Correcting Climate Model Forecasts Using Forced Autoregressive Models

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Problem: Forecasts have biases

Solution: Subtract the lead-time and start-month climatology of the forecast errors

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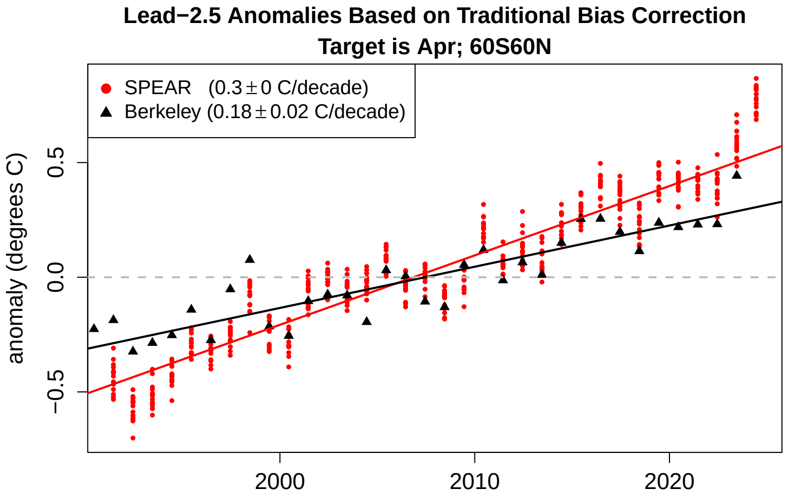
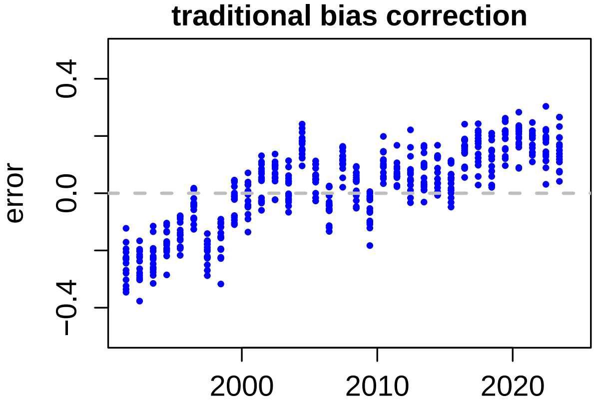
But the solution still has a problem

Data

- Forecasts from North American Multi-Model Ensemble (NMME).
- Focus on SPEAR model developed at GFDL.
- SPEAR is a coupled ocean-atmosphere-land-sea ice modeling system
- Version: SPEAR_MED, 50km resolution in the atmosphere and 1° resolution in the ocean, with refinements to $1/3^\circ$ in the tropics.
- hindcast period 1991-2020 and a forecast period 2021-2024
- 15-member ensemble forecasts
- initialized at beginning of month from January 1991 to April 2024
- ocean initial condition from an Ocean Data Assimilation system based on a 2-step Ensemble Adjustment Kalman Filter
- variable: area-weighted average 2m-temperature 60°S-60°N
- observations: Berkeley Earth data set


Lead−2.5 Anomalies Based on Traditional Bias Correction
Target is Apr; 60S60N
SPEAR (0.3 ± 0 C/decade)
Berkeley (0.18 ± 0.02 C/decade)
anomaly (degrees C)
0.5
0.0
−0.5
2000
2010
2020



If forecast model incorrectly simulates trends, forecast errors also will have a trend. Traditional bias correction cannot correct a year-dependent error because it is independent of year.

New Approach

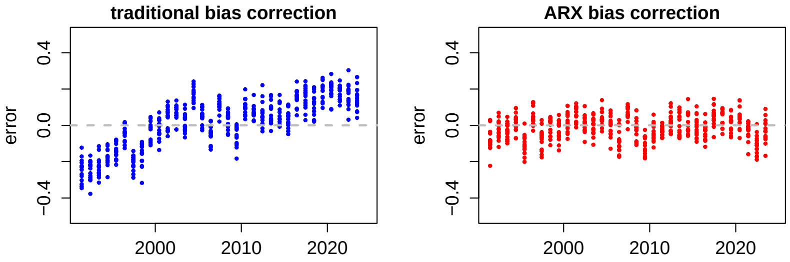
- Fit observations and forecasts to forced autoregressive models

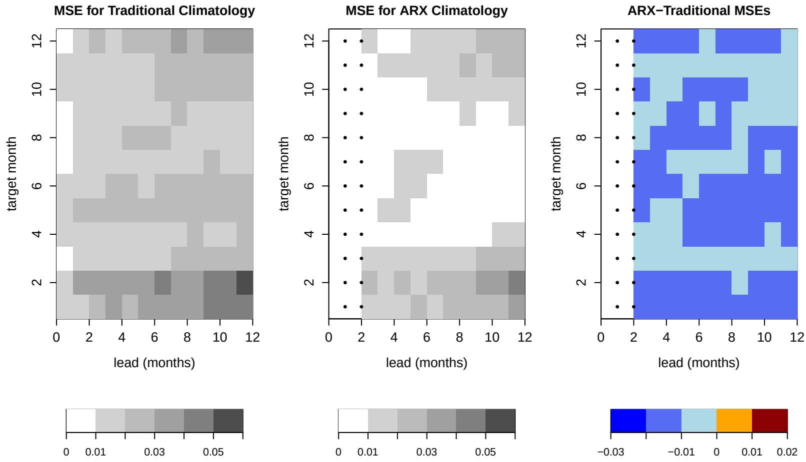
$$O(t) = \phi_1^o O(t-1) + \phi_2^o O(t-2) + \sum_{j=1}^{J} d_j^o g_j(t) + \epsilon_o(t)$$

$$F(t,\tau) = \phi_1^f F(t,\tau-1) + \phi_2^f F(t,\tau-1) + \sum_{j=1}^{J} d_j^f g_j(t+\tau) + \epsilon_f(t,\tau),$$

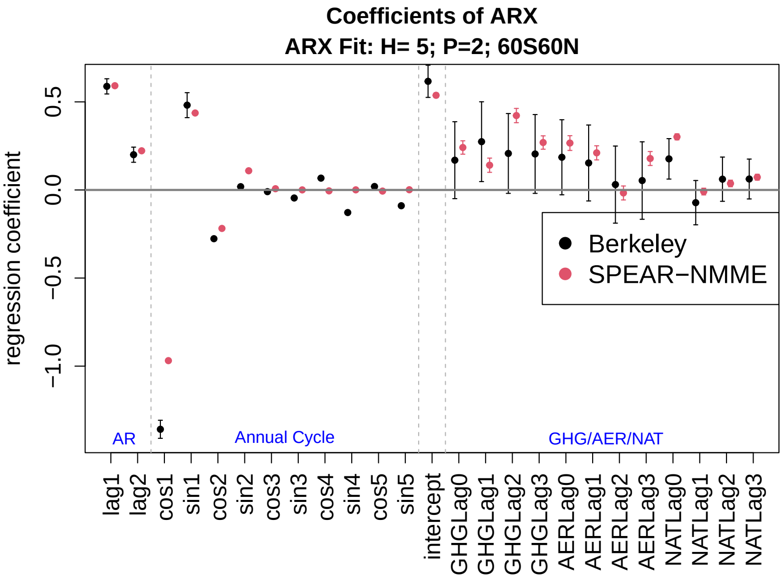
- The forcing time series $g_j(t)$ include
  - five annual harmonics to capture the annual cycle
  - radiative forcings from greenhouse gases (GHG), volcanic and solar variability (NAT), and aerosols (AER) from RFMIP.
- ARX models *predict* the drift given the initial condition and forcings. This is very different from the traditional bias correction.
- The ARX prediction is based on the *noise-free* solution.
- The difference in ARX predictions is a prediction of the error.
- This predicted error is subtracted from the actual error.

Lead−2.5 Errors of SPEAR
Target is Apr; ARX Fit: H= 5; P=2; 60S60N



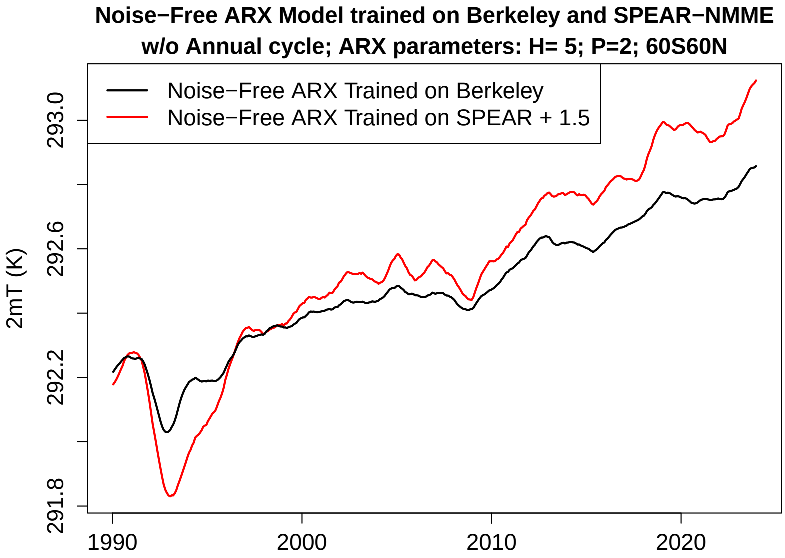

MSE for Traditional Climatology
MSE for ARX Climatology
ARX−Traditional MSEs
target month
lead (months)
0 0.01 0.03 0.05
−0.03 −0.01 0 0.01 0.02

What are the Sources of Errors?

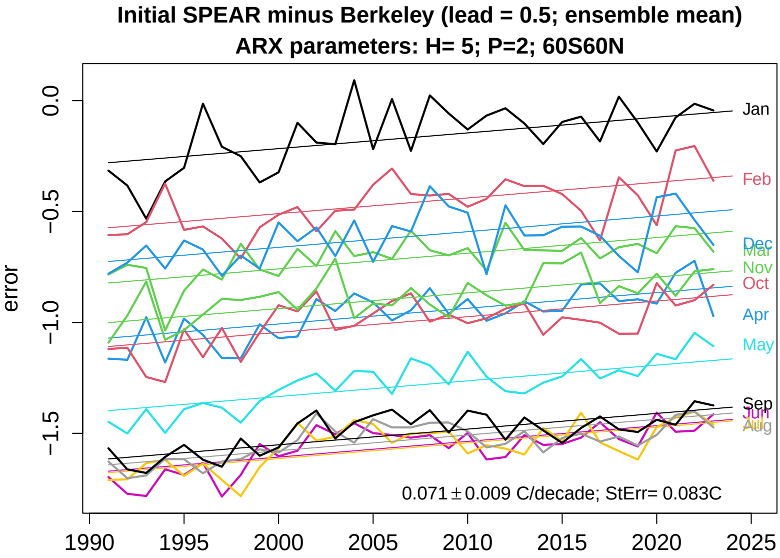


Coefficients of ARX
ARX Fit: H= 5; P=2; 60S60N
regression coefficient
0.5
0.0
−0.5
−1.0
AR
Annual Cycle
GHG/AER/NAT
Berkeley
SPEAR−NMME
lag1
lag2
cos1
sin1
cos2
sin2
cos3
sin3
cos4
sin4
cos5
sin5
intercept
GHGLag0
GHGLag1
GHGLag2
GHGLag3
AERLag0
AERLag1
AERLag2
AERLag3
NATLag0
NATLag1
NATLag2
NATLag3

SPEAR has an exaggerated response to radiative forcing.

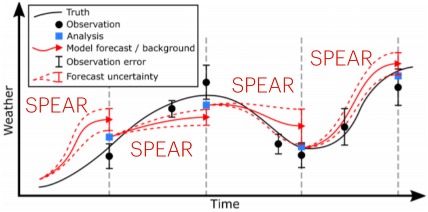


SPEAR has a large trend error in the very first month



Such IC errors are expected from using SPEAR to generate the first guess in a data assimilation system.

Data Assimilation Experiment with ARX



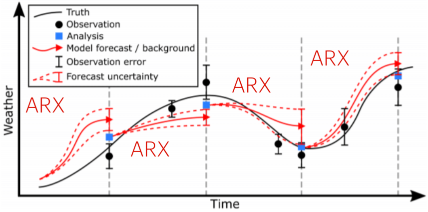
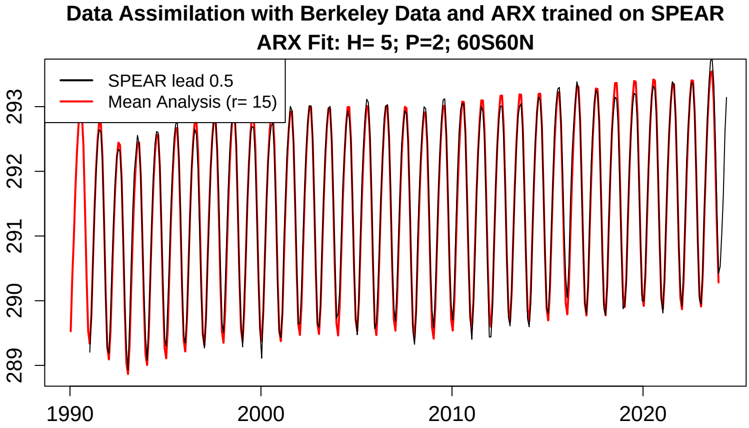


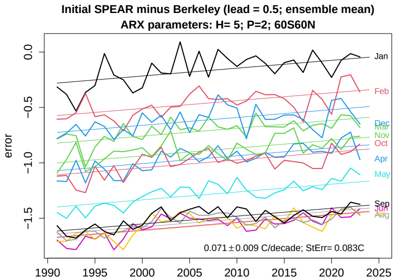
figure adapted from Max Aragón, Thesis for BSc in Earth Sciences

Data Assimilation Experiment with ARX ($r = 15\sigma_W^2$)

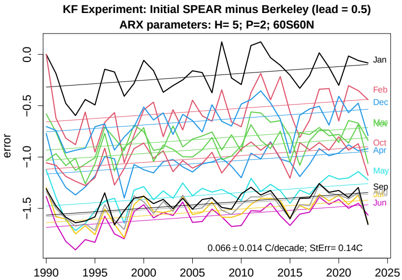


Such IC errors are expected from using SPEAR to generate the first guess in a data assimilation system.

Actual Initial Error



Simulated Initial Error



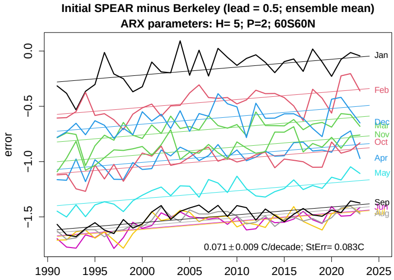
New Experiment

"Correct" the response to forcing by replacing the transfer coefficients in the SPEAR ARX model with those obtained by training on observations

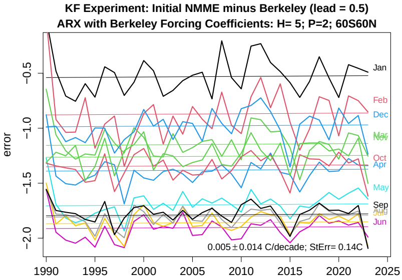
$$O(t) = \phi_1^o O(t-1) + \phi_2^o O(t-2) + \sum_{j=1}^{J} d_j^o g_j(t) + \epsilon_o(t)$$

$$F(t,\tau) = \phi_1^f F(t,\tau-1) + \phi_2^f F(t,\tau-1) + \sum_{j=1}^{J} \boxed{d_j^o} g_j(t+\tau) + \epsilon_f(t,\tau),$$

Actual Initial Error



Simulated Initial Error Corrected Response



Summary

- We use ARX models to predict forecast error and then subtract it.
- This approach can correct trend errors, unlike traditional correction.
- Resulting ARX models can be compared to diagnose errors.
- SPEAR reasonably captures internal variability but has muted annual cycle and exaggerated response to external forcing.
- Data assimilation using SPEAR will inherit these biases (for large r).
- Data assimilation using ARX model produces similar IC errors.
- Fixing the response to forcing removes the trend in IC error.