Retrieval of Solar-induced Chlorophyll Fluorescence from Satellite Measurements: Comparison of SIF between TanSat and OCO-2

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Abstract. Solar-induced chlorophyll fluorescence (SIF) is emitted during photosynthesis in plant leaves. It constitutes a small additional offset to reflected radiance and can be observed by sensitive instruments that with high signal-to-noise ratio and spectral resolution. The Chinese global carbon dioxide monitoring satellite (TanSat), as its mission, acquires greenhouse gas column density. The advanced technical characteristics of the hyper-spectrum grating spectrometer (ACGS) onboard TanSat enable SIF retrieval from space observations in the O_2-A band. In this study, one-year SIF data for each sounding was retrieved from Orbiting Carbon Observatory-2 (OCO-2) and TanSat measurements using the IAPCAS/SIF algorithm. A comparison between the SIF results retrieved from OCO-2 spectra and the official OCO-2 SIF product (OCO2_Level 2_Lite_SIF.8r) shows their strong linear relationship ($R^2 > 0.85$) and suggests the reliability of the SIF retrieval algorithm. The global distribution showed that the SIF retrieved from the two satellites shared the same spatial pattern for all seasons with the gridded SIF difference less than 0.3 W m^{-2} μm^{-1} sr^{-1}, and they also agreed well with the official OCO-2 SIF product with the difference less than 0.2 W m^{-2} μm^{-1} sr^{-1}. The retrieval uncertainty of seasonal-gridded TanSat SIF is less than 0.03 W m^{-2} μm^{-1} sr^{-1} whereas the uncertainty of each sounding ranges from 0.1 to 0.6 W m^{-2} μm^{-1} sr^{-1}. The relationship between annually-averaged SIF products and FLUXCOM gross primary productivity (GPP) was also estimated for six vegetation types in a $1° \times 1°$ grid over the globe, indicating that the SIF data from the two satellites have the same potential in quantitatively characterizing ecosystem productivity. The spatiotemporal consistency between TanSat and OCO-2 and their comparable data quality make the comprehensive usage of the two mission products possible. Data supplemented by TanSat observations are expected to contribute to the development of global SIF maps with more spatiotemporal detail, which will advance global research on vegetation photosynthesis.

1 Introduction

Terrestrial vegetation accounts for a large part of the ecosystem, with its photosynthesis and respiration processes playing important roles in the global carbon cycle. Incoming radiation is absorbed, reflected, and/or transmitted by plant leaves. A portion of the absorbed radiation is used by the chlorophyll in plant leaves for carbon fixation, while the rest is either dissipated as heat or re-emitted as solar-induced chlorophyll fluorescence (SIF) at longer wavelengths (Frankenberg et al., 2011a, 2014). In contrast to the traditional remotely sensed vegetation indices obtained from some studies (Frankenberg et al., 2011b; Guanter et al., 2014; Li et al., 2018; Sun et al., 2017a; Yang et al., 2015; Zhang et al., 2014), SIF offers the potential to measure photosynthesis activity and gross primary production (GPP), due to the strong correlation between these measures (Frankenberg et al., 2011b; Guanter et al., 2012, 2014). The fluorescence emission (Fs) adds a low-intensity radiance less than $10 \ \mathrm{W \ m^{-2} \ \mu m^{-1} \ sr^{-1}}$ and fills in the solar absorption features of the reflected spectrum (Frankenberg et al., 2011a). The filling-in effect of the solar lines (Fraunhofer lines) is the basic principle applied to measure SIF from space using the capabilities of hyperspectral observation (Frankenberg et al., 2011b; Guanter et al., 2012).

The first attempt at SIF research based on space-based observations was performed using images acquired by the Medium Resolution Imaging Spectrometer (MERIS) onboard the ENVIronmental SATellite (ENVISAT) (Guanter et al., 2007). This led to a new idea for conducting SIF studies on a global scale. The first global SIF map was retrieved with high-resolution spectra from the Greenhouse-gases Observing SATellite (GOSAT) (Joiner et al., 2011; Frankenberg et al., 2011b). After that, SIF retrievals were implemented from a variety of satellite measurements, such as those from the Global Ozone Monitoring Experiment-2 (GOME-2) instruments onboard meteorological operational satellites, SCIAMACHY on board ENVISAT, and Orbiting Carbon Observatory-2 (OCO-2) (Joiner et al., 2016; Köhler et al., 2015). The TROPOspheric Monitoring Instrument (TROPOMI) on board Sentinel 5 Precursor (S-5P) provides more efficient SIF observations in terms of global coverage and new opportunities for exploring the application potential of SIF data in the terrestrial biosphere as well as in climate research (Doughty et al., 2019; Köhler et al., 2018b). Furthermore, an upcoming European Space Agency mission called FLuorescence EXplorer (FLEX), the first satellite dedicated to SIF emission observation, will launch in the middle of 2024 (Drusch et al., 2017). Many studies on SIF applications have been initiated with the accumulation of SIF products in recent years. The responses of satellite-measured SIF to environmental conditions have been applied to drought dynamics monitoring and regional vegetation water stress estimation (Lee et al., 2013; Sun et al., 2015; Yoshida et al., 2015). As a proxy of photosynthesis, SIF acts as a powerful constraint parameter in estimating carbon exchange in an ecosystem between the atmosphere, ocean, and soil; as such, the analysis of the relationship between SIF and GPP has become an important research topic (Li et al., 2018; Köhler et al., 2018a; Sun et al., 2017a; Zhang et al., 2018). The strong linear relationship between them paves the way for improving terrestrial ecosystem model simulation of GPP, along with consequent improvement of global carbon flux estimation (MacBean et al., 2018; Yin et al., 2020). GPP estimations based on satellite-measured SIF have proven to be an effective method validated by in-situ flux observations (Joiner et al., 2018; Qiu et al., 2020). However, uncertainty in the factors that determine the relationship between SIF and GPP still exists and is a key

68 limitation in the application of SIF to flux estimation. Based on multi-satellite SIF products, eddy covariance flux tower

69 observations, and ecological models, the relationship between SIF and GPP under different environmental conditions has

70 been discussed in a number of studies to analyze the dominant factors for the growing status of different biomes, such as

71 temperature, soil moisture, and vegetation types (Chen et al., 2020; Doughty et al., 2019; Li et al., 2020; Qiu et al., 2020; Yin

72 et al., 2020).

73 The Chinese global carbon dioxide monitoring satellite (TanSat) was launched in December 2016. Aiming at acquiring CO_2

74 concentrations as OCO-2, TanSat flies in a sun-synchronous orbit at approximately 700 km in height with a 16-day repeat

75 cycle and an equator crossing time of ~1:30 p.m. local time (Cai et al., 2014; Liu et al., 2018; Yang et al., 2018). Onboard

76 TanSat, the hyperspectral Atmospheric Carbon-dioxide Grating Spectrometer (ACGS) is designed to separately record solar

77 backscatter spectra in three channels centered at 0.76 μm (O_2-A band), 1.61 μm (weak CO_2 absorption band), and 2.06 μm

78 (strong CO_2 absorption band). With the recorded spectra, many Optimal Estimation Method (OEM) full physics retrieval

79 algorithms have been developed and applied for XCO_2 retrievals (Boesche et al., 2009; Butz et al., 2009, 2011; O'Dell et al.,

80 2012; Reuter et al., 2010; Yang et al., 2015b; Yoshida et al., 2011, 2013). The Institute of Atmospheric Physics Carbon

81 Dioxide Retrieval Algorithm for Satellite Remote Sensing (IAPCAS) algorithm has been applied for TanSat retrieval (Yang

82 et al., 2018; Yang et al., 2021) and was also previously tested on GOSAT and OCO-2 missions (Yang et al., 2015b).

83 However, the fluorescence feature causes substantial biases when retrieving surface pressure and scattering parameters from

84 the O_2-A band, and the associated errors propagate into the XCO_2 retrievals. In previous XCO_2 retrieval, the surface

85 emissions were well modeled as a continuum zero offset of the O_2-A band to reduce errors (Frankenberg et al., 2011a, 2012;

86 Butz et al., 2009, 2010; Joiner et al., 2012). The high spectral resolution of ~0.044 nm and a signal-to-noise ratio of ~360 in

87 the O_2-A band makes it possible to obtain SIF from space measurements, with a spatial resolution of 2 km × 2 km in nadir

88 mode (Liu et al., 2018).

89 Various approaches have been used to infer SIF from satellite measurements (Frankenberg et al., 2011b, 2014a, 2014b;

90 Guanter et al., 2007, 2012, 2015; Joiner et al., 2011, 2013, 2016; Köhler et al., 2015, 2018b). The SIF signal induces a

91 filling-in effect of solar lines, which can be used for SIF retrieval, as the fractional depth of solar Fraunhofer lines does not

92 change during radiation transmission in the atmosphere. To recognize the filling-in features by SIF, high-resolution spectra

93 and an instrument spectral response function (ISRF) are required to describe subtle changes in the spectral absorption lines.

94 With the detailed spectral features, a method was developed based on solar line fitting and the Beer-Lambertian law. This

95 method is robust and accurate when the spectrum is out of the influence of telluric absorptions, even in the presence of

96 aerosols (Frankenberg et al., 2011a; Joiner et al., 2011); in the current study, this method was applied to develop the

97 IAPCAS/SIF algorithm. Another SIF retrieval method is the data-driven algorithm based on the singular value

98 decomposition (SVD) technique (Joiner et al., 2011; Guanter et al., 2012), which has been broadly applied in GOSAT, OCO-

99 2, TanSat and TROPOMI SIF retrieval (Joiner et al., 2011; Guanter et al., 2012, 2015; Frankenberg et al., 2014a; Du et al.,

100 2018; Köhler et al., 2018b). In the data-driven method, the spectrum is represented as a linear combination of the SIF signal

101 and several singular vectors that are trained from non-fluorescent scenes by SVD; thus, the SIF signal can be obtained with

102   linear least-squares fitting (Du et al., 2018; Guanter et al., 2012). The first TanSat SIF map was obtained by the SVD

103   method (Du et al., 2018). In a previous study, a new TanSat SIF product retrieved by IAPCAS/SIF algorithm was introduced

104   and the two kinds of TanSat SIF product by IAPCAS/SIF and SVD methods were compared. The preliminary comparison

105   between the two TanSat SIF products shows that the two SIF products share a similar global pattern and signal magnitude

106   for all seasons while different biases still exist in four seasons (Yao et al., 2021). The different biases in four seasons may be

107   caused by the different training samples of the SVD method, which indicates that the training samples have a significant

108   impact on the retrieval results. In order to obtain stable SIF data products from TanSat and other subsequent satellite

109   missions, it is particularly important to establish a stable and high-precision SIF inversion algorithm. To detailed validate the

110   IAPCAS/SIF algorithm and test the potential of comprehensive usage of multi-satellites SIF data in analysis, in this study,

111   we detailed the TanSat SIF retrieval using the IAPCAS/SIF algorithm and made a comparison of SIF products between

112   TanSat and OCO-2 in variety of temporal-spatial scales, although a preliminary test was shown in previous work.

113   **2 Data and retrieval algorithm**

114   **2.1 Retrieval Principle and Method**

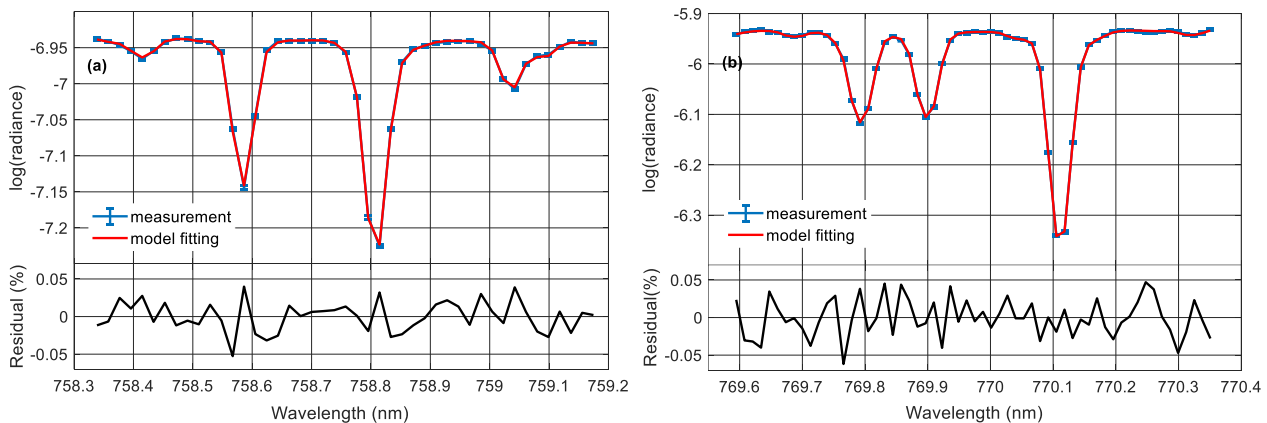
115   We used TanSat version 2 Level 1B (L1B) nadir-mode earth observation data in the retrieval process. The measurements

116   covered the period from March 2017 to February 2018. Polarized radiance in the O_2-A band with a spectral resolution of

117   0.044 nm was provided in the L1B data, and two micro-windows near 757 nm (758.3-759.2 nm) and 771 nm (769.6-770.3

118   nm) were chosen to retrieve the top-of-atmosphere (TOA) SIF while avoiding the contamination from strong lines of

119   atmospheric gas absorption. The retrieval was independent for each micro-window as shown in Figure 1. To avoid

120   duplication of information, we use the SIF product at 757 nm as the example in the analysis.

121

122   **Figure 1: The fitted spectra and residuals for the (a) 757 nm and (b) 771 nm micro-windows of TanSat measurement. The error**

123   **bar of the measured spectra depicts the estimated precision of each TanSat sounding.**

124

125 Filling-in on solar lines by chlorophyll fluorescence in the O_2-A band can be detected in the hyperspectral measurements

126 from TanSat. This effect on spectral radiance is different from the impact of atmospheric and surface processes, e.g.,

127 scattering and absorption. For example, scattering by aerosols and clouds does not change the relative depth of clear solar

128 lines, unlike the SIF emission signal. We applied the differential optical absorption spectroscopy (DOAS) technique to

129 IAPCAS/SIF algorithm for TanSat measurement (Frankenberg, 2014b; Sun et al., 2018).

130 The TOA spectral radiance (L_{TOA}^λ) at wavelength λ can be represented as follows:

131 $L_{TOA}^\lambda = I_t^\lambda \cdot \mu_0 \cdot (\rho_0^\lambda + \frac{\rho_s^\lambda \cdot T_\downarrow^\lambda \cdot T_\uparrow^\lambda}{\pi}) + F_{TOA}^\lambda$ (1)

132 where I_t^λ is the incident solar irradiance at the TOA, μ_0 is the cosine of the solar zenith angle (SZA), ρ_0^λ is atmospheric path

133 reflectance, ρ_s^λ is surface reflectance, and $T_\downarrow^\lambda$ and $T_\uparrow^\lambda$ are the total atmospheric transmittances along the light-path in the

134 downstream and upstream directions, respectively. F_{TOA}^λ is the SIF radiance at TOA.

135 The first term on the right of Eq. (1) represents the transmission process of solar radiance. In the micro-windows used in SIF

136 retrieval, gas absorption is very weak and smooth, and hence, the atmosphere term $\mu_0 \cdot (\rho_0^\lambda + \frac{\rho_s^\lambda \cdot T_\downarrow^\lambda \cdot T_\uparrow^\lambda}{\pi})$ can be simplified to a

137 low-order polynomial that varies with λ (Joiner et al., 2013; Sun et al., 2018); this is always valid as long as the spectrum

138 fitting range is out of sharp atmospheric absorptions. In the retrieval, the spectral radiance measurement was converted to

139 logarithmic space by the instrument and the radiative transfer process $f(F_s^{rel}, \boldsymbol{a})$ was represented as follows:

140 $f(F_s^{rel}, \boldsymbol{a}) = log(< I_t + F_s^{rel} >) + \sum_{i=0}^{n} a_i \cdot \lambda^i$ (2)

141 where $< >$ denote the convolution with the ISRF from line-by-line spectra. The polynomial coefficient $\boldsymbol{a}$ determines the

142 wavelength dependence polynomial for the atmosphere term; in the retrieval, we used a second-order polynomial ($n = 2$).

143 The radiance is normalized to the continuum level; hence, I_t is a normalized disk-integrated solar transmission model, and

144 F_s^{rel} is the normalized relative SIF. In the micro-window, SIF was regarded as a constant signal due to its small changes.

145 Although the atmospheric gas absorption was very weak in the micro-window, the weak absorption and the far-wing effects

146 (O_2 lines) can still change spectral features, which induces errors in spectrum fitting. In other physical-based retrievals, the

147 surface pressure data of the European Centre for Medium-Range Weather Forecasts (ECMWF) is usually used as the true

148 surface pressure to simulate the molecular absorption cross-section. However, there is still a difference between the true

149 surface pressure and the model surface pressure, so we introduced a factor here to reduce the influent of the inaccurate

150 surface pressure. In IAPCAS/SIF algorithm, we used the ECMWF interim surface pressure ($0.75° \times 0.75°$) to estimate O_2

151 absorption firstly and then modified the absorption feature by a scale factor. The scale factor is obtained simultaneously in

152 SIF retrieval to reduce the error induced by the uncertainty in surface pressure. As described by Yang (2020), there is also a

153 continuum feature in TanSat L1B data that needs to be considered for the high-quality fitting of the O_2-A band. However, in

154 this study, this continuum feature was not corrected, as the impact of such a smooth continuum variation in the micro-

155 window is weak and the polynomial continuum model is capable of compensating for most of this effect.

156 The state vector list in the retrieval includes the relative SIF signal F_s^{rel}, a wavenumber shift, the scale of O_2 column

157 absorption for surface pressure correction, and coefficients of the polynomial. The continuum level radiance I_{cont} within the

158 fitting window is calculated using the radiance outside the absorption features in the micro-window and is then used for the

159 actual SIF signal calculation thus: $F = F_s^{rel} \cdot I_{cont}$.

160 In the IAPCAS/SIF algorithm, we used an OEM for state vector optimization in the retrieval process. Unlike XCO$_2$ retrieval,

161 SIF retrieval employs a state vector with fewer elements and a much simpler forward model, so there is no need to perform

162 complex radiation transmission calculations. Considering the low complexity of SIF retrieval, the Gauss-Newton method

163 was applied in inversion iteratively to find the optimal solution.

2.2 Bias Corrections

165 A systematic error remains in the raw SIF retrieval output if no bias correction is performed; similar results have been

166 reported in GOSAT and OCO-2 SIF retrieval studies (Frankenberg et al., 2011a, 2011b; Sun et al., 2018). This is because the

167 SIF signal is weak (e.g., typically ~1-2% of the continuum level radiance), which means that even a small issue in the

168 measurement, such as a zero-offset caused by radiometric calibration error, could induce significant bias. Unfortunately, the

169 lack of knowledge on in-flight instrument performance makes it difficult to perform a direct systematic bias correction in the

170 measured spectrum. In the retrieval, a continuum level radiance bin fit was used to estimate the bias. The bins have a

171 continuum level radiance interval of 5 W m^{-2} µm^{-1} sr^{-1}. In each bin, the mean bias was estimated using all non-fluorescence

172 measurements, and a piecewise linear function was built from the mean bias of each continuum level radiance interval.

173 The non-fluorescence soundings that were used in the bias estimation were based on the dataset "sounding_landCover" in

174 TanSat L1B data. This dataset depends on the MODIS land cover product and provides a scheme consisting of 17 land cover

175 classifications defined by the International Geosphere-Biosphere Programme. These retrieved measurements marked as

176 "snow and ice," "barren," and "sparsely vegetated" were chosen to estimate the bias. Calibrations compensated for most of

177 the instrument degradations, but this alone was not perfect. To reduce the impact from the remaining minor discrepancies,

178 we built the bias correction function daily to obtain bias for each sounding via interpolation of the continuum level radiance

179 (Sun et al., 2017b, 2018).

180 The bias curves shown in Figure 2 differ significantly between TanSat and OCO-2. This is mostly due to the differences in

181 instrument performance and radiometric calibration. In general, the TanSat bias curves exhibited two peaks at radiance levels

182 of approximately 40 and 125 W m^{-2} µm^{-1} sr^{-1}, separately, and most biases were larger than 0.015. For OCO-2, the curves

183 dropped sharply at low radiance levels, reaching the valley at a radiance level of approximately 40 W m^{-2} µm^{-1} sr^{-1}, and then

184 increased slowly with the radiance level.

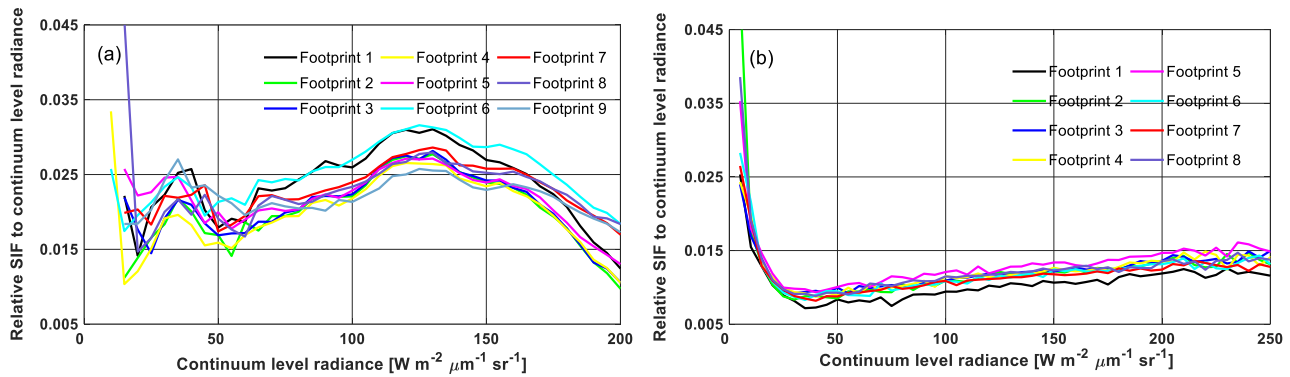



Figure 2: Variations in the bias correction curves of continuum level radiance from (a) TanSat on July 7, 2017, and (b) Orbiting Carbon Observatory-2 (OCO-2) on June 16, 2017. The different colors in the legend present different footprints of the satellite frame.

2.3 Data Quality Controls

Only data that passed quality control were used in further applications. There were two data quality control processes for the SIF products: pre-screening and post-screening. Pre-screening focused mainly on cloud screening; only cloud-free measurements were used in SIF retrieval. A surface pressure difference (SPD), defined as:

$$\Delta P_0 = |P_{retrieval} - P_{ECMWF}| \tag{3}$$

was used to evaluate cloud contamination along with a chi-square test

$$\chi^2 = \sum \frac{(y_{sim} - y_{obs})^2}{y_{noise}^2} \tag{4}$$

where y_{sim}, y_{obs}, and y_{noise} represent the model fitting spectrum, observation spectrum, and spectrum noise, respectively. $P_{retrieval}$ is the apparent surface pressure obtained from O_2-A band surface pressure retrieval, assuming a single scattering atmosphere. P_{ECMWF} is the ECMWF interim (0.75° × 0.75°) surface pressure. A "cloud-free" measurement was required to simultaneously satisfy an SPD of less than 20 hPa and a χ^2 value of less than 80. Here, post-screening was applied to filter out "bad" retrievals; this screening process involved the following steps: (1) SIF retrievals with reduced χ^2 (χ^2_{red}) values ranging from 0.7 to 1.3 were considered "good" fitting, (2) continuum level radiance outside the range of 15 ~ 200 W m^{-2} μm^{-1} sr^{-1} was screened out to avoid scenes too bright or too dark, and (3) soundings with the SZA higher than 60° were also filtered out.

2.4 IAPCAS versus IMAP-DOAS OCO-2 SIF Retrieval

Before applied to TanSat retrievals, we tested the IAPCAS/SIF algorithm on the OCO-2 L1B data first (OCO2_L1B_Science.8r) and then compared the retrieval results with the OCO-2 L2 Lite SIF product (OCO2_Level 2_Lite_SIF.8r) retrieved by the Iterative Maximum A Posteriori-Differential Optical Absorption Spectroscopy (IMAP-DOAS) algorithm (Frankenberg, 2014b). The Lite product provides the SIF value for each sounding on a daily basis and hence the SIF comparison could be performed on the sounding scale for each month.

Table 1 displays the relationship of OCO-2 SIF values between the IAPCAS/SIF and IMAP-DOAS at 757 nm micro-window. Overall, the two SIF products were in good agreement. The linear fitting of the two SIF products suggests that they are highly correlated, as indicated by the strong linear relationship with R^2 mostly larger than 0.85 and the root mean square error (RMSE) of about 0.2 W m^{-2} μm^{-1} sr^{-1}. Good consistency between the two SIF products implies the reliability of the IAPCAS/SIF algorithm; thus, it was further applied to TanSat SIF retrieval. However, there was still a small bias in the comparisons, which was due, most likely, to the impact of differences in the bias correction method, retrieval algorithm, and fitting window.

Table 1: Summary of the relationship between the Institute of Atmospheric Physics Carbon Dioxide Retrieval Algorithm for Satellite Remote Sensing (IAPCAS) OCO-2 and Iterative Maximum A Posteriori-Differential Optical Absorption Spectroscopy (IMAP-DOAS) OCO-2 solar-induced chlorophyll fluorescence (SIF) products at 757nm micro-window.

month	Number of soundings	Slope	Intercept	R^2	RMSE/ W m^{-2} μm^{-1} sr^{-1}
2017/03	1097277	0.85	0.034	0.86	0.18
2017/04	1119464	0.86	0.045	0.87	0.19
2017/05	1054235	0.88	0.041	0.88	0.19
2017/06	1014848	0.91	0.032	0.90	0.19
2017/07	965309	0.92	0.011	0.91	0.19
2017/09	211219	0.88	0.005	0.81	0.23
2017/10	473359	0.88	0.031	0.88	0.17
2017/11	579009	0.87	0.022	0.85	0.19
2017/12	645134	0.87	0.020	0.88	0.16
2018/01	788655	0.87	0.019	0.88	0.17
2018/02*	629995	0.86	0.024	0.87	0.18

* Due to the lack of OCO-2 measurements in August 2017, the comparison is only performed for 11 months.

3 Results and Discussion

3.1 Comparison between TanSat and OCO-2 SIF Measurements

The comparison between TanSat and OCO-2 SIF Measurements is a useful and powerful method for further verification of the IAPCAS/SIF algorithm. The reason for adopting OCO-2 data is that OCO-2 and TanSat have similar observation modes, including scanning method, transit time, spatial resolution, spectral resolution, and spectral range. The similarities mean that the SIF product from the two satellite missions can be directly compared. Directly comparing OCO-2 and TanSat SIF measurements could provide information on joint data application at the sounding scale for further studies. However, an identical sounding overlap barely exists because the two satellites often have different nadir tracks on the ground, which is induced by the different temporal and spatial intervals of the two satellite missions. Fortunately, the ground tracks of the two satellites were relatively close from April 17 to April 23, 2017. A couple of overlapping orbits were found in the measurements obtained from Africa with the orbit number of 1733 from TanSat and 14890a from OCO-2 (Figure 3). In the

232 comparison, the OCO2_Level 2_Lite_SIF.8r product was used to present the SIF emission over the study area. These

233 overlapping measurements encompassed multiple land cover types, in which the SIF varied within an acceptable time

234 difference (<5 min).

235 Overall, measurements from the two satellites indicated SIF variation with land cover type. The SIF emission over evergreen

236 broadleaf forests was larger than that over savannas, and grasslands exhibited the lowest SIF emission in April (Figure 3a,b).

237 The mean SIF emission over evergreen broadleaf forests was approximately 0.9-1.1 W m^{-2} μm^{-1} sr^{-1}, whereas those over

238 savannas and grasslands were 0.5-0.7 W m^{-2} μm^{-1} sr^{-1} and less than 0.1 W m^{-2} μm^{-1} sr^{-1}, respectively (Figure 3c,d).

239 Furthermore, we also found a significant difference in the SIF emission intensity over tropical savannas, which was observed

240 by both satellites (Figure 3c,d).

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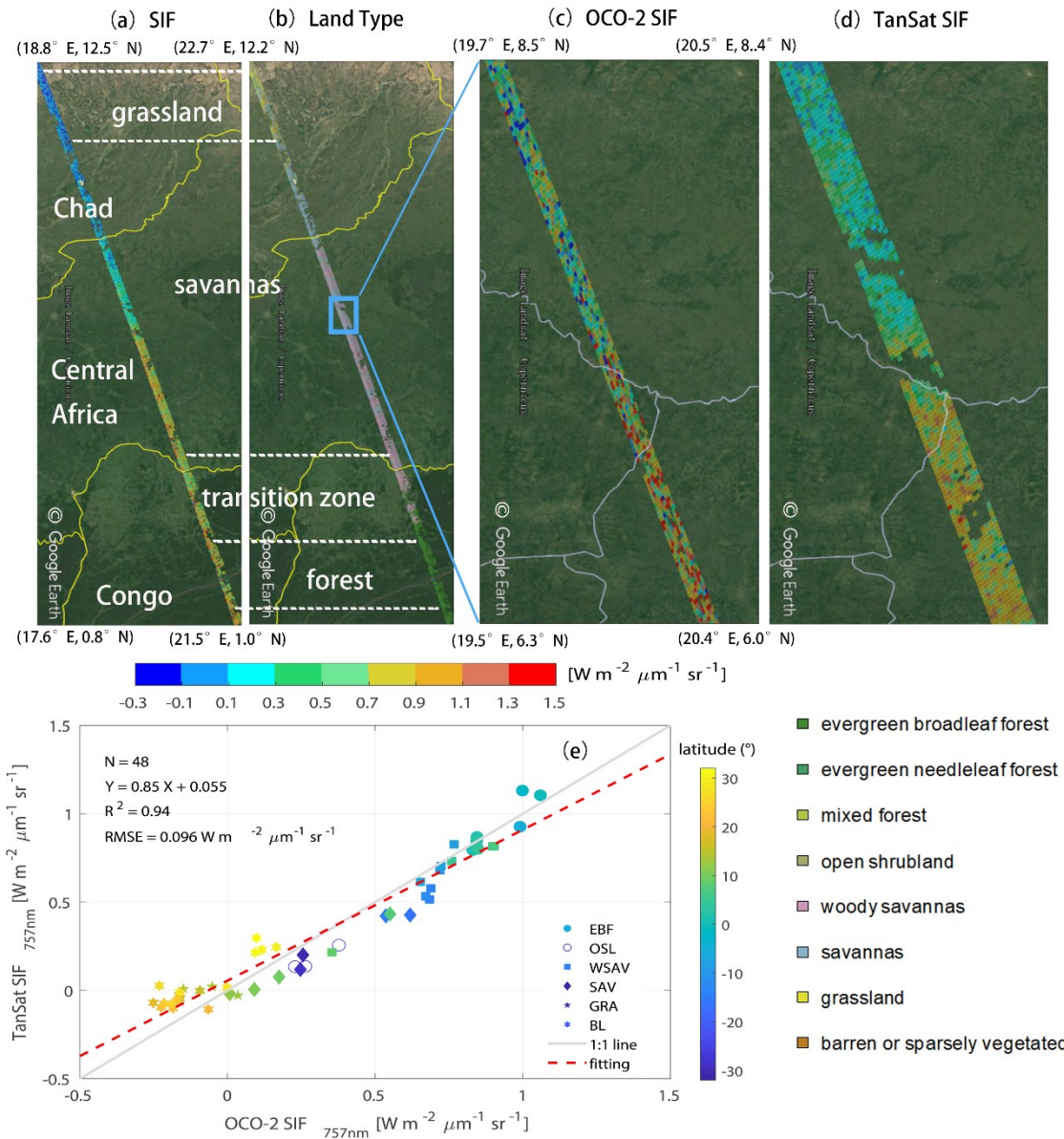
Figure 3: Overlapping orbits of TanSat and OCO-2 on April 19, 2017 over Africa displayed in Google Earth, (a) the SIF measurements from both the two satellites and (b) the footprint land cover type were compared. Compared to OCO-2, TanSat has a wider swath width. A zoom-in view over savannas shows variations in the SIF signal measured by (c) OCO-2 and (d) TanSat. The land surface image shown in Google earth is provided by Landsat/Copernicus team. Following the International Geosphere-Biosphere Programme classification scheme, the vertical legend on the bottom right corner depicts the land cover type that occurs in the study area. The middle horizontal color bar represents the intensity of the SIF radiance. (e) Small-area SIF comparison between OCO-2 and TanSat; each data point represents the mean SIF of a degree in latitude (colors) along the track. The marker legend that is shown on the bottom right of the plot indicates the dominant land cover (defined as the majority land cover type of each sounding) in each small area. There are six land cover types including evergreen broadleaf forest (EBF), open shrubland (OSL), woody savanna (WSAV), savanna (SAV), grassland (GRA), and barren land (BL). The red dashed line represents the linear fit between the two SIF products with statistics shown in the upper left of the plot. The gray line indicates a 1:1 relationship for reference.

256

257 Because the footprint sizes of the two satellites are different, it is difficult to make a direct footprint-to-footprint comparison.

258 Therefore, we made the comparison between the two satellite measurements based on a small area average. Each small area

259 spans a degree in latitude and continues along the track. The small area-averaged SIF comparison is shown in Figure 3e. The

260 results indicate good agreement, with an R^2 of 0.94 and an RMSE of 0.096 W m^{-2} μm^{-1} sr^{-1}. Additional ground-based SIF

261 measurement setups (Guanter et al., 2007; Liu et al., 2019; van der Tol et al., 2016; Yang et al., 2015a; Yu et al., 2019)

262 should allow for direct evaluation of satellite retrieval accuracy in the future.

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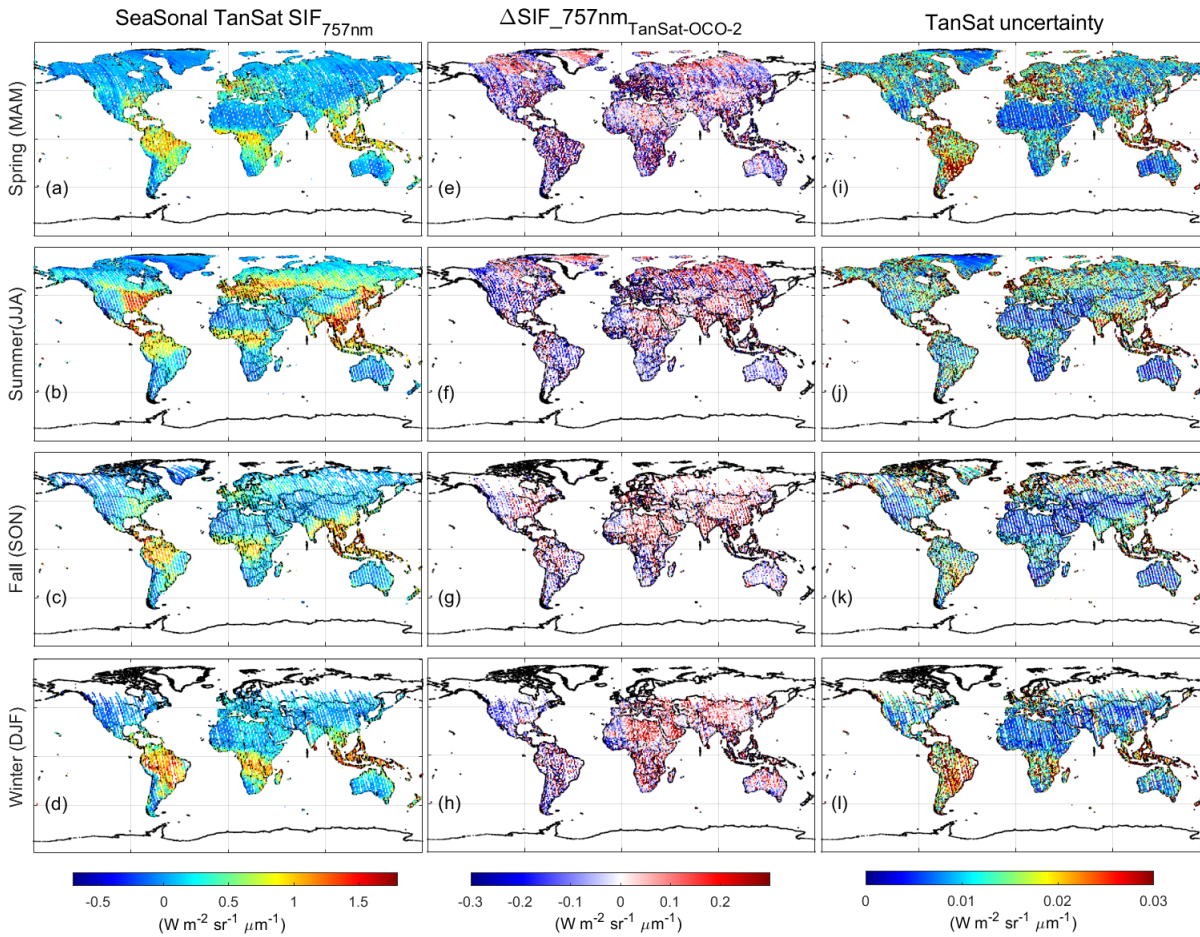
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265 **Figure 4: Global TanSat SIF (left, a-d), differences between TanSat and IAPCAS OCO-2 SIF values (middle, e-h), and the grid-**
266 **cell retrieval uncertainty estimated from TanSat (right, i-l) at 1° × 1° spatial resolution. The maps in each row represent a**
267 **Northern Hemisphere season, i.e., spring (MAM), summer (JJA), fall (SON), and winter (DJF).**

268

269 Figure 4 shows the global SIF comparison between IAPCAS/SIF retrieved OCO-2 and TanSat; this comparison is only
270 performed at $1° \times 1°$ spatial resolution. In general, the difference in SIF globally is mostly less than 0.3 W m^{-2} μm^{-1} sr^{-1} for
271 all seasons, and on average, the smallest difference appears in fall. There are regional biases observed in North Africa, South
272 Africa, South America, and Europe in all seasons except fall. This is mainly caused by the differences in instrument
273 performance between TanSat and OCO-2, such as the Instrument Respond Function and the Signal-to-Noise. The instrument
274 performance difference is represented by the different structural characteristics of the bias curves. The bias correction
275 compensates for most of the bias caused by instrument performance; however, small biases could remain. Furthermore, the
276 hundreds of kilometers of distance between the OCO-2 and TanSat footprints, for example, over different vegetation regions,
277 will also cause some measurement discrepancies. The global distribution of the two satellites was also compared with the
278 official OCO-2 SIF data on the global scale, the results show that the difference between the retrieved SIF maps and the
279 official map is less than 0.2 W m^{-2} μm^{-1} sr^{-1}, indicating that the retrieved SIF data from OCO-2 and TanSat both have good
280 SIF characterization capabilities on a global scale. The uncertainty σ of each sounding was estimated to validate SIF
281 reliability and is provided in the product. σ is derived from the retrieval error covariance matrix, $S_e = (K^T S_0^{-1} K)^{-1}$, where K
282 is the Jacobian matrix from the forward model fitting and S_0 is the measurement error covariance matrix that is calculated
283 from the instrument spectrum noise. In general, σ ranges from 0.1 to 0.6 W m^{-2} μm^{-1} sr^{-1} for both TanSat and OCO-2
284 measurements in the 757 nm fitting window, which is of a similar magnitude and data range as those of previous studies (Du
285 et al., 2018; Frankenberg et al., 2014a). Meanwhile, the standard error of the mean SIF in each grid $σ_{meas}$ was estimated to
286 represent the gridded retrieval error and natural variability, which is calculated from TanSat SIF values with $σ_{meas} = \frac{σ_{std}}{\sqrt{n}}$

287 and $σ_{std} = \sqrt{\frac{\sum_{i=1}^{n}(SIF_i - \overline{SIF})^2}{n}}$, where $σ_{std}$ represents the standard deviation of the grid cell with n soundings, SIF_i is the
288 retrieved SIF values of each sounding, and $\overline{SIF}$ is the mean SIF value for all measurements in the grid. As depicted in the
289 right column of Figure 4, the $σ_{meas}$ of each grid cell is much lower than the precision of a single sounding. The $σ_{meas}$ for
290 South America is larger than that for any other region on the globe (Figure 4i-l). This is similar to that of OCO-2 SIF
291 retrieval and caused by fewer effective measurements due to the South Atlantic Anomaly (Sun et al., 2018). The difference
292 in SIF emission values between the two satellites indicates that the collaborative usage of two satellite SIF products still
293 requires analysis of the impact of instrument differences, although the two satellite SIF products share the same
294 spatiotemporal pattern on a global scale.

3.2 SIF Global Distribution and Temporal Variation

296 The SIF emission intensity reflects the growth status of vegetation due to its correlation with photosynthetic efficiency;
297 hence, the overall global vegetation status can be represented by global SIF maps for each season. TanSat SIF over a whole
298 year's cycle, from March 2017 to February 2018, is represented seasonally as a $1° \times 1°$ grid spatially. The seasonal variation

299 in SIF emission is clear in the Northern Hemisphere, i.e., it is enhanced from spring to summer and then decreases (Sun et al.,

300 2018).

301 In general, the SIF emission varied with latitude and the vegetation-covered areas near the equator maintained a continuous

302 SIF emission throughout the year. Large SIF emissions in the Northern Hemisphere, above 1.5 W m^{-2} μm^{-1} sr^{-1}, mostly from

303 the eastern U.S., southeast of China, and southern Asia in summer, were due to the large areas of cropland. There was also

304 an obvious SIF emission of 1-1.2 W m^{-2} μm^{-1} sr^{-1} observed over Central Europe and northeastern China during the summer.

305 In these regions, croplands and deciduous forests contribute to SIF emissions. In the Southern Hemisphere, the strongest SIF

306 emission occurred in the Amazon, with a level of approximately 1-2 W m^{-2} μm^{-1} sr^{-1} in DJF (Northern Hemisphere winter),

307 where there is an evergreen broadleaf rainforest. Africa, which is covered by evergreen broadleaf rainforests and woody

308 savannas, had an average SIF value of 0.7-1.5 W m^{-2} μm^{-1} sr^{-1} during the year.

309 The SIF-GPP relationship over different vegetation types was also investigated by comparing the annual mean satellite SIF

310 measurements with the FLUXCOM GPP (Jung et al., 2020; Tramontana et al., 2016) dataset in a 1° × 1° grid over the globe.

311 The FLUXCOM GPP dataset used in the study comprises monthly global gridded flux products with remote sensing and

312 meteorological/climate forcing (RS+METEO) setups, which are derived from mean seasonal cycles according to MODIS

313 data and daily meteorological information (Jung et al., 2020; Tramontana et al., 2016). In the correlation analysis, the high

314 spatial resolution (0.5°× 0.5°) of the FLUXCOM GPP was first resampled to 1°× 1° to keep the same temporal-spatial scale

315 of SIF and GPP data. The satellite-measured SIF is an instantaneous emission signal that varies with incident solar radiance

316 within the day. To reduce the differences caused by the observation time and SZA at different latitudes, we applied a daily

317 adjustment factor to convert the instantaneous SIF emission into a daily mean SIF (Du et al., 2018; Frankenberg et al., 2011b;

318 Sun et al., 2018). The daily adjustment factor d is calculated as follows:

319 $$d = \frac{\int_{t=t_0-12h}^{t=t_0+12h} cos\,(SZA(t)) \cdot dt}{cos(SZA(t_0))} \tag{5}$$

320 where t_0 is the observation time in fractional days and $SZA(t)$ is a function of latitude, longitude, and time for calculating

321 the SZA of the measurements. The annual averaged SIF is calculated from the daily mean SIF. To evaluate the relationship

322 between SIF and GPP on the periodic scale of vegetation growth status, annually-averaged data were used in the regression

323 fitting analysis.

324
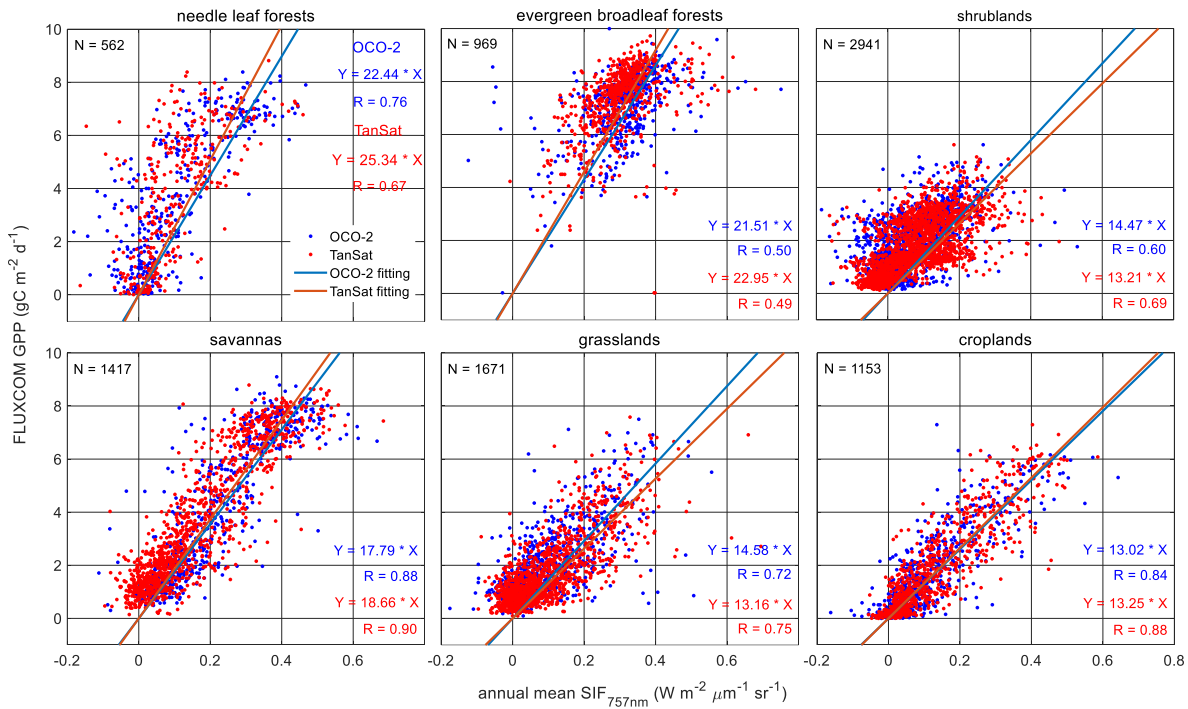
Figure 5: Relationship between annual mean SIF and FLUXCOM gross primary production (GPP) from March 2017 to February 2018. Blue and red dots represent OCO-2 and TanSat SIF grids, respectively. Fitted lines and statistics for OCO-2 and TanSat are shown in each plot.

Figure 5 shows the linear fits for six vegetation types, including needle leaf forest, evergreen broadleaf forest, shrubland, savanna, grassland, and cropland. Recent studies have shown a strong linear correlation between SIF and GPP. The TanSat SIF and the OCO-2 official SIF data were used to estimate the SIF-GPP correlation. To make a direct comparison of the relationship between SIF and GPP among various vegetation types, we used non-offset linear fitting to indicate the correlation between satellite SIF and FLUXCOM GPP. For savanna and cropland, there were strong relationships between the mean SIF and GPP with an R-value above 0.84. The fitting results show that the SIF products of the two satellites have similar capabilities in characterizing GPP, especially for the evergreen broadleaf forest, savanna, and cropland, with slopes of approximately 21, 18, and 13, respectively. For shrubland and grassland, the slope of OCO-2 SIF with GPP is higher than that of TanSat and has a worse correlation. For forests, OCO-2 SIF presents a better correlation with GPP, especially in the needle leaf forest. As a whole, for the same vegetation type, the SIF-GPP correlations for the two satellites are rather similar, indicating that the two satellite SIF products have similar capabilities in characterizing GPP. It shows the strong feasibility of the comprehensive application of different satellite SIF products. For different vegetation types, the SIF-GPP correlations were significantly different, indicating the different ability of SIF to characterize GPP of different vegetation. It represents that vegetation type is a key factor in determining the SIF-GPP relationship. The markedly different fitting slopes across various biomes suggest that the application of SIF in GPP estimation needs more detailed analysis although the evidence of the strong linear relationship between them.

4 Conclusions

In this paper, we introduced the retrieval algorithm IAPCAS/SIF and its application in TanSat and OCO-2 measurements. One-year (March 2017-February 2018) TanSat SIF data was introduced and compared with OCO-2 measurements in this study. The TanSat and OCO-2 SIF products based on the IAPCAS/SIF algorithm are available on the Cooperation on the Analysis of carbon SAtellites data (CASA) website, www.chinageoss.org/tansat. Comparisons between TanSat and OCO-2 measurements directly, using a case study, and indirectly, with global 1°×1° grid data, showed consistency between the two satellite missions, indicating that the coordinated usage of the two data products is possible in future studies. The correlation analysis between SIF and GPP further verified the feasibility of the comprehensive application of SIF products from different satellite missions. Meanwhile, it should be noticed that the difference in the ability of satellite SIF products to characterize different vegetation types in data applications. With increasing satellites becoming available for SIF observations, space-based SIF observations have recently expanded in range to provide broad spatiotemporal coverage. The next-generation Chinese carbon monitoring satellite (TanSat-2) is now in the preliminary design phase, which is designed to be a constellation of six satellites to measure different kinds of greenhouse gases and trace gases in a more efficient way, including CO_2,CH_4, CO, NOx, as well as SIF. SIF measurements from TanSat-2 will provide global data products over broader coverage areas with less noise. The improvement in the spatiotemporal resolution of SIF data will benefit GPP predictions based on the numerous studies of the linear relationship between SIF and GPP. In future work, the measurement accuracy should be validated directly using ground-based measurements to ensure data quality.

Data availability

The SIF products of TanSat and OCO-2 by IAPCAS/SIF algorithm are available on the Cooperation on the Analysis of carbon SAtellites data (CASA) website (www.chinageoss.org/tansat).

Author contributions

L.Y. and D.Y. developed the retrieval algorithm, designed the study, and wrote the paper. Y.L. led the SIF data process and analysis. Y.L., D.Y., Z.C., and J.W. contributed to manuscript organization and revision. C.L. and Y.Z. provided information on the TanSat instrument performance. L.T. provided TanSat in-flight information. M.W. and S.W. provided information on the scientific requirement for data further application. N.L. and D.L. led the TanSat data application. Z.Y. led the TanSat in-flight operation.

Competing interests

The authors declare that they have no conflict of interest.

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