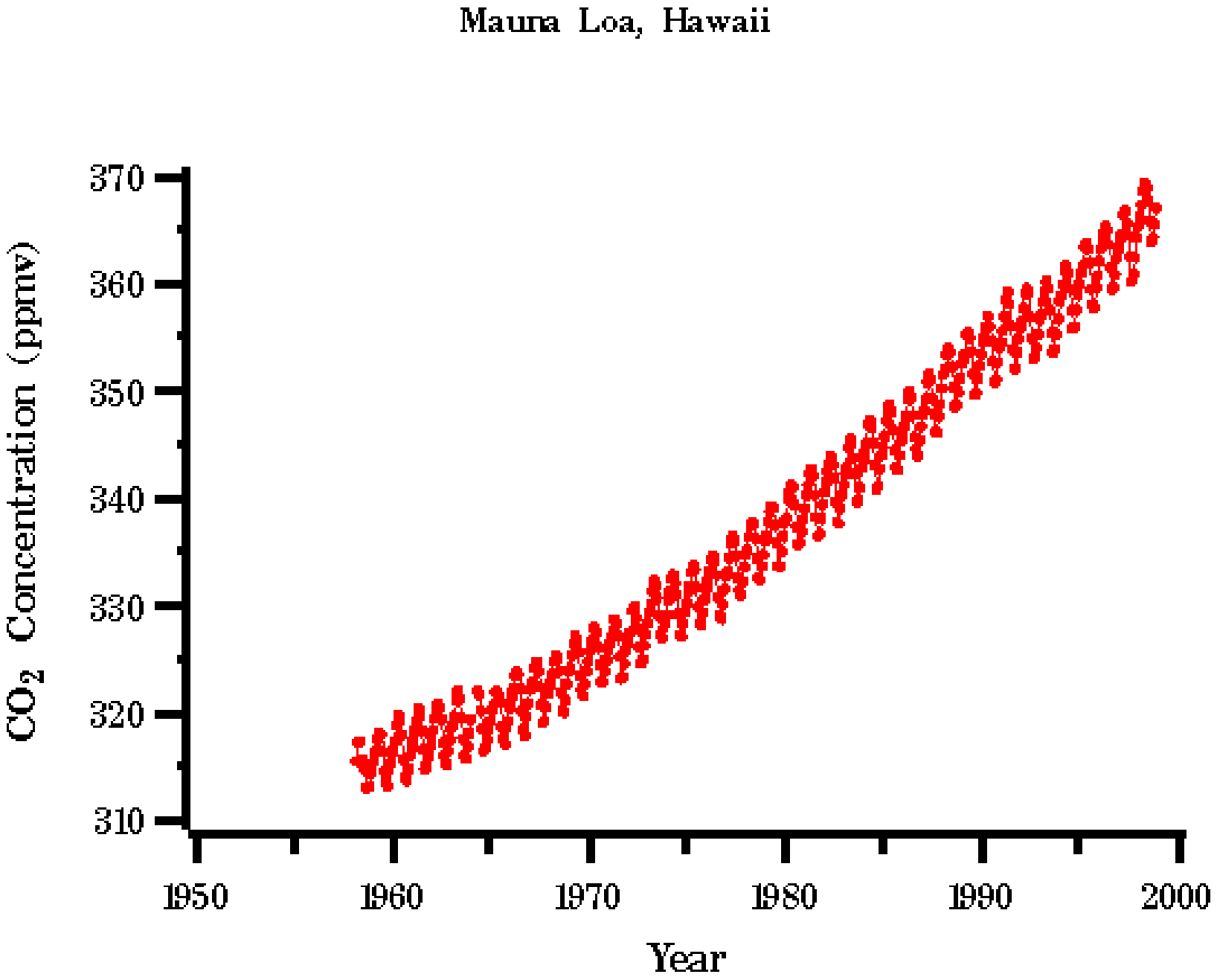
Designing Monitoring Systems to Detect Trends: Setting Quantitative Criteria

Betsy Weatherhead, Greg Reinsel, George, Tiao, Sandy MacDonald

Designing Monitoring Systems to Detect Trends

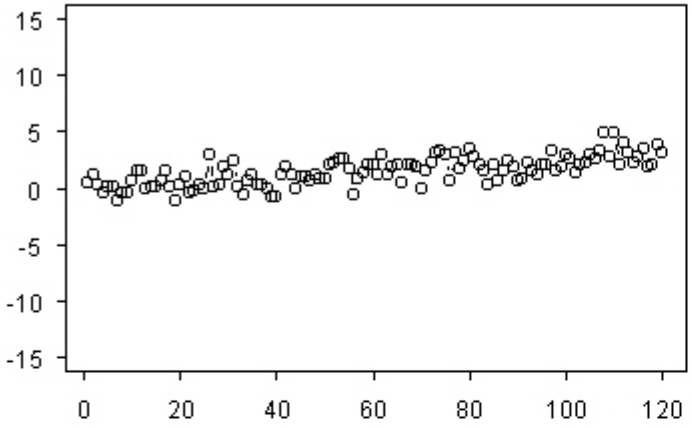
E. C. Weatherhead, J. E. Frederick, T. Karl, A. McDonald, G. C. Tiao, G. Reinsel, X.-L. Meng, A. J. Miller, D. Wuebbles, M. Stein, R. Voss


Mauna Loa, Hawaii
370
360
350
340
330
320
310
CO_2 Concentration (ppmv)
1950
1960
1970
1980
1990
2000
Year

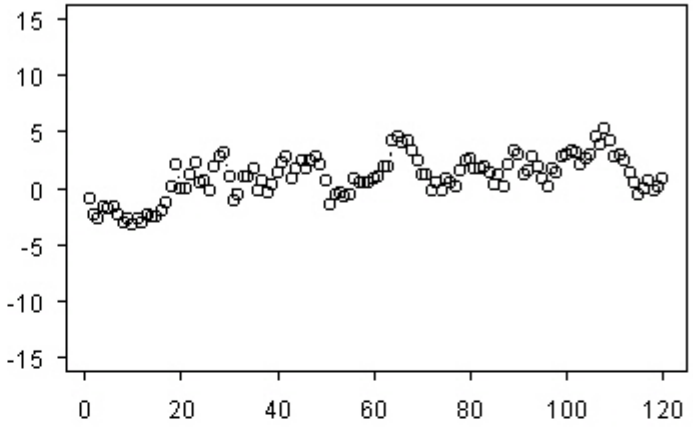
Trend Detection

- “Finding a change which is large relative to natural variability.”
- Both the magnitude of variability and the memory hinder our ability to detect trends.
- Finding a change which is large relative to natural variability and instrument uncertainty.

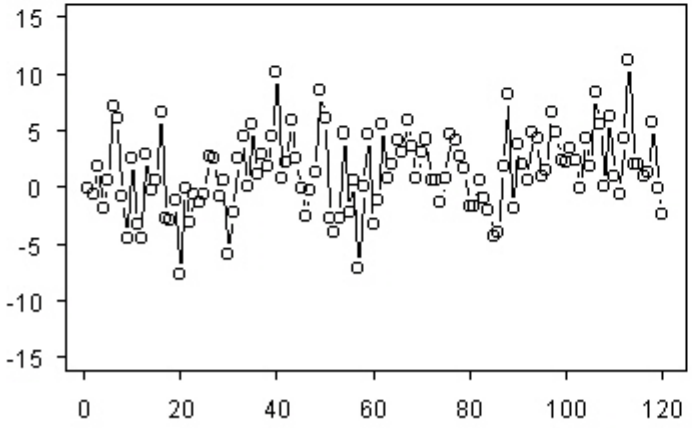
Low Noise, Low Autocorrelation



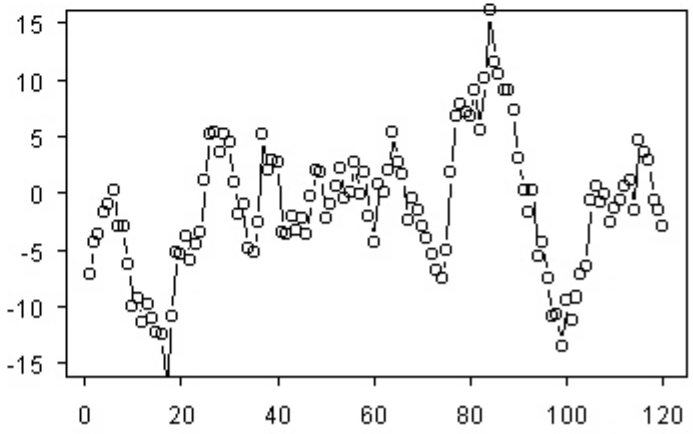
Low Noise, High Autocorrealtion



High Noise, Low Autocorrelation



High Noise, High Autocorrelation



Number of Years needed to detect a trend

- Approximately:

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

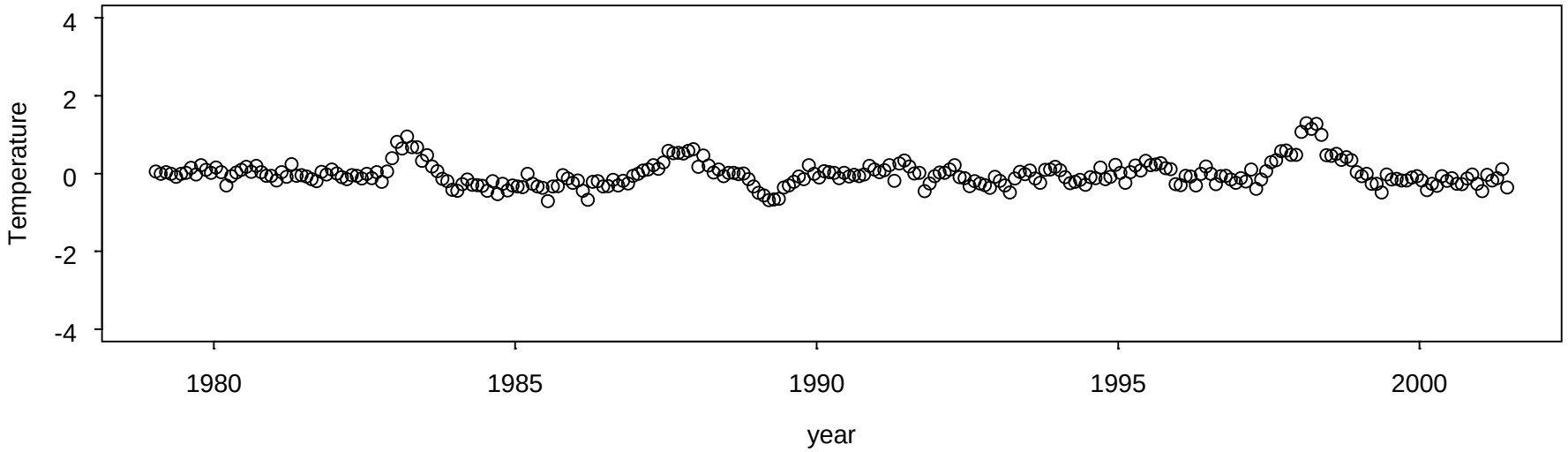
- Assuming that detection is declared at the 95% confidence level
- This estimate allows for 50% likelihood of detection

Years to Detect .2 Degrees per Decade Trend in Temperature

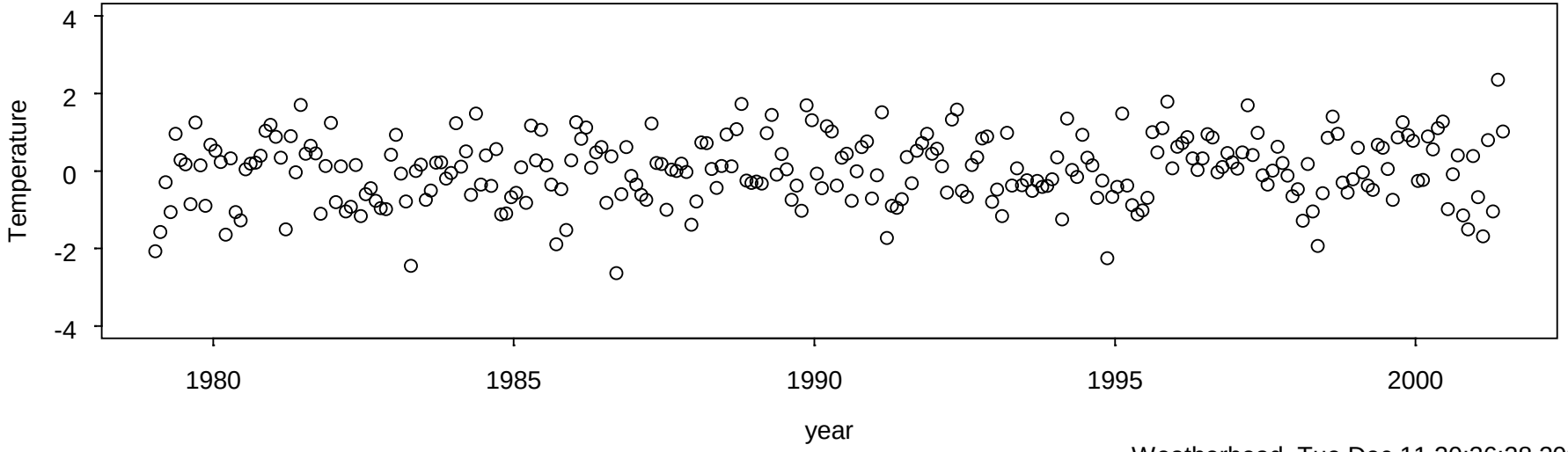
	0	.3	.6	.9
.5	14	17	21	35
1	22	26	34	56
3	45	55	71	100+
5	63	77	100+	100+

MSU Channel 2

Equator

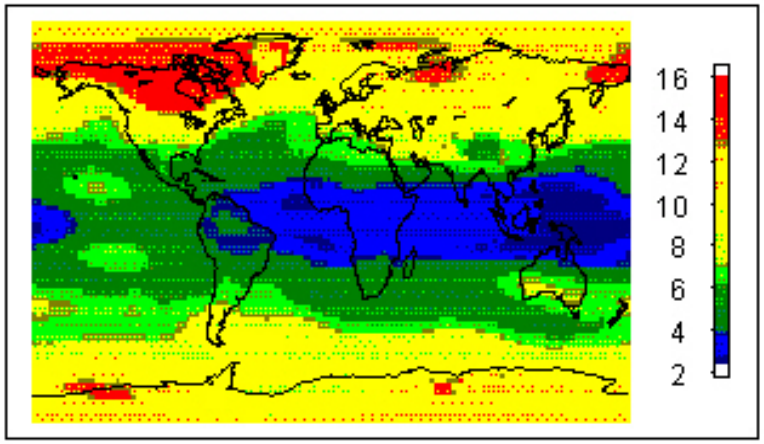


San Francisco

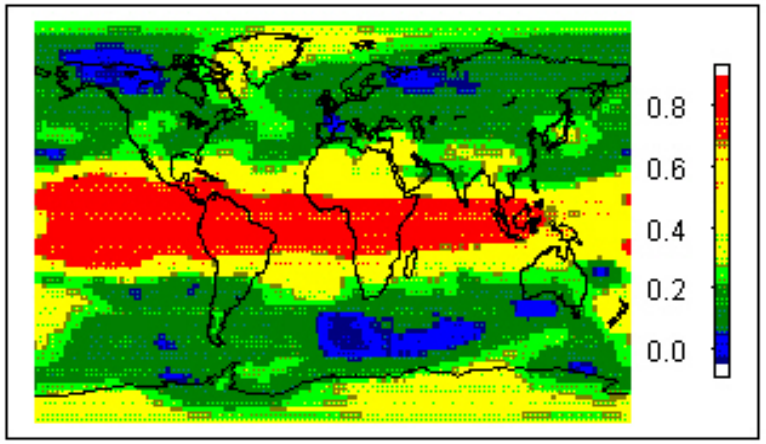


Weatherhead Tue Dec 11 20:36:28 2001

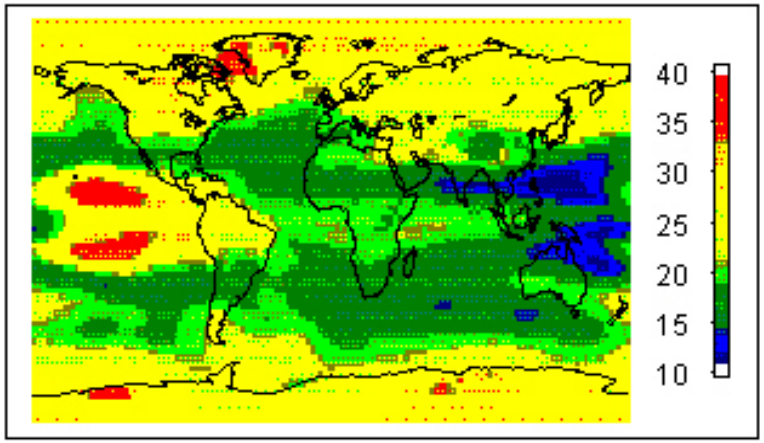
MSU channel 2, sigma_n



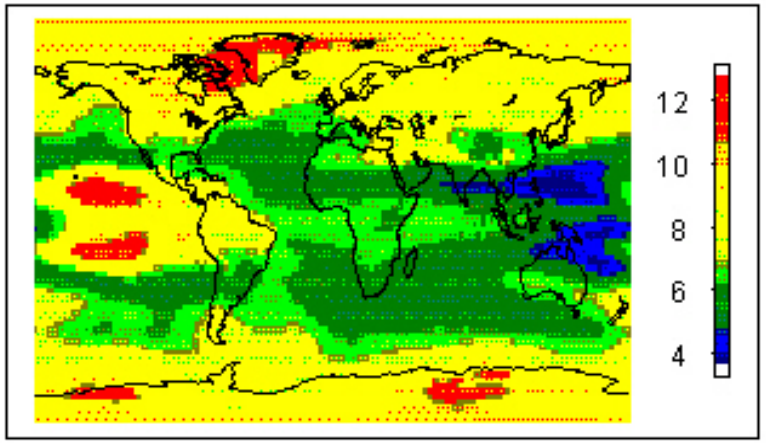
MSU channel 2, phi



MSU channel 2, years to detect .2 deg/decade



MSU channel 2, years to detect 1 deg/decade

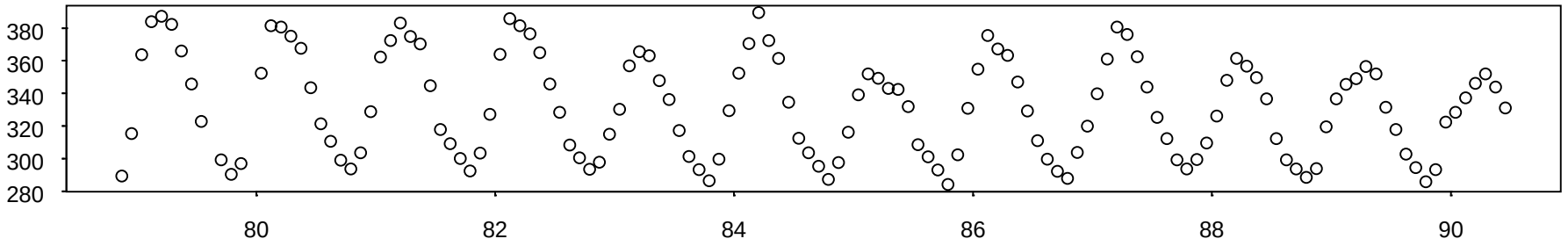


Visual Example

- 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

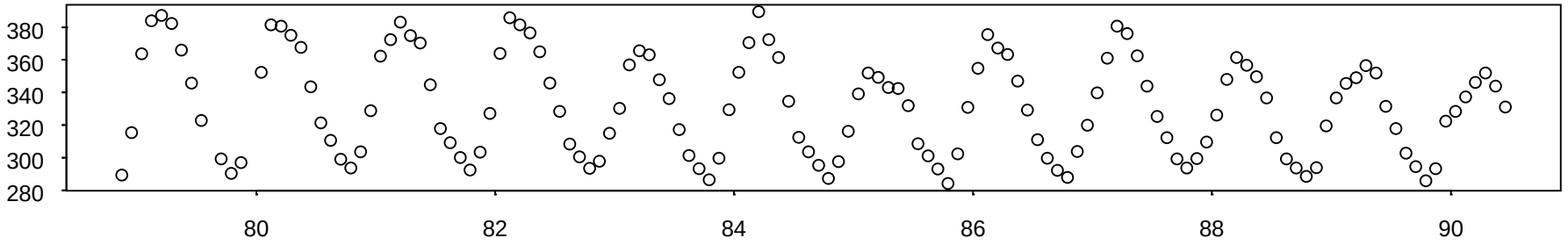
Original Monthly Averaged Data



Weatherhead Fri Nov 2 11:38:10 2001

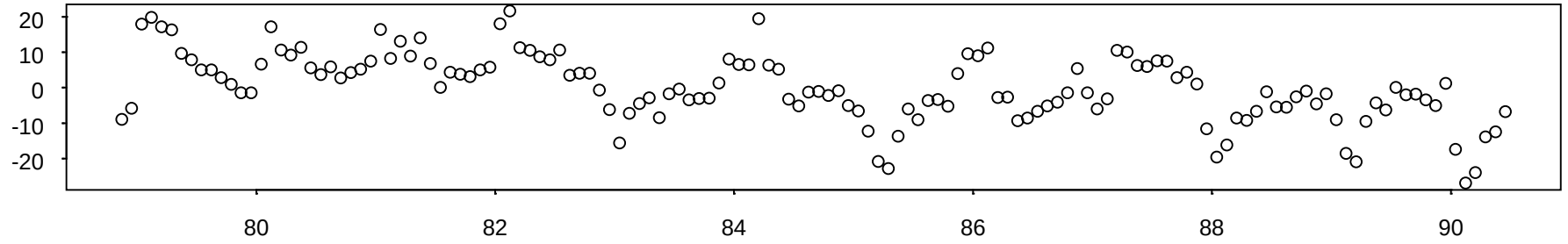
SBUV OZONE TOTAL COLUMN OZONE - 40N

Original Monthly Averaged Data



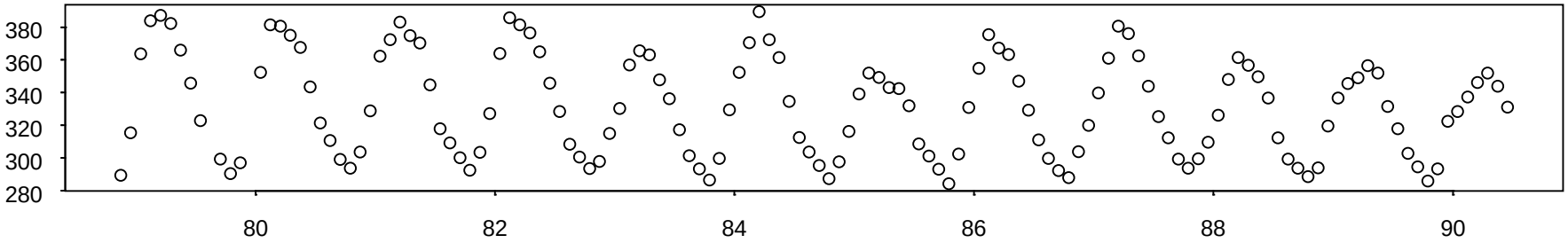
Weatherhead Fri Nov 2 11:48:50 2001

Monthly Means Removed, Lowess Line Fit Superimposed



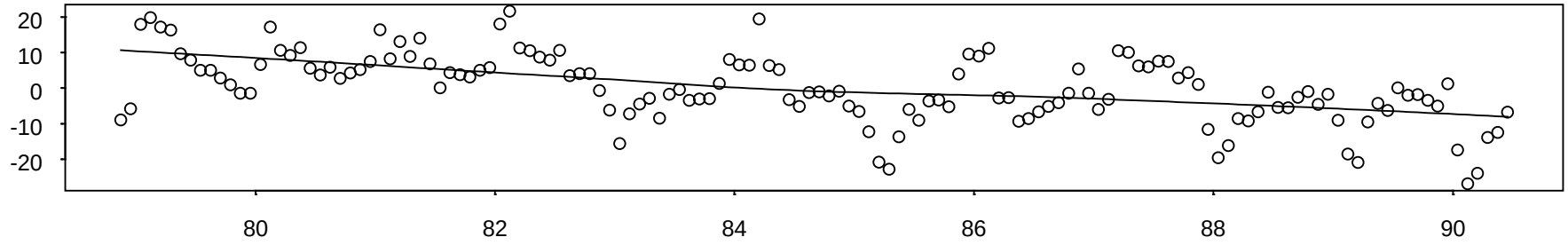
SBUV OZONE TOTAL COLUMN OZONE - 40N

Original Monthly Averaged Data



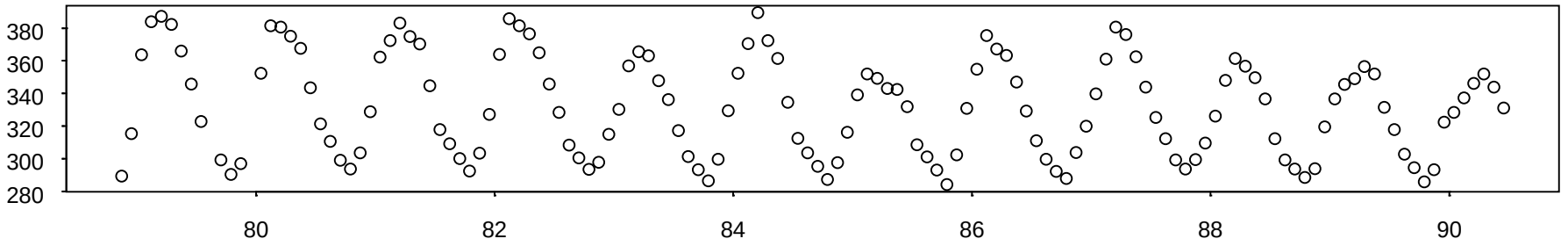
Weatherhead Fri Nov 2 11:48:50 2001

Monthly Means Removed, Lowess Line Fit Superimposed



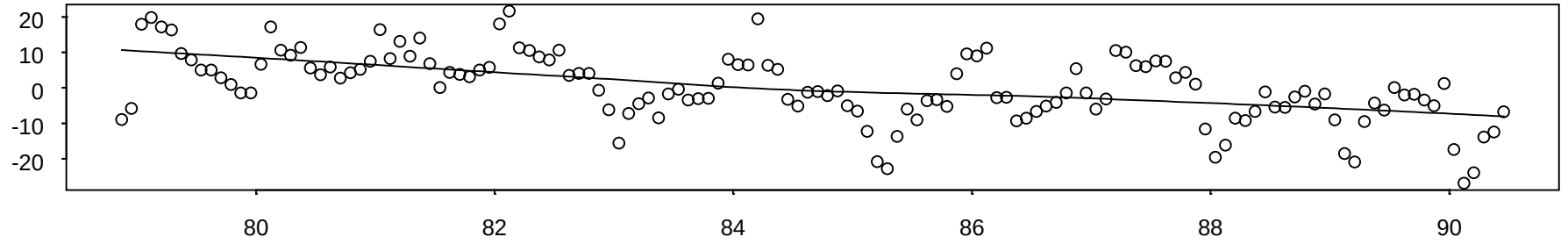
SBUV OZONE TOTAL COLUMN OZONE - 40N

Original Monthly Averaged Data

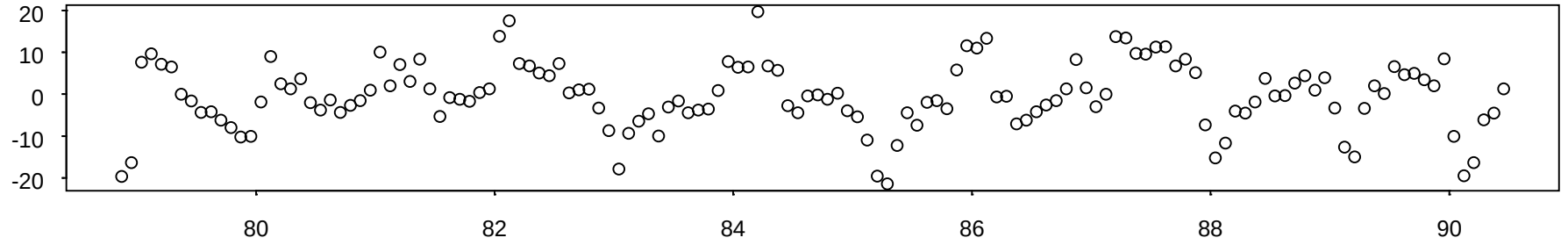


Weatherhead Fri Nov 2 11:48:50 2001

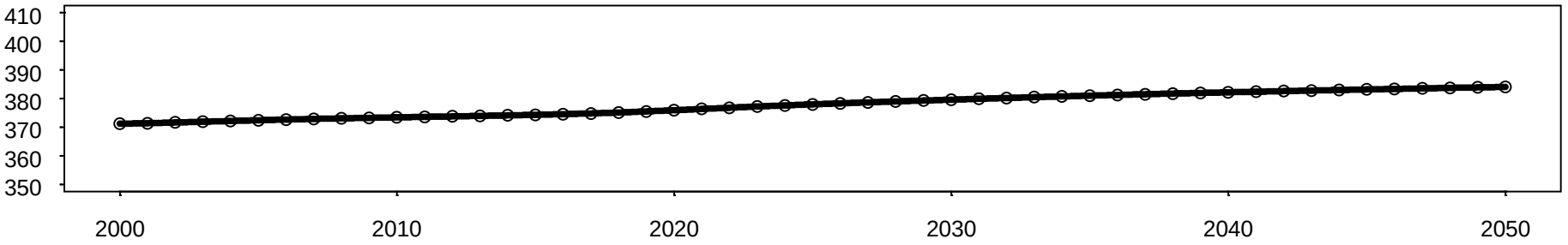
Monthly Means Removed, Lowess Line Fit Superimposed



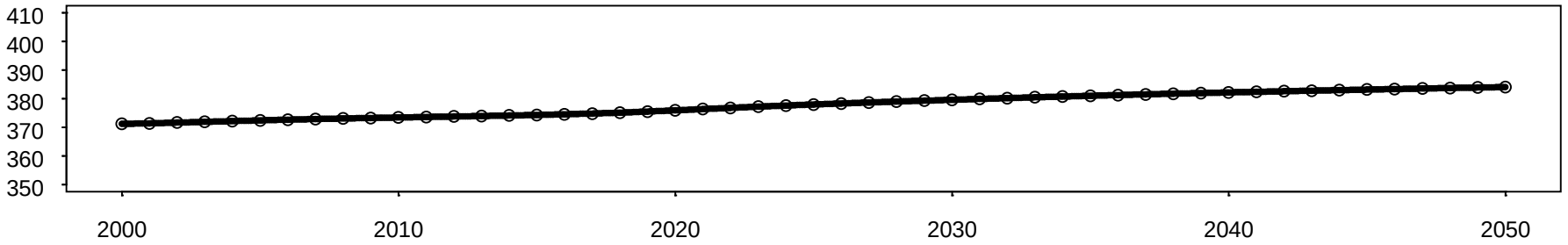
Residuals From Lowess Line Fit



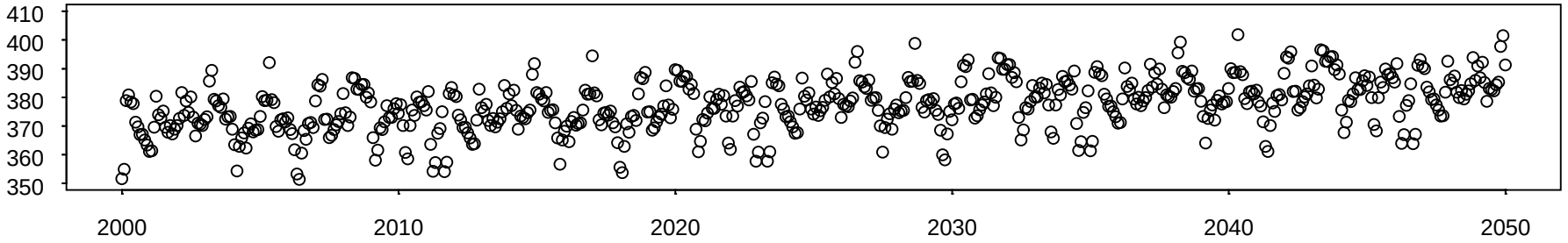
GSFC Predictions - without climate change



GSFC Predictions - without climate change



GSFC Predictions with SBUV Lowess Residuals



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

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

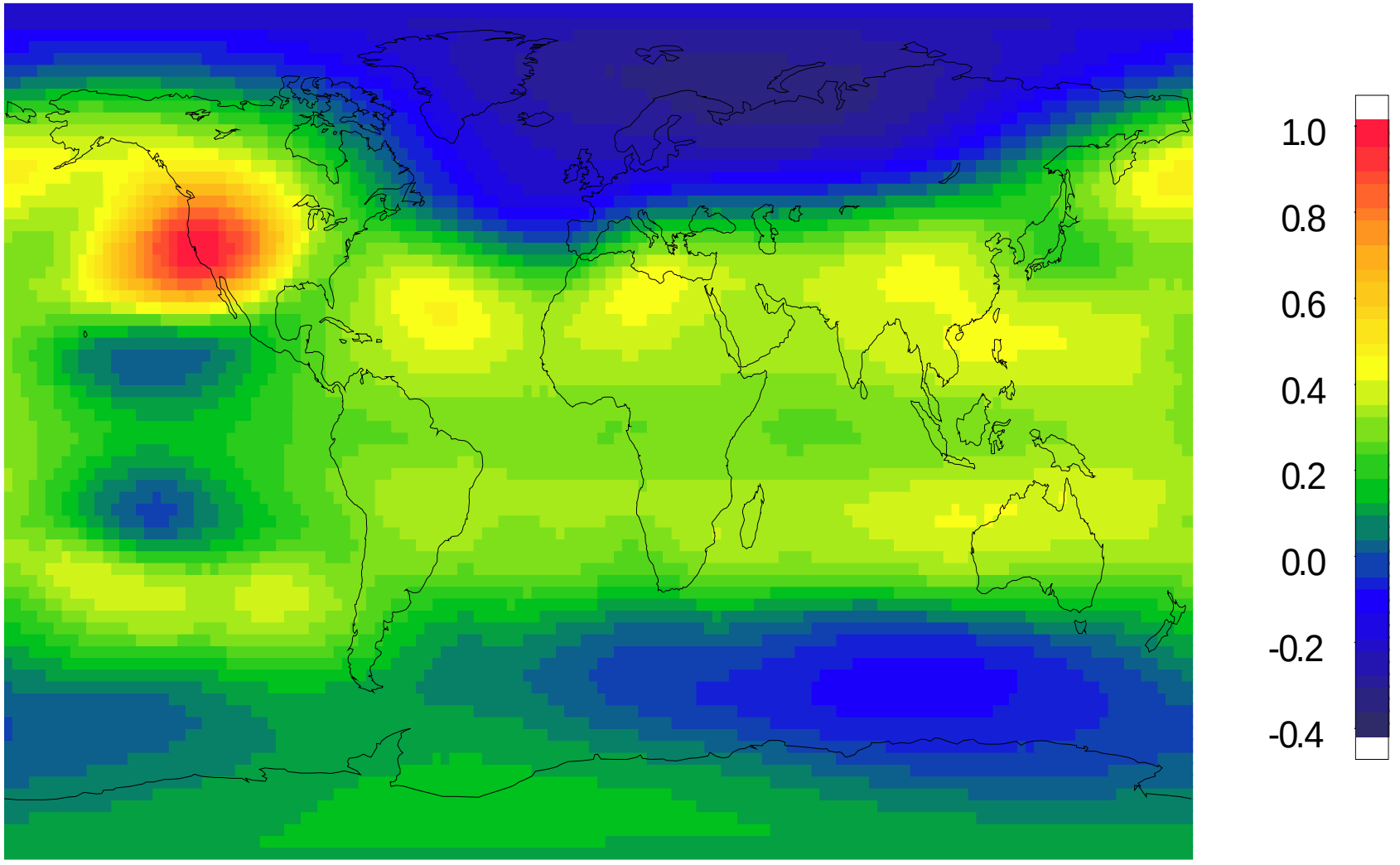
Where do we monitor?

- 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

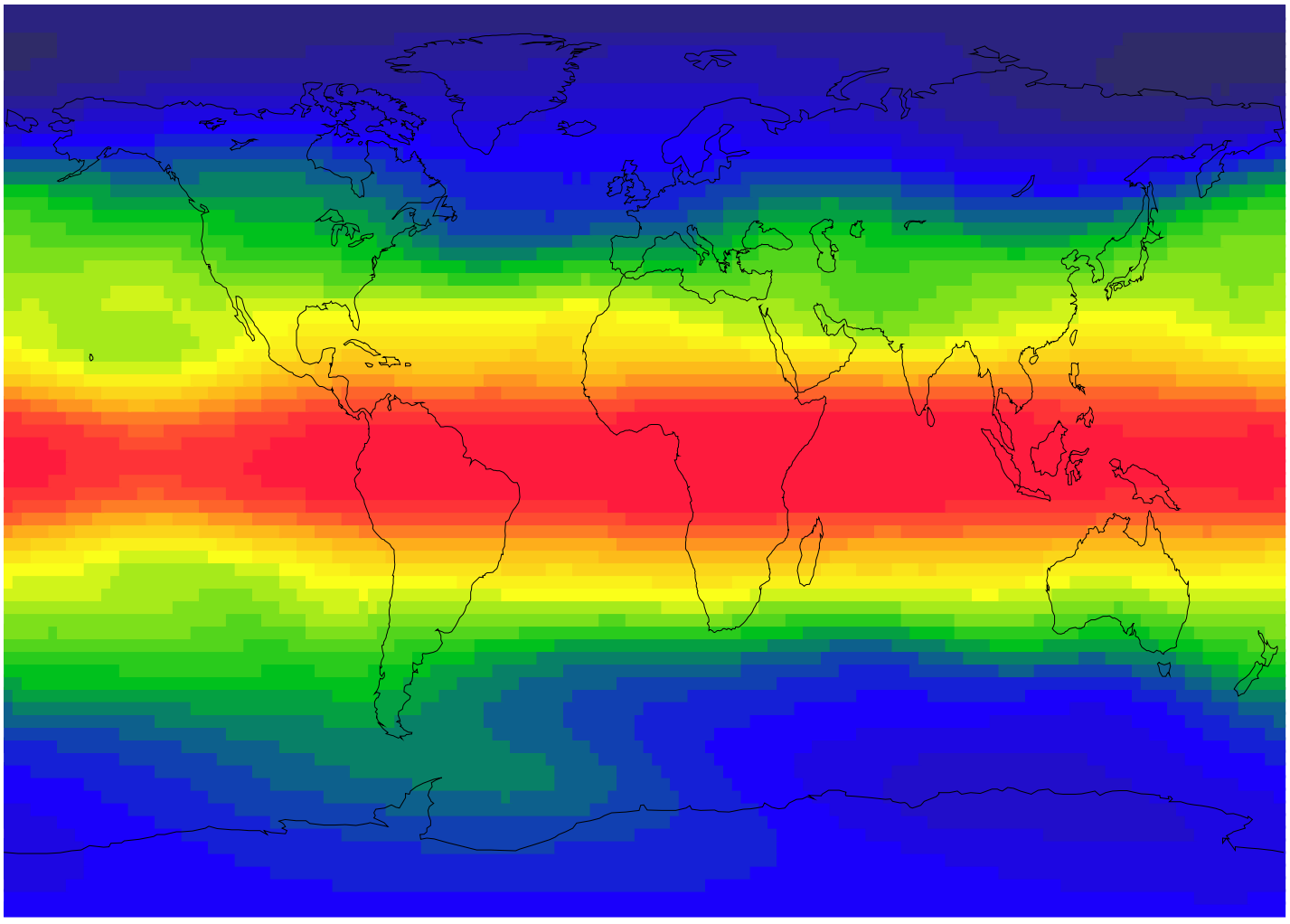
How many single stations do we need?

- 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.

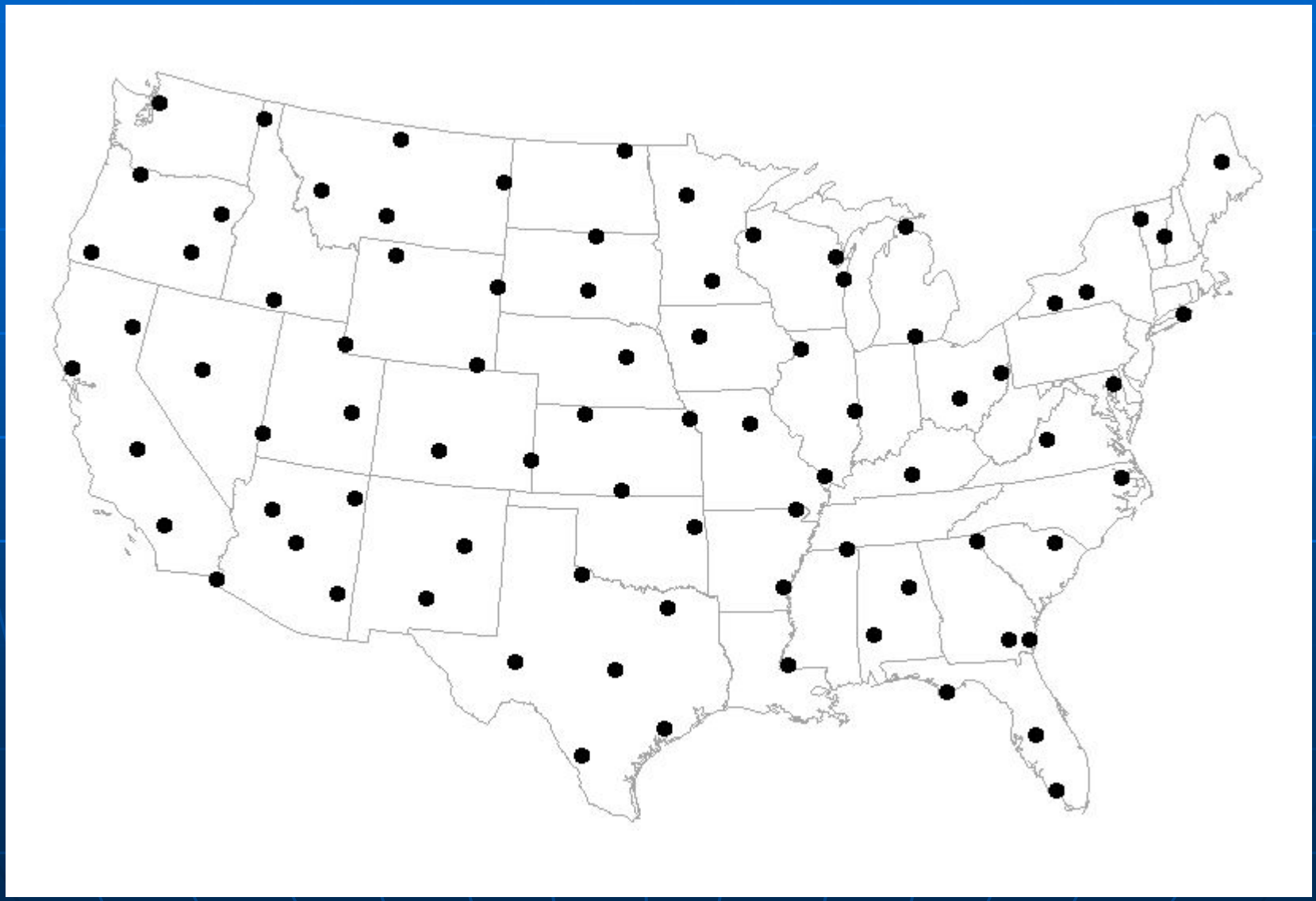


MSU Channel 4
Correlation with lat=0 and long=0

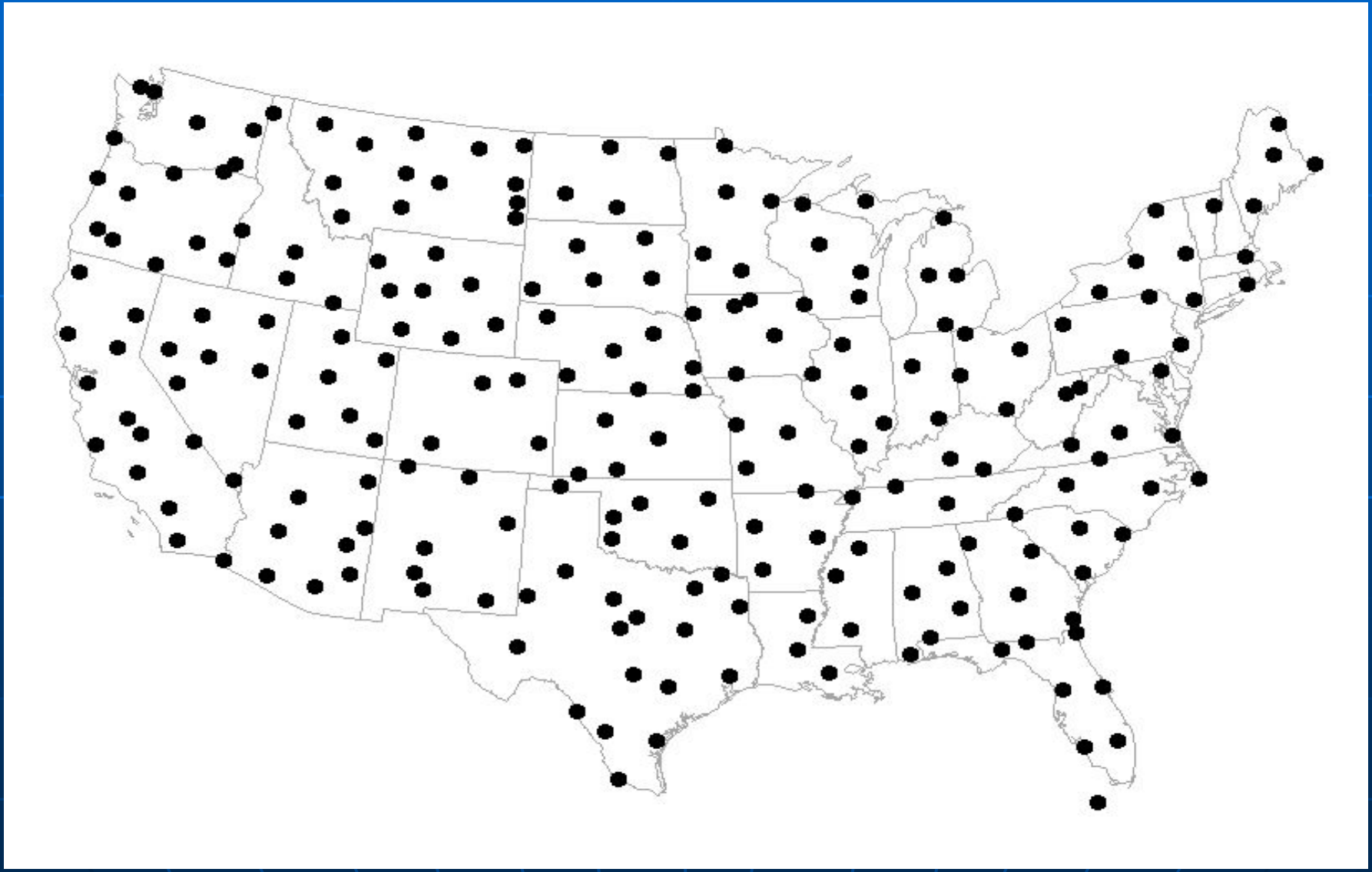


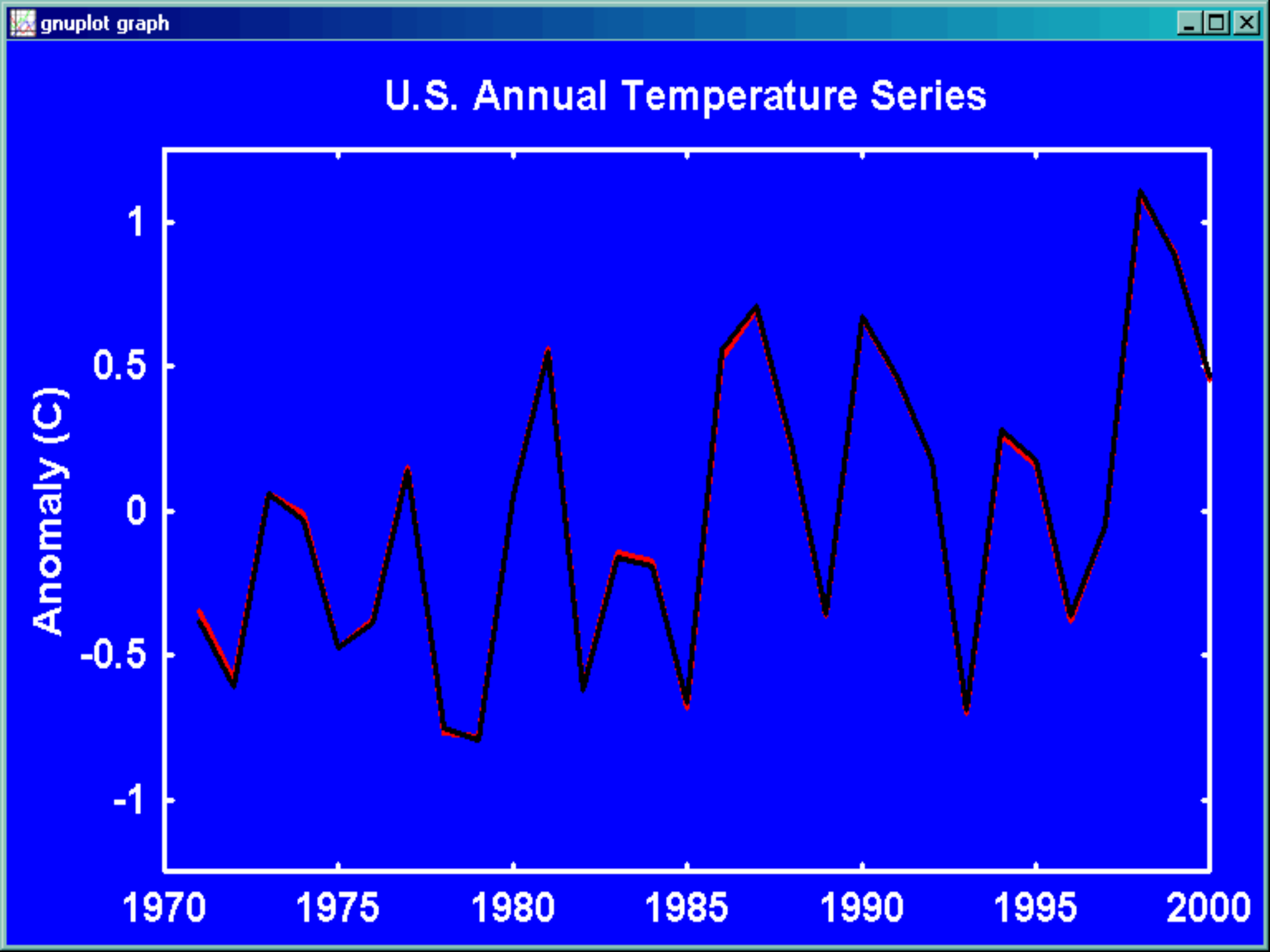
How does spatial redundancy affect our ability to detect trends?

82 Station Subset of HCN Network



225 Station Subset of HCN Network



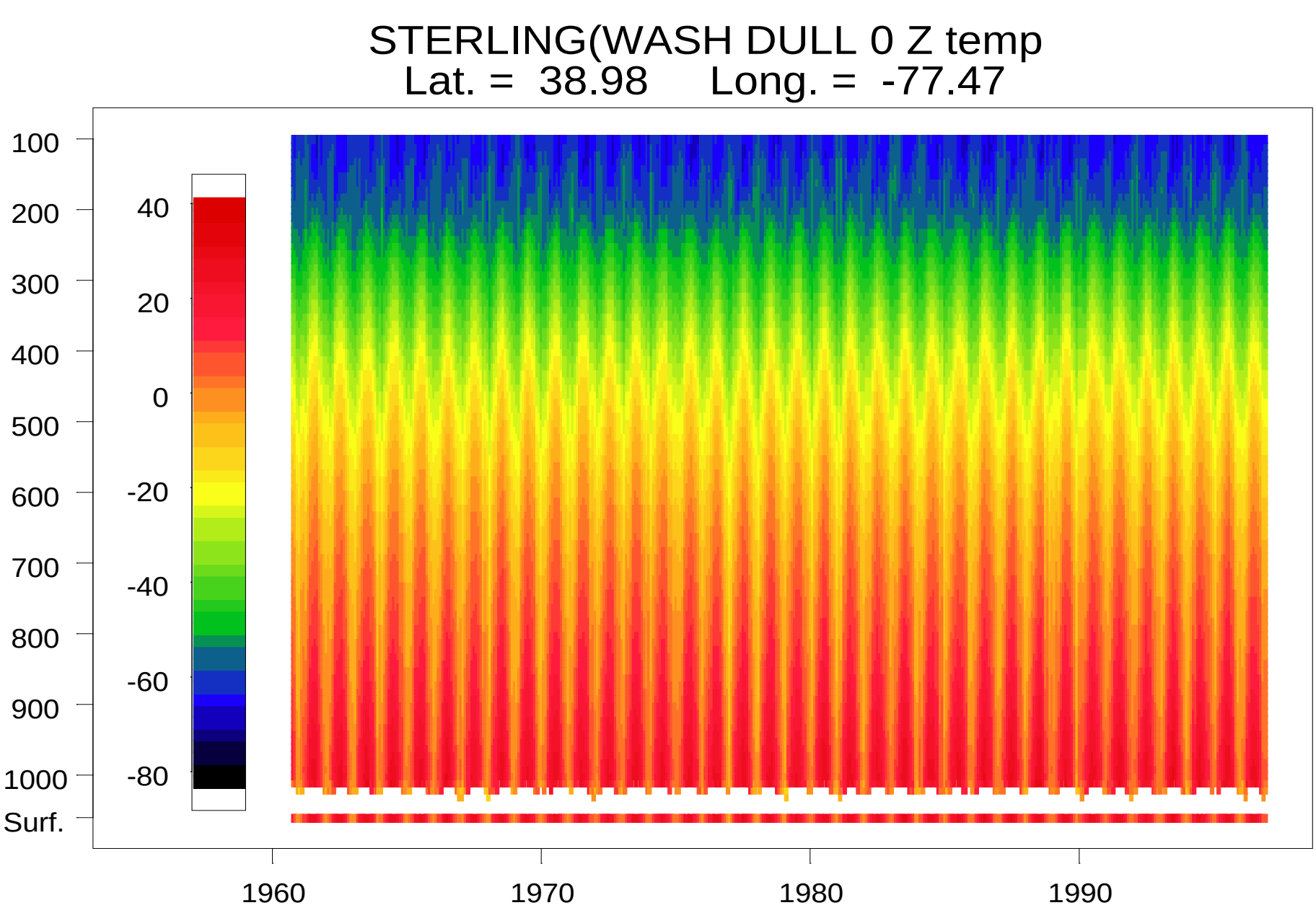

gnuplot graph
U.S. Annual Temperature Series
Anomaly (C)
1
0.5
0
-0.5
-1
1970
1975
1980
1985
1990
1995
2000

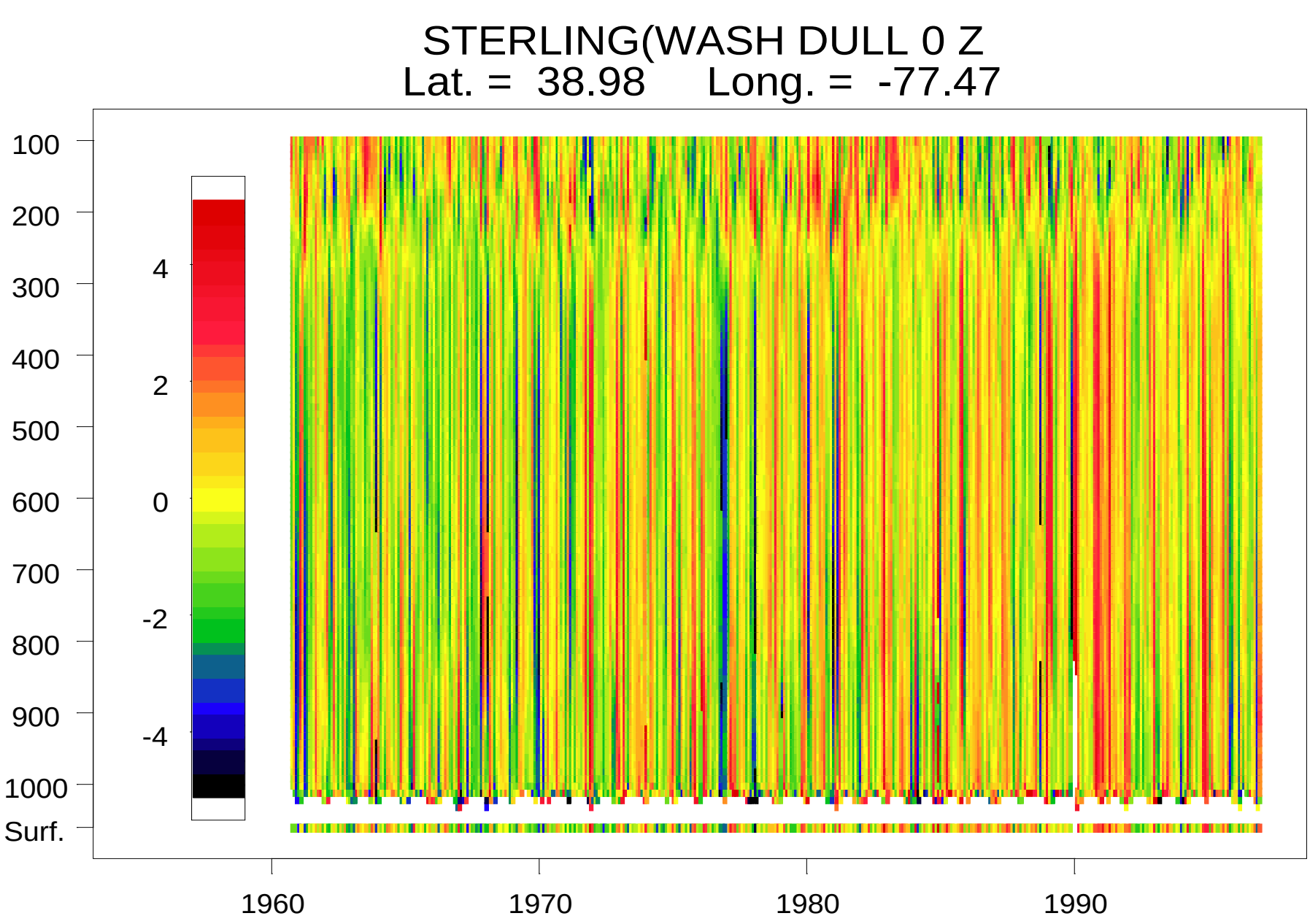
We can control only four aspects of monitoring to detect trends

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

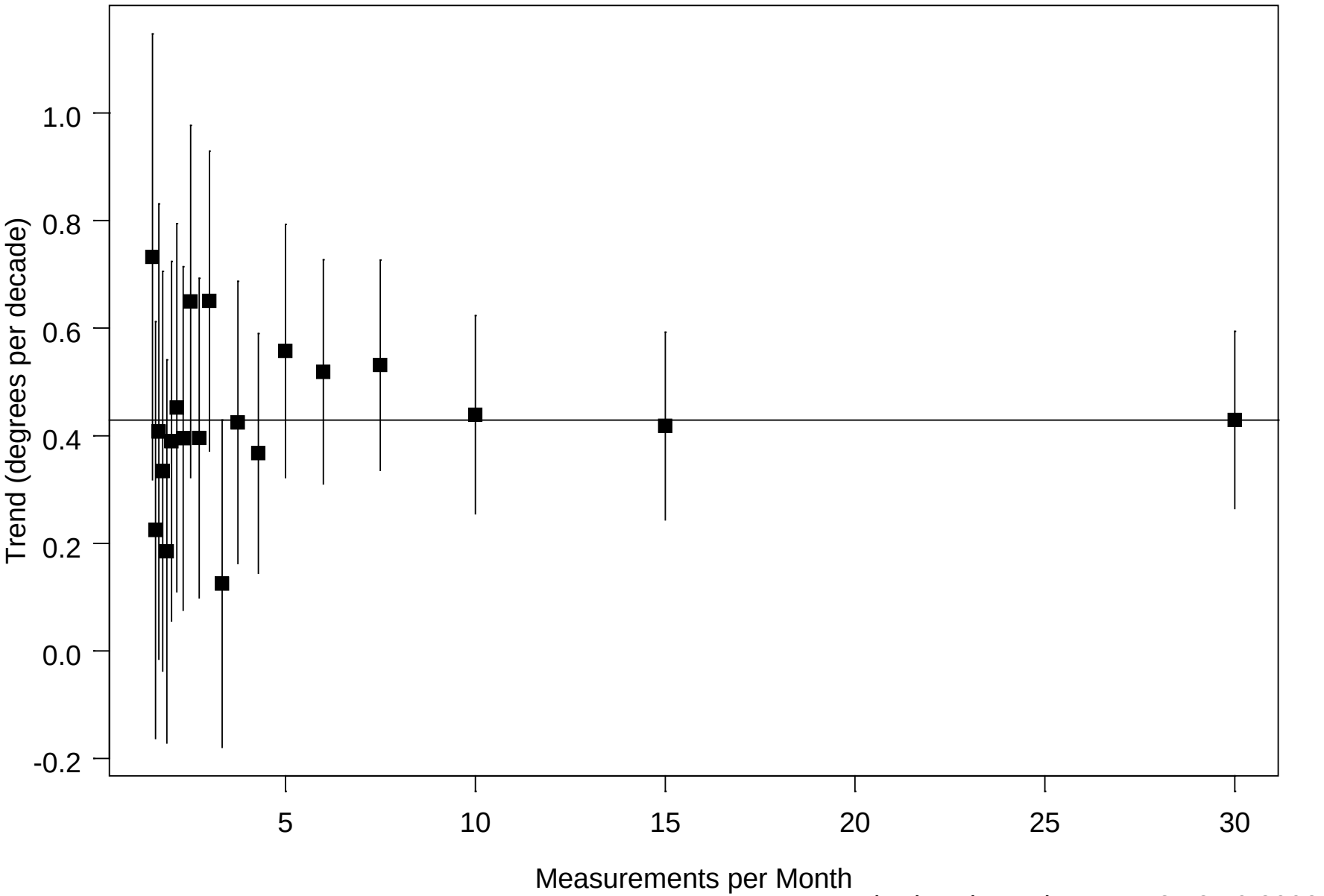
What frequency?

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

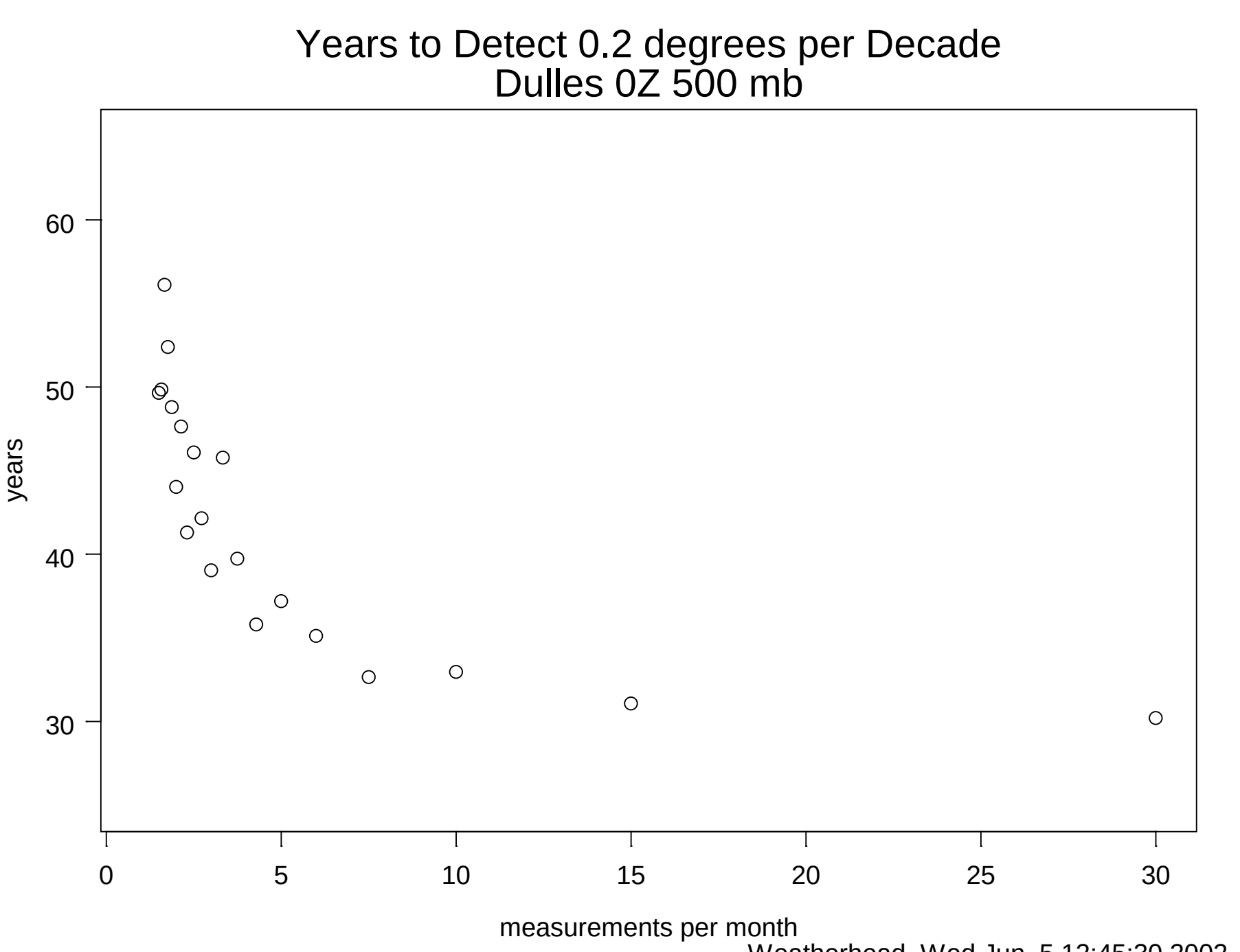

STERLING(WASH DULL 0 Z temp
Lat. = 38.98 Long. = -77.47
100
200
300
400
500
600
700
800
900
1000
Surf.
40
20
0
-20
-40
-60
-80
1960
1970
1980
1990
Weatherhead Wed Mar 13 13:30:52 200


STERLING(WASH DULL 0 Z
Lat. = 38.98 Long. = -77.47
100
200
300
400
500
600
700
800
900
1000
Surf.
4
2
0
-2
-4
1960
1970
1980
1990
Weatherhead Wed Mar 13 13:36:18 2002

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


500 mb Temperature Trend, Dulles
Trend (degrees per decade)
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
5
10
15
20
25
30
Measurements per Month
Weatherhead Wed Jun 5 12:52:10 2002

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?)

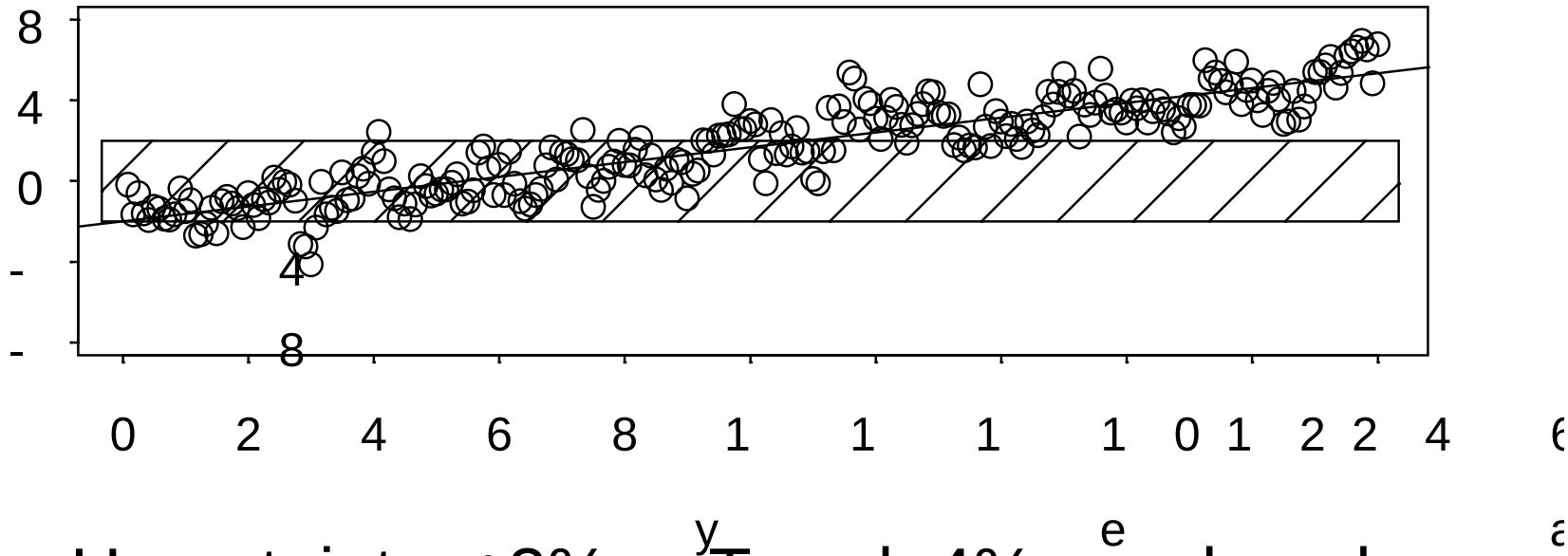
We can control only four aspects of monitoring to detect trends

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

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

Measurement Uncertainty is Not Generally Random

- Trends generally require decades to detect
- Reference instruments and calibration mechanisms often change over the period of several decades
- Most materials for both instrumentation and calibration drift or shift preferentially in one direction

Absolute Accuracy vs. Precision

- Absolute Accuracy is generally larger than precision
- Precision, or repeatability, is all that is needed to detect relative trends.
- Over many decades, repeatability is extremely hard to quantify without absolute accuracy
- Some estimate of uncertainty for the full time period must be established

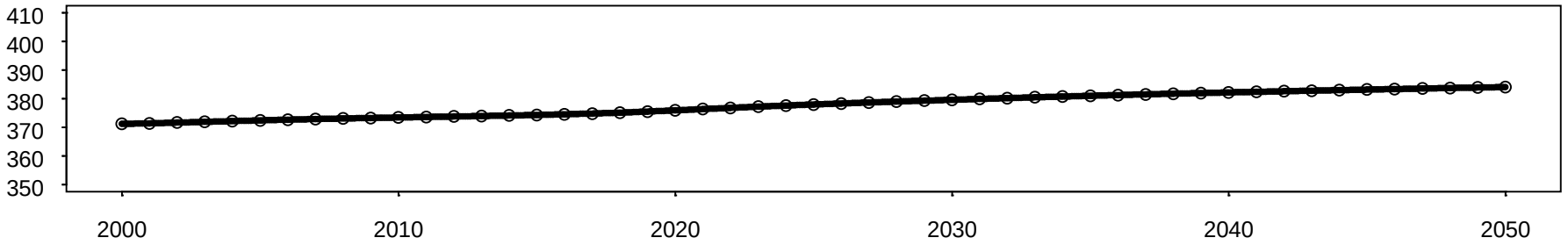
Number of Years

- Approximately:

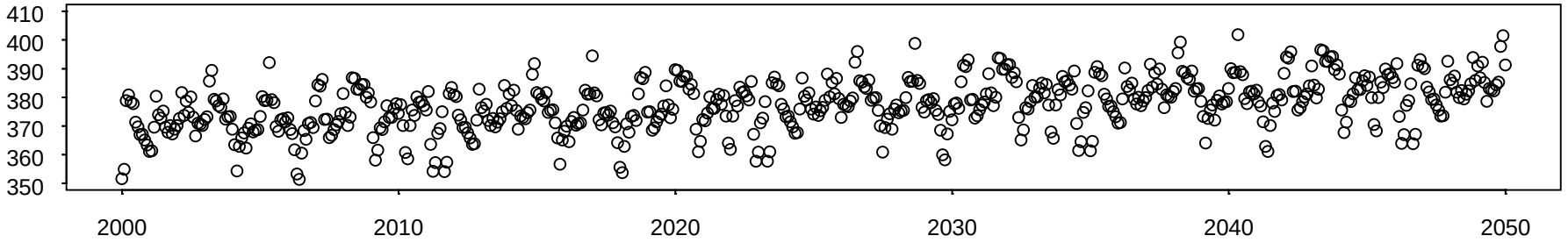
$$n = \{ \; (2 * \sigma_n \; / \; |\omega_o| \;) \; \text{sqrt}\,(1+\phi)/(1-\phi) \; \}^{2/3} + \; 2 * \text{uncertainty}_{\pm} \; / \; |\omega_o|$$

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

GSFC Predictions - without climate change

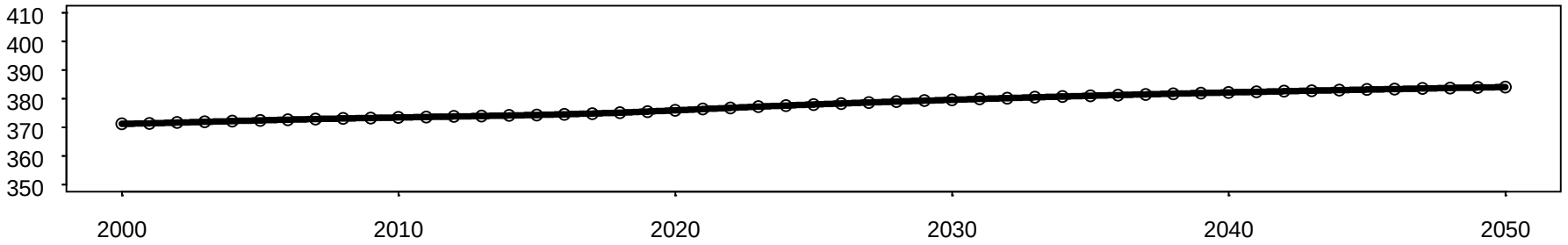


GSFC Predictions with SBUV Lowess Residuals

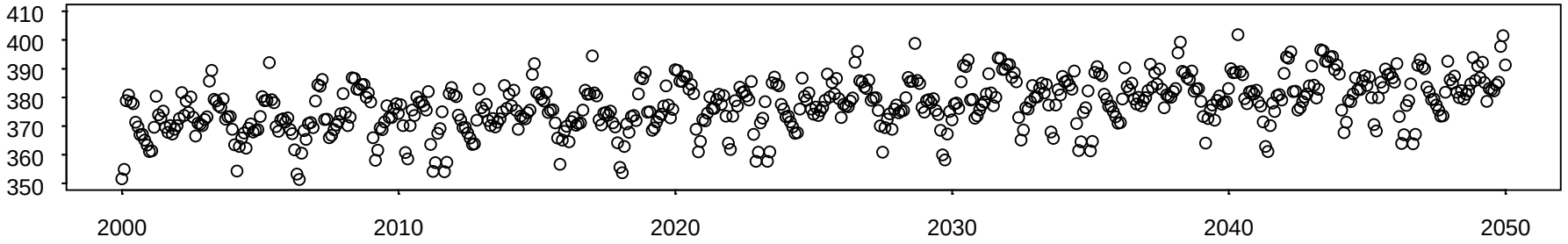


GSFC 2d Predictions with SBUV Residuals of Total Col. Ozone (d.u.) 40N

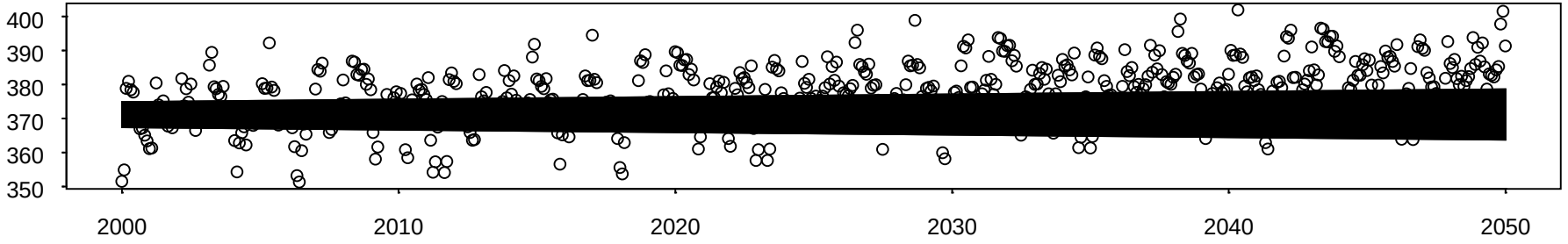
GSFC Predictions - without climate change



GSFC Predictions with SBUV Lowess Residuals

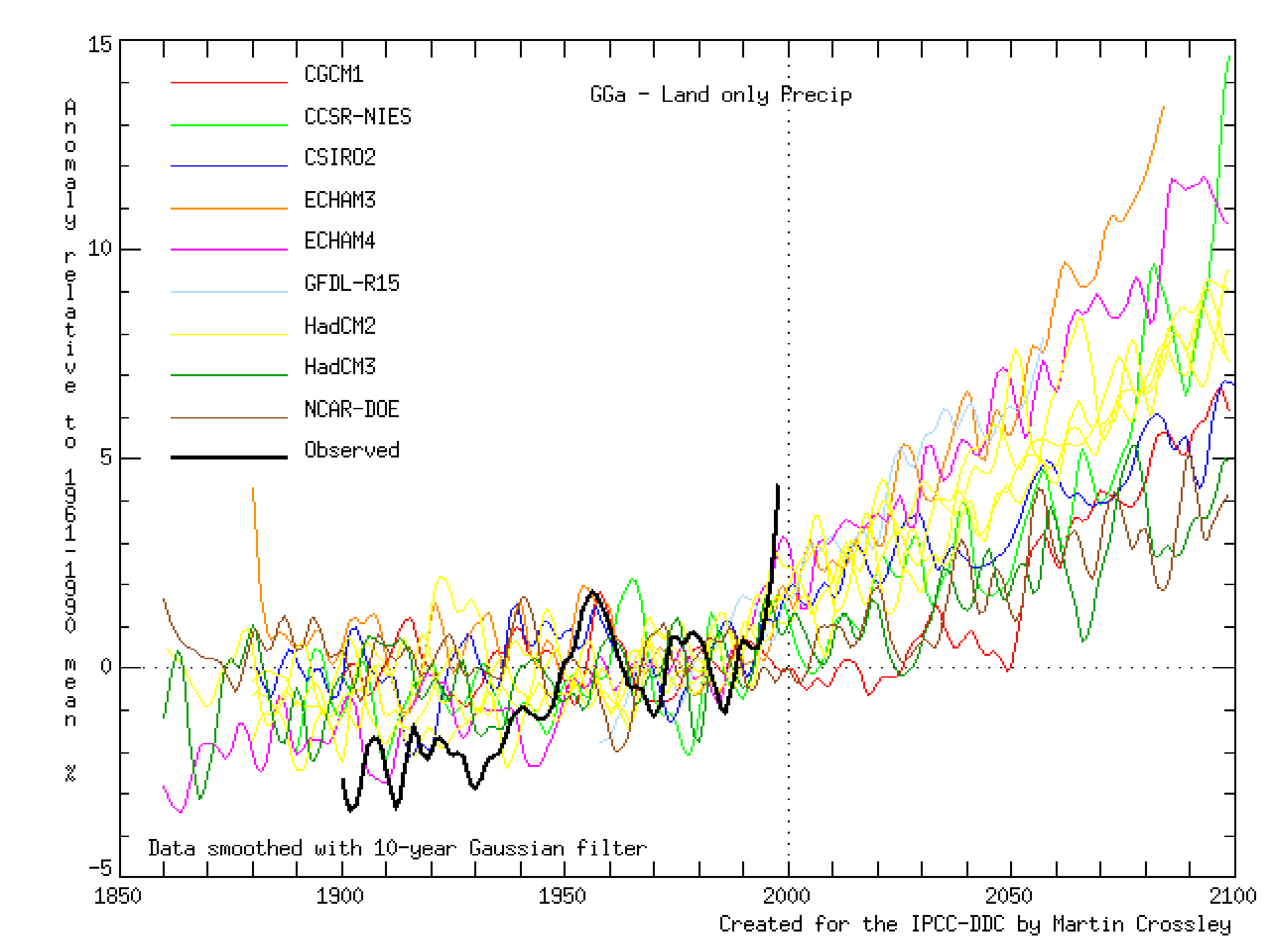


with +-1% error plus +-1% drift

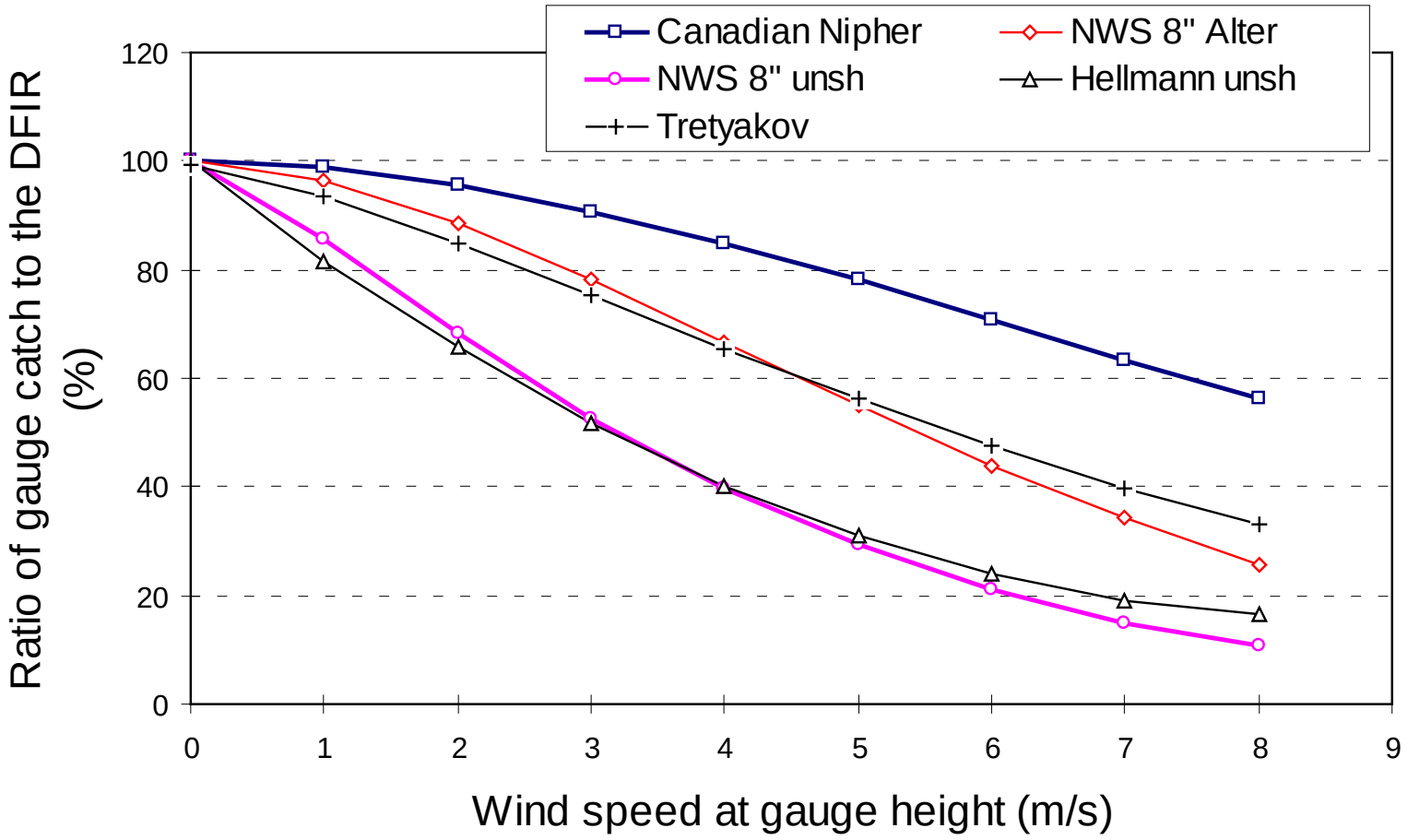


Weatherhead Fri Nov 2 11:53:23 2001

Is accuracy ever the limiting factor in detecting trends?


GGa - Land only Precip
CGCM1
CCSR-NIES
CSIRO2
ECHAM3
ECHAM4
GFDL-R15
HadCM2
HadCM3
NCAR-DOE
Observed
Anomaly relative to 1961-1990 mean %
15
10
5
0
-5
1850
1900
1950
2000
2050
2100
Data smoothed with 10-year Gaussian filter
Created for the IPCC-DDC by Martin Crossley

Wind-induce undercatch: WMO intercomparison results



Accuracy directly influences our ability to detect trends

- In some cases, our measurement uncertainty is considerably larger than the signal we detect
- Estimating appropriate measurement uncertainty over decades of monitoring is extremely

We can control only four aspects of monitoring to detect trends

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

Is there a canary parameter?

What is meant by this?

A parameter where the signal is considerably larger than the variability.*

A parameter where change can only imply anthropogenic influence

- this requires considerably understanding over long time scales.

A parameter where a change can imply significant changes at the Earth's surface.

* and measurement uncertainty?

What we monitor

- Change is expected in many parameters: temperature, water vapor, dynamics, trace gases, cloud cover, radiation, etc.
- What we monitor is key to understanding causes of change.
- Trends can be detected earlier if we can remove some of the variability.

Optimization

- More sites or higher accuracy?
- More frequent measurements at a few sites or more sites?
- Higher vertical resolution or higher photon count (accuracy)?

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. Trends are difficult to detect:
   - Small trends, large variability, measurement uncertainty.
2. We can control only four aspects to detect trends:
   - Location, frequency, accuracy, parameters
3. We can optimize systems to detect trends most efficiently with the following benefits:
   - Answering scientific questions earlier
   - Confirming, improving models
   - Allowing for earliest policy decisions
   - Maintaining prudent use of available funds