Time Series Analysis Techniques

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Preface

"All models are wrong ..." ***G. Box***

"… but some models are useful."

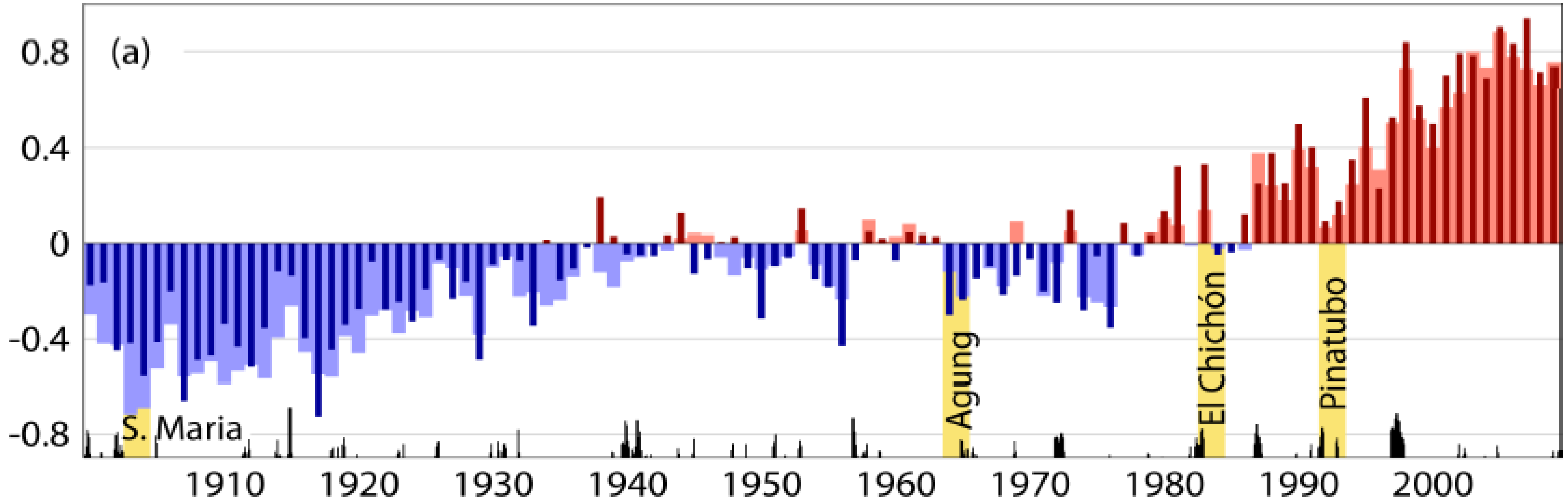
Although they may need a bit of help …

And in seasonal forecasting they need a lot of help.

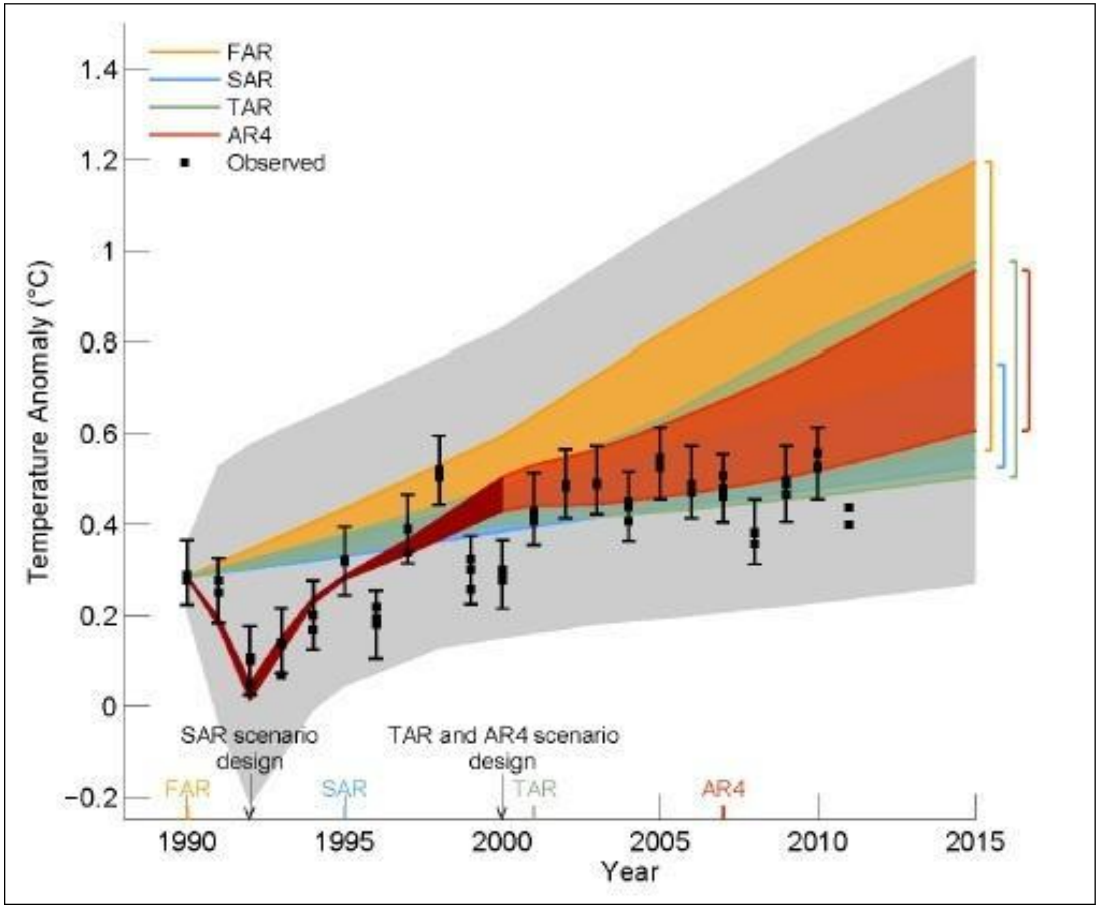
MOTIVATION

REANALYSIS ERA 20 CM

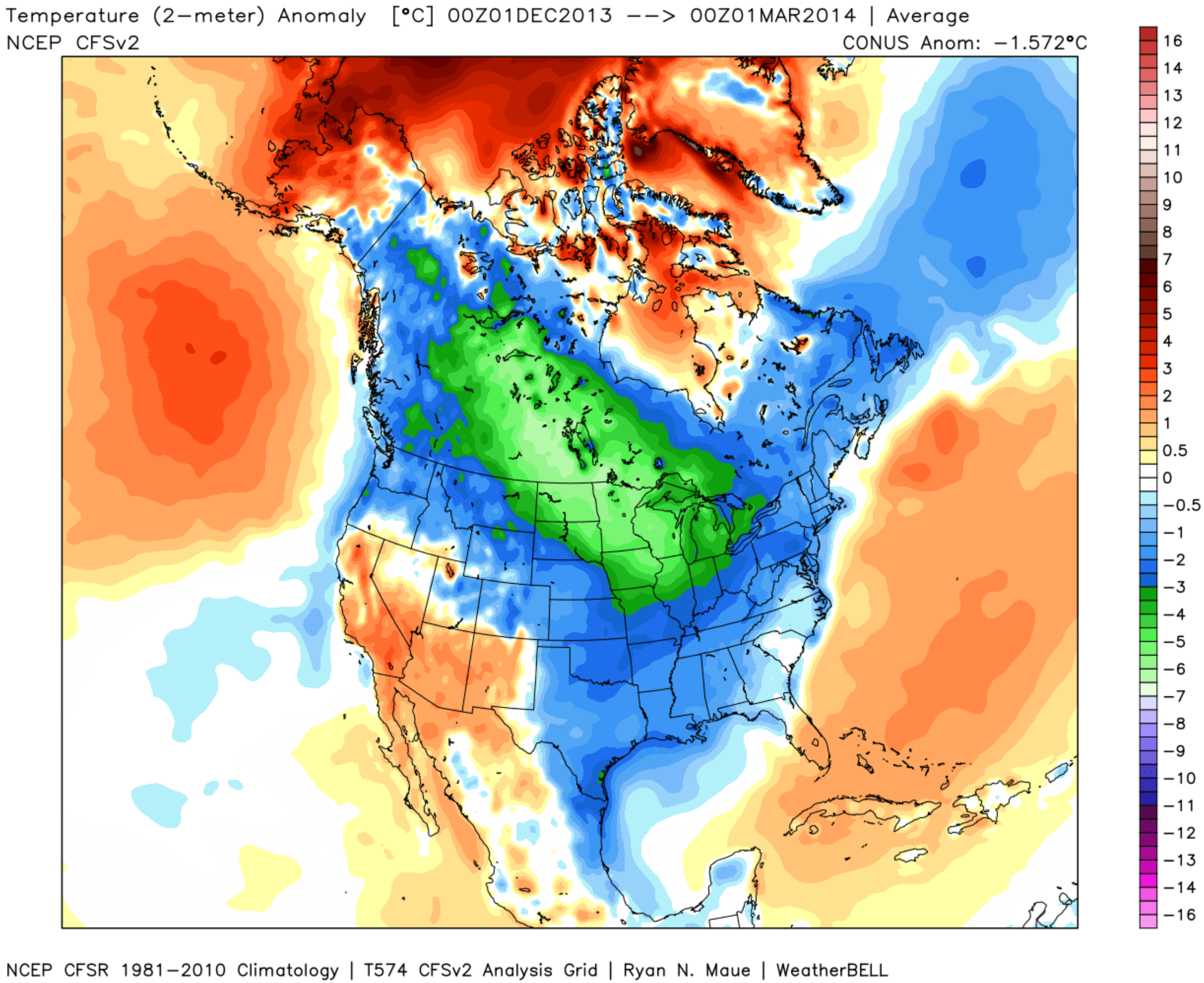
Figure 7: *Annual-mean temperature anomalies (K) relative to 1961-1990 for the ERA 20CM ensemble mean (broader, lighter-coloured bars) and CRUTEM4 (version 2.0.0 from www.metoffice.gov.uk/hadobs; narrower, darker-coloured bars) for area weighted averages taken over all grid boxes for which CRUTEM4 has values. Timings of El Niño events and volcanic eruptions are indicated as described in Hersbach et.al 2013.*



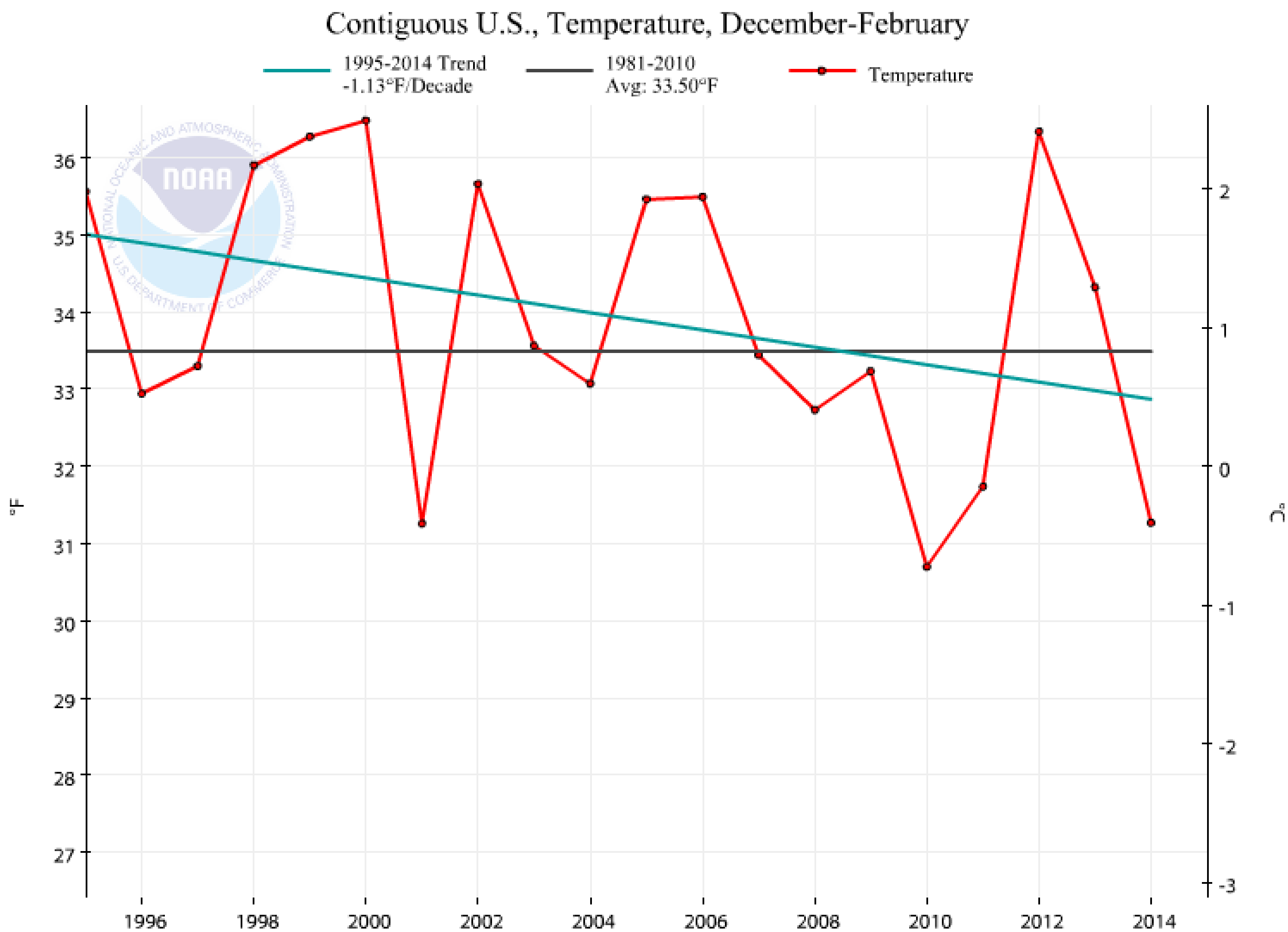
Forbes, 2012, December



Средняя температурная аномалия зимы 2013-14 гг (декабрь-февраль) в Северной Америке (данные НОАА)



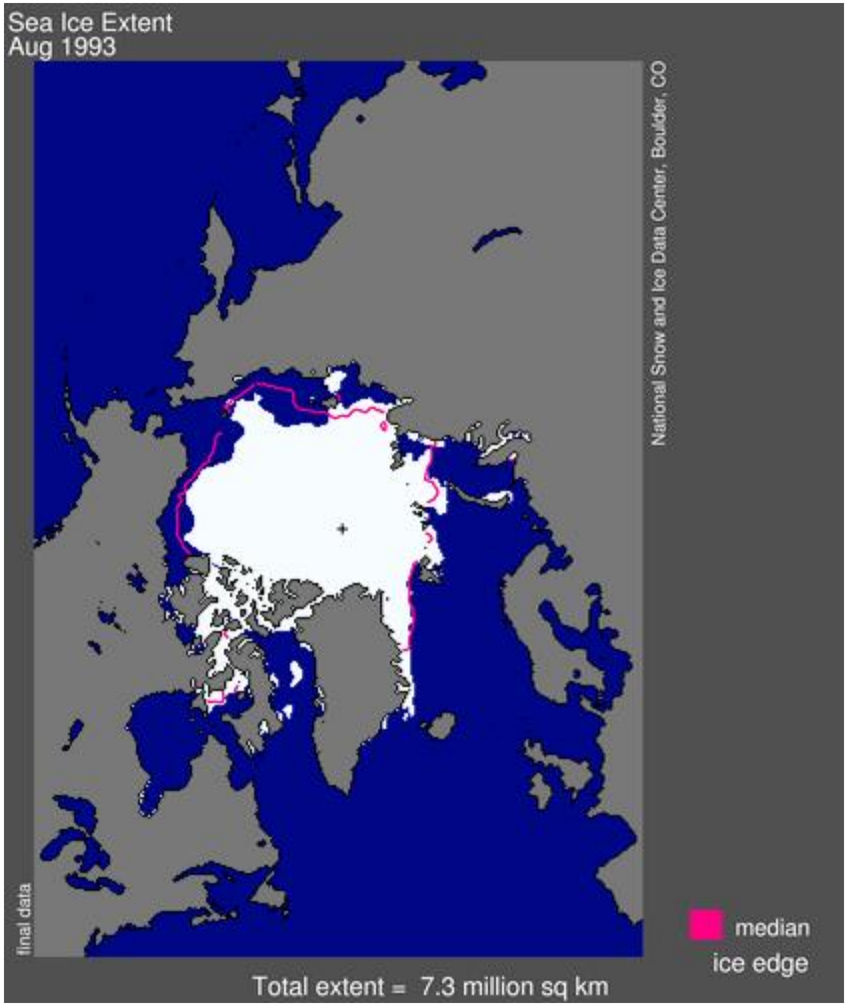
Климатический температурный тренд за 1994-2013 гг на территории США (данные НОАА)

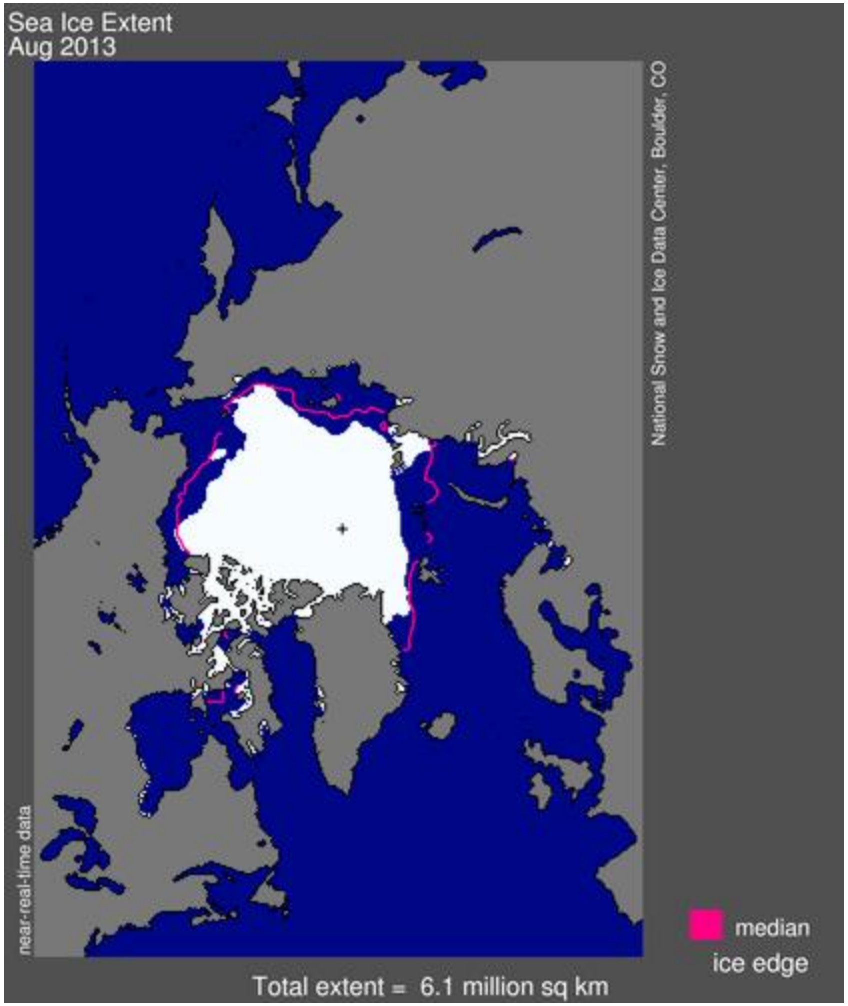


August 1993

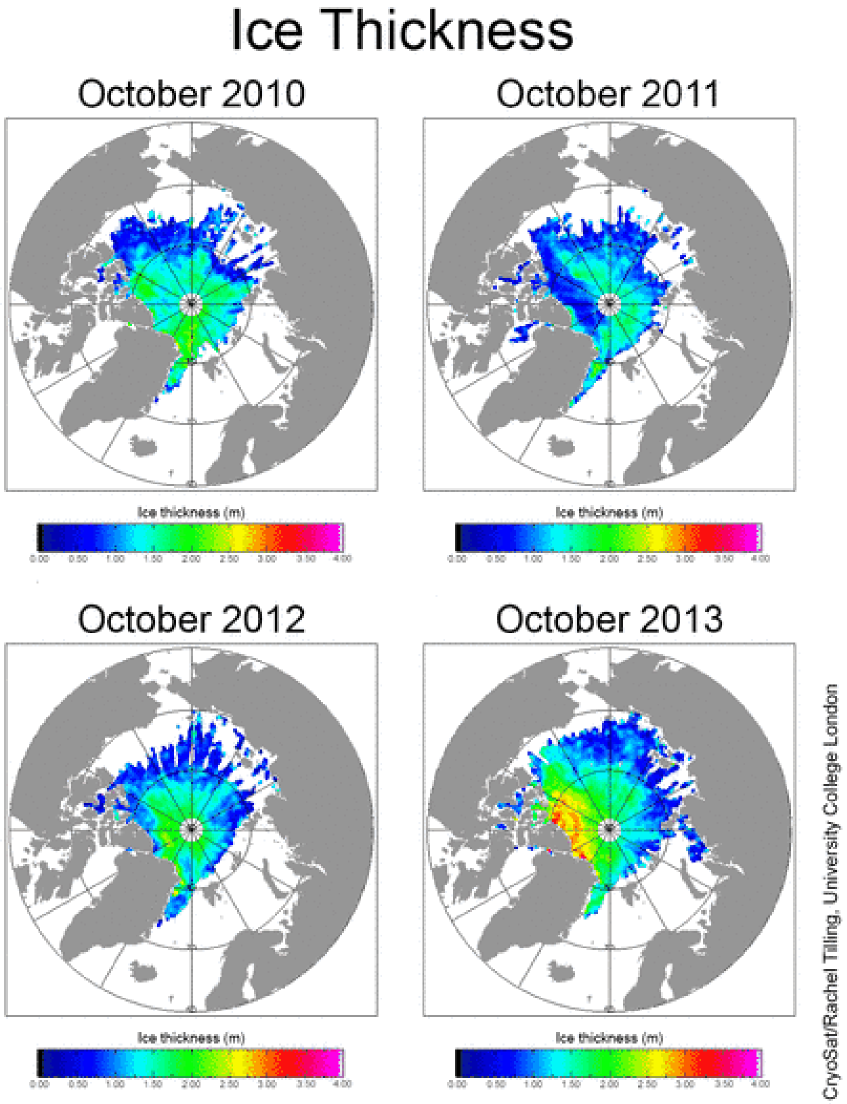
$(7.3-6.1)*100/7.3=16.4\%$

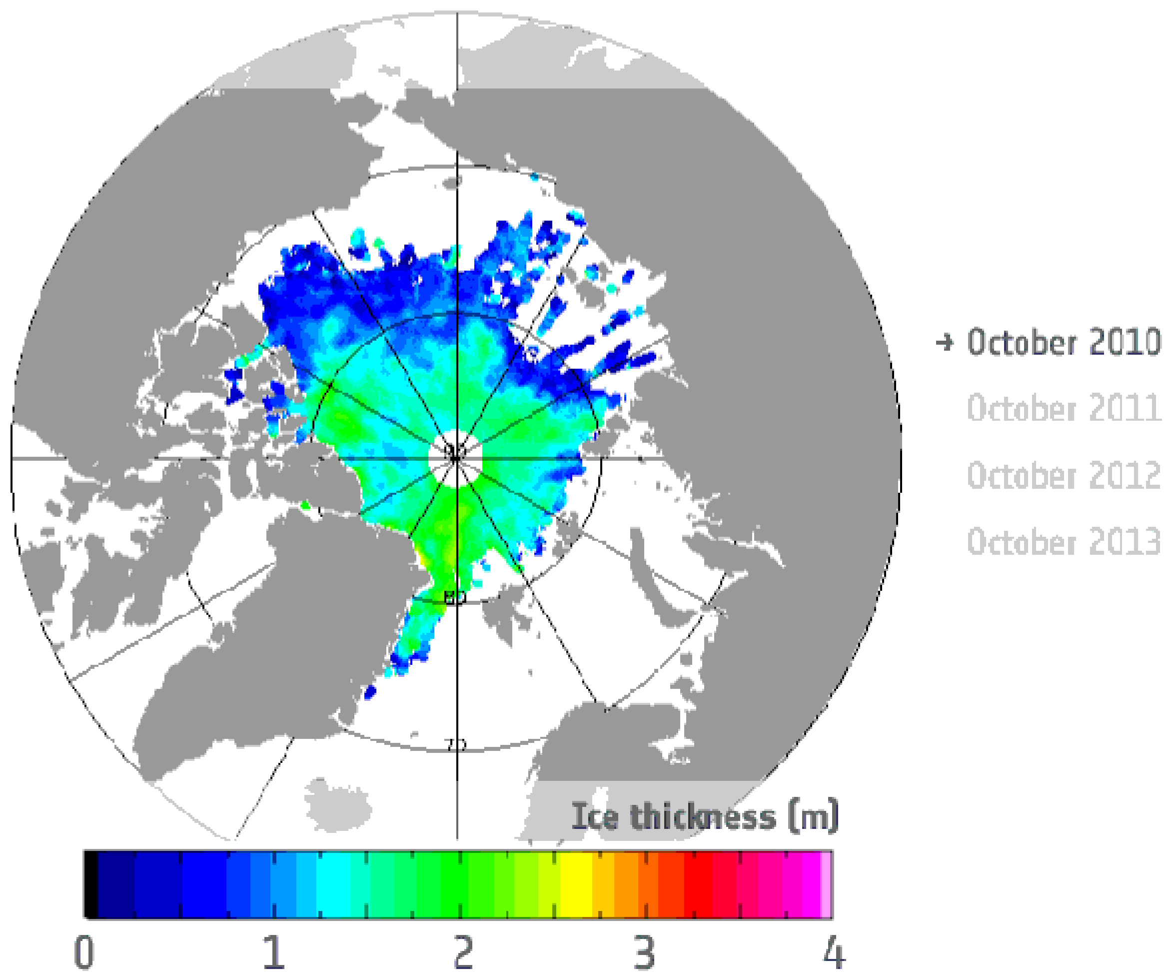
August 2013



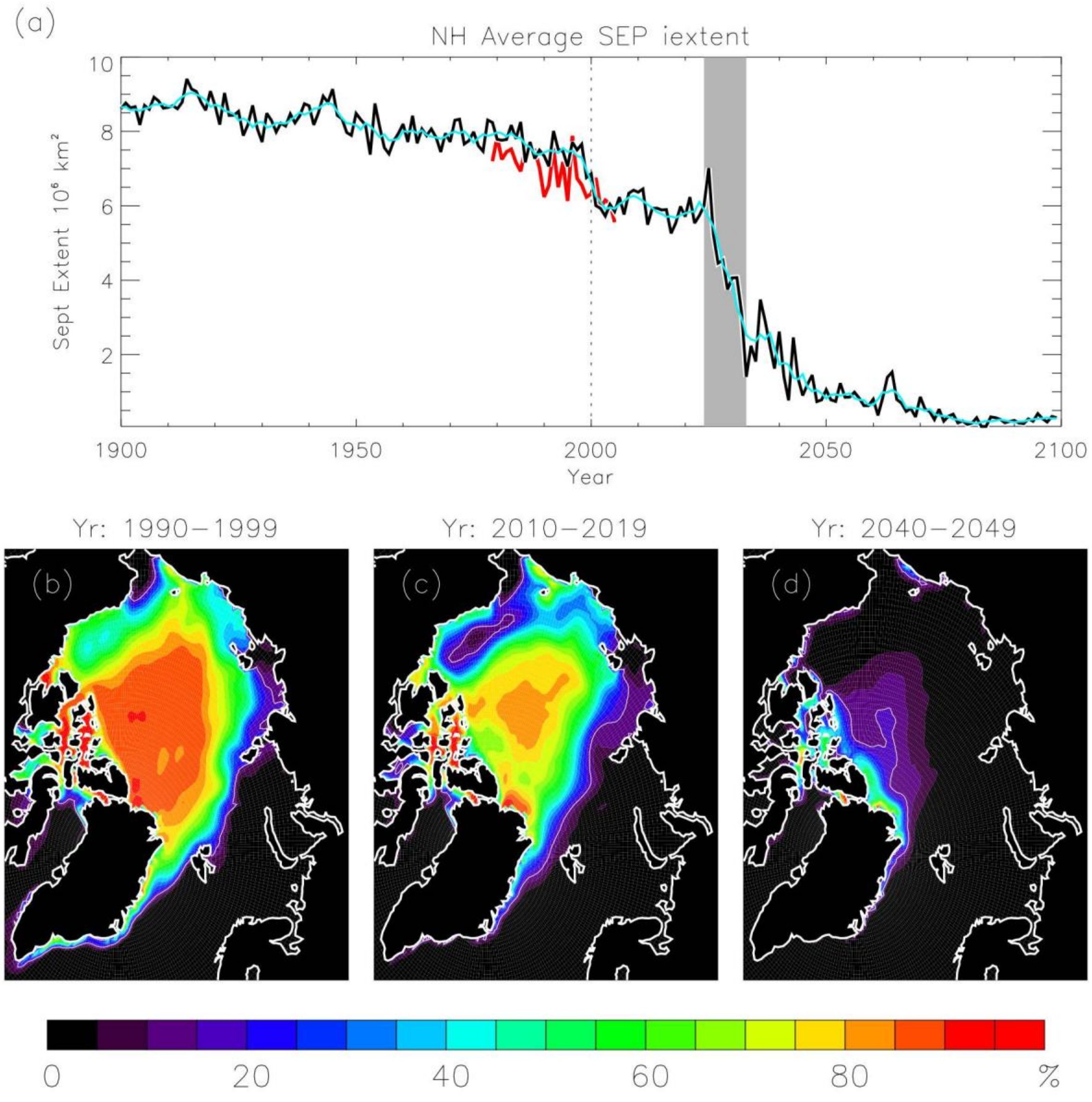


Толщина Арктического льда увеличивается в последние годы




→ October 2010
October 2011
October 2012
October 2013
Ice thickness (m)
0
1
2
3
4

Противоречие с прогнозом климатологов-моделельеров IPCC

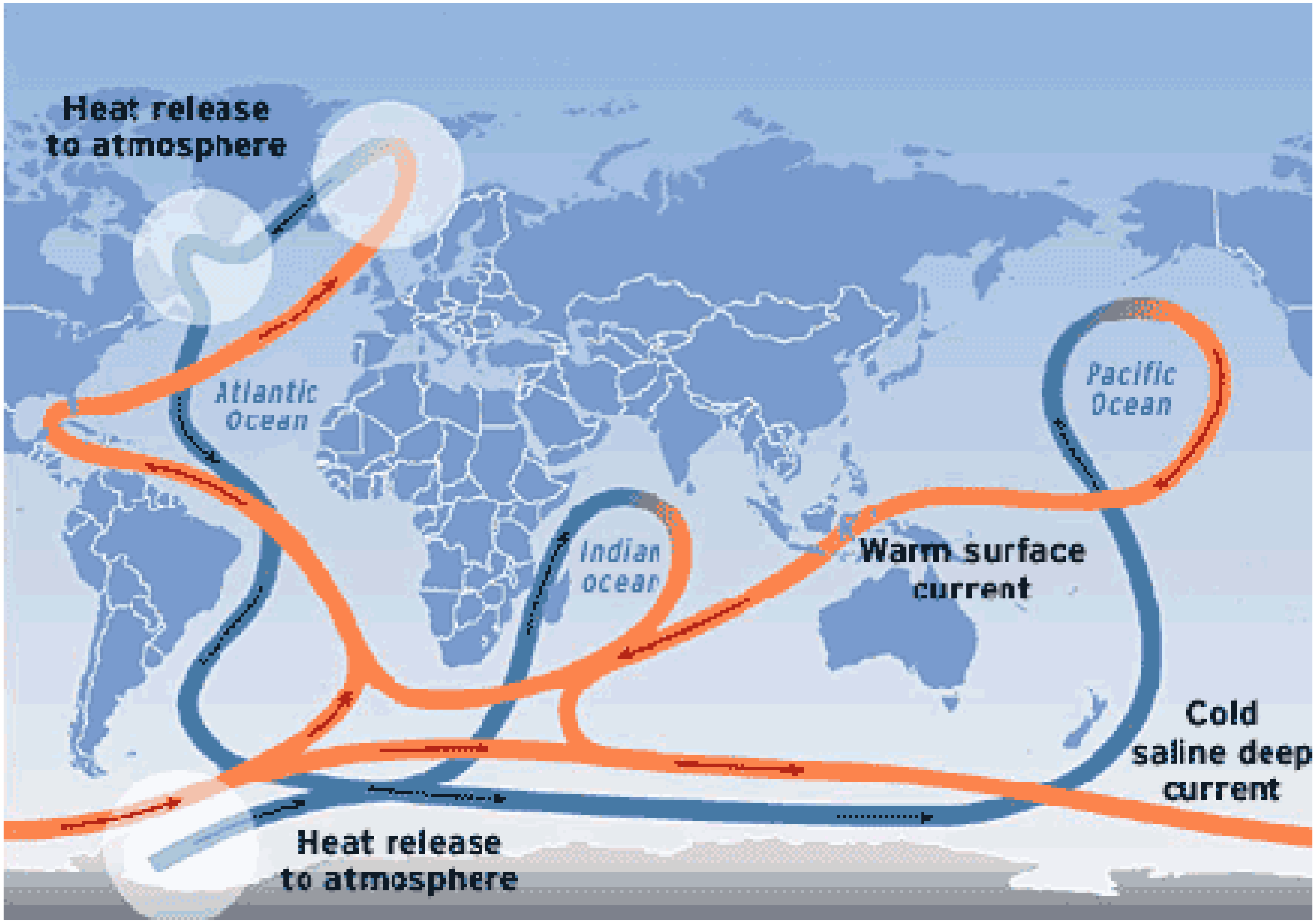


Author lectures are now available at YOUTUBE via site of virtual laboratory http://meteovlab.meteorf.ru/index.php?option=com_content&view=article&id=767&Itemid=206&lang=ru

Outlines:

- Physical background of the changes in the SST time series: impact on other parameters of climate system
- Stationary and non-stationary series: transition from Fourier to Wavelet analysis
- Trends: Linear and Non-linear
- Coherence between various climate time series

Global Ocean Conveyer (Brocker)



Two impact mechanisms on Arctic Sea Ice Extent

- **Atlantic sector of Arctic Sea:**

Inflow of Atlantic waters

- **Pacific sector of Arctic Sea:**

Atmospheric winds generated by SST anomaly in North Pacific

Stationary time series:

- **Fourier Analysis**
- **Auto-Regression Moving Average**

Non-stationary Time Series

- Wavelet Analysis
- Smoothing (non-linear trend):
- Cross-Validation (Wahba, 1978)
- Influence observation selection (non-stationarity)& local polynomial approximation

(Cleveland, 1991)

- Regularization (Tikhonov, 1968)

Experimental data smoothing

$$S(f,\lambda) = \sum_i \{y_i - f(t_i)\}^2 + \lambda \int_{t_1}^{t_n} f''(t)^2 d$$

y_i - *measurement data*

f - *spline or a set of fitting functions (e.g., polynomials)*

$\lambda -$ *smoothing parameter*

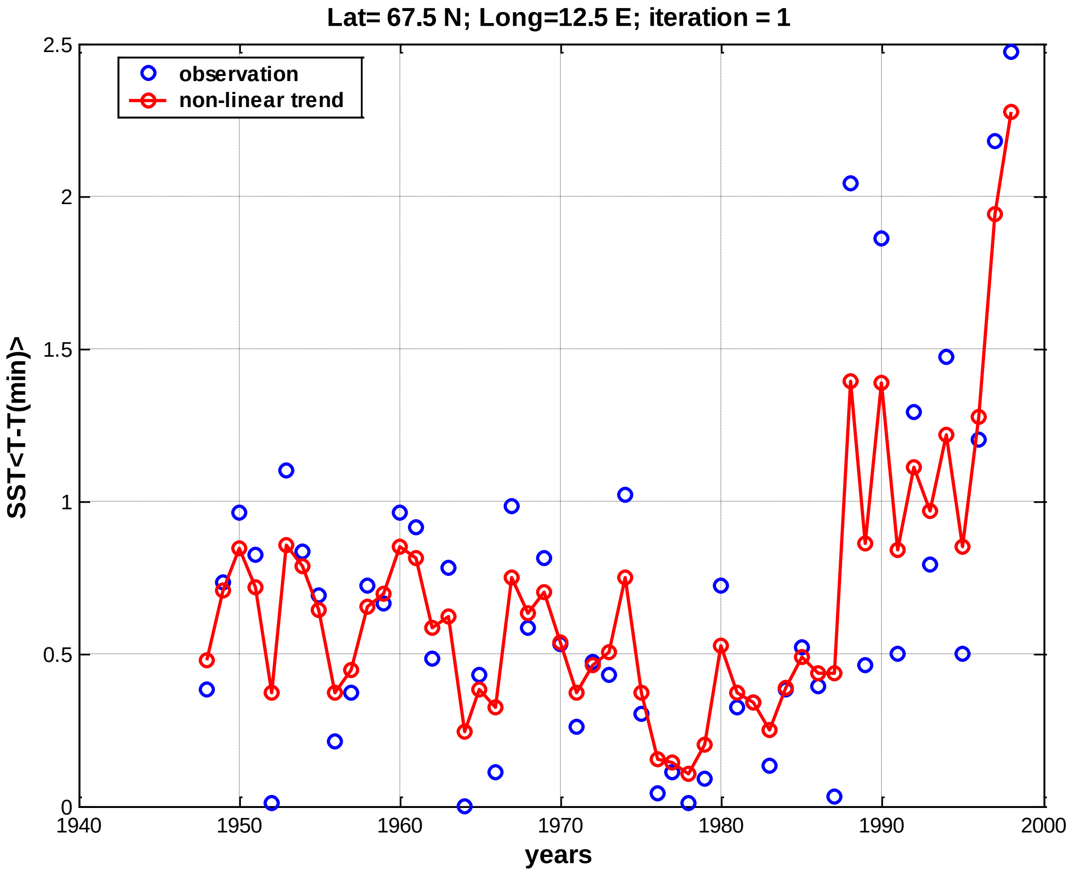
The best" value of $\lambda -$ ¸ will be one that minimizes the mean square error:

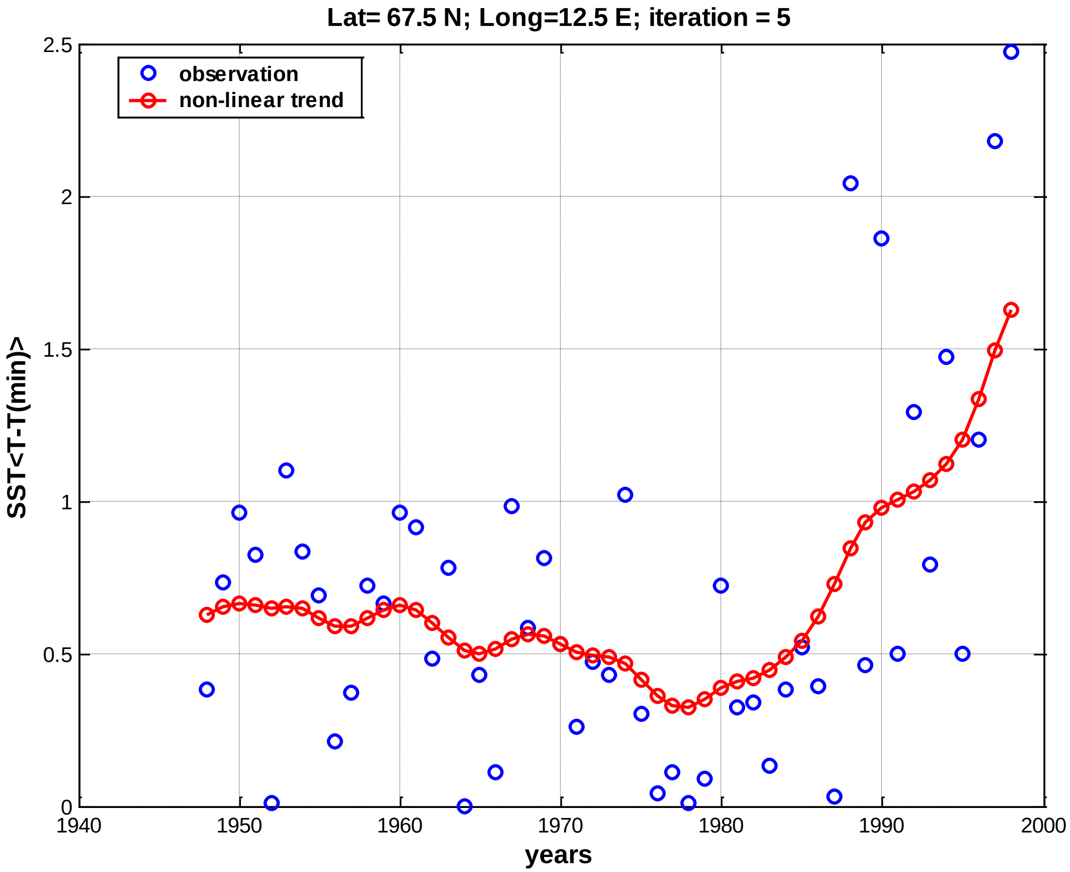
$$L(\lambda) = n^{-1} \sum_{i=1}^{n} \{f(t_i) - f_\lambda(t_i)\}^2$$

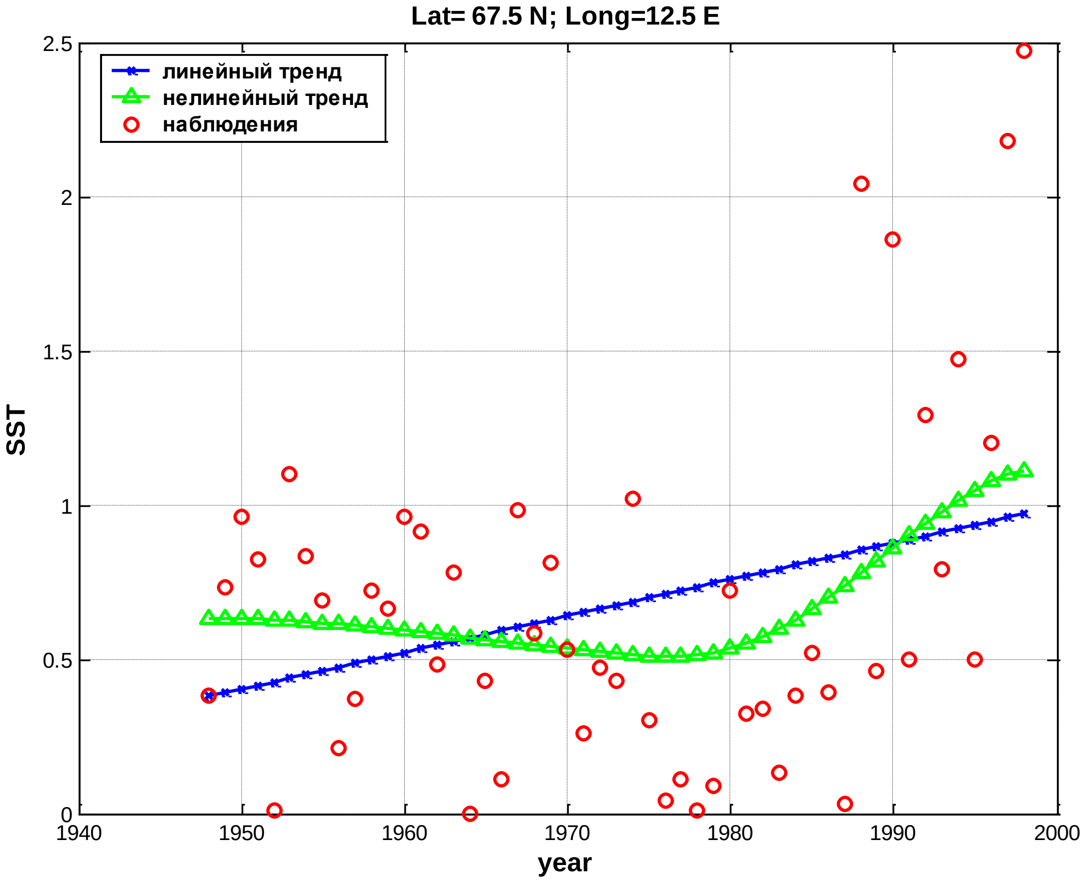
Ordinary cross-validation:

$$v(\lambda) = \frac{1}{n} \sum_{i=1}^{n} \{\hat{f}^{(-i)} - y_i\}^2$$

The ***cross validation score*** *is calculated from* ***leaving out one value of*** y_i *in the fitting model to the remaining data and calculating the squared difference between the missing datum and its predicted value* $\hat{f}^{(-i)}$.

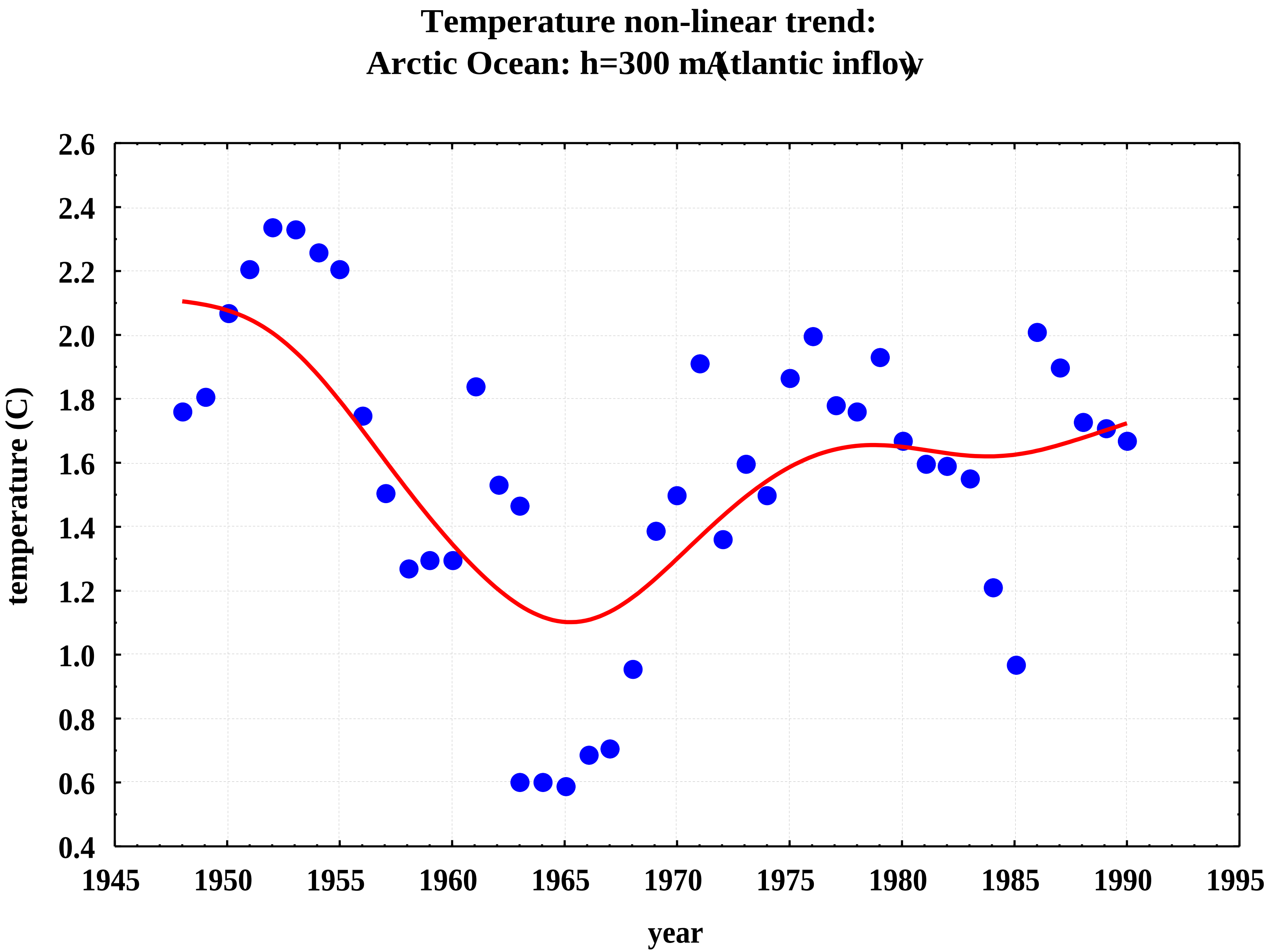

Lat= 67.5 N; Long=12.5 E; iteration = 1
observation
non-linear trend
SST<T-T(min)>
years
0
0.5
1
1.5
2
2.5
1940
1950
1960
1970
1980
1990
2000


Lat= 67.5 N; Long=12.5 E; iteration = 5
observation
non-linear trend
SST<T-T(min)>
years
2.5
2
1.5
1
0.5
0
1940
1950
1960
1970
1980
1990
2000

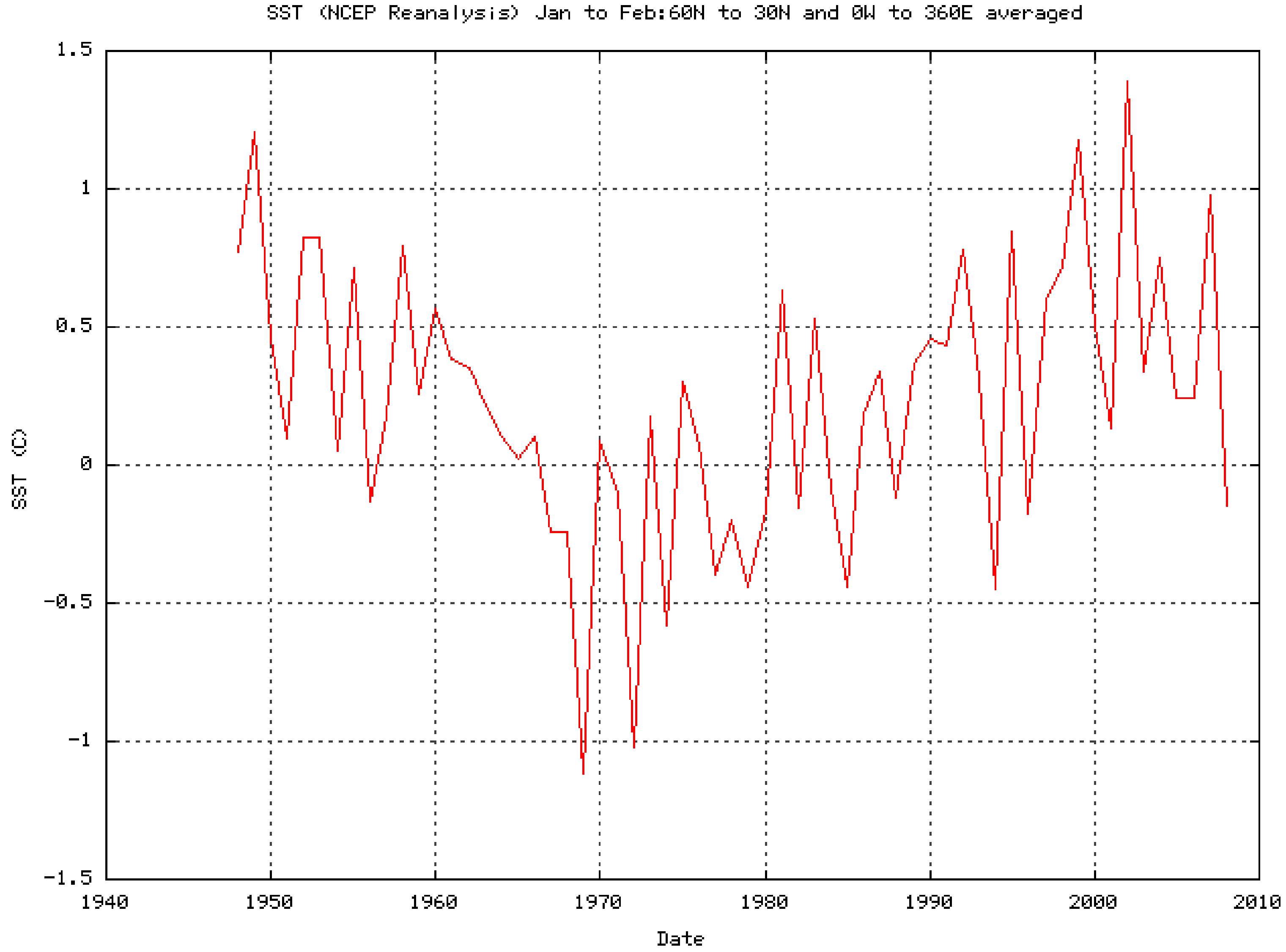

Lat= 67.5 N; Long=12.5 E
линейный тренд
нелинейный тренд
наблюдения
SST
year
0
0.5
1
1.5
2
2.5
1940
1950
1960
1970
1980
1990
2000

Comparison of linear and non-linear trend efficiencies

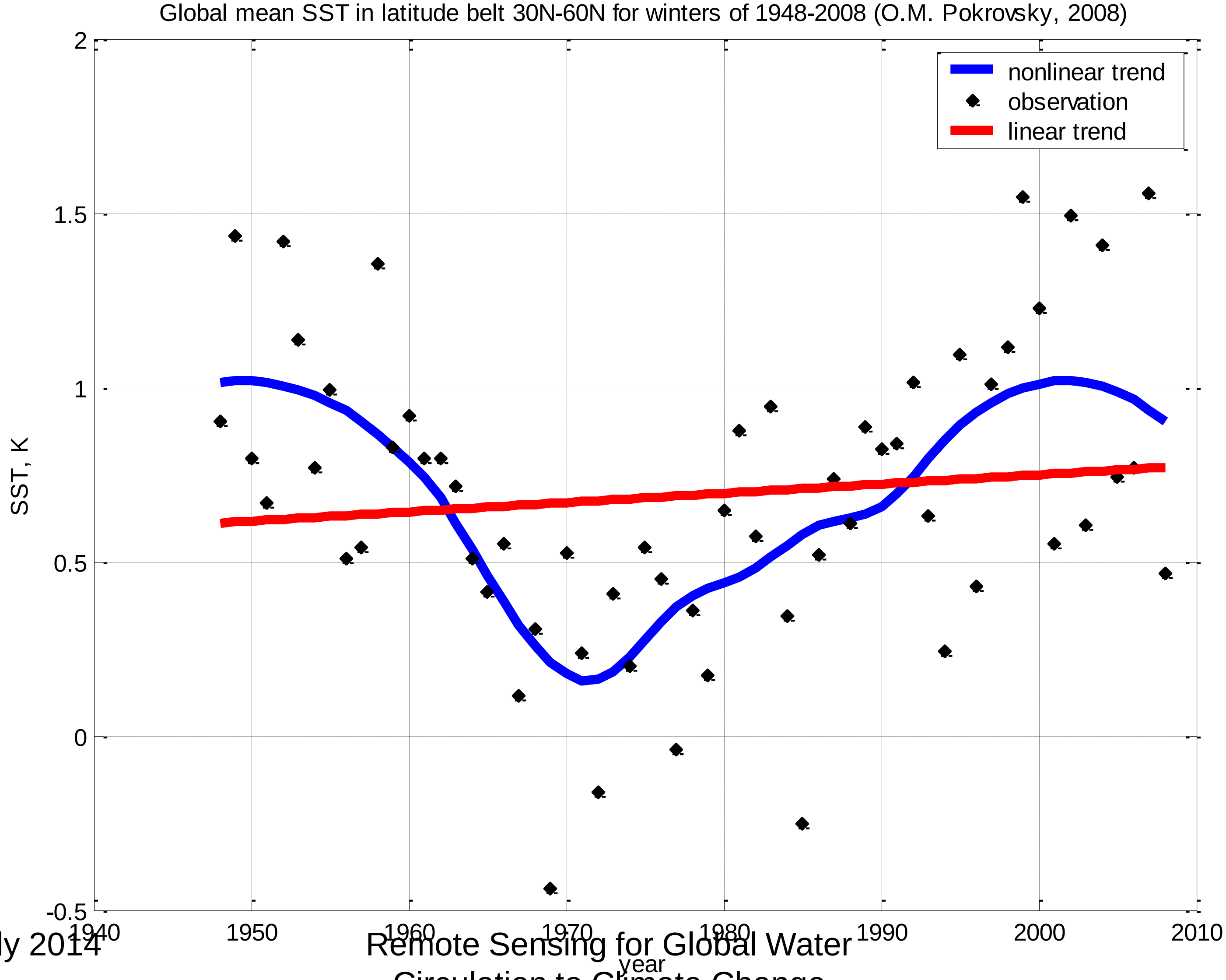
	Correlation With observing data	STD	Rate of explained variance (Fisher Statistics)(%)
Linear trend	0.31	0.53	5
Non-linear trend	0.63	0.46	32


Temperature non-linear trend:
Arctic Ocean: h=300 m (Atlantic inflow)
temperature (C)
2.6
2.4
2.2
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
1945
1950
1955
1960
1965
1970
1975
1980
1985
1990
1995
year

Global SST for 30N-60N band (winters, 1948-2008): NCEP reanalysis

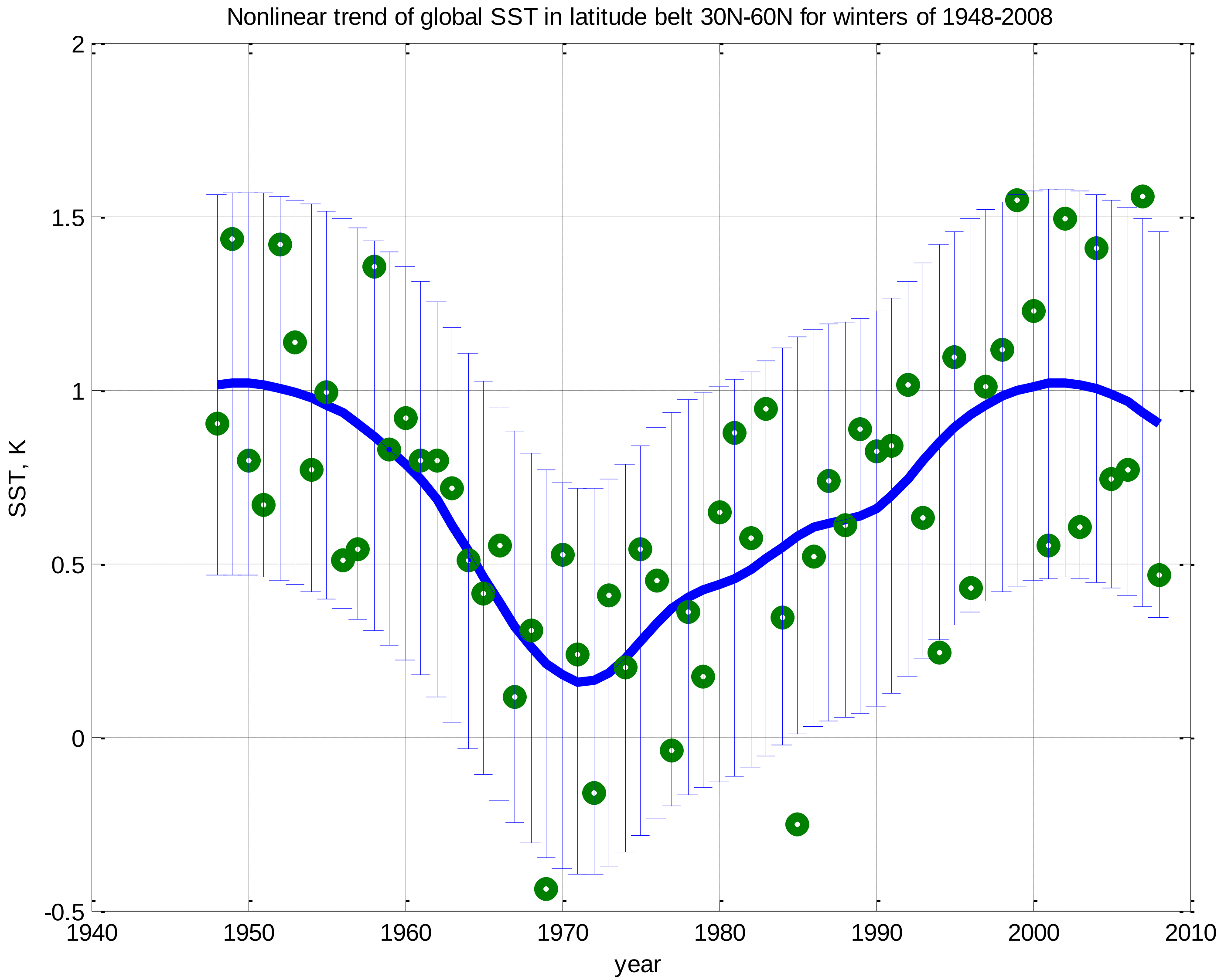


Non-Linear Global Trend of Winter SST:
for 1948-1998

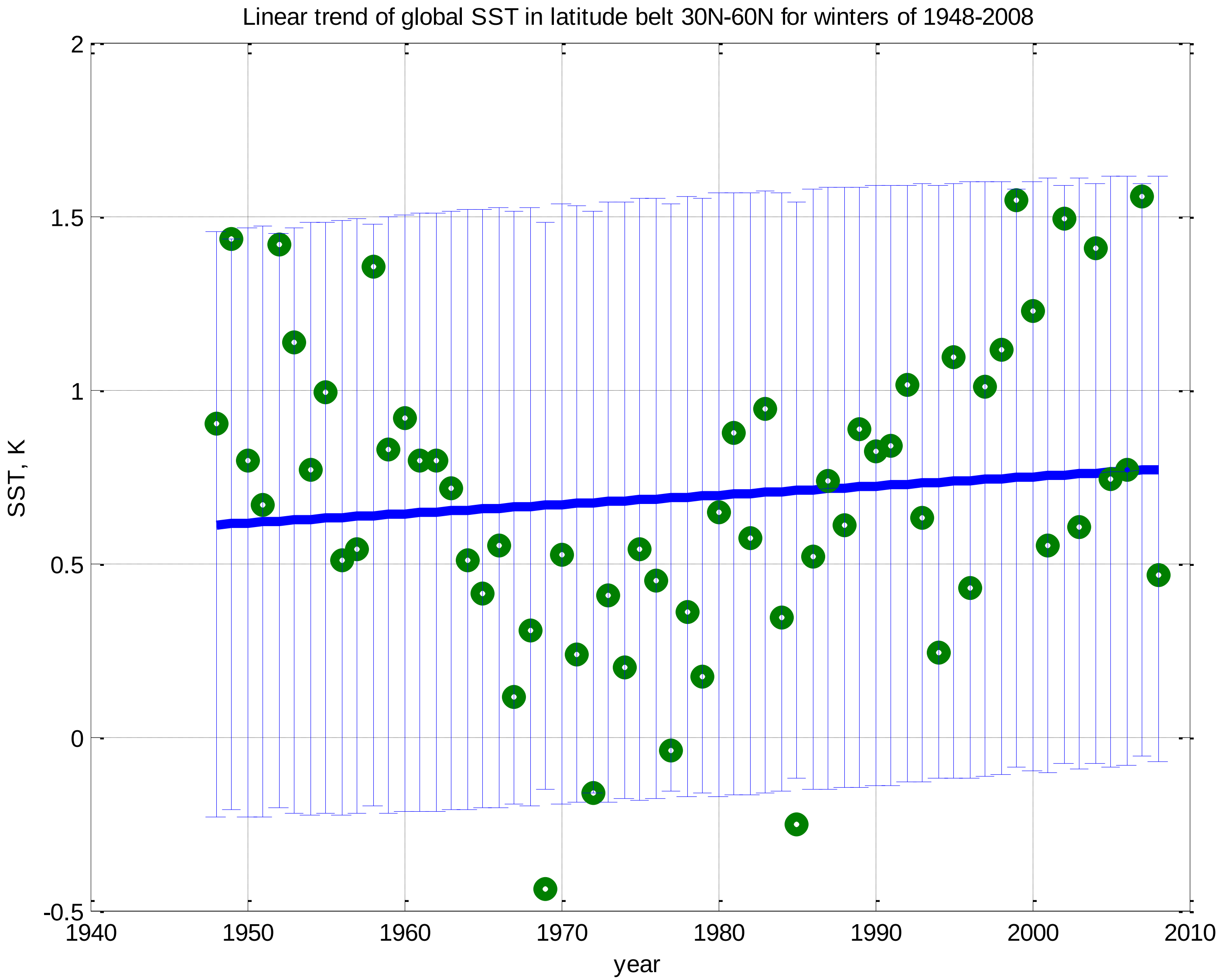


Non-linear trend and error bars for **significance level**: **0.01 (p=0.99)**

Lambda=0.47



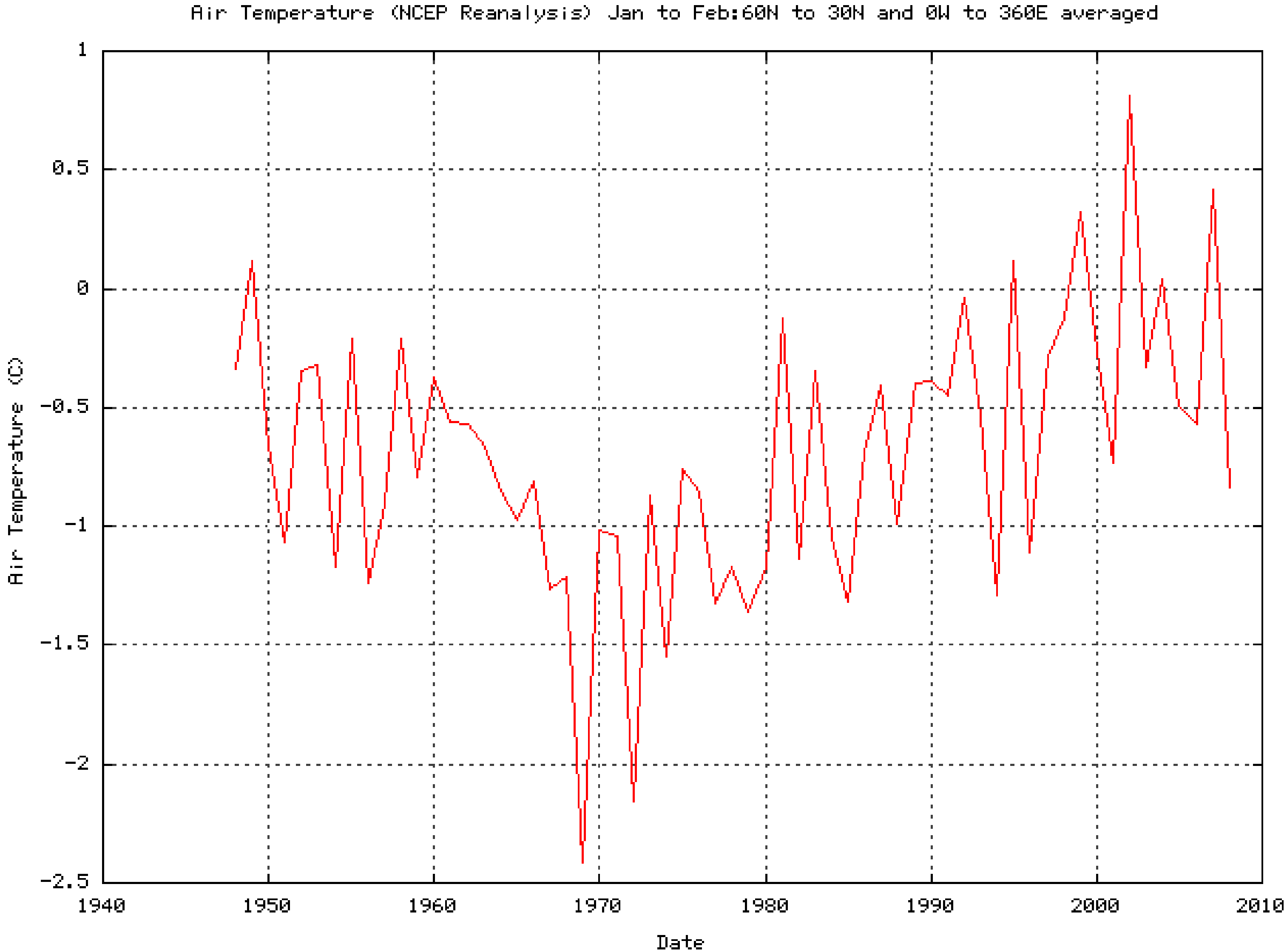
Linear trend and error bars for **significance level**: **0.01 (p=0.99)**



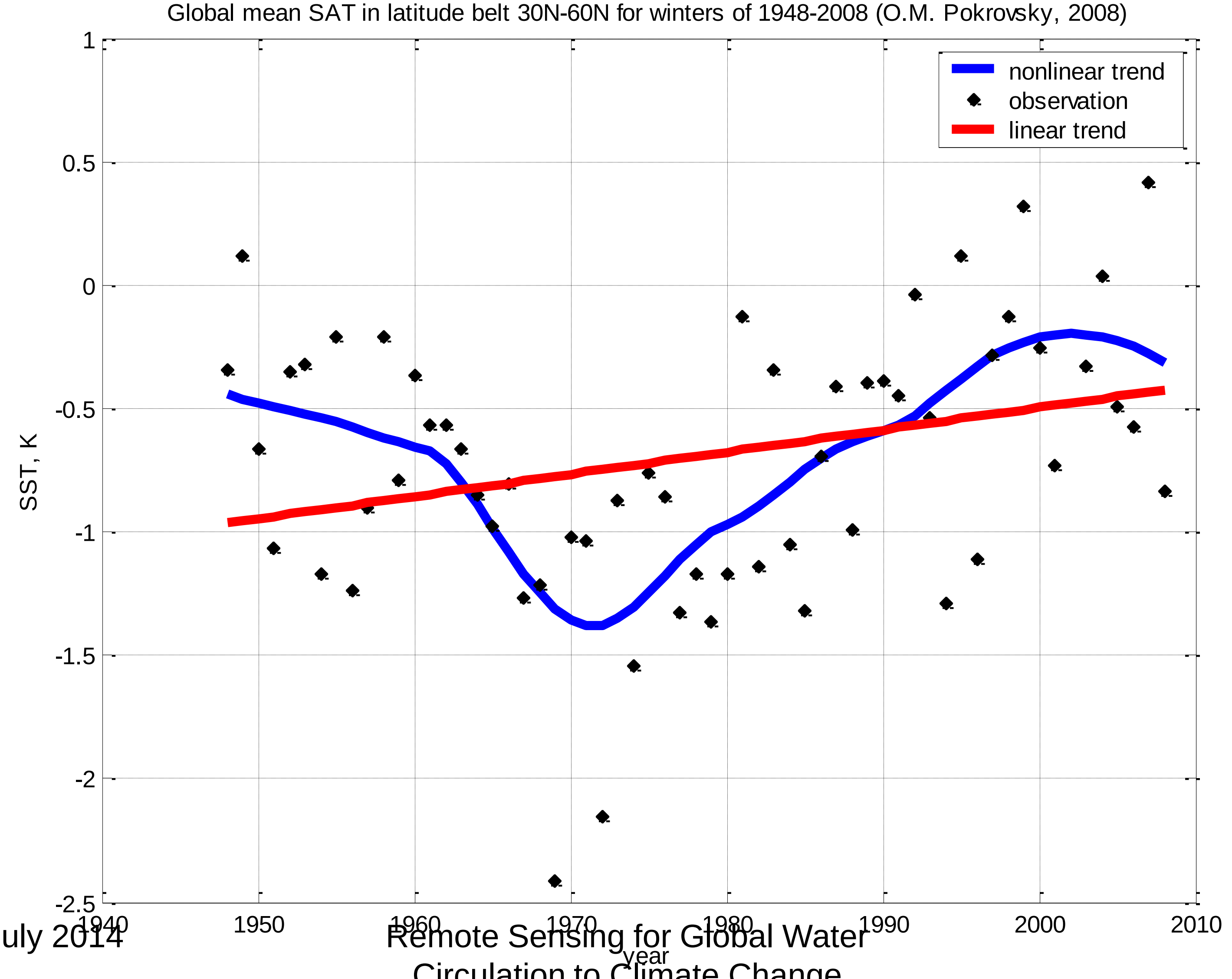
Comparison of standard statistics for linear and non-linear SST trends:

	Mean Error Bar "Width" (C) ***significance level: 0.01 (p=0.99)***	Correlation coefficient to observational data	Fisher statistics (Rate of predicted variance)
linear	1.78	0.11	0.72
Non-linear	1.12	0.69	1.16

Global SAT for 30N-60N band (winters, 1948-2008): NCEP reanalysis

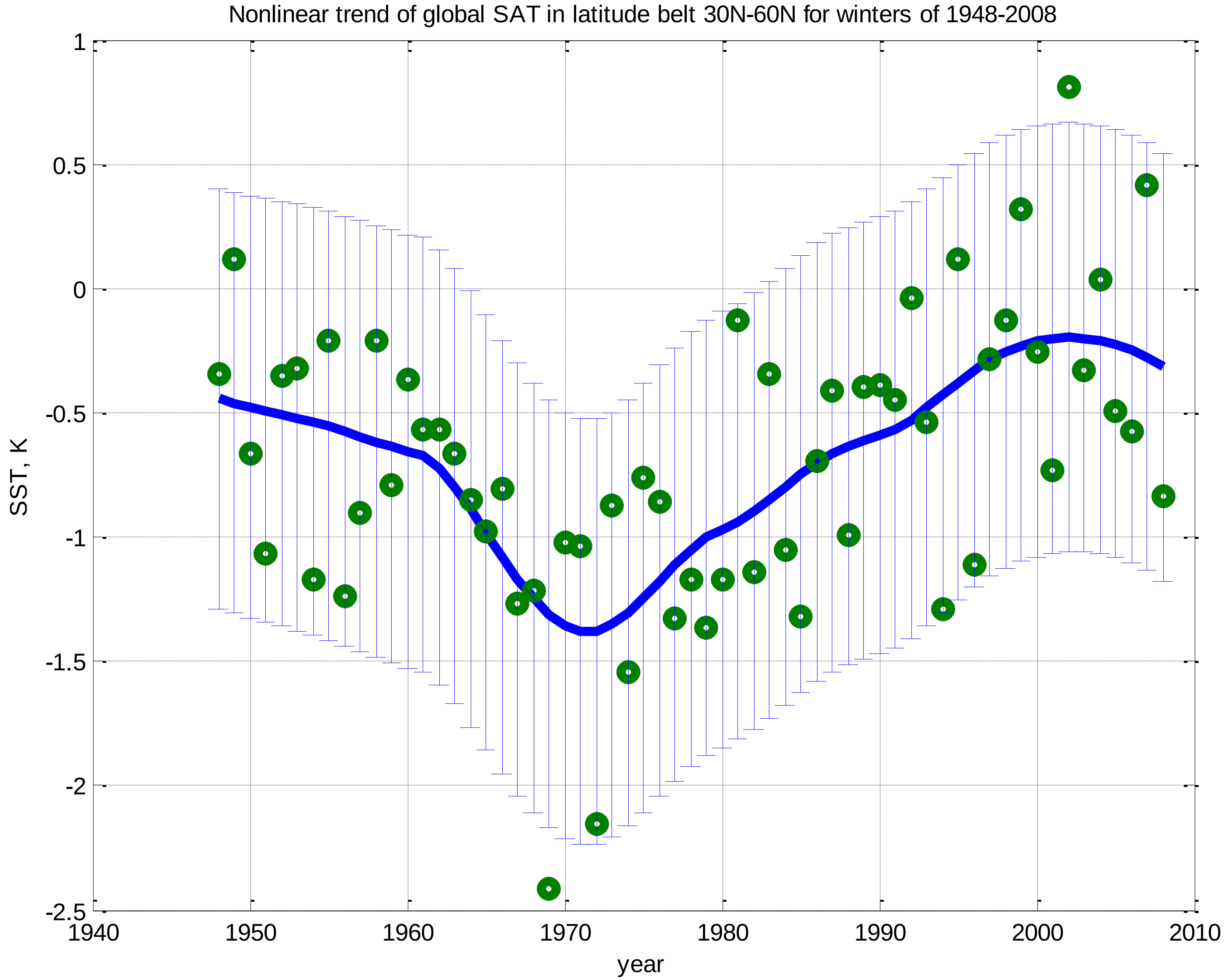


Non-Linear Global Trend of Winter SAT:
for 1948-1998

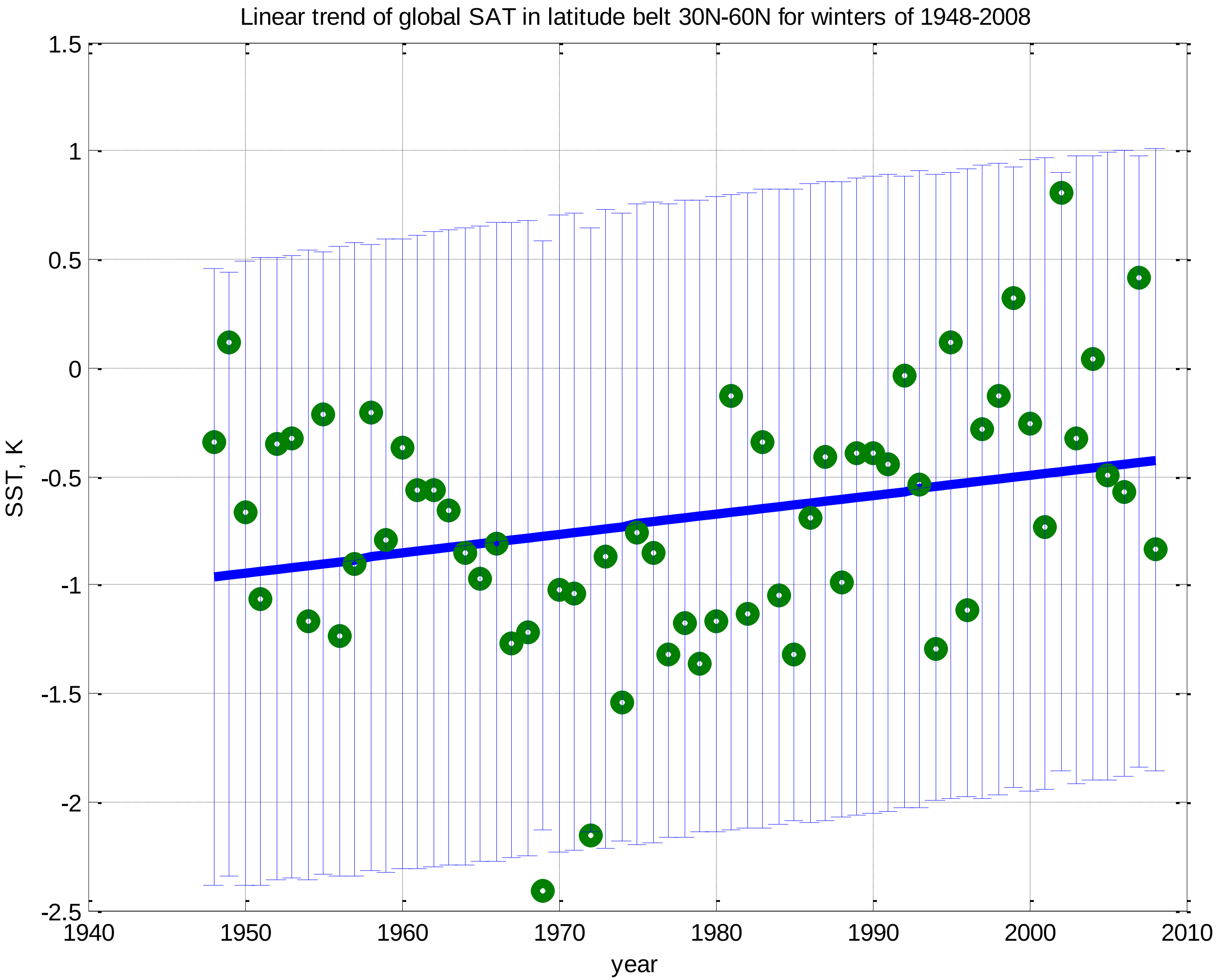


Non-linear trend and error bars for significance level: **0.01 (p=0.99)**

Lambda=0.47



Linear trend and error bars for **significance level**: **0.01 (p=0.99)**



Comparison of standard statistics for linear and non-linear SST trends:

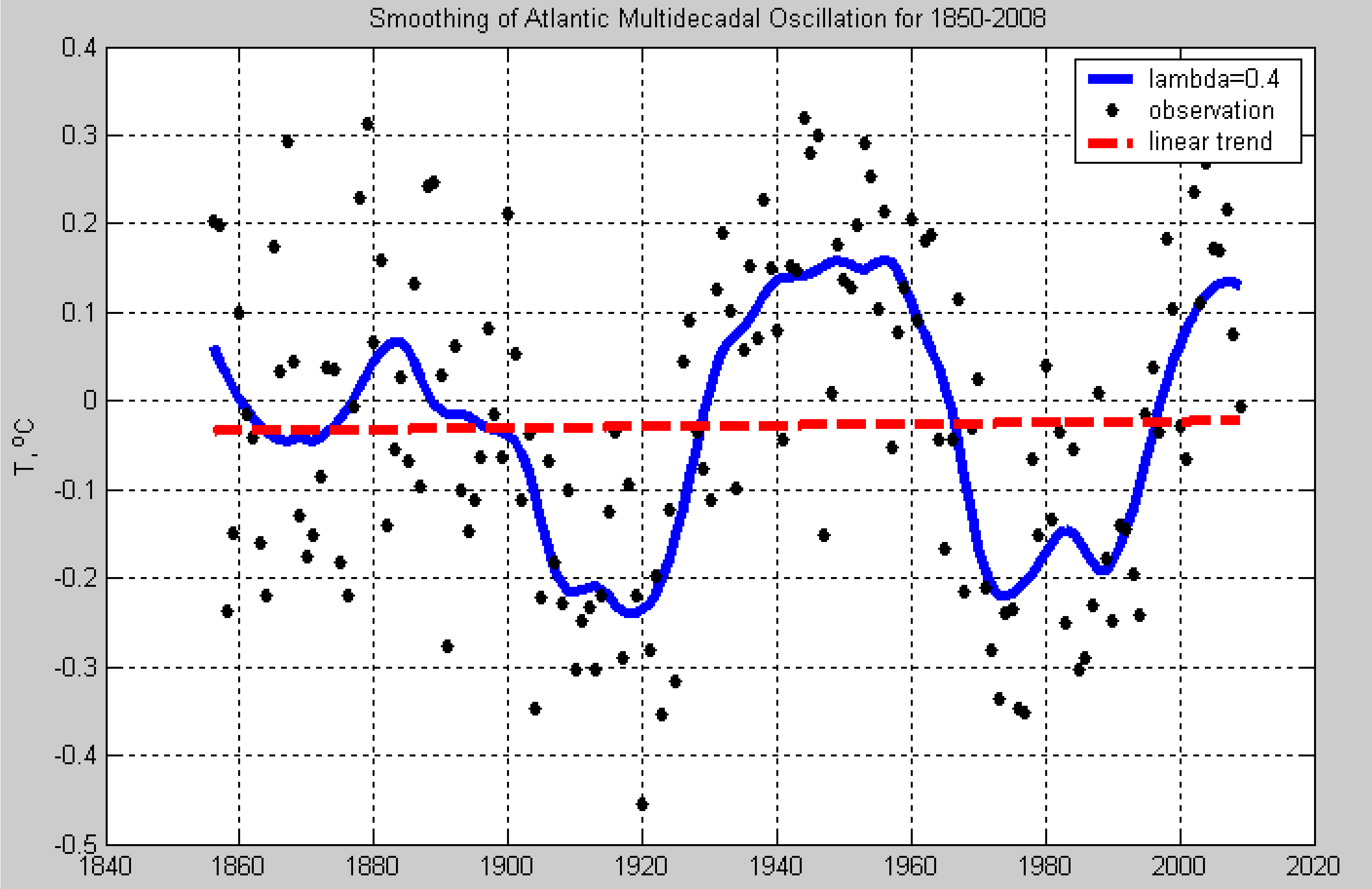
	Mean Error Bar "Width" (C) ***significance level*: 0.01 (p=0.99)**	Correlation coefficient to observational data	Fisher statistics (Part of predicted dispersion)
linear	2.91	0.27	11.9
Non-linear	1.72	0.65	4.9

North Atlantic:

Atlantic Multidecadal Oscillation

(**Source:** Enfield, et al, GRL, 2001)

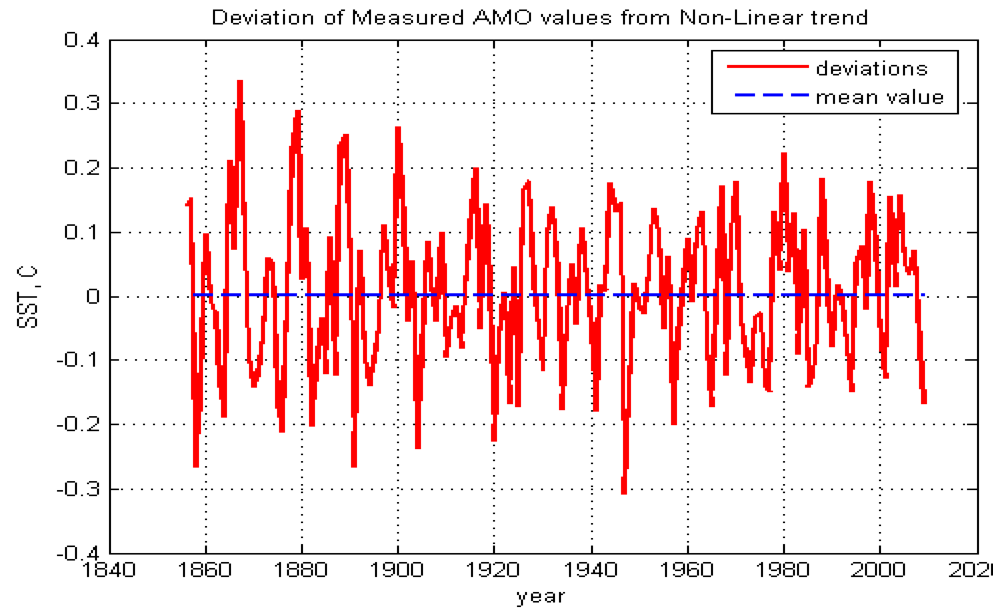
Atlantic Multidecadal Oscillation (AMO), winters 1856-2009: smoothing by regularization technique



Comparison of Linear and Non-Linear Trend Efficiencies

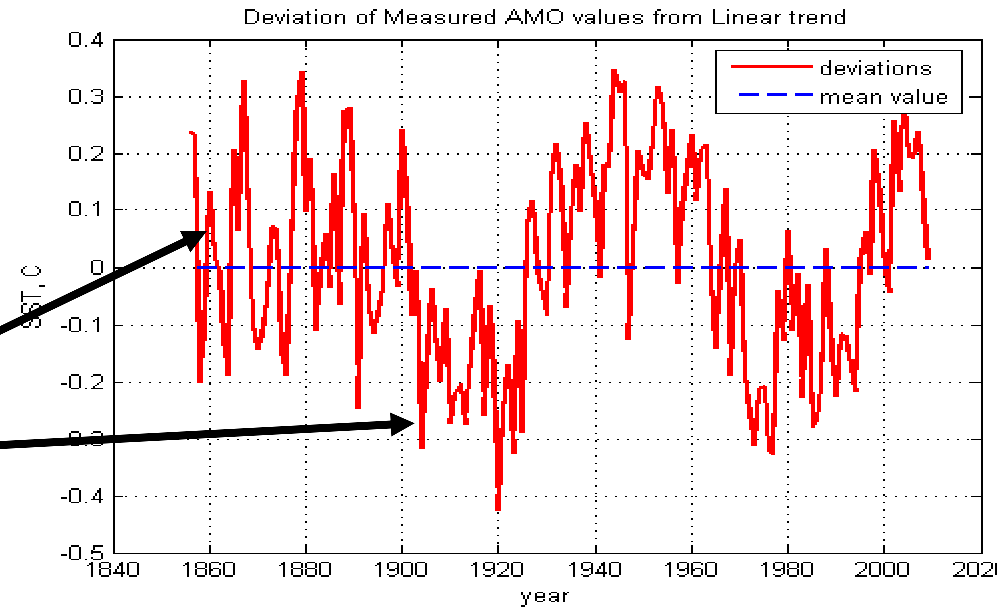
DEVIATIONS FROM:

Nonlinear trend →



Quasi-white noise:
Model of "climate noise"

Linear trend →

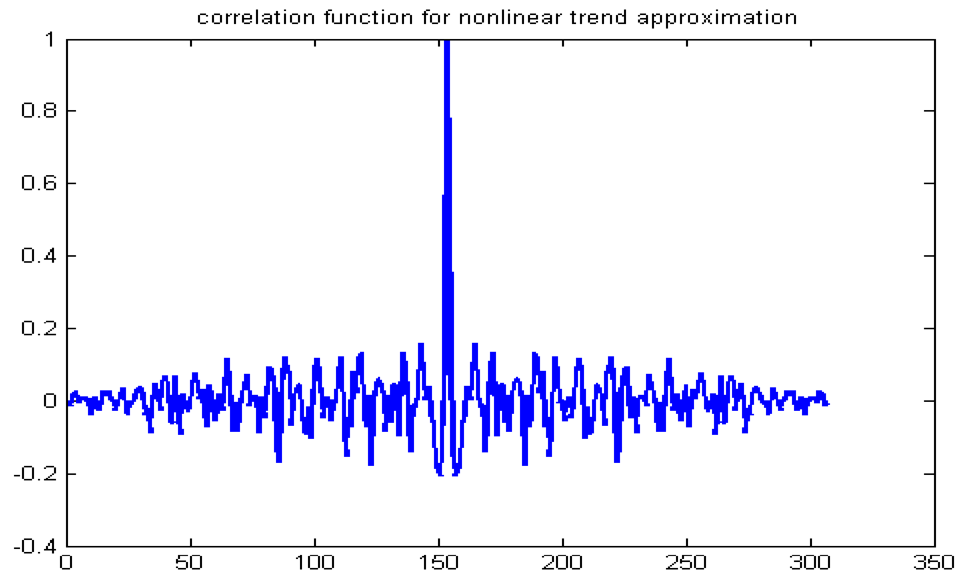


Non-Stationarity

Correlation function of deviations from:

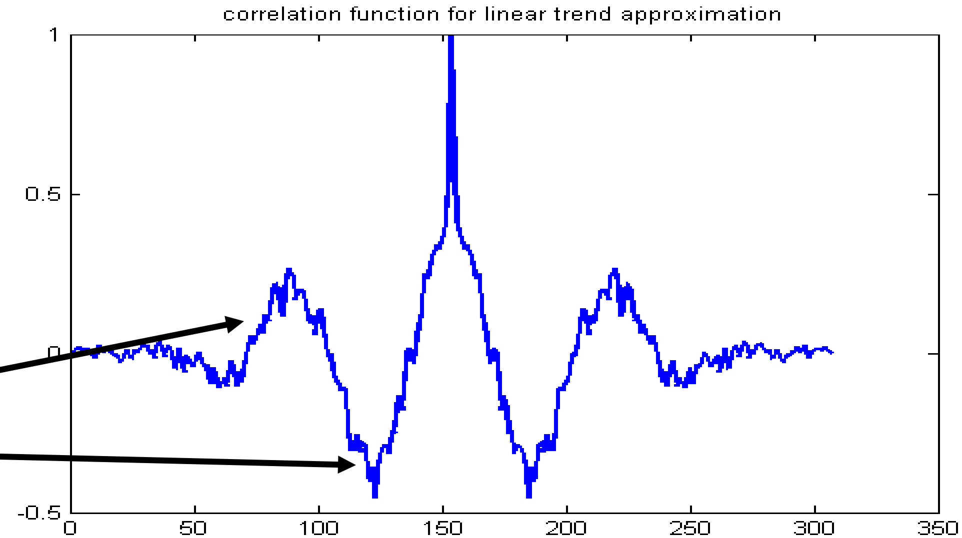
Nonlinear trend

Close to
Delta-function



Linear trend

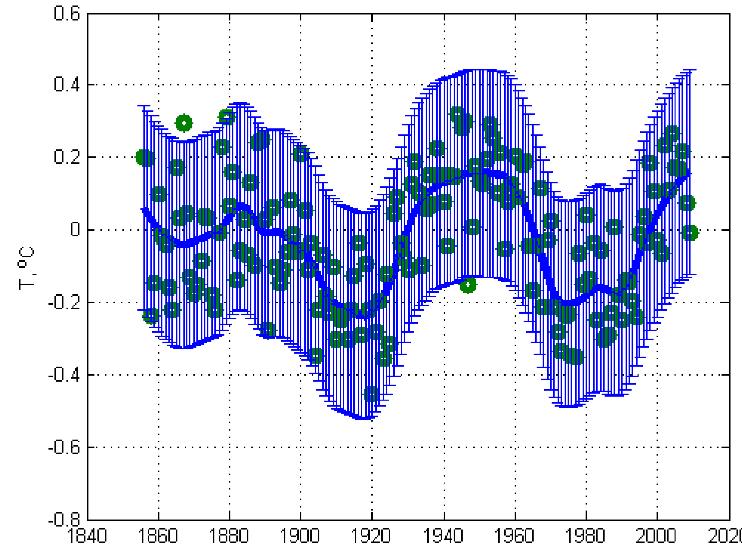
Non-Stationarity



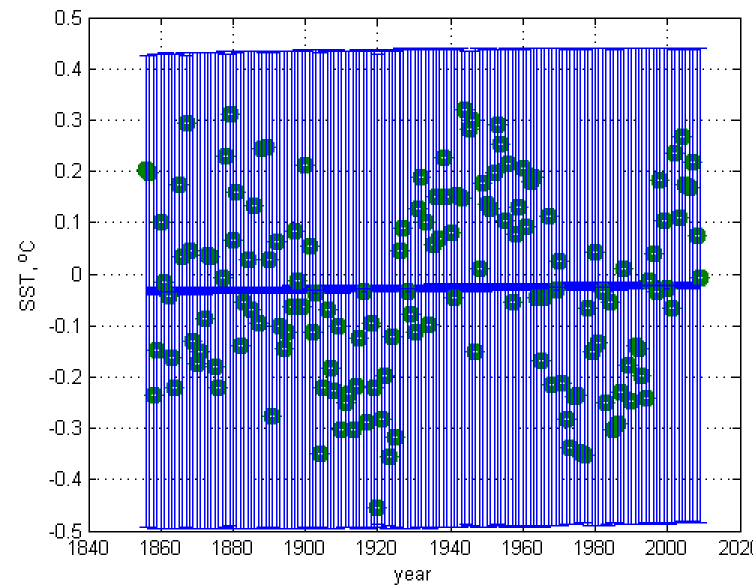
Confidential interval widths for:

Nonlinear trend: ± **0.22**

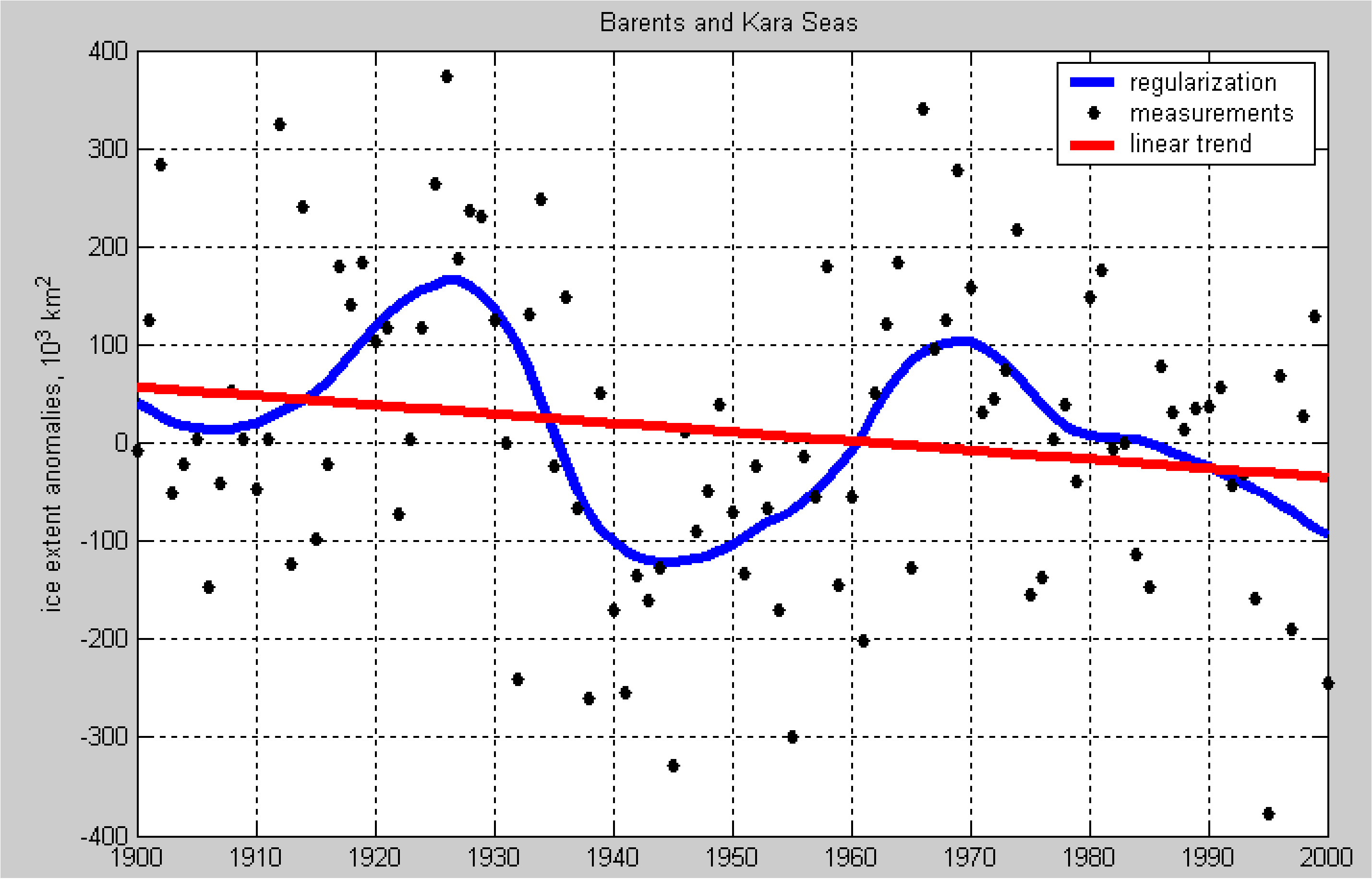
±



Linear trend: ± **0.48**

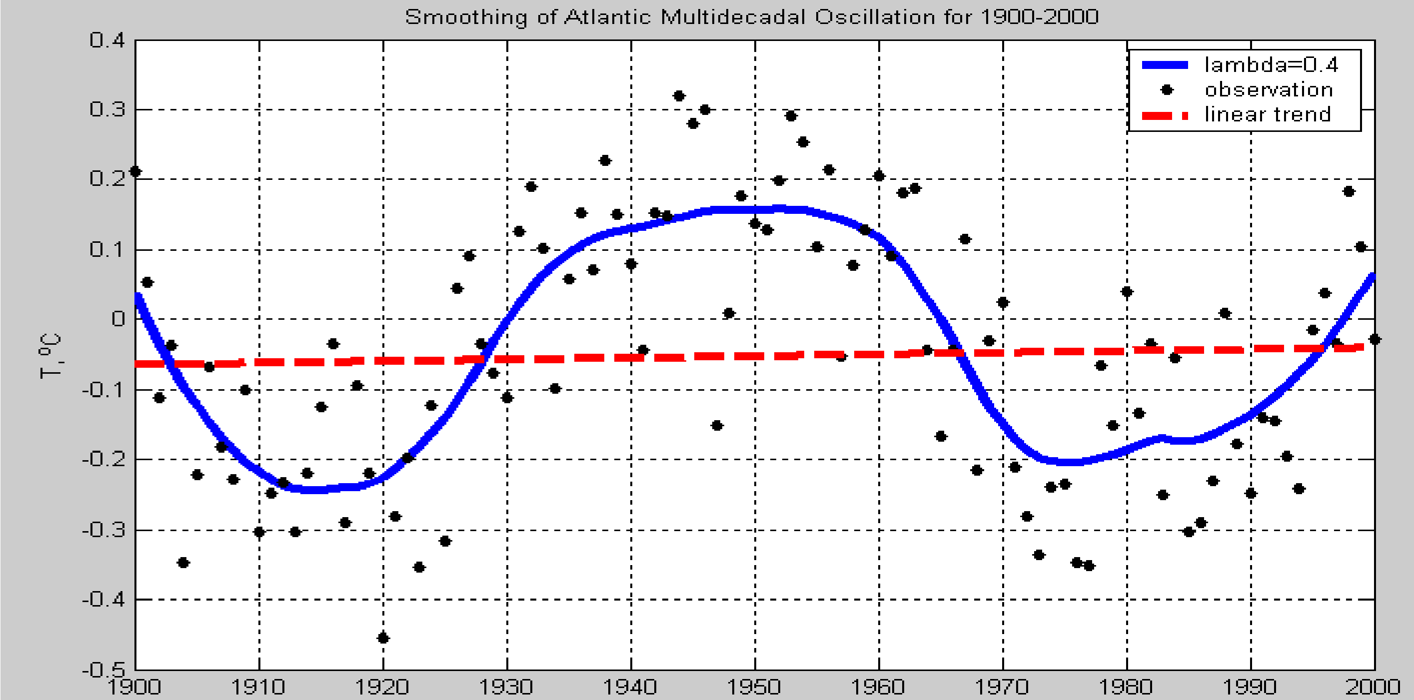


Ice Extent Anomaly in Barents and Kara Seas, Septembers, 1900-2000: smoothing by regularization technique



AMO:

1900-2000

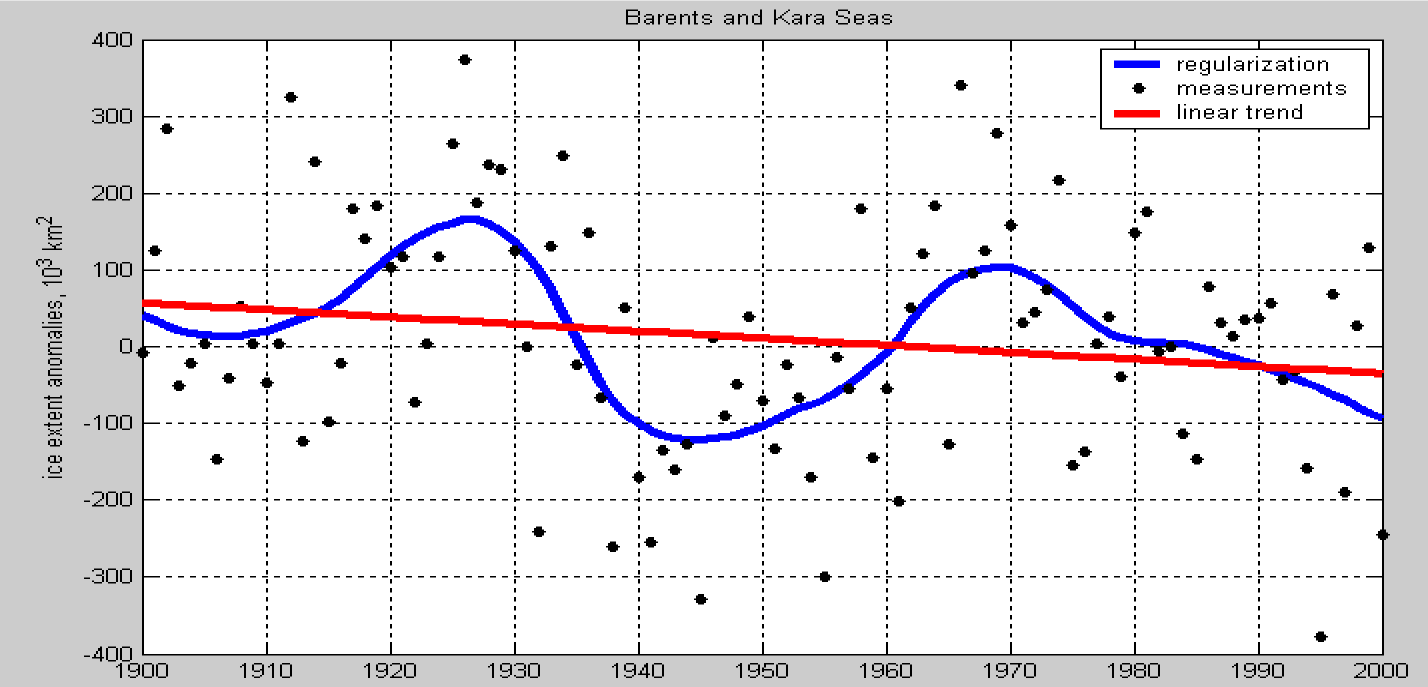


Ice extent

Barents&

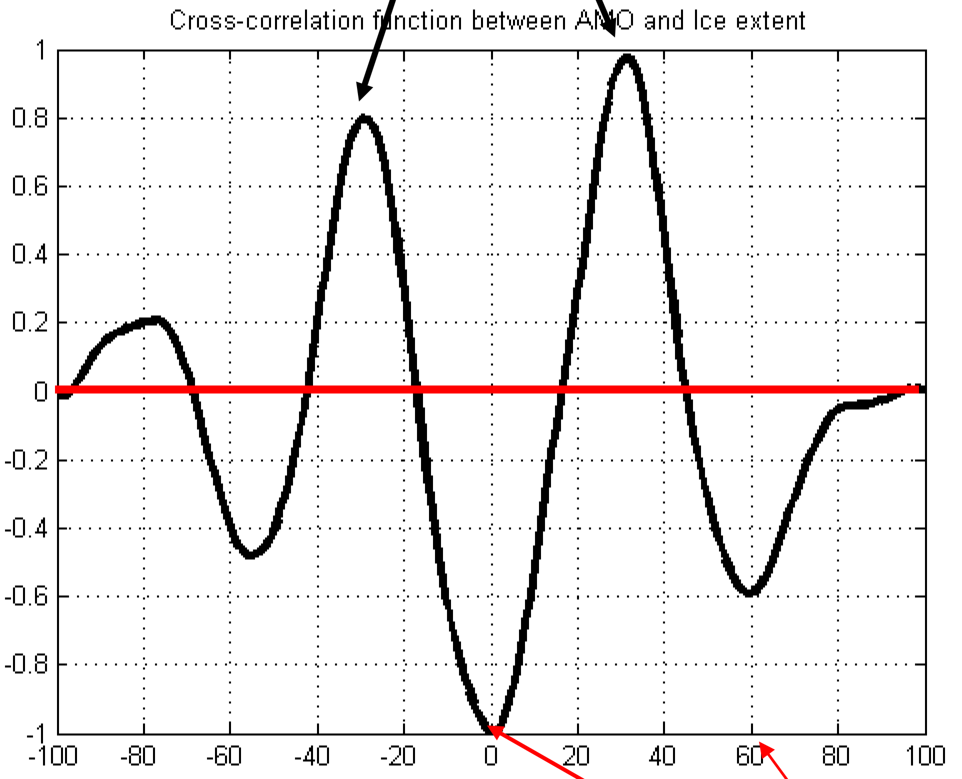
Kara seas:

1900-2000



Cross-Correlation Function between AMO and Ice extent

Positive correlation with phase ~ 60 years

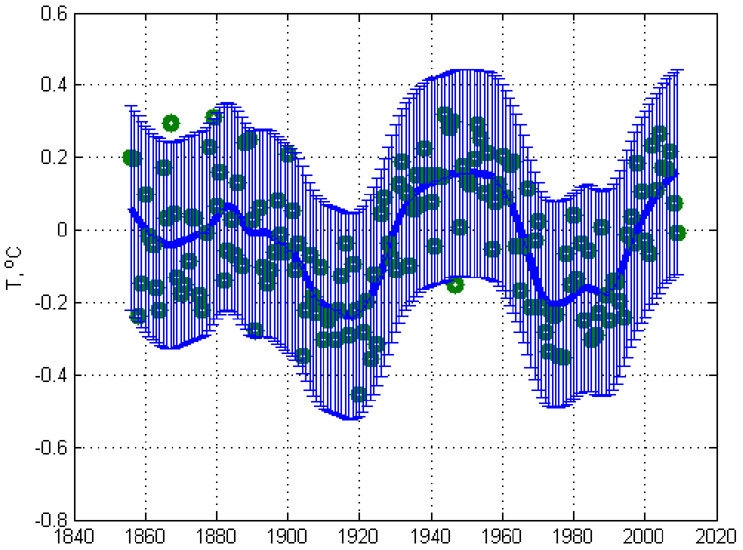


Anti-Correlation

Phase ~ 60 years

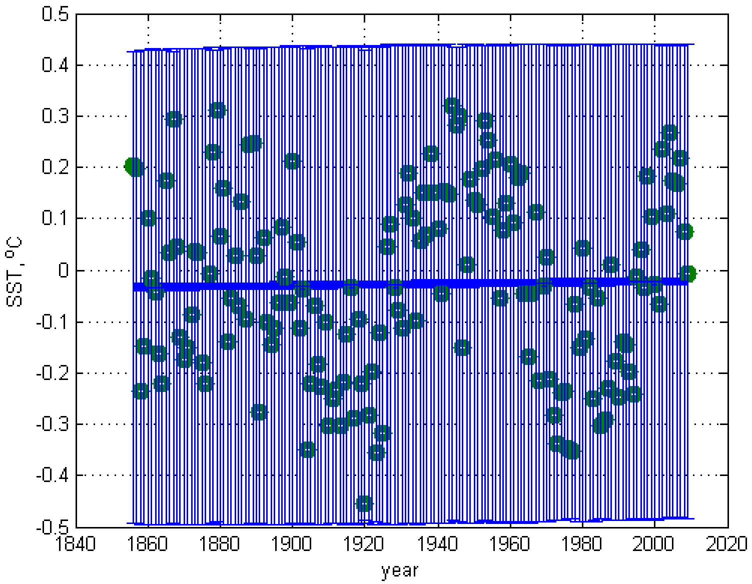
Confidential interval widths for:

Nonlinear trend: ± **0.22**

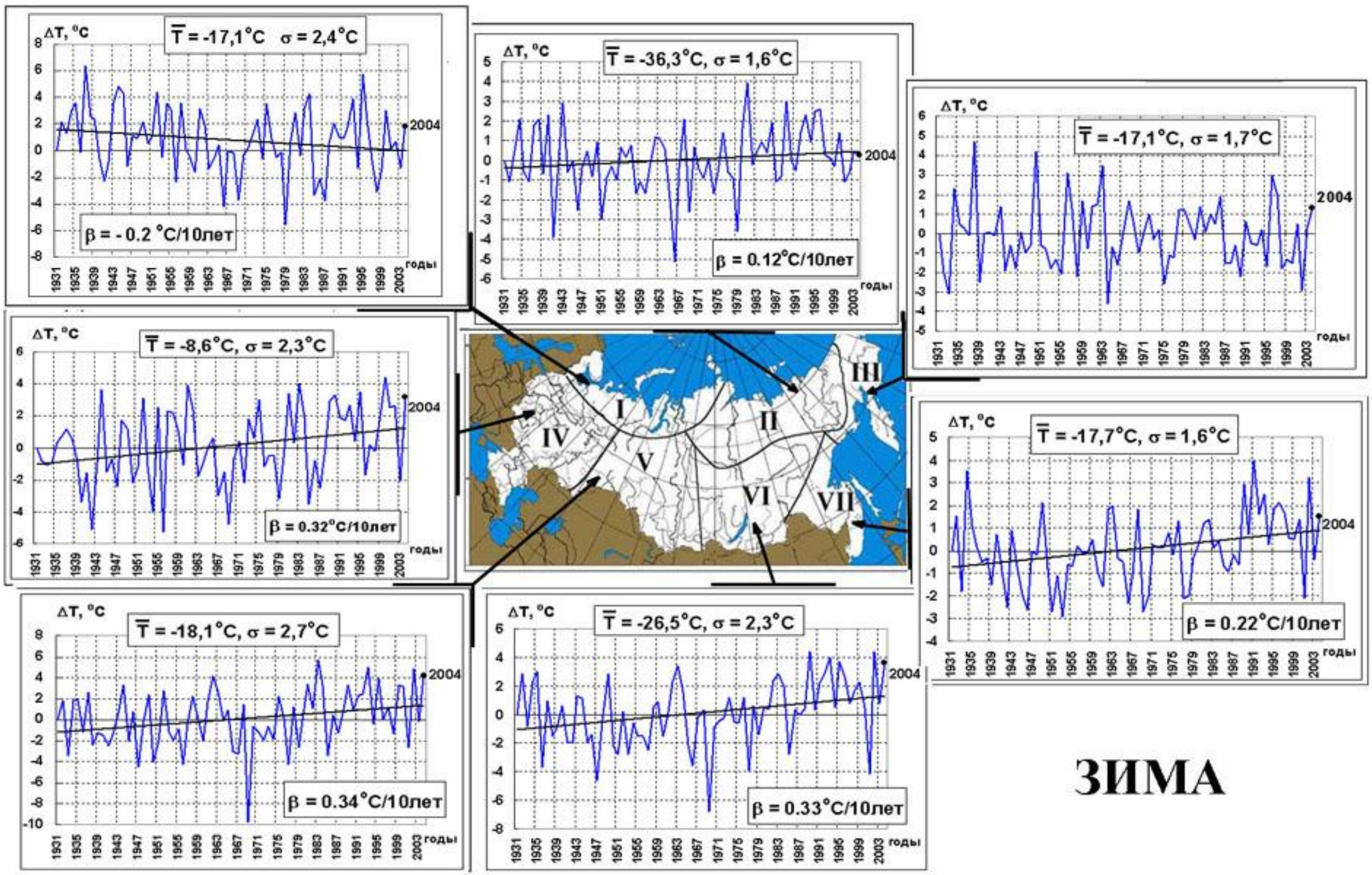


±

Linear trend: ± **0.48**



Russian Arctic Stations: surface air temperature trends (1931-2003, winters)



ЗИМА

Spectral methods for time series analysis: Wavelet

Стандартный Фурье анализ временных рядов ориентирован на применение к стационарным рядам. Отклонение от стационарности влечет за собой зависимость Фурье спектров от базового интервала анализа. Фурье спектры зависят от фазы изучаемого процесса, которая изменяется в нестационарном случае. Для того чтобы полностью охватить все особенности нестационарного процесса был разработан метод получения вейвлет спектров, которые в отличие от одномерных Фурье спектров оказываются двумерными. Остановимся на описании данного метода спектрального анализа временных рядов.

Consider time series .

$$x(t)$$

Wavelet has following form:

$$\Psi_X^{\psi}(\tau, s) = \int x(t) \cdot \psi_{\tau,s}^{*}(t) dt$$

Function of spectral transformation:

$$\psi_{\tau,s} = \frac{1}{\sqrt{s}}\psi\left(\frac{t-\tau}{s}\right)$$

Depended on two new variables: time delay τ

and scaling variable **S**.

Mostly used spectral function is

Morly function

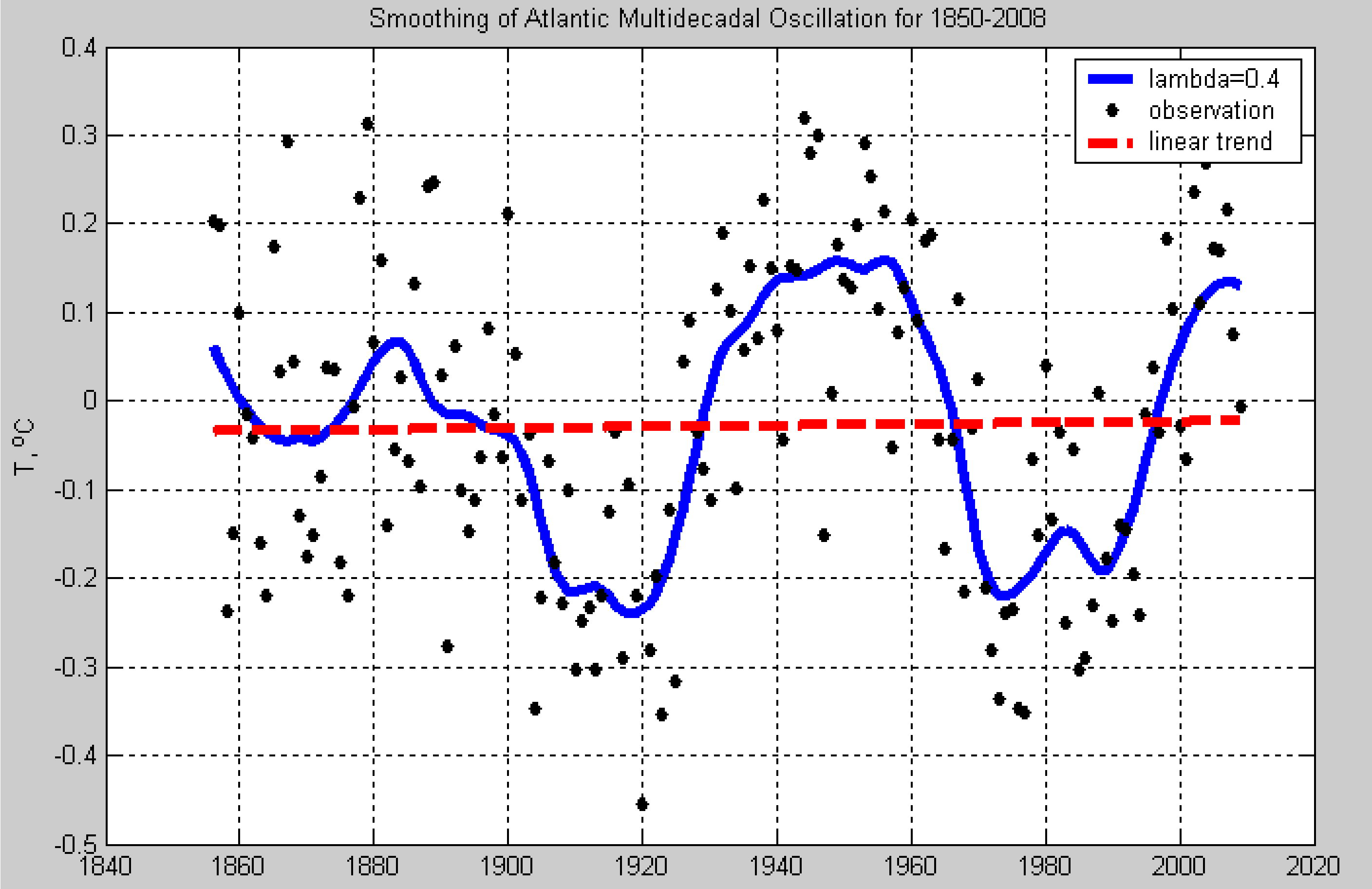
$$\psi(t) = \frac{1}{\sqrt{2\pi\sigma^3}} (e^{\frac{-t^2}{2\sigma^2}} \cdot (\frac{t^2}{\sigma^2} - 1))$$

North Atlantic:

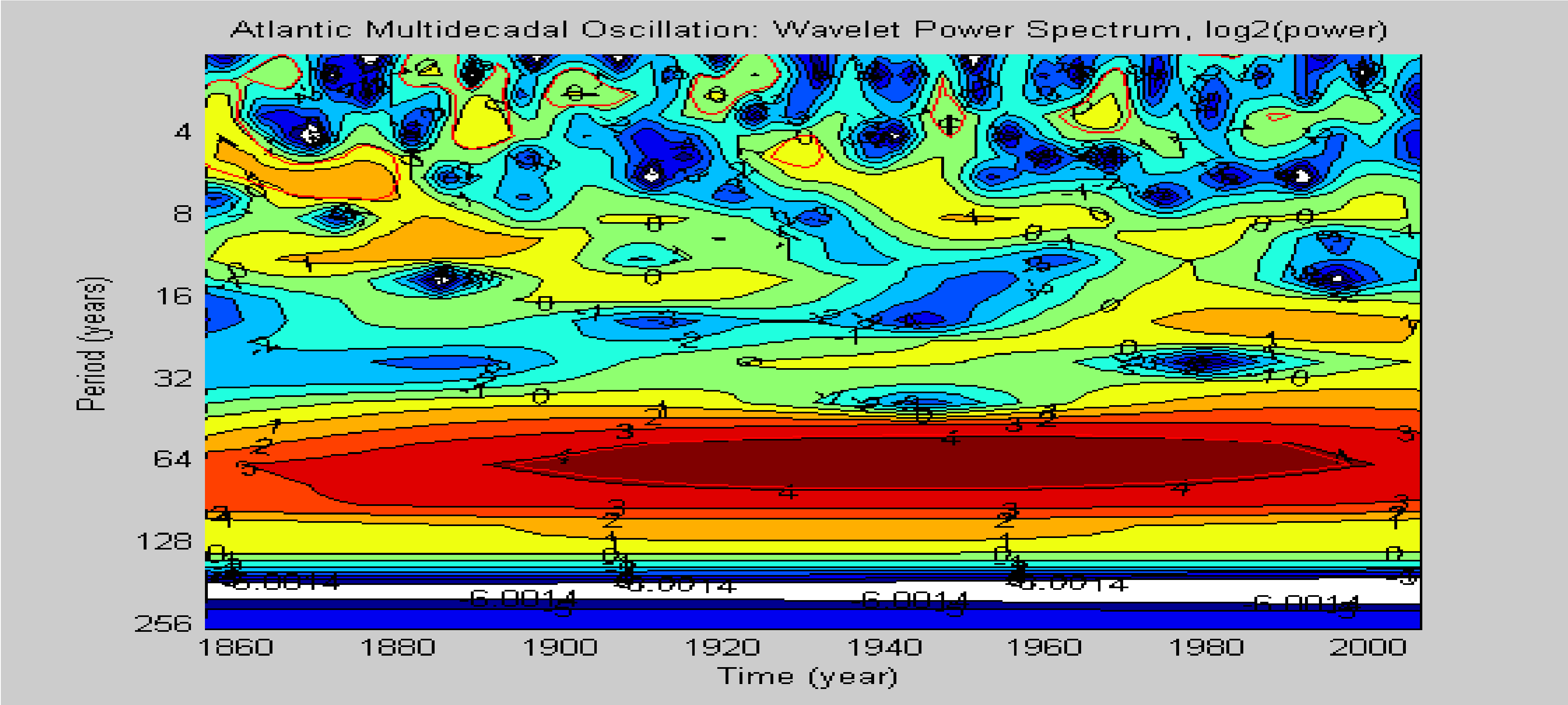
Atlantic Multidecadal Oscillation

(**Source:** Enfield, et al, GRL, 2001)

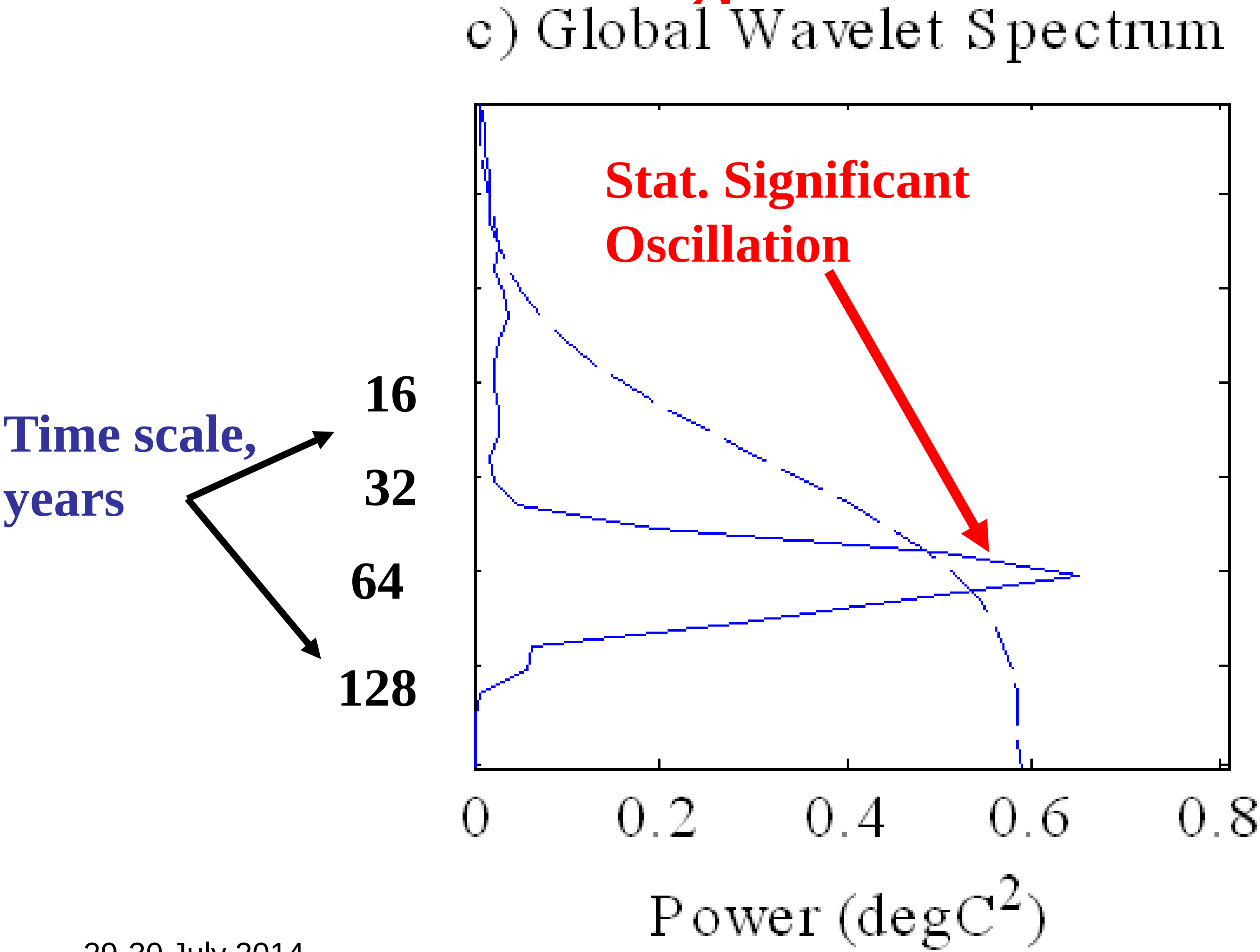
Atlantic Multidecadal Oscillation (AMO), winters 1856-2009: smoothing by regularization technique



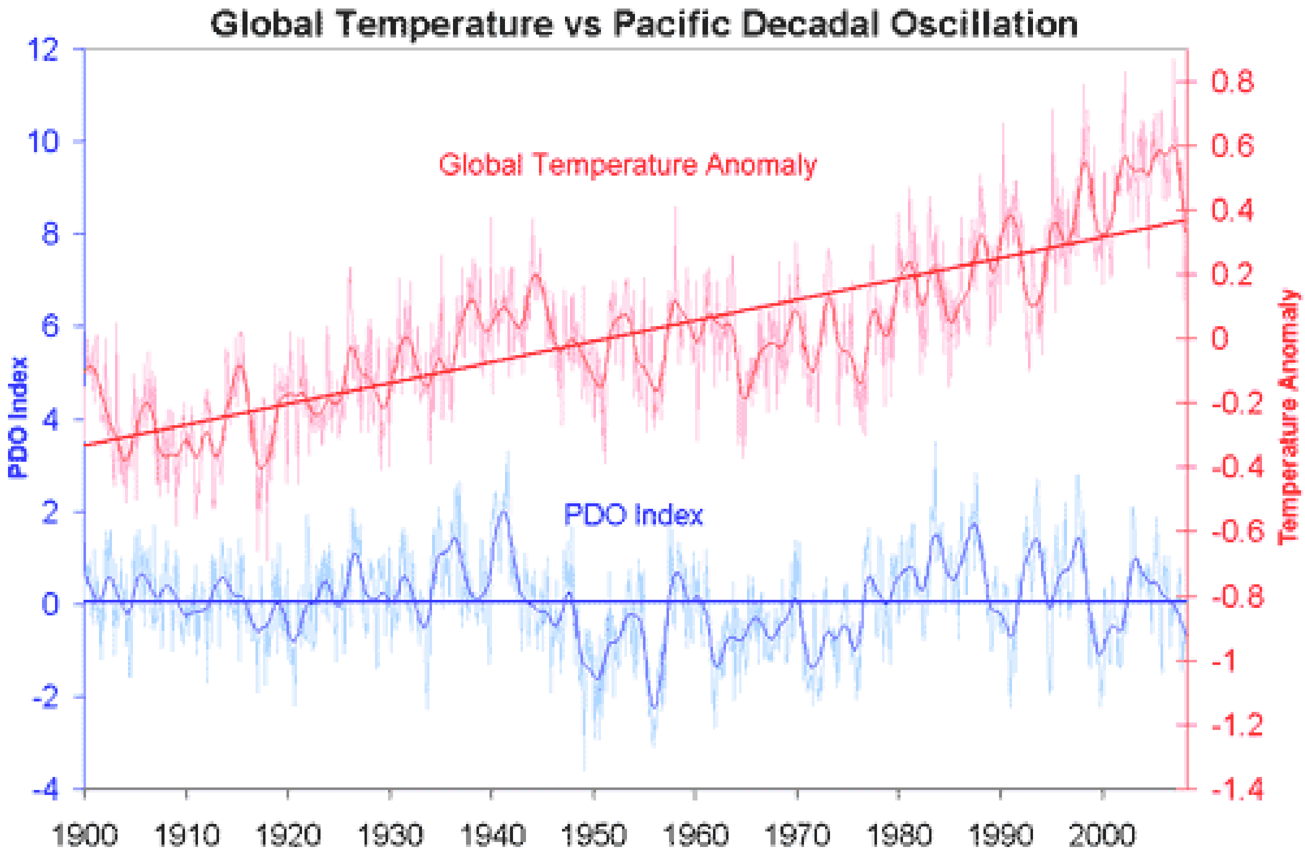
Atlantic Multidecadal Oscillation (AMO), winters 1856-2009: wavelet analysis



Wavelet spectrum: Statistical Significance Estimation

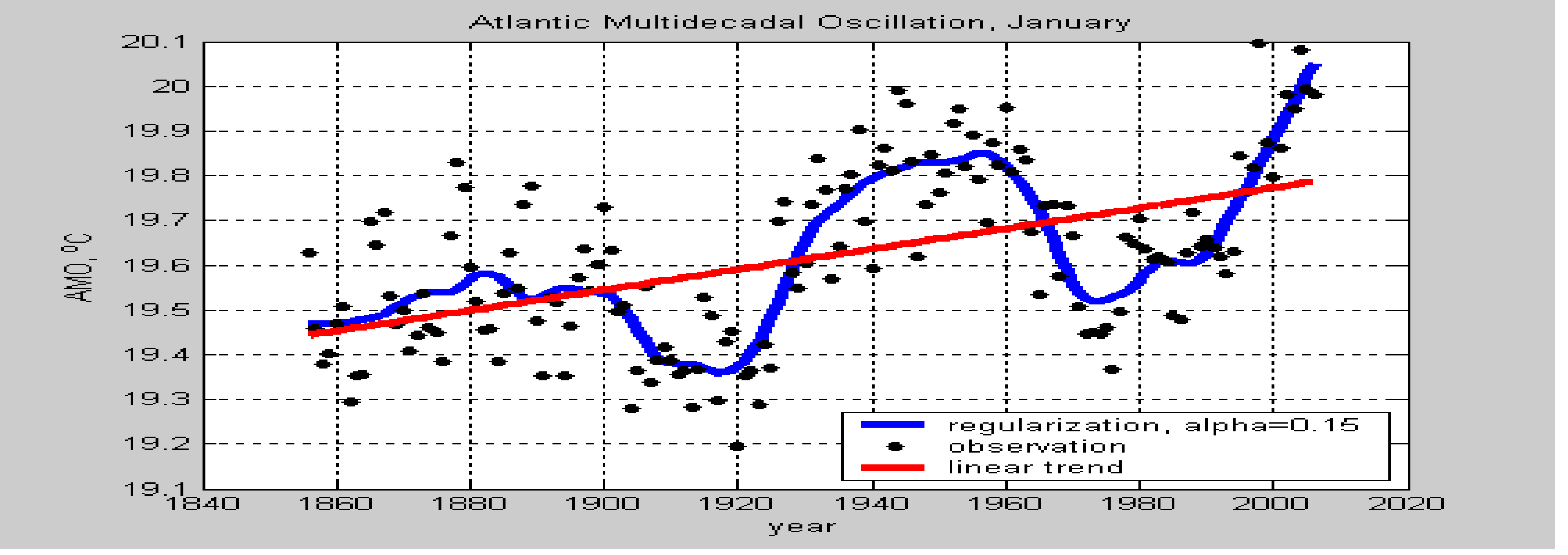


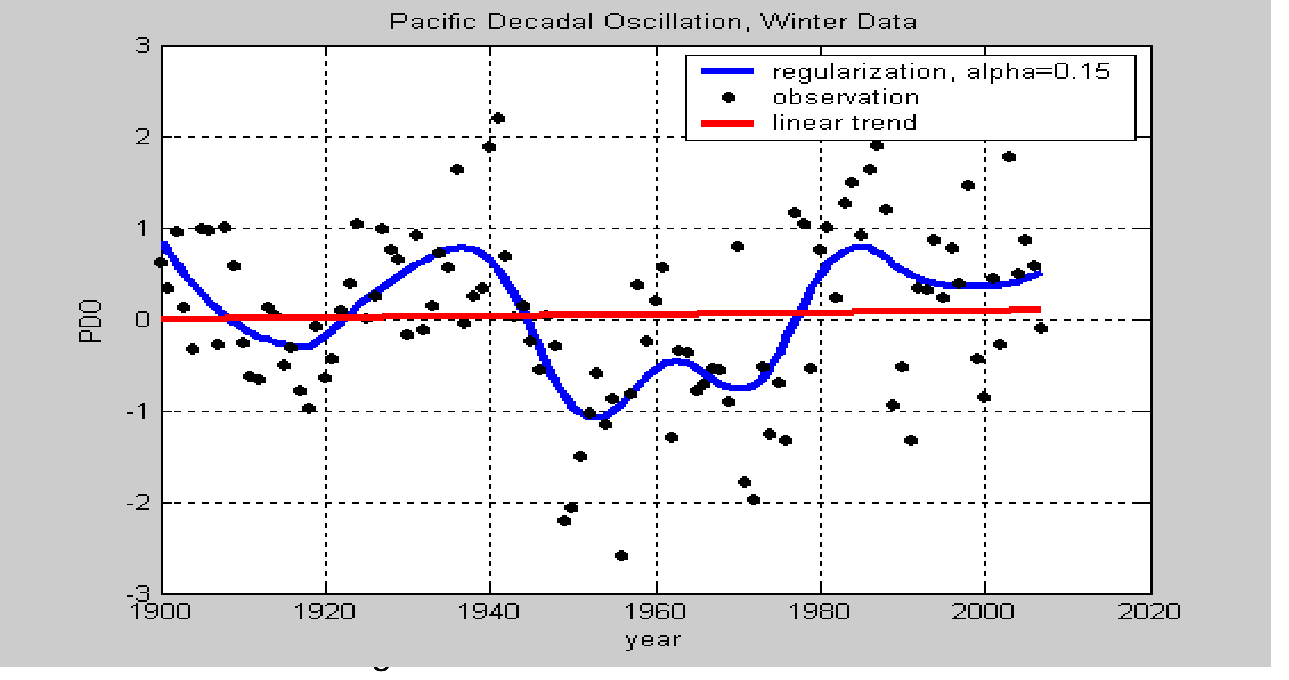
Relationships between SAT and PDO


Global Temperature vs Pacific Decadal Oscillation
Global Temperature Anomaly
PDO Index
PDO Index
Temperature Anomaly
12
10
8
6
4
2
0
-2
-4
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
-1.2
-1.4
1900
1910
1920
1930
1940
1950
1960
1970
1980
1990
2000

Связь АМО и PDO

- Сходные масштабы колебаний
- Сдвиг фаз
- Связь частоты Эль-Ниньо\Ла-Ниньо с периодами потепления\похолодания

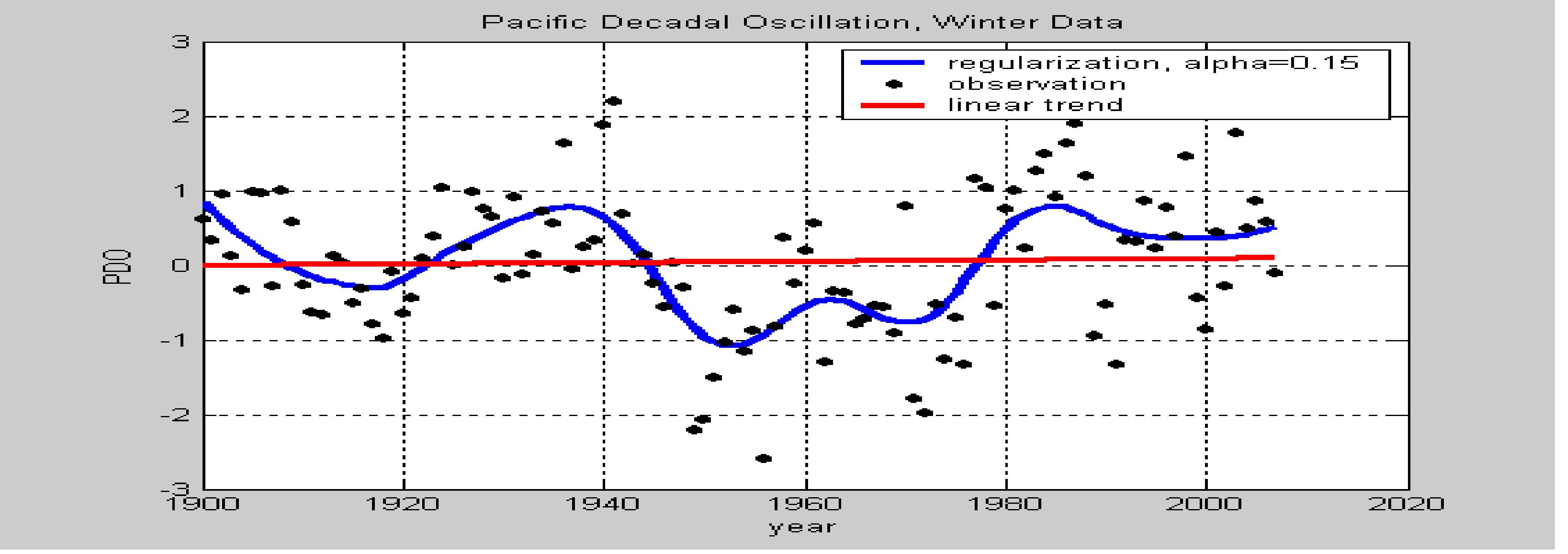




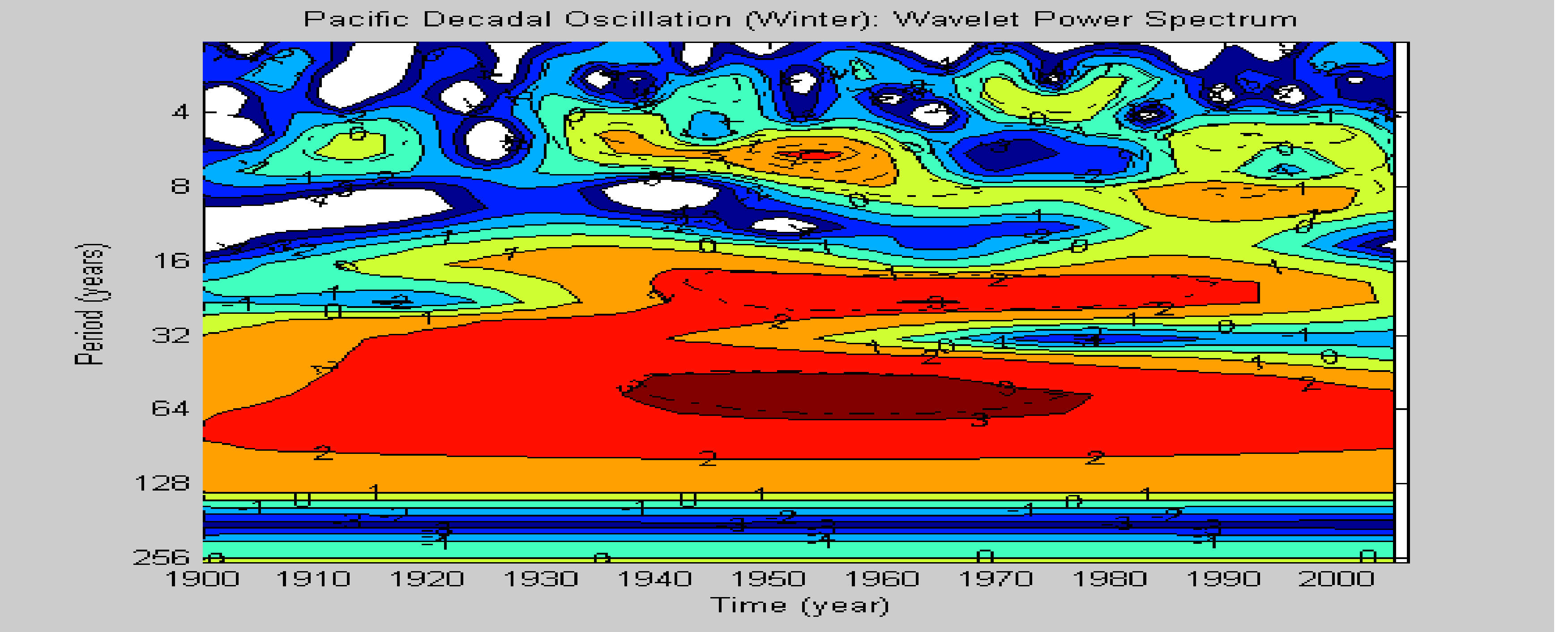
29-30 July 2014

Circulation to Climate Change

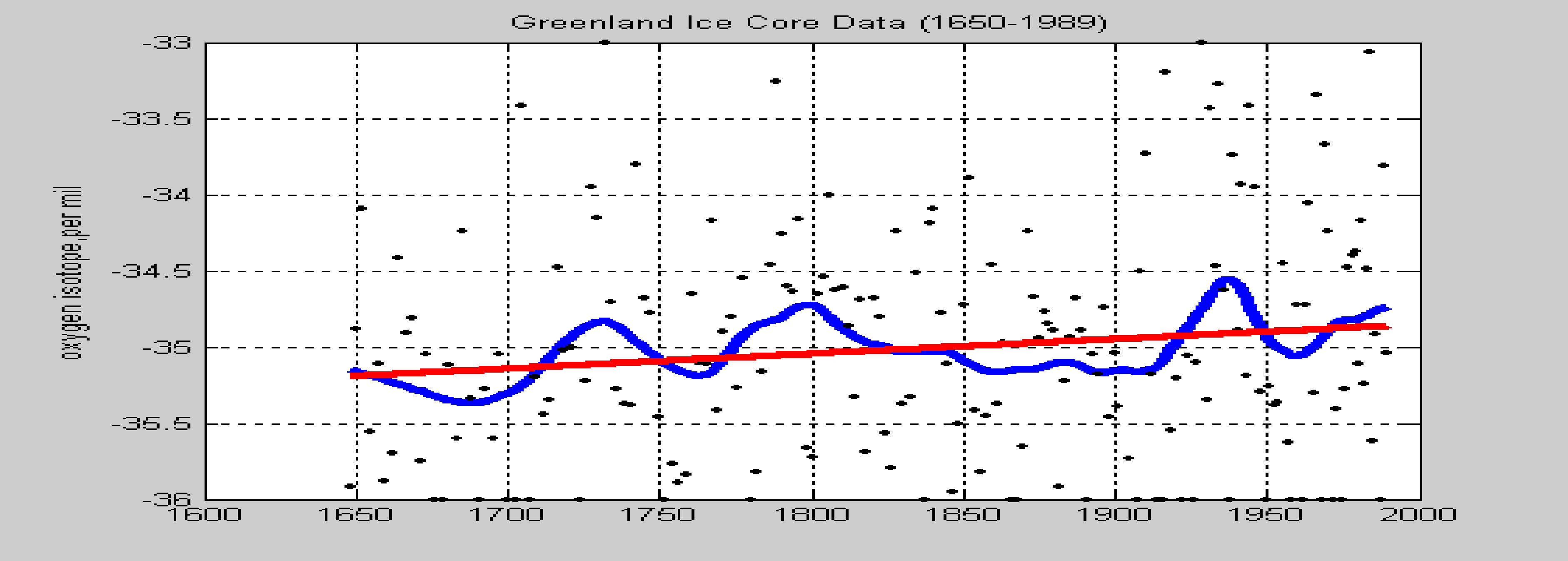
Comparison of the AMO and PDO time series phases



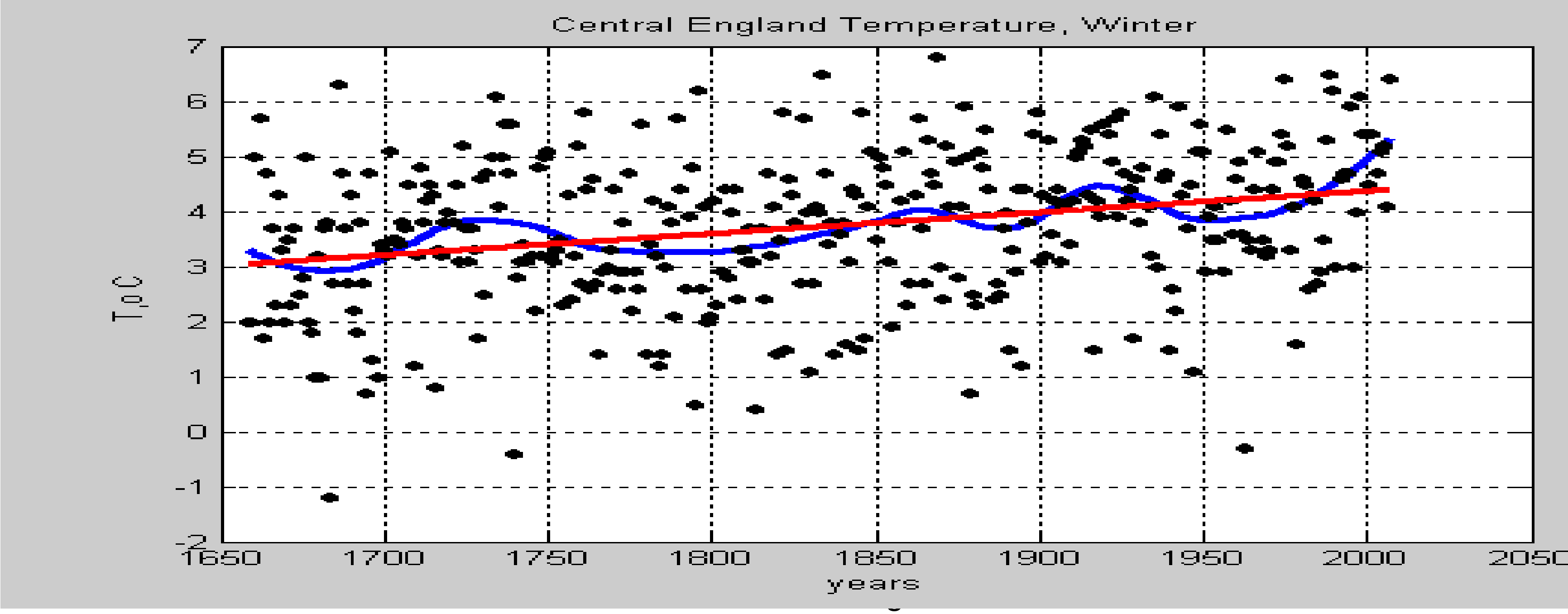
Source: EOF analyses were calculated of the monthly SST anomalies poleward of 20N in the Pacific basin. http://www.atmos.washington.edu/~mantua/abst.PDO.html



- **Comparison of Paleo Climate time series and analogical instrumental data for SAT in Central England: 1659-2005**



Source: Grootes, et al., Comparison of oxygen isotope records from the GISP and GRIP Greenland ice cores. Nature 366, 1993, pp. 552-554.

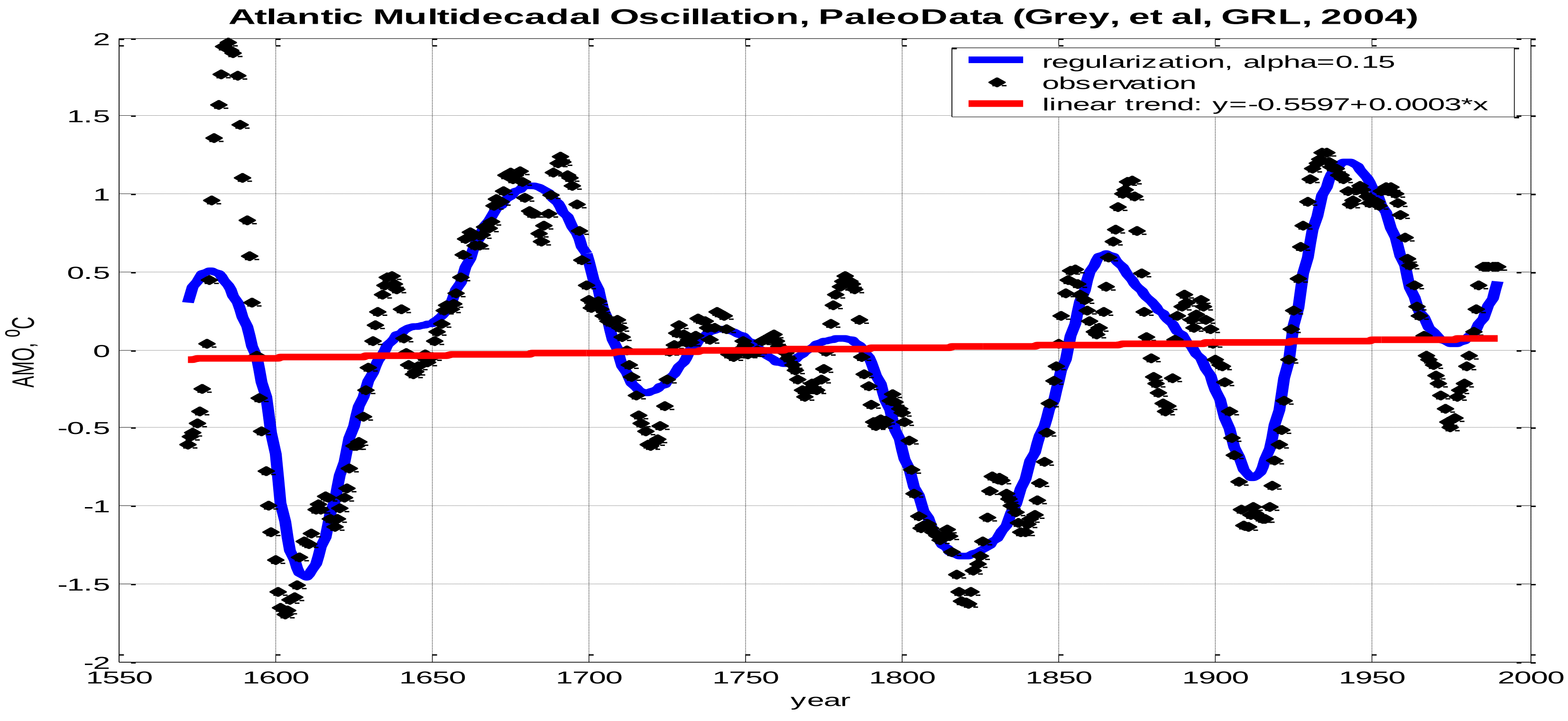


PaleoClimate data on AMO

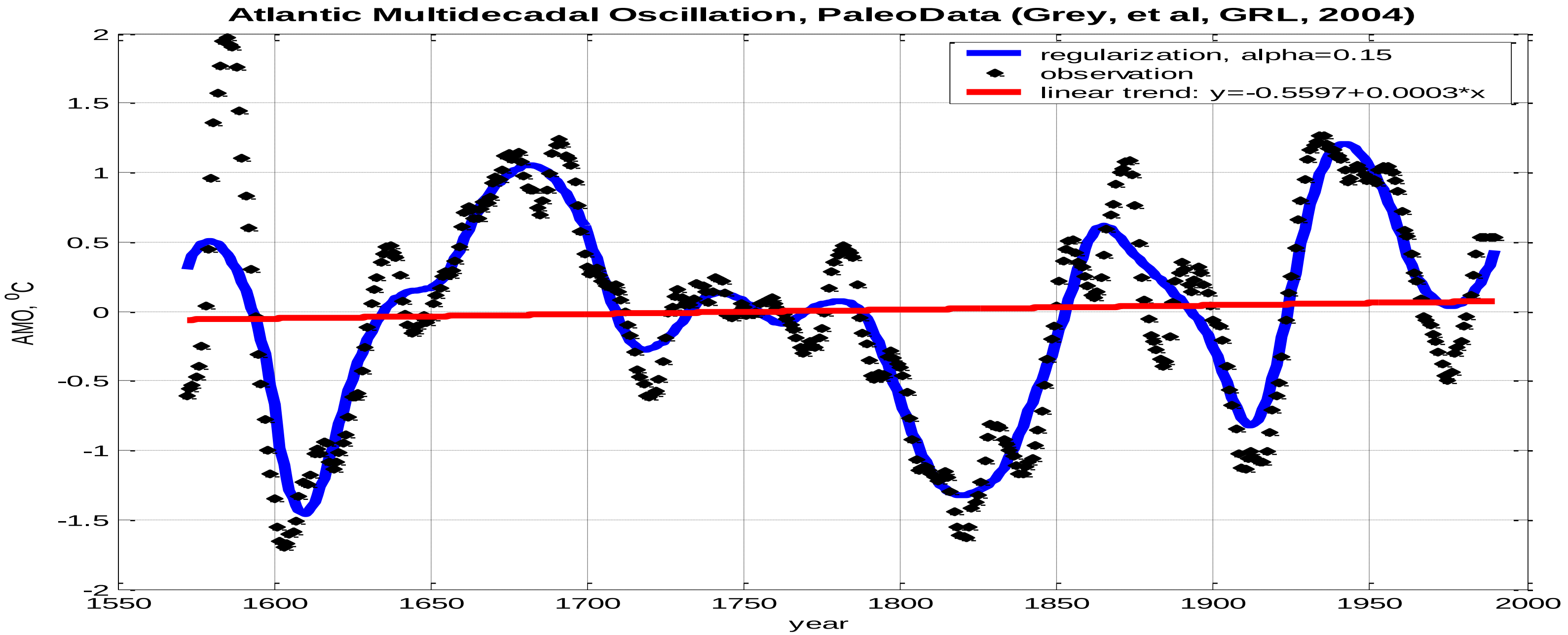
(Grey, et al, 2004, G.R.L.)

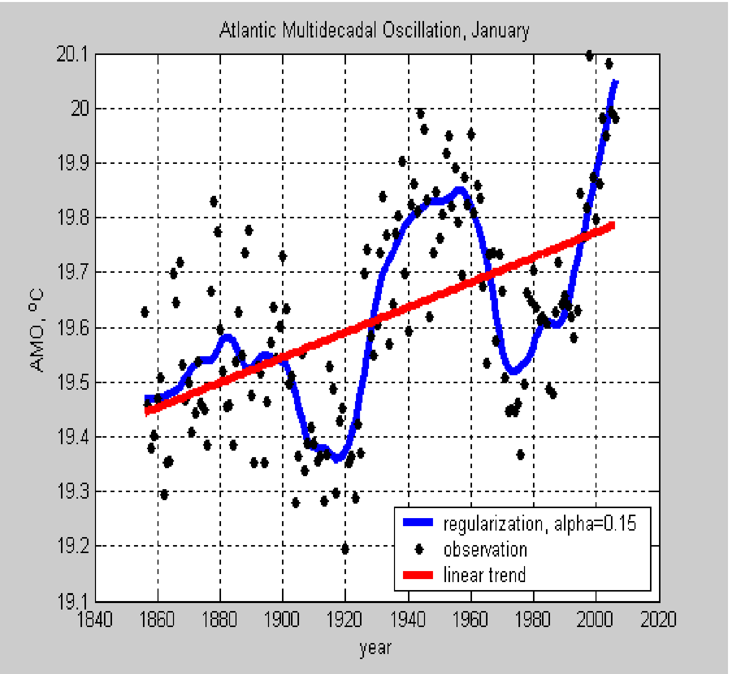
AMO, Paleo Climate Data 1570-1970

(Grey, et al, 2004, JGR)

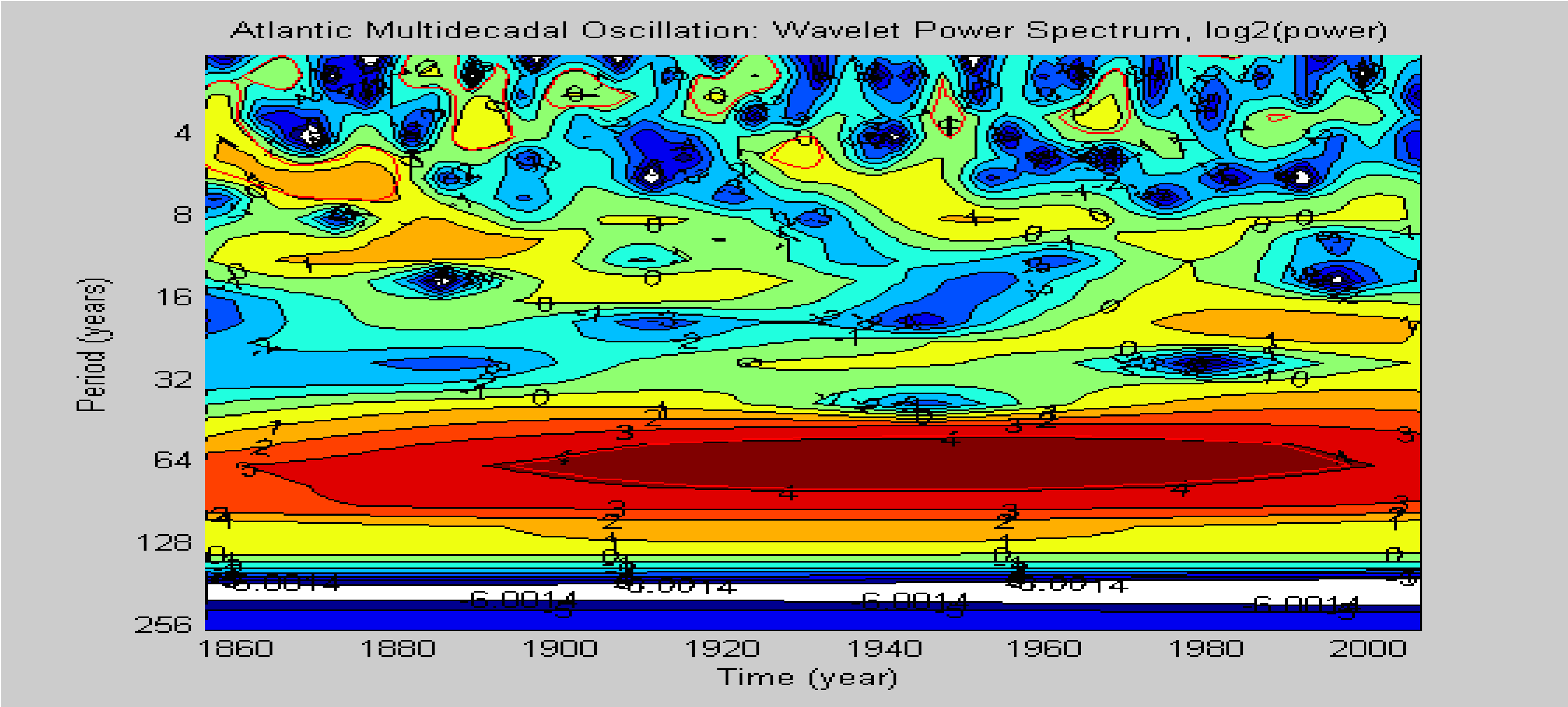


1600 **1700** **1800** **1900**

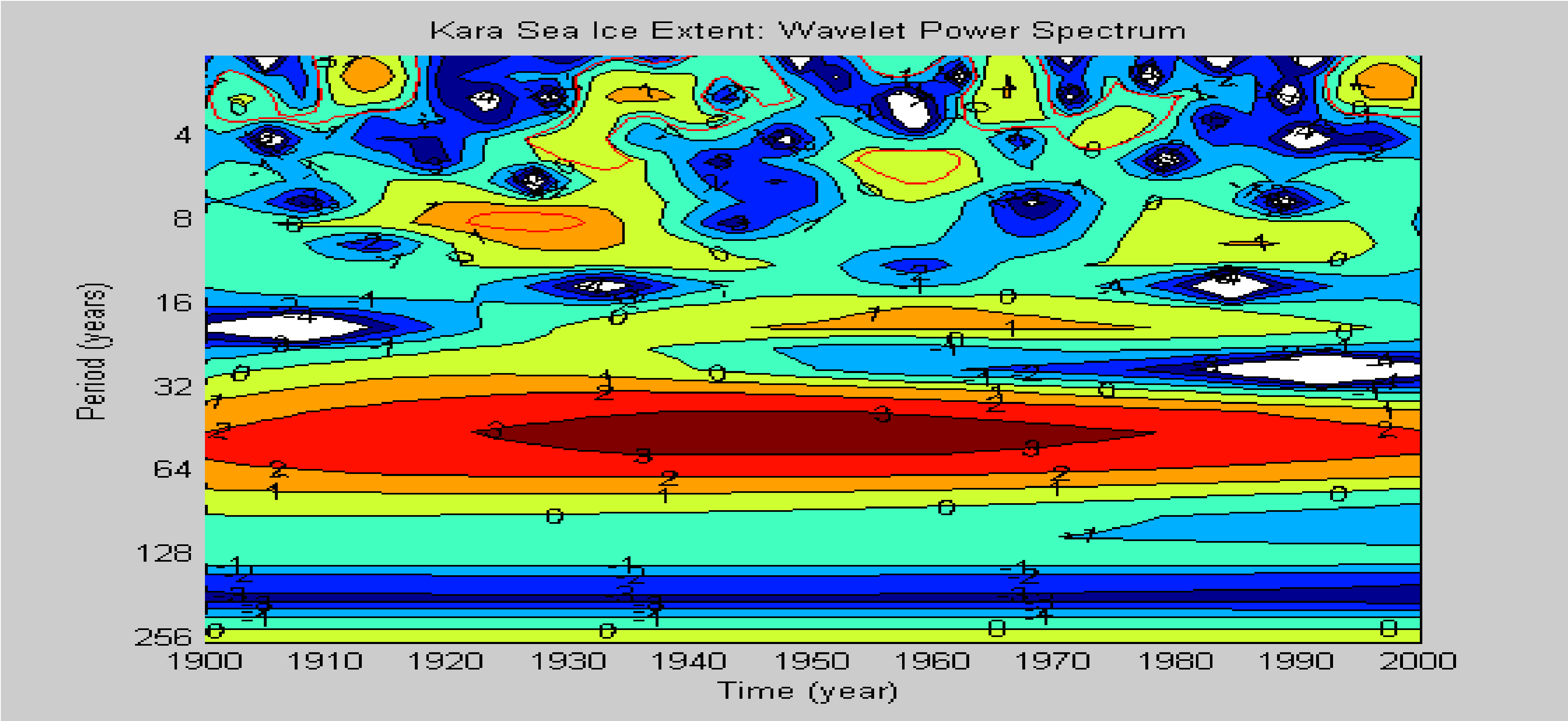

Atlantic Multidecadal Oscillation, PaleoData (Grey, et al, GRL, 2004)
regularization, alpha=0.15
observation
linear trend: y=-0.5597+0.0003*x
AMO, °C
year
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
1550
1600
1650
1700
1750
1800
1850
1900
1950
2000


Atlantic Multidecadal Oscillation, January
regularization, alpha=0.15
observation
linear trend
AMO, °C
year
20.1
20
19.9
19.8
19.7
19.6
19.5
19.4
19.3
19.2
19.1
1840
1860
1880
1900
1920
1940
1960
1980
2000
2020

Atlantic Multidecadal Oscillation (AMO), winters 1856-2009: wavelet analysis



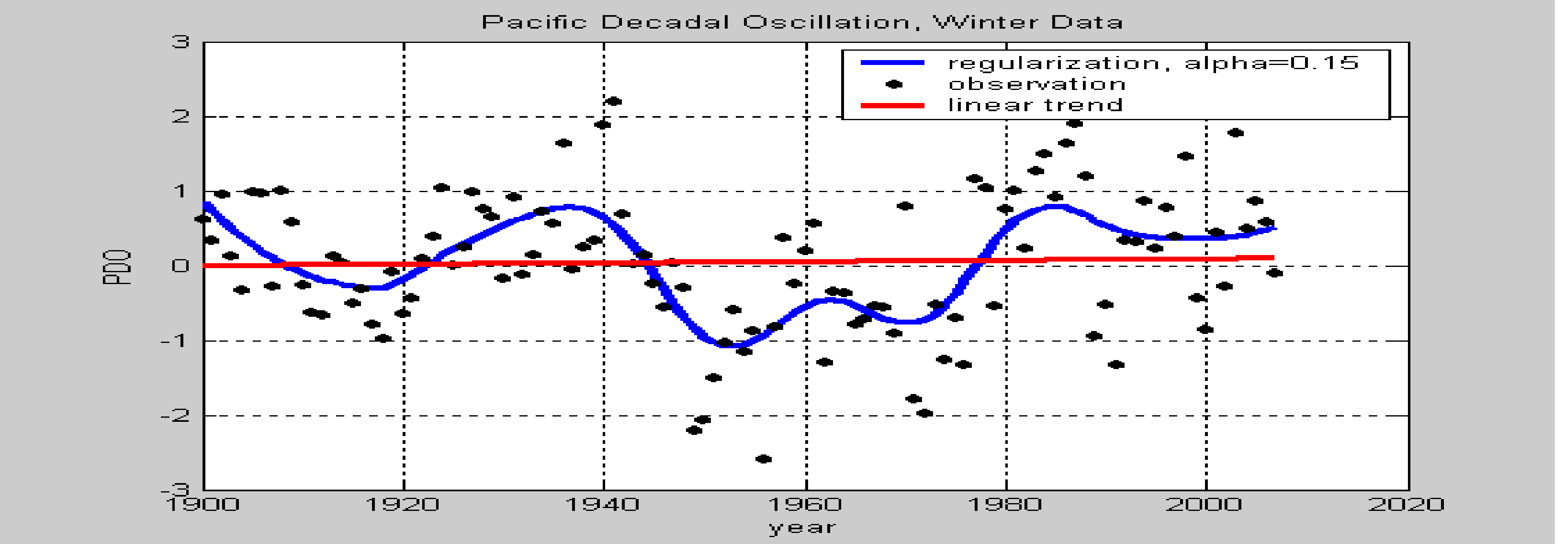
Ice Extent Anomaly in Barents and Kara Seas, Septembers, 1900-2000: wavelet analysis



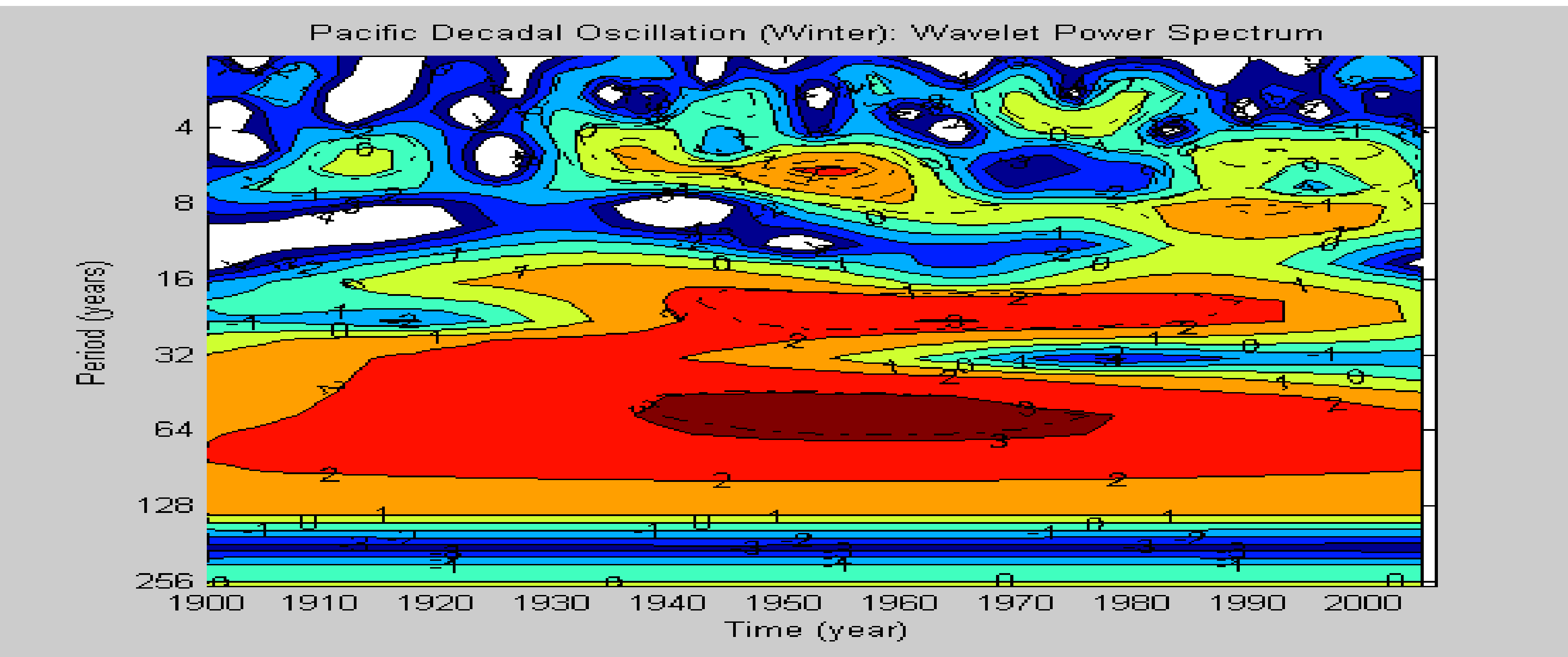
North Pacific:

Pacific Decadal Oscillation

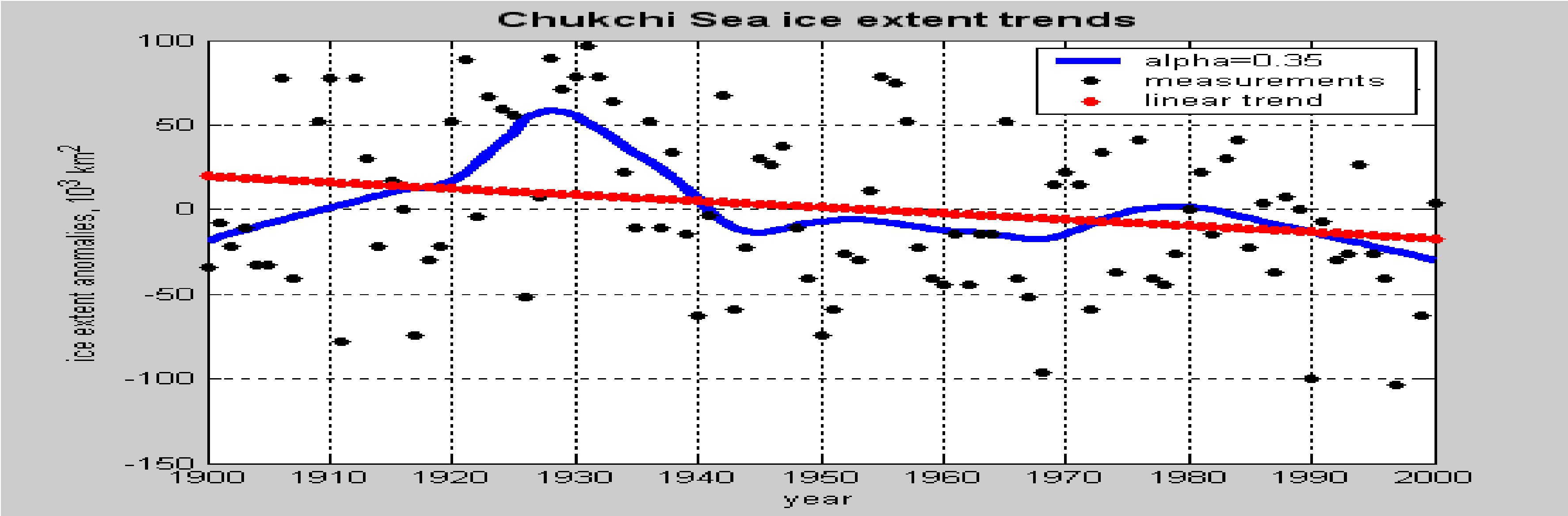
(EOF analyses were calculated of the monthly SST anomalies poleward of 20N in the Pacific basin.
http://www.atmos.washington.edu/~mantua/abst.PDO.html)

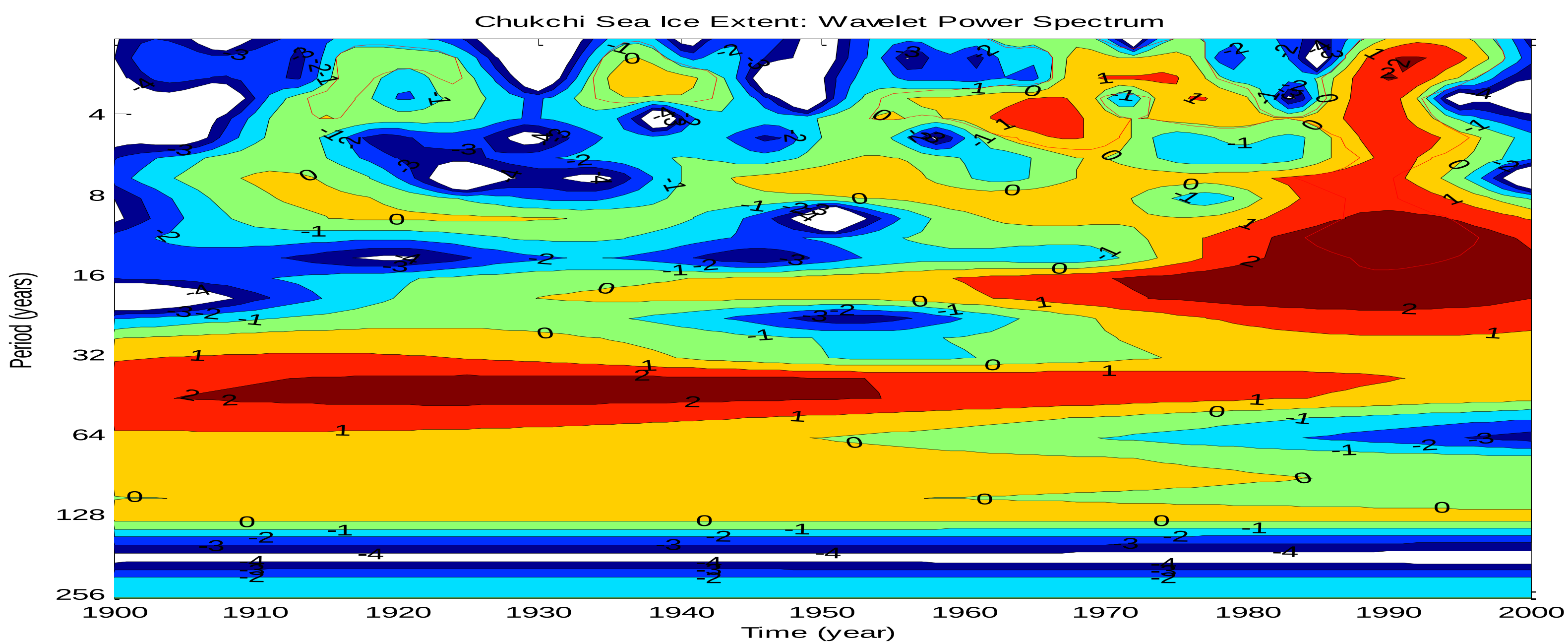


Source: EOF analyses were calculated of the monthly SST anomalies poleward of 20N in the Pacific basin. http://www.atmos.washington.edu/~mantua/abst.PDO.html



Relationship between PDO and ice extent in Chukcha Sea

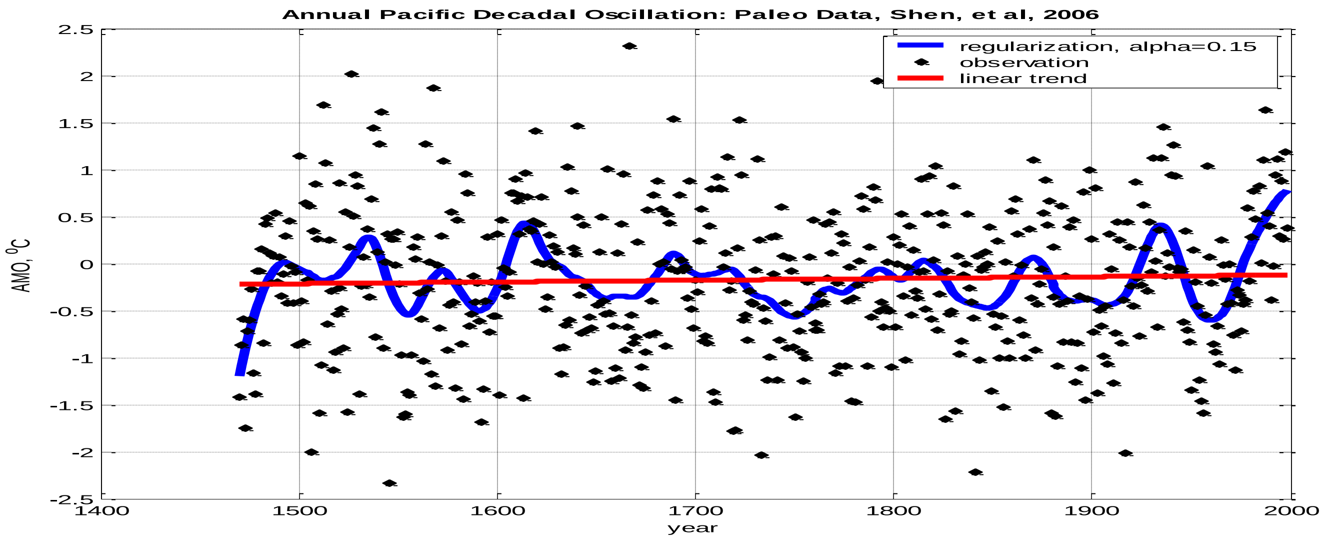




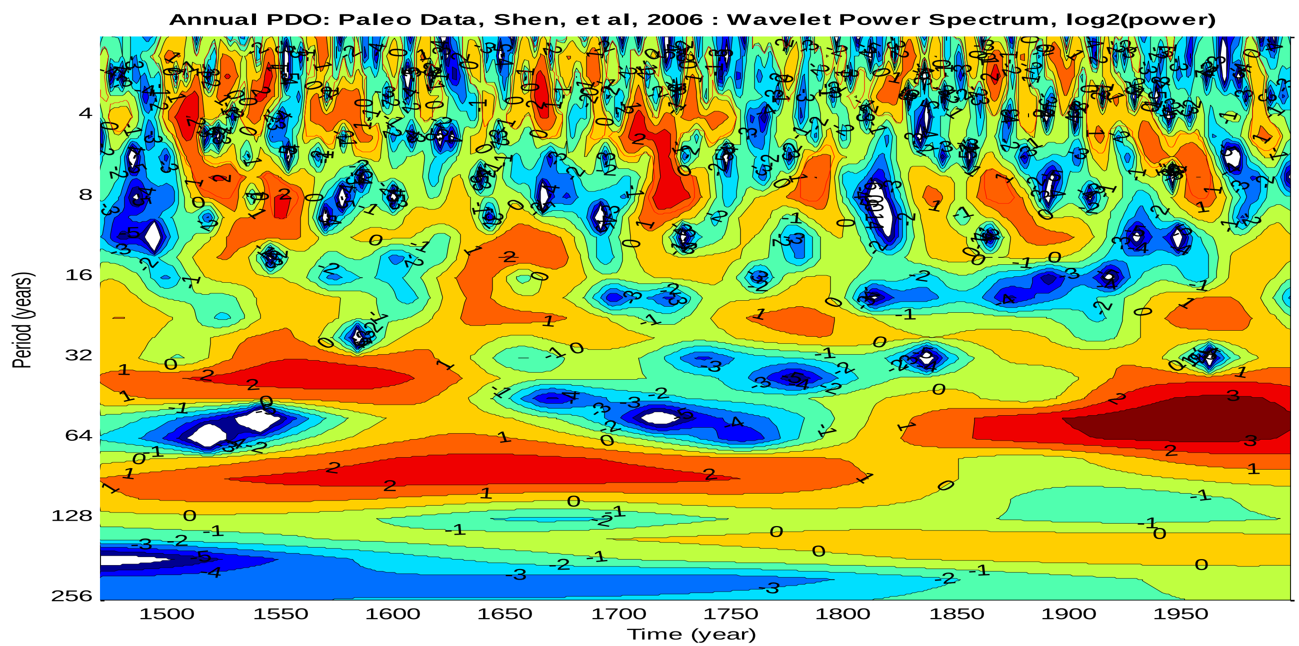
Circulation to Climate Change

Pacific Decadal Oscillation: Paleo Climate Data

after Shen, et al, GRL, 2006, NOAA/World Data Center for Paleoclimatology

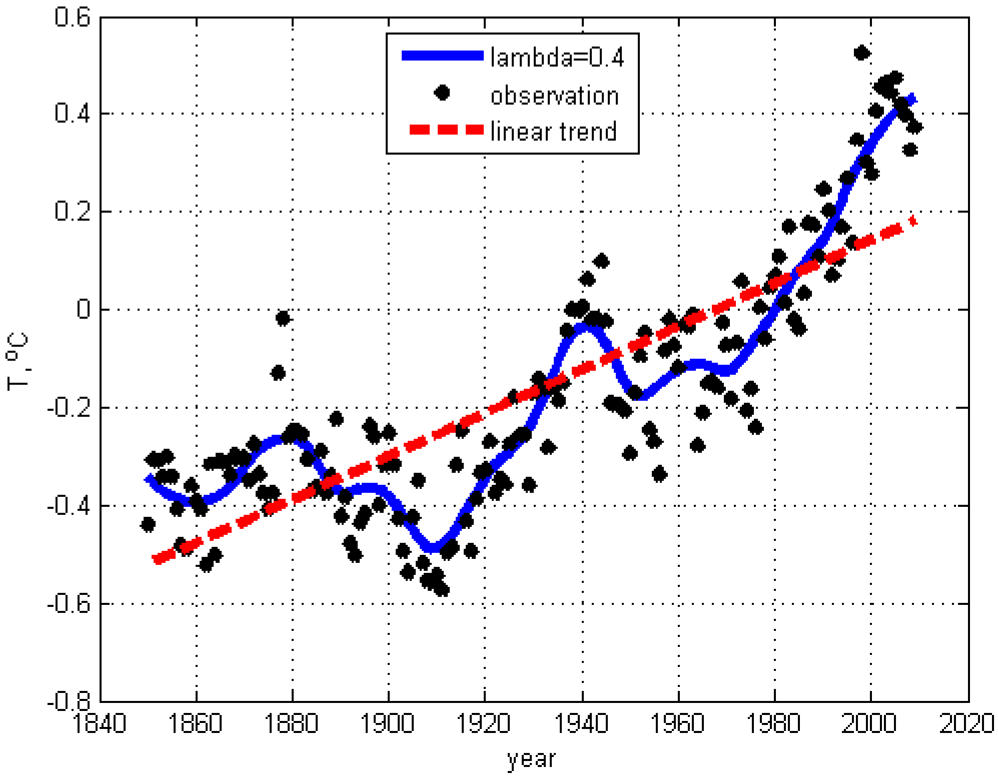


Source: Shen, C., W.-C. Wang, W. Gong, and Z. Hao. 2006. A Pacific Decadal Oscillation record since 1470 AD reconstructed from proxy data of summer rainfall over eastern China.Geophysical Research Letters, vol. 33, February 2006.

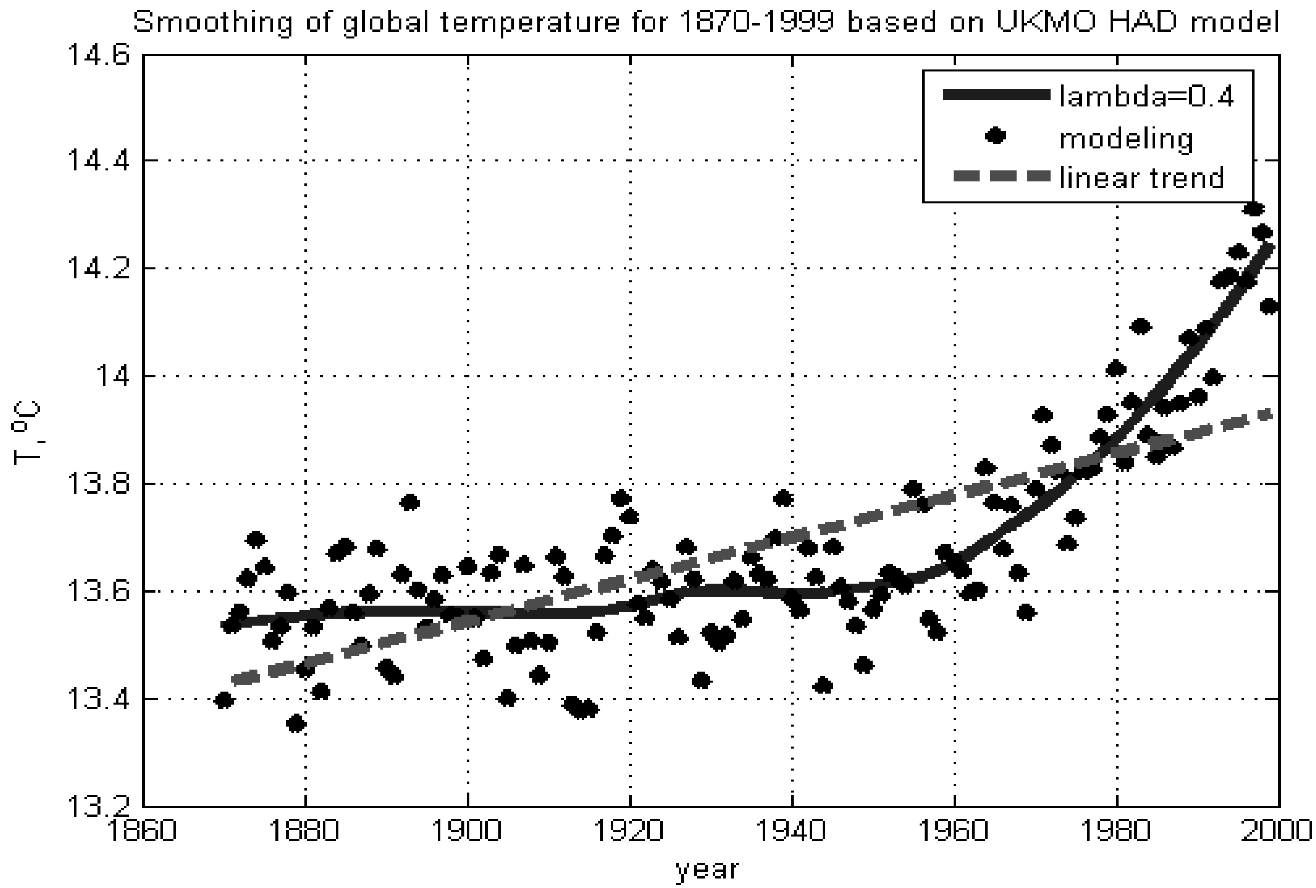


Global Surface Air Temperature (SAT)

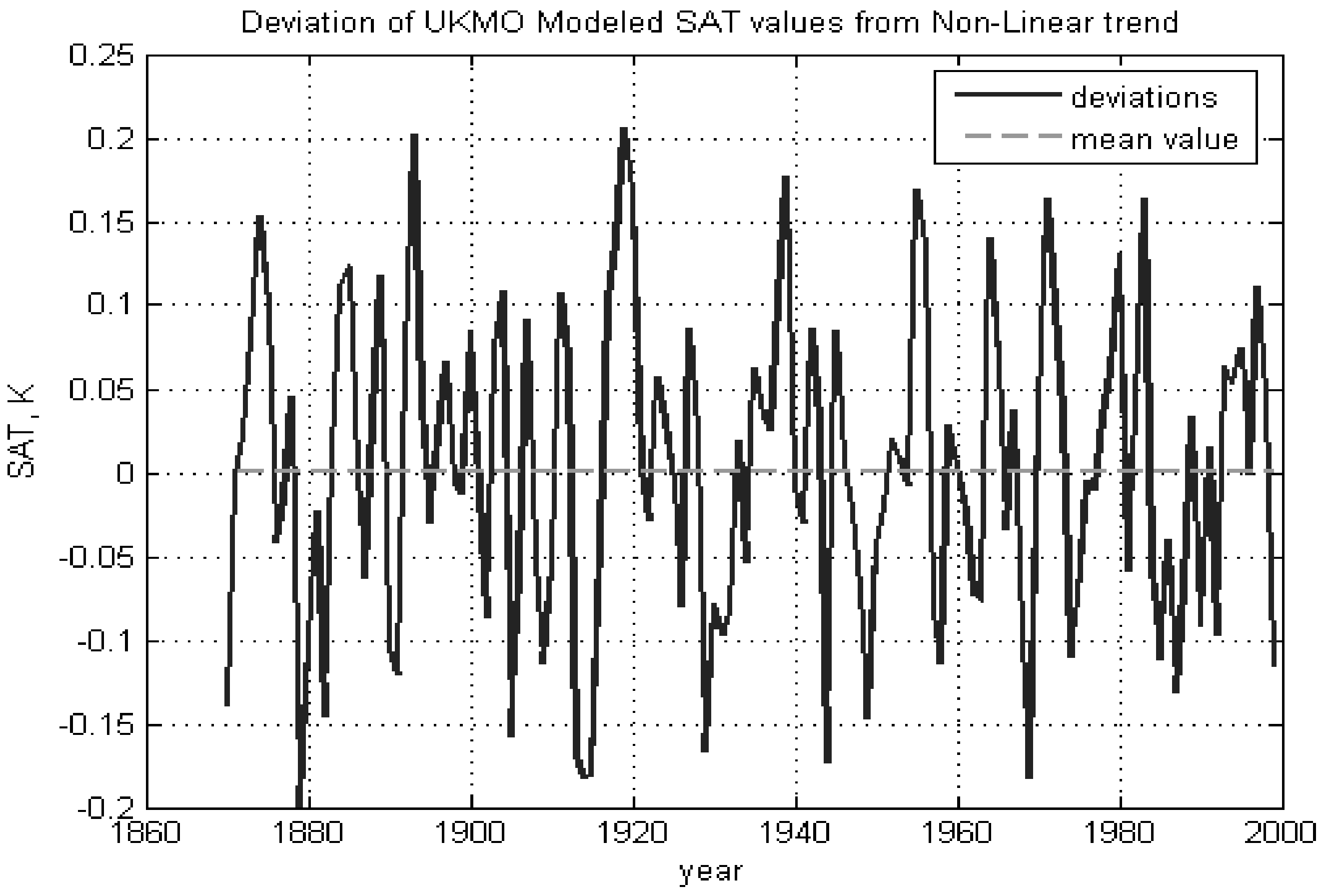
Global annual anomaly temperature CRU Met Office version CRUTEM3



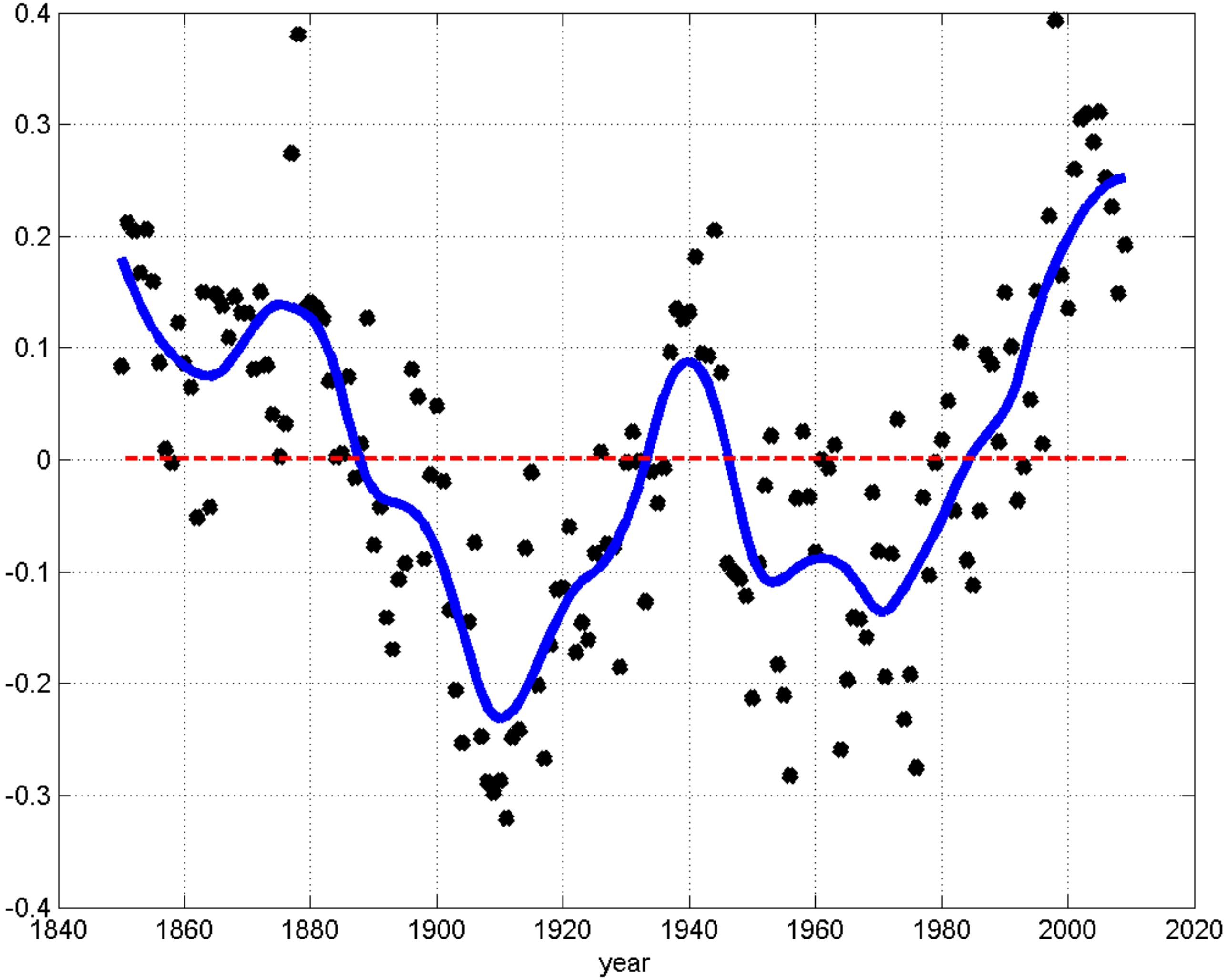
Global SAT by UKMO climate model for 1870-1999



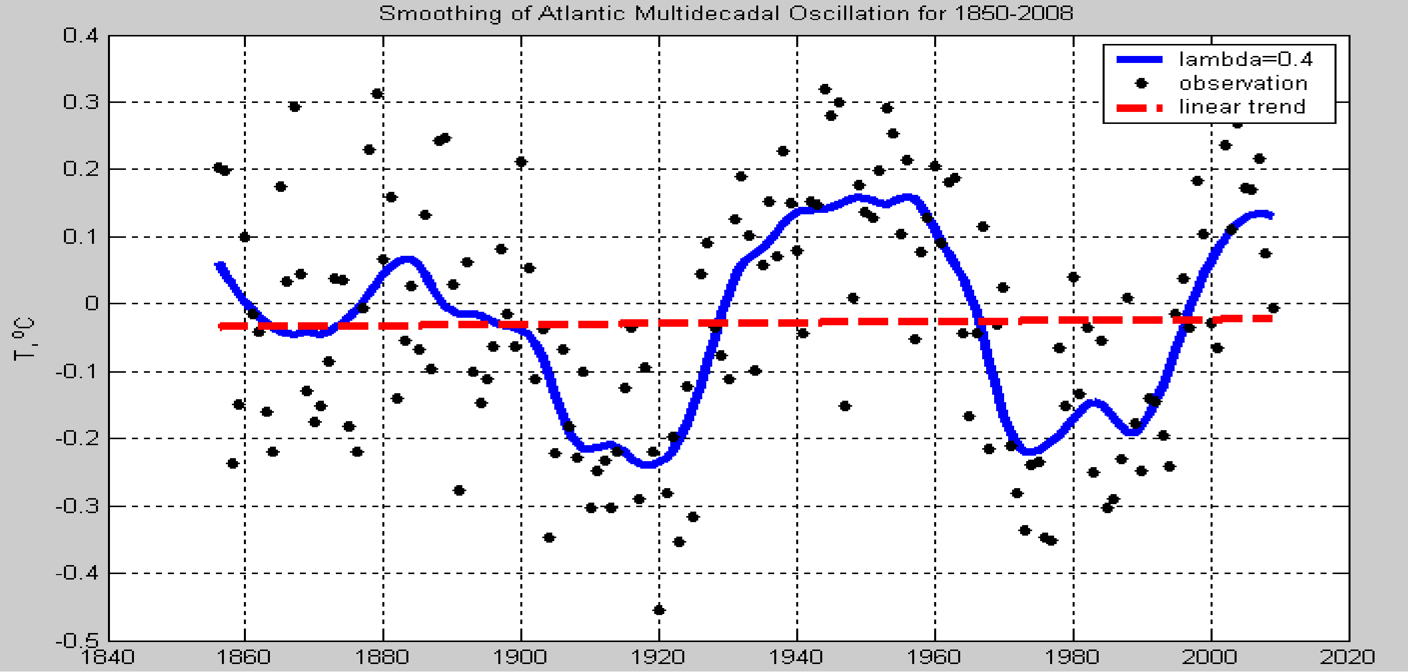
Deviation of global UKMO modeled SAT from its non-linear trend



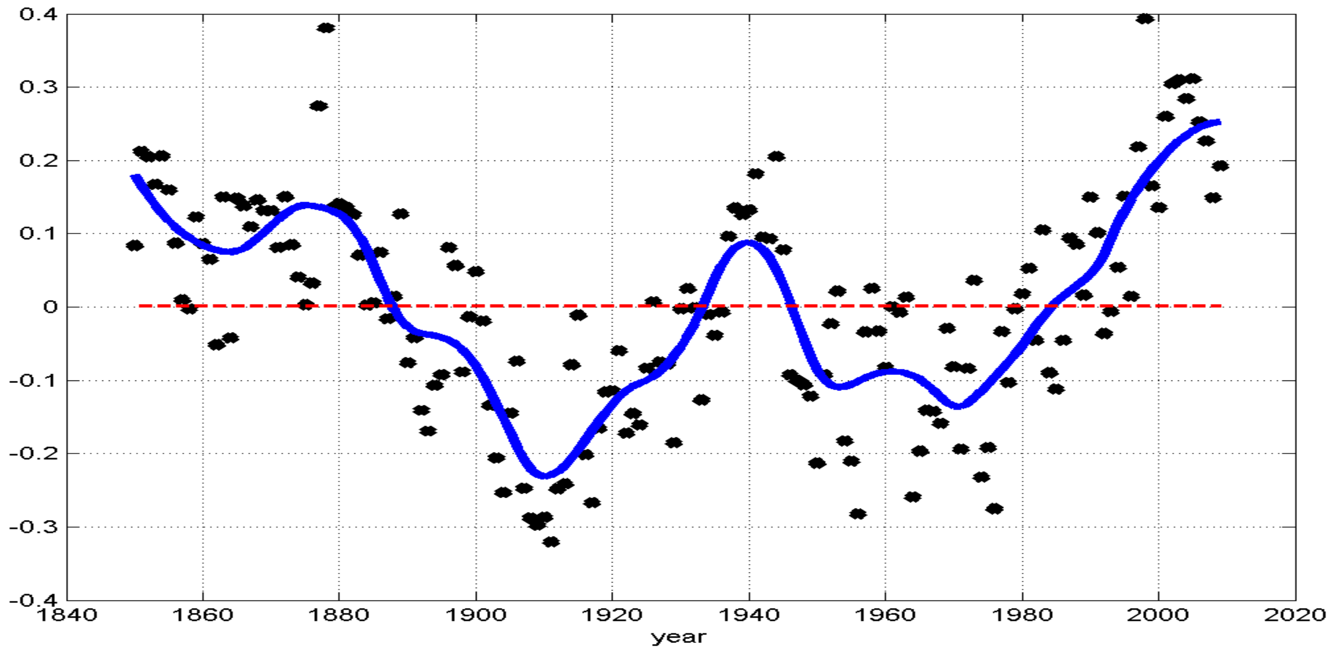
Detrended (excluded linear trend) global annual temperature CRU Met Office version CRUTEM3



AMO



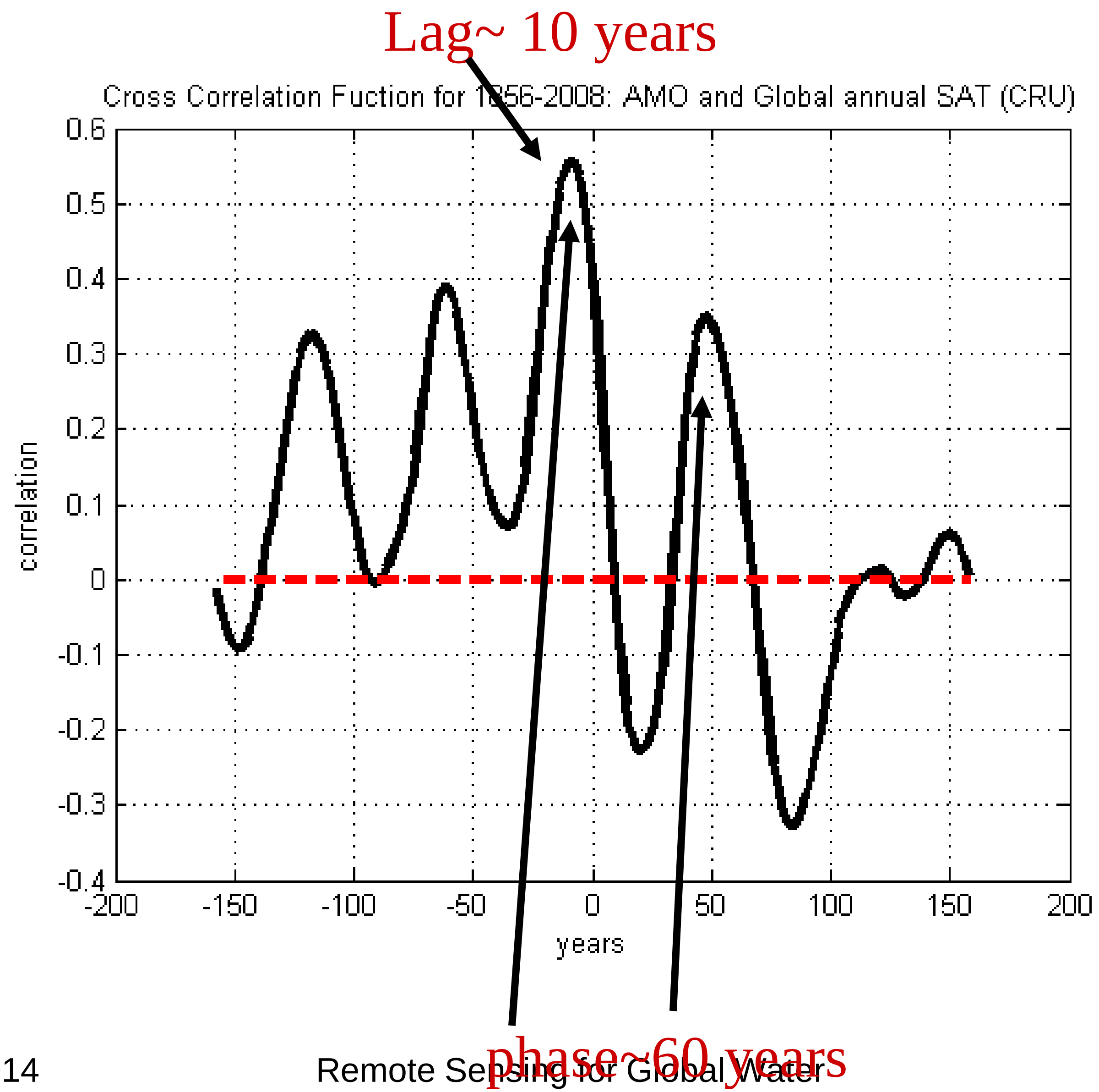
Global SAT



CONCLUSIONS:

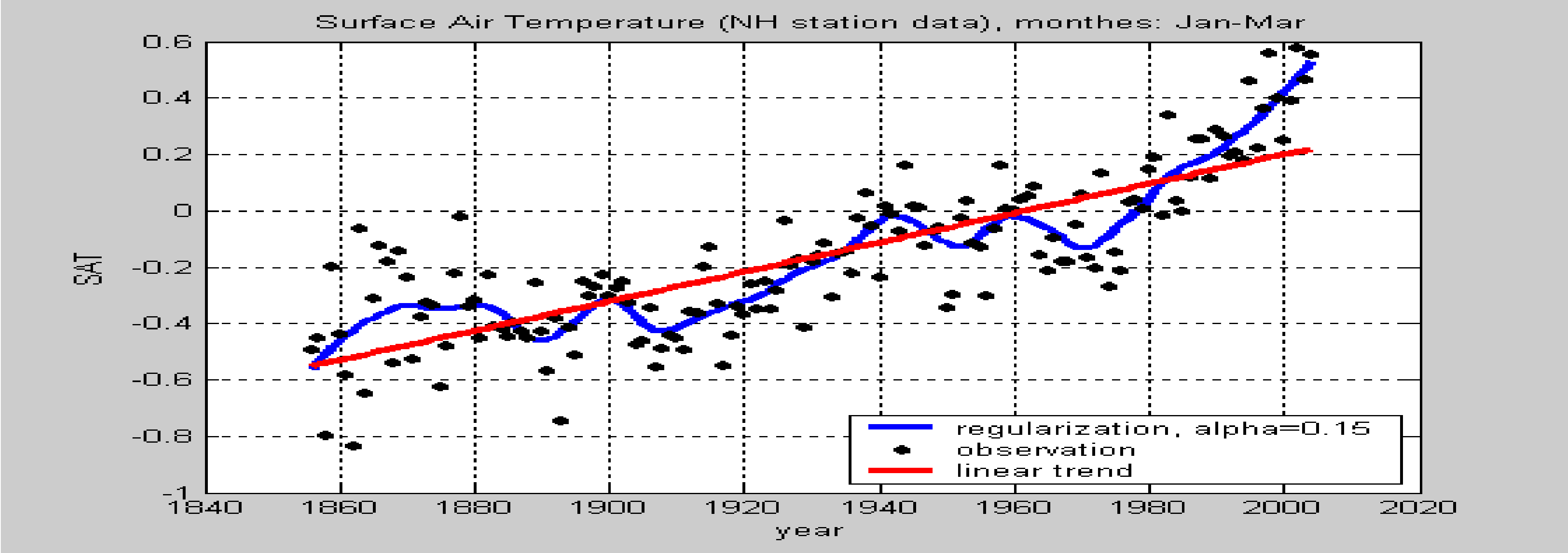
- Ice extent in Russian Seas are closely related to Atlantic and Pacific Multidecadal Oscillations
- Climate indexes revealed a high rate of a coherency with account to 60-70 year cyclicity and now those are in its positive phases, which are close to achieve its maximum values, probably, in 10-15 years
- Now Arctic Ice Extent series is in a negative phase and close to reach its minimum value, probably, in twenties
- Atlantic Multidecadal Oscillation demonstrates coherency with de-trended global annual surface air temperature for last 160 years

Cross-correlation function: AMO and Global SAT (1856-2008)

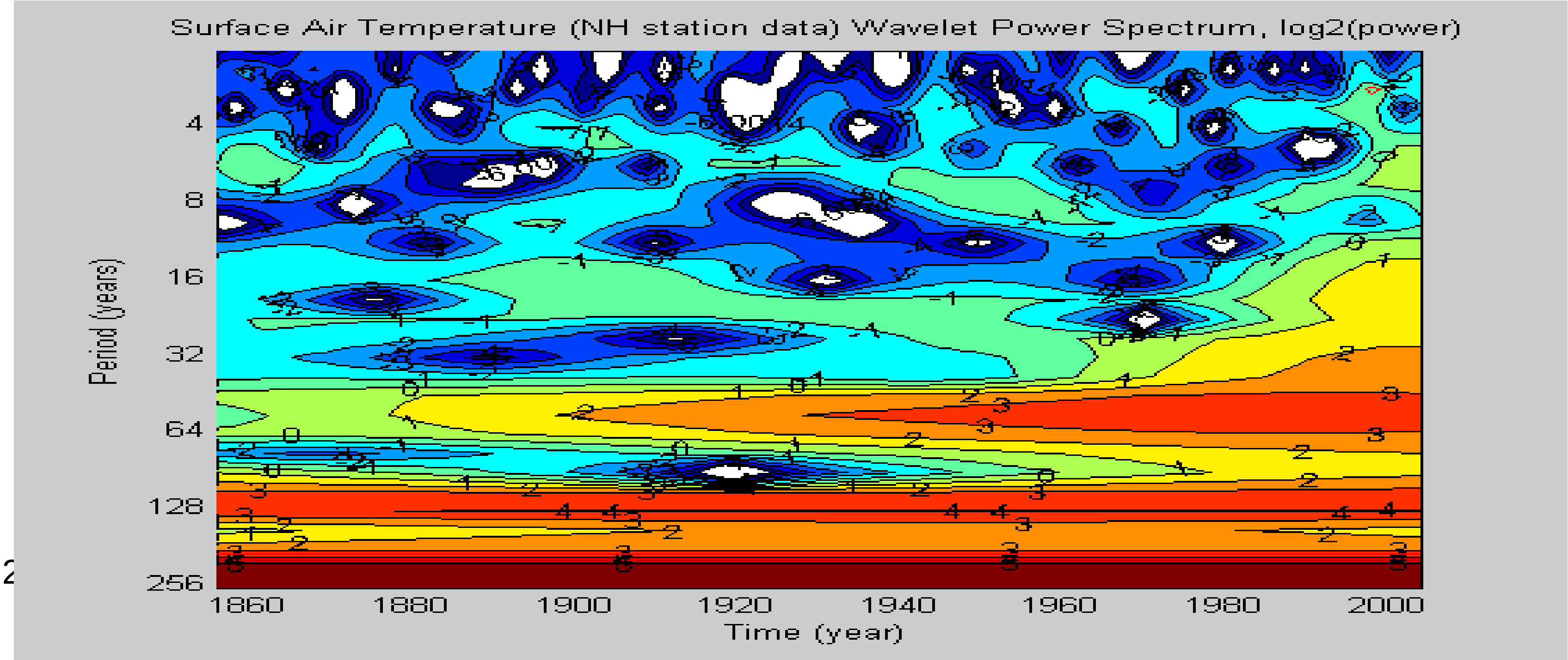


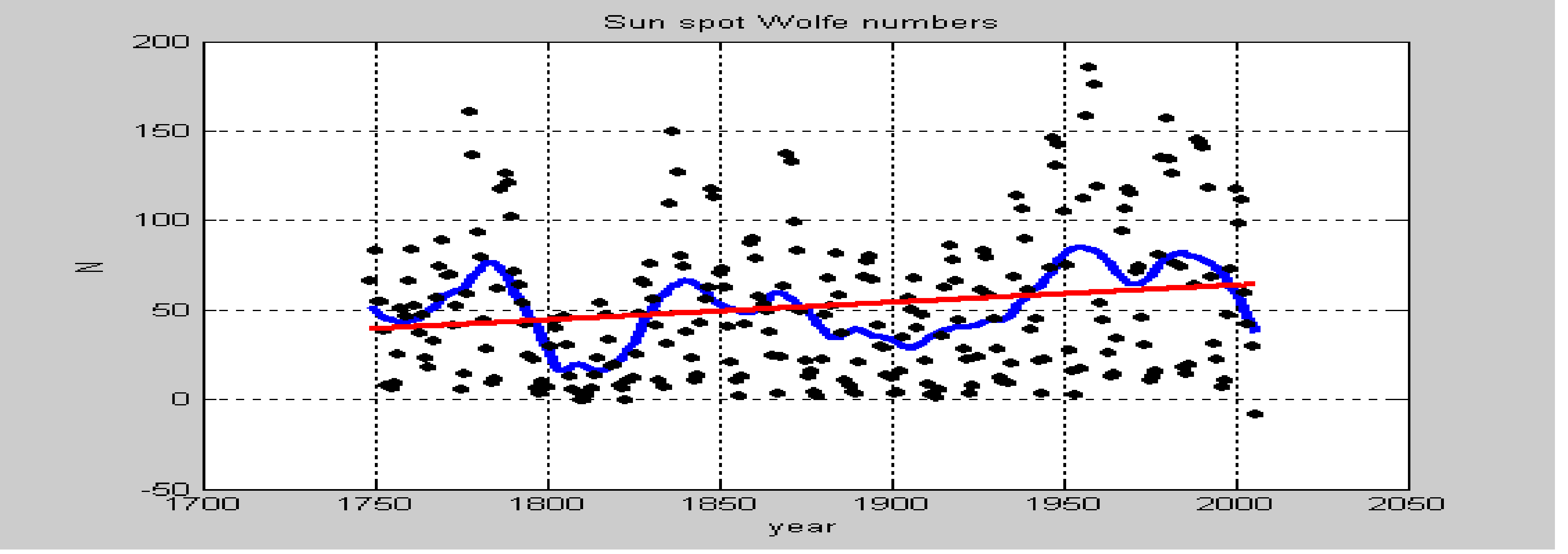
Coherence in fluctuation of SAT in Northern Hemisphere for last 150 years

and Solar Wolf numbers for last 250 years

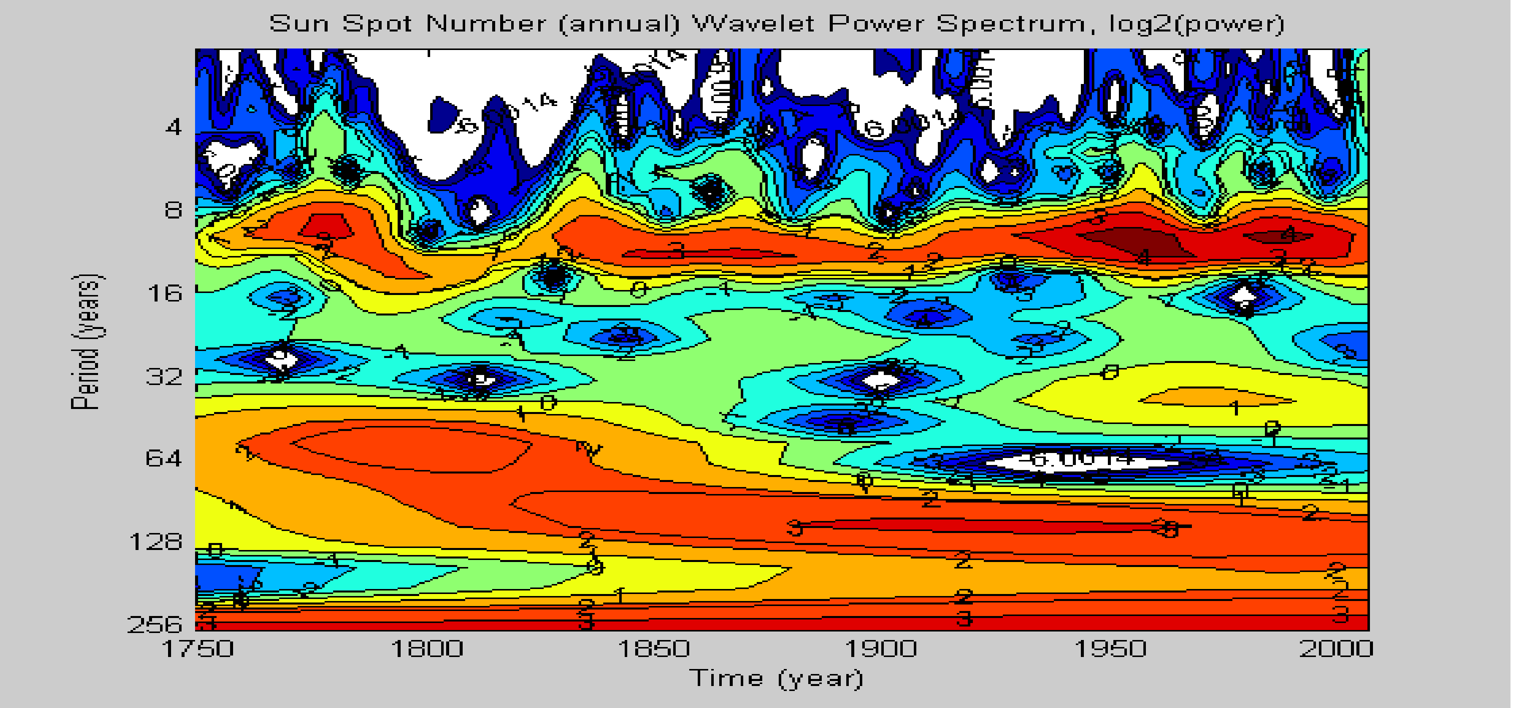


Source: Brohan, et al, 2006: J. Geophysical Research 111, D 121 N 06, http://www.cru.uea.ac.uk/cru/data/temperature/





Source: World Data Centre for the Sunspot Index, Royal Observatory of Belgium online catalogue of the sunspot index, http://sidc.oma.be/html/sunspot.html

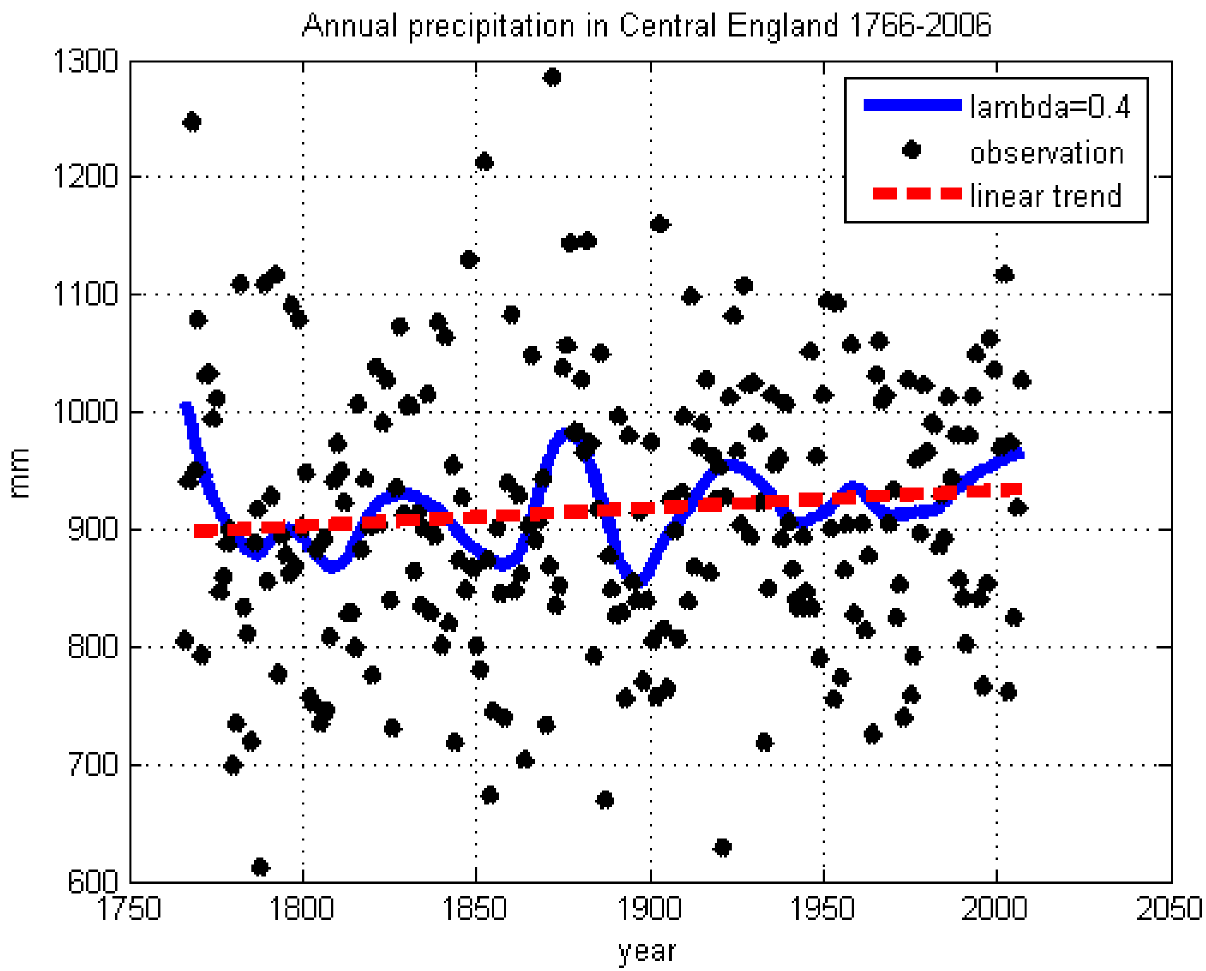


Precipitation

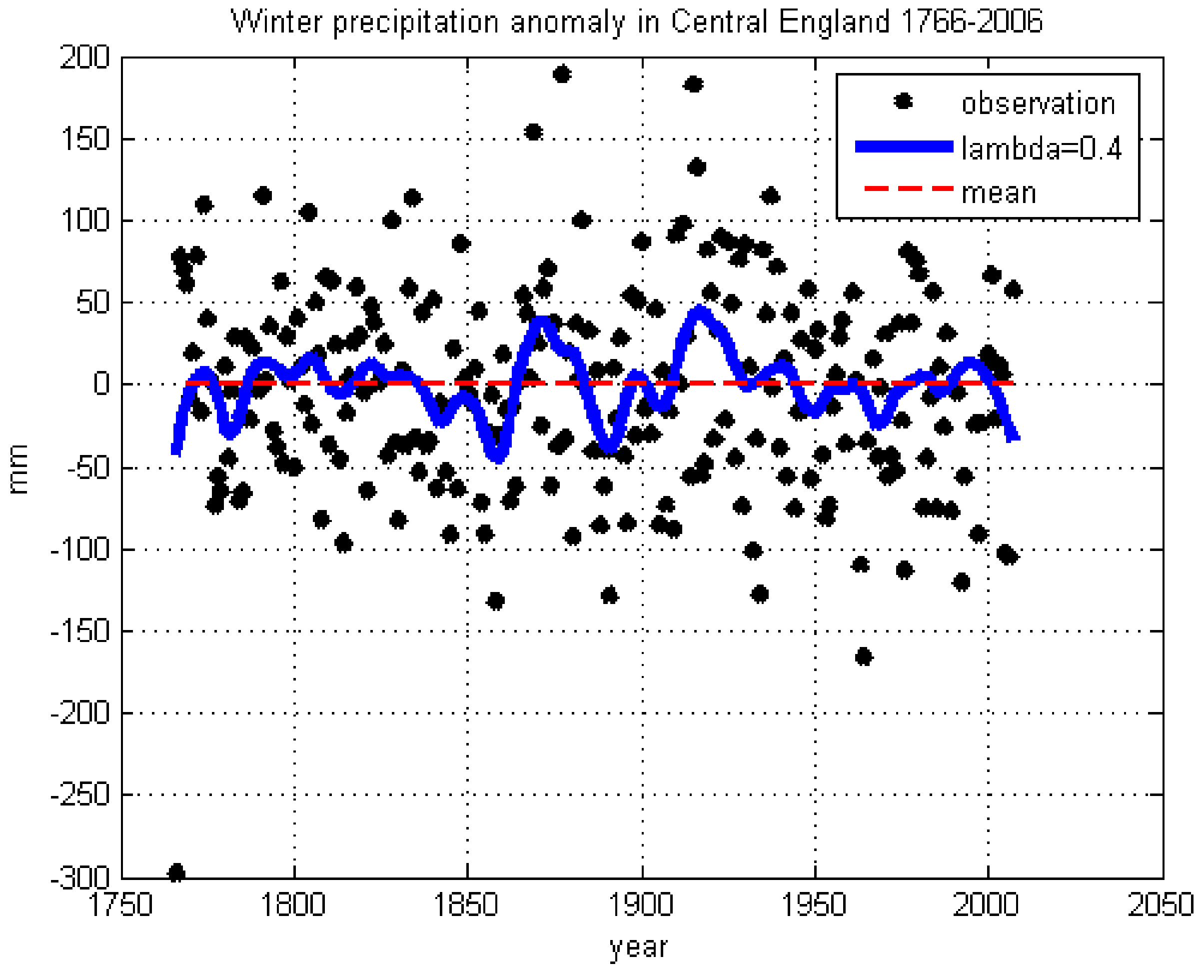
1. Central England
2. Ukraine (Kiev)
3. Siberia
4. Global fields

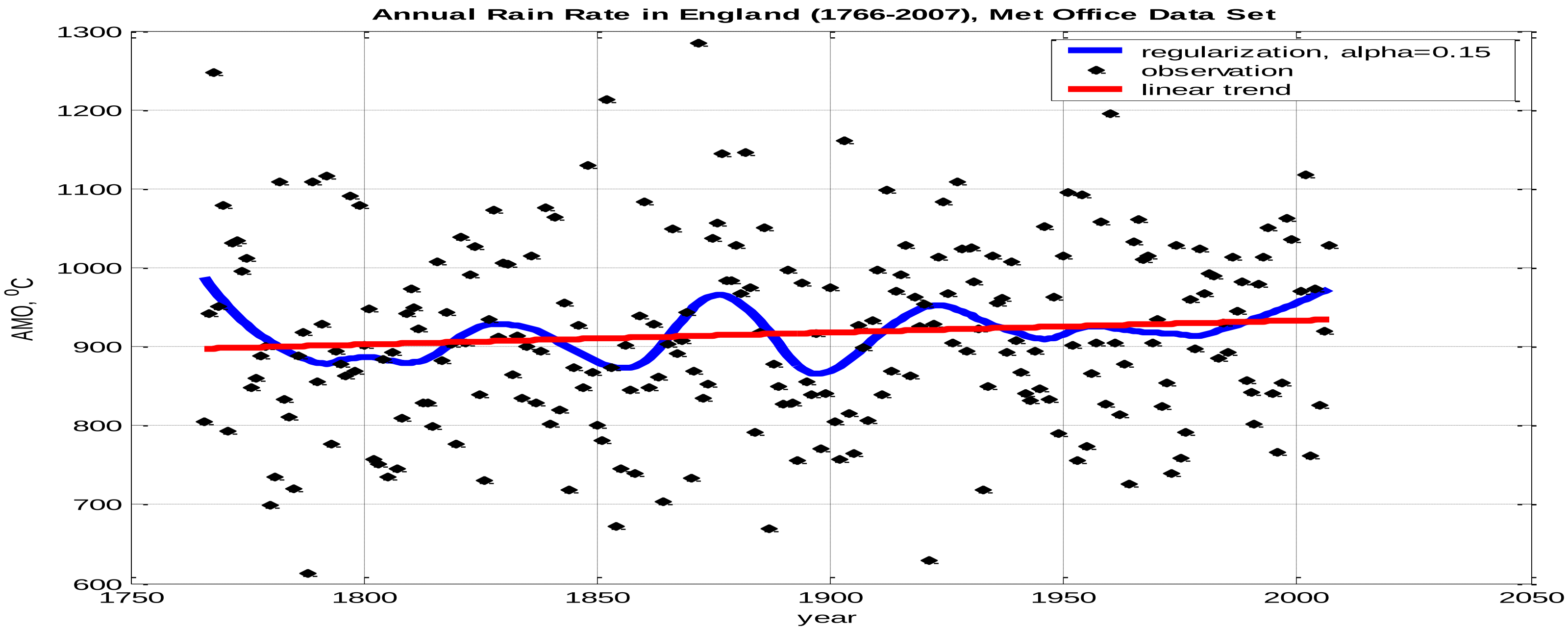
Annual precipitation in England, 1766-2007, Met Office data

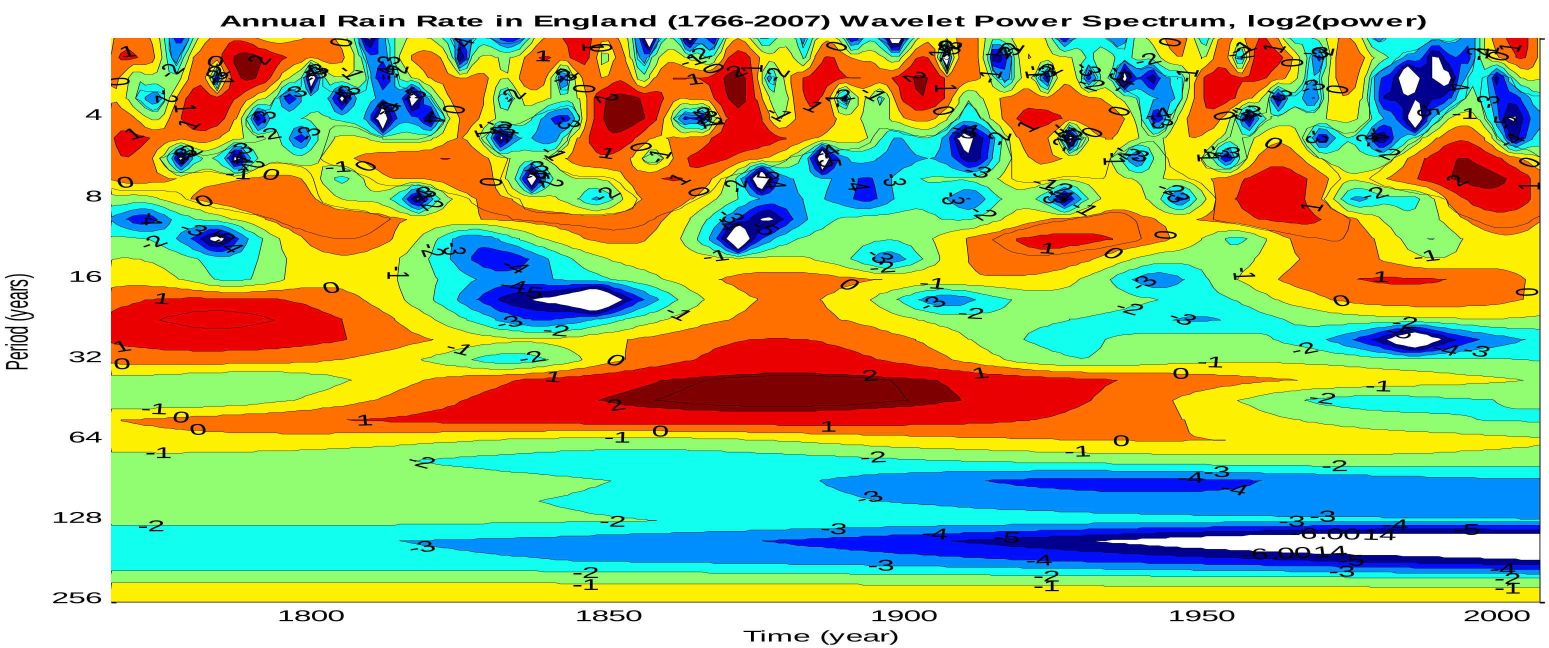
Annual precipitation in Central England: 1766-2006



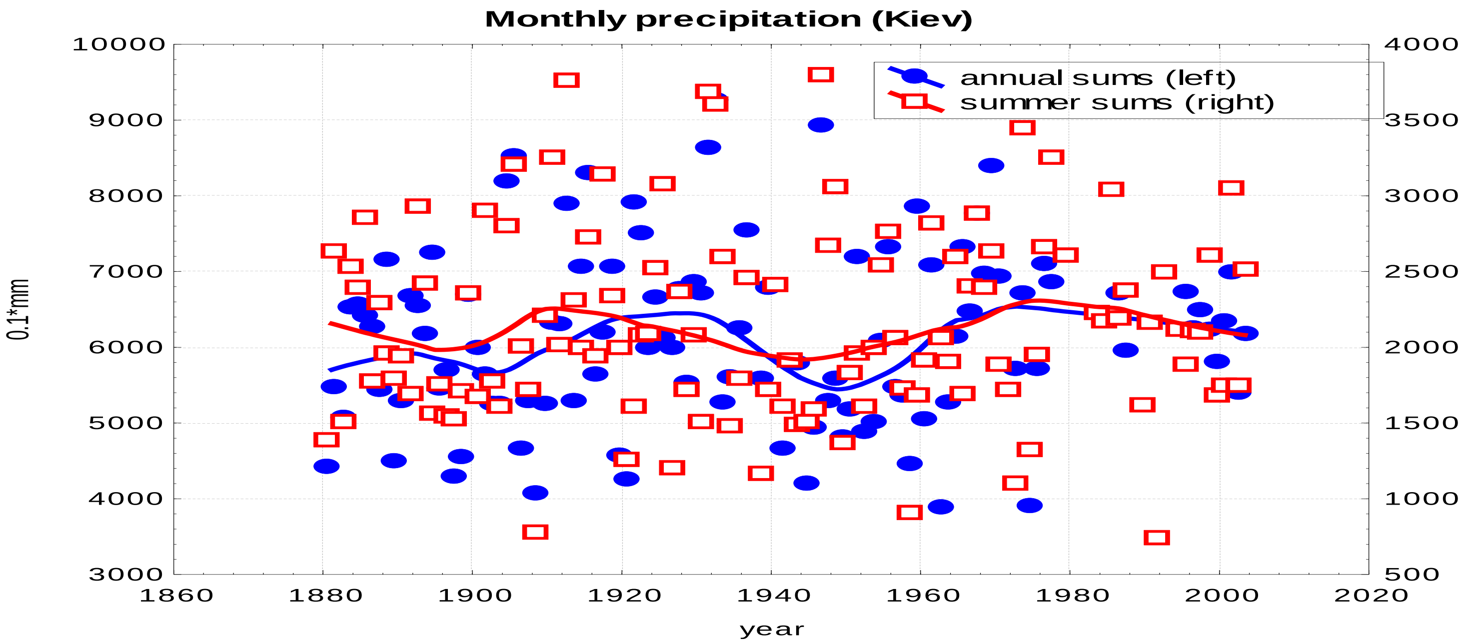
Winter precipitation in Central England: 1766-2006

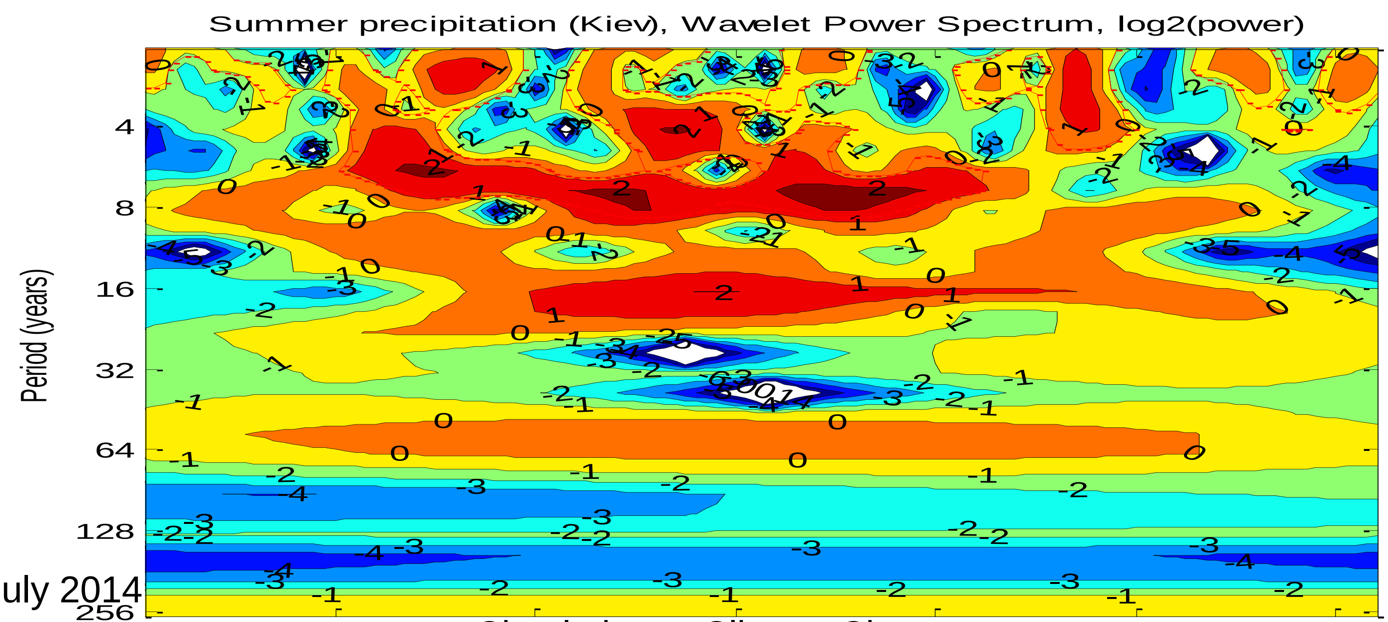



Annual Rain Rate in England (1766-2007), Met Office Data Set
regularization, alpha=0.15
observation
linear trend
AMO, °C
year
1300
1200
1100
1000
900
800
700
600
1750
1800
1850
1900
1950
2000
2050

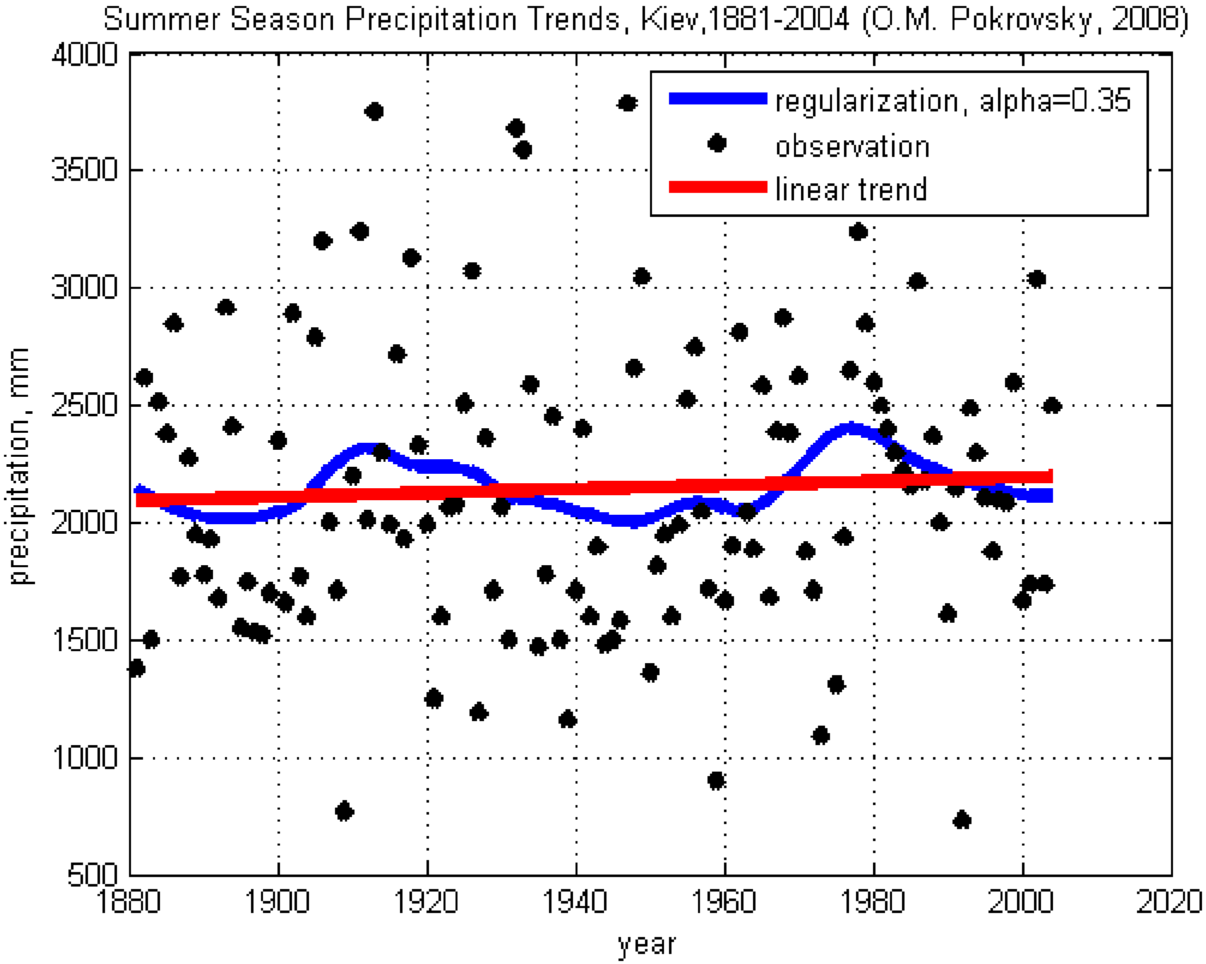

Annual Rain Rate in England (1766-2007) Wavelet Power Spectrum, log2(power)
Period (years)
Time (year)
4
8
16
32
64
128
256
1800
1850
1900
1950
2000

Annual Precipitation for summer months (JJA): 1880-2000, Ukraine

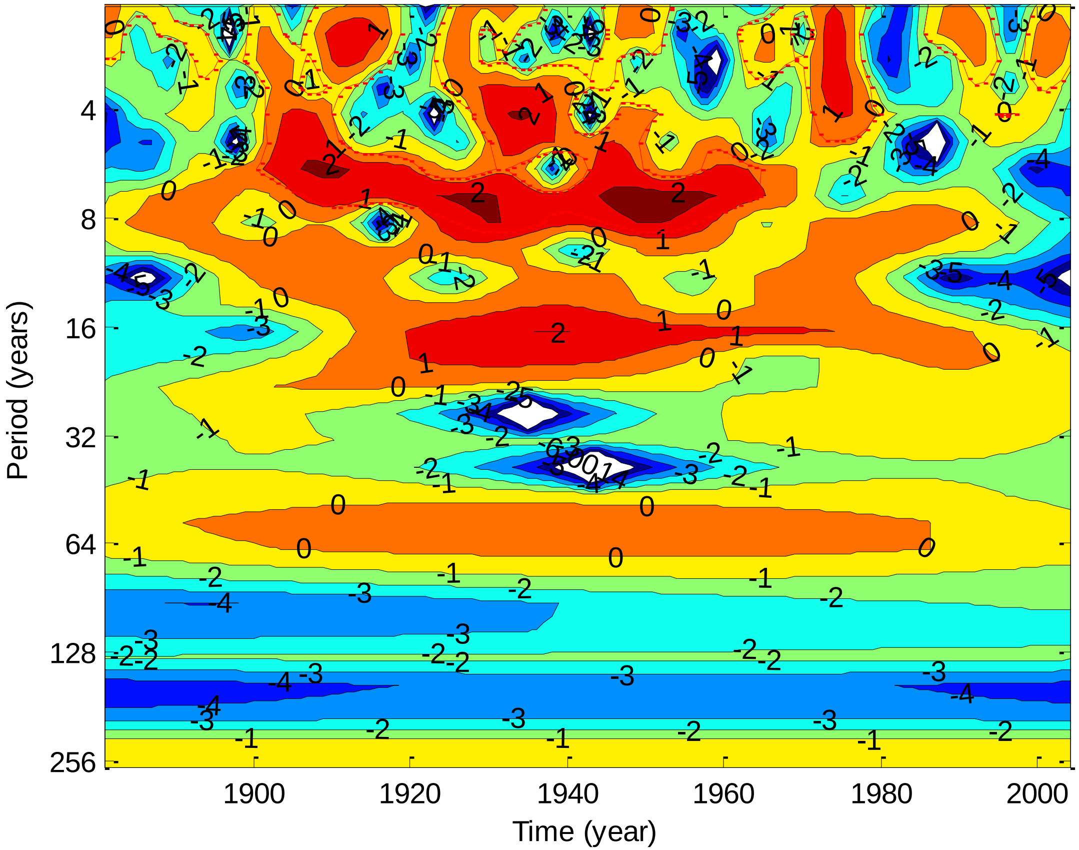

Monthly precipitation (Kiev)
annual sums (left)
summer sums (right)
0.1*mm
year
10000
9000
8000
7000
6000
5000
4000
3000
4000
3500
3000
2500
2000
1500
1000
500
1860
1880
1900
1920
1940
1960
1980
2000
2020


Summer precipitation (Kiev), Wavelet Power Spectrum, log2(power)
Period (years)
Time (year)
4
8
16
32
64
128
256
1900
1980
2000

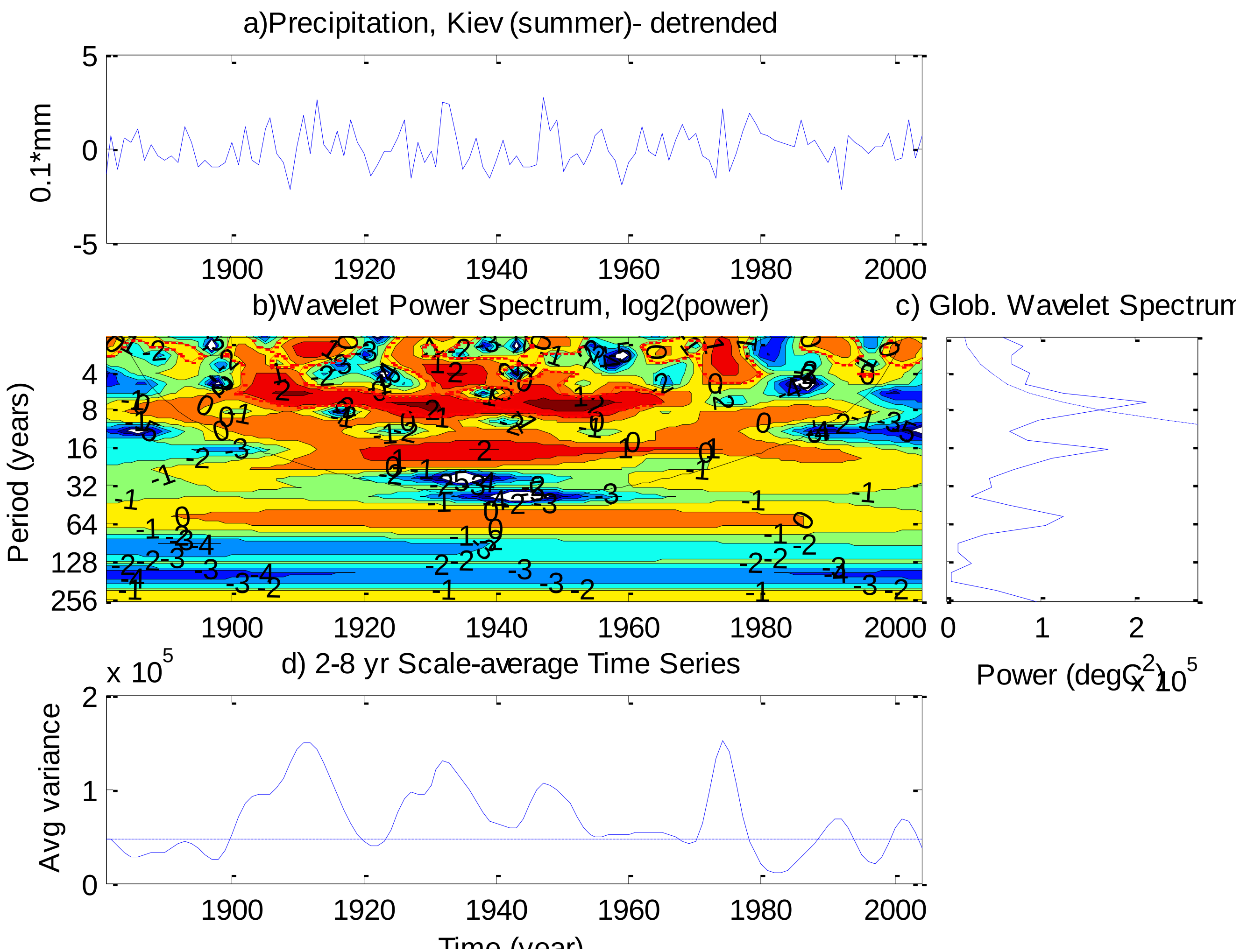
Summer precipitation amount in Ukraine (Kiev): 1880-2006

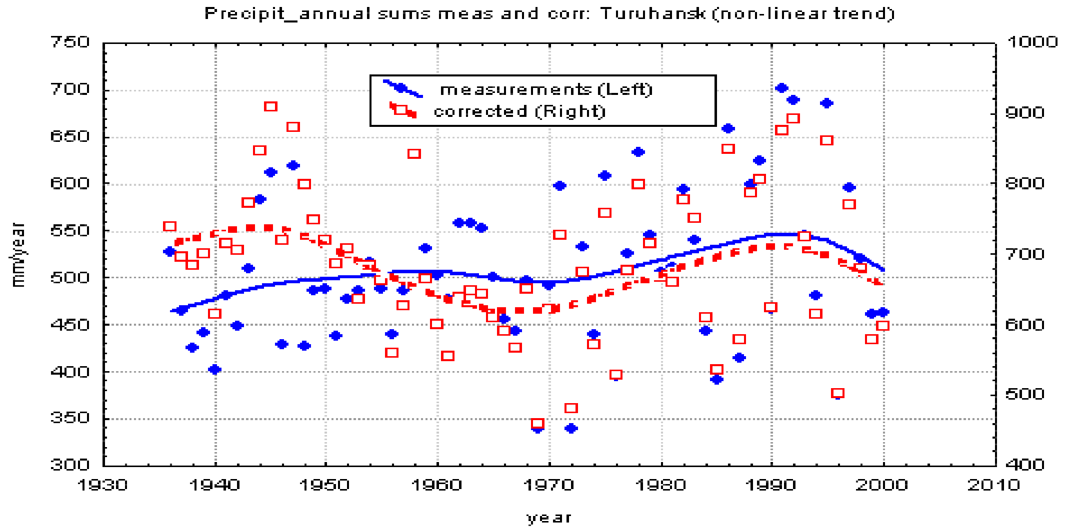


Summer precipitation (Kiev), Wavelet Power Spectrum, log2(power)



Precipitation : wavelet analysis





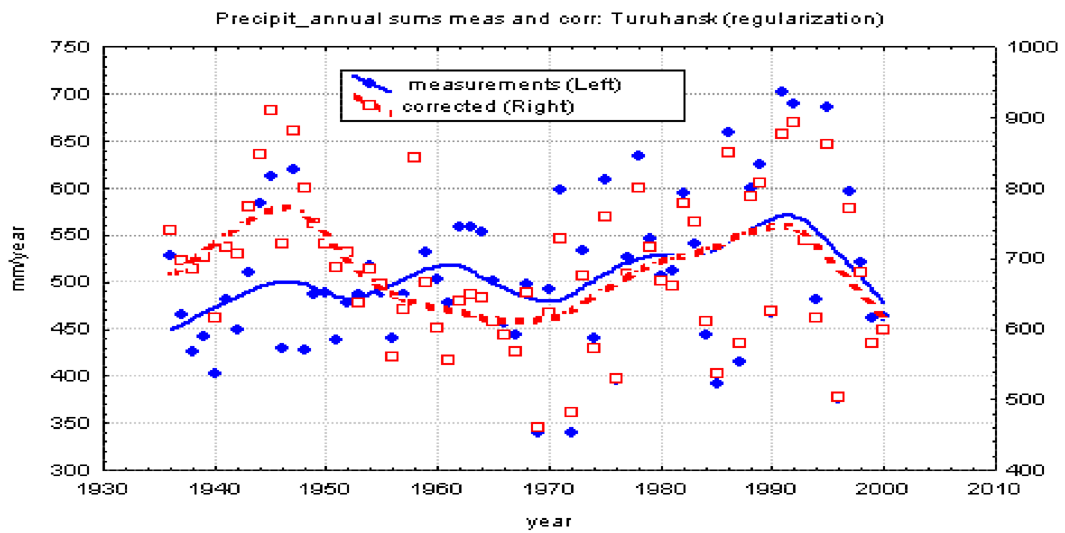
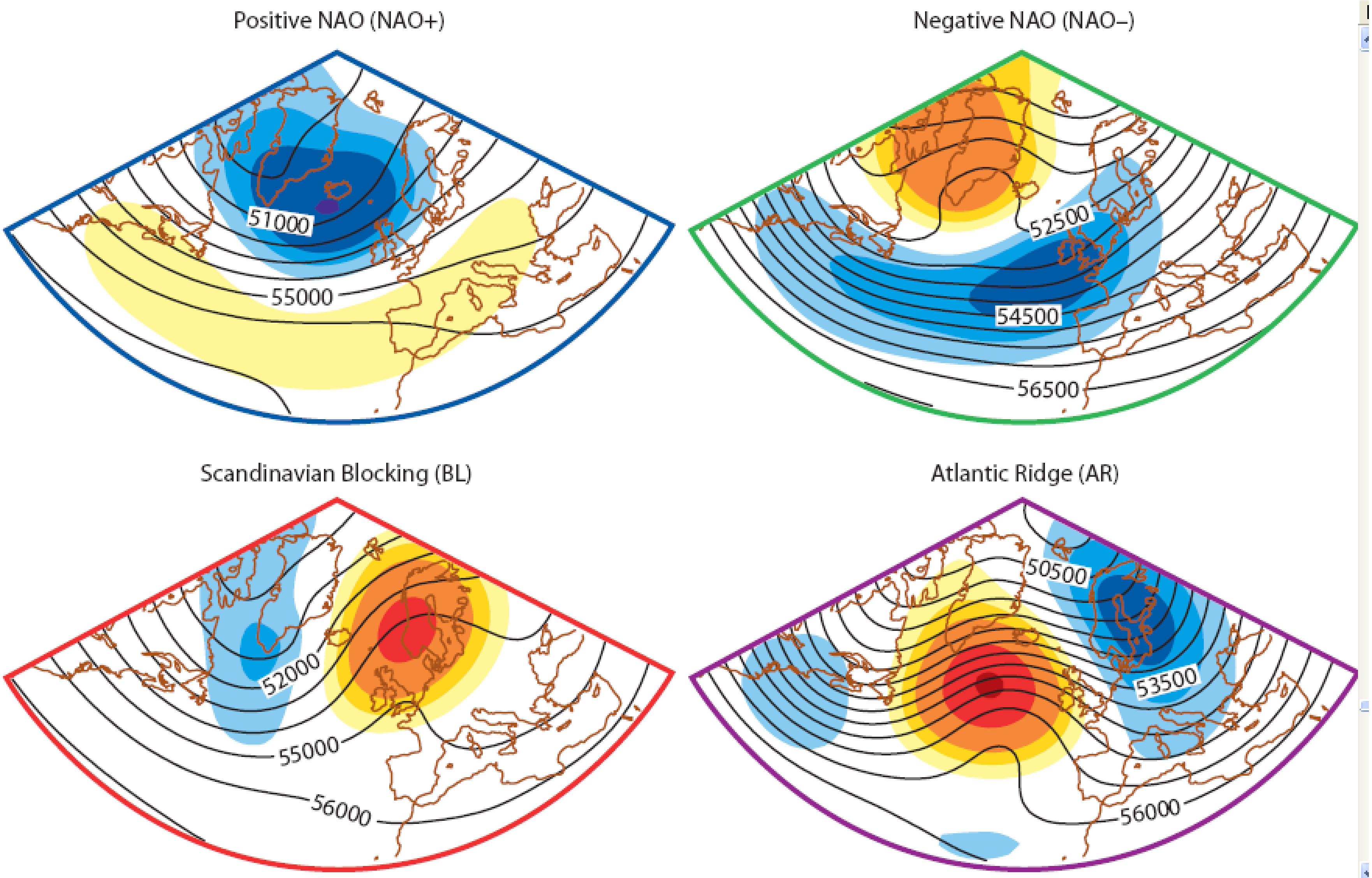
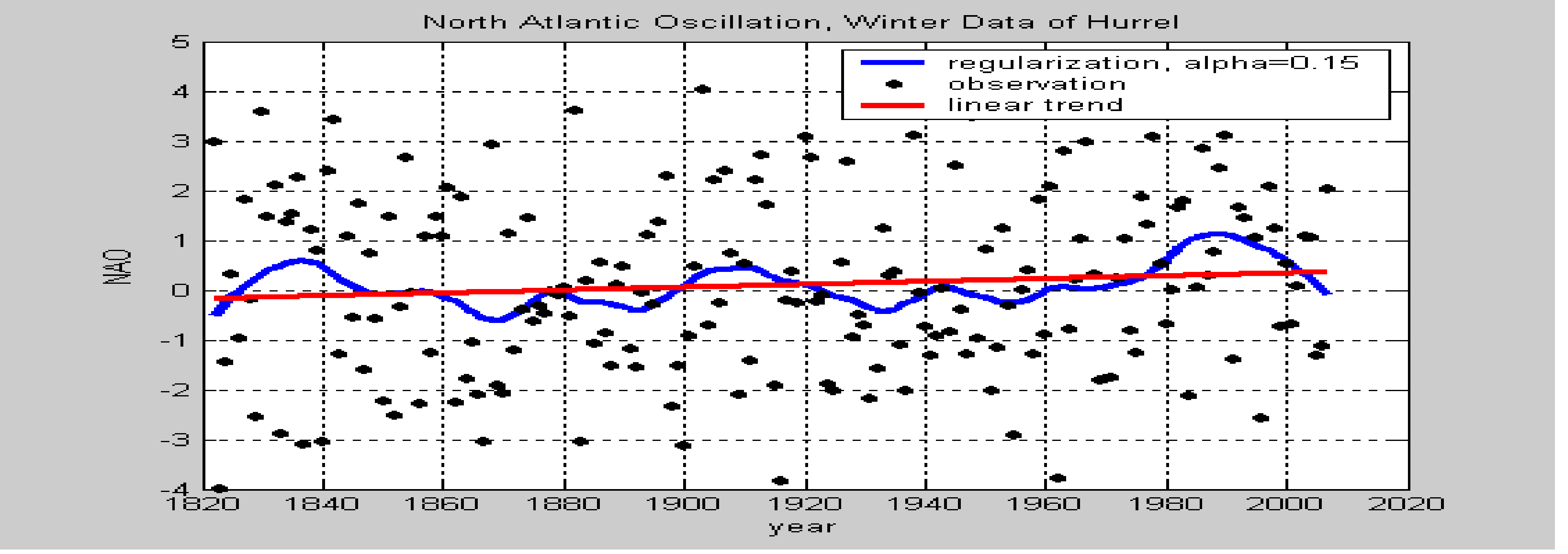


Figure . Comparison of the precipitation annual sums (mm/year) at site Turuhansk for 1936-2000 smoothed by different techniques.

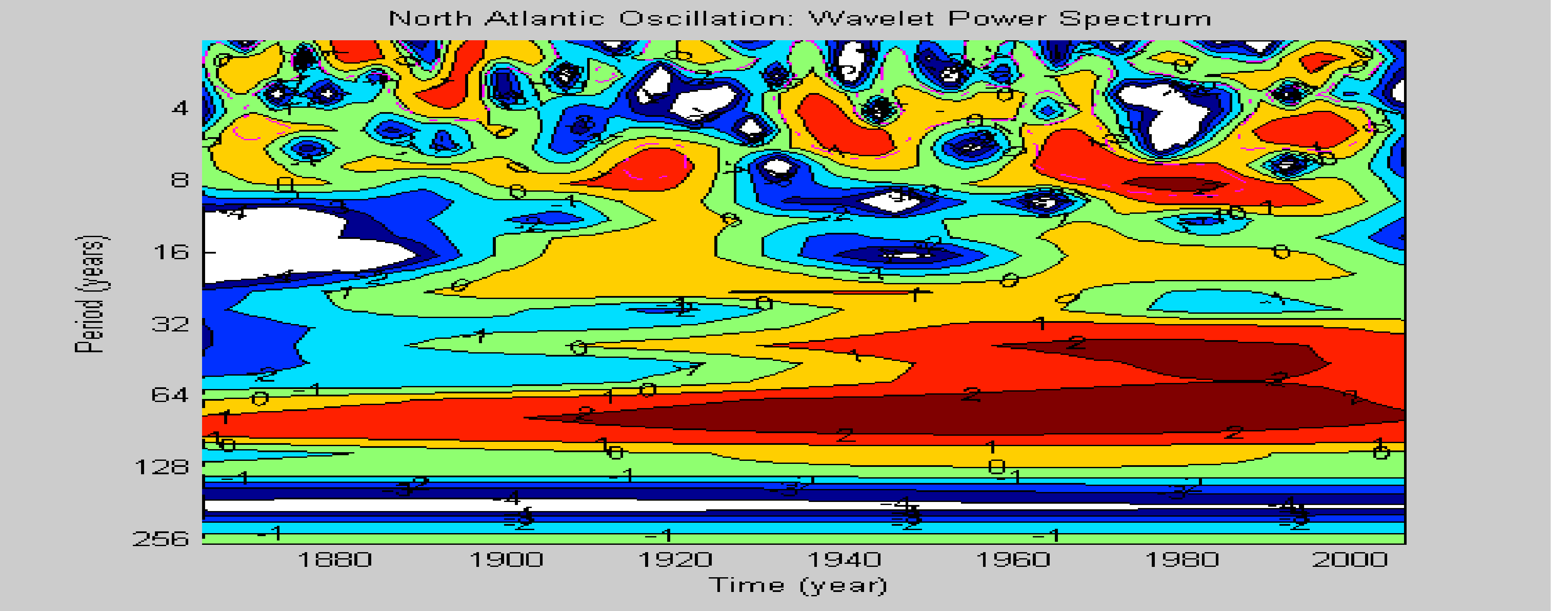
Impact of NAO on the regimes of atmospheric circulation and rain rate in Europe

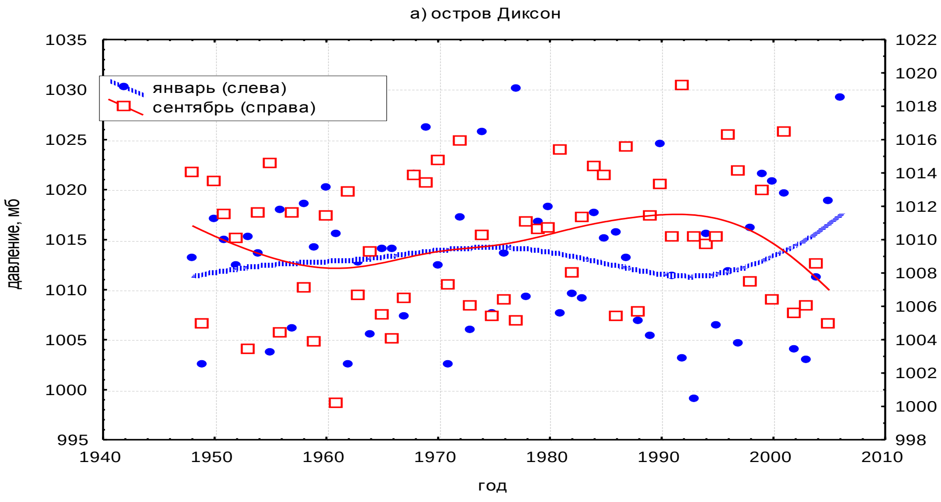
- Shift in NAO
- Arctic dipole appearance
- Enhancing in meridional circulation in North Atlantics and Pacific
- Absence of noticeable warming in Arctic meteorological stations
- Coherence of fluctuation in precipitation amount at South of Russia and changes in AMO

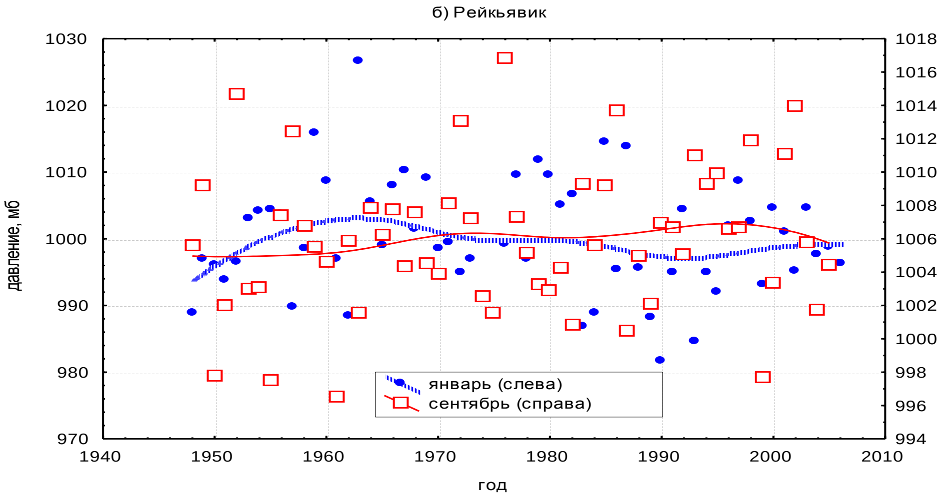

Positive NAO (NAO+)
51000
55000
Negative NAO (NAO–)
52500
54500
56500
Scandinavian Blocking (BL)
52000
55000
56000
Atlantic Ridge (AR)
50500
53500
56000



Source: http://www.cru.uea.ac.uk/cru/data/nao.htm

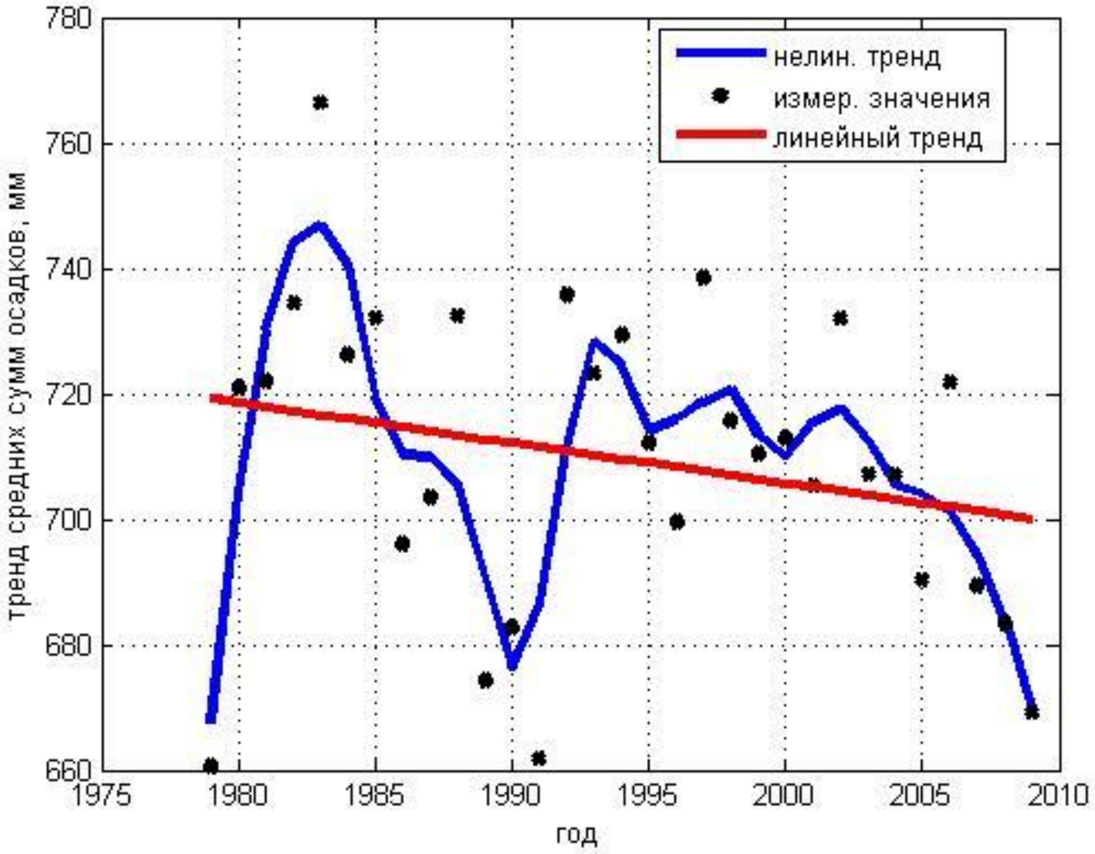



а) остров Диксон
январь (слева)
сентябрь (справа)
давление, мб
год
1035
1030
1025
1020
1015
1010
1005
1000
995
1022
1020
1018
1016
1014
1012
1010
1008
1006
1004
1002
1000
998
1940
1950
1960
1970
1980
1990
2000
2010


б) Рейкьявик
январь (слева)
сентябрь (справа)
давление, мб
год
1030
1020
1010
1000
990
980
970
1018
1016
1014
1012
1010
1008
1006
1004
1002
1000
998
996
994
1940
1950
1960
1970
1980
1990
2000
2010

Global Precipitation Time series

Global average annual precipitation amounts (mm) for 1979-2009: Linear and Nonlinear Trends



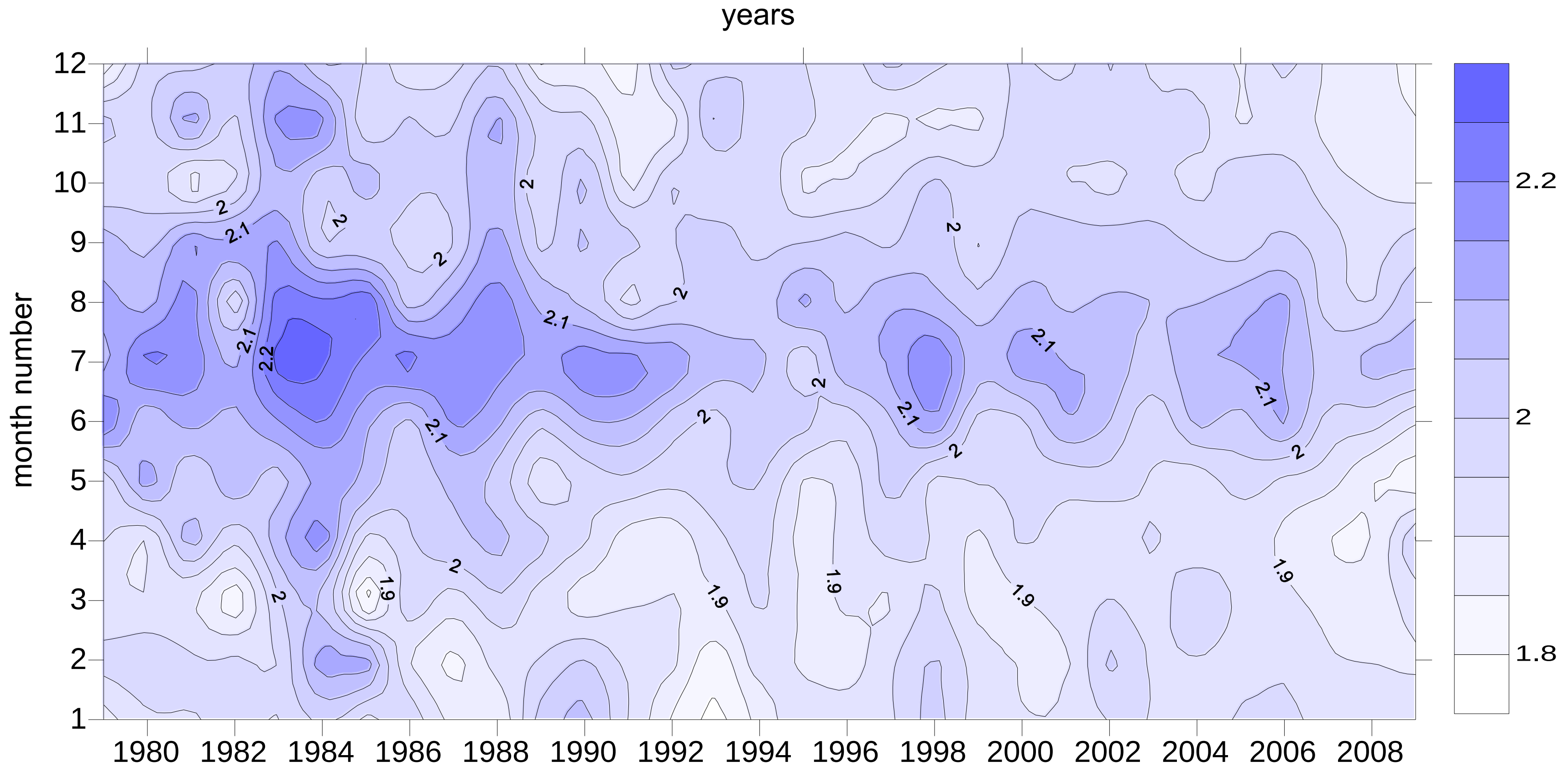
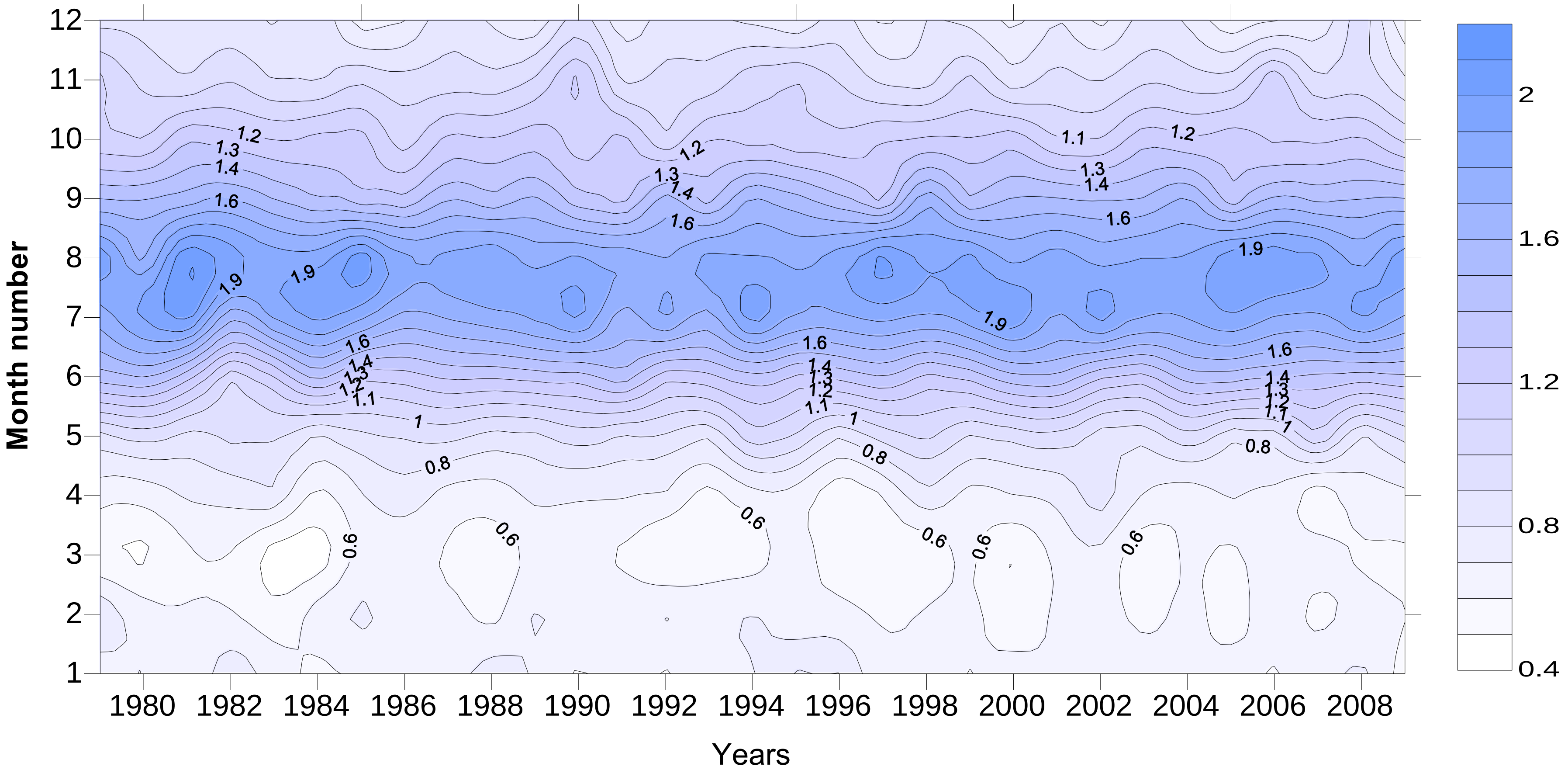
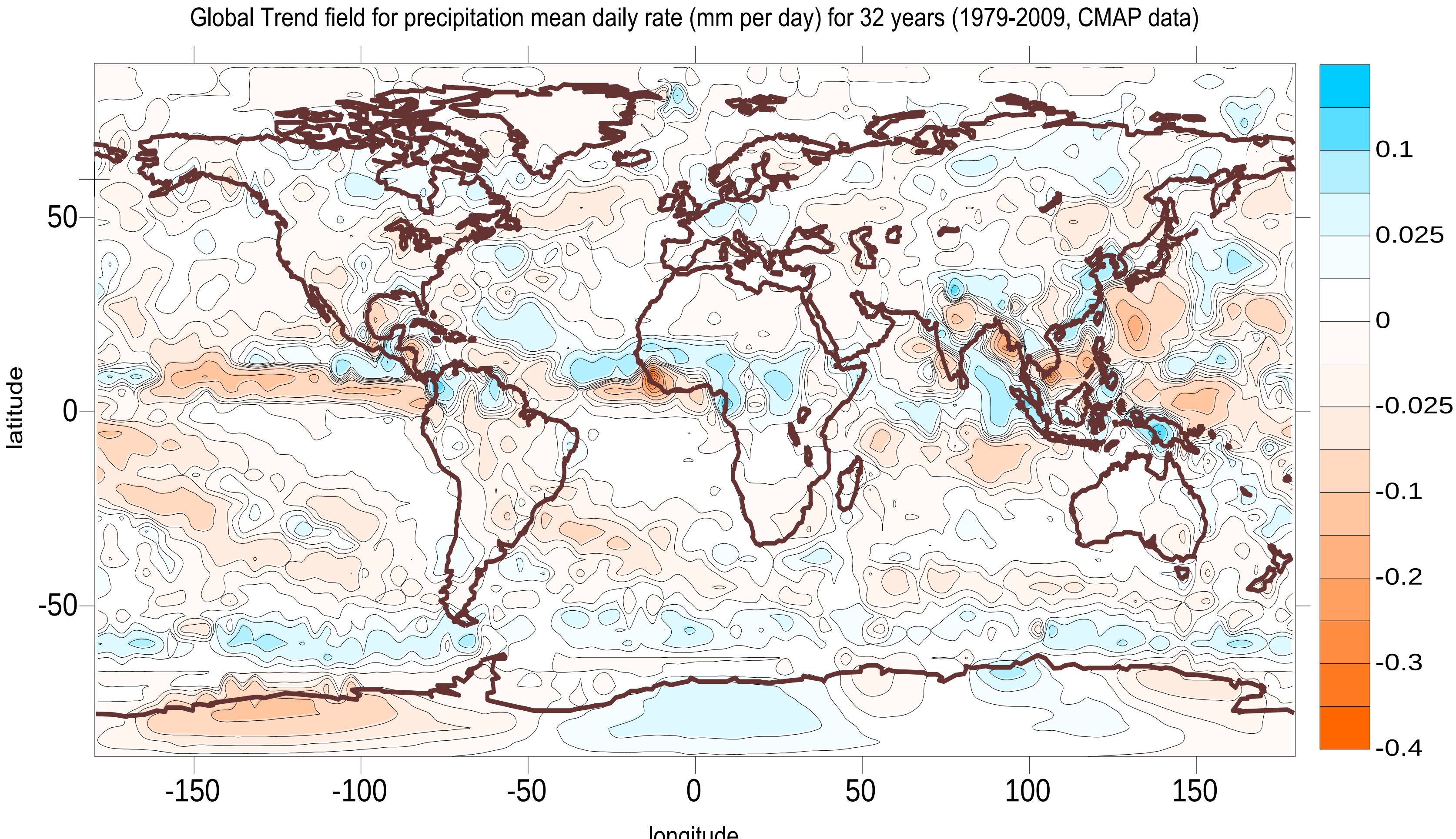


Fig. Global average rain rate (mm/day): intrannual dependencies for 1979-2009

Average over Northern Asia Precipitation Rate (mm/day) distribution by years and monthes

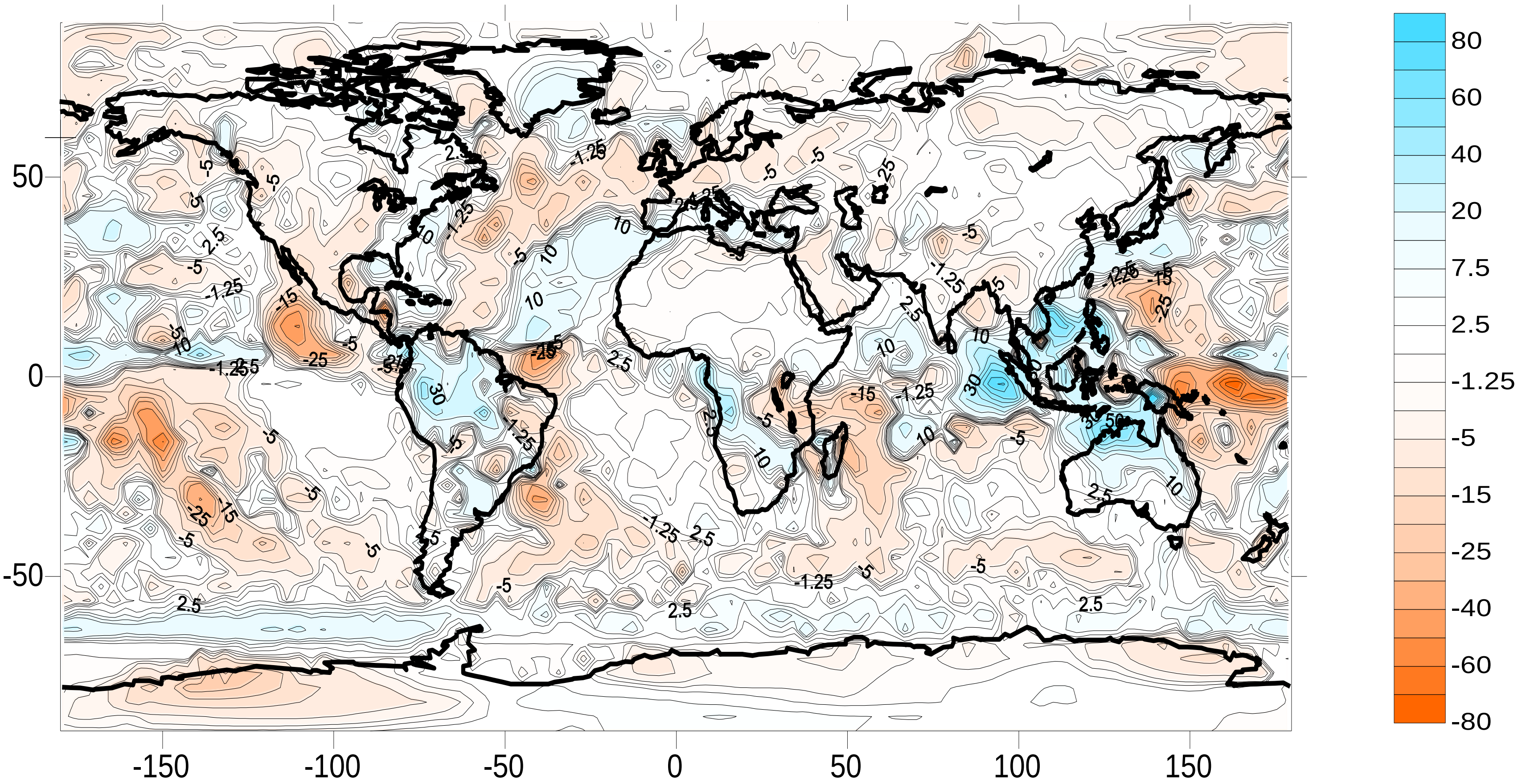


Monthly Precipitation Trend for 32 years



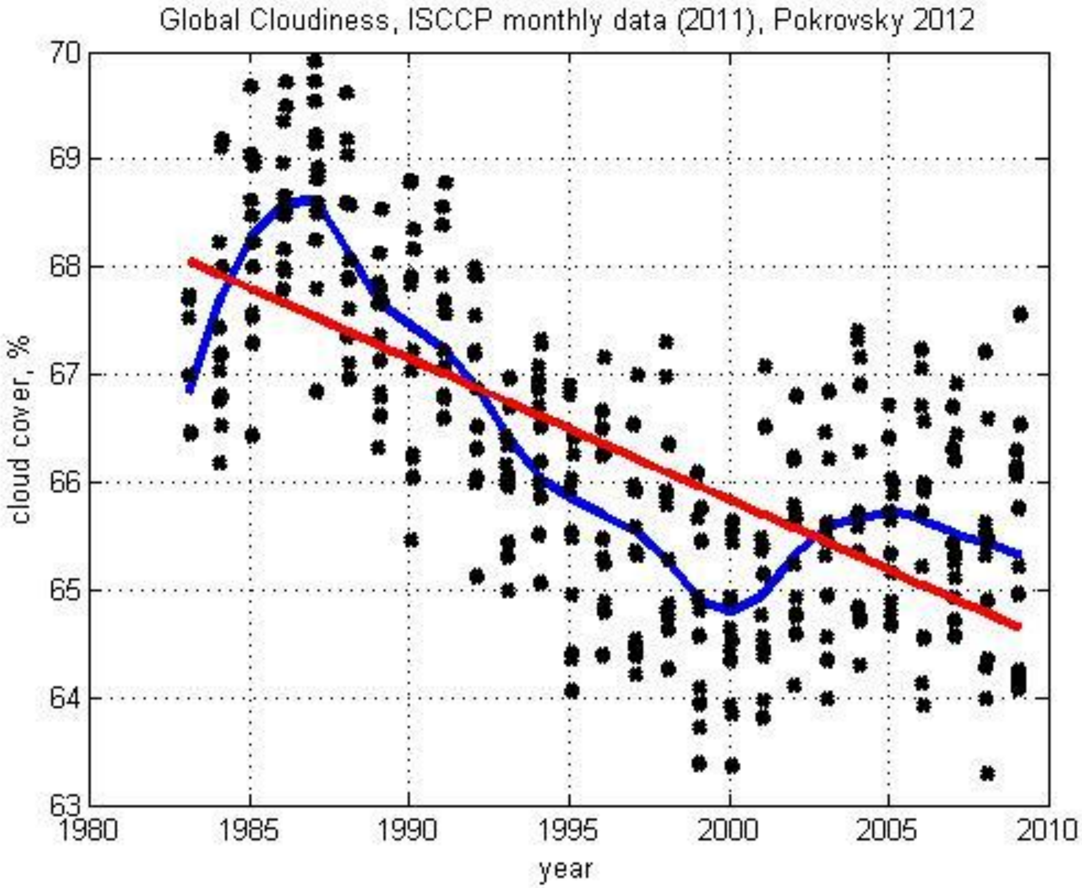
Annual precipitation sum trend for 32 years

Global Trend field for precipitation annual sums (mm per year) for 32 years (1979-2009, CMAP data)

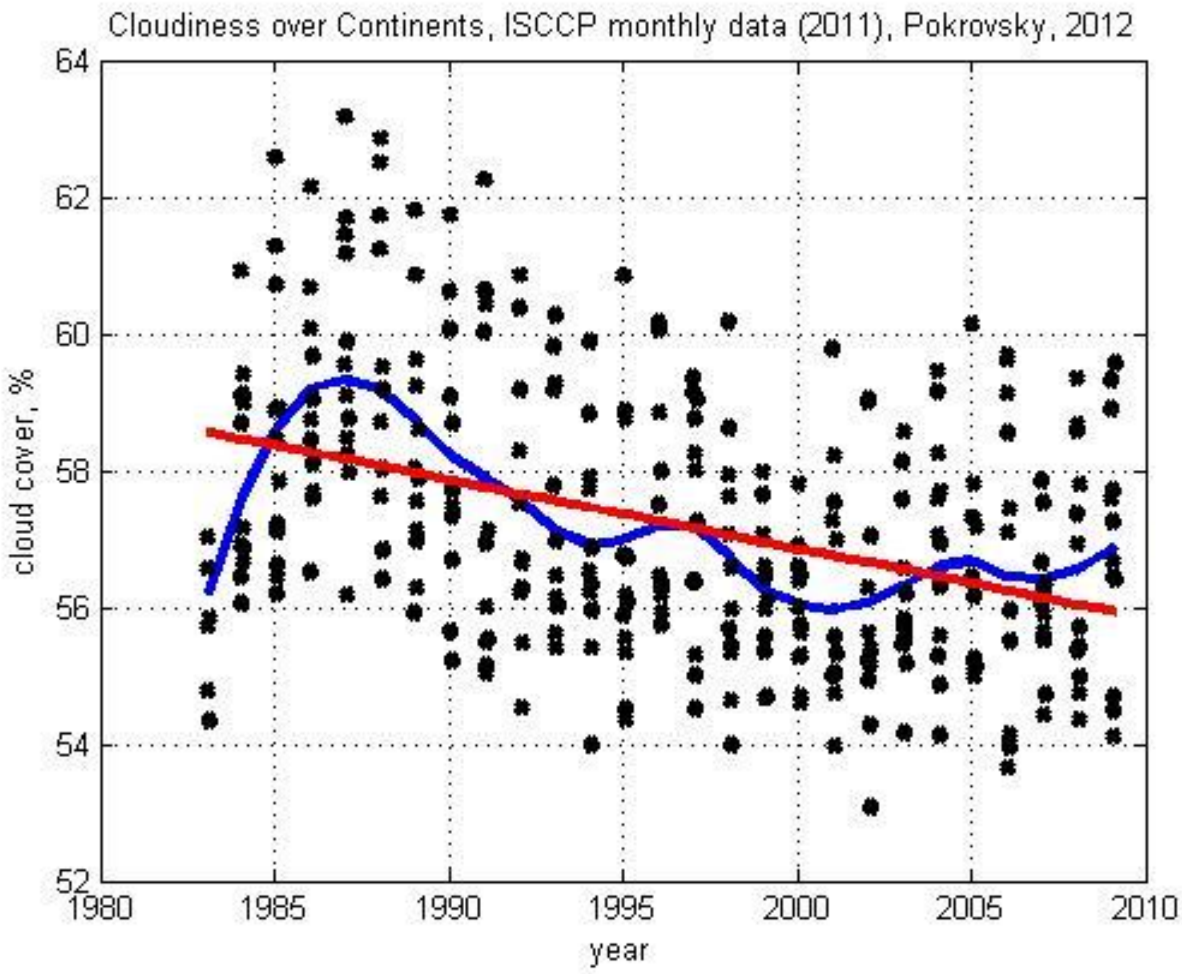


Global and regional cloudiness time series (ICSSP)

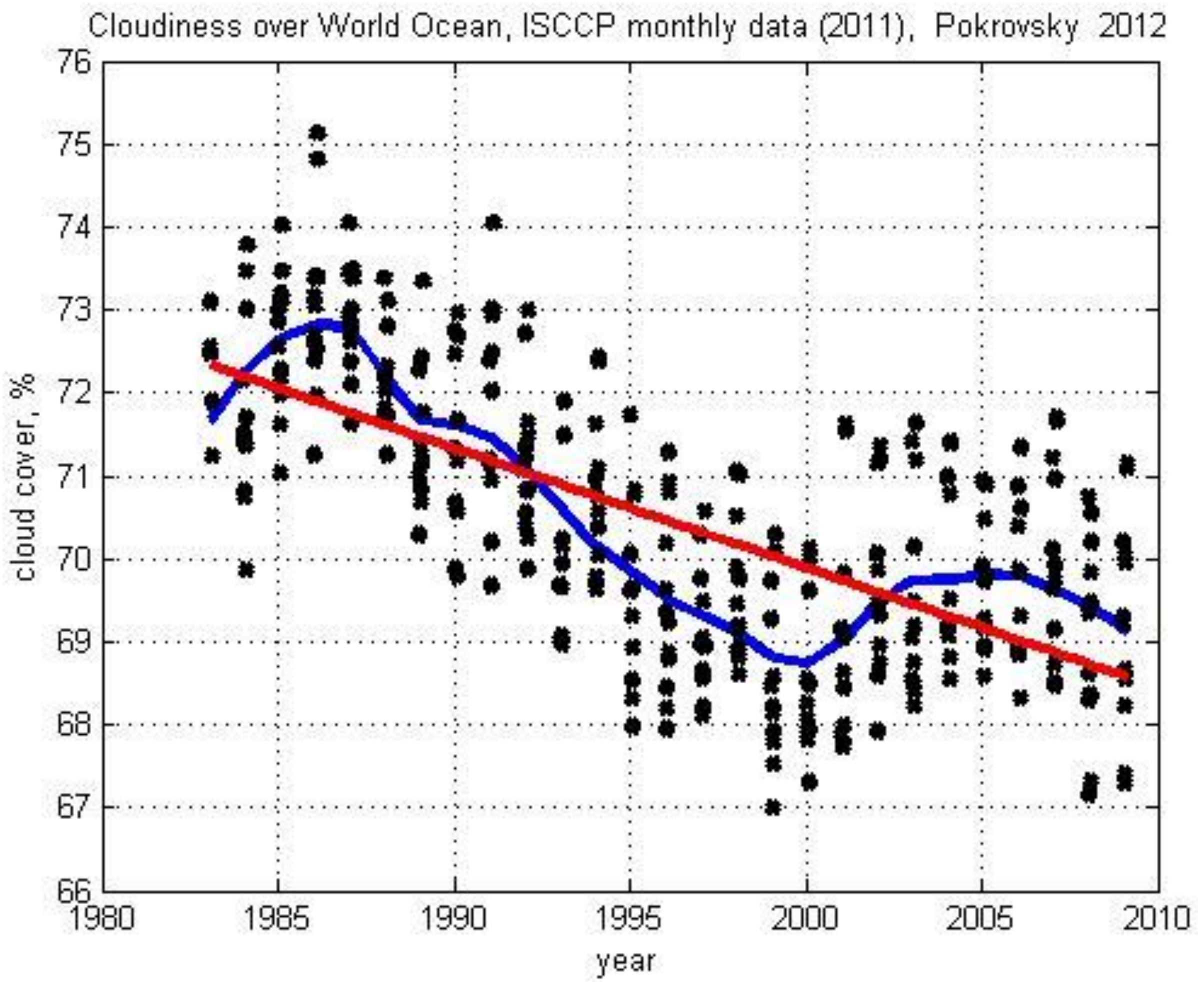
Global cloudiness



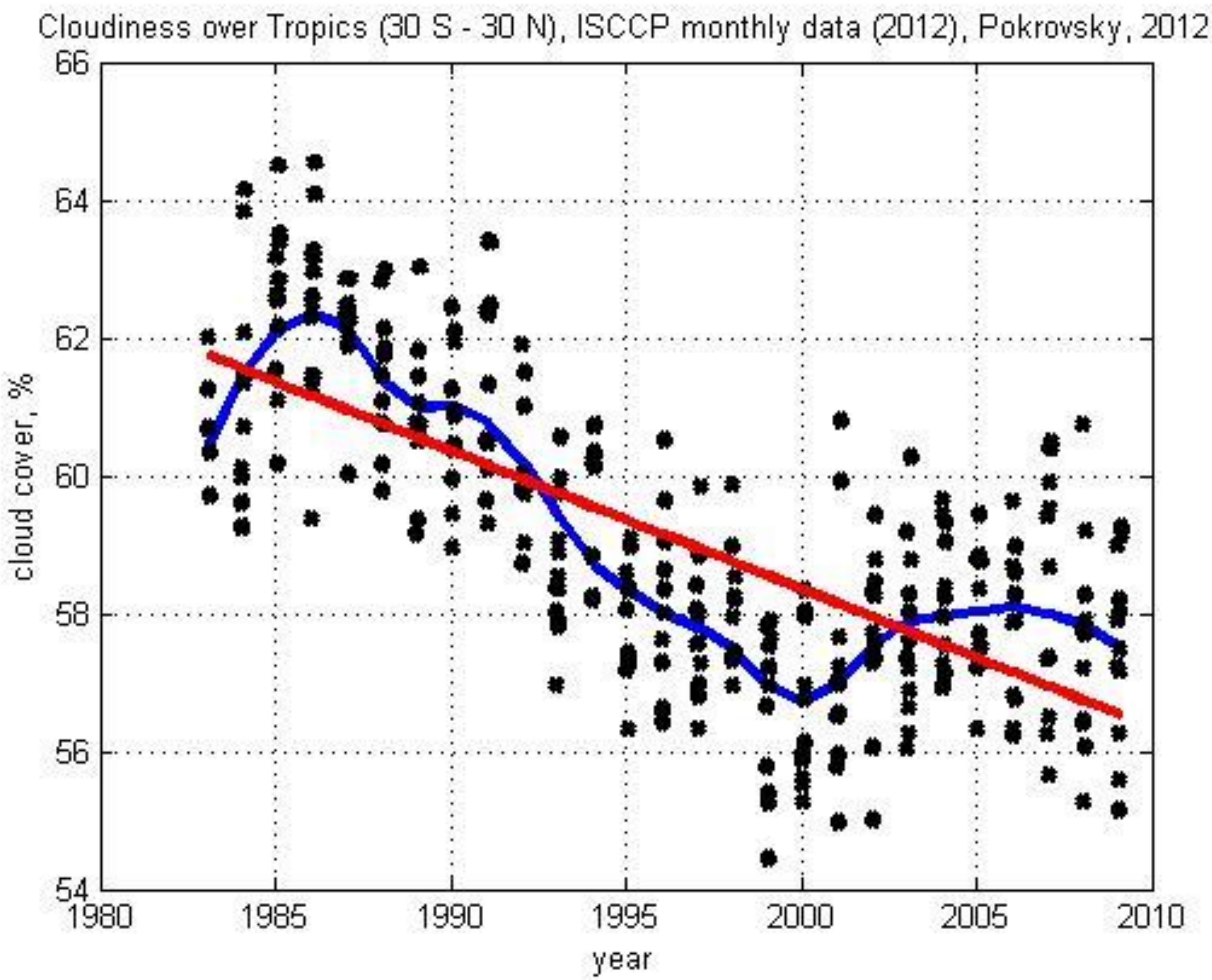
Cloudiness over continents



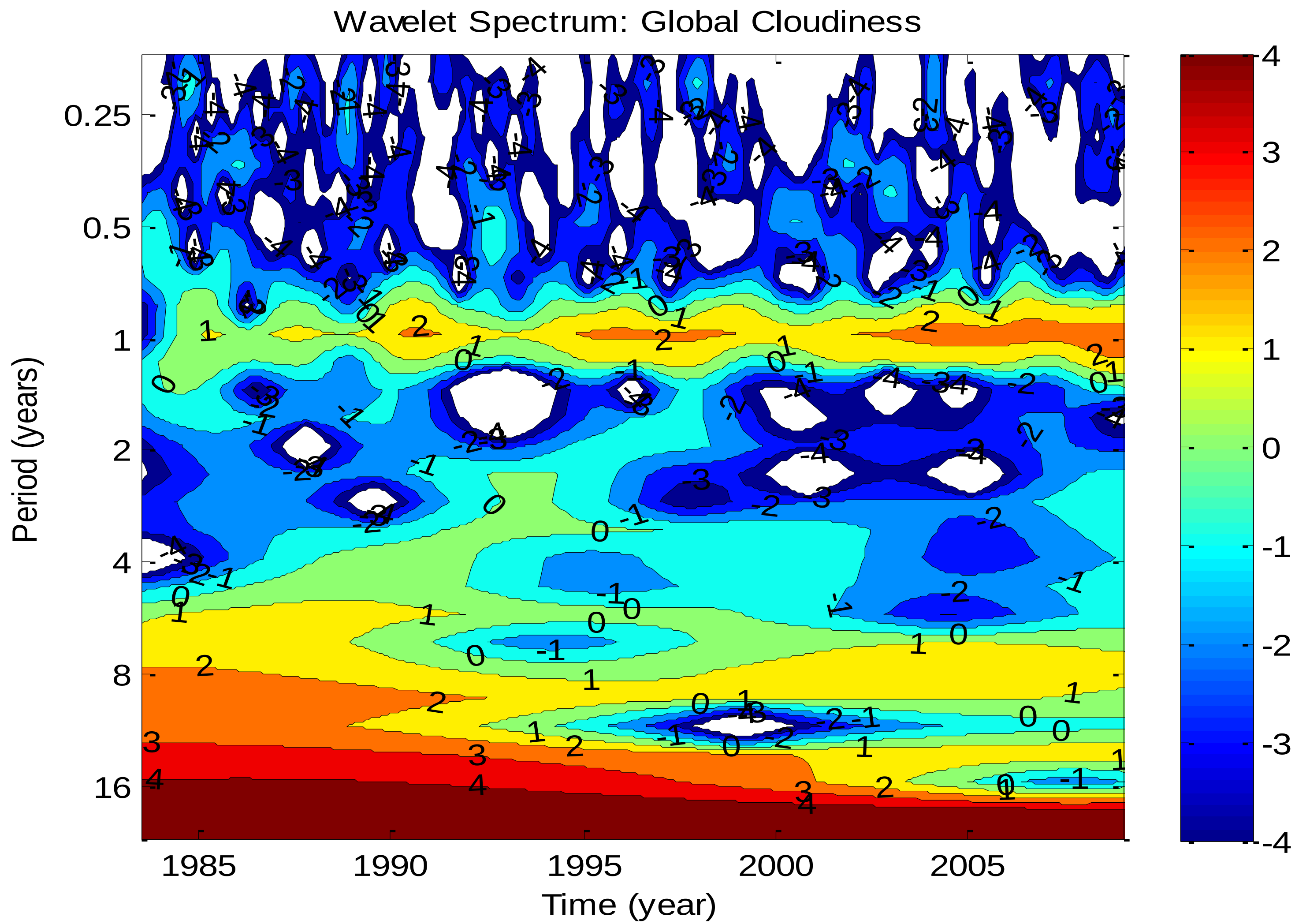
Cloudines over World Ocean



Cloudiness in Tropics



Wavelet Spectrum: Global Cloudiness



Add Conclusion

- Climate cooling and warming periods are closely related to the SST anomalies in Atlantic and Pacific
- More frequent El-Nino events are found in periods of warming.
- More frequent La-Nino events were observed in periods of cooling.
- There is coherency between the SST and precipitation amount.
- There is coherency between the cloudiness and the SST and the SAT

THANK YOU
FOR YOUR ATTENTION

St. Petersburg

Author lectures now available at YOUTUBE
via
http://meteovlab.meteorf.ru/index.php?option=com_content&view=article&id=767&Itemid=206&lang=ru