (1) as well as the surface heat flux in tropical climate3). Such short-time variations would bring the inconsistency and the uncorrectable ambiguity into the latent heat flux derived by parameters measured at the different time (time-lagged latent heat flux), as the local time of the each observation of individual satellites is different from every other. Fig. 1 shows the schematic view of the difference between the lagged observation of the latent heat flux (Q′) and the instantaneous

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observation (Q). Q′, which is derived from the parameters measured by different satellites, equals neither the instantaneous value of the latent heat flux (Q) nor the time average of Q (Qave). Therefore, it is very difficult to evaluate the accuracy of the "time-lagged" satellite-derived latent heat flux by in situ observation. The instantaneous latent heat flux could be directly compared and evaluated by the in situ observation.

Additionally, the accumulation of the individual errors of the physical parameters should affect the accuracy of the satellite-derived latent heat flux. In particular, the uncertainty of the SSWS should have a serious impact on the computation of the latent heat flux especially at its large value, because the role of the SSWS for the latent heat flux significantly increases with the larger SSWS[4]. Several studies[5]~[7] have reported that the brightness temperature (BT) can change according to the angle between the sensor azimuth and the in-situ wind direction (relative wind direction, hereafter RWD). The change of the BT due to the RWD allows some errors to creep into the SSWS retrieval. The error approximately amounts to $2–3\,\mathrm{ms}^{-1}$[8][9].

Konda et al. (2006)[10], hereafter KSEA06, attempted to correct the RWD effect on the AMSR-E wind speed retrieval algorithm, based on the method proposed by Konda and Shibata (2004)[9]. They attempted to evaluate the change of the BT due to the RWD effect, by using SSWS collocated with wind vector cells derived by SeaWinds on QuikSCAT. They proposed an experimental approach to reduce the RWD effect without knowing the information of the wind direction.

KSEA06[10] evaluated their method to correct the RWD effect by a comparison with the wind speed by the collocated wind vector measured by QuikSCAT. They showed that the RWD effect on the SSWS had an impact on the accuracy of the latent heat flux of about $28\,\mathrm{Wm}^{-2}$, and that was reduced by 60% by the correction. However, the validation was based on the data for only one month, and the collocation was obtained only in the high latitudes over 50 degrees because of the orbital difference. Moreover, recent studies[11][12] point out that the radar scatterometer is sensitive not to the ocean wind vector but to the stress, which can be affected by the vector difference between the ocean winds and currents. It is needed to make further validation by the in situ measurement of the ocean wind under other climatic regimes and for the longer period. The objective of this paper is first to validate the RWD effect correction in the wind speed derived by AMSR and AMSR-E by the ocean surface buoy data, and second to evaluate the impact of the simultaneous measurement of boundary layer parameters on obtaining the physically consistent latent heat flux.

2. Data and Method

In this study, the AMSR-E SSWS (U_K) is retrieved from the measured BTs provided by Japan Aerospace Exploration Agency (JAXA) in a form of the AMSR level 1B data set, according to the method described in KSEA06[10]. We also use the latest versions 4 and 5 (version 4 before February 2007) of the AMSR-E standard product (U_S) for the purpose of comparison. The difference between U_K and U_S is almost attributable to that of the method how to correct the RWD effect[10].

As KESA06[10] evaluated the U_K by using the SSWS measured at the Tropical Atmosphere Ocean project (TAO) array in the tropical Pacific[13], we will conduct another evaluation in the mid latitude. Pacific Marine Environment Laboratory (PMEL)/National Oceanic and Atmospheric Administration (NOAA) operates the Kuroshio Extension Observatory (KEO) buoy at 144.6°E, 32.4°N, while Japan Agency for Marine-Earth Science and Technology (JAMSTEC) does JAMSTEC KEO (JKEO) buoy at 146.5°E, 38.0°N. We will use the high resolution (every 10 minutes) and the real time daily average data for validation. These buoys are measuring the surface meteorology and the underwater physical properties at the south and the north across the Kuroshio Extension SST front[14].

The method we use to correct the RWD effect on AMSR-E SSWS is same as that of KSEA06[10], where a look-up table based on the relationship between BTs with the vertical ($BT36_V$) and the horizontal polarization ($BT36_H$) at 36.5 GHz is used for the RWD effect correction. According to KSEA06[10], an index, PS36, representing the partial shift of the $BT36_H$ caused by the SSWS is determined as the deviation from the bottom value of $BT36_H$ at each SST ($BBT36_{ssws=0}$), which is defined as that under the windless condition. PS36 is then obtained from the BT and the SST of the level 2B product of AMSR.

$$PS36 = \langle BT36_H - BBT36|_{SSWS=0} \rangle |_{SST}. \tag{2}$$

A look-up table correlating PS36 with SST, IWV, cloud liquid water (CLW), SSWS, and RWD is obtained by many collocations of observations of AMSR and SeaWinds on ADEOS-II.

$$PS36_T = PS36(SST, IWV, CLW, U6, RWD), \tag{3}$$

where $PS36_T$ indicates the value in the look-up table. We obtain the change of $BT37_H$ caused by the RWD effect, using only AMSR-E standard products and $PS36_T$, as done in KSEA06[10]. In $PS36_T$, an index of the SSWS (U6) is used instead of the SSWS. See KSEA06[10] for details of these definitions.

The latent heat flux can be obtained only from the AMSR-E products. We will use the standard products of the SST and the IWV. The atmospheric specific humidity is to be computed by the empirical relationship between the precipitable water and the mixing ratio[2]. As AMSR-E provides these variables without a time lag, instantaneous latent heat flux at individual observation pixels can be obtained. In contrast, traditional estimation of the surface turbulent heat flux is obtained from parameters, each of which is derived by the sensors on the different satellites. That can cause the time lag between the boundary layer parameters in eq (1) (Fig. 1).

The impact of such time lags of these parameters is evaluated by a comparison between the latent heat flux measured at TAO and that obtained by the SST, SSWS, and surface specific humidity derived by Advanced Very High Resolution Radiometer (AVHRR) on NOAA-17, SeaWinds on QuikSCAT, and AMSR on ADEOS-II. Considering the difference of the orbit of these satellites, level 3 daily map-projected data both in the morning and the nighttime are used.

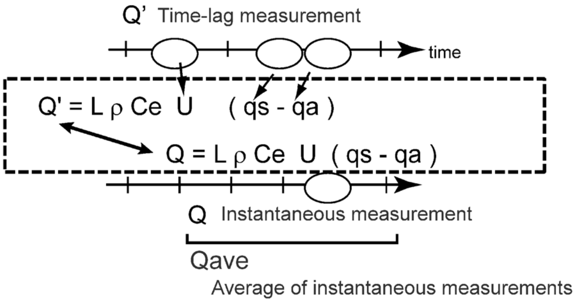

Fig. 1 Schematic view of the difference between the time-lagged latent heat flux and the instantaneous latent heat flux.

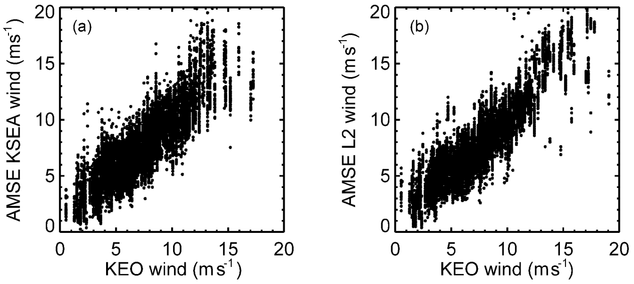

Fig. 2 Scatter plot of (a) the KEO wind speed and the SSWS derived according to KSEA06, and (b) the KEO wind and the SSWS of AMSR-E standard product.

3. Results

3.1 Validation of the wind speed

In the mid latitude, AMSR-E SSWS (U_K) is compared with KEO buoy wind. Fig. 2 (a) shows the result of the comparison between U_K and the KEO wind of 8881 collocations from 2004 June to 2007 December. The RMS error is 1.7 ms^{-1}. In the same way, the comparison with AMSR-E standard algorithm, Us, (Fig. 2 (b)) of 9454 collocations shows that the RMS error is 1.6 ms^{-1}. The difference between the KESA06 method and the standard algorithm to correct the RWD effect is not significant. Both of the comparisons show that the error at the KEO is slightly worse than in the tropical region (1.1 ms^{-1}) reported by KSEA06[10].

The further evaluation shows that there is a seasonal difference in errors between the winter (November, December, January and February) and the summer (May, June, July and August). The bias and the standard deviation of mean error were -0.6 ms^{-1} ± 1.5 ms^{-1} in summer, and 0.4 ms^{-1} ± 1.9 ms^{-1} in winter. Almost the same tendency is seen with the error of Us (-0.4 ms^{-1} ± 1.4 ms^{-1} in summer, and 0.9 ms^{-1} ± 1.8 ms^{-1} in winter). The contrast between the winter and the summer suggests some systematic error in the algorithm.

Additionally, we conducted a comparison of the SSWS at the JKEO, another buoy platform in the north of the Kuroshio Extension. The comparison is done for the data derived in 2007 because JKEO was deployed in February 2007. The SSWS at JKEO is the daily average because of the telemetry. The RMS error of the daily average of U_K at JKEO is 2.6 ms^{-1}. The error of the daily average U_K at KEO (2.8 ms^{-1}) is almost the same as that at JKEO. RMS errors of Us at JKEO and KEO are 2.6 ms^{-1} and 2.9 ms^{-1}, respectively. The spatial difference of the error does not seem to be significant.

We consider that there is no significant difference between the SSWS obtained by the method of this study and that of the standard algorithm. On the other hand, the large error in both of the north and south of the Kuroshio Extension suggests that more validation using the in situ observation in the mid latitude is needed to improve the accuracy of the SSWS.

3.2 Obtaining instantaneous latent heat flux

The uncertainty of the SSWS estimation should have a serious impact on the computation of the latent heat flux, because the role of the SSWS for the latent heat flux shows a marked increase with increasing SSWS[4]. Therefore, the correction of the RWD effect on the SSWS should contribute to improvement in accuracy of the satellite-derived latent heat flux. We have already shown that the RWD correction was generally good, but that we have some systematic errors in U_K and Us, derived by AMSR and AMSR-E. Nevertheless, AMSR and AMSR-E have a merit to measure boundary layer parameters simultaneously and therefore the instantaneous

Table 1 The mean difference and the standard deviation of the latent heat flux and the other environmental physical parameters of SST, SSWS, and specific humidity as well as the number of the available data (parenthesis). (Top) The difference between the AMSR and the synchronous observation at TAO arrays. (Middle) the difference between the variables obtained by the combination of the different satellites and the average of the TAO observation during the morning or the nighttime, (Bottom) and the difference of the TAO observations between the variables obtained at the different times synchronous with the corresponding satellites observation and those averaged during the morning or the nighttime are tabulated.

	Latent heat flux	SST	Wind	Sp. Humidity
	W/m^2	°C	m/s	g/Kg
AMSR - TAO	17.7±51.0(2873)	-0.7±0.7(2946)	0.3±1.1(2900)	-1.5±1.9(2878)
Satellites(combined) - TAO (average)†	48.8±68.3(449)	-0.7±2.7(1423)	0.9±1.9(3652)	-1.2±2.1(4196)
TAO (time-lag) ‡ -TAO (average) †	-1.3±44.3(7040)	0.0±0.1(7292)	-0.1±1.0(7003)	0.0±0.5(7068)

† : Average from 6AM to 10:30AM or from 6PM to 10:30PM against the morning orbit and the nighttime orbit, respectively.

‡ : The SST(10AM/10PM), wind speed(6AM/6PM), and specific humidity(10:30AM/10:30PM) at the different time are used to compute the latent heat flux.

latent heat flux.

We conduct a comparison of the instantaneous observation of the latent heat flux derived by AMSR with the in situ observation at TAO arrays from April to September, 2003. As observation at TAO array is recorded every 10 minutes, the comparison is made by using the closest record in time and within 10 minutes of difference in time. Generally, the AMSR latent heat flux agrees well with the in situ observation, but tends to be overestimated when the in situ latent heat flux is large (not shown). The error in the surface-level specific humidity seems to be the most responsible for it. Direct estimation of the surface humidity is a future important problem, whereas algorithms for the SST and the SSWS are being developed by the standard algorithms and others.

The first line in Table 1 shows the result of the comparison between the instantaneous observation of the latent heat flux and the other parameters by AMSR and TAO. As the AMSR latent heat flux derived here is internally consistent without a time lag, the error of the estimation is attributable to that caused by the accumulation of the individual measurement errors of the parameters. The mean and standard deviation of the error is 17.7±51.0 Wm^{-2}. Although there is still large variance around the mean error, the estimation of the source of the error becomes easier than the multi-satellite estimation with a several hours of time lag between measurements of individual parameters.

When the latent heat flux is obtained by different satellite sensors, the latent heat flux to be determined is not physically consistent as shown in Fig. 1, e.g., the SST, the SSWS, and the IWV are respectively observed by AVHRR on NOAA17 at 10 : 00 AM/PM, SeaWinds on QuikSCAT at 6 : 00 AM/PM, and AMSR at 10 : 30 AM/PM. There is no truth data for such a value in its correct meaning. Nevertheless, it is worth while to compare the time-lagged satellite latent heat flux with a representative of the realistic latent heat flux, in order to estimate how large the ambiguity caused by the time-lagged measurement is. Considering the difference of equator crossing time, an example of validation is done using the latent heat flux derived by the TAO array, averaged during the morning (6AM-10 : 30AM) and the nighttime (6PM-10 : 30PM). The second low of Table 1 shows that the difference is 48.8±68.3 Wm^{-2} (figure is not shown). Note that the mean difference here is the accumulation of the error of the individual satellite observations and the inaccuracy caused by the time-lagged observation of the SST, the SSWS and the IWV. For example, the second low in Table 1 also shows mean differences of the individual satellite-derived variables from the morning and the nighttime mean of the in situ observation. Comparing with the mean differences of the collocated comparison shown in the first low in Table 1, the bias of the difference of the SSWS derived by SeaWinds is almost 3 times as large as that measured by AMSR. This might affect the mean error of the latent heat flux.

Another validation may be possible by comparing the time-lagged satellite latent heat flux with the latent heat flux measured at some time in the morning or the nighttime. The differences between the time-lagged satellite latent heat flux and that measured at TAO buoys at 6 AM/PM (AVHRR),

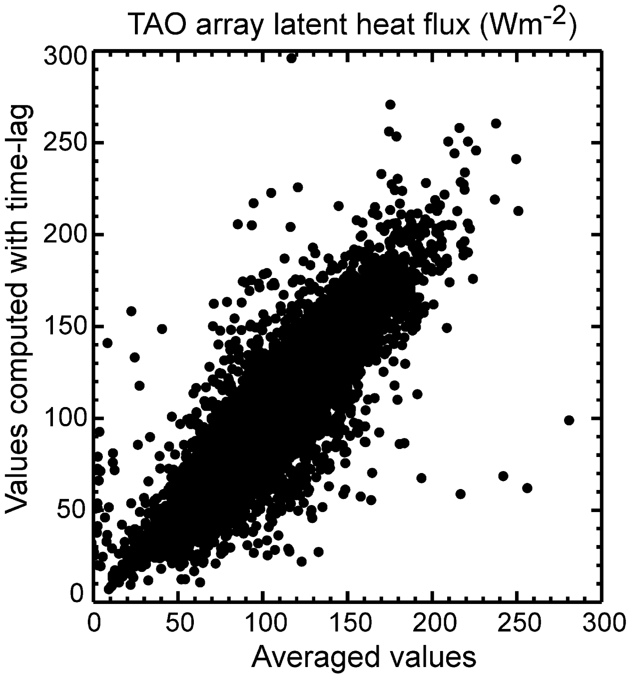

Fig. 3 Scatter plot of the average of the instantaneous latent heat flux and the time-lagged latent heat flux using data at TAO array from April to September 2003.

10 AM/PM (SeaWinds) and 10 : 30 AM/PM (AMSR) are respectively 46.4±68.2 Wm^{-2}, 47.9±69.8 Wm^{-2} and 46.4±69.6 Wm^{-2}. As these values are almost the same as the previous comparison, one should know that it is difficult to attribute the large bias and the standard deviation to one particular parameter in Table 1.

In order to extract the ambiguity of the latent heat flux due to the time-lagged measurement, a time-lagged latent heat flux is virtually computed by using only the TAO data, avoiding the contamination of individual satellite estimation errors. Fig. 3 shows the comparison of the latent heat flux computed from each variable at the corresponding satellite's equator crossing time (10 : 00 AM/PM for the SST, 6 : 00 AM/PM for the SSWS, 10 : 30 AM/PM for the specific humidity) and the average of the instantaneous latent heat flux from 6 : 00 to 10 : 30 AM/PM.

The difference between these values is identified as the uncertainty of the latent heat flux caused by the observation of the individual variables with a time lag. The difference caused by this inconsistency in the latent heat flux amounts to −1.3±44.3 Wm^{-2}. This is the ambiguity, which is more serious than the accumulation of the estimation errors of individual variables in eq (1), as described in 3.1. The difference is characterized by the small bias and the large standard deviation. This suggests that the error caused by the time-lag between the individual measurements affects the inaccuracy rather than the bias.

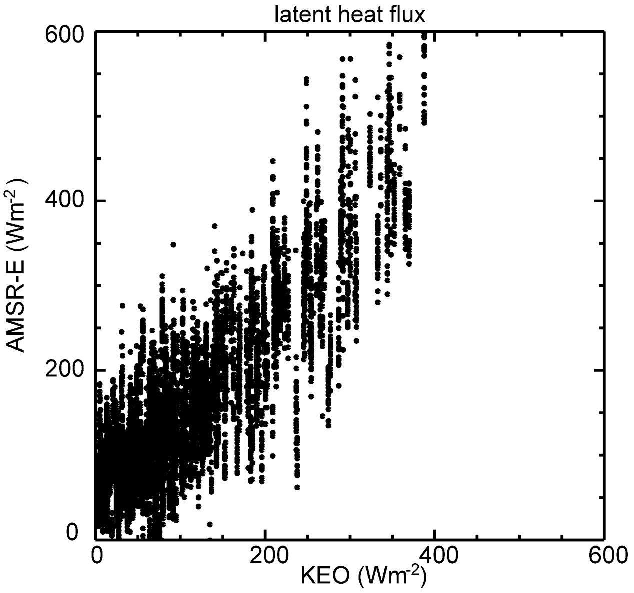

Fig. 4 Scatter plot of the 5181 collocations of the instantaneous latent heat flux derived by AMSR-E and that derived at KEO buoy from 2004 to 2007.

It is almost the same as the boundary layer parameters as indicated in Table 1. It is not evident which parameter is the most responsible for the large standard deviation in the latent heat flux, which is a quite different point from the analysis of the instantaneous measurement. The multi-satellites observation of the latent heat flux necessarily includes such amount of error to the average in situ observation, even if each variable is observed correctly. This fact clearly explains the merit of the simultaneous observation of the boundary layer parameters, which is achieved by AMSR and AMSR-E.

4. Discussions

Results obtained in the previous section might be affected by the climatic regime of the individual measurements. We compare the latent heat flux derived by AMSR-E with the observation at KEO to validate the instantaneous satellite-derived heat flux (Fig. 4) in the mid latitude condition. As the boundary layer parameters are observed simultaneously by AMSR-E, the instantaneous value of the latent heat flux can be obtained. Therefore, the disagreement between the in situ and the satellite-derived latent heat fluxes is for the most part attributable to the accumulation of the estimation error of individual parameters. Comparison is made using 5181 collocations of the KEO and AMSR-E observations. The mean difference and the standard deviation are 28.9 Wm^{-2}± 41.9 Wm^{-2}, respectively. The satellite-derived latent heat flux tends to be overestimated when the latent heat flux is large.

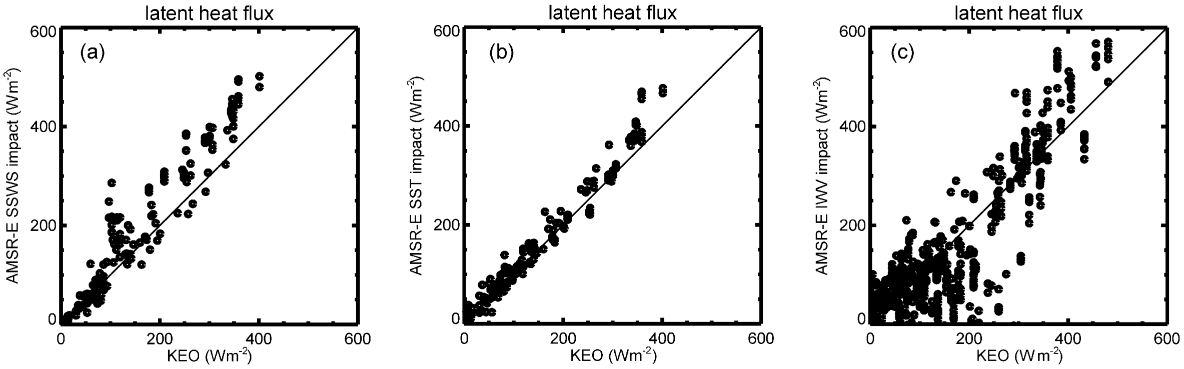

Fig. 5 Comparisons of the latent heat flux derived at KEO and the latent heat flux computed by substituting AMSR-E-derived parameters for (a) the SSWS, (b) the SST and (c) the specific humidity.

This is consistent with the tendency of the U_K, which is likely to be overestimated in winter as shown in section 3. 1.

Fig. 5 shows the impact of errors of individual boundary layer parameters on the latent heat flux, by the sensitivity analysis comparing the in situ latent heat flux with that derived by substituting satellite-derived parameters for one parameter in eq. (1). The impacts of the estimation error of individual variables of the SSWS, the SST and the specific humidity are respectively $3.7\,\mathrm{Wm}^{-2} \pm 24.1\,\mathrm{Wm}^{-2}$, $11.6\,\mathrm{Wm}^{-2} \pm 20.7\,\mathrm{Wm}^{-2}$ and $11.1\,\mathrm{Wm}^{-2} \pm 43.8\,\mathrm{Wm}^{-2}$. The error of the SSWS (U_K) has the smallest impact possibly because of the successful correction of the RWD effect. However, the tendency of the error of U_K shown in Fig. 4 is almost the same as that of the SST. The similar tendency of these impacts suggests a multiplier effect of these errors. In fact, Fig. 5 shows that both the SST and the SSWS error tend to make a larger overestimation in larger latent heat flux regime. A large bias in the error of the AMSR-E latent heat flux should be affected by that. On the other hand, the error of the specific humidity works on the variance rather than the mean bias. This is attributable to the method estimating the surface mixing ratio from the IWV.

5. Conclusions

The correction of the RWD effect on the retrieval of the SSWS by AMSR and AMSR-E has been validated using the mid-latitude ocean surface buoys (KEO and JKEO) as well as the tropical Pacific (TAO). The accuracy of the SSWS derived by the method using the look-up table proposed by KSEA06[10] is almost same as that of the standard algorithm. However, both of them tend to be overestimated in winter and underestimated in summer. Further validation is needed to determine the source of such systematic error.

The importance to obtain the accurate SSWS by AMSR and AMSR-E for the instantaneous latent heat flux is proposed in this study, which indicates the possibility to monitor the earth environment by microwave sensors. We showed that the time-lagged measurement of the boundary layer parameters measured by different sun-synchronized satellites brings an uncorrectable ambiguity into the estimation of the latent heat flux. It was found that the typical value in the tropical Pacific amounts to about $44.9\,\mathrm{Wm}^{-2}$. This result suggests the difficulty to evaluate the source of the error of the time-lagged latent heat flux beyond this ambiguity.

The estimated error of the satellite-derived latent heat flux can be affected by the climatic regime and seasons. The comparison with KEO buoy gives the mean difference of $28.9\,\mathrm{Wm}^{-2} \pm 41.9\,\mathrm{Wm}^{-2}$. Judging from the sensitivity analysis, the error of the SSWS has the smaller impact than the SST and the specific humidity. However, the bias observed is related to the overestimation of the SSWS in the winter in this region, while the standard deviation is almost the same as that in the tropics. Possibly, the similarity of the tendency of the error of the SSWS and the SST generates the large bias because of the multiplier effect. The error expanded in this way should be validated more in the future study. On the other hand, the error of the specific humidity works on the variance rather than the mean bias. The direct estimation of the surface humidity from the BTs should be improved in the future.

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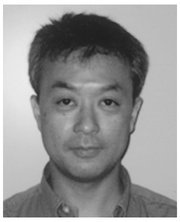

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