BJERKNES CENTRE
for Climate Research

Mechanisms for climate variability

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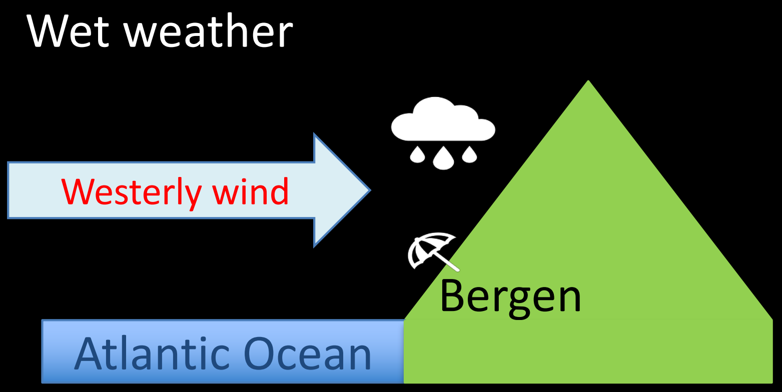
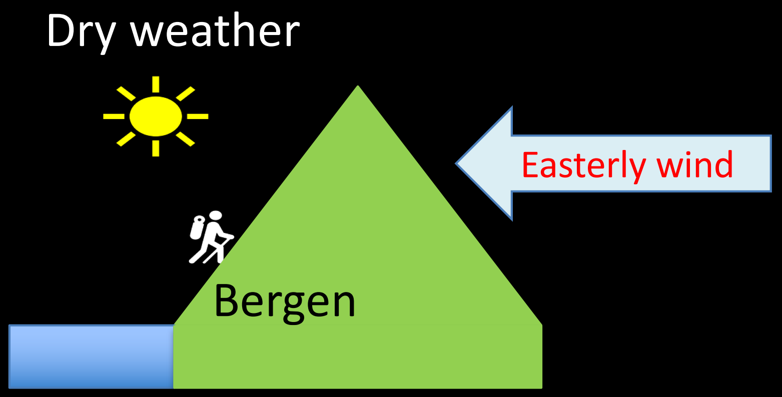
“Climate is what you expect, weather is what you get”, E. Lorenz

Climate and weather





Climate is determined by how often different types of weather occur

	Cause of unusual summer conditions
Wet and cold	More frequent westerly wind regimes
Dry and warm	More frequent easterly wind regimes

Take home message:

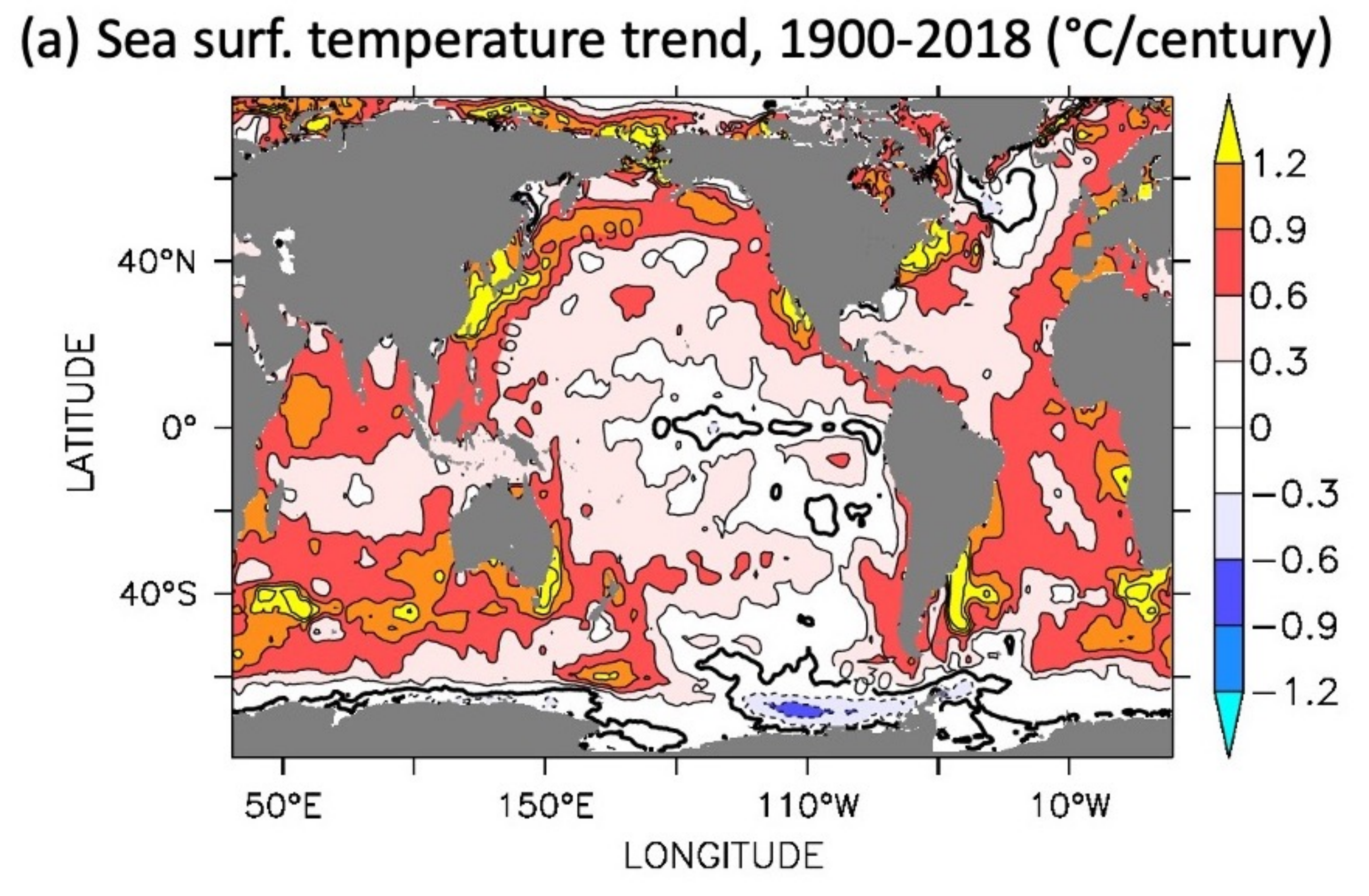
“For climate variability, red noise is what you expect”, Hasselmann 1976

Mechanisms for climate variability

- Externally forced
  - Anthropogenic (e.g., greenhouse gas emissions)
  - Natural (e.g., solar forcing, volcanic eruptions)
- Internally generated
  - Stochastic climate models
  - Uncoupled oscillations (e.g., basin modes, MJO)
  - Coupled ocean-atmosphere oscillations

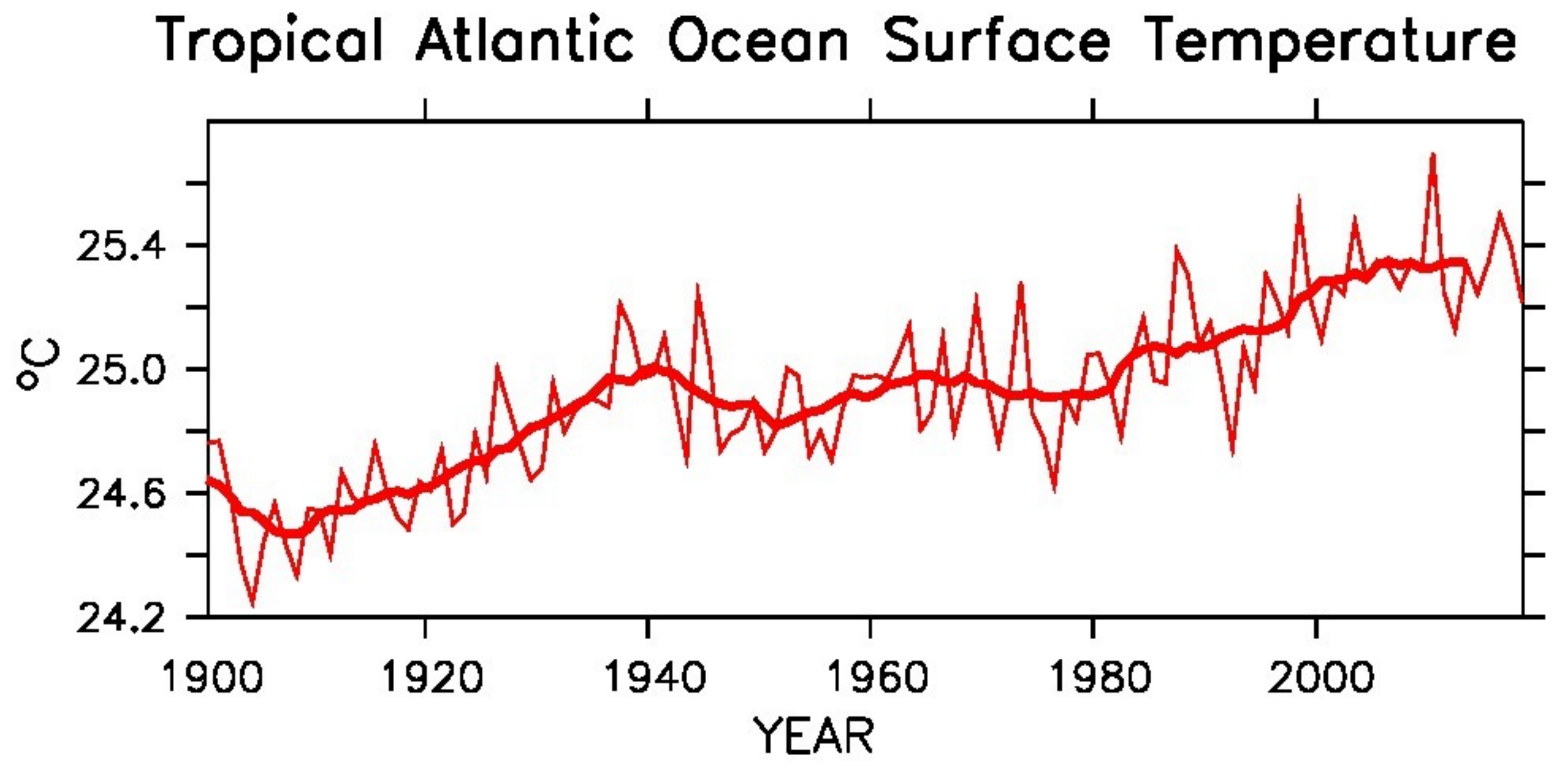
Global have warmed by around 1 degree since 1900

Tropical Atlantic and Indian Ocean have seen some of the strongest warming

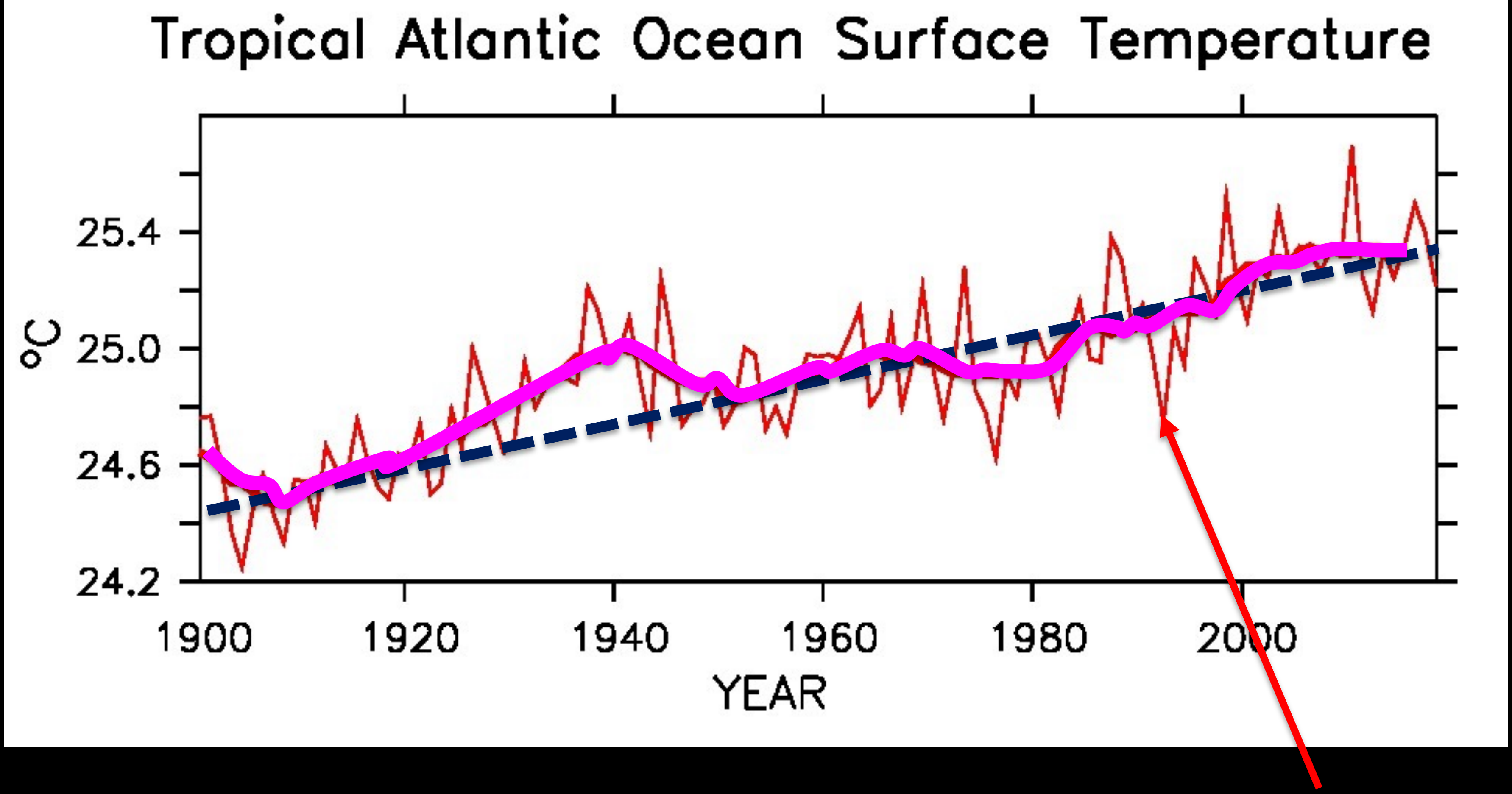


HadISST [Rayner et al., 2003]

The long-term warming is superposed by variability



Causes of short and long-term changes in climate



Long-term trend caused mainly by global warming

Decade to decade changes caused by both natural and anthropogenic factors

Year to year fluctuations caused by natural processes in the climate system

Regional differences in surface temperature variability

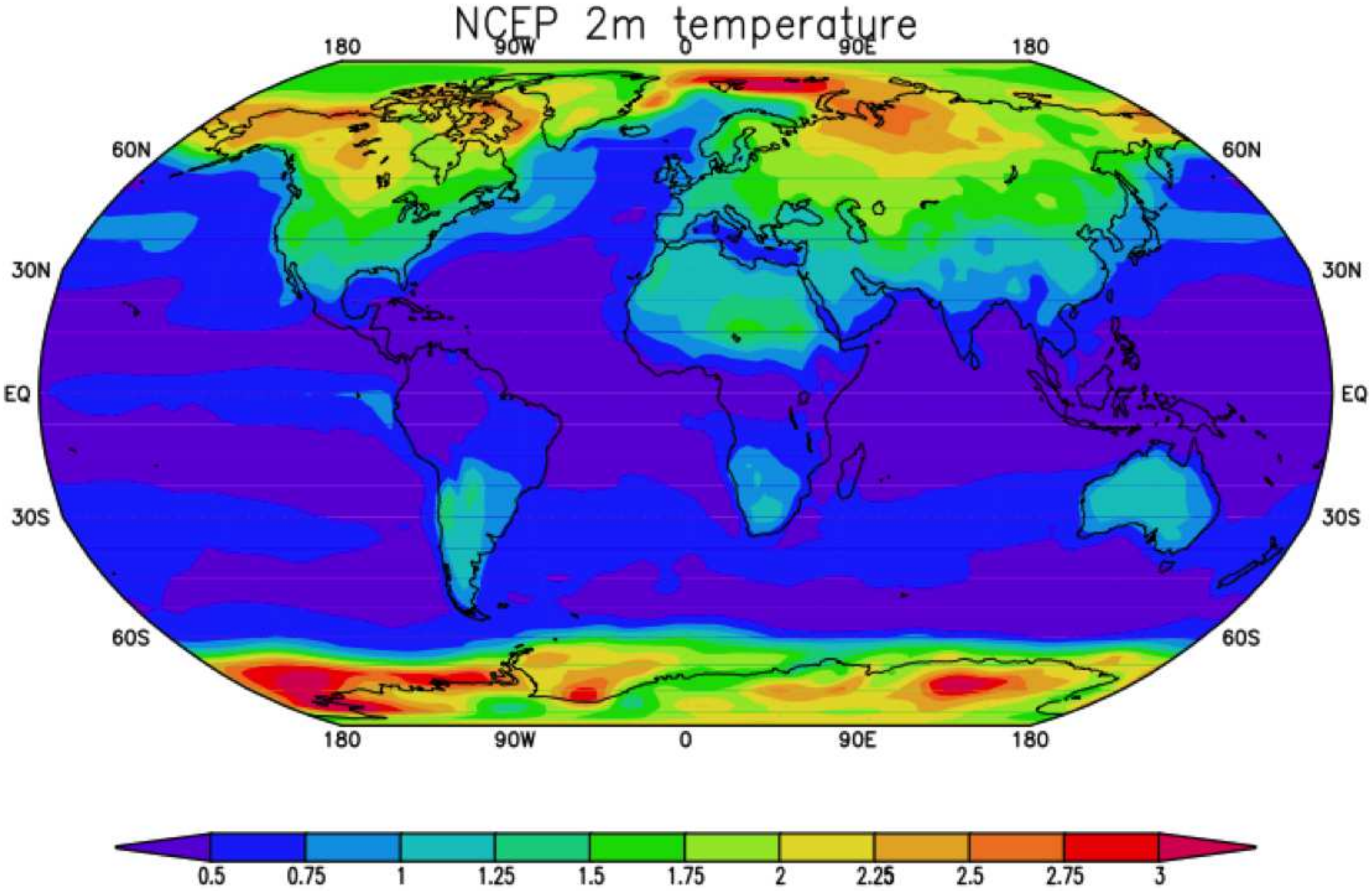


Figure 6.11: Surface temperature monthly mean standard deviation.

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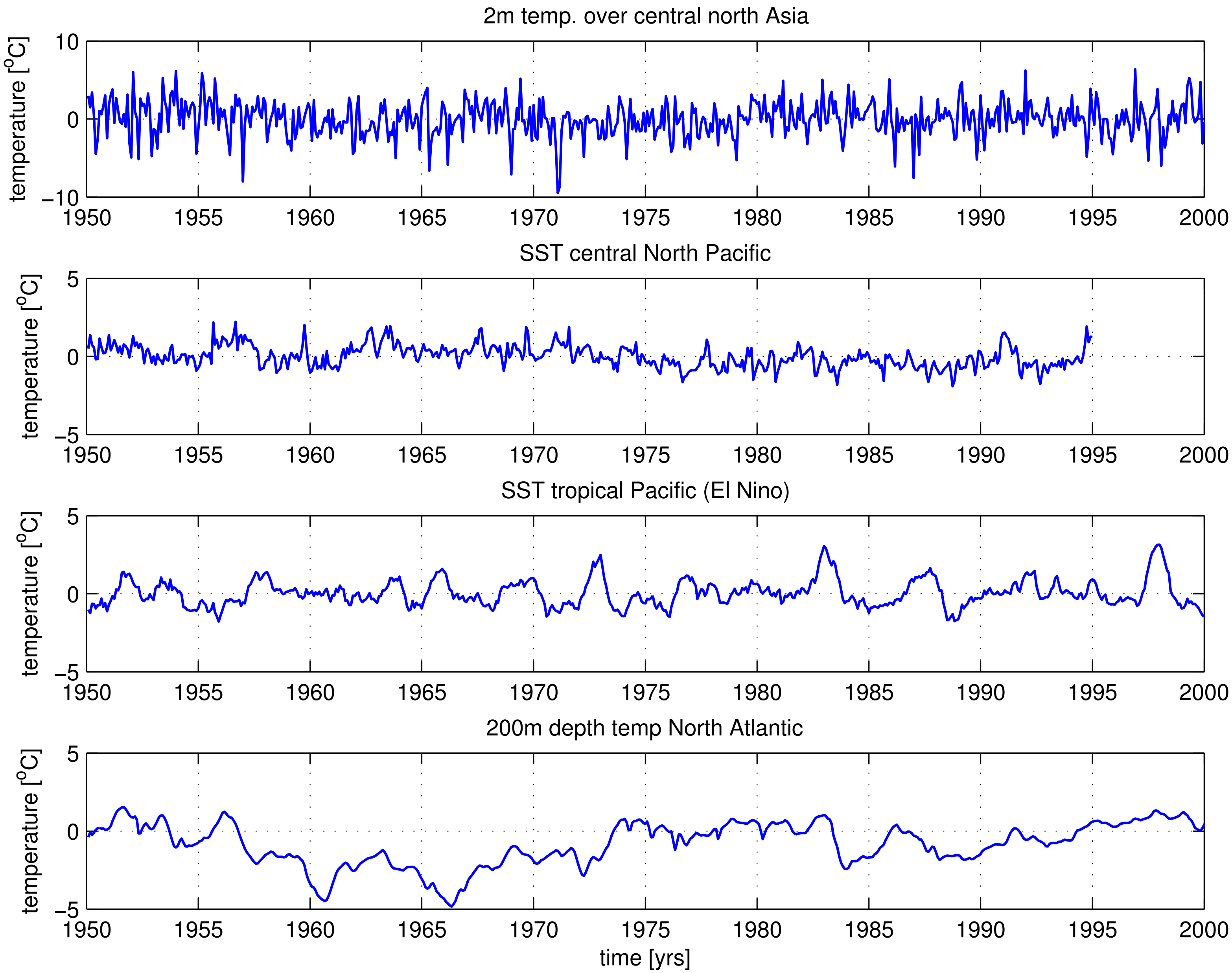
Different characteristics of land and ocean temperature



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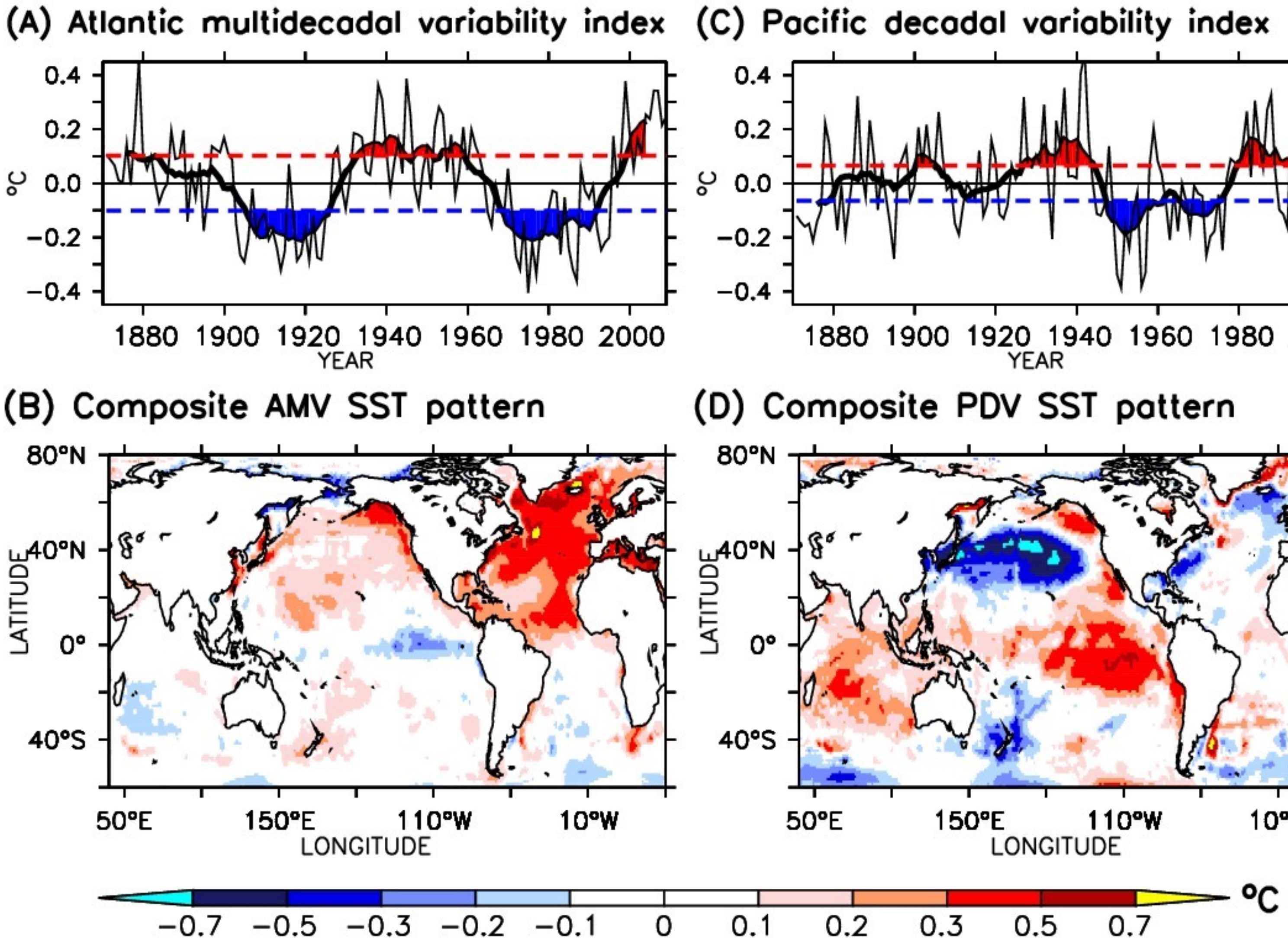
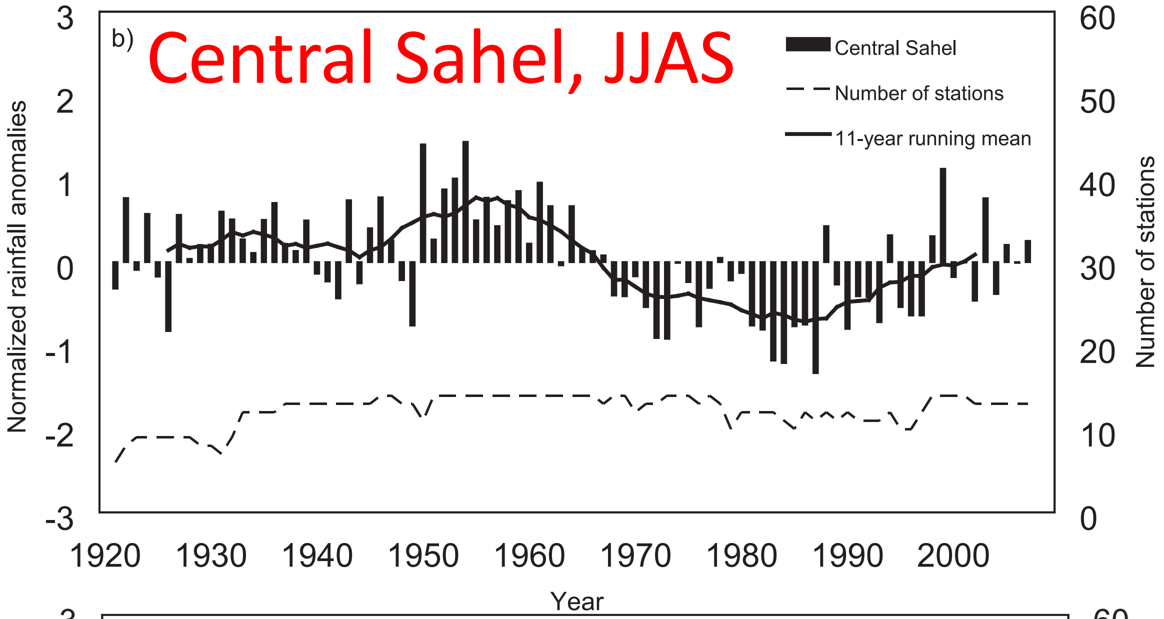
Observed internal decadal-to-multidecadal variability in the Atlantic and Pacific

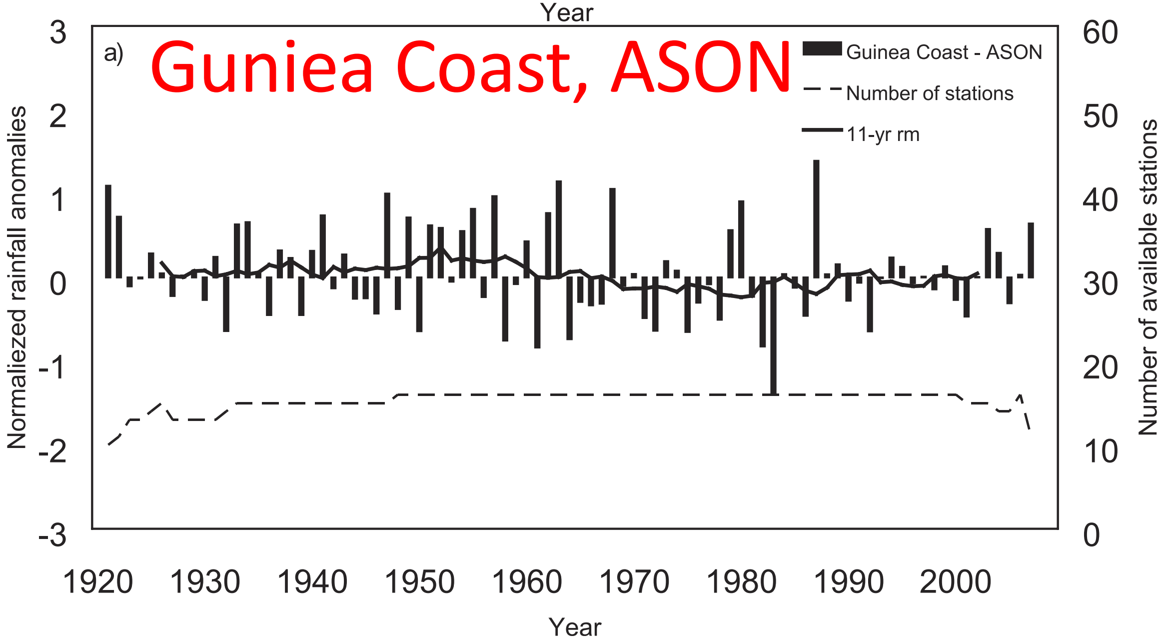


Keenlyside and Ba, 2010

Rainfall over Central Sahel and Guniea Coast



Linked to Atlantic Multi-decadal variability



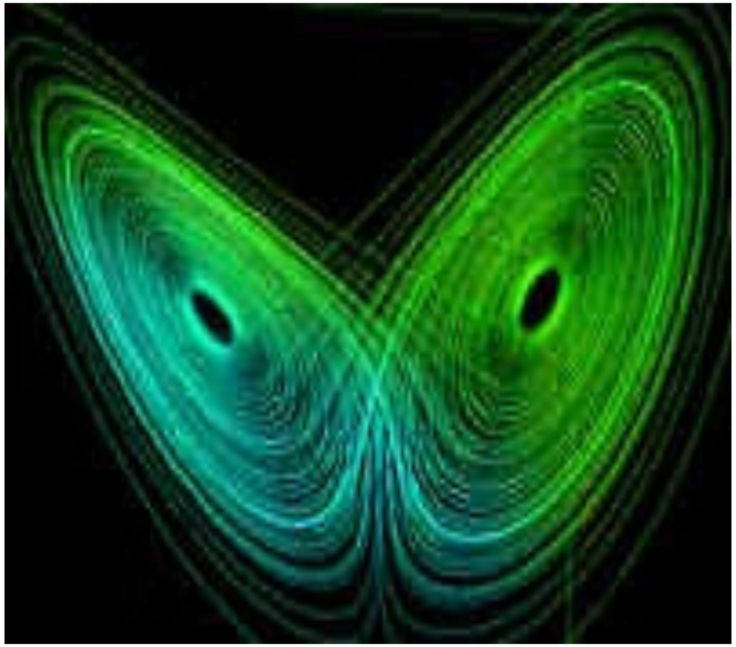
Linked to Gulf of Guinea SST

Fink et al. 2010

Stochastic climate models

Chaotic nature of the atmosphere

Weather forecasting limited to 14 days

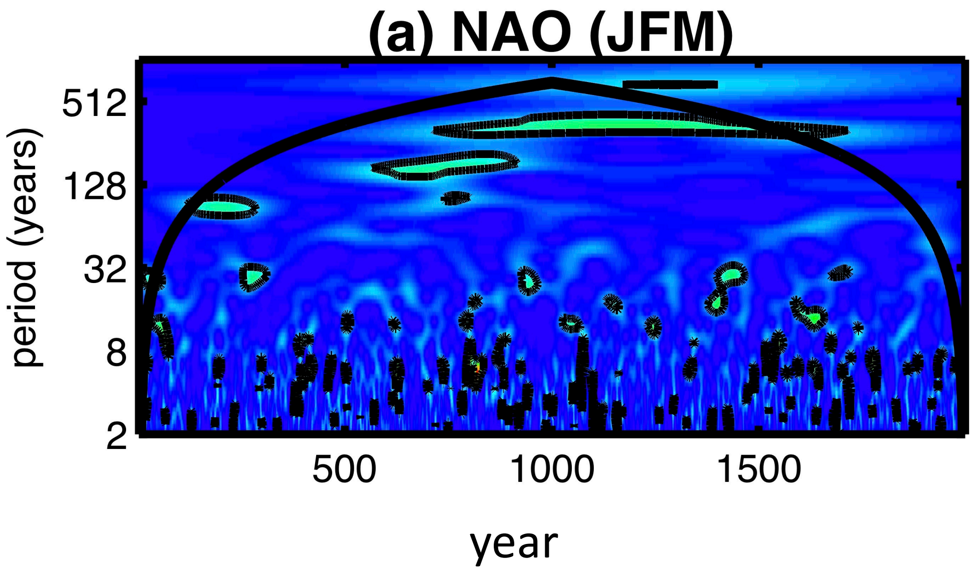


[Lorenz 1963]

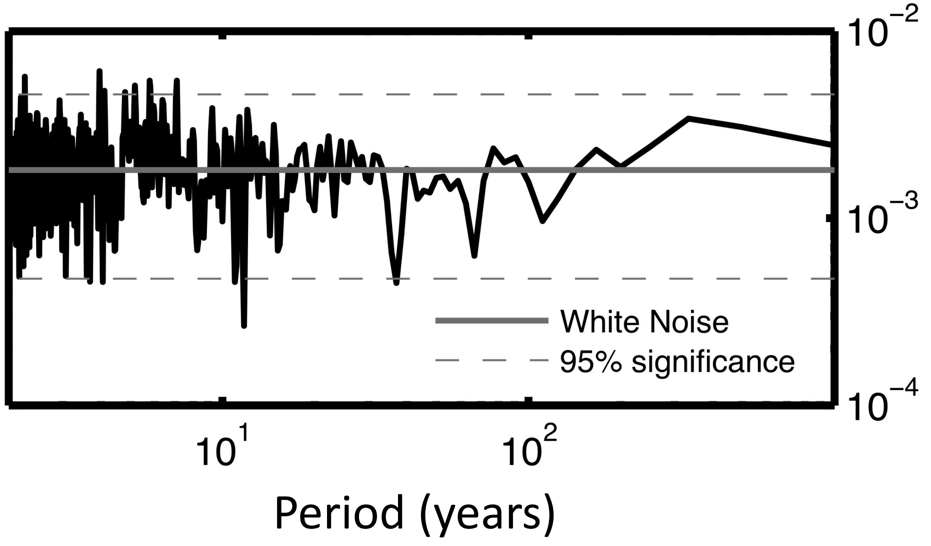
- Climate system is deterministic chaotic system (Lorenz model 1963)
- Non-linearity associated with convection and instabilities cause atmospheric variability to be chaotic
- For climate timescales this high-frequency weather type variability can be considered as stochastic noise

Stochastic uncoupled climate variability

- Stochastic process has a white spectrum (i.e., an uncorrelated time series of normally distributed random values)
- By definition variability occurs on all time scales, and this can explain large-part of observed atmospheric climate variability



Wavelet



Power Spectrum

Keenlyside et al. 2016

Stochastic climate model

The interaction between atmosphere and other components of the climate system can be conceptual separated into a fast unresolved stochastic process driving slow climate dynamics

$$\frac{d\boldsymbol{X}(\boldsymbol{t})}{d\boldsymbol{t}} = \boldsymbol{f}_{\boldsymbol{m}}(\boldsymbol{t}) * \vec{\boldsymbol{A}}[\boldsymbol{X}(\boldsymbol{t})] + \boldsymbol{f}_{\boldsymbol{a}}(\boldsymbol{t})$$

X(t) is the state vector (e.g., field of density, velocity, temperature etc)

$\vec{A}$ are the dynamics (slow, e.g., SST, ice cover, vegetation)

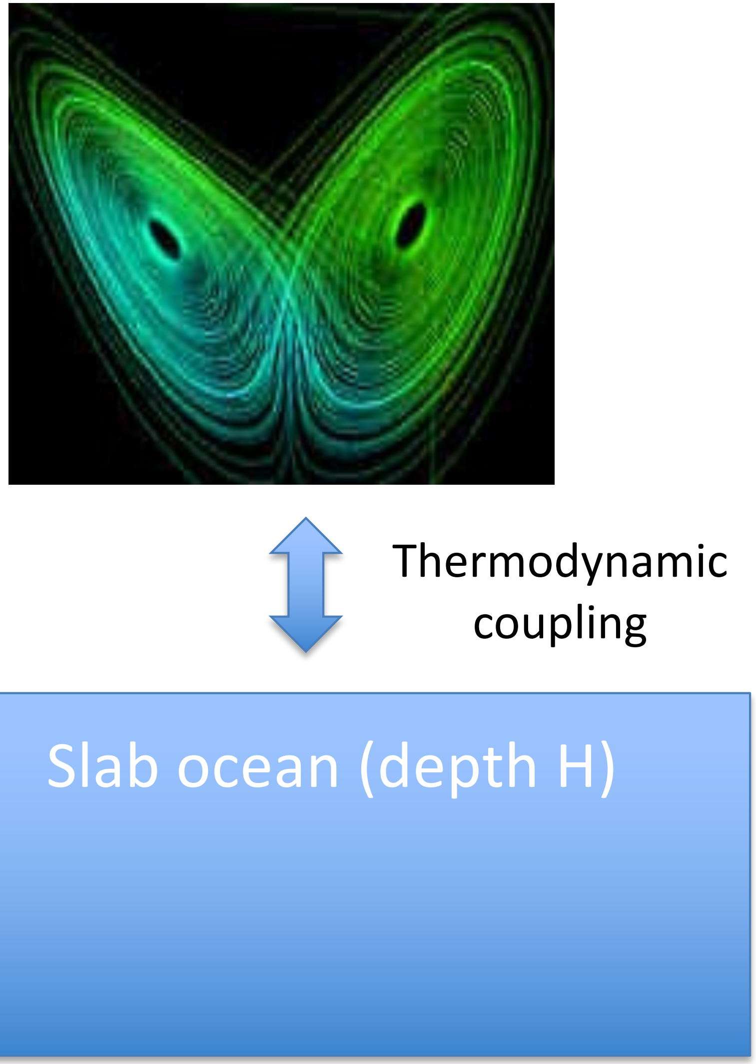
$f_m(t)$, $f_a(t)$ are multiplicative and additive noise (fast, e.i., random/chaotic weather)

Simplest stochastic climate model

- Simplest assumption is that the atmosphere interacts with the ocean mixed layer, neglecting ocean dynamics:

$$\frac{\partial T}{\partial t} = \frac{Q_{net}}{\rho C_p H}$$

- Where H is the mixed layer depth



Thermodynamic coupling

Slab ocean (depth H)

Hasselmann (1976)

Heat-flux drives SST variations on short time scales in the extra-tropics

Correlation of DT/dt in winter with turbulent fluxes
Based on 2 month differences, COADS data

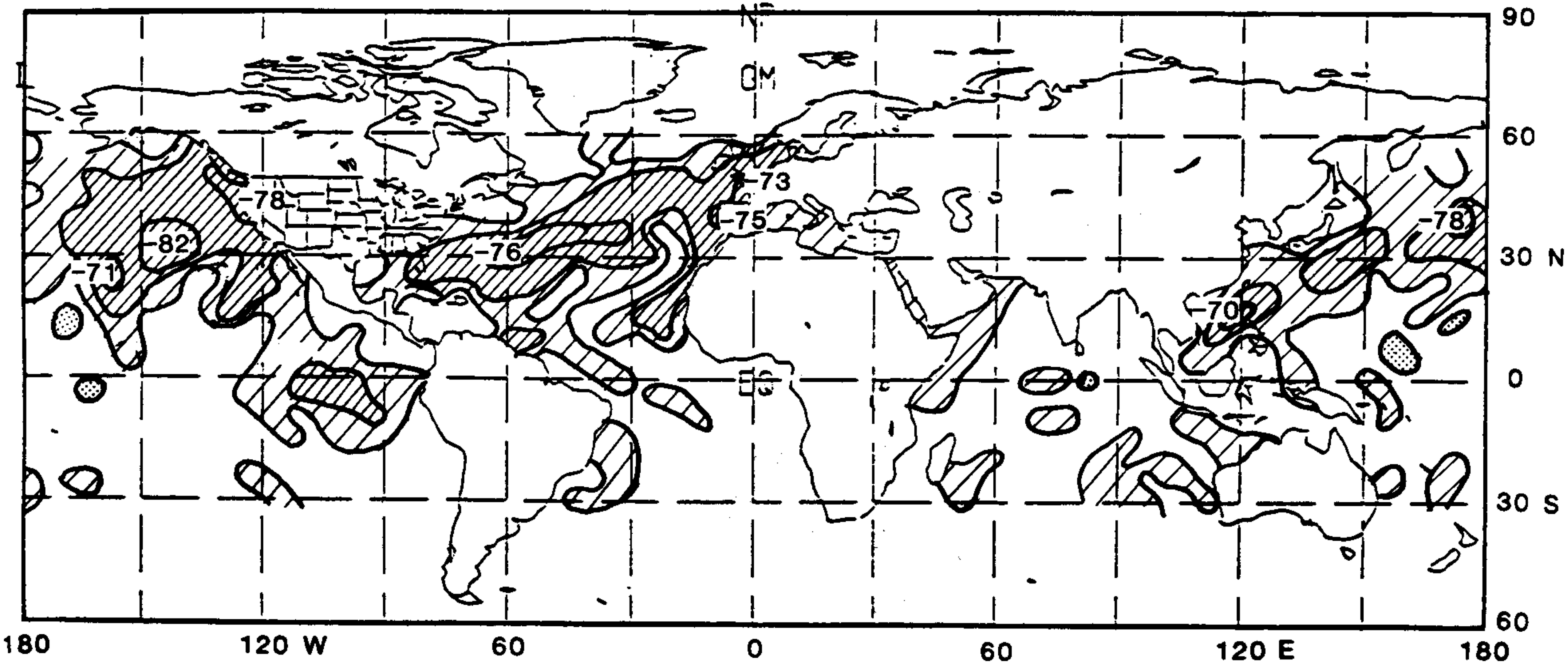


FIG. 2. Correlation coefficients (×100), mapped for global ocean F'_{l+s} vs $\Delta SST'/\Delta t$ at each grid point, for winters 1946–86. Contours at 0, ±0.3, ±0.5, ±0.7. Light and heavy shading indicates correlations $\leqslant 0.3$ and $\leqslant 0.5$. Hatching and stippling denote negative and positive correlations.

Cayan 1992

The relation can change on longer timescales, e.g., Bjerknes 1964
(Rhys lecture tomorrow)

Simplest stochastic climate model (Red-noise null hypothesis)

- Surface heat flux is assumed to be related to atmospheric variability. Assuming general form for turbulent fluxes, we can parameterize the heat flux as follows

$Q_{net} = c_t(T_a - T),$ c_t = thermal heat transfer coefficient

- From $\frac{\partial T}{\partial t} = \frac{Q_{net}}{\rho C_p H}$, we then get: $\frac{\partial T}{\partial t} = \frac{c_t(T_a - T)}{\rho C_p H}$

- Which has the general form

$\boldsymbol{\frac{\partial T}{\partial t} = -cT + cT_a \qquad = -cT + f_a}$ **where c** $\boldsymbol{= \frac{c_t}{\rho C_p H}}$ **= constant**

(where we have represented the atmosphere by noise $\boldsymbol{f_a}$)

Simplest stochastic climate model (Red-noise null hypothesis)

$$\frac{\partial T}{\partial t} = -cT + f_a$$

- The heat capacity of the ocean acts to damp the variability! Typical values of $c = 40Wm^{-2}K^{-1}$

- The equation represents a first order autoregressive process AR1 (red noise), this can be seen by discretizing: $T^{n+1} = \alpha T^n + f^n$

AR(1) - First order autoregressive process

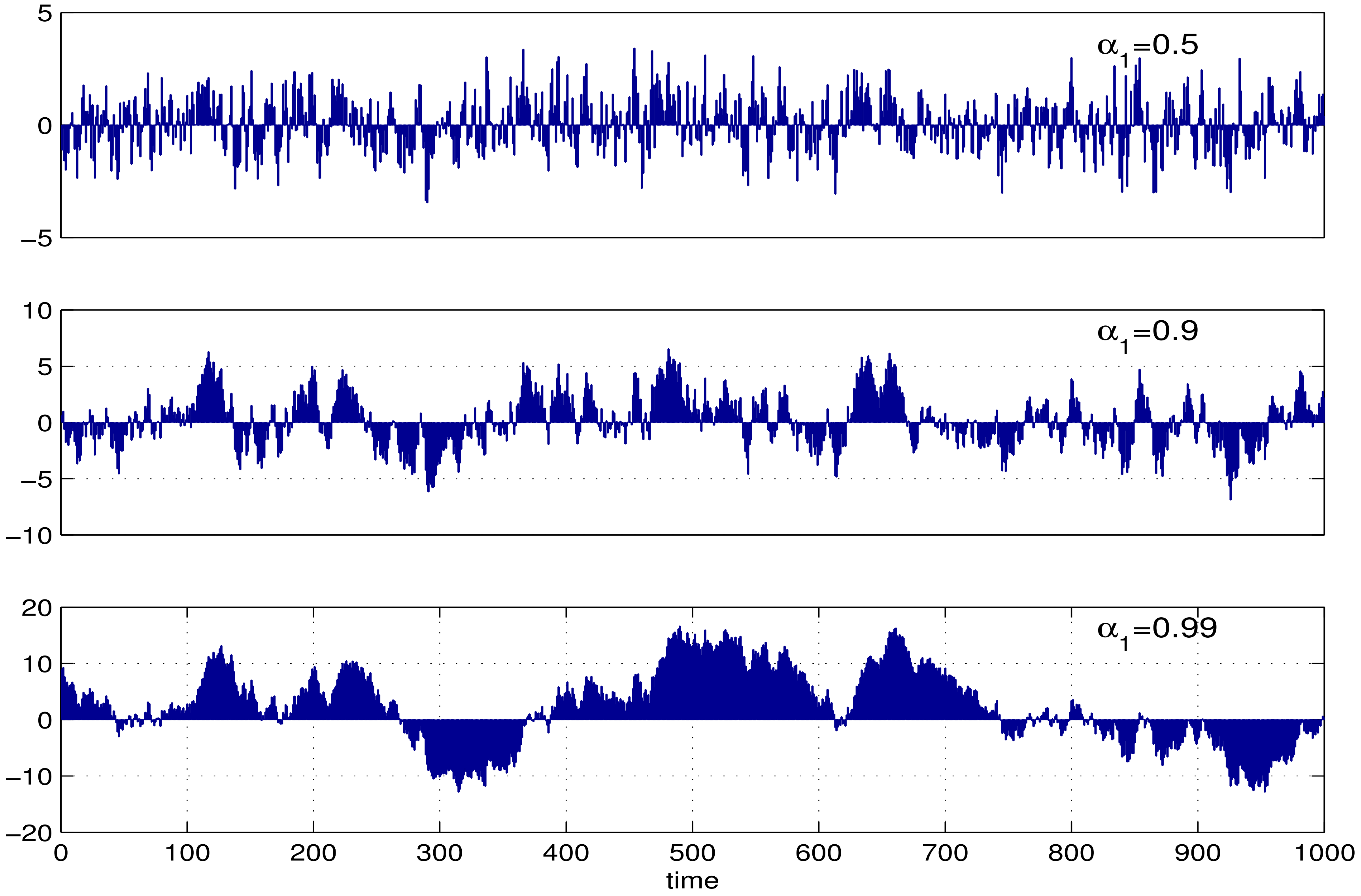
- AR(1) processes in discretized form: $\mathbf{X_t} = \alpha_1 \mathbf{X_{t-1}} + \mathbf{Z_t}$
- The variance is given $Var(\mathbf{X_t}) = \frac{\sigma_z^2}{1-\alpha_1^2}$
- Where $\alpha_1 = \rho_1$ is the lag 1 auto-correlation
- To understand the case for the slab-ocean, we can put this into the alternate form:

$$\frac{dx(t)}{dt} = a_1 x(t) + z(t)$$

$$a_1 = \frac{\alpha_1 - 1}{\alpha_1}$$

- We can see because correlation is positive that the coefficient is negative and greater than -1, and the slab ocean damps the variability and integrates it!

AR(1) integrates the noise to produce low-frequency variability



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Spectra of AR(1) processes

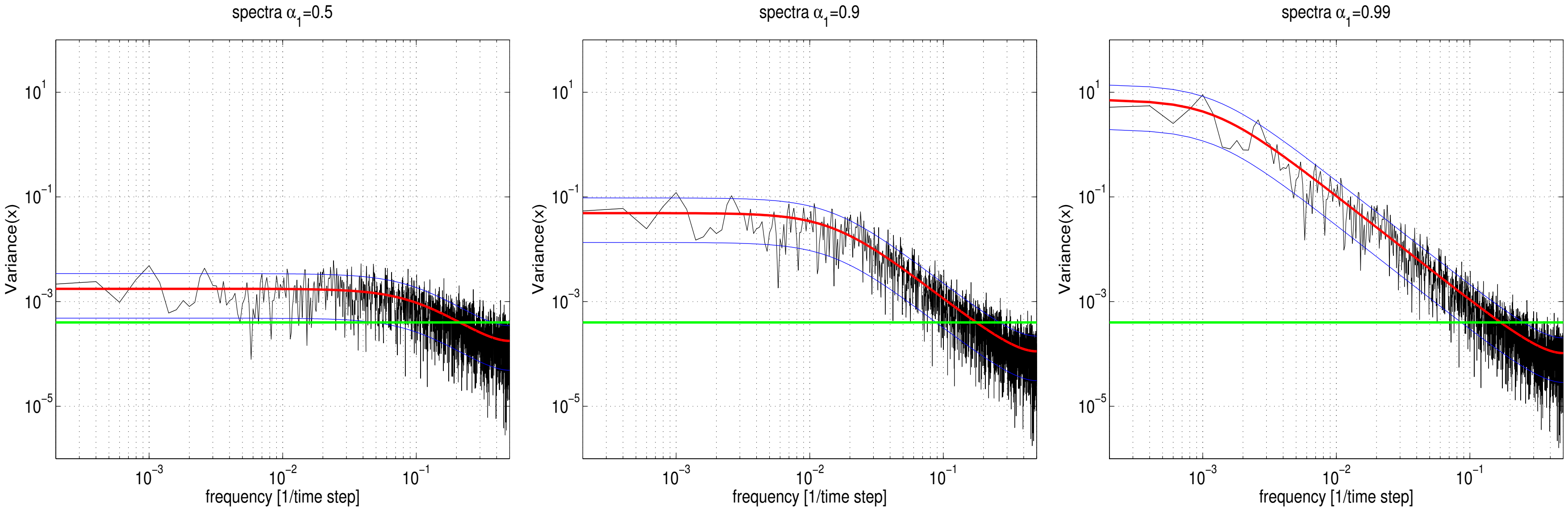

Figure 9.6: The spectra of AR(1) processes with different α_1 compared with the spectrum of the driving white process. The spectra correspond to the time series in Fig. 7.2.

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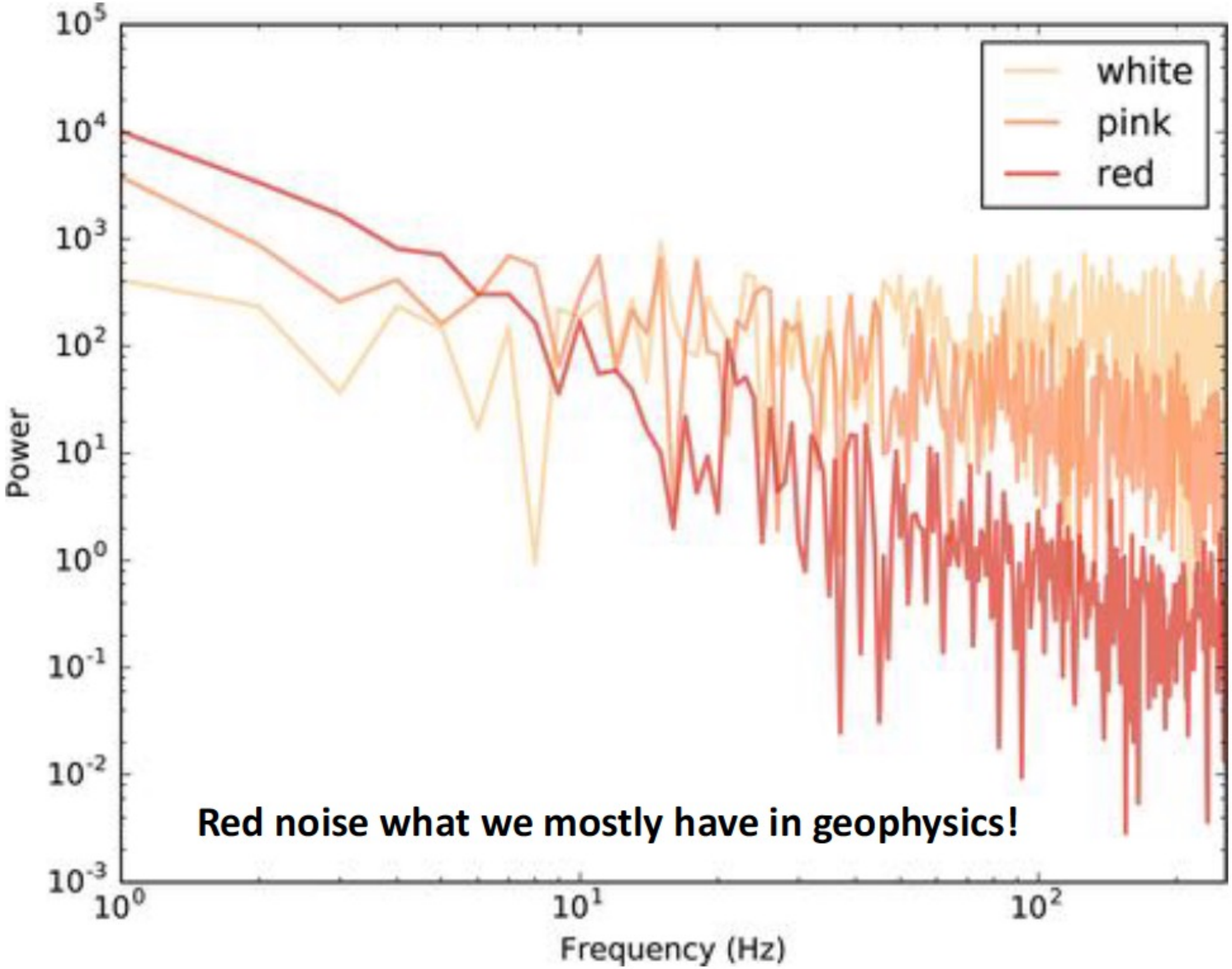
White Noise vs. Red Noise



Red noise what we mostly have in geophysics!

https://www.oreilly.com/library/view/think-dsp/9781491938508/assets/tdsp_0407.png

What causes climate to vary?

Mechanisms for climate variability

- Externally forced
  - Anthropogenic (e.g., greenhouse gas emissions)
  - Natural (e.g., solar forcing, volcanic eruptions)
- Internally generated
  - Stochastic climate models
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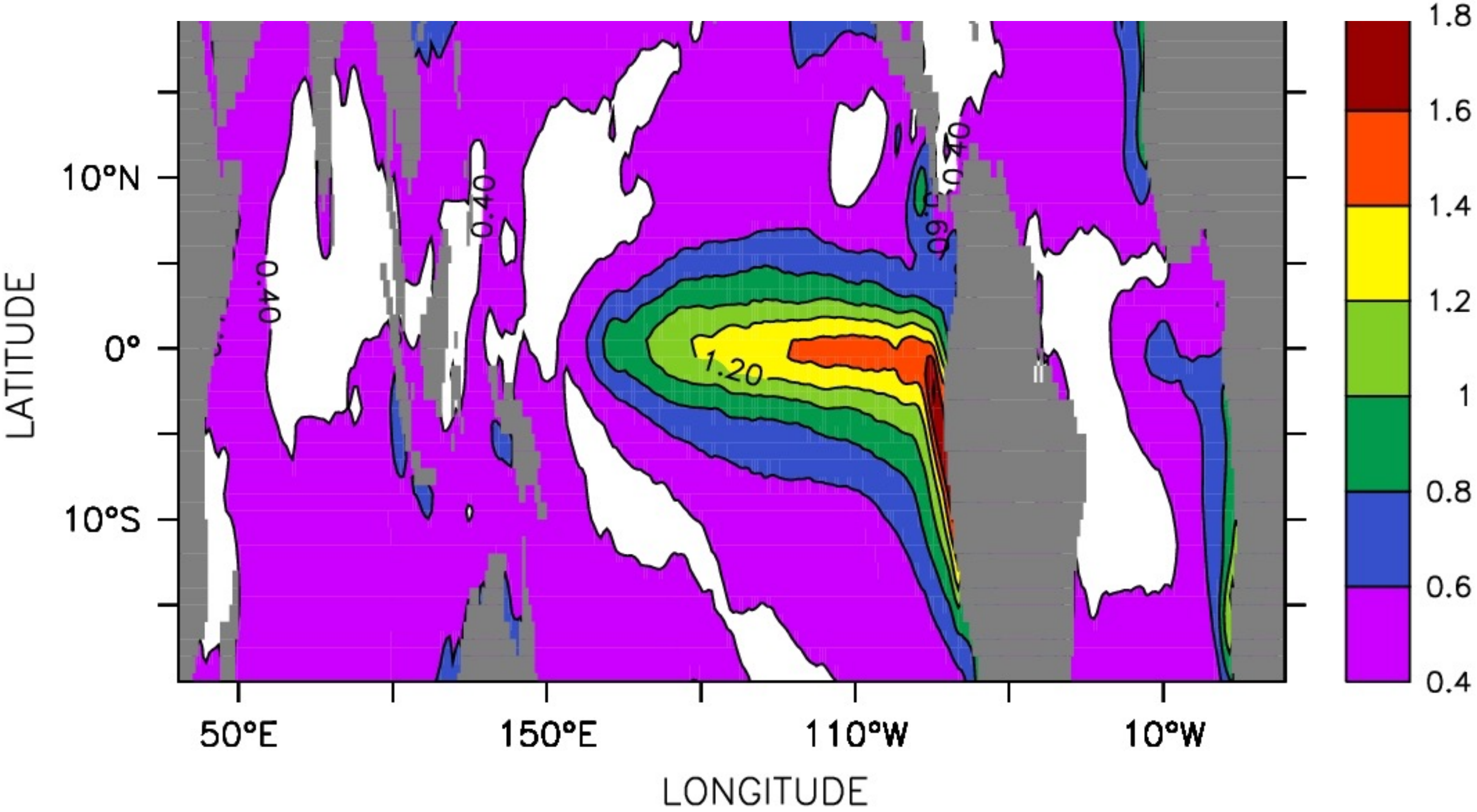
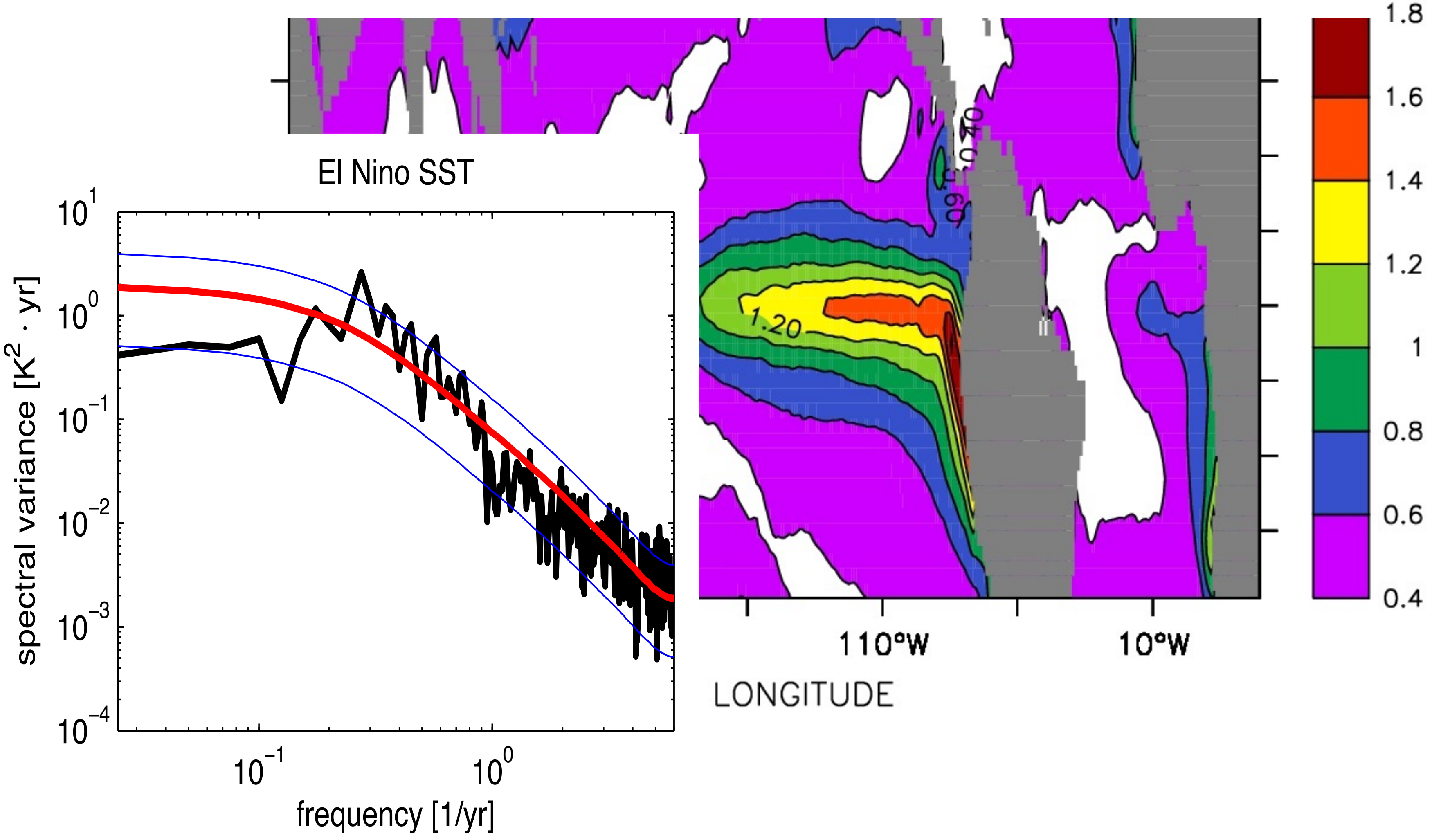
Standard deviation of SST anomalies

NOAA OI, 1982-2006 (K)



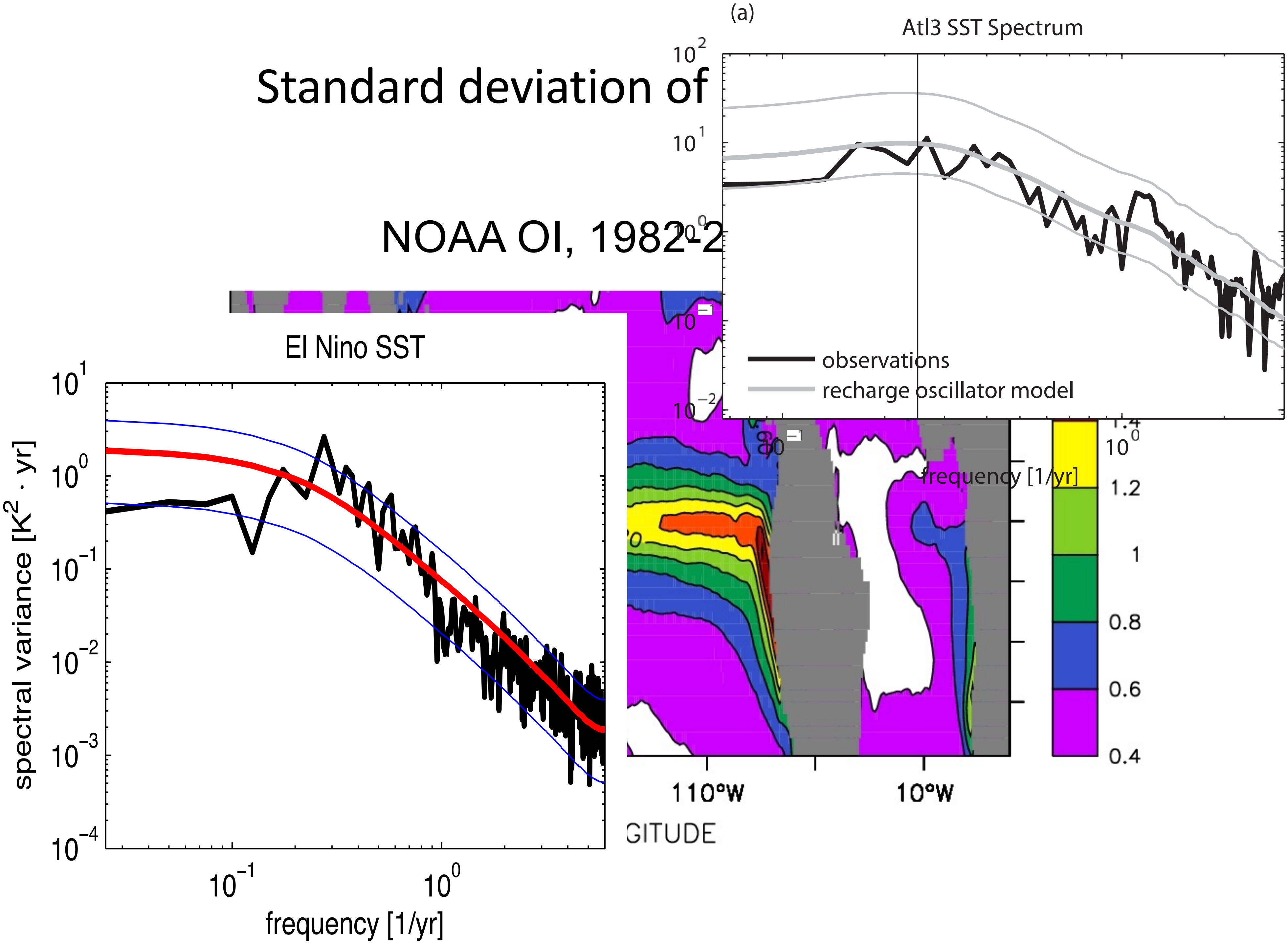
Standard deviation of SST anomalies

NOAA OI, 1982-2006 (K)



Standard deviation of

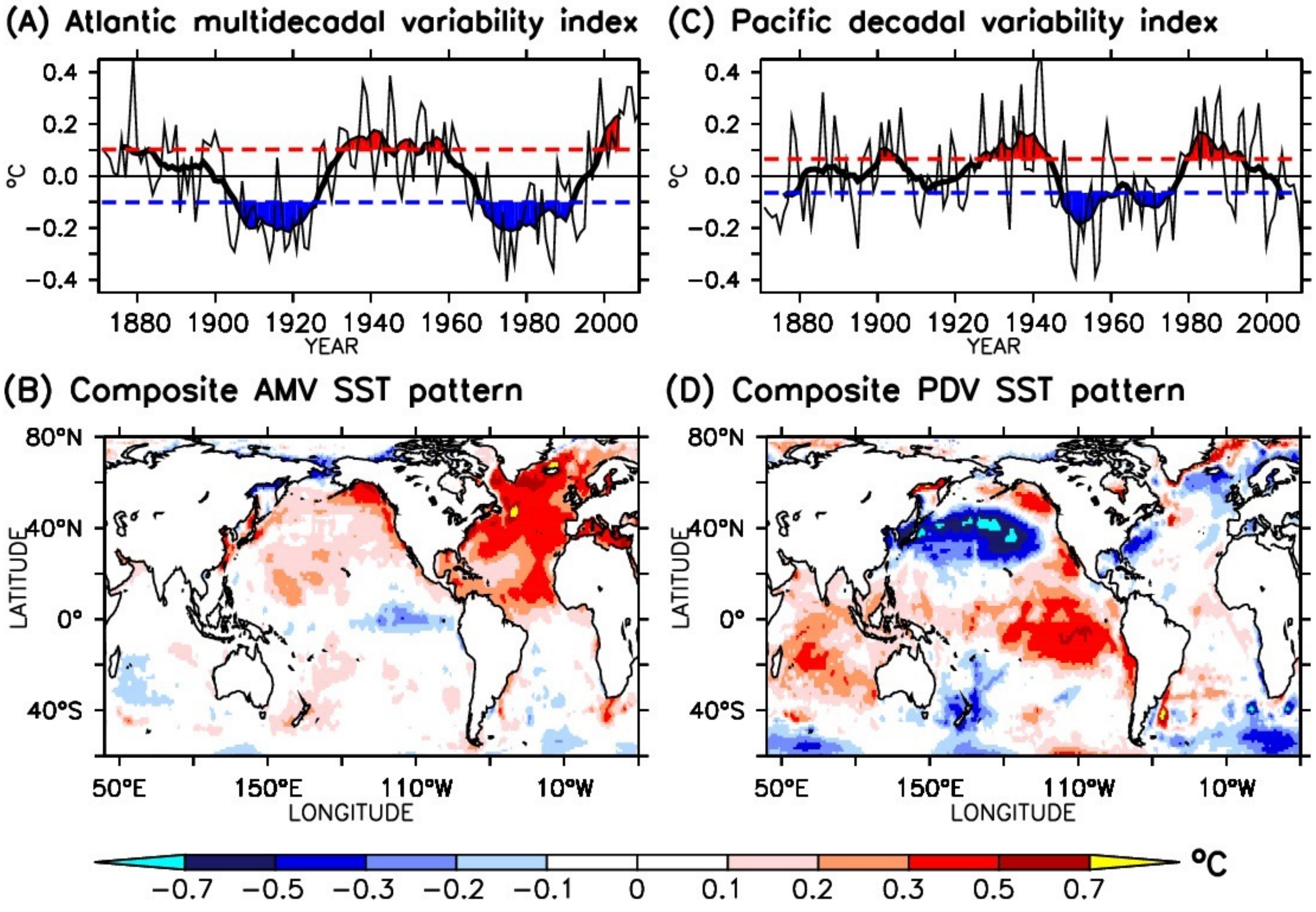
NOAA OI, 1982-2



Causes decadal to multi-decadal climate variability are greatly debated

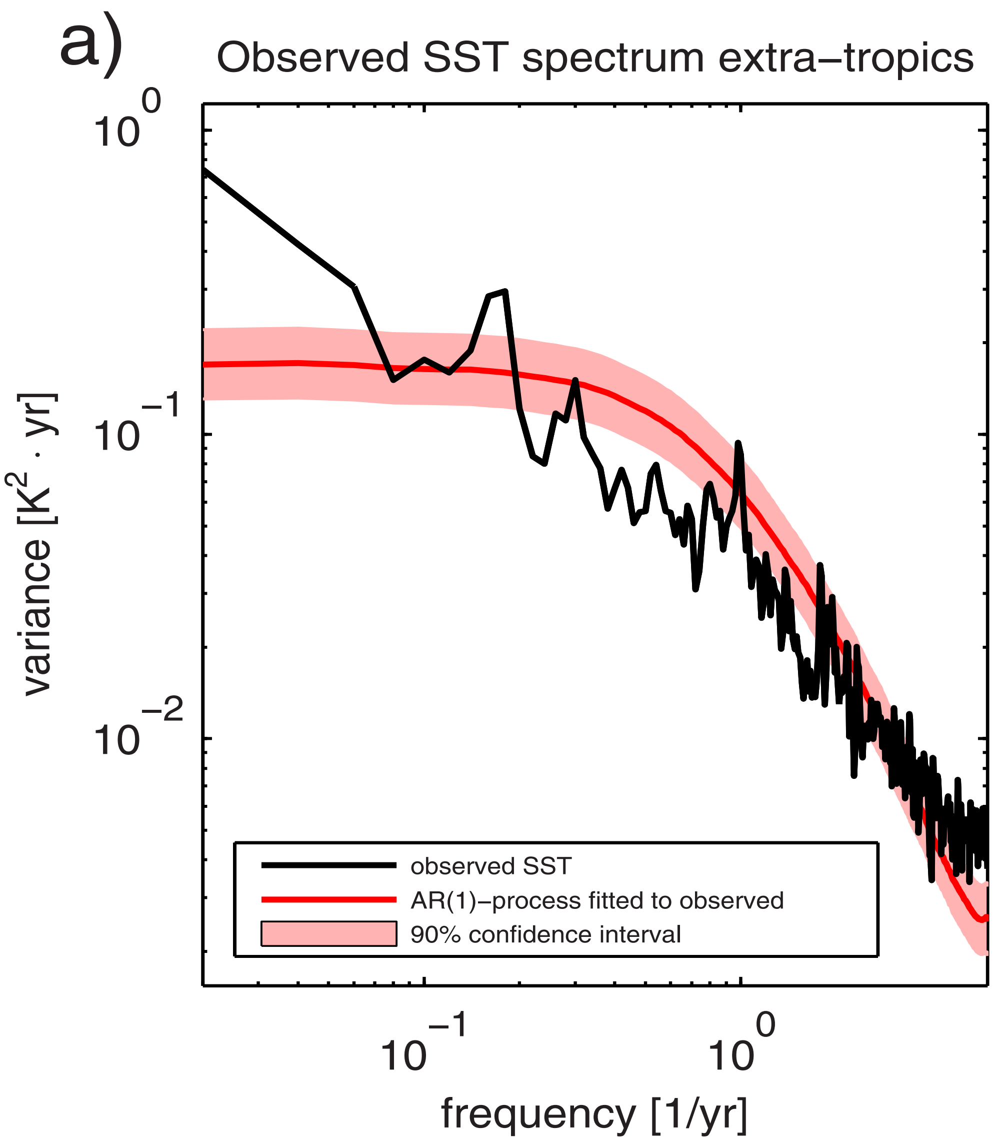
- Instrumental observational records are comparatively short
- Paleo proxy records show large uncertainties
- Model simulations show large uncertainties

Observed internal decadal-to-multidecadal variability in the Atlantic and Pacific



Keenlyside and Ba, 2010

Spectrum of mid-latitude (30-55N) SST similar to AR-1 processes



Dommenget and Latif (2008)

A more complete stochastic model: Linear Inverse Model (LIM) of the PDO

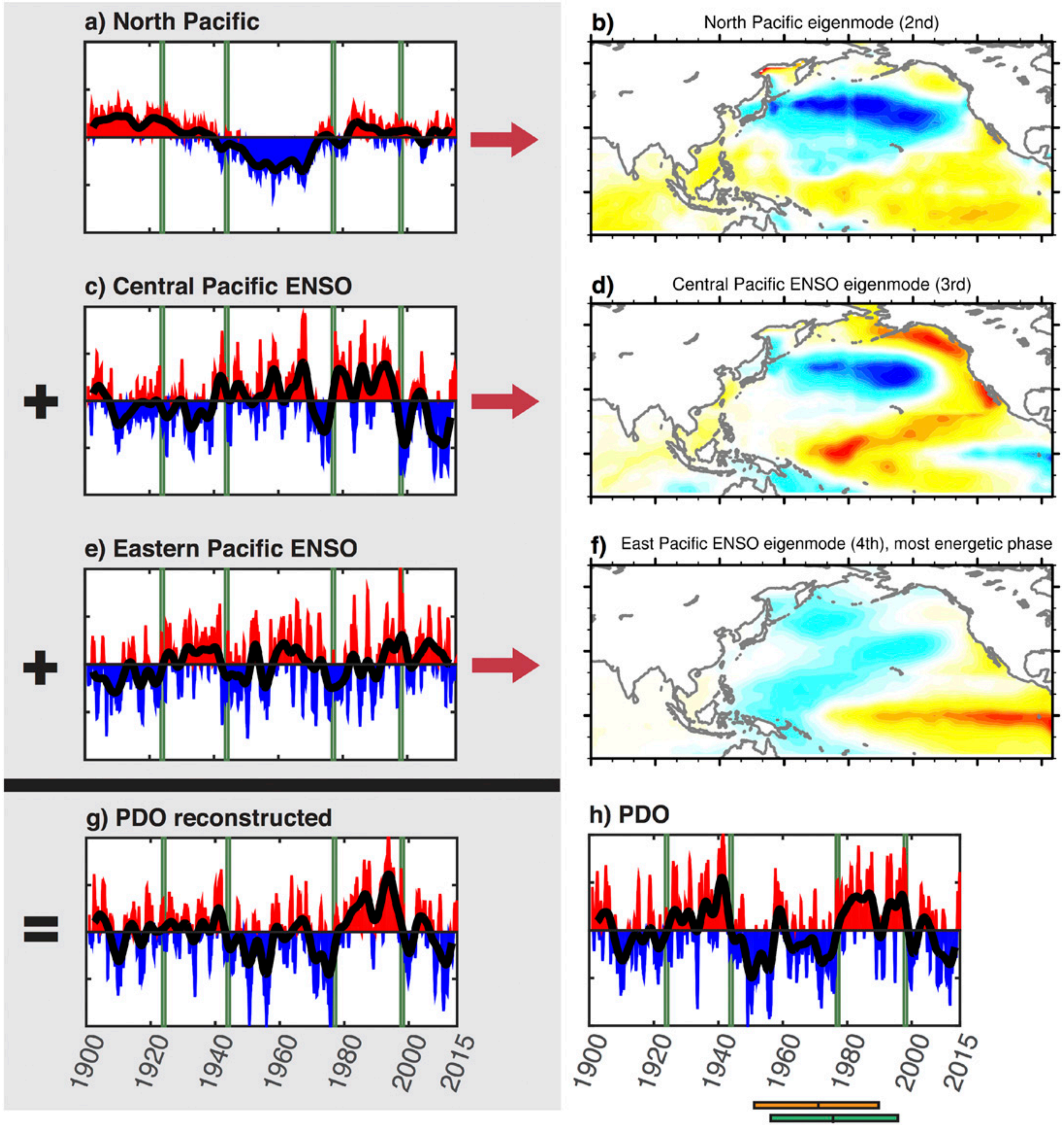
- LIM is a generalized form of the stochastic climate model:

$$\mathbf{x}(n) = \mathbf{G}\mathbf{x}(n-1) + \boldsymbol{\eta}_s\,,$$

- X is multi-variate vector
- η is stochastic forcing
- G is a linear operator capturing the dynamics of the system, and can represent the process described above:
  - Local impacts, local ocean dynamics, re-emergence mechanism, remote teleconnections
- Eigen vectors of G describe the dynamics, each one can be considered as stochastic mode with its own damping timescale

Newman et al. 2016

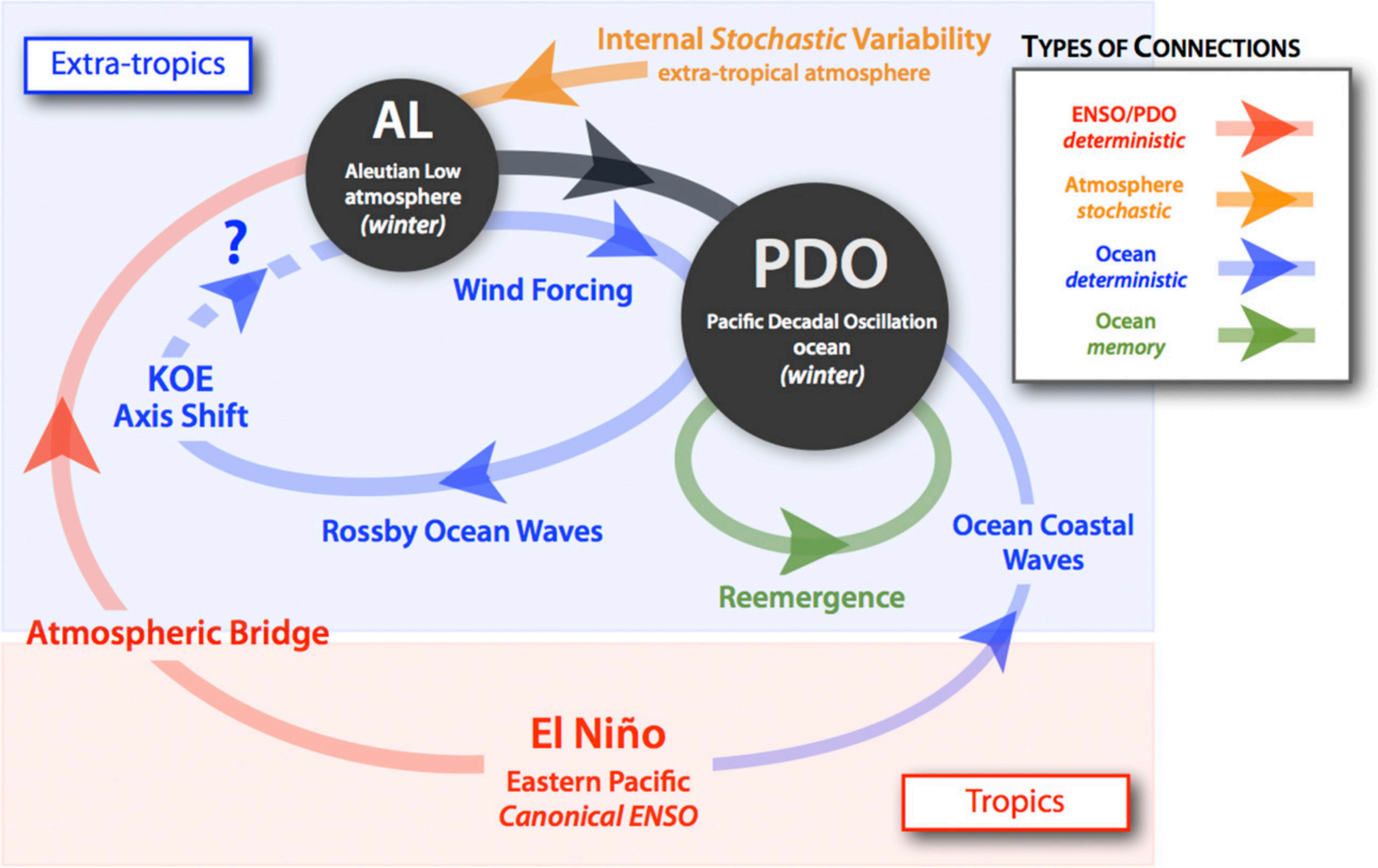
Linear Inverse Model (LIM) of the PDO



Newman et al. 2016

Summary View

MECHANICS OF THE PACIFIC DECADAL OSCILLATION



Extra-tropics

Internal *Stochastic* Variability
extra-tropical atmosphere

AL
Aleutian Low
atmosphere
(winter)

PDO
Pacific Decadal Oscillation
ocean
(winter)

?

Wind Forcing

KOE
Axis Shift

Rossby Ocean Waves

Reemergence

Ocean Coastal
Waves

Atmospheric Bridge

El Niño
Eastern Pacific
Canonical ENSO

Tropics

TYPES OF CONNECTIONS

ENSO/PDO
deterministic

Atmosphere
stochastic

Ocean
deterministic

Ocean
memory

FIG. 14. Summary figure of the basic processes involved in the PDO.

Newman et al. 2016

Extended stochastic climate model with one column ocean

- We can extend the model to include vertical mixing with the deep ocean, and this gives a more realistic representation of the spectra

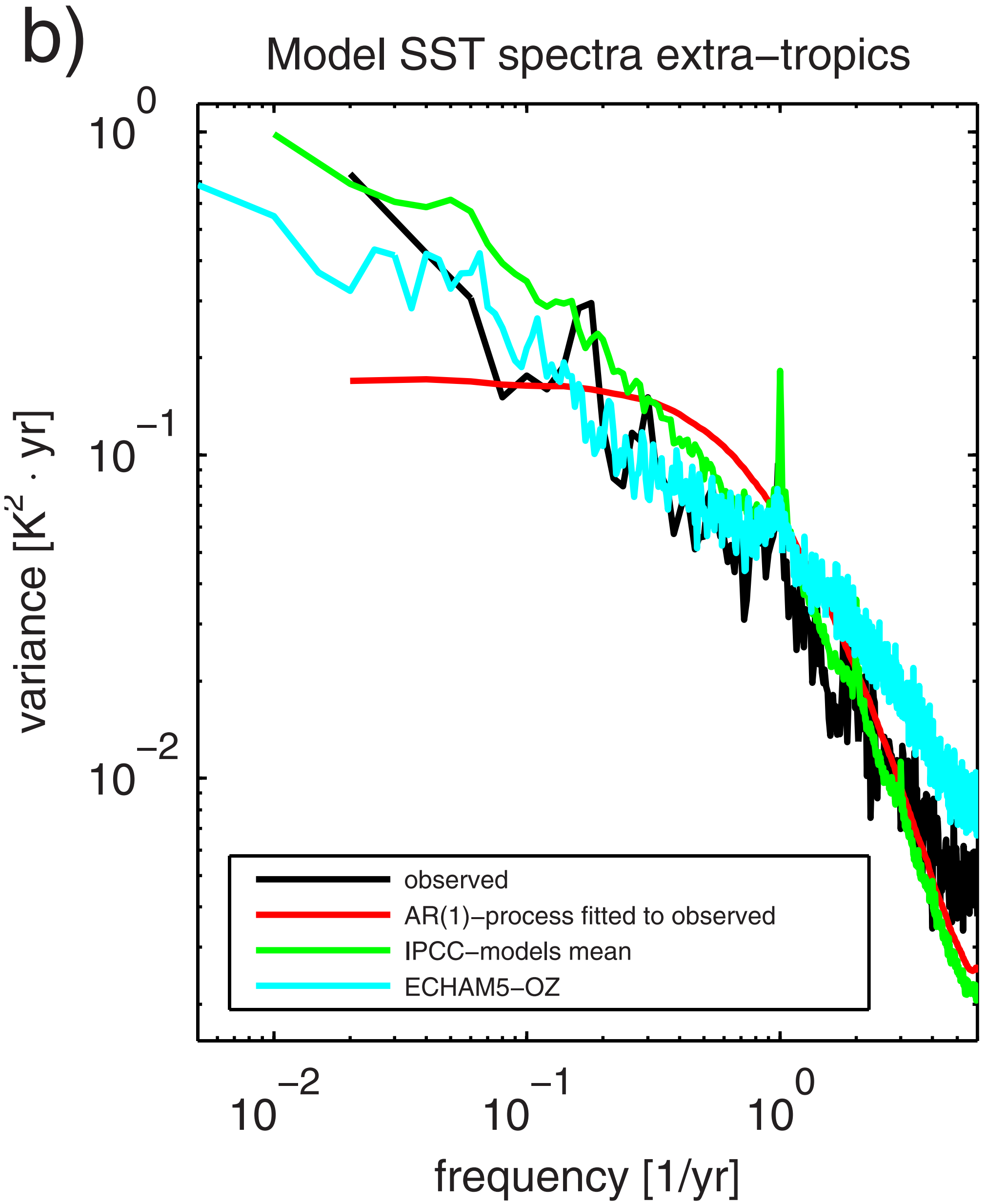
$$\gamma_{surf}\frac{dT_{surf}}{dt} = -cT_{surf} + \kappa_z \nabla_z^2 T_{ocean} + \xi_{surf}$$

$\gamma_{surf} =$ surface layer heat capacity
$T_{surf} =$ surface layer temperature
$c =$ damping by interaction with atmosphere
$\kappa_z =$ vertical diffusivity coeffecient
$T_{ocean} =$ temperature of ocean
$\xi_{surf} =$ surface forcing

$\gamma_{surf} = H \cdot c_p$
$H =$ surface layer thickness
$c_p =$ heat capacity of layer per m^3

Dommenget 2018

Mid-latitude (30-55N) SST variability in climate models consistent with stochastic climate model



BLACK
Observations

RED
AR-1 fit (red noise)

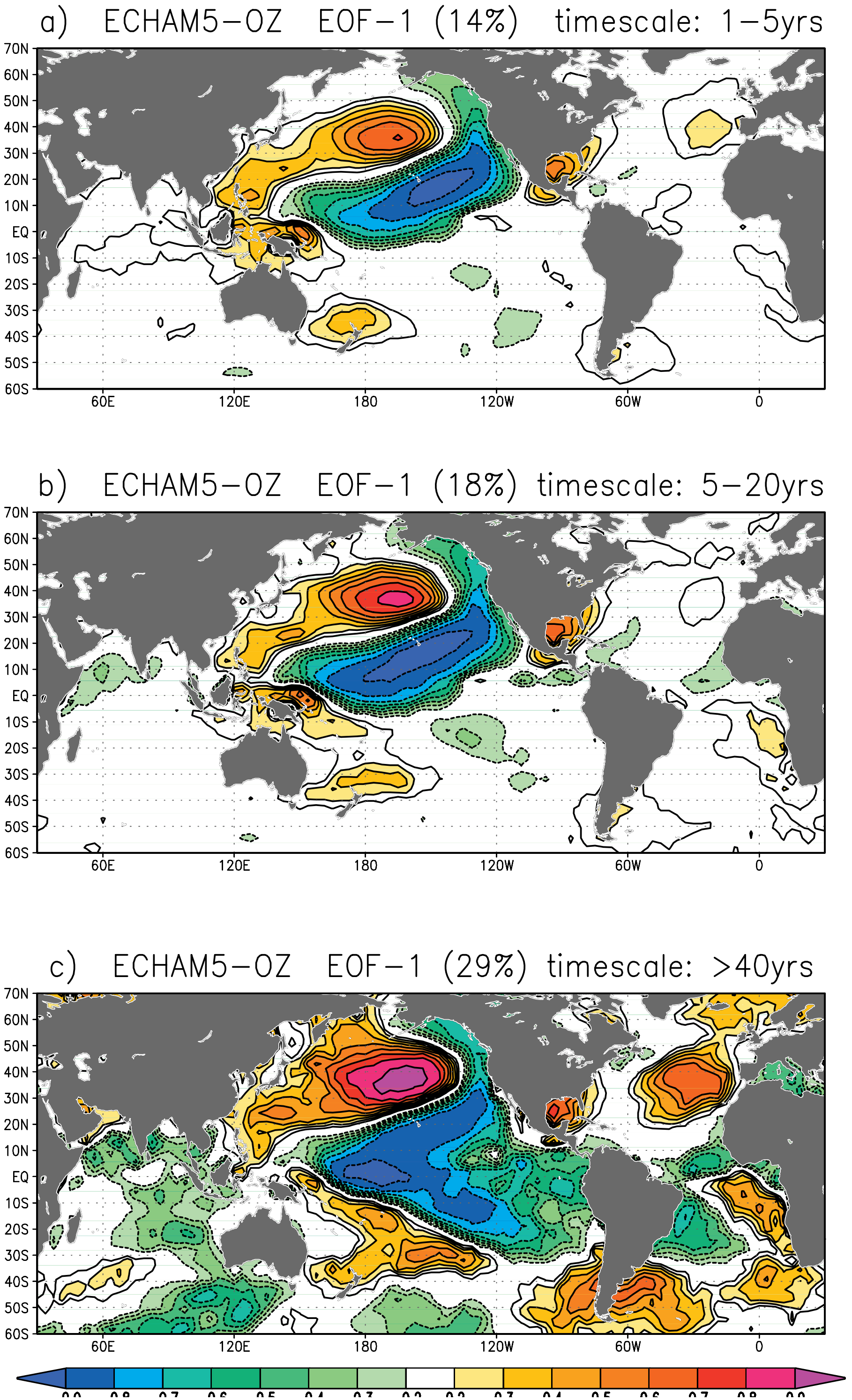
GREEN
CMIP3 Climate Models

CYAN
Climate model with no ocean dynamics

Dommenget and Latif (2008)

Extend one-column ocean stochastic climate model

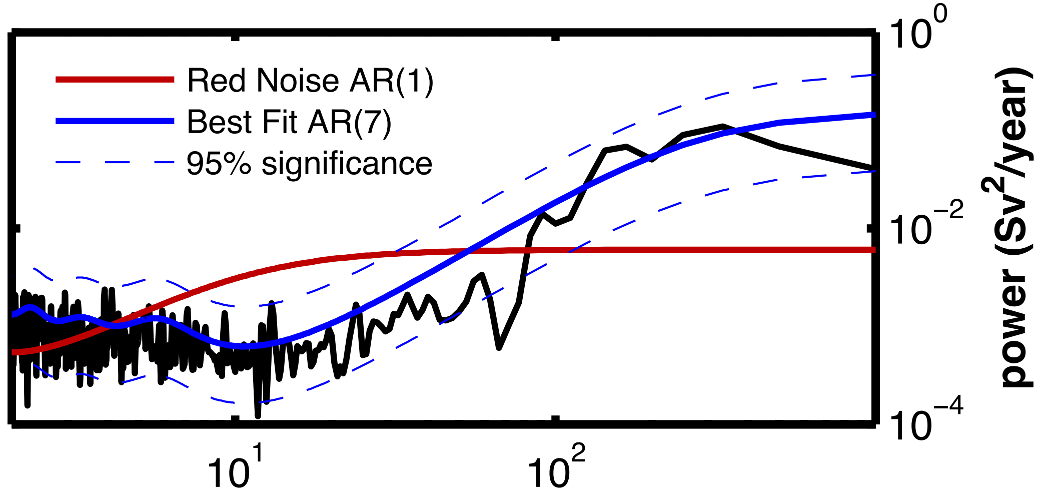
- Captures spatial patterns well
- Spatial structure increases with timescale
- This is because of atmospheric teleconnections



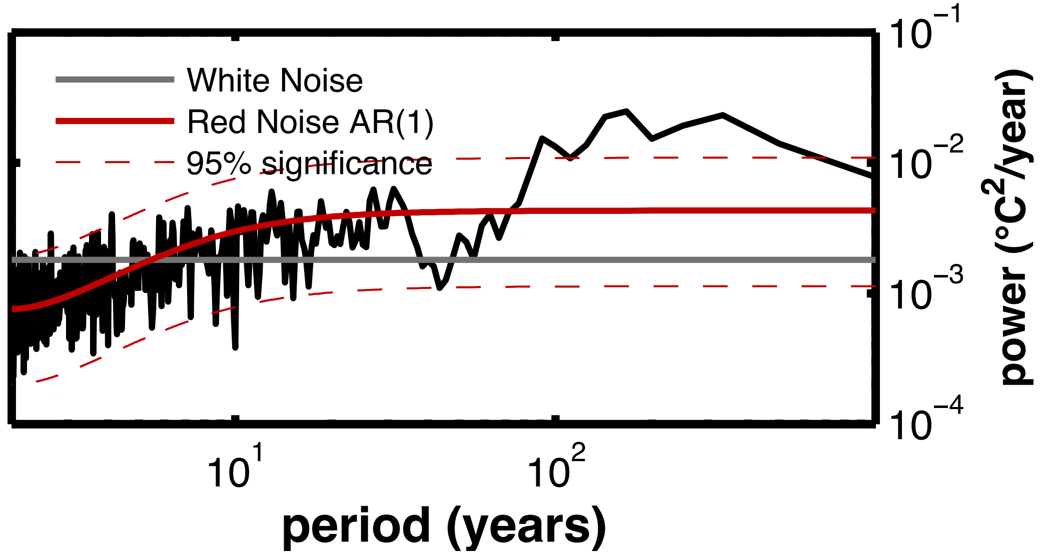
Extended stochastic climate model: Ocean driven by stochastic atmospheric variability (Mecking et al. 2013)

Results from an 1000 year ocean model simulation driven by stochastic NAO forcing – power spectrum

North Atlantic Ocean circulation

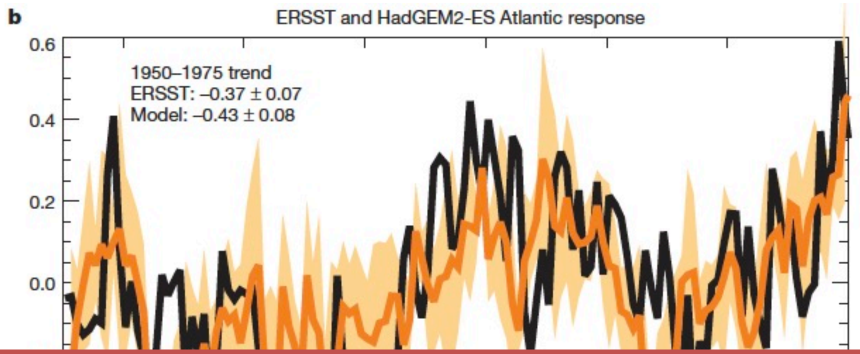


North Atlantic Sea Surface Temperature

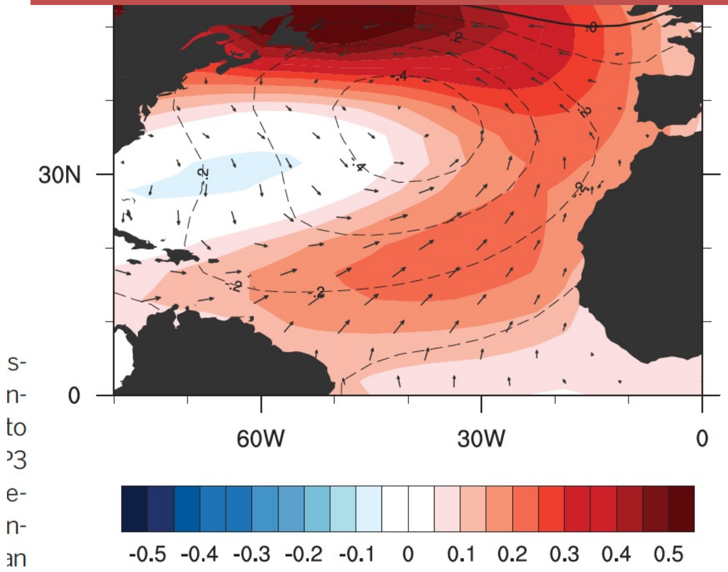


Atlantic multi-decadal variability: Stochastic, external forced, ocean dynamics?

External forced climate models reproduce the observed AMV
Otterå et al. 2010, Booth et al. 2012



But, ocean dynamics shown to be important in driving the extra-tropical SST (e.g. Zhang et al. 2016)

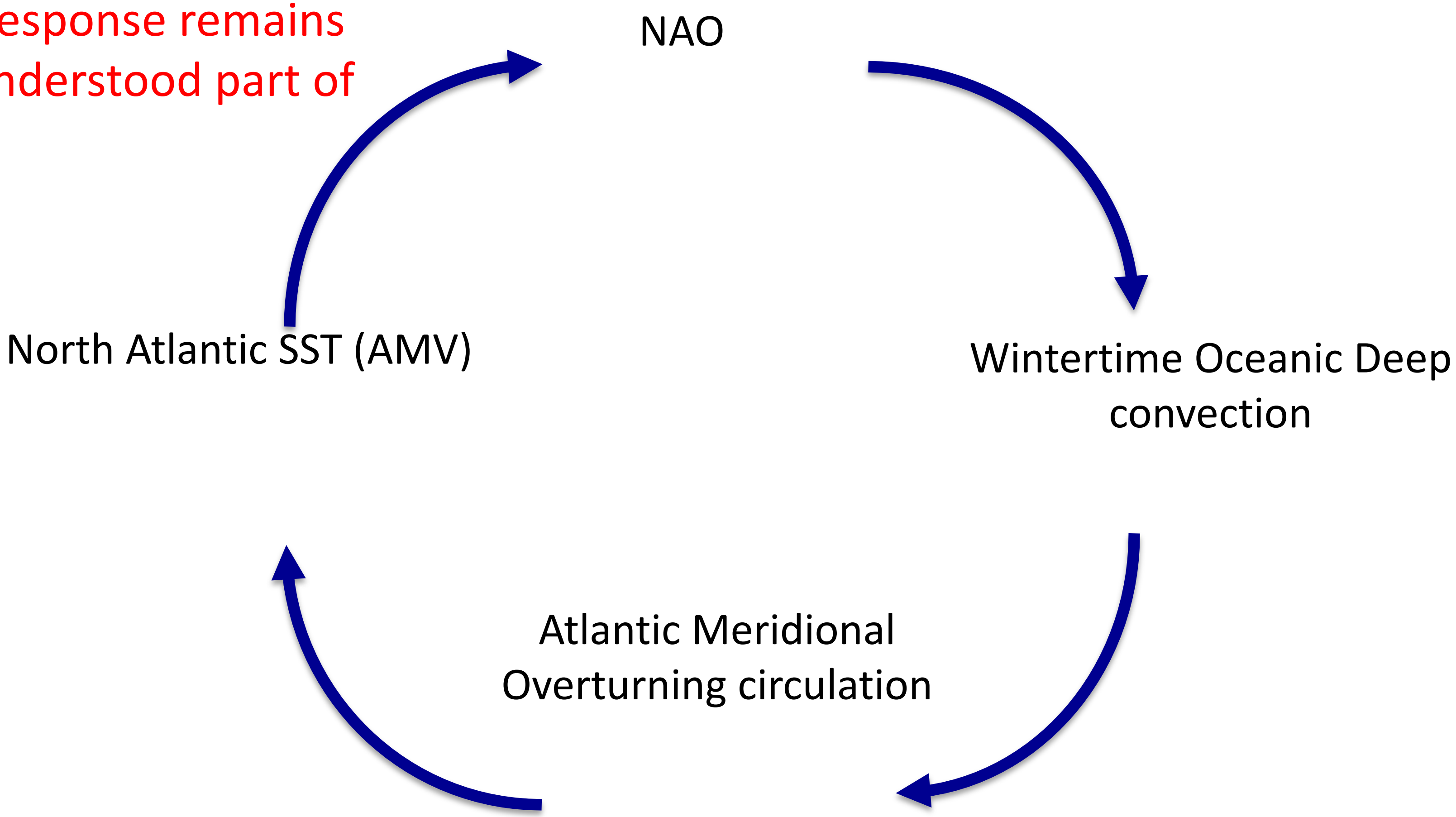


Atmosphere-slab ocean models reproduce the pattern,
Clement et al, 2015

Coupled perspective for Atlantic multi-decadal variability

1. Understanding of ocean-atmosphere interaction

Atmospheric response remains most poorly understood part of the loop



NAO

Wintertime Oceanic Deep convection

Atlantic Meridional Overturning circulation

North Atlantic SST (AMV)

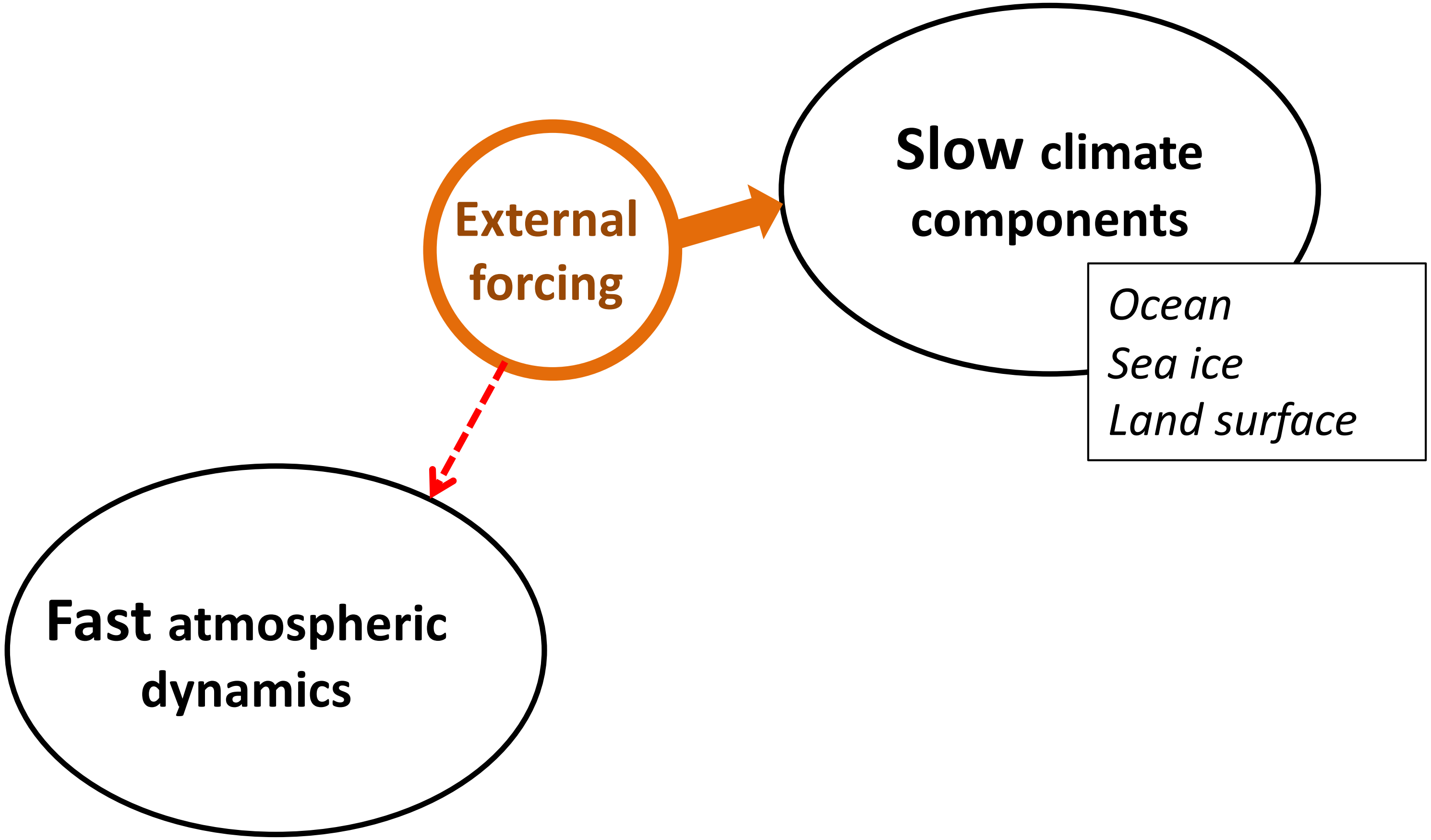
Omrani et al. 2022

Summary

Mechanisms for climate variability

- Externally forced
  - Anthropogenic (e.g., greenhouse gas emissions)
  - Natural (e.g., solar forcing, volcanic eruptions)

Climate Variability before Hasselmann



External forcing

Slow **climate components**

Ocean
Sea ice
Land surface

Fast **atmospheric dynamics**

Mechanisms for climate variability

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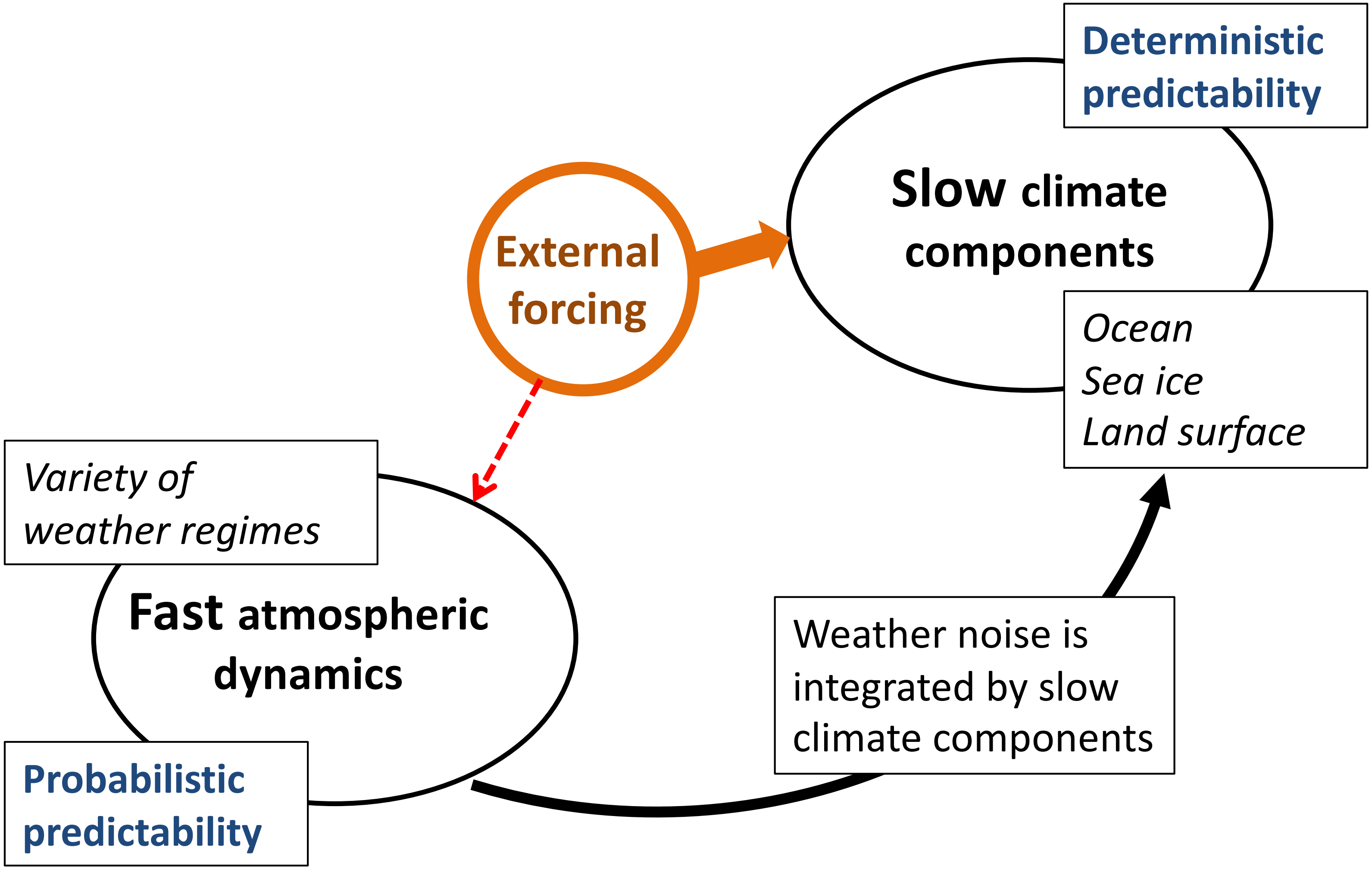
Hasselmann's stochastic climate model



Deterministic predictability

Slow **climate components**

Ocean
Sea ice
Land surface

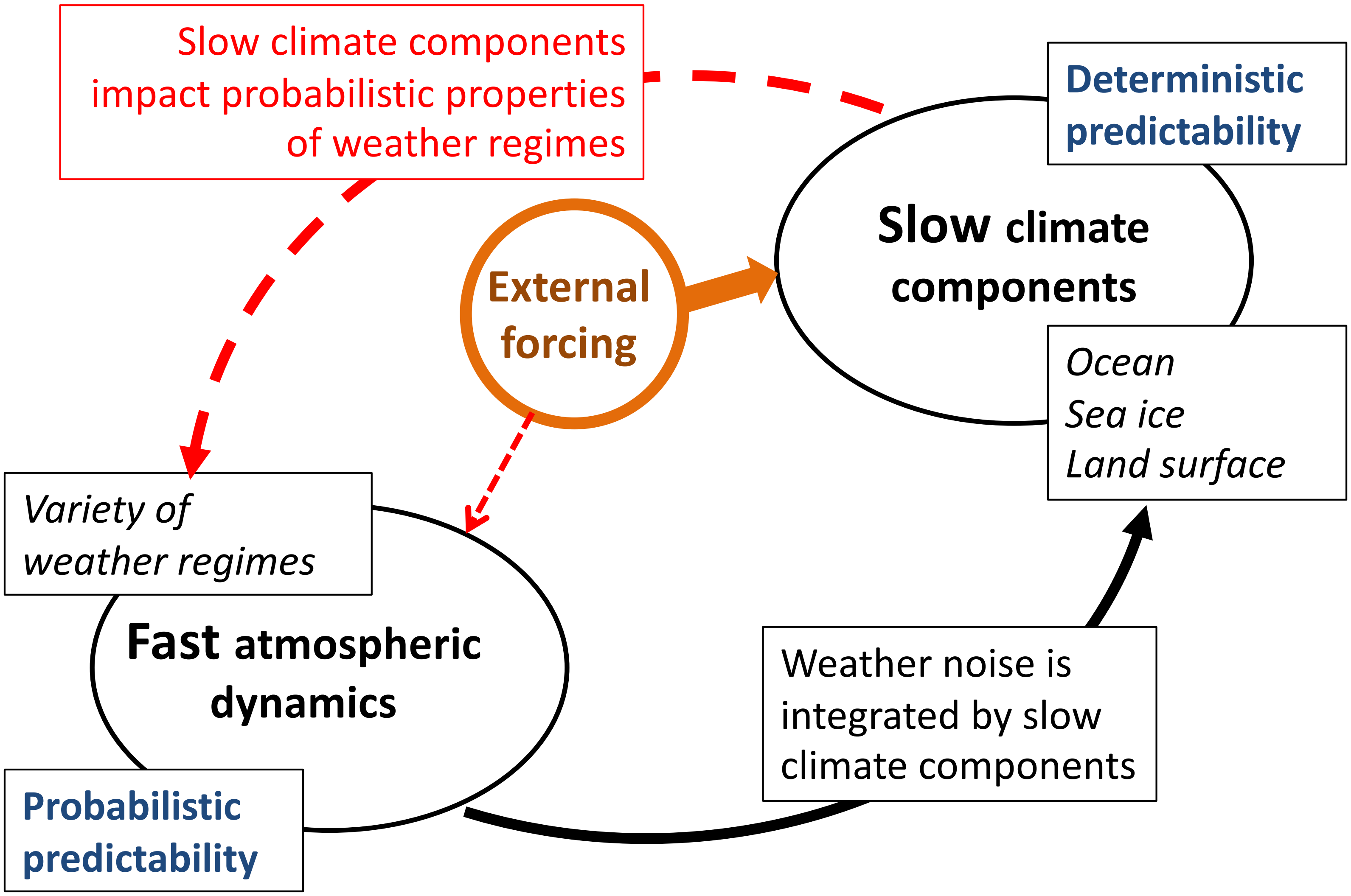
External forcing

Variety of weather regimes

Fast **atmospheric dynamics**

Probabilistic predictability

Weather noise is integrated by slow climate components


Slow climate components impact probabilistic properties of weather regimes
Deterministic predictability
External forcing
Slow climate components
Ocean
Sea ice
Land surface
Variety of weather regimes
Fast atmospheric dynamics
Weather noise is integrated by slow climate components
Probabilistic predictability