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16. Abstract

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JASA ARTICLE

Secondary sonic boom predictions for U.S. coastlines

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ABSTRACT:
This study examines the behavior of secondary sonic booms on United States (U.S.) coastlines to have a more complete understanding of the impact of supersonic travel on communities. Secondary sonic booms occur when the atmospheric conditions are such that the atmospheric refraction causes the sound that would ordinarily not reach the ground to bend toward the ground. NASA's PCBoom software is a preferred simulation tool to predict the location and pressure signatures of sonic booms. It was expanded to include secondary boom propagation but has not yet been rigorously used for secondary sonic booms in a variety of conditions. This study looks at how secondary sonic booms change throughout the year and how they behave at different U.S. coastline locations. A detailed analysis of the variability of the atmospheric conditions and how they affect the arrival locations of secondary sonic booms is provided. Good agreement is found between PCBoom and previous work for the arrival locations of secondary sonic booms, which are shown to affect the U.S. east coast predominantly during the summer months and the U.S. west coast during the winter months for projected U.S. inbound supersonic flight scenarios of potential overseas travel.

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I. INTRODUCTION

In the past few years, the possibility of resuming civilian supersonic flight has become more realistic. The first step in making widespread supersonic travel possible will be operating conventional boom aircraft over water. With the return of these aircraft, the understanding of where they can safely fly without negatively impacting coastlines is crucial. An examination of the historical impacts of the Concorde can help identify potential problem areas requiring further investigation.

In 1980, Rickley and Pierce (1980) investigated the source of complaints along the eastern seaboard of strange low frequency sounds. They found that the most likely cause was the Concorde. This was initially surprising because previous complaints related to the Concorde were typical sonic boom sounds that were very loud and had an N-wave signature with large overpressures and distinct shocks. The new offending sounds were recorded during the investigation and showed predominantly low frequency content at a sound level much lower than that for the traditional sonic boom. However, the arrival times and locations were consistent with the Concorde arriving at east coast airports. The source was identified as secondary sonic booms, sometimes referred to as over the top (OTT) booms. These types of signatures result from atmospheric conditions that bend the sonic boom emitted from the top of the aircraft or the bending of the boom that has bounced on the ground toward the earth, and are referred to as type 1 and type 2 secondary sonic booms, respectively (Rickley and Pierce, 1980). A graphic representation of type 1 and type 2 rays is provided in Fig. 1. The atmospheric conditions that cause the refraction of these sonic booms are largely due to the upper atmospheric winds. Due to refraction, the energy that would normally escape into the atmosphere bends back down toward the ground. These booms may turn downward in the stratosphere and thermosphere. The arrivals considered in this study are the stratospheric arrivals. The thermospheric arrivals are not considered for this study due to the extended travel distances, which would reduce the pressure signatures on the ground substantially and are not expected to have as large of an impact.

Secondary sonic booms from the Concorde were also detected in Europe, but they were observed to be stronger in the winter months as compared to the summer months (Liszka and Waldenmark, 1995). The Concorde's secondary sonic booms could make houses shake and cause rattle. As a result of the investigation by Rickley and Pierce (1980), the Concorde's operations were modified by moving supersonic flights farther from the coastline, and this change solved the problem at the time but further reduced the allowable areas for supersonic flight. The earliest recorded observation of these secondary sonic booms was at a flight test in 1959 (Rogers and Maglieri, 2015), therefore, early researchers were aware of the existence of these secondary booms before the complaints recorded in 1980. There are some studies looking at the trajectories and effects of the secondary sonic booms, but most of the early research focused on the primary carpet. A recent literature review is available that includes a comprehensive review of previous work

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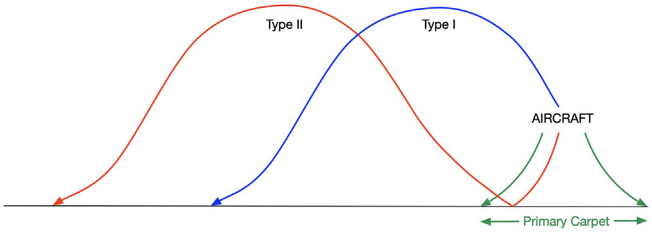


FIG. 1. (Color online) The ray trajectories of type I and type II secondary sonic booms.

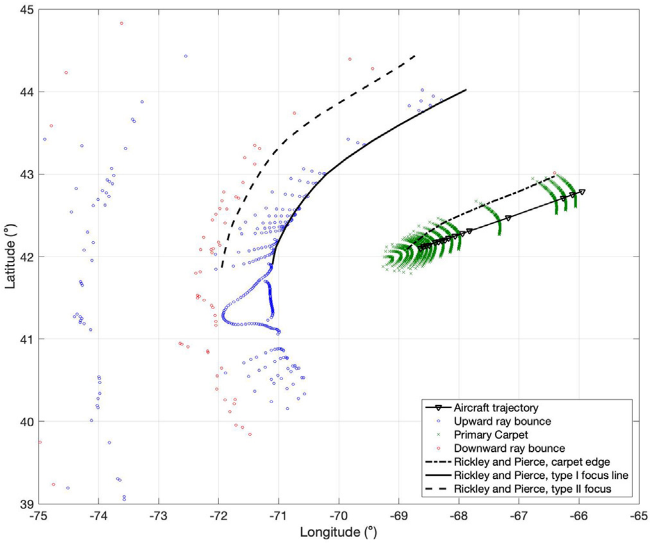


FIG. 2. (Color online) A comparison between the original predicted arrival locations of secondary sonic booms from the 1980 Rickley and Pierce report (in black) and the arrival locations predicted by PCBoom (in color) for an approach to the east coast of the U.S. Type I rays are shown with the blue dots compared to the solid focus line that shows the predicted results from Rickley and Pierce. The triangular markers depict the location points of the aircraft along the trajectory. The speed of the aircraft is decelerating from Mach 2.0 to Mach 1.18. The dashed lines show the type II prediction as compared to the red dots from PCBoom. The term focus line in the report indicates the region where the arrival of each type of secondary boom begins (Rickley and Pierce, 1980).

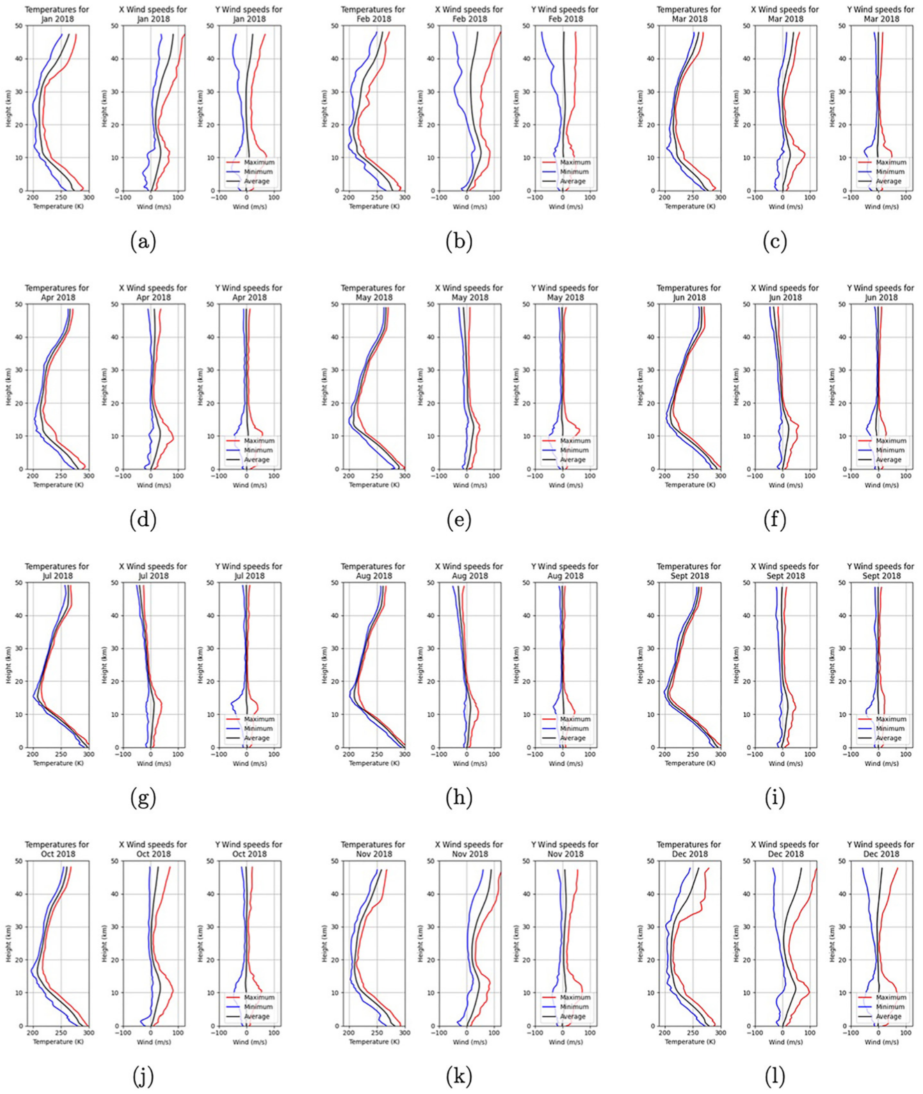
regarding secondary booms (Sparrow and Riegel, 2020). In this study, the NASA tool PCBoom was used to further investigate how sonic booms propagate from the aircraft in different atmospheric conditions to better predict and understand the arrival of secondary sonic booms, particularly for United States (U.S.) coastlines (Plotkin *et al.*, 2007). Understanding these arrival locations will provide valuable insight to the aircraft regulators as well as the airlines to comprehend the limitations on the overwater routes available. The results presented will focus on the arrival locations of the secondary sonic booms. Although the current state of the software does not allow us to accurately predict the pressure versus time signature, it is important to predict the landing positions of the secondary booms to allow for planning the resumption of overwater supersonic flight. The current plan of industry is to initially bring back aircraft having *N*-wave sonic booms similar to the Concorde where supersonic operation will only be overwater. Hence, we expect the secondary sonic booms of these new aircraft to be similar if not identical to those from the Concorde.

II. COMPARISON WITH 1980 REPORT

To ensure that the PCBoom software (Page *et al.*, 2020) correctly propagated the secondary sonic booms, the conditions and results from the original report by Rickley and Pierce (1980) were used as a test case to simulate the arrival locations for a Concorde flight trajectory on the east coast. Rickley and Pierce previously predicted the arrivals on the east coast and validated them using measurements during actual Concorde flights. The predicted arrival locations from the Rickley and Pierce report were compared to the predicted arrival locations from PCBoom. The arrival locations of the sonic booms as calculated by PCBoom compared to Rickley and Pierce are shown in Fig. 2. In Fig. 2, the arrival locations of type I (initially upward) and type II (initially downward) are shown, and the border of the primary carpet is also identified. The comparison between the two methods shows good agreement, which provides some confidence that PCBoom can accurately predict the arrival locations of both types of secondary sonic booms. The triangles show the aircraft trajectory, and the green crosses surrounding the trajectory show the primary sonic boom carpet. The trajectory points are not evenly spaced as they were in the original data provided by Rickley and Pierce for British Airways flight 171 into John F. Kennedy Airport in New York (JFK) on 6/20/1979. For these calculations, the atmospheric wind and temperature profiles were matched to those provided in the Rickley and Pierce report. The arrivals that are shown between −73° and −75° longitude were not given in the original report. They is a second arrival of the rays, for example, a ray that initially went upward and then reached the ground at approximately −71° longitude would then bounce off the ground and be refracted back down by the atmosphere again for a second arrival. These locations are expected to have much lower pressure levels due to their longer propagation distances.

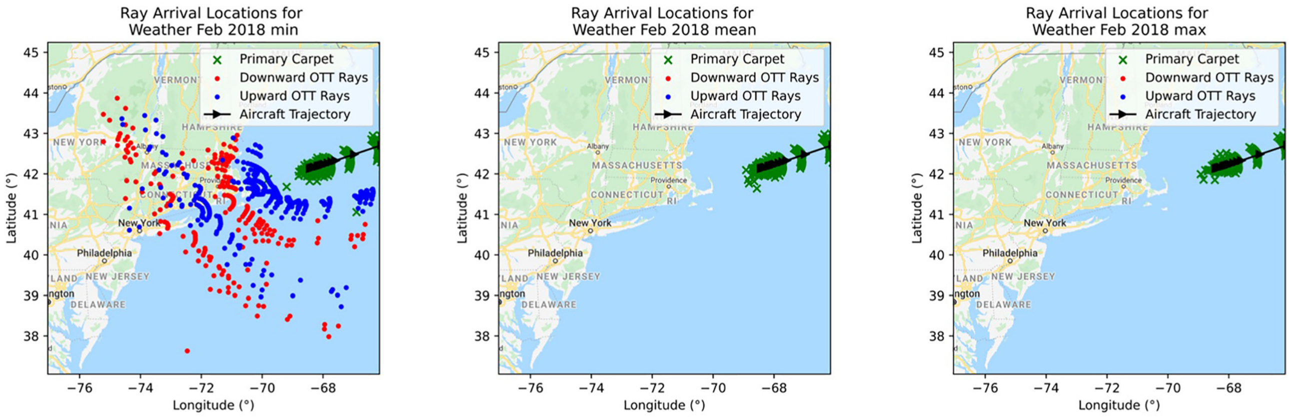
III. AIRCRAFT AND TRAJECTORY

To ensure a realistic aircraft trajectory for an aircraft approaching a U.S. coastline, the same Concorde trajectory outlined in the report by Rickley and Pierce (1980) will be used as the basis for all of the trajectories used in this study. The Concorde was used as the aircraft because it has a well-studied signature, and the near-field pressure signatures are built into PCBoom. Although the speed location and heading were given in the original report, the acceleration and changes in acceleration were not included. PCBoom contains a feature called TADVNCE, which will advance the trajectory for the given time step appropriately and determine the acceleration and any changes in acceleration that need to be included to ensure that these aspects of the kinematics were accurately simulated. This was performed by using the original trajectory as a guide and creating a final enhanced trajectory. The use of these trajectory points



(a) (b) (c) (d) (e) (f) (g) (h) (i) (j) (k) (l)

FIG. 3. (Color online) The minimum weather profiles present for each month of the year are shown in red. The maximum weather profiles present for each month are shown in blue, and the mean weather profile appears in black. These profiles show the variability in the temperature and wind speeds off the east coast of New York City.



(a) (b) (c)

FIG. 4. (Color online) The arrival locations resulting from the extreme weather profiles for the month of February 2018. The minimum profiles (a) show the arrivals of secondary sonic booms while the mean profile (b) and maximum profile (c) do not show any secondary sonic boom arrivals.

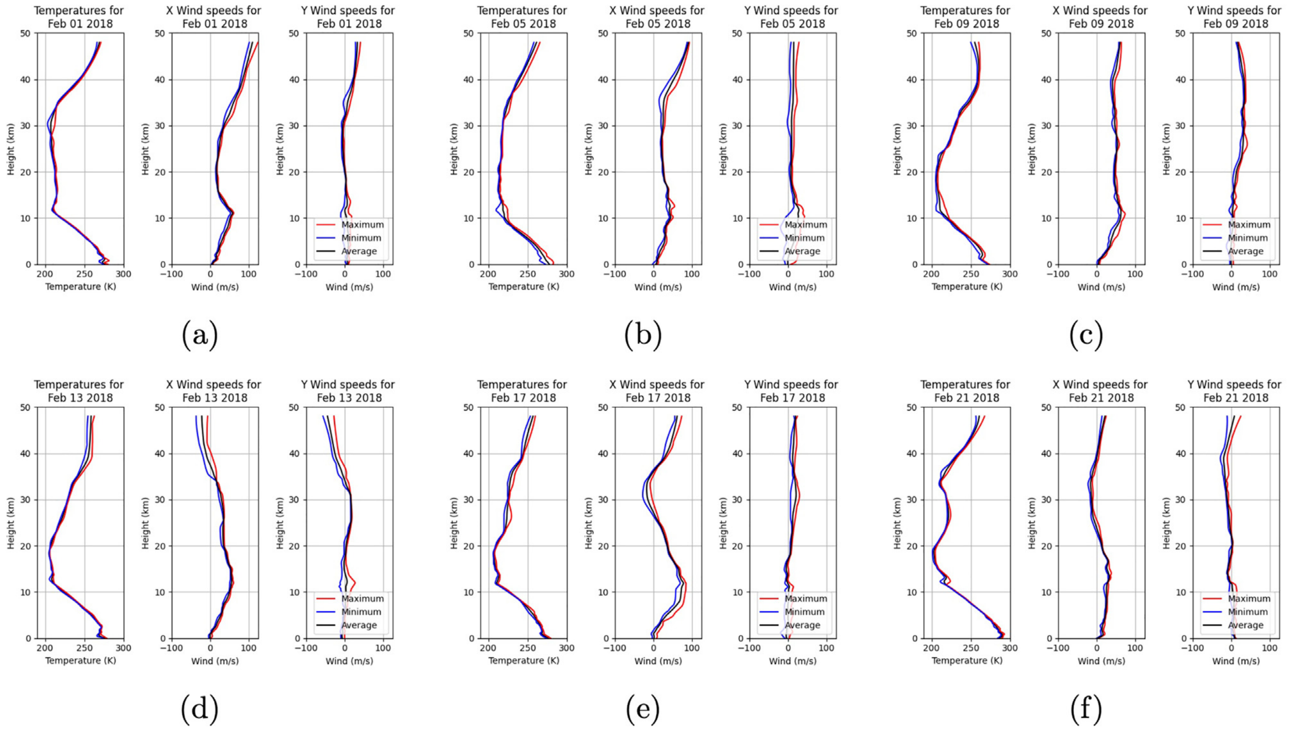


FIG. 5. (Color online) The weather profiles for six example days in February. The profiles vary little between different times of day for each day.

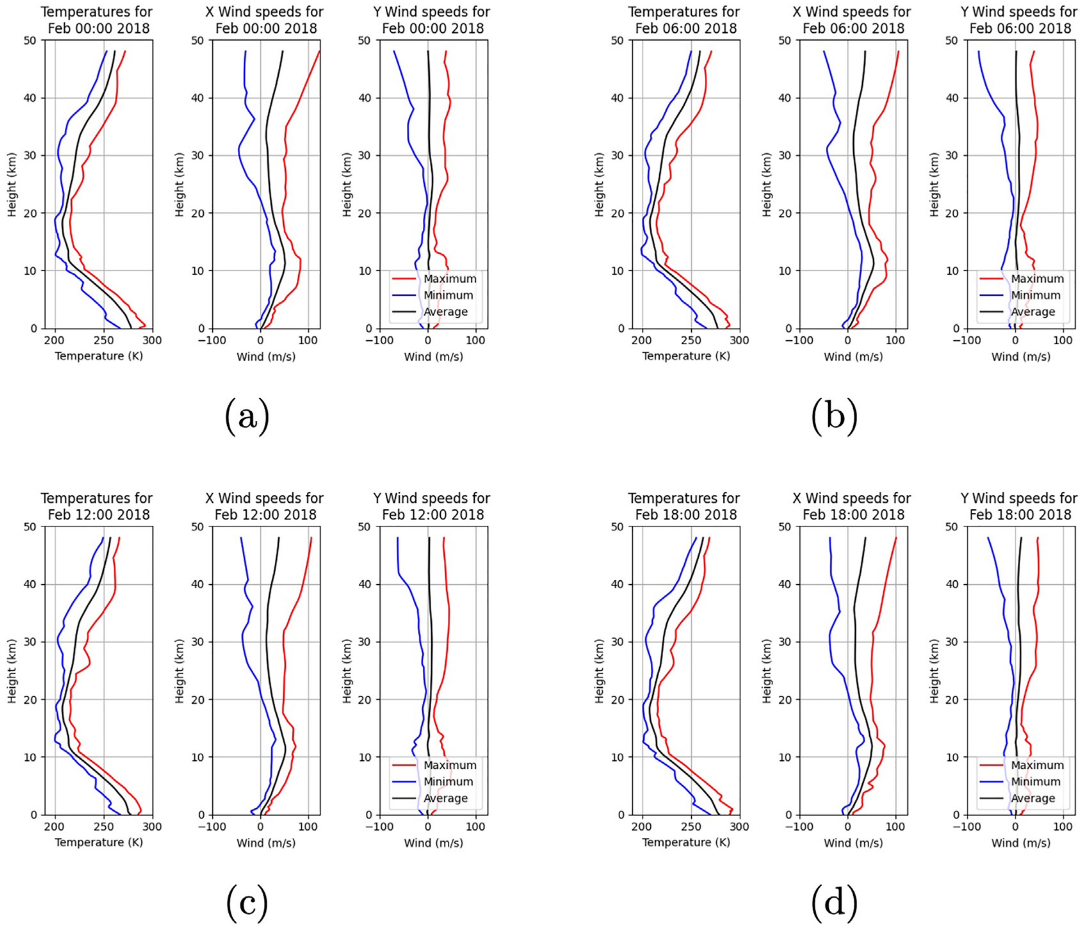


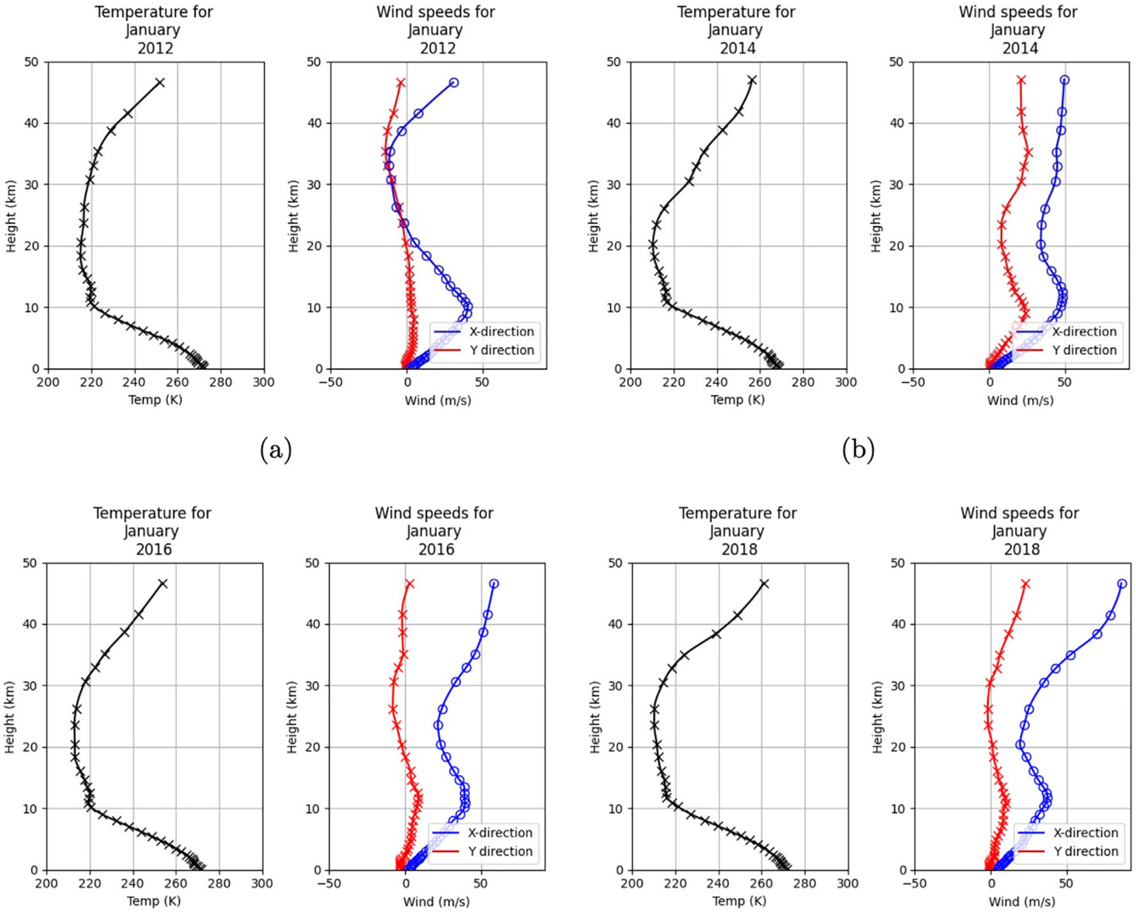
FIG. 6. (Color online) The maximum, minimum, and mean profiles for the month of February. The average values for the month show the time of day. There are substantial variations in weather throughout the month.

means that the origin points of the trajectory are not necessarily uniformly spaced. This causes some gaps in the resulting arrival locations, but the regions of effect from the secondary booms are clearly visible. In each of the figures provided (Figs. 2, 4, 9, 10, 12, 14, 16, and 17), this aircraft trajectory is shown by the triangular markers. All three trajectories, the New York approach, LAX (Los Angeles) approach, and Seattle approach, use the same speeds and acceleration profiles. The speed of the aircraft starts at Mach 2.0 and decelerates to Mach 1.18. The closest trajectory point to the coastline for each of the east coast simulations is approximately 175 km off of the coastline. Using the rate of deceleration toward the end of the trajectory, the aircraft is expected to reach subsonic speeds approximately 160 km off of the coast. For the LAX approach trajectory, the aircraft is coming from the south as it approaches LAX for a landing. The closest trajectory point is approximately 225 km away from the west coast and expected to reach subsonic at approximately 220 km away from the coast because the trajectory is approximately parallel to the coast. A supersonic aircraft arrival into Seattle from the west to simulate an inbound flight from Tokyo was also created. The distance from the coast is approximately 270 km, and the aircraft is expected to reach subsonic speeds approximately 255 km off of the west coast.

IV. VARIABILITY OF WEATHER PROFILE DATA

To determine the variability of the impact of secondary sonic booms due to fluctuations in the weather on an hourly, daily, and monthly basis, the weather profiles from different times of day, different days, and different months were examined. The atmospheric conditions up into the stratosphere are required for the secondary boom calculations. To obtain these atmospheric conditions, the National Centers for Environmental Prediction (NCEP) Climate Forecast System Version 2 (CFSv2) was used (Saha *et al.*, 2011). This database provides weather data at six hour intervals, 00:00 UTC, 06:00 UTC, 12:00 UTC, and 18:00 UTC, which correspond to 19:00 EST, 01:00 EST, 07:00 EST, and 13:00 EST.

The atmospheric profiles (every 6 h for each month) were compiled. The maximum, minimum, and mean temperatures, east-west winds (x-direction), and north-south winds (y-direction) for each height were determined. This creates a mean profile but also shows the variability in the



(a) (b)

(c) (d)

FIG. 7. (Color online) The average temperature profiles and wind speed profiles with altitude are shown for January, a month representative of the winter weather. The x-direction winds in the upper atmosphere are consistently easterly, and the temperature profiles are consistent over all four years.

weather throughout the month. These weather profiles for each of the 12 months in 2018 for a point off of the east coast of New York are presented in Fig. 3.

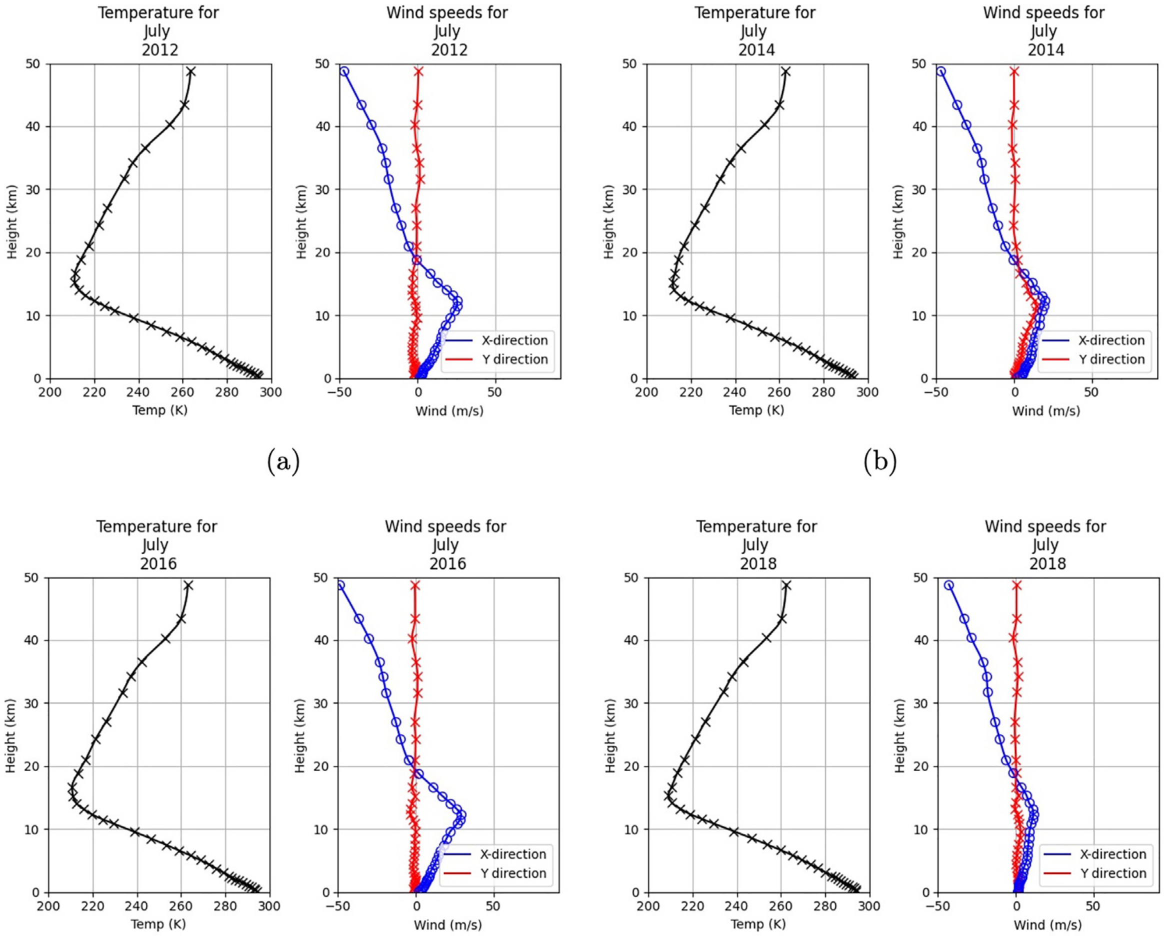
Figure 3 shows that for many months of the year, especially in the summer, the weather profile shows very little variation. In particular, the upper atmosphere variation is small. The winter months show considerably more variability. To determine how this affects the arrival locations of the secondary sonic booms, these extreme profiles were used as the atmospheric profiles for PCBoom. In general, the results for the maximum, minimum, and mean are very similar with a few notable exceptions. February, December, and April had at least one profile that predicted secondary sonic booms when the others did not. This is not unexpected for a month like April in which the seasonal transition produces large changes in the weather. Figure 4 shows the secondary sonic boom arrivals resulting from the three profiles for February. Discrepancies between the predictions using the mean and minimum profiles are apparent. In Secs. IV A–IV C, February and December are examined in more detail to better understand the differences in the results.

A. Hourly data

To further study some of the months that showed differences between the mean value and extreme profiles, the data were further broken down into the average weather profiles for each day to determine the variability as the time of day changed. Figure 5 shows minimum, maximum, and mean profiles for some example days of February. The tight grouping of these profiles exhibits that there is very little variation during any given day. This shows that the time of day does not have a substantial impact on the resulting weather profile and, therefore, the arrival of secondary sonic booms does not vary greatly during any given day. December and April, the other months that had significant variation in their extreme profiles, show similar trends where there were very small variations throughout each day.

B. Daily data

To illustrate the variability through the month on a daily basis, the daily averages for each time of day are depicted in



(a) (b)

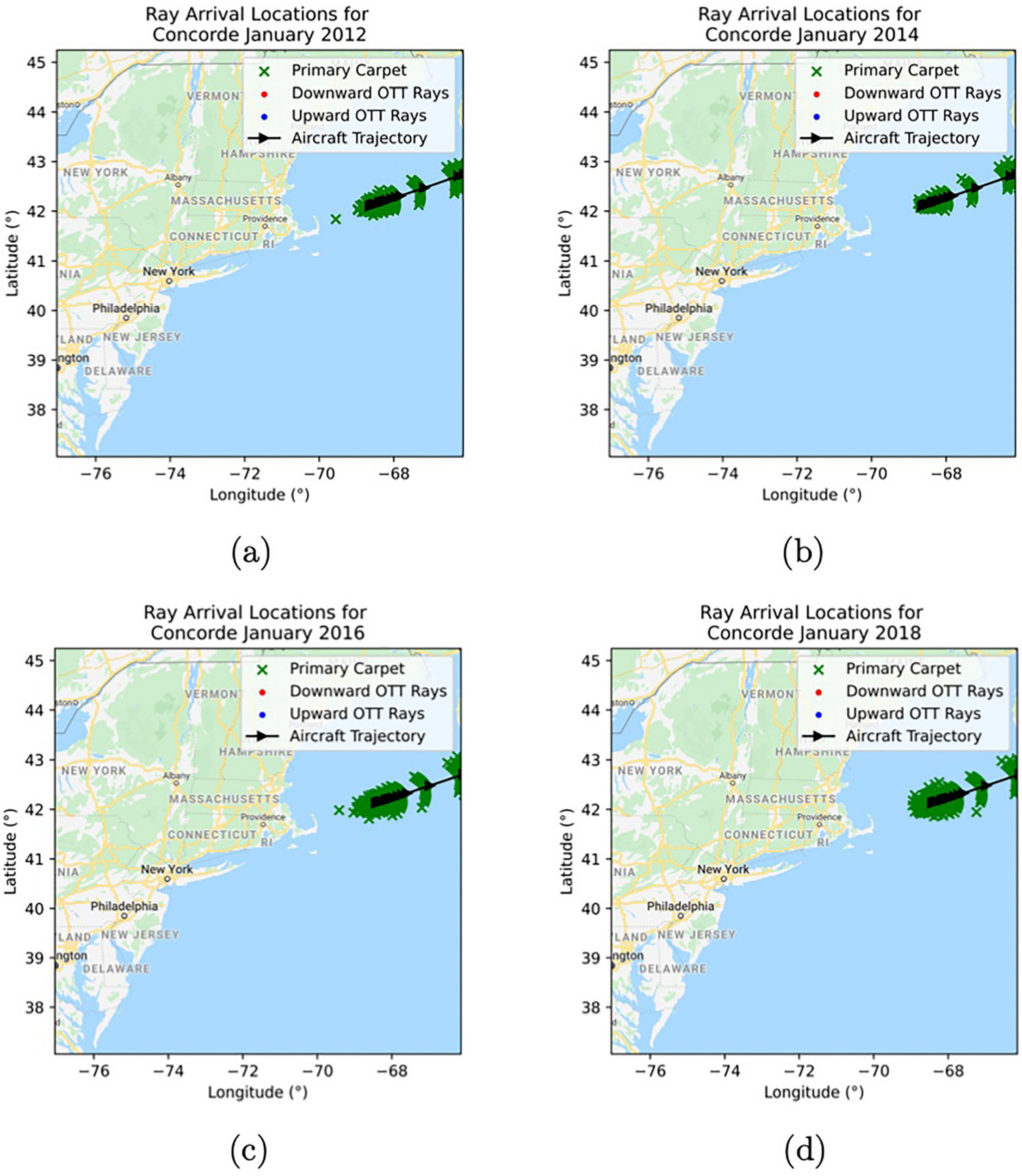
(c) (d)

FIG. 8. (Color online) The average temperature profiles and wind speed profiles with altitude are shown for July, a month representative of the summer weather. In contrast to the wind profiles shown for the winter months (Fig. 7), the upper atmosphere x-direction winds are in the easterly direction.

Fig. 6. Figure 6 shows that the majority of the variability throughout the month is based on the daily fluctuations. The prediction of secondary sonic booms was determined with the mean daily weather profiles that were simulated for each of the highly variable months. For all three months, the mean profiles did not predict any secondary boom arrivals. In February, 7 of 28 days resulted in the arrival of secondary booms, and 2 of those days did not impact the coast. For December, 6 days resulted in the arrival of secondary sonic booms with 5 impacting the coast. In April, only three daysresulted in the arrival of secondary sonic booms, all of which took place very late in the month.

C. Overall weather profile stability

The time of day, day of the month, and monthly variability were examined to determine the impact on the arrival locations of secondary sonic booms. The time of day did not change the atmospheric profiles substantially nor affect the secondary sonic boom predictions. The three months that showed differences between the monthly averages and extreme daily profiles had a small percentage of days that did not agree. For February, the daily averages agreed with the monthly average about impact to the coastline approximately 82% of the time. For December, this agreement was 84% and for April, it was 90%. For all of the other months,



(a) (b) (c) (d)

FIG. 9. (Color online) The arrival locations for booms on the east coast for January in the years 2012 (a), 2014 (b), 2016 (c), and 2018 (d) to represent the behavior for the winter months. The triangular markers show the origin points of the aircraft along the trajectory. It is shown that there is no impact on the east coast from secondary sonic booms for the winter months.

the agreement was 100%. This means that for the year, the agreement was at 96.5%. This is evidence that, in general, the average monthly atmosphere profiles are sufficient for predicting the impact on the coastlines from secondary sonic booms.

V. SECONDARY SONIC BOOMS THROUGH TIME

To determine if consistent trends were observable during different years for the east coast of the U.S., the arrival locations for the years 2012, 2014, 2016, and 2018 were simulated. The average atmospheric data from the CFSv2 database for each month at a latitude of 41.5° N and longitude of −70.5° W were used for the years 2012, 2014, 2016, and 2018. The weather varies from year to year, but a common characteristic of the winter months is an average westerly (positive *x*) wind in the upper atmosphere. In the summer months, the winds in the upper atmosphere change and blow in an easterly (negative *x*) direction. Figure 7 shows the temperatures and wind profiles for January, representative of the winter months, for all four years used in the simulations. Figure 8 shows the temperatures and wind profiles for July, representative of the summer months, for all four years used in the simulations. The average atmospheric profiles off of the coast of Seattle for each month of 2018 were used to predict the secondary sonic booms.

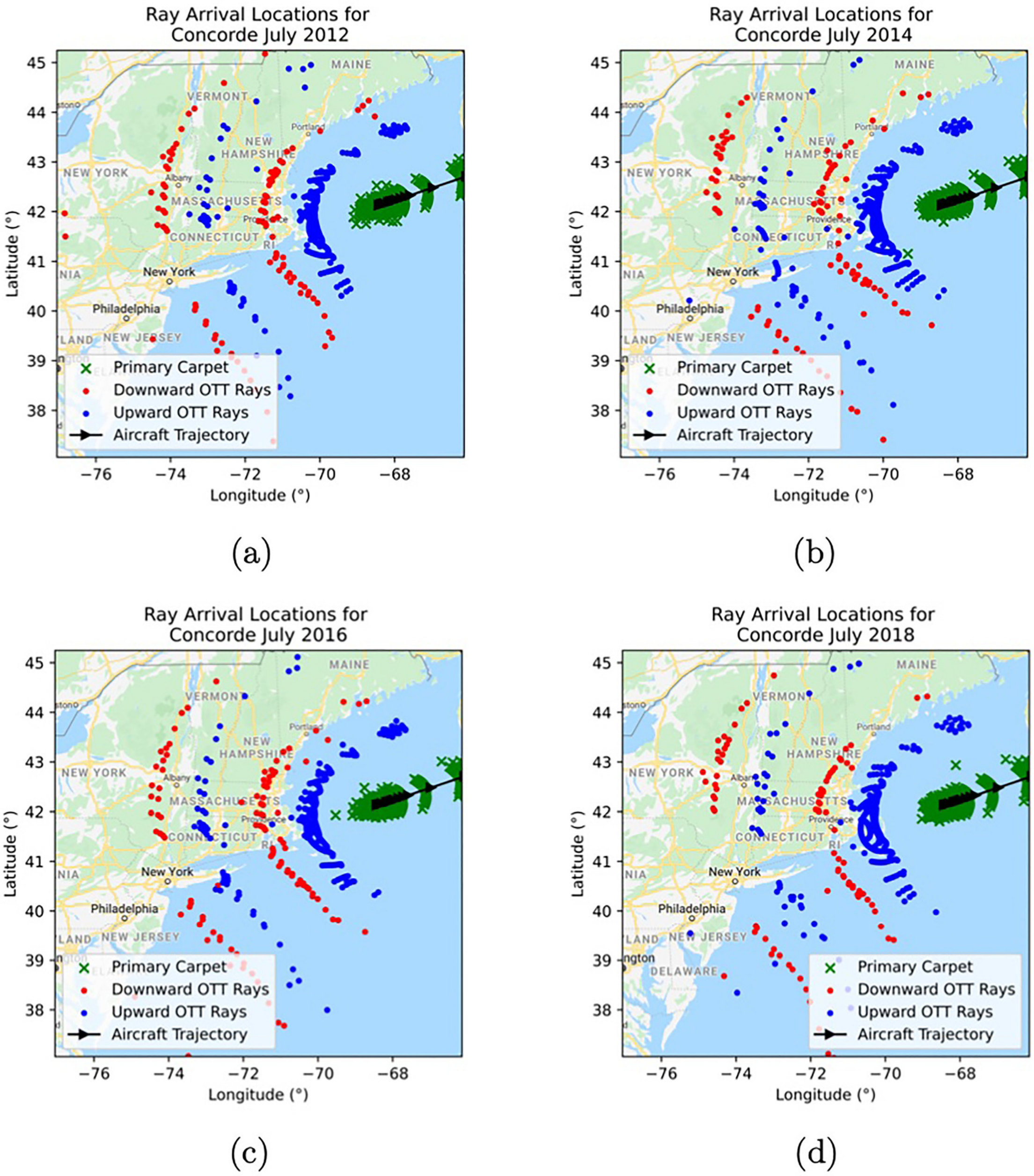


FIG. 10. (Color online) The arrival locations for booms on the east coast for July in the years 2012 (a), 2014 (b), 2016 (c), and 2018 (d) to represent the behavior for the summer months. The triangular markers show the origin points of the aircraft along the trajectory. It is shown that there is a substantial impact on the east coast for the summer months.

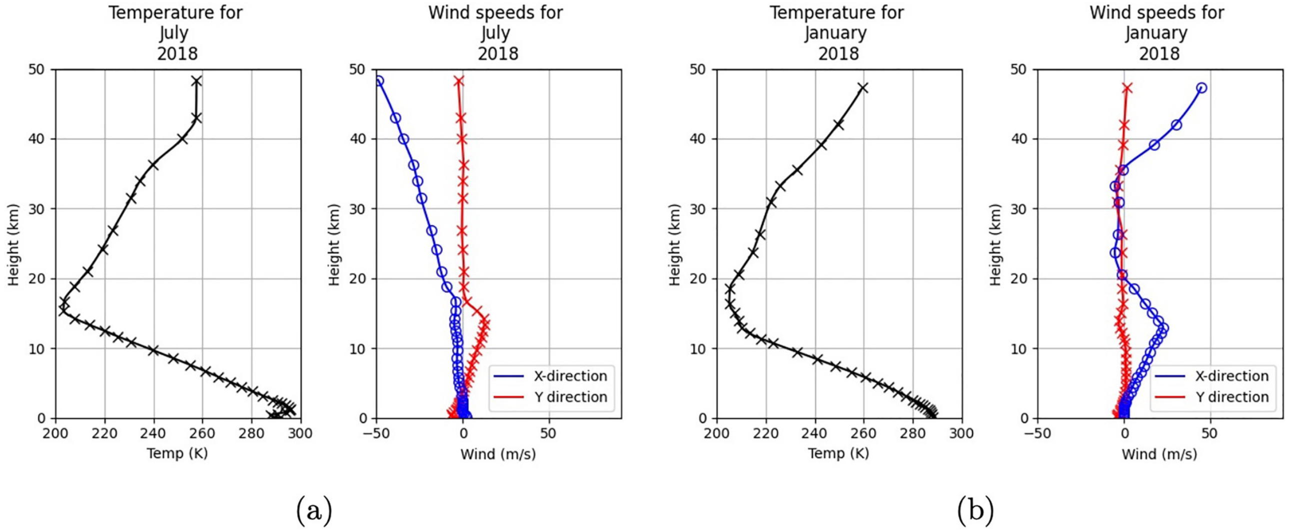


FIG. 11. (Color online) The average monthly temperature profile and wind speed profiles with altitude are shown for July and January of 2018 to depict the atmospheric conditions for the summer and winter for Los Angeles.

PCBoom was used to propagate the secondary sonic boom to arrival locations using the average atmospheric profiles for each month for the years 2012, 2014, 2016, and 2018. Figure 9 shows the arrival locations from PCboom for an aircraft arriving on the east coast during January, which is representative of the winter months. Figure 10 shows the arrival locations during July to illustrate the behavior of the arrivals during the summer months. The blue dots show the initially upward rays, the red x's depict the initially downward rays, and the green dots show the primary boom location. Figures 9 and 10 illustrate that the U.S. east coast is consistently affected by the secondary sonic booms during the summer months. The summer months see many more arrivals of type I and type II rays. This impact is consistent across all four years that were assessed.

VI. WEST COAST ARRIVAL LOCATIONS

To determine the behavior of the secondary sonic booms for the U.S. west coast, the differences between the northern west coast and southern west coast as well as the variability over time were examined.

A. Los Angeles approach

The average atmospheric profiles off of the coast of Los Angeles for each month of 2018 were used to predict the

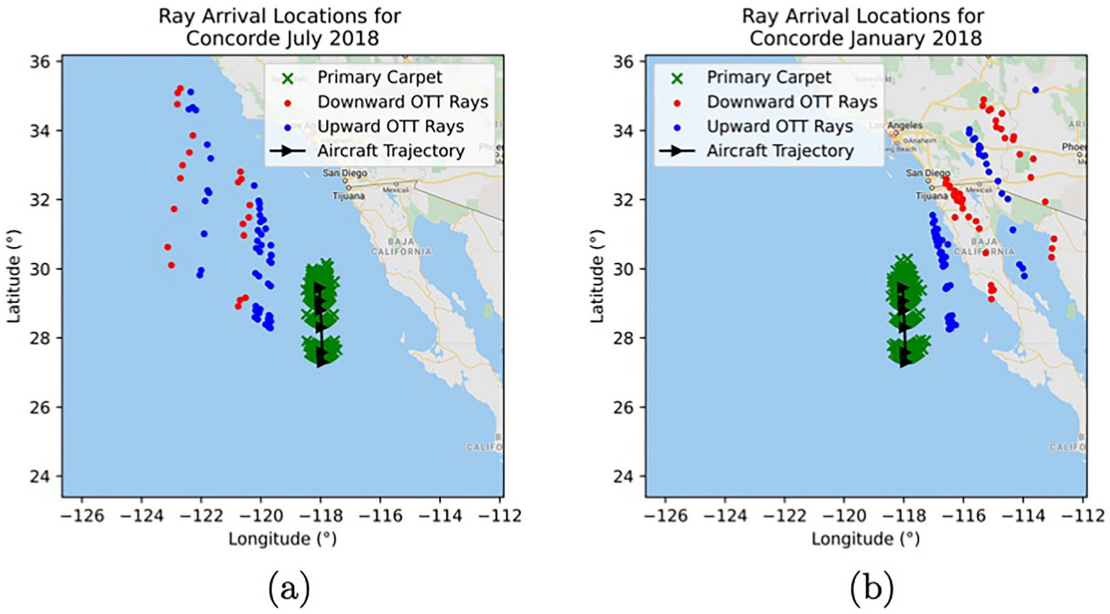
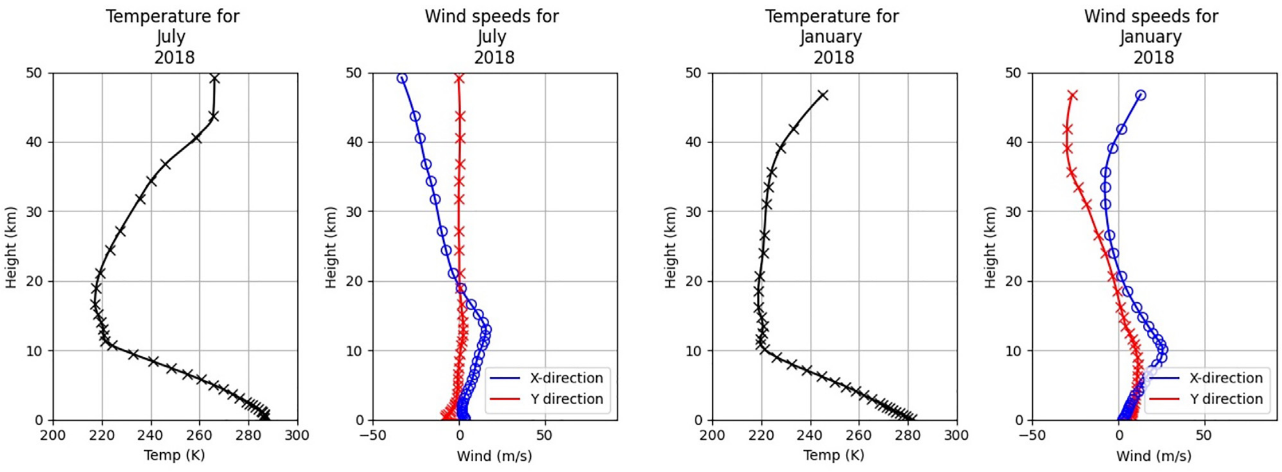


FIG. 12. (Color online) The arrival locations of the sonic booms for Los Angeles on the west coast for July (a) and January (b). The locations of the secondary sonic boom arrivals only impact the coast during the winter months. The triangular markers show the origin points of the aircraft long the trajectory. The arrival locations are computed using average monthly weather conditions in 2018.



(a) (b)

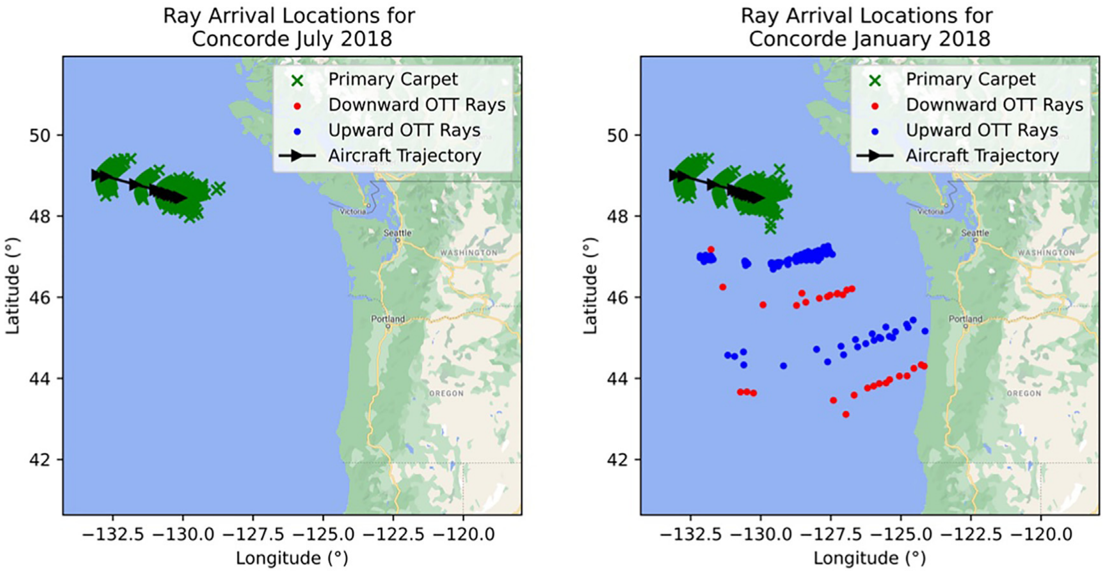
FIG. 13. (Color online) The average temperature profile and wind speed profiles with altitude are shown for July and January of 2018 to depict the atmospheric conditions for the summer and winter for Seattle during this year.

arrival locations of sonic booms along the U.S. west coast. Figure 11 shows the meteorological conditions used for Los Angeles. The trajectory is depicted by the triangular markers in Fig. 12, which shows the arrival locations of the secondary sonic booms for the summer and winter months. In contrast to the east coast, the west coast is most affected during the winter months. This is due to the strong easterly (+*x*-direction) winds during the winter months in the upper atmosphere, which is shown in Fig. 11.

B. Seattle approach

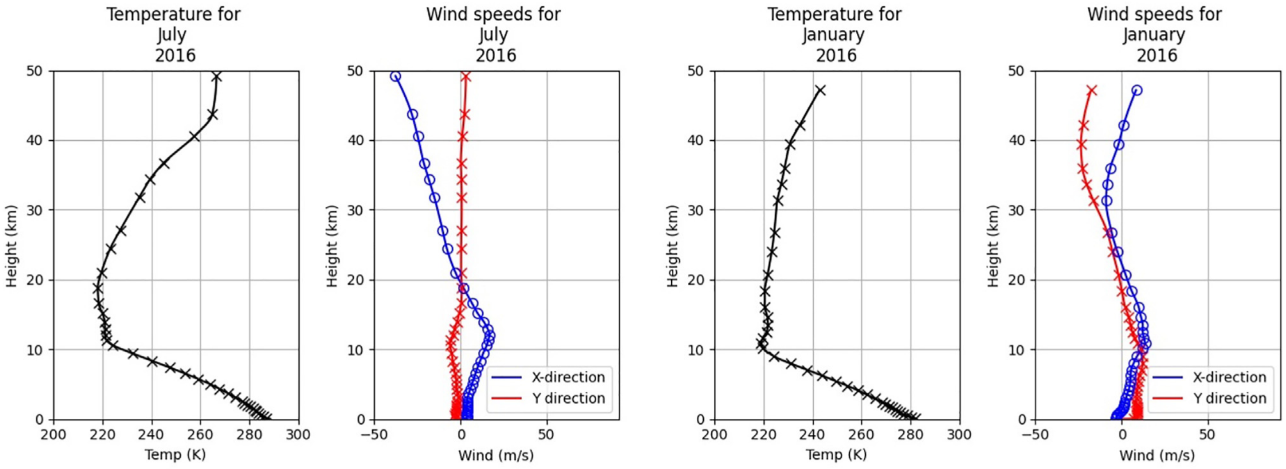
Figure 13 shows the average atmospheric conditions used for Seattle. The profiles for January and July are shown to demonstrate the conditions for winter and summer. Compared to the weather in Los Angeles, shown illustrated in Fig. 11, there are substantial differences but the overall direction of the wind in the upper atmosphere during the summer and winter is consistent.

Figure 14 shows the arrival locations of the secondary booms for these conditions. The summer shows no secondary sonic booms, and there is no impact on the coastline. This is similar to the results for the Los Angeles approach in the summer. In the months October, November, February, and March, impact on the coastline was predicted. Whereas December and January did not show any impact on the coast, there are secondary sonic booms present over the ocean.



(a) (b)

FIG. 14. (Color online) The arrival locations of the sonic booms for Seattle for July (a) and January (b) of 2018. The winter months show arrivals for the secondary sonic booms. The triangular markers depict the origin points of the aircraft along the trajectory. The arrivals do not impact the coast, and the boom arrivals are located over the ocean.



(a)

(b)

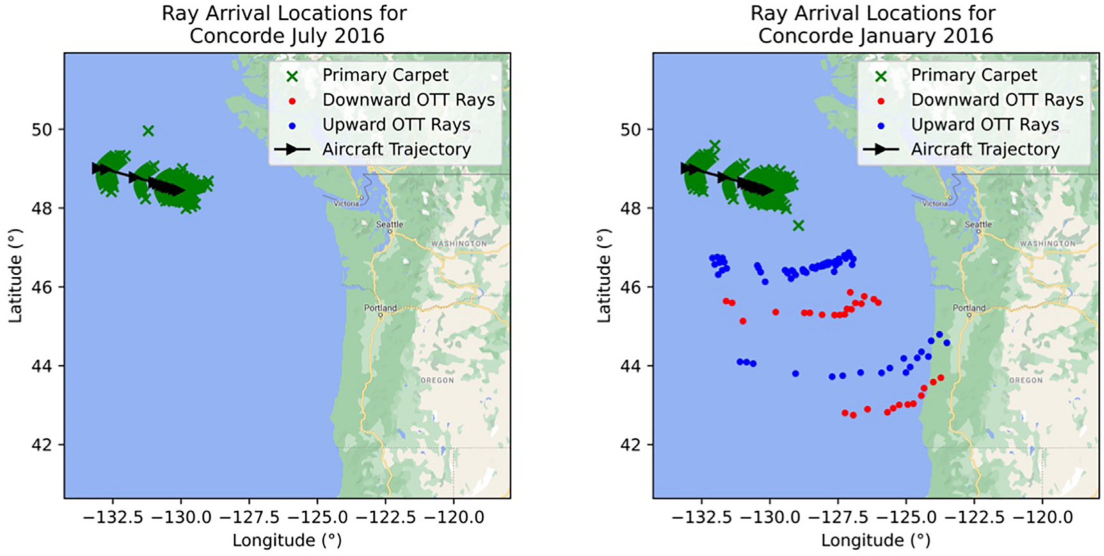
FIG. 15. (Color online) The average temperature profile and wind speed profiles with altitude are shown for July and January of 2016 to show the atmospheric conditions for the summer and winter for Seattle during this year.

To determine how stable the atmospheric conditions were between years, 2016 meteorological data were used in addition to the 2018 data to model the secondary sonic boom arrivals. The atmospheric data are presented in Fig. 15. The meteorological conditions are very similar to the conditions in 2018.

The same trajectory and aircraft as in the 2018 simulation were used. The results were very similar in both years. There were other months in the winter which showed a substantial impact on the coastline, and it should be mentioned that most winter months had many arrivals impacting the coastline in the U.S. and Canada for an approach into Seattle (Fig. 16). To demonstrate this, the arrival locations for November 2016 and November 2018 appear in Fig. 17.

VII. CONCLUSIONS

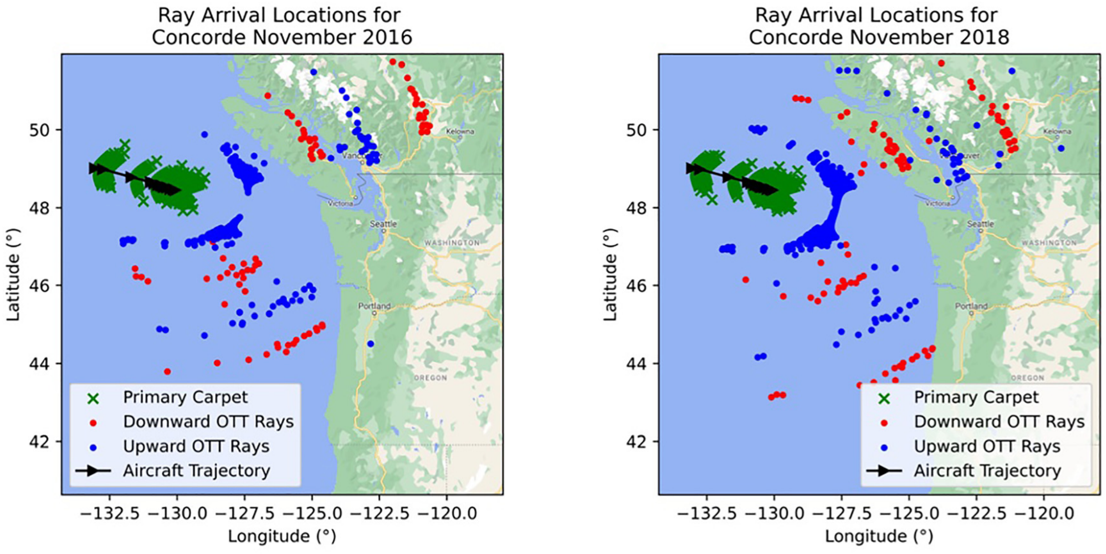
This study used PCBoom to determine the impact on the U.S. coastlines from the arrival locations of secondary sonic booms. The variability of atmospheric profiles was studied and it was shown that, in general, the monthly average accurately predicts the coastline impact. Examining the behavior of the sonic boom propagation over several years, it shows that the U.S. east coast is consistently more affected in the summer months than in the winter months. The U.S. west coast analysis, in contrast, exhibits that the coastline is more affected in the winter months than in the summer months. Although there were some differences in the northern and southern coastal conditions, this overall trend is



(a)

(b)

FIG. 16. (Color online) The arrival locations of the sonic booms for Seattle for July (a) and January (b) 2016. The triangular markers show the origin points of the aircraft along the trajectory. The winter months show arrivals for the secondary sonic booms. The secondary sonic booms have a minimal effect on the coastline but are predominently present over the ocean.



(a) (b)

FIG. 17. (Color online) The arrival locations of the sonic booms for Seattle for November 2016 (a) and November 2018 (b). The triangular markers show the origin points of the aircraft along the trajectory. Although the month of January shows arrivals only over the ocean, there is still a substantial impact for other cold weather months.

consistent over location and time. The weather profiles show that the parameter that most strongly impacts the arrival locations is the upper atmosphere wind directions when compared to the trajectory heading. The simulations in this work illustrate that secondary sonic booms impacting the coastlines can vary as a result of the choice of how far away the aircraft was when it transitioned from supersonic to subsonic flight before landing. The Concorde experience showed that secondary sonic boom impacts along coastlines can be avoided if the deceleration of the aircraft to subsonic occurs further from the coastline. This pushes the secondary sonic boom impacts out to sea. Such coastal buffer distances must be respected when planning supersonic aircraft operations overwater. The subsequent steps in this project are to continue to use PCBoom to predict the behavior of secondary sonic booms. The next major characteristics that must be considered are the pressure signatures of the Concorde and other proposed low boom aircraft that will be observed at each of the arrival locations addressed in this study. The capability to study these pressures is not currently included in the available prediction tools; however, the addition of this important piece is being investigated. It is expected that the levels of the secondary sonic booms will be much lower than those of the primary carpet booms and mostly low frequency energy. In light of past resident complaints during the Concorde era, the impact on residents needs to be thoroughly considered as the reality of supersonic flight approaches.

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Liszka, L., and Waldenmark, K. (**1995**). "High resolution observations of infrasound generated by the supersonic flights of Concorde," J. Low Freq. Noise Vib. **14**(4), 181–192.

Page, J. A., Lonzaga, J. B., Shumway, M. J., Kaye, S. R., Downs, R. S., Loubeau, A., and Doebler, W. J. (**2020**). "PCBoom version 7.1 user's guide," Technical Report NASA/TM–20205007703 (NASA, Washington, DC).

Plotkin, L., Page, J., and Haering, E. (**2007**). "Extension of PCBoom to over-the-top booms, ellipsoidal earth, and full 3-D ray tracing," in *13th AIAA/CEAS Aeroacoustics Conference* (AIAA, New York), pp. 2007–3677.

Rickley, E. J., and Pierce, A. D. (**1980**). "Detection and assessment of secondary sonic booms in New England," Technical Report FAA-AEE-80-22 (Federal Aviation Administration, Washington, DC).

Rogers, P. H., and Maglieri, D. J. (**2015**). "Concorde booms and the mysterious east coast noises," Acoust. Today **11**(2), 34–42.

Saha, S., Moorthi, S., Wu, X., Wang, J., Nadiga, S., Tripp, P., Behringer, D., Hou, Y.-T., ya Chuang, H., Iredell, M., Ek, M., Meng, J., Yang, R., Mendez, M. P., van den Dool, H., Zhang, Q., Wang, W., Chen, M., and Becker, E. (**2011**). "NCEP Climate Forecast System version 2 (CFSv2) 6-hourly products," available at https://doi.org/10.5065/D61C1TXF (Last viewed November 2021).

Sparrow, V., and Riegel, K. (**2020**). "2020 literature review on secondary sonic boom," in *e-Forum Acusticum 2020*, pp. 1013–1019, available at https://hal.archives-ouvertes.fr/FA2020/hal-03229476 (Last viewed November 2021).