The Role of Ocean Dynamics in Multi-year Predictability

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Atmospheric Predictability

Weather forecast at 45N, 60W
21 slightly different initial conditions

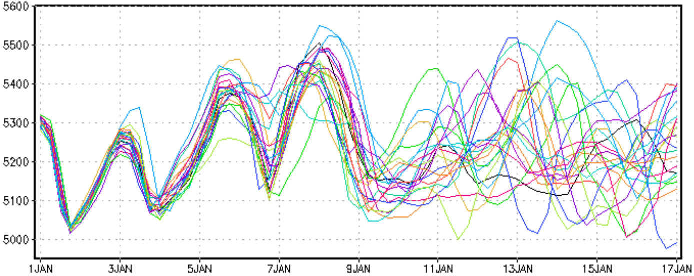


figure from http://cola.gmu.edu/grads/gadoc/ensembles.html

Oceanic Predictability

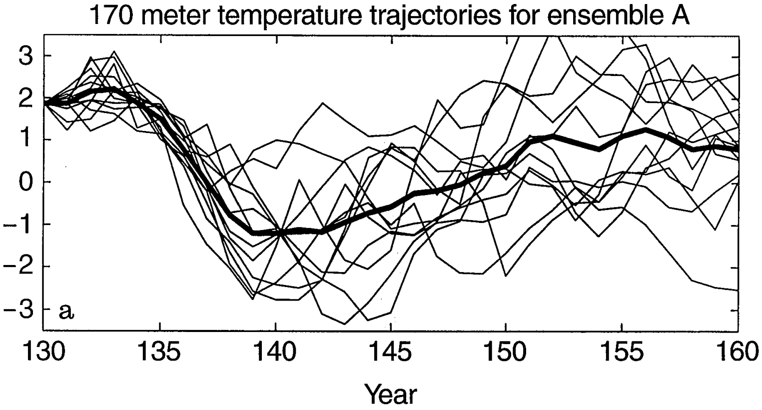


Figure : Trajectories of leading principal component of 170m ocean temperature simulated by GFDL model; from Griffies and Bryan (1997).

Measure of Predictability

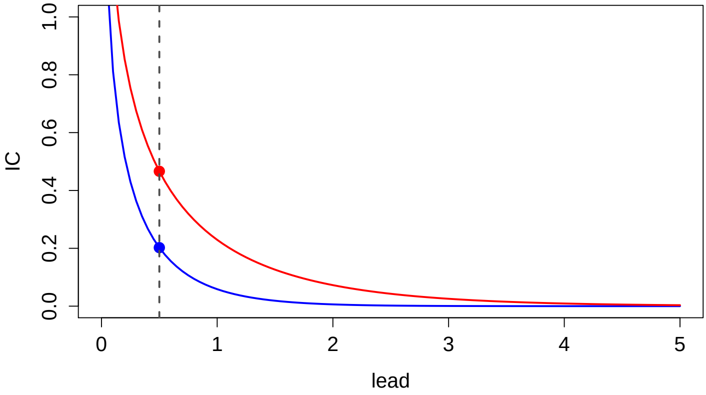
$$\frac{\text{ensemble spread}}{\text{total variance}} = \frac{N}{T}.$$

Equivalent measure: signal-to-total ratio

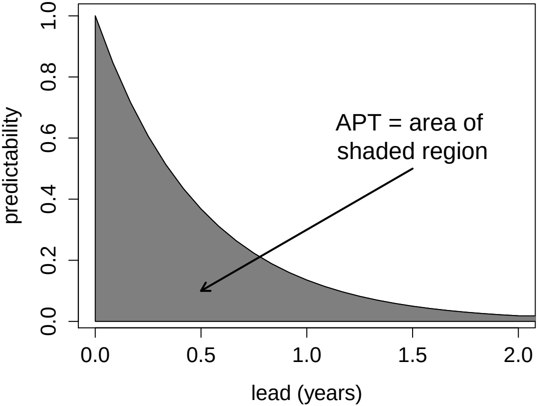
$$\frac{S}{T} = 1 - \frac{N}{T}$$

Predictable Component Analysis

Find the linear combination of variables that maximizes average initial-condition predictability



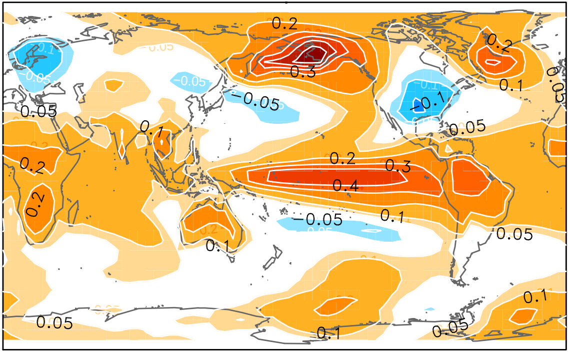
Average Predictability Time (APT)



$$APT = \int_0^\infty \frac{S}{T} d\tau$$

DelSole and Tippett (2009, J. Atmos. Sci.)

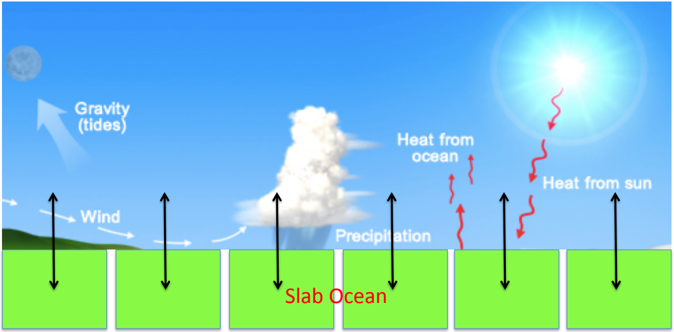
Most Predictable Component in Climate Models



- Maximizes Average Predictability Time (APT).
- CMIP3 pre-industrial control simulations
- 10 Laplacian eigenfunctions
- monthly mean sea surface temperature

Srivastava and DelSole (2016; PNAS)

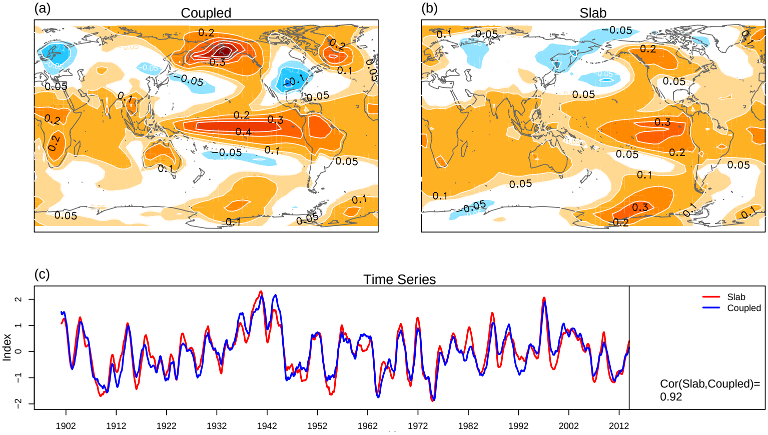
Atmosphere- Slab Ocean Model



No ocean circulation!

courtesy of Abhishekh Srivastava. upper figure from COMET program

Predictable Component 1

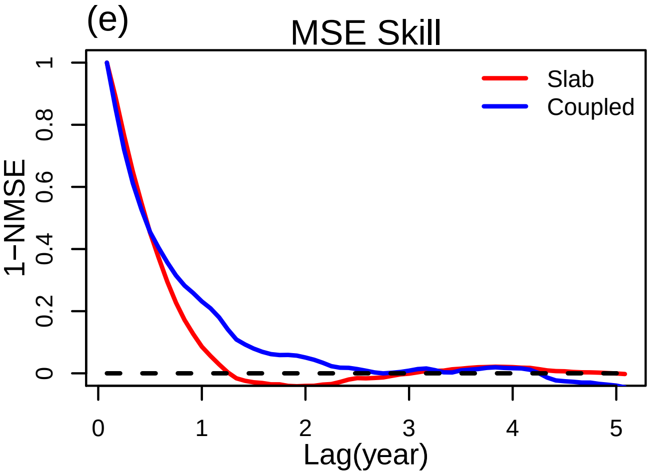


Srivastava and DelSole (2016; PNAS)

Interactive ocean circulations are not essential in determining the most predictable pattern.

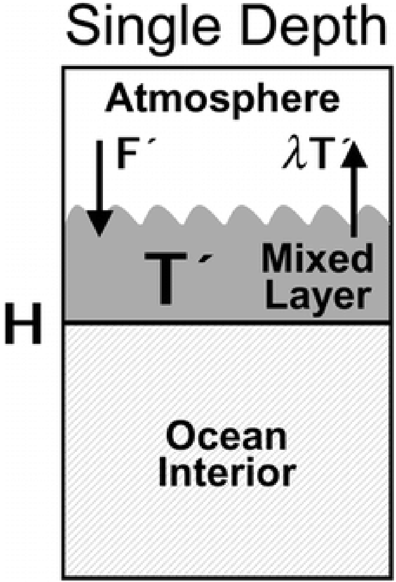
Empirical Prediction Model $\quad \hat{\mathbf{r}}_{t+\tau} = \mathbf{L}_\tau \mathbf{r}_t$

Skill of Most Predictable Component



Srivastava and DelSole (2016; PNAS)

Interactive ocean circulations seem to enhance predictability that already exists without ocean dynamics.



Frankignoul & Hasselmann (1977)

Energy Balance

$$\rho_o c_p H \frac{dT'}{dt} = -\lambda T' + F'$$

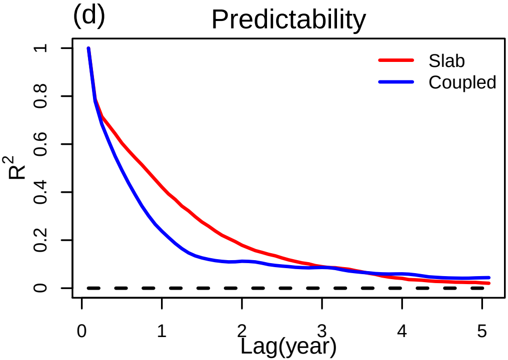
Deser et al. (2003): Understanding the Persistence of Sea Surface Temperature Anomalies in Midlatitudes, J. Climate, 16, 57-72

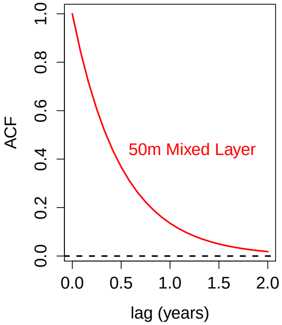
Dynamics of Mixed Layer Model

$$\tau_D = \frac{\rho_o c_p H}{\lambda} \approx 5.4 \text{ months.}$$

feedback parameter	λ	15 W m^{-2} K^{-1}
density of seawater	ρ_o	1000 kg m^{-3}
specific heat of seawater	c_p	4180 J kg^{-1} K^{-1}
depth of mixed layer	H	50m

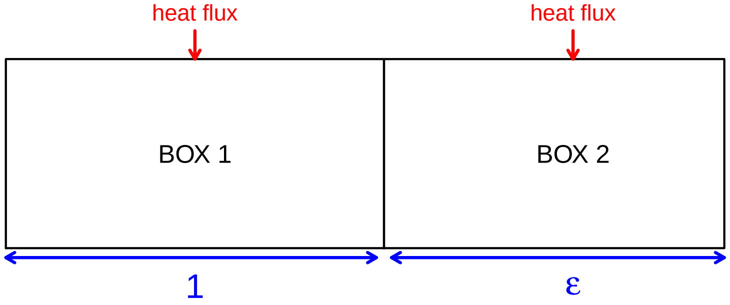
Skill of Most Predictable Component





Srivastava and DelSole (2016; PNAS)

Two-Box Model



$$\dot{T}_1 = -\lambda T_1 + n_1$$
$$\epsilon \dot{T}_2 = -\lambda T_2 + n_2$$

If stochastic forcing of the two boxes are independent, then APT is bounded by the predictabilities of the individual boxes:

$$\frac{\epsilon}{\lambda} \leq \mathsf{APT} \leq \frac{1}{\lambda}$$

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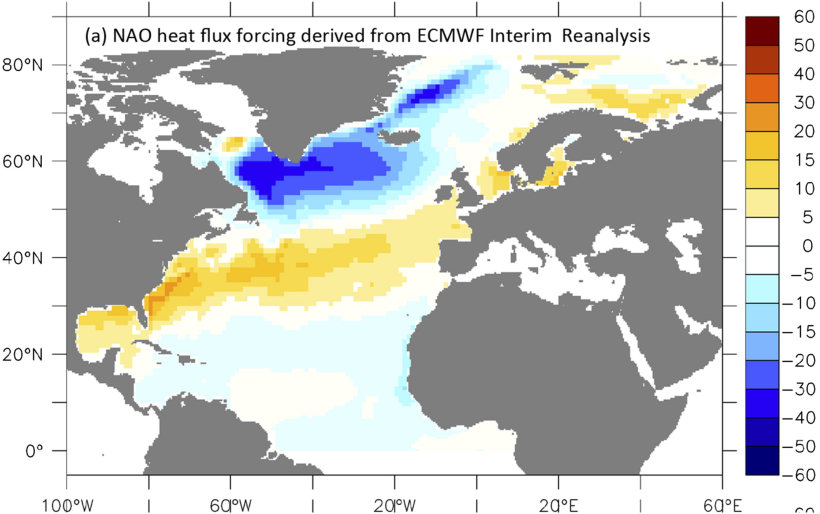
No enhancement of predictability.

But atmospheric heat fluxes are spatially coherent.

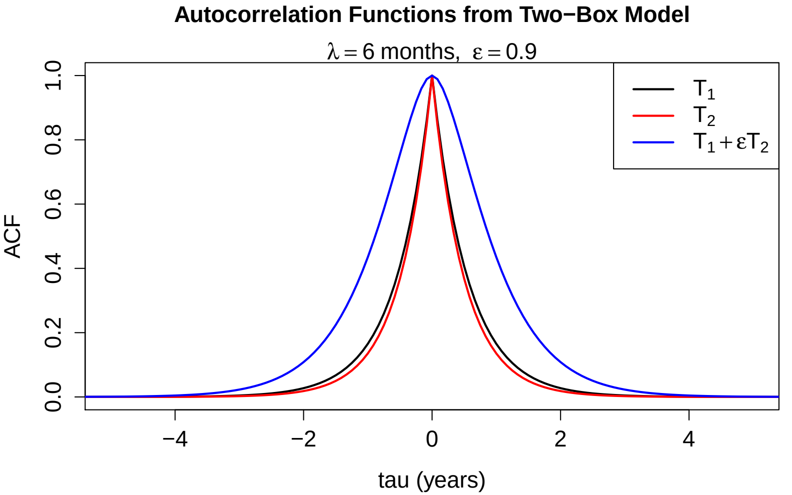


Delworth, T.L. and F. Zeng, 2016: J. Climate, 29, 941-962.

Assume forcing is spatially coherent

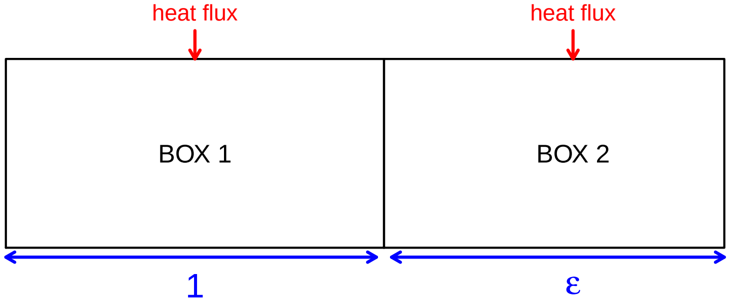
$$\begin{pmatrix} \dot{T}_1 \\ \dot{T}_2 \end{pmatrix} = \begin{pmatrix} -\lambda & 0 \\ 0 & -\lambda/\epsilon \end{pmatrix} \begin{pmatrix} T_1 \\ T_2 \end{pmatrix} + n(t) \begin{pmatrix} 1 \\ -1/\epsilon \end{pmatrix}$$

Note that the forcing term is energetically balanced:
it cancels out in the linear combination $T_1 + \epsilon T_2$.



Autocorrelation Functions from Two−Box Model
λ = 6 months, ε = 0.9
ACF
tau (years)
T1
T2
T1 + εT2
0.0
0.2
0.4
0.6
0.8
1.0
−4
−2
0
2
4

What's the Mechanism



$$T_1(t) = \int_{-\infty}^{t} e^{-\lambda_1(t-s)} n_1(s)ds \quad T_2(t) = \int_{-\infty}^{t} e^{-\lambda_2(t-s)/\epsilon} n_2(s)ds$$

Theorem from Tippett and Chang (2002):

- The linear stochastic model with minimum predictability is uncorrelated in normal-mode space.
- The minimum predictability depends only on the eigenvalues.

Corollary: For diagonal dynamical operator, correlated stochastic forcing yields higher predictability than uncorrelated forcing.

An atmospheric response to SST (i.e, “feedback”) is not necessary to enhance predictability.

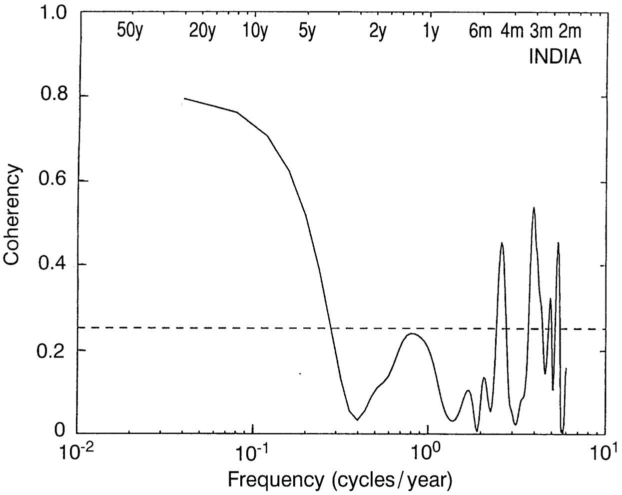
Criticisms

Ocean slab models...

- give inconsistent time-lagged (low-pass) heat flux-temperature relations relative to observations and coupled models.
- cannot explain the high coherence of North Atlantic temperature and salinity at decadal-or-longer time scales.
- cannot explain the two-time scale decay of the autocorrelation of North Atlantic SST.
- produce unrealistic responses to NAO forcing.

Hall and Manabe (1997; J. Climate); Zhang et al. (2016; J. Climate); Cane et al. (2017; J. Climate); Delworth et al. (2017; J. Climate)

Coherence between SST and SSS in Observations



Hall and Manabe (1997, Climate Dynamics)

Stochastic Models Can Reproduce SST-SSS Coherence

Surface fluxes of heat and freshwater both involve evaporation:

$$
\begin{aligned}
c_p h \dot{T} &= -L\color{red}{E} && + \text{sensible} + \text{radiative} + \text{diffusion} + \text{entrainment} \\
h \dot{S} &= +S(\color{red}{E} - P) && + \text{diffusion} + \text{entrainment}
\end{aligned}
$$

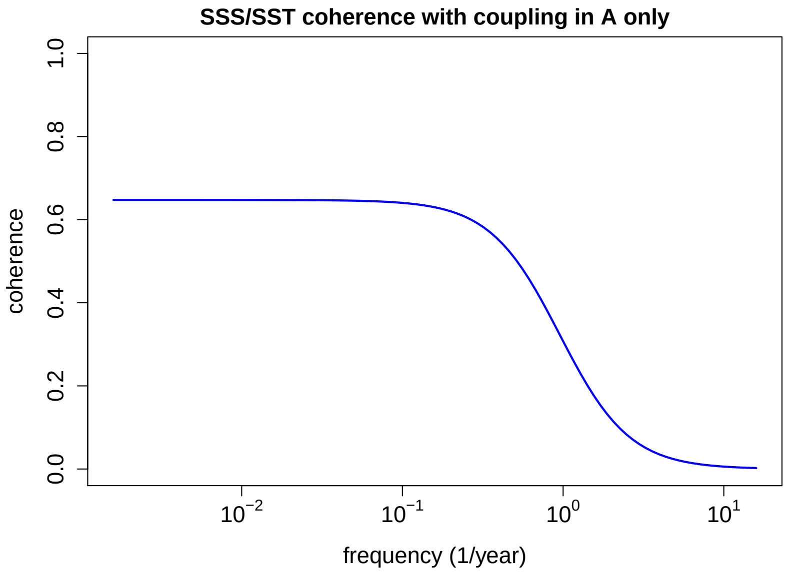
Parameterized evaporation as

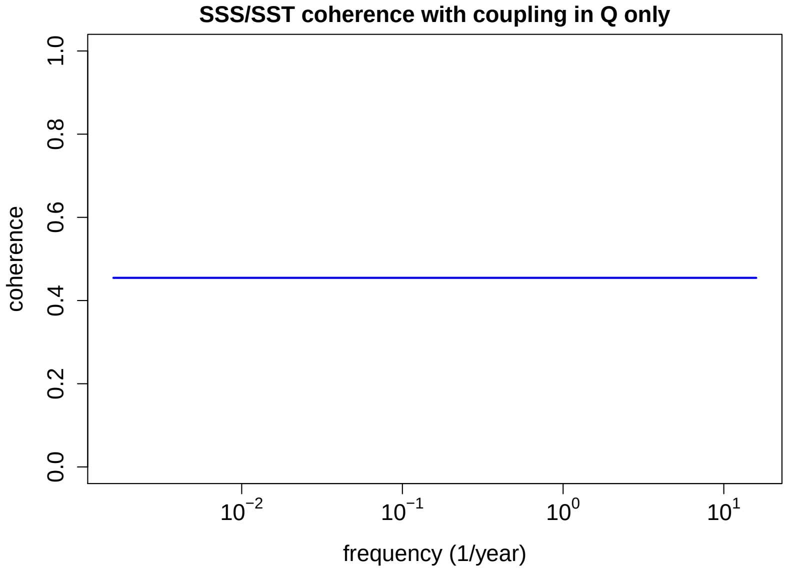
$$E \approx -\lambda_E T + n_E$$

This leads to the coupled stochastic model

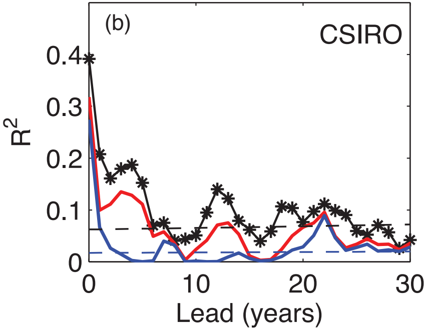
$$\begin{pmatrix} \dot{T} \\ \dot{S} \end{pmatrix} = \begin{pmatrix} -\lambda_T - \lambda_E & 0 \\ -\lambda_E & -\lambda_S \end{pmatrix} \begin{pmatrix} T \\ S \end{pmatrix} + \begin{pmatrix} n_T \\ n_S \end{pmatrix} + n_E \begin{pmatrix} L/C_p \\ -1 \end{pmatrix}$$

There is coupling in the dynamical operator and in the forcing.


SSS/SST coherence with coupling in A only
coherence
0.0
0.2
0.4
0.6
0.8
1.0
10^{-2}
10^{-1}
10^{0}
10^{1}
frequency (1/year)


SSS/SST coherence with coupling in Q only
coherence
frequency (1/year)
0.0
0.2
0.4
0.6
0.8
1.0
10^{-2}
10^{-1}
10^{0}
10^{1}

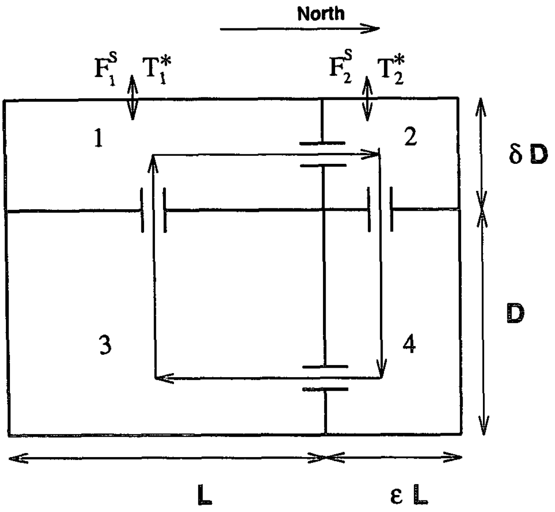
Predictions of AMO: AMOC is a Useful Predictor



blue line	AMO(t+lead) = ϕ AMO(t)
red line	AMO(t+lead) = ϕ AMO(t) + β_1 Index1
black line	AMO(t+lead) = ϕ AMO(t) + β_2 Index2

Trenary and DelSole, 2016: Does the Atlantic Multidecadal Oscillation Get its Predictability from the Atlantic Meridional Overturning Circulation?, J. Climate, 29, 5267-5280

Stommel-like Box Model (Griffies and Tziperman)



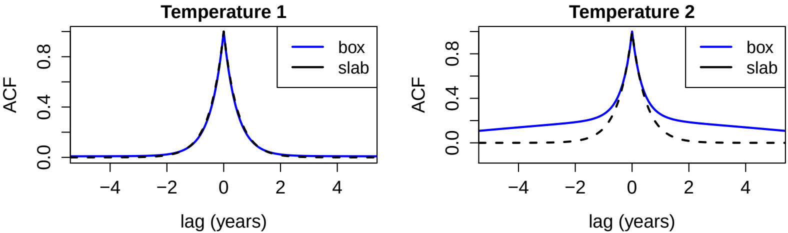
Griffies and Tziperman 1995, J. Climate

Stommel Box Model Equations

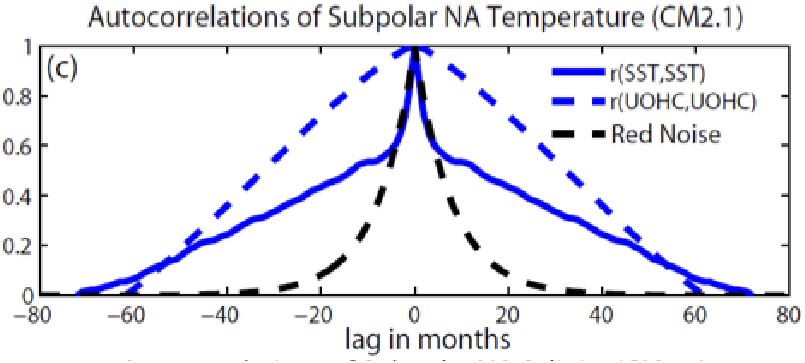
$$
\begin{aligned}
\dot{T}_1 &= \frac{U}{\delta V}\left(T_3 - T_1\right) + \gamma_T\left(T_1^* - T_1\right)\\
\dot{T}_2 &= \frac{U}{\epsilon\delta V}\left(T_1 - T_2\right) + \gamma_T\left(T_2^* - T_2\right)\\
\dot{T}_3 &= \frac{U}{V}\left(T_4 - T_3\right)\\
\dot{T}_4 &= \frac{U}{\epsilon V}\left(T_2 - T_4\right)\\
\dot{S}_1 &= \frac{U}{\delta V}\left(S_3 - S_1\right) + F_1^S\\
\dot{S}_2 &= \frac{U}{\epsilon\delta V}\left(S_1 - S_2\right) + F_2^S\\
\dot{S}_3 &= \frac{U}{V}\left(S_4 - S_3\right)\\
\dot{S}_4 &= \frac{U}{\epsilon V}\left(S_2 - S_4\right)
\end{aligned}
$$

No T-S coupling through surface fluxes

Autocorrelation Function of Temperature

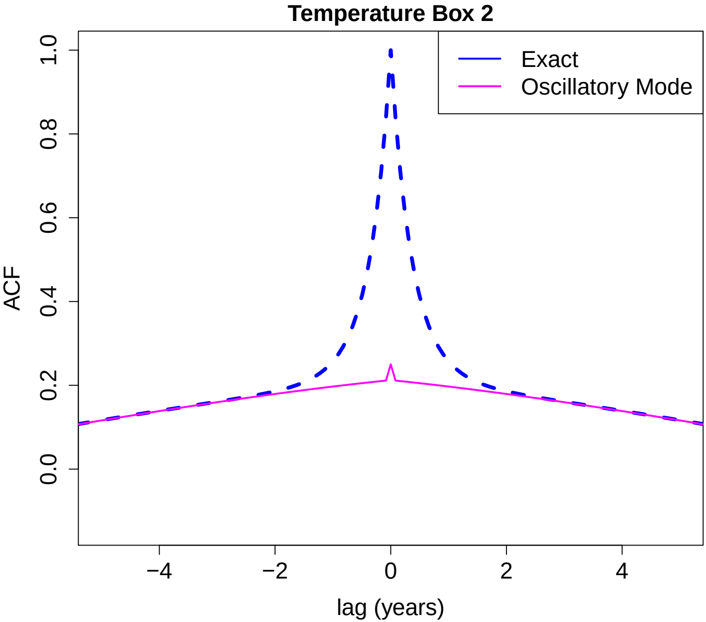


CMIP5 Autocorrelation Function of Temperature

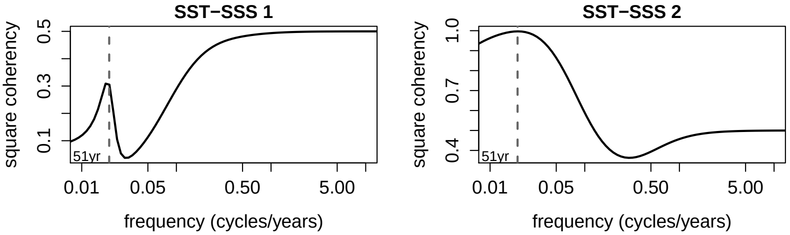


R. Zhang (2017, GRL)

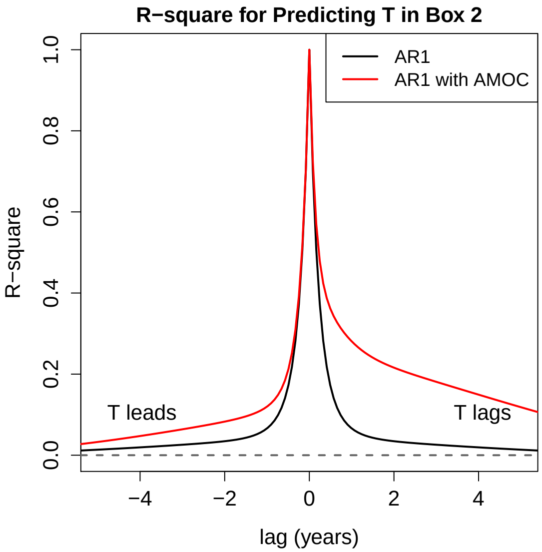
ACF Based on Oscillatory Mode



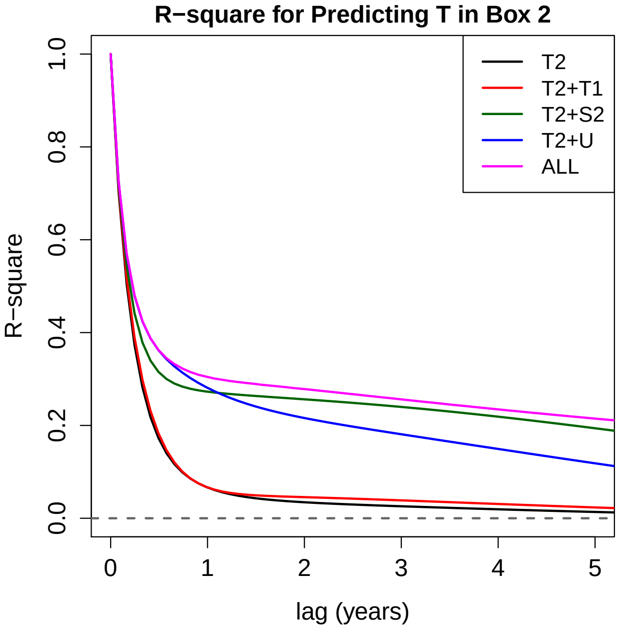
Squared Coherency



R-Square with and without AMOC index



Predictability



The low-frequency coherence between SST and SSS is not a discriminating feature for ocean circulation, since stochastic models with and without ocean circulation can reproduce it.

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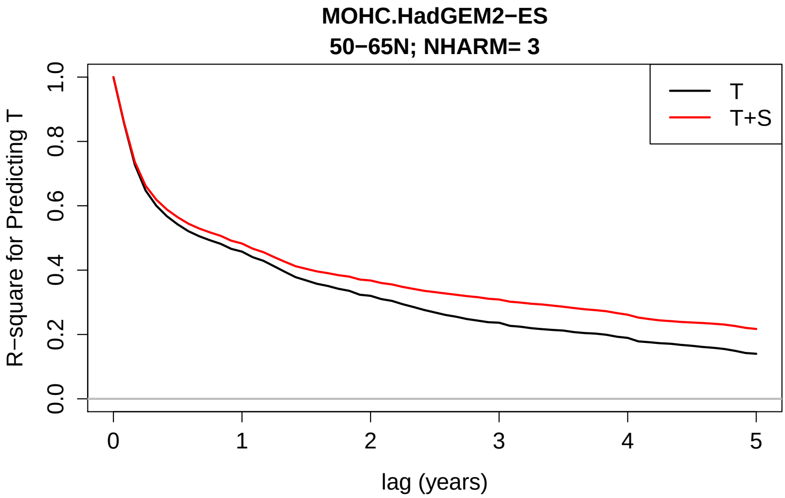
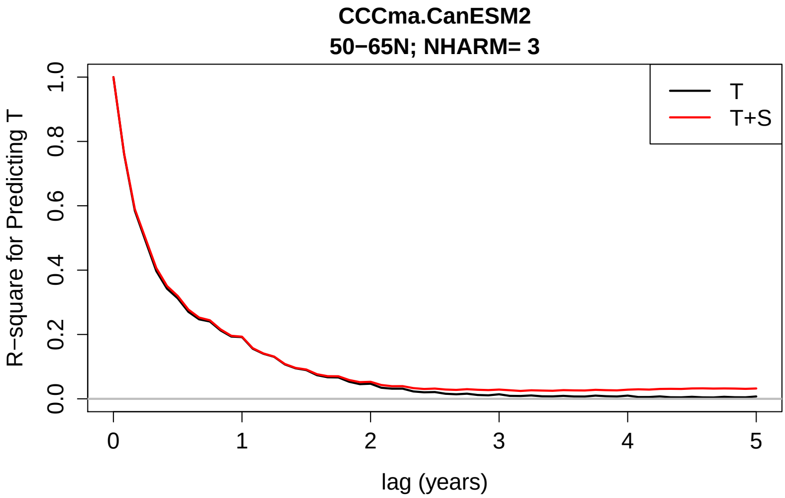
However, the enhanced predictability of SST after adding SSS as a predictor is a discriminating feature.

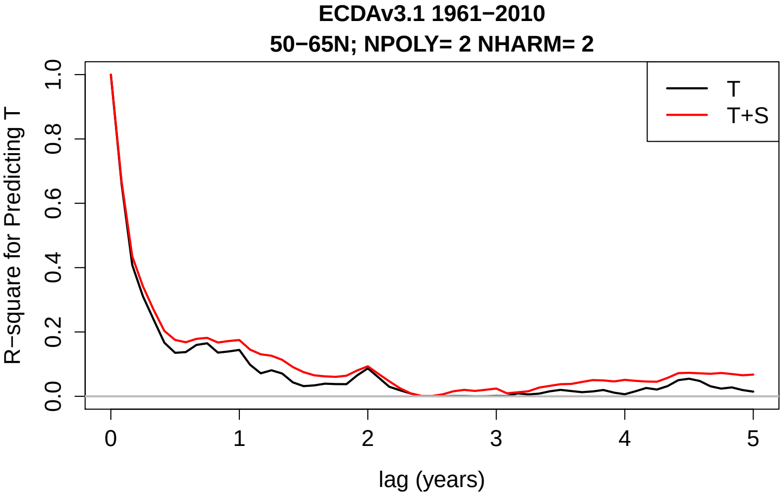
Predictability of North Atlantic in CMIP5 Models



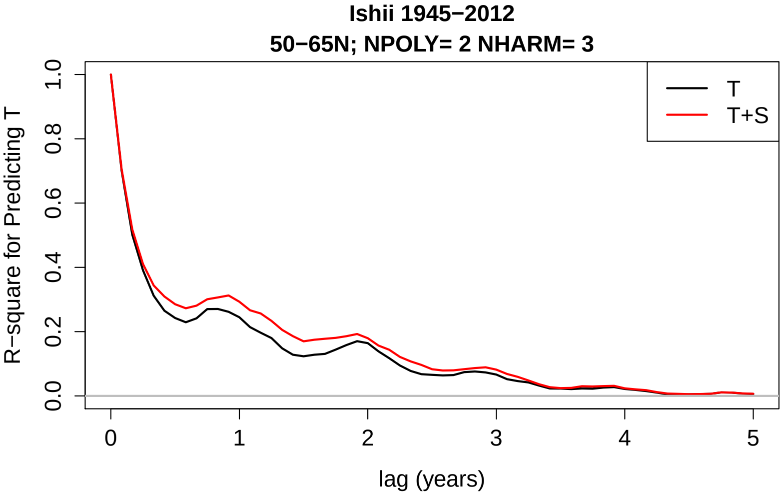
Predictability of North Atlantic in CMIP5 Models



Predictability of North Atlantic in ODA



Predictability of North Atlantic in ODA



Summary

1. The most predictable components of climate models with and without interactive ocean circulation are remarkably similar.
2. This result implies that ocean dynamics is not essential for the existence of multi-year predictability.
3. Predictability of certain individual patterns are longer in the coupled model than in slab model.
4. Predictability of slab models can be higher than that of individual slabs for spatially correlated stochastic forcing.
5. Slab models can reproduce coherence between temperature and salinity at low frequencies, if the influence of evaporation is taken into account.
6. Stommel box model can
    - Generate 2-time scale decay of ACF of temperature
    - Reproduce coherence between temperature and salinity
    - Reproduce enhanced predictability when AMOC included.
    - Reproduce predictive skill due to including salinity as predictor.