Observing a Volatile Organic Compound from a Geostationary Infrared Sounder: HCOOH from FengYun-4B/GIIRS

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April 26, 2024

Abstract

Formic acid (HCOOH) is one of the most abundant volatile organic compounds (VOCs) in the Earth's atmosphere and an important source of atmospheric acidity. Here we present the first retrieval of HCOOH from a geostationary orbit using observations from the Geostationary Interferometric Infrared Sounder (GIIRS) on board FengYun-4B. The results from July 2022 to June 2023 show the monthly variation of the HCOOH distribution in Asia due to emissions from biomass burning and biogenic sources. FY-4B/GIIRS effectively tracks HCOOH enhancements from wildfires and biogenic sources both during the day and at night. Finally, cross-comparison with IASI HCOOH data shows good agreement, indicating that FY-4B/GIIRS observations have comparable sensitivity to IASI. This study is an important first step towards monitoring VOCs from geostationary infrared sounders, including the existing and future GIIRS on board the FY-4 series and the forthcoming European geostationary infrared sounder (IRS) on board Meteosat Third Generation (MTG).

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13 Key Points:

- First retrieval of atmospheric HCOOH from a geostationary sounder is demonstrated
- HCOOH in fire plumes can be continuously tracked with FY-4B/GIIRS
- FY-4B/GIIRS HCOOH observations have comparable sensitivity to IASI

17 Abstract

18 Formic acid (HCOOH) is one of the most abundant volatile organic compounds (VOCs) in the 19 Earth's atmosphere and an important source of atmospheric acidity. Here we present the first 20 retrieval of HCOOH from a geostationary orbit using observations from the Geostationary 21 Interferometric Infrared Sounder (GIIRS) on board FengYun-4B. The results from July 2022 to 22 June 2023 show the monthly variation of the HCOOH distribution in Asia due to emissions from 23 biomass burning and biogenic sources. FY-4B/GIIRS effectively tracks HCOOH enhancements 24 from wildfires and biogenic sources both during the day and at night. Finally, inter-comparison 25 with IASI HCOOH data shows good agreement, indicating that FY-4B/GIIRS observations have 26 comparable sensitivity to IASI. This study is an important first step towards monitoring VOCs 27 from geostationary infrared sounders, including the existing and future GIIRS on board the FY-4 28 series and the forthcoming European geostationary infrared sounder (IRS) on board Meteosat 29 Third Generation (MTG).

30

31 Plain Language Summary

32 Formic acid (HCOOH) is one of the most abundant volatile organic compounds (VOCs) in the 33 Earth's atmosphere and an important source of atmospheric acidity. Satellite observations play an 34 indispensable role in improving our understanding of global HCOOH sources and sinks. However, 35 existing polar-orbiting satellites that are sensitive to tropospheric HCOOH only provide up to two 36 overpasses per day over the same spot, one during the day and one during the night. The diurnal 37 variations of tropospheric HCOOH are therefore under-constrained to track its evolution in the 38 lower troposphere and transport in the free troposphere. The Geostationary Interferometric 39 Infrared Sounder (GIIRS) onboard China's FengYun-4 satellite series is the world's first 40 geostationary hyperspectral infrared sounder. Using observations from FY-4B/GIIRS, this study 41 presents the first retrieval of HCOOH from a geostationary satellite instrument that captures the 42 HCOOH variation in Asia driven by biomass burning emissions and biogenic sources. In addition, 43 FY-4B/GIIRS effectively tracks HCOOH plumes in Southeast Asia and Siberia. Finally, inter-44 comparison with IASI HCOOH data shows good agreement, indicating that FY-4B/GIIRS 45 observations have comparable sensitivity to IASI. This study is an important first step towards 46 monitoring VOCs from geostationary infrared sounders.

47 1 Introduction

48 Formic acid (HCOOH) is one of the most abundant volatile organic compounds (VOCs) in 49 the Earth's atmosphere and an important source of atmospheric acidity. It contributes significantly 50 to precipitation acidity by facilitating the nucleation of cloud droplets (e.g., Andreae et al., 1988; 51 Keene and Galloway, 1984; Keene and Galloway, 1988). The production of HCOOH in the 52 atmosphere is dominated by photochemical oxidation of biogenic and anthropogenic VOCs 53 (Millet et al., 2015) and direct emissions from vegetation (Keene and Galloway, 1984), biomass 54 and biofuel burning (Goode et al., 2000), and fossil fuel combustions (Kawamura et al., 1985). 55 Yet, advanced global models underestimate the observed atmospheric levels of HCOOH, pointing 56 to major gaps in our understanding of its emissions and formation mechanisms.

57 Over the past decade, studies have showcased the essential role of satellite observations in 58 enhancing our understanding of global sources and sinks of HCOOH. For instance, Stavrakou et 59 al. (2012) showed that a large source of HCOOH from boreal and tropical forests is misrepresented 60 in models based on satellite observations from the Infrared Atmospheric Sounding Interferometer 61 (IASI; Razavi et al., 2011). Using measurements from the same sounder, Franco et al. (2021) 62 proposed an HCOOH production mechanism in which formaldehyde is efficiently converted to 63 gaseous HCOOH via a multiphase pathway. In addition, it has been shown that the HCOOH 64 emissions from wildfires have been largely underestimated using satellite observations (e.g., 65 Cady-Pereira et al. 2014; Chaliyakunnel et al., 2016; Pommier et al., 2017).

66 Satellite observations of HCOOH provide global coverage from polar-orbiting nadir-67 looking infrared hyperspectral sounders including IASI (e.g., Razavi et al., 2011; Franco et al., 68 2018) and the Tropospheric Emission Spectrometer (TES) (e.g., Cady-Pereira et al., 2014). In 69 addition, solar occultations from the limb sounders Michelson Interferometer for Passive 70 Atmospheric Sounding (MIPAS) and Atmospheric Chemistry Experiment – Fourier Transform 71 Spectrometer (ACE-FTS) provide measurements of the HCOOH abundance in the upper 72 troposphere – lower stratosphere (e.g., González Abad et al., 2009; Grutter et al., 2010), 73 However, existing polar-orbiting satellites that are sensitive to tropospheric HCOOH can only 74 provide up to two overpasses per day over the same spot, with one in the daytime and the other in 75 the nighttime. The diurnal change of tropospheric HCOOH is therefore under-constrained. 76 Although it is relatively short-lived with a global tropospheric lifetime of 3-4 days (Paulot et al., 77 2011; Stavrakou et al., 2012), HCOOH produced or released into the free troposphere can be

transported over relatively long distances due to its slow photochemical loss (**Paulot et al., 2011**).

Hence, continuous high-temporal-resolution observations of HCOOH are required to track its
 evolution and to characterize its intra-day variability in the troposphere.

81 The Geostationary Interferometric Infrared Sounder (GIIRS) onboard China's FengYun-4 82 satellite series is the world's first geostationary hyperspectral infrared sounder primarily designed 83 to observe the three-dimensional distributions of atmospheric water vapor and temperature. GIIRS 84 on board FY-4B (FY-4B/GIIRS) was launched in 2021 with an improved signal-to-noise ratio 85 (SNR) compared to its predecessor FY-4A/GIIRS, launched in 2016 (Yang et al., 2017). The high 86 spectral resolution (~0.625 cm⁻¹) and SNR of FY-4B/GIIRS have enabled 2-hourly measurements 87 of carbon monoxide and ammonia over eastern Asia (Zeng et al., 2023a; Zeng et al., 2023b). 88 Applying the optimal estimation method (OEM) on the FY-4B/GIIRS spectra, this study aims to 89 assess for the first time the information content within spectra recorded by a geostationary sounder 90 for retrieving diurnal HCOOH over eastern Asia. Additionally, it investigates how geostationary 91 observations can aid in tracking the long-range transport of HCOOH in the free troposphere. The 92 rest of this paper is organized as follows. An introduction to FY-4B/GIIRS and the observed 93 spectra is given in Section 2, and the retrieval algorithm based on optimal estimation is presented 94 in Section 3. The results are shown in Section 4, followed by discussion and conclusions in 95 Section 5.

96 **2 FY-4B/GIIRS**

97 FY-4B/GIIRS is an infrared Fourier transform spectrometer located at an altitude of 98 ~36,000 km above the Equator at 133° E overlooking eastern Asia. FY-4B/GIIRS scans the full 99 region with a 2-hour measurement cycle. In total, 12 cycles are made per day starting at 0, 2, 4, ..., 100 22h UTC before September 06, 2022, and 1, 3, 5, ..., 23h UTC after. In the 2-hour measurement 101 cycle, scanning the full region takes about 1.5 hour, followed by external spectral calibration for 102 about 0.5 hour. At nadir, the spatial footprint on the Earth's surface has a diameter of about 12 km. 103 FY-4B/GIIRS covers a long-wave IR band (680-1130 cm⁻¹) and a mid-wave IR band (1650-2250 104 cm⁻¹) with a spectral resolution of 0.625 cm⁻¹. Blackbody calibration experiments (Li et al., 2022) 105 carried out before launch showed that the typical noise equivalent differential radiance (NedR) around the HCOOH absorption channel at 1105 cm⁻¹ (Figure 1(a)) is less than 0.3 mW/(m²·sr·cm⁻ 106 107 ¹), which is about 0.2K for a blackbody at 300K. Figure 1(b) shows examples of brightness

108 temperature changes in the micro-window for varying HCOOH abundances (1, 2, 4 and 8 times 109 the a priori used in the retrieval, see Section 3). In the latter three cases, the HCOOH spectral 110 signature exceeds the spectral noise level in FY-4B/GIIRS. A more detailed description of FY-111 4B/GIIRS can be found in Zeng et al. (2023b). Similar to Zeng et al. (2023a; 2023b), only clear-112 sky or near-clear-sky pixels are used for the retrieval. We adopted the level-2 cloud mask (CLM) 113 data product from the Advanced Geostationary Radiation Imager (AGRI) onboard FY-4B to filter 114 out cloudy pixels. After cloud filtering and excluding data with a satellite zenith angle larger than 115 70° , the number of observations available for an entire day is typically of approximately 100,000.

116 **3 Retrieval algorithm based on optimal estimation**

We apply the FengYun-Geostationary Atmospheric Infrared Retrieval (FY-GeoAIR) 117 118 algorithm, originally developed for carbon monoxide (Zeng et al., 2023a), for retrieving HCOOH 119 using FY-4B/GIIRS spectra. Here, a brief introduction to FY-GeoAIR is given with descriptions 120 of changes necessary for the HCOOH retrieval. More details about the retrieval algorithm can be 121 found in Zeng et al. (2023a) and Zeng et al. (2023b). Essentially, FY-GeoAIR consists of a 122 forward radiative transfer model (RTM) for simulating upwelling radiation in the thermal infrared 123 and an OEM-based inverse model for retrieving atmospheric parameters. In the forward RTM, the 124 upwelling radiance has four major components: the upwelling surface thermal emission, the 125 upwelling atmospheric thermal emissions, the surface-reflected downwelling atmospheric thermal 126 emission, and the solar radiation from surface reflection (Clough et al., 2006; Hurtmans et al., 127 **2012**). Under clear sky conditions, scattering by clouds and aerosols can be ignored. In the forward 128 model, surface parameters (surface skin temperature and surface pressure) and atmospheric 129 parameters (temperature, H₂O, and ozone profiles) are extracted from the European Centre for 130 Medium-Range Weather Forecasts (ECMWF) Reanalysis v5 (ERA5; Hersbach et al., 2020). The 131 a priori HCOOH profiles over land and ocean are adopted from an updated version of the IASI a 132 priori (Franco et al. 2018), as shown in Figure S1(a). The absorption coefficients for gas 133 absorption are pre-calculated as look-up tables based on the Line-By-Line Radiative Transfer 134 Model (LBLRTM v12.11; Clough et al., 2005). FY-GeoAIR retrieves the atmospheric layers 135 below 200 hPa. In the inverse model, the retrieval algorithm searches for a solution x that 136 minimizes the following cost function (Rodgers, 2000):

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$$J(\mathbf{x}) = [\mathbf{y} - \mathbf{F}(\mathbf{x}, \mathbf{b})]^T \mathbf{S}_{\varepsilon}^{-1} [\mathbf{y} - \mathbf{F}(\mathbf{x}, \mathbf{b})] + (\mathbf{x} - \mathbf{x}_a)^T \mathbf{S}_a^{-1} (\mathbf{x} - \mathbf{x}_a)$$
(1)

138 where x is the state vector to be retrieved, which includes a set of parameters, including HCOOH 139 profile, H₂O profile, column scale factors for other interfering gases (ozone, carbon dioxide, 140 methanol, ammonia, and CFC-12), surface skin temperature, and scale factor for the atmospheric 141 temperature profile. y is the spectral radiance observation of the micro-window (1090-1120 cm⁻¹) 142 for retrieval; F represents the forward RTM; b is a set of model parameters not to be retrieved, such as observation geometries. S_{ε} is the measurement error covariance matrix; x_a is the a priori 143 state vector; \mathbf{S}_a is the a priori covariance matrix for the state vector. The instrument noise (NedR) 144 145 for each spectral channel is used as the measurement noise for calculating S_{ϵ} . Different from Zeng et al. (2023b), the spectral noise is not enlarged to force the reduced χ^2 from the cost function to 146 147 be close to 1. The Levenberg-Marquardt modification of the Gauss-Newton method is used to find 148 the solution for the cost function (Rodgers, 2000). The one-sigma variability in the a priori 149 HCOOH profile from model simulations is about 70%, which is enlarged by a factor of 5 for 150 calculating S_a to relax the a priori constraint, as shown in Figure S1(b).

151 As described by Rodgers (2000), the Degree of Freedom for Signal (DOFS) and Averaging 152 Kernel (AK) matrix, two statistics generated from OEM, can be used to interpret the retrieval 153 results. AK is a metric that quantifies the sensitivity of the retrieval to the true state. Ideally, a 154 sufficiently good sensitivity of an observing system generates an AK close to an identity matrix. 155 In reality, due to the limited detectivity of the observing system, the AK can be very different. In 156 this case, the rows of AK represent the smoothing functions that vertically smooth the information 157 from the true state over different layers. DOFS is defined as the trace of the AK matrix, which 158 represents the number of independent information from the spectra for constraining the vertical 159 distribution of HCOOH. For example, a DOFS of 1.0 means that, given the assumed a priori 160 uncertainty, one independent piece of information from the spectral can be used to constrain 161 HCOOH vertically.

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163 Figure 1. FY-4B/GIIRS observation spectra and the spectral window for HCOOH retrieval. 164 (a) Example of measured longwave spectra in brightness temperature (BT) covering the HCOOH absorption micro-window centred around 1090-1120 cm⁻¹, indicated by the 165 rectangle inset. The micro-window covers the strong absorption features of the HCOOH v6 166 167 vibrational-rotational band: (b) Sensitivity experiment comparing absorptions of different HCOOH abundances in the 1090–1120 cm⁻¹ micro-window. The difference in BT is relative 168 169 to spectra without HCOOH. The simulated spectra are generated using four different HCOOH abundances based on the a priori profile with a total column of 3.1×10¹⁵ molec/cm²; 170 171 the simulation is based on an observation at noon time on 11 April 2023 with thermal 172 contrast of 13K. The noise level is derived from the spectral noise estimate in the FY-173 4B/GIIRS data product. (c) The spectral fit residual in BT averaged over all post-filtered 174 retrievals on the 15th of all months from July 2022 to June 2023. The filters include DOFS>0.3 175 and the fitting residual rmse less than the monthly mean plus two sigma The standard 176 deviations of the fitting errors are consistent across the different channels, which is about 0.4 177 K. The light-red band indicates the strong HCOOH absorption between 1104 and 1106 cm⁻¹.

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180 Figure 2. Monthly mean of HCOOH column retrievals at 13:00–15:00 Beijing time. These

181 HCOOH retrievals are filtered by DOFS>0.3 and the fitting residual rmse less than the mean

182 plus two sigma, and then gridded in 0.5° by 0.5°.



183 Figure 3. Example of HCOOH retrievals in each 2-hour measurement cycle from early

184 morning to late evening on 10-12 June 2023. The data have been filtered by DOFS>0.3 and 185 the fitting residual rmse less than the mean plus two sigma, and then gridded in 0.5° by 0.5°.

186 **4 Results**

187

4.1 HCOOH column retrievals and the information content

188 Retrieval outputs for each HCOOH observation include the HCOOH column derived from 189 the retrieved profile, the associated posterior error covariance, the AK matrix and resulting DOFS, 190 and the root-mean-square-error (RMSE) of the spectral fitting residual. The histograms of the 191 fitting residual RMSE are shown in Figures S2. The fitting residual RMSE for all retrievals is 192 about 0.7K on average with a standard deviation of about 0.1K. The spectral fitting residuals are shown in Figure 1(c), averaged over all post-filtered retrievals on the 15th of all months from July 193 194 2022 to June 2023. Although there is a systematic pattern that can be seen in the averaged fitting 195 residual, probably due to imperfect spectroscopy or the forward radiative transfer model, this 196 pattern is not correlated with the absorption feature of the target gas HCOOH. To ensure high 197 quality retrievals, the HCOOH column retrievals for each month are filtered by DOFS>0.3 and the 198 fitting residual RMSE is less than the monthly mean plus two standard deviations.

199 Figure 2 shows the monthly mean of the retrieved HCOOH columns after post-filtering 200 for the 13:00–15:00 BJT measurement cycle, when the land surface temperature and DOFS are 201 expected to be the highest during the day, from July 2022 to June 2023. The results show the 202 monthly changes in the HCOOH distribution over Asia, which are mainly due to the seasonality 203 of emissions from biomass burning and biogenic sources. The largest HCOOH columns are 204 observed in Southeast Asia in March and April, when fire emissions peak from the burning of crop 205 residues from the so-called "slash and burn" agriculture (Li et al., 2014; Lasko et al., 2017). By 206 examining the relationships between IASI-observed HCOOH, biogenic emissions, and fire 207 radiative power, Franco et al. (2020) suggested that in Southeast Asia the high HCOOH emissions 208 in spring are contributed jointly from terrestrial vegetation and wildfires. The authors indicated 209 that photochemical production by various previously-identified sources lead to a stronger HCOOH 210 enhancement over Southeast Asia. Over these regions, the HCOOH columns exceed 2.5×10^{16} 211 molec/cm², which is more than 8 times the a priori column. In addition, relatively high abundances 212 are observed over Siberia and the surrounding regions in June and July, probably due to a

combination of wildfire emissions and biogenic related emissions, as suggested by Stavrakou et al. (2012) and Franco et al. (2021).

215 Figures S3 and S4 show the monthly means of HCOOH columns from, respectively, the 216 FY-4B/GIIRS retrievals covering the observation cycles at 09:00-11:00 BJT, and the daytime 217 overpasses (~9:30 am, local solar time) of IASI/Metop-B. Similar patterns in spatial distribution 218 can be observed for retrievals between FY-4B/GIIRS and IASI/Metop-B. Note that the morning 219 observations in Figs S3 and S4 provide slightly lower abundances compared to the noontime 220 observations (Fig. 2), mainly due to the weaker thermal contrast (TC) conditions at the time of the 221 IASI overpass (Clarisse et al., 2010) and probably to the diurnal difference in production/loss 222 processes as introduced in Millet et al. (2015). Here, TC is defined as the temperature difference 223 between the surface and the lower atmosphere.

224 The information content as quantified by the DOFS is summarized in Figure S5. The 225 DOFS is about 0.5 on monthly average with a standard deviation of 0.2, indicating that about half 226 of one piece of information is available from the spectra for HCOOH retrieval based on the 227 retrieval algorithm settings. The DOFSs over the fire plumes detected in Southeast Asia in March-228 April are close to 1.0, indicating that the observations provide a stronger constraint on the retrieval 229 of fire-induced HCOOH emissions. As expected, we found that the DOFS is closely related to the 230 TC, which is an inherent property of thermal infrared sounding (Clarisse et al., 2010). Such a 231 correlation is shown in Figure S6 for different months. Here, TC is calculated from the retrieved 232 surface temperature and the temperature of the bottom atmospheric layer. From the correlation 233 plots, there is a significant positive correlation between TC and DOFS, when TC is positive. The 234 correlation coefficients are mostly larger than 0.6. The DOFS also increases slightly when TC is 235 more negative. A similar relationship exists for the retrieval of ammonia from FY-4B/GIIRS 236 (Zeng et al., 2023b). In essence, for a given HCOOH abundance, large positive TC results in 237 strong HCOOH absorption spectral signatures. For large negative TC, HCOOH emission spectral 238 signatures can be detected. When TC is close to zero, corresponding to the situation where the 239 lower atmosphere with concentrated HCOOH has a similar temperature to the surface, it is difficult 240 to decorrelate the surface layer with the rest of the lower troposphere which hampers the trace gas







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Figure 4. The diurnal cycle in Southeast Asia. (a) Diel cycle of HCOOH columns (for every measurement cycle of two hours) averaged for all data in April 2023 over the wildfire regions in southeast Asia (100°E-105°E, 15°N-20°N) in the upper panel and the associated DOFS and TC in the bottom panel. Error bars represent 1 sigma; Data have been filtered by DOFS>0.3 and the spectral fitting residual less than the sum of the mean and 2 sigma; (c) Averaged AK diagonal vectors for every measurement cycle in April 2023 over the same region as (a)

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4.2 Diurnal variations of HCOOH column retrievals

252 FY-4B/GIIRS from the geostationary orbit has the advantage of observing at high temporal 253 resolution in both the daytime and nighttime, allowing the characterization of the HCOOH diel 254 cycle over East and Southeast Asia. Here, two cases are shown separately for the wildfire 255 emissions in Southeast Asia (Figure 3) and the biogenic emissions in Siberia (Figure S7), 256 separately. These events serve as good case studies to demonstrate the tracking capability of FY-257 4B/GIIRS from geostationary orbit. From Figure 3, the strong enhancement of the HCOOH 258 columns over Southeast Asia and the transport to the surrounding oceans can be clearly observed 259 for all day and night observations. As expected, the columns are highest in the mid-afternoon and 260 lowest in the night. On average, the afternoon HCOOH columns, which peak around 14:00 BJT, 261 are twice as high as the nighttime values, as shown in Figure 4(a). This diurnal cycle of HCOOH 262 columns is consistent with fire radiative power from satellite-based active fire products (Giglio, 263 2007; Roberts et al., 2009), which is associated with the diurnal changes in temperature, humidity, 264 and human activity. Similar patterns can be seen between the daytime and nighttime overpasses of 265 the IASI HCOOH retrievals, as shown in Figure S8.

266 However, the diel cycle detectivity of GIIRS is influenced by the diurnal variations of TC 267 over land, as has been demonstrated for other trace gases (Zeng et al., 2023a; 2023b), which 268 affects the information content available from the observed spectra. This effect can be seen in the 269 HCOOH retrievals from FY-4B/GIIRS, as shown in Figure 4(b). The diurnal cycles of the 270 HCOOH columns and the associated DOFS and TC over the source region are highly correlated. 271 Fortunately, when the TC is low, during the night, the DOFS is still high (on average about 0.5), 272 providing a good constraint for the detection of HCOOH columns from the nighttime spectral measurements. As a result, the nighttime HCOOH columns ($\sim 1.5 \times 10^{16}$ molec/cm²) are about 5 273 times larger than the a priori total column $(3.1 \times 10^{15} \text{ molec/cm}^2)$ used in the retrieval algorithm. 274 275 The change in detectivity from day to night is also reflected in the AK matrix, which indicates the 276 sensitivity of the retrieved HCOOH partial columns in each atmospheric layer to the "truth". 277 Figure 4(c) shows the averaged AK diagonal vectors, which quantify the detectivity of each layer 278 from the observed spectra. FY-4B/GIIRS has a higher detectivity during the day than at night.

From midnight (i.e., 0h) to midday (i.e., 12h), the AK values increase, and the most sensitive layer shifts towards the lower atmosphere.

281 During the summer, large plumes of HCOOH can be observed in Siberia and the 282 surrounding areas, transported over long distances from the source regions towards the east. These 283 plumes usually escape from the boundary layer to reach the free troposphere where they undergo 284 long-range transport (Pommier et al., 2017; Franco et al., 2020). One of these events in early 285 June resulted in the formation of an elongated plume with a high HCOOH abundance, extending 286 from central Siberia to northern China, as is shown in Figure S7. The propagation and dilution of 287 the same plume of HCOOH columns can be observed from early morning to late evening on 09-288 11 June 2023. The retrieved columns show considerable diurnal variations. The HCOOH 289 enhancements from the nighttime retrievals are less pronounced than those from the daytime 290 retrievals. With a lifetime of several days in the free troposphere, significant intraday variations of 291 the HCOOH abundance are usually not expected. However, in the case of a plume where secondary 292 formation of HCOOH associated with photochemical production along the transport is intense, 293 such a diurnal change may be possible. However, the change can also be partially attributed to the 294 diel cycle of TC. Similar patterns can be seen from the IASI HCOOH retrievals, as shown in 295 Figure S9.

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4.3 Inter-comparison with IASI HCOOH retrievals

297 Independent column measurements from ground-based FTIR for validation, as in Franco 298 et al. (2020), are unfortunately not available over this region. Instead, accuracy assessment of the 299 FY-4B/GIIRS HCOOH retrievals is performed by inter-comparison with IASI retrievals. The first 300 generation of IASI HCOOH (Razavi et al., 2011; Pommier et al., 2016) was retrieved using a 301 fast algorithm based on brightness temperature differences, which were then converted to HCOOH 302 columns using conversion factors derived from OEM performed over source regions. A new IASI 303 HCOOH product has been developed by **Franco et al. (2018)** using the Artificial Neural Network 304 for IASI (ANNI) retrieval framework, which is based on machine learning and a hyperspectral 305 range index that shows good sensitivity to the weak spectral absorption signature of HCOOH. IASI 306 HCOOH data have been used in combination with model simulations and have significantly

improved our understanding of HCOOH sources and sinks globally (e.g., Stavrakou et al., 2012;
Pommier et al., 2016; Franco et al., 2021).

309 In this study, we use the ANNI HCOOH v4 product from IASI/Metop-B and perform 310 collocated point-by-point comparisons. A collocated point pair between GIIRS and IASI is defined 311 as observation footprints that are less than 20 km apart in space and differ by less than 1 hour apart 312 in observation time. Theoretically, the comparison between two different instruments need to 313 reconcile the retrieval a priori profiles and the vertical sensitivity as quantified by the AK matrix. 314 Both IASI and GIIRS use the same a priori profiles, which is an advantage for the comparison. In 315 addition, **Pommier et al. (2016)** showed that the vertical sensitivity of IASI in observing HCOOH 316 peaks between 1km and 6km, which is consistent with GIIRS as shown in Figure 4. Therefore, in 317 this study, we carry out direct comparisons of HCOOH columns between GIIRS and IASI. The 318 comparison results are shown in Figure 5 and Figure S10 for the day and night overpasses of 319 IASI. We specifically focus on the months when there are strong HCOOH emissions in March, 320 April, June, and July of 2023. The correlations are analyzed for three different DOFS filters of 321 GIIRS representing different levels of observational information content. Overall, the two datasets 322 show good agreement, especially for the daytime observations when there is a higher TC. A 323 persistent difference can be observed in all cases where GIIRS shows slightly higher HCOOH columns compared to IASI. The RMSE is between 4.5×10^{15} and 6.0×10^{15} molec/cm², which may 324 325 be dominated by the retrieval uncertainty related to spectral noise. As expected, the agreement 326 improves as the DOFS filter becomes more stringent, suggesting that part of the systematic 327 difference is due to the lack of information content. Examples of scene-by-scene comparisons are 328 also made that compare the re-gridded IASI retrievals (in 0.5° by 0.5° grids) in a single track with 329 the re-gridded GIIRS retrievals from the closest measurement cycle. The retrieval noise is expected 330 to be reduced for the gridded averages of the HCOOH columns. Figures S11-S12 show examples 331 of the comparison on April 10 and June 10 for scenes with significant emissions. These results 332 show that FY-4B/GIIRS overlooking East and Southeast Asia from a geostationary orbit has 333 comparable detectivity of HCOOH columns to IASI in the low Earth orbit.

334



Figure 5. Comparison of HCOOH columns between GIIRS and IASI retrievals in April 2023 and

- June 2023, separately for day and night. Collocated point pairs are defined as observation
 footprints that are less than 20 km apart in space and differ by less than 1 hour in observation time.
- The black dashed line is the 1:1 line while the red line is the linear fit through the origin. The slope,
- 339 correlation coefficient (r), and root-mean-square-error (rmse) are also given. These IASI HCOOH
- retrievals are filtered by the "postfilter" variable in the data product. GIIRS HCOOH retrievals
- 341 are filtered by DOFS>0.3 and fitted residual rmse less than the mean plus two sigma.

342 **5** Conclusions

343 This study presents the first results of retrieved atmospheric HCOOH retrieval from a 344 geostationary orbit using infrared hyperspectral observations from FY-4B/GIIRS. By applying the 345 FY-GeoAIR retrieval algorithm based on OEM, this study quantifies the information content of 346 the spectra in retrieving the diurnal HCOOH over Asia from July 2022 to June 2023, and 347 investigates how geostationary observations can facilitate continuous tracking of diurnal wildfire 348 emissions and the long-range transport of HCOOH. Our results show that the DOFS, which 349 represents the detectivity of HCOOH, is about 0.5 on a monthly average with a standard deviation 350 of 0.2, indicating that about half of a piece of information from the spectra is available for HCOOH 351 retrieval. In addition, the DOFS is closely related to the diurnal variation of TC, resulting in the 352 highest DOFS during the day and the lowest during the night. Nevertheless, when the TC is low 353 during the night, the DOFS is still sufficiently high to provide a constraint for the measurement of 354 HCOOH columns from wildfire emissions. In addition, from midnight (i.e., 0h) to midday (i.e., 355 12h), the atmospheric layer with the highest detectivity, as indicated by the AK matrix, changes 356 from the upper to the lower troposphere. Finally, inter-comparison with IASI HCOOH retrievals 357 shows good agreement, indicating that FY-4B/GIIRS observations have comparable detectivity of 358 HCOOH columns to IASI in the low Earth orbit. Ideally, GIIRS HCOOH columns should be 359 compared with independent column measurements such as ground-based FTIR measurements, 360 similar to Franco et al. (2020). The ground-based measurements would provide a more robust 361 validation of the GIIRS HCOOH data. There are a few FTIR stations over the GIIRS coverage 362 area. Unfortunately, they do not provide publicly available retrievals of HCOOH.

363 Tracking the abundance of HCOOH is important for understanding the complex processes 364 of HCOOH production, evolution, and loss in the atmosphere, especially for HCOOH plumes that 365 reach the free troposphere and survive for long distances. For example, GIIRS observations with 366 HCOOH-to-CO enhancement ratios can be used to study the secondary formation of HCOOH 367 along a plume. FY-4B/GIIRS in the geostationary orbit provides such important information with 368 its HCOOH retrievals every two hours from early morning to late evening. Given the diurnal 369 change in the information content available from the observed spectra, it is important to include 370 the AK matrix in further analysis such as data assimilation. Future work will focus on verifying 371 chemical transport model simulations of HCOOH with satellite observations to understand the diel

- 372 characteristics of sources and sinks of HCOOH in Asia, especially over major source regions, and
- 373 to track the evolution of HCOOH in the atmosphere.
- 374 This study is an important first step towards monitoring VOCs from geostationary infrared
- 375 sounders from a constellation of geostationary infrared sounders, including the existing and future
- 376 GIIRS on board the FY-4 series over Asia and the forthcoming European geostationary infrared
- 377 sounder (IRS) on board Meteosat Third Generation (MTG) over Europe.
- 378

379 Acknowledgment

380 The authors would like to thank Prof. Yuk L Yung at Caltech and Prof. Yuanlong Huang at Eastern 381 Institute of Technology, Ningbo (EIT) for stimulating discussions. Z.-C. Zeng acknowledges 382 funding from the National Key R&D Program of China (grant no. 2022YFA1003801) and the 383 National Natural Science Foundation of China (grant no. 42275142 and no. 12292981). This work 384 was also supported by High-performance Computing Platform of Peking University. Research at 385 the National Satellite Meteorological Center (NSMC) was funded by NSMC of China 386 Meteorological Administration (CMA) under the program of Calibration Technology 387 Development and Level-1 Data Production for the Hyperspectral Imaging and Sounding 388 Instruments onboard FY-3E and FY-4B Satellites (FY-APP-2021.0507). IASI is a joint mission 389 of EUMETSAT and the Centre National d'Etudes Spatiales (CNES, France). The authors 390 acknowledge the AERIS data infrastructure for providing access to the IASI data. The research at 391 ULB has been supported by the IASI.Flow Prodex arrangement (ESA-BELSPO). Lieven Clarisse 392 is a research associate supported by the F.R.S.-FNRS.

393

394 Open Research

395 The HCOOH retrieval data from FY-4B/GIIRS in this study are available at 396 [https://disk.pku.edu.cn/link/AA9FDC4AD607334B718F6A21E7870837F8%20Folder%20 397 Name:%20FY4B GIIRS HCOOH v2] and will be made publicly available upon publication. 398 FY-4B/GIIRS Level 1 data are publicly available from the FengYun Satellite Data Center at 399 http://satellite.nsmc.org.cn/portalsite/default.aspx; The surface emissivity datasets are 400 downloaded from the Global Infrared Land Surface Emissivity: UW-Madison Baseline Fit 401 Emissivity Database at https://cimss.ssec.wisc.edu/iremis/; The ECMWF ERA5 reanalysis 402 available Copernicus Data datasets are from the Climate Store at 403 https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-pressure-levels and 404 https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-single-levels; The ECMWF 405 atmospheric composition datasets are available from the Copernicus Atmosphere Data Store at 406 https://ads.atmosphere.copernicus.eu/cdsapp#!/dataset/cams-global-atmospheric-composition-forecasts. 407 The IASI/Metop-B HCOOH columns presented in this paper are publicly available on Zenodo

408 (<u>https://doi.org/10.5281/zenodo.10894008</u>).

409 **Competing interest**

410 The authors declare that they have no conflict of interest.

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Journal of Geophysical Research: Atmospheres

Supporting Information for

Observing a Volatile Organic Compound from a Geostationary Infrared Sounder: HCOOH from FengYun-4B/GIIRS

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Figures S1 to S12



Figure S1. The a priori HCOOH profiles over land and ocean adopted from an updated version of the IASI a priori (Franco et al. 2018) in (a) and the a priori covariance matrix for land retrieval as an example in (b) from the surface to 200 hPa (i.e., layer #1 to #11). The one sigma variability of the a priori HCOOH profile derived from model simulations is about 70%, which is enlarged by a factor of 5 to relax the a priori constraint. The covariance matrix is constructed in the same way as in Zeng et al. (2023b).



Figure S2. Histograms of the root-mean-square-error (RMSE) of fitting residuals in brightness temperature for every month from July 2022 to June 2023. The values in the parentheses are the monthly mean and standard deviation, respectively.



HCOOH Column (x10¹⁶ molec/cm²)

Figure S3. Monthly mean of HCOOH column retrievals at 09:00–11:00 Beijing Time. These HCOOH retrievals are filtered by DOFS>0.3 and the fitting residual rmse less than the mean plus two sigma, and then gridded into 0.5° by 0.5°.



Figure S4. Monthly mean of IASI HCOOH in the daytime from July 2022 to June 2023. These IASI HCOOH retrievals are filtered by the "postfilter" variable in the data product and then re-gridded into 0.5° by 0.5°. IASI HCOOH data product comes from the Daily IASI/Metop-B ULB-LATMOS HCOOH L2 product (columns) - version 4 Reanalysis. The overpass local time crossing equator is about 09:30 am.



Figure S5. Histograms of the degree of freedom for signal (DOFS) from the retrieval algorithm for every month from July 2022 to June 2023. The values in the parentheses are the monthly mean and standard deviation, respectively.



Figure S6. Monthly scatter plots between DOFS and TC from GIIRS HCOOH retrievals from July 2022 to June 2023. The data have been filtered by the fitting residual rmse less than the monthly mean plus two sigmas. The value in the parentheses is the correlation coefficient.



Figure S7. Example of HCOOH retrievals in each 2-hour measurement cycle from early morning to late evening on June 09-11 in 2023. Data have been filtered by DOFS and spectral fit as in Figure 2, and then gridded into 0.5° by 0.5°.



Figure S8. IASI maps of the HCOOH distribution over Asia on April 10, April 11, and April 12 in 2023. These IASI HCOOH retrievals are filtered by the "postfilter" variable in the data product and then re-gridded into 0.5° by 0.5°. IASI HCOOH data product comes from the ANNI HCOOH v4 product from IASI/Metop-B.



Figure S9. IASI maps of the HCOOH distribution over Asia on June 09, June 10, and June 11 in 2023. These IASI HCOOH retrievals are filtered by the "postfilter" variable in the data product and then re-gridded into 0.5° by 0.5°. IASI HCOOH data product comes from the ANNI HCOOH v4 product from IASI/Metop-B.



Figure S10. Comparison of HCOOH columns between GIIRS and IASI retrievals in the daytime and nighttime in March 2023 and July 2022. Collocated point pair between GIIRS and IASI is defined as observation footprints that are less than 20 km apart in space and differ by less than 1 hour in observation time. The dotted line in black is the 1:1 line while the red line is the linear fit crossing the origin. The slope, correlation coefficient (r), and root-mean-square-error (rmse) are also indicated. These IASI HCOOH retrievals are filtered by the "postfilter" variable in the data product. GIIRS HCOOH retrievals are filtered by DOFS>0.3 and fitting residual less than the sum of mean and 2 sigma.



Figure S11. Comparison of IASI in (a) and GIIRS in (b) on 11 April 2023. The Collocated point pairs in (c) are defined as observation footprints that are less than 20 km apart in space and differ by less than 1 hour in observation time. The black dashed line is the 1:1 line while the red line is the linear fit through the origin. The slope, correlation coefficient (r), and root-mean-square-error (rmse) are also given. These IASI HCOOH retrievals are filtered by the "postfilter" variable in the data product. GIIRS HCOOH retrievals are filtered by DOFS>0.3 and fitted residual rmse less than the mean plus two sigma.



Figure S12. The same as Figure S12 but for 10 June 2023.