Influence of Oceanic Parameters on Aquarius L-Band Sea Surface Emissivity

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Abstract. A systematic assessment of the effects of various oceanic parameters on sea surface emissivity based on Aquarius measurements is presented in this paper. The results show that the influence of wind speed on wind-driven emissivity increment $\Delta E$ is most significant. The magnitude of change in $\Delta E$ related to $W$ can be as large as 8.02 K. The wind direction signal has been found to be small at low and moderate wind speeds, whereas it is significant at high wind speed and reaches a maximum of 1.37 K at 22.5 m/s. The influence of backscatter under HH polarization is notable and as large as, or larger than backscatter under VV polarization. The effects of the SST and SWH on $\Delta E$ are relatively small with the max magnitude of change in $\Delta E$ of 0.86 K and 0.49 K, respectively. Furthermore, strong correlations are found among wind speed, microwave backscatter under VV and HH polarization, which are higher than ninety percent. Therefore, the decorrelation of oceanic parameters is recommended to be considered in the process of emissivity correction because of the high correlations among oceanic parameters.

1. Introduction

Sea surface salinity (SSS) is of primary importance to ocean circulation [1-3]. One of the major error sources for SSS retrieval is the effect of ocean roughness; it can be characterized by microwave backscatter ($\sigma_0$) and can increase the sea surface emissivity [4, 5]. Many oceanic parameters, such as wind, significant wave height (SWH) and sea surface temperature (SST), can dramatically worsen the accuracy of SSS measurements by causing changes in the sea surface emissivity [6, 7].

In general, wind is the major cause of excess sea surface emissivity [8, 9]. The effect of the wind speed on the L-band brightness temperature (TB), which is equal to the emissivity multiplied by the SST, has been studied based on field data from the WInd and Salinity Experiment (WISE) 2000 and 2001 [10, 11]. A wind direction signal has also been found in TB [12] and has been further analyzed by several scholars [13, 14]. The wind direction signal has been found to be small at low and moderate wind speeds [15]. Direction dependence in the Aquarius TB with peak-to-peak modulations increases from about a few tenths to 2 K in the range of 10–25 m/s wind speed [16]; Additionally, the SWH also has some impact on TB [17]. Based on tower-based radiometer data, significant influence of SWH on airborne C- and Ku-band radar data has been found at low wind speeds, but negligible for moderate wind speeds [18]. Furthermore, the effect of the SST on microwave measurements has been...
investigated in several studies [19-22]. The sensitivity of the SSS to the SST has been found to be greater in cold water (below 10 ℃) and decrease with increasing SST [21]. However, most of the studies only focus on one or two of the factors and the TB dataset they used are different. This paper aims to systematically assess the effects of various oceanic parameters on sea surface emissivity based on Aquarius measurements.

2. Data
To investigate the performance of sea surface emissivity, the following data were used in this study:

1) Basic data used in this paper are Aquarius Data Processing System (ADPS) Level-2 (L2) version 5.0 orbital product, including: radiometer brightness temperature data ($T_b$), scatterometer HH-polarization observations ($\sigma_{0,HH}$), scatterometer VV-polarization observations ($\sigma_{0,VV}$), HHH wind speeds ($W$) which were retrieved from scatterometer HH-polarization and radiometer H-polarization observations[23, 24].

2) Wind direction data ($\varphi$) were obtained from the NCEP Global Data Assimilation System (GDAS) given at 1° special and 6-hour temporal resolution.

3) Daily SST data ($T$) were obtained from the National Oceanic and Atmospheric Administration (NOAA) daily Reynolds Optimum Interpolation (OI) 0.25° version 4 product [25].

4) SWH data ($WH$) were obtained from the NOAA/NCEP Wave Watch III model 3-hour, 0.5° product at 10 m.

5) Daily SSS data ($S$) were from the Hybrid Coordinate Ocean Model HYCOM (www.hycom.org) that were resampled on a 0.25° by 0.25° map.

The orbital TB measurements have been matched with the concurrent wind direction, SST, SWH and SSS data mentioned above, and the collocated results which have been contained in Aquarius ADPS L2 orbital product were used in this paper. The data under rain condition were excluded. The number of matched data points without rain from September 2011 to May 2015 for near-global region within ±60° was approximately $7.1 \times 10^7$.

In this paper, all ocean surface emissivity $E$ values, which are related to ocean surface brightness temperature ($T_b$) by $T_b = E \cdot T$, are multiplied by a common surface temperature of 290 K and therefore have units of Kelvin [8].

3. Method
The sea surface emissivity ($E_p$) can be separated into two components which are the flat surface emissivity ($E_{0p}$) and the wind-driven emissivity increment ($\Delta E_p$), here $P = V, H$ is polarization.

The sea surface emissivity $E_p$ can be calculated from TB measurements via $T_b / T$. Here $T_b$ is the sea surface TB measured by the Aquarius L-band microwave radiometer and $T$ is the concurrent SST.

The emissivity of the smooth sea surface, $E_{0p}$, is related to the sea water permittivity $\varepsilon_r$ by means of the Fresnel equations and Debye equation [26, 27] [28]. Therefore, the wind-driven component $\Delta E_p$ that is mainly related to oceanic parameters can be calculated by subtracting $E_{0p}$ from $E_p$.

The conditionally averaged $\Delta E_p$ are used to analyze the dependence of excess surface emissivity on wind speed $W$, relative wind direction $\varphi$, and SST $T$ or SWH $WH$. The cosine series for the modeling of $\Delta E_p$ refers to references [8, 29] and deforms slightly.

$$\Delta E_p(W, \varphi, T) = A_{0p}(W, T) + A_{1p}(W, T) \cdot \cos(\varphi) + A_{2p}(W, T) \cdot \cos(2 \cdot \varphi)$$ (1)

The harmonic coefficients $A_kp$, $k = 0, 1, 2$ are estimated for each of Aquarius antenna beams (incidence angles) and polarizations.

4. Results
The matched data points were screened to retain the data with $T = 18.9 \pm 1.7$ ℃, $W = 8.1 \pm 0.7$ m/s and $WH = 3.0 \pm 0.3$ m to study the $\Delta E$ change under different polarization and incidence angle (horn). Figure 1 plots the wind-driven component $\Delta E$ versus different oceanic parameters. Figure 1 shows that $\Delta E$ increases rapidly with the increasing wind speed. The $\Delta E$ change causing by wind
speed is approximately 3.89 K as wind speed increase from 0 to 15 m/s. \( \Delta E \) first decreases and then slightly increases as the SST rises from 0 °C to 30 °C, with the magnitude of the change in \( \Delta E \) being approximately 0.42 K. The change of \( \Delta E \) with SWH is not obvious and the magnitude of the change in \( \Delta E \) is only 0.15 K as SWH rises from 1 m to 7 m. The overall \( \Delta E \) decreases with the increasing \( \sigma_{0VV}^\prime \) and \( \sigma_{0HH}^\prime \), and the magnitudes of the change in \( \Delta E \) are 0.35 K and 0.41 K, respectively. \( \Delta E \) changes periodically with \( \phi \) with the magnitude of the change in \( \Delta E \) being approximately 0.18 K. Obviously, wind is the main cause of \( \Delta E \) and the magnitude of change in \( \Delta E \) related to wind speed is much larger than that related to other factors.

Figure 1 The wind-driven component \( \Delta E \) versus (a) \( W \), (b) SST, (c) SWH, (d) \( \sigma_{0VV}^\prime \), (e) \( \sigma_{0HH}^\prime \) and (f) \( \phi \). The values have been multiplied by a common surface temperature of 290 K. The red curves show the average value of \( \Delta E \), and the error bars indicate ±1 STD of \( \Delta E \) in each bins.

However, Figure 1 shows only the performances under certain cases, that is, \( W = 8.1 \pm 0.7 \) m/s, \( T = 18.9 \pm 1.7 \) °C, \( WH = 3.0 \pm 0.3 \) m and \( \phi = 0^\circ \pm 10^\circ \). The \( \Delta E \)s were averaged into five equal two-dimensional intervals, namely, \([W,T] \), \([W,WH] \), \([W,\sigma_{0VV}^\prime] \), \([W,\sigma_{0HH}^\prime] \) and \([W,\phi] \). The step sizes for each parameter are 1 m/s for \( W \), 1 °C for \( T \), 0.4 m for \( WH \), 0.005 for \( \sigma_{0VV}^\prime \), 0.005 for \( \sigma_{0HH}^\prime \), and 10° for \( \phi \), respectively. The more complete performances for SST, SWH, \( \sigma_{0VV}^\prime \), \( \sigma_{0HH}^\prime \) and \( \phi \) are, then, illustrated in terms of their differences with mean \( \Delta E \) data at each \( W \), as shown in Figure 2a – 2e. The performance for \( W \) is illustrated in terms of its difference with mean \( \Delta E \) data at each \( T \), that is shown in Figure 2f.

When \( W \) is lower than 12 m/s, \( \Delta E \) decreases as SST increases and then increases slightly after approximately 20 °C. When \( W \) is higher than 12 m/s, no increasing trend is found with the increasing SST and the change range is larger than that for \( W \) lower than 12 m/s (Figure 2a). The influence of WH on \( \Delta E \) is relatively small, especially when \( W \) is lower than 12 m/s. When \( W \) is higher than 14 m/s, \( \Delta E \) decreases obviously with the increasing WH (Figure 2b). Decreasing trends of \( \Delta E \) are also found with increasing \( \sigma_{0VV}^\prime \) and \( \sigma_{0HH}^\prime \), especially for higher wind speed, and they look very similar (Figure 2c and 2d). An interesting phenomenon can be seen from Figure 2e. When \( W \) is higher than 4 m/s and lower than 9 m/s, \( \Delta E \) for crosswind is smaller than that for upwind and downwind. An opposite phenomenon is observed when \( W \) is lower than 4 m/s or higher than 9 m/s; that is, \( \Delta E \) for crosswind is larger than that for upwind and downwind. Figure 2f indicates that \( \Delta E \) increases rapidly with increasing wind speed whatever \( T \) is.
Figure 2 The wind-driven component $\Delta E$ versus (a) $W$ and SST, (b) $W$ and SWH, (c) $W$ and $\sigma_0^{VV''}$, (d) and $\sigma_0^{HH''}$, (e) $W$ and $\phi$ in terms of its difference with the mean data in each $W$ for H polarization and horn 1. (f) is wind-driven component $\Delta E$ versus $W$ and SST in terms of its difference with the mean data in each SST.

Figure 3 was drawn to quantitatively evaluate the magnitude of change in $\Delta E$ related to various oceanic parameters. Figure 3a indicates that the magnitude of change in $\Delta E$ related to $W$ can be as large as 8.02 K when SST is 0 °C and it decreases as SST increases. The magnitudes of change in $\Delta E$ related to other factors (Figure 3b) are far less than that related to $W$. The magnitude of change in $\Delta E$ related to $\sigma_0^{HH}$ is slightly larger than that related to $\sigma_0^{VV}$, and both are larger than that related to SST and SWH for most $W$s. They increase with increasing wind speed and reach maximums at 23.5 m/s for $\sigma_0^{HH}$ and 24.5 m/s for $\sigma_0^{VV}$. The maximums for the magnitude of change in $\Delta E$ related to $\sigma_0^{VV}$ and $\sigma_0^{HH}$ are 1.32 K and 1.22 K, respectively. When $W$ is lower than 9 m/s, the magnitude of change in $\Delta E$ related to $\phi$ is the smallest among these factors, then increases rapidly with increasing wind speed. When $W$ is higher than 16.5 m/s, the magnitude of change in $\Delta E$ related to $\phi$ reaches that related to $\sigma_0^{VV}$ and $\sigma_0^{HH}$, then exceeds them. It reaches a maximum of 1.37 K at 22.5 m/s. The magnitude of change in $\Delta E$ related to SST increases with $W$ when $W$ is lower than 21.5 m/s, reaches a maximum of approximately 0.86 K, and then decreases with $W$. It is higher than that related to SWH for almost all the wind speeds. The magnitude of change in $\Delta E$ related to SWH decreases slightly with $W$ when $W$ is lower than 9 m/s, then increases slightly with $W$. The maximum it reaches is only 0.49 K. Actually, both $\Delta E$ and $\sigma_0$ are strongly related to SWH [8], so what Figure 3 does not show is that the effect of SWH is actually largely accounted for in the $\sigma_0$ variation with WS.

The $\Delta E_p$ was then expanded into a Fourier series of even harmonic functions via Equation (4) to evaluate the dependence of excess surface emissivity on $W$, $\phi$, and $T$. The $A_{k\ell p}$, $k = 0,1,2$ coefficients for H polarization and horn 1 are shown in Figure 4.
Figure 3 The magnitude of change in $\Delta E$ related to (a) $W$ in each SST, and (b) related to other factors in each $W$.

The $\Delta E$ is dominated by $A_0$, for the magnitudes of $A_1$ (Figure 4b) and $A_2$ (Figure 4c) are far smaller than $A_0$ (Figure 4a), and $A_0$ is dominated by $W$; therefore $\Delta E$ is dominated by $W$. $A_1$ increases slightly with $W$ when $W$ is lower than 16 m/s, and then decrease with $W$ when $W$ is higher than 16 m/s. Most $A_2$ values are negative and $A_2$ decreases rapidly with increasing $W$ when $W$ is higher than 7 m/s. The effects of SST and SWH are observable in $A_1$ and $A_2$. The SST effects on $A_1$ and $A_2$ especially when $W$ is higher than 10 m/s are relatively obvious (Figure 4b and 4c). $A_1$ is higher for low SST than that for high SST when $W$ is higher than 10 m/s and lower than 20 m/s, whereas $A_1$ is lower for low SST than for high SST when $W$ is higher than 20 m/s (Figure 4b). The change of $A_2$ with SST is complicated and no obvious pattern is observed in Figure 4c.

Figure 4 Aquarius $A_{kP,k=0,1,2}$ coefficients versus $W$ and SST for H polarization and horn 1. The values have been multiplied by a common surface temperature of 290 K.

The correlation coefficients between the oceanic parameters are also calculated. It shows that $W$ and SST are negatively correlated with a correlation coefficient of -0.45. The correlation coefficient between $W$ and SWH is 0.72. $W$ is strongly related to $\sigma'_{VV}$ and $\sigma'_{HH}$, with correlation coefficients of 0.97 and 0.99, respectively. Simultaneously, $\sigma'_{VV}$ and $\sigma'_{HH}$ are also strongly related.

5. Conclusions
In summary, the influences of various oceanic parameters on sea surface emissivity have been evaluated based on Aquarius measurements and concurrent oceanic parameters, e.g., wind speed, relative wind direction, SST, SWH, microwave backscatter under VV and HH polarization.

The influence of wind speed on $\Delta E$ is far larger than other factors. The wind direction signal has been found to be small at low and moderate wind speeds, whereas it is significant at high wind speed.
The influence of $\sigma_{\text{HHH}}^0$, which was barely considered in previous studies, is notable and larger than $\sigma_{\text{VVV}}^0$ and the rest factors. The effects of the SST and SWH on $\Delta E$ are relatively small, but they need to be considered.

Thus, it is recommended that in the process of correcting the excess sea surface emissivity, the prime consideration should be given to the effect of the wind speed and wind direction. Note that the influence of $\sigma_{\text{HHH}}^0$, which was barely considered in previous studies, is notable and should also be considered. The effects of the SST and SWH are relatively small, but they still need to be considered. Especially for SST, which was considered in some emissivity correction model, but its effect was not fully taken into account. Therefore, the full performance of SST should also be considered in correction model. Furthermore, the decorrelation of oceanic parameters should be considered in the process of correction because of the high correlations among oceanic parameters.

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