Berkeley Earth Methodology

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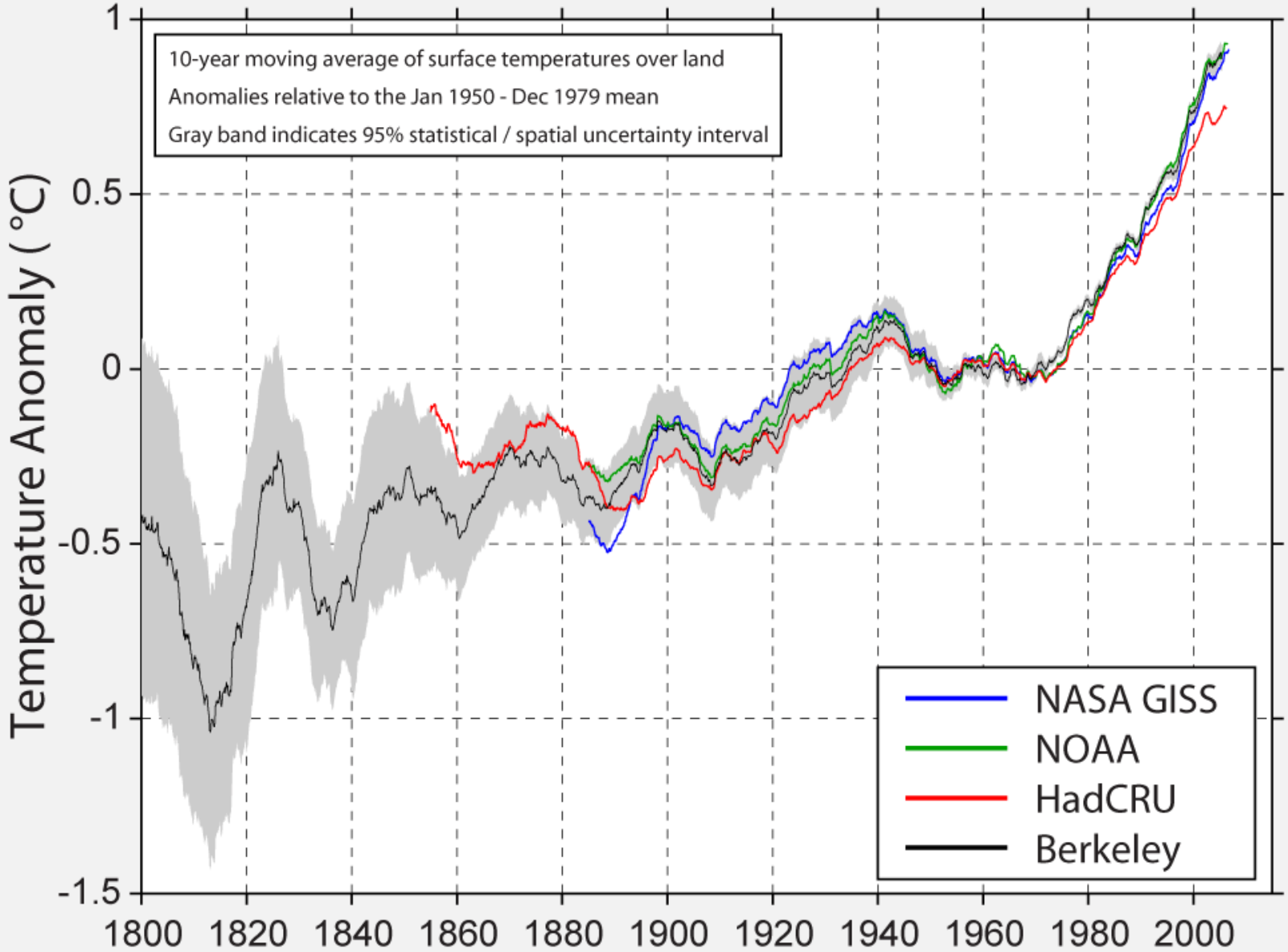
Decadal Land-Surface Average Temperature



Innovations

- More Data
- Using Kriging for spatial relationships
- “Scalpel” as a tool for bias handling
- Simultaneous baseline determination
- Integrated outlier and reliability assessment
- Top-down approach to uncertainty quantification

Database

Monthly

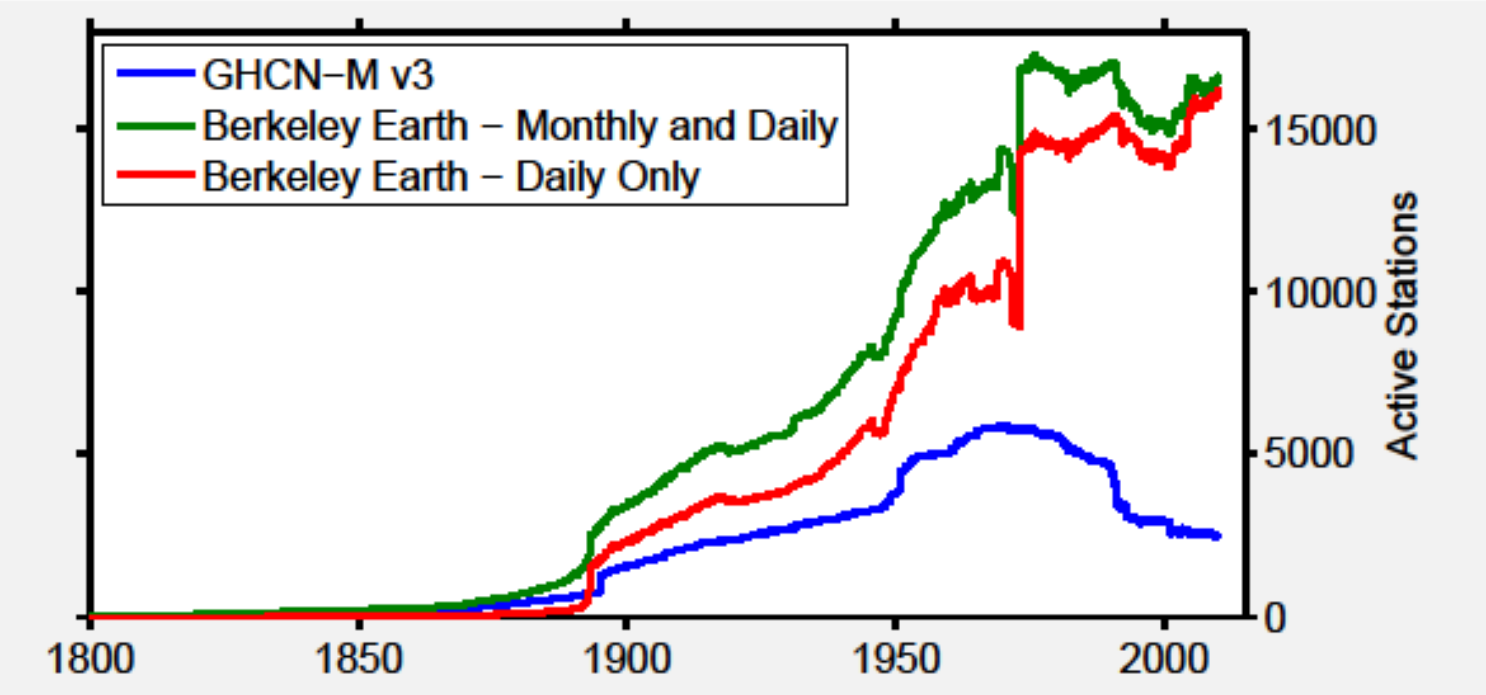
- Global Historical Climatology Network (GHCN 3)
- US Historical Climatology Network (USHCN)
- Monthly Climatic Data of the World (MCDW)
- World Monthly Surface Station Climatology (WMSSC)
- HadCRU Data Set Release (HadCRU)
- US Summary of the Month (USSOM)
- Scientific Committee on Antarctic Research (SCAR)
- GSN Monthly Archive (GSNMON)
- GCOS monthly summaries created by DWD (GCOS)
- World Weather Records (WWR)
- Colonial Era Weather Archive (CE)

Daily

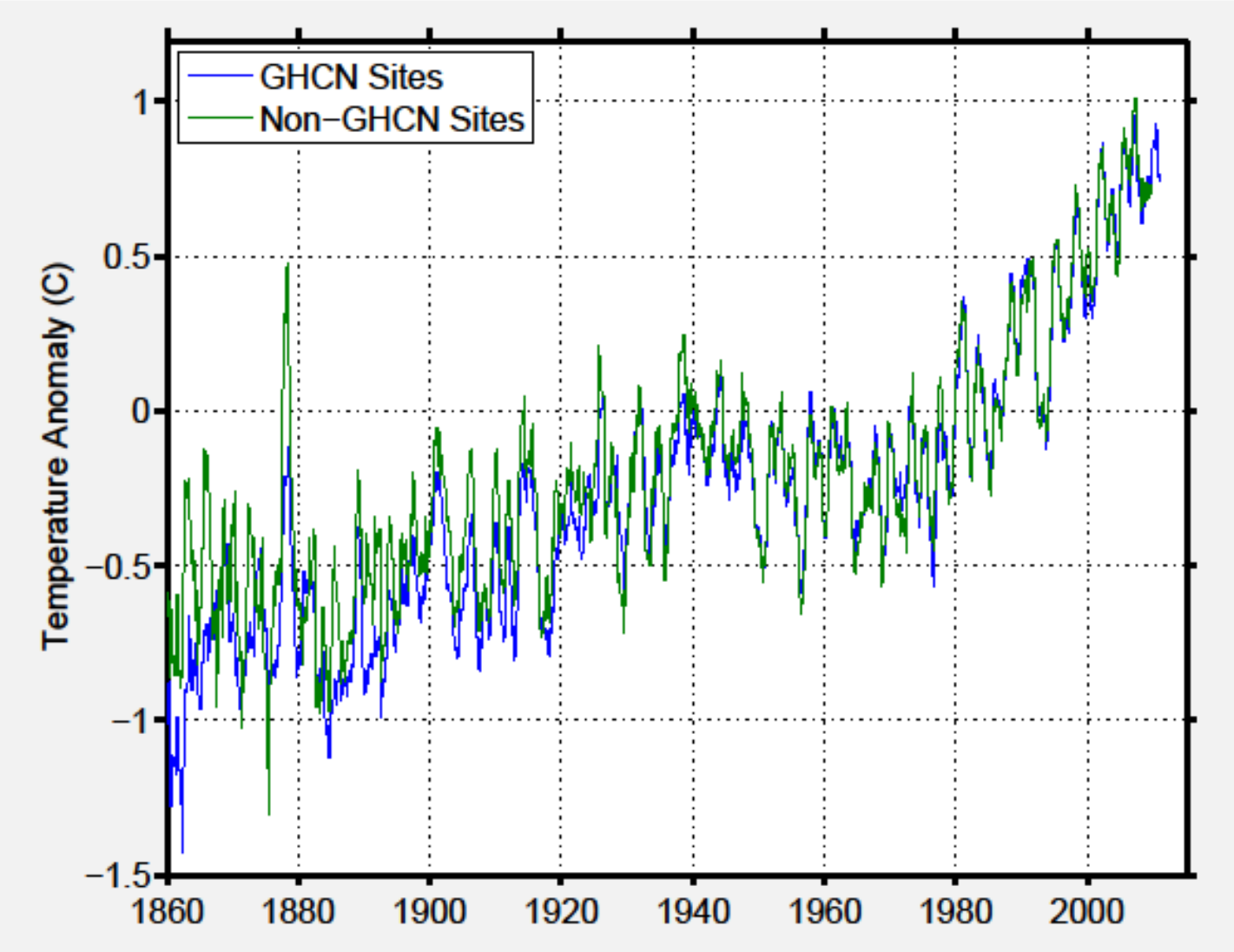
- GHCN - Daily (GHCN-D)
- US Cooperative Summary of the Day (USSOD-C)
- US First Order Summary of the Day (USSOD-FO)
- Global Summary of the Day (GSOD)

Database

Dataset	Berkeley Earth	GHCN-M v3
Number of Stations	39,028	7,280
Monthly Observations	14,786,160	5,150,496
Median Record Length	25.8 Years	58.5 Years



Analysis of GHCN to Non-GHCN sites separately



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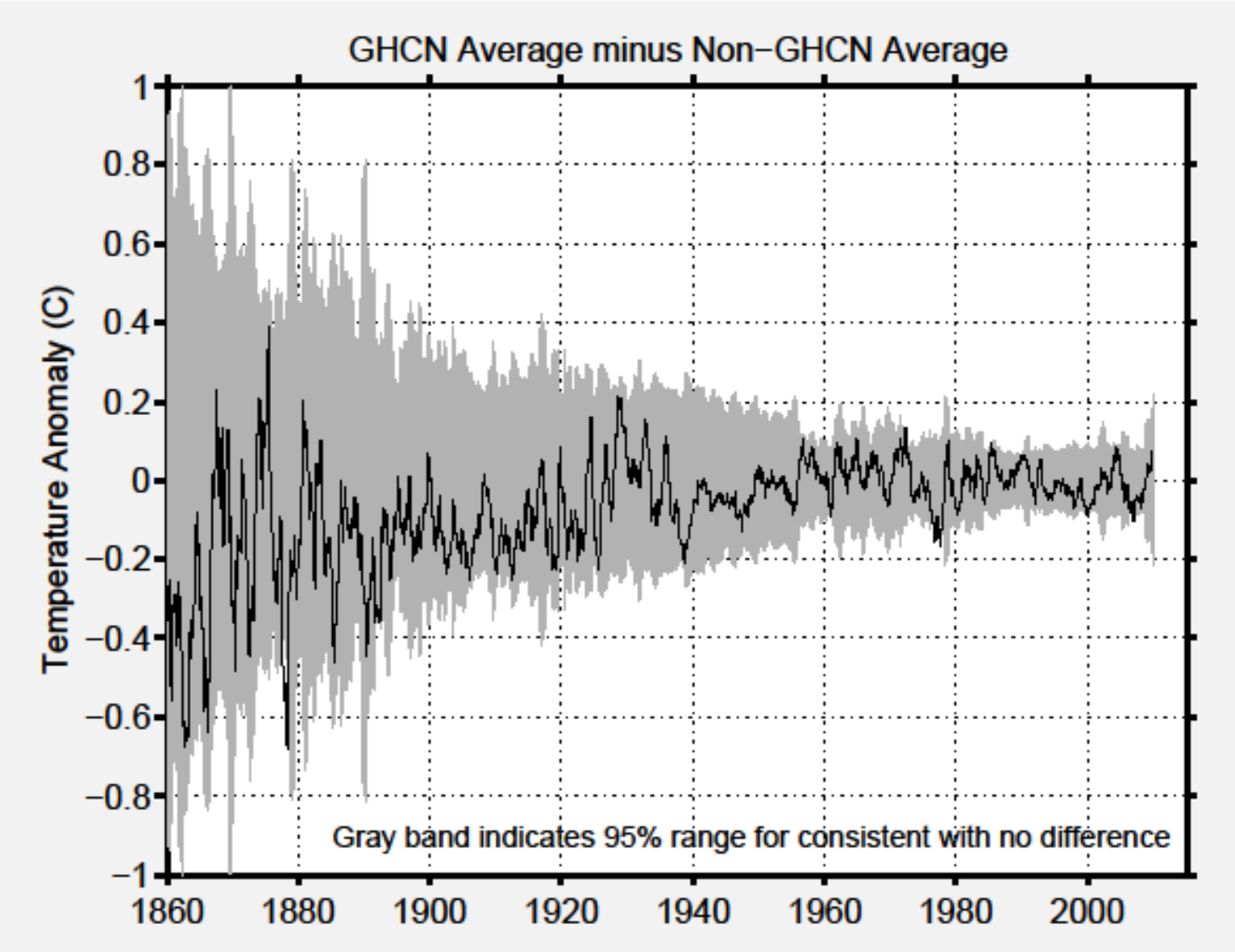
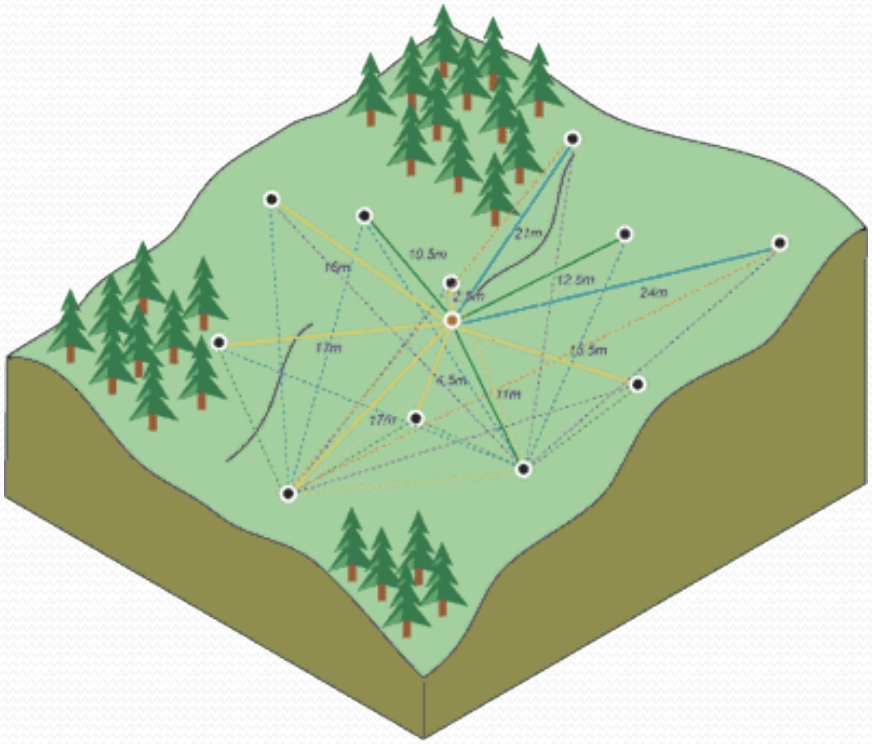


Spatial Interpolation (Kriging)

- Can create an interpolated field everywhere based on discrete measurements
- Best linear unbiased estimator is known as Kriging

$$\widehat{M}(\vec{x}) = \sum_{i=1}^{N} K_i(\vec{x})\, M_i$$



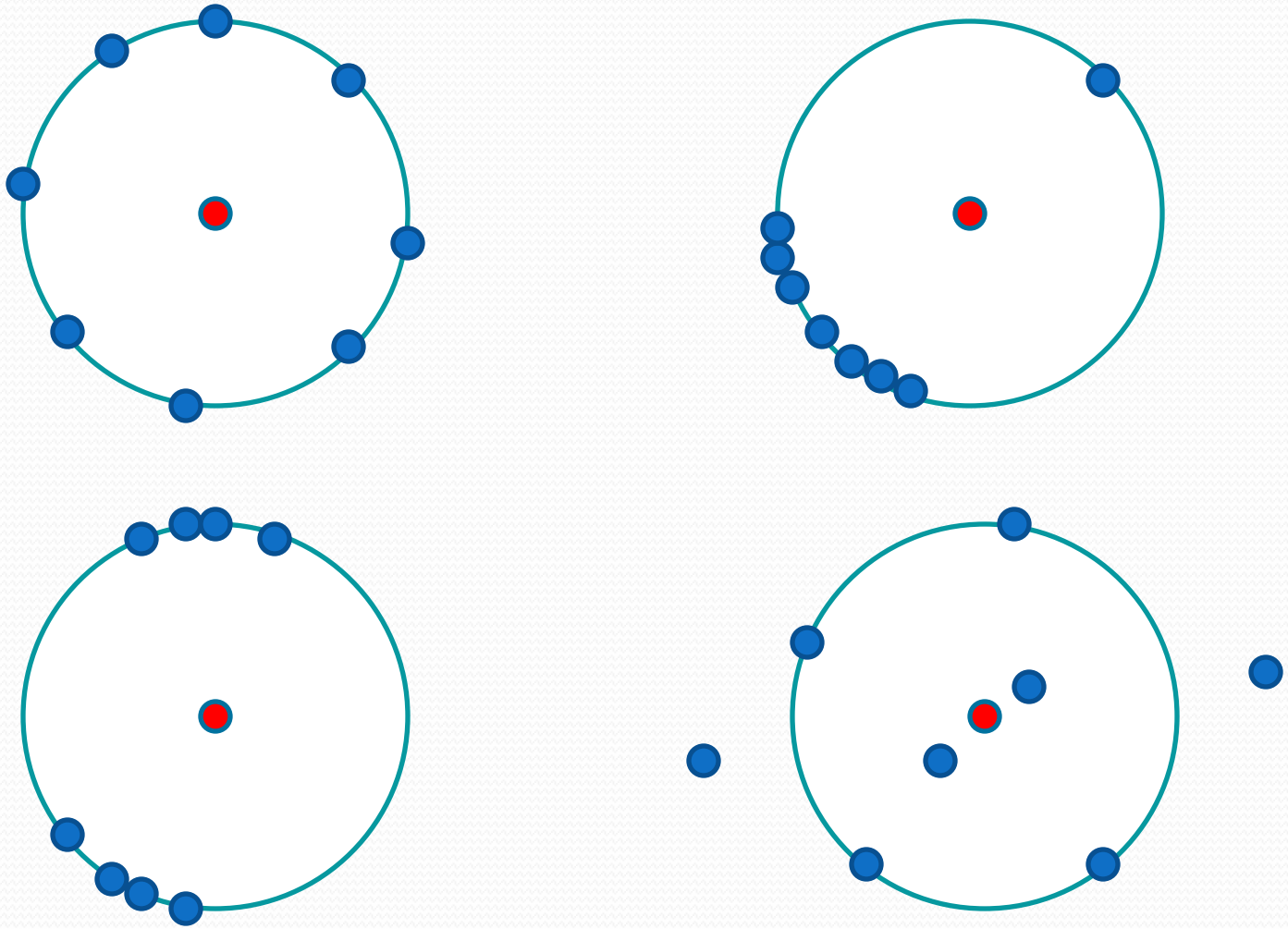
Uses Correlation Information

$$\widehat{M}(\vec{x}) = \sum_{i=1}^{N} K_i(\vec{x})\, M_i$$

$$\begin{pmatrix} K_1(\vec{x}) \\ \vdots \\ K_N(\vec{x}) \end{pmatrix} = \begin{pmatrix} \sigma_1^2 & \mathrm{Cov}(\vec{x}_1,\vec{x}_2) & \cdots & \mathrm{Cov}(\vec{x}_1,\vec{x}_N) \\ \mathrm{Cov}(\vec{x}_2,\vec{x}_1) & \sigma_2^2 & & \mathrm{Cov}(\vec{x}_2,\vec{x}_N) \\ \vdots & & \ddots & \vdots \\ \mathrm{Cov}(\vec{x}_N,\vec{x}_1) & \mathrm{Cov}(\vec{x}_N,\vec{x}_2) & \cdots & \sigma_N^2 \end{pmatrix}^{-1} \begin{pmatrix} \mathrm{Cov}(\vec{x},\vec{x}_1) \\ \vdots \\ \mathrm{Cov}(\vec{x},\vec{x}_N) \end{pmatrix}$$

$$\approx \begin{pmatrix} 1 & \mathrm{R}(\vec{x}_1,\vec{x}_2) & \cdots & \mathrm{R}(\vec{x}_1,\vec{x}_N) \\ \mathrm{R}(\vec{x}_2,\vec{x}_1) & 1 & & \mathrm{R}(\vec{x}_2,\vec{x}_N) \\ \vdots & & \ddots & \vdots \\ \mathrm{R}(\vec{x}_N,\vec{x}_1) & \mathrm{R}(\vec{x}_N,\vec{x}_2) & \cdots & 1 \end{pmatrix}^{-1} \begin{pmatrix} \mathrm{R}(\vec{x},\vec{x}_1) \\ \vdots \\ \mathrm{R}(\vec{x},\vec{x}_N) \end{pmatrix}$$

Kriging captures spatial relationships



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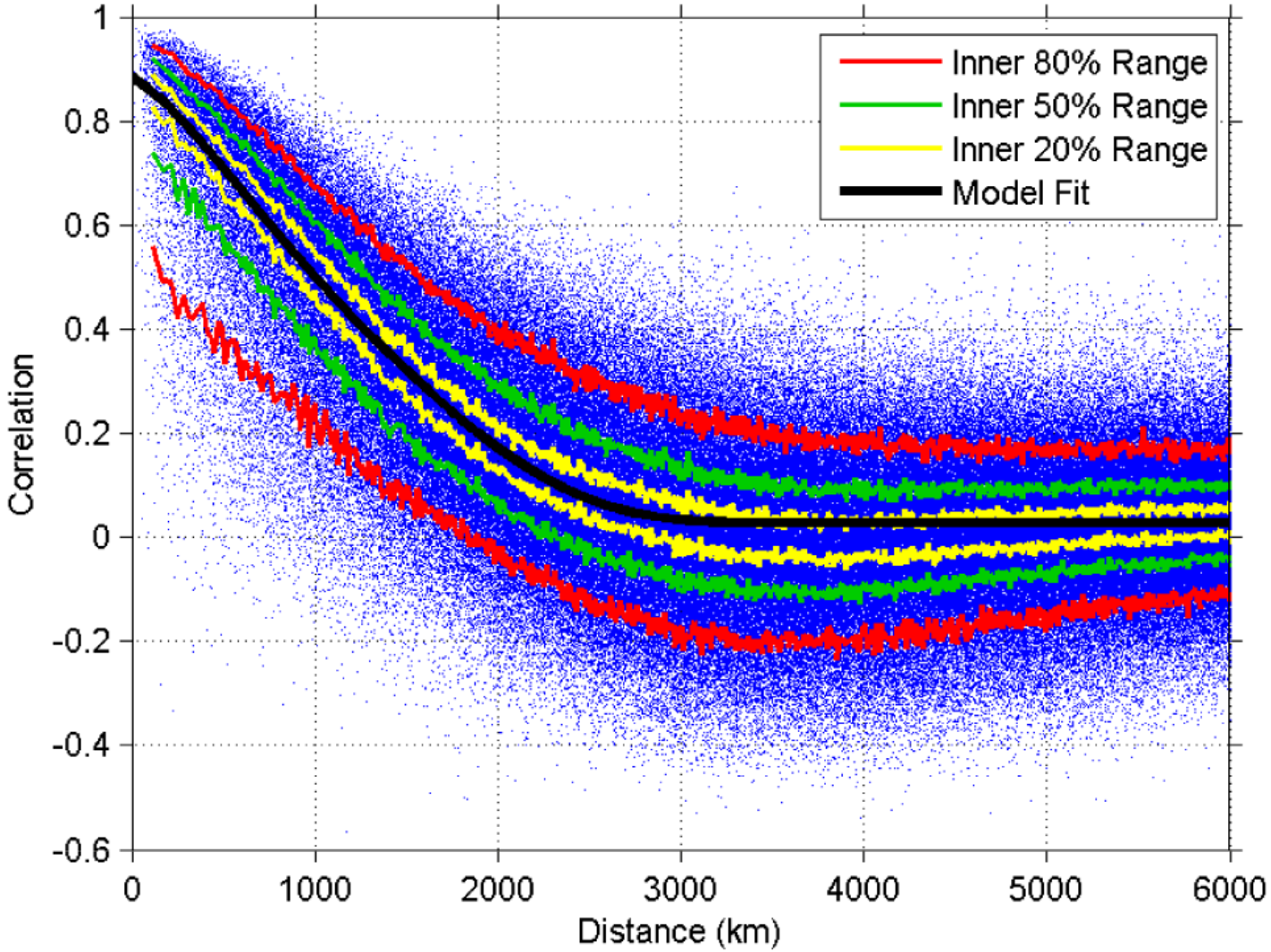
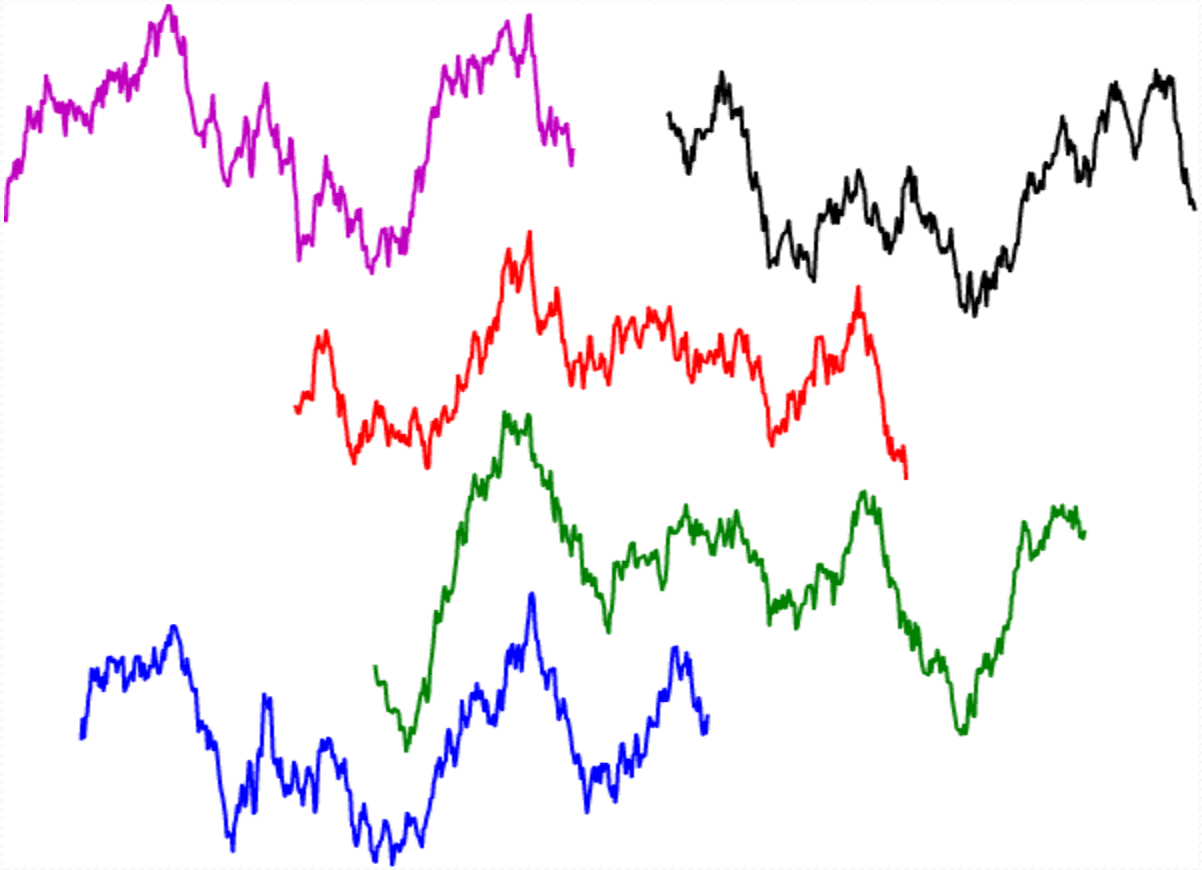


500,000 pairwise comparisons

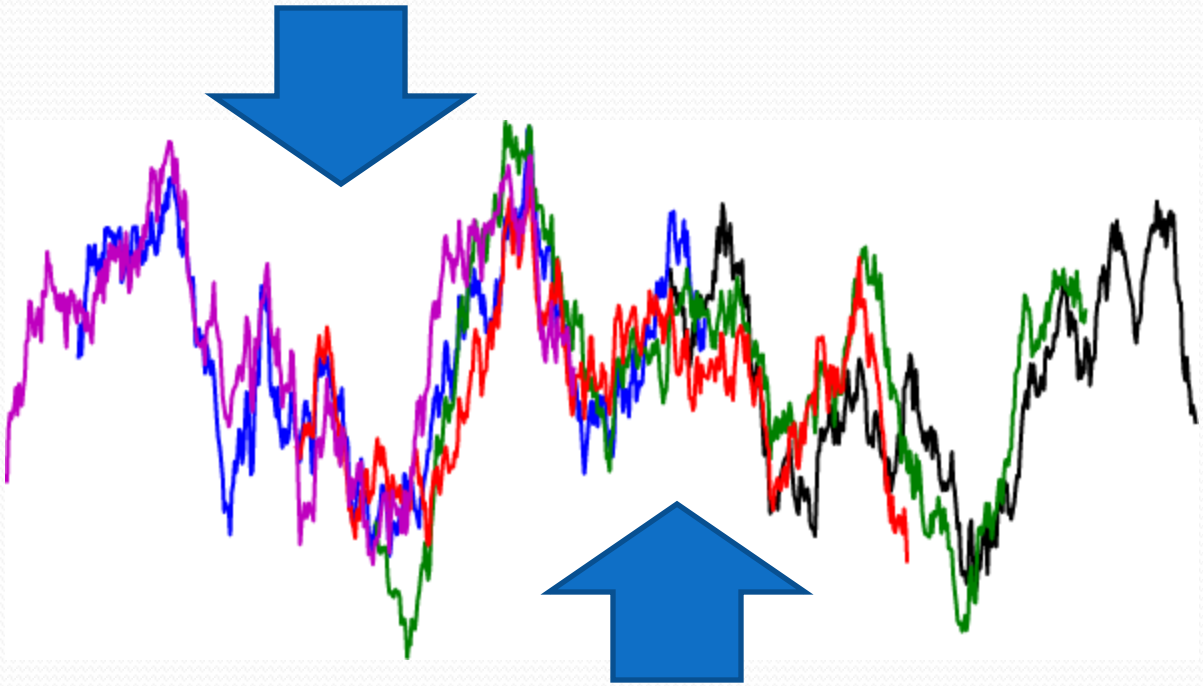
Assembling the Record

Local factors such as latitude and elevation have a very large effect on the mean climate at each site



Assembling the Record

Local factors such as latitude and elevation have a very large effect on the mean climate at each site. In order to detect common long-term behavior we need to compensate for these effects.



The “Scalpel”

- Rather than “correcting” bias shifts, our default position is to split the record into multiple pieces at each inhomogeneity.
- These fragments are assembled along with all other data in the normal way, and that assembly determines the relative alignments.

Reasons for Breaks

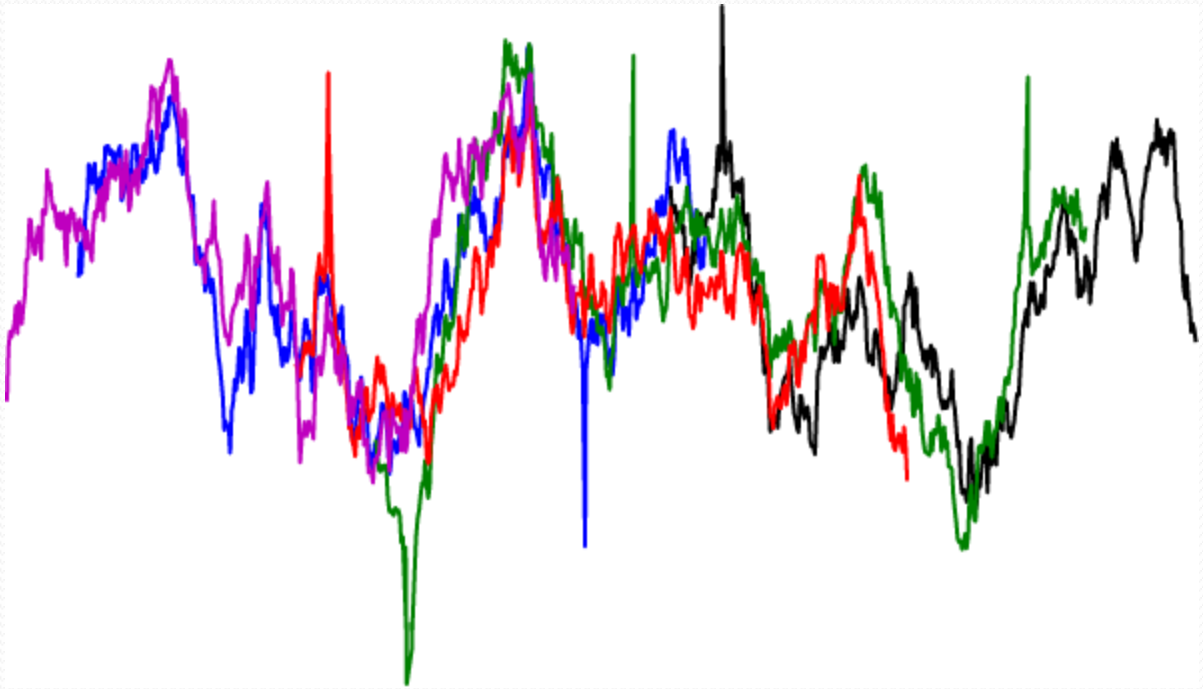
- Record gaps (> 1 year)
- Station Moves
- Station Time of Observation Changes
- Apparent changes in baseline greater than 4 standard deviations (as compared with local neighbors)

Scalpel Results

- One empirical break for every ~12 years of record on average
- After scalpel the mean record fragment is about 7.1 years (median: 5.1 years)
- Whole analysis process was designed to work with small pieces.

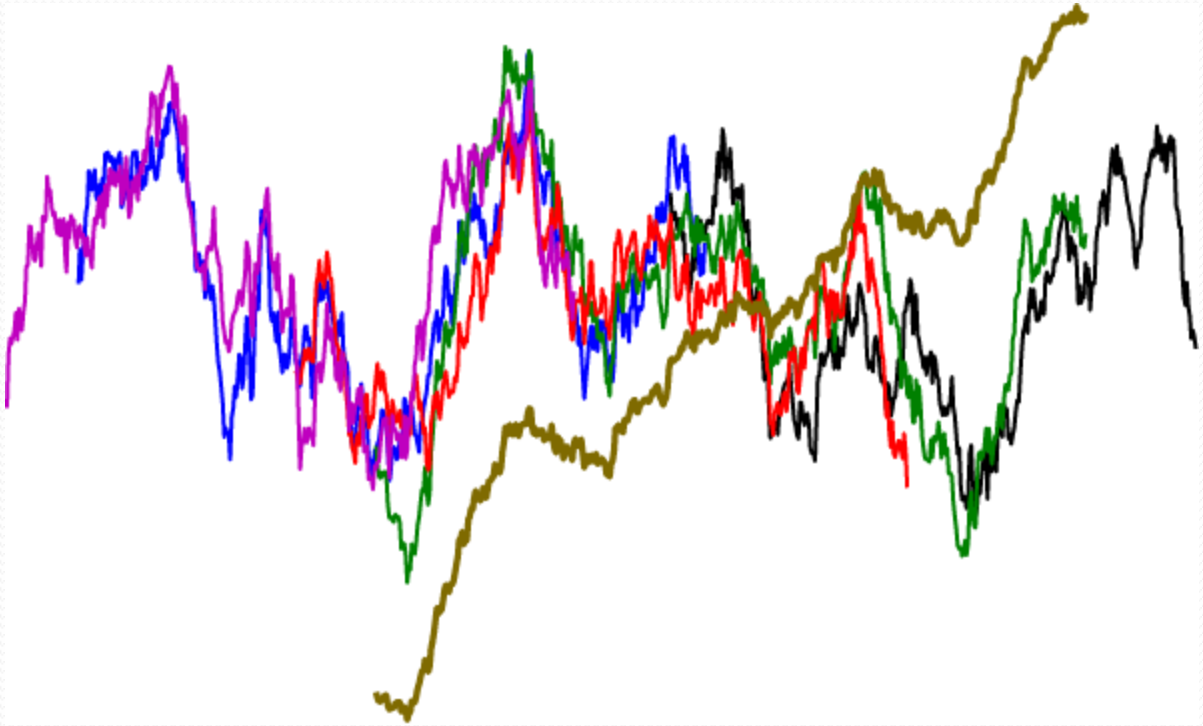
Integrated Outlier / Reliability Assessment

- Local outlier points are deweighted via an iterative process



Integrated Outlier / Reliability Assessment

- Highly anomalous series are also deweighted

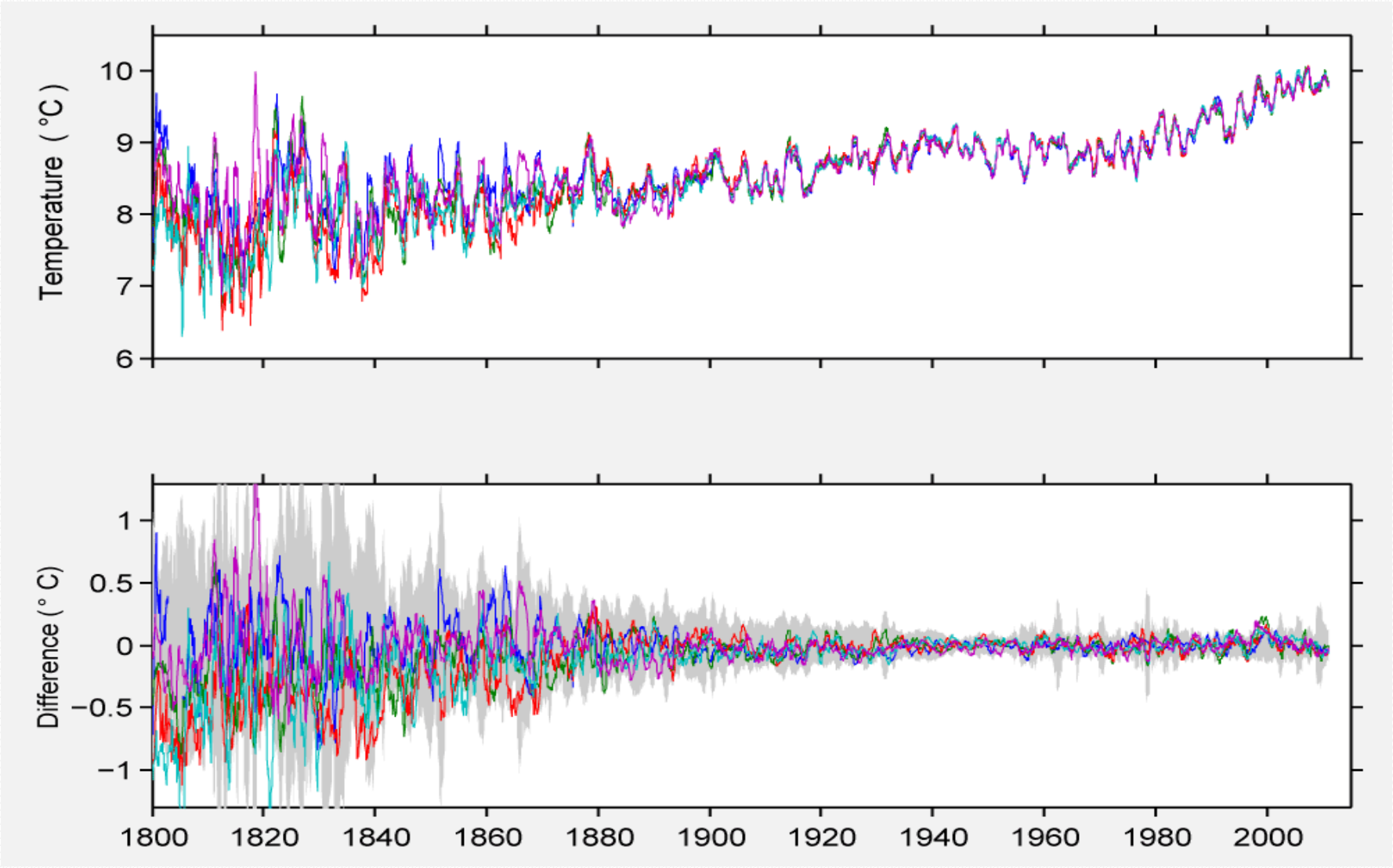


Top-down Assessment of Uncertainty

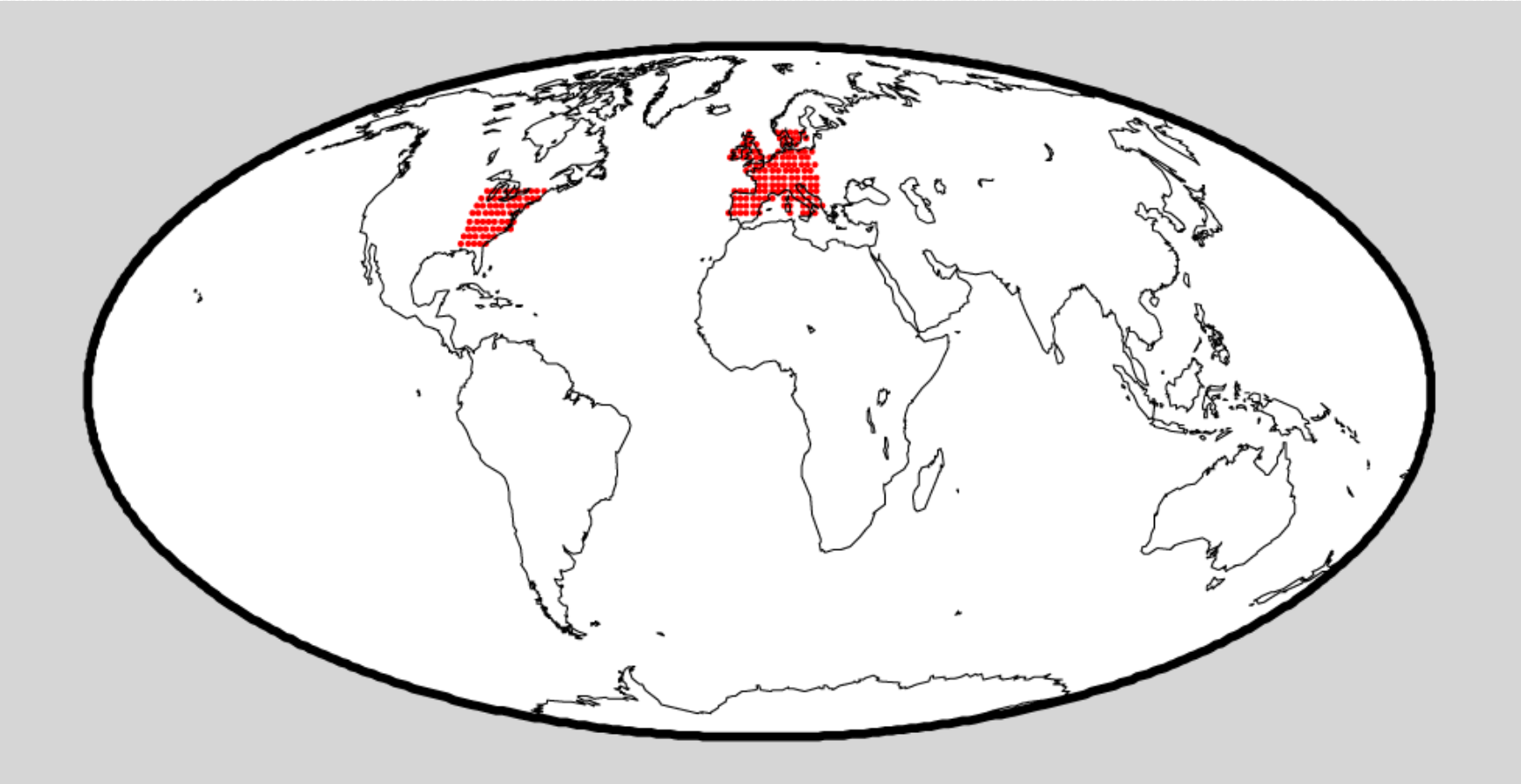
- Rather than assigning an error bar to each datum and each analysis step, we measure the statistical consistency of the data and the spatial completeness.

- How much would the result change if some data were excluded?
- How much uncertainty occurs because some regions aren't sampled?
- Look at impact of other possible biases (Urban Heating, Station Quality, …)?

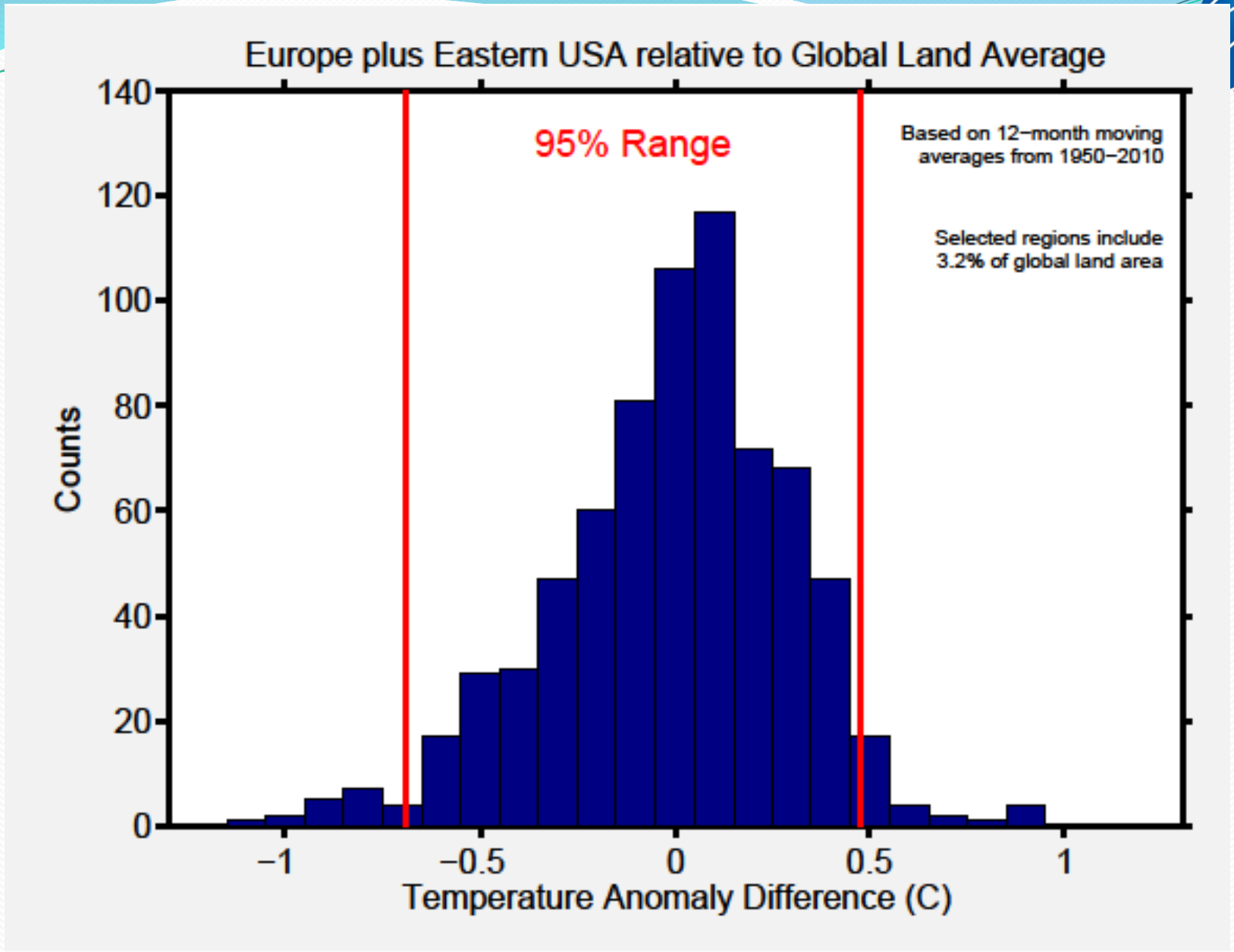
Five Independent 20% Samples



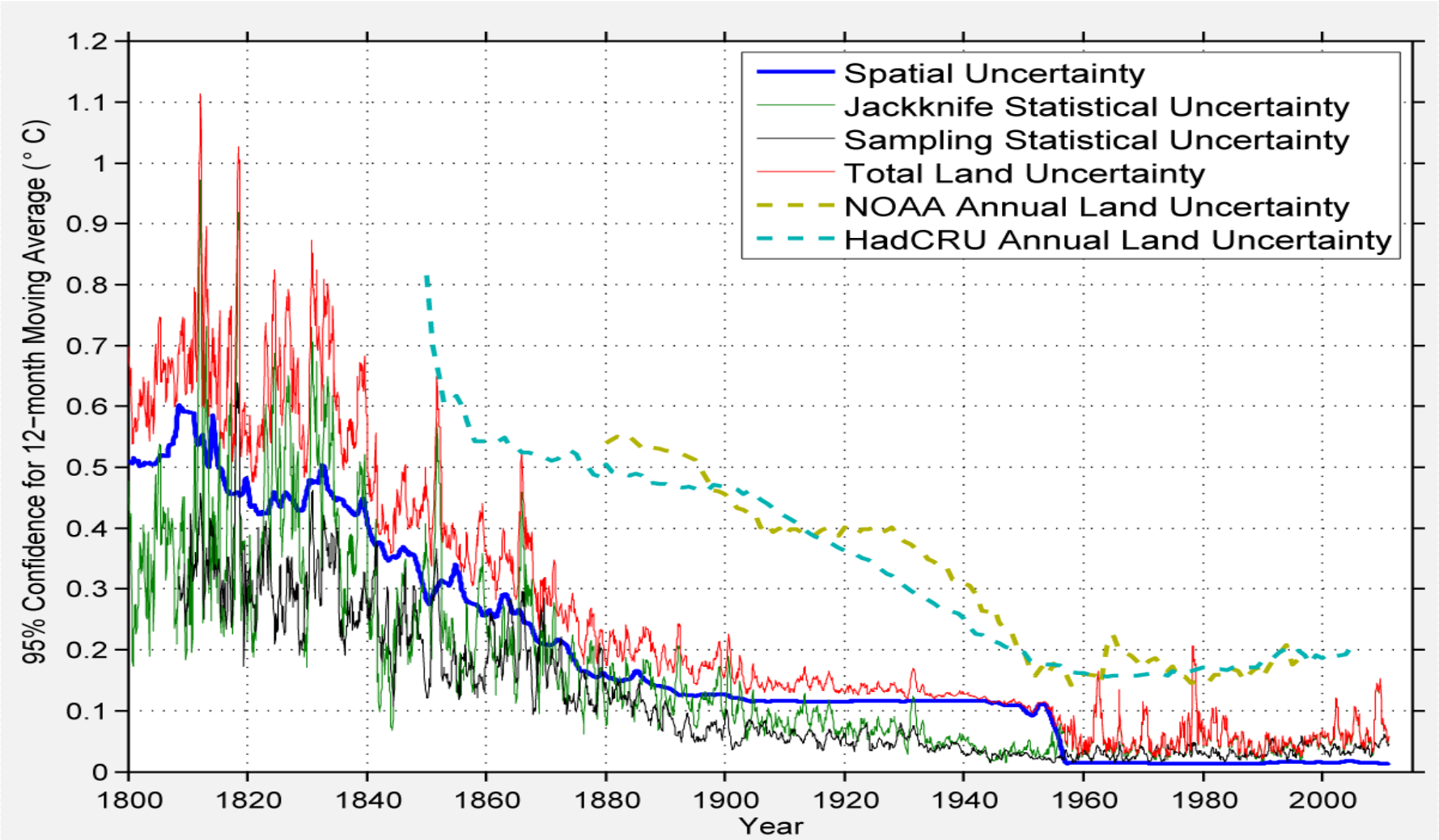
Spatial Incompleteness



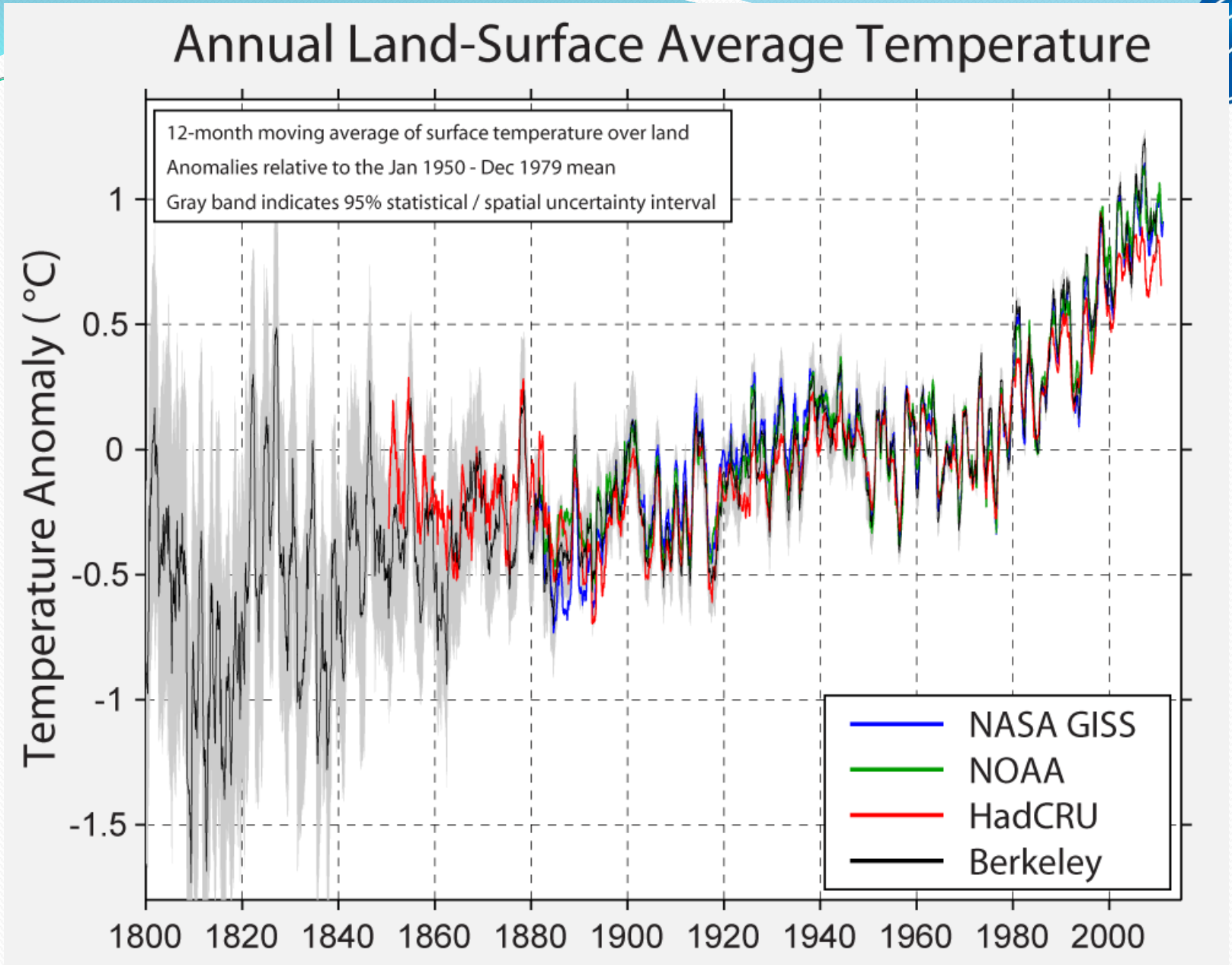
3.2% of Land Surface Highlighted


Europe plus Eastern USA relative to Global Land Average
95% Range
Based on 12−month moving averages from 1950−2010
Selected regions include 3.2% of global land area
Counts
140
120
100
80
60
40
20
0
−1
−0.5
0
0.5
1
Temperature Anomaly Difference (C)

Comparison to Prior Uncertainties



Based on Analysis of GHCN Data



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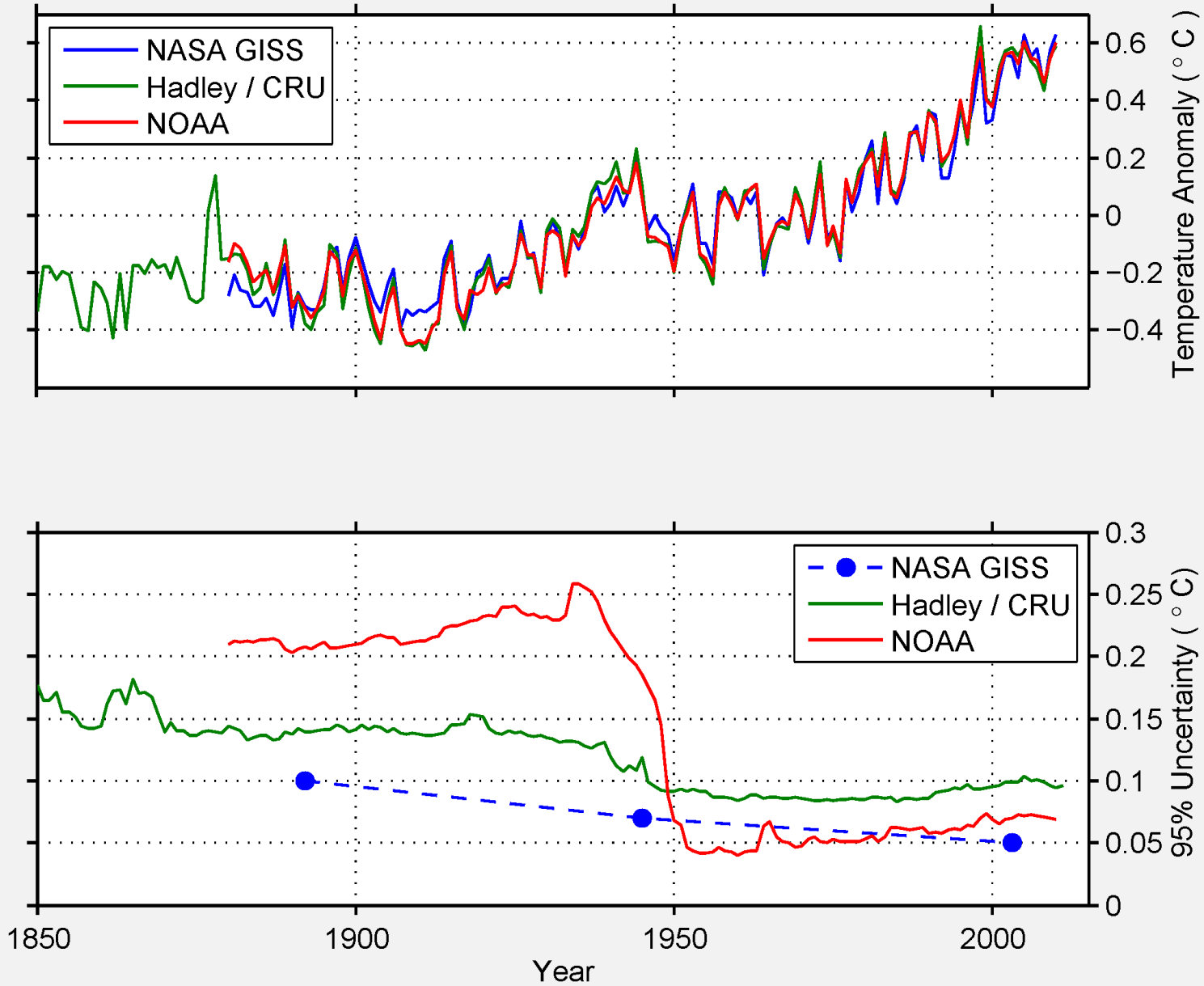
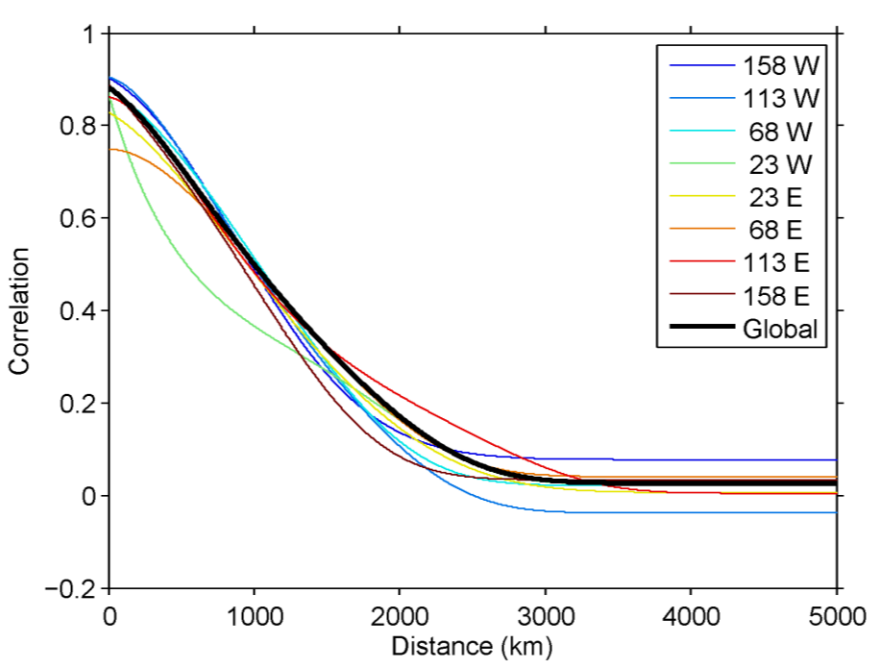
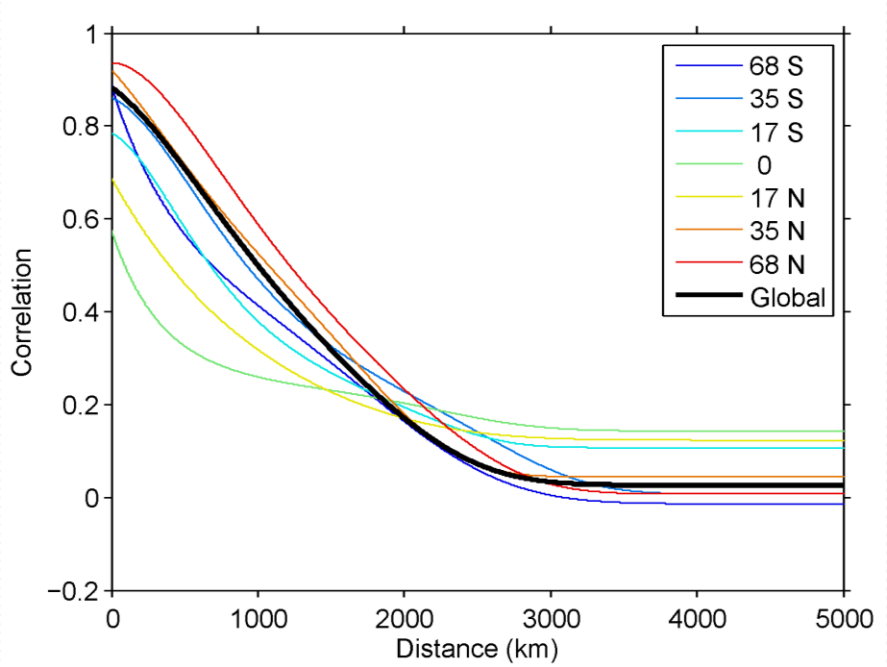
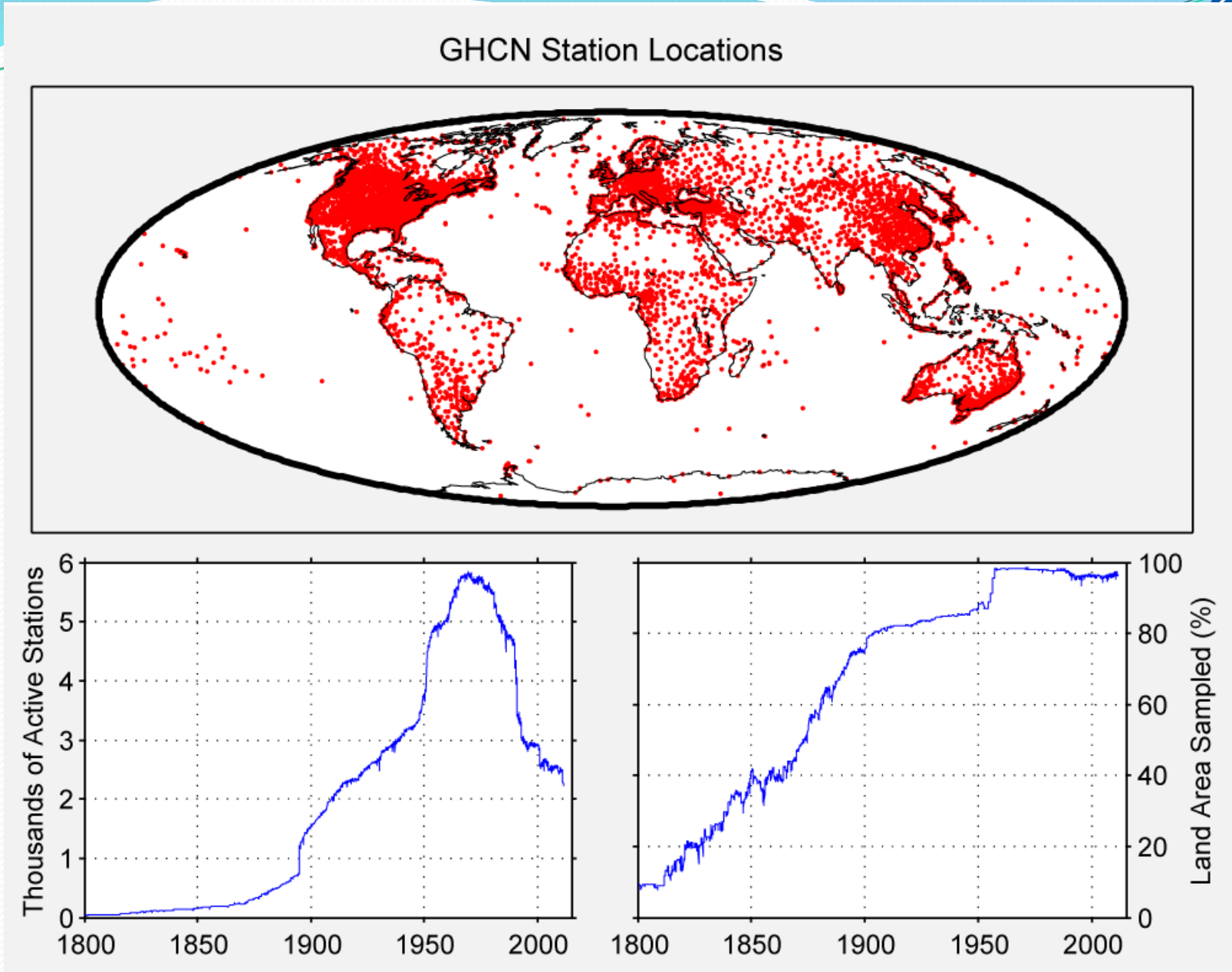
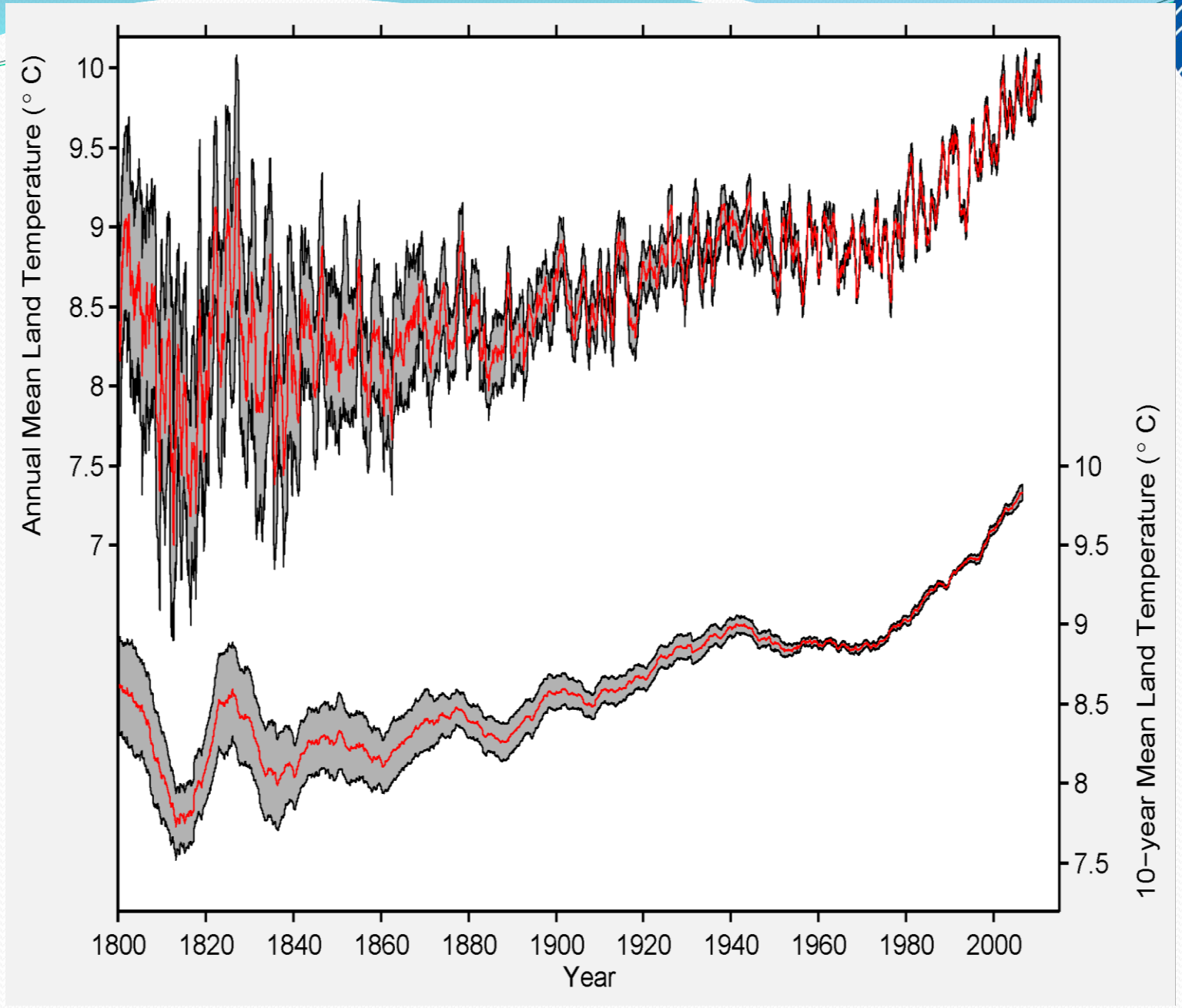
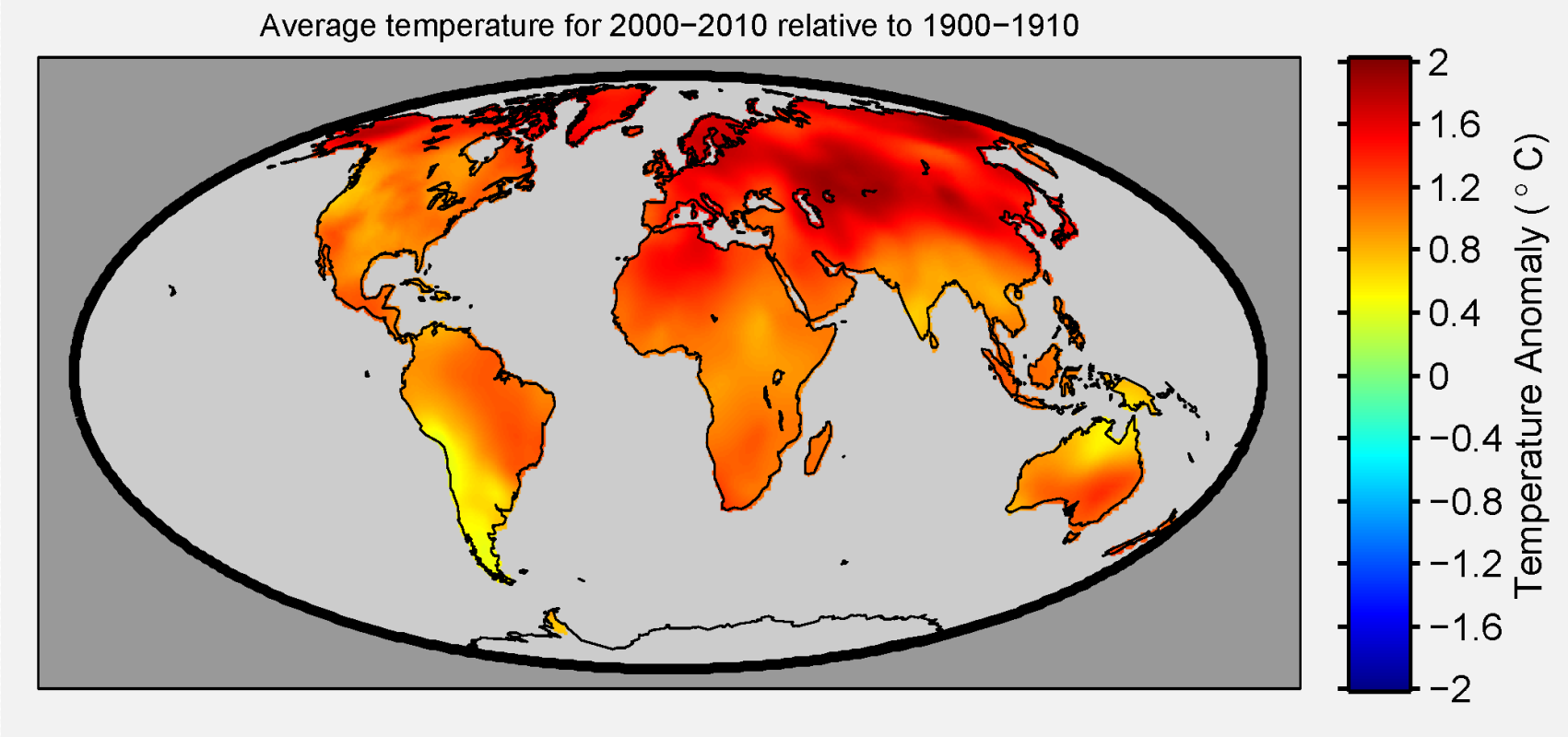

NASA GISS
Hadley / CRU
NOAA
0.6
0.4
0.2
0
−0.2
−0.4
Temperature Anomaly (° C)
NASA GISS
Hadley / CRU
NOAA
0.3
0.25
0.2
0.15
0.1
0.05
0
95% Uncertainty (° C)
1850
1900
1950
2000
Year

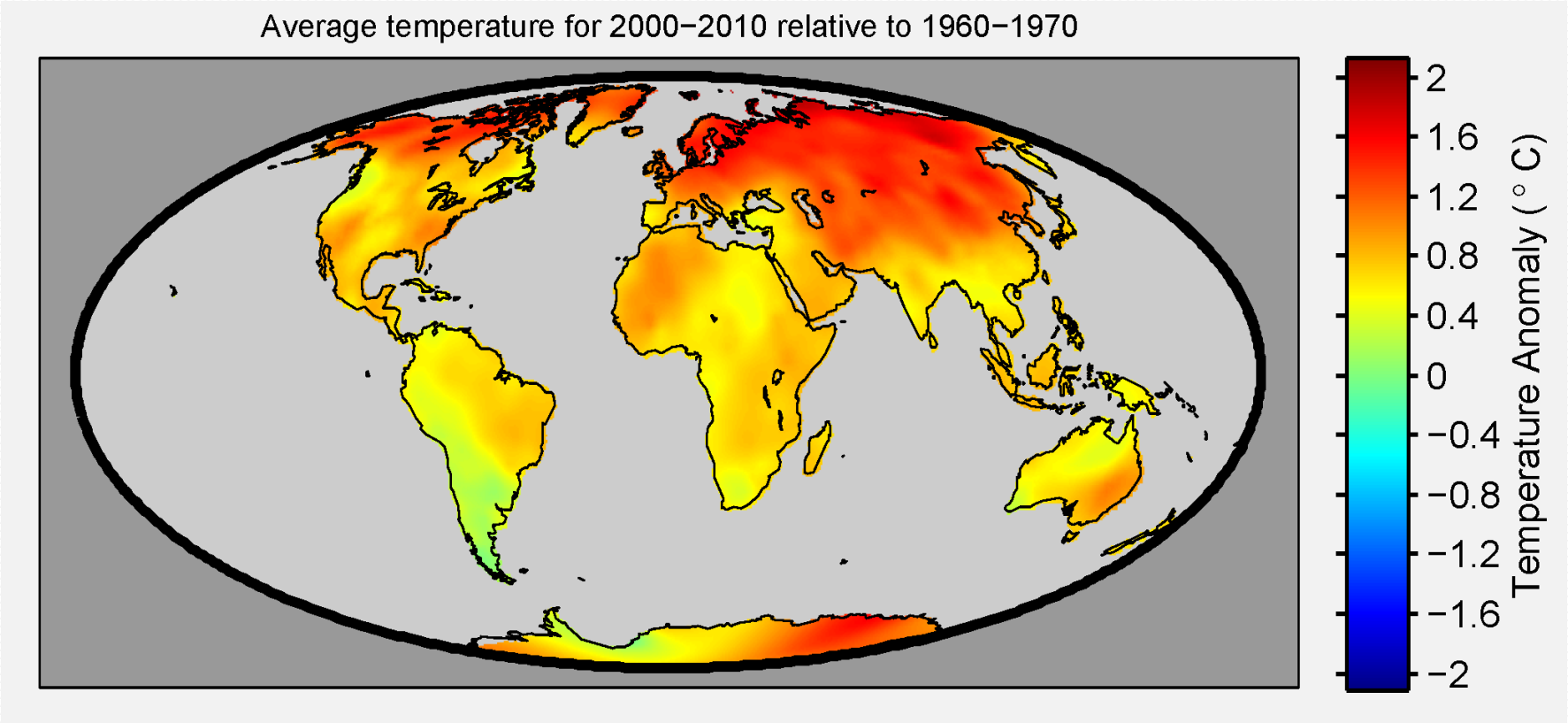

Correlation
Distance (km)
158 W
113 W
68 W
23 W
23 E
68 E
113 E
158 E
Global

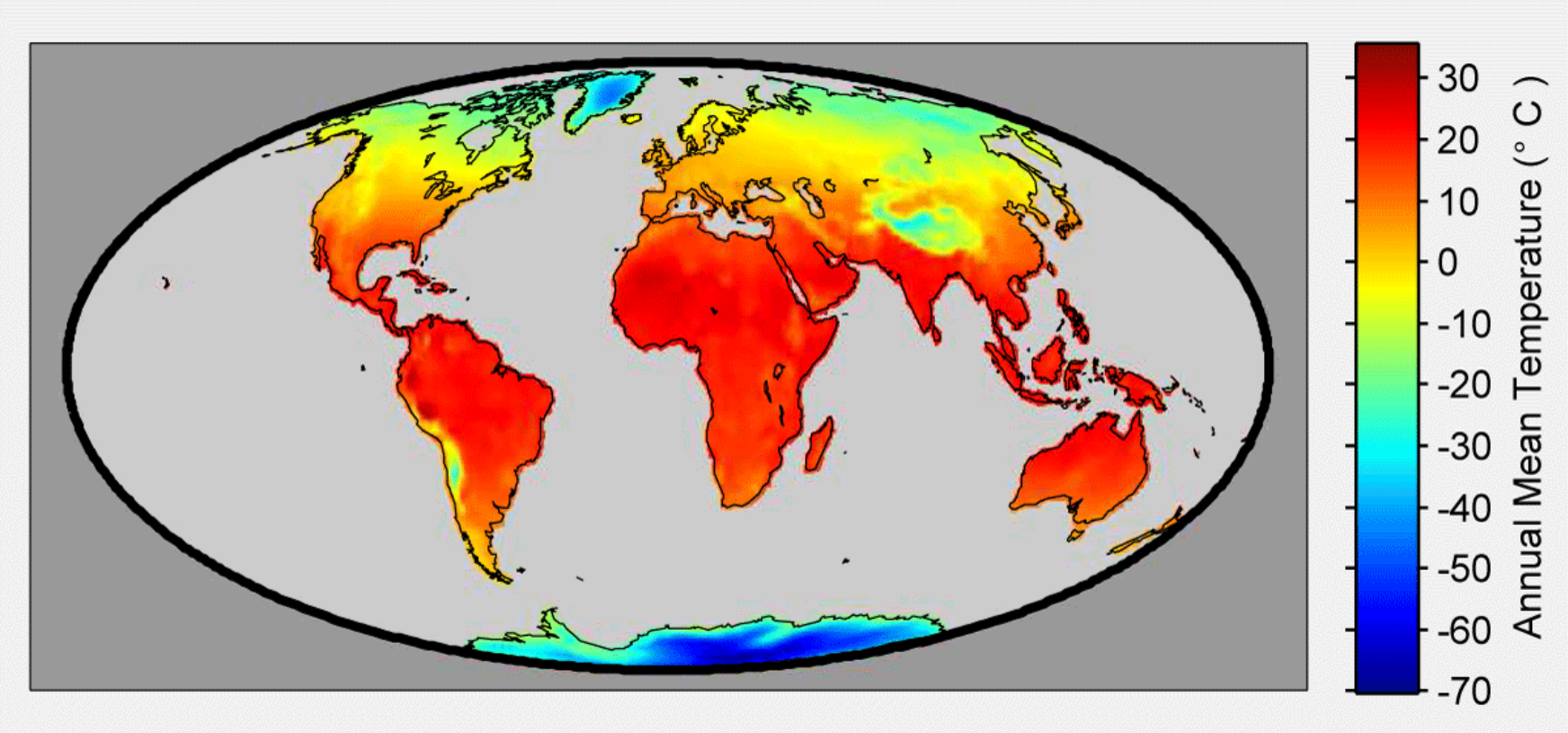

Correlation
Distance (km)
68 S
35 S
17 S
0
17 N
35 N
68 N
Global

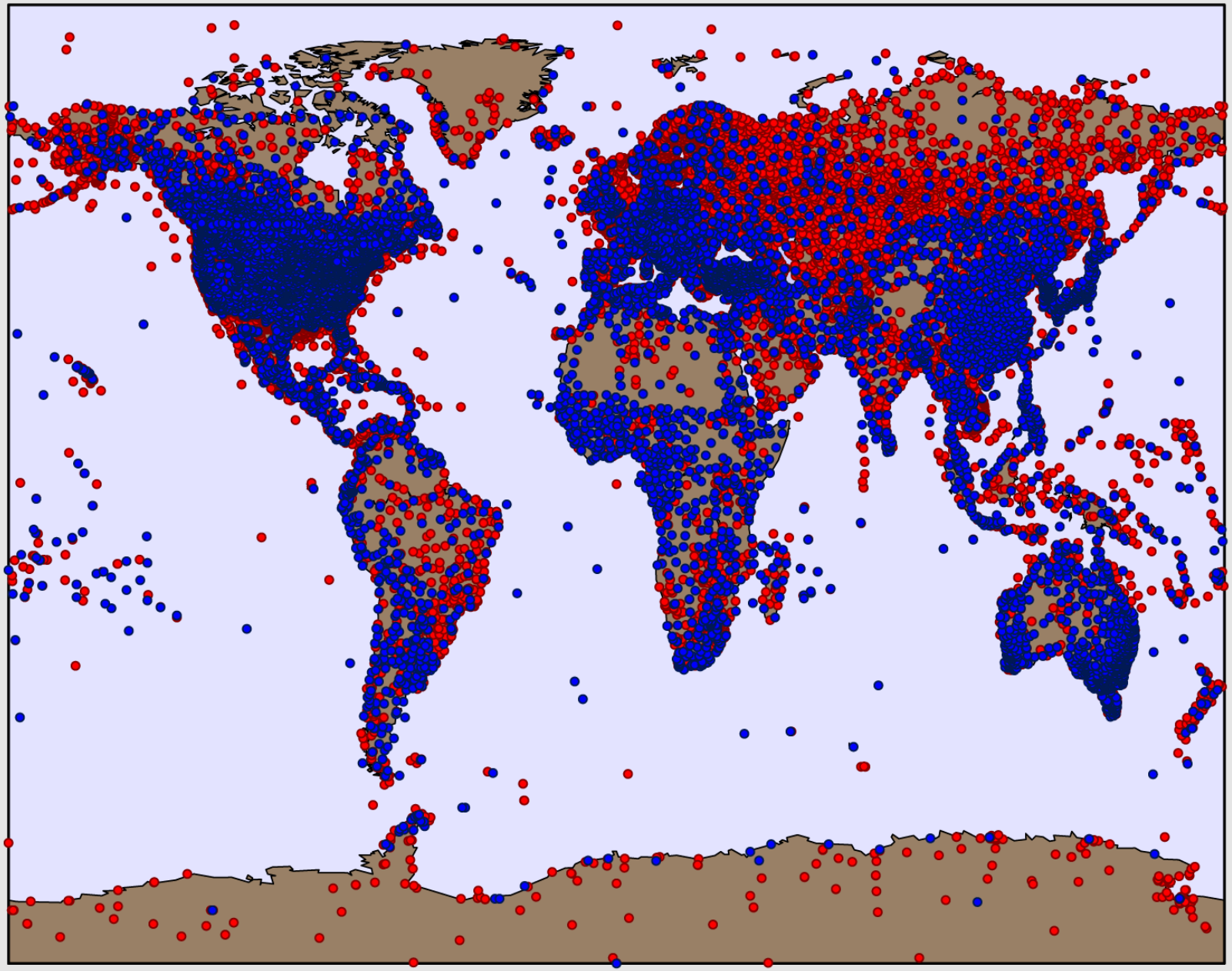

GHCN Station Locations
Thousands of Active Stations
0
1
2
3
4
5
6
1800
1850
1900
1950
2000
Land Area Sampled (%)
0
20
40
60
80
100
1800
1850
1900
1950
2000


Annual Mean Land Temperature (° C)
10
9.5
9
8.5
8
7.5
7
10−year Mean Land Temperature (° C)
10
9.5
9
8.5
8
7.5
1800
1820
1840
1860
1880
1900
1920
1940
1960
1980
2000
Year


Average temperature for 2000−2010 relative to 1900−1910
2
1.6
1.2
0.8
0.4
0
−0.4
−0.8
−1.2
−1.6
−2
Temperature Anomaly (° C)


Average temperature for 2000−2010 relative to 1960−1970
2
1.6
1.2
0.8
0.4
0
−0.4
−0.8
−1.2
−1.6
−2
Temperature Anomaly (° C)


30
20
10
0
-10
-20
-30
-40
-50
-60
-70
Annual Mean Temperature (° C)



Existing GHCN-M Stations (7,280; plotted in front)

Additional Berkeley Stations (32,110; plotted in back)

$$\hat{\theta}(t_j) + \hat{W}(\vec{x}, t_j) = \hat{\theta}(t_j) + \sum_i S_i(\vec{x}, t_j)\left(d_i(t_j) - \hat{b}_i - \hat{\theta}(t_j)\right)$$

$$= \left(1 - F(\vec{x}, t_j)\right)\hat{\theta}(t_j) + \sum_i S_i(\vec{x}, t_j)\left(d_i(t_j) - \hat{b}_i\right)$$

$$T(\vec{x},t) = \theta(t) + C(\vec{x}) + W(\vec{x},t)$$

$$\int_{\text{Earth's surface}} C(\vec{x})d\vec{x} = 0$$

$$\int_{\text{Earth's surface}} W(\vec{x},t)d\vec{x} = 0$$

$$\int_{\text{Earth's surface}} W(\vec{x},t)dt = 0$$

$$\widehat{W}(\vec{x}, t_j) = \sum_{i=1}^{N} S_{a_i}(\vec{x}, t_j)\left(d_{a_i}(t_j) - \hat{\theta}(t_j) - \hat{b}_{a_i}\right)$$