https://doi.org/10.5194/amt-2020-12
Preprint. Discussion started: 5 March 2020

Monitoring compliance with fuel sulfur content regulations of sailing ships by unmanned aerial vehicle (UAV) measurements of ship emissions in open water

Fan Zhou[1], Liwei Hou[2], Rui Zhong[1], Wei Chen[3], Xunpeng Ni[3], Shengda Pan[1], Ming Zhao[1,4], Bowen An[1]

[1]College of Information Engineering, Shanghai Maritime University, Shanghai 201306, China
[2]College of Ocean Science and Engineering, Shanghai Maritime University, Shanghai 201306, China
[3]Pudong Maritime Safety Administration of the People's Republic of China, Shanghai 200137, China
[4]Key Laboratory of Intelligent Infrared Perception, Chinese Academy of Sciences

Correspondence to: Fan Zhou (fanzhou_cv@163.com)

Abstract. Due to technical and cost limitations, the monitoring of emissions from ships sailing in open water within the ship emission control areas (ECAs) is relatively rare. The present study adopts a monitoring method that uses an unmanned aerial vehicle (UAV) that takes off from a patrol boat to measure the sulfur dioxide and carbon dioxide emissions from sailing ships. Our method aims to provide a low-cost, remote approach for estimating the fuel sulfur content (FSC) of sailing ships in open water, which overcomes the limitations of ground-based and small aircraft methods. The selected monitoring area was the Yangtze River estuary, a domestic ECA with an FSC limit of 0.5% (m/m) implemented by the Chinese government. A total of 27 sailing ships were monitored, 14 of which were found to have an FSC of > 0.5% (m/m). Moreover, the FSCs of the sailing ships were found to be higher than those of berthing ships in the study area. According to the monitoring results, four of the monitored ships were intercepted by the maritime law enforcement, and fuel samples were collected and analyzed in a laboratory; the results confirmed that all four FSCs were > 0.5% (m/m). Among them, one offending ship was tracked down on July 15, 2019, which was the first time that a sailing ship had been caught for having failed the FSC regulations in China. Overall, the present study provides scientific support for evaluating the effectiveness of ECA policies, and recommends that emissions from sailing ships should be monitored more often in the open water in the future.

1. Introduction

With the rapid development of the shipping industry (UNCTAD, 2017) over the past decades, air pollution caused by ship emissions has received an increasing amount of attention (Eyring et al., 2010; Wan et al., 2016). The pollutant gases emitted by ships not only affect the global climate (Huebert, 1999; Corbet, 2016), but also local air quality and can harm people's health. (Yang et al., 2016; Wang et al., 2019). Shipping accounted for 15%, 13%, and 3% of the annual global anthropogenic emissions of NOx, SOx, and CO_2 from 2007 to 2012, respectively (Smith et al., 2014). In Europe, estimated ship emissions were responsible for 3.0 million tons of NOx, 1.2 million tons of SOx, and 0.2 million tons of fine particulate matter (PM2.5)

https://doi.org/10.5194/amt-2020-12
Preprint. Discussion started: 5 March 2020

in 2011 (Jalkanen et al., 2016). In East Asia, shipping emissions accounted for 16% of global shipping CO_2 in 2013, whereas they only accounted for 4–7% during 2002–2005 (Liu et al., 2016).

To reduce the negative impacts of ship emissions, the International Maritime Organization (IMO) regulates emissions through the International Convention for the Prevention of Pollution from Ships and its Annex VI (MARPOL, 1997). The air-pollution limits for shipping were adopted in 1997, but only came into force in 2005. The global cap for the fuel sulfur content (FSC) of seagoing ships was set at 3.5% (m/m) in 2012, and was reduced to 0.5% (m/m) in 2020. To date, four emission control areas (ECAs) (the Baltic Sea, the North Sea, the United States Caribbean, and the North American and United States Caribbean Sea) have been set up, and the corresponding FSC limit for seagoing ships in these areas was set at 0.1% (m/m) in 2015 (IMO, 2017).

The IMO has not yet set up ECAs in East Asia, which includes the world's ten largest container ports, for example, Shanghai, Ningbo-Zhoushan, and Shenzhen ports. To limit the air pollution caused by ship emissions, the Chinese government established three domestic emission control areas (DECAs) in 2015: the Yangtze River delta, the Pearl River delta, and the Bohai Sea. DECAs was expanded to cover a wider area since 2020, and include most of the coastal ports, the Yangtze River main line, and the Xijiang River main line. The FSC limit for sailing and berthing ships in the DECAs has been set at 0.5% (m/m) since January 1, 2019.

A key problem regarding the implementation of the policy of the ECAs is the question of how to supervise the FSC of ships. Several studies have suggested monitoring ship emissions to estimate the FSC of the target ship (Berg et al., 2012; Balzani Lööv et al., 2014). At present, the main method to monitor the emissions of surrounding ships is to place monitoring equipment either on the wharf, shore, port area, or bridge (i.e., ground-based methods) (Alföldy et al., 2013; Pirjola et al., 2013; Beecken et al., 2015; Kattner et al., 2015; Mellqvist et al., 2017a; Cheng et al., 2019; Zhang et al., 2019). Although ground-based methods can provide continuous monitoring, the results obtained depend on the wind speed, wind direction, and the relative position of a ship to the monitoring equipment. Additionally, the boundaries of the ECAs that are designated by the IMO are 200 nautical miles from the coast (Viana et al., 2015); hence, ground-based methods are not able to monitor the fuel that is used on the open sea in ECAs because sailing ships are too far from the shore or bridges.

Therefore, some researchers have used sensors that are carried by small aircrafts to monitor navigation ships within ECAs (Berg et al., 2012; Beecken et al., 2014). However, because this kind of monitoring method is costly, the monitoring of navigation ships is relatively rare. Beecken et al. (2015) observed 434 plumes during ground-based measurements and 32 plumes from a helicopter. Balzani Lööv et al. (2014) took 475 measurements using "sniffing" instruments from ground-based measurements, whereas only 25 measurements were obtained using this method from mobile platforms. In the study undertaken by Mellqvist et al. (2017b), 114 individual ships were measured effectively during 27 flight hours at a cost of approximately 470 Euro per ship, which was for the airplace cost and did not included the ferry, operator, or instrument rental costs. Therefore, the high cost of flying precludes extensive monitoring of ship emissions.

As a result of the aforementioned factors, there is less monitoring of ships on the open sea in ECAs. This is despite the fact that numerous studies (Pirjola et al., 2014; Kattner et al., 2015; Zhang et al., 2019) have shown that the FSC of ships were

https://doi.org/10.5194/amt-2020-12
Preprint. Discussion started: 5 March 2020

significantly reduced by the implementation of the ECA policy. However, most of these studies did not involve the monitoring of ships on the open water, which could lead to inaccurate assessments for the implementation of policies. At the same time, the lack of open sea monitoring results in a blind area for maritime supervision and is not conducive to the implementation of ship ECA policy by maritime departments. Therefore, the present study used an unmanned aerial vehicle (UAV) to monitor the emissions of sailing ships on the open sea in the Yangtze River estuary DECA. In comparison to the small aircraft method, this monitoring method can be used to monitor ship emissions at a lower cost to understand the emissions of sailing ships in open waters.

2 Experimental methods

The research undertaken in the present study forms part of the project "Monitoring and inspecting ship exhaust emissions in the Shanghai free-trade zone" (MISEE). In this project, an unmanned aircraft system (UAS) was designed and developed, and mainly included a pod for measuring the exhaust gas from ships and a UAV to carry the pod. In previous research (Zhou et al., 2019), the plumes of 23 berthing ships were measured using the first-generation pod. The deviation of the estimated FSC obtained by the UAS was < 0.03% (m/m) for an FSC of between 0.035% (m/m) and 0.24% (m/m).

In the present monitoring for sailing ships, we developed the second-generation pod by optimizing the structure and layout of the first-generation pod to achieve a lighter weight and smaller volume. A short overview of the instrumentation is provided in Section 2.1. We measured the plumes of 11 berthing ships to verify the accuracy of the second-generation pod, and the plumes of 27 sailing ships to estimate the FSC.

2.1 Instrumentation

The UAS that was used for monitoring the FSC of sailing ships is shown in Fig 1. The UAV was a MATRICE 600 PRO (SZ DJI Technology Co., Ltd., Shenzhen, China). This type of UAV cannot be used on rainy days or when the wind speed is higher than 8 m/s. The white box installed underneath the UAV in Fig. 1 is the aforementioned second-generation pod for measuring the exhaust gas. When the UAV approaches a ship's plume, the gas pump in the pod extracts gas using the gas probe. The water vapor in the gas is subsequently removed by the filter. The sensors detect the gas and measurement information is sent out by communication modules. The pod has dimensions of 20 mm × 12 mm × 9 mm and weighs 900 g.

The sensors used were able to measure both SO_2 and CO_2, and were purchased from Shenzhen Singoan Electronic Technology Co., Ltd., China. The SO_2 sensor is based on the electrochemical method, and has a measuring range of 0–10 ppm, an accuracy of ±5% (full range), and a response time (t_{90}) of < 1 s. The CO_2 sensor is based on the non-dispersive infrared analyzer method, and has a measuring range of 0–5000 ppm, an accuracy of ±3% (full range), and a t_{90} of < 1 s. The t_{90} represents the time taken to reach 90% of the stable response following a step change in the sample concentration. These sensor characteristics were provided by the instrument manufacturer and were ensured to be within the tolerances by our own examination and calibration.

https://doi.org/10.5194/amt-2020-12
Preprint. Discussion started: 5 March 2020

2.2 Monitoring region

As illustrated in Fig. 2, the monitoring region was the channel of the Yangtze River estuary, near the Waigaoqiao port area to the north of Shanghai. The Yangtse River is the first (third) longest river in China (the world). Shanghai is one of the most prosperous cities in the world, and at the end of 2017 that city had a permanent resident population of approximately 24 million people (Shanghai Municipal Bureau of Statistics, 2017). The Waigaoqiao port area is only 20 km away from the city center, and the air pollution caused by ship emissions directly affects the urban air environment and the health of residents (Wang et al., 2019; Feng et al., 2019). The experimental area of the MISEE project is mainly within the Waigaoqiao port and the Yangtze River estuary.

2.3 Measurement method

During the experiment, the operator took a patrol boat to the channel and then selected a target ship at random. After identifying the target ship for monitoring, the patrol boat would accelerate to a distance to the left or right ahead of the vessel. The patrol boat would then stop and the UAV was operated to takeoff from its deck, and would then fly towards the plume of the target ship and measure the concentrations of SO_2 and CO_2 (Fig. 3). The distance between the patrol boat and the target ship was approximately a few hundred meters.

During the measurements, the operator adjusted the position of the UAV to ensure that it was in the ship's plume. Real-time measurements of SO_2 and CO_2 were made such that the pod could effectively detect the plume. Generally, it was necessary for the UAV to follow the ship's funnel mouth for approximately 5 minutes, as illustrated in Fig. 4. The target ship continued to move during the measurements; hence, it was followed by the patrol boat in order to avoid the UAV moving too far away from the operator. When the operator was sure that valid data had been collected, the patrol boat stopped and the UAV returned and landed back on the deck of the patrol boat.

2.4 Calculation

The FSC in this study was obtained directly by sampling the gas concentrations in the ship plumes using the UAS. The enhancements of SO_2 and CO_2 in measurements that were affected by exhaust gases were calculated, and the ratio of these SO_2 and CO_2 peaks was used to calculate the FSC (Eqs. 1 and 2). This method has been widely used to calculate the FSC in related studies (Alföldy et al., 2013; Pirjola et al., 2014; Balzani Lööv et al., 2014; Beecken et al., 2014; Beecken et al., 2015; Kattner et al., 2015; Zhou et al., 2019). In the calculation, the molecular weights of carbon and sulfur are 12 g mol^{-1} and 32 g mol^{-1}, respectively, and the carbon mass percent in the fuel is 87 $\pm$1.5% (Cooper et al., 2003). By assuming that 100% of the carbon content of the fuel is emitted as CO_2, and sulfur is emitted as SO_2 and other forms, the FSC mass percent can be determined using Eq. (1):

$$FSC[\%] = \frac{S[kg]}{fuel[kg]} = \frac{SO_2[ppm]\cdot A(S)}{CO_2[ppm]\cdot A(C)}\cdot 87[\%] + R = 0.232\frac{\int(SO_{2,peak}-SO_{2,bkg})dt[ppb]}{\int(CO_{2,peak}-CO_{2,bkg})dt[ppm]}[\%] + R = \frac{1}{20}EF + R, \quad (1)$$

https://doi.org/10.5194/amt-2020-12
Preprint. Discussion started: 5 March 2020

Atmospheric Measurement Techniques Discussions

where R represents the sulfur content that is emitted in forms other than SO_2 because preliminary studies have shown that 1–19% of the sulfur in fuel is emitted in other forms, possibly SO_3 or SO_4 (Schlager et al., 2006; Alföldy et al., 2013; Balzani Lööv et al., 2014). EF is the emission factor and bkg is the abbreviation of background. In Eq. (1), if the sensors measuring SO_2 and CO_2 have approximately the same t_{90} and can be set to be synchronized, the peak concentrations of SO_2 and CO_2 can be used to calculate the FSC, otherwise integrals need to be used. In our research, integrals were used because the two sensors could not be completely synchronized. In addition, the t_{90} of the sensors were not the same, although they were both < 1 s. A typical calculation is as follows.

The sampling rate of the SO_2 and CO_2 sensors was 1 s. The continuous measurements obtained during one UAV flight are exhibited in Fig. 5a. The graph shows that the time point of the SO_2 peak is not synchronous with CO_2, which was mainly caused by different sensor response times. The selection of peak values is highly uncertain. When the area ratio is selected for the calculation, the selection of the starting and ending time points of the area is still associated with great uncertainty.

Figure 5b depicts the averages of the SO_2 and CO_2 measurements (in Fig. 5a) for 10 s periods. The peak value of the average was selected for the calculation. This process is equivalent to selecting the area ratio of SO_2 to CO_2 within 10 s for the calculation, as shown in Eq. (2).

$$FSC[\%] = 0.232 \frac{\int (SO_{2,peak} - SO_{2,bkg}) dt[ppb] / 10}{\int (CO_{2,peak} - CO_{2,bkg}) dt[ppm] / 10} [\%] + R \approx 0.232 \frac{AVG(SO_{2,peak}) - AVG(SO_{2,bkg})}{AVG(CO_{2,peak}) - AVG(CO_{2,bkg})} [\%], \quad (2)$$

where AVG (·) is the calculated function for the average measurement value. Therefore, the data in this study are the average values of measurements in 10 s. When the UAV took off from the patrol boat and flew high into the air, the SO_2 and CO_2 concentrations were relatively low. The background concentrations were obtained at this stage as the minimum SO_2 and CO_2 concentrations. As shown in Fig. 5b, the time frame was between 10:11:41 and 10:12:06. As the UAV flew into the plume, the measured concentrations of SO_2 and CO_2 increased. The stable, obvious, and maxima values in the observations of the average measurement values were selected as the peak values (time point 10:14:11).

2.5 Uncertainties

In previous research, the main uncertainties of UAV measurements were summarized as sensor uncertainty, measurement uncertainty, calculation uncertainty, and exhaust uncertainty. The instrument calibration method, UAV flight procedures, and data treatment methods reported by Zhou et al. (2019) were incorporated in this study to reduce these uncertainties. In addition, a distinction between good- and poor-quality data was made and some plume data were rejected. Good-quality data for a plume was reflected by obvious, easily distinguished peak values, whereas less obvious peaks that still corresponded to a result were considered as poor-quality data. When results could not be obtained, the plumes were rejected.

In this research, additional uncertainties were encountered during our monitoring of sailing ships because the UAV was usually hundreds of meters away from the operator. The location of a plume depended primarily on the following three aspects. 1. The position of most plumes with black smoke could be identified through the operator's visual judgment. 2. The real-time image shot by the camera can be used to assist in finding the ship's funnel mouth. 3. In the measurement process, the real-time measured concentration sent to the receiving equipment gradually increased, thus indicating that the UAV was approaching the center of the plume. However, the operator occasionally faced difficulties in accurately determining the ship's plume, which led to failed measurements. We attempted to measure more than 40 ship plumes in open water; however, only 27 of them resulted in good- or poor-quality data, i.e., usable data.

The deviation of the estimated FSC value obtained by the first-generation pod was < 0.03% (m/m) for an FSC level ranging from 0.035% (m/m) to 0.24% (m/m) (Zhou et al., 2019). The second-generation pod was also verified on berthing ships by using this method at a similar FSC level and the accuracy was approximately the same (see Section 3.1). These verifications of the deviation were based on the FSC measurement of berthing ships, which did not exceed the Chinese DECA FSC limit of 0.5% (m/m). However, some of the sailing ships did exceed this limit. It should be noted that the deviations for different FSC levels were not the same. Based on previous studies, the deviation of the FSC obtained from high-sulfur plume should be greater, for example, Van Roy and Scheldeman (2016a, b) estimated relative uncertainties of 20% (m/m) at a level of 1% (m/m) FSC and 50–100% at 0.1% (m/m) FSC. Therefore, the deviation of sailing ships may > 0.03% (m/m) when the FSC exceeds 0.5% (m/m). Nonetheless, our UAS was still able to accurately detect an FSC that obviously exceeded 0.5% (m/m).

3. Results

3.1 Berthing ships

Before monitoring the sailing ships, we first monitored 11 berthing ships between March and April 2019 in the Waigaoqiao port to verify the accuracy of the second-generation pod. Whilst one person operated the UAV to monitor one of the plumes, two maritime law enforcement officers boarded the corresponding ship to collect a fuel sample. Both processes took approximately 10–20 min. The fuel samples, which are considered to represent the true FSC values, were then sent for chemical analysis in a laboratory. The estimated (UAV) and true FSC values are listed in Table 1 along with the identification number of each plume and the time and serial number. Table 1 shows that the deviation did not generally exceed 0.03% (m/m) for an FSC level of between 0.03% (m/m) and 0.22% (m/m) (except for plume 2019-4-3A). Additionally, when the FSC of a target ship was low, for example, when light diesel fuel was used, the measured SO_2 concentrations were mostly zero. When this occurred, the FSC was generally < 0.02% (m/m), for example, as for plumes 2019-4-3A and 2019-4-12A.

3.2. Sailing ships and comparison with berthing ships

Between March and December 2019, effective monitoring of 27 sailing ships was undertaken using the UAV that took off from the patrol boat (Table 2). The FSC of 23 berthing ships measured by the first-generation monitoring equipment and the FSC of 11 berthing ships (Table 1) measured by the second-generation monitoring equipment in this study were taken as the FSC monitoring results for berthing ships. We compared the distribution of the FSCs of these 34 berthing ships with those of the 27 sailing ships. Figure 6 shows that the FSCs of the sailing ships were considerably higher than those of the berthing ships;

the FSC of all 27 sailing ships exceeded 0.1% (m/m) and the FSC of 14 of these exceeded the Chinese DECA FCS limit of 0.5% (m/m), which included 5 exceedances of 2% (m/m). Despite the uncertainties described in Section 2.5, the current situation regarding the FSC of sailing ships has not been optimistic to date. The reason for this is that although berthing ships are sometimes boarded by maritime law enforcement officers for examination, an effective approach for monitoring the FSC of sailing ships in open water that leads to prosecution by China's maritime authorities has not existed prior to the present study.

According to the monitoring results, law enforcement officers of the Pudong maritime safety administration intercepted four sailing ships for which the UAV FSC results were of a good-quality and all exceeded 2% (m/m). The officers boarded these ships for inspection on July 15, August 14, August 20, and September 27, 2019, and took fuel samples, which were sent for chemical analysis in a laboratory. The FSC of all four fuels was also found to exceed 0.5% (m/m): 0.534% (m/m), 0.744% (m/m), 0.813% (m/m), and 1.991% (m/m) (in chronological order). The reason that all of these laboratory results did not exceed 2% related to the fact that ships cannot stop immediately in the channel for inspection and have to sail to the anchorage point; when the officers boarded the ships to take samples they found the crew taking various measures to drain the high-sulfur fuel in the main engine fuel oil pipeline. This means that the chemical analysis results of the sampled fuels were obviously lower than those of the UAV monitoring. Nevertheless, the four inspections successfully confirmed that the FSC of the fuels exceeded the standard for sailing ships. The inspection on July 15, 2019, was the first time that a sailing ship's FSC failed to meet Chinese regulations, and this aroused wide concern in the shipping community.

4. Conclusions

In this research, we used a UAV that took off from a patrol boat to monitor emissions from sailing ships in open water. Of the 27 sailing ships that were successfully monitored, 14 were found to have an FSC that exceeded 0.5% (m/m) and 5 exceeded 2% (m/m). Based on the monitoring results, law enforcement officers of the Pudong maritime safety administration caught the first case of excessive FSC for a sailing ship and confirmed three other cases. Additionally, the UAV monitoring results demonstrated that the FSC values of sailing ships in the surrounding waters of Waigaoqiao port were higher than those determined for berthing ships in the port.

Although a global cap on the FSC in marine fuel was set at 3.5% (m/m) in 2012 following the IMO regulation, this was reduced to 0.5% (m/m) in 2020 and has already been implemented in China. According to our monitoring results, the current situation for meeting the 0.5% limit is not optimistic. Successful compliance with this regulation by ship owners involves many challenges. We conclude that there is a need for further monitoring data on sailing ships in open water to ascertain the degree of exceedance and work toward compliance.

In addition, there are still some improvements to be made to the UAS. 4G transmission is the communication method for detecting information transmission; hence, in locations without a 4G signal (e.g., offshore), the receiving equipment cannot obtain real-time measurement results. Potential solutions include setting-up small base-stations on patrol boats or using satellite

https://doi.org/10.5194/amt-2020-12
Preprint. Discussion started: 5 March 2020

Atmospheric Measurement Techniques Discussions
Open Access

transmission. Although carrying an infrared camera on the UAV would make it easier to find the plume, this would require to replace the camera in Fig. 1 with an infrared camera and establish new data communication.

Data availability

Please address requests for data sets and materials to Fan Zhou (fanzhou_cv@163.com).

Author contribution

FZ designed the study and authored the article. FZ and LH analyzed the experimental data. RZ, WC and XN contributed to the experiments. SP contributed to setting instruments. LH, MZ and BA provided constructive comments on this research.

Competing interests

The authors declare that they have no conflict of interest.

Acknowledgements

We thank Megan Anne for English language editing.

Financial support.

This research has been supported by the National Natural Science Foundation of China (grant No. 41701523), the Special Development Fund for China (Shanghai) Pilot Free Trade Zone, and Open Project Program of Key Laboratory of Intelligent Infrared Perception, Chinese Academy of Sciences.

References

Alföldy, B., Lööv, J. B., Lagler, F., Mellqvist, J., Berg, N., Beecken, J., Weststrate, H., Duyzer, J., Bencs, L., Horemans, B., Cavalli, F., Putaud, J.-P., Janssens-Maenhout, G., Csordás, A. P., Van Grieken, R., Borowiak, A., and Hjorth, J.: Measurements of air pollution emission factors for marine transportation in SECA, Atmos. Meas. Tech., 6, 1777–1791, https://doi.org/10.5194/amt-6-1777-2013, 2013.

Berg, N., Mellqvist, J., Jalkanen, J.-P., and Balzani, J.: Ship emissions of SO_2 and NO_2: DOAS measurements from airborne platforms, Atmos. Meas. Tech., 5, 1085–1098, https://doi.org/10.5194/amt-5-1085-2012, 2012.

https://doi.org/10.5194/amt-2020-12
Preprint. Discussion started: 5 March 2020

Atmospheric Measurement Techniques Discussions

Balzani Lööv, J. M., Alfoldy, B., Gast, L. F. L., Hjorth, J., Lagler, F., Mellqvist, J., Beecken, J., Berg, N., Duyzer, J., Westrate, H., Swart, D. P. J., Berkhout, A. J. C., Jalkanen, J.-P., Prata, A. J., van der Hoff, G. R., and Borowiak, A.: Field test of available methods to measure remotely SOx and NOx emissions from ships, Atmos. Meas. Tech., 7, 2597–2613, https://doi.org/10.5194/amt-7-2597-2014, 2014.

Beecken, J., Mellqvist, J., Salo, K., Ekholm, J., and Jalknen, J.-P.: Airborne emission measurements of SO2, NOx and particles from individual ships using a sniffer technique, Atmos. Meas. Tech., 7, 1957–1968, http://dx.doi.org/10.5194/amt-7-1957-2014, 2014.

Beecken, J., Mellqvist, J., Salo, K., Ekholm, J., Jalkanen, J.-P., Johansson, L., Litvinenko, V., Volodin, K., and Frank-Kamenetsky, D. A.: Emission factors of SO_2, NO_x and particles from ships in Neva Bay from ground-based and helicopter-borne measurements and AIS-based modeling, Atmos. Chem. Phys., 15, 5229–5241, https://doi.org/10.5194/acp-15-5229-2015, 2015.

Cheng, Y., Wang, S., Zhu, J., Guo, Y., Zhang, R., Liu, Y., Zhang, Y., Yu, Q., Ma, W., and Zhou, B.: Surveillance of SO2 and NO2 from ship emissions by MAX-DOAS measurements and implication to compliance of fuel sulfur content, Atmos. Chem. Phys. Discuss., https://doi.org/10.5194/acp-l2019-369, in review, 2019.

Corbett, J.: Shipping emissions in East Asia, Nature Climate Change 6, 983–984, doi:10.1038/nclimate3091, 2016.

Eyring, V., Isaksen, I. S., Berntsen, T., Collins, W. J., Corbett, J. J., Endresen, O., Grainger, R. G., Moldanova, J., Schlager, H., and Stevenson, D. S.: Transport impacts on atmosphere and climate: Shipping, Atmos. Environ., 44, 4735–4771, https://doi.org/10.1016/j.atmosenv.2009.04.059, 2010.

Cooper, D. A.: Exhaust emissions from ships at berth, Atmos. Environ., 37, 3817–3830, https://doi.org/10.1016/s1352-2310(03)00446-1, 2003.

Feng, J., Zhang, Y., Li, S., Mao, J., Patton, A. P., Zhou, Y., Ma, W., Liu, C., Kan, H., Huang, C., An, J., Li, L., Shen, Y., Fu, Q., Wang, X., Liu, J., Wang, S., Ding, D., Cheng, J., Ge, W., Zhu, H., and Walker, K.: The influence of spatiality on shipping emissions, air quality and potential human exposure in the Yangtze River Delta/Shanghai, China, Atmos. Chem. Phys., 19, 6167–6183, https://doi.org/10.5194/acp-19-6167-2019, 2019.

Huebert, B. J.: Sulphur emissions from ships, Nature 400(6746), 713–714. doi:10.1038/23357, 1999.

International Maritime Organization (IMO), Emission Control Areas (ECAs) designated under MARPOL Annex VI.

http://www.imo.org/en/OurWork/Environment/PollutionPrevention/AirPollution/Pages/Emission-Control-Areas-(ECAs)-designated-under-regulation-13-of-MARPOL-Annex-VI-(NOx-emission-control).aspx. Last access 10 December 2019. 2017.

Jalkanen, J.-P., Johansson, L., and Kukkonen, J.: A comprehensive inventory of ship traffic exhaust emissions in the European sea areas in 2011, Atmos. Chem. Phys., 16, 71–84, https://doi.org/10.5194/acp-16-71-2016, 2016.

Kattner, L., Mathieu-Üffing, B., Burrows, J. P., Richter, A., Schmolke, S., Seyler, A., and Wittrock, F.: Monitoring compliance with sulfur content regulations of shipping fuel by in situ measurements of ship emissions, Atmos. Chem. Phys., 15, 10087–10092, doi:10.5194/acp-15-10087-2015, 2015.

https://doi.org/10.5194/amt-2020-12
Preprint. Discussion started: 5 March 2020

Atmospheric Measurement Techniques Discussions

Liu, H., Fu, M., Jin, X., Shang, Y., Shindell, D., Faluvegi, G., Shindell, C., and He, K.: Health and climate impacts of ocean-going vessels in East Asia, Nature Climate Change 6, 1037–1041, doi:10.1038/nclimate3083, 2016.

MARPOL: International Convention for the Prevention of Pollution from Ships, 1973 as modified by the Protocol of 1978–Annex VI: Prevention of Air Pollution from Ships, International Maritime Organization (IMO), 1997.

Mellqvist, J., Beecken, J., Conde, V., and Ekholm J.: Surveillance of Sulfur Emissions from Ships in Danish Waters. Chalmers University of Technology, Göteborg, Sweden. December 30, 2017a.

Mellqvist, J., Conde, V., Beecken, J., and Ekholm, J.: Certification of an aircraft and airborne surveillance of fuel sulfur content in ships at the SECA border, CompMon (https://compmon.eu/, last access: 6 November 2018), 2017b.

Pirjola, L., Pajunoja, A., Walden, J., Jalkanen, J.-P., Rönkkö, T., Kousa, A., and Koskentalo, T.: Mobile measurements of ship emissions in two harbour areas in Finland, Atmospheric Measurement Techniques 6(4), 7149–7184. doi:10.5194/amtd-6-7149-2013, 2013.

Schlager, H., Baumann, R., Lichtenstern, M., Petzold, A., Arnold, F., Speidel, M., Gurk, C., and Fischer, H.: Aircraft-based Trace Gas Measurements in a Primary European Ship Corridor, Proceedings TAC-Conference, 26–29 June, Oxford, 83–88, 2006.

Shanghai Municipal Bureau of Statistics. The statistic communique of Shanghai on the 2017 national economy and social development, 2017.

Smith, T. W. P. et al. Third IMO Greenhouse Gas Study 2014. International Maritime Organization, 2014.

UNCTAD: World seaborne trade by types of cargo and by group of economies, annual, United Nations Conference on Trade and Development, available at: https://unctadstat.unctad.org/wds/TableViewer/tableView.aspx?ReportId=32363, last access: 5 March, 2017.

Van Roy, W. and Scheldeman, K.: Results MARPOL Annex VI Monitoring Report Belgian Sniffer Campaign 2016, CompMon (https://compmon.eu/, last access: 6 November 2018), 2016a.

Van Roy, W. and Scheldeman, K.: Best Practices Airborne MARPOL Annex VI Monitoring, CompMon (https://compmon.eu/,last access: 6 November 2018), 2016b.

Viana, M., Fann, N., Tobías, A., Querol, X., Rojas-Rueda, D., Plaza, A., Aynos, G., Conde, J., Fernàndez, L., and Fernández, C.: Environmental and health benefits from designating the marmara sea and the Turkish straits as an emission control area (ECA), Environ. Sci. Technol., 49, 3304–3313, https://doi.org/10.1021/es5049946, 2015.

Wan, Z., Zhu, M., Chen, S., and Sperling, D.: Pollution: Three steps to a green shipping industry, Nature 530, 275–277, doi:10.1038/530275a, 2016.

Wang, X., Shen, Y., Lin, Y., Pan, J., Zhang, Y., Louie, P. K. K., Li, M., and Fu, Q.: Atmospheric pollution from ships and its impact on local air quality at a port site in Shanghai, Atmos. Chem. Phys., 19(9), 6315–6330. doi:10.5194/acp-19-6315-2019, 2019.

https://doi.org/10.5194/amt-2020-12
Preprint. Discussion started: 5 March 2020

Atmospheric Measurement Techniques Discussions

Yang, M., Bell, T. G., Hopkins, F. E., and Smyth, T. J.: Attribution of atmospheric sulfur dioxide over the English Channel to dimethyl sulfide and changing ship emissions, Atmos. Chem. Phys., 16, 4771–4783, https://doi.org/10.5194/acp-16-4771-2016, 2016.

Zhang, Y., Deng, F., Man, H., Fu, M., Lv, Z., Xiao, Q., Jin, X., Liu, S., He, K., and Liu, H.: Compliance and port air quality features with respect to ship fuel switching regulation: a field observation campaign, SEISO-Bohai, Atmos. Chem. Phys., 19, 4899–4916, https://doi.org/10.5194/acp-19-4899-2019, 2019.

Zhou, F., Pan, S., Chen, W., Ni, X., and An, B.: Monitoring of compliance with fuel sulfur content regulations through unmanned aerial vehicle (UAV) measurements of ship emissions, Atmos. Meas. Tech., 12, 6113–6124, https://doi.org/10.5194/amt-12-6113-2019, 2019.

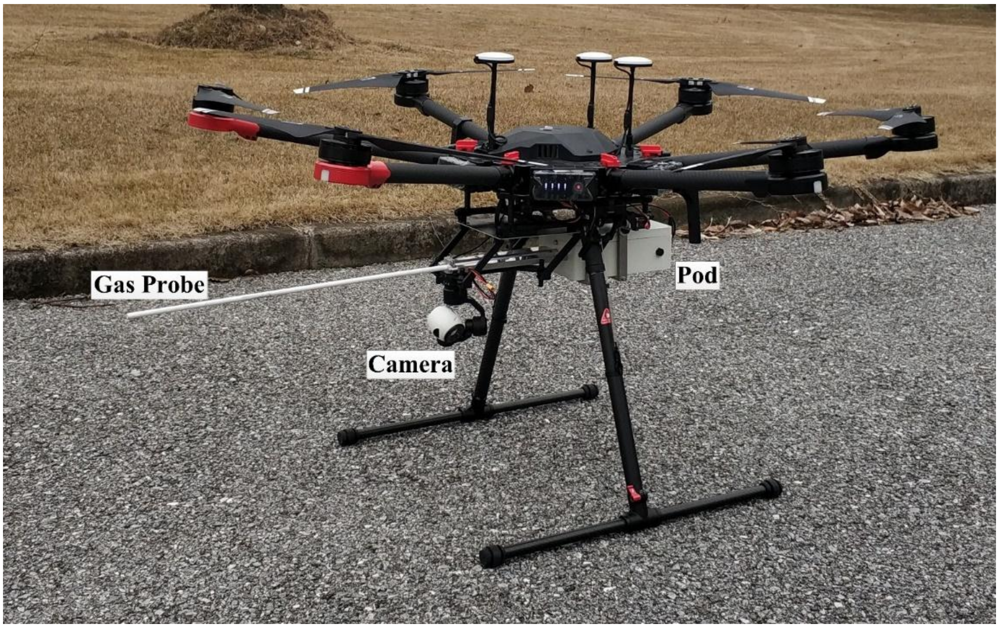
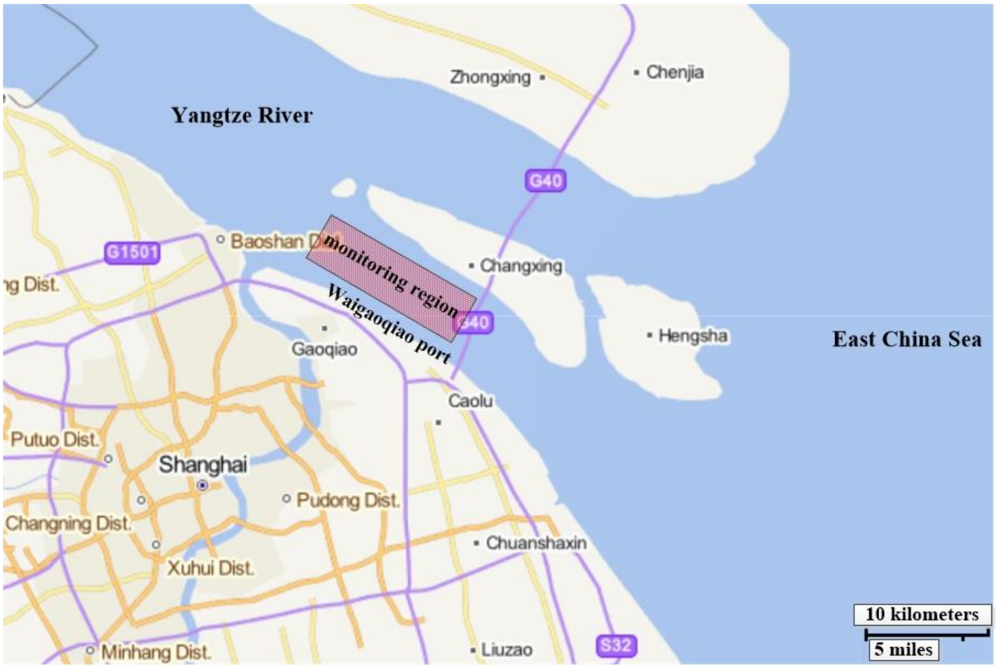


Figure 1. Image of the unmanned aircraft system. A gas probe, camera, and pod are installed under the unmanned aerial vehicle (UAV). The gas probe is used to collect the ship's exhaust gas, and the camera is used to assist in finding the ship's funnel mouth during flight. The pod is used to carry a gas pump, gas circuit, filter, small motor, sensors for SO_2 and CO_2, and communication modules.

https://doi.org/10.5194/amt-2020-12
Preprint. Discussion started: 5 March 2020

Atmospheric Measurement Techniques
Discussions



325 **Figure 2. Monitoring regions in the channel of Yangtze River estuary, which belong to the DECAs of China. This area is to the north of Shanghai, on the southwest side of Changxing Island. The distance between the two sides is ~6–7 km. Ships leave the Yangtze River and sail into the East China Sea through this channel. Map data: @MapWorld (http://www.tianditu.gov.cn, last access: 5 March 2020).**

https://doi.org/10.5194/amt-2020-12
Preprint. Discussion started: 5 March 2020

Figure 3. Operator controlling the takeoff of the UAV from a patrol boat.

Figure 4. UAV (marked by a red circle) monitoring a ship's emissions in the open sea. An enlarged image of the UAV is shown at the top right. This picture was captured by another UAV.

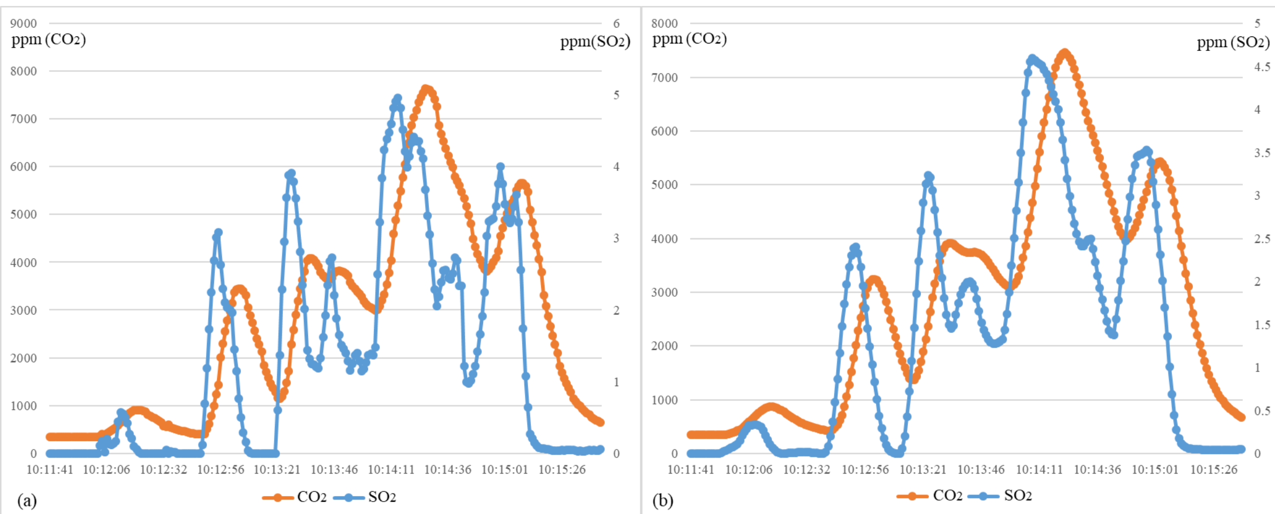


Figure 5. Typical calculations of data for the FSC, a) SO_2 and CO_2 measurement values, and b) SO_2 and CO_2 measurements averaged over 10 s periods.

https://doi.org/10.5194/amt-2020-12
Preprint. Discussion started: 5 March 2020

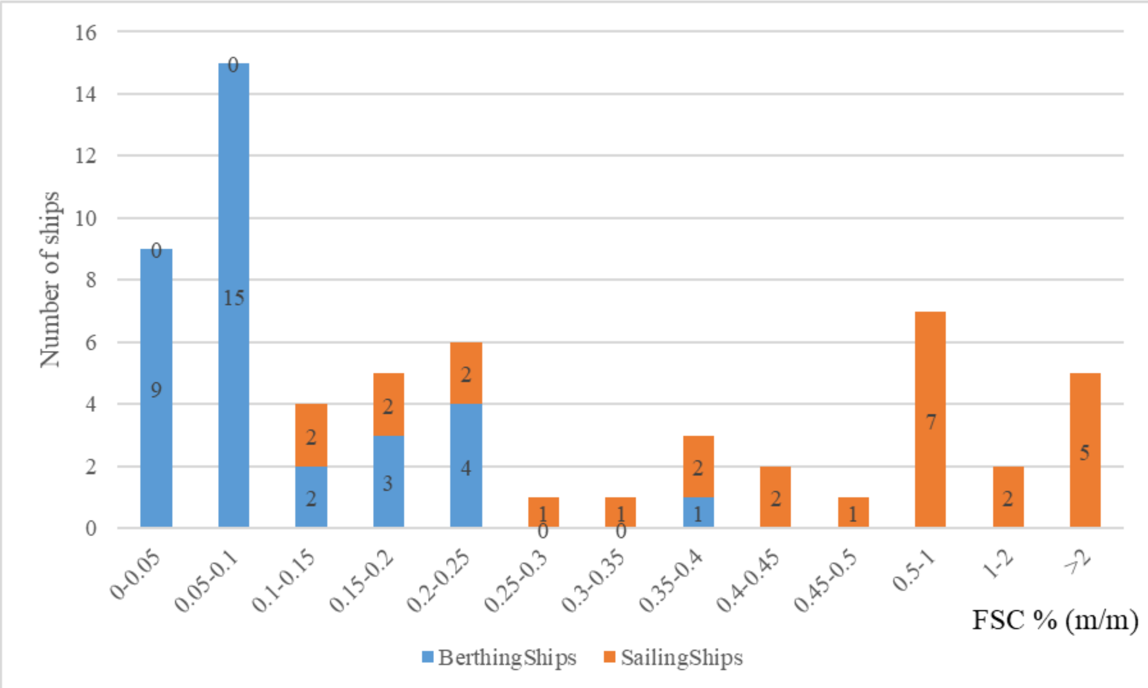


Figure 6. Comparison between the monitoring results of berthing ships and sailing ships.

https://doi.org/10.5194/amt-2020-12
Preprint. Discussion started: 5 March 2020

Atmospheric Measurement Techniques
Discussions

Table 1: Comparison and verification of the estimated (UAV) and true (sampled fuel) values of the FSC from 11 berthing ships.

ID	Estimated value of FSC (ppm)	True value of FSC (ppm)	Deviation (ppm)	Quality
2019-3-18A	2171	2221	-50	Good
2019-3-22A	690	985	-295	Good
2019-3-22B	464	424	40	Good
2019-3-29A	574	345	229	Poor
2019-4-1A	895	787	108	Good
2019-4-3A	<200	128	N	Poor
2019-4-3A	566	917	-351	Good
2019-4-12A	<200	40	N	Poor
2019-4-12B	924	798	126	Good
2019-4-15A	527	440	87	Good
2019-4-15B	1675	1682	-7	Good

Table 2: The estimated (UAV) values of the FSC from 27 sailing ships. "*" indicates that the ship was boarded by the maritime authority for inspection.

ID	Estimated value of FSC (ppm)	Quality	ID	Estimated value of FSC (ppm)	Quality
2019-7-12A	7805	Good	2019-8-22A	1862	Good
2019-7-15A	6464	Good	2019-8-22B	3851	Poor
2019-7-15B*	33687	Good	2019-8-22C	4153	Good
2019-7-25A	5803	Good	2019-8-22D	1122	Poor
2019-7-25B	6752	Good	2019-8-22E	1043	Good
2019-8-14A*	26723	Good	2019-8-22F	2386	Poor
2019-8-15A	3817	Good	2019-9-17A	2021	Good
2019-8-15B	6941	Poor	2019-9-17B	6276	Poor
2019-8-16A	1746	Poor	2019-9-27A	4191	Poor
2019-8-16B	2672	Poor	2019-9-27B*	34495	Good
2019-8-16C	11273	Good	2019-10-9A	21158	Poor
2019-8-16D	7008	Poor	2019-10-17A	4813	Good
2019-8-20A	15076	Poor	2019-10-24A	3258	Good
2019-8-20B*	40913	Good			