https://doi.org/10.5194/egusphere-2024-1015
Preprint. Discussion started: 30 April 2024

Consistency evaluation of tropospheric ozone from ozonesonde and IAGOS aircraft observations: vertical distribution, ozonesonde types and station-airport distance

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Abstract: The vertical distribution of tropospheric O_3 from ozonesondes is compared with that from In-service Aircraft for a Global Observing System (IAGOS) measurements at 23 pairs of sites between about 30°S and 55°N, from 1995 to 2021. Profiles of tropospheric O_3 from IAGOS aircraft are in generally good agreement with ozonesonde observations, for Electrochemical concentration cells (ECC), Brewer-Mast, and Carbon-Iodine sensors, with average biases of 7.03 ppb, 6.28 ppb, and -4.48 ppb, and correlation coefficients (R) of 0.72, 0.86, and 0.82, respectively. Agreement between the aircraft and Indian-sonde observations is poor, with an average bias of 24.07 ppb and R of 0.41. The O_3 concentration observed by ECC sondes is on average higher by 5-10% than that observed by IAGOS aircraft, and the relative bias increases modestly with altitude. For other sonde types, there are some seasonal and altitude variations in the relative bias with respect to IAGOS measurements, but these appear to be caused by local differences.

The distance between station and airport within 4° has little effect on the comparison results. For the ECC ozonesonde, the overall bias with respect to IAGOS measurements varies from 5.7 to 9.8 ppb, when the station pairs are grouped by station-airport distances of <1° (latitude and longitude), 1-2°, and 2-4°. Correlations for these groups are R = 0.8, 0.9 and 0.7. These comparison results

https://doi.org/10.5194/egusphere-2024-1015
Preprint. Discussion started: 30 April 2024

provide important information for merging ozonesonde and IAGOS measurement datasets. They can also be used to evaluate the relative biases of the different sonde types in the troposphere, using the aircraft as a transfer standard.

Key words: WOUDC; IAGOS; tropospheric O_3; vertical distribution; ozonesonde; aircraft

1 Introduction

Ozone (O_3) is a trace gas with small concentrations in the atmosphere (Ramanathan et al., 1985); it is an important greenhouse gas in the atmosphere. In the planetary boundary layer, it is a major air pollutant (Lefohn et al., 2018; Monks et al., 2015). It can endanger human health, damage ecosystems, and affect climate change (Fu and Tai, 2015; Lefohn et al., 2018; Percy et al., 2003). Therefore, it is of importance to study the temporal and spatial distribution and the factors and mechanisms affecting the variation of tropospheric O_3 including near-surface O_3 (Logan, 1985; Ma et al., 2020; Sharma et al., 2017; Young et al., 2018).

A large number of studies have been carried out on the spatiotemporal distribution, formation mechanism, and transport characteristics of ground O_3 (Li et al., 2020, 2021; Vingarzan, 2004; Wang et al., 2017, 2023; Xu et al., 2021; Yu et al., 2021). However, due to the limitation of observations, there are many unknowns on tropospheric ozone, especially the vertical distribution of tropospheric O_3. Satellites provide an effective platform for measuring O_3 globally. Satellite O_3 instruments, including TES, GOME, GOME-2, SCIAMACHY, OMI, and TROPOMI, have been in operation for decades (David et al., 2013; Ebojie et al., 2016; Hegarty et al., 2009; Hoogen et al., 1999; Hubert et al., 2021; Miles et al., 2015). Although satellite observations can provide detailed temporally- and horizontally-resolved maps of tropospheric O_3 columns, in general satellite data lack vertical resolution. While tropospheric differential absorption lidar can also provide vertical distribution information for tropospheric O_3 (Keckhut et al., 2004; Yang et al., 2023), there are very few routinely operating stations.

The principal sources of vertically-resolved, trend-quality observations of tropospheric O_3 are therefore balloon-borne ozonesondes, and IAGOS aircraft observations. The World Ozone and Ultraviolet Radiation Data Centre (WOUDC) and the In-service Aircraft for a Global Observing System database (IAGOS) house the data from these two observation programs with the longest

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duration and the most global stations, which are the most widely used for tropospheric O_3 studies (Gaudel et al., 2020; Liao et al., 2021; Tarasick et al., 2019; Wang et al., 2022). These two datasets are used to study the distribution, variability and trends of tropospheric O_3, and its sources and transport, as well as satellite and model validation (Hu et al., 2017; Gaudel et al., 2018; 2020; Wang et al., 2022; Zhang et al., 2008). The first phase of the Tropospheric Ozone Assessment Report (TOAR-I), initiated in 2014, utilized available surface, ozonesonde, aircraft, and satellite observations to assess tropospheric O_3 trends from 1970 to 2014 (Schultz et al., 2017). Hu et al. (2017) found that the largest bias in a chemical transport model, GEOS-Chem, with respect to ozonesondes and IAGOS observations, is in high northern latitudes in winter-spring, where the simulated ozone is 10-20 ppb lower. Wang et al. (2022) examined observed tropospheric O_3 trends, their attributions, and radiative impacts from 1995 to 2017, using aircraft observations from IAGOS, ozonesondes, and a multi-decadal GEOS-Chem chemical model simulation, and found increases in tropospheric ozone (950 - 250 hPa) of 2.7 ± 1.7 ppbv per decade from IAGOS observations in the Northern Hemisphere and at 19 of 27 global ozonesonde sites averaging 1.9 ± 1.7 ppbv per decade. There are also a number of comparative studies on these two datasets (Zbinden et al., 2013; Staufer et al., 2013, 2014; Tanimoto et al., 2015; Tarasick et al., 2019). Staufer et al. (2013, 2014) used trajectory calculations to match air parcels sampled by both sondes and aircraft. Zbinden et al. (2013) compared coincidences (±24 hours) at three site pairs, while Tanimoto et al. (2015) examined simultaneous observations (±3 hours for sonde versus aircraft) at several site pairs less than 100 km apart. In general, these studies show small (6% or less) negative biases of aircraft measurements against ECC sondes. Tarasick et al. (2019) compared trajectory-mapped averages over 20-70 N of ozonesonde and MOZAIC/IAGOS profiles and concluded that over 1994-2012 ozonesonde measurements were about 5 ± 1% higher in the lower troposphere and 8 ± 1% higher in the upper troposphere.

In this study, we attempt to make the most comprehensive evaluation to date of the relative biases of IAGOS and sonde profiles, using as many station pairs as possible. We identify 23 suitable pairs of sites in the WOUDC and IAGOS datasets from 1995 to 2021, compare the average vertical distribution of tropospheric O_3 shown by ozonesonde and aircraft measurements, and analyze their differences by ozonesonde type and by station-airport distance.

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2 Data and methods

2.1 MOZAIC-IAGOS observations

The MOZAIC (Measurements of OZone and water vapor on Airbus In-service airCraft) program, initiated in 1994 and incorporated into the IAGOS (In-service Aircraft for a Global Observing System; www.iagos.org) program since 2011, takes advantage of commercial aircraft to provide worldwide in-situ measurements of several trace gases (e.g., O_3 and CO) and meteorological variables (e.g., water vapor) throughout the troposphere and the lower stratosphere (Marenco et al., 1998; Petzold et al., 2015; Nédélec et al., 2015). O_3 measurements are performed using a dual-beam UV-absorption monitor (time resolution of 4 seconds) with an instrumental uncertainty of ±2 ppbv+2% (Thouret et al., 1998; Blot et al., 2021). It should be noted that this is only the instrumental uncertainty, and does not include sampling uncertainties (possible losses) caused by the inlet line and the compressor before the UV-photometric measurements are made. Loss of ozone on the inlet pump was an issue in earlier aircraft ozone sampling programs (Brunner et al., 2001; Dias-Lalcaca et al., 1998; Schnadt Poberaj et al., 2007), but Thouret et al. (1998) found it negligible for MOZAIC/IAGOS.

More details on the new IAGOS instrumentation can be found in Nédélec et al. (2015). The continuity of the dataset between the MOZAIC and IAGOS programs has been demonstrated based on their 2-year overlap (2011~2012) (Nédélec et al., 2015). Blot et al. (2021) performed an evaluation of the internal consistency of the O_3 and CO measurements since 1994, which confirmed the instrumental uncertainty of ±2 ppbv. Moreover they found no drift in the bias amongst the different instrument units (six O_3 and six CO IAGOS-MOZAIC instruments, nine IAGOS-Core Package1 and the two instruments used in the IAGOS-CARIBIC aircraft).

2.2 WOUDC ozonesonde observations

The World Ozone and Ultraviolet Radiation Data Centre (WOUDC) is part of the Global Atmosphere Watch (GAW) program of the World Meteorological Organization (https://woudc.org/data/explore.php). The WOUDC is operated by Environment and Climate Change Canada. WOUDC ozonesonde data have been evaluated in a number of WMO-sponsored international field intercomparisons (Attmannspacher and Dütsch, 1970, 1981; Kerr et al, 1994) and

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more recently in laboratory simulation chamber experiments using a standard reference photometer (Smit et al., 2007, 2024; Thompson et al., 2019). In the global ozonesonde network, while different ozonesonde types were common in the past, more than 95% of current sounding stations use electrochemical concentration cells (ECC). ECC ozonesondes have a precision of 3-5% (1-σ) while the precision of other sonde types is somewhat poorer, at about 5–10% for Brewer-Mast and the Japanese KC (Carbon-Iodine) sonde, and somewhat larger for the Indian-sonde (Kerr et al., 1994; Smit et al., 2007). Biases with respect to UV reference spectrometers have been estimated for ECC sondes at 1-5% in the troposphere (Smit et al., 2021; Tarasick et al., 2019, 2021).

2.3 Data processing

The two datasets were first screened for airport-sonde station pairs within a latitude separation of <4° and a longitude separation of <4°. Many sonde stations have observational records that do not overlap with the IAGOS period (1994-present). In addition, the IAGOS dataset has large gaps at many airports, because the frequency of visits to airports by aircraft that take part in IAGOS depends on commercial airlines' operating constraints. In total, 23 station pairs (Fig. 1) were identified with a separation of less than 4° in both latitude and longitude, and coincident observations over at least nine months. The majority of the 23 ozonesonde site records are ECC (17), while four are Indian-sonde, one Brewer-Mast, and one Carbon-Iodine (the Japanese KC sonde). These stations were divided into 3 groups according to the distance (D) between the ozonesonde station and the airport: D<1°, 1°<D<2°, and 2°<D<4°. Specific information on the comparison stations is shown in Table 1.

The observation times of the ozonesonde and aircraft are generally not the same. Ozonesondes are typically launched once a week, although a few stations have more frequent launches. The aircraft records generally contain more frequent observations, but observation times vary. For the selected 23 stations, we calculated the mean ozone vertical profiles at 1km resolution (the first layer is from the surface to 1 km above sea level) for each month during the observational period for the two datasets. A minimum of four aircraft profiles were required to estimate a monthly mean profile; because ozonesonde launches are typically only a few times per month, no minimum was required to estimate a monthly mean profile. Only data with monthly means in both datasets were included for further analysis. Comparisons between the two datasets were made by ozonesonde type and by

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station-airport distance.

3. Results and discussion

3.1 Comparison of the vertical profiles of tropospheric O_3 from four types of ozonesondes and aircraft observations

Previous intercomparisons of sondes launched on the same balloon (Attmannspacher and Dütsch, 1970, 1981; Beekmann et al, 1994, 1995; Deshler et al., 2008; Hilsenrath et al., 1986; Kerr et al, 1994; Smit et al., 2007) have shown that sondes of different types respond somewhat differently to the same ozone profile; that is, they have relative biases, that vary with altitude. Fig. 2 therefore compares the mean vertical profiles of tropospheric O_3 from ozonesonde and aircraft measurements, separated by ozonesonde type. Both O_3 concentrations and absolute differences between ozonesonde and aircraft increase with altitude, especially above 9 km. Average tropospheric O_3 profiles observed by ECC, Brewer-Mast, and Carbon-Iodine sondes are in good agreement with aircraft measurements, with biases of 7.03 ppb, 6.28 ppb and -4.48 ppb, respectively, and correlation coefficients (R) of 0.72, 0.86 and 0.82, respectively (Fig. 3a-3c). The Indian-sonde average shows a linear increase with altitude, while the aircraft measurements indicate an ozone decrease with altitude above 8 km (Fig. 2b). This behaviour is most clearly related to the comparisons of stations 2°-4° apart in spring (Fig. S8). The agreement between the Indian-sonde and aircraft observations is poor, with a bias of 24.07 ppb, and R of only 0.41 (Fig. 3d). The RMSE of O_3 observed with the four types of ozonesondes (ECC, Brewer-Mast, Carbon-Iodine and Indian-sonde) and the aircraft is small, at 49.15 ppb, 42.08 ppb, 33.55 ppb and 45.90 ppb, respectively.

Fig. 2 shows that the mean differences between ozonesonde and aircraft measurements vary significantly with altitude. This can also be observed clearly from the relative differences (RD), expressed as $(O_{3\text{-ozonesonde}} - O_{3\text{-aircraft}})/ O_{3\text{-aircraft}} \times 100\%$ (Fig. 4). O_3 concentrations from ECC measurements are higher than those from aircraft measurements in all altitudes except at the surface. Mean O_3 concentrations reported by Brewer-Mast sondes are lower than those from IAGOS below 7 km, but higher between 7 and 12 km. O_3 concentrations reported by Carbon-Iodine sondes are higher than those observed from aircrafts below 2 km, but significantly lower above 8 km. In relative terms, the bias between ECC sonde and aircraft measurements has only a very modest variation

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with altitude, except near the ground. The mean relative bias for Brewer-Mast measurements is at an absolute maximum of -19 % near the ground, but increases slowly above 3 km, and is positive above 7 km, reaching more than +10 % at 10~11 km. The relative bias for Carbon-Iodine measurements is about 8% below 2 km, is quite small from 2 – 8 km, and becomes large and negative above ~8 km.

The Indian-sonde observations show much larger mean differences from the aircraft measurements. Biases are everywhere positive, and as high as nearly 60% or 30 ppb, with much higher uncertainty (standard errors) at each altitude as well (Fig. 2b, Fig. 4).

These results are broadly consistent with those from JOSIE 1996 (Smit et al. 1996; Smit and Kley, 1998; Thompson et al., 2019), and with the northern hemisphere average result from Tarasick et al. (2019). (Their Figure 20b; note that it is largely based on ECC sondes, and the scale is inverted (IAGOS-sondes) from the sense we use here.)

It should be noted that these comparisons only give an average relative bias between sondes and IAGOS. The true value of the ozone profile remains unknown, as do the absolute biases of sondes and IAGOS.

3.2 Seasonal dependence of relative biases

Fig. 5 compares mean profiles observed by ECC ozonesondes and IAGOS, separated by season. There are modest seasonal differences in the relative bias profiles, with somewhat larger average biases in winter and spring, but average biases are all positive (ECC sondes higher) and at all levels the average seasonal biases are not statistically different at the 95% confidence level.

The modest seasonal differences that are apparent in Fig. 5 and in Figs. S1-S3 are likely due to the modest sample size (for ECC sondes) and small sample sizes (for other types). The actual coincidence in time for profiles can range from less than one day to about 1-3 weeks, depending on the number of ozonesonde and aircraft O_3 profiles collected within each month-bin. This means the larger the atmospheric variability of O_3 is, the larger the real differences between ozonesonde and aircraft O_3 can become, particularly when the number of profiles within a month-bin are small. In addition, there are errors due to variations in the aircraft take-off and landing trajectories and the balloon rise rate, the geographical location of the observation stations (and any associated

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meteorological differences) and any systematic difference in standard observational times.

Table 2 indicates that in all four seasons ECC data correlate well with aircraft observations, with R ranging from 0.71 to 0.76, but with larger average biases in winter and spring, as noted. It is not clear if these seasonal average differences in bias are significant, as the uncertainty ranges on the seasonal averages (lower plot of Fig. 5) overlap.

The vertical distribution of tropospheric O_3 observed by Brewer-Mast and IAGOS aircraft in the four seasons is similar (Fig. S1). Differences are also similar, except above 7 km, where the uncertainties are larger, and in general the uncertainty ranges on the seasonal difference averages overlap. Since these comparisons come from only one station pair, some of the differences may be attributable to local differences in topography and meteorology. Table 2 shows that correlations for the ensemble of Brewer-Mast stations are higher than those for ECC stations. Like the ECC sondes, average biases are all positive, but this is determined by the biases above 7 km (Fig. 4); unlike the ECCs, biases are negative in the lowest 3 km.

The vertical distribution of tropospheric O_3 concentrations observed by Carbon-Iodine sondes and IAGOS aircraft in the four seasons are similar, except in summer when the tropopause is high (Fig. S2). The difference plots are fairly similar, except in the lowest 3 km, where differences become quite large in summer. Like the previous comparison for Brewer-Mast sondes, these comparisons come from only one station pair, and so the large differences in the boundary layer in summer are likely due to local ozone production sampled by the sonde but not the aircraft. Likely for this reason, the consistency between Carbon-Iodine and aircraft observations is poor in summer, with R being only 0.46 (Table 2). For the other three seasons it is fairly good.

The tropospheric O_3 observed by Indian-sondes displays a consistently high bias relative to IAGOS in all seasons, and the seasonal difference plots are quite similar, except in the lowest 3 km in winter (Fig. S3). This different behavior in winter is likely due to local ozone production sampled by the aircraft but not the sonde. Temperature inversions are common in the winter in northern India and trap local pollution. The very low values registered by the aircraft near the surface in summer also suggest local effects, in this case titration by NOx.

Table 2 indicates poor consistency between Indian-sonde and aircraft observations in all four seasons, with R in winter only 0.18.

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3.3 Dependence of relative biases on station-airport distances

A major concern with comparing IAGOS and ozonesonde observations is that the stations and airports are not generally co-located, and even where they are close, the flight paths taken by balloon and aircraft are quite different. Fig. 6 compares the average vertical distribution of tropospheric O_3 observed at different station-airport distances by ECC sondes and IAGOS aircraft. Note that we continue to separate sonde station data by type --- only ECC data are used here. Sonde-aircraft pairs have been grouped by station-airport distance (Table 1). The differences in average bias vary only very modestly between the different station-airport distance categories, and those differences are not statistically different at the 95% confidence level (Fig. 6d). This, partially owing presumably to the use of mean monthly averages, is encouraging, as this provides further evidence that the average bias we have derived is an artifact strictly of instrument differences.

Table 3 indicates that the bias variation between ECC and aircraft observations at different station-airport distances is small, ranging from 5.7 ppb to 9.8 ppb. Correlations for these groupings are also fairly similar, at R = 0.8, 0.9 and 0.7.

Compared with ECC sondes, the consistency between the Indian-sonde and aircraft observations is poor at all station-airport distances, with much larger biases, and poor correlations, with R = 0.2 to 0.4. Nevertheless, Fig. S4 shows that the profiles of average differences are quite similar for station-airport distances < 1°, and distances of 2°~4° (Fig. S4c).

Fig. 7 and Figs. S5-S7 examine possible seasonal variation in the differences at different station-airport distances, for ECC sondes. The mean differences for the different station-airport distance categories are larger than for the annual averages (Fig. 6), but in general those differences are not statistically different at the 95% confidence level (Figs. 7d and S5d-S7d).

3.4 Comparison of ozonesonde relative biases under operational conditions using IAGOS observations as a transfer standard

The foregoing discussion demonstrates that, consistent with previous work, there is a fairly constant relative bias between IAGOS and sondes, with considerable dependence on sonde type, as expected from previous sonde intercomparisons like JOSIE 1996. Although uncertainties are sizeable due to the relatively sparse nature of the available data, we find consistent differences at all sites, with little

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dependence on season or on station-airport separation, and little regional dependence (not shown). Notwithstanding this overall sonde-IAGOS bias, we can use these station-airport comparisons to derive relative biases of the different sonde types in use in the global network.

This does not assume that the aircraft data are unbiased. The true value of the ozone profile (or even its average) remains unknown, as do the absolute biases of sondes and IAGOS. It does assume:

1. That the measurement errors are random and normally distributed;
2. That there is one, constant bias for each measurement type (that is, if, for example, the Indian sonde has changed over the period of comparison, or the IAGOS instruments have different biases, there would be additional error that is not included in our uncertainty estimate);
3. That the measurement biases are not dependent on the geographic location or other variability of the ozone profile. This does not assume that the average ozone profile is the same, just that the instruments respond in the same way.

With these assumptions we can use the results of Fig. 2 to estimate the relative biases of each sonde type to each other. The uncertainty of the comparisons will be the quadratic sum of the uncertainties of the two IAGOS-sonde comparisons. The results are shown in Table 4. This intercomparison of the different sonde types has an important advantage: it compares ozonesonde relative biases under operational conditions, as it compares the data that are actually in databases like the WOUDC. It also fills a gap, as the last WMO international intercomparison involving all four sonde types was JOSIE 1996. These results are broadly consistent with those from JOSIE 1996 (Smit and Kley, 1998; their Table 8 and Fig. 11).

In fact, the types of ozonesonde have changed during long-term observations at some stations (e.g. Uccle and Payerne). De Backer et al. (1998) showed that with the use of an appropriate correction procedure, accounting for the loss of pump efficiency with decreasing pressure and temperature, it is possible to reduce the mean difference between ozone profiles obtained with both types of sondes below 3%, which is statistically insignificant over nearly the whole operational altitude range (from the ground to 32 km). Stübi et al. (2008) also found that the O_3 difference between the Brewer-Mast and the ECC ozonesonde data shows good agreement between the two sonde types, and the profile of the O_3 difference is limited to ±5% (±0.3 mPa) from the ground to 32 km. The results for Brewer-Mast sondes in Table 4 should also be applicable to the older Payerne and Uccle records, and are

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generally consistent with these results and with those for the older Canadian records (Tarasick et al., 2002; 2016).

The results in Table 4 will be quite valuable for addressing the problem of relative biases when merging ozonesonde data into global climatologies (e.g. McPeters et al., 2007; McPeters and Labow, 2012; Bodeker et al., 2013; Liu et al., 2013; Hassler et al., 2018;).

4 Conclusions

The vertical distribution of tropospheric O_3 observed by ozonesondes and IAGOS aircraft sensors are compared at 23 pairs of sites between ~30°S and 55°N from 1995 to 2021. Overall, ECC, Brewer-Mast, and Carbon-Iodine sondes agree reasonably well with aircraft observations, with average biases of 7.03 ppb, 6.28 ppb, and -4.48 ppb, and correlation coefficients of 0.72, 0.86, and 0.82, respectively. The agreement between the aircraft and Indian-sonde observations is poor, with an average bias of 24.07 ppb and R of 0.41.

Notwithstanding this general agreement, all sonde types show significant average biases with respect to IAGOS. The O_3 concentration observed by ECC sondes is on average higher by 5-10% than that observed by IAGOS aircraft, and the relative bias increases modestly with altitude. Seasonal variations in the relative bias are not in general statistically significant at the 95% confidence level. The distance between station and airport within 4° also has little effect on the comparison results. When the ECC station pairs are grouped by station-airport distances of <1° (latitude and longitude), 1-2°, and 2-4°, biases with respect to IAGOS measurements vary from 5.7 to 9.8 ppb, and correlations from 0.7 to 0.9.

Thus, the observed average relative bias between sondes and IAGOS found in this study, also noted by previous authors (Zbinden et al., 2013; Staufer et al., 2013, 2014; Tanimoto et al., 2015; Tarasick et al., 2019), is a robust result. Possible reasons for the difference include: side reactions that cause sondes to produce excess iodine (Saltzman and Gilbert, 1959), and/or loss of ozone on the inlet pump that could cause IAGOS monitors to read low at pressures below 800 hPa. The latter was an issue in earlier aircraft ozone sampling programs (Schnadt Poberaj et al., 2007; Dias-Lalcaca et al., 1998; Brunner et al., 2001), but Thouret et al. (1998) found it negligible for MOZAIC/IAGOS.

This result implies that care must be taken when merging ozonesonde and IAGOS measurement datasets. While the aircraft and sonde measurements are often complementary, filling in important

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spatial gaps that would otherwise exist if only one type were used, the records are not typically over the same period, and so merging can introduce spurious jumps if relative biases are not taken into account.

The importance of ozone in the troposphere as an air pollutant and a greenhouse gas, and therefore of accurate measurements of its temporal and spatial distribution implies that it will be important to resolve the causes of this bias, and so further research involving more direct comparisons of IAGOS instrumentation and ozonesondes, e.g. in the WCCOS chamber, are strongly recommended.

These results are also useful to evaluate the relative biases of the different sonde types in the troposphere, using the aircraft as a transfer standard. This intercomparison of the different sonde types has the advantage that it compares ozonesonde relative biases under operational conditions; that is, the data that are actually in databases like the WOUDC. These results will be invaluable for addressing relative biases when merging ozonesonde data into global climatologies (e.g. Bodeker et al., 2013; Hassler et al., 2018; Liu et al., 2013; McPeters et al., 2007; McPeters and Labow, 2012).

Competing interests. The contact authors have declared that none of the authors has any competing interests.

Data availability. The global ozone sounding data were acquired from the World Ozone and Ultraviolet Radiation Data Center (http://www.woudc.org) operated by Environment Canada. The IAGOS data are created with support from the European Commission, national agencies in Germany (BMBF), France (MESR), and the UK (NERC), and the IAGOS member institutions (http://www.iagos.org/partners).

Author contributions. **HW**: Data curation, Methodology, Validation, Visualization, Writing - original draft preparation, Writing - review & editing, Funding acquisition. **LS**: Methodology, Investigation, Writing - original draft. **DWT**: Data curation, Resources, Conceptualization, Supervision, Writing - original draft preparation, Writing - review & editing. **JL**: Data curation, Resources, Methodology, Conceptualization, Supervision, Writing - original draft preparation, Writing - review & editing, Funding acquisition. **TZ**: Funding acquisition, Writing - review & editing. **HGJS** and **RVM**: Writing - review & editing.

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Preprint. Discussion started: 30 April 2024

Acknowledgments. We thank many whose dedication makes datasets used in this study possible. The global ozone sounding data were acquired from the World Ozone and Ultraviolet Radiation Data Center (http://www.woudc.org) operated by Environment Canada, Toronto, Canada, under the auspices of the World Meteorological Organization. Flight-based atmospheric chemical measurements are from IAGOS. IAGOS is funded by the European Union projects IAGOS-DS and IAGOS-ERI. The IAGOS data are created with support from the European Commission, national agencies in Germany (BMBF), France (MESR), and the UK (NERC), and the IAGOS member institutions (http://www.iagos.org/partners). The participating airlines (Lufthansa, Air France, Austrian, China Airlines, Iberia, Cathay Pacific, Air Namibia, Sabena) supported IAGOS by carrying the measurement equipment free of charge since 1994. We are also thankful to the Digital Research Alliance of Canada at the University of Toronto for facilitating data analysis.

Financial support. This study was supported by the Natural Science and Engineering Council of Canada (Grant No. RGPIN-2020-05163), the National Key Research and Development Program of China (Grant No., 2022YFC3701204), the National Natural Science Foundation of China (42275196 and 41830965), the Natural Science Foundation of Jiangsu Province (BK20231300), and Wuxi University Research Start-up Fund for Introduced Talents (2023r035).

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Figures

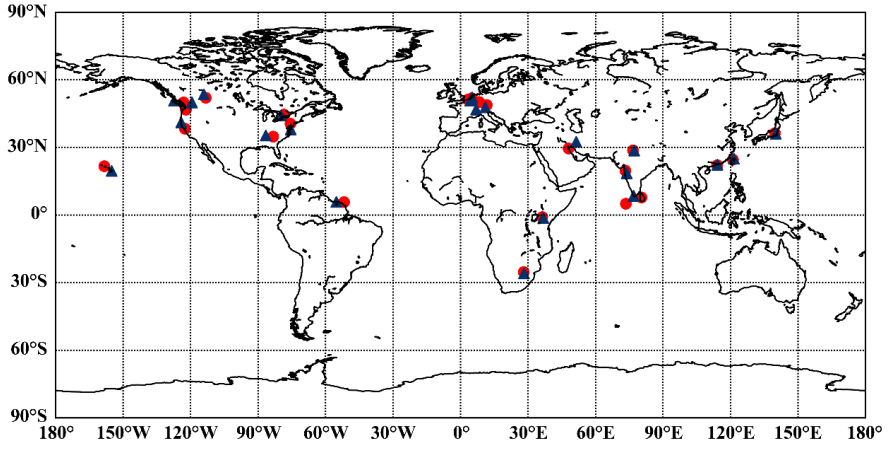

Figure 1. Map of 23 pairs of sites used in this study. Red circle markers are IAGOS sites, blue triangle markers are WOUDC sites.

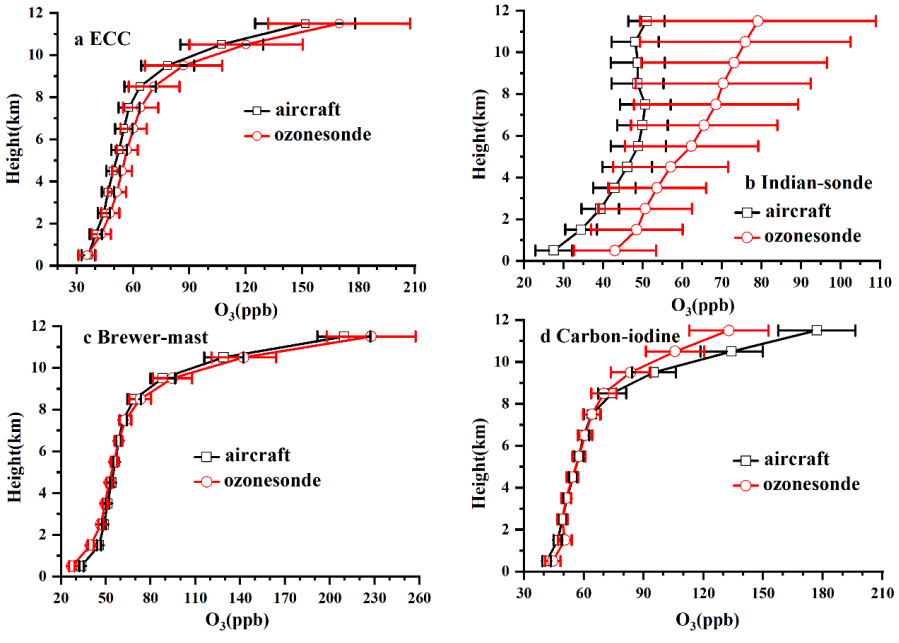

Figure 2. Comparison of the vertical profiles of tropospheric O_3 observed between aircraft measurements and four types of ozonesondes, ECC, Indian-sonde, Brewer-mast, and Carbon-iodine. The error bar length is 4 times the standard error (SE) of the mean (equivalent to 95% confidence limits on the averages).

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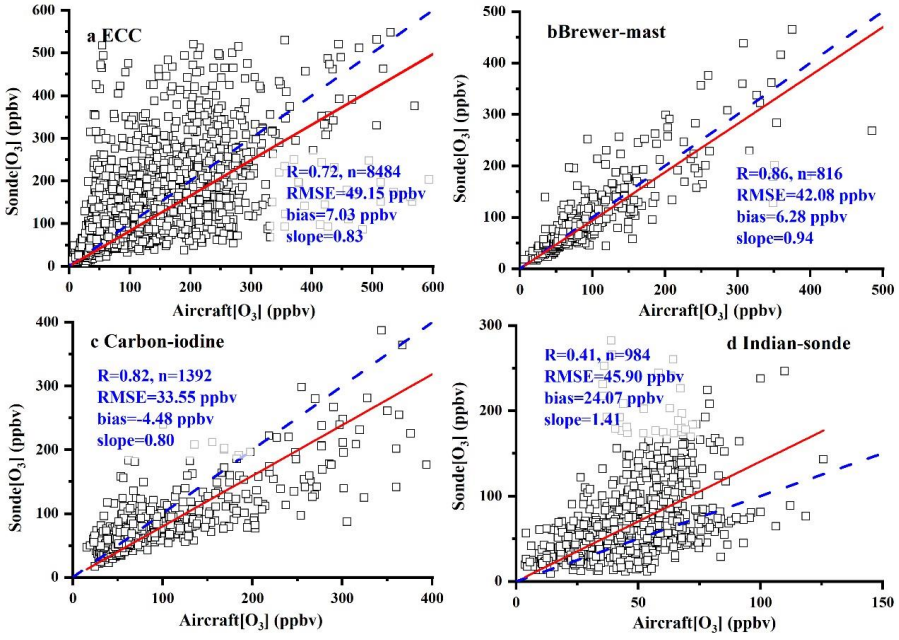

Figure 3. Correlation (R) of ozone mixing ratios between ozonesonde and aircraft measurements. The blue dashed line shows the 1:1 axis. Correlations are significant at the 99% level (p <0.01). N denotes the number of data points, and RMSE is the root mean square error.

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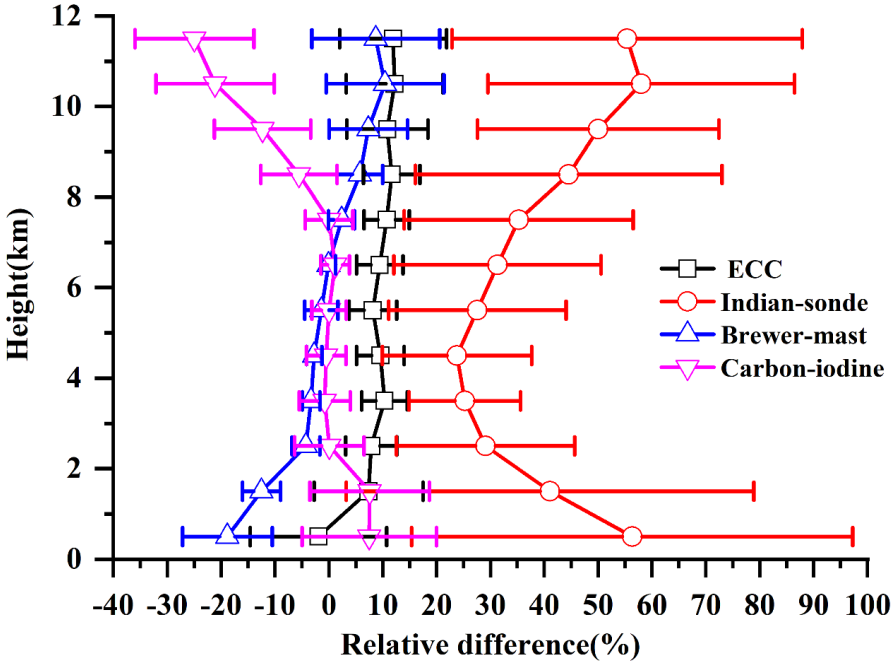

Figure 4. Mean relative difference (RD) between the ozonesonde O_3 and aircraft O_3 data. RD is calculated from ($O_{3\text{-ozonesonde}}$ - $O_{3\text{-aircraft}}$)/ $O_{3\text{-aircraft}}$×100%.

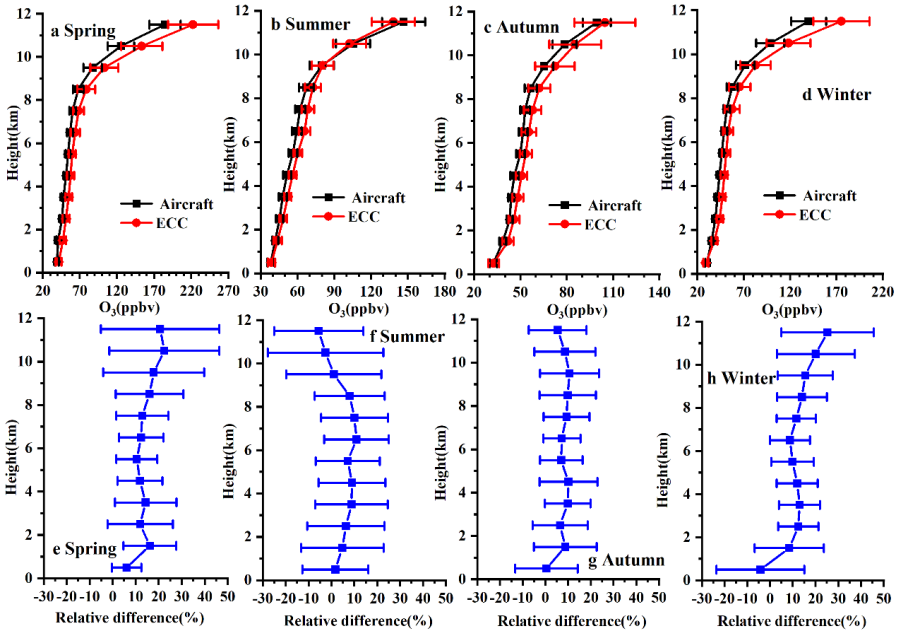

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Figure 5. The mean difference in vertical profiles of the tropospheric O_3 between ECC ozonesonde and aircraft observations in four seasons (a-d) and their mean relative difference (e-h).

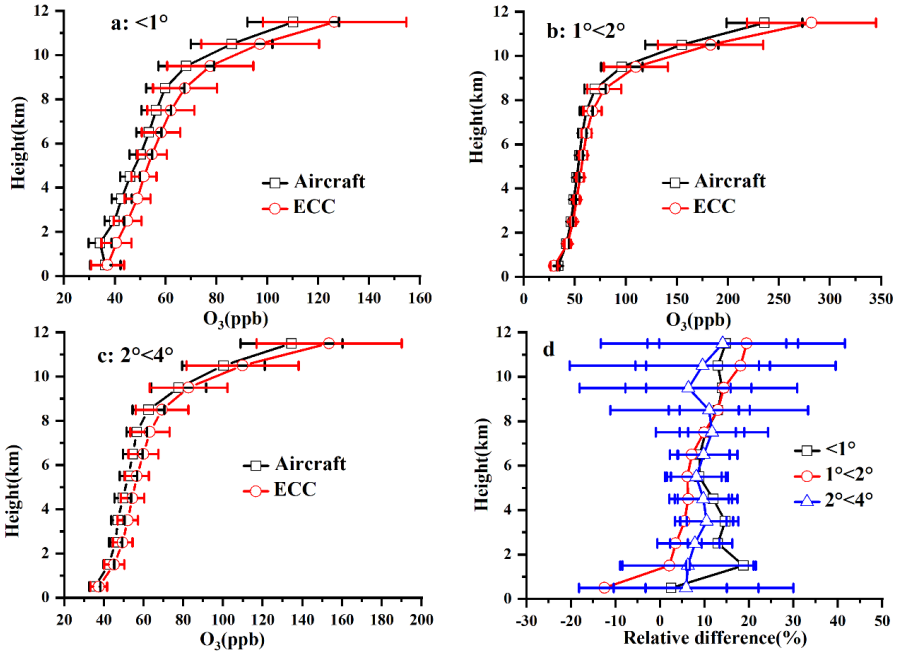

Figure 6. The annual mean vertical profiles of tropospheric O_3 between ECC ozonesonde and aircraft observations at station-pair distances (D) of D<1° (a), 1°< D <2° (b), and 2°< D <4°. The relative differences for the three categories are shown in (d).

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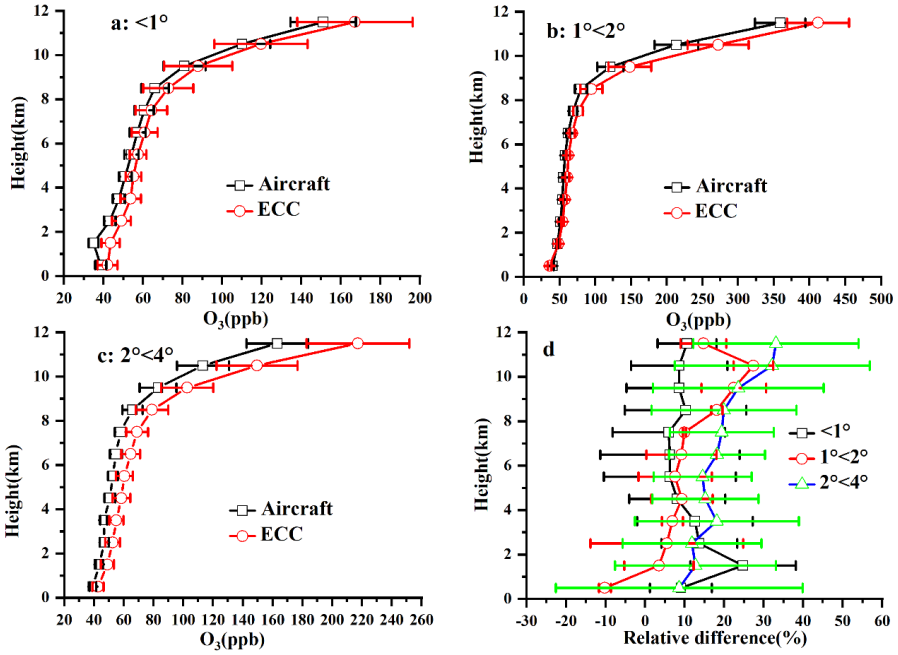

Figure 7. The seasonal mean vertical profiles of tropospheric O_3 in spring between ECC ozonesonde and aircraft observations at station-pair distances (D) of D<1° (a), 1°< D <2° (b), and 2°< D <4°.The relative differences for the three categories are shown in (d).

Tables

Table 1. Summary of the station information, including station's name, geolocation, the number of profiles, observational period, and the station-pair distance used in this study.

MOZAIC-IAGOS				WOUDC					No. valid data months	observation period	station- airport distance
Station name	Lon	Lat	No. profiles	Station name	Lon	Lat	No. profiles	Type			
Toronto	-78.50	44.58	321	Egbert	-79.78	44.23	181	ECC	33	2004-2008	
Dusseldorf	4.96	51.82	412	De Bilt	5.18	52.10	333	ECC	63	1995-2013	
Munich	11.63	48.84	2136	Hohenpeissenberg	11.01	47.80	1032	Brewer-mast	67	1996-2006	
Johannesburg	28.07	-25.32	199	Irene	28.22	-25.91	135	ECC	26	1998-2003	
Nairobi	36.33	-0.94	114	Nairobi	36.75	-1.30	42	ECC	10	1997-1998	<1°
Mumbai	73.27	19.70	122	Pune	73.85	18.53	56	Indian-sonde	35	1996-2003	
Delhi	76.65	28.73	342	New Delhi	77.18	28.63	88	Indian-sonde	50	1995-2016	
Hongkong	114.11	22.10	123	King's Park	114.17	22.31	115	ECC	25	2000-2005	
Taipei	121.08	24.59	2115	Taipei	121.48	25.02	58	ECC	31	2014-2018	
Tokyo	139.73	36.33	1342	Tateno (Tsukuba)	140.13	36.05	655	Carbon-iodine	116	1995-2006	
Calgary	-113.25	52.03	170	Edmonton	-114.10	53.55	112	ECC	17	2009-2011	1°~2°
Brussels	3.24	51.21	2412	Uccle	4.36	50.80	736	ECC	55	1997-2009	
Honolulu	-158.33	21.66	169	Hilo (HI)	-155.07	19.58	107	ECC	16	2015-2017	2°~4°

Vancouver	-123.14	49.95	595	Kelowna	-127.38	50.69	594	ECC	68	2003-2015
San-Francisco	-122.50	38.30	34	Trinidad Head (CA)	-124.15	41.05	53	ECC	10	1999-2001
Portland	-122.06	46.76	385	Kelowna	-119.38	49.97	317	ECC	45	2003-2009
Atlanta	-83.28	34.78	34	Huntsville (AL)	-86.58	35.28	85	ECC	10	1999-2006
Washington	-75.59	40.52	610	Wallops Island (VA)	-75.46	37.94	616	ECC	80	1994-2014
Cayenne	-51.78	5.75	200	Paramaribo	-55.21	5.81	64	ECC	9	2002-2013
Frankfurt	8.30	50.16	12742	Payerne	6.94	46.81	2673	ECC	204	2002-2020
Kuwait-City	48.01	29.52	105	Esfahan	51.43	32.48	34	ECC	17	2001-2004
Male	73.49	5.00	76	Trivandrum	76.95	8.48	45	Indian-sonde	24	1997-2000
Colombo	80.41	7.79	31	Trivandrum	76.95	8.48	37	Indian-sonde	11	1998-2000

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Table 2. Bias, correlation coefficient (R), and RMSE for four types of ozonesonde and aircraft observations in four seasons.

Type	Season	Bias ($O_{3\text{-ozonesonde}}$ - $O_{3\text{-aircraft}}$) (ppb)	R	RMSE (ppb)
ECC	Spring	17.34	0.76	65.52
	Summer	1.96	0.76	40.15
	Autumn	1.75	0.71	34.47
	Winter	7.61	0.71	51.74
Brewer-mast	Spring	10.22	0.94	43.51
	Summer	2.99	0.83	48.79
	Autumn	6.53	0.79	29.40
	Winter	6.11	0.88	45.45
Carbon-iodine	Spring	-9.19	0.84	38.34
	Summer	3.83	0.46	29.31
	Autumn	2.33	0.68	15.10
	Winter	-16.68	0.88	44.72
Indian-sonde	Spring	19.64	0.44	44.30
	Summer	19.58	0.57	37.44
	Autumn	20.38	0.45	37.30
	Winter	40.07	0.18	64.99

Table 3. Bias, correlation coefficient(R) and RMSE for ECC and Indian-sonde ozonesonde and aircraft observations at different station-airport distances.

Type	Station-pair distance	Bias ($O_{3\text{-ozonesonde}}$ - $O_{3\text{-aircraft}}$) (ppb)	R	RMSE (ppb)
ECC	<1°	9.78	0.78	47.46
	1°~2°	8.91	0.90	40.73
	2°~4°	5.65	0.67	51.00
Indian-sonde	<1°	26.71	0.37	49.54
	2°~4°	15.35	0.24	30.86

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Table 4. Comparison of the sondes of each type to IAGOS. (average ± 2 times the standard error (SE)) Indian-sonde/ECC is (Indian-sonde/IAGOS)/(ECC/IAGOS), Brewer-mast/ECC is (Brewer-mast/IAGOS)/(ECC/IAGOS), Carbon-iodine/ECC is (Carbon-iodine /IAGOS)/(ECC/IAGOS)

Altitude(km)	Indian-sonde/ECC	Brewer-mast/ECC	Carbon-iodine/ECC	ECC/ IAGOS
0~1	1.59 ±1.74	0.83 ±0.96	1.10 ±1.36	0.98 ±1.28
1~2	1.31 ±1.83	0.81 ±0.90	1.00 ±1.05	1.07 ±1.58
2~3	1.20 ±1.62	0.89 ±0.97	0.93 ±0.85	1.08 ±1.54
3~4	1.14 ±1.57	0.88 ±0.94	0.90 ±0.87	1.10 ±1.48
4~5	1.13 ±1.61	0.89 ±1.02	0.91 ±0.99	1.10 ±1.44
5~6	1.18 ±1.76	0.91 ±1.05	0.92 ±1.04	1.08 ±1.37
6~7	1.20 ±1.89	0.91 ±1.00	0.92 ±0.82	1.09 ±1.54
7~8	1.22 ±1.92	0.92 ±0.94	0.90 ±0.64	1.11 ±1.69
8~9	1.29 ±2.09	0.95 ±0.99	0.85 ±0.55	1.12 ±1.61
9~10	1.35 ±2.35	0.97 ±1.09	0.79 ±0.62	1.11 ±1.46
10~11	1.41 ±3.26	0.98 ±1.21	0.70 ±0.68	1.12 ±1.37
11~12	1.39 ±4.61	0.97 ±1.19	0.67 ±0.72	1.12 ±1.42