Design of Experiments: X-59 Sonic Thump Carpets in the Eastern United States

Will Doebler, Sara Wilson, Alexandra Loubeau

NASA Langley Research Center

Victor Sparrow

Penn State

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william.j.doebler@nasa.gov

Motivation for simulating propagation of low-booms

- **A noise limit has to be set in order to certify supersonic aircraft**
- **The noise limit must be effective in all regions of the USA**
- **Geographical location / climate may play a role in low-boom loudness**

- **Goal:**
  - Quantify effects of atmosphere on low-boom
- **Approach:**
  - Simulate propagation of low-booms through atmospheric profiles across the USA
    - This talk: determine appropriate spatial and temporal resolution of propagation simulation across USA
      - Do this by examining a subset of propagation simulations in the Northeast USA

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Background: X-59 Quiet Supersonic Technology Aircraft

- **NASA is building a low-boom demonstration aircraft**
- **X-59 will fly supersonically over several communities**

- **Design cruise condition**
  - 54,000 ft (16.46 km)
  - Mach 1.4

- **Use X-59 nearfield as noise source for propagation simulations across the USA**

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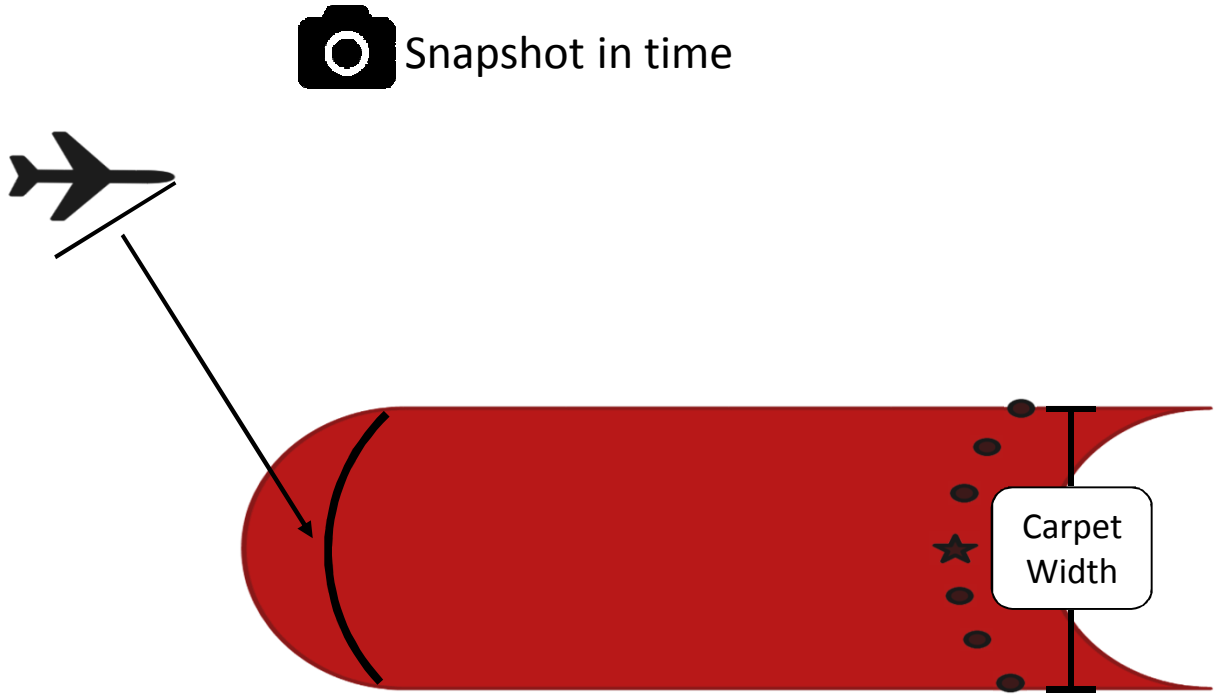
Approach to quantify effects of atmosphere on X-59 carpets

- **Simulate propagation of CFD-generated X-59 nearfield pressure aloft to the ground through many realistic atmospheric profiles**



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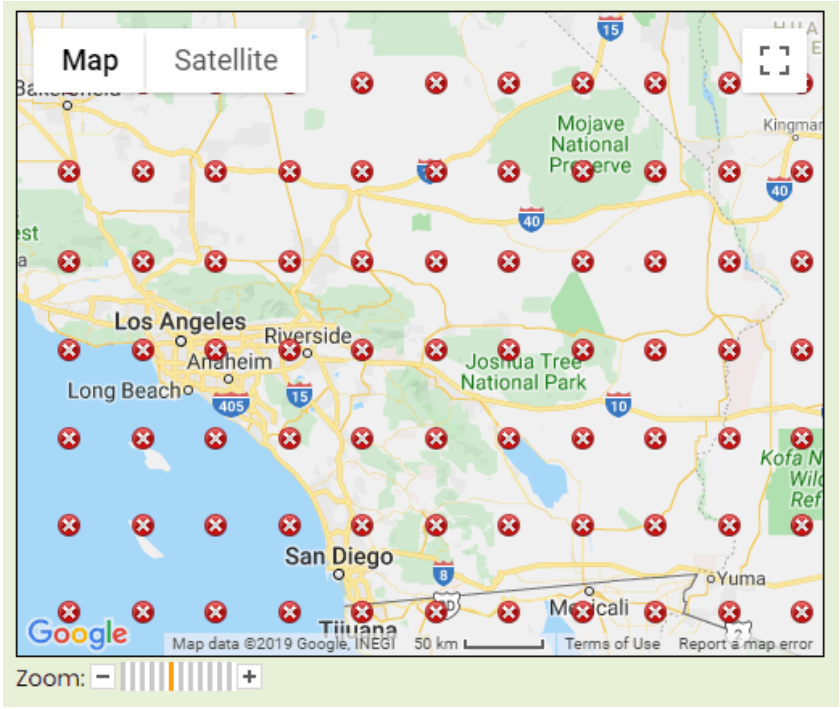
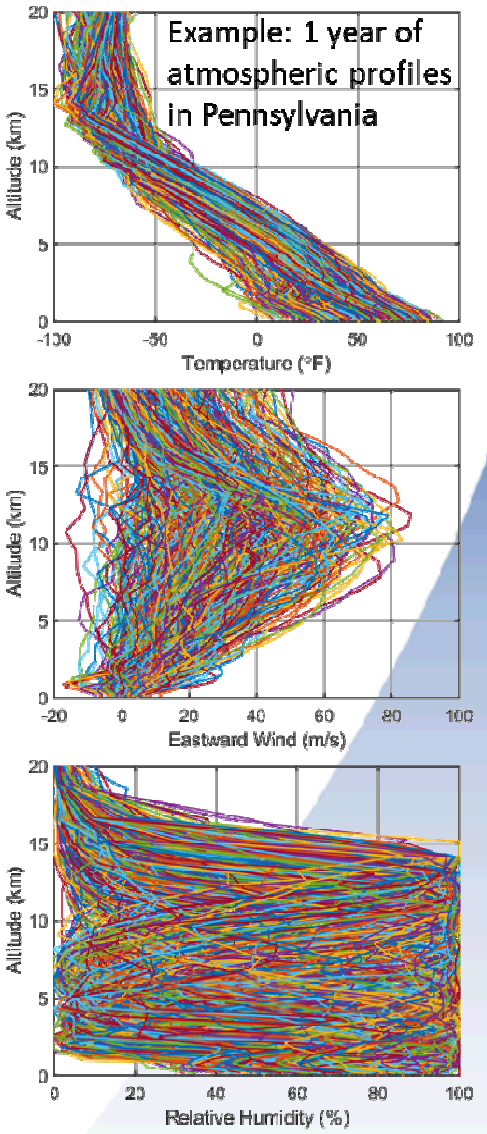
Atmospheric profiles taken from Climate Forecast System Reanalysis database

- **Spatial resolution**
  - 0.5° by 0.5° latitude/longitude
- **Temporal resolution**
  - 6 hourly from 1979 to present
- **Vertical resolution**
  - Varies, 37 isobaric pressure levels
- **Atmospheric profile variables used**
  - Ground elevation
  - 2-D Winds
  - Temperature
  - Relative humidity





- **Need to balance resolution with computation time**

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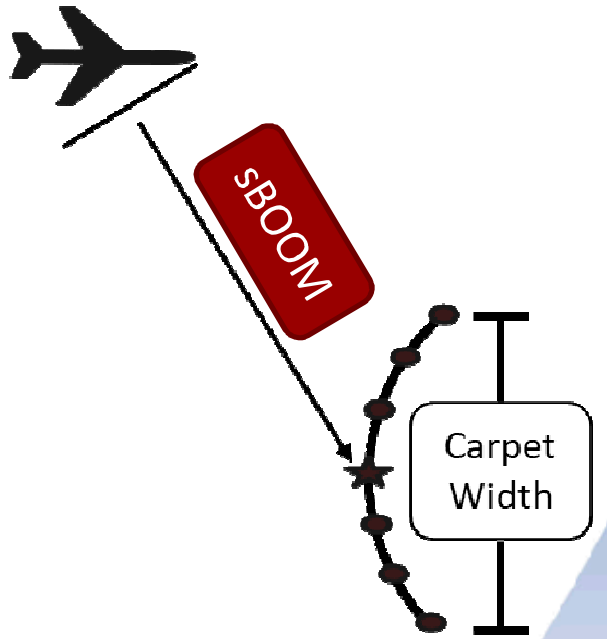
Propagation code information

- **sBOOM version 2.8**
  - Augmented Burgers Equation and ray tracing solved in time domain
  - Horizontally stratified atmosphere, no vertical winds
  - Hydrostatic atmospheric pressure approximation
- **Input parameters**
  - Aircraft heading
  - Mach 1.4 cruising at 54,000 ft (16.46 km)
  - X-59 C609 CFD nearfield solution with 2 degree resolution
  - Atmospheric profile
  - Ground elevation
- **Outputs**
  - Ground waveforms at “virtual microphones”
    - Calculate Perceived Level (PL)
  - Carpet Width (CW)
  - Approx. 30 seconds per ray



Determination of feasible resolution

- **2160 hours (90 days) of compute time assumed**
- **~70,000 propagated rays per hour was feasible**
- **Assumed 2-mile (3.2 km) cross-carpet resolution was reasonable**
  - From previous work, sonic boom carpets are 20 to 80 miles (32 to 128 km) wide with 45 miles (72 km) typical
  - Allows 10 ground signatures per carpet at the lowest expected carpet size
- **Use 60 miles as a conservative mean carpet width for estimation**
- **Assumed 5 years of weather profile data was reasonable**
  - 4 atmospheric profiles per day = 7304 atmospheric profiles per year
- **Assumed 4 cardinal aircraft headings was reasonable**
- **Allow a 10% margin of estimation error**
- Approx. maximum number of locations =

$$2160\ \text{hr} \cdot 70{,}000\ \frac{\text{rays}}{\text{hr}} \cdot 2\ \frac{\text{miles}}{\text{ray}} \cdot \frac{1}{60}\ \frac{\text{carpet}}{\text{miles}} \cdot \frac{1}{7304}\ \frac{\text{heading}}{\text{carpets}} \cdot \frac{1}{4}\ \frac{\text{location}}{\text{headings}} \cdot 0.9$$

$$= \mathbf{154\ locations}$$

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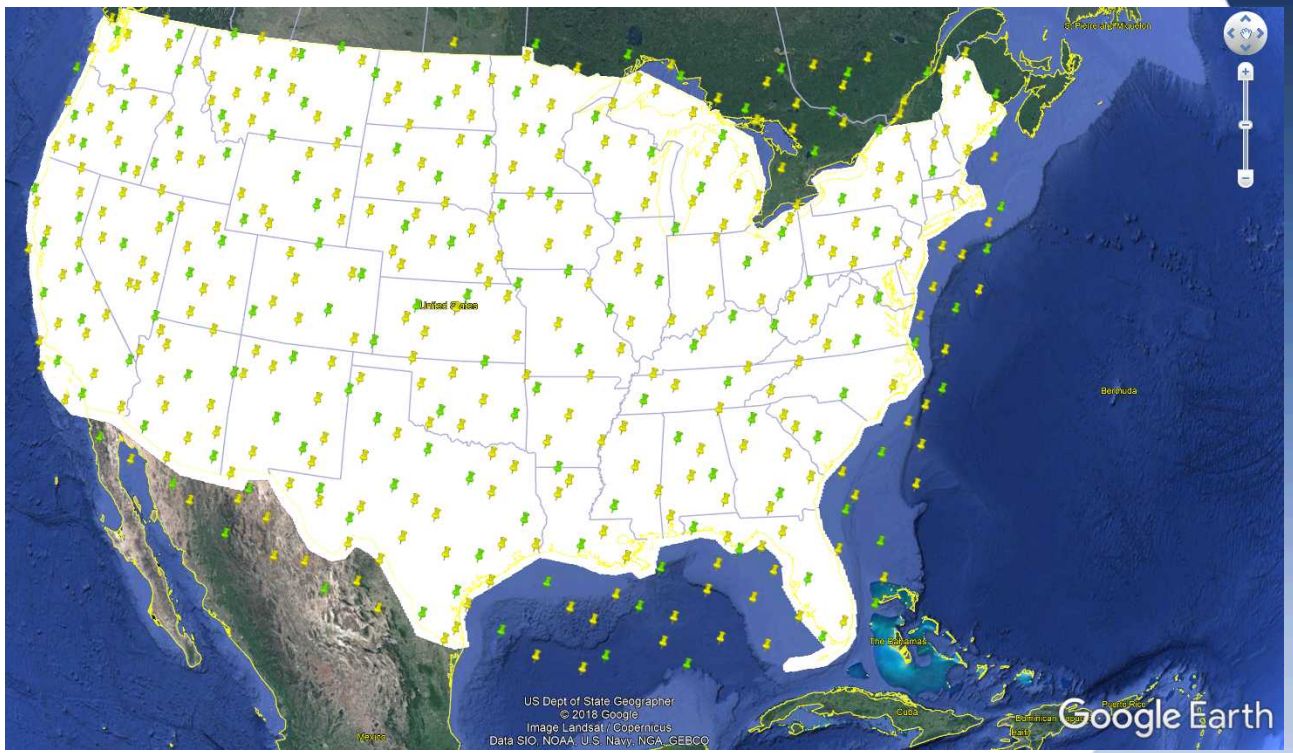
Design of Experiments Approach

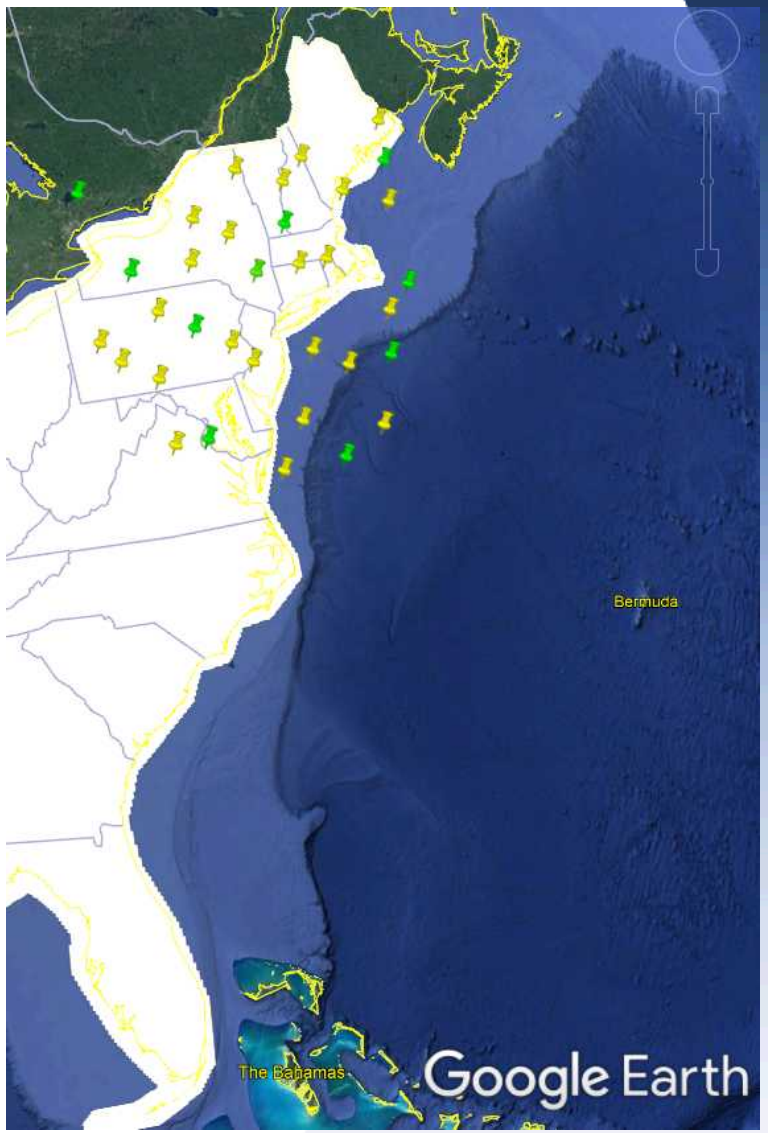
- **Need to determine appropriate locations and times of atmospheric profiles through which to propagate**
- **Locations across USA chosen using Fast Flexible Filling Design**
  - Provides good space filling properties and can accommodate irregular shapes like the contiguous USA
- **Two spatial resolutions:**
  - 150 and 450 locations across USA



Lekivetz, R. and Jones, B., (2015) "Fast Flexible Space-Filling Designs for Nonrectangular Regions," *Qual. Reliab. Engng. Int.*, 31(5), 829-837

Propagate through a subset of locations in USA to decide spatial and temporal resolution

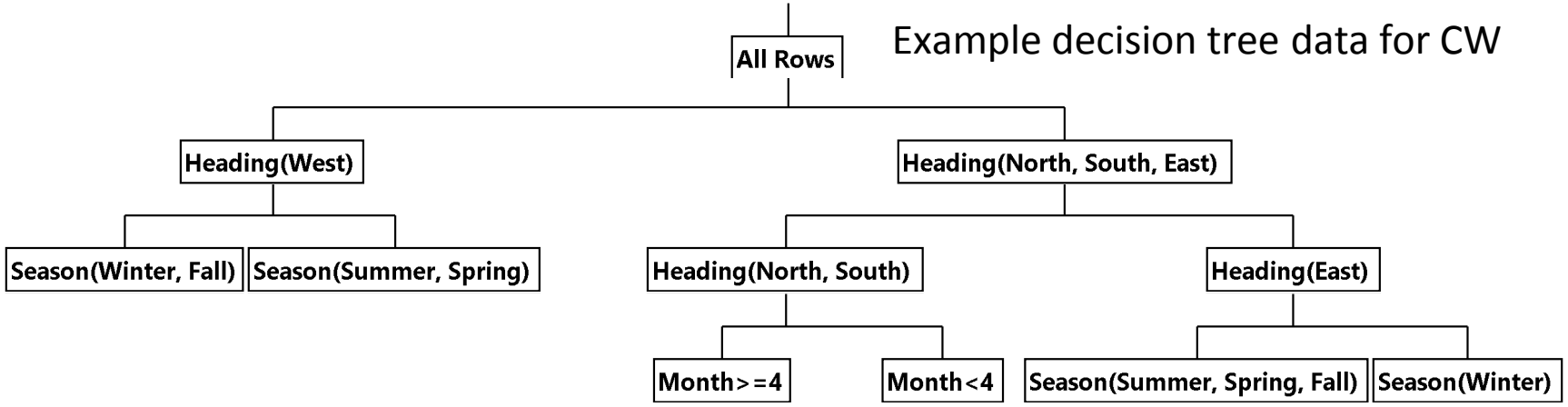
- **Simulated propagation at subset of locations in the Northeast using sBOOM code**
- **Compared results of designs with higher and lower spatial and temporal resolutions**
  - 34 vs. 10 locations in Northeast
  - 4 vs. 1 atmospheric profiles per day
- **5 years of atmospheric profiles, 4 aircraft headings**
- **Propagation and post-processing were parallelized**
  - Sonic boom metrics (e.g., PL) were calculated on the ground waveforms
- **Subset storage size**
  - About 1.5 TB total for nearly 1 million carpets

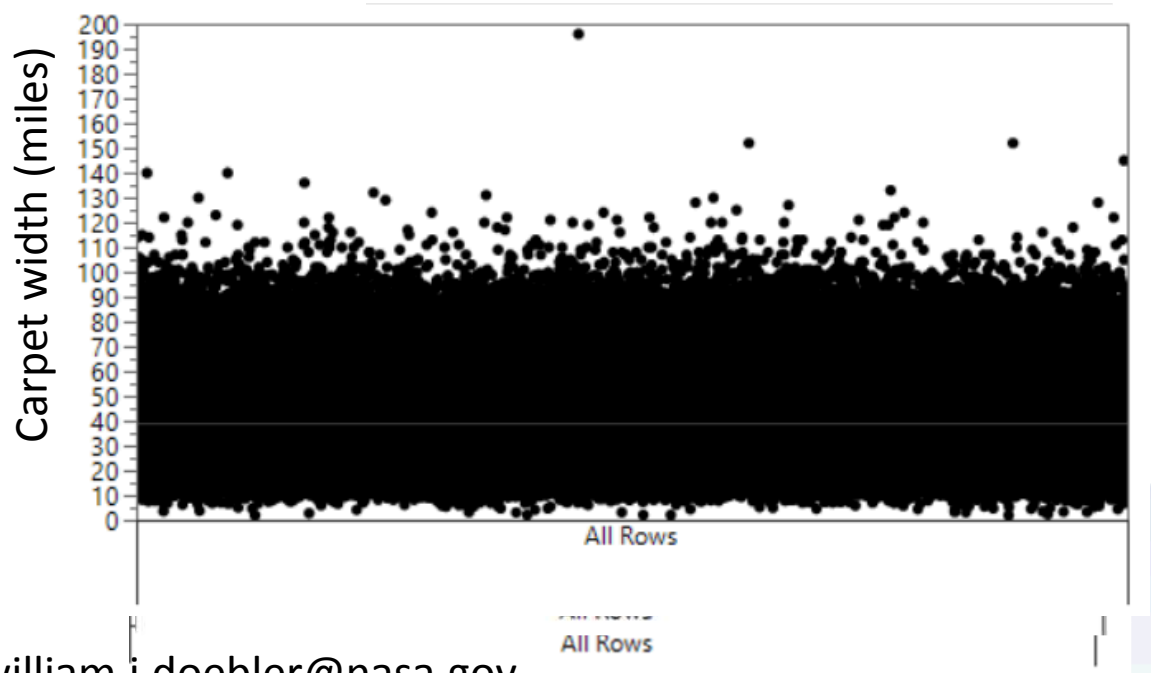


To determine importance of input factors, used decision tree and bootstrap forest analysis

- **Input factors**
  - Heading
  - Latitude/longitude
  - Season
  - Datetime
  - Ground elevation
- **Carpet quantifiers**
  - Carpet width (CW)
  - Undertrack Perceived Level (PL)
  - Range of PL

Example decision tree data for CW





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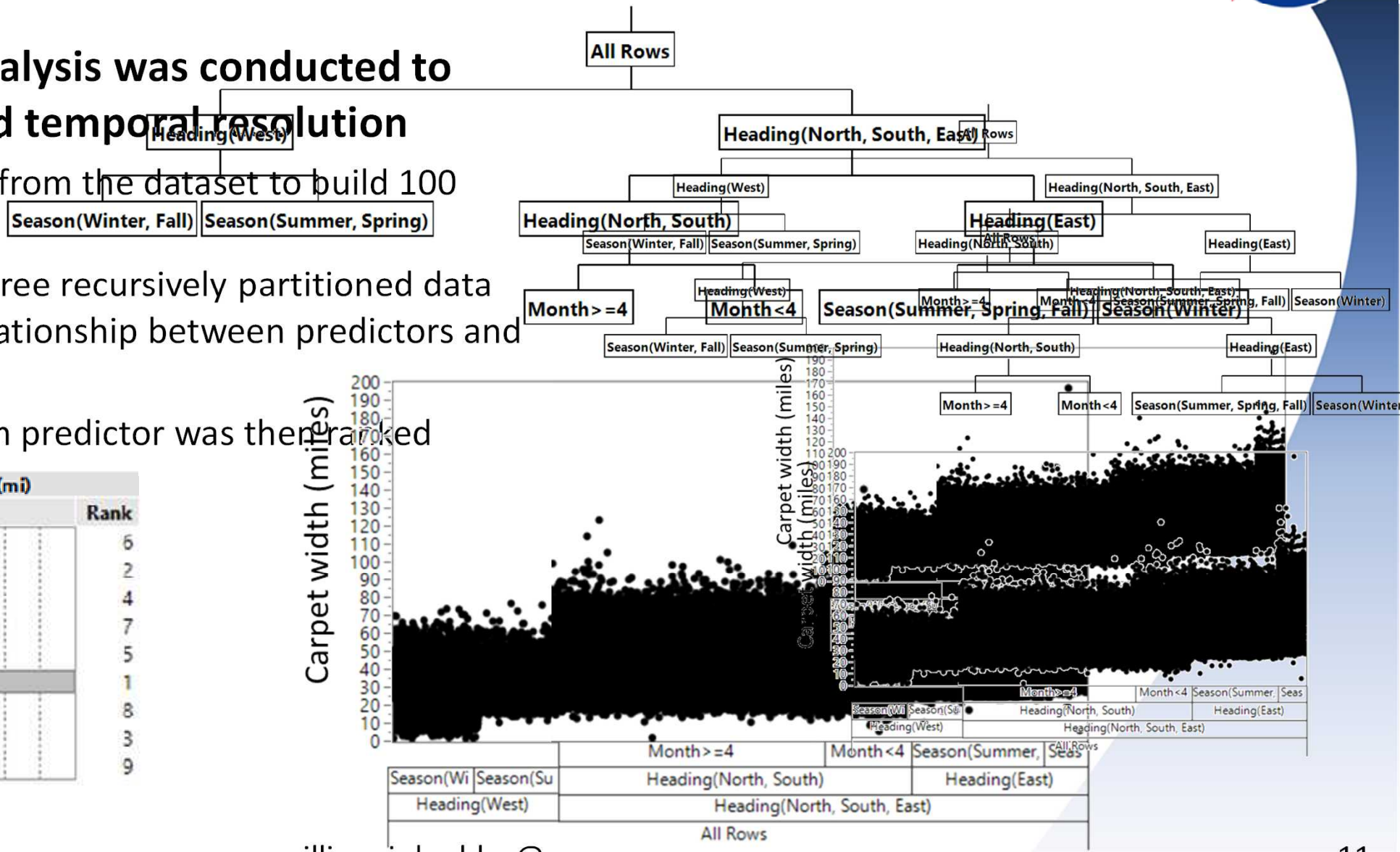
Bootstrap forest analysis description

- **Bootstrap forest analysis was conducted to evaluate spatial and temporal resolution**
  - Randomly sampled from the dataset to build 100 decisions trees
  - Statistical decision tree recursively partitioned data according to the relationship between predictors and response variables
  - Contribution of each predictor was then ranked

Predictor	CW (mi)	Rank
Climate		6
Season		2
Latitude		4
Longitude		7
Ground Altitude (ft)		5
Heading		1
Year		8
Month		3
Time		9



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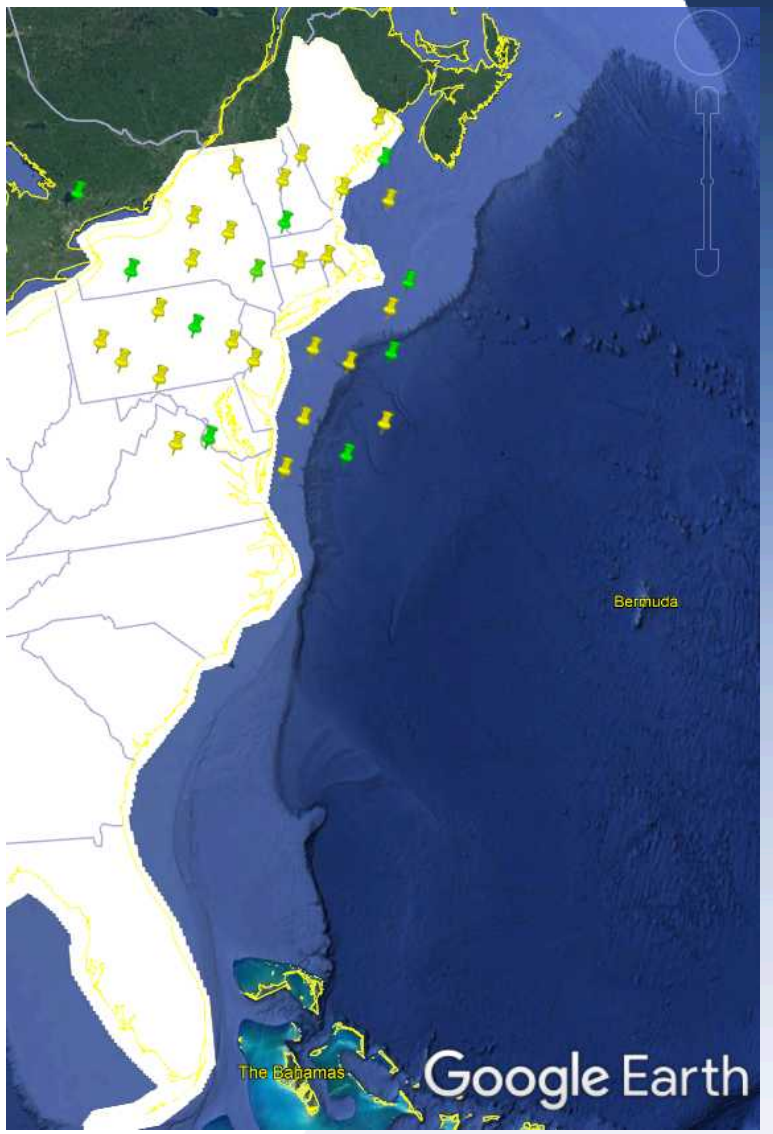
Bootstrap forest results

Fine spatial resolution (green + yellow)

Predictor	PL (dB) Rank	PL range Rank	CW (mi) Rank
Climate	6	9	6
Season	2	2	2
Latitude	4	7	4
Longitude	8	5	7
Ground Altitude (ft)	5	4	5
Heading	3	1	1
Year	7	8	8
Month	1	3	3
Time	9	6	9

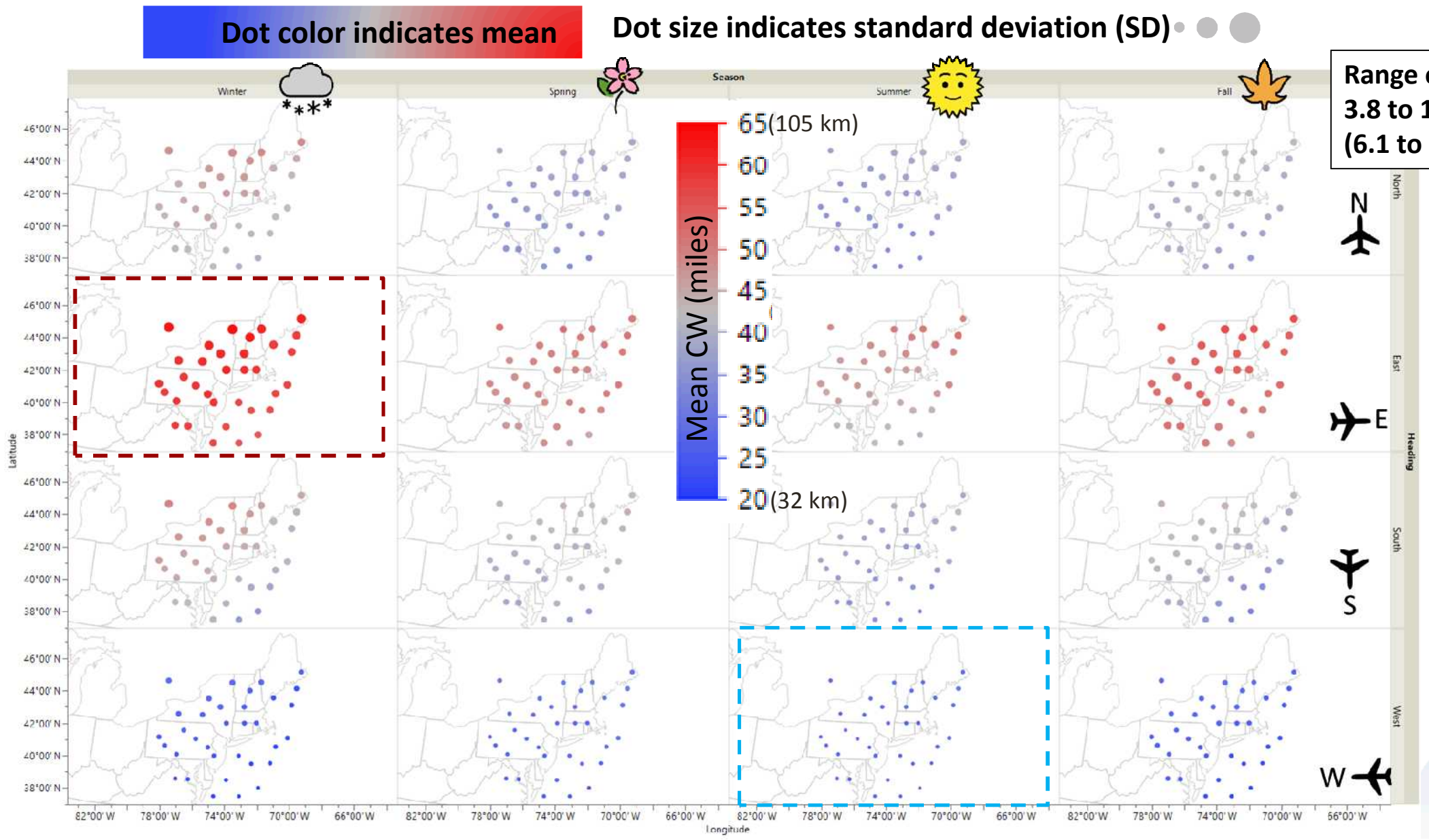
Coarse spatial resolution (green only)

Predictor	PL (dB) Rank	PL range Rank	CW (mi) Rank
Climate	8	9	7
Season	2	2	3
Latitude	4	7	4
Longitude	5	5	6
Ground Altitude (ft)	6	4	5
Heading	3	1	1
Year	7	8	8
Month	1	3	2
Time	9	6	9



- **Time of day was not important**
- **Equivalent predictor importance for both spatial resolutions**

Carpet width (CW) mean and standard deviation (SD) results

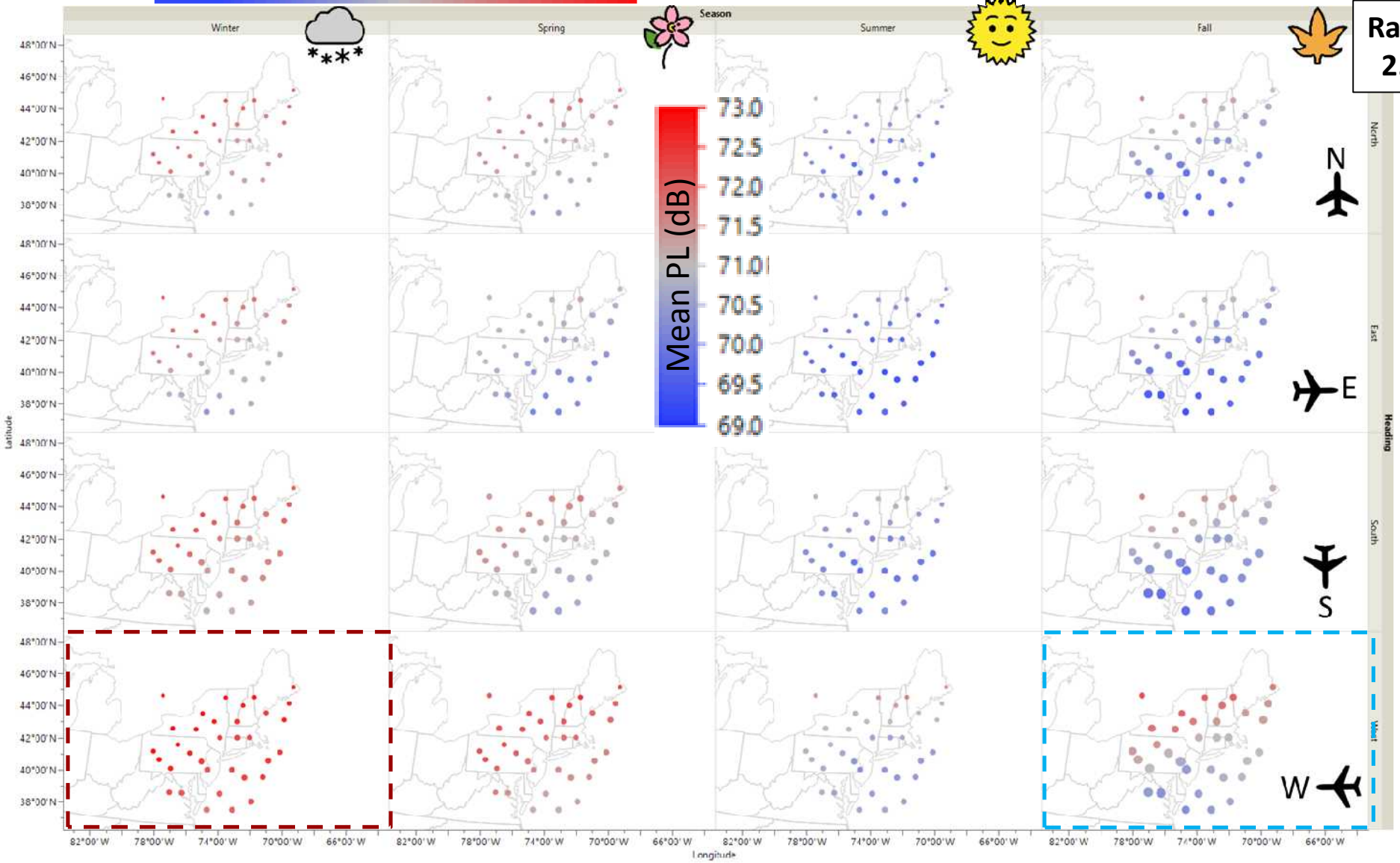


- Widest CW in winter with east heading
- Lowest CW SD in summer with west heading
- Values vary smoothly between nearby points

Undertrack Perceived Level (PL) mean and standard deviation

Dot color indicates mean

Dot size indicates standard deviation (SD)

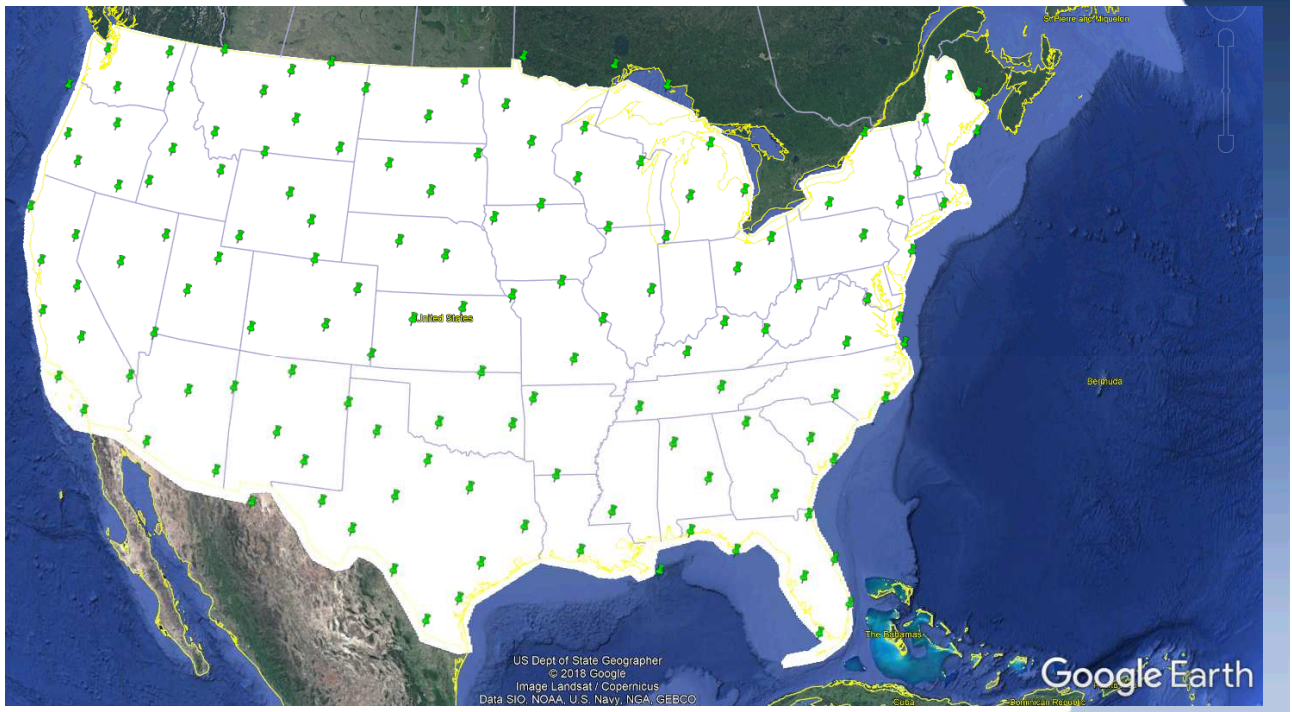


Range of PL SD: 2.2 to 3.5 dB

- Highest PL in winter heading west
- Most variable PL in fall heading west
- Values vary smoothly between nearby points

Final Experiment Design

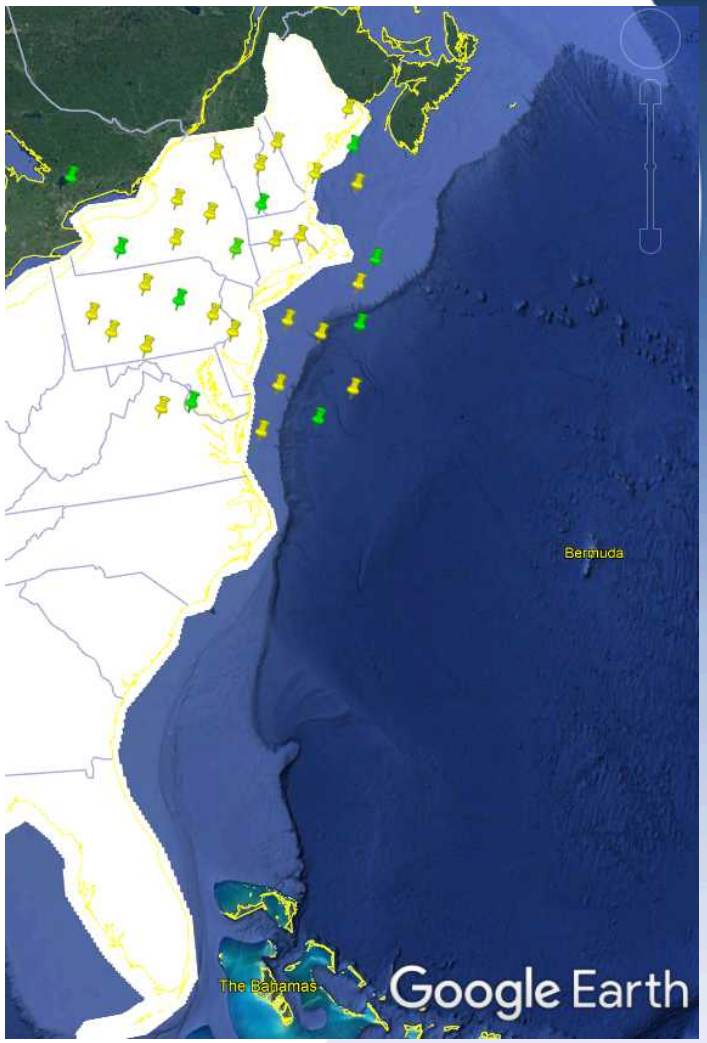
- **5 years of atmospheric profiles with lower temporal resolution**
  - 1 profile per day
- **Spatial resolution of approximately 120 miles (200 km) expected to yield useful results**
  - 138 locations



- **Use CONUS propagation results to:**
  - Assess climate and season effects on booms
  - Assist with X-59 community test planning
    - Help select locations, seasons, and flight profile

Summary

- **X-59 booms were propagated through 5 years of atmospheric profiles for 34 locations in the eastern USA**
- **Nearly 1 million sonic boom carpets generated at 2-mile (3.2 km) resolution**
- **Bootstrap forest analysis performed on propagation results to rank input factors**
- **One atmosphere per day will be used for follow on study of full contiguous USA**
  - Time of day was not found to be important
- **138 locations will be used for follow on study of full contiguous USA**
  - Equivalent predictor importance for both spatial resolutions
  - Smoothly varying results at both spatial resolutions



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Backup slides

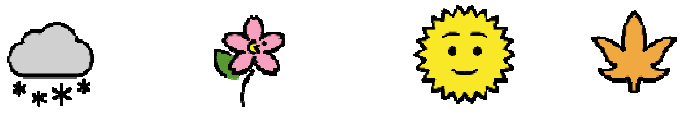
Description of visualization of northeast subset results

Information on plots which follow this slide:

Dot color indicates mean

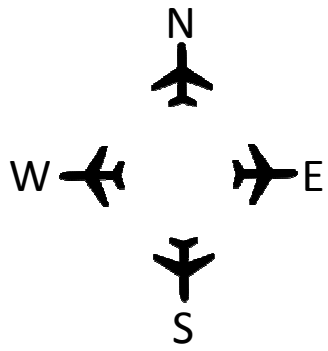
Dot size indicates standard deviation (SD)

Season:

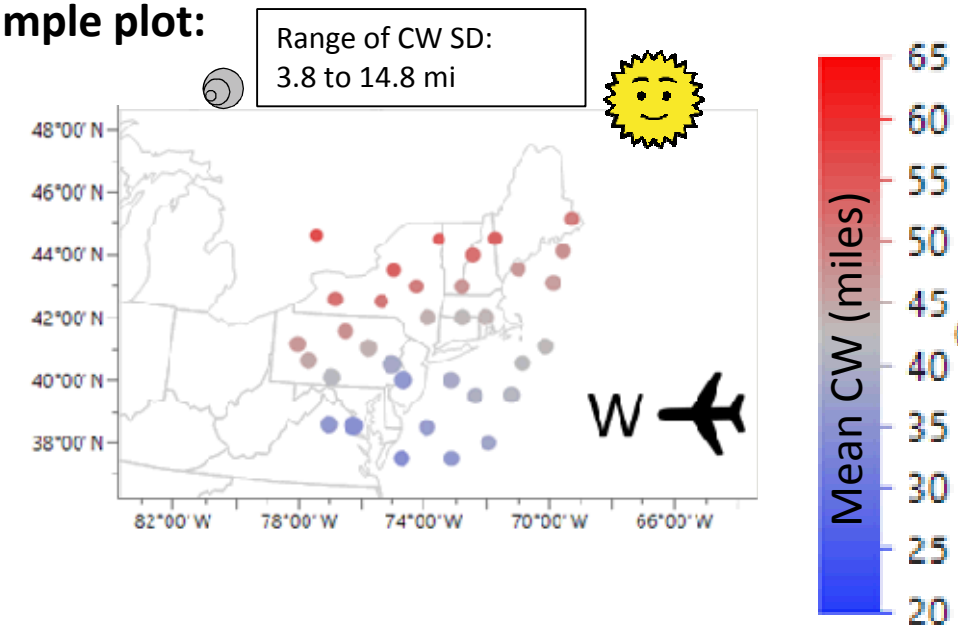


Winter Spring Summer Fall

Aircraft Heading:



Example plot:



This example plot shows:

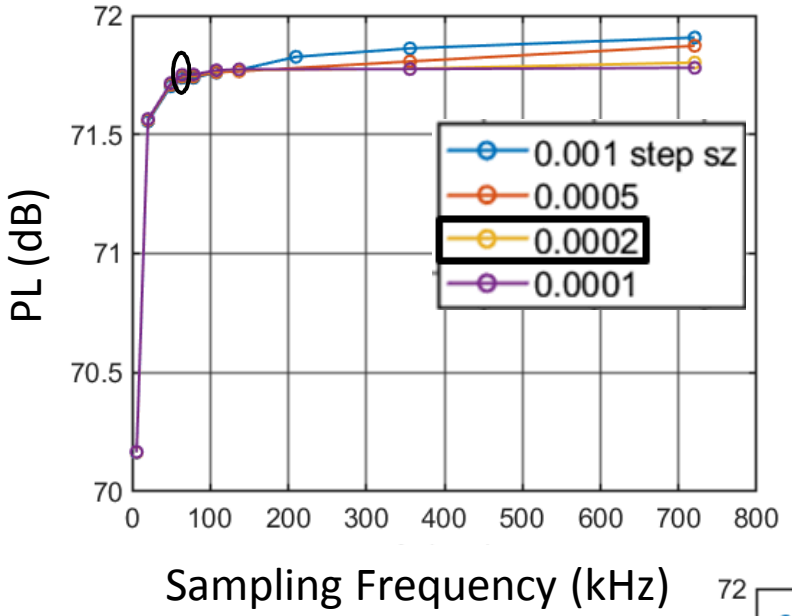
- Mean Carpet Width (CW) via color
- Standard Deviation of CW via dot size

For:

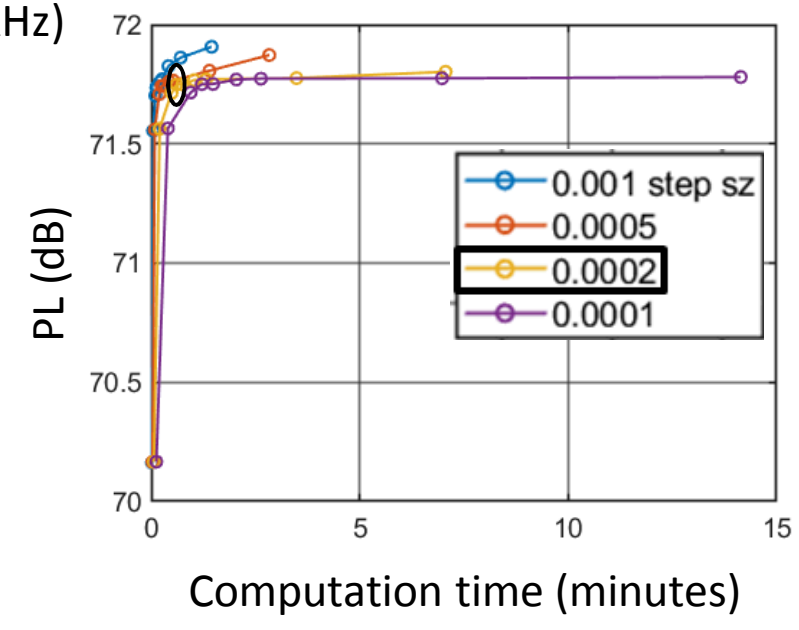
- West heading W
- Summer

Choosing sBOOM input parameters

- **Propagated X-59 boom varying:**
  - Sampling frequency (fs):
    - 6 kHz to 720 kHz
  - Nondimensional step size:
    - $1x10^{-4}$ to $10x10^{-4}$
- **Balance accuracy with runtime**



- **Chose step size: $2x10^{-4}$**
- **Chose sampling rate: 64.2 kHz**



- **Expected accuracy: within 0.1 PLdB**
- **Expected runtime: 30 seconds per ray**

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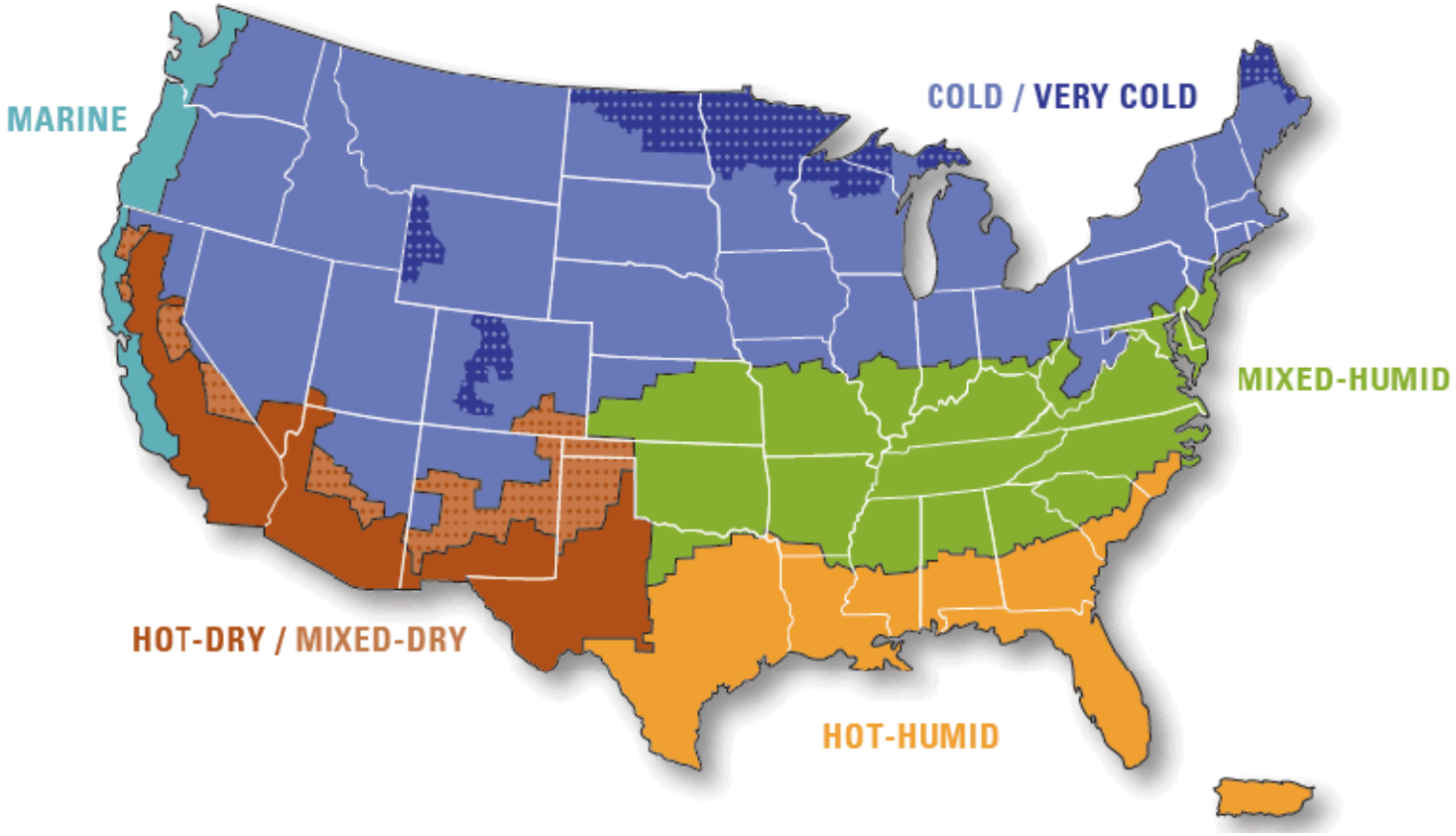
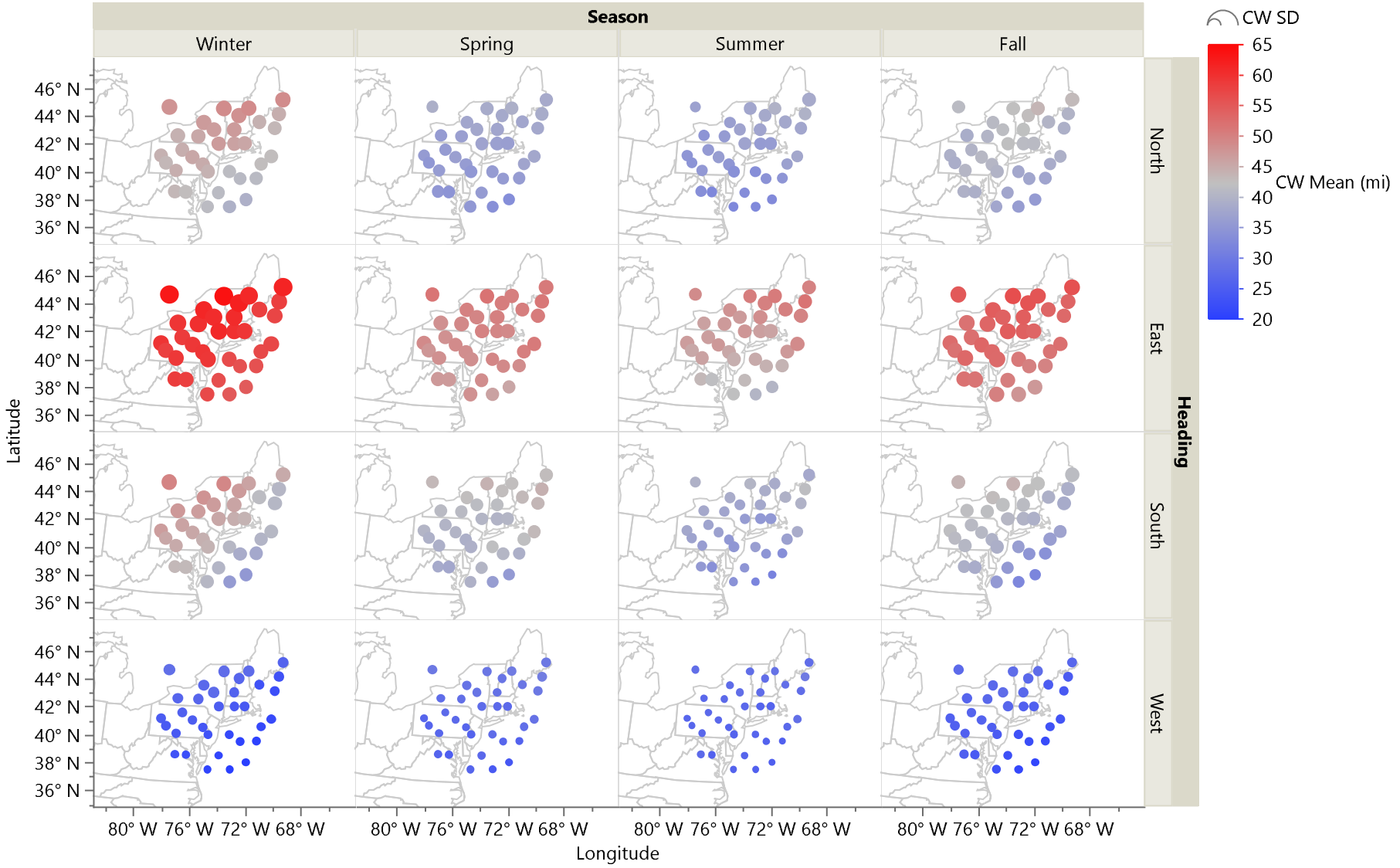
Climate zone

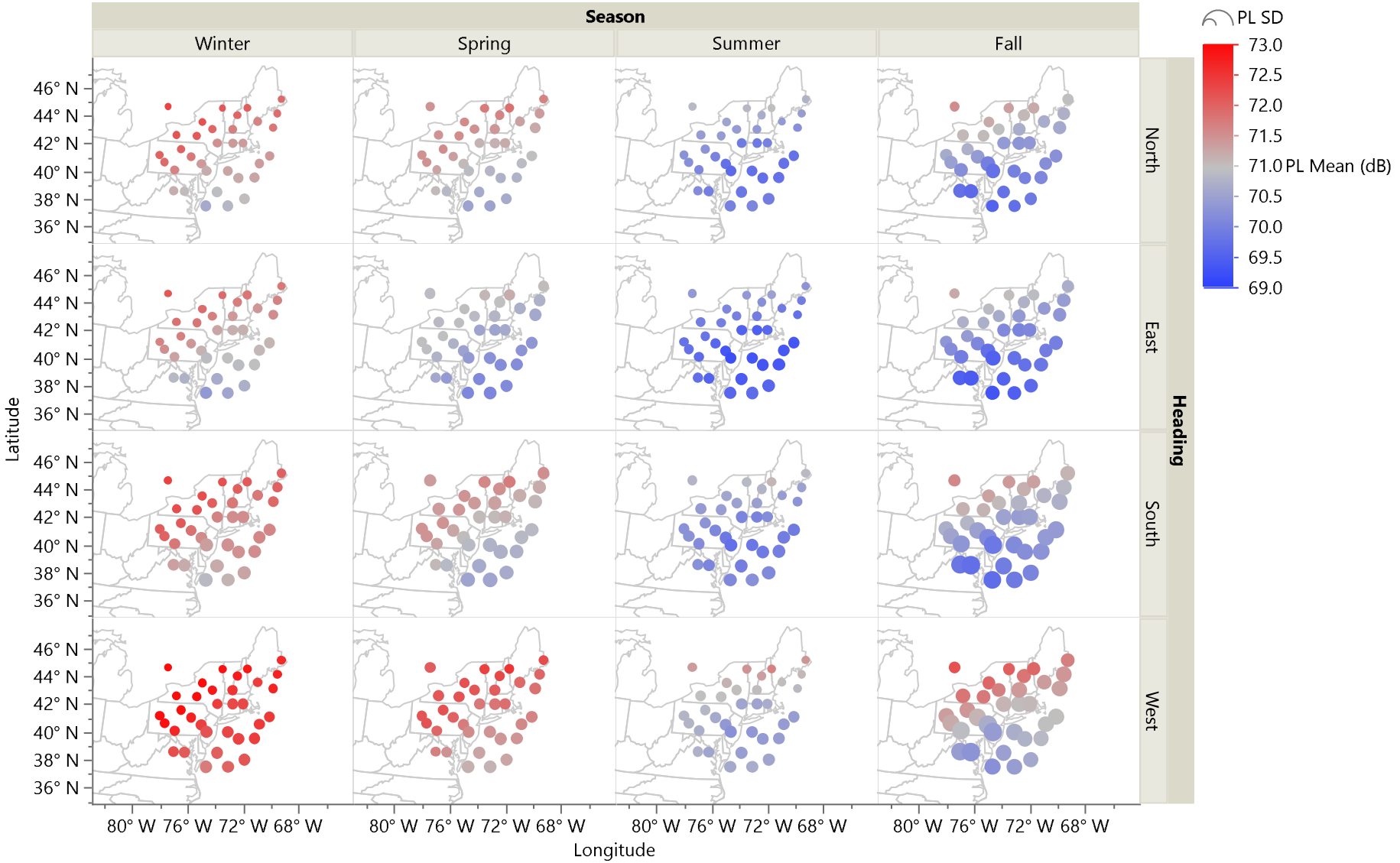


Building America Best Practices Series, Volume 7.3, U.S. Department of Energy

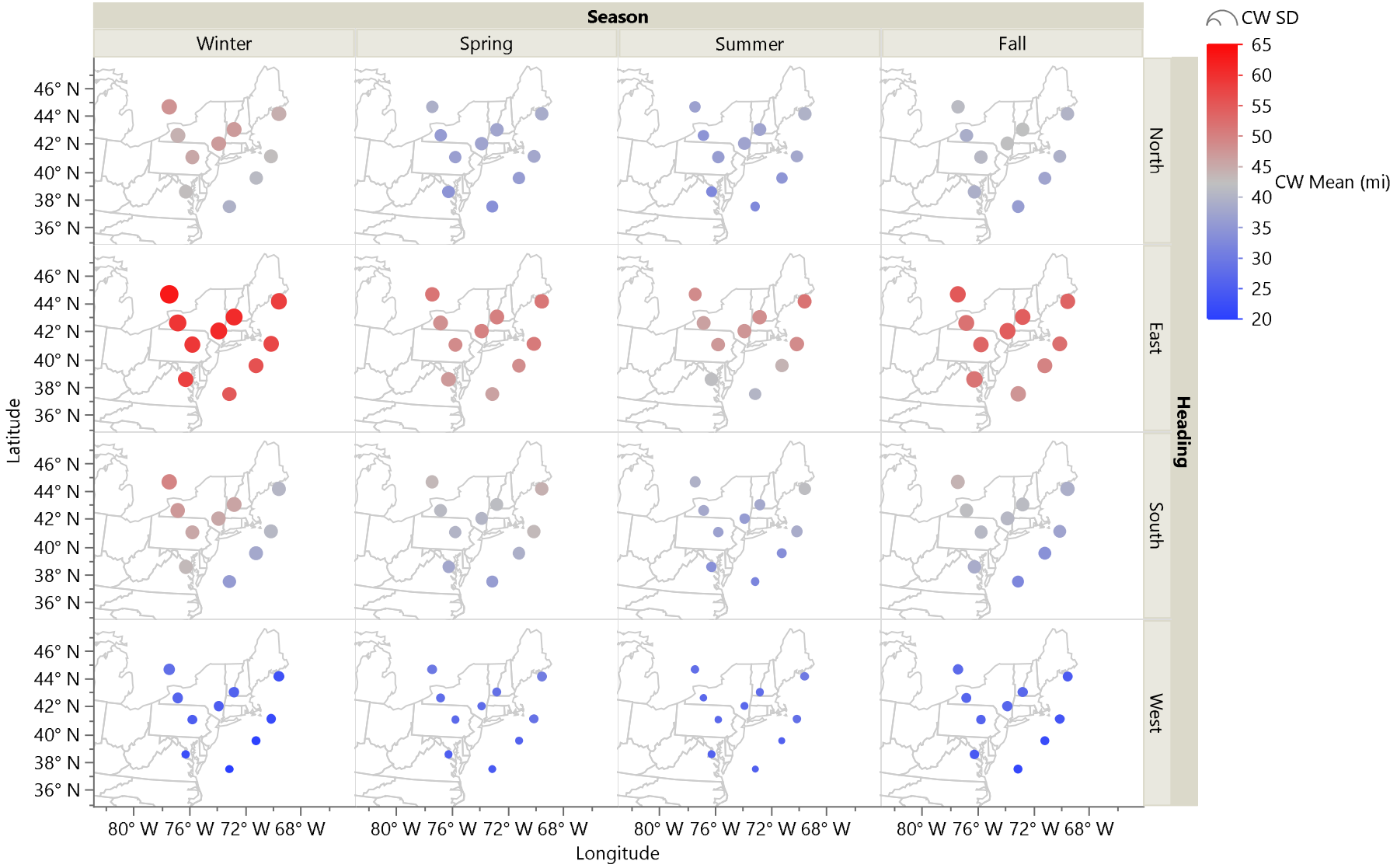
34 Locations, 4 times per day, CW SD = 3.8 to 14.8



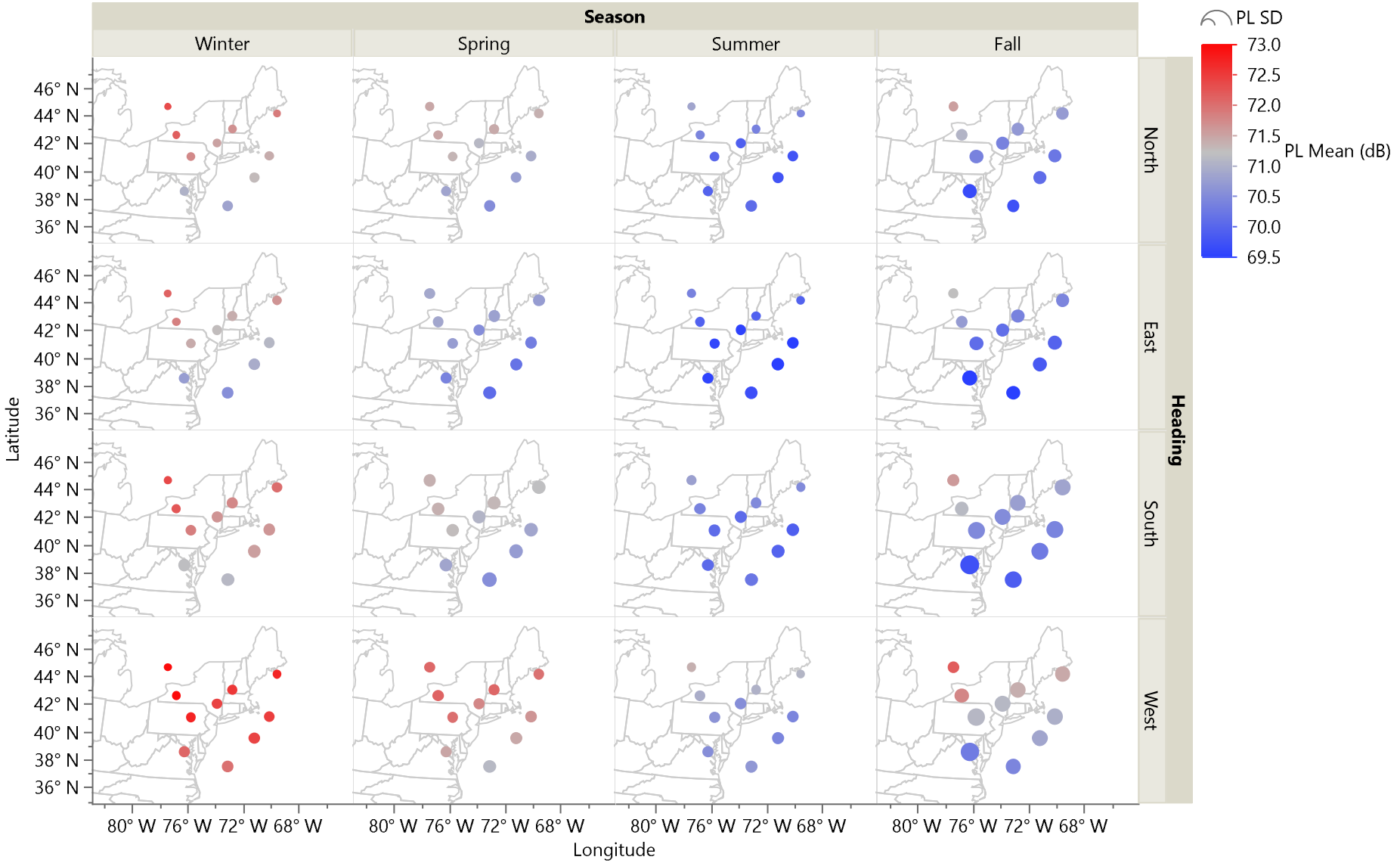
34 locations, 4 times per day, PL SD = 2.2 to 3.5



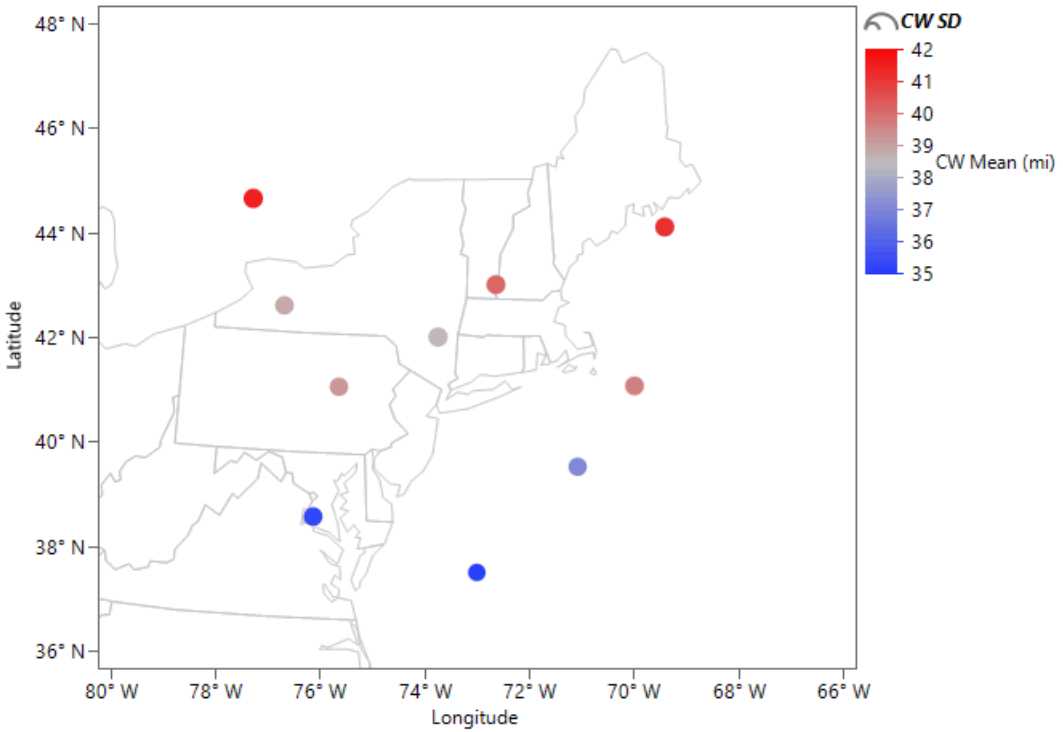
10 locations, 4 times per day, CW SD = 4.0 to 14.6



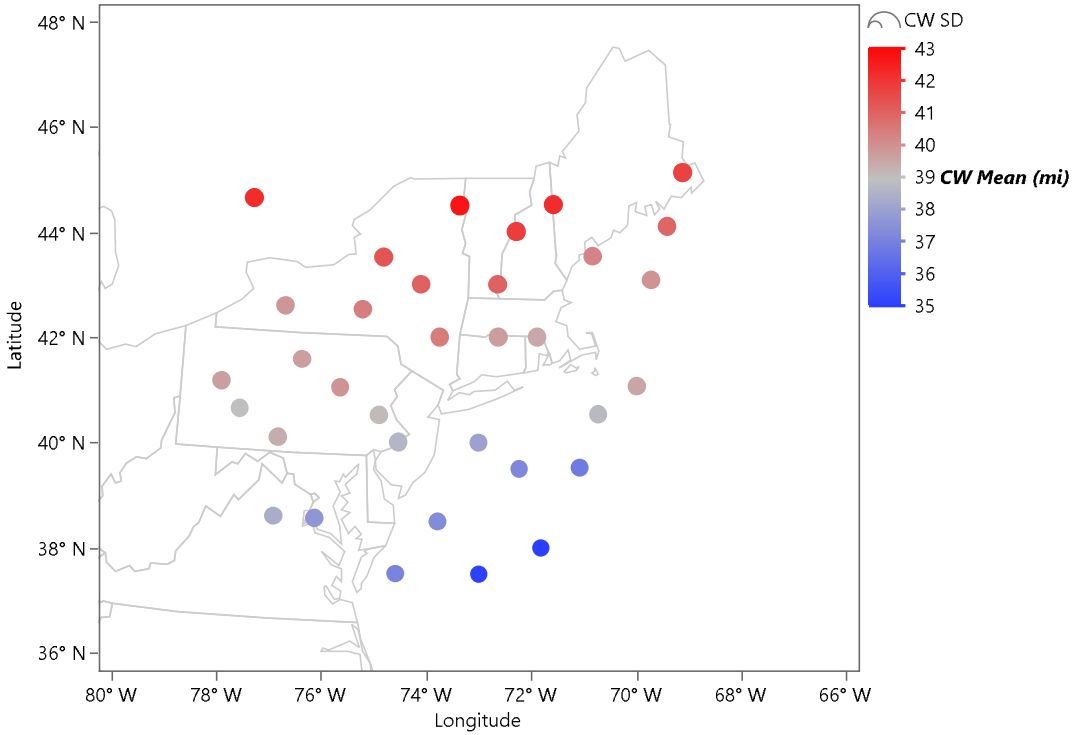
10 locations, 4 times per day, PL SD = 2.2 to 3.5



Mean across seasons and headings

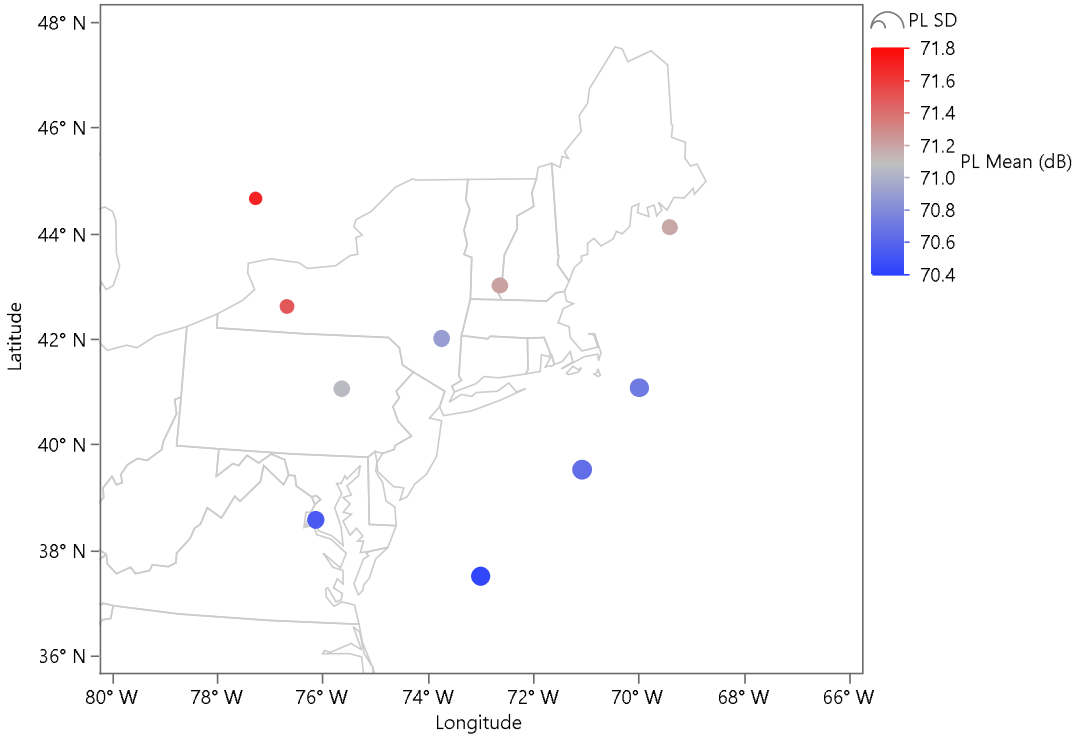


10 locations, 1 time per day
SD = 12.4 to 14.1

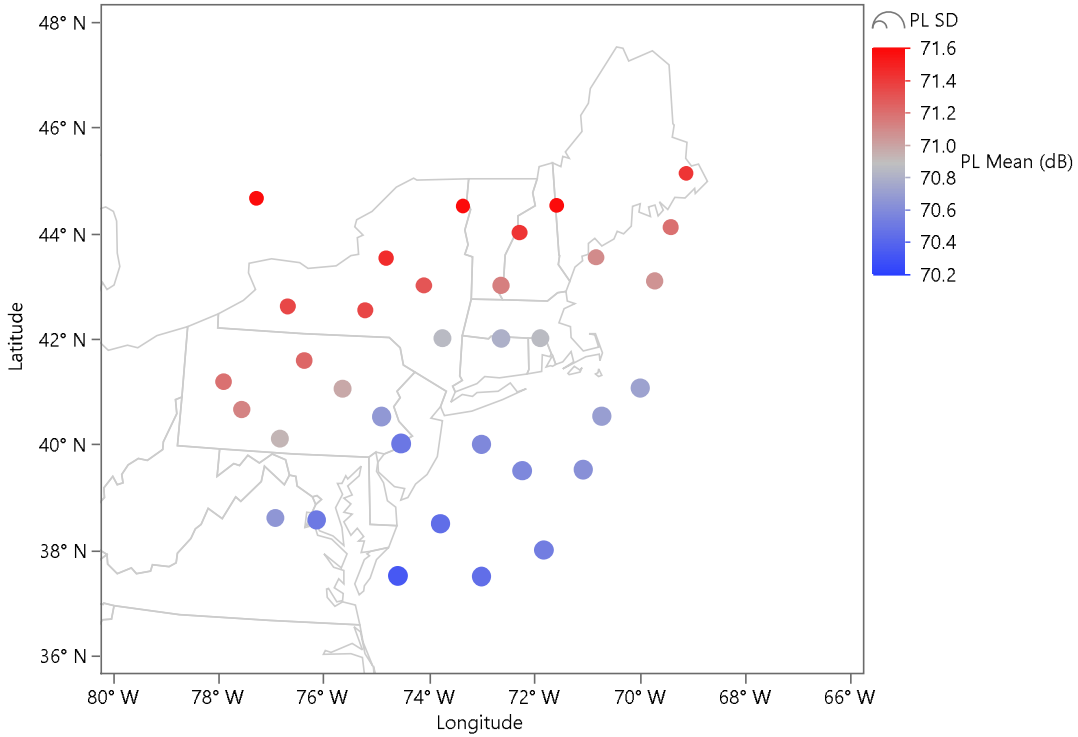


34 locations, 4 time per day
SD = 12.4 to 14.5

Mean across seasons and headings



10 locations, 1 time per day
SD = 2.7 to 3.2



34 locations, 4 time per day
SD = 2.8 to 3.1