# Supersonic Flight Routing in Consideration of Secondary Sonic Booms

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**This paper discusses the issue of secondary sonic booms (SSBs) in the context of civil supersonic flight operations. It presents a ray-tracing methodology to calculate sonic-boom impact locations for realistic flight routes and realistic atmospheric conditions. Secondary-boom footprints are calculated for flight missions between several city pairs in weather of all seasons. These capabilities form the basis for automated, realistic, sonic-boom-compliant flight routing.**

## I. Introduction

Sonic booms remain a major obstacle to civil supersonic flight (next to airport noise, pollutant emissions, and economic viability concerns). There are two major approaches to sonic boom abatement: one technological, and one operational.

Currently, NASA is working towards first flight of the X-59 QueSST supersonic experimental aeroplane [1]. Its airframe is designed to produce sonic booms that are intended to be tolerable when heard on the ground. The implemented “low-boom technology” is hoped to enable supersonic overland flight which is currently banned – explicitly or implicitly – in the United States, Europe, Canada, and Australia. Achieving public approval to abolish the bans could roughly double the addressable market [2] and enhance the economic viability of future supersonic transports (SSTs) significantly.

The second way of tackling sonic booms is to produce them only where they cannot disturb the public, namely above seas and oceans. Many metropolises can be linked with flight routes that mainly lie on water and that require only small detours; e.g., London with New York City, Paris with Boston, and all connections between Western Europe and the North American east coast; Singapore with Seoul, Tokyo with Bangkok, and many more city pairs in southeast Asian seas [3]. Concurrently, flight paths have to keep sufficient distance from coasts so that *the sonic boom* does not make landfall.

Thus far however, research in both areas has, with few exceptions, largely sidelined the issue of *secondary sonic booms (SSBs)* [4]. They occur under certain atmospheric conditions, and the resulting shock reaches the ground far beyond the primary-boom carpet. After it was proven that the Concorde’s SSBs were the cause of frequent rumble that triggered public complaints [5], the operators of the supersonic airliner had to adapt their flight routes and decelerate earlier before reaching the coast in order to resolve the matter.

Even though SSBs are of lesser strength, they have been proven to be a potential nuisance to the public and hence require considering in the sonic boom abatement complex. That, in turn, asks for tools and methodologies to assess where they will impact and what their loudness will be. This work mainly examines geometrical propagation, whereas the loudness issue is discussed qualitatively.

The urgency of tackling sonic booms in general and secondary booms in particular has increased since a very recent U.S. Presidential Executive Order directed the Federal Aviation Administration (FAA) to replace the blanket supersonic ban with a noise-based standard within two years (see Chapter IV).

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## II. Disambiguation of secondary sonic booms

Secondary sonic booms have been a secondary subject in sonic boom research to this day. Compared to primary booms, they are covered by a manageable number of publications. In 2020, Riegel & Sparrow published a comprehensive and thorough review [4] that summarizes the historic findings of 50 sources on the topic of SSBs.

The expression "secondary sonic boom" covers all types of noise from shock waves induced by aircraft flying at supersonic speeds that do not originate from direct downward propagation of the sonic boom. At least five distinct propagation types are recognized (see Figure 1).

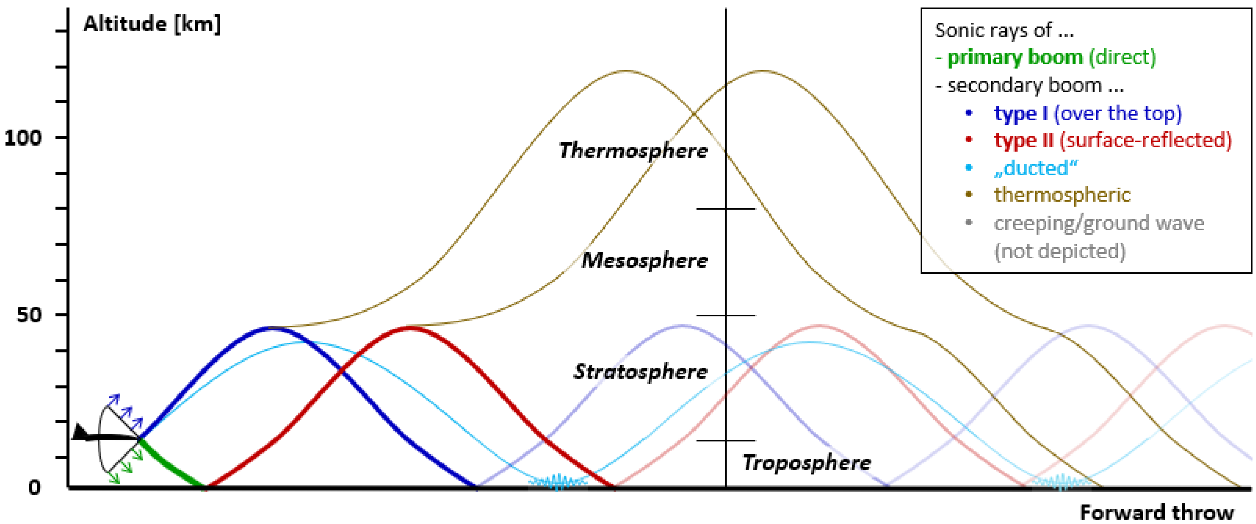


**Figure 1. Sonic boom types of propagation (schema)**

*Type-I ("over-the-top")* SSBs are emitted upward, get refracted downward, and reach the ground far beyond the primary carpet. *Type-II* SSBs result from a primary boom that is reflected from soil or water and is refracted to once again reach the surface, beyond the type-I impact points. In the seminal New-England SSB study by Rickley & Pierce [5], water-reflected type II was measured to be consistently louder despite its longer propagation distance.

Type-I and type-II SSBs strike land or sea only when the *effective speed of sound*, i.e., the speed of sound plus wind speed in the direction of propagation, at some altitude above emission surpasses the effective sound speed on the surface. Usually, this requires strong stratospheric tailwinds. [5, 6]

*Ducted* booms arise when shock waves get trapped in a stratospheric "acoustic duct" (or "wave guide") and get close to the surface, but never reach it directly. The energy leaked laterally to their propagation path can be detected when they approach the ground, whereas their signal mainly consists of hardly perceivable infrasonic frequencies [6].

*Thermospheric* booms emerge when a stratospheric boom continues to the thermosphere, gets refracted downward by strong temperature gradients, and eventually reaches the surface. Thermospheric SSBs are weaker than type-I and type-II booms and have been concluded unlikely to be noticed by the public [7–9].

*Creeping (ground) waves* are weak surface-diffracted offshoots of the sonic-boom field that are launched by ground-grazing shockwaves, i.e., at carpet edges [6]. Their amplitude diminishes exponentially with range, rendering their broadband impulse inaudible within several kilometers of distance from the primary-carpet edge [10].

Immediately beyond a carpet edge, in the "shadow zone", the creeping wave mixes with the low-frequency radiation of near-grazing rays passing overhead. Within the first few kilometers, listeners chiefly hear the creeping pulse; beyond that distance, the audible band drops out, leaving a weak rumble. [10]

Because of their long travel distance, SSBs are usually much weaker in amplitude than direct booms, their signal loses most of its high-frequency content, and their rumbling sound can last several seconds, similar to thunder. Overall amplitude falls with distance, except near the type-I/II "focus" (see below) where overpressure can return to the audibility limit (see below) before declining again [10].

SSBs can reflect from water or soil more than once. Whereas there are reports of instrumental recordings beyond the first (type I) and second (type II) impact (e.g. [11–13]), there seem to be none of actual hearings. When the primary boom reflects from water, the process is nearly specular [14]. This preserves amplitude and makes the type-II focus the worst case for coastal routes [5]. Over rough land, ground reflection involves significant loss of sound energy [15].

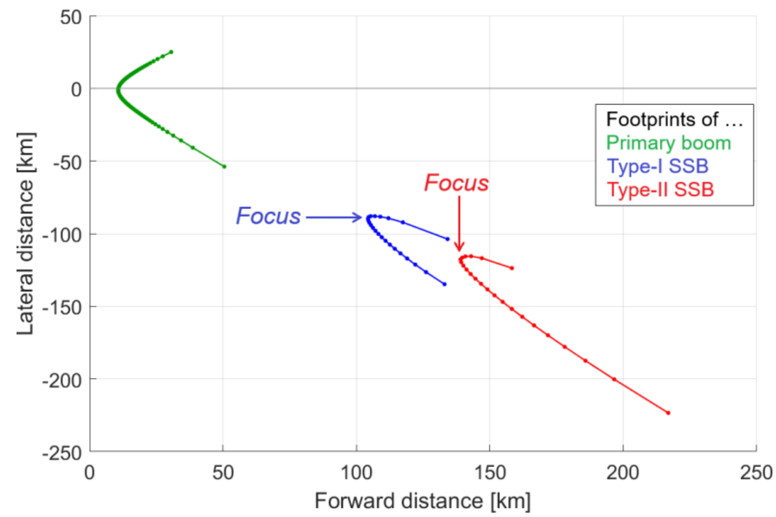


**Figure 2. Exemplary sonic-boom ground impact profiles (footprints). Focus is closest to emission location.**

Type-I and type-II "focus lines" are of special interest. These are the ground positions where rays converge most tightly, several rays arrive simultaneously [10], and overpressure therefore reaches its maximum (see Figure 2). Small atmospheric changes can shift those lines by dozens of kilometers [5].

During the New-England field study, listeners reported hearing secondary booms only when peak-to-peak overpressure exceeded about 0.1 lbf/ft² (≈ 5 Pa). Weaker events, although measurable, drew no complaints. [5] Therefore, 5 Pa might constitute a practical annoyance limit.

## III. Historic Concorde operations

The Anglo-French Concorde airliner was the only civil supersonic aircraft that operated over an extended period of time, so relevant operational experience originates only from there.

Even before entering service in 1976, Concorde's primary boom had to be kept away from the public because it was strong and startling. Thus, flights were routed over water from the start and a standoff distance from shores of typically 30 nmi (about 50 km) was employed for supersonic segments. [16]

Over time however, complaints about rumbling noise accumulated in south-west Britain and New England. Parliamentary records show that by late 1978, the UK Government acknowledged the link to Concorde and explored operational slow-down[2]. Eventually, the noise was conclusively traced back to Concorde flights [5].

This finding compelled British Airways and Air France to seasonally shift their flight tracks seaward and to begin decelerating to subsonic speed earlier [16].

## IV. Current legal situation

In 1973, the Federal Aviation Administration (FAA) adopted § 91.55 (now § 91.817), prohibiting any civil sonic boom from reaching U.S. soil (38 FR 8051, "Civil Aircraft Sonic Boom"). ICAO Annex 16 Vol I, Ch. 13 (11th ed., Jul 2022) qualitatively prohibits routine sonic boom exposure ("shall not create an unacceptable situation for the public"). Neither distinguishes between primary and secondary booms. Implicitly, this was treated as an absolute ban of supersonic flight over land or close to shores.

Recently however, a U.S. Presidential Executive Order[3] instructed the FAA "to repeal the prohibition on overland supersonic flight in 14 CFR 91.817 within 180 days of the date of this order and establish an interim noise-based certification standard" and to issue a final rule "within 24 months of the date of this order". Also, "global alignment" and "bilateral […] agreements" shall be targeted "for the safe international operation of supersonic aircraft".

The new rule, if implemented, would likely require all types of incoming sonic booms to stay below certain noise limits. Effectively, it could permit "Mach cut-off" flight [17] over land.

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[2] UK House of Commons Hansard, 23 Mar 1978 (Penhaligon debate). https://hansard.parliament.uk/commons/1978-03-23/debates/d0e89030-bd0a-49fd-aa69-bc57f2d587bf/Concorde(SonicBoom).

[3] "Leading the World in Supersonic Flight", White House, 2 Jun 2025, Doc. No. 2025-13726. https://www.whitehouse.gov/presidential-actions/2025/06/leading-the-world-in-supersonic-flight/.

## V. Simulation methodology and validation

SSBs can be simulated quite well numerically regarding their geometric propagation through the atmosphere, whereas the knowledge for acoustic propagation is still incomplete [4]. This work focuses on spatial calculations.

The simulation tool to be employed is DLR's proprietary ray-tracing code DBoom. It can be considered particularly suitable for the present topic involving long-range propagation because it features

- the handling of 3-D atmospheres including 3-D winds, supported by higher-order interpolation
- curved-Earth geometrical formulation (WGS84 ellipsoid)
- global topography[4]
- a Runge-Kutta time-stepping scheme with auto-adaptive step size for enhanced accuracy.

Figure 3 displays an example of ray-tracing in a certain 3-D atmosphere at a certain position, speed, and heading. Sonic-boom rays are emitted at all possible angles normal to the Mach cone and followed on their propagation through the atmosphere. Rays starting upward constitute potential type-I SSBs, and those reflected from the primary impact points constitute potential type-II SSBs. In this particular example where the rays launch in 2-degree increments around the circular spectrum, nine type-I and nine type-II impacts are registered, all at similar horizontal directions. Their impact points describe the approximate extent of the respective SSB carpets. Pinpointing the carpet edges more exactly is probably not necessary because loudness should be considerably higher toward the focus points anyway.

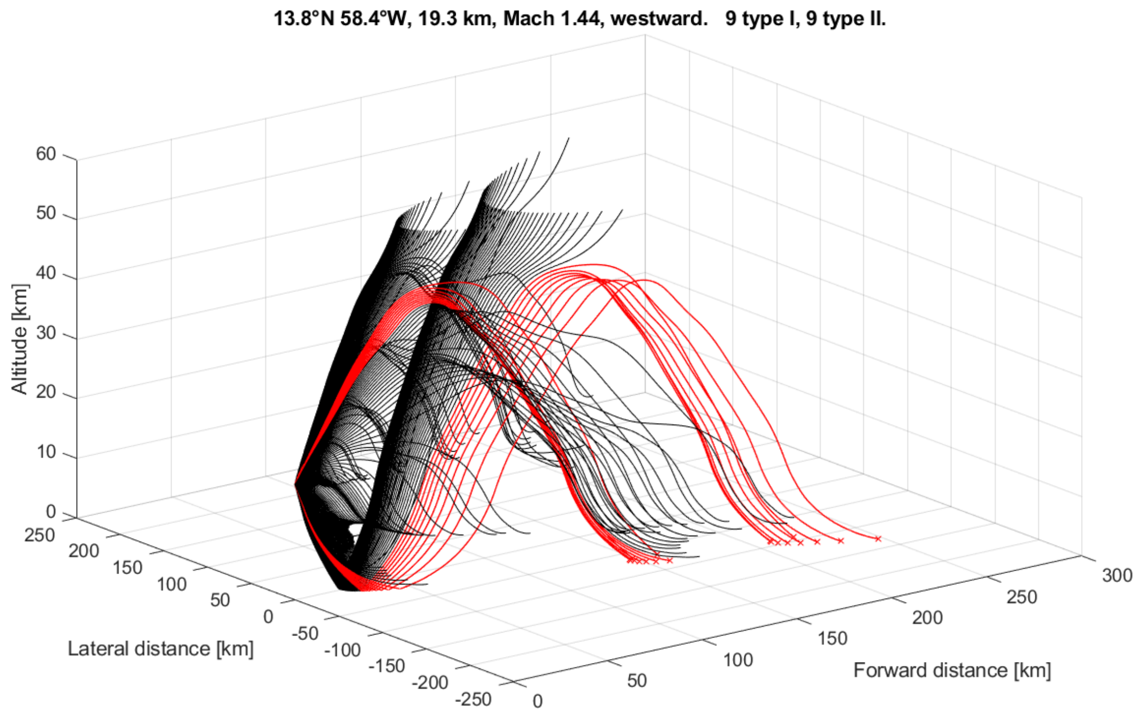


**Figure 3. Example of an all-aspect ray-tracing simulation of sonic-boom propagation. Red rays impinging.**

To review DBoom's proper function, the historical study by Rickley & Pierce [5] was revisited. Their documentation contains measured atmospheric data (temperature and winds) from the ground to 55 km of altitude for June 20, 1979, in the region of Boston, MA, as well as that day's flight trajectory (position and Mach number) of the supersonic Concorde airliner inbound for New York City. With that information as input, they performed ray-tracing numerically to find the secondary-boom focus lines. In our work, we attempted to retrieve those focus lines with DBoom. This exercise was already performed by Riegel & Sparrow [18] using NASA's PCBoom code.

In our simulation results, the focus points and lines, respectively, did not match satisfactorily with the ones computed by Rickley & Pierce, neither using regular DBoom, nor a DBoom modification with high Earth radius rendering it quasi-flat, nor a custom flat-Earth code programmed for this very application. When finally employing PCBoom, however, its results matched closely with the ones computed by our tools. See Figure 4.

[4] USGS GMTED2010; available via https://www.usgs.gov/coastal-changes-and-impacts/gmted2010.

Rickley & Pierce's paper does not give much detail on their ray-tracing code, but purportedly, it was flat-Earth and "pretty straightforward". Moreover, they deemed their own focus line locations to be "of dubious accuracy. The meteorological information available is not sufficiently detailed […]. A rough guess is that the accuracy in focus line prediction is of the order of +- 20 km"[5]. For the present case, this means that the reported focus lines do not represent a target to hit, but merely a broad range within which our results appear to fit adequately (Figure 4).

In conclusion, DBoom verifies well against NASA's proven legacy tool PCBoom and validates, within the supposed ±20 km experimental uncertainty, against the 20 June 1979 Concorde data.

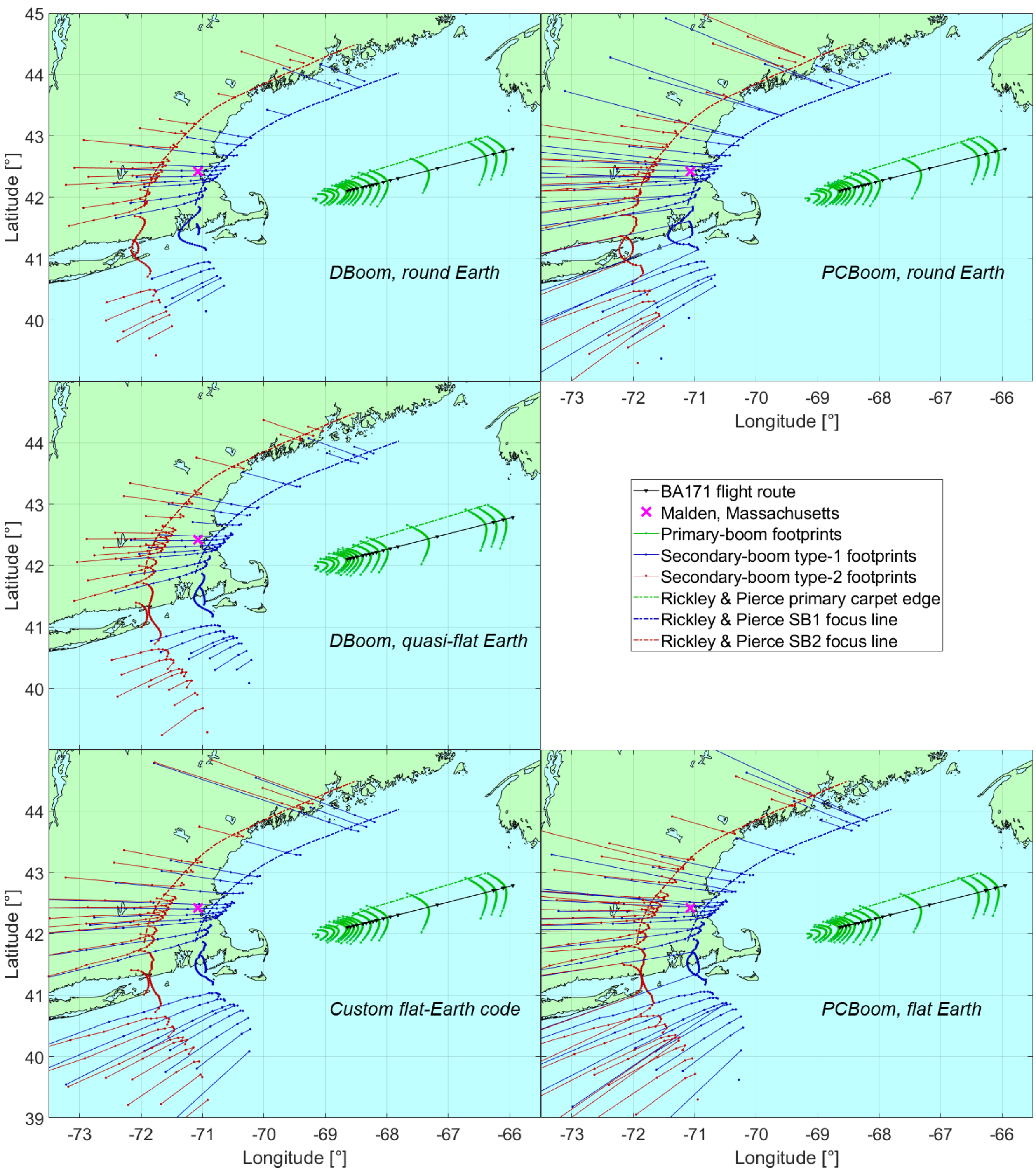


**Figure 4. DBoom validation calculations**

## VI. Design of Experiments

A tool chain is set up to design overwater flight routes, simulate flight missions with realistic aircraft performance in realistic weather, and to calculate the resulting SSB footprints.

Whereas a methodology for automated supersonic route drafting is already at hand [19], it only considers primary boom carpets (in fact, this work takes steps toward the goal of SSB integration). Therefore, flight routes are drawn manually (as in [3]) while respecting the historical 50-km coastal stand-off. The considered city pairs are London–New York (as the prime intercontinental business link [2] and as repeatedly used in SSB studies) next to London–Jeddah and Singapore–Brisbane, both chosen for particularly difficult routing through straits.

For mission simulation, DLR's high-fidelity Supersonic Trajectory Calculator (SuperTraC) is employed [3, 17, 20]. The input flight performance data (masses, aerodynamic polars, engine maps, reference speeds) are taken from a Mach-1.4 supersonic business jet design ("FSTB-L") out of DLR's current STORMIE project [21].

DBoom is used for ray-tracing. Since secondary-boom propagation is computation-intense, it is only performed in increments of 100 km in cruise and slightly finer during supersonic climb and descent, respectively.

Both mission simulation and consecutive sonic-boom ray-tracing are done in realistic global 3-dimensional atmospheres including 3-D winds[5], with 1460 atmospheric sets at hand (one in every six hours of the year 2015).

An exemplary result is shown in Figure 5. It displays the New York–London flight route and the calculated impact lines both for primary and secondary sonic booms. In this particular example, the SSB footprints touch both the North-American East Coast and the southwestern British Isles. (Again, the footprints only indicate relative loudness by their shape; quantitative levels are not computed.)

Because ducted, thermospheric, and creeping SSBs appear uncritical (see Chapter II), only type-I and type-II SSBs are considered.

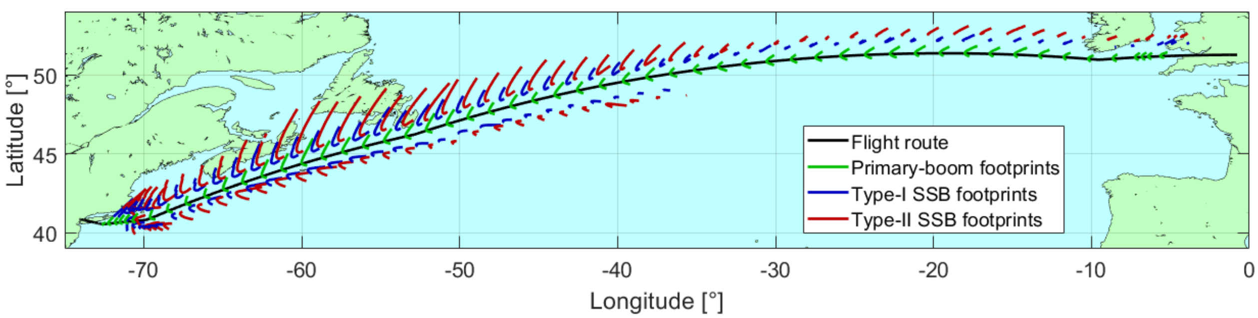


**Figure 5. Sonic-boom footprints on a New York–London mission, January 1st, 0:00 hours, 2015.**

## VII. Results

Figure 6 and Figure 7 display the sonic-boom footprints for every first day of a month on the New York–London city pair. Seasonal tendencies are clearly visible: Winter westerly winds support SSB appearance in the eastward flight direction, whereas flying westward, SSBs are recorded mainly in the summer season.

At the same time, SSBs appear unexpectedly (Figure 6: May, after missing in April; Figure 7: February) and are absent unexpectedly (Figure 7: no hits all summer on the East Coast).

Figure 8 to Figure 13, displaying the footprints for every day of the year 2015 at 0:00 hours, provide more nuance:

Flying eastward, SSBs populate the winter season quite reliably, except for a short unusual episode in January. Their frequency declines during spring, they are virtually absent in summer, and they reappear early in fall.

Flying westward, secondary booms occur for a short mid-winter period (January 4-21), slowly build up in spring, occur continuously from mid-May to mid-August, and are virtually absent between September and December. The appearance on February 1st from Figure 7 seems to be a stark outlier (same as February 9 and 12).

The monthly panels alone under-state how often SSBs occur, they miss most of westbound hits in summer, and they under-represent late-autumn eastbound activity. The daily strips reveal far more activity between May and August (westbound) and between November and March (eastbound).

Looking at the contours, SSBs oftentimes appear only on one side of the flight track and oftentimes do not touch land despite being present. Day-to-day, the focus lines can drift by dozens of kilometers. Type-I and type-II impacts usually occur concurrently, and when they do, type-II contours reach farther.

[5] ECMWF Era-Interim recalculation; available via www.ecmwf.int/en/forecasts/dataset/ecmwf-reanalysis-interim.

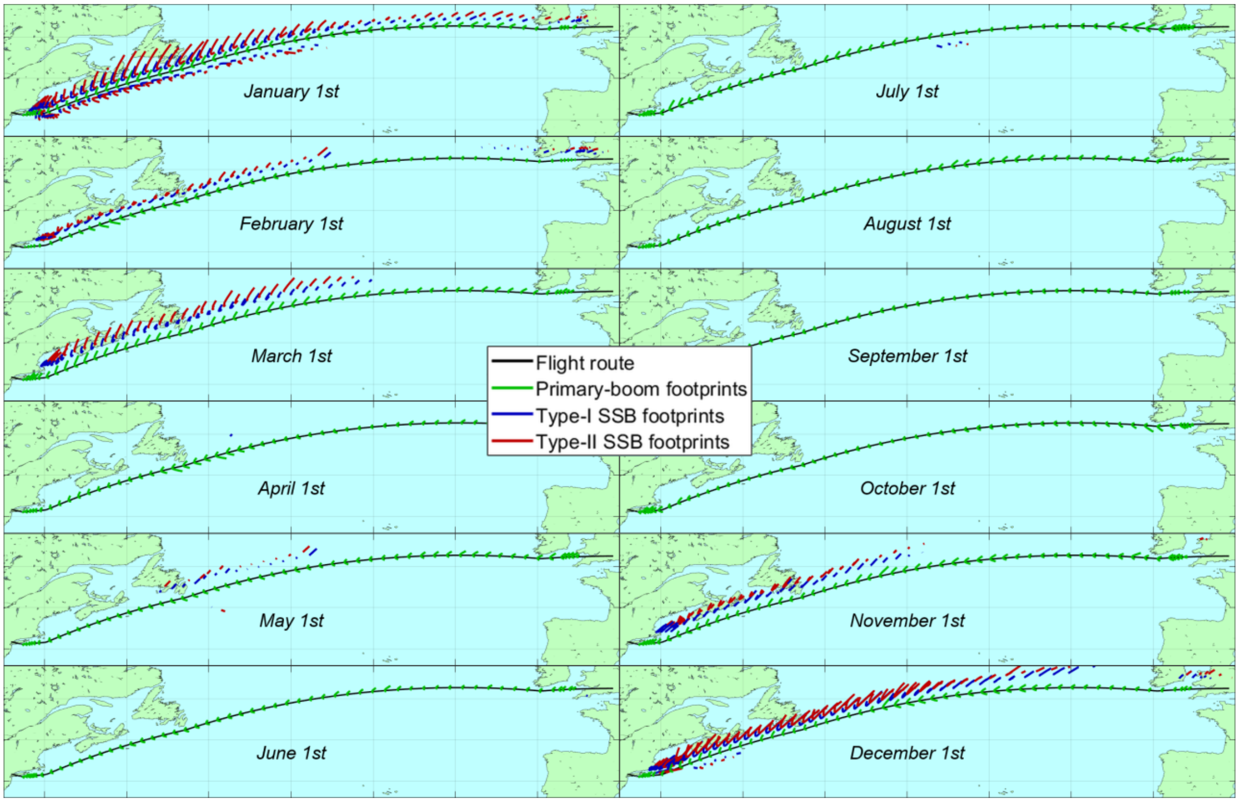


**Figure 6. New York–London footprints at the beginning of every month, 2015**

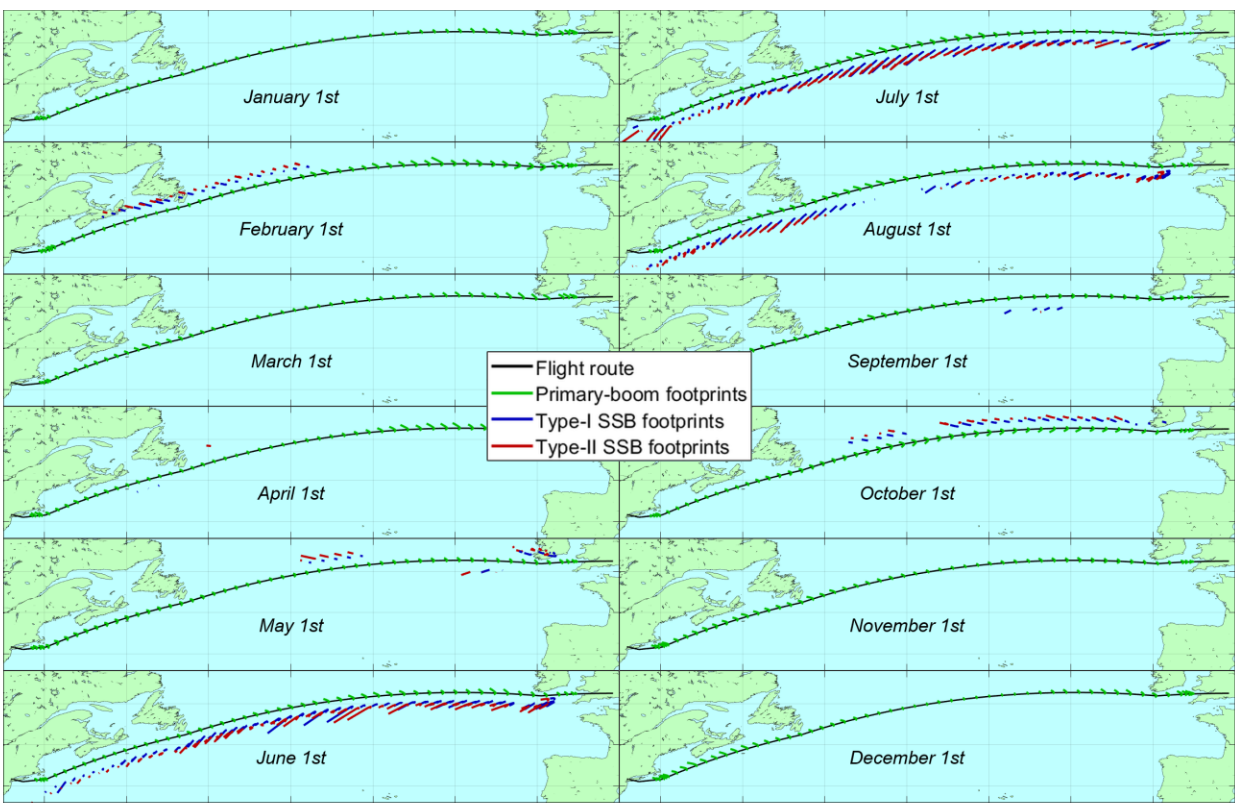


**Figure 7. London–New York footprints at the beginning of every month, 2015**

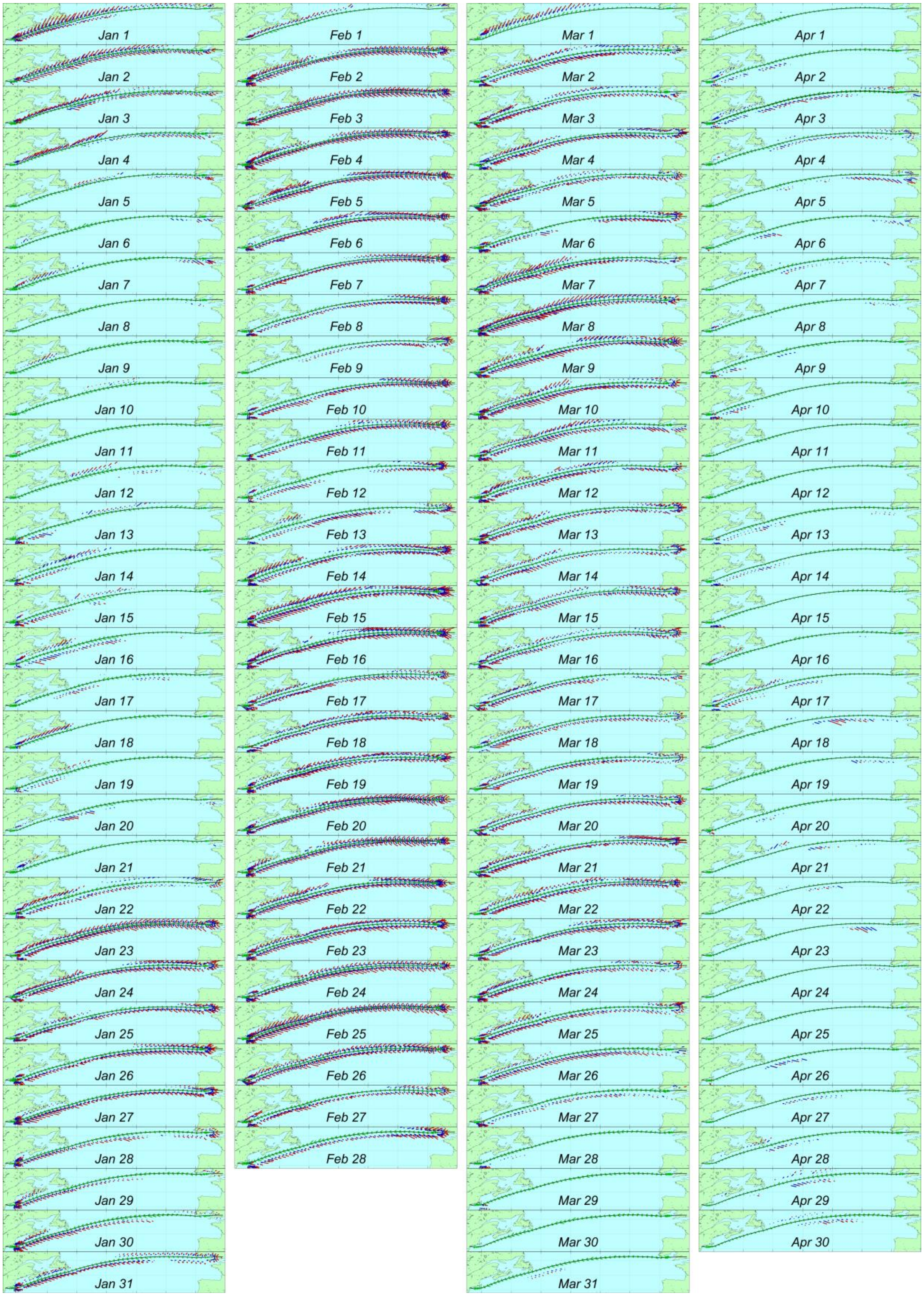


**Figure 8. Daily sonic-boom footprints for New York–London flights, 1st term of 2015**

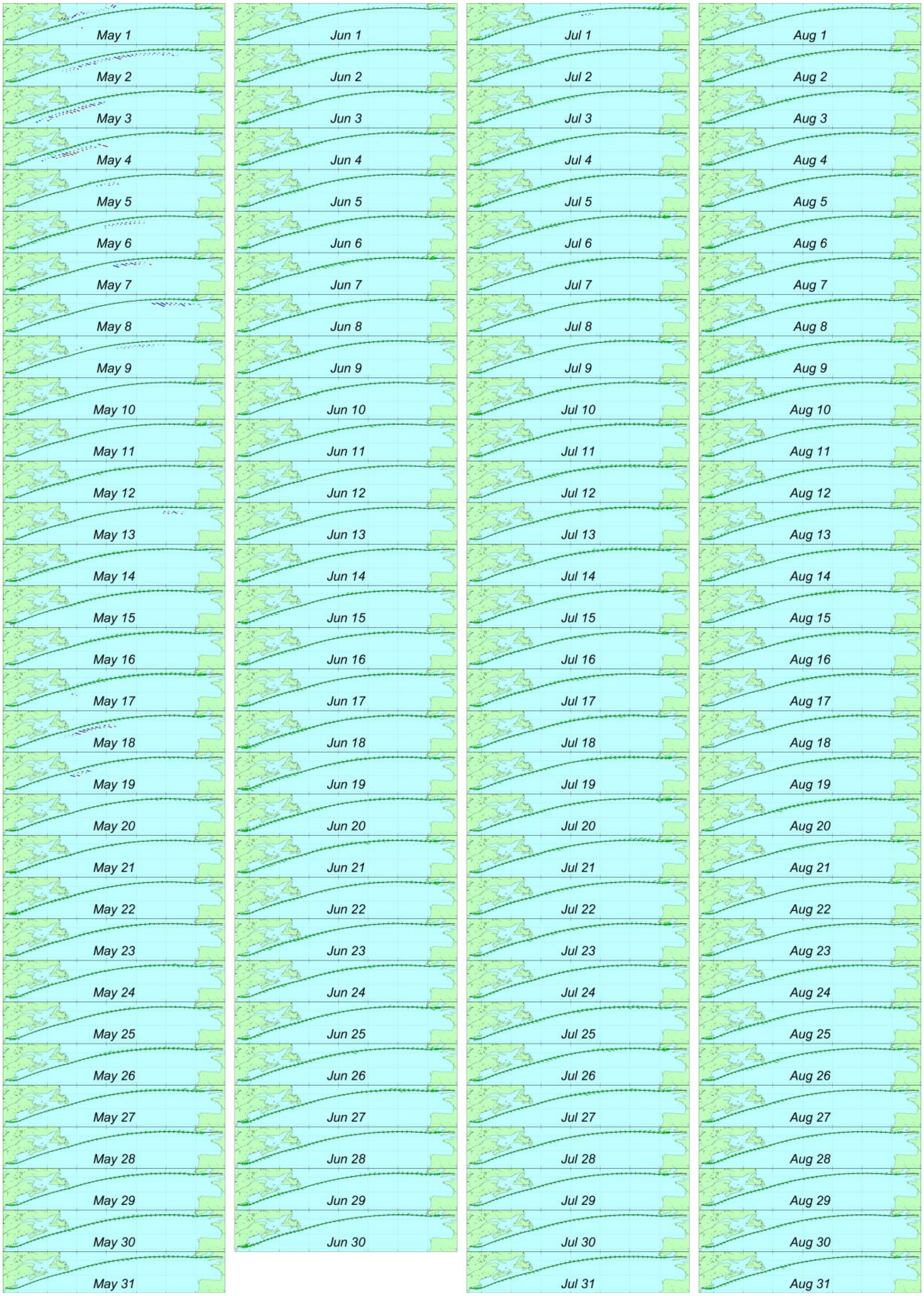


**Figure 9. Daily sonic-boom footprints for New York–London flights, 2nd term of 2015**

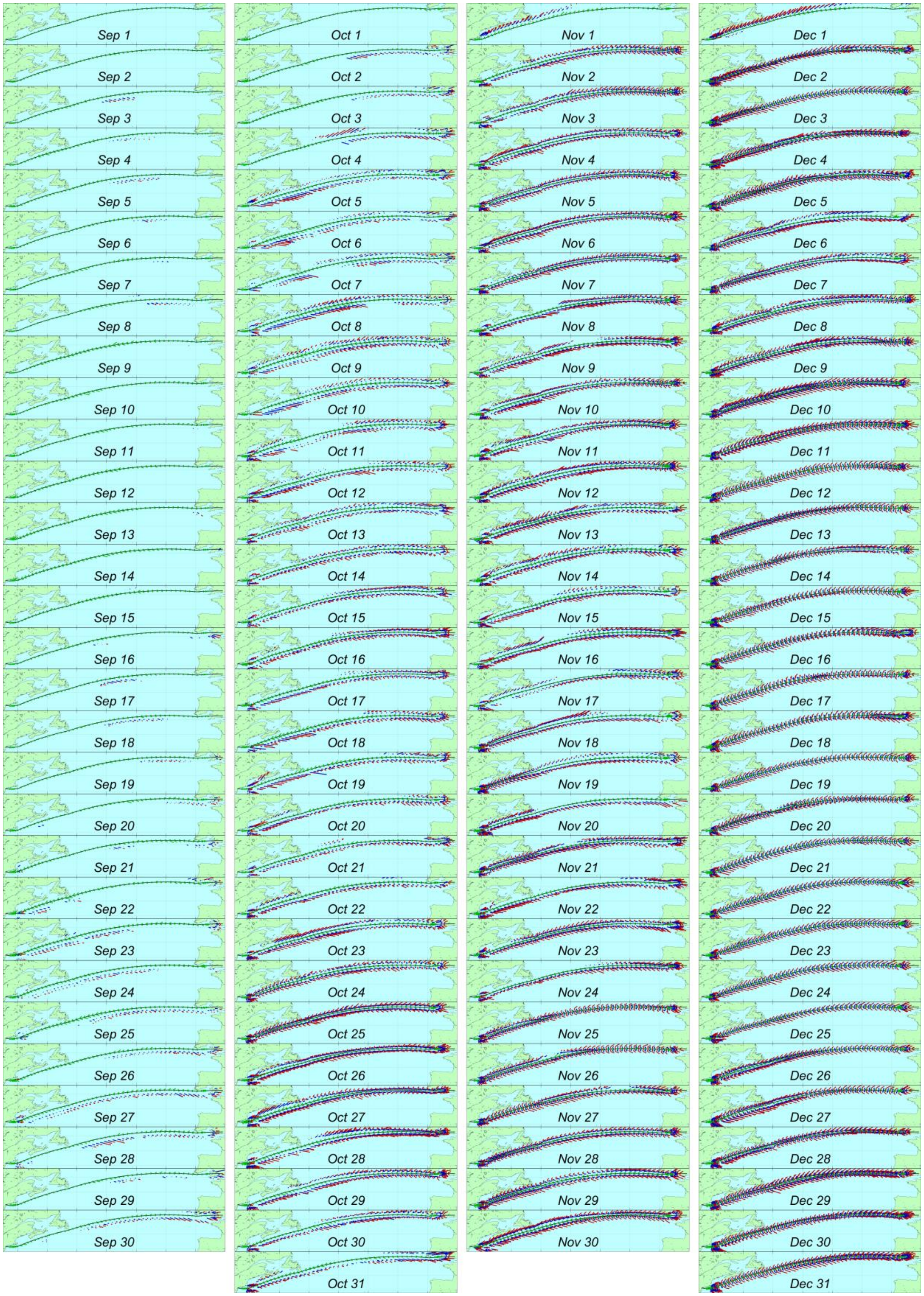


**Figure 10. Daily sonic-boom footprints for New York–London flights, 3rd term of 2015**

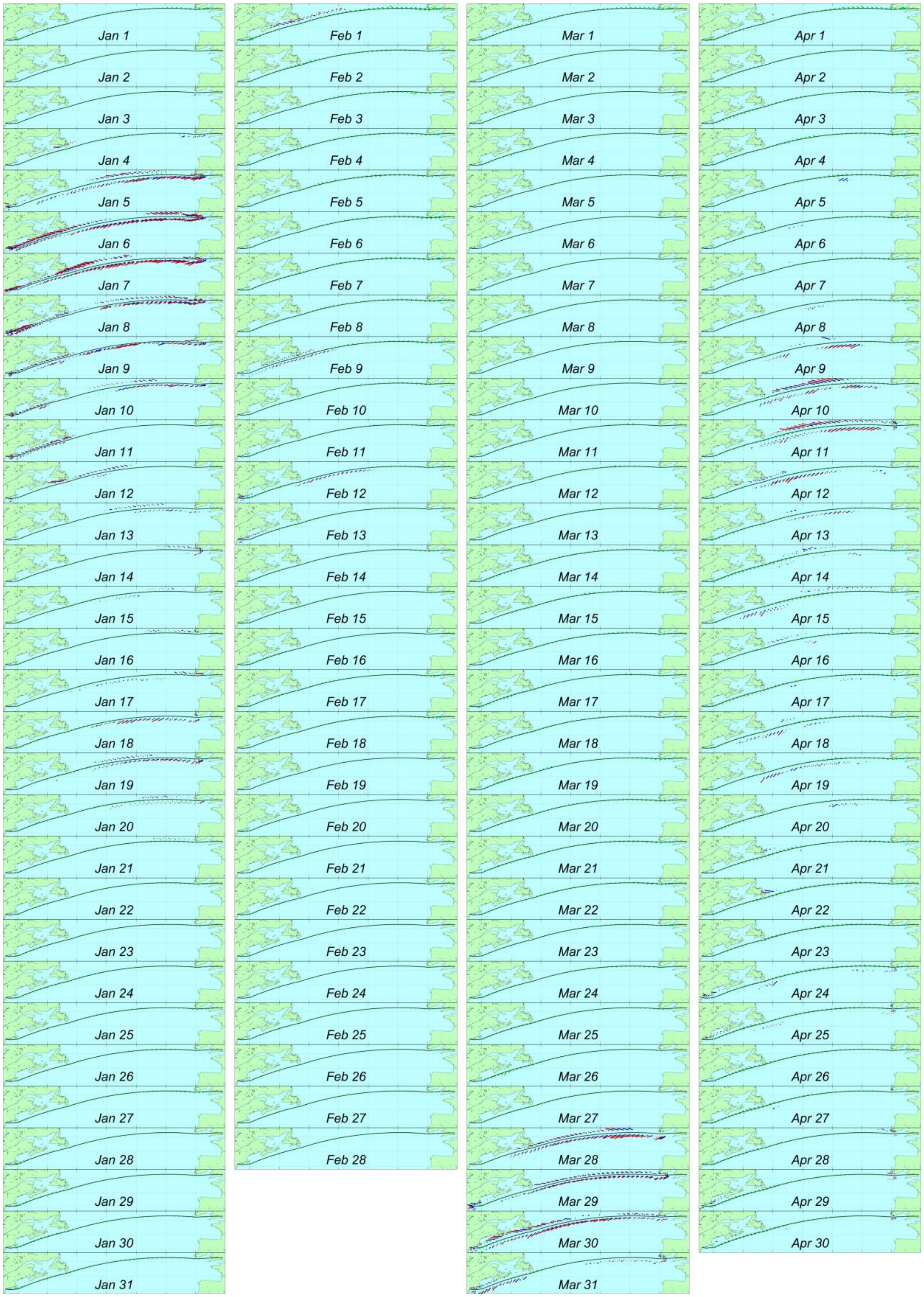


**Figure 11. Daily sonic-boom footprints for London–New York flights, 1st term of 2015**

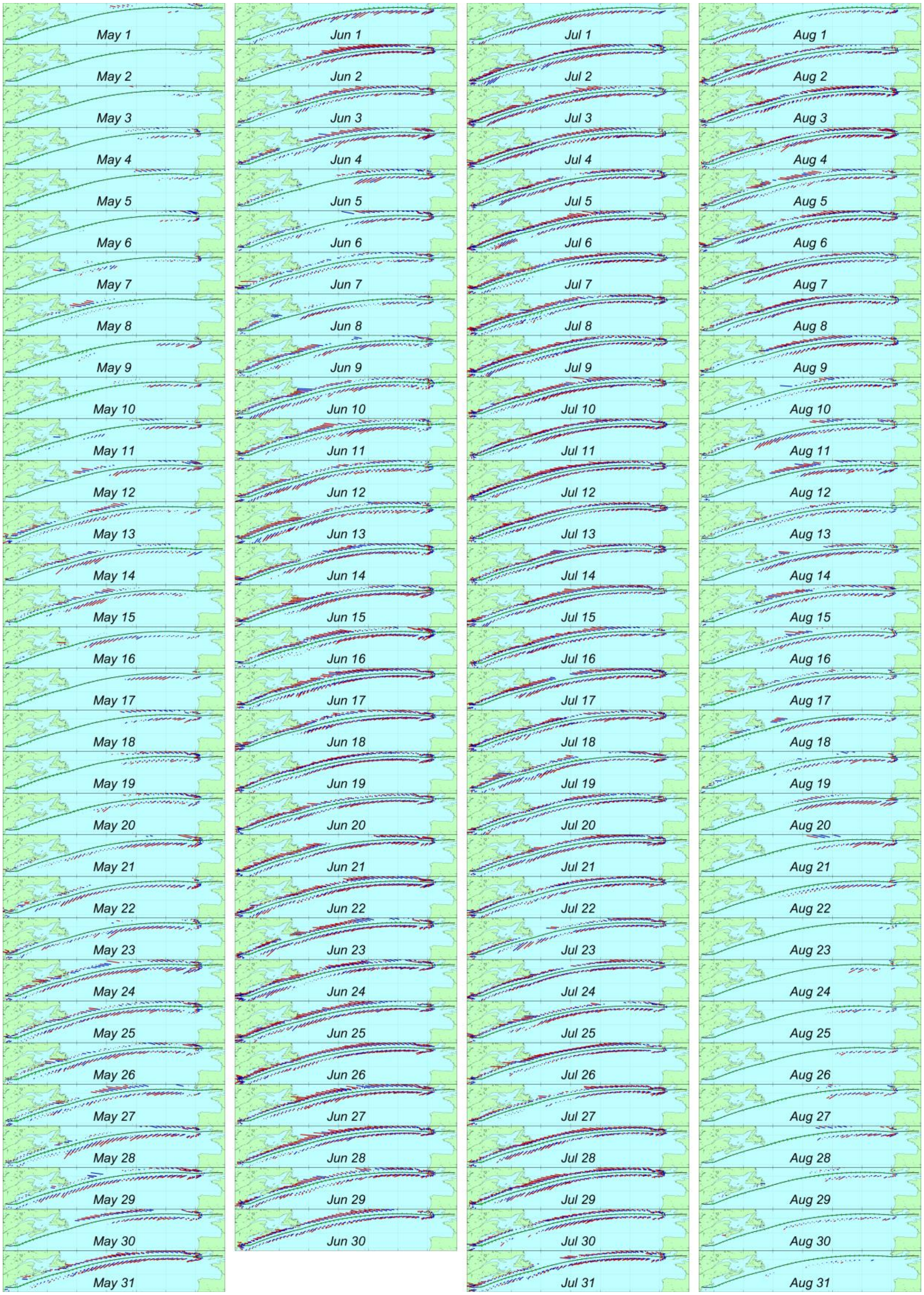


**Figure 12. Daily sonic-boom footprints for London–New York flights, 2nd term of 2015**

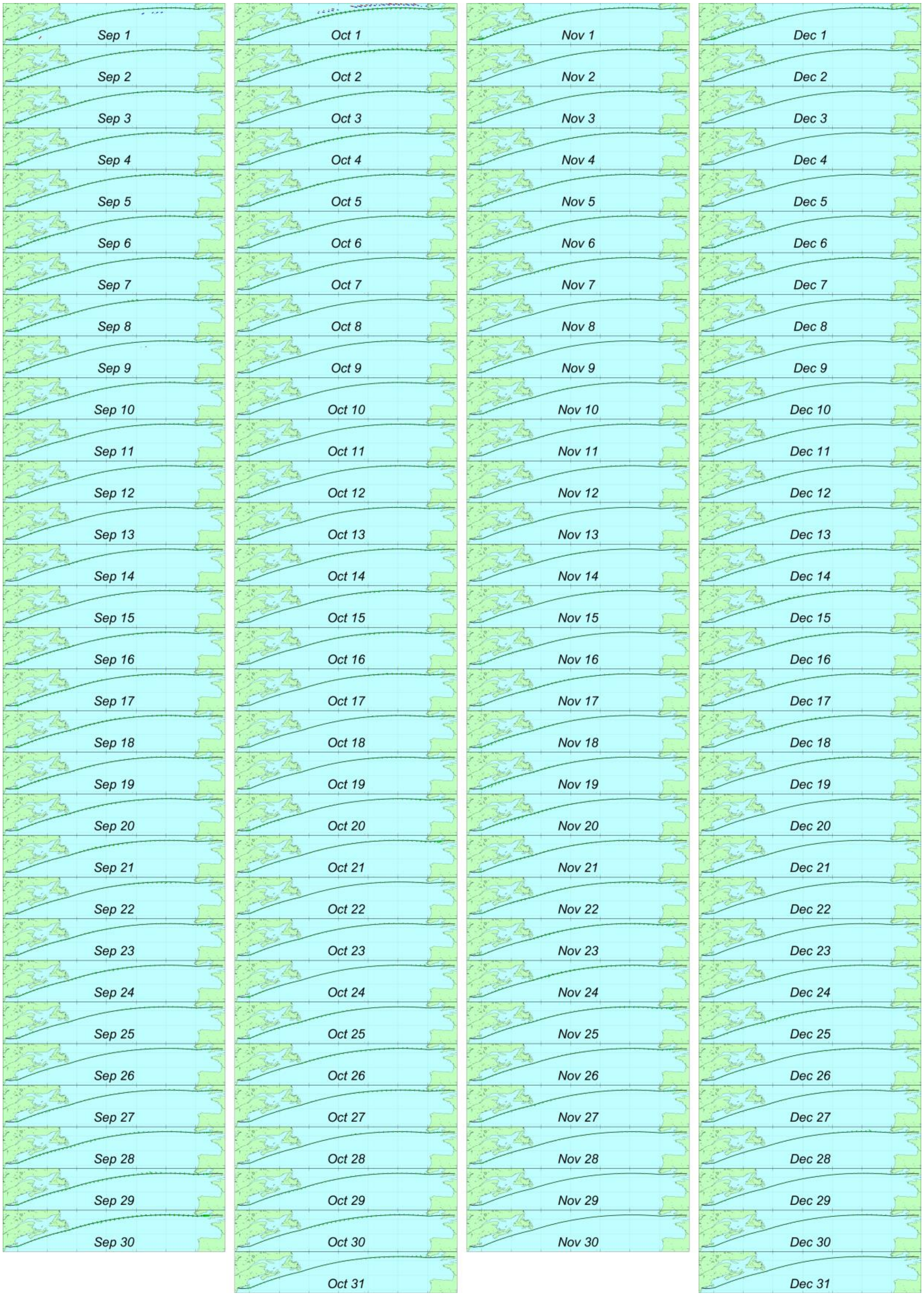


**Figure 13. Daily sonic-boom footprints for London–New York flights, 3rd term of 2015**

Figure 14 and Figure 15 display the occurrence of SSBs in monthly steps for flights between London and Jeddah. Only one day per month was considered to limit computational effort.

Heading northwest (Figure 14), SSB activity within distinct clusters is seen in the summer months, whereas SSBs appear in small, localized footprints between December and April.

In the opposite direction (Figure 15), the pattern flips and there appears to be stronger and consistent SSB activity in the winter season, whereas, again, these are just snapshots and cannot convey the true day-to-day incidence.

As on the North-Atlantic route, the switch apparently follows the sign of the upper-stratosphere winds in similar latitudes.

In any case, since most of the flight route is surrounded by land, SSBs have a high probability of making landfall. Type-II SSBs remain the critical case.

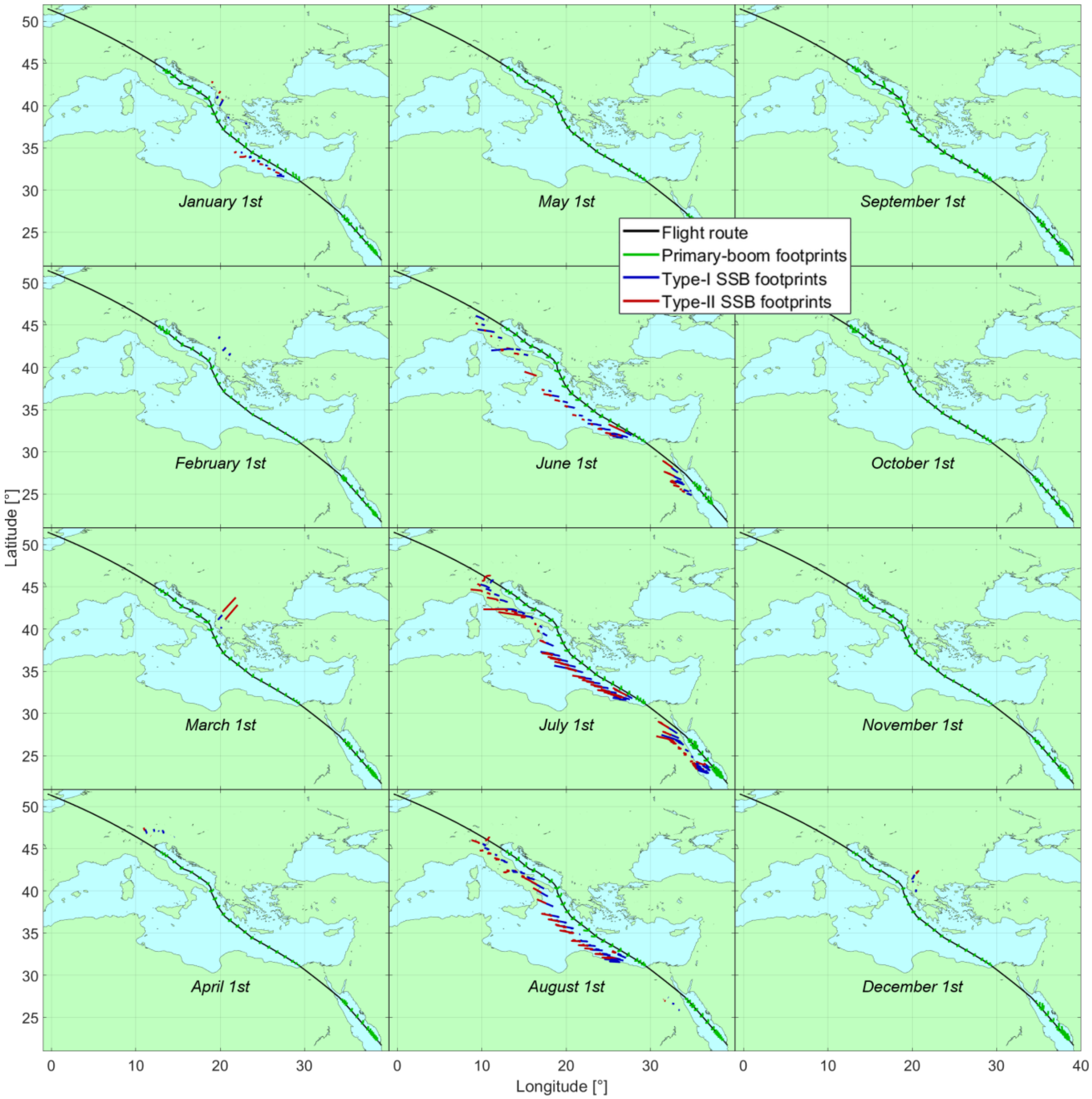


**Figure 14. Jeddah–London footprints at the beginning of every month, 2015**

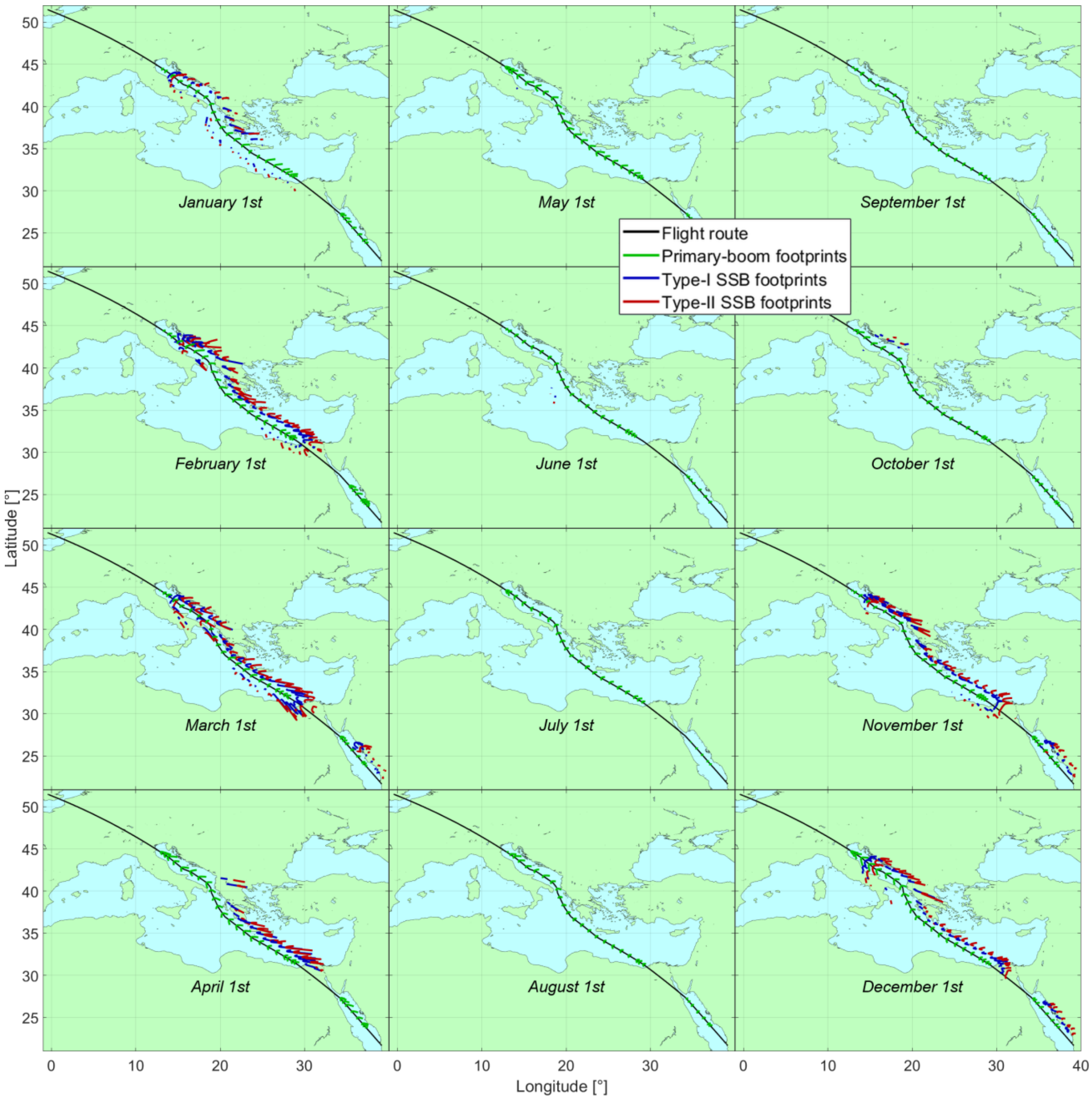


**Figure 15. London–Jeddah footprints at the beginning of every month, 2015**

The simulation results for the Singapore–Brisbane itinerary are shown in Figure 16 and Figure 17. Here as well, one day per month was assessed.

Considering primary-boom coastal buffers only, the fastest route cuts through Indonesia and the Java Sea, circumventing numerous islands of which most are populated.

Flying westward, relevant SSBs only appear on the first of January, February, and October. Eastward, they happen between March and July, first of September, and first of November. This unusual pattern probably results from the lesser constancy of tropical winds.

In any case, this route also implies a high probability of SSBs touching land any time they appear.

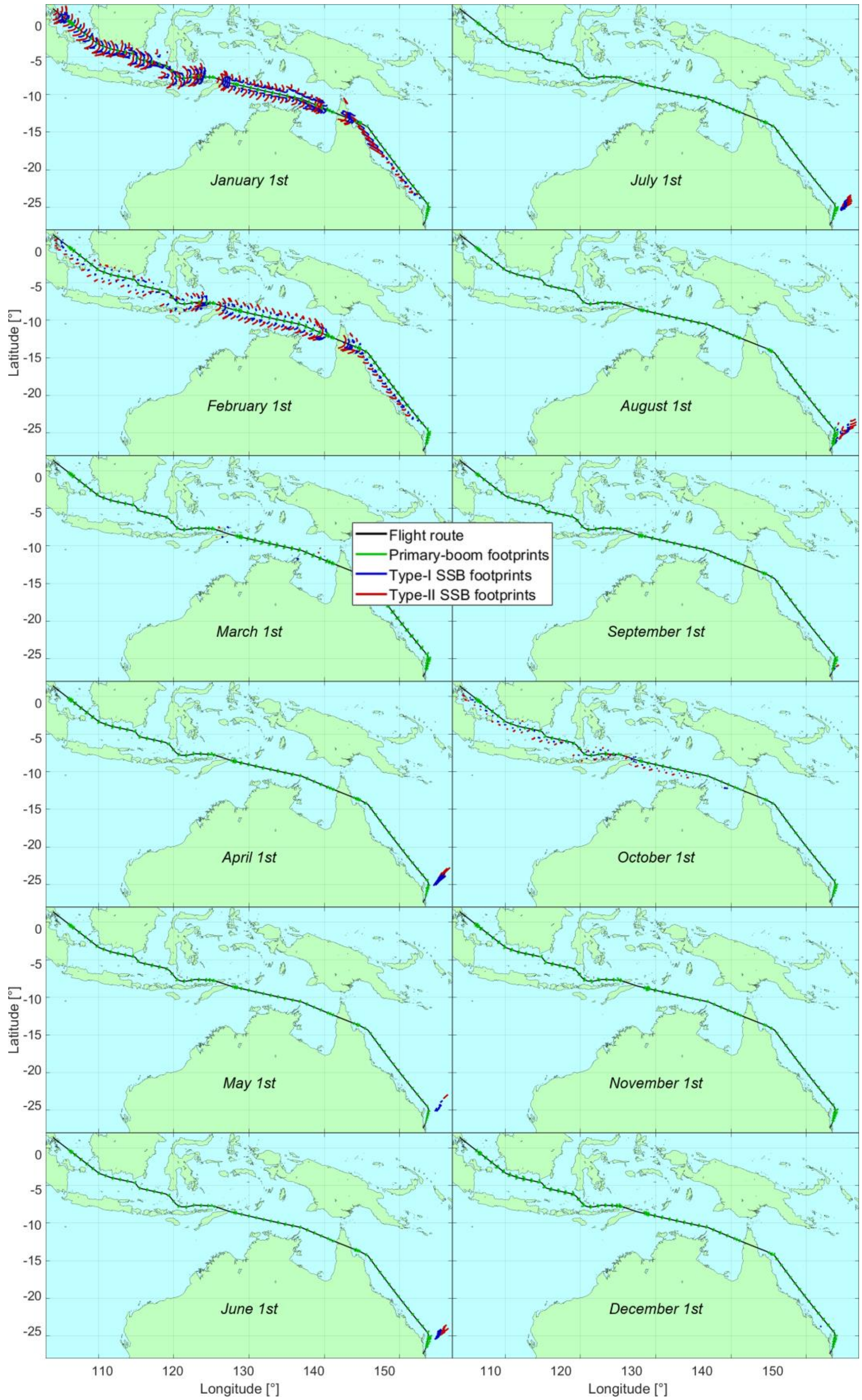


**Figure 16. Brisbane–Singapore footprints at the beginning of every month, 2015**

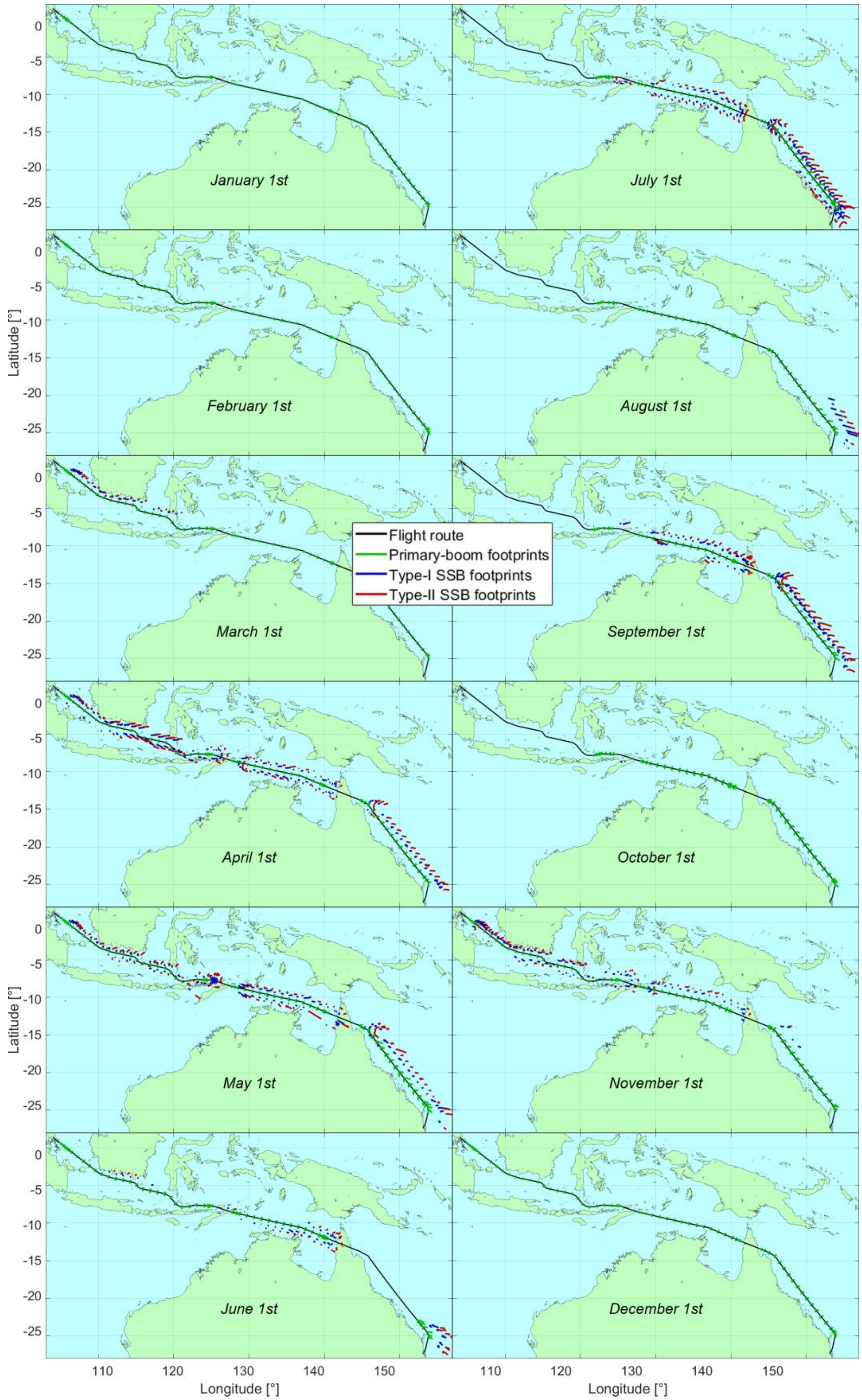


**Figure 17. Singapore–Brisbane footprints at the beginning of every month, 2015**

## VIII. Discussion

By public complaints, political discussion, and compelled operational adaptations, Concorde proved that secondary booms are an issue that cannot be ignored in civil supersonic operations. Low-boom shaping, which targets high-frequency content, does not eliminate the predominantly low-frequency secondary boom.

The solution either lies in

- conservative (seasonal) stand-off distances from coasts (which enabled more than 20 years of complaint-free service for Concorde), or
- dynamic flight routing, enabled by accurate weather forecasts and sophisticated acoustic propagation simulation.

The current simulation runs provide geometric footprints only; overpressure and loudness cannot be computed with DLR's DBoom suite yet. Other tools have basic capabilities for acoustic secondary-boom propagation, but multiple technical issues remain unresolved for realistic and accurate modelling[6] [4, 22].

What can and should be done short-term, however, is locating the focus lines[7], because that is where loudness can be expected to be highest [5] and where future flight routing might be oriented at, at least medium-term. Focus lines will likely also enable an update of our flight-route optimizer [19].

The simulation results indicate that seasonal or monthly simulations, or monthly averages, are not sufficient to cover day-to-day atmospheric changes because multiple off-season SSBs have been encountered in this dataset of a single year. However, the changes in SSB occurrence mostly span several days, so that intra-day changes might not require coverage.

In the tropics, wind systems are considerably less tied to the calendar than in the mid-latitudes (30-60° N/S). Their quasi-biennial oscillation (QBO) and the monsoon/trade-wind system render these latitudes less eligible for season-based schemes than for weather-based operations.

The simulations showcase that SSB footprints can only appear on one side of the flight track so that the other side is "safe", or that they only appear locally. For predictions of local safety, accurate weather forecasts and accurate geometric propagation might even suffice because SSB impacts can be excluded with high probability.

Type-II SSBs are critical because they reach farther than type I and because at least for Concorde, they were measured to be louder – hypothetically due to the initially downward-pointing shockwaves being stronger than the upward-pointing ones [5]. It remains to be seen whether this also applies to dedicatedly low-boom aircraft as these are designed to emit particularly "benign" shockwaves downward.

Routing through straits that provide just enough width for the primary carpet will not work in case SSBs do appear and their loudness is deemed critical – at least at full supersonic speed. A straightforward solution would be for the aircraft to slow down to Mach-cutoff speed during the passage. Mach cutoff might also be sufficient when approaching, leaving, or even crossing land segments, particularly when loudness-based regulations apply instead of complete bans. At the same time, secondary booms could be measured with another loudness metric than primary booms, because their types of disturbance – long rumble vs. sudden bang – differ. Hypothetically, compliance could be monitored with coastal microphone arrays.

The SSB problem might be relieved by supersonic jets smaller than the Concorde, e.g. supersonic business jets, that do not produce as strong a sonic boom. With respect to small aircraft, perhaps something can be learned from the planned X-59 test flights [1].

Finally, flight planning compliant to sonic booms can only be as good as the underlying weather forecast. Separate studies should be dedicated to the latter.

[6] ASCENT Project 057 Annual Report, 2023, issued by the Pennsylvania State University. https://s3.wp.wsu.edu/uploads/sites/2479/2024/05/ASCENT-Project-057-2023-Annual-Report.pdf.

[7] It shall be noted that during the present studies, SSB ground profiles were encountered that had more than one focus point. In that case, the one most remote from the flight track would be critical.

## IX. Conclusion

This work discussed the implications of having to consider secondary sonic booms (SSBs) in the operation of civil supersonic aircraft. Moreover, DLR's sonic-boom propagation toolset DBoom was used for a year-round ray-tracing survey across three long oversea corridors. The simulation results lead to the following qualitative insights:

Seasonality reverses with direction: The months that invite secondary-boom landfall tend to be the quiet in the opposite flight direction, tracking the sign of the high-stratospheric wind. At the same time, SSBs appear intermittently in unusual months, preventing reliable predictability by season only.

Short-term variability: SSB focus lines shift noticeably from one day to the next. A single, fixed coastal margin that guarantees clearance under all synoptic states might be unnecessarily conservative.

Type-II SSB governs compliance: Whenever the reflected (type-II) path remains offshore, the refracted (type-I) path does likewise. Also, type II is supposedly louder.

Geometry versus loudness: DBoom locates focus lines reliably, but, just as all other codes, lacks the comprehensive set of physics needed for trusted SSB overpressure and loudness output. Pending integration of, e.g., non-linear propagation, frequency-dependent absorption, and ray focusing in one comprehensive tool suite, the preliminary operational rule would be to keep the type-II focus offshore or to execute Mach cutoff before landfall.

Future steps include finishing a focus-line solver and linking it to our routing optimizer, extending the propagation chain to acoustic metrics, and validating the complete process against forthcoming flight-test data. These are prerequisites for informing a noise-based supersonic regulatory framework.

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