On the Role of Unforced Natural Coupled Ocean-Atmosphere Multidecadal Variability in Twentieth Century Global Warming

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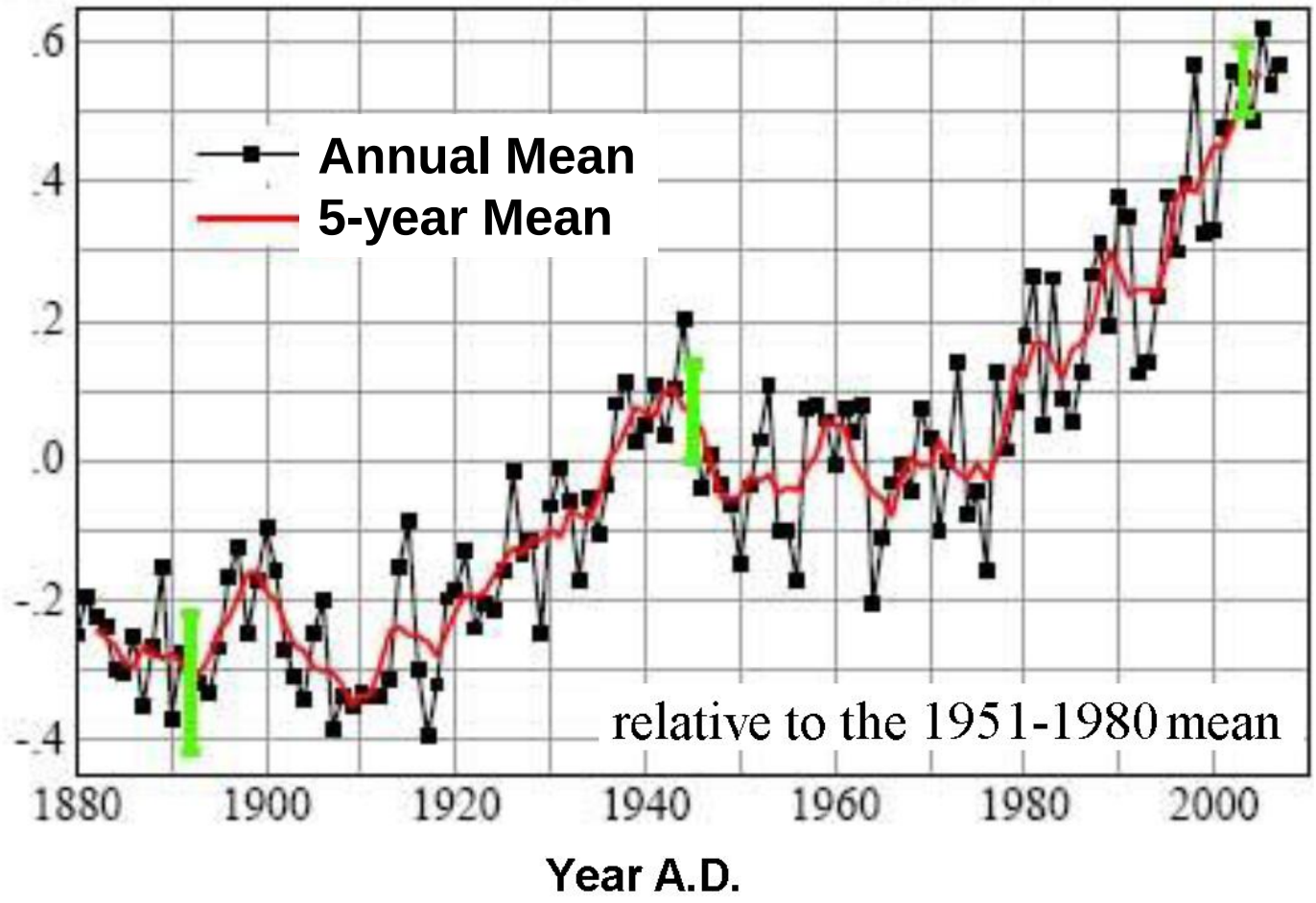
Global Warming

Global Warming is the increase in the average temperature of the Earth's near surface air and oceans since the mid-20th century and its projected continuation. (Wikipedia)

Global Temperature Change (°C)



0.76 C (1.4 F) since 1900

0.55 C (1.0 F) since 1979

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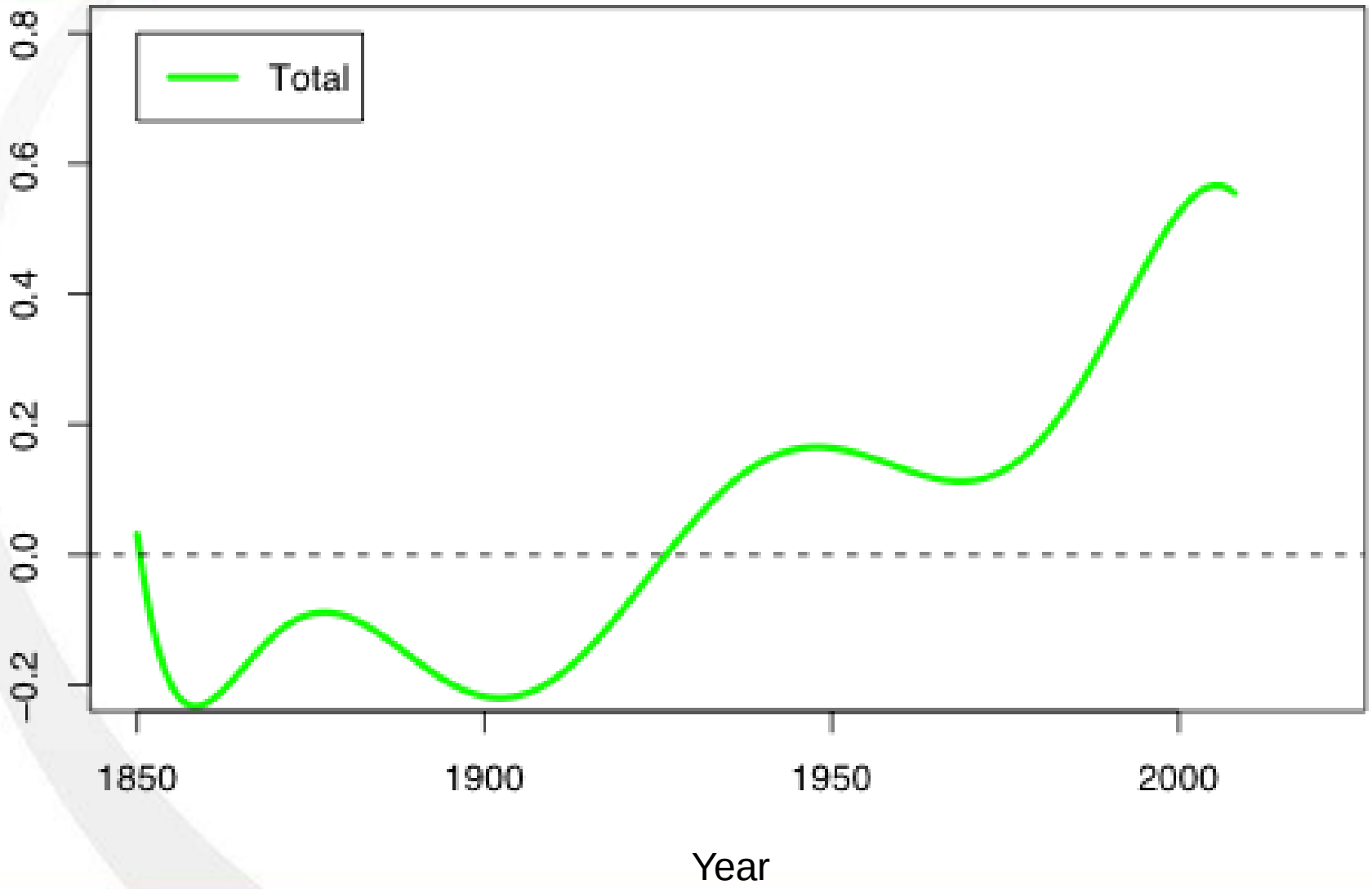
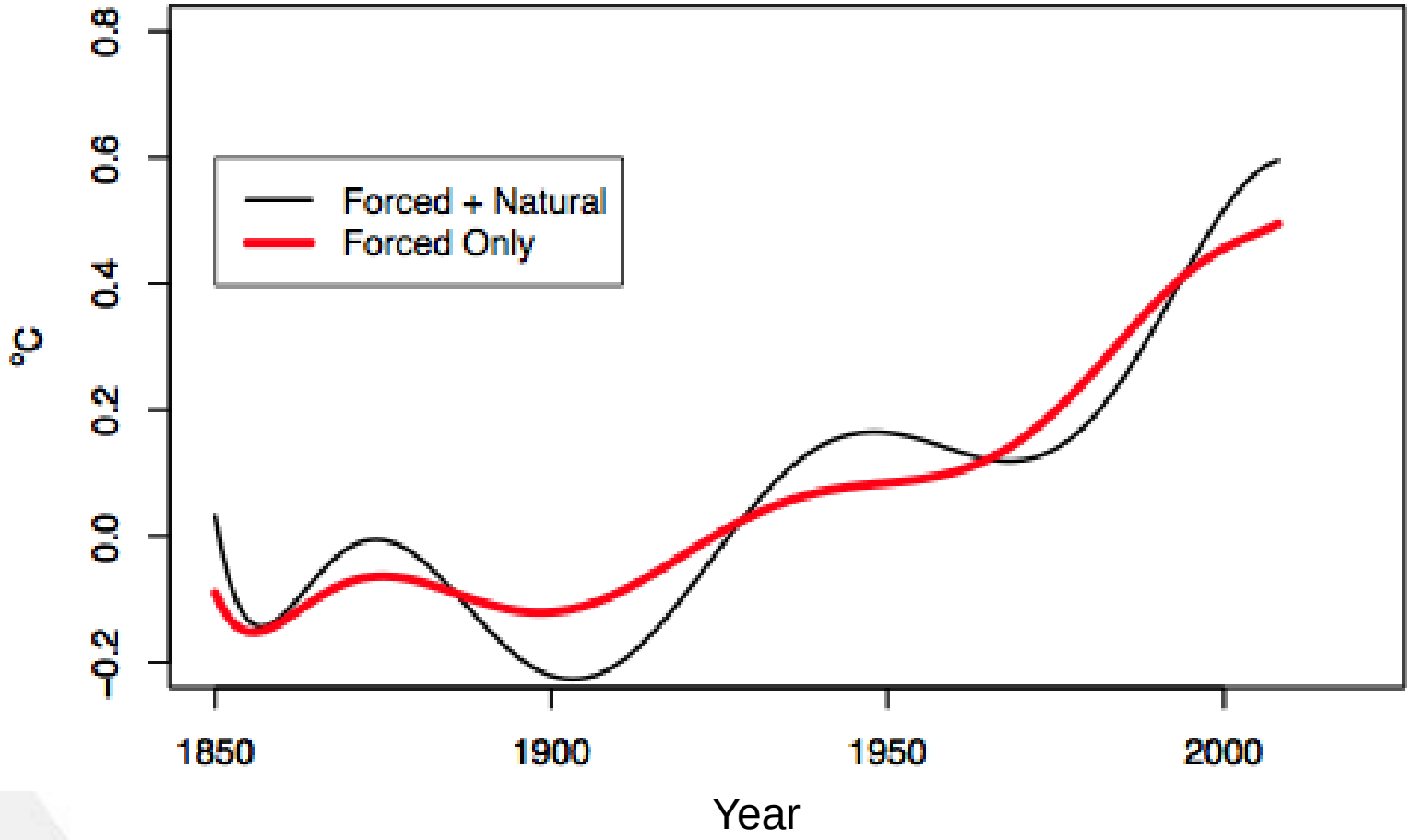
Low-Pass Spatially Averaged Observed SST on 'Well-Observed' Grid



Low-Pass Spatially Averaged Surface Temperature on 'Well-Observed' Grid



- **Use S/N and Trend to calculate forced pattern.**
- **Use IPCC pre-industrial control runs to calculate internal variability pattern.**

Recent Papers

"A significant Component of Unforced Multidecadal Variability in Twentieth Century Global Warming"

Timothy DelSole, Michael K. Tippett, Jagadish Shukla

(Under Review: Journal of Climate)

"The Impact of North Atlantic-Arctic Multidecadal Variability on Northern Hemisphere Surface Air Temperature"

Vladimir A. Semenov, Mojib Latif, Dietmar Dommenget, Noel S. Keenlyside, Alexander Strehz, Thomas Martin, Wonsun Park

(To Appear: Journal of Climate)

"On the Trend of the Global Mean Surface Temperature"

Norden E. Huang, Zhaohua Wu, John M. Wallace, Xianyao Chen, Brian Smoliak, Compton J. Tucker

(Under Review: Science)

How To Define Patterns of Multidecadal Predictability?

EOF?	Optimizes variance, not time scale.
EMD?	Ignores spatial correlations, hence is suboptimal.
SSA?	Ignores spatial correlations, hence is suboptimal.
EEOF?	Not specifically optimized for multidecadal predictability.

How To Define Patterns of Multidecadal Predictability?

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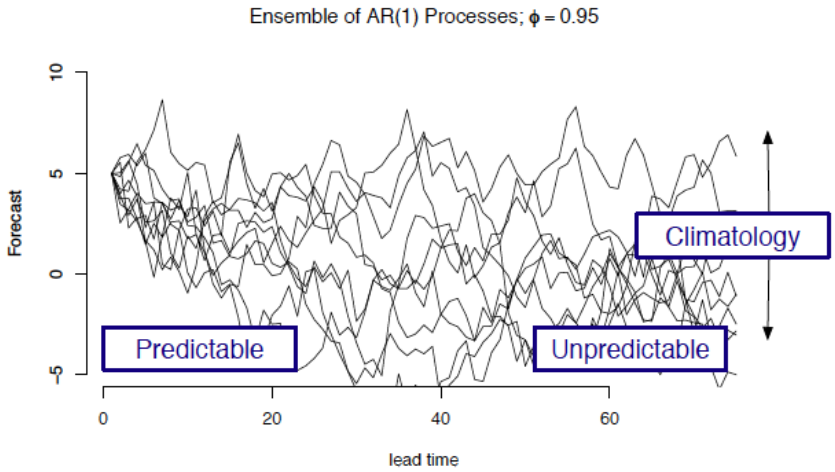
EEOF? Not specifically optimized for multidecadal predictability.

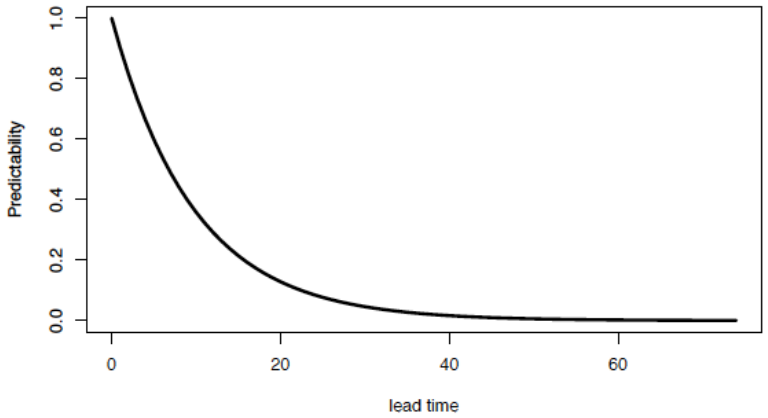
New approach: Average Predictability Time (APT)

Definition of Predictability



Measure of Predictability

$$P = \frac{\sigma^2_{clim} - \sigma^2_{forecast}}{\sigma^2_{clim}}$$



$\sigma^2_{forecast}$: Variance of forecast.
σ^2_{clim}: Variance of climatology.

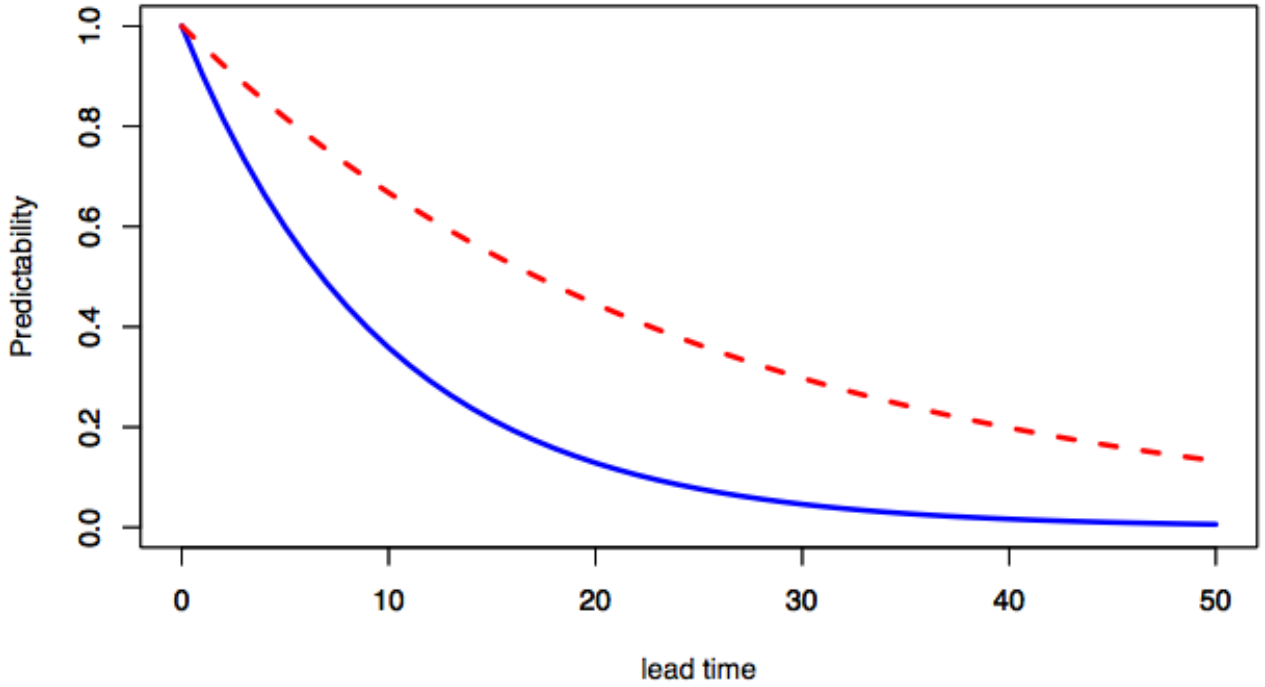
Identifying Internal Multidecadal Patterns (IMP)

Find a pattern that maximizes "persistence" (unlike EOF which maximizes variance).

Average Predictability Time (APT)

Average predictability can be characterized in a way that is independent of lead time by integrating the predictability metric, which always decreases with time. For example, the rate of decay is much slower and enhance the integral is much higher for decadal variation than seasonal variation.

Average Predictability Time (APT)



APT = integral of 2P over all lead times

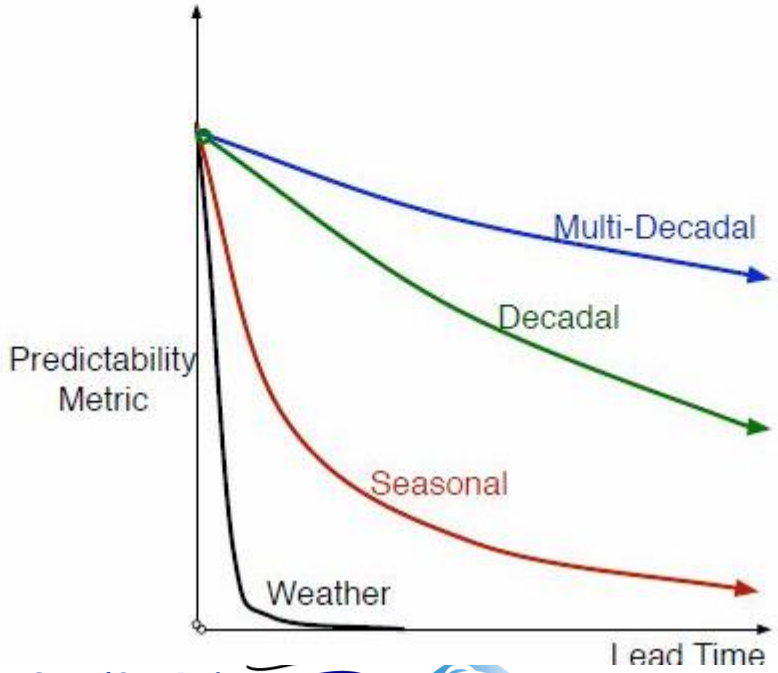
$$APT = 2\int_0^\infty \left(\frac{\sigma_c^2 - \sigma_f^2}{\sigma_c^2}\right) d\tau$$

Decomposing Predictability

Characterize predictability independent of lead time by integrating over lead time:

$$APT = 2\int_0^\infty \left(\frac{\sigma^2_{clim} - \sigma^2_{forecast}(\tau)}{\sigma^2_{clim}} \right) d\tau$$

Find component that maximizes APT (DelSole and Tippett 2009).



Signal-to-Noise EOFs: Response Pattern to Forcings

(Anthropogenic and Natural (Solar, Volcanic)

Find components that maximize the ratio of variances:

- **Discriminant analysis (Fisher 1938)**
- **Seasonal Predictability (Straus et al. 2003)**
- **Decadal Predictability (Venzke et al. 1999)**
- **Climate Change (Ting et al. 2009) (No IPCC Control Runs)**

Response pattern to climate forcing estimated by finding the pattern that maximizes the ratio

$$\frac{\text{variance in twentieth century runs}}{\text{variance in pre-industrial control runs}} = \frac{\sigma^2_{20c3m}}{\sigma^2_{picntrl}}$$

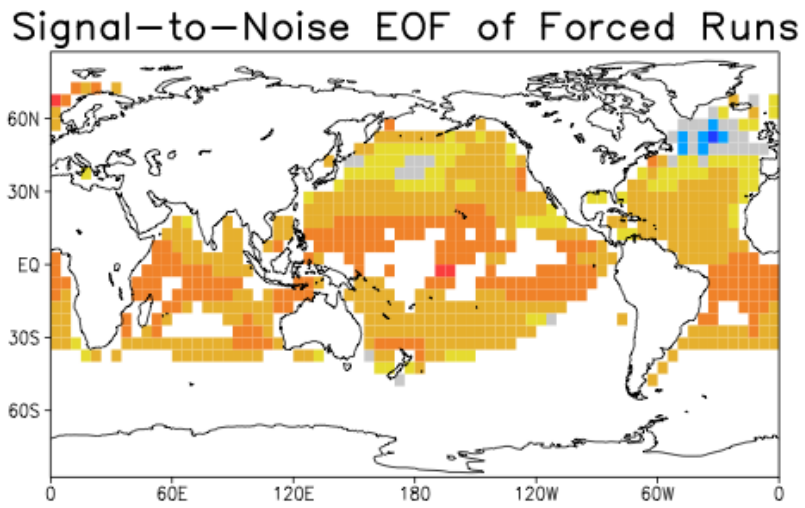
If forced response is additive, $\sigma^2_{20c3m} = \sigma^2_{picntrl} + \sigma^2_{\text{forced response}}$

Trend Patterns:

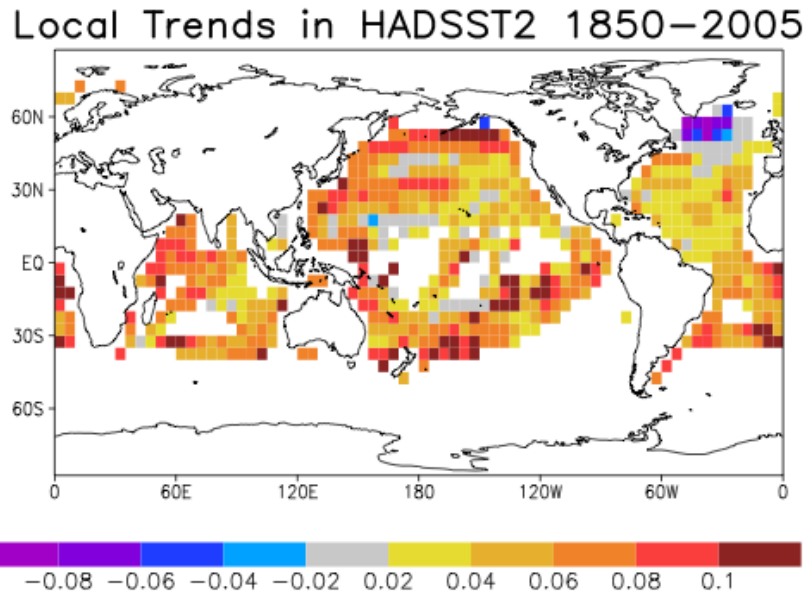
To be interpreted as Response Pattern to Forcings

Fit linear trend between 1850-2005, plot the slope expressed as degrees per decade.

Estimated Response to Anthropogenic and Natural Forcings



Signal to Noise EOF



Local Trend Pattern

IGES

COLA

Center for Research on Environment and Water

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Fingerprinting Method

Fit observed annual average SST to

$$\underset{\text{Observed}}{T_{obs}(x,y,t)} = \underset{\substack{\text{Forced}\\\text{Response}}}{a_{for}(t)T_{for}(x,y)} + \underset{\substack{\text{Internal}\\\text{Pattern}}}{a_{imp}(t)T_{imp}(x,y)} + \underset{\substack{\text{Random}\\\text{Noise}}}{w(x,y,t)}$$

- Define spatial response to external forcing $T_{for}(x,y)$.
- Define spatial structure of IMP $T_{imp}(x,y)$.
- Define statistics of internal variability (from 'control runs').
- Fit equation using generalized least squares:

Detection: Test hypothesis $a_{for}(t) = 0$.

Attribution: Test hypothesis $a_{for}(t) =$ predicted amplitude.

How To Define The Response To Climate Forcing?

Pattern should characterize response to natural and anthropogenic forcing, but also filter out as much internal variability as possible.

Hypothesis:

$$\underset{}{\text{Total}} = \underset{\textit{Signal}}{\text{Forced Response}} + \underset{\textit{Noise}}{\text{Internal Variability}}$$

Find projection vector that maximizes the ratio of the variance in the forced run to variance in the control run:

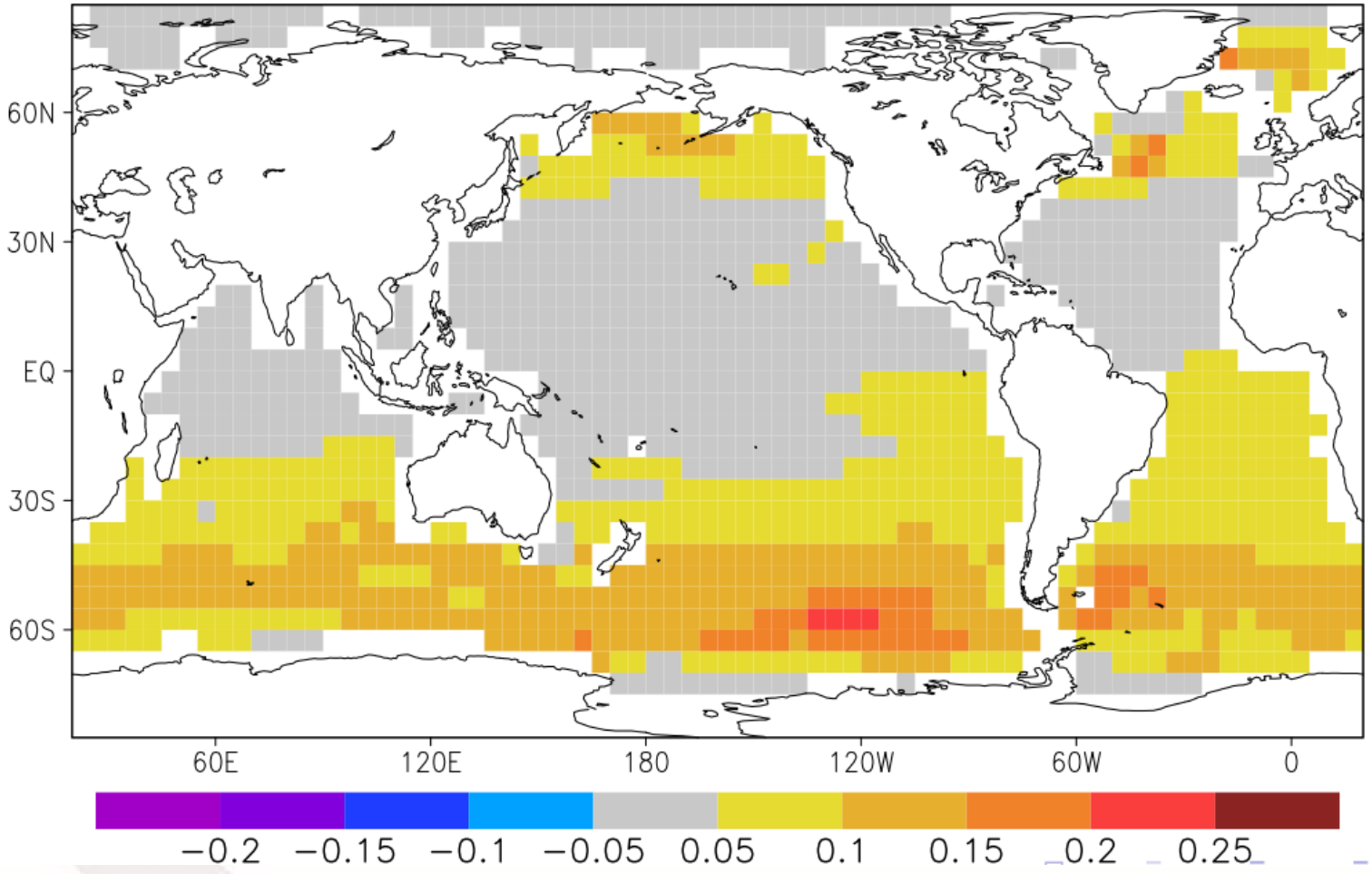
$$\frac{\sigma^2_{forced}}{\sigma^2_{control}} = \frac{\sigma^2_S + \sigma^2_N}{\sigma^2_N} = \frac{\sigma^2_S}{\sigma^2_N} + 1$$

Optimize APT in Control Runs

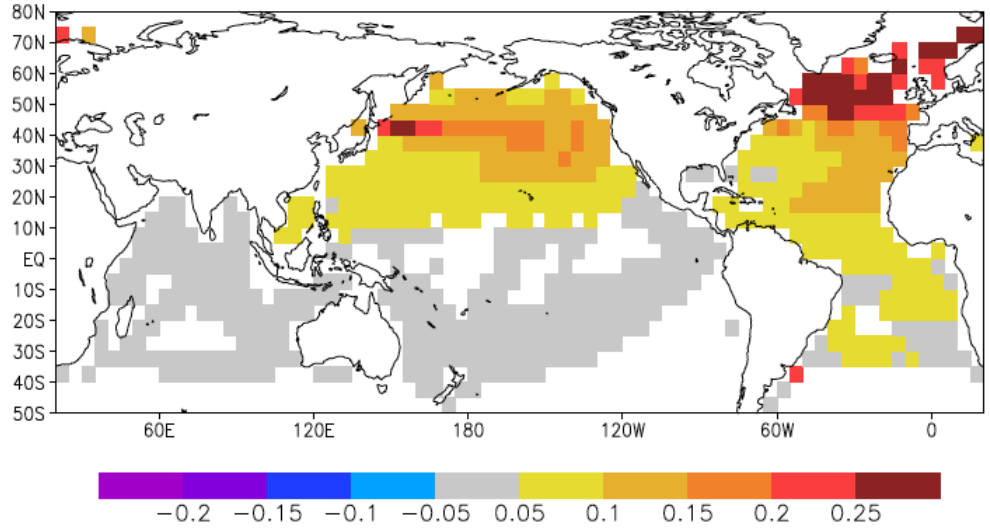
- Use IPCC AR4 data set (also called CMIP3).
- Last 300 years of PICNTRL are used.
- Model grids interpolated onto HadSST2 grid.
- Only "well-observed" grid points in the model are analyzed.
- Annual averaged sea surface temperature.
- Each model's climatology subtracted out.
- All runs pooled to compute "total EOF" and "total APT."
- The "outliers" IAP, GISS-EH, GISS-ER were omitted.
- 14 models, effective time series length = 4200 years.
- 40 EOF truncation, 20-year maximum lag for APT.
- No Detrending
- Null hypothesis: white noise when sampled every 2 years.

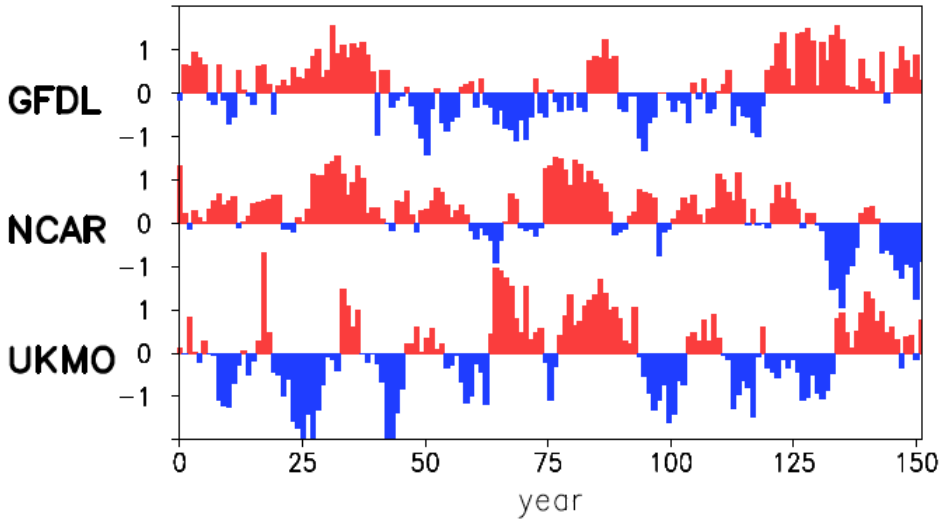
Leading Predictable Component (APT)
Internal Multi-decadal Pattern (IMP)

tos.ann.terp.glo apt(5.92yr) Mode-1 (40EOFs; 300yrs; 20yr Lag)

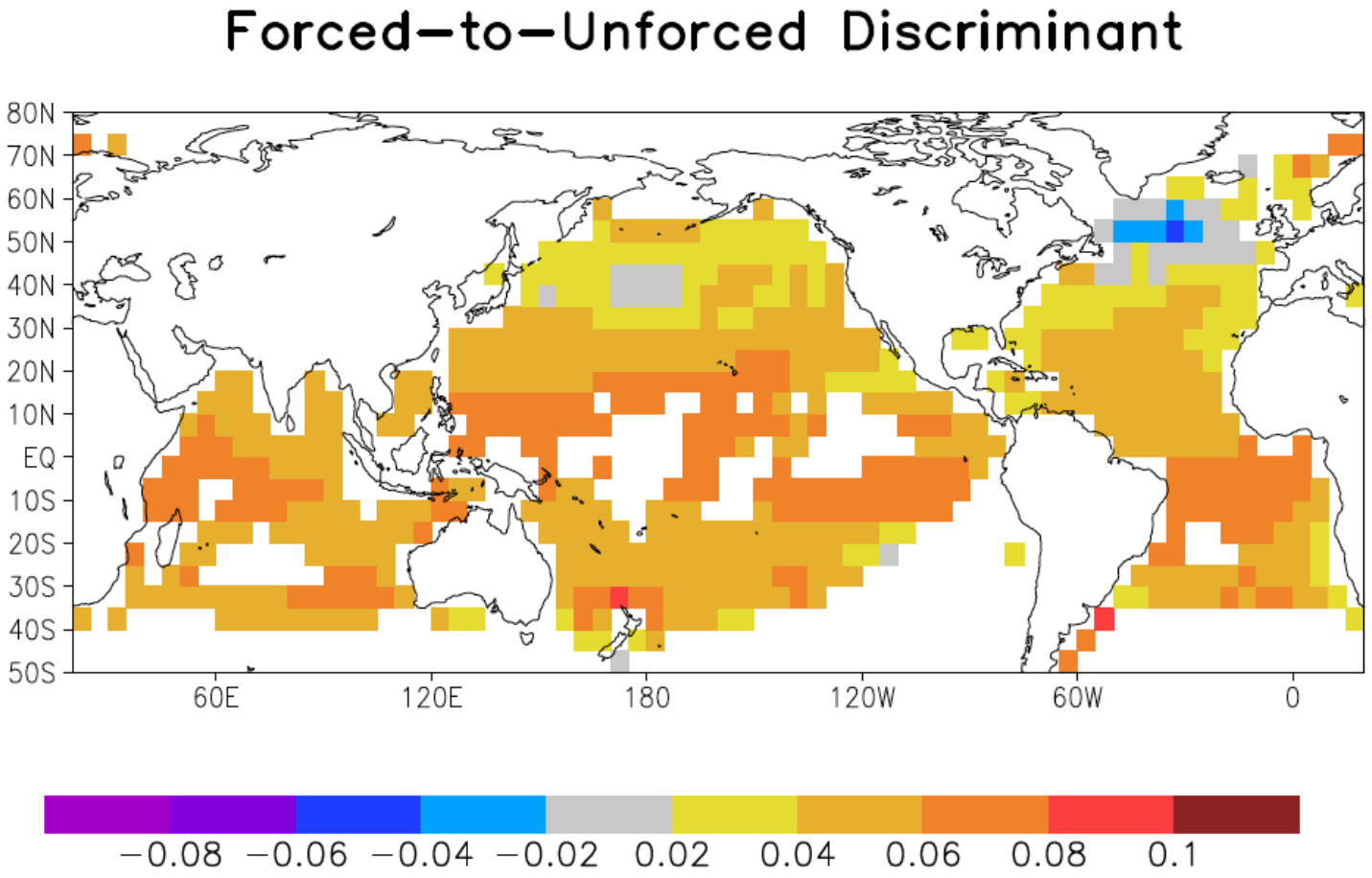


Leading Predictable Component: "Internal Multidecadal Pattern (IMP)"

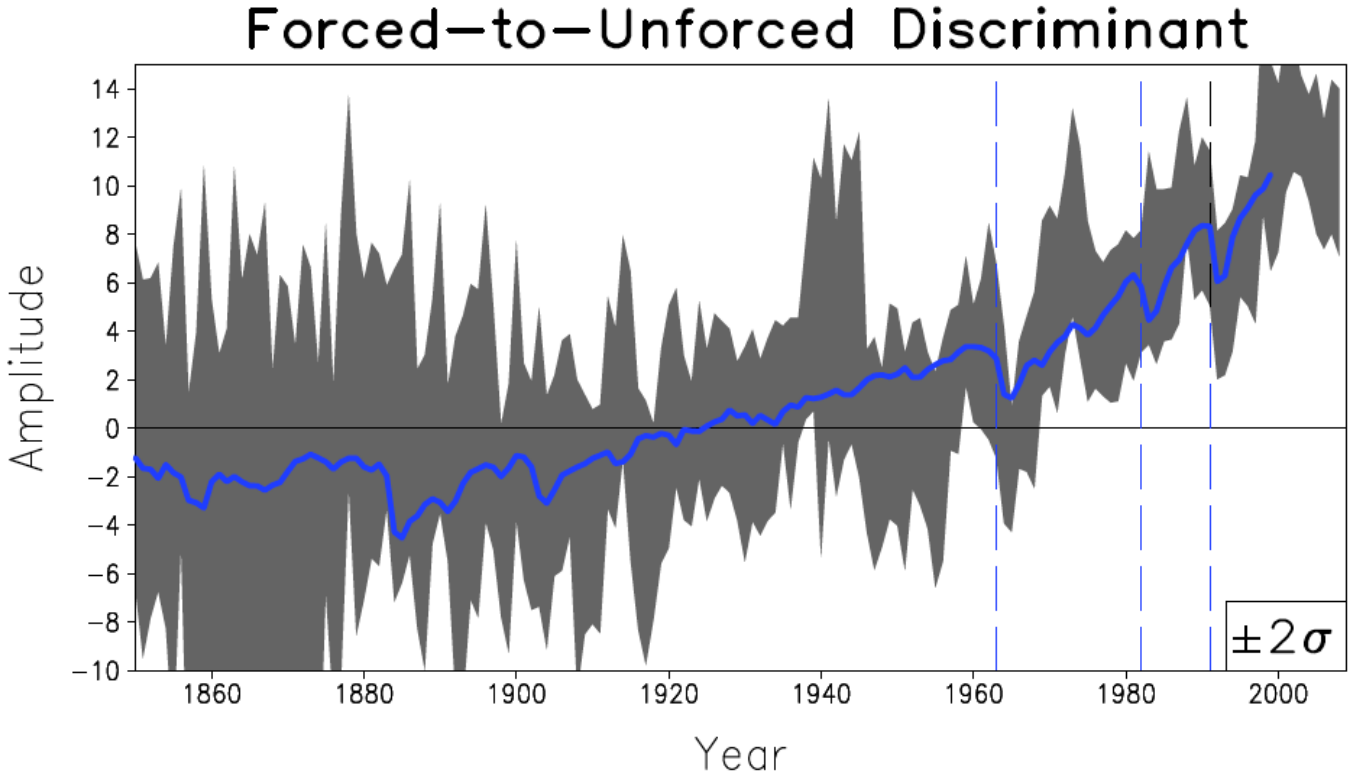




Forced-to-Unforced Discriminant from Control Runs



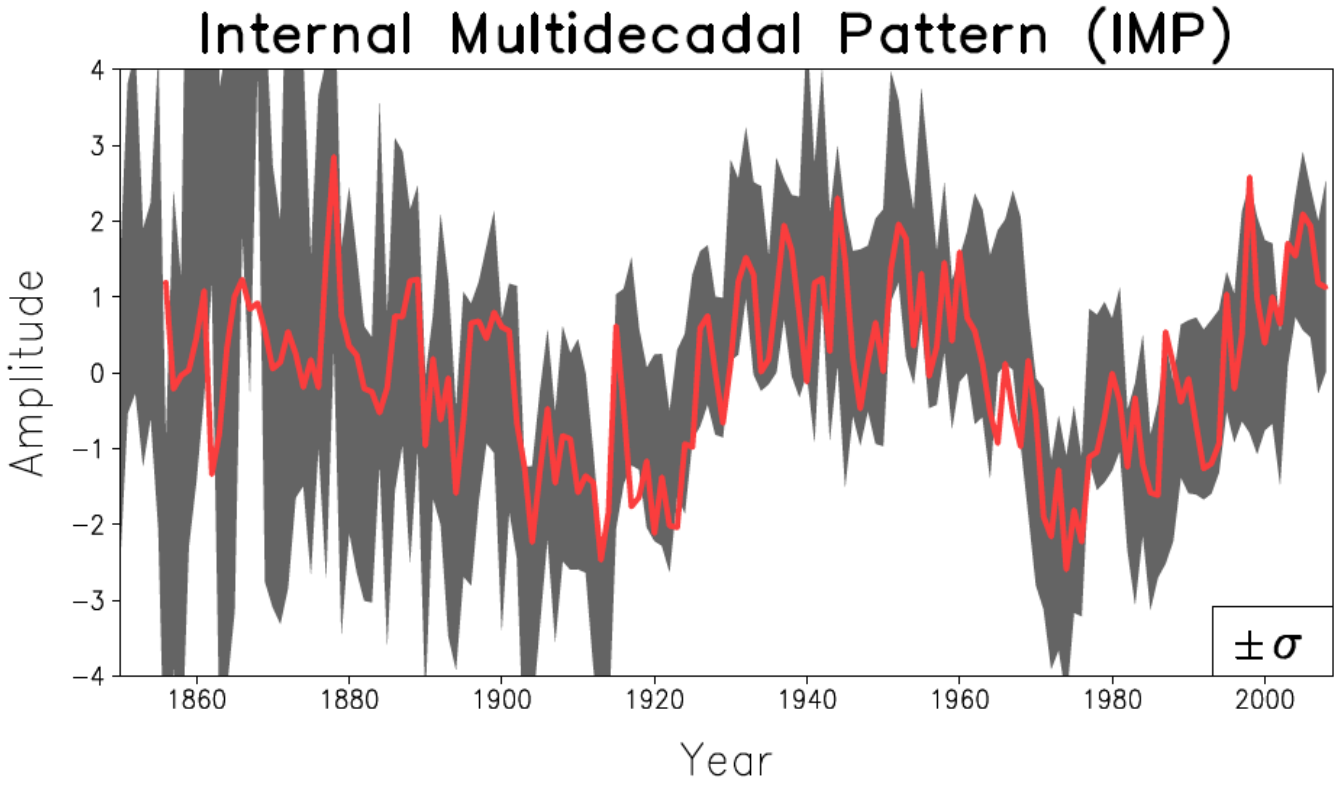
Forced Pattern



shaded area: 95% confidence interval of forced pattern in observations.

blue line: Ensemble mean amplitude of forced pattern in models

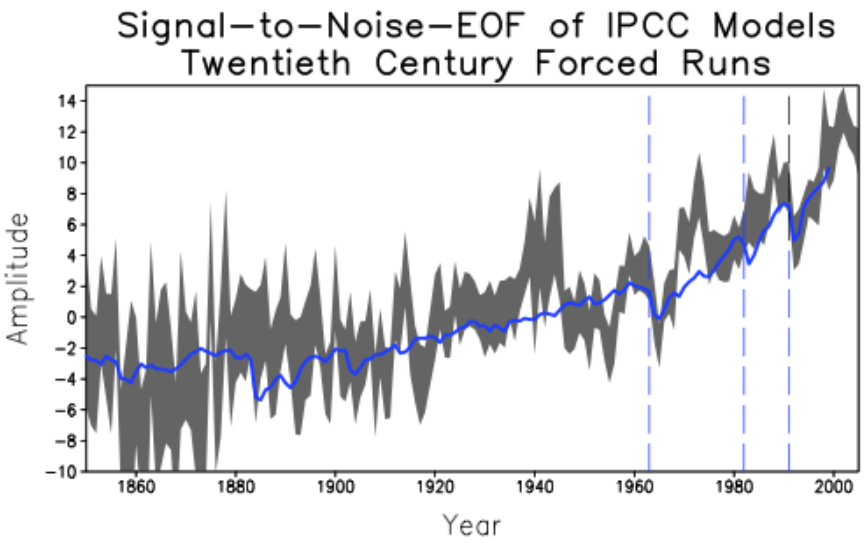
Internal Multidecadal Pattern



shaded area: 66% confidence interval of IMP in observations.

red line: Observed Atlantic Multidecadal Oscillation (AMO) index.

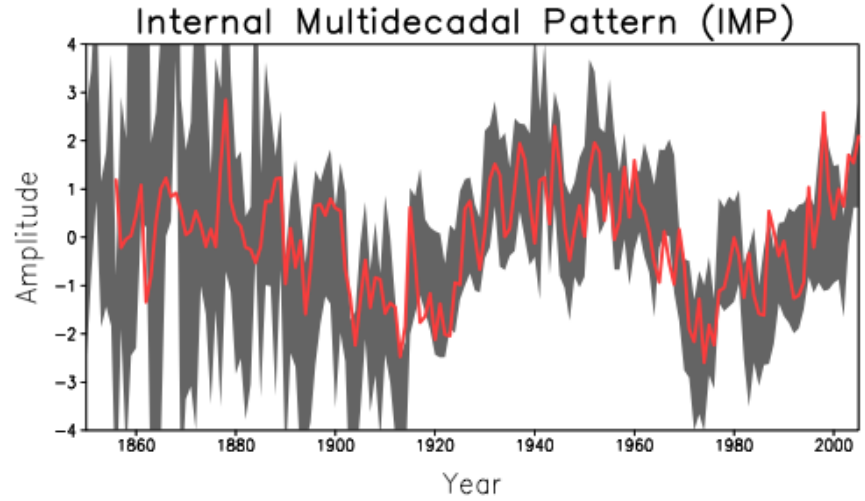
Amplitude of Forced and Unforced Patterns



Shading: $\pm\sigma$ Fingerprint Amplitude

Blue Solid Line: Signal-to-noise PC

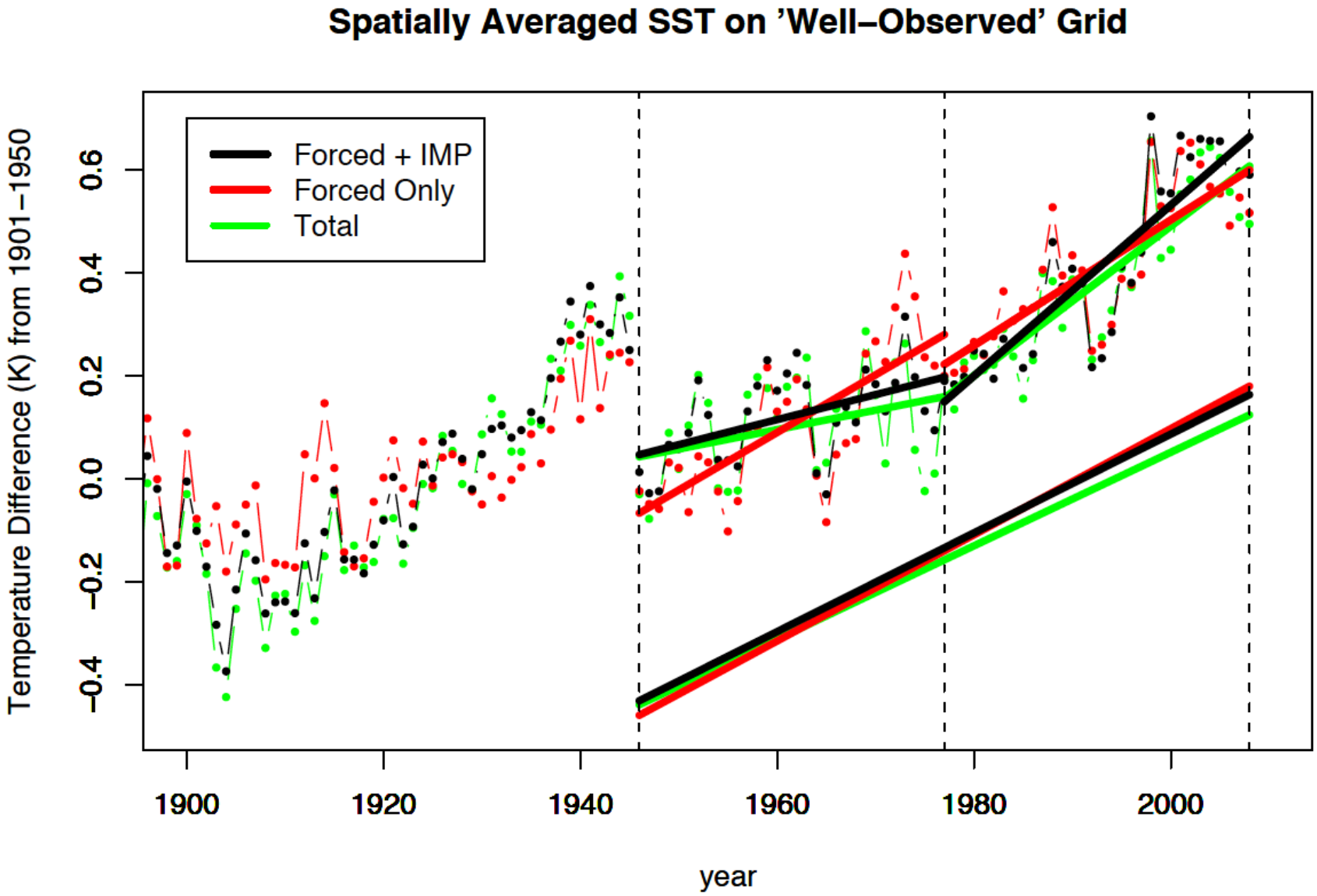
Blue Dashed Line: Major Volcanic eruptions

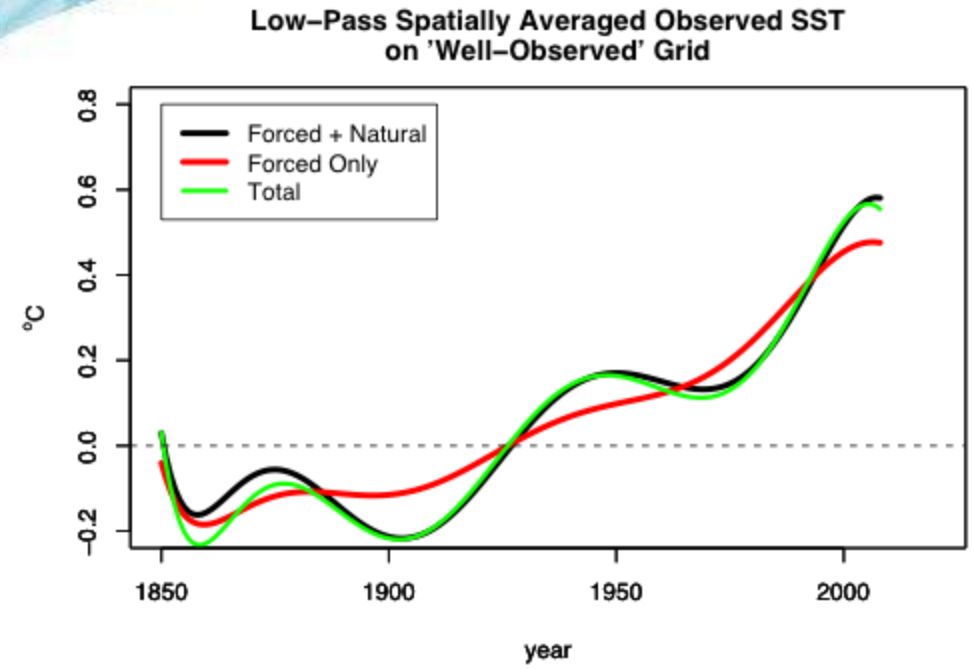


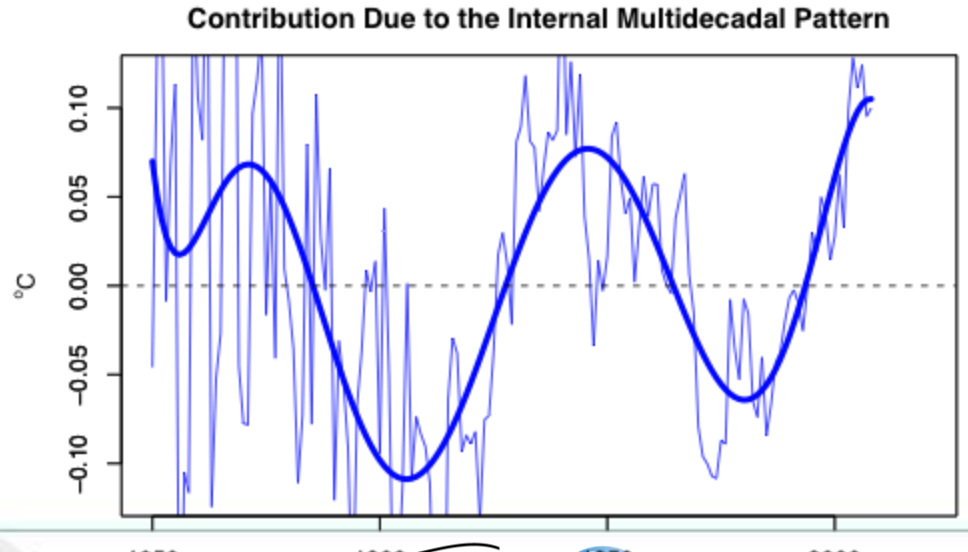
Shading: $\pm\sigma$ Fingerprint Amplitude

Blue Solid Line: AMO Index

Global Mean Sea Surface Temperature

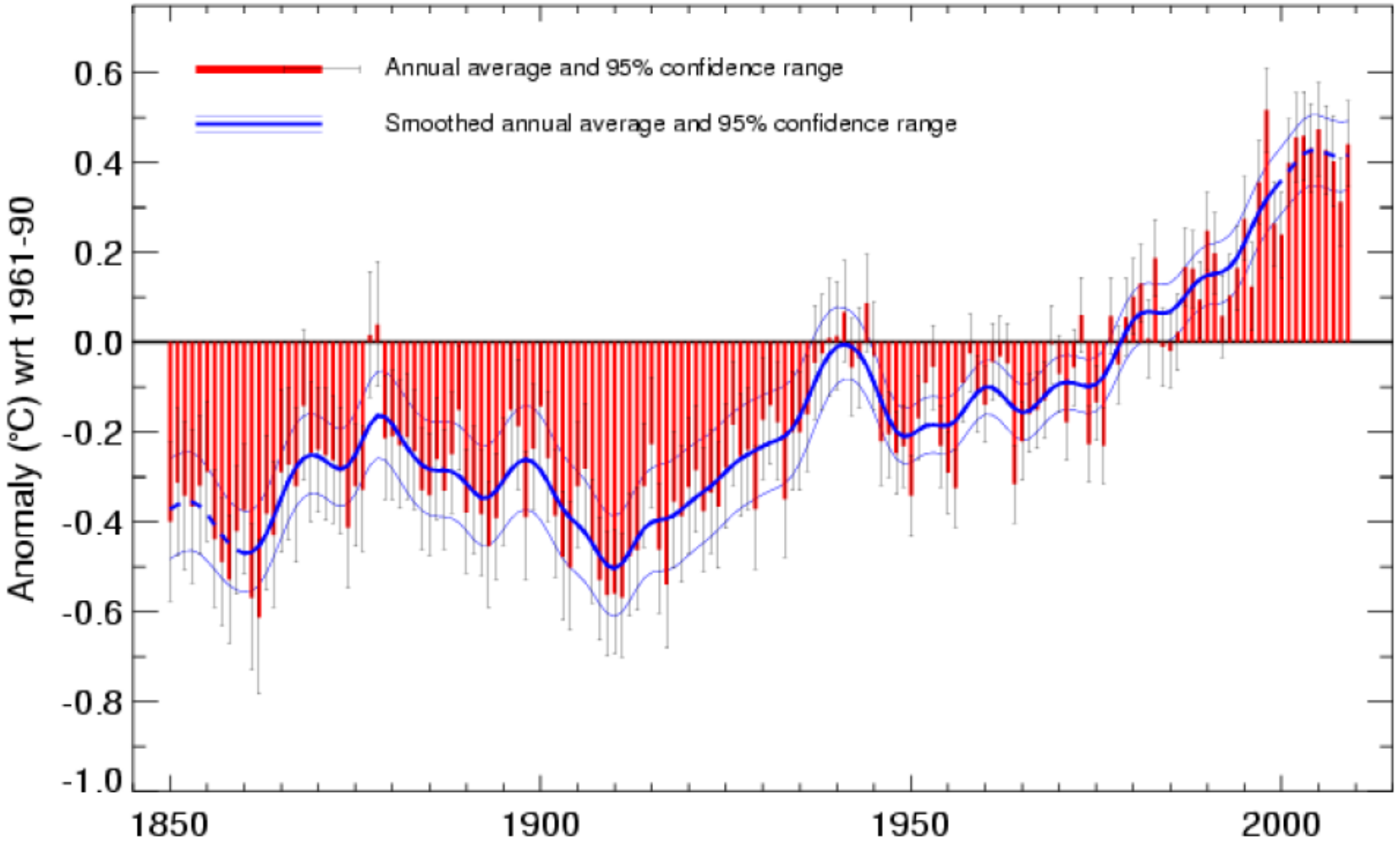



Low–Pass Spatially Averaged Observed SST
on 'Well–Observed' Grid
Forced + Natural
Forced Only
Total
°C
0.8
0.6
0.4
0.2
0.0
–0.2
1850
1900
1950
2000
year


Contribution Due to the Internal Multidecadal Pattern
°C
0.10
0.05
0.00
–0.05
–0.10
1850
1900
1950
2000
year

Global average temperature 1850-2009

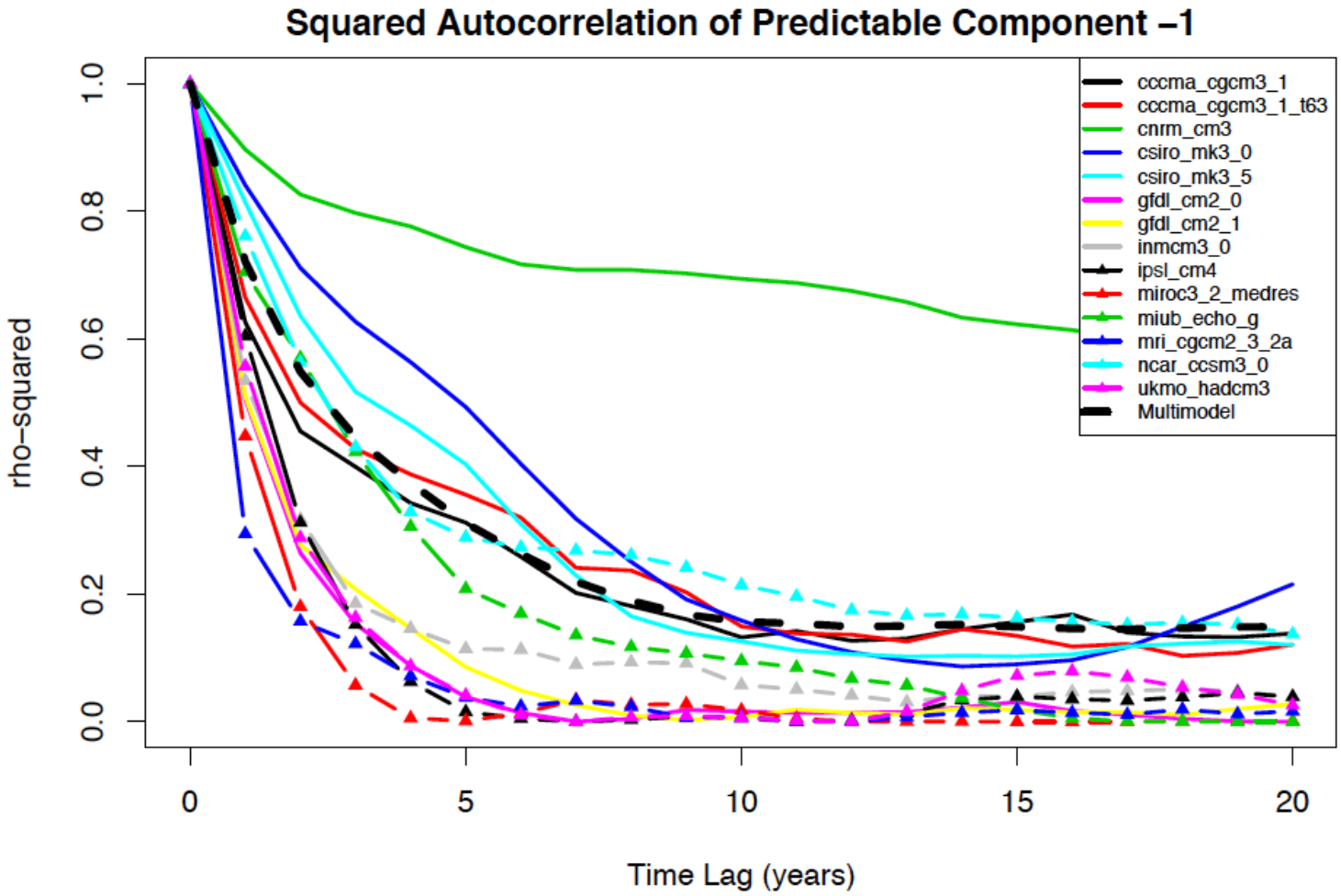
Based on Brohan et al. 2006



Met Office Hadley Centre

Source: www.metoffice.gov.uk/hadobs

Scientific Basis for Decadal Predictability



Summary

1. An unforced, multidecadal SST pattern is identified in simulations and observations by a new statistical method.

2. Maximizing the ratio of forced to internal variability indicates only one forced pattern in SST. Pattern has cooling in N. Atlantic.

3. Fingerprinting shows that post-1970 amplitude of forced pattern is very unlikely to have occurred by internal variability ("detection") and consistent with warming predicted by models ("attribution").

4. Forced component contributes uniform 0.1K/decade of warming.

Summary

1. **Forced component contributes uniform 0.1K/decade of warming.**

2. **Amplitude of IMP matches AMO and is sufficient amplitude to explain acceleration in warming between 1946-1977 and 1977-2008.**

3. **Forced response projects only weakly on IMP, if at all.**

4. **Contribution of IMP to global trends can be comparable to forced component for 25-year periods, but is stronger for shorter periods.**

5. **Cooling trend over 10-year periods not statistically significant.**

Summary

1. Patterns of internal multi-decadal variability are calculated by using IPCC pre-industrial control runs.

2. Both the forced and unforced patterns are estimated by optimal spatial filtering techniques.

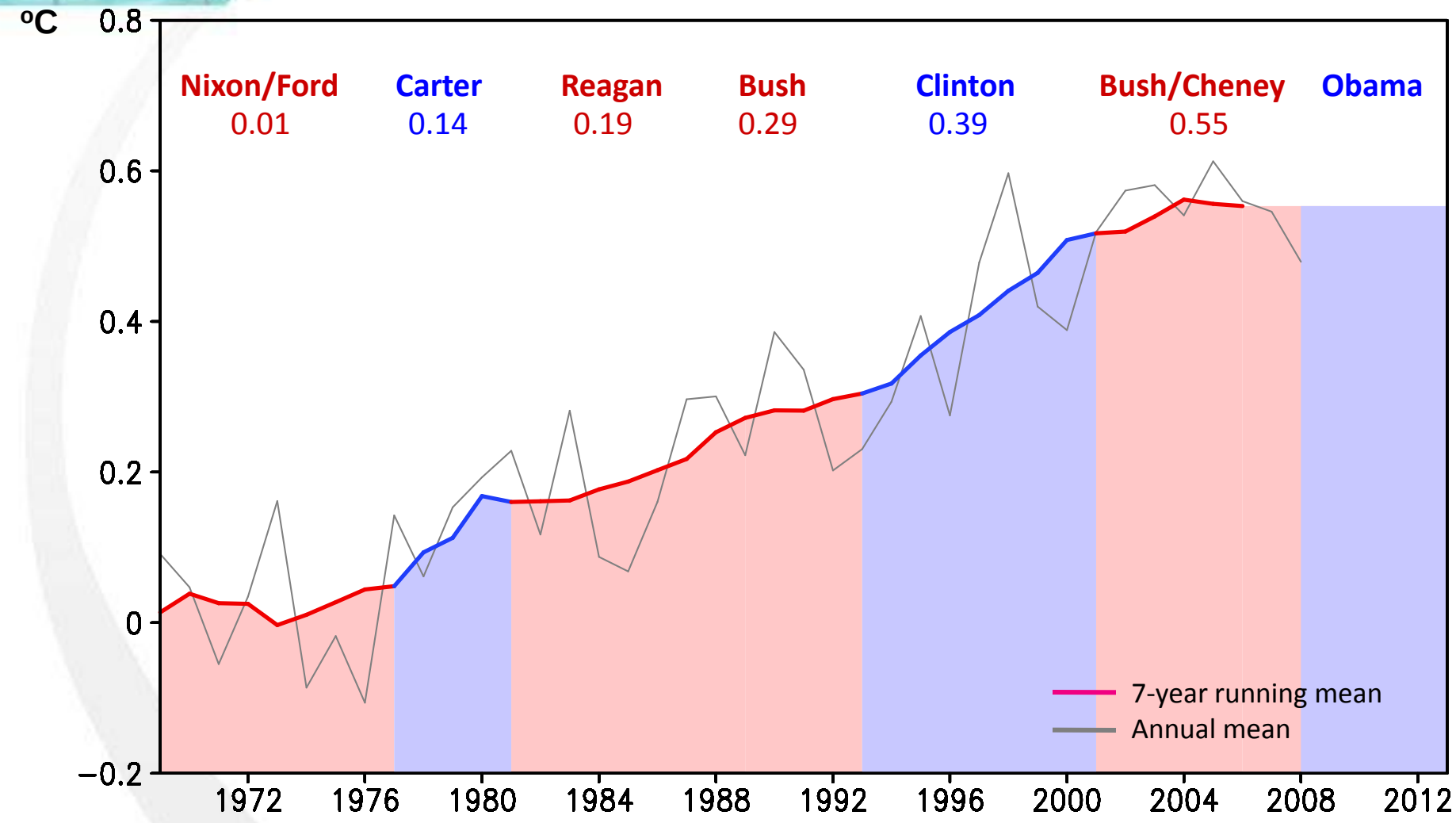
3. An Internal Multi-decadal Pattern (IMP) is identified that explains about 0.1C fluctuations in low-pass, global average SST.

4. Amplitude of this pattern helps explain major multi-decadal fluctuations in global mean temperature in the 20th century. This explains about half of global warming in the past 30 years.

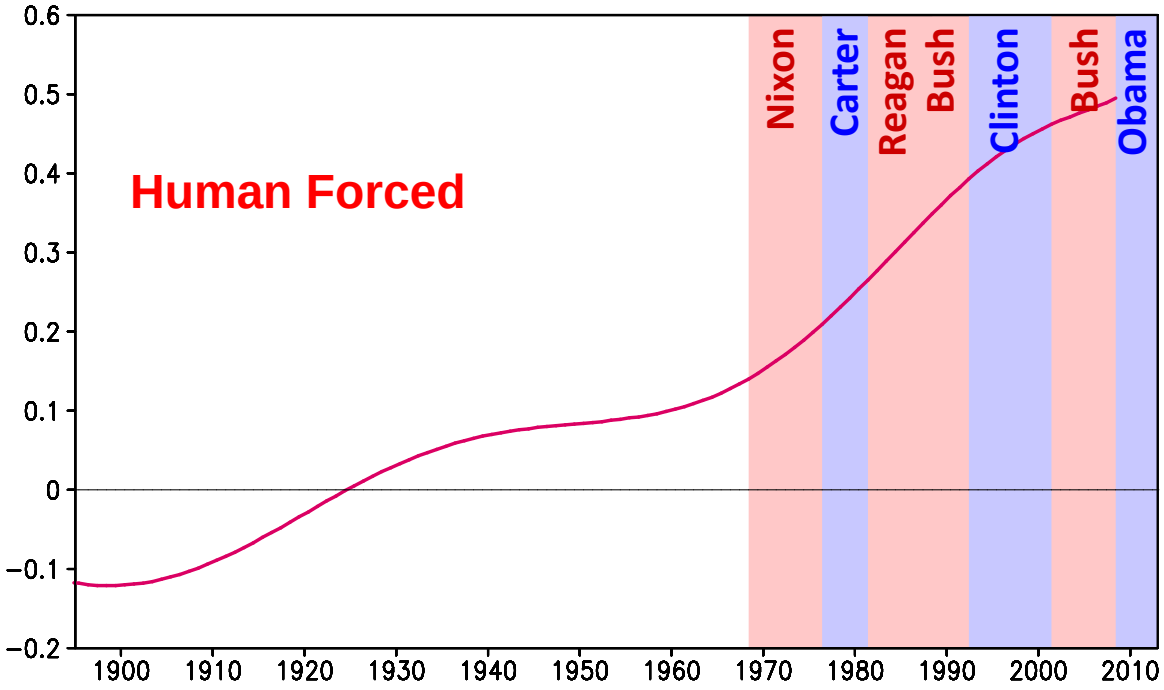
5. The apparent acceleration of warming in the last 30 years can be explained by the warming phase of the IMP.

6. Nature poses a challenge to President Obama.

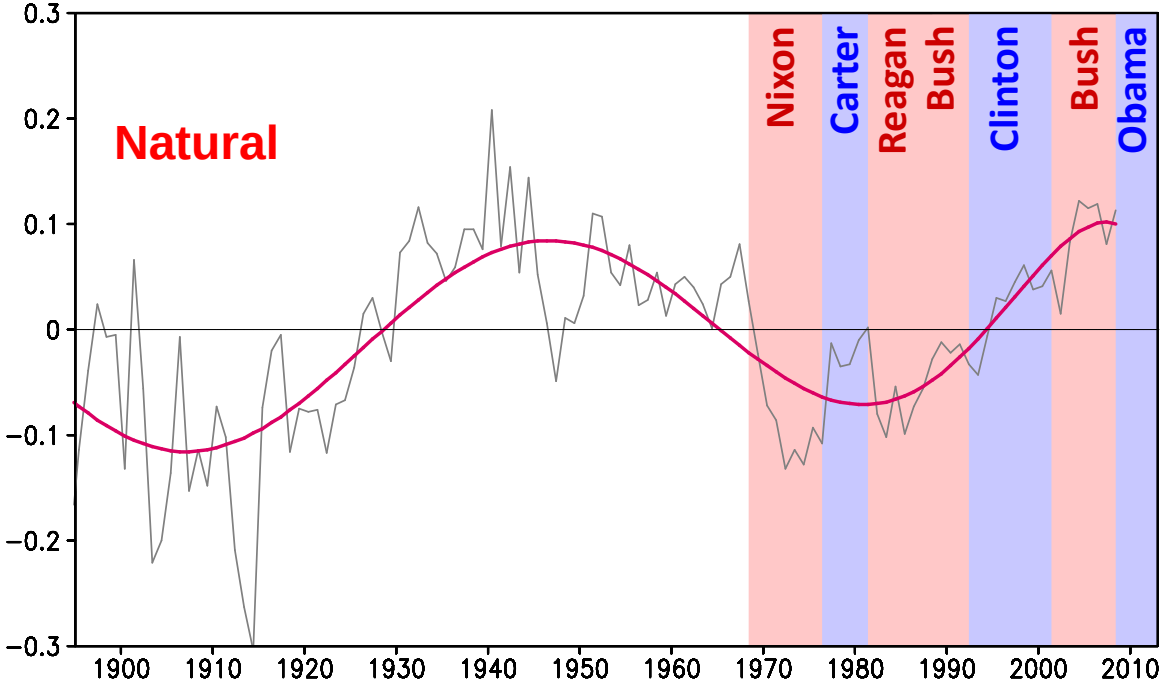
Nature Poses a Challenge to President Obama



HadCRU3 Global Mean Surface Temperature Anomalies, departure from 1901-2000 climatology (13.9°C)

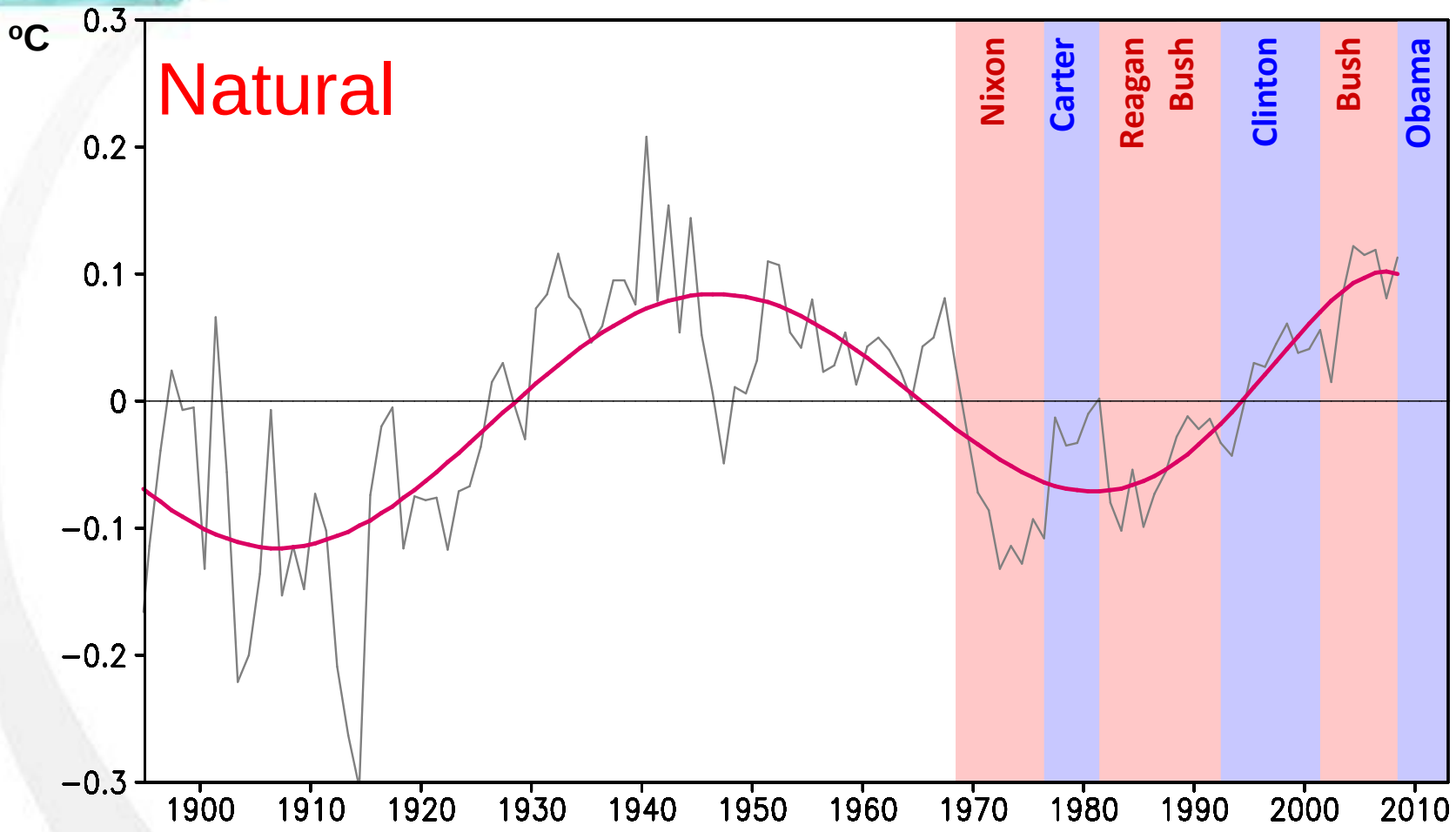


Low-pass Spatially Averaged Sea Surface Temperature on "Well-Observed" Grid



Contribution due to the Global Multi-decadal Oscillation

Global Multi-decadal Natural Oscillation



Averaged Sea Surface Temperature on "Well-Observed" Grid

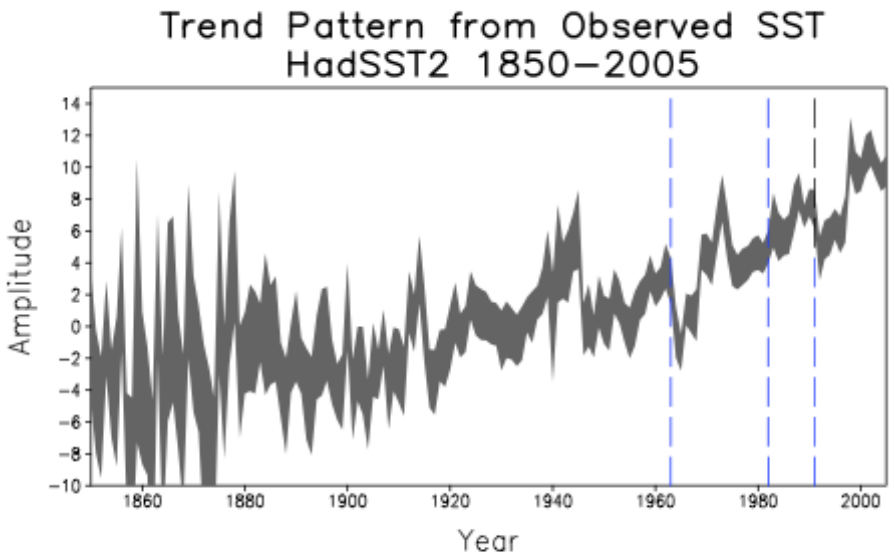
Delsole et al. 2009

THANK YOU!

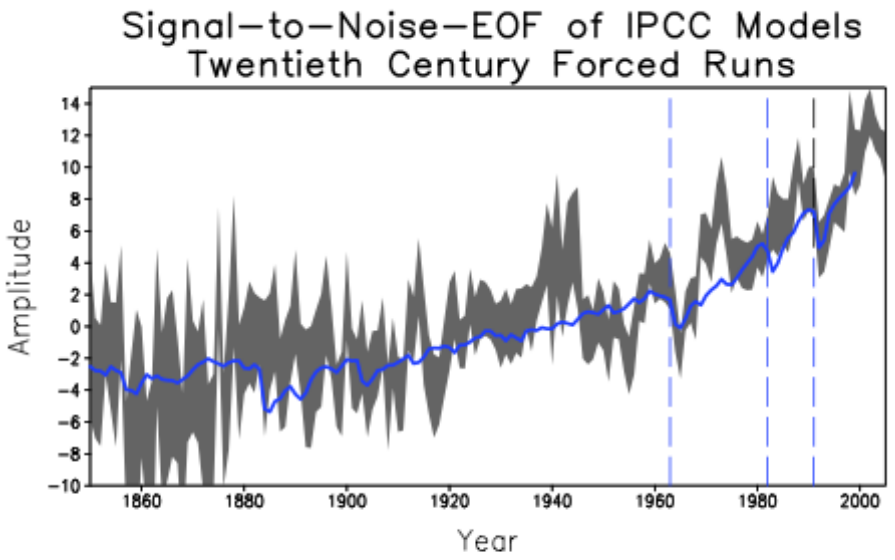
ANY QUESTIONS?

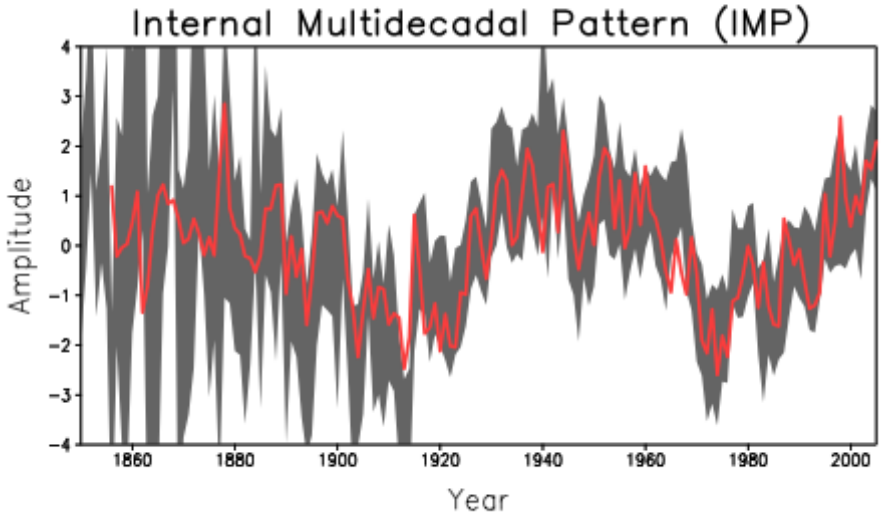
Amplitude of Forced Patterns and Unforced Patterns

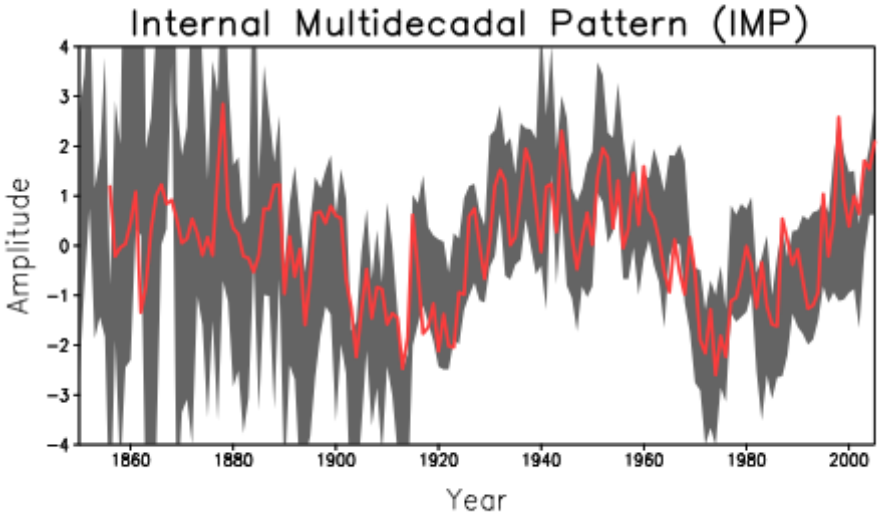
Trend



Signal-to-Noise

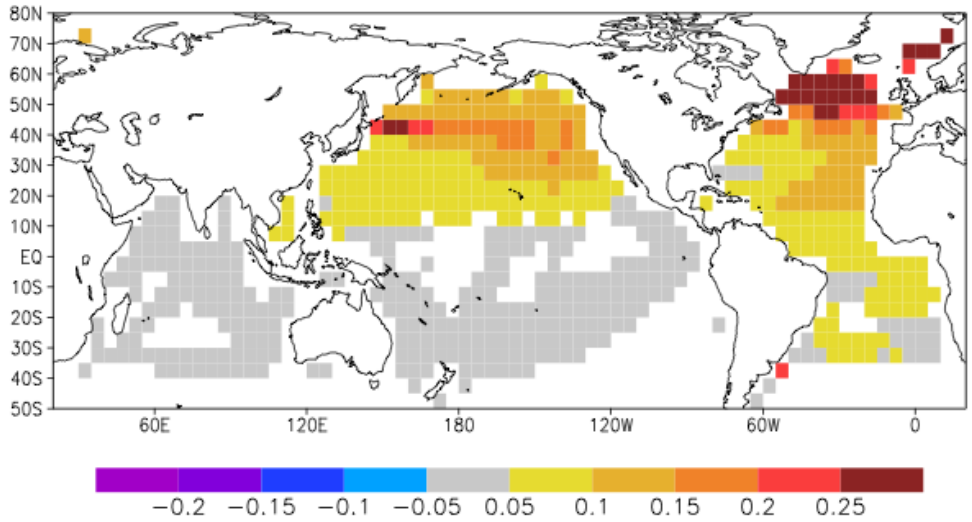


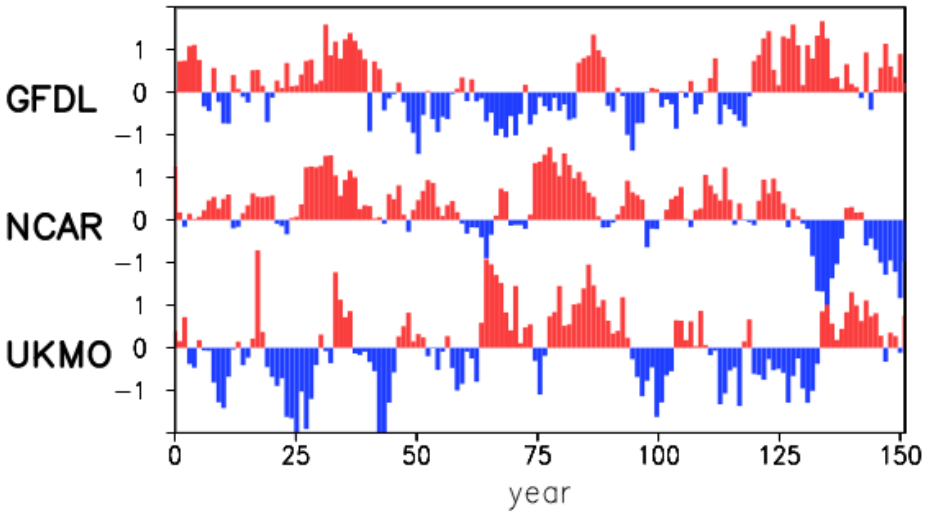




Optimize APT on "Well-Observed" Grid

tos.ann.terp.mis apt(5.07yr) Mode-1 (40EOFs; 300yrs; 20yr Lag)





Challenges in Separating Forced and Un-Forced Patterns

- **Forcing may project strongly on un-forced patterns.**
  - Time series of IMP in dierent ensemble members are uncorrelated in most (but not all) models.
- **Model estimates of forced pattern may be wrong.**
  - Results are the same if observed trend pattern is used for the \forced pattern" (no model is used to estimate forced pattern).
- **Forced response may not be captured by one pattern.**
  - Including second SN-EOF does not change the results.
  - Second signal-to-noise EOF is statistically insignificant.

Optimize APT

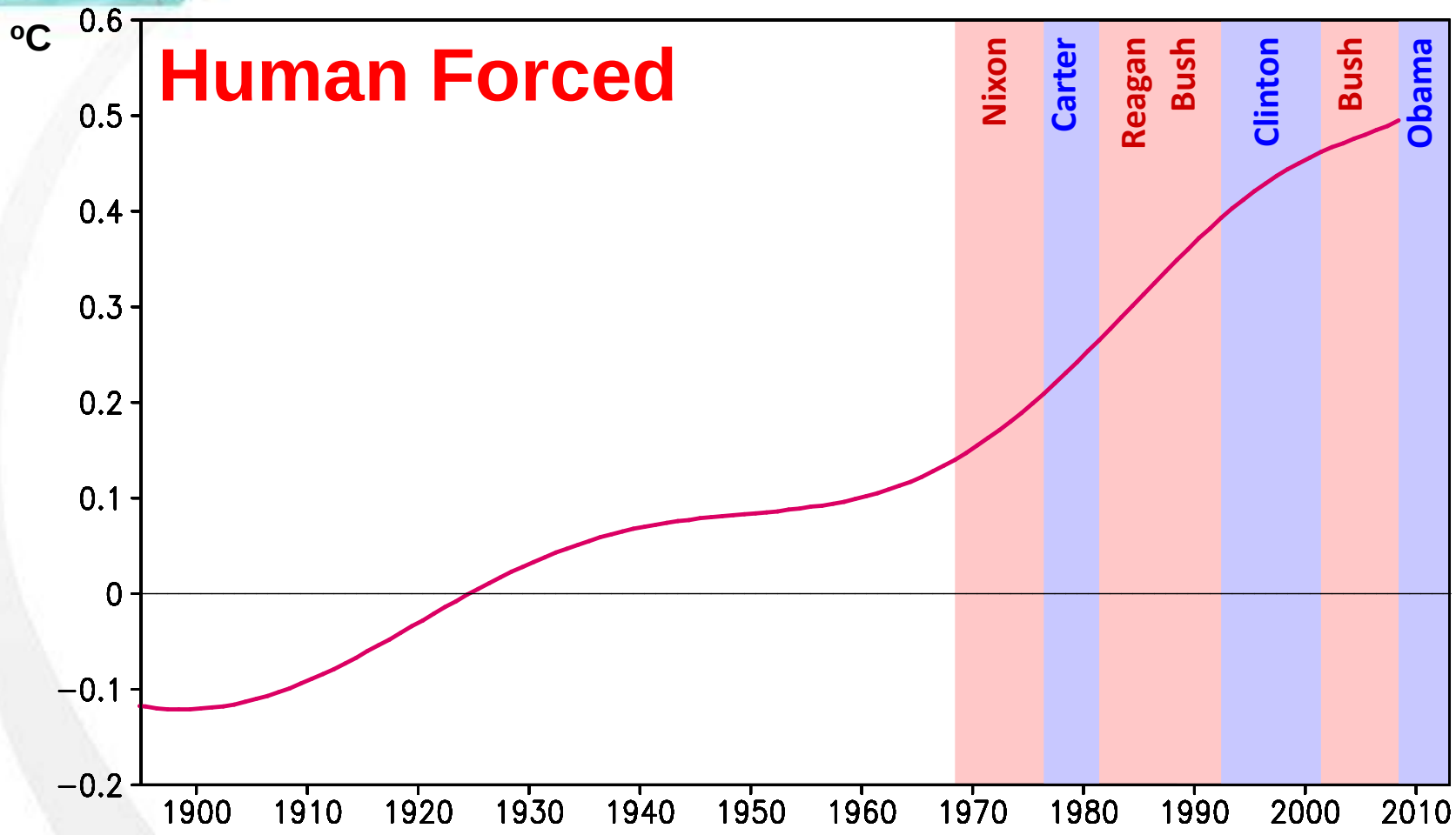
Find projection of the data that maximizes APT. Solution:

$$\left(2\int_0^\infty \mathbf{\Sigma}_c - \mathbf{\Sigma}_f(\tau)d\tau\right)\mathbf{q} = \lambda\mathbf{\Sigma}_c\mathbf{q}$$

where $\mathbf{\Sigma}_f$ and $\mathbf{\Sigma}_c$ are the forecast and climatological covariance matrices.

- Eigenvalue λ gives the APT.
- Eigenvectors $\mathbf{q}$ are projection vectors for generating time series.
- Resulting time series are uncorrelated in time.
- Each projection vector is associated with physical pattern $\mathbf{p} = \mathbf{\Sigma}_c\mathbf{q}$.
- Physical pattern $\mathbf{p}$ is called a predictable component.
- Product of $\mathbf{p}$ * (time series), summed over all components, recovers original time series.

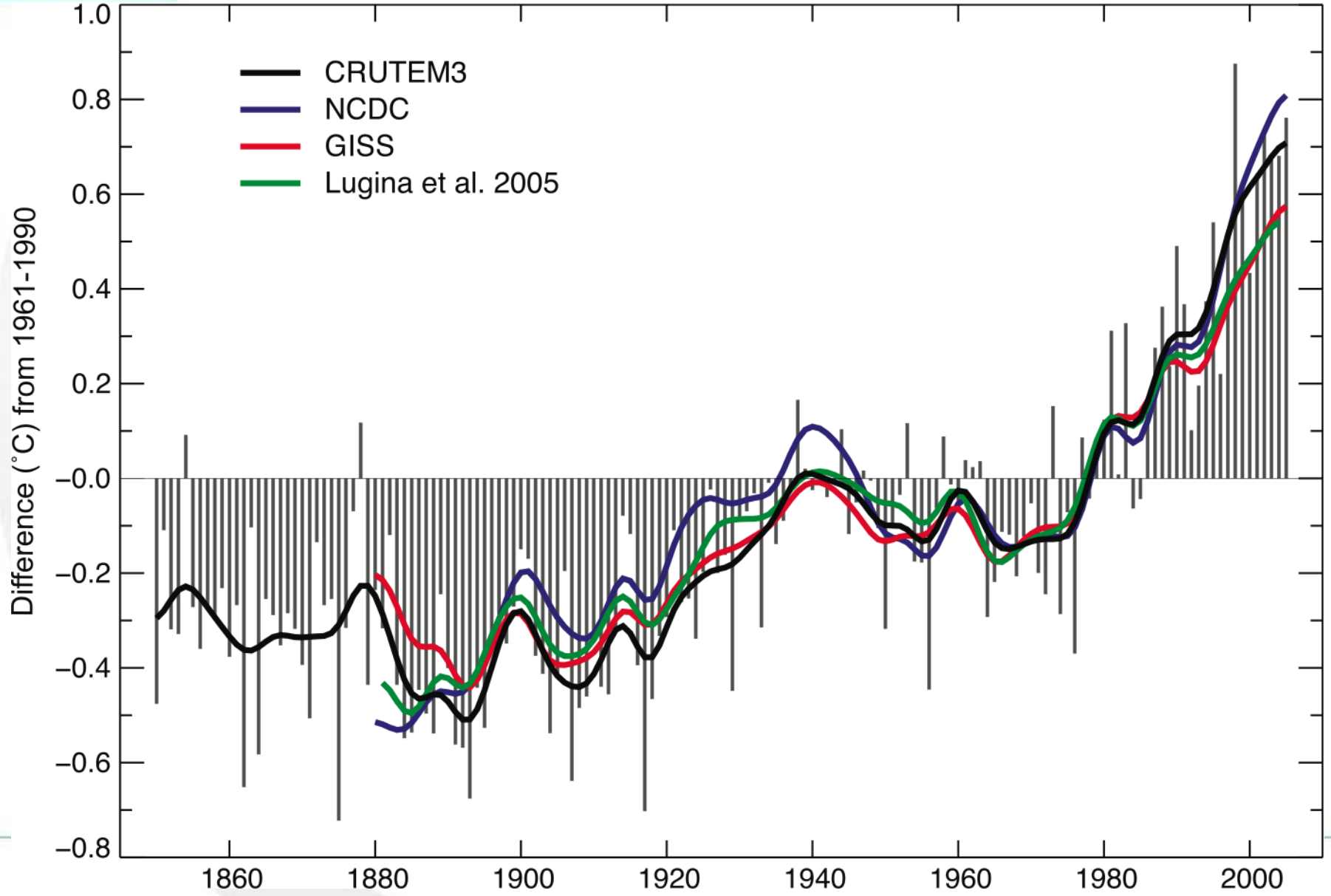
Global Warming (SST)



Averaged Sea Surface Temperature on "Well-Observed" Grid

Delsole et al. 2009

Annual Anomalies of Global Mean Land-surface Air Temperature (°C)



Models and the APT of the Most Predictable Component

Index	Model	APT-1D
1	cccma_cgcm3_1	6.4
2	cccma_cgcm3_1_t63	6.7
3	csiro_mk3_0	26.4
4	csiro_mk3_5	18.7
5	gfdl_cm2_0	21.3
6	gfdl_cm2_1	9.8
7	inmcm3_0	22.6
8	ipsl_cm4	6.2
9	miroc3_2_medres	8
10	miub_echo_g	9.3
11	mri_cgcm2_3_2a	5
12	ncar_ccsm3_0	14.7
13	ukmo_hadcm3	7.2

Estimating APT With Only One Ensemble Member

- Project data onto M principal components $\mathbf{r}(t)$.
- Construct multivariate linear regression model

$$\mathbf{r}(t+\tau) = \mathbf{L}_\tau \mathbf{r}(t) + \epsilon(t).$$

- Determine forecast variance from standard regression formula

$$\mathbf{\Sigma}_f = \mathbf{\Sigma}_r - \mathbf{L}_\tau \mathbf{\Sigma}_r \mathbf{L}_\tau^T.$$

  where $\mathbf{\Sigma}_r$ is the covariance matrix of $\mathbf{r}$.
- Optimize APT using $\mathbf{\Sigma}_f$ defined above and $\mathbf{\Sigma}_c = \mathbf{\Sigma}_r$.
- **Limitations:** May miss non-linear predictability.

Optimize APT in Unforced Climate Runs

- Last 300 years of PICNTRL are used (only 17 models).
- Model grids interpolated onto HadSST2 grid.
- Annual averaged sea surface temperature.
- Each model's climatology subtracted out.
- All runs pooled to compute "total EOF" and "total APT."
- IAP, GISS-EH, GISS-ER, CNRM dropped due to significantly different variances in the leading multi-model PCs.
- Total of 13 models.
- Effective length = 3900 years.
- 40 EOF truncation, 20-year maximum lag for APT.

Separating Forced and Un-Forced Patterns

Observed annual averaged SST field $T_{obs}(x, y, t)$ fitted to

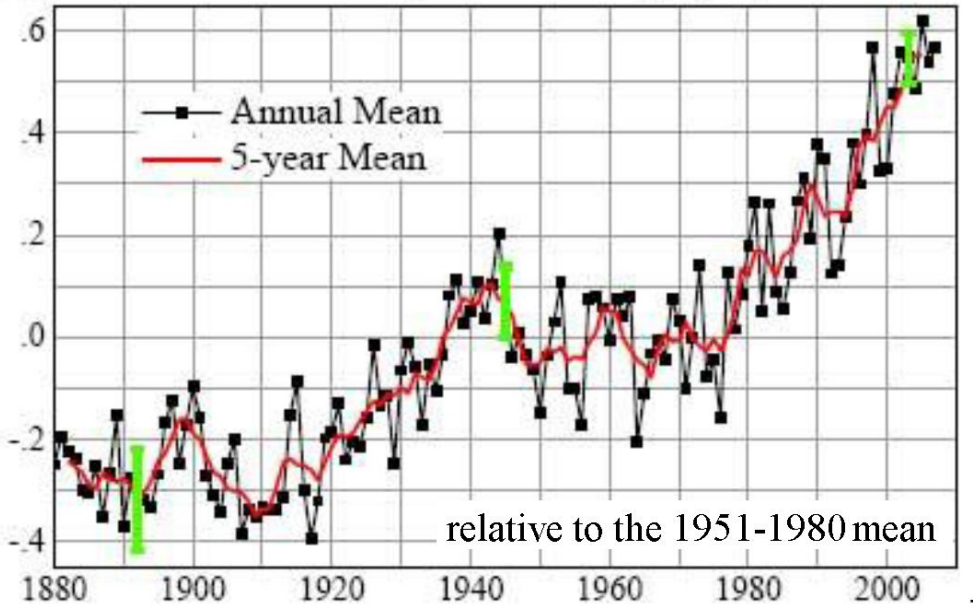
$$T_{obs}(x, y, t) = a_{imp}(t)\, T_{imp}(x, y) + a_{for}(t)\, T_{for}(x, y) + \epsilon(x, y, t)$$

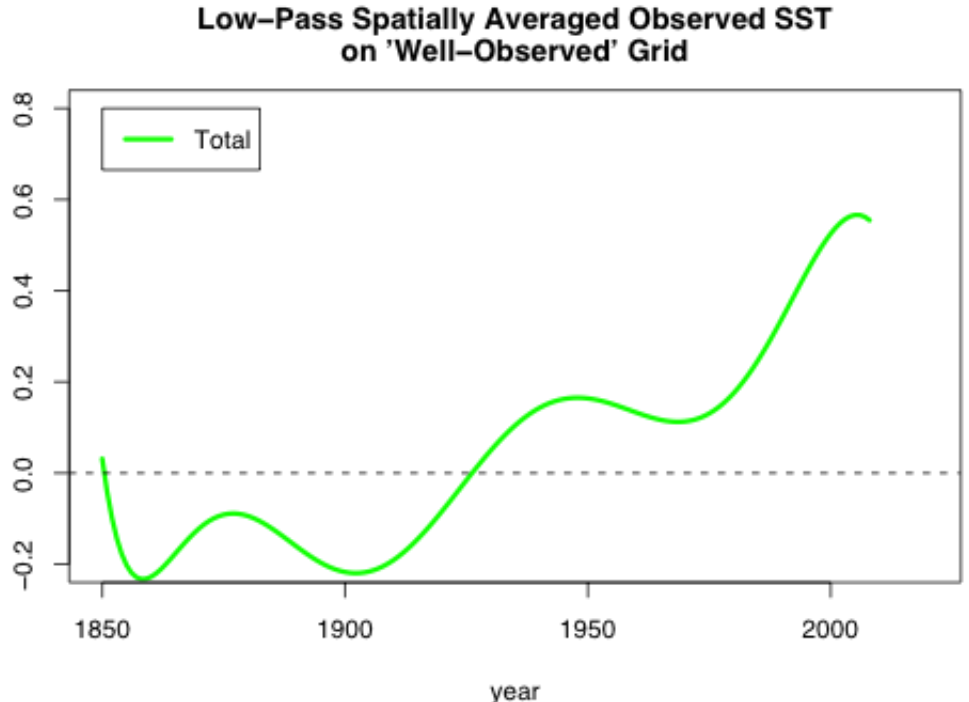
where

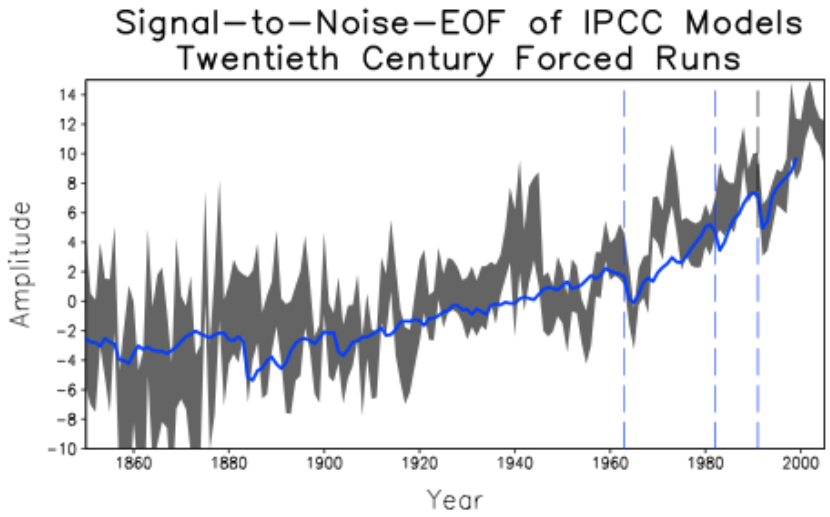
- T_{imp} is the leading Internal Multidecadal Pattern (IMP).
- T_{for} is the response pattern due to climate forcing (e.g., leading signal-to-noise EOF).
- ϵ is the residual error.
- The time series a_{imp} and a_{for} are estimated by generalized least squares, which accounts for spatial correlations in ϵ (which in turn are estimated from the control runs).

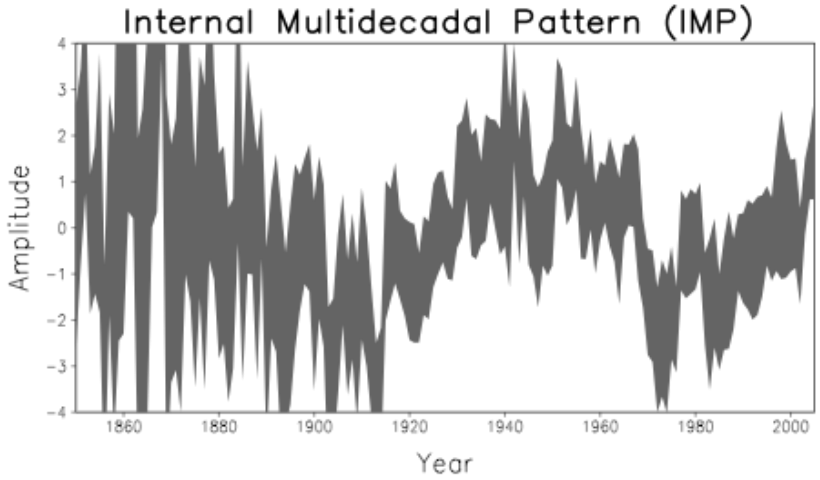
Also known as fingerprinting (Hasselman 1979, 1997; Allen and Tett 1999; IPCC-AR4 Chapter 9).

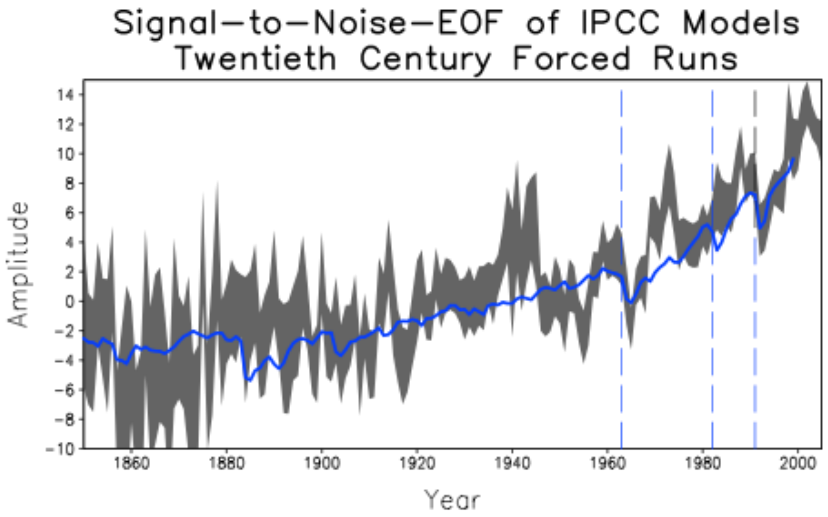
Global Temperature Change (°C)

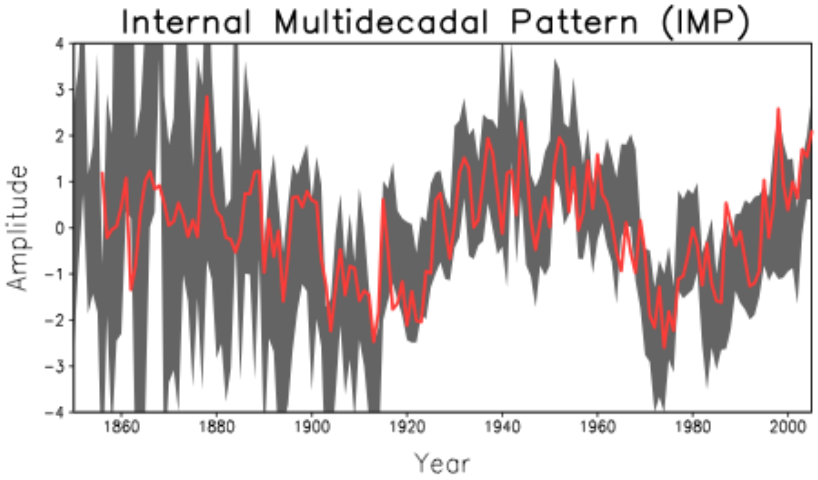


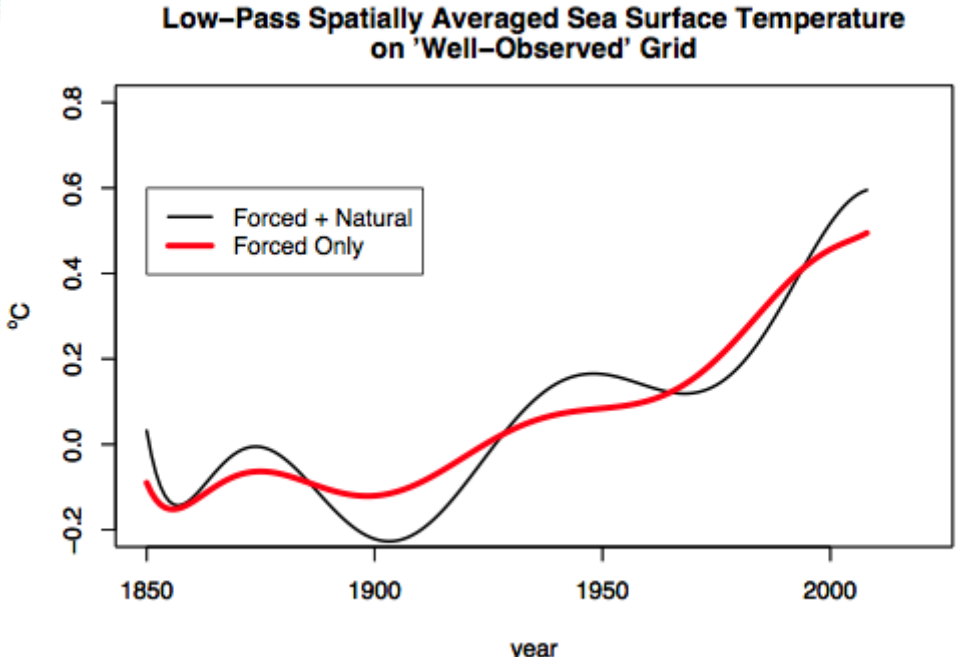


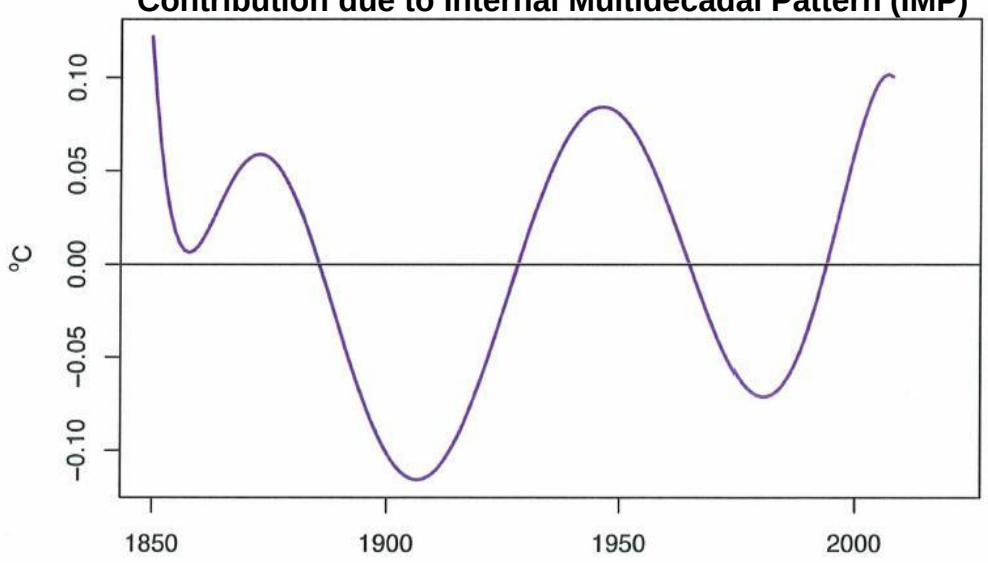

Signal–to–Noise–EOF of IPCC Models
Twentieth Century Forced Runs
Amplitude
Year
14
12
10
8
6
4
2
0
-2
-4
-6
-8
-10
1860
1880
1900
1920
1940
1960
1980
2000

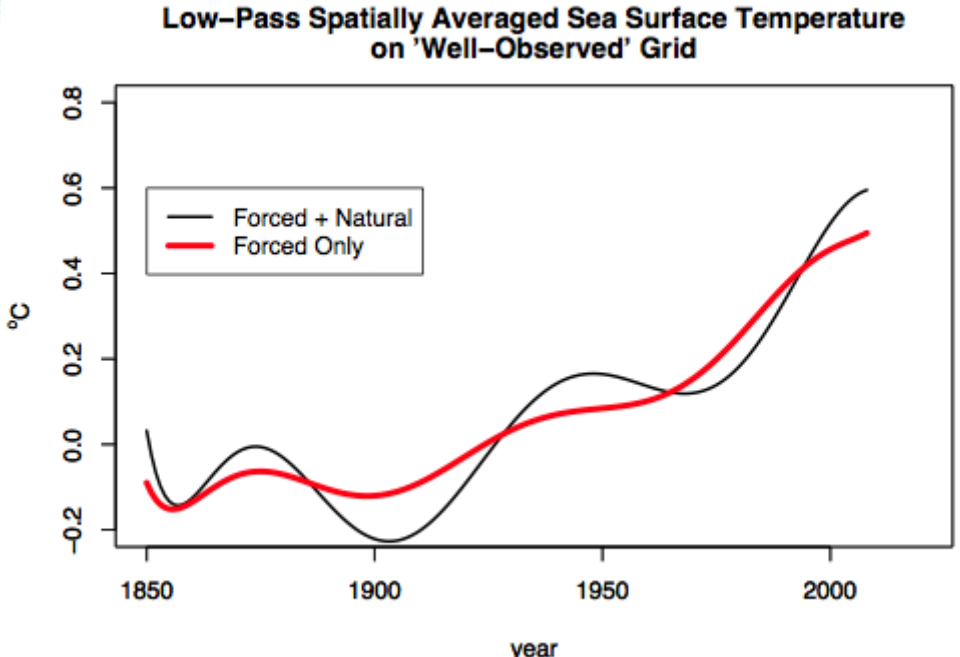

Internal Multidecadal Pattern (IMP)
Amplitude
Year
4
3
2
1
0
-1
-2
-3
-4
1860
1880
1900
1920
1940
1960
1980
2000

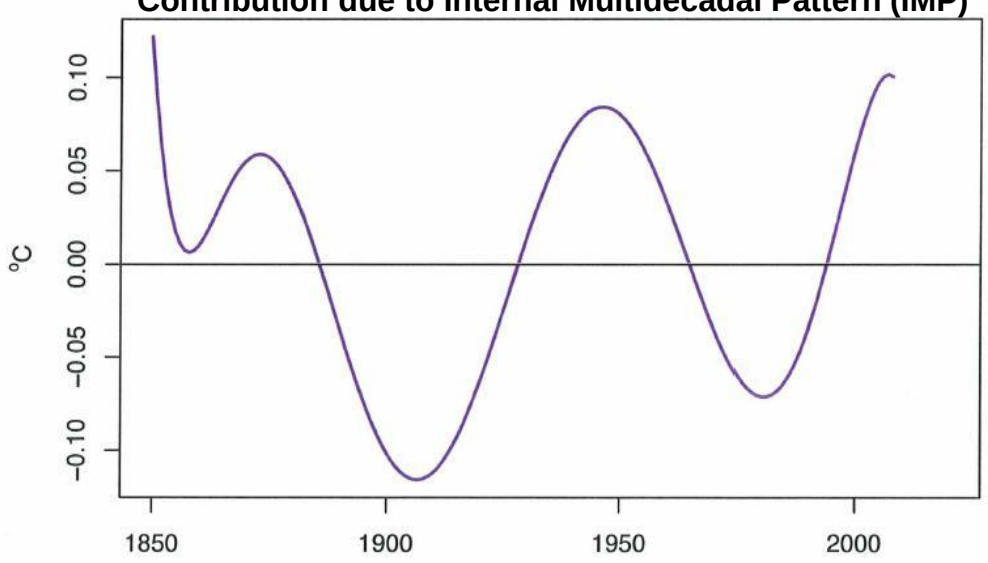

Signal–to–Noise–EOF of IPCC Models
Twentieth Century Forced Runs
Amplitude
Year
14
12
10
8
6
4
2
0
−2
−4
−6
−8
−10
1860
1880
1900
1920
1940
1960
1980
2000

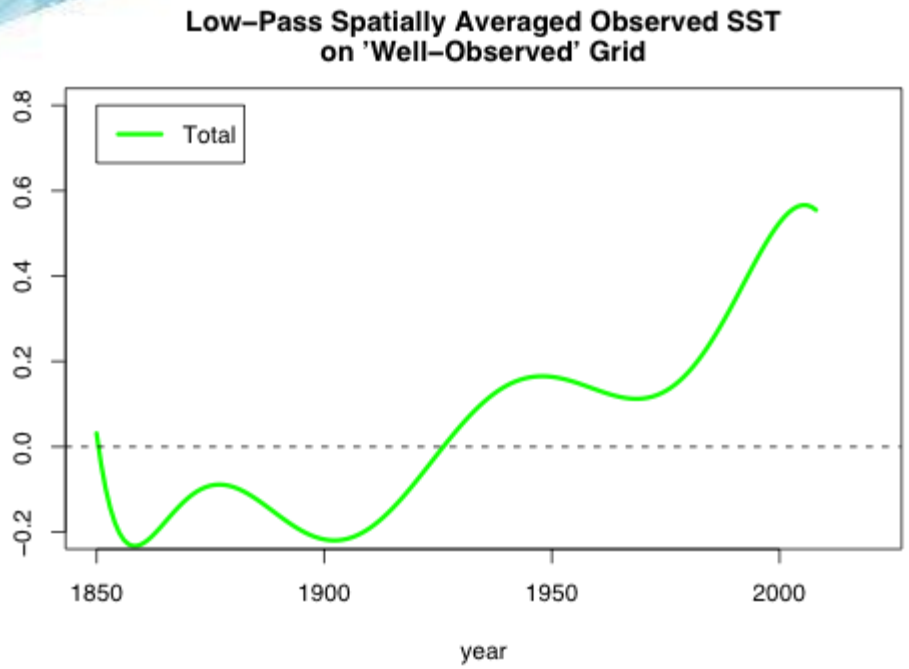

Internal Multidecadal Pattern (IMP)
Amplitude
Year
4
3
2
1
0
−1
−2
−3
−4
1860
1880
1900
1920
1940
1960
1980
2000

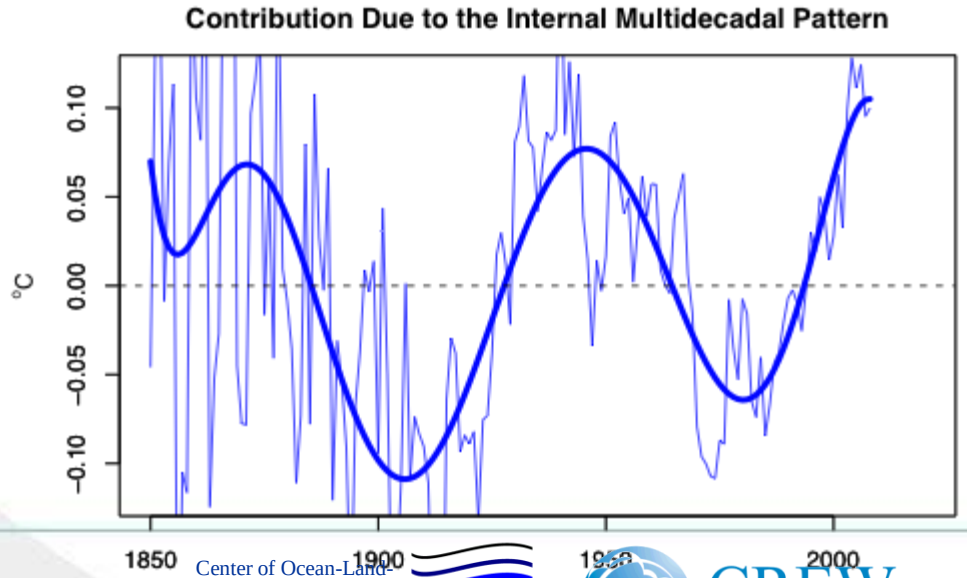

Low–Pass Spatially Averaged Sea Surface Temperature
on 'Well–Observed' Grid
Forced + Natural
Forced Only
°C
0.8
0.6
0.4
0.2
0.0
−0.2
1850
1900
1950
2000
year


Contribution due to Internal Multidecadal Pattern (IMP)
°C
0.10
0.05
0.00
−0.05
−0.10
1850
1900
1950
2000
year


Low–Pass Spatially Averaged Sea Surface Temperature
on 'Well–Observed' Grid
Forced + Natural
Forced Only
°C
0.8
0.6
0.4
0.2
0.0
−0.2
1850
1900
1950
2000
year


Contribution due to Internal Multidecadal Pattern (IMP)
°C
0.10
0.05
0.00
−0.05
−0.10
1850
1900
1950
2000
year


Low–Pass Spatially Averaged Observed SST
on 'Well–Observed' Grid
Total
0.8
0.6
0.4
0.2
0.0
−0.2
1850
1900
1950
2000
year


Contribution Due to the Internal Multidecadal Pattern
°C
0.10
0.05
0.00
−0.05
−0.10
1850
1900
2000