

Analyses of virtual ship-tracks systematically underestimate aerosol-cloud interactions signals

Tianle Yuan^{1,2}, Hua Song^{1,3}, Lazaros Oreopoulos¹, Robert Wood⁴, Kerry Meyer¹, Alice Crawford⁵, William Smith⁶, Ryan Eastman⁴

¹Earth Division, NASA Goddard Space Flight Center

²GESTAR-II, UMBC

³SSAI Inc.

⁴Department of Atmospheric Sciences, University of Washington

⁵NOAA Air Resource Lab

⁶Science Directorate, NASA Langley Research Center

Key Points:

- Positional error in virtual ship-tracks systematically reduces the contrast between polluted and clean clouds
- Assumed fixed width also artificially diminishes signals of aerosol effects
- Improvements in reanalysis winds are needed to realize the potential of virtual ship-tracks

Corresponding author: Tianle Yuan, tianle.yuan@nasa.gov

Abstract

Ship-tracks are important natural/opportunistic experiments to study aerosol-cloud interactions (ACIs). However, detectable ship-tracks are not produced in many instances. Virtual ship-tracks have been conceived to expand the scale of ACIs analyses. Cloud responses in virtual ship-tracks differ strongly from those of detected ones. Here we show that the current approach of virtual ship-tracks can lead to systematic biases and errors and suggest necessary improvements. Errors in trajectory modeling introduce mismatches between areas actually affected by ship-emissions and virtual ship-track locations, i.e., positional errors. Positional errors systematically underestimate ACI signals and the underestimation is severe as indicated by analysis of cloud droplet number concentration changes. The assumption of fixed ship-track width also systematically diminishes resulting aerosol effects by more than 10%, which leads to a forcing difference of around 0.1 Wm^{-2} . We make suggestions to improve the simulation of virtual ship-tracks so that their full potential for studying ACIs can be unleashed.

Plain Language Summary

Ship-tracks are ideal opportunistic experiments that help us understand aerosol-cloud interactions. However, most ships do not produce detectable ship-tracks. Virtual ship-tracks have been conceived to expand the scale of analyses and have revealed new insights. We show here that current methods of virtual ship-tracks has two major errors that systematically bias aerosol-cloud interaction results. We suggest ways to reduce these errors and realize the potential of virtual ship-tracks.

1 Introduction

Ship-tracks are opportunistic experiments (Christensen et al., 2022) that allow attribution of cloud changes to aerosols. They are formed as a result of ship-emitted aerosols modifying cloud properties (Coakley et al., 1987; Hobbs et al., 2000). Such cloud changes can lead to brighter polluted clouds in the shortwave infrared, sometimes even visible, wavelengths that can be directly detected in satellite observations (Conover, 1966; Plattnick et al., 2000; Yuan et al., 2019). Analyses of ship-tracks have improved our understanding of aerosol-cloud interactions (ACIs) (Christensen & Stephens, 2011; Toll et al., 2019; Christensen et al., 2022; Yuan et al., 2023; Gryspeerdt et al., 2020), which helps to expose important processes and reduce the current uncertainty of aerosol indirect forcing (Forster et al., 2021), the leading source of uncertainty in all climate forcings.

However, most ship-emitted aerosols do not form detectable ship-tracks in any wavelength (Yuan et al., 2022; Manshausen et al., 2022) due to causes such as unfavorable cloud types, weak emission strength, and background cloud conditions. For example, strong variability of background clouds can overwhelm the contrast between ship-track and background clouds (Ackerman et al., 1995); Clouds are too broken to form coherent tracks in the trade cumulus region (Yuan et al., 2022; Possner et al., 2018). Absence of detectable ship-tracks however does not mean the lack of impact of emitted aerosols on cloud properties (Manshausen et al., 2022; Diamond et al., 2020). In addition, conditional appearance of ship-tracks leads to preferential sampling of background cloud conditions, which has to be mitigated through large-scale sampling (Yuan et al., 2023) and/or novel techniques to capture cloud responses under diverse conditions. Virtual ship-track is a novel technique developed to study ACIs when explicit detection is not available (Manshausen et al., 2022; Yuan et al., 2023). It is worth noting that we adopt the terms *virtual* and *detected* tracks instead of *invisible* and *visible* tracks because the term 'invisible ship-tracks' assumes the existence of a ship-track, which may or may not be the case. Furthermore, the word 'visible' can be confusing since one may associate it to *visible* wavelength while many times ship-tracks can only be detected in the shortwave infrared wavelength.

Virtual ship-tracks are produced by combining ship location data, reanalysis wind fields, and a trajectory model (Manshausen et al., 2022; Yuan et al., 2023). Cloud adjustments can be studied using these vastly more numerous samples covering diverse conditions. Surprising and important discoveries have been made with virtual ship-track samples (Manshausen et al., 2022).

Here we present evidence that the current method of using virtual ship-tracks to analyze ACIs introduces systematic biases in resulting ACI signals that always dilute true ACI signals. Two major factors contribute to this systematic dilution: positional errors of virtual ship-tracks and assumed fixed track width. We suggest ways to mitigate both to better utilize virtual ship-tracks such as better representation of plume growth and improving wind fields in reanalysis data. We present our method and data in Section 2, results in section 3, and conclusions in Section 4.

2 Method and Data

To obtain virtual ship-tracks, we adopt similar approaches as in previous studies (Manshausen et al., 2022; Yuan et al., 2023). Virtual air parcels are released based on ship location data at regular intervals. Such virtual parcels are advected using a trajectory model, e.g., the HYSPLIT model (Stein et al., 2015) driven by reanalysis wind fields. For any given time and area, we can connect the locations of advected virtual parcels from a ship, released in previous hours, to form the center lines of a virtual ship-track. If a ship-track width is assumed, a virtual ship-track mask can be produced (Manshausen et al., 2022; Yuan et al., 2023). Ship location data are from automatic identification system (AIS) records. The NOAA HYSPLIT model is used to advect virtual parcels driven by the MERRA-2 reanalysis data (Gelaro et al., 2017).

We include 30-hours of AIS data prior to the Moderate Resolution Imaging Spectroradiometer (MODIS) overpass time to produce virtual ship-tracks that would be seen by MODIS. The 30-hour window is chosen to cover a full 24-hour cycle and further increase may introduce larger errors. A width of 10 pixels is assumed for virtual ship-tracks following Manshausen et al. (Manshausen et al., 2022). It is worth pointing out that the actual width of a MODIS pixel can differ substantially from roughly 1-km in size at nadir to a few kilometers at the edge of a swath. We produce more than 6 million virtual ship-tracks in the Northeast Pacific region between 2009 and 2021.

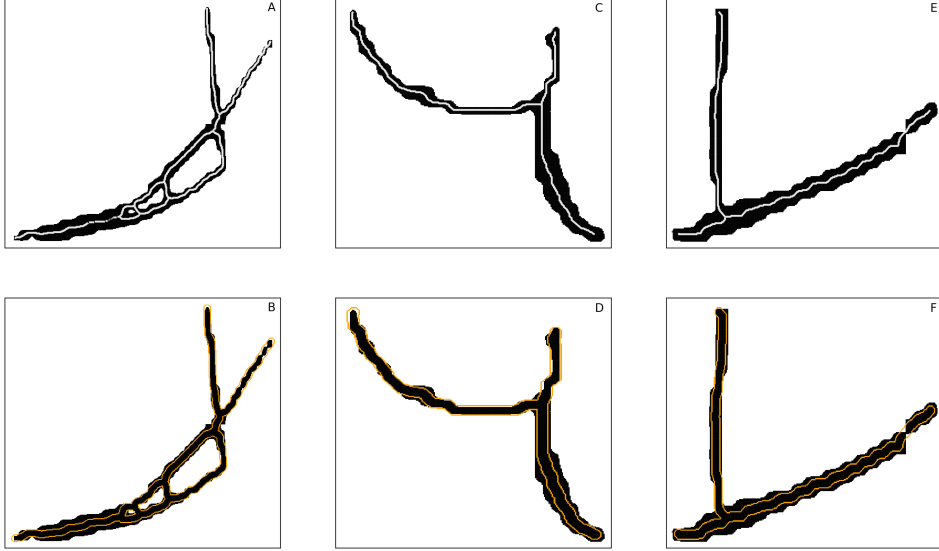


Figure 1. Examples of three detected ship-tracks in black mask, their center lines in white (A, C,E), and corresponding virtual tracks outlined with orange lines (B,D,F). The orange lines are created based on ship-track masks so that both have the same center lines and have a fixed width of 10 pixels. These cases are taken on Dec 2, 2016 at 2140 UTC by Aqua MODIS.

Detected ship-tracks are found with our algorithms applied to MODIS $2.1 \mu m$ reflectance data (Yuan et al., 2019, 2022, 2023). They are used for two purposes. First, detected ship-tracks are taken as the ground truth for the locations of ship-tracks and used to assess the quality of virtual ship-track simulations, i.e., the position and width of ship-tracks. Second, detected ship-tracks are used to assess the impact of assumption of fixed ship-track width on ACI signals in virtual ship-tracks. For the first purpose, we select MODIS granules that contain detected ship-tracks and compare their locations to virtual ship-tracks to assess the quality of virtual tracks. For the second purpose, we take detected ship-track masks and obtain their 'center lines' (Figure 1, top row). We then create their virtual ship-track counterparts that have the same center lines and a fixed width of 10 pixels, as shown in the bottom row of Figure 1. By comparing ACI signals from these two versions that have the same center line positions, we can isolate and quantify the impact of the fixed width assumption. It is important to note that in this exercise, the virtual ship-tracks are created based on the center lines of detected ship-tracks, not through trajectory modeling.

Three examples of detected ship-tracks and corresponding virtual tracks with the same center lines are shown in Figure 1. The top row shows the detected track masks and their center lines. Their corresponding virtual tracks that have the same center line are shown in the bottom row of Figure 1. The virtual tracks can be wider or narrower than the actual tracks at different places. This illustrates the error introduced by the fixed width assumption.

Cloud adjustments are derived through a procedure similar to the one by Yuan et al. (Yuan et al., 2023). Briefly, for each ship-track mask, we apply an algorithm that finds background cloud pixels that are near the ship-track pixels. The cloud responses to aerosols are taken as the difference in cloud properties between background and ship-track pixels. Cloud adjustments are taken as the derivatives of liquid water path (LWP) and cloud fraction with respect to cloud droplet number concentration (N_d). We apply the same cloud adjustment calculation to the two versions of the same tracks, i.e., tracks with fixed

width and actual detected tracks (Yuan et al., 2023). The resulting difference reflects the impact of the assumption of a fixed width.

Level-2 MODIS retrievals (Platnick et al., 2017) are used to analyze the changes in cloud droplet size, cloud optical depth and cloud fraction inside and outside of ship-tracks. N_d and LWP are derived from MODIS cloud droplet size and cloud optical depth retrievals (Grosvenor et al., 2018). For details of data processing, we refer to our previous work (Yuan et al., 2023).

3 Results

3.1 Qualitative assessment of virtual tracks

Since we do not have ground truth for the positions and shapes of virtual ship-tracks, we cannot quantitatively assess the quality of all virtual ship-tracks. Instead, we apply expert judgment to provide qualitative assessment of virtual ship-tracks when corresponding detected tracks are present. Figure 2 shows two MODIS granules that contain detected ship-tracks together with virtual ship-tracks distributions. Some of the detected ship-tracks match virtual tracks in terms of the locations of center lines. The agreement demonstrates the potential of virtual ship-tracks (Manshausen et al., 2022). and also provides validation for the detected ship-tracks (Yuan et al., 2023). This agreement has been noted in previous studies with examples in the southeast Pacific region (Manshausen et al., 2022) and the northeast Pacific region (Yuan et al., 2023). There are also unmatched detected ship-tracks, which can be due to missing AIS data, detected ship-tracks being older than time limit of our trajectory modeling, and positional errors in virtual ship-tracks.

We highlight a few pairs of tracks with white and orange arrows that point to detected and matched virtual tracks, respectively. These pairs of detected and virtual tracks are close to each other, share similar shapes, but do not match perfectly in space. There is a noticeable displacement between the two paired tracks, which suggests that there are errors in virtual trackpositions when compared to detected tracks that we take as ground truth. The positional errors can range from a few pixels to dozens of pixels, or roughly a few kilometers to tens of kilometers. In the examples presented in Figure 2, it is also clear that the width of actual ship-tracks varies. Typically, ship-tracks become wider with time (McMichael et al., 2024) and the mean width for detected ship-tracks is about 10.2 pixels from our global samples (Yuan et al., 2022), which is consistent with the assumed width for virtual tracks. However, the standard deviation of detected ship-track width is 6.5 pixels, a substantial fraction of the mean. Assuming a fixed width thus introduces errors.

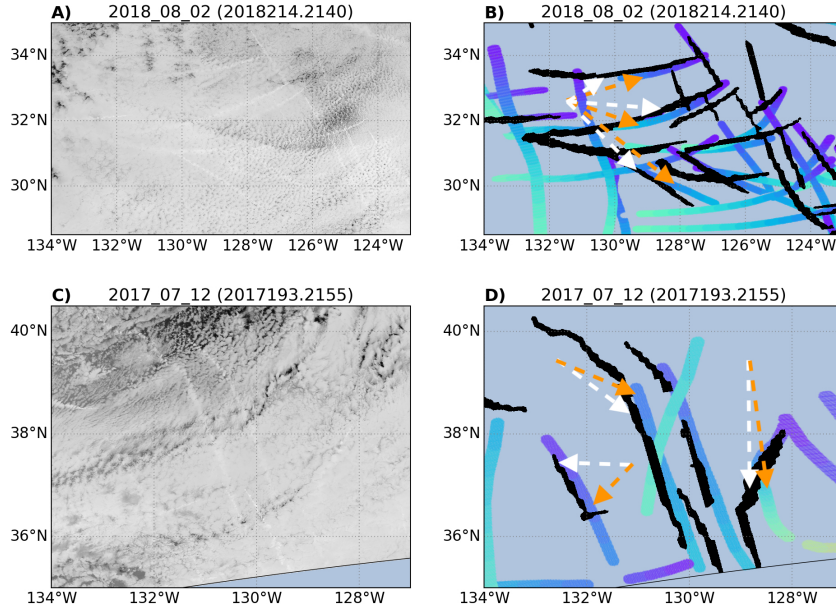


Figure 2. A & C) MODIS 2.1μm reflectance images containing multiple ship-tracks; B & D) virtual ship-tracks in color with fixed width and detected tracks in black-filled masks. We highlight a few pairs of tracks that have noticeable positional errors with orange and white arrows in track mask figures. They are paired based on our best judgment given the data. Positional errors vary in magnitudes, ranging from around 10 pixels to dozens of pixels. e.g., lower right corner in D.

3.2 Impact of mismatch and fixed track width on ACIs

The positional error introduced by virtual ship-tracks can affect ACI analyses based on these samples. Virtual ship-tracks that have positional errors would mix background clean cloud pixels into the polluted population (Figure 3 for an illustration). Similarly, if the positional errors are not large enough to create sufficient separation between detected track positions and virtual ones, the polluted pixels would be taken as the background clean clouds. Indeed, in extreme cases, the cloud responses could be of opposite sign than the actual responses if the positional errors place virtual ship-tracks completely outside of the actual tracks while their control, background pixels overlap with the actual ship-tracks.

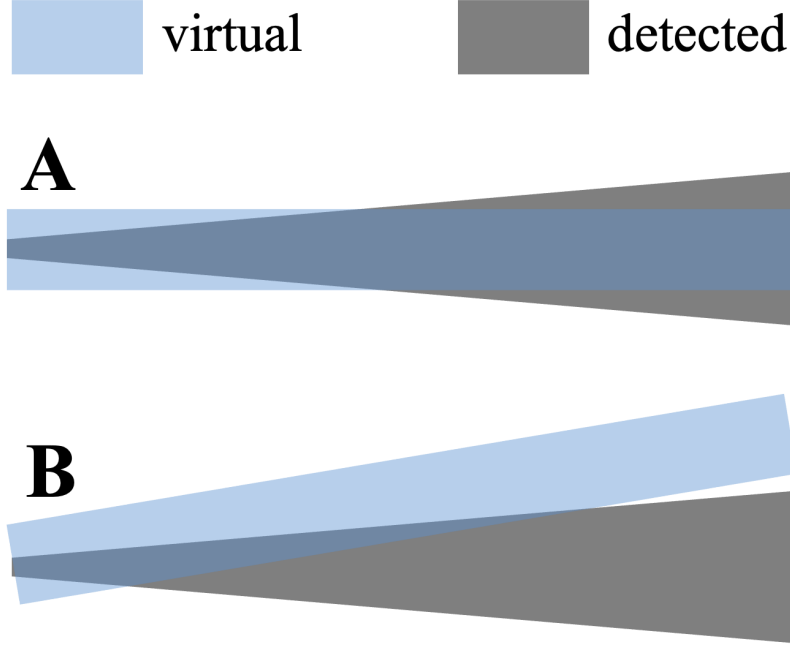


Figure 3. Illustration of how fixed width assumption (A) and positional error (B) of virtual ship-tracks (in light blue color) can affect ACI signals. In A, background cloud pixels are treated as polluted ones when they are close to the head of a ship-track (in dark gray), i.e., more fresh, while the opposite happens when ship-tracks widen as they age. In both scenarios, the contrast between background and ship-track pixels is reduced. In B, we show one possible configuration of positional error. For more aged pixels, ACI analysis would treat polluted ship-track pixels as background while background pixels as polluted, which explains some of the results in Table 1.

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3.2.1 Impact of positional error

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Most of the time, the positional error mixes background pixels into the polluted and part of the polluted with the background, which reduces the contrast in cloud properties between the background and the polluted and makes the analyzed ACI signal weaker than its actual value. The most straightforward example is the difference in ΔN_d . $\frac{\Delta N_d}{N_d}$ reported in the virtual ship track analysis (Manshausen et al., 2022) peaks at about 4-5% while in-situ and analysis of detected tracks often indicate values an order of magnitude larger (Durkee et al., 2000; Christensen & Stephens, 2011; Yuan et al., 2023; Gryspeerdt et al., 2020; Rahu et al., 2022). We believe the positional errors contribute to the order of magnitude difference because the mixing of polluted and background clouds tends to dilute the signal. It is difficult to systematically quantify the impact of positional errors on the ACI signal because it is hard to automatically pair detected ship-tracks with virtual ones. For example, when a mismatch occurs, there are often multiple virtual tracks that could be a match candidate to the detected one. It is hard to automatically select the exact virtual track to pair with the detected one, which prevents us from systematically quantifying the impact of positional error. However, the order of magnitude difference in ΔN_d indicates severe mixing of background and polluted pixel populations due to positional errors.

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Here we illustrate the impact of the positional error on ACI analysis through manually analyzing the ΔN_d , ΔR_{eff} (cloud droplet effective radius), and ΔLWP for the de-

Table 1. Cloud responses derived from actual and virtual track pairs

Track pair	ΔN_d (cm^{-3})		ΔLWP (gm^{-2})		ΔR_{eff} (μm)	
	Detected	virtual	Detected	virtual	Detected	virtual
1	+24.7	+9.2	+1.03	-3.9	-1.5	+0.05
2	+17.3	+4.2	+0.27	+0.26	-0.5	-0.09
3	+36.7	+5.9	+0.39	-5.24	-0.9	-0.4

tected and virtual ship-track pairs in Figure 2D. The results are shown in Table 1. Both ΔN_d and ΔR_{eff} are systematically underestimated. Even the sign of ΔR_{eff} is flipped from negative to positive for track 2. The same happens for ΔLWP . The underestimation of ΔN_d is systematic as discussed above and its deviation from the truth is large, which would strongly bias cloud adjustment calculation since ΔN_d is the denominator. All these factors give rise to substantial biases to the ACI signals based on virtual ship-tracks as shown in Table 1.

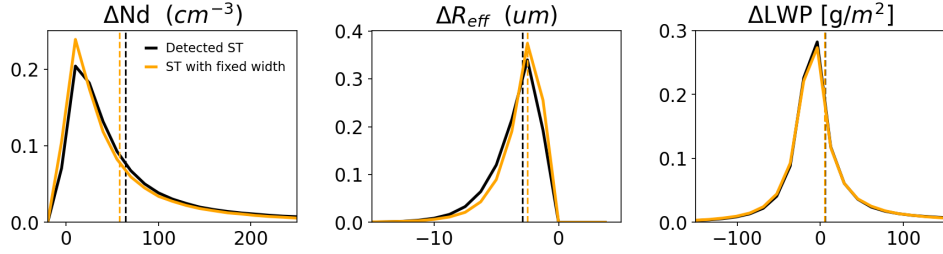


Figure 4. Probability distribution functions of ΔN_d , ΔR_{eff} , and ΔLWP for detected and corresponding virtual tracks. The difference is driven by the fixed width assumption. ST in the legend stands for ship-track.

3.2.2 Impact of fixed width assumption

We can quantitatively assess the impact of assumed ship-track width on the ACI signal. Using detected ship-track samples, we compare ACI signals from detected ship-tracks and their corresponding virtual tracks that have the same center lines. The virtual tracks created from detected ones have no positional errors since their center lines are exactly the same as the detected tracks. The only difference is their width. Figure 4 shows distributions of ΔN_d , ΔR_{eff} , and ΔLWP for both samples. The cloud responses in ΔN_d and ΔR_{eff} are systematically weaker in the virtual tracks with fixed width. The mean ΔN_d and ΔR_{eff} decrease from $-64 cm^{-3}$ to $-58 cm^{-3}$ and from $-2.9 \mu m$ to $-2.5 \mu m$, respectively. Or, a decrease of around 10% and 14% in the magnitude of ΔN_d and ΔR_{eff} . Because ΔLWP can be either positive or negative, it actually increases from $4.9 gm^{-2}$ to $5.8 gm^{-2}$.

The cause of systematic weakening of ΔN_d and ΔR_{eff} can be easily understood as illustrated in Figure 3. Actual ship-tracks are similar to a plume from a point source, narrow at the head and wider with increasing distance from the head. Assuming a fixed width that is close to the mean width always misclassifies background pixels as polluted ones close to the head. The opposite happens for pixels that are farther away from the head. The mixing reduces the true contrast and thus ACI signals.

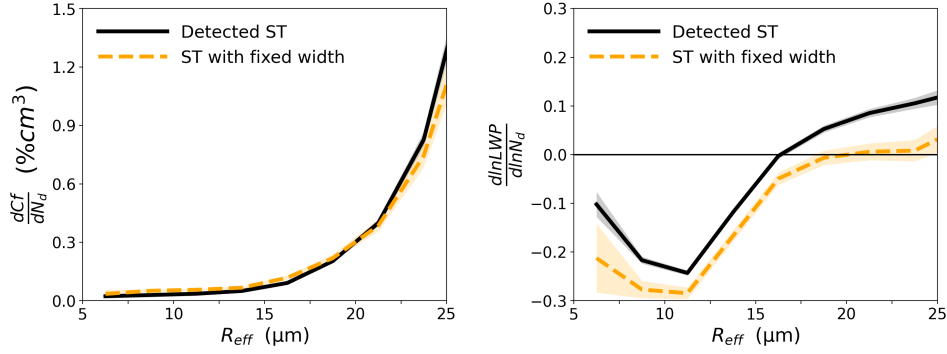


Figure 5. The dependence of cloud LWP and Cf adjustments as a function of background R_{eff} . The solid lines are for actually detected ship-tracks (ST) and dashed yellow lines are for the same tracks but assuming a fixed width of ship-track. The difference between these lines illustrate the impact of the fixed width assumption.

The impact on cloud adjustments, $\frac{d\ln LWP}{d\ln N_d}$ and $\frac{d\ln Cf}{d\ln N_d}$, is shown in Figure 5, where Cf stands for cloud fraction. We use the same analysis procedure to derive them based on detected and virtual ship-tracks. Under clean conditions, i.e., larger R_{eff} , $\frac{dCf}{dN_d}$ is underestimated while it is slightly overestimated when R_{eff} is smaller than around $20 \mu m$. $\frac{d\ln LWP}{d\ln N_d}$ is consistently more negative for virtual tracks. We apply these adjustment functions to estimate global aerosol indirect forcing in the same way as Yuan et al. (2023). The forcing due to LWP adjustment changes from $-0.01 Wm^{-2}$ to $+0.11 Wm^{-2}$, an increase of $+0.12 Wm^{-2}$. The forcing due to cloud fraction adjustment changes from $-0.39 Wm^{-2}$ to $-0.42 Wm^{-2}$, an increase of $-0.03 Wm^{-2}$.

4 Discussion and conclusions

Virtual ship-tracks have great potential as a powerful tool to study ACIs under diverse conditions (Manshausen et al., 2022). However, our study shows that its current implementation suffers from positional errors and the assumption of fixed width. Both result in systematic mixing of clean pixels into polluted ones and vice versa, which always tends to reduce the true contrast between polluted and clean clouds, i.e., the ACI signal. ACI signals from such analyses are systematically biased and thus not trustworthy both quantitatively and even qualitatively. For quantities such as ΔN_d and ΔR_{eff} , they will be systematically underestimated because the true ACI signals have an unambiguous sign. For quantities such as ΔLWP and cloud fraction adjustments $\frac{d\ln LWP}{d\ln N_d}$ and $\frac{dCf}{dN_d}$, neither the sign nor the magnitude of this bias from these errors is clear because LWP can be either positive or negative and the reduced ΔN_d due to mixing could outweigh the underestimation of ΔCf to produce a larger $\frac{dCf}{dN_d}$. It is also important to note that the underestimate discussed here is orthogonal to other potential error sources (Tippett et al., 2024).

The fixed width assumption alone changes ΔN_d and ΔR_{eff} by more than 10%. Their impact on forcing induced by LWP adjustment is strong when compared to the true value of $-0.01 Wm^{-2}$. Its impact on forcing due to cloud fraction adjustment is about 8%. We did not systematically quantify the impact of positional errors on cloud adjustments, but expect it to be more substantial than the impact of fixed width assumption.

The sources of positional errors are multiple. First, the reanalysis wind fields are not perfect. We tested the impact of reanalysis data source by using ERA-5 instead of MERRA-2, and find similar positional errors, but not necessarily for the same cases, in-

dicating neither reanalysis is perfect. This suggests that wind fields may have biases over the remote oceans, which is not a surprise since wind fields are mostly derived from remote sensing rather than direct observations in these regions. The fact that portion of virtual tracks match up with detected tracks showcases the utility of these techniques while mismatches indicate room for improvements. Effort to improve the quality of such wind fields is needed to reduce the positional error. Second, errors in AIS data could also contribute to the positional errors of virtual ship-tracks. Third, it is possible that numerical errors introduced by 3-hourly reanalysis data may have an effect on the position of virtual ship-tracks.

The width of virtual tracks can be better modeled by imposing a width growth model that mimics the actual ship-tracks. However, the plume spreading can have different behaviors depending on the factors such as mesoscale circulation, boundary layer depth, boundary layer stability, and entrainment (McMichael et al., 2024). Detected ship-tracks can be used to constrain such efforts. It is also possible to smartly combine virtual ship-tracks with detected ship-tracks and other airborne or ground-based data sources to provide useful constraints. Fixing the positional errors along with improved width modeling will unleash the full potential of virtual ship-tracks to study ACIs.

Acknowledgments

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Open research

The HYSPLIT model is public and available at <https://www.ready.noaa.gov/HYSPLIT.php>. It is maintained by NOAA's Air Research Laboratory. The MODIS data is also publicly available at <https://modis-images.gsfc.nasa.gov/products.html>. MERRA-2 is open access at <https://gmao.gsfc.nasa.gov/reanalysis/merra-2/>.

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