Global Variability in Sonic Boom Exposure due to Macroscopic Atmospheric Effects



Will Doebler
Penn State PhD Defense | 2/22/2024

Outline

- Introduction and Background
  - Supersonic flight prohibition
  - NASA Quesst mission
  - Research questions
  - Definitions
    - Carpet width
    - Sonic boom perception metrics
    - Inner carpet mean loudness
    - Climate zones
  - PCBoom propagation model
  - Atmospheric model data
  - Informative results from the literature
- USA Propagation Study with the X-59
  - Determination of propagation simulation resolution
  - Effects of location, season, heading, and climate zone
- Global Propagation Study with multiple aircraft
  - Determination of propagation simulation resolution
  - Effects of location, season, heading, and climate zone
  - Effects of climate change
- Summary

Bottom line up front: goals of this dissertation

- Perform two sonic boom propagation simulation studies: US and global
- Aid in NASA Quesst mission planning
  - Estimate the capable noise dose range of the X-59 for the US and globally
  - Generate models to suggest the season and flight direction for optimal noise exposure at any location
- Determine impact of atmospheric model selection on sonic boom simulation predictions
- Inform development of new supersonic aircraft noise regulations
  - Show the effectiveness of aircraft noise reduction technology across the world
  - Identify regions that are likely to experience elevated noise exposure
  - Determine if N-waves and shaped sonic booms have similar global trends in noise exposure
  - Estimate the effects of climate change on sonic boom noise exposure

Anatomy of a sonic boom propagation simulation study

- Select
  - Aircraft
  - Aircraft flight conditions
  - Locations for propagation
  - Timespan
  - Temporal atmospheric profile sampling rate
  - Atmospheric profile database
- Perform propagation simulations
  - PCBoom software
- Report quantities of interest
  - Sonic boom noise exposure region size: the “carpet width”
  - Loudness directly below the aircraft
  - Mean loudness over an inner portion of the carpet

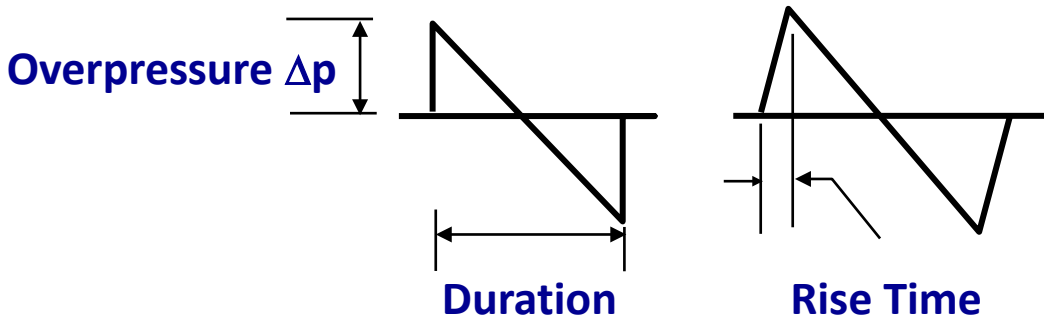
Research questions

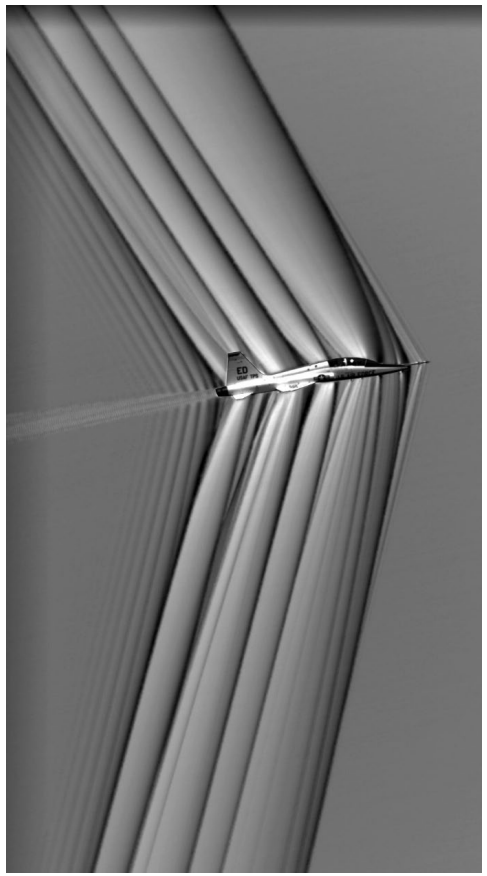
1. Does use of different atmospheric models result in significantly different sonic booms in terms of loudness metric levels and carpet width?
2. For a fixed location, how far apart in time should atmospheric profiles be sampled to produce booms with significantly different levels or carpet widths?
3. For a fixed location, how many observations are need to characterize distributions of boom metrics and carpets?
4. At a fixed time, how far apart in space should atmospheric profiles be sampled to produce booms with significantly different levels or carpets?
5. Do N-waves and low-booms have the same global variability?
6. What will be the effect of a changing climate on sonic boom loudness?

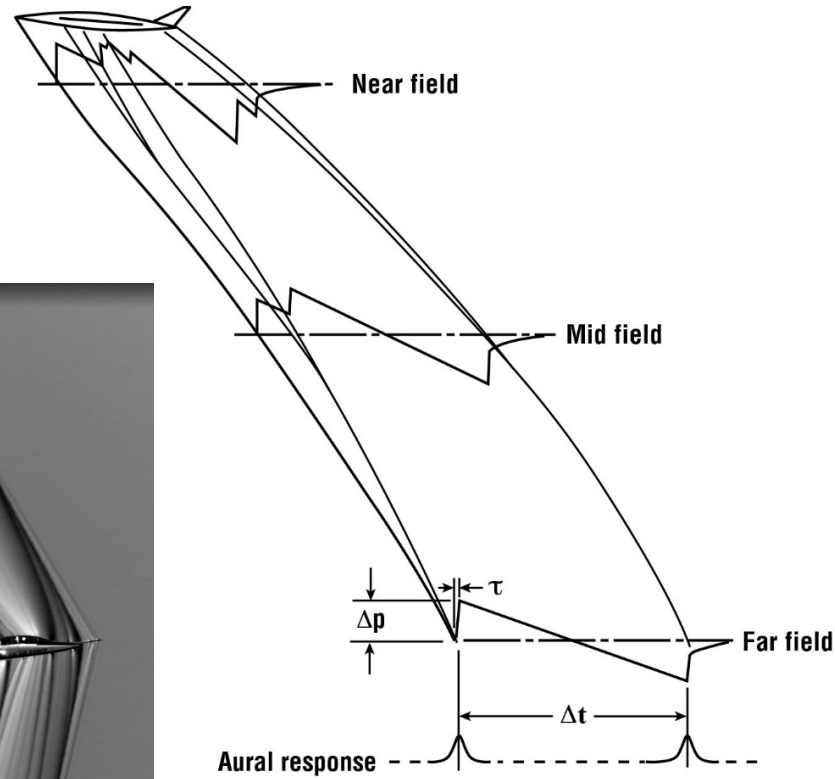
Introduction and Background

Sonic boom basics

- Supersonic flight ➡ aircraft flies faster than speed of sound
  - Shockwaves travel away from vehicle
  - Shockwaves merge as they travel through the atmosphere
  - Heard on the ground as a sonic boom
- For traditional supersonic aircraft
  - Shockwaves eventually merge into bow and tail shocks
  - Sonic boom is an “N-wave” signature





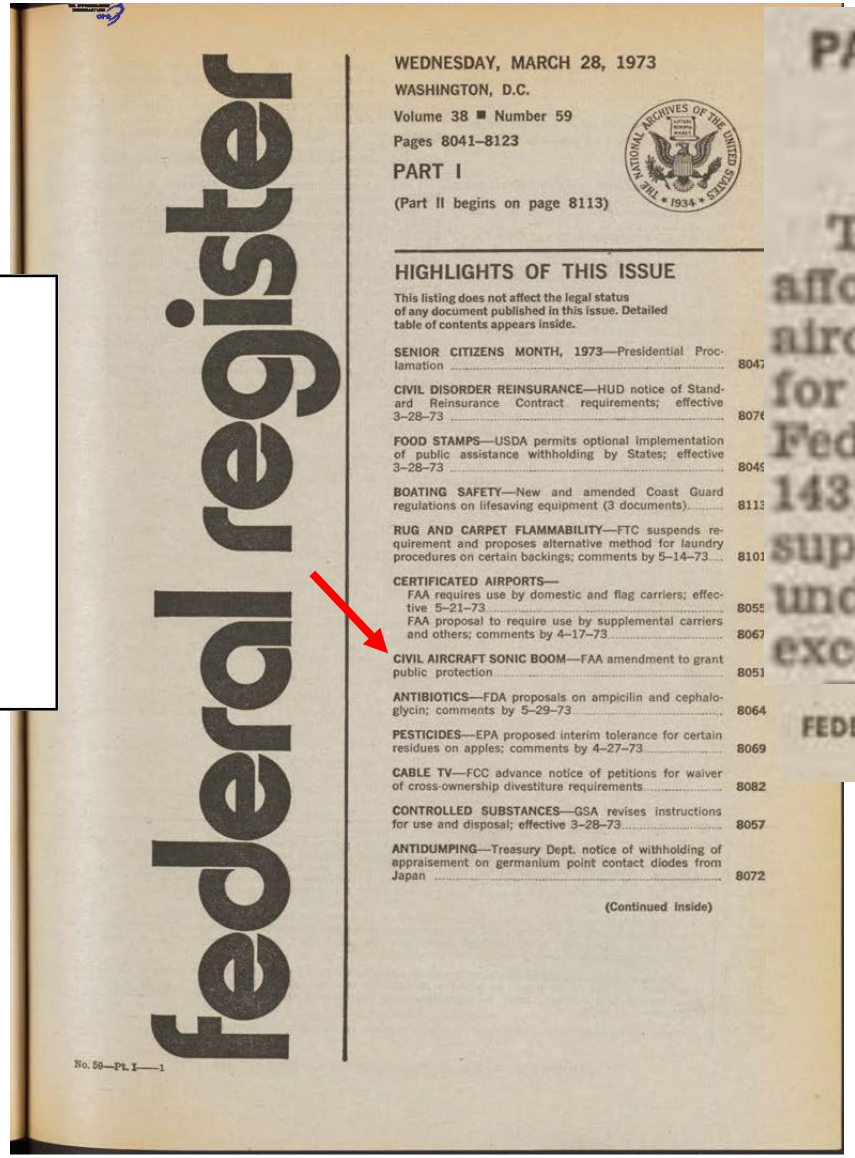


Supersonic flight over land has been prohibited since 1973

- 26 years after Chuck Yeager broke the sound barrier

NASA ID:
ARC-20171010-AAV3040-Supersonic-GfxPkg-NASAWeb

- Concorde was able to fly supersonic over water
  - Last flight: 2003



federal register

WEDNESDAY, MARCH 28, 1973
WASHINGTON, D.C.
Volume 38 ■ Number 59
Pages 8041–8123
PART I
(Part II begins on page 8113)

HIGHLIGHTS OF THIS ISSUE

This listing does not affect the legal status of any document published in this issue. Detailed table of contents appears inside.

SENIOR CITIZENS MONTH, 1973—Presidential Proclamation ... 8047

CIVIL DISORDER REINSURANCE—HUD notice of Standard Reinsurance Contract requirements; effective 3–28–73 ... 8076

FOOD STAMPS—USDA permits optional implementation of public assistance withholding by States; effective 3–28–73 ... 8045

BOATING SAFETY—New and amended Coast Guard regulations on lifesaving equipment (3 documents) ... 8113

RUG AND CARPET FLAMMABILITY—FTC suspends requirement and proposes alternative method for laundry procedures on certain backings; comments by 5–14–73 ... 8101

CERTIFICATED AIRPORTS—
FAA requires use by domestic and flag carriers; effective 5–21–73 ... 8055
FAA proposal to require use by supplemental carriers and others; comments by 4–17–73 ... 8067

CIVIL AIRCRAFT SONIC BOOM—FAA amendment to grant public protection ... 8051

ANTIBIOTICS—FDA proposals on ampicilin and cephaloglycin; comments by 5–29–73 ... 8064

PESTICIDES—EPA proposed interim tolerance for certain residues on apples; comments by 4–27–73 ... 8069

CABLE TV—FCC advance notice of petitions for waiver of cross-ownership divestiture requirements ... 8082

CONTROLLED SUBSTANCES—GSA revises instructions for use and disposal; effective 3–28–73 ... 8057

ANTIDUMPING—Treasury Dept. notice of withholding of appraisement on germanium point contact diodes from Japan ... 8072

(Continued inside)

No. 59—Pt. I——1

PART 91—GENERAL OPERATING AND FLIGHT RULES

Civil Aircraft Sonic Boom

The purpose of this amendment is to afford the public protection from civil aircraft sonic boom. The primary basis for this amendment is section 611 of the Federal Aviation Act of 1958 (49 U.S.C. 1431). This amendment prohibits the supersonic flight of civil aircraft except under the terms of an authorization to exceed mach 1.

FEDERAL REGISTER, VOL. 38, NO. 59—WEDNESDAY, MARCH 28, 1973



The supersonic prohibition is being reconsidered given the emergence of sonic boom noise reduction technology

- Change the “speed limit” to a “noise limit”
  - New regulations are needed
  - Must be globally effective
  - Cut travel times in half

- NASA Quesst mission goal:
  - Provide data to support the development of potential new regulations

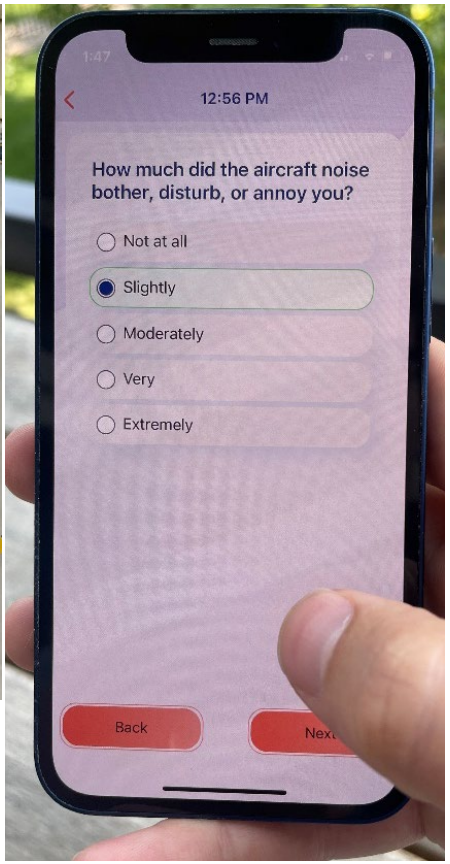
What is the NASA Quesst mission?

- Background:
  - Supersonic flight over land is currently prohibited due to sonic boom loudness
- Main goal
  - Provide data from community noise annoyance surveys to international aircraft noise regulators
- Step 1: Design a quiet supersonic aircraft, the X-59
- Step 2: Build the X-59
- Step 3: Fly it safely
- Step 4: Verify its noise performance
- Step 5: Measure people's perception of the sound
- Step 6: Provide data for noise regulations

- Lots of intermediate steps!







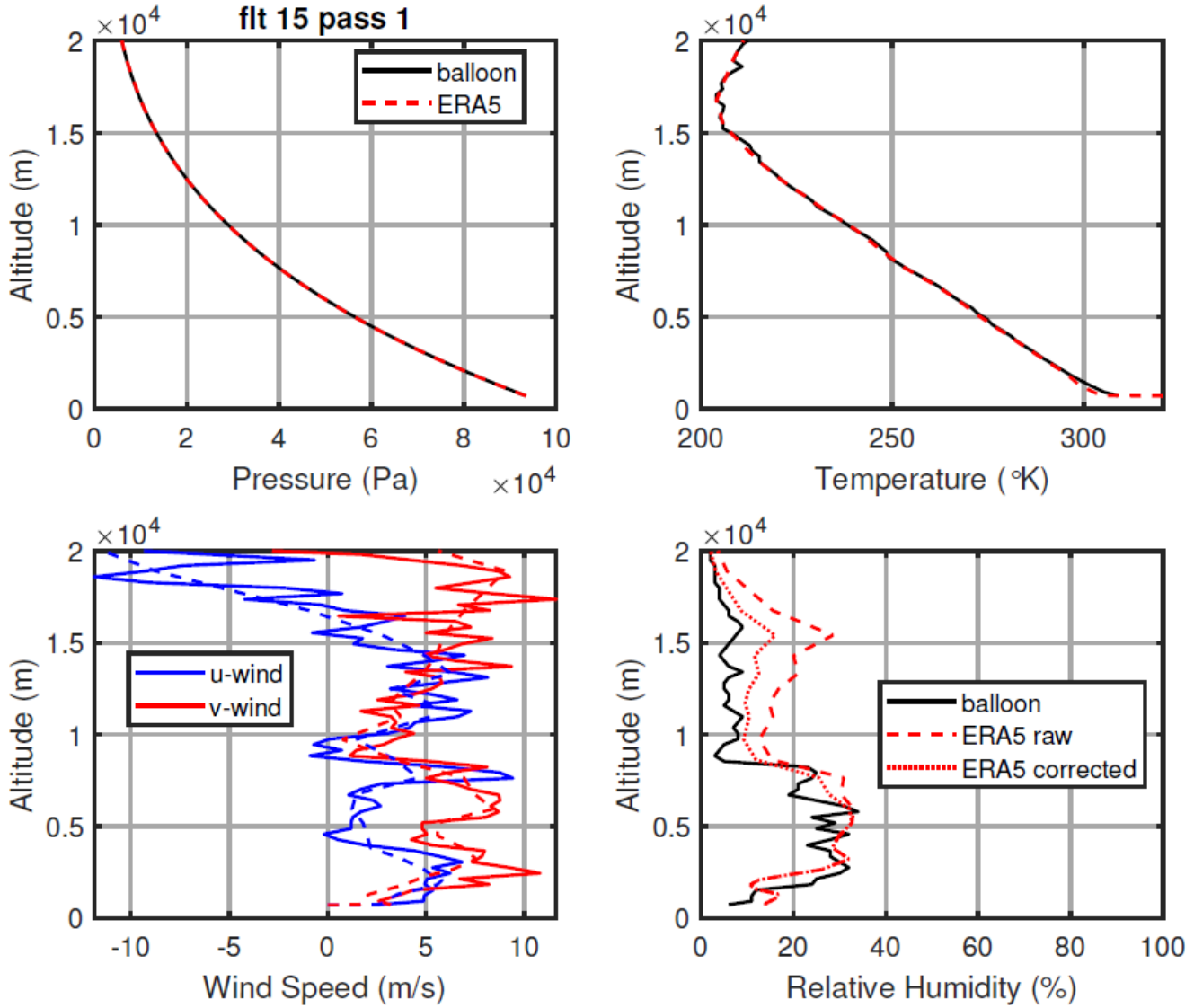
Definitions for sonic boom simulation studies

- Atmospheric profile
- Carpet width
- Sonic boom perception metrics
- Inner carpet mean level
- Climate zones

For sonic boom propagation simulations, the atmospheric profile that the boom moves through is needed

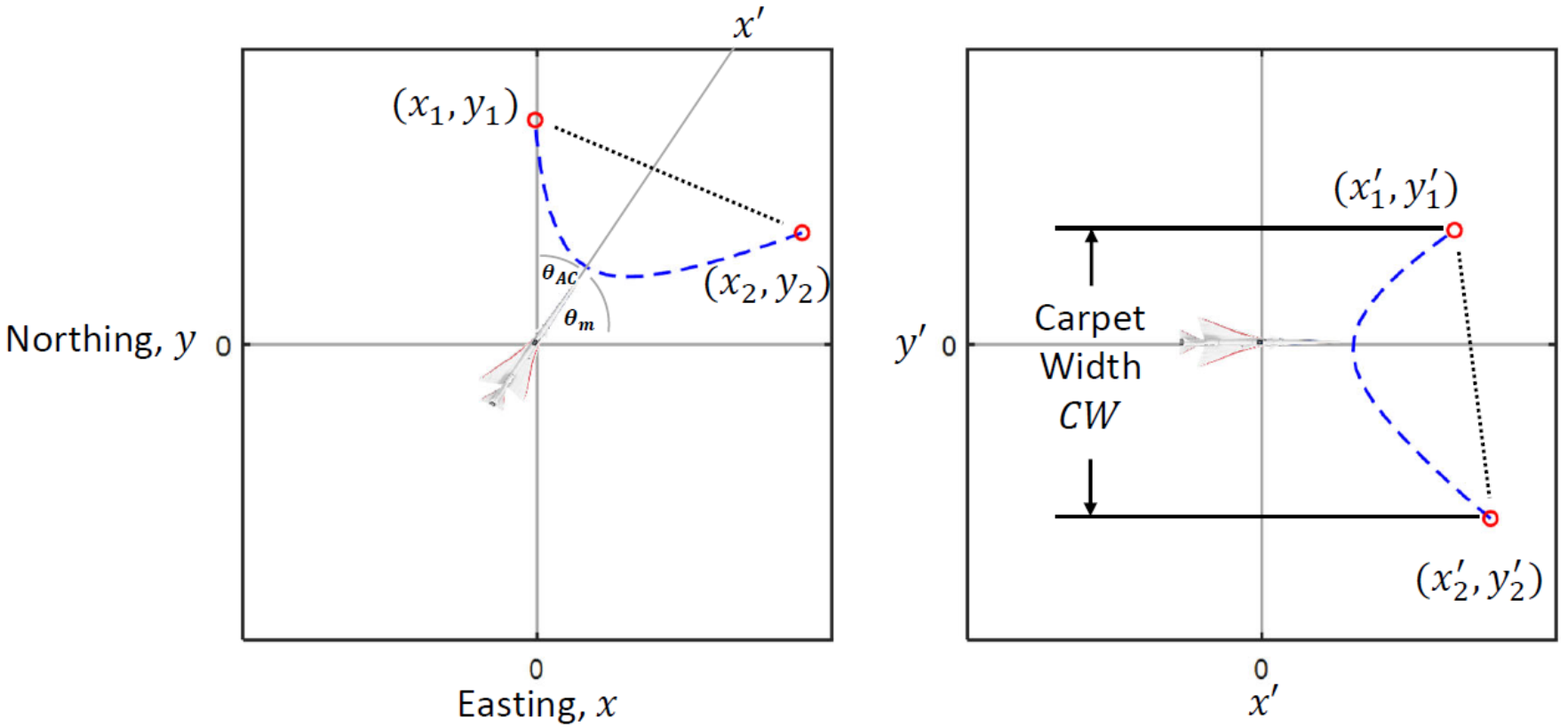
- Defined as ambient
  - pressure,
  - temperature,
  - horizontal wind speed, and
  - relative humidity

  as a function of altitude at an instant in time and space



Carpet width (CW) definition

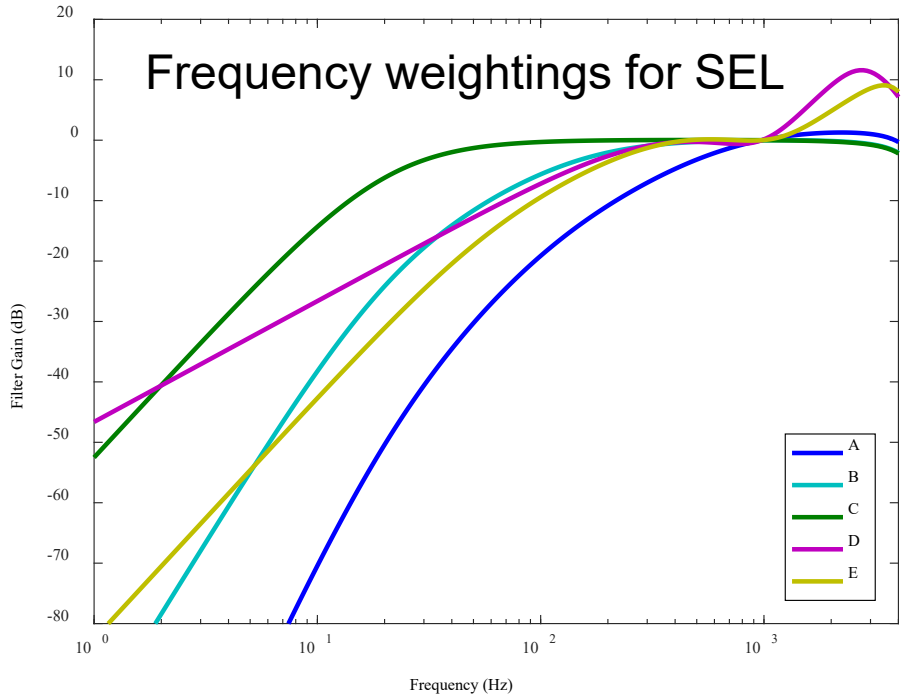
- Flight-track-parallel distance from the lateral cutoff rays



Sonic boom perception metrics

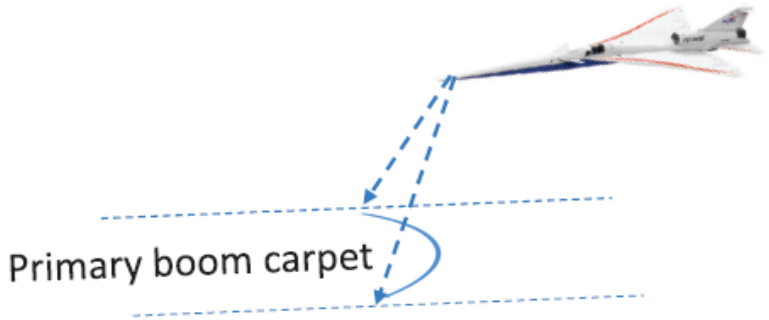
- Metrics to describe perception of subsonic aircraft are not effective for describing perception of sonic booms

- Six metrics under consideration for use in supersonic aircraft noise certification standards
  - A-, B-, D-, and E-weighted Sound Exposure Level (SEL)
    - Sum the square of frequency-weighted pressure
  - **Perceived Level (PL)**
    - More complex, level-dependent frequency weighting and summation procedure
  - Indoor Sonic Boom Annoyance Predictor (ISBAP)
    - Hybrid metric of PL, ASEL, and CSEL
    - Emphasizes lower frequency sound
- Correlate well with sonic boom perception



A. Loubeau et al., "Updated evaluation of sonic boom noise metrics," J. Acoust. Soc. Am., 144: 1706, 2018.

Inner Carpet Mean (ICM) Level



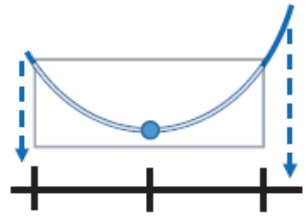
Isopemp on which boom data is available

Undertrack ray

Data included in inner carpet mean

(a)

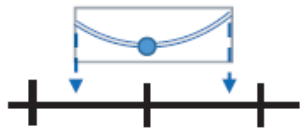
Offtrack distance (km)



Case 1

Compute mean PL for simulated ground data between ± 20 km

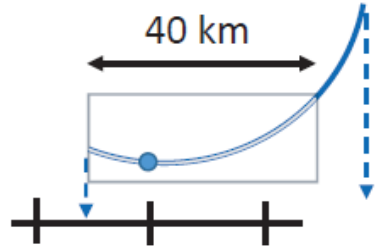
(b)



Case 2

Compute mean PL for all simulated ground data

(c)



Case 3

Use the carpet edge on the narrower side as the anchor point. Compute mean of PL within 40 km of the anchored point

Climate zones are correlated with building construction, which can influence indoor sonic boom perception

- US definition
  - Dept. of Energy Building America Best Practices Volume 7.3 climate zones
- Global definition
  - Koppen-Geiger climate zones

DoE Building America Best Practices Climate Zones

- 7 zones in CONUS
- Defined with varying thresholds of
  - Precipitation
  - Heating Degree Days
  - Temperature/wet bulb temperature
- Used to help plan X-59 community noise survey locations
- Defined only for USA

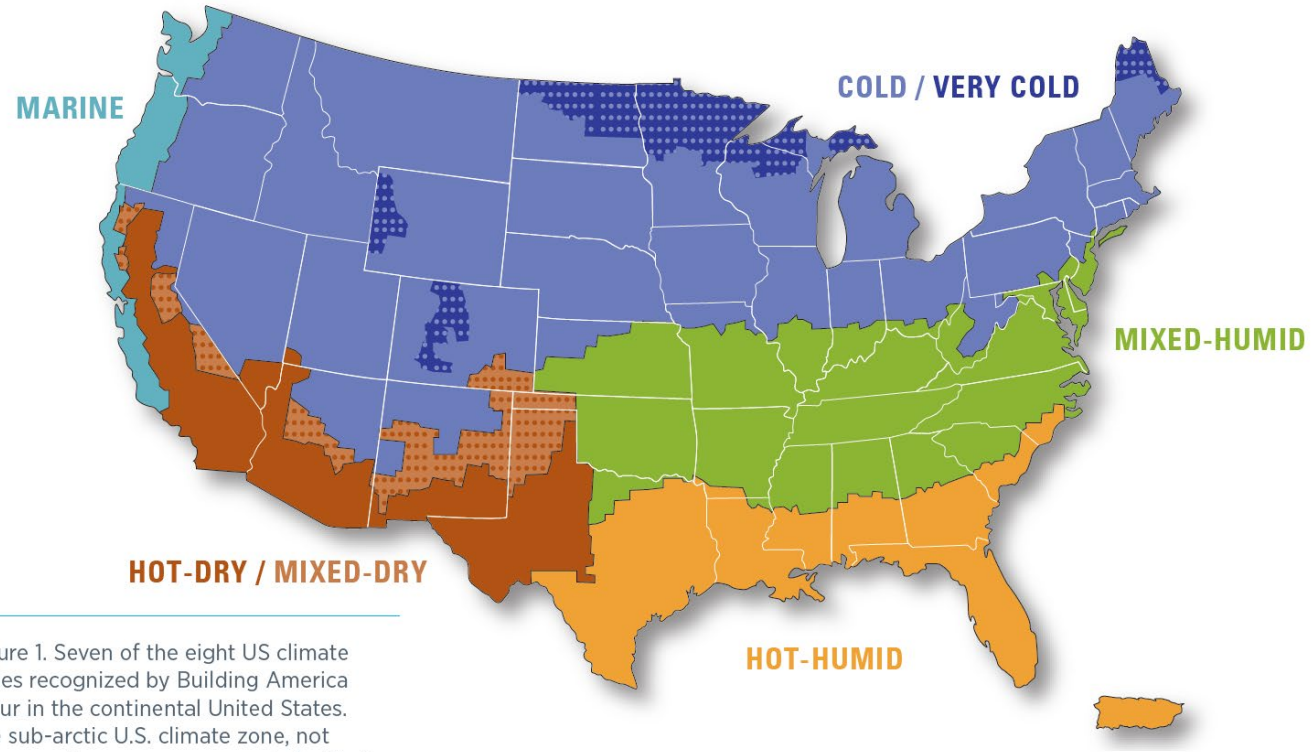


Figure 1. Seven of the eight US climate zones recognized by Building America occur in the continental United States. The sub-arctic U.S. climate zone, not shown on the map, appears only in Alaska.

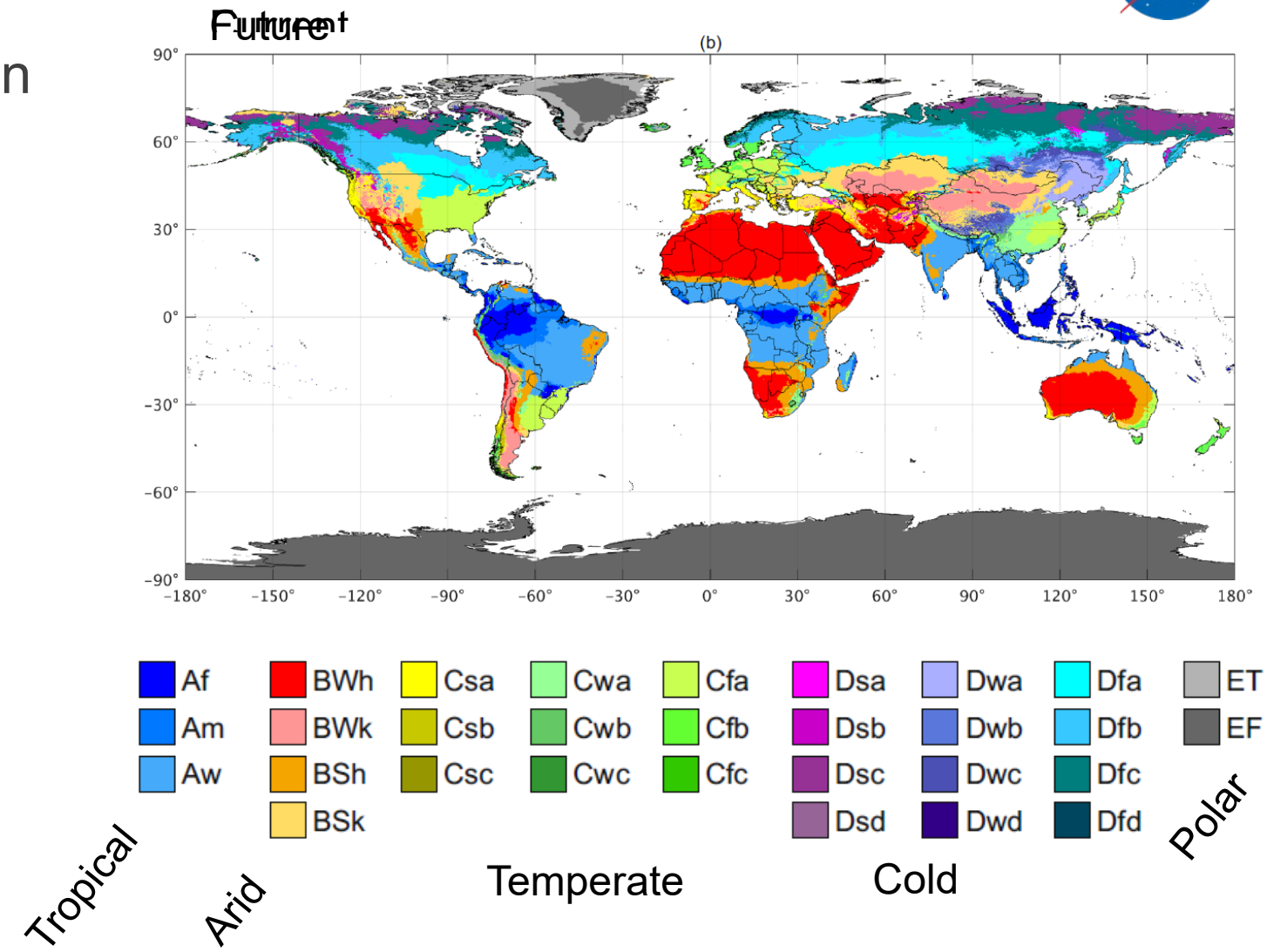
Heating Degree Days

The degree-day measurement is the difference in temperature between the mean (average) outdoor temperature over a 24-hour period and a given base temperature for a building space, typically 65°F (25°C in Canada). For example, if the mean temperature at a given location for January 3 is 35°F, then the heating degree days measurement for that day is 30 (65 - 35 = 30).

"Guide to Determining Climate Regions by County," *BUILDING AMERICA BEST PRACTICES SERIES VOLUME 7.3,* Pacific Northwest National Laboratory, (2015)

Koppen-Geiger Climate Zones

- Beck et al. provided high resolution Koppen-Geiger global climate zones
- Total of 30 zones
  - 5 top-level, with 2 or 3 subclassification
- Includes
  - Current climate zones
  - Future estimated climate zones
- Enables assessment of climate change effects on sonic boom exposure



PCBoom

- Suite of NASA sonic boom modeling tools
- Enhanced Burgers module
- Assumptions
  - Geometrical spreading from ray tracing
  - Flat ground
  - Constant ground reflection factor
  - No diffraction
  - No atmospheric turbulence
  - No cloud effects
- Inputs
  - Near-field pressure
  - Flight trajectory
  - Atmospheric profile
- Outputs
  - Ground waveforms
  - Loudness metrics

Solved along the ray path, s:

$$\frac{\partial U}{\partial s} = \frac{i\omega\tilde{\beta}}{4\pi}\int U(\omega')U(\omega-\omega')d\omega' - \alpha_t(\omega)U(\omega)$$

where

$U =$ Fourier transform of the scaled acoustic pressure u

$\omega =$ $2\pi f$, the angular frequency

$\alpha_t =$ Doppler shifted and convected absorption coefficient

$\tilde{\beta} = \frac{\beta p_i^{(p)} B\Omega\chi}{\rho_o c_o^3}$, a scaled coefficient of nonlinearity

$\beta =$ 1.2, the coefficient of nonlinearity of air

$\chi = c_o/v$, the convective index

$c_o =$ quiescent sound speed

$v = \|\overrightarrow{v_r}\|$, the ray velocity magnitude

$\Omega = 1 - \overrightarrow{v_o}\cdot\left(\frac{\hat{n}}{c_o+\overrightarrow{v_o}\cdot\hat{n}}\right)$, the Doppler shift

$\overrightarrow{v_o} =$ wind velocity vector

$\hat{n} =$ wavefront-normal unit vector

$B = \sqrt{\frac{\rho_o c_o \chi \Omega A_r}{\rho_{o,r} c_{o,r} \chi_r \Omega_r A}}$, Blokhintzev scaling factor that includes the wind effects.

The scaled acoustic pressure satisfies $p = p_r^{(p)} Bu$

Lonzaga, et al., "PCBoom Version 7 Technical Reference," NASA/TM-20220007177, (2022).

Data from atmospheric models can be used as input to PCBoom for sonic boom simulations

- Three models studied
  - Two forecast models from NOAA NCEP
    - GFS: Global Forecast System
    - CFSv2: Climate Forecast System Version 2
  - One reanalysis model from ECMWF
    - ERA5: European Centre for Medium-range Weather Forecast Reanalysis Generation 5

	CFSv2	ERA5	GFS
Database Availability	2011-present	1940-present	2015-present
Spatial Resolution	0.5° by 0.5°	0.25° by 0.25°	0.25° by 0.25°
Temporal Resolution	6 hr	1 hr	3 hr
Vertical Resolution	37 isobars	37 isobars	42 isobars

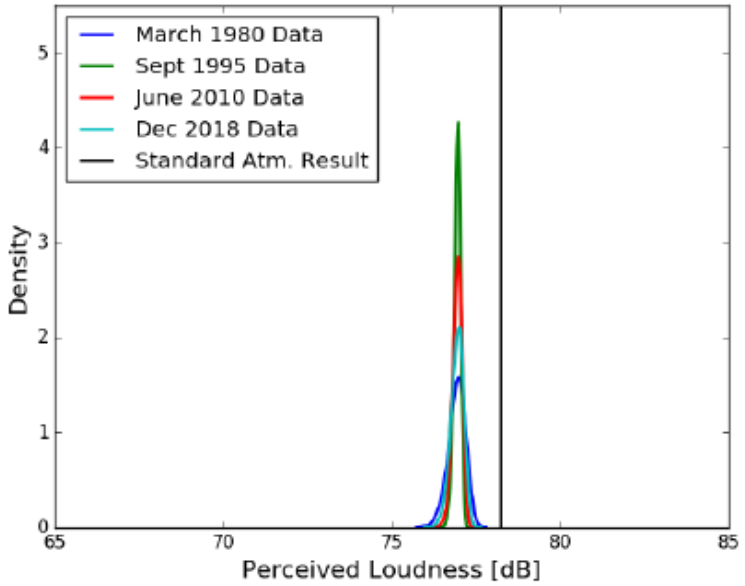
Results from the literature informed decisions about the propagation simulation studies

- Should atmospheric profiles be randomly generated or obtained from a database?
- Is it appropriate to use atmospheric model databases in sonic boom simulation studies?
- What separation distance between propagation locations is necessary?

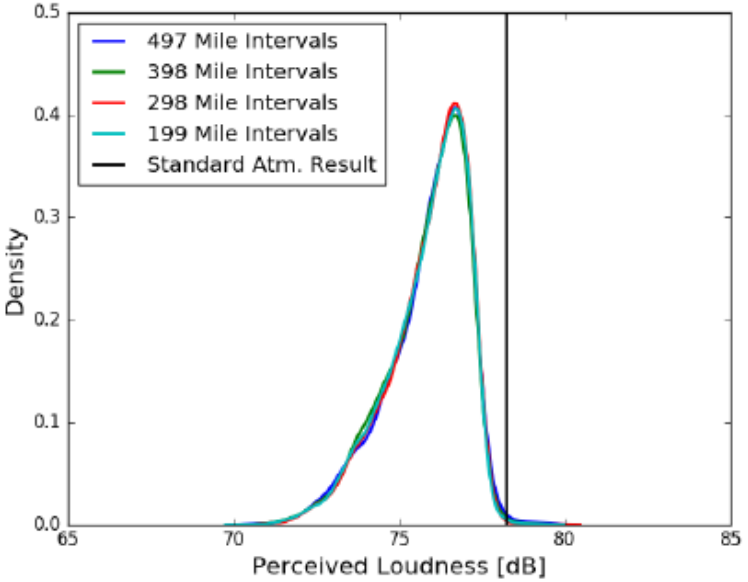
Should atmospheric profiles be randomly generated or obtained from a database?

- Lazzara et al. (2020)
  - Sonic boom simulations using
    - Realistic atmospheric profiles
    - Monte Carlo generated atmospheric profiles
      - Accounted for vertical correlation of profile variables
  - Loudness statistics did not match
    - Much more variability with realistic profiles

Predictions using Monte Carlo profiles



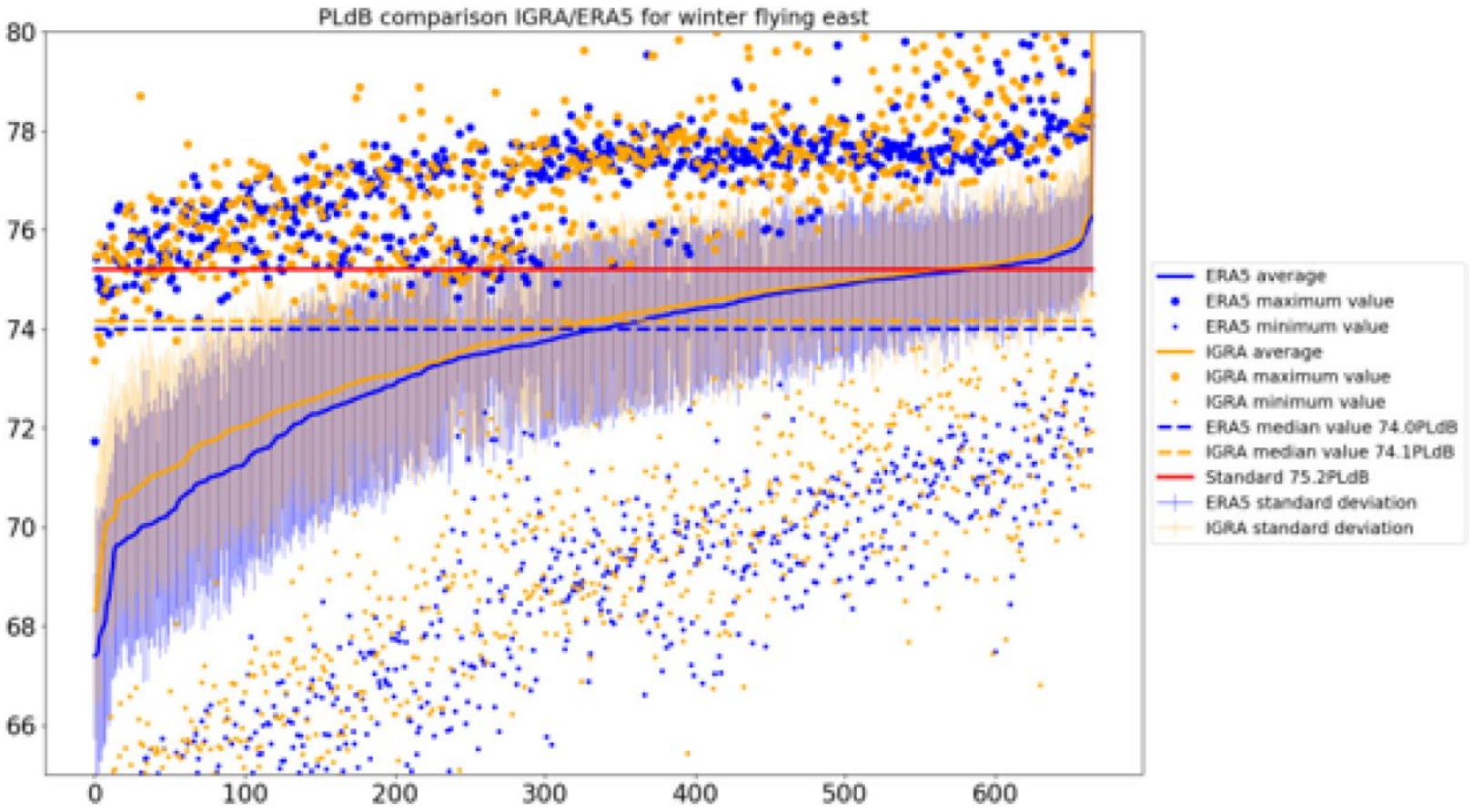
Predictions using realistic profiles



From Lazzara, D. S., T. Magee, H. Shen, and J. H. Mabe (2020) "Sonic boom performance of low-boom aircraft in non-standard atmospheres," in *AIAA Scitech 2020 Forum*, 0792; doi: 10.2514/6.2020-0792; © Copyright, reprinted by permission of the American Institute of Aeronautics and Astronautics, Inc.

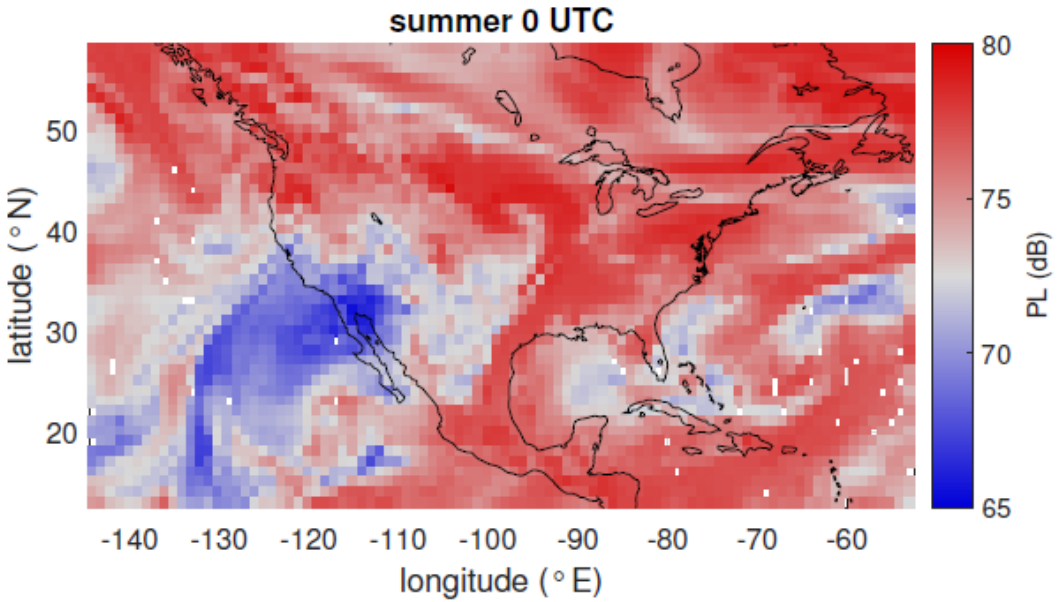
Is it appropriate to use modeled atmospheric data for sonic boom propagation simulations?

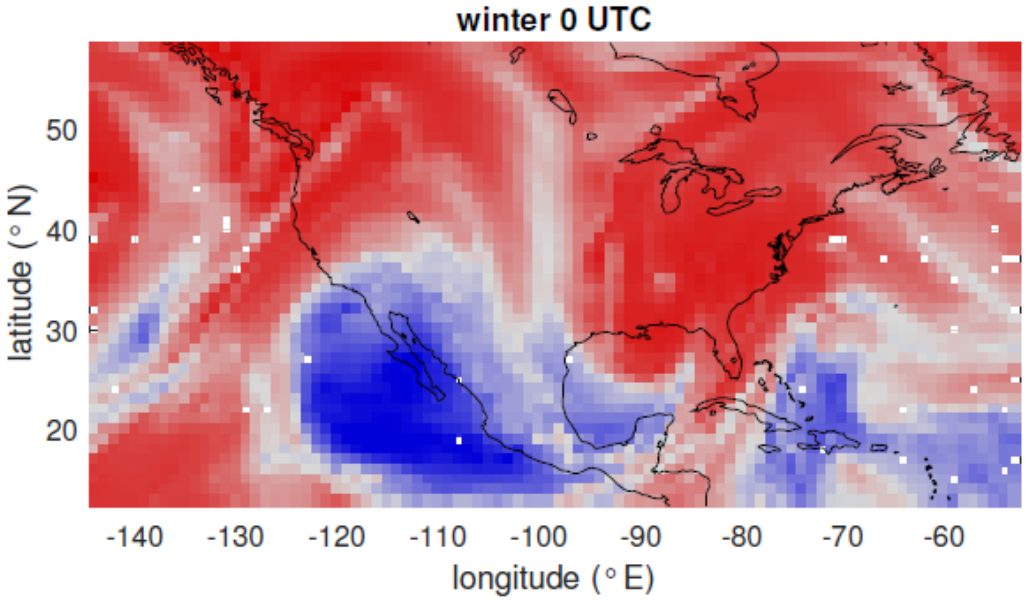
- Normand et al. (2021)
  - Weather balloon profiles vs. modeled profiles
    - Profile variables were in good agreement
      - Some humidity differences
    - Sonic boom loudness predictions within a few tenths of a dB



What separation distance between propagation locations is necessary?

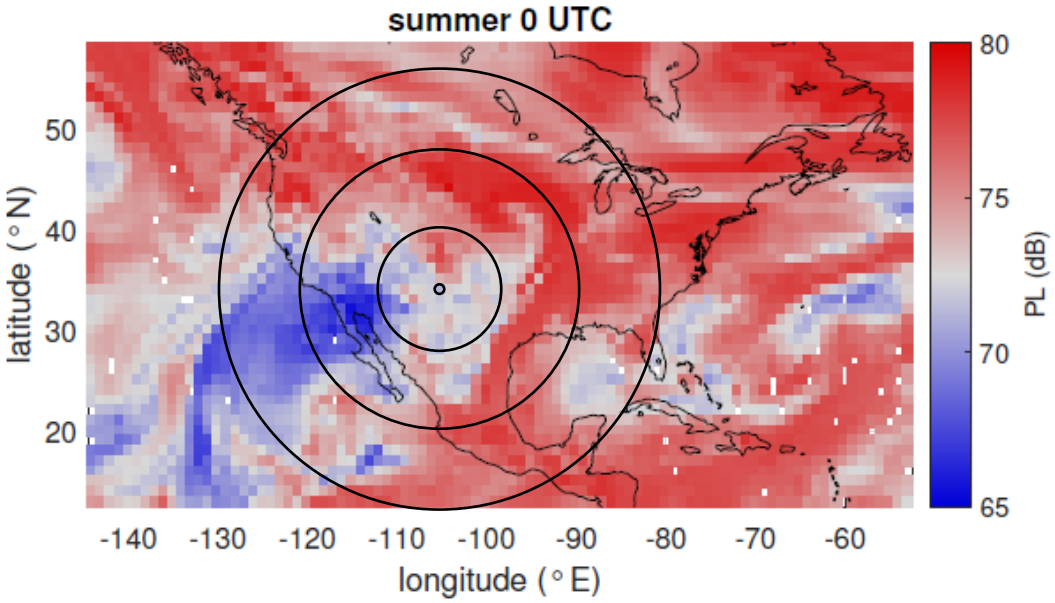
- Leal et al. (2021)
  - 1 deg by 1 deg propagation predictions at fixed instant in time
  - Enables spatial correlation computation
  - Spatial correlation informs resolution needed for propagation simulations

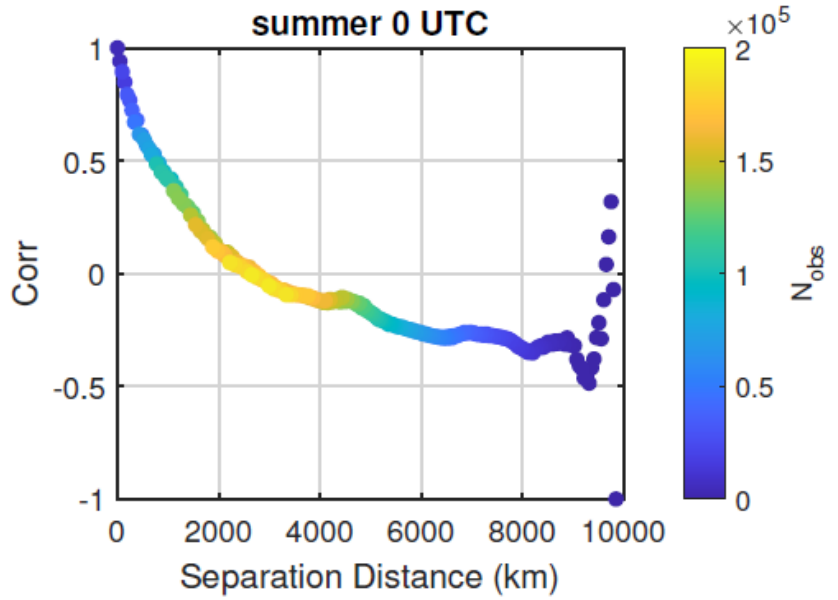


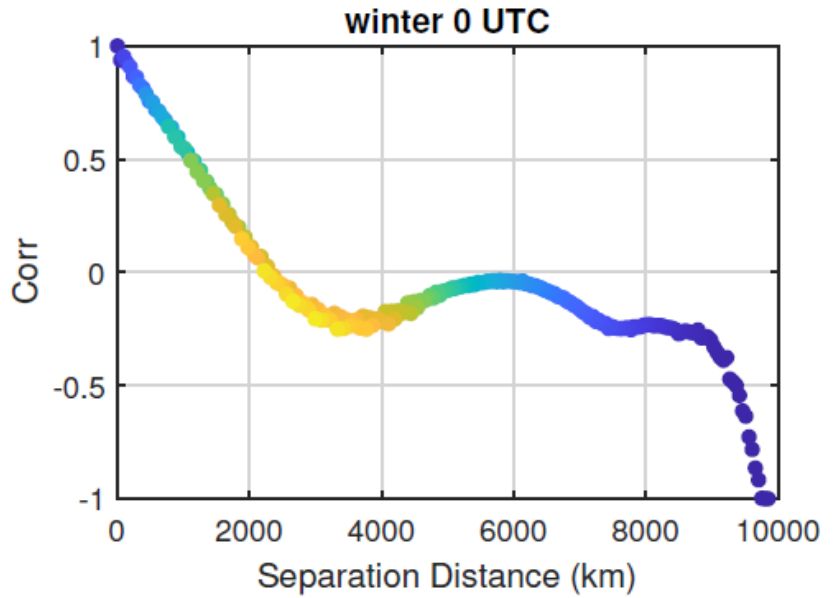


What separation distance between propagation locations is necessary?

- Compute Pearson correlation coefficient as a function of separation distance
  - Corr ≈ 1: little information gained
  - Corr = 0: “polka dot” plots, cannot interpolate between locations
    - ~2000 km, which is the synoptic length scale in meteorology
- Correlation of 0.5 occurs between 675 and 1100 km







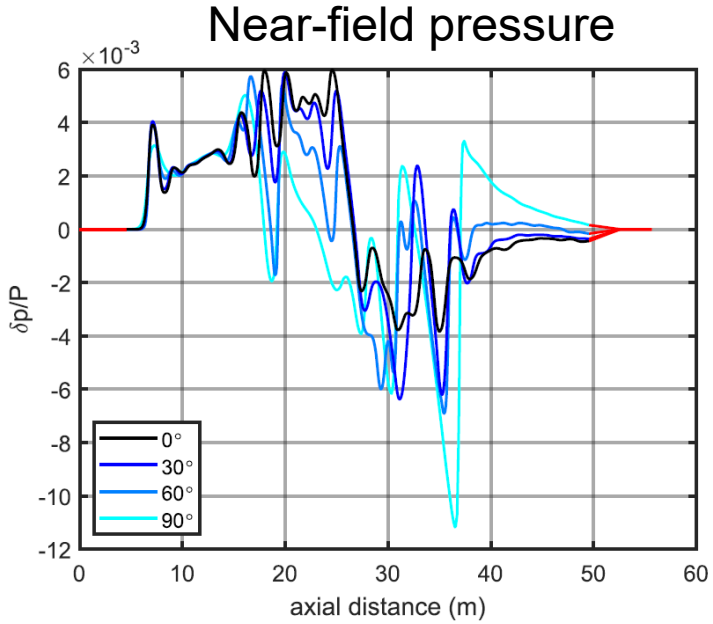
USA Propagation Simulation Study

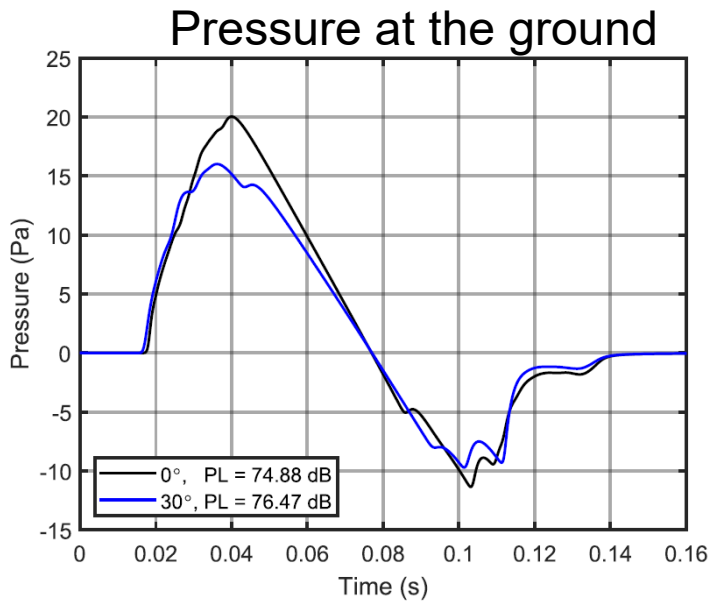
Recall: Anatomy of a sonic boom propagation simulation study

- Select
  - Aircraft
  - Aircraft flight conditions
  - Locations for propagation
  - Timespan
  - Temporal atmospheric profile sampling rate
  - Atmospheric profile database
- Perform propagation simulations
  - PCBoom software
- Report quantities of interest
  - Sonic boom noise exposure region size: the “carpet width”
  - Loudness directly below the aircraft
  - Mean loudness over an inner portion of the carpet

Anatomy of the US propagation simulation study

- Select
  - Aircraft: X-59 “C609”
  - Aircraft flight conditions: steady, level cruise at 4 headings
  - Locations for propagation:
  - Timespan:
  - Temporal atmospheric profile sampling rate:
  - Atmospheric profile database:
- Perform propagation simulations
  - PCBoom software
- Report quantities of interest
  - Sonic boom noise exposure region size: the “carpet width”
  - Loudness directly below the aircraft
  - Mean loudness over an inner portion of the carpet

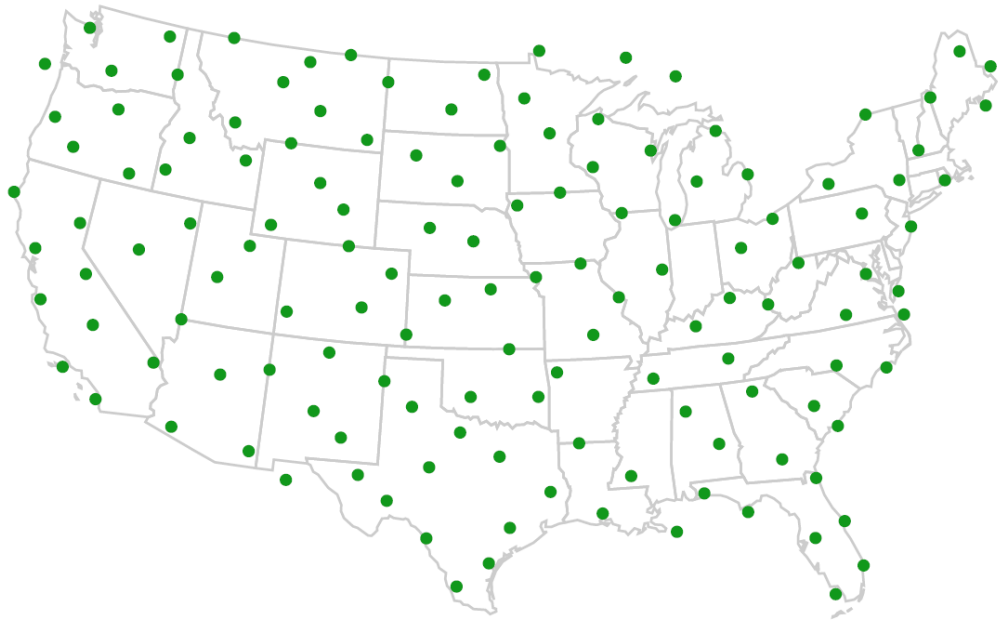




Design of experiments to select simulation resolution

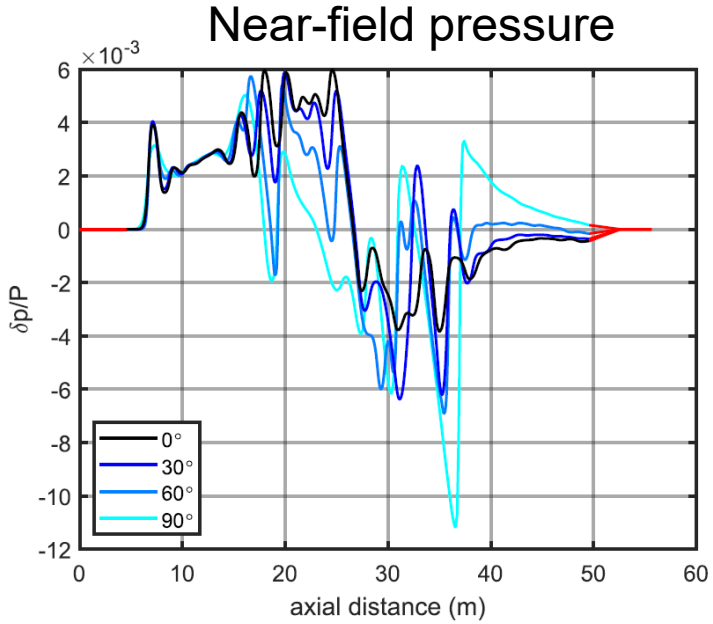
- Constrained by computational time
- Complete propagation for subset
  - Region: northeast US
    - Test two spatial resolutions: 60 km, 200 km chosen using Fast Flexible Space-filling design
  - Atmospheric model: CFSv2
  - Timespan: 5 years
  - Temporal sampling rate:
    - Test two resolutions: every 6 hours, every 24 hours
- Bootstrap forest model for predictor screening
  - Response variables: CW, Undertrack PL
  - Important factors: climate zone, latitude, ground elevation, season, and heading
  - Unimportant factors: time of day, spatial resolution
- Select
  - 200 km spatial resolution → 138 locations
  - 24 hr temporal resolution

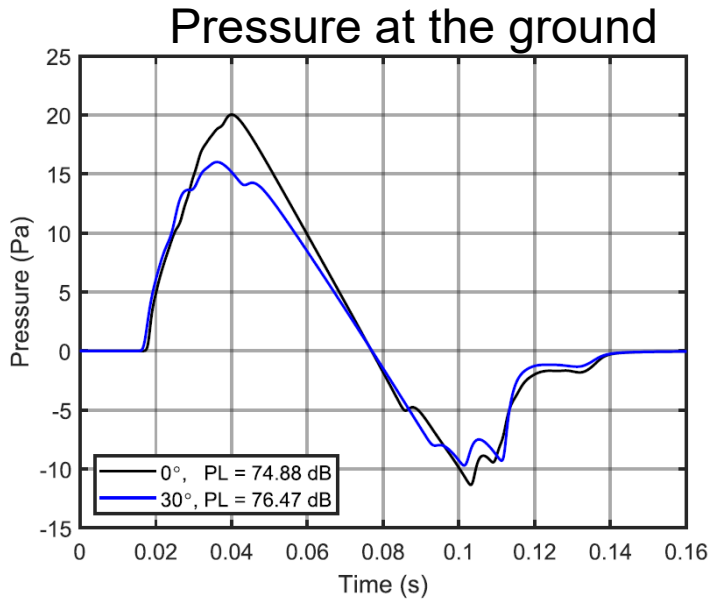
138 locations selected for US study



Anatomy of the US propagation simulation study

- Select
  - Aircraft: X-59 “C609”
  - Aircraft flight conditions: steady, level cruise at 4 headings
  - Locations for propagation: 138 US locations
  - Timespan: 5 years
  - Temporal atmospheric profile sampling rate: 24 hr
  - Atmospheric profile database: CFSv2
- Perform propagation simulations
  - PCBoom software
- Report quantities of interest
  - Sonic boom noise exposure region size: the “carpet width”
  - Loudness directly below the aircraft
  - Mean loudness over an inner portion of the carpet



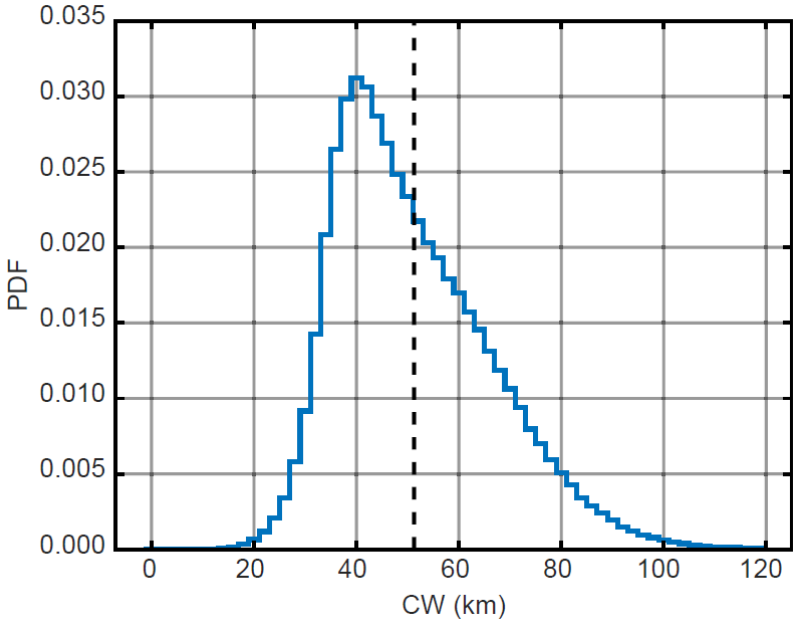


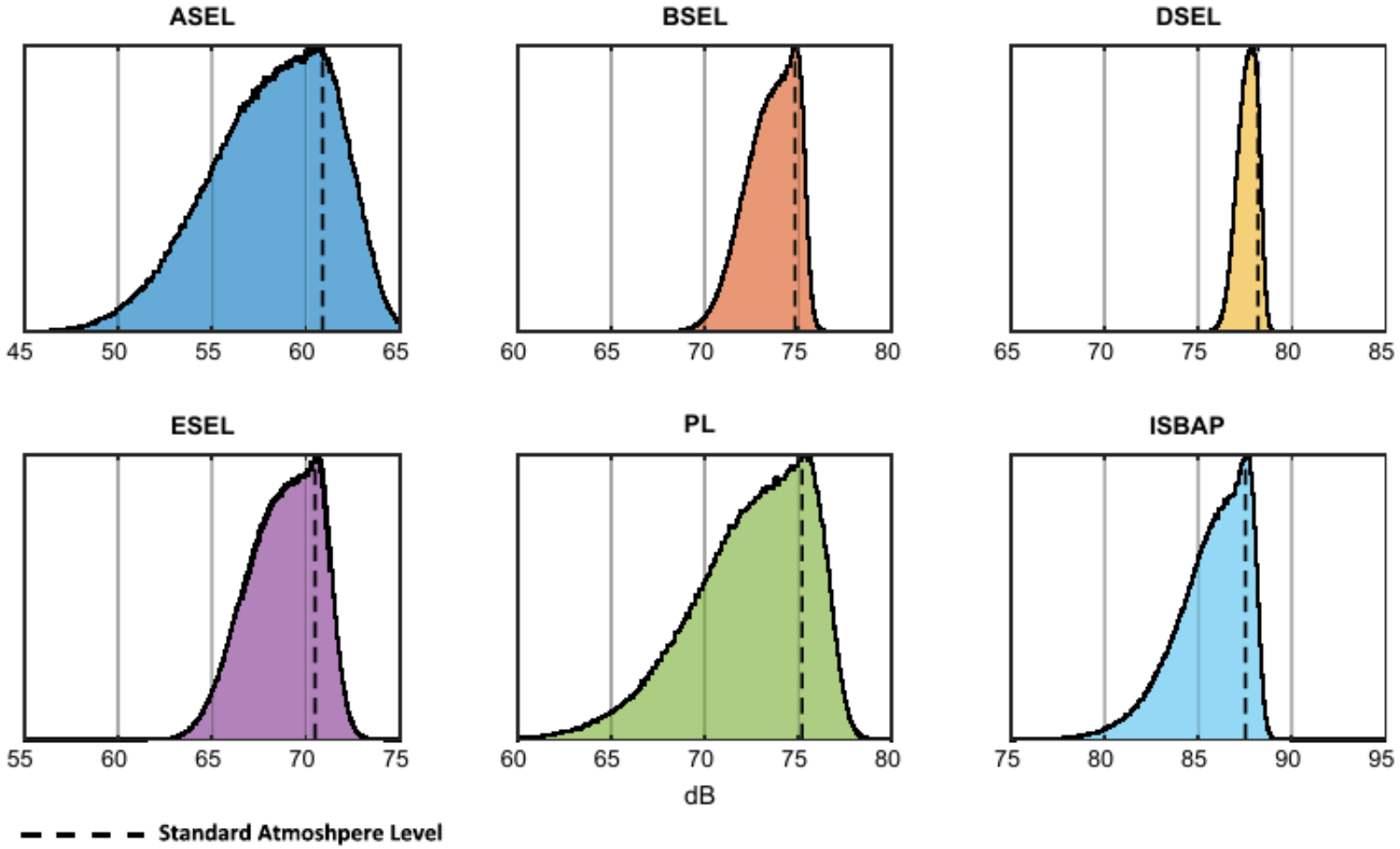
US study results

Over 1 million X-59 carpets generated

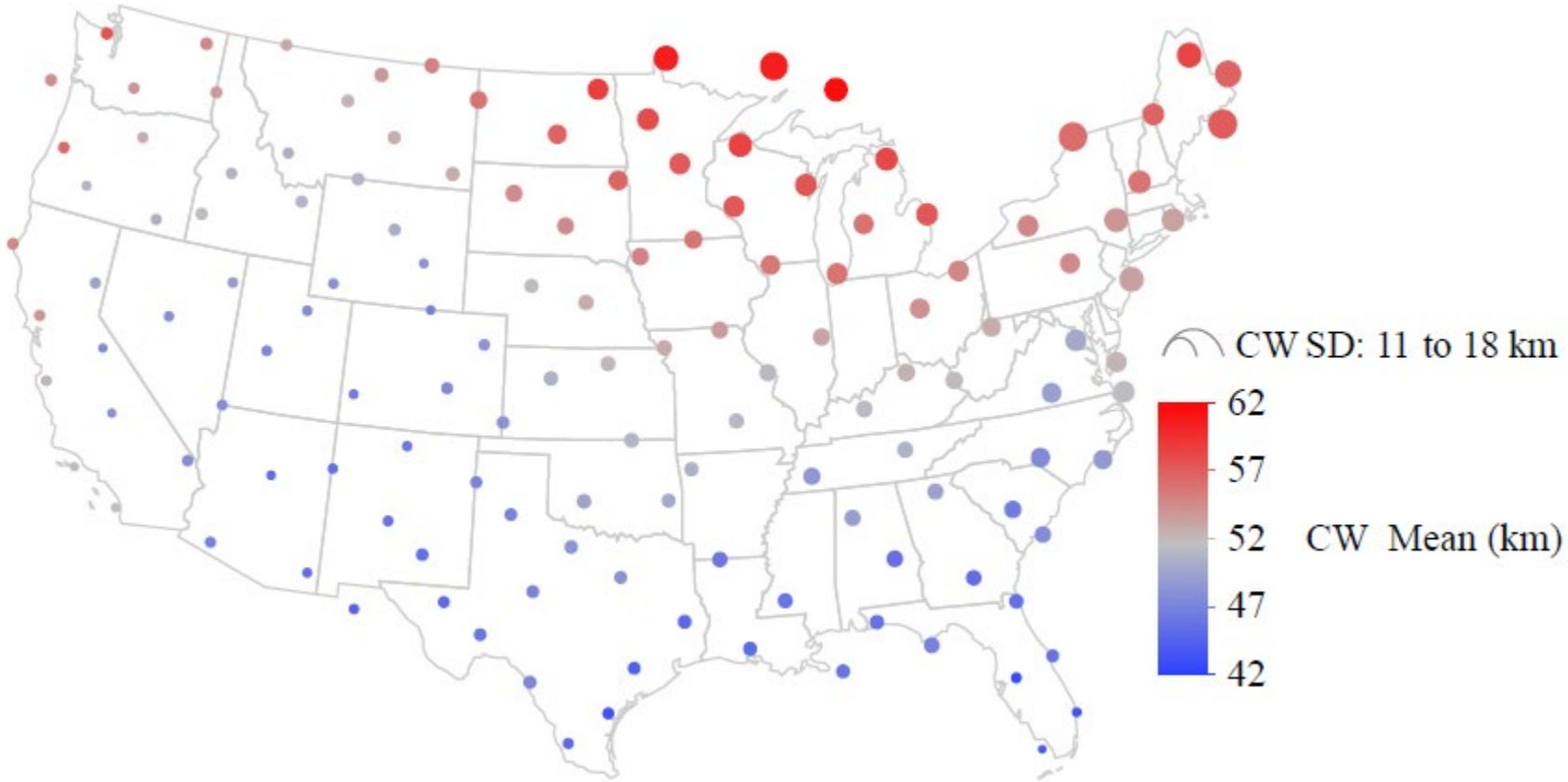
Variability in CW and sonic boom metrics undertrack

- Peak-normalized probability density functions (PDF) show DSEL and BSEL have lower variability than other metrics
- Typically below standard atmosphere prediction

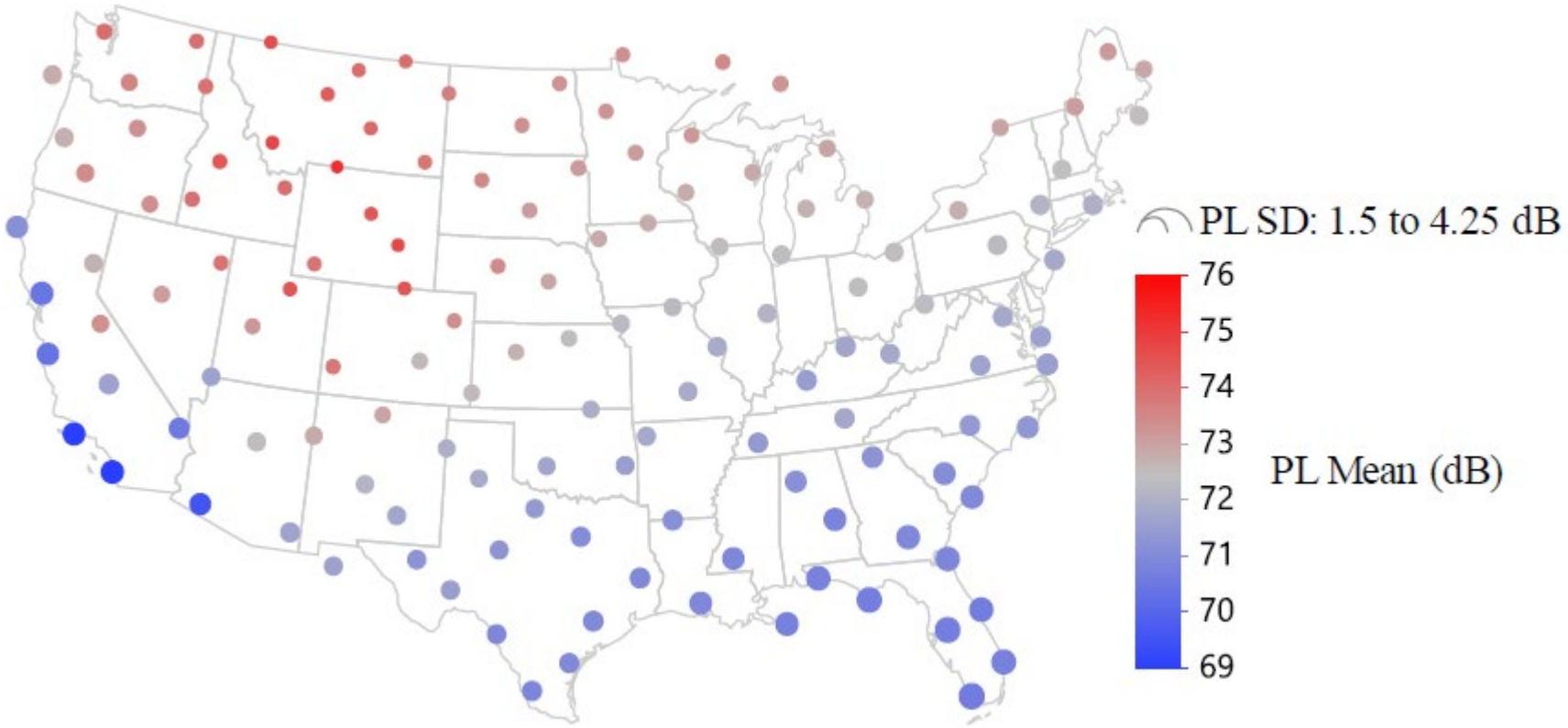




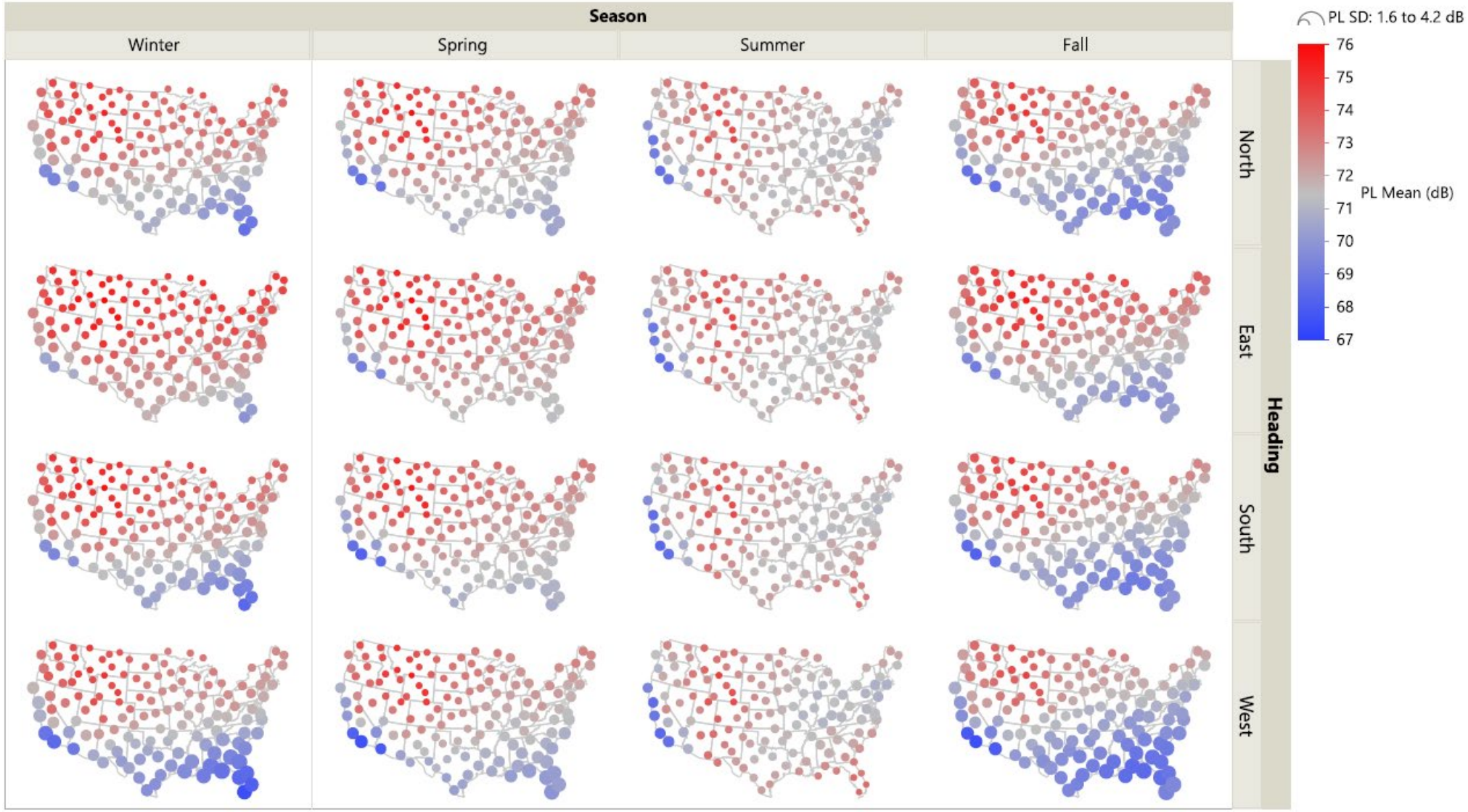
Mean and standard deviation of CW



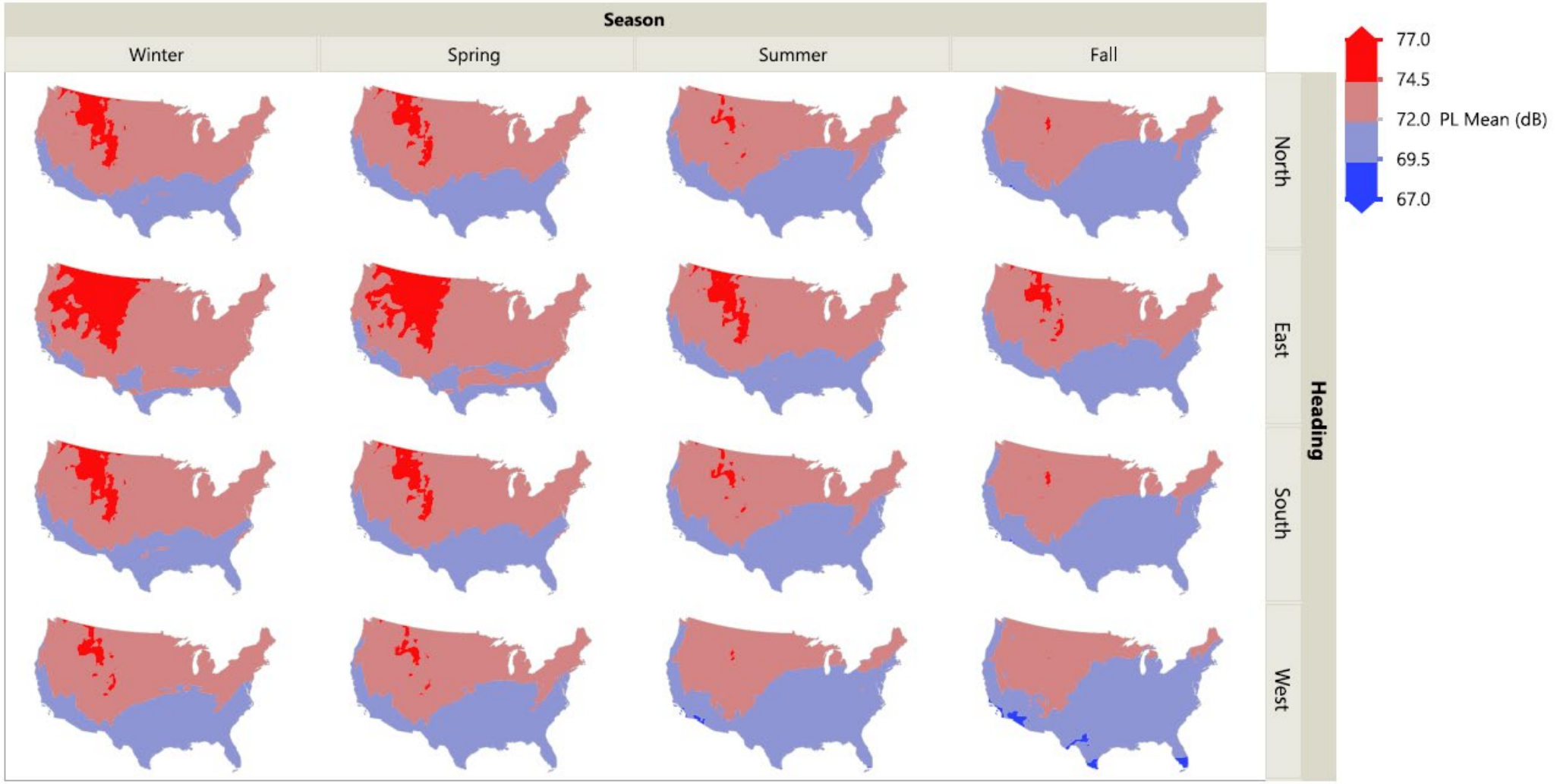
Mean and standard deviation of Undertrack PL



Splitting by heading and season shows expected levels to aid in flight test planning



Multiple linear regression models fit to predict Undertrack PL, CW, and their SD anywhere in the US



Global Propagation Simulation Study

Recall: Anatomy of a sonic boom propagation simulation study

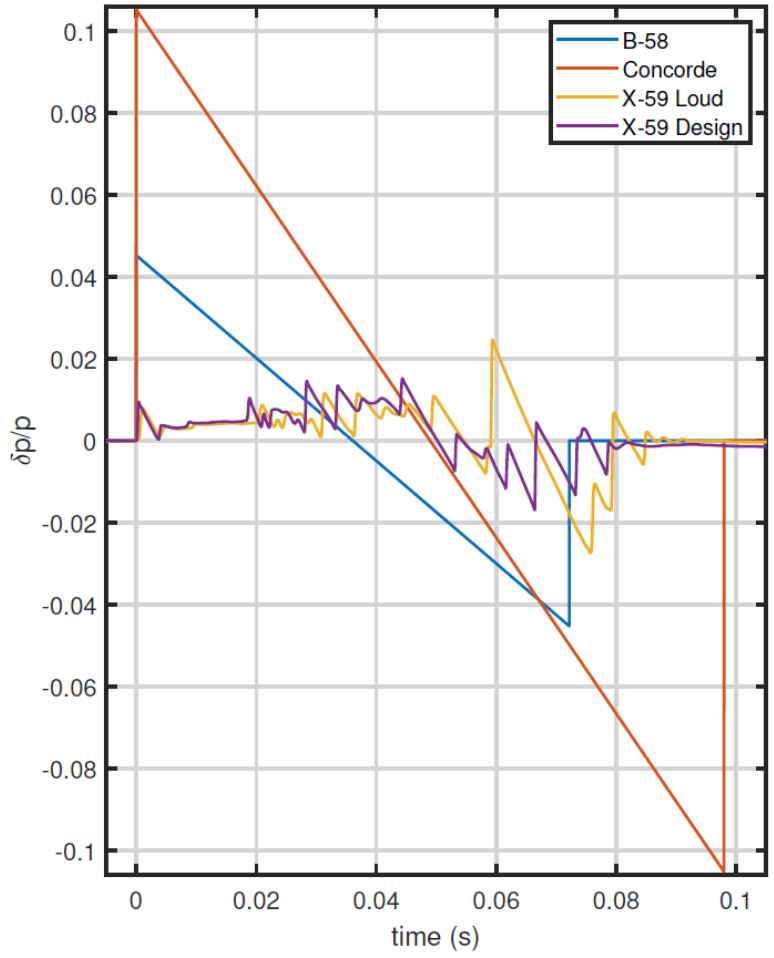
- Select
  - Aircraft
  - Aircraft flight conditions
  - Locations for propagation
  - Timespan
  - Temporal atmospheric profile sampling rate
  - Atmospheric profile database
- Perform propagation simulations
  - PCBoom software
- Report quantities of interest
  - Sonic boom noise exposure region size: the “carpet width”
  - Loudness directly below the aircraft
  - Mean loudness over an inner portion of the carpet

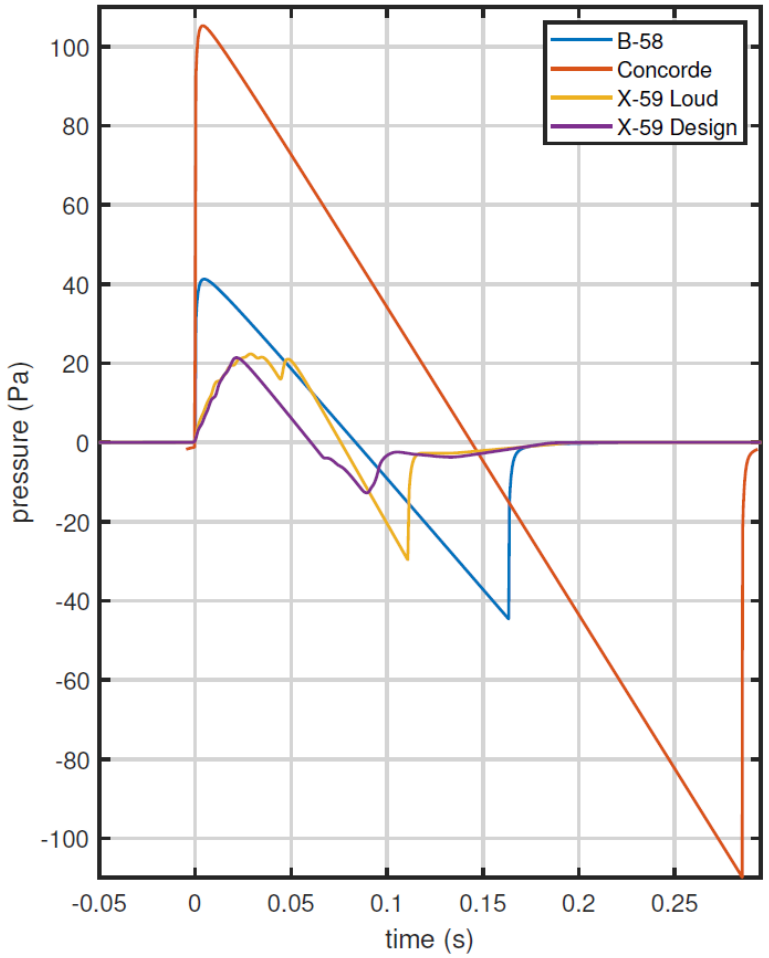
Select a mixture of low-boom, partial N-wave, and N-wave aircraft to compare global statistics

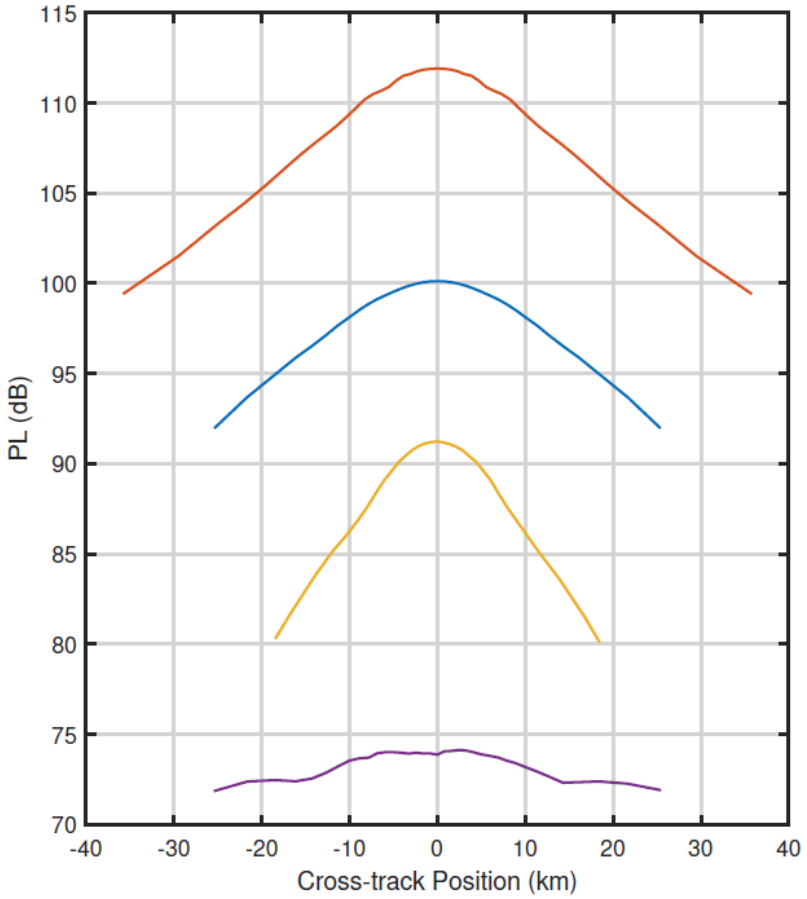








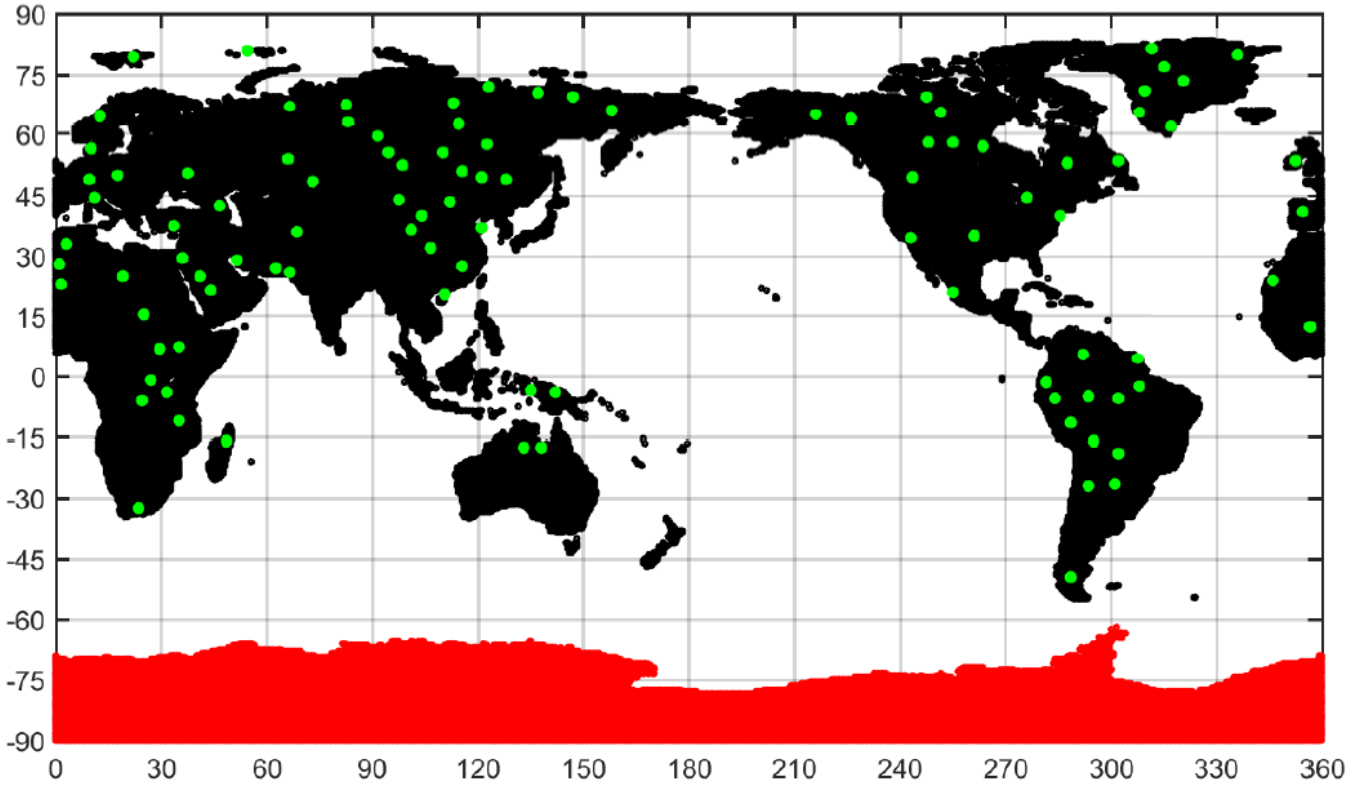


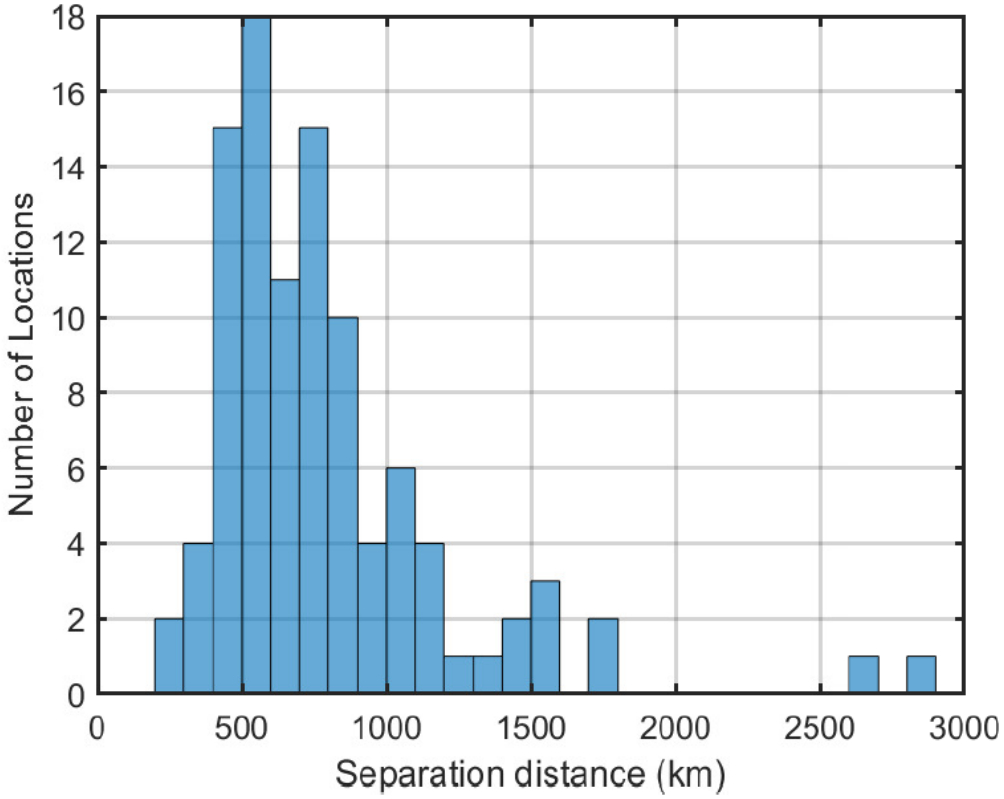


Anatomy of the global propagation simulation study

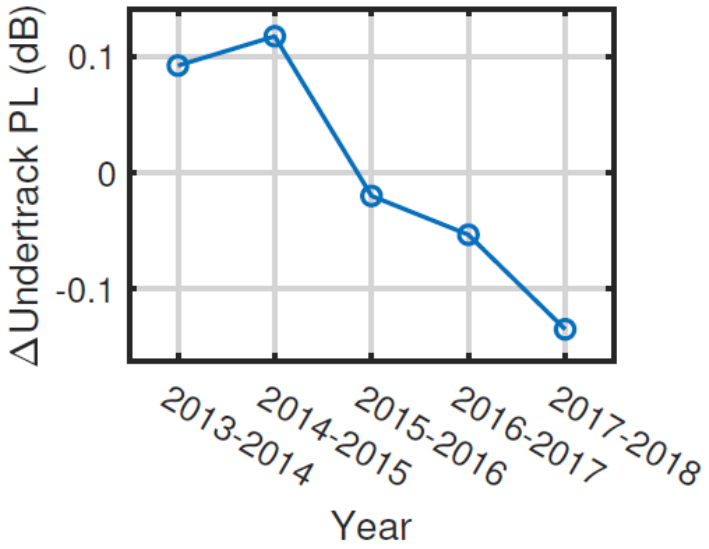
- Select
  - Aircraft: X-59 Design, X-59 Loud, B-58, Concorde
  - Aircraft flight conditions: Various steady cruise
  - Locations for propagation
  - Timespan
  - Temporal atmospheric profile sampling rate
  - Atmospheric profile database
- Perform propagation simulations
  - PCBoom software
- Report quantities of interest
  - Sonic boom noise exposure region size: the “carpet width”
  - Loudness directly below the aircraft
  - Mean loudness over an inner portion of the carpet

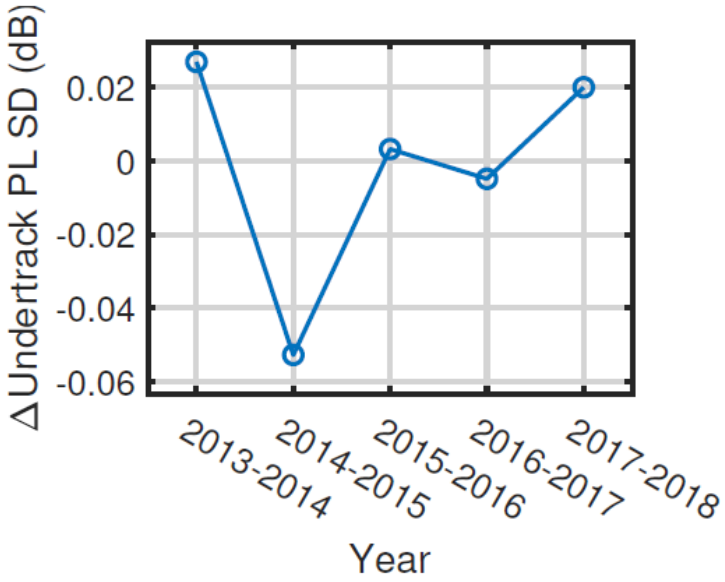
Locations selected by distance-restricted Monte Carlo

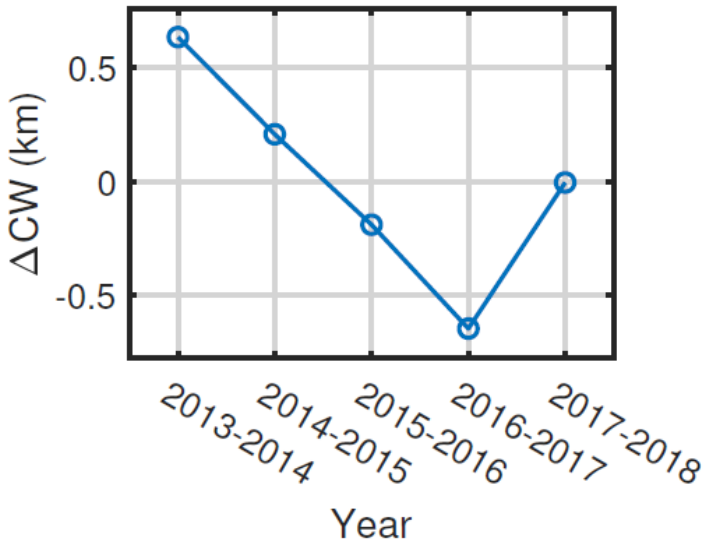


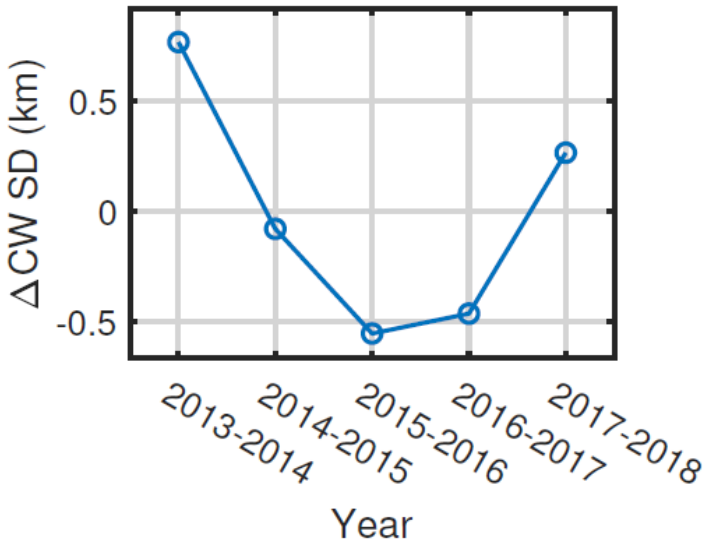


Analysis of the US study found that propagation through 1 year was sufficient for summary statistics of PL and CW









Anatomy of the global propagation simulation study

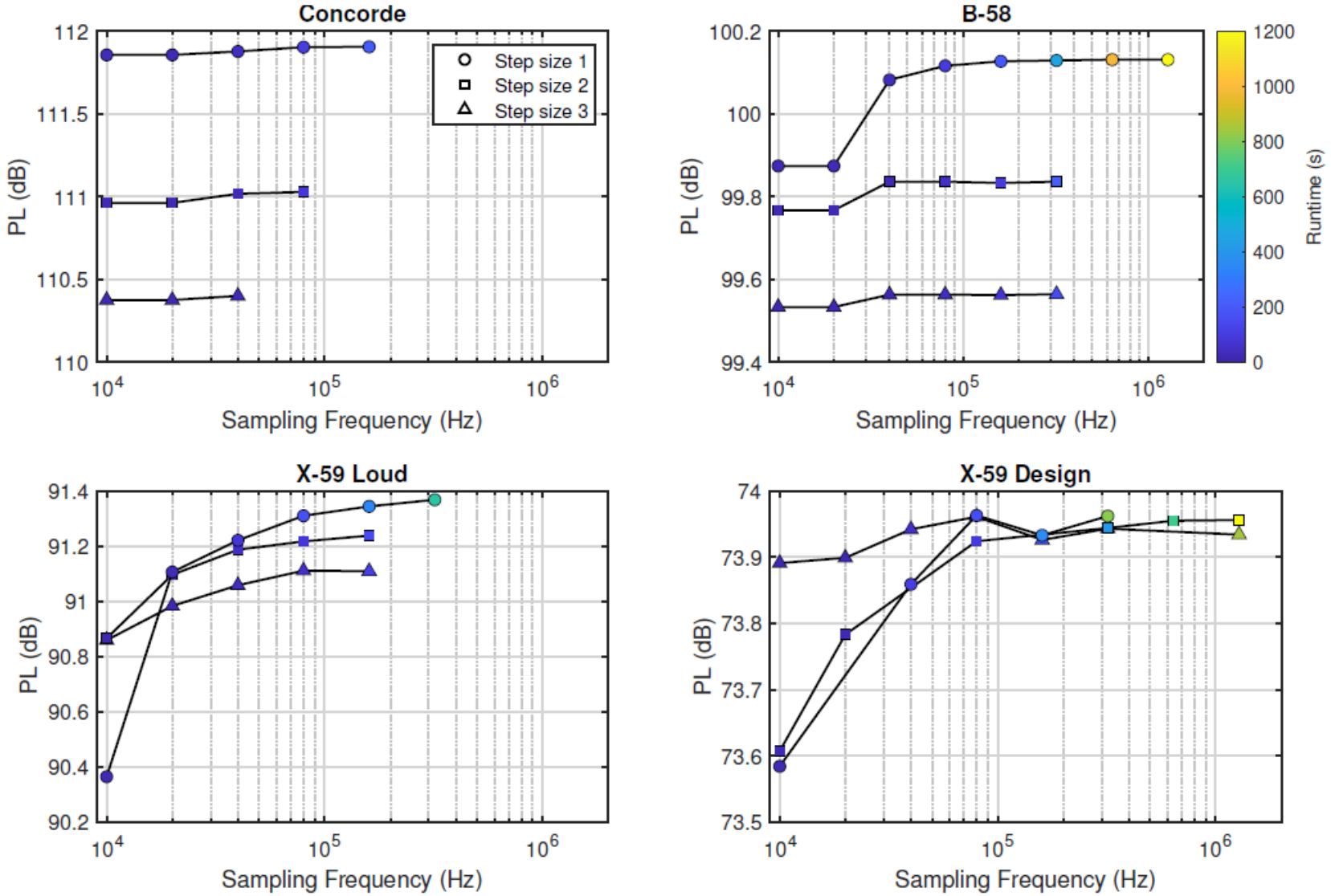
- Select
  - Aircraft: X-59 Design, X-59 Loud, B-58, Concorde
  - Aircraft flight conditions: Various steady cruise
  - Locations for propagation: 100 global locations
  - Timespan: 1 year
  - Temporal atmospheric profile sampling rate: every 6 hours
  - Atmospheric profile database: GFS, CFSv2, and ERA5

- Perform propagation simulations
  - PCBoom software

- Report quantities of interest
  - Sonic boom noise exposure region size: the “carpet width”
  - Loudness directly below the aircraft
  - Mean loudness over an inner portion of the carpet

PCBoom convergence

- Select step size 1 and 100 kHz sampling rate



Parallelization and supercomputing

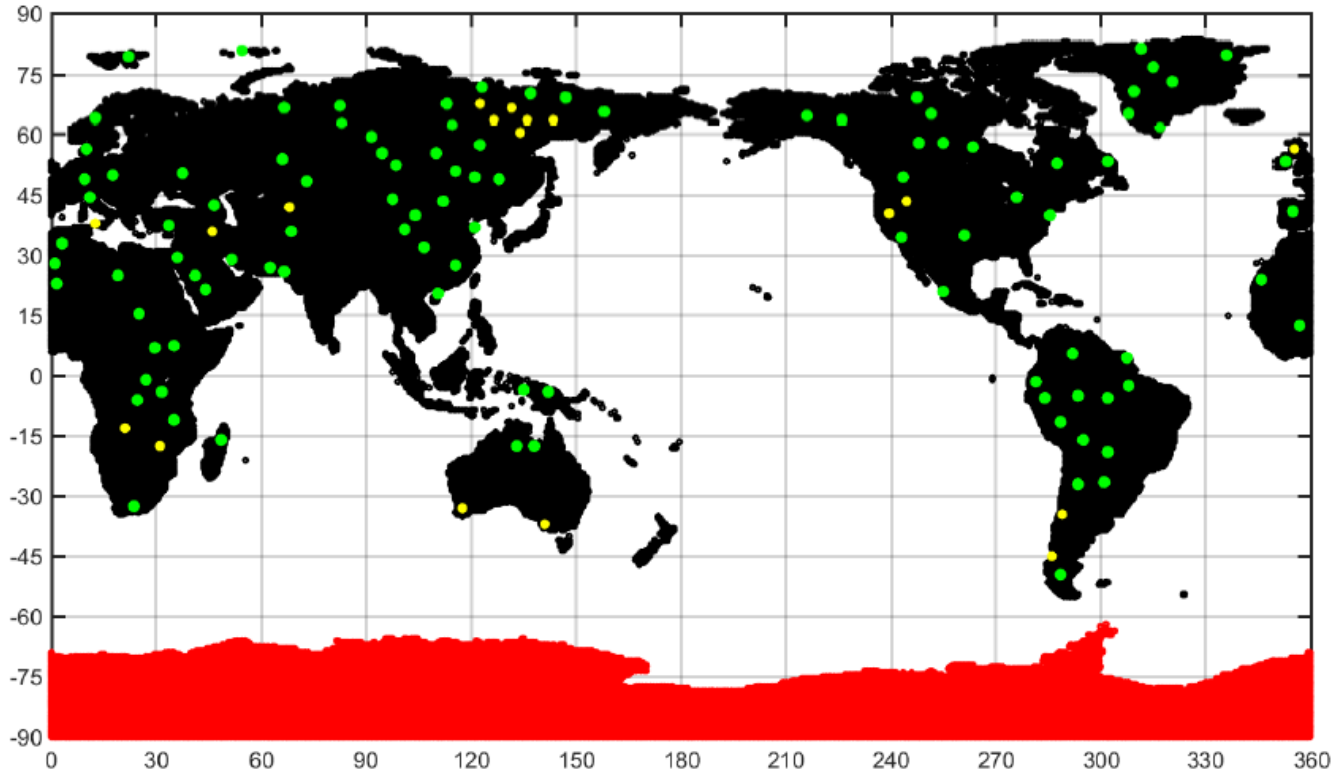
- “Embarrassingly parallel” problem
- Use NASA K-cluster supercomputer
- Create master list of all runs to be completed
  - Over 7 million runs on the master list = 366 days * 4 times per day * 4 aircraft near-fields * 4 headings * 3 models * 100 locations
- Group them into batches to be run with one run per CPU
- ~3.5 minutes per run → 410,000 compute hours (~50 years)

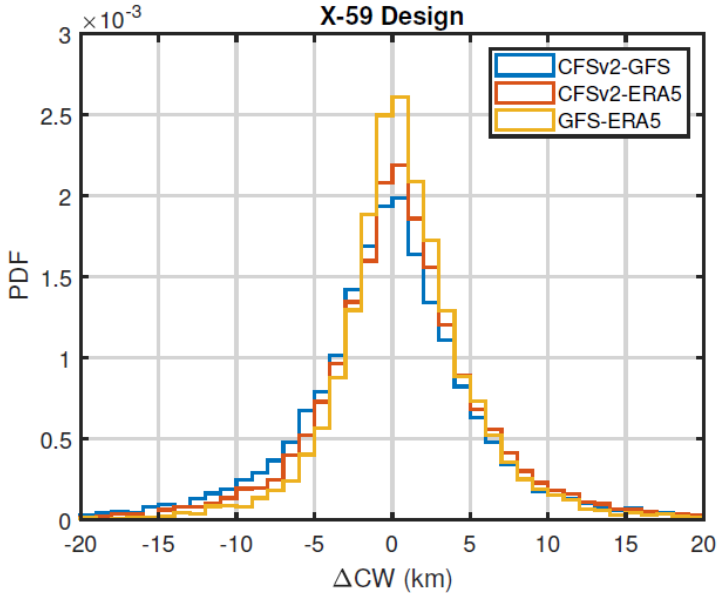
Problems with Concorde results

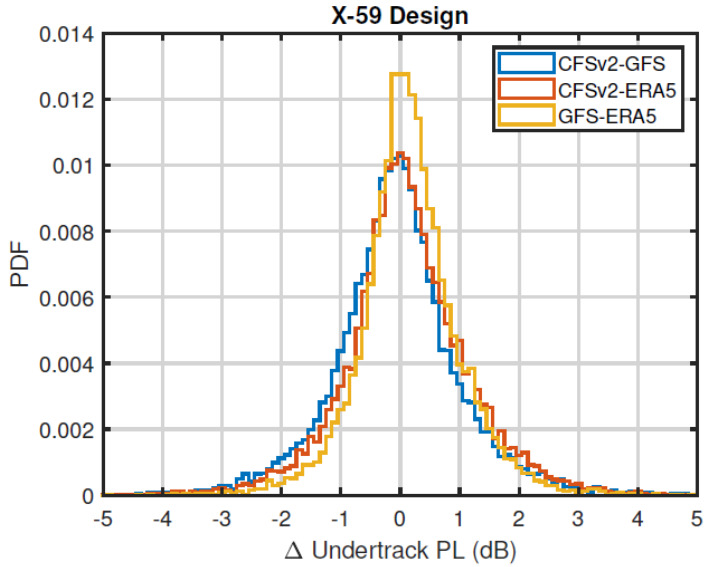
- PCBoom bug identified that prevented about 30% of the Concorde runs from completing
- Bug fix not able to be implemented prior to dissertation deadlines
- Results are still shown, but should be used with caution
- Most of the missing data is in the winter

Bootstrap forest predictor screening indicated time of day and atmospheric model were unimportant

- Move forward with only the ERA5 model
- Supplement with 18 additional locations to ensure all climate zones are sampled



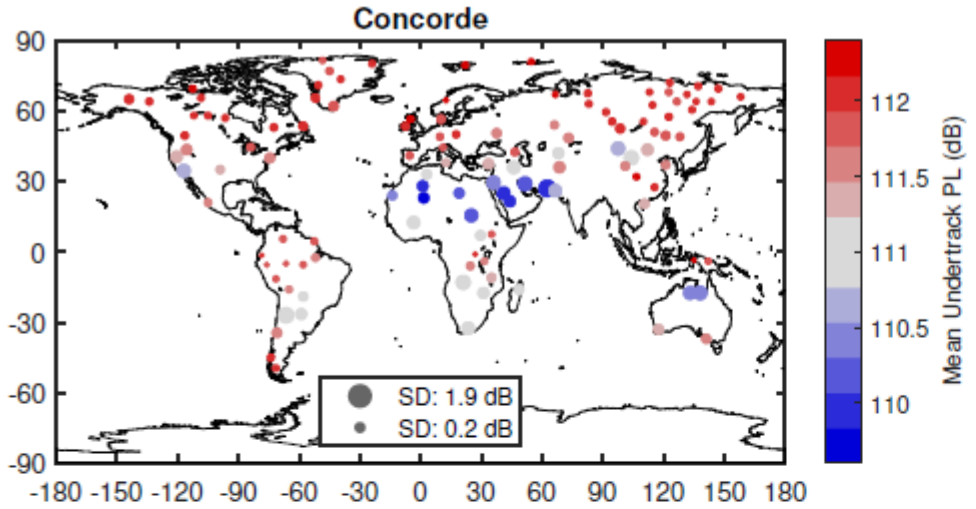


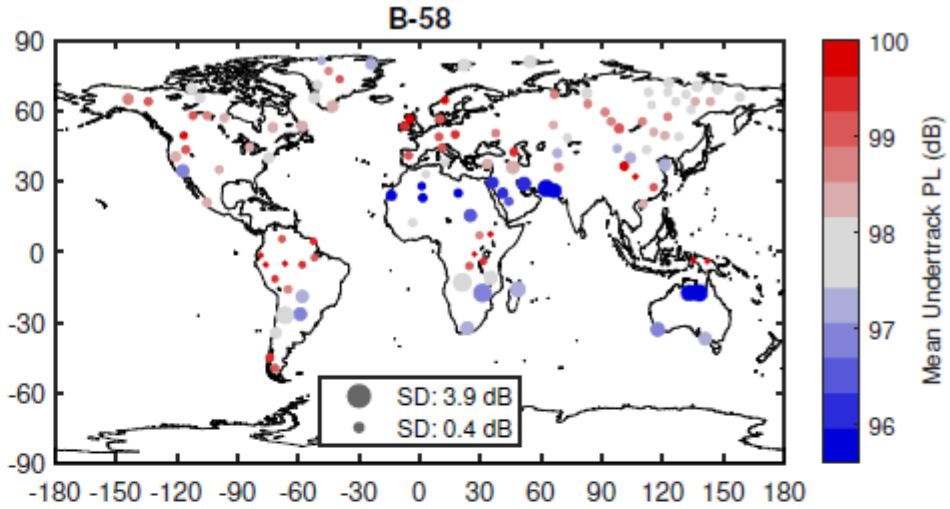


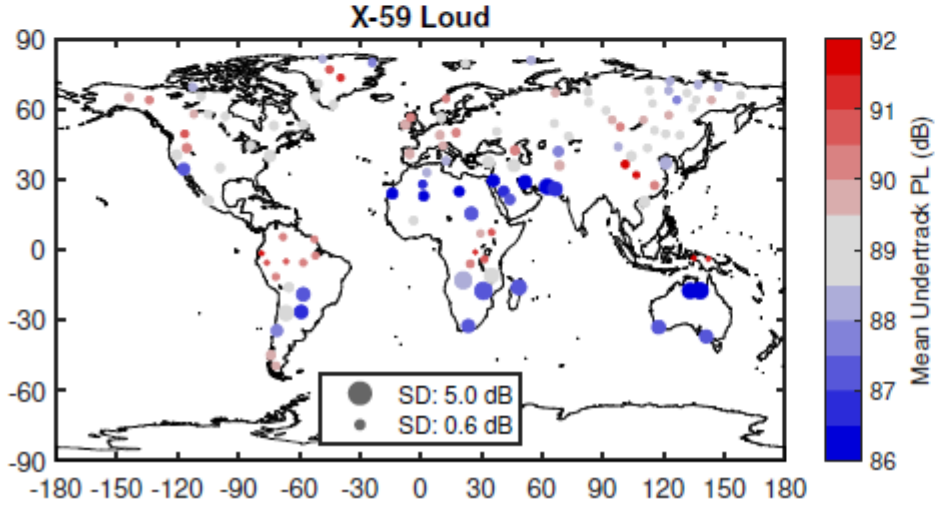
Global propagation study results

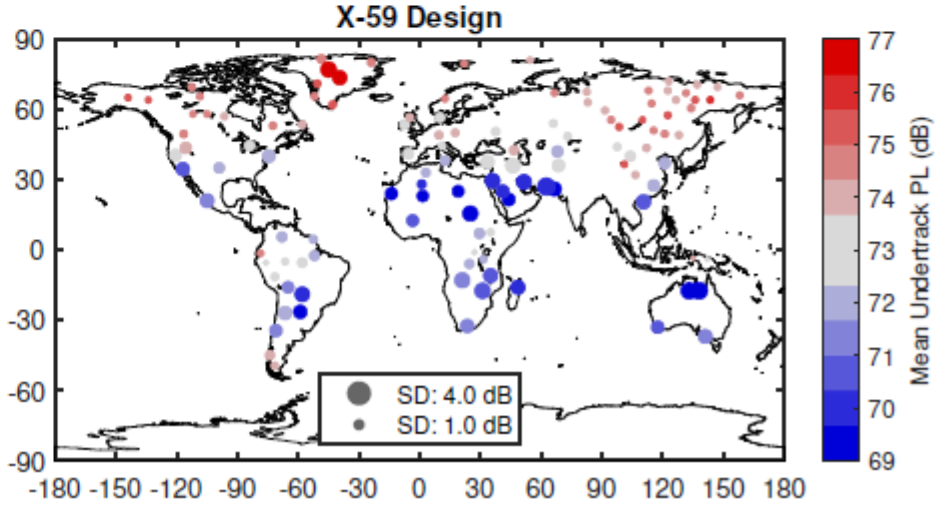
Over 6 million carpets generated

Mean level varies by up to 8 dB

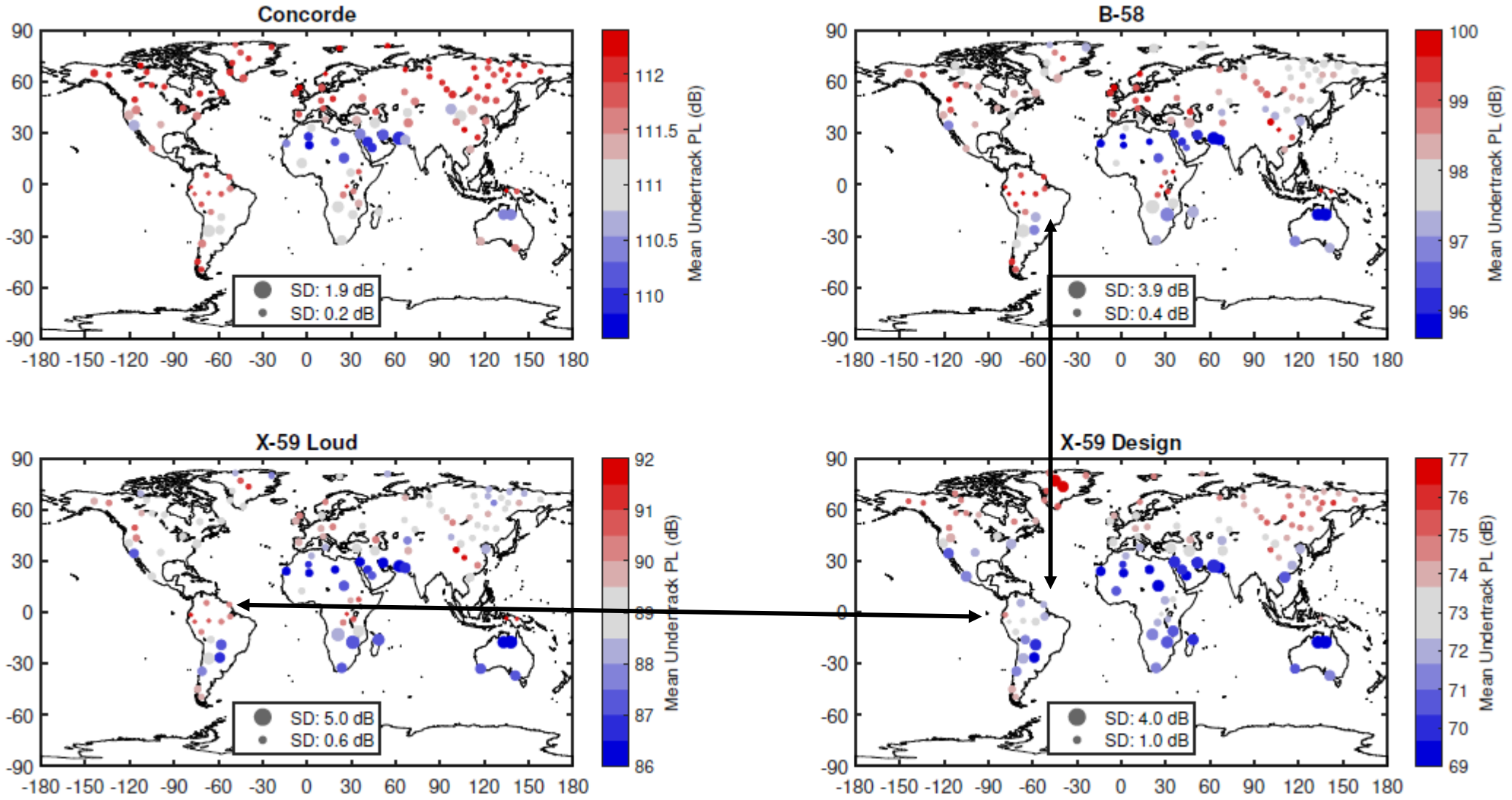




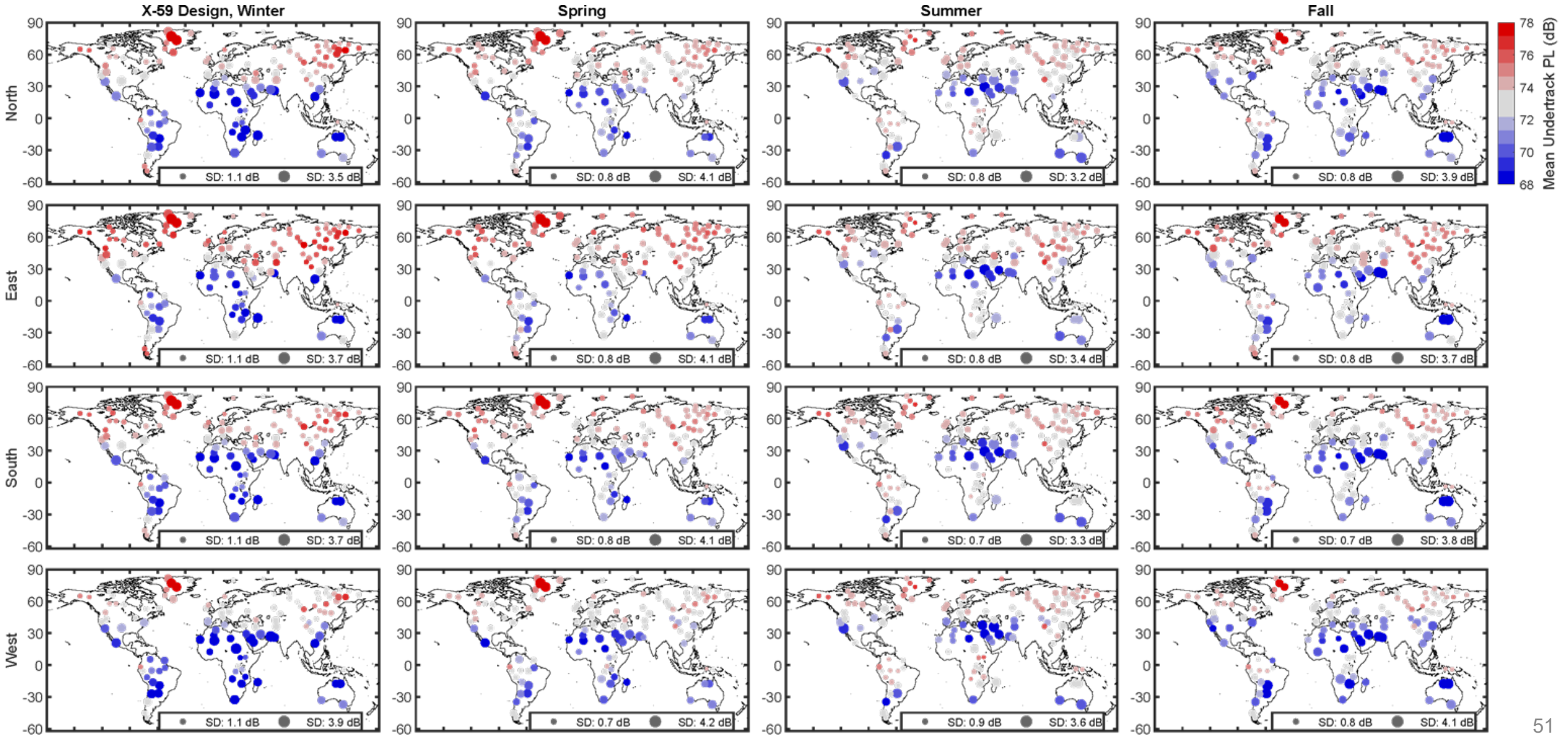




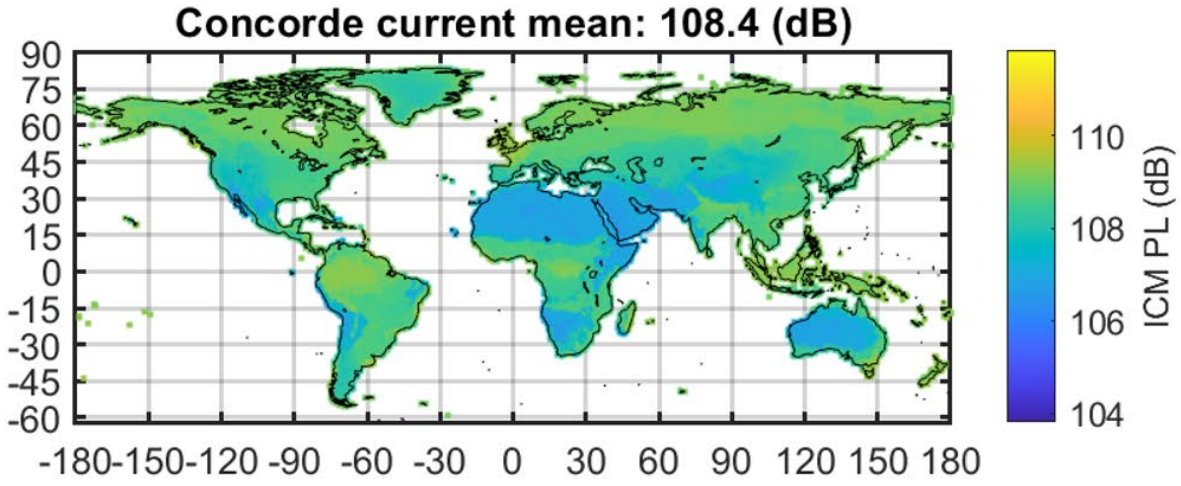
There are some regions where N-waves/partial N-waves and low-booms differ

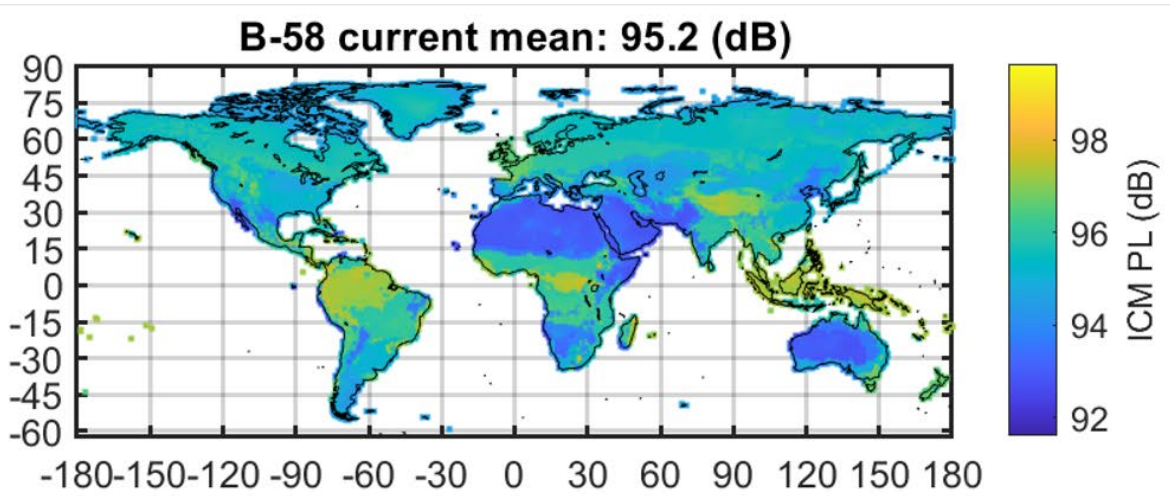


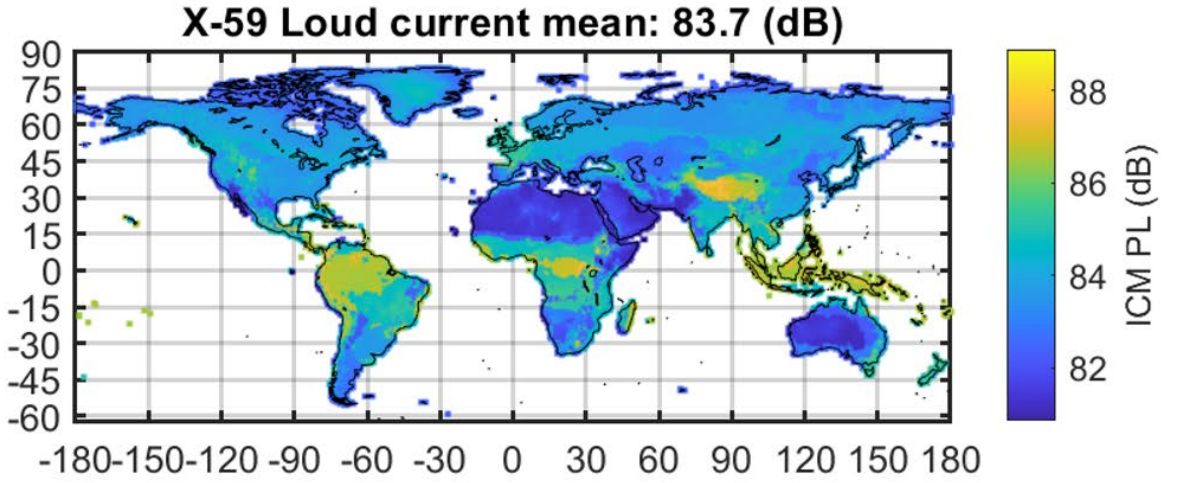
Effect of season and heading

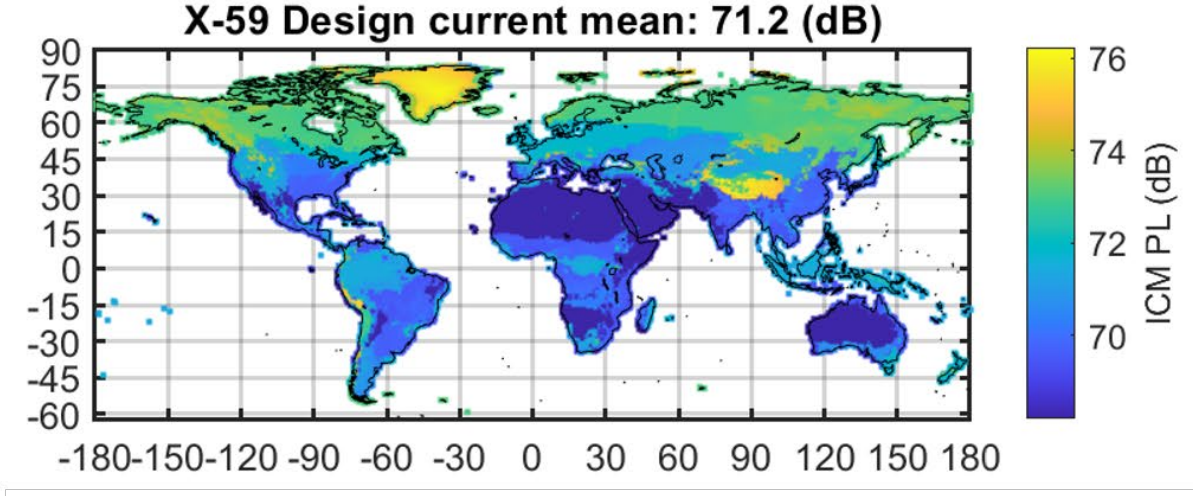


Multiple linear regression models fit to predict CW, Undertrack PL, ICM PL and their variability anywhere

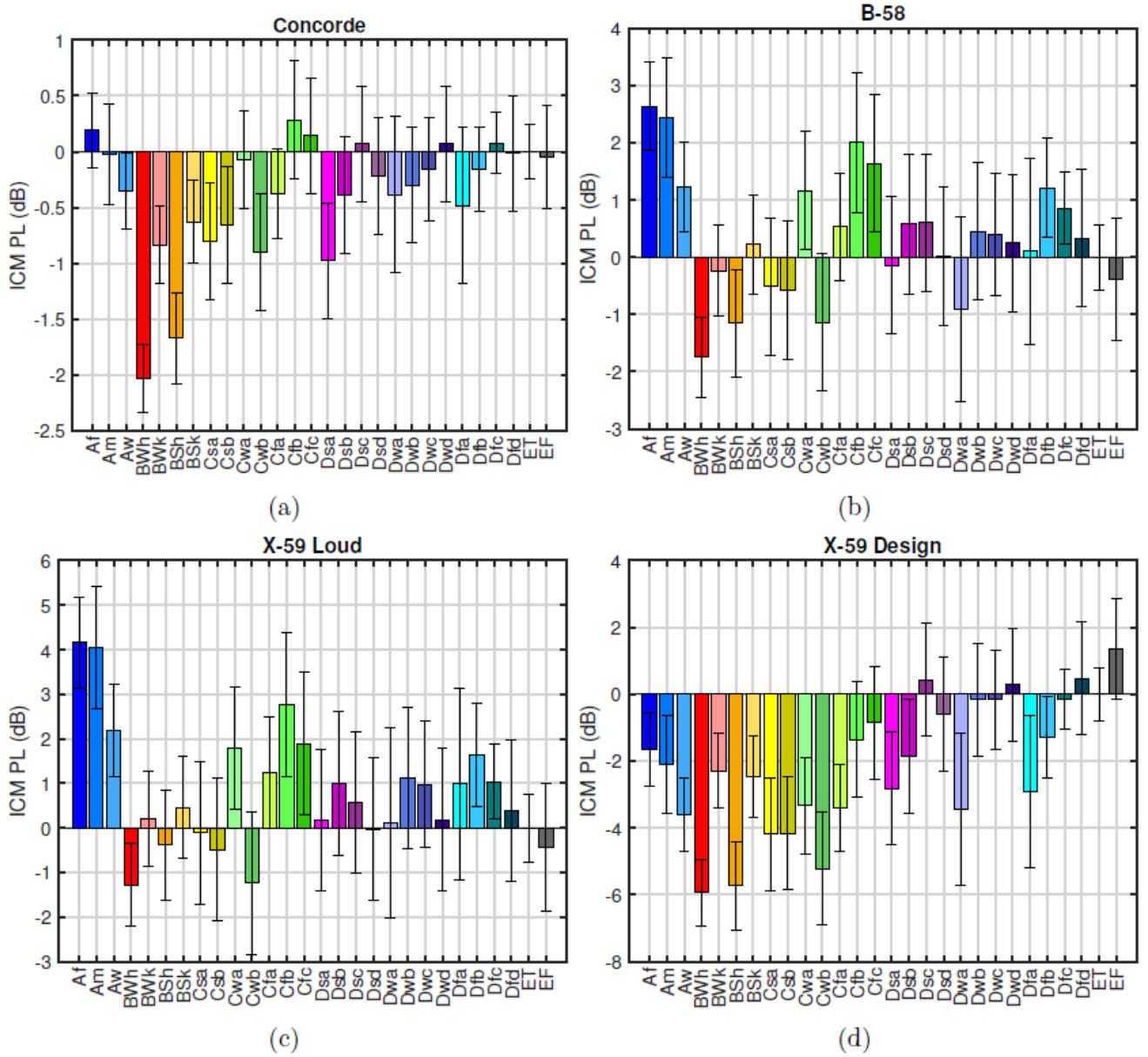




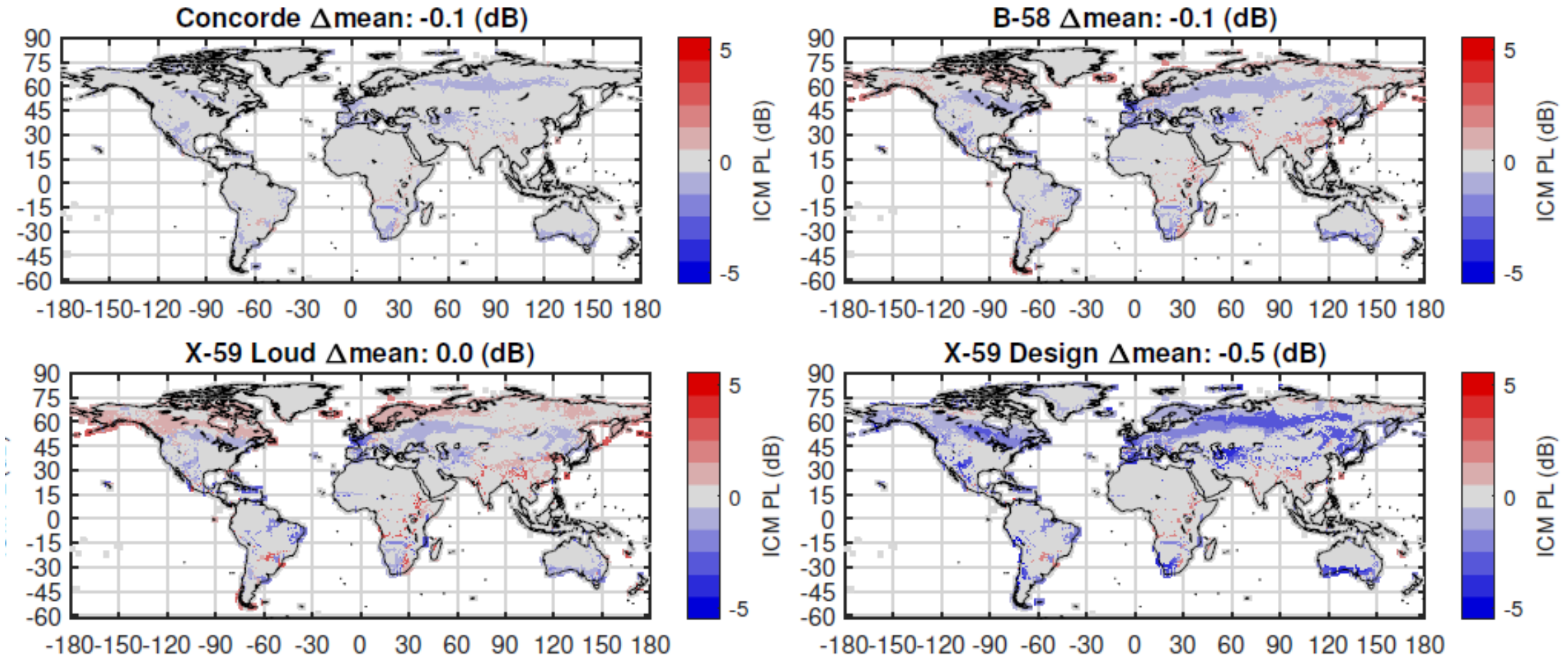




Impact of climate zone: range of 5 to 7 dB



Effect of climate change is minimal



Summary

- Supersonic prohibition
- X-59 Quesst mission
- Defined quantities of interest
- Outlined atmospheric models

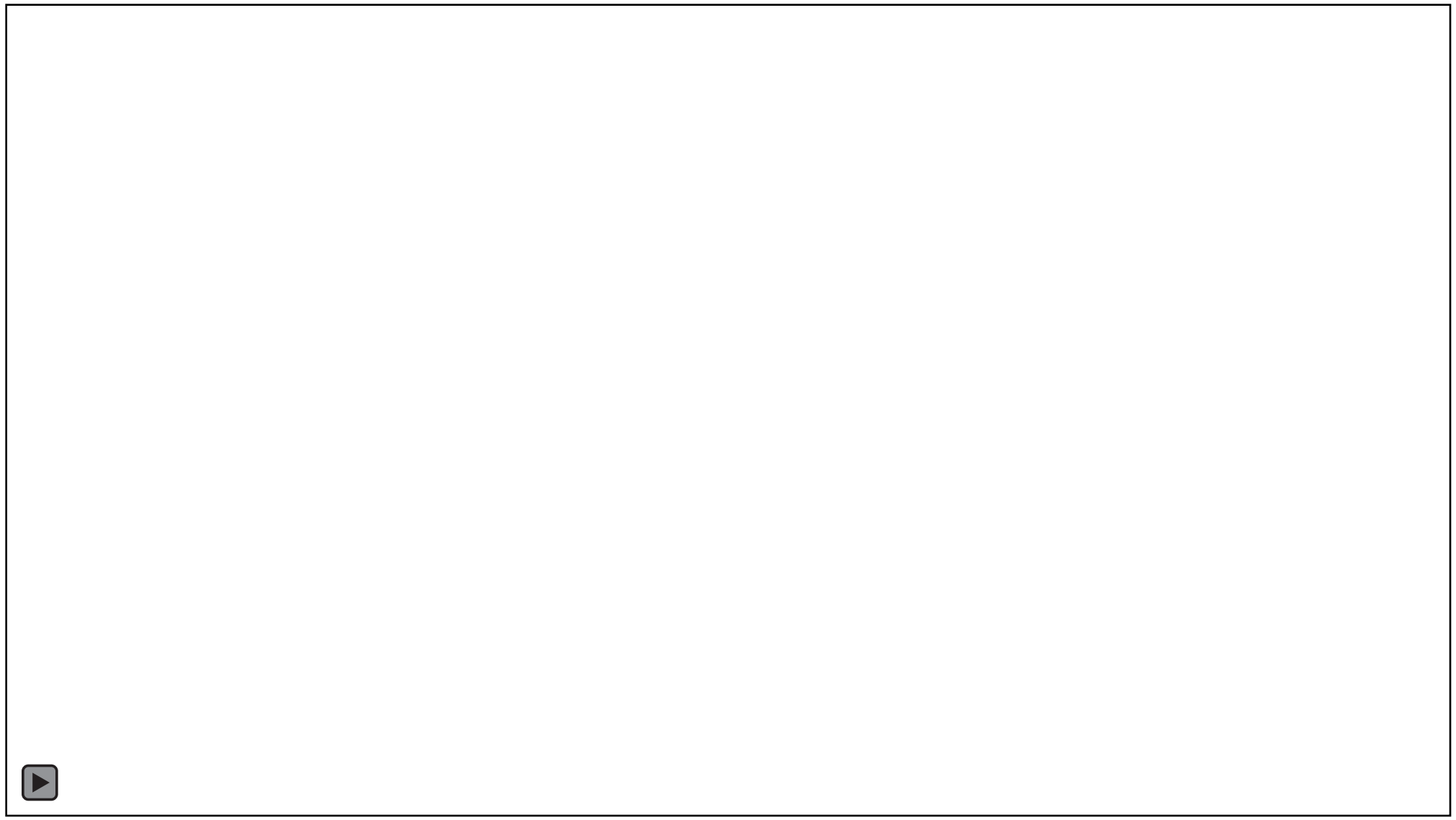
- US propagation study of X-59
- Global study with multiple aircraft

Research questions

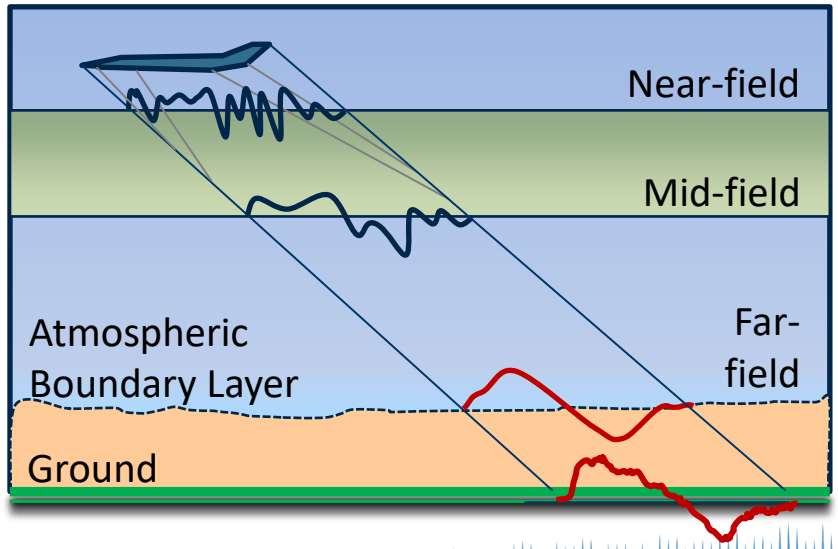
1. Does use of different atmospheric models result in significantly different sonic booms in terms of loudness metric levels and carpet width?
   - No
2. For a fixed location, how far apart in time should atmospheric profiles be sampled to produce booms with significantly different levels or carpet widths?
   - 24 hours
3. For a fixed location, how many observations are need to characterize distributions of boom metrics and carpets?
   - One year, once per day
4. At a fixed time, how far apart in space should atmospheric profiles be sampled to produce booms with significantly different levels or carpets?
   - Between 675 and 1100 km
5. Do N-waves and low-booms have the same global variability?
   - Not everywhere
6. What will be the effect of a changing climate on sonic boom loudness?
   - Only minor effects observed


QUESST

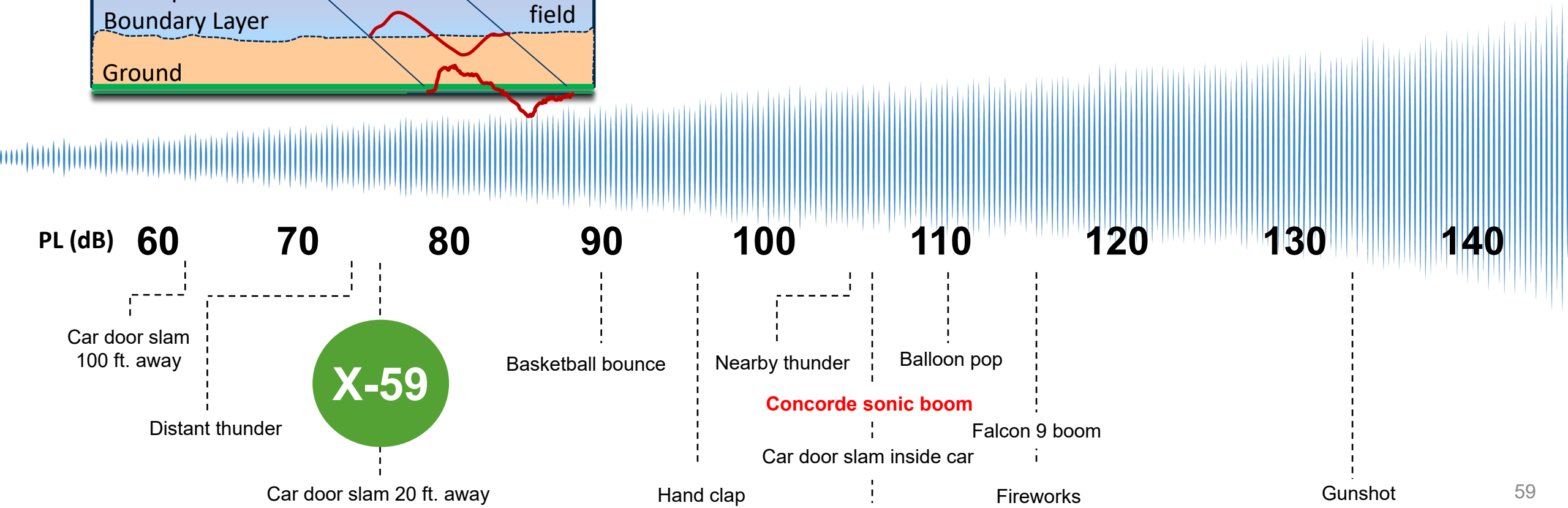
How large is the region that is exposed to sound from a supersonic overflight?



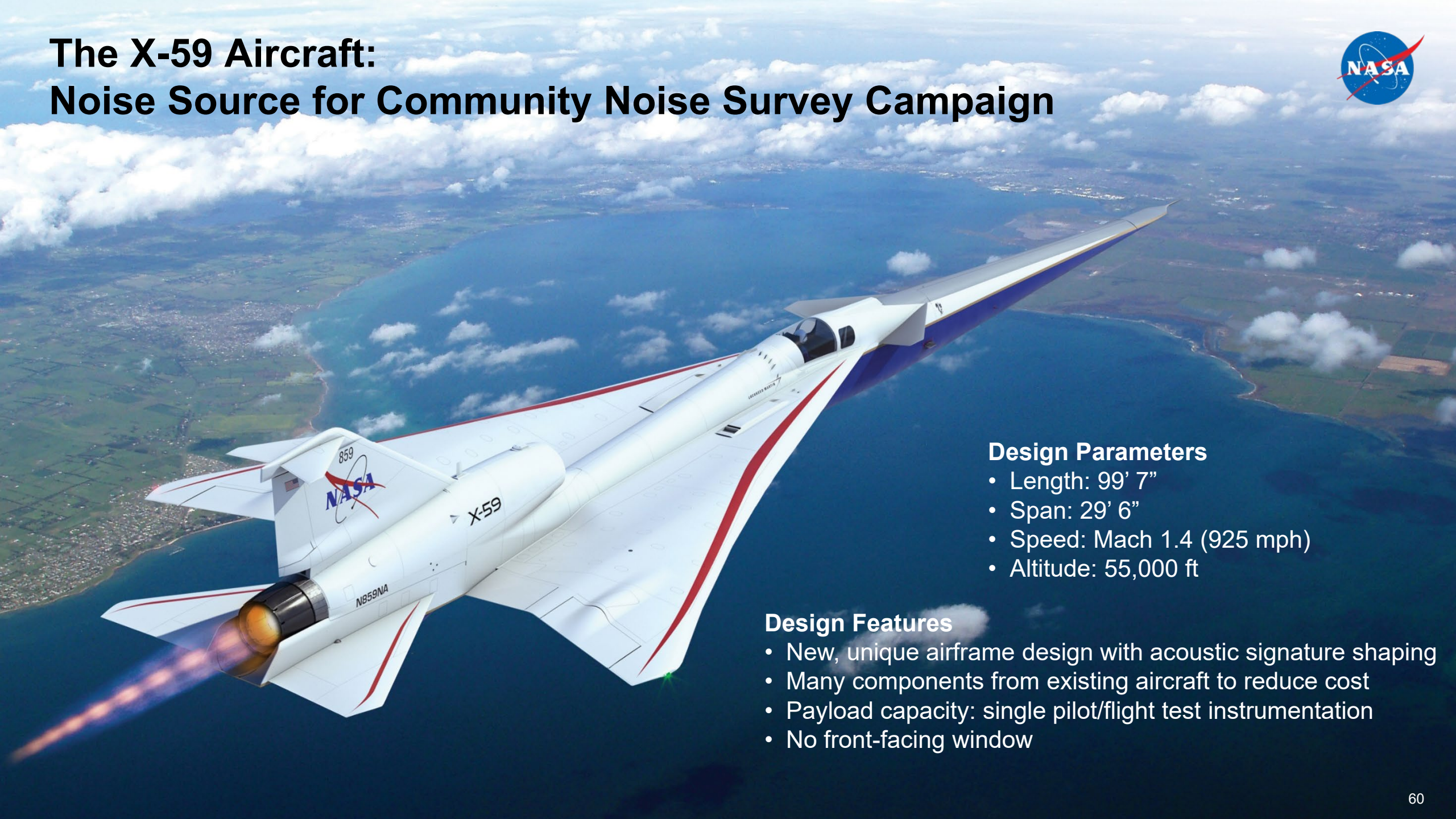
How is the boom reduced to a thump?



- Acoustic pressure wave is “shaped” by controlling the strength and position of shock waves generated by aircraft components
- Shocks do not merge into an N-wave



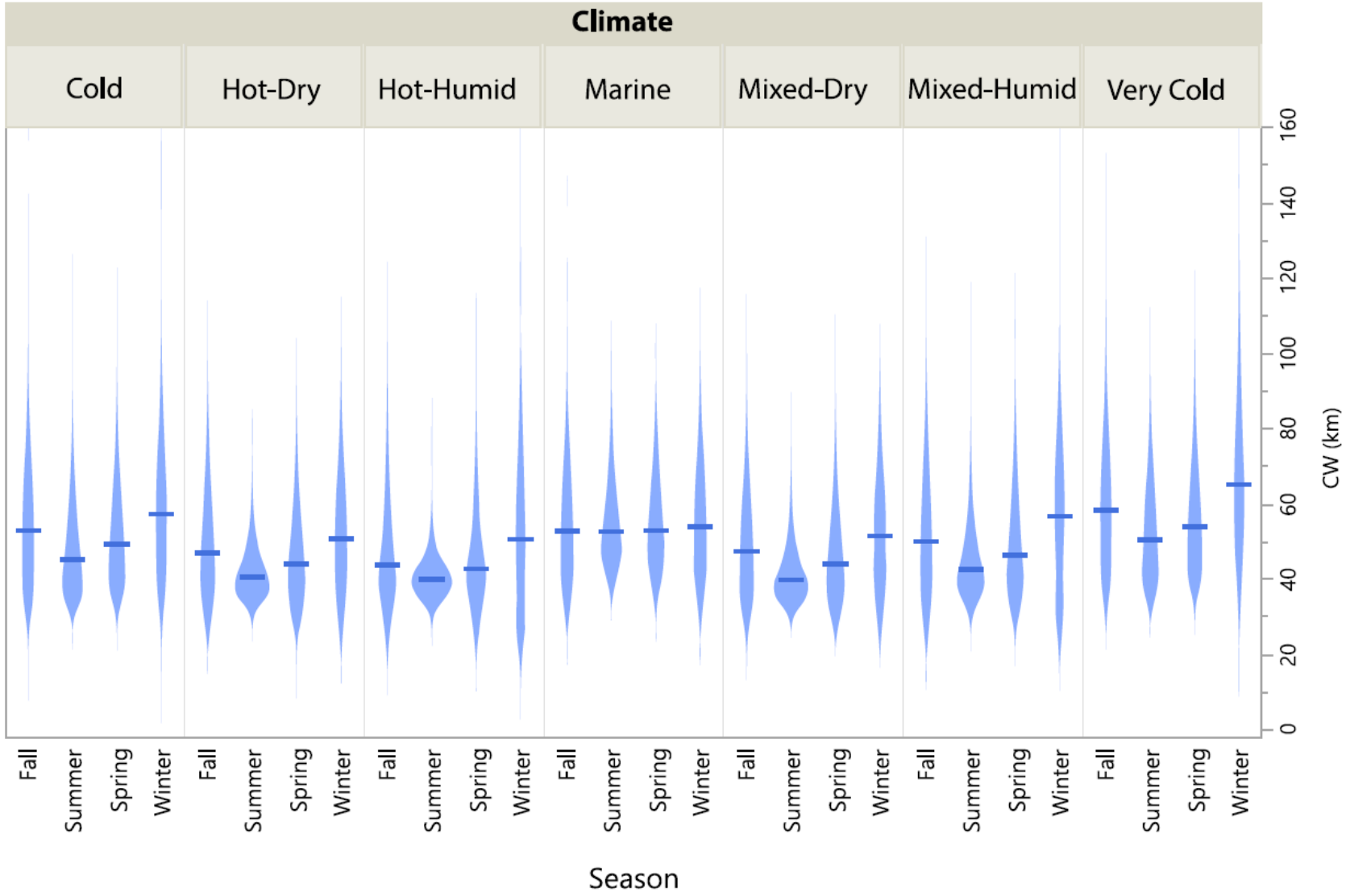
The X-59 Aircraft:
Noise Source for Community Noise Survey Campaign



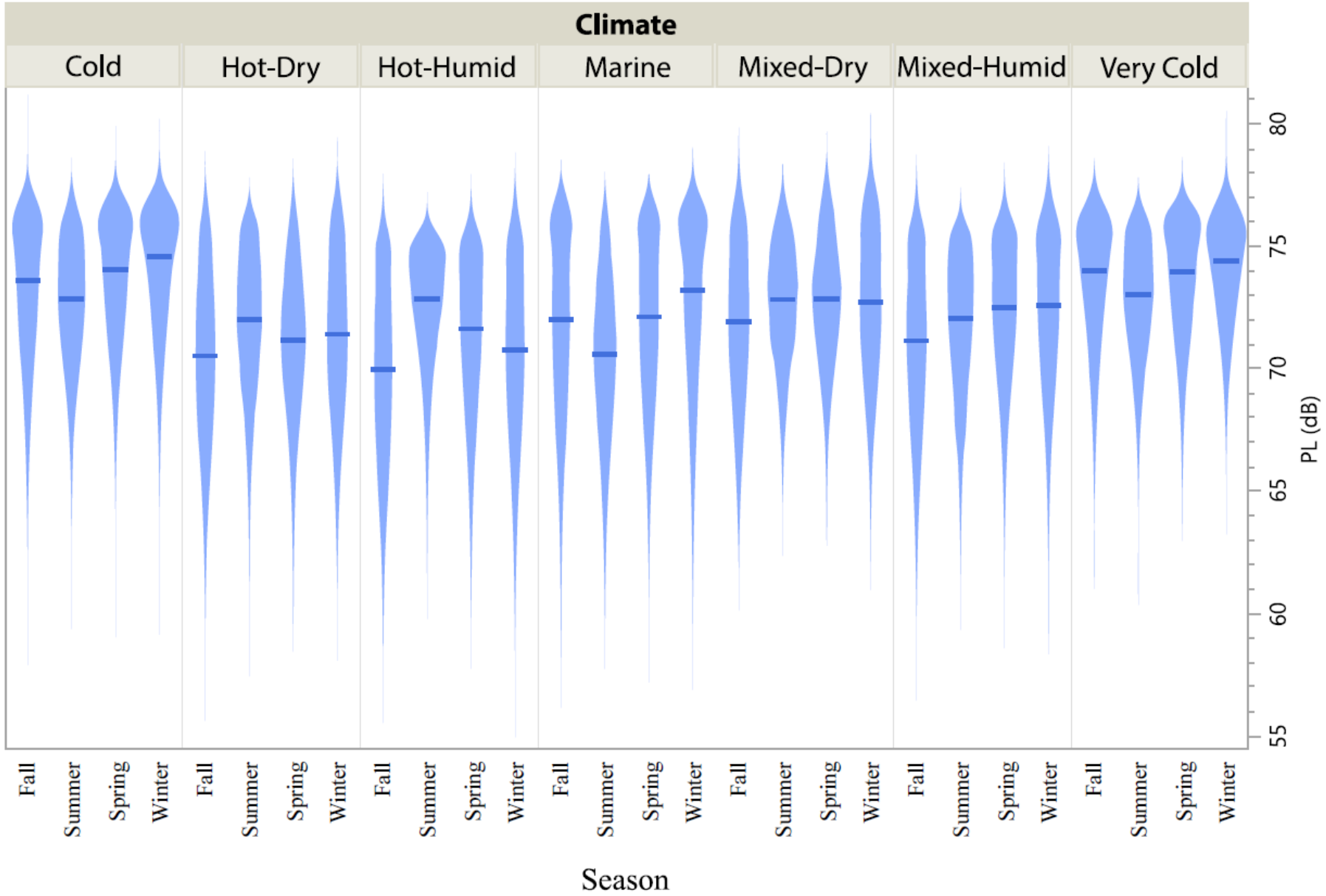
Design Parameters
- Length: 99’ 7”
- Span: 29’ 6”
- Speed: Mach 1.4 (925 mph)
- Altitude: 55,000 ft

Design Features
- New, unique airframe design with acoustic signature shaping
- Many components from existing aircraft to reduce cost
- Payload capacity: single pilot/flight test instrumentation
- No front-facing window

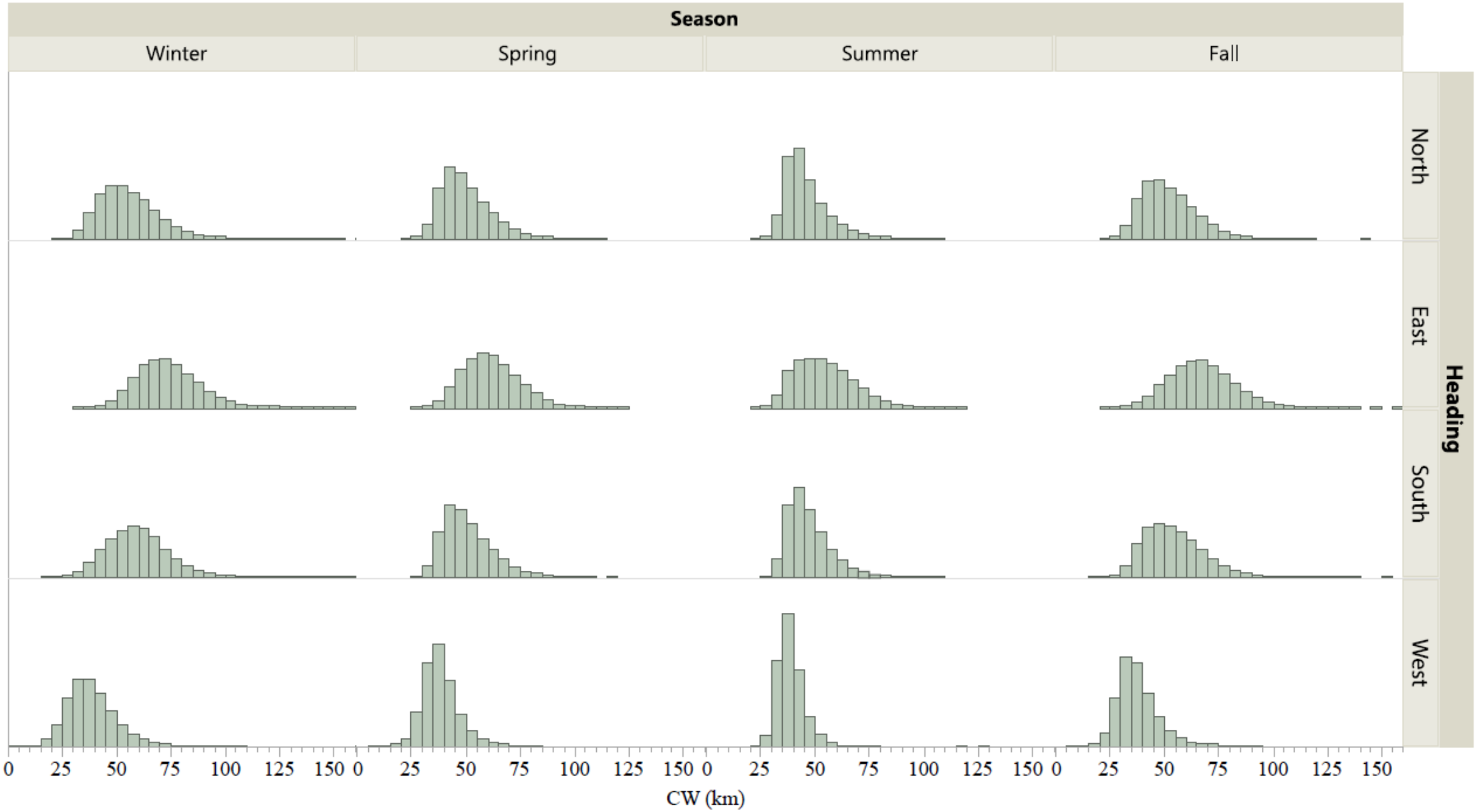
Effects of climate zone and season on CW



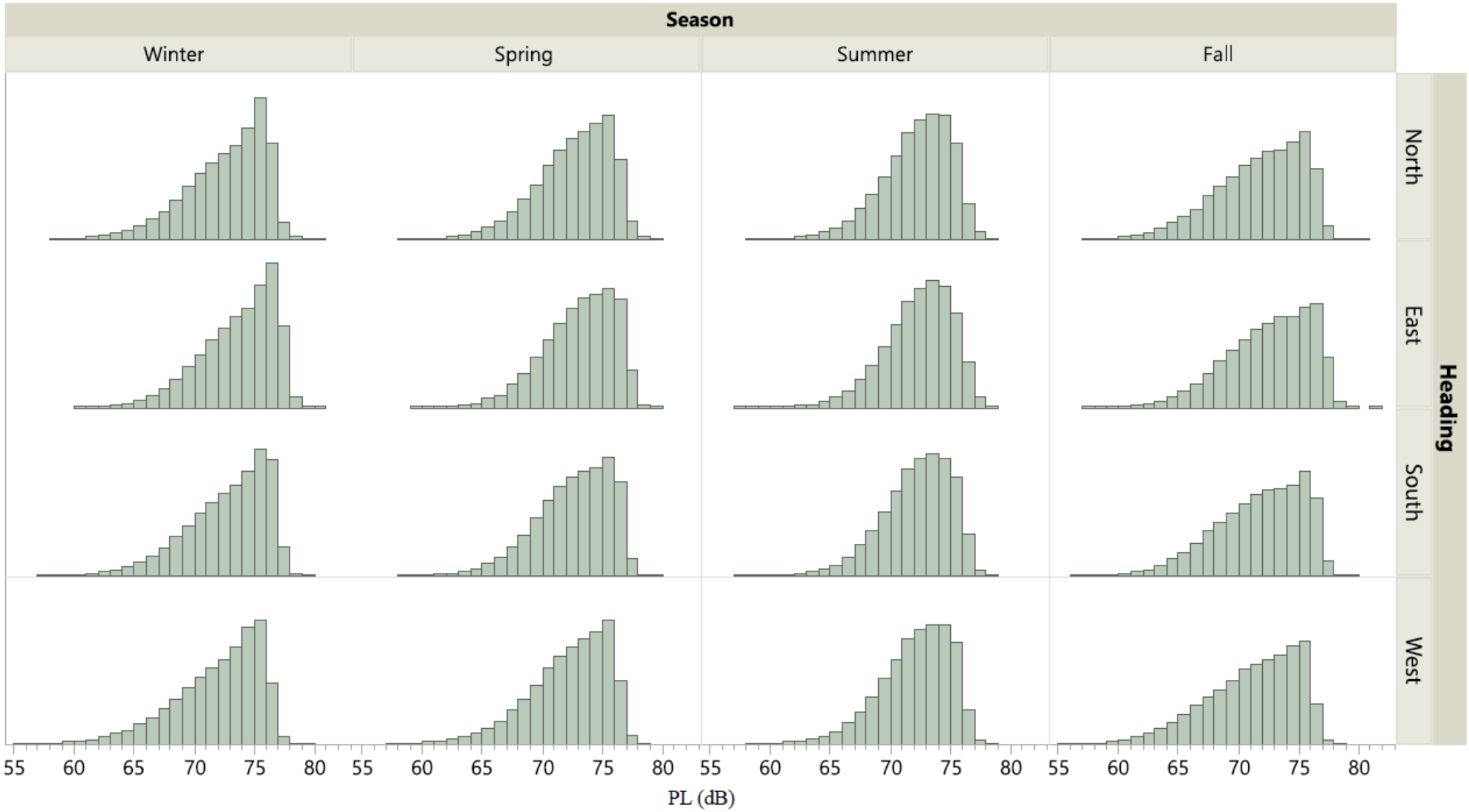
Effects of climate zone and season on Undertrack PL



Carpet width is widest for the east heading and in winter



Undertrack PL is insensitive to heading but is greatest in winter

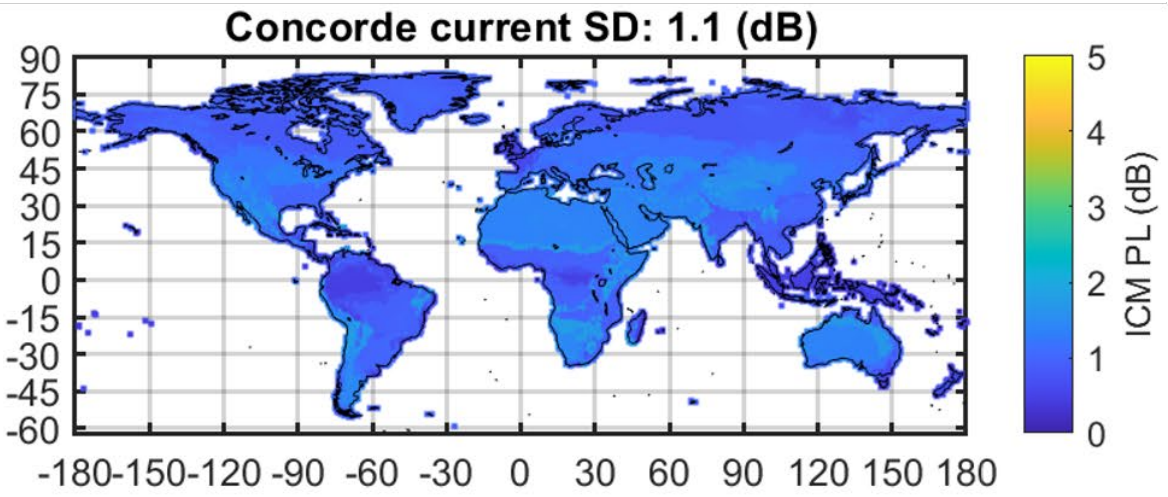


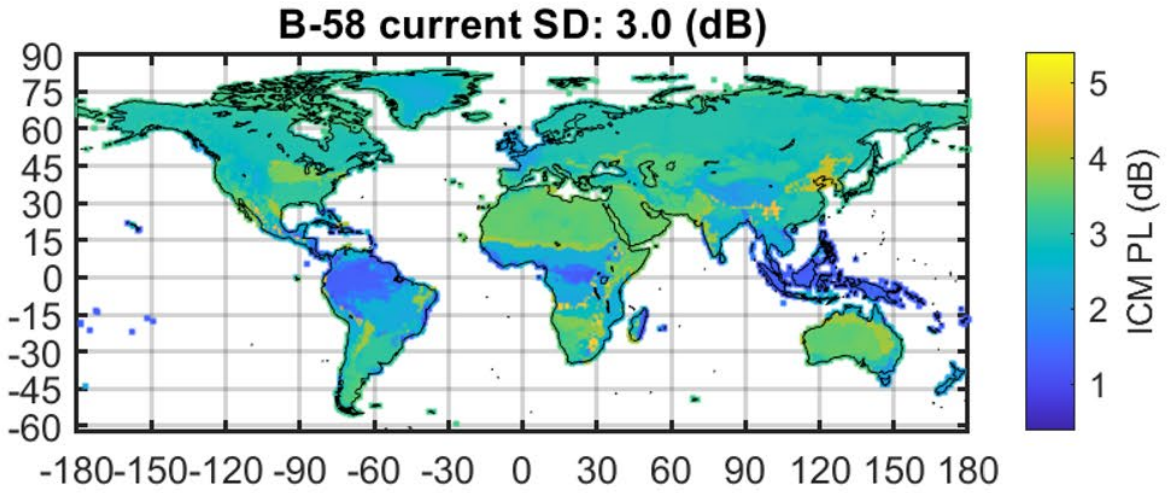
Koppen-Geiger climate zone definitions

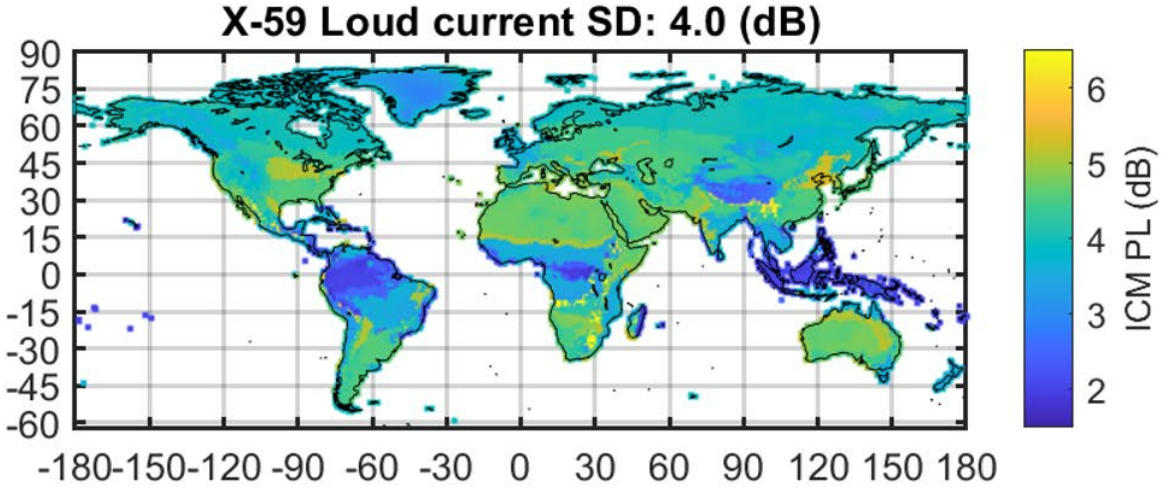
1st	2nd	3rd	Description	Criteria*
A			Tropical	$T_{cold} \geq 18$
	f		- Rainforest	$P_{dry} \geq 60$
	m		- Monsoon	Not (Af) & $P_{dry} \geq 100 - MAP/25$
	w		- Savannah	Not (Af) & $P_{dry} < 100 - MAP/25$
B			Arid	$MAP < 10 \times P_{threshold}$
	W		- Desert	$MAP < 5 \times P_{threshold}$
	S		- Steppe	$MAP \geq 5 \times P_{threshold}$
		h	- Hot	$MAT \geq 18$
		k	- Cold	$MAT < 18$
C			Temperate	$T_{hot} > 10$ & $0 < T_{cold} < 18$
	s		- Dry Summer	$P_{sdry} < 40$ & $P_{sdry} < P_{wwet}/3$
	w		- Dry Winter	$P_{wdry} < P_{swet}/10$
	f		- Without dry season	Not (Cs) or (Cw)
		a	- Hot Summer	$T_{hot} \geq 22$
		b	- Warm Summer	Not (a) & $T_{mon10} \geq 4$
		c	- Cold Summer	Not (a or b) & $1 \leq T_{mon10} < 4$
D			Cold	$T_{hot} > 10$ & $T_{cold} \leq 0$
	s		- Dry Summer	$P_{sdry} < 40$ & $P_{sdry} < P_{wwet}/3$
	w		- Dry Winter	$P_{wdry} < P_{swet}/10$
	f		- Without dry season	Not (Ds) or (Dw)
		a	- Hot Summer	$T_{hot} \geq 22$
		b	- Warm Summer	Not (a) & $T_{mon10} \geq 4$
		c	- Cold Summer	Not (a, b or d)
		d	- Very Cold Winter	Not (a or b) & $T_{cold} < -38$
E			Polar	$T_{hot} < 10$
	T		- Tundra	$T_{hot} > 0$
	F		- Frost	$T_{hot} \leq 0$

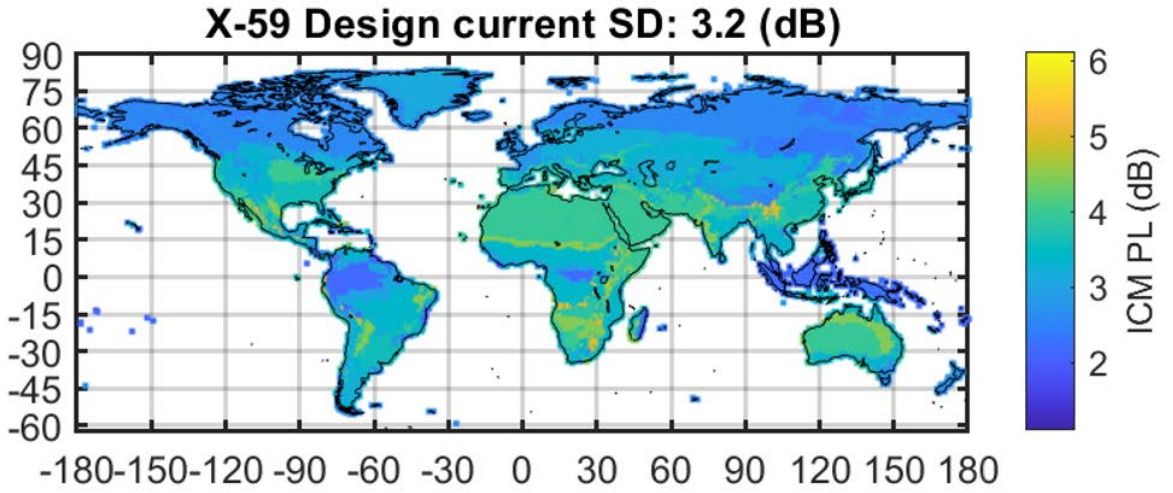
*MAP = mean annual precipitation, MAT = mean annual temperature, T_{hot} = temperature of the hottest month, T_{cold} = temperature of the coldest month, T_{mon10} = number of months where the temperature is above 10, P_{dry} = precipitation of the driest month, P_{sdry} = precipitation of the driest month in summer, P_{wdry} = precipitation of the driest month in winter, P_{swet} = precipitation of the wettest month in summer, P_{wwet} = precipitation of the wettest month in winter, $P_{threshold}$ = varies according to the following rules (if 70% of MAP occurs in winter then $P_{threshold}$ = 2 x MAT, if 70% of MAP occurs in summer then $P_{threshold}$ = 2 x MAT + 28, otherwise $P_{threshold}$ = 2 x MAT + 14). Summer (winter) is

ICM PL SD


Concorde current SD: 1.1 (dB)
90
75
60
45
30
15
0
-15
-30
-45
-60
-180 -150 -120 -90 -60 -30 0 30 60 90 120 150 180
5
4
3
2
1
0
ICM PL (dB)


B-58 current SD: 3.0 (dB)
90
75
60
45
30
15
0
-15
-30
-45
-60
-180 -150 -120 -90 -60 -30 0 30 60 90 120 150 180
5
4
3
2
1
ICM PL (dB)


X-59 Loud current SD: 4.0 (dB)
90
75
60
45
30
15
0
-15
-30
-45
-60
-180 -150 -120 -90 -60 -30 0 30 60 90 120 150 180
6
5
4
3
2
ICM PL (dB)


X-59 Design current SD: 3.2 (dB)
90
75
60
45
30
15
0
-15
-30
-45
-60
-180 -150 -120 -90 -60 -30 0 30 60 90 120 150 180
6
5
4
3
2
ICM PL (dB)

A note on humidity convention in atmospheric models

- Relative humidity computed with respect to ice instead of liquid water at low temperatures
- PCBoom expects humidity to be with respect to liquid water
- Correct model data to PCBoom's expected input

