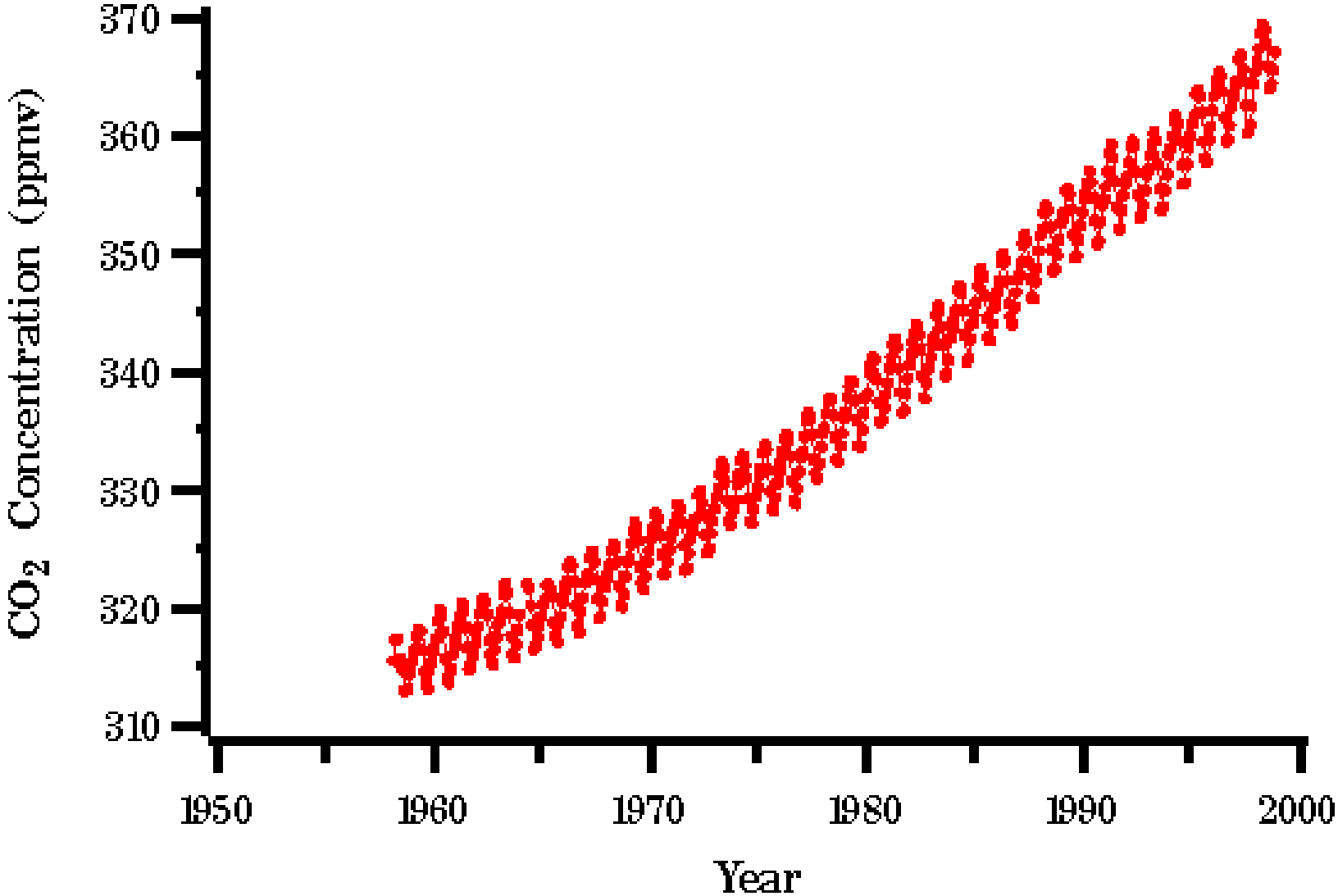
Spatial and Temporal Considerations for a Reference Network

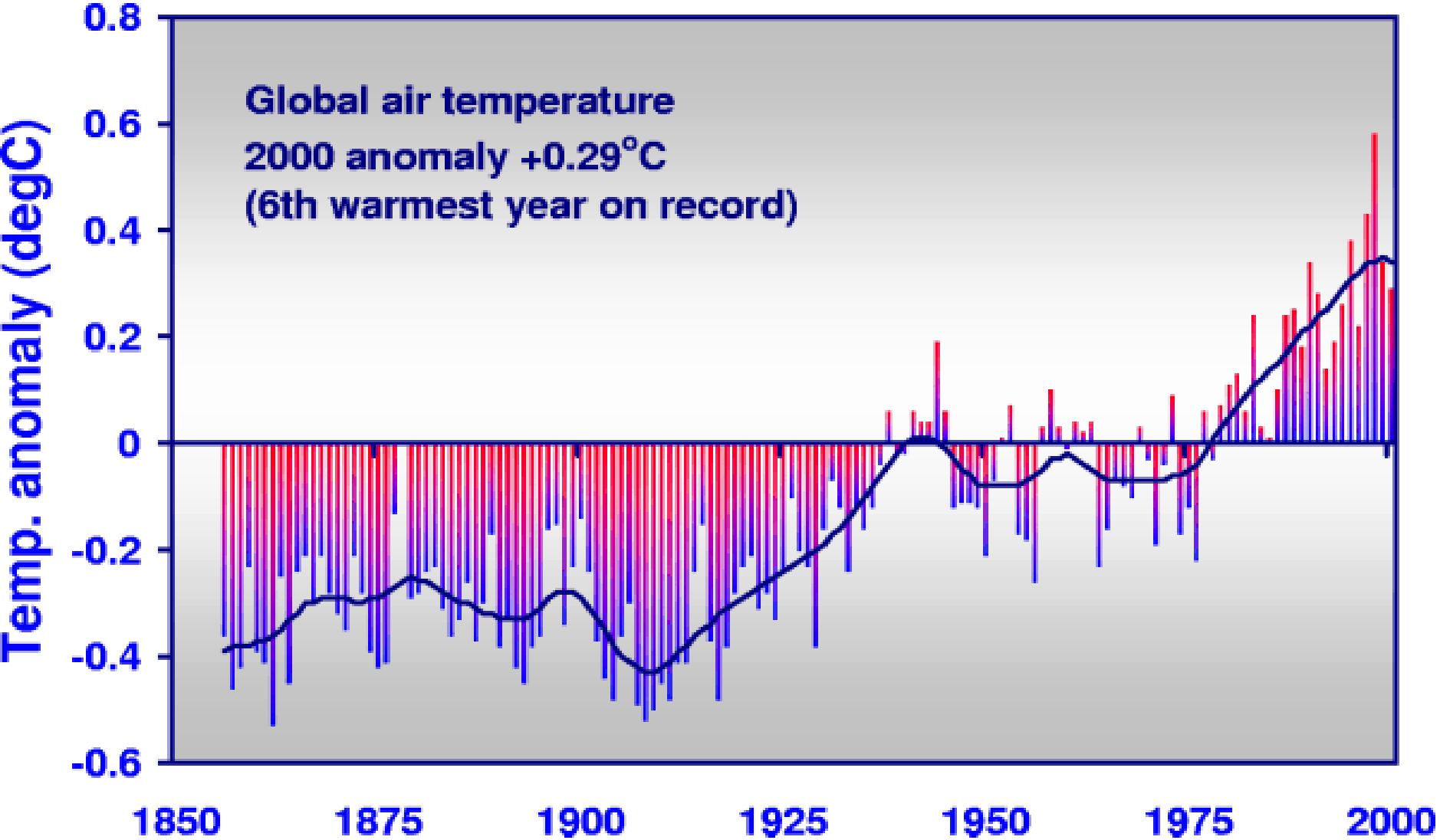
Betsy Weatherhead

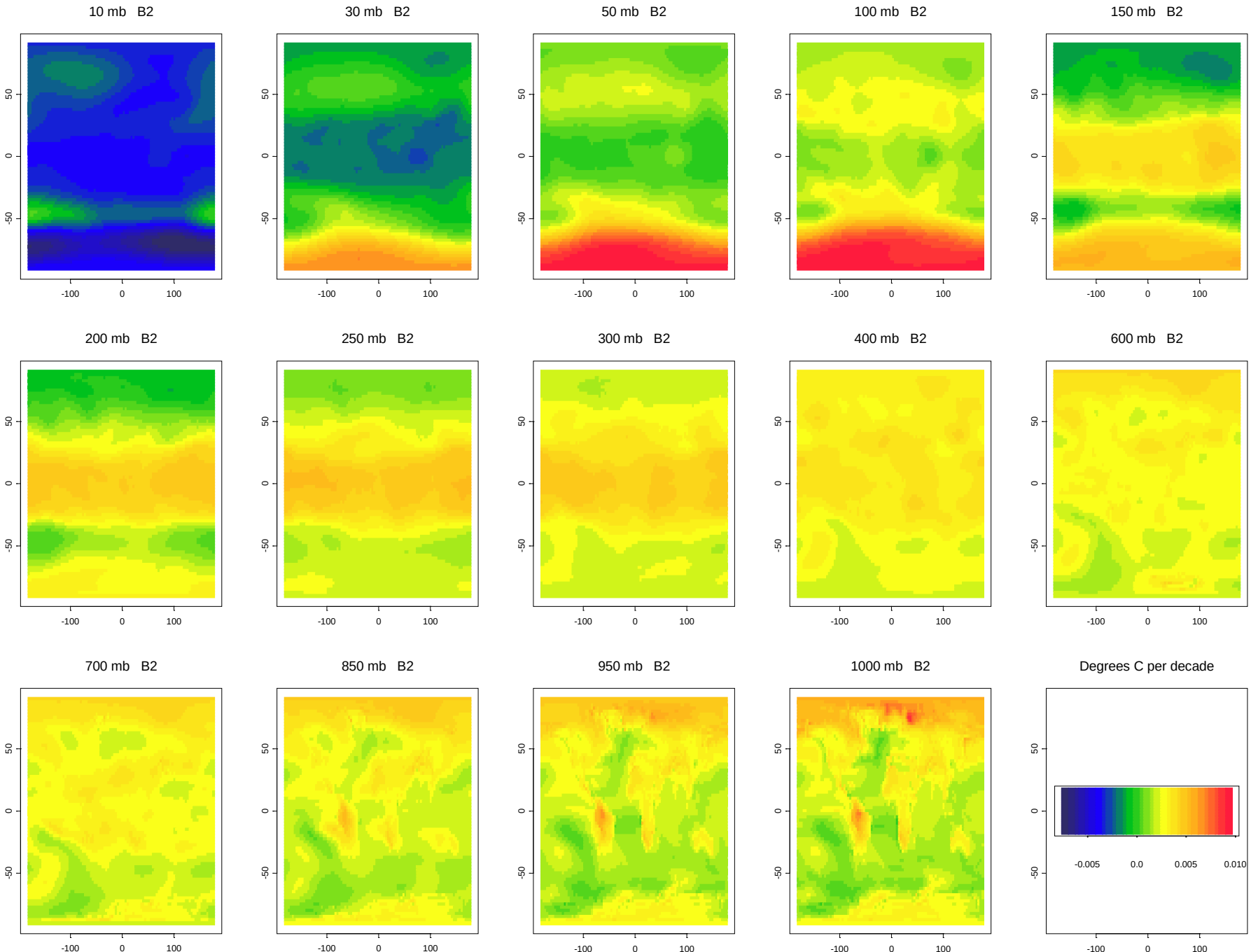
Mauna Loa, Hawaii



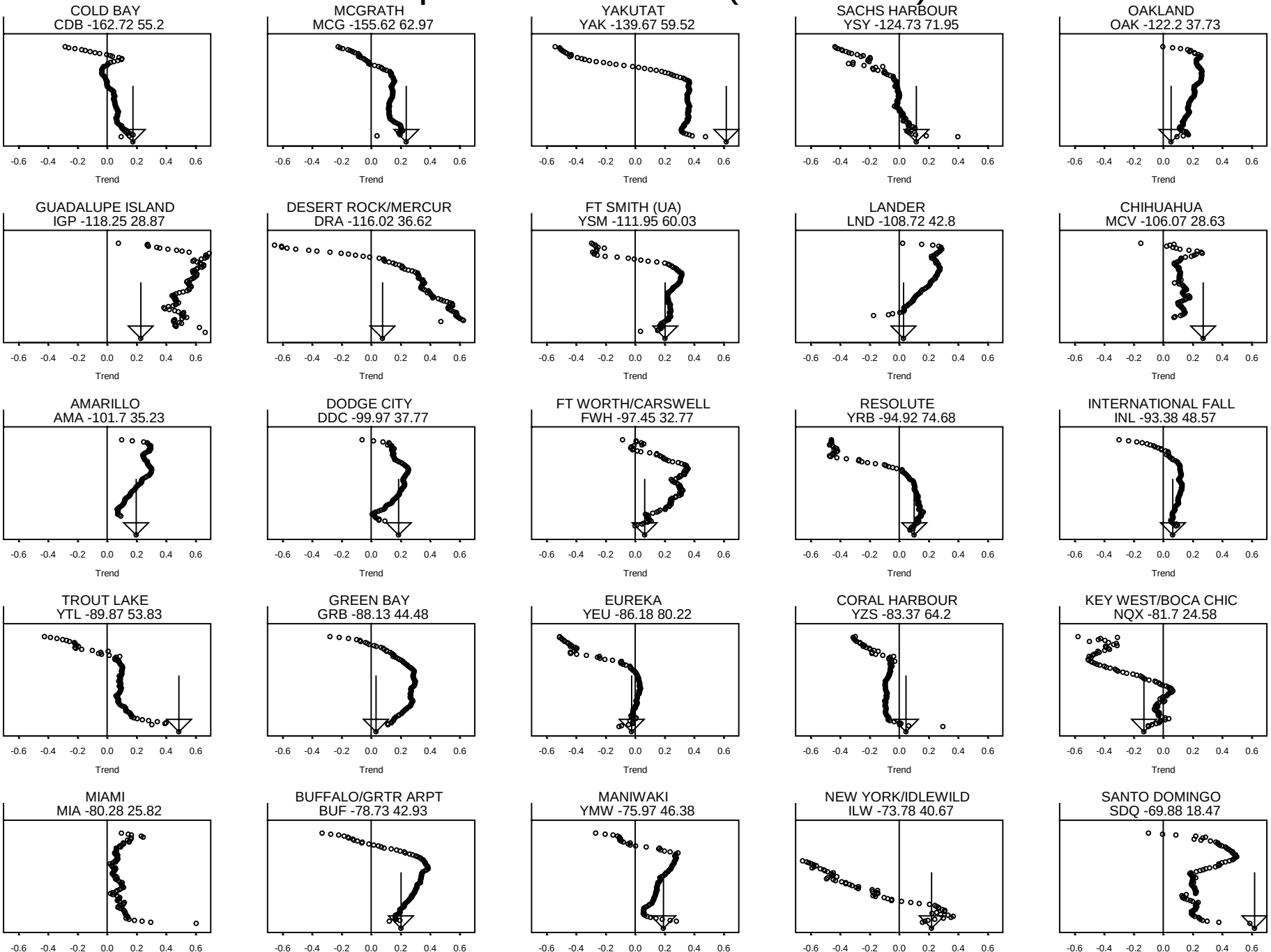
Source: Dave Keeling and Tim Whorf (Scripps Institution of Oceanography)

Nature’s response is not always so linear.




10 mb B2
30 mb B2
50 mb B2
100 mb B2
150 mb B2
200 mb B2
250 mb B2
300 mb B2
400 mb B2
600 mb B2
700 mb B2
850 mb B2
950 mb B2
1000 mb B2
Degrees C per decade
-100
0
100
50
0
-50
-0.005
0.0
0.005
0.010

Sonde Temperature Trends (C/decade) at 0 Z



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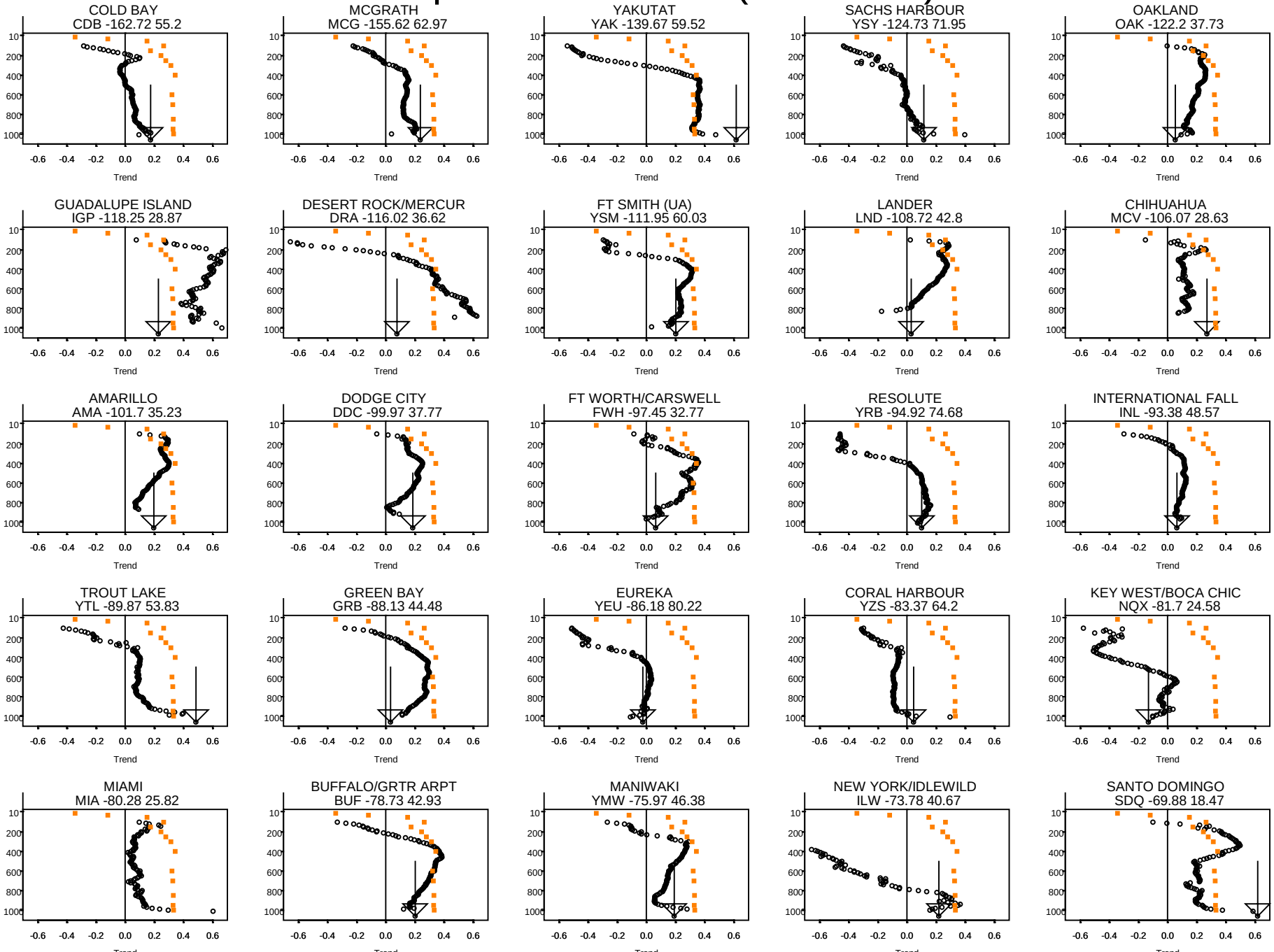
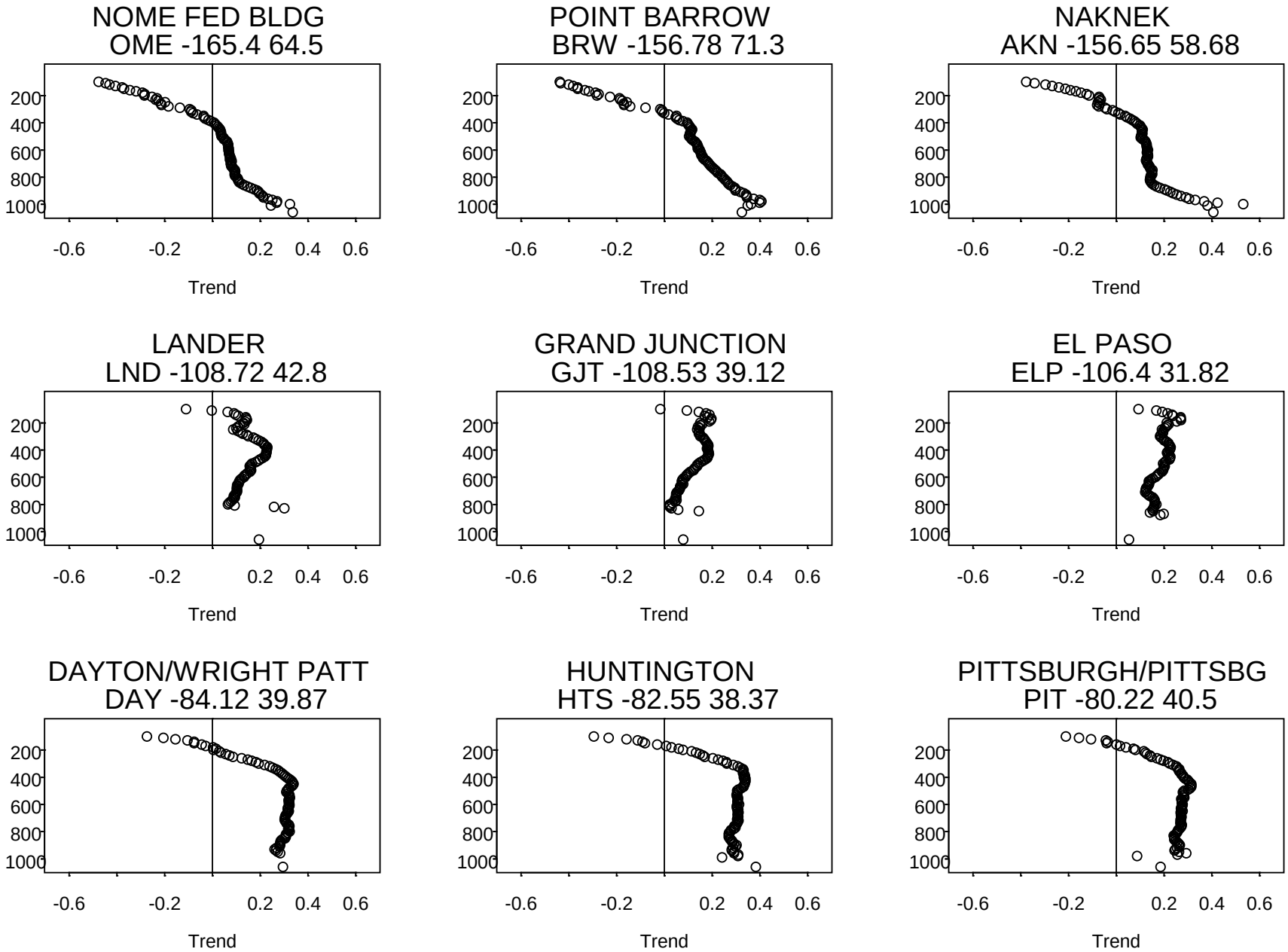


Are there patterns?

Sonde Temperature Trends (C/decade) at 12 Z



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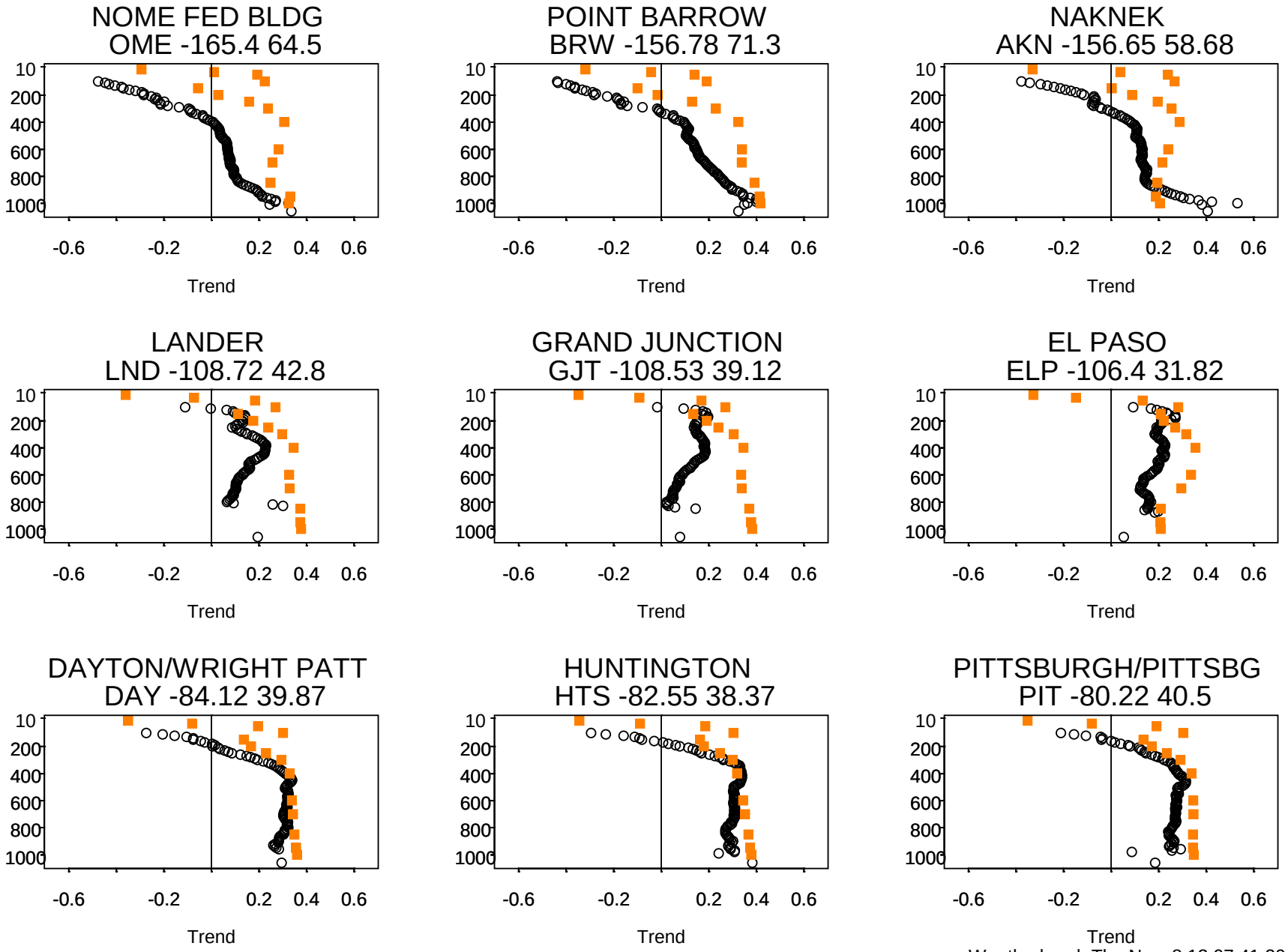
Sonde Temperature Trends (C/decade) at 12 Z



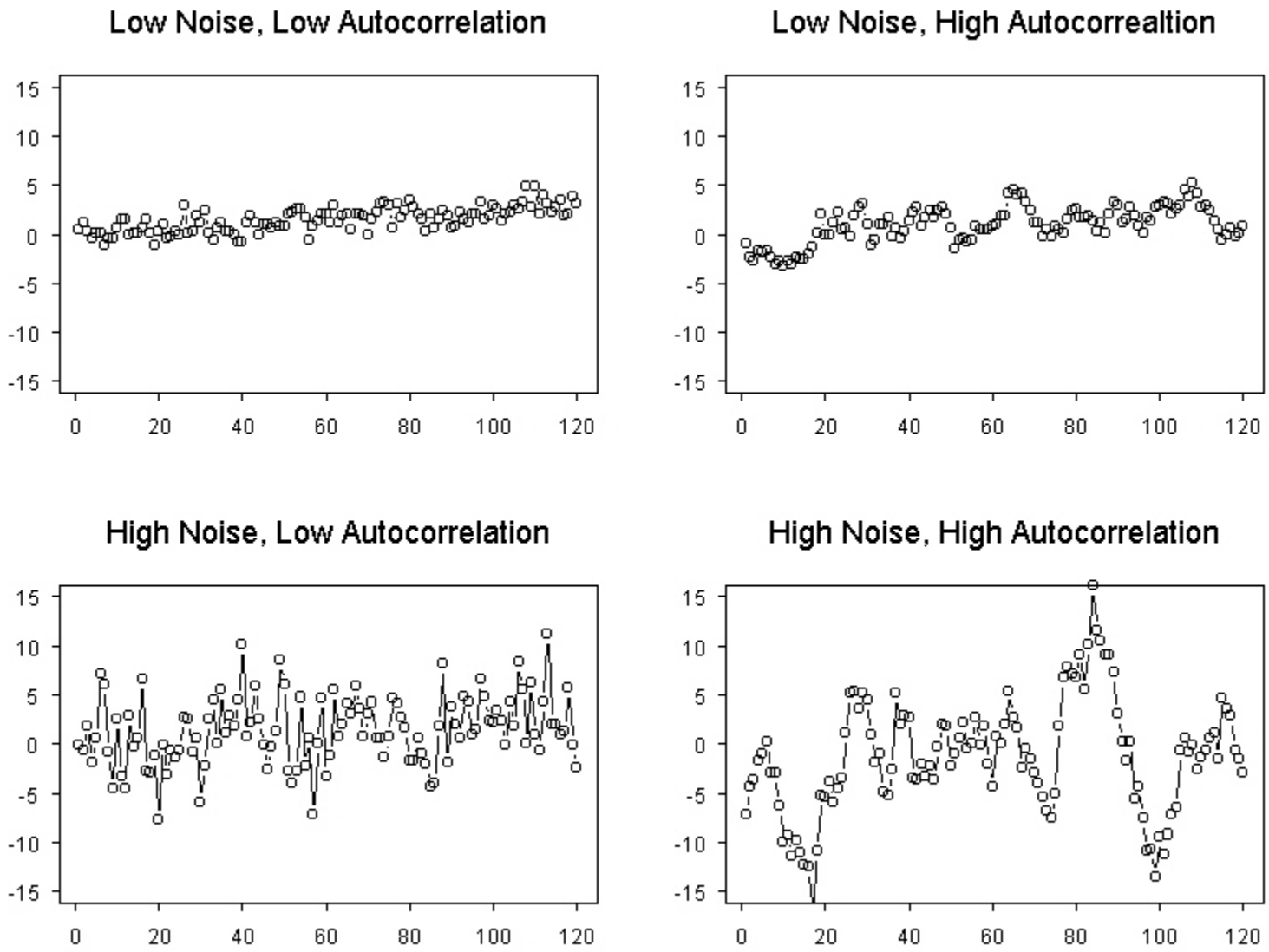
Weatherhead Thu Nov 8 13:07:41 2001

What is the primary goal of a Reference Network?

- Detection of Representative Trends?
  - Spatially: site in representative areas
  - Temporally: monitor consistently to establish trends
- Understand errors and transfer standards?
  - Spatially: site with existing instrumentation and expertise
  - Temporally: make measurements when they can add to knowledge.

Trend Detection

- “Finding a change which is large relative to natural variability.”
- For environmental data both the magnitude of variability and the memory (autocorrelation) hinder our ability to detect trends.

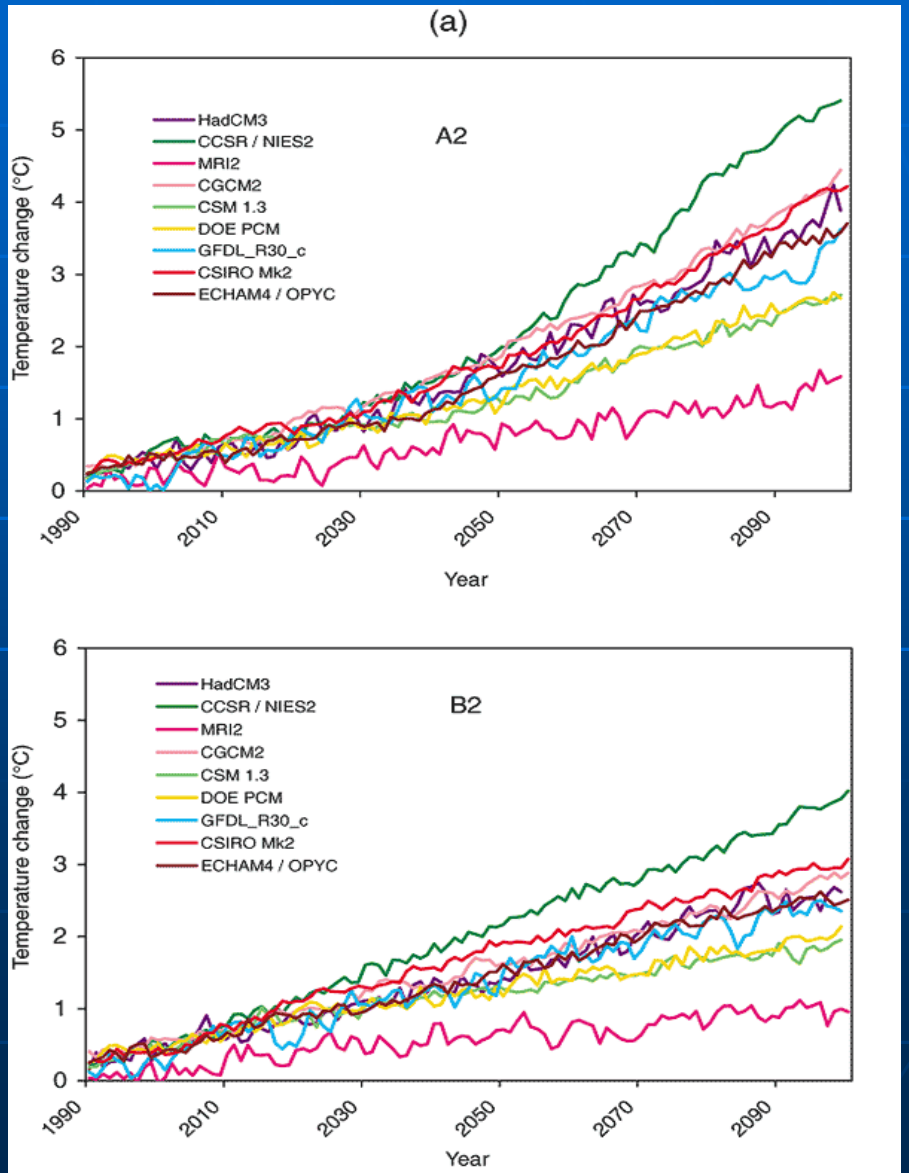

Low Noise, Low Autocorrelation
Low Noise, High Autocorrealtion
High Noise, Low Autocorrelation
High Noise, High Autocorrelation
15
10
5
0
-5
-10
-15
0
20
40
60
80
100
120

The key

- All four parameters which affect our ability to detect trends vary by location:
  - Magnitude of variability
  - Autocorrelation
  - Size of the trend
  - Stability of the measurements

One example: temperature trends

- Temperature trends are predicted by a number of different models.
- How long will we need to monitor to detect trends?



Temperature Trend Analysis

- As for most environmental data, trends are usually derived using a statistical model such as:

- Temperature = trend + seasonal + Noise
  - Where the trend may be linear or not.
  - Where the noise involves both the magnitude of variability and autocorrelation.

Estimating the Number of Years for Trend Detection

- If we understand the size of trend we are looking for;
- If we know the typical magnitude of variability;
- If we know the amount of temperoral memory in the system;
- We can estimate how long we need to monitor.

Number of Years needed to detect a trend

- Approximately:

$$n = \{ \ (2 * \sigma_n / |\omega_o| \ ) \ \text{sqrt}\ (1+\phi)/(1-\phi) \ \}^{2/3}$$

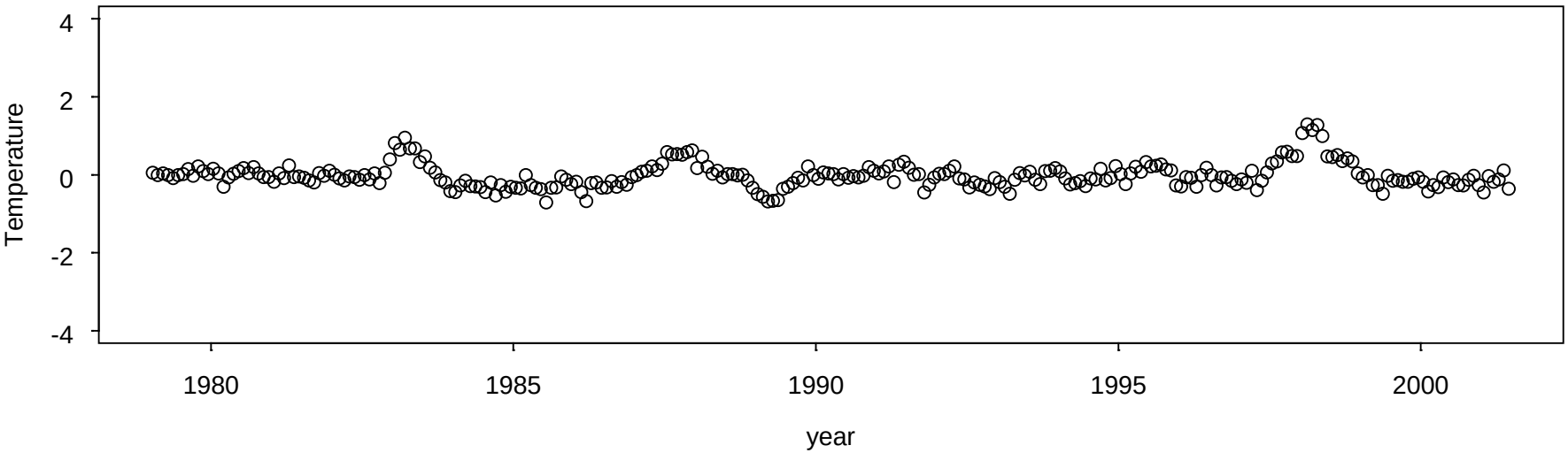
- Assuming that detection is declared at the 95% confidence level
- This estimate allows for 50% likelihood of detection

Years to Detect .2 Degrees per Decade Trend in Temperature

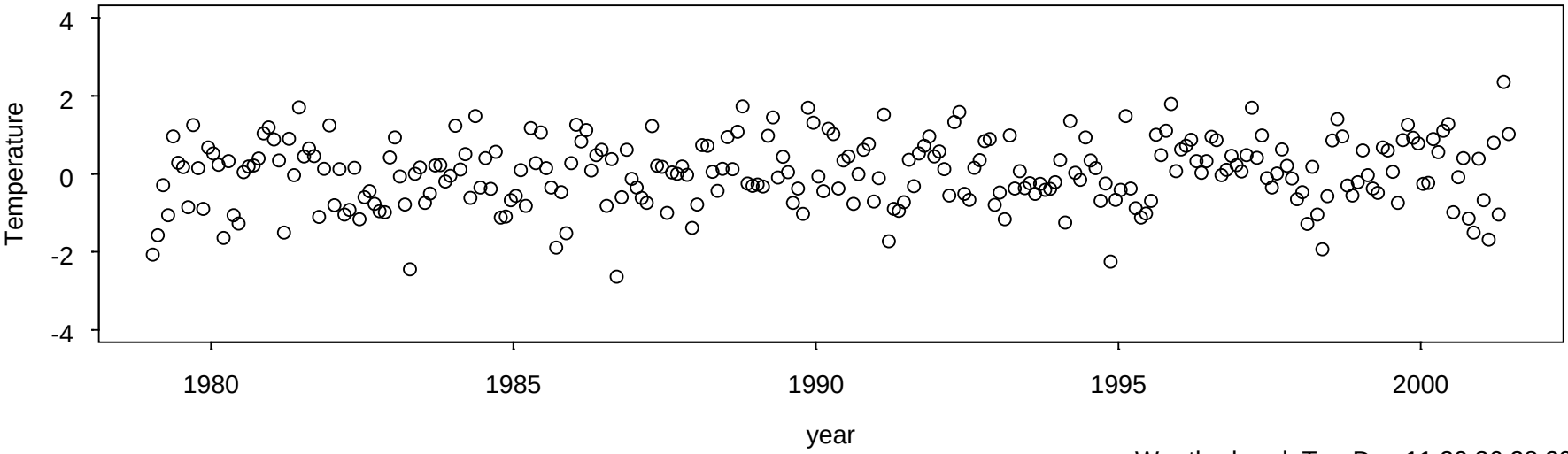
	0	**.3**	**.6**	**.9**
.5	14	17	21	35
1	22	26	34	56
3	45	55	71	100+
5	63	77	100+	100+

MSU Channel 2

Equator



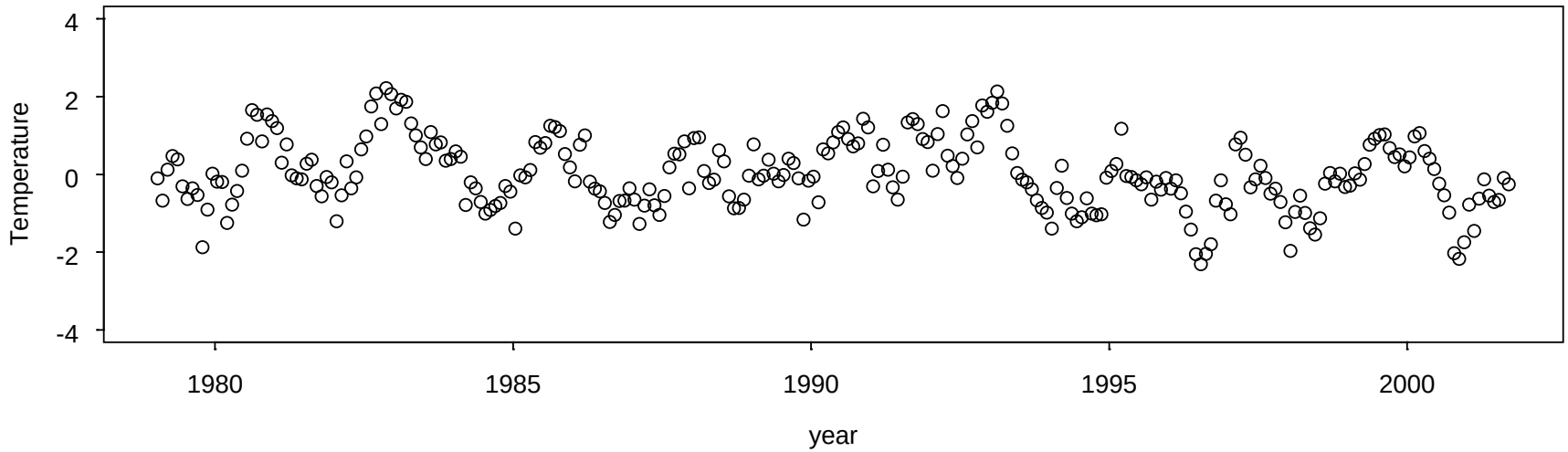
San Francisco



Weatherhead Tue Dec 11 20:36:28 2001

MSU Channel 4

Equator



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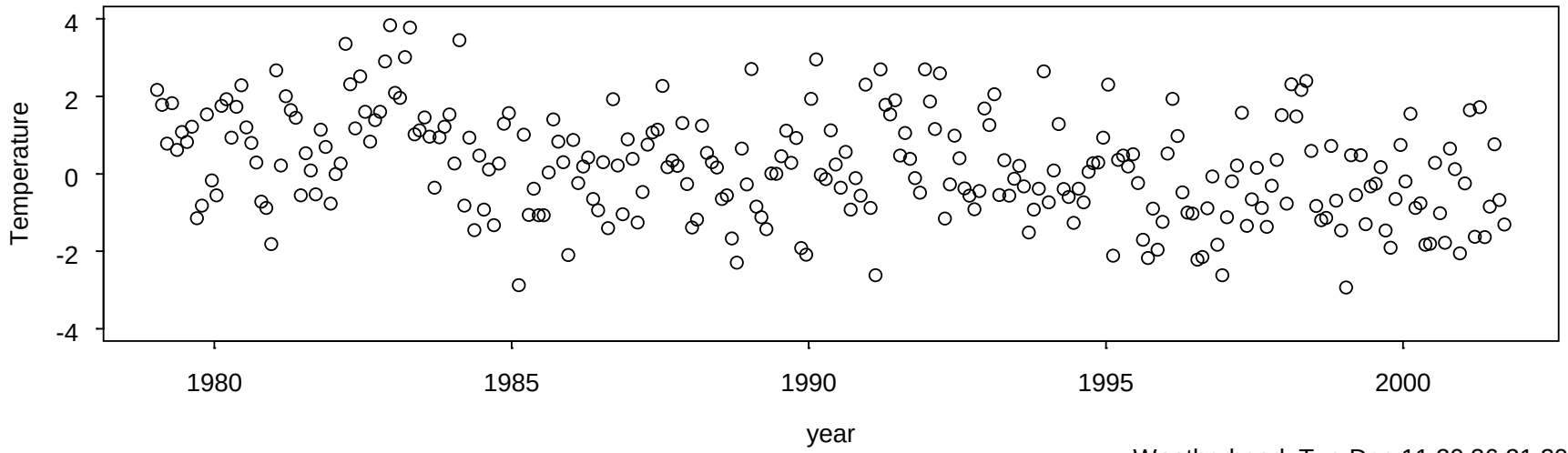


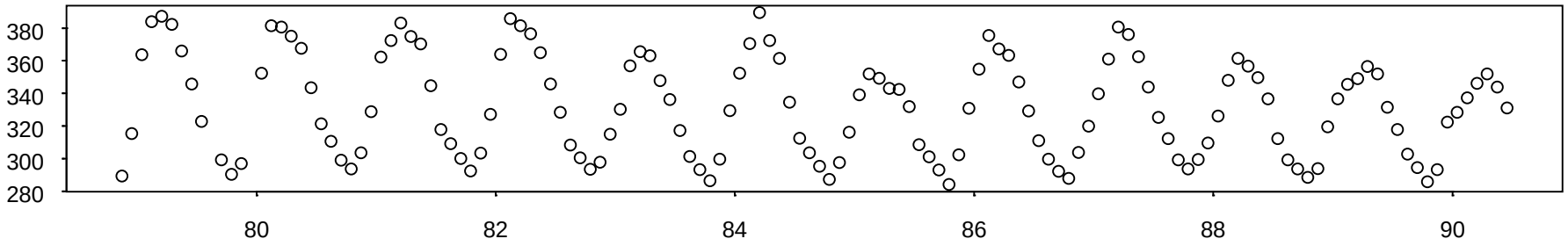
Weatherhead Tue Dec 11 20:36:21 2001

Visual Example

- How many years does it take to detect a trend in ozone?
- Use our understanding of variability;
- Use our understanding of the predicted trends
- Estimate visually how long it will take to detect a trend.

SBUV OZONE TOTAL COLUMN OZONE - 40N

Original Monthly Averaged Data



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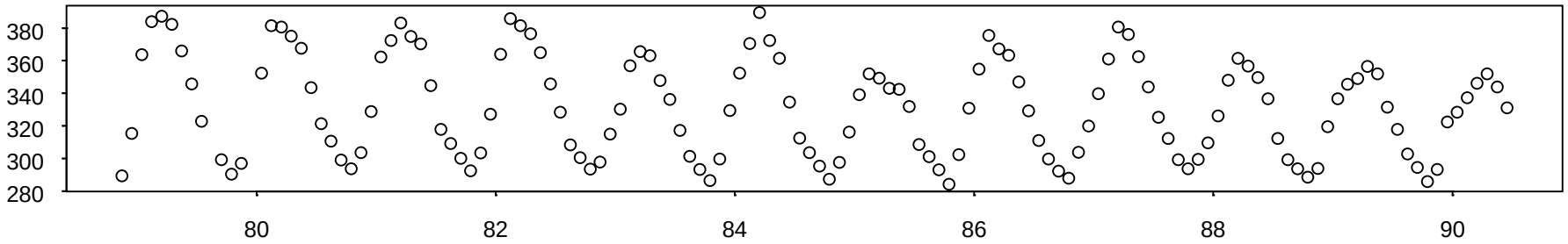
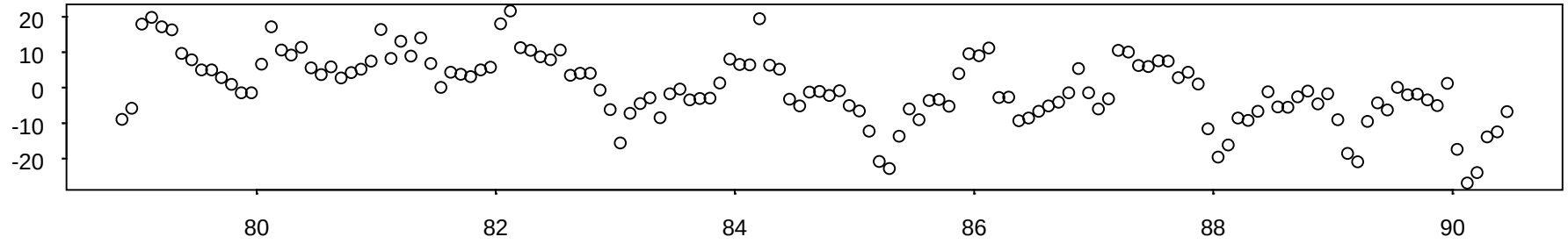
SBUV OZONE TOTAL COLUMN OZONE - 40N

Original Monthly Averaged Data



Weatherhead Fri Nov 2 11:48:50 2001

Monthly Means Removed, Lowess Line Fit Superimposed



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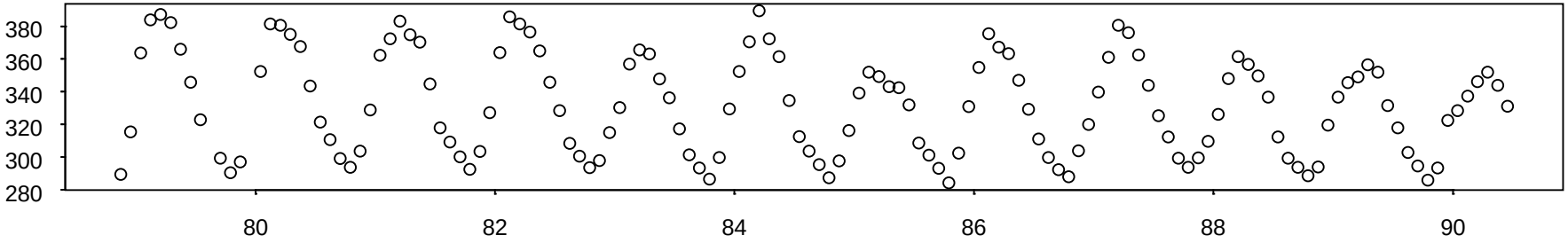

Weatherhead Fri Nov 2 11:48:50 2001

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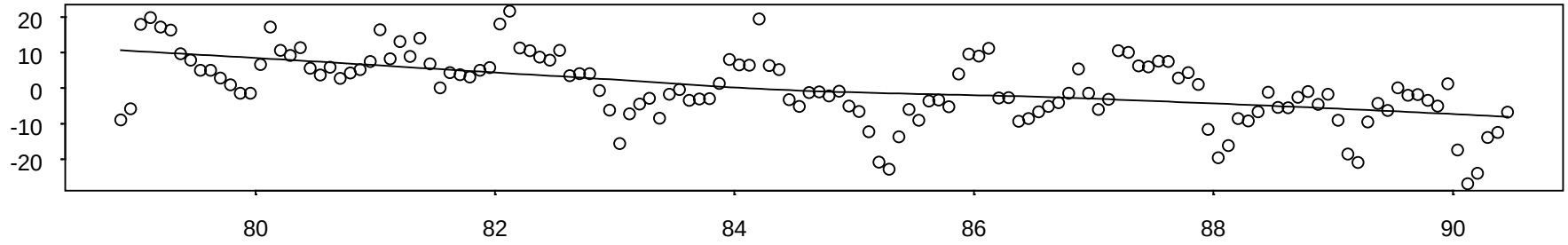

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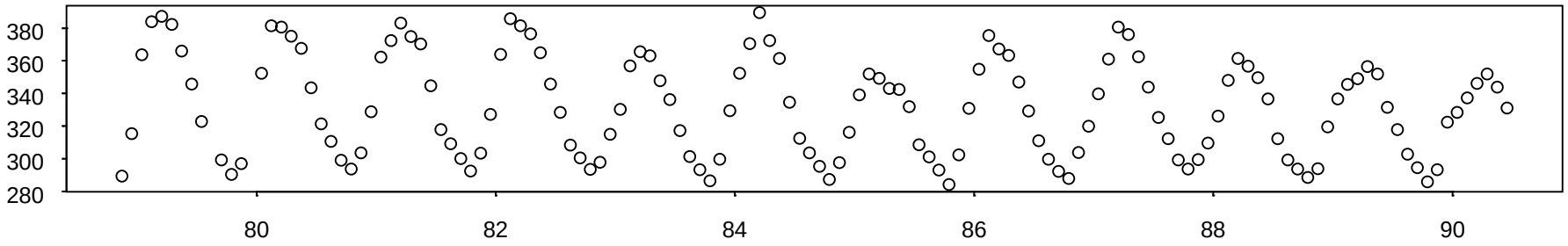
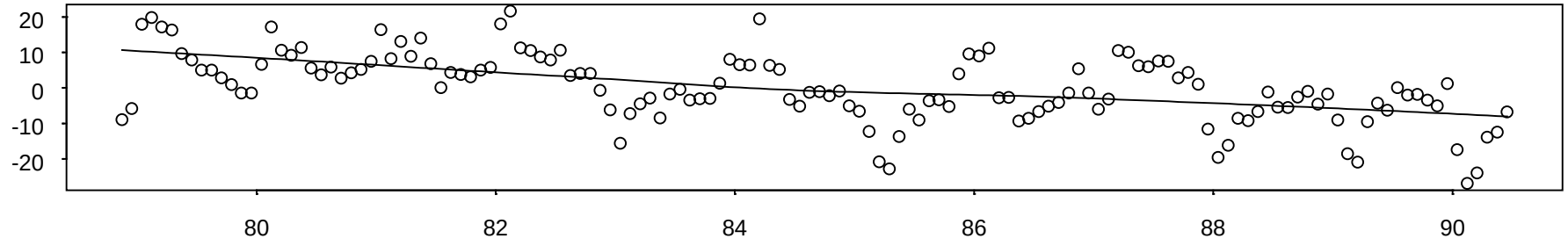
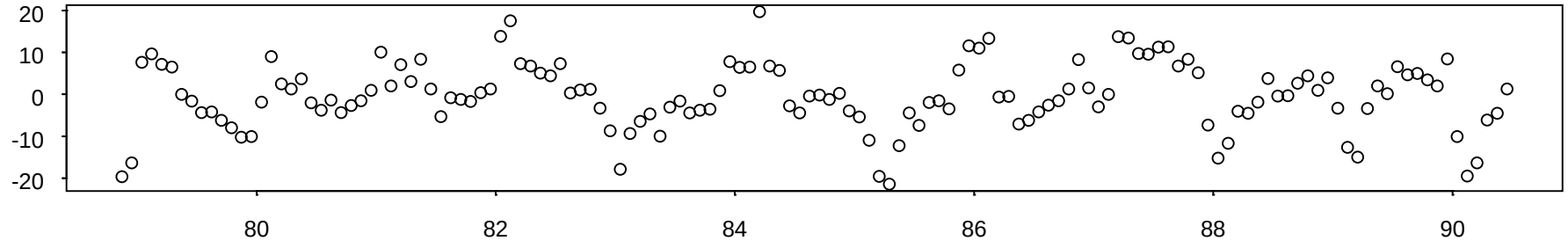


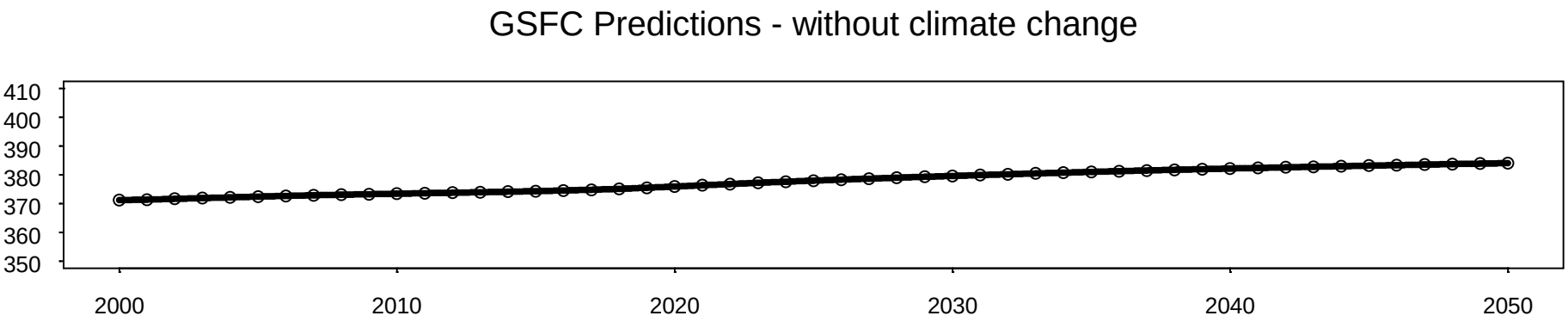
Weatherhead Fri Nov 2 11:48:50 2001

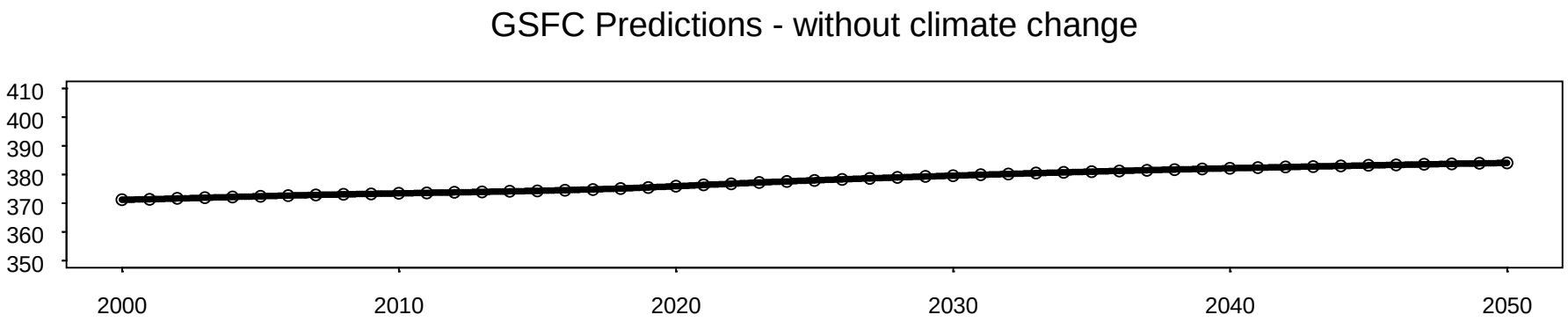
Monthly Means Removed, Lowess Line Fit Superimposed



Residuals From Lowess Line Fit




GSFC Predictions - without climate change
410
400
390
380
370
360
350
2000
2010
2020
2030
2040
2050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2000
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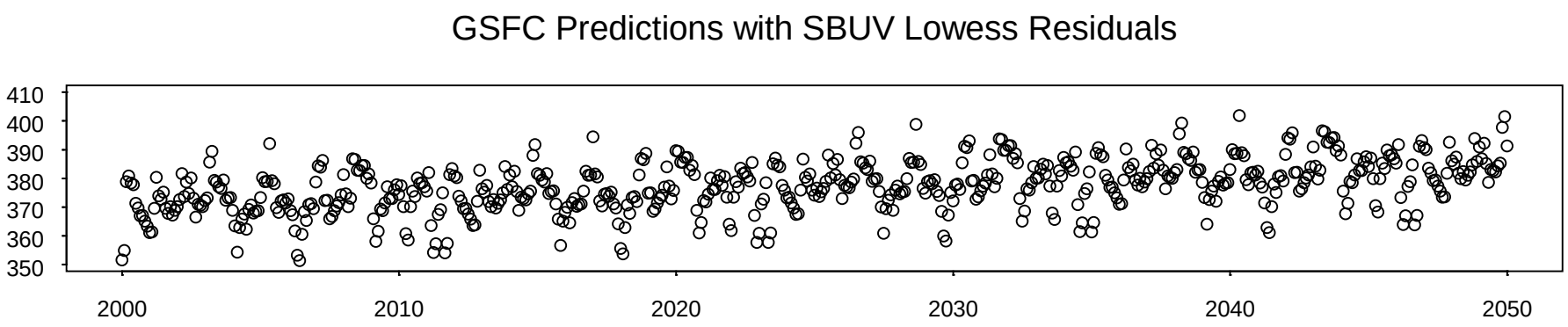
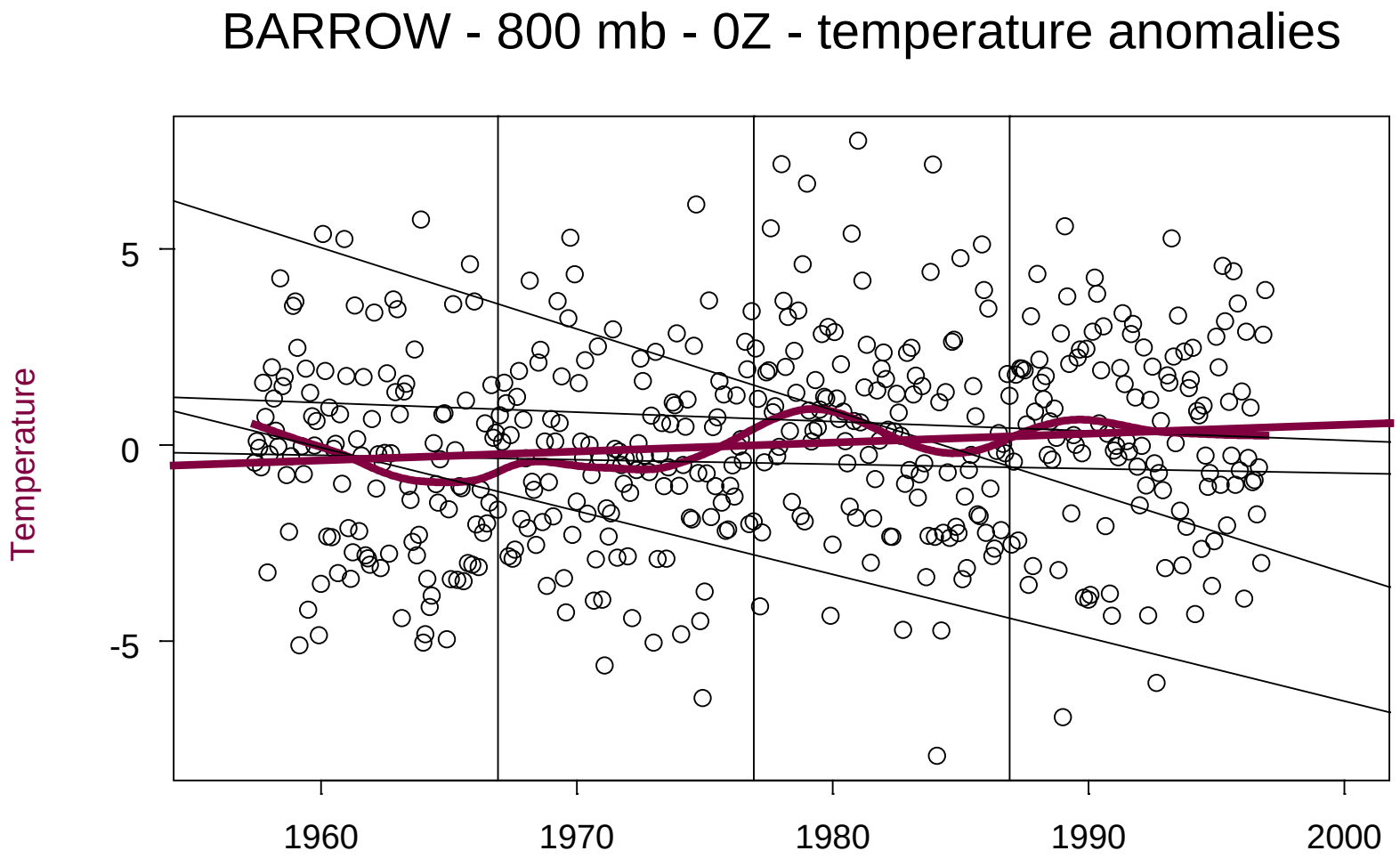

GSFC Predictions with SBUV Lowess Residuals
410
400
390
380
370
360
350
2000
2010
2020
2030
2040
2050


BARROW - 800 mb - 0Z - temperature anomalies
Temperature
5
0
-5
1960
1970
1980
1990
2000

Metric: Number of years

- Our ability to detect trends is limited by natural variability
- We can estimate how long it will take to detect trends
- Some parameters, some places, some monitoring approaches may take considerably less time than others.

- What can we control?

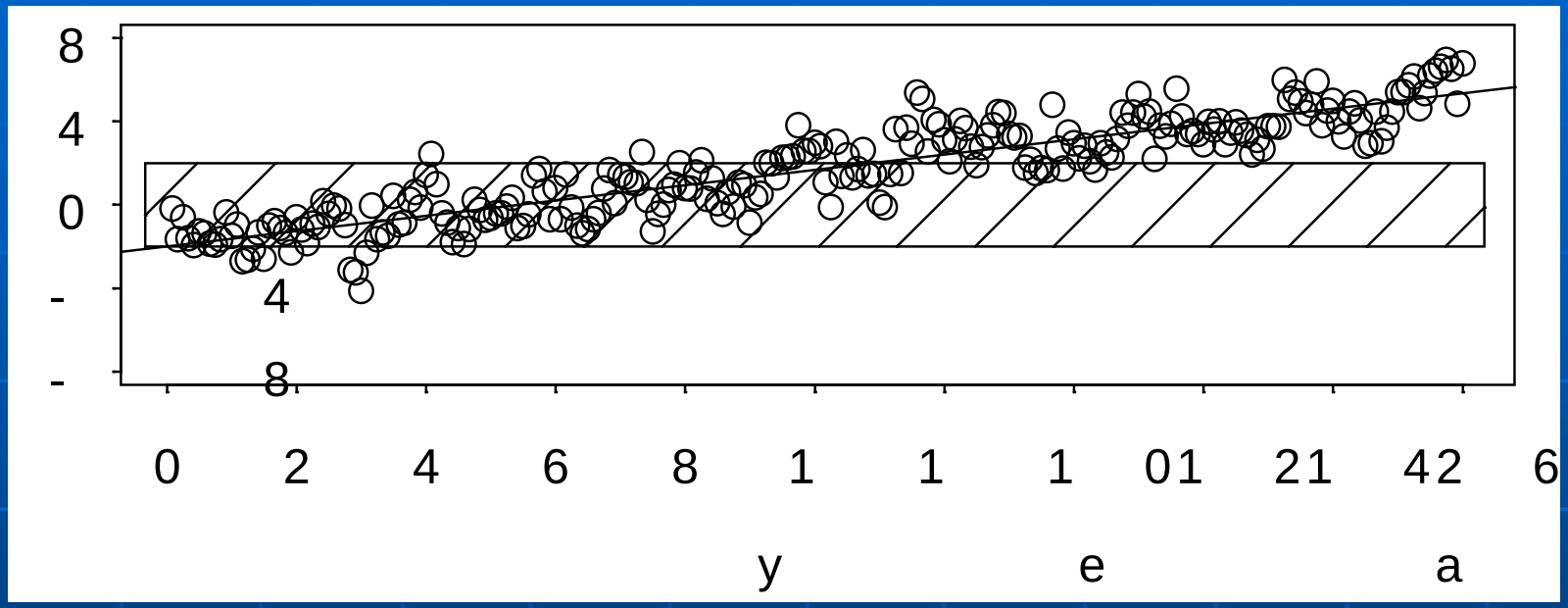
We can control only four aspects of monitoring to detect trends

- **What we monitor**
- **What accuracy**
- **Where we monitor**
- **What frequency**

What accuracy?

- Relative accuracy is all that's needed for trend detection.
- Relative accuracy is extremely hard to maintain for decades without absolute accuracy.
- Improved accuracy may save decades in monitor or may be irrelevant.

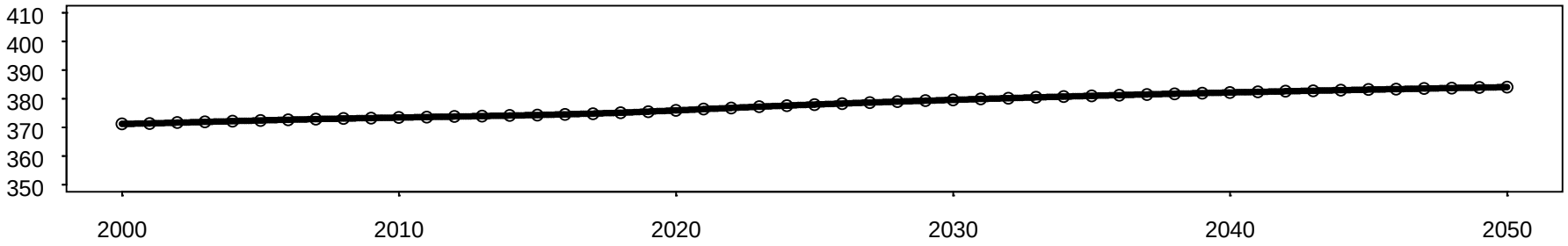
Case Example



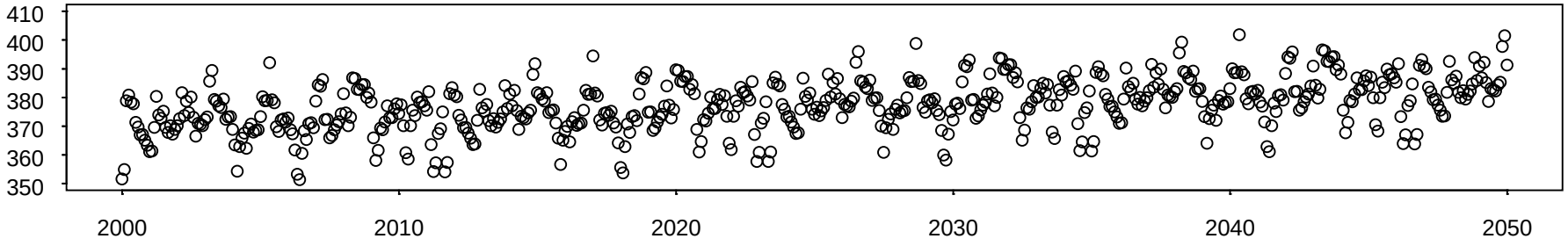
- Uncertainty: ±2% ; Trend: 4% per decade
- Result:
  - First ten years of data are still unsubstantial
- Improving Accuracy to ±1% saves five years of monitoring

GSFC 2d Predictions with SBUV Residuals of Total Col. Ozone (d.u.) 40N

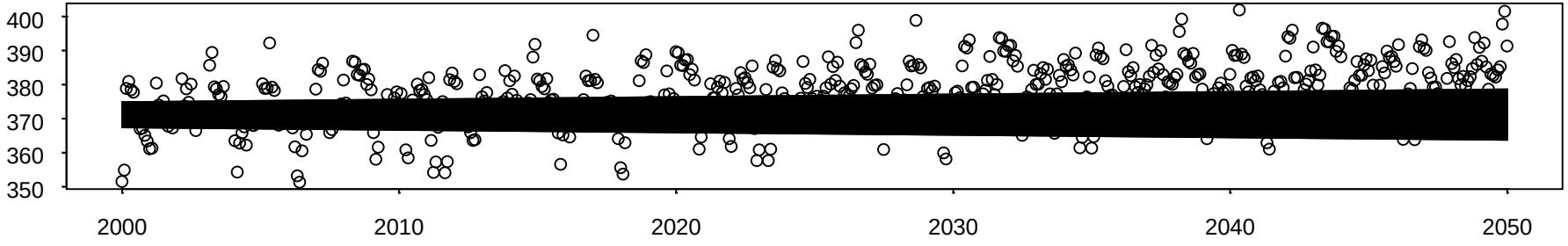
GSFC Predictions - without climate change



GSFC Predictions with SBUV Lowess Residuals



with +-1% error plus +-1% drift



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Incorporating Long Term Stability estimates in our estimate of our ability to detect trends

- In some cases, our measurement uncertainty is considerably larger than the signal we want to detect.
- Estimating appropriate measurement uncertainty over decades of monitoring is extremely difficult.
- Measurement stability and statistical variability are likely to be independent, thus:

$$\sigma^2_{total} = \sigma^2_{statistical} + \sigma^2_{stability}$$

For temperature: 0.1 may add ten years to monitoring

For humidity: uncertainty is larger.

Identifying a metric gives guidance to decision making and resource allocation.

We can control only four aspects of monitoring to detect trends

- **What we monitor**
- **What accuracy**
- **Where we monitor**
- **What frequency**

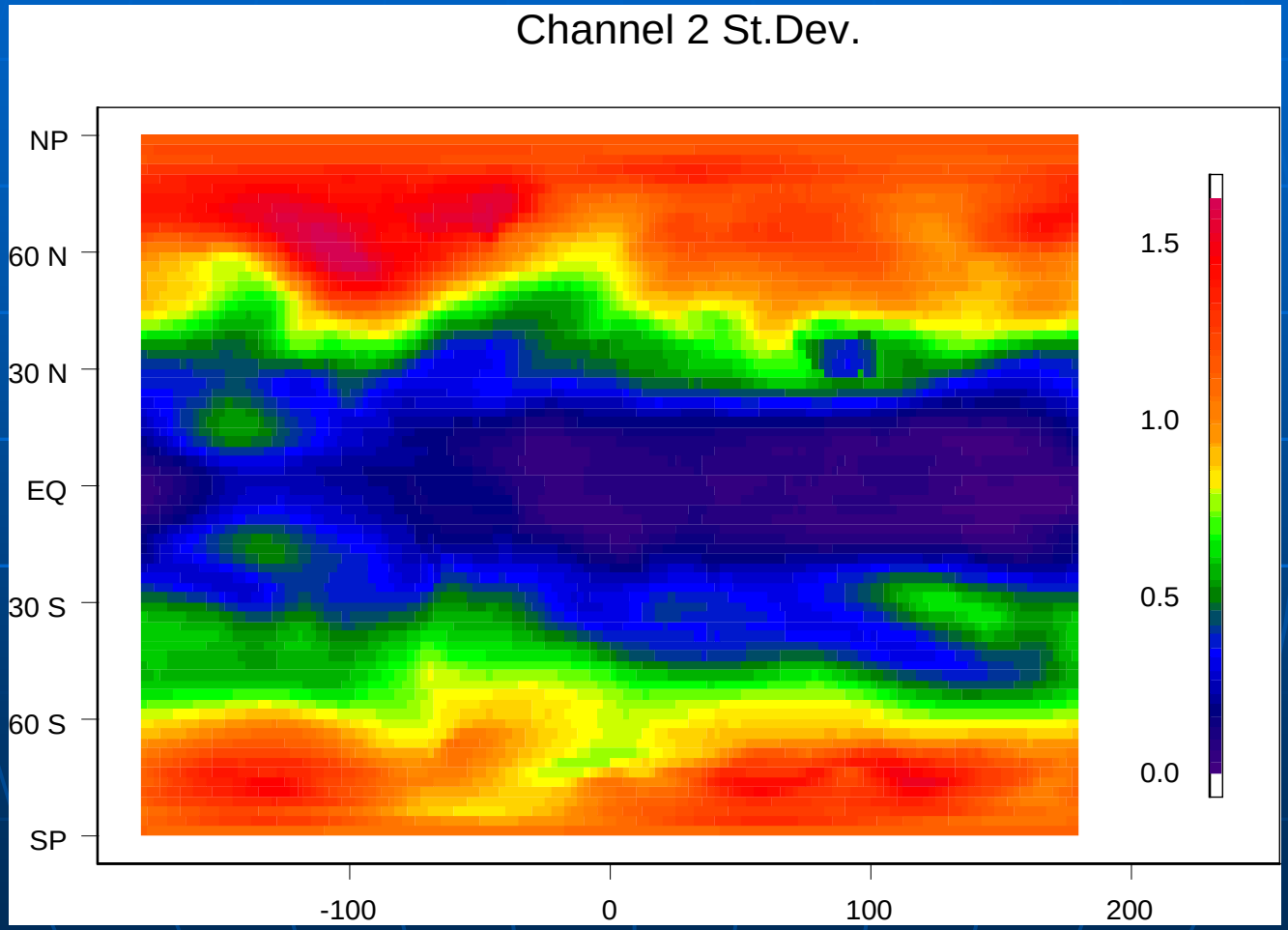
Where do we monitor?

- Some places are inherently better for detecting trends than others.
- Monitoring by satellite involves averaging over height, longitude and latitude.
  - Measurement smoothing can damage our ability to detect trends

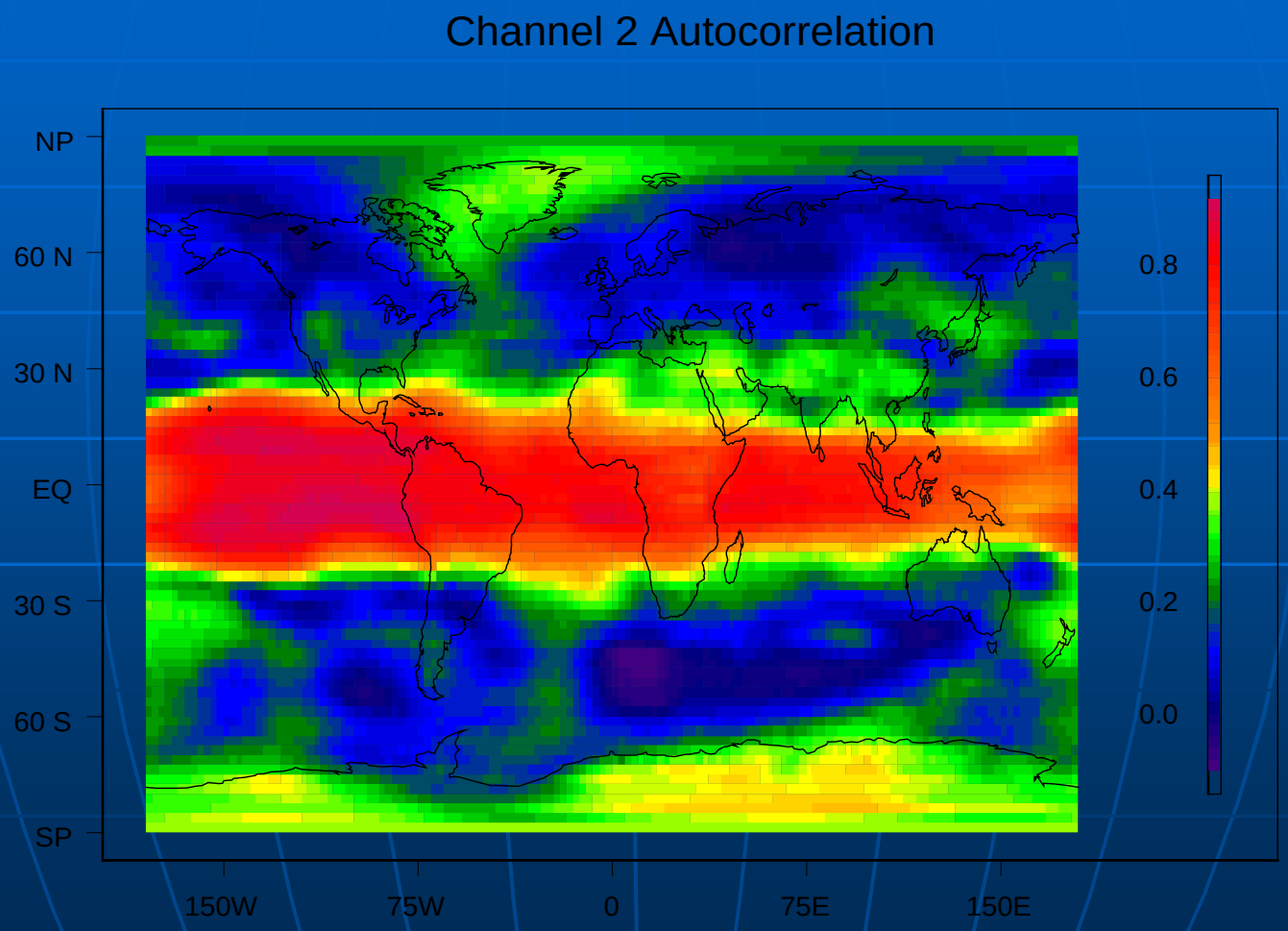
Where do we monitor: single locations

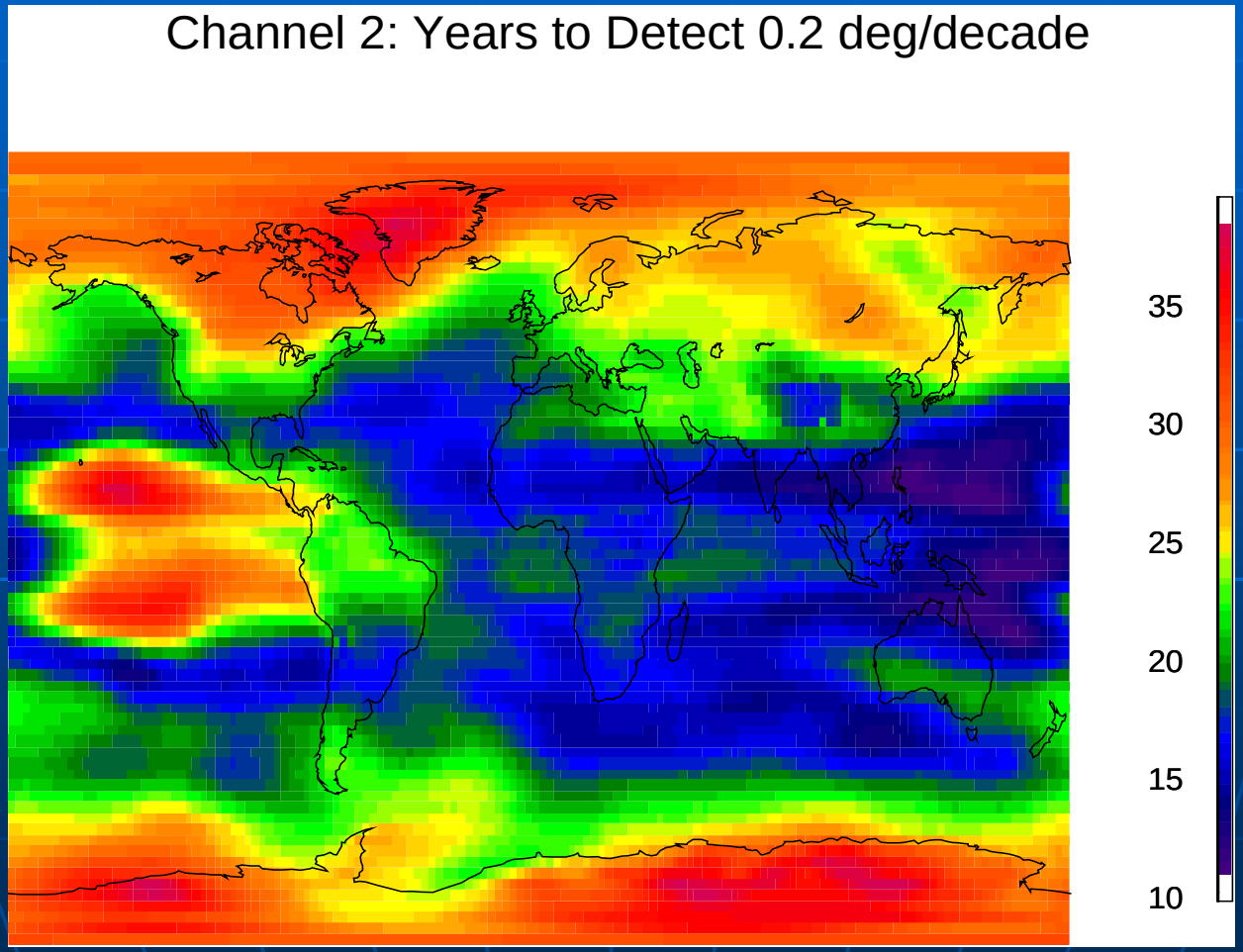
- Some places are inherently better for detecting trends than others.
- Natural variability, memory and magnitude of trend vary by location
- The difference in number of years can vary by more than a factor of two.

Magnitude of temperature swings

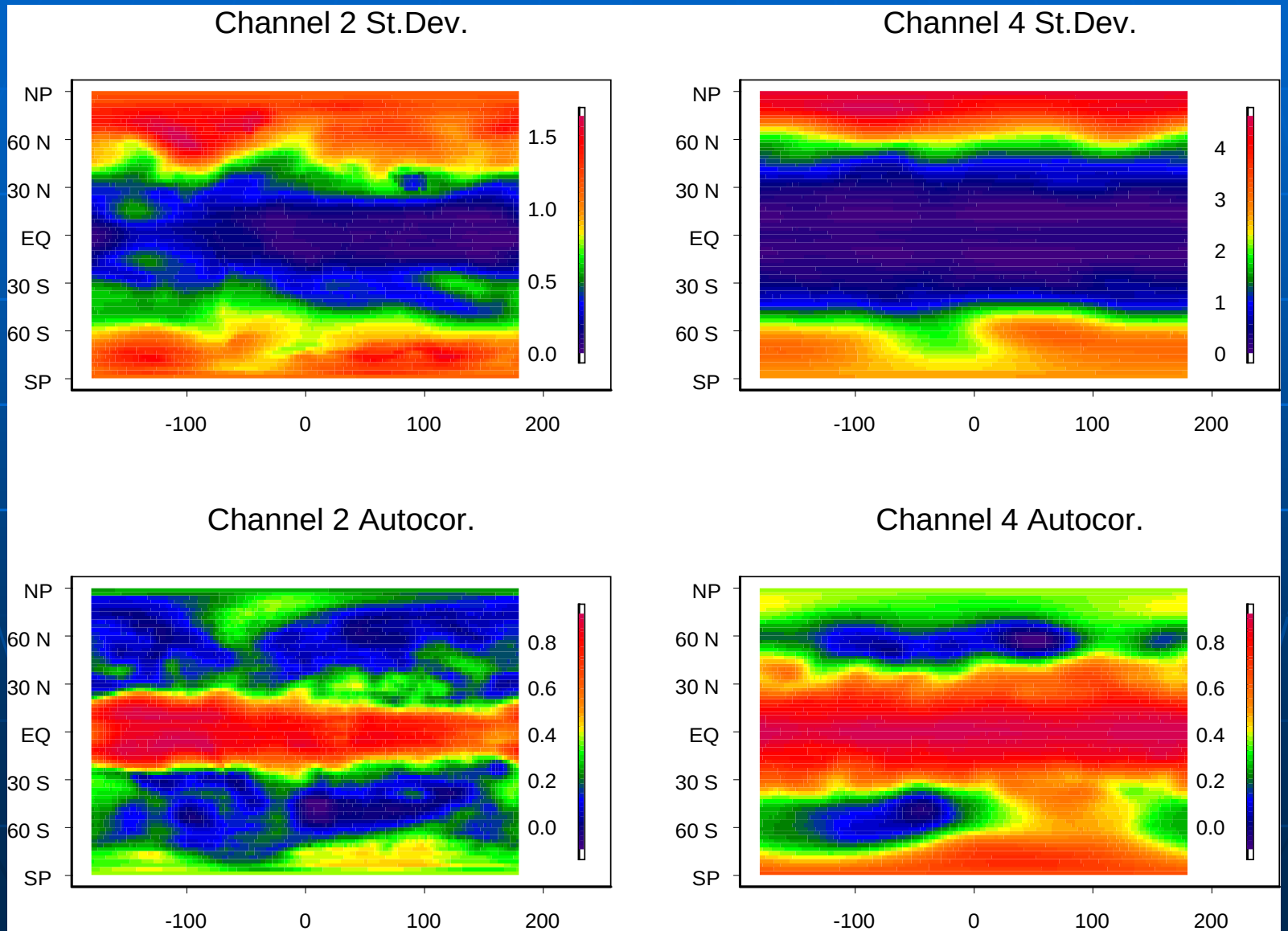


Autocorrelation of monthly data



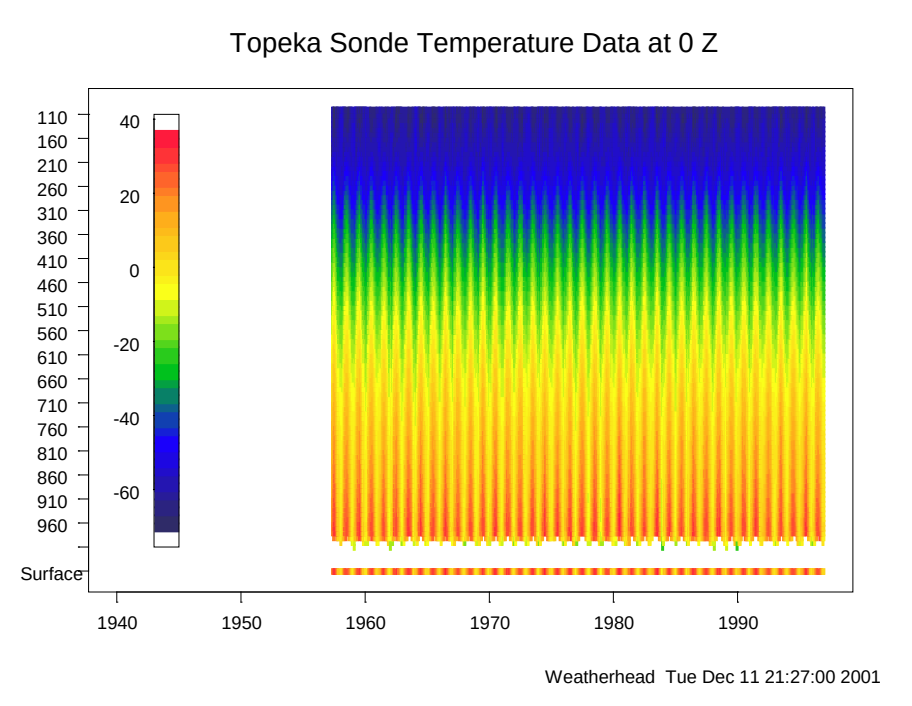

Channel 2: Years to Detect 0.2 deg/decade
35
30
25
20
15
10

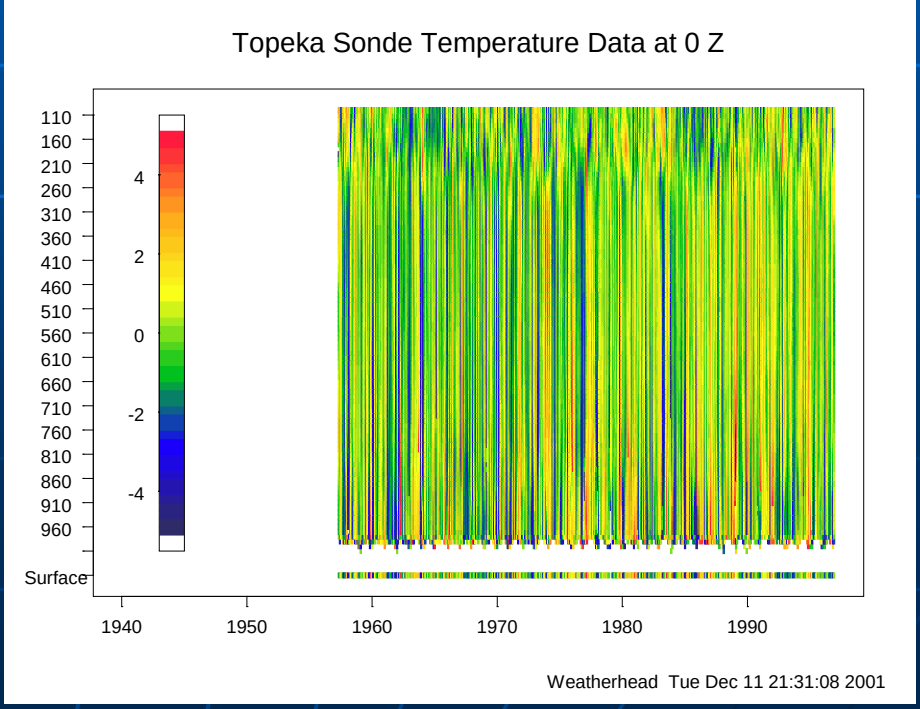
MSU channels 2 & 4 characteristics



Looking in the vertical

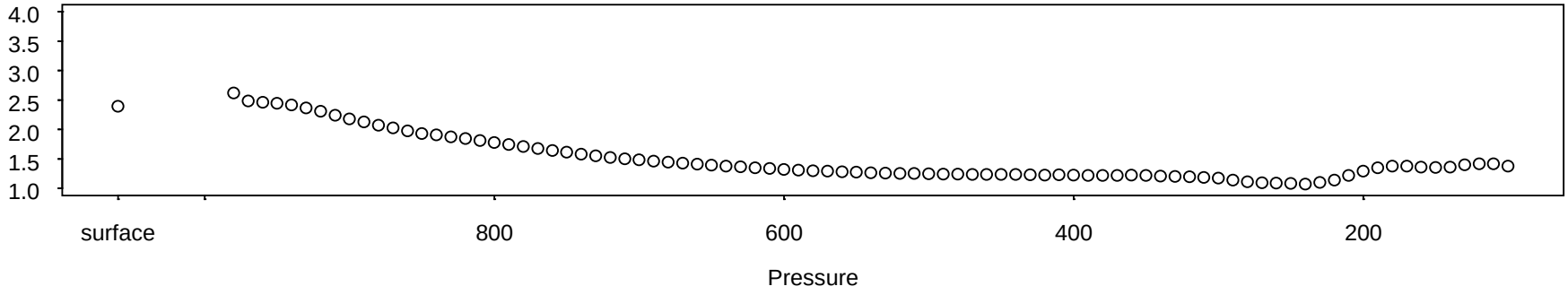
- Near constant trends are predicted throughout the troposphere
- Is there an optimal place to detect trends?



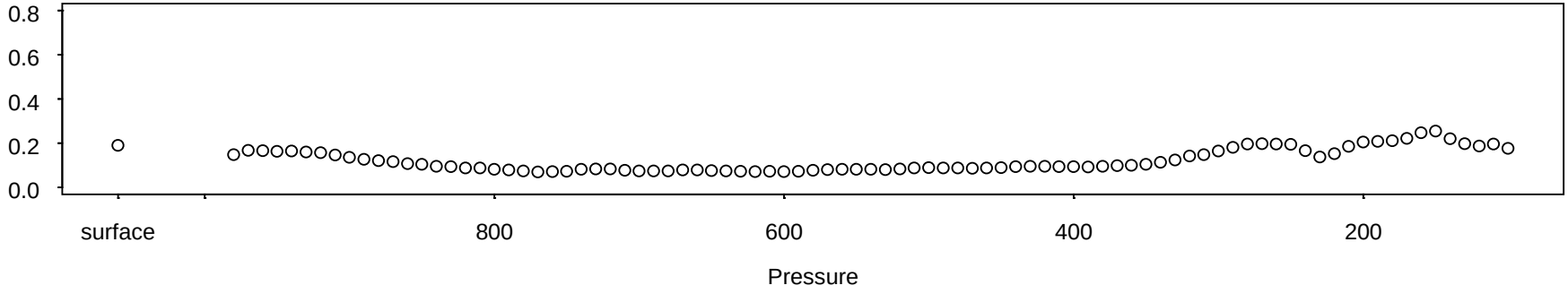


Topeka temperature detectability

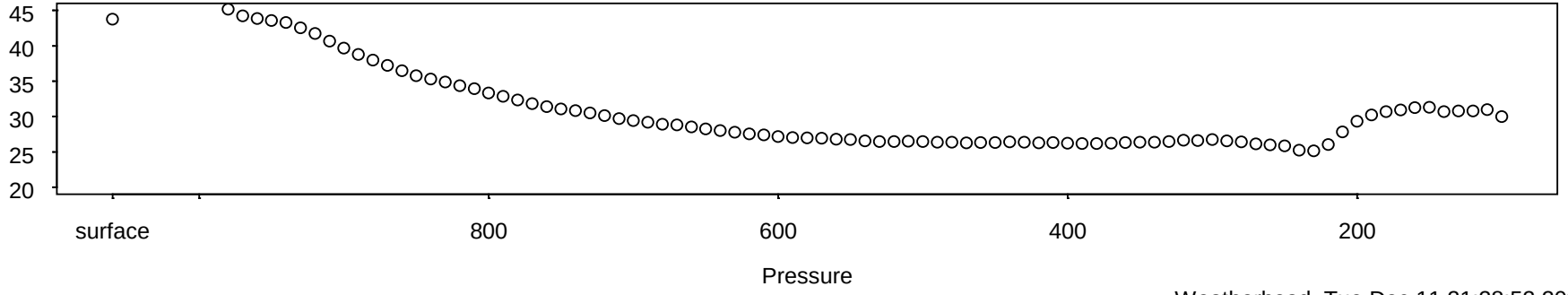
Noise



Autocorrelation



Years to Detect a .2 deg/decade trend



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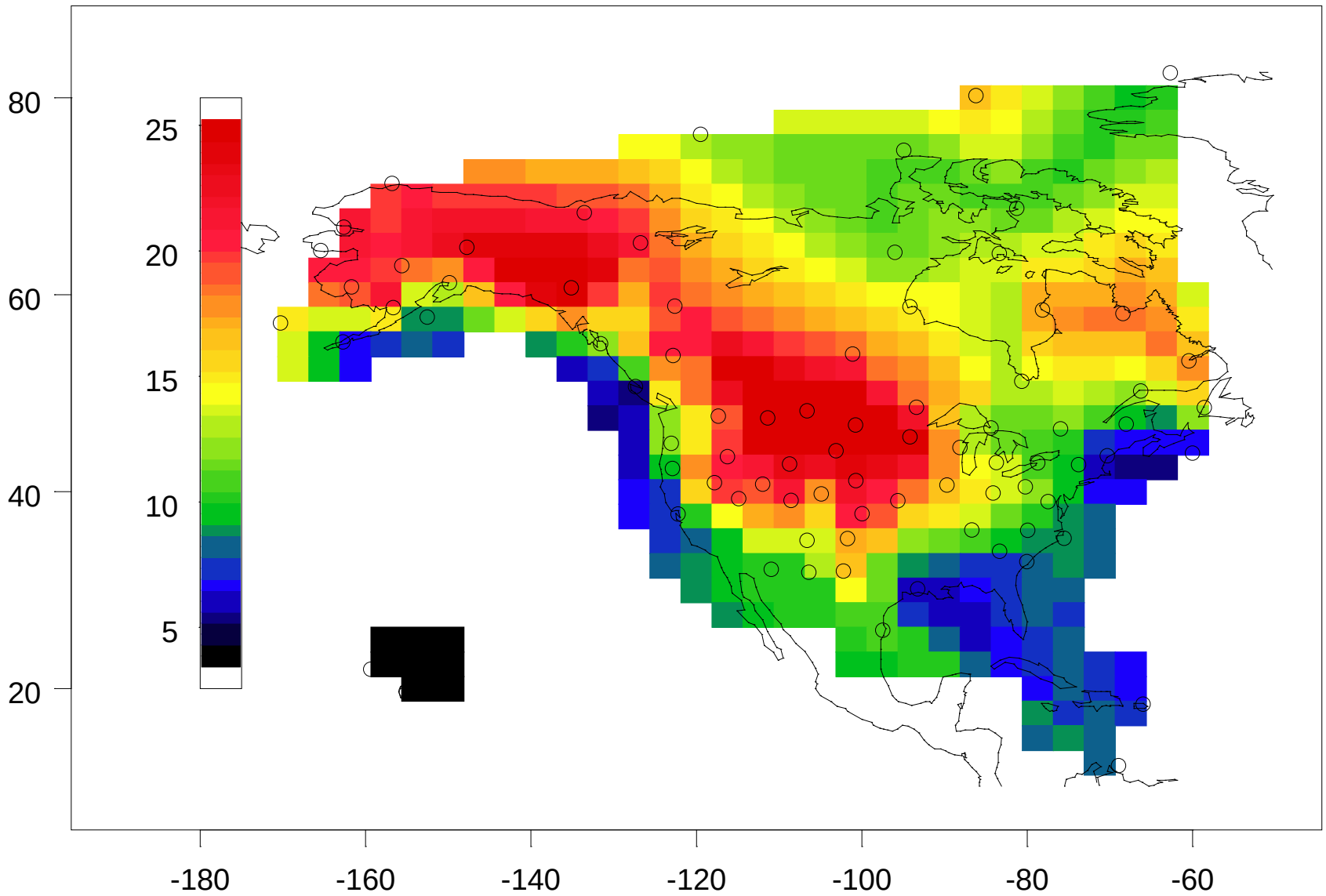
Years Saved by Monitoring Free Troposphere 0Z

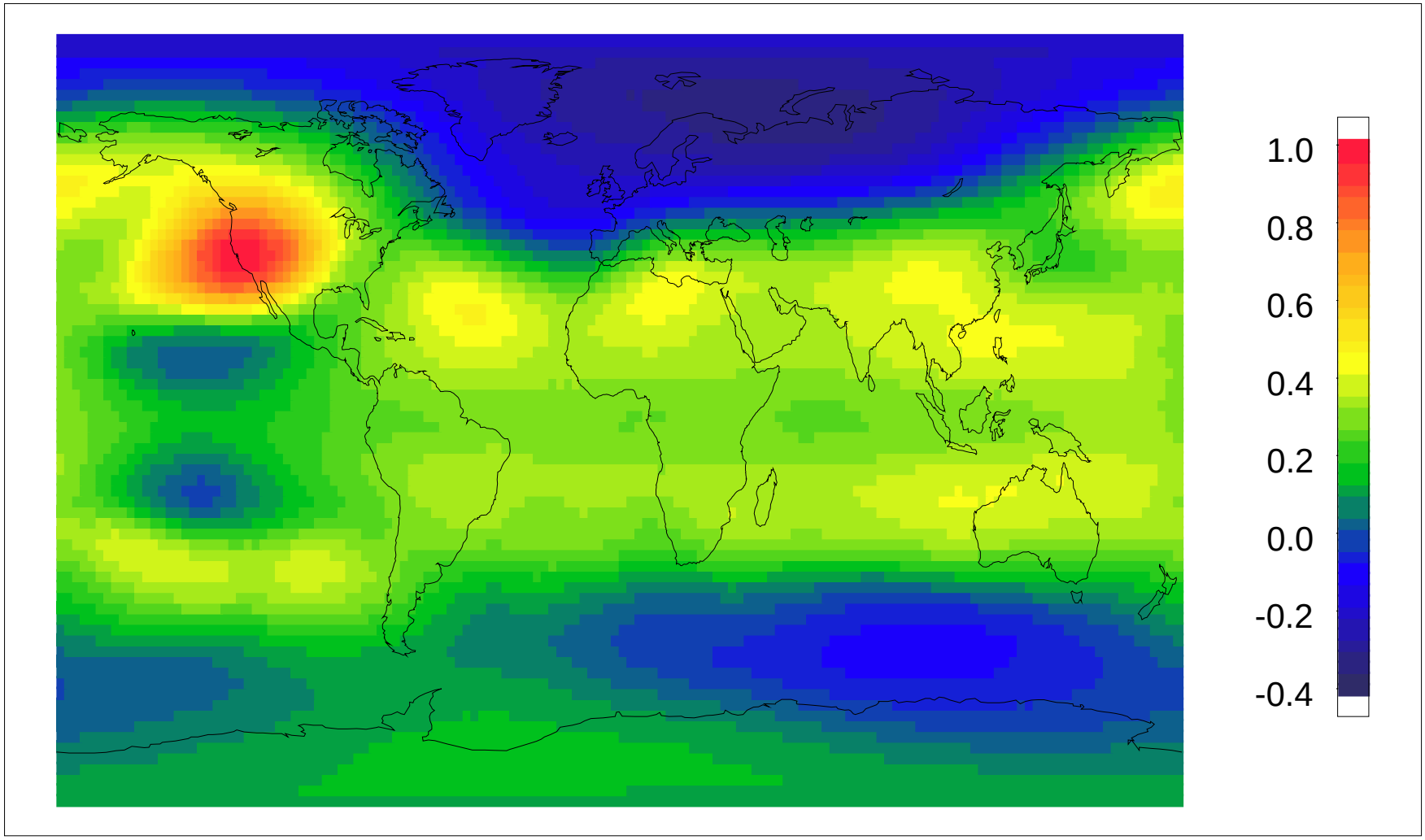


Weatherhead Tue May 21 12:14:04 2002 True Range of Data: (3 to 36)

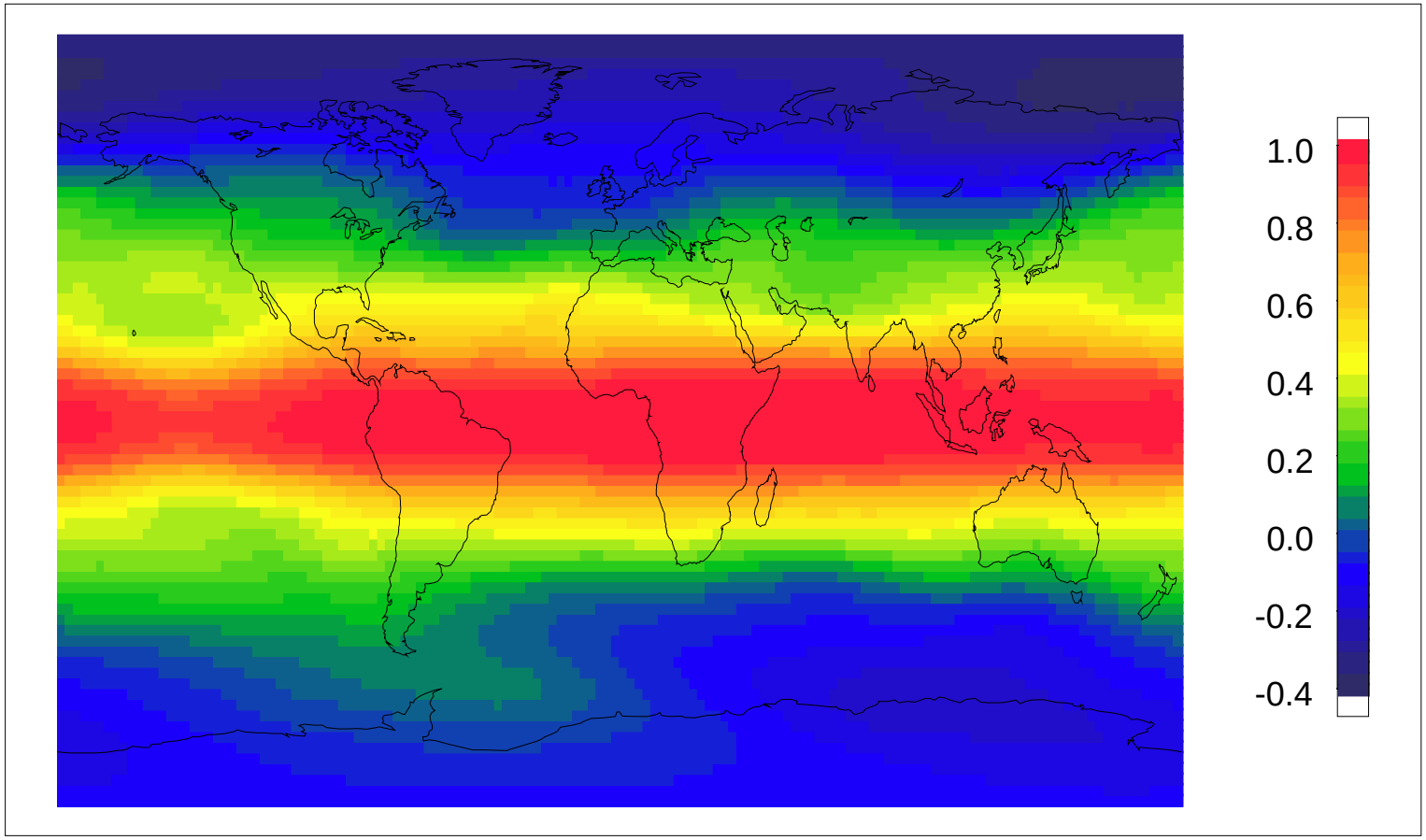
How many single stations do we need?

- Spatial coherence means that averaging many different locations does not always reduce error bars significantly.
- Spatial coherence can be estimated from past data.

MSU Channel 4
Correlation with S.F.

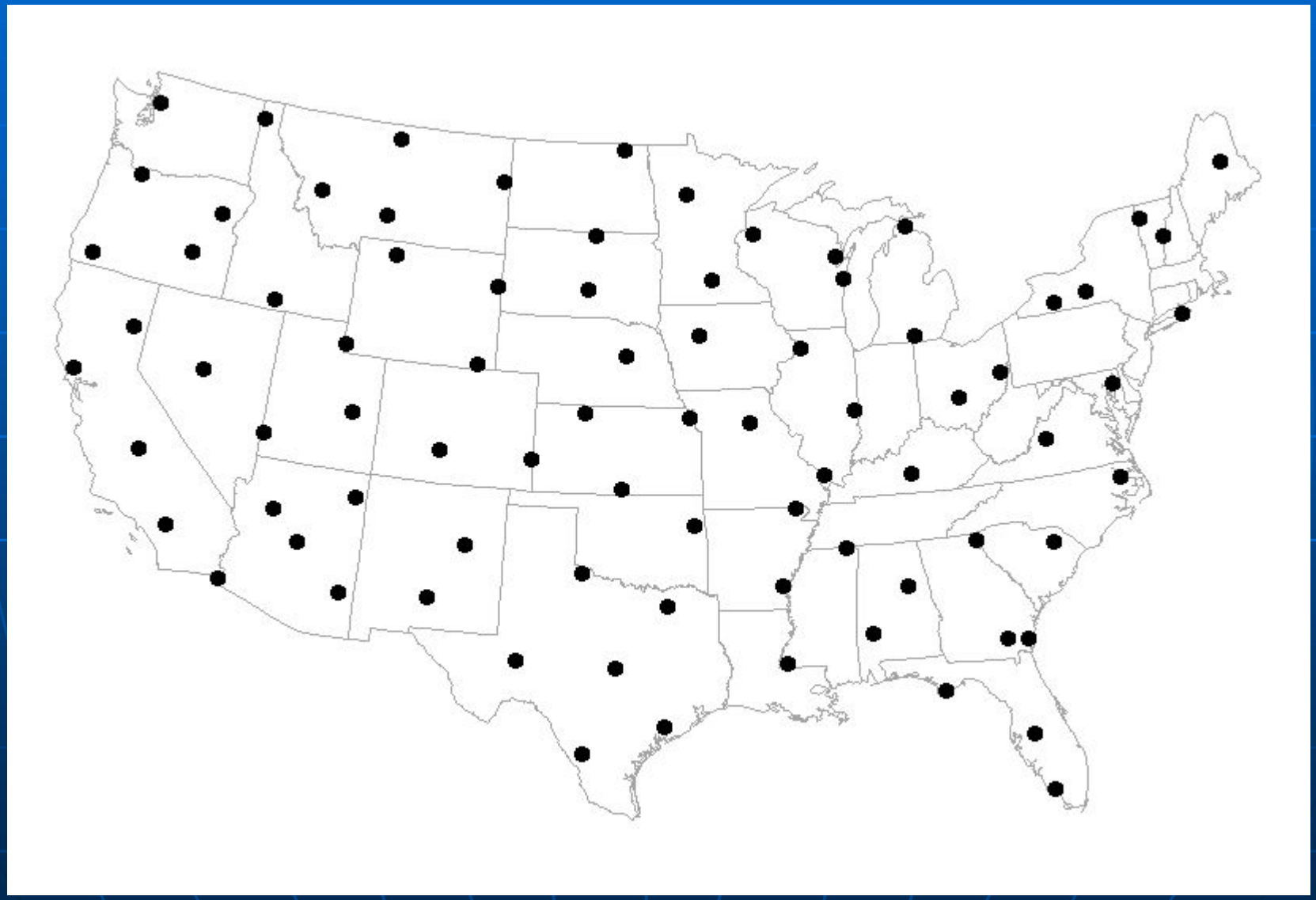


MSU Channel 4
Correlation with lat=0 and long=0

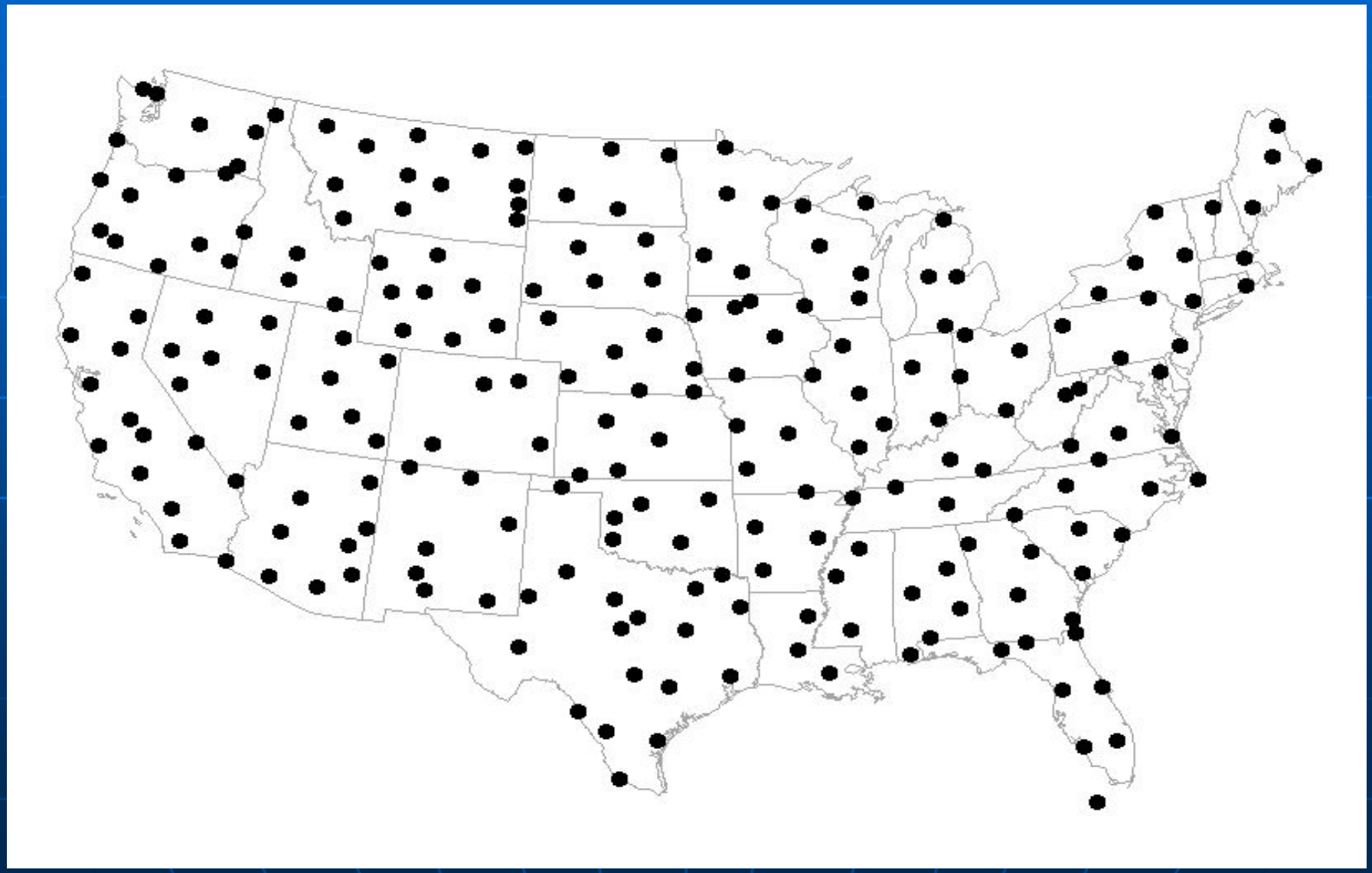


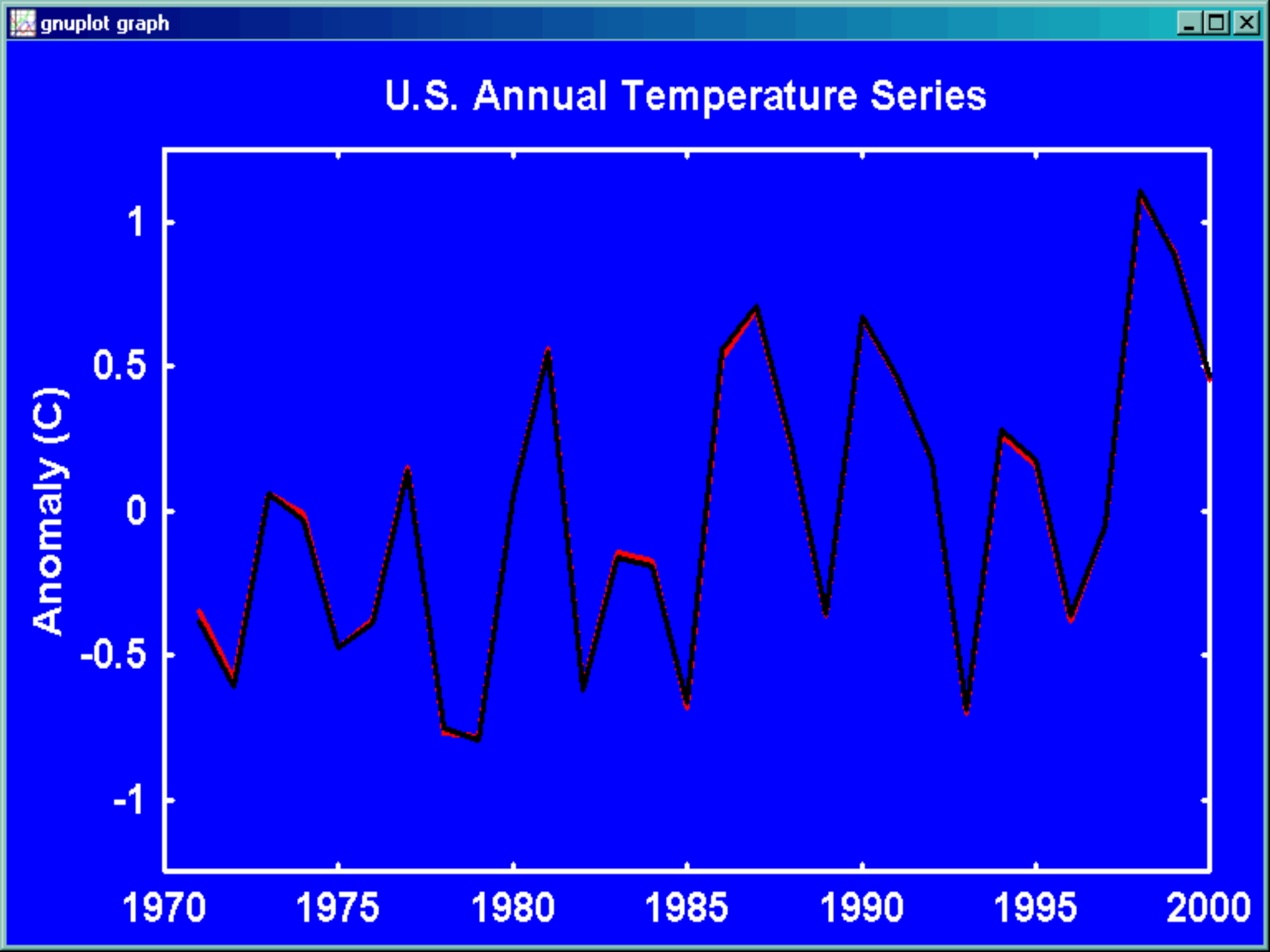
How does spatial redundancy affect our ability to detect trends?

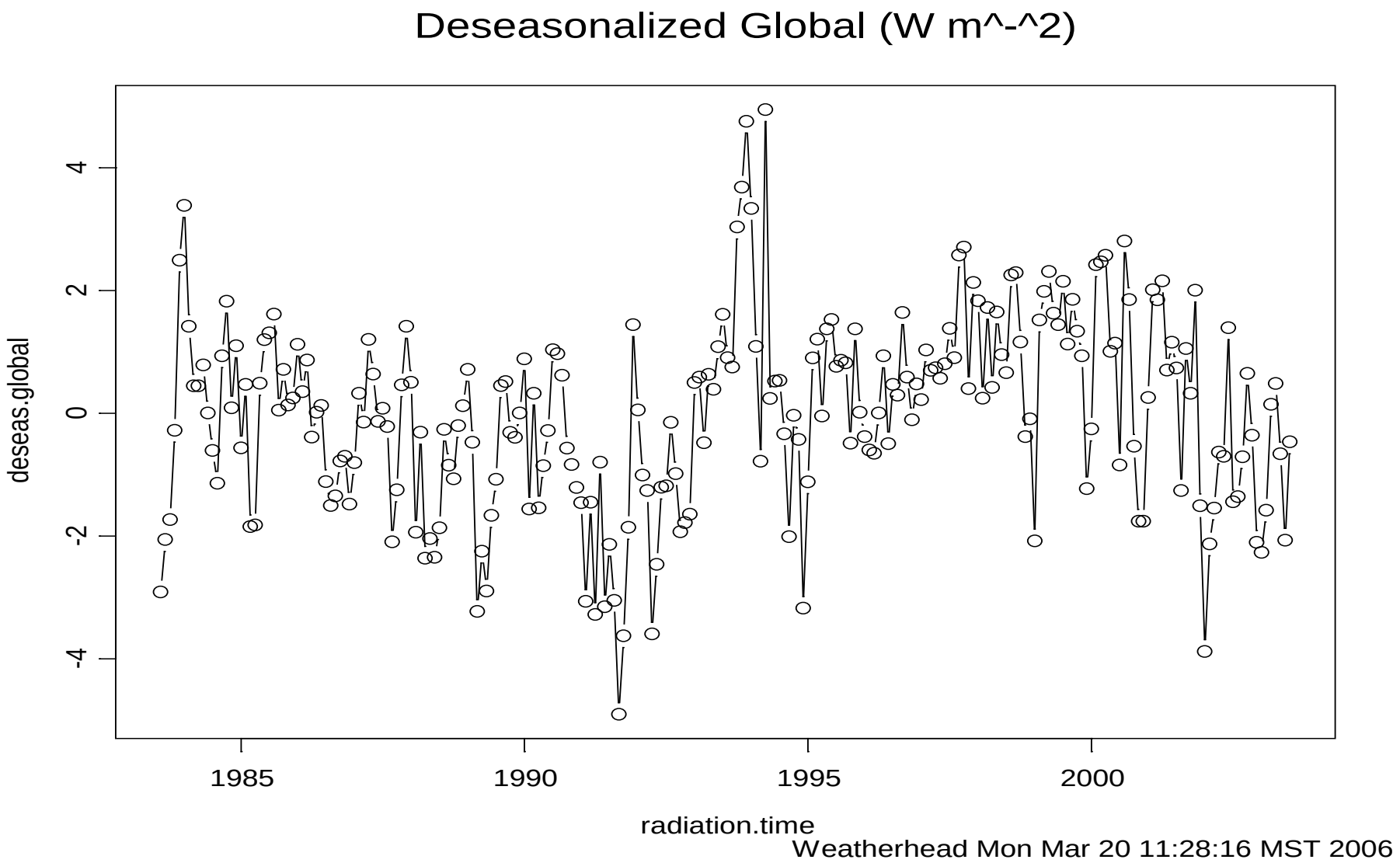
82 Station Subset of HCN Network



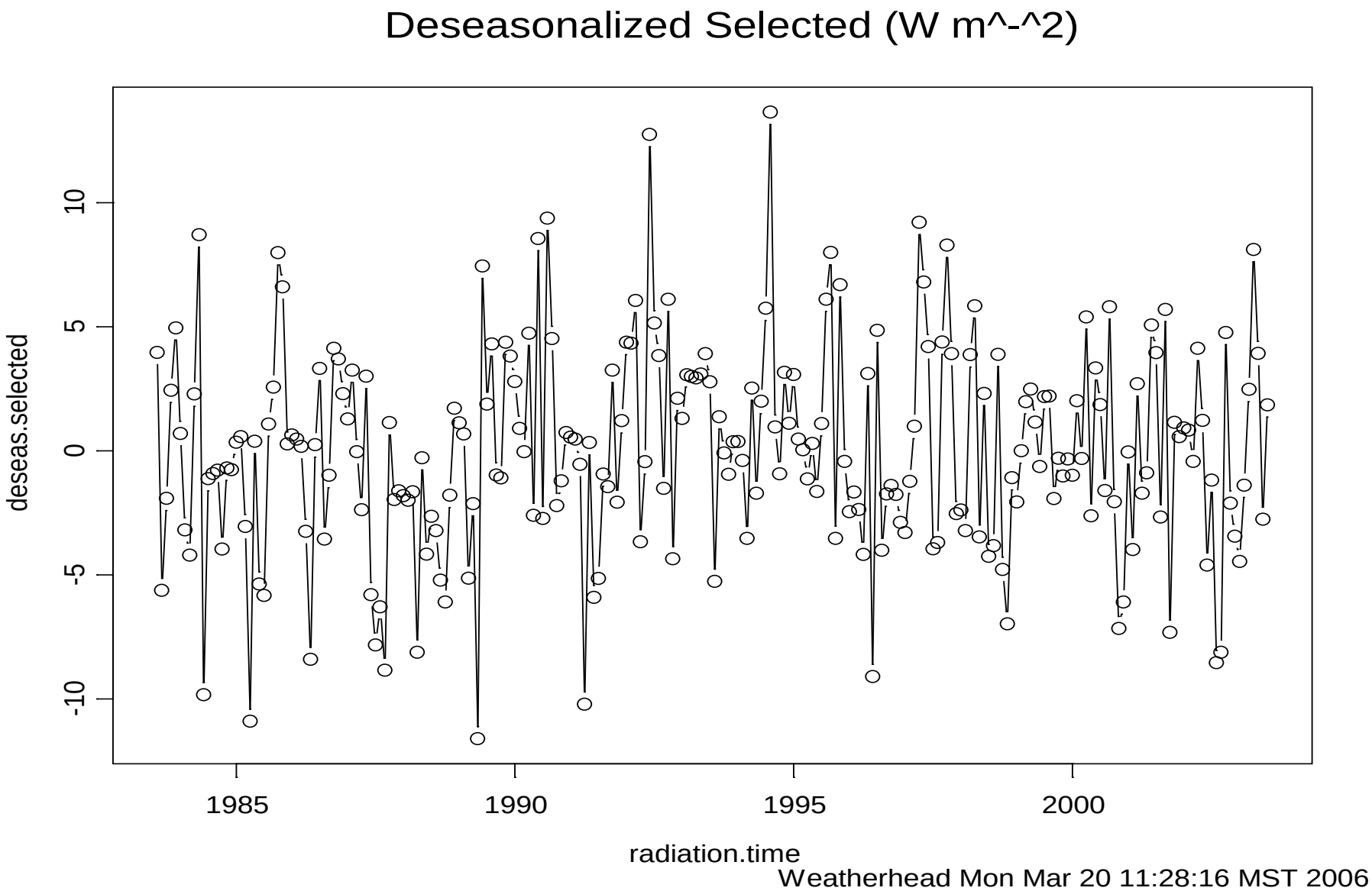
225 Station Subset of HCN Network




gnuplot graph
U.S. Annual Temperature Series
Anomaly (C)
1
0.5
0
-0.5
-1
1970
1975
1980
1985
1990
1995
2000

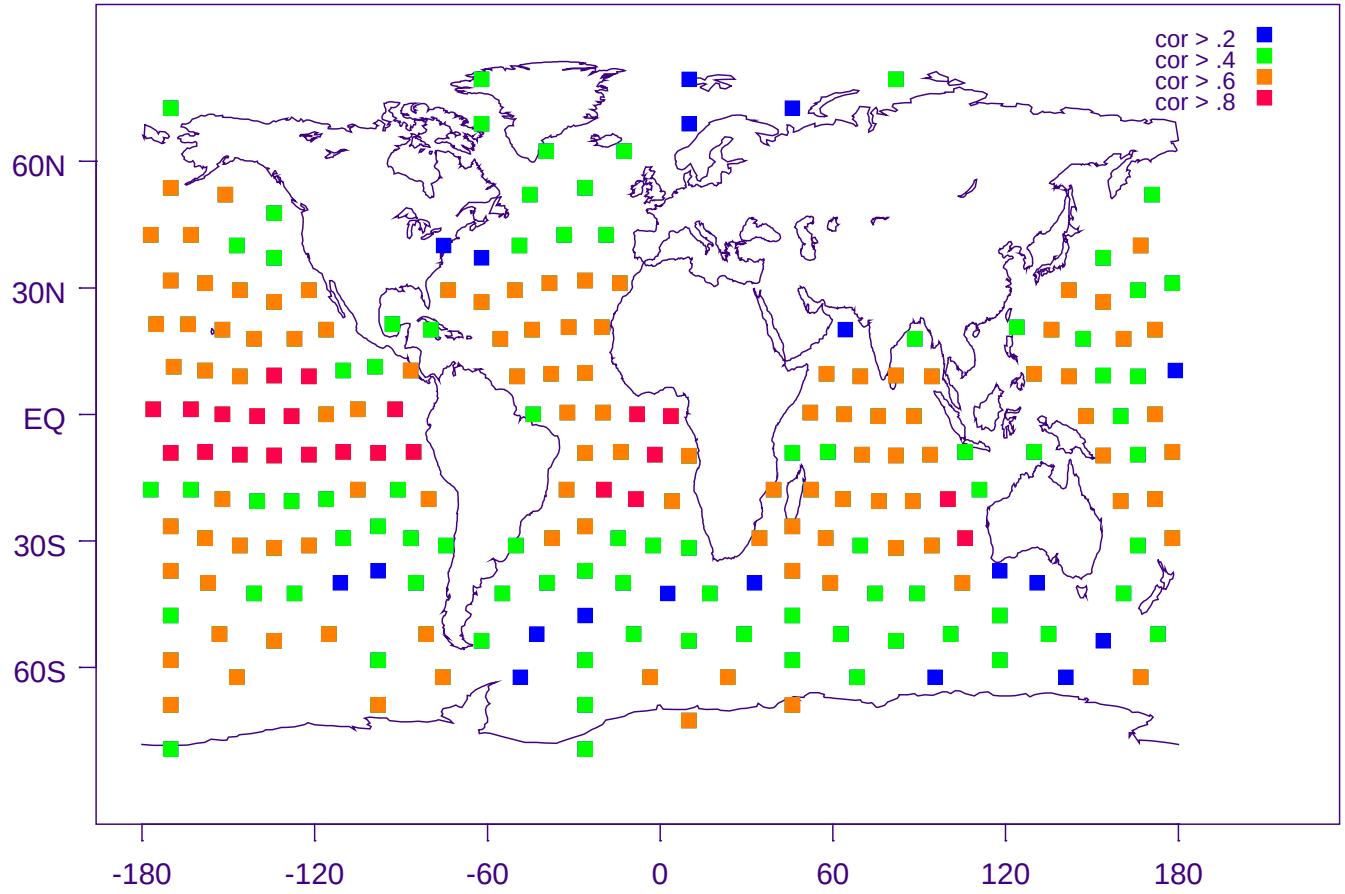


From Laura Hinkelman



From Laura Hinkelman.

Redundancy in Surface Data for Proposed Locations.



Choosing locations for monitoring

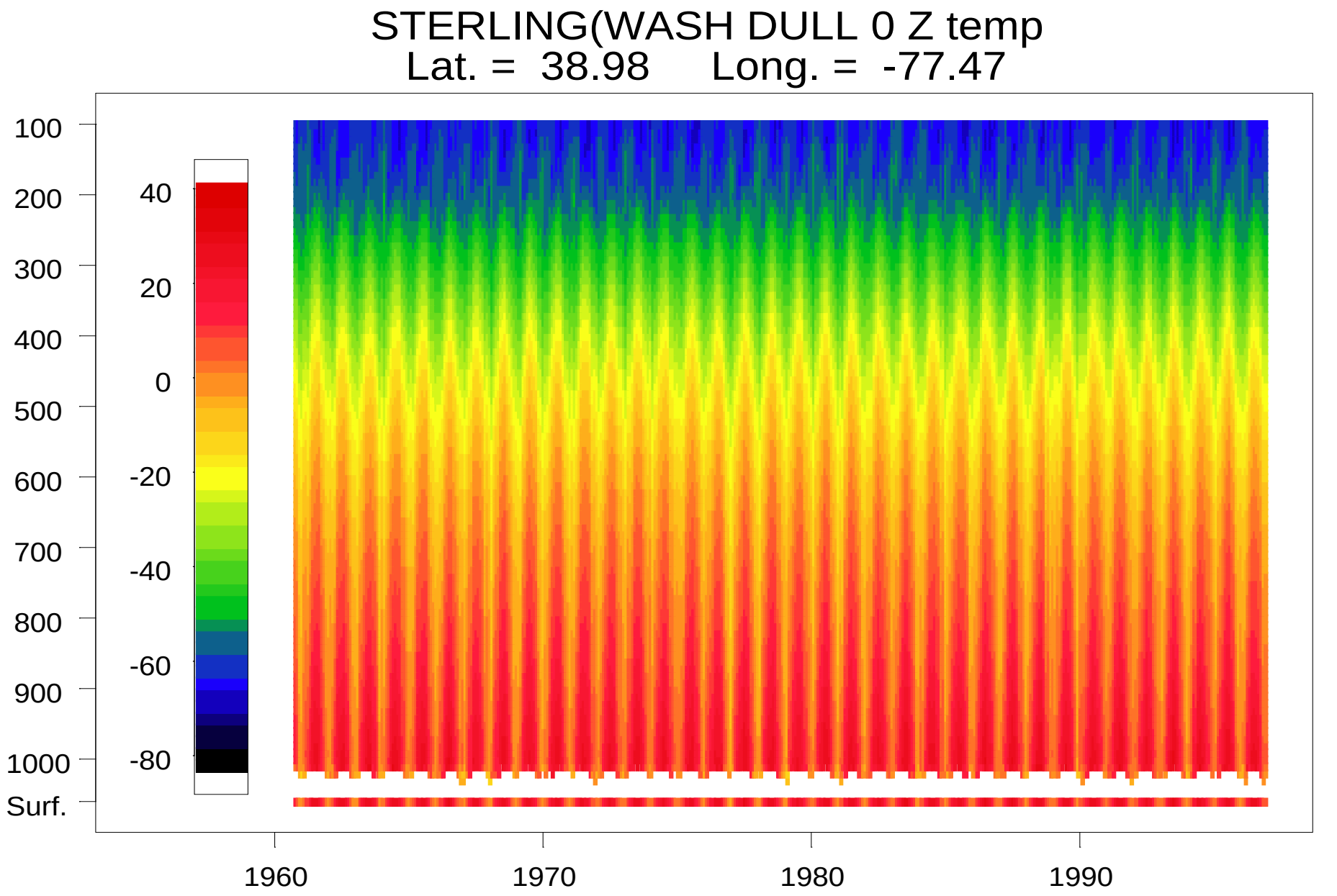
- Some locations are better than others for detecting trends.
- Sub-regional differences are likely small.
  - Define spatial scales
- What is the primary goal:
  - Estimating global change
  - Annual/seasonal/diurnal trends?
  - Understanding specific regional change
    - QBO, AO, NAO, ENSO effects?
  - Transferring standards/undersanding errors.
- Once the goal is clear, we can quantify the best approach.

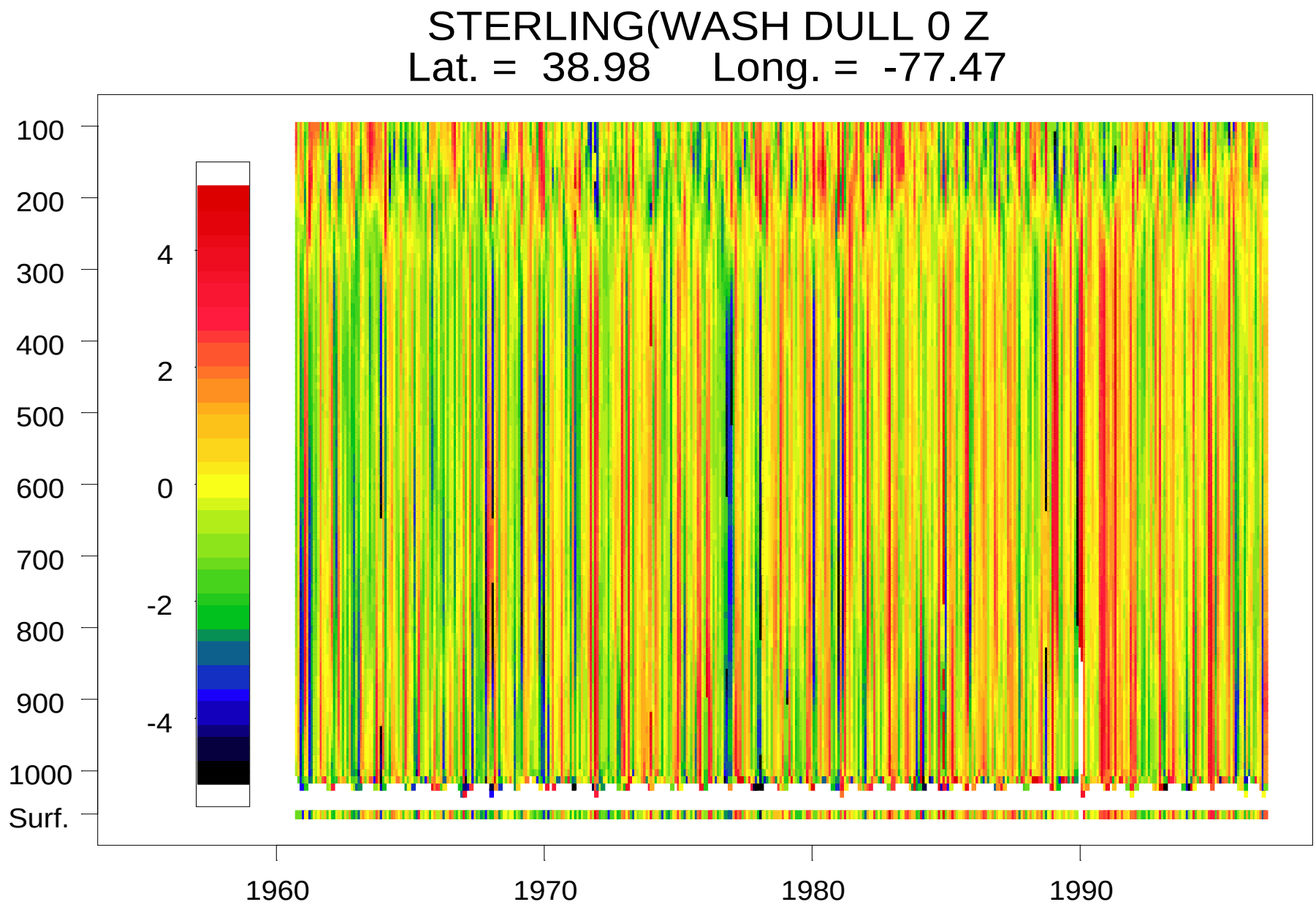
We can control only four aspects of monitoring to detect trends

- **What we monitor**
- **What accuracy**
- **Where we monitor**
- **What frequency**

What frequency?

- Inherent memory in environmental data results in redundancy of measurements.
- Daily data may be more than needed.
- Less than daily measurements may obscure diurnal changes

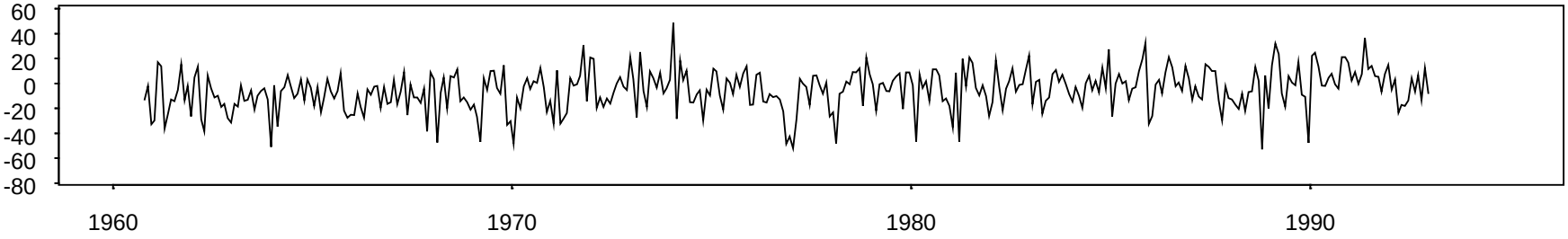

STERLING(WASH DULL 0 Z temp
Lat. = 38.98 Long. = -77.47
100
200
300
400
500
600
700
800
900
1000
Surf.
40
20
0
-20
-40
-60
-80
1960
1970
1980
1990
Weatherhead Wed Mar 13 13:30:52 200



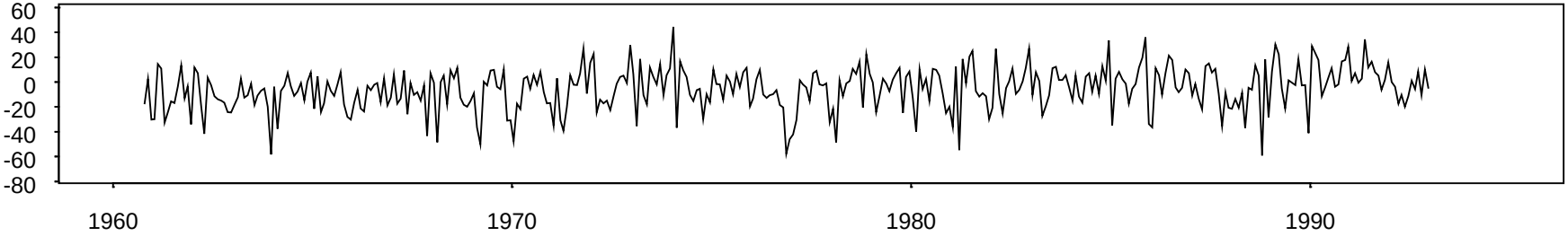
Weatherhead Wed Mar 13 13:36:18 2002

Monthly Deseasonalized Averages, 500 mb Temperature, Dulles

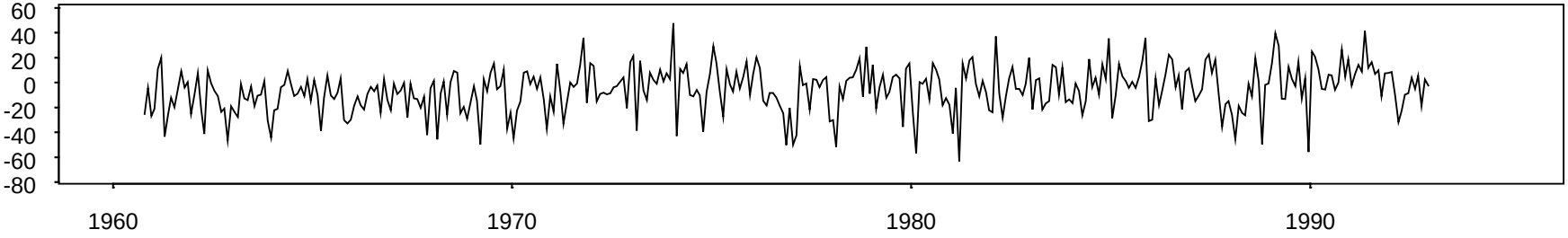
Measure Every 1 Days



Measure Every 2 Days

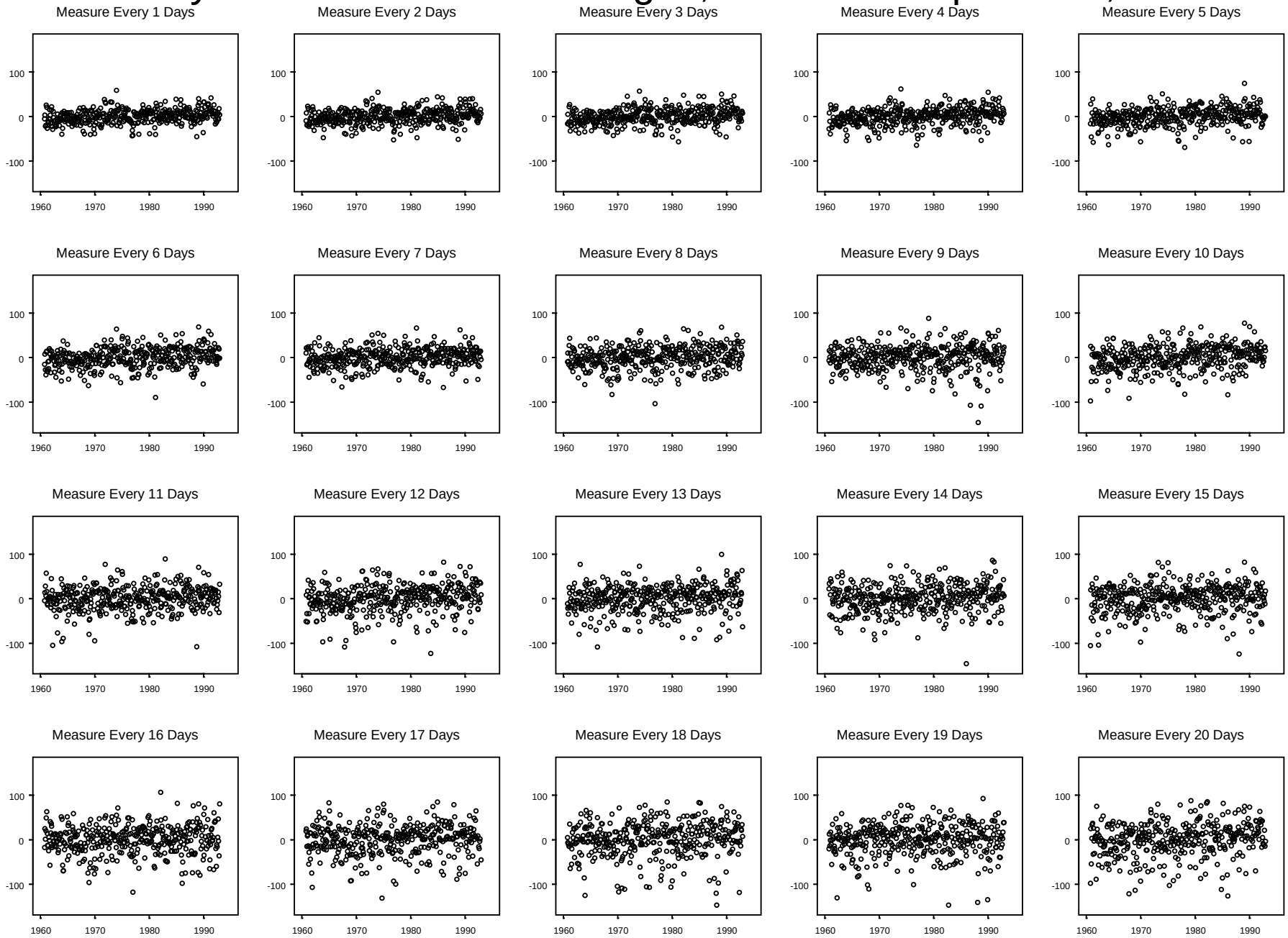


Measure Every 3 Days



Weatherhead Thu Mar 14 10:43:10 2002

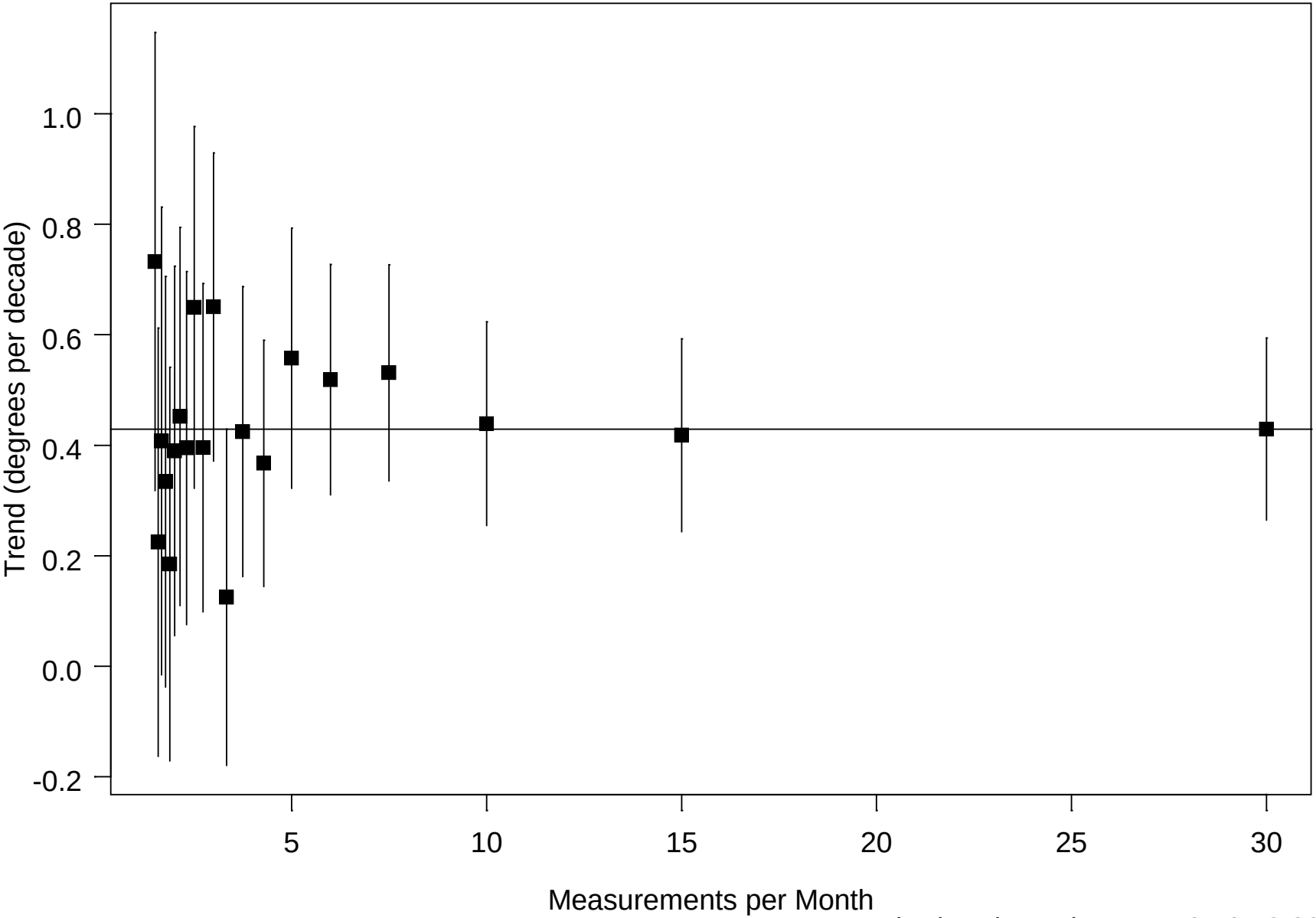
Monthly Deseasonalized Averages, 500 mb Temperature, Dulles



Weatherhead Wed Mar 13 12:50:01 2002

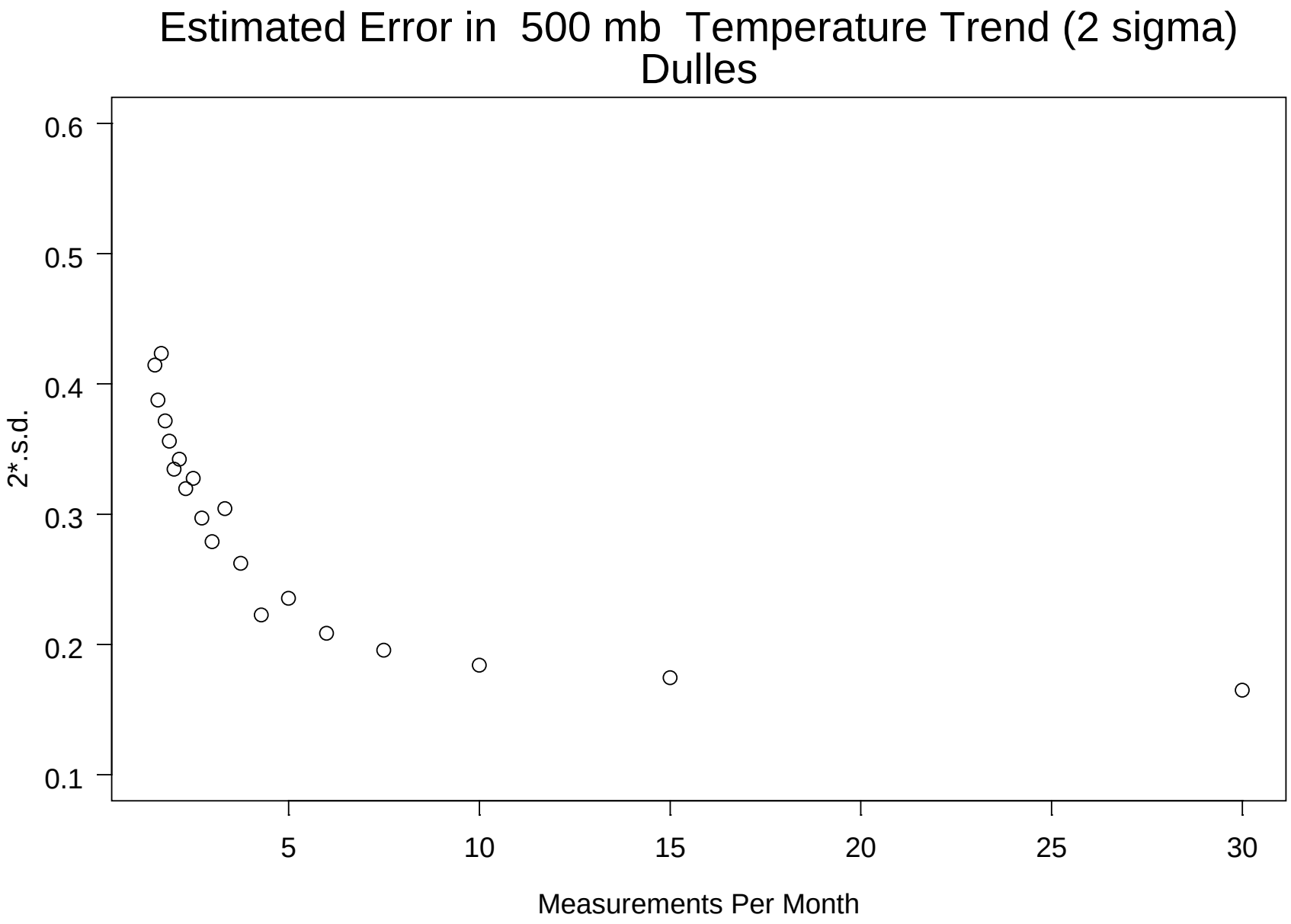
How do the trends change when we take data less frequently than every day?

500 mb Temperature Trend, Dulles

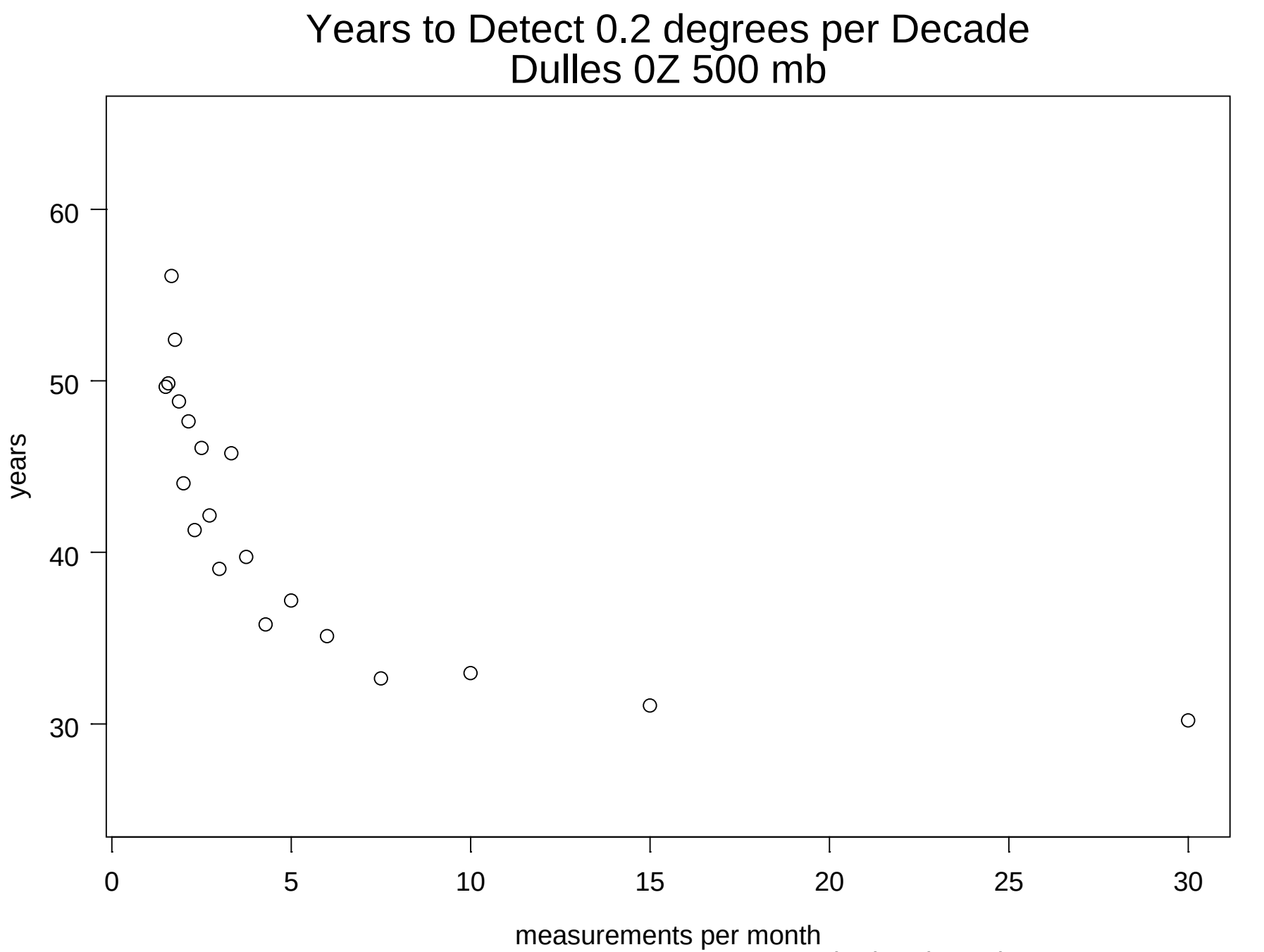


Weatherhead Wed Jun 5 12:52:10 2002

How do the error bars on our trends change when we take data less frequently than every day?


Estimated Error in 500 mb Temperature Trend (2 sigma)
Dulles
0.6
0.5
0.4
0.3
0.2
0.1
2*.s.d.
5
10
15
20
25
30
Measurements Per Month

How long will it take to detect trends?


Years to Detect 0.2 degrees per Decade
Dulles 0Z 500 mb
years
60
50
40
30
0
5
10
15
20
25
30
measurements per month
Weatherhead Wed Jun 5 12:45:30 2002

How does frequency of measurement affect how long we will have to monitor to detect trends?

In general: Monitoring less frequency:

- Increases magnitude of variability (bad for trends)
- Decreases autocorrelation (good for trends)
- Reduces representativeness (do we really know what happened?)

Decreasing the data frequency

- We can estimate the cost (in number of years of monitor) to decrease the data frequency.
- Decreasing the data frequency can reduce our ability to:
  - Detect extreme events
  - Detect diurnal (or perhaps seasonal) signals

We can control only four aspects of monitoring to detect trends

- **What we monitor**
- **What accuracy**
- **Where we monitor**
- **What frequency**

Integration

- We make choices about all four of the parameters we control.
- These choices have direct impact on how long we will likely need to monitor in order to detect trends.
- Optimal choices exist.
  - e.g. More sites or higher accuracy?
- All choices will affect our ability to detect trends and the scientific questions we may ask of the emerging data.

Improved Accuracy or More Sites?

- **Improved Accuracy**

- Clearer understanding of what we've measured
- Costs often increase exponentially
- Time for trend detection decreases

- **Additional Sites**

- Costs increase in a known manner
- Time for trend detection decreases - usually slightly
- Representativeness improves and expands
- "Insurance" for site failures

Conclusion

1. We can control only four aspects to detect trends:
   - What we monitor; Where we monitor;
   - What frequency; What accuracy
2. We can optimize systems when we have a clear goal.
   - Establish accuracy and transfer ability
   - Establish global trends
   - Establish regional trends
   - Monitor key climate features
3. Optimization provides the following benefits:
   - Answering scientific questions earlier
   - Confirming, improving models
   - Allowing for earliest policy decisions
   - Maintaining prudent use of available funds