A STATISTICAL MODEL OF THE GLOBAL CARBON BUDGET

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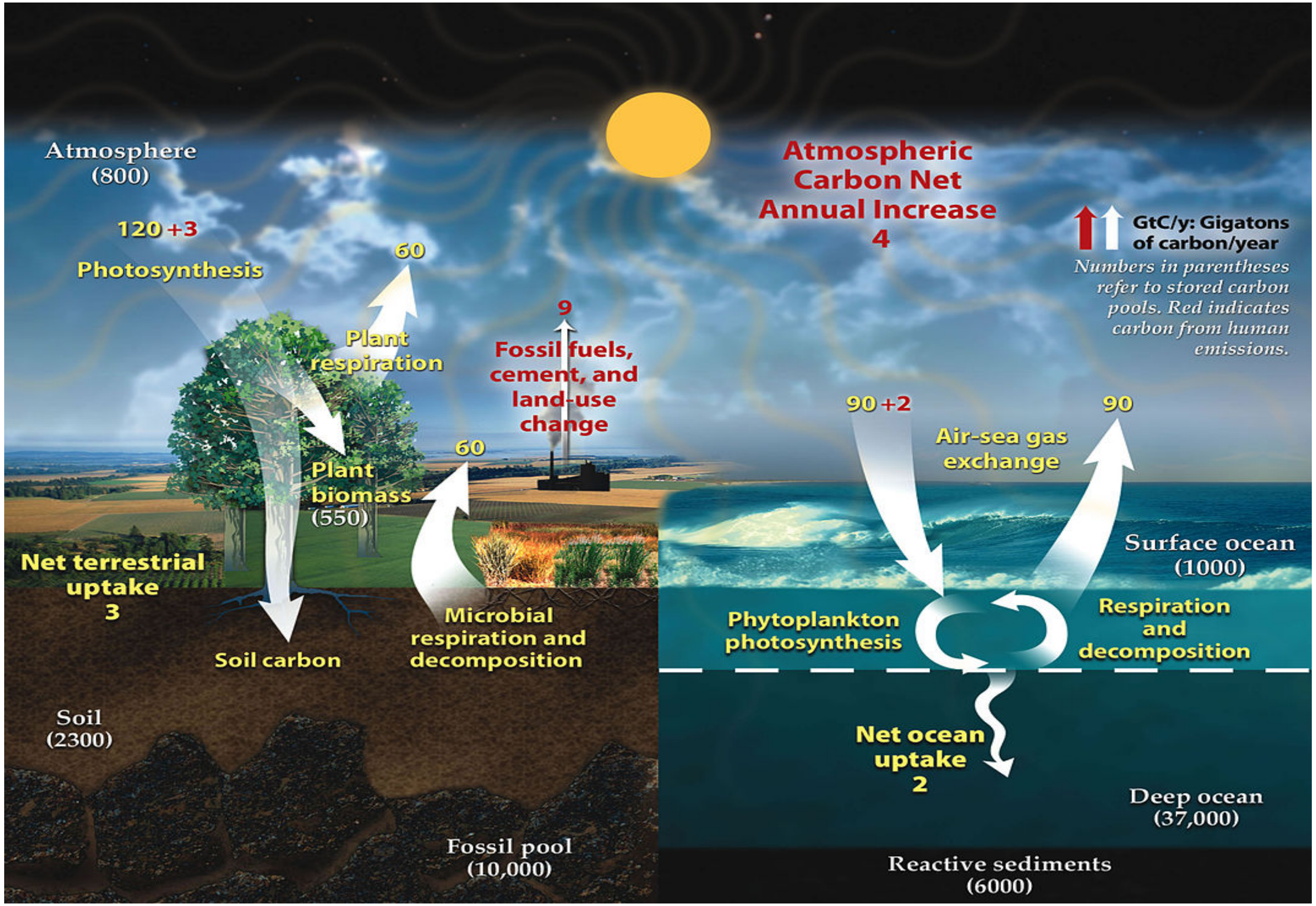
GLOBAL CARBON CYCLE



Source: Wikipedia

DATA

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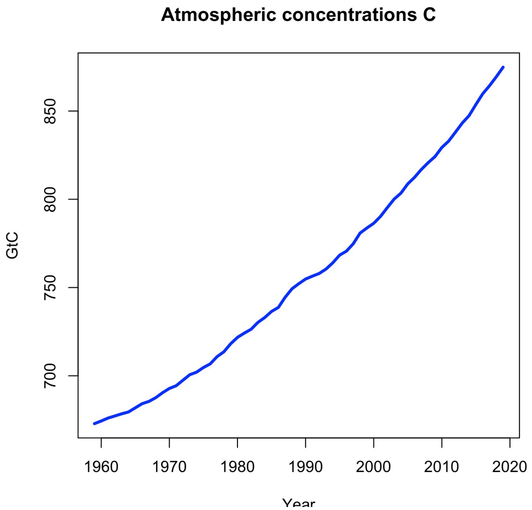

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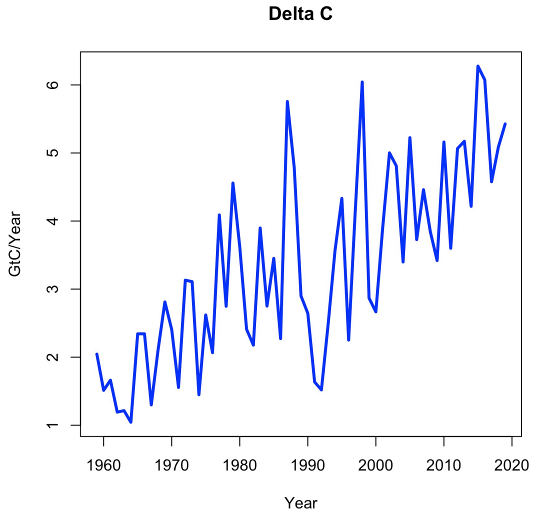

GLOBAL CARBON PROJECT

www.globalcarbonproject.org

Friedlingstein et al. (2020),
The gobal carbon budget 2020,
Earth System Science Data 12,
3269-3340

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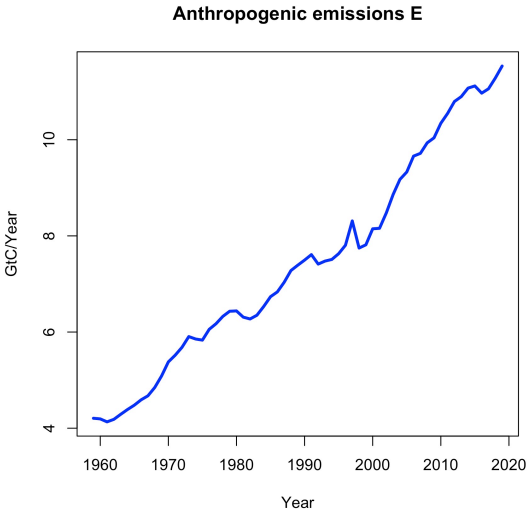

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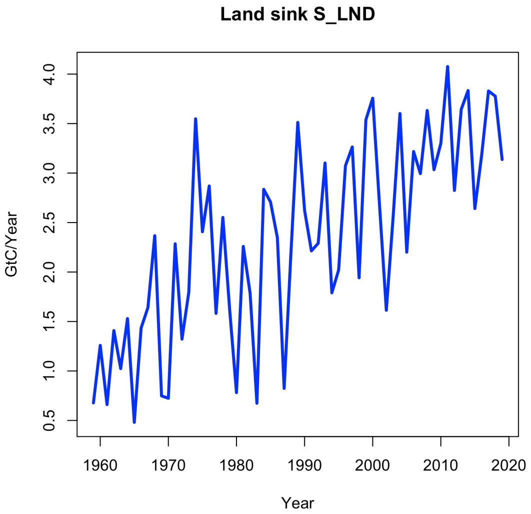

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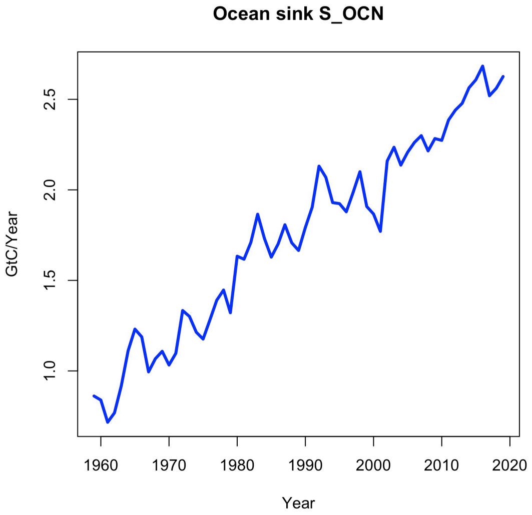

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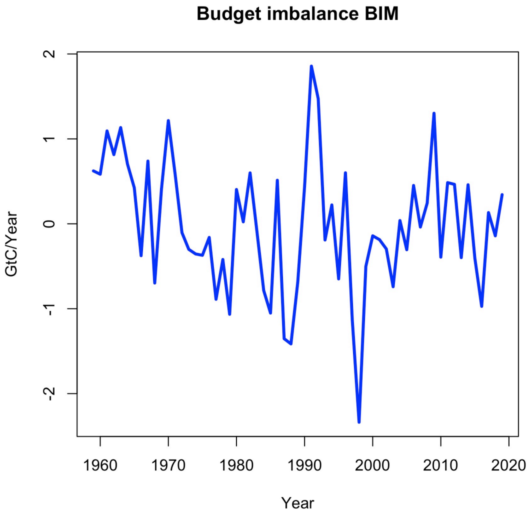
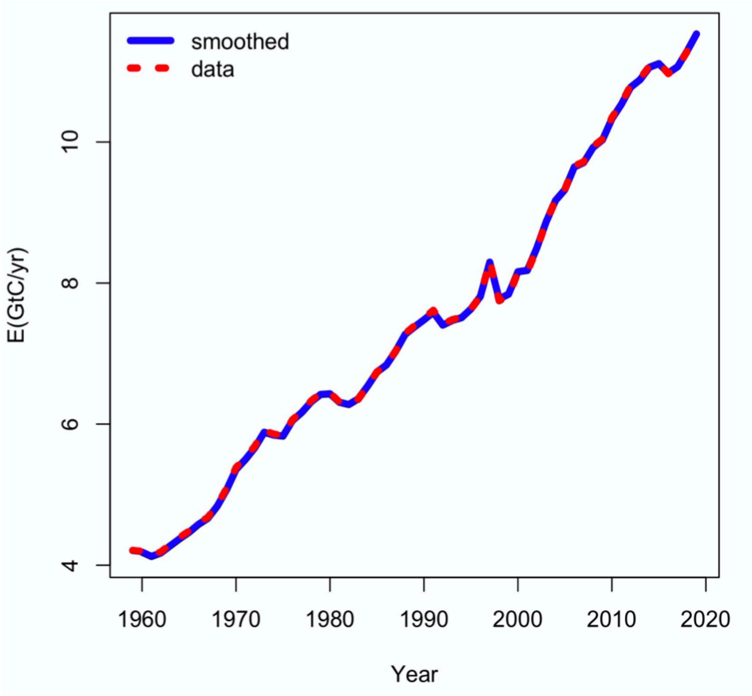


OUTLINE OF THE TALK

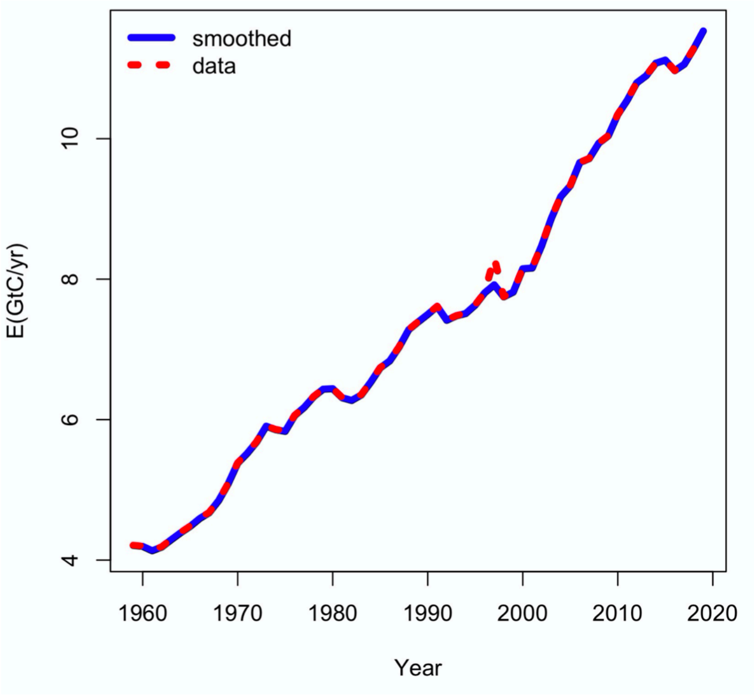
1. Models for the components of the global carbon budget
2. The dynamics of atmospheric concentrations C
3. The system model
4. Residual diagnostics
5. Simulation
6. Airborne fraction, sink rate
7. Nowcasts and forecasts
8. Projections: Long-term scenarios until 2100
9. Conclusions

ANTHROPOGENIC EMISSIONS



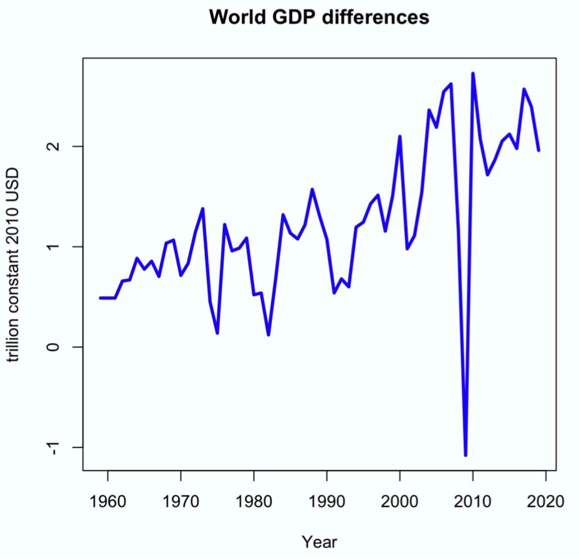
$$\Delta E_t = \underset{(0.02)}{0.14} + X_t^E,$$

$$X_{t+1}^E = \underset{(0.26)}{0.06} X_t^E + \eta_{5,t},\ \eta_{5,t} \sim N(0, \underset{(0.032)}{0.024})$$



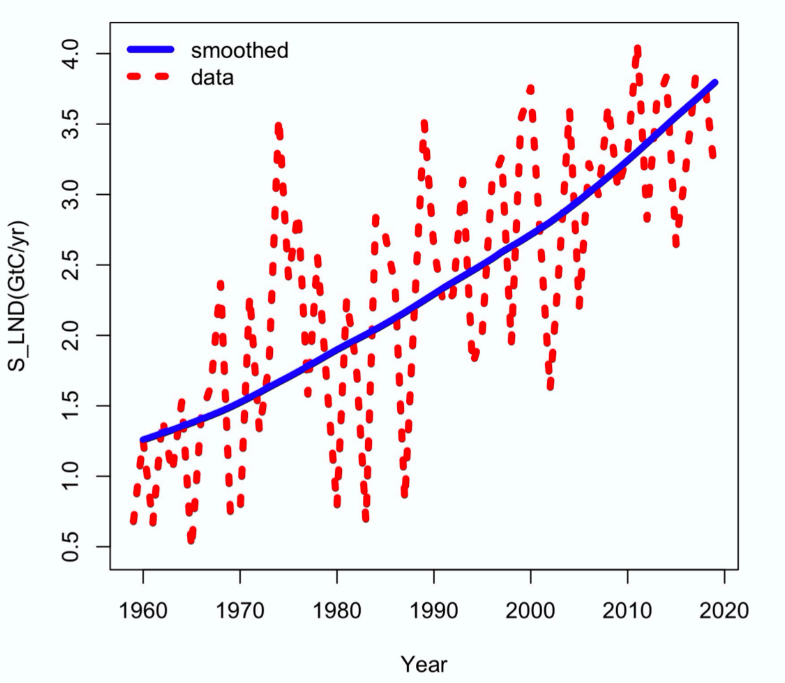
$$\Delta E_t = \underset{(0.01)}{0.11} \Delta GDP_t - \underset{(0.06)}{0.29} I1991 + X_t^E,$$

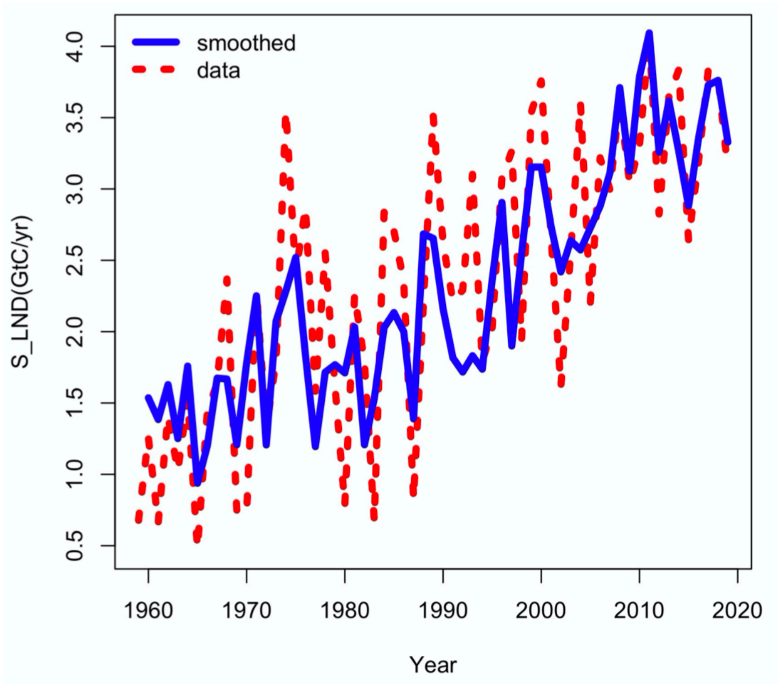
$$X_{t+1}^E = \underset{(0.12)}{0.39} X_t^E + \eta_{4,t},\ \eta_{4,t} \sim N(0, \underset{(0.001)}{0.004})$$

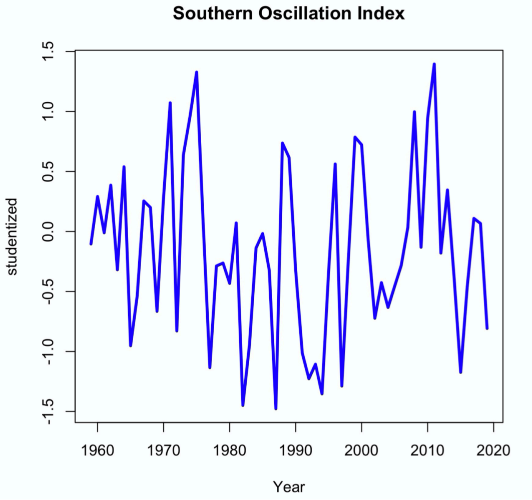


Friedlingstein et al. (2020)
Bennedsen, Hillebrand, Koopman (2021)

LAND SINK







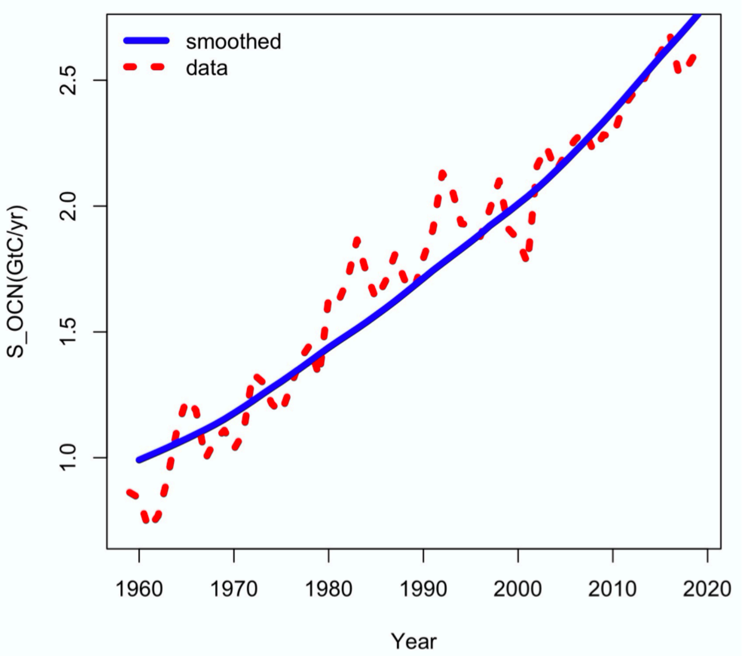
"Moisture sensitivities of both productivity and decomposition are important for capturing the response of the net flux to such [La Nina] events." Haverd et al. (2018, p. 3013)

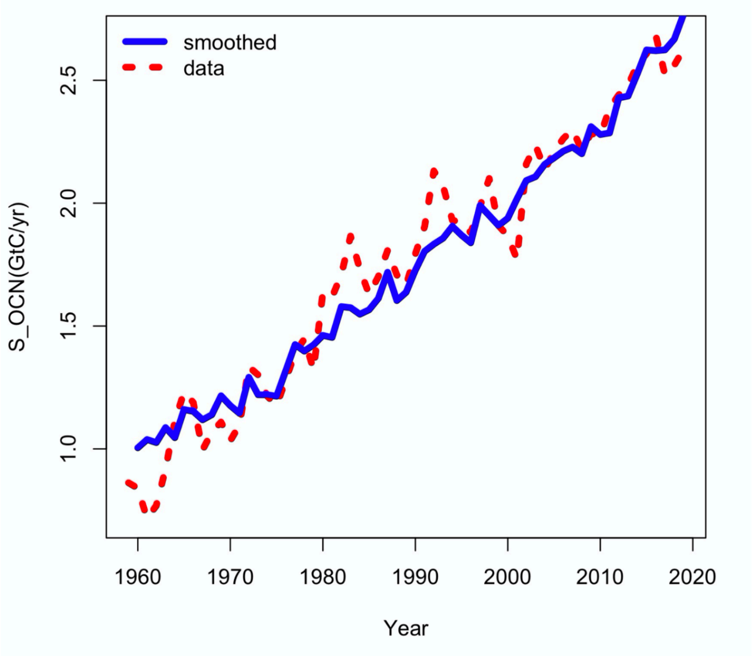
$$S\_LND_t = \underset{(0.05)}{-7.22} + \underset{(0.97)}{7.48}\,\frac{C_t}{C_0}$$

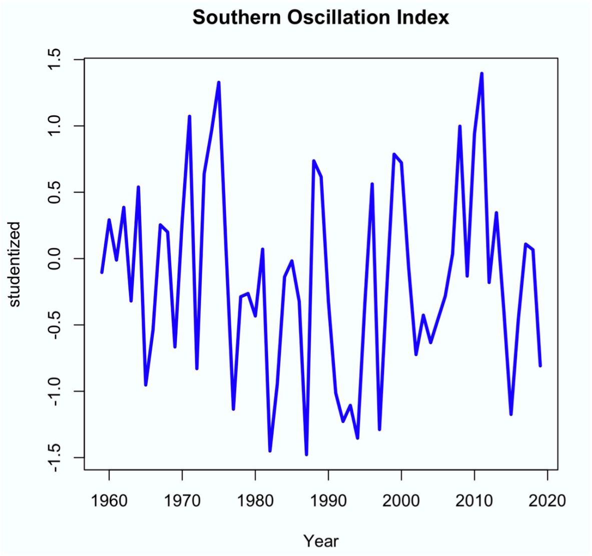
$$S\_LND_t = \underset{(0.04)}{-6.70} + \underset{(0.49)}{7.12}\,\frac{C_t}{C_0} + \underset{(0.09)}{0.57}\,SOI_t$$

Raupach et al. (2014), Raupach (2013), Gloor et al. (2010), Canadell et al. (2007)

OCEAN SINK







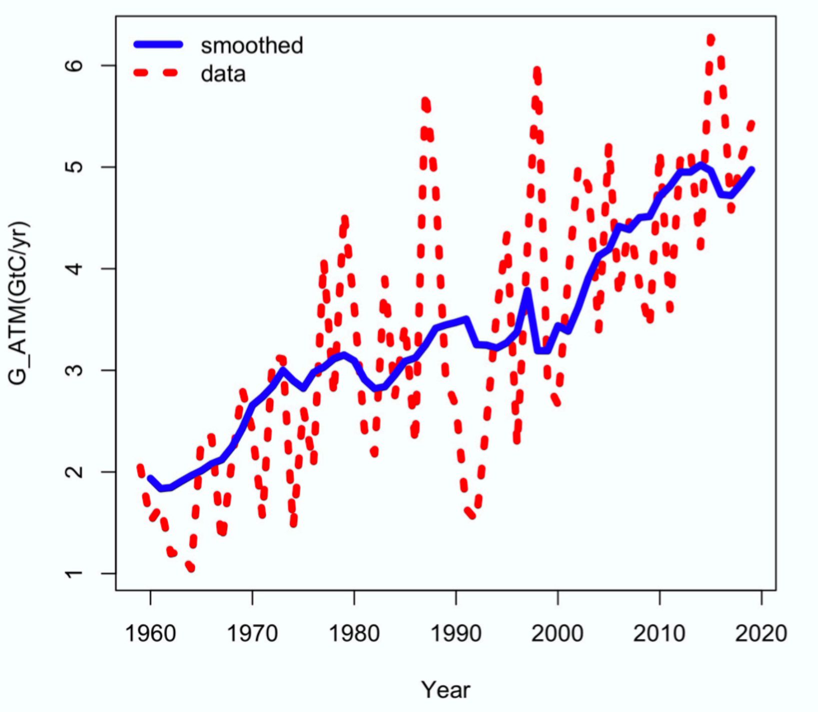
"When the winds are strongest during the cold cycle of ENSO deep upwelling occurs and [ocean CO2 partial pressure] values are at a maximum." Feely et al. (1999, p. 599)

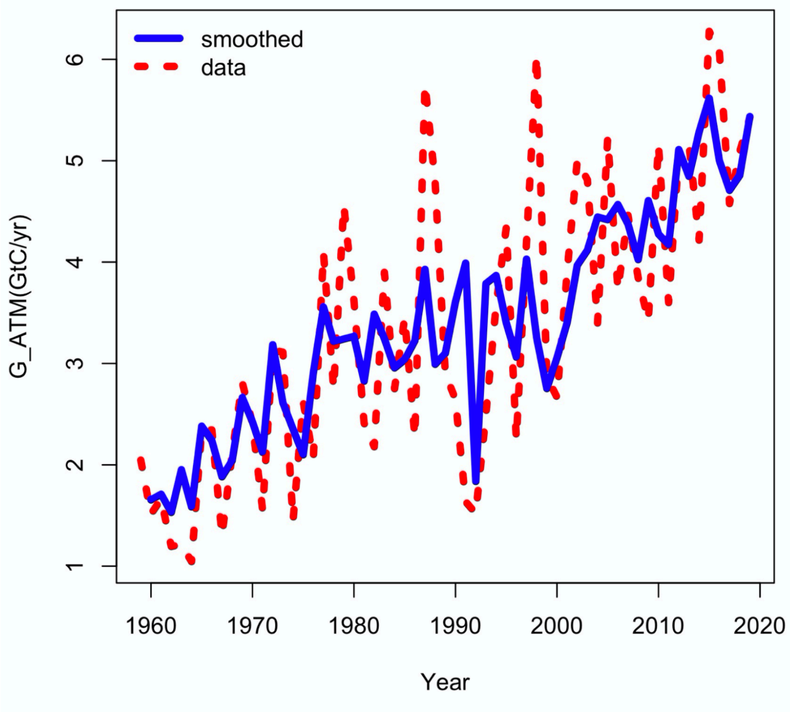
$$S\_OCN_t = \underset{(0.04)}{-4.93} + \underset{(0.41)}{5.22}\frac{C_t}{C_0}$$

$$S\_OCN_t = \underset{(0.03)}{-4.63} + \underset{(0.29)}{4.99}\frac{C_t}{C_0} - \underset{(0.02)}{0.06}SOI_t$$

Raupach et al. (2014), Raupach (2013), Gloor et al. (2010), Canadell et al. (2007)

ΔC = GROWTH IN ATM. CONCENTRATIONS





$$\Delta C_t = E_t - S\_LND_t - S\_OCN_t$$

THE DYNAMICS OF C

$$\Delta C_t = E_t - S\_LND_t - S\_OCN_t$$

$$= E_t - c_1 - c_2 - \beta_1^* C_t - \beta_2^* C_t + \varepsilon_t, \quad \varepsilon_t \sim I(0)$$

$$(1 + \beta_1^* + \beta_2^*)C_t - C_{t-1} = c + dt + x_t + \varepsilon_t$$

$$(1 - qL)C_t = qc + qdt + qx_t + q\varepsilon_t$$

$$\beta_i^* = \frac{\beta_i}{C_0} \approx 0.01$$

$$x_t = \sum_{i=1}^{t} \eta_{5,i}$$

$$q := \frac{1}{1 + \beta_1^* + \beta_2^*} \approx \frac{1}{1.02}$$

Three insights:

$$C_t = q^t \left[C_0 - \frac{qc}{1-q} + \frac{dq^2}{(1-q)^2}\right] + \left[\frac{qc}{1-q} - \frac{dq^2}{(1-q)^2}\right] + \frac{dq}{1-q}t + \sum_{j=0}^{t-1} q^{j+1} x_{t-j} + \sum_{j=0}^{t-1} q^{j+1} \varepsilon_{t-j}$$

$$= o(1) + O(1) + O(t) + I(1) + I(0) = O(t) + I(1)$$

Thus,

$$\Delta C_t = I(0)$$

But,

$$(1 - qL)(1 - L)C_t = qd + q\Delta x_t + q\Delta\varepsilon_t = I(0)$$

THE SYSTEM MODEL

State equation **Model 1**

$$S\_LND^*_{t+1} = c_1 + \frac{\beta_1}{C_0} C^*_{t+1}$$

$$S\_OCN^*_{t+1} = c_2 + \frac{\beta_2}{C_0} C^*_{t+1}$$

$$E^*_{t+1} = E^*_t + d + X^E_t$$

State equation **Model 2**

$$S\_LND^*_{t+1} = c_1 + \frac{\beta_1}{C_0} C^*_{t+1} + \beta_3 SOI_{t+1}$$

$$S\_OCN^*_{t+1} = c_2 + \frac{\beta_2}{C_0} C^*_{t+1} + \beta_4 SOI_{t+1}$$

$$E^*_{t+1} = E^*_t + \beta_5 \Delta \log GDP^{World}_{t+1} + \beta_8 I1991 + X^E_t$$

Measurement equation

$$C_t = C^*_t + X_{1,t}$$

$$S\_LND_t = S\_LND^*_t + X_{2,t}$$

$$S\_OCN_t = S\_OCN^*_t + X_{3,t}$$

$$E_t = E^*_{t-1} + \beta_6 I1997$$

$$C^*_{t+1} = C^*_t + G\_ATM^*_{t+1}$$

$$G\_ATM^*_{t+1} = E^*_{t+1} - {S_{LND}}^*_{t+1} - {S_{OCN}}^*_{t+1} + \beta_7 I1991$$

$$X_{1,t} = \phi_1 X_{1,t-1} + \eta_{1,t}$$

$$X_{2,t} = \eta_{2,t}$$

$$X_{3,t} = \phi_3 X_{3,t-1} + \eta_{3,t}$$

$$X^E_t = \phi_E X^E_{t-1} + \eta_{4,t}$$

$$\begin{bmatrix} \eta_{1,t} \\ \eta_{2,t} \\ \eta_{3,t} \\ \eta_{4,t} \end{bmatrix} \sim N \left[0, \begin{bmatrix} \sigma_1^2 & r_{12}\sigma_1\sigma_2 & r_{13}\sigma_1\sigma_3 & 0 \\ r_{12}\sigma_1\sigma_2 & \sigma_2^2 & 0 & 0 \\ r_{13}\sigma_1\sigma_3 & 0 & \sigma_3^2 & 0 \\ 0 & 0 & 0 & \sigma_4^2 \end{bmatrix} \right]$$

$$\eta_{4,t} \sim N(0, \sigma_4^2\, s_E^2\, I_{t \geq 1996})$$

RESIDUAL DIAGNOSTICS

Model 1

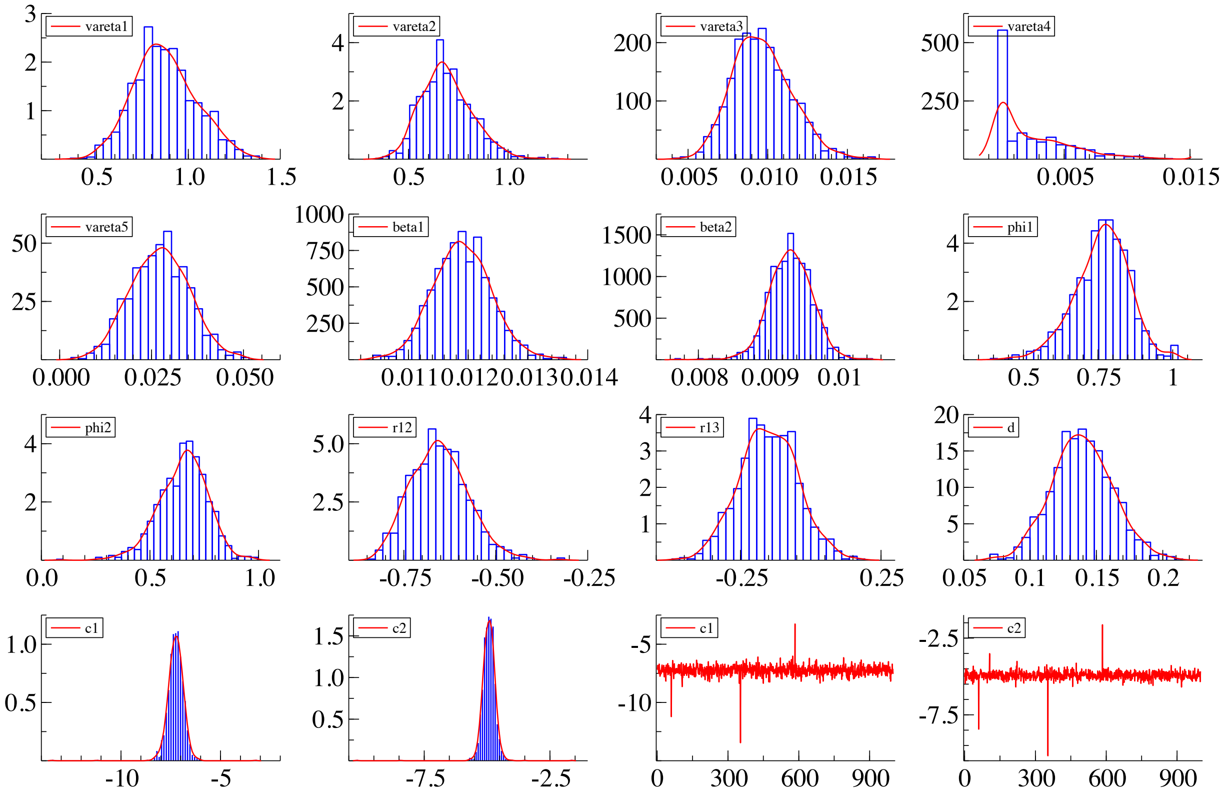
Residual	mean	std dev	skew	kurt	JB	LB(1)	DW
C	-0.183	0.964	0.205	2.765	0.568	1.607	1.653
E	-0.033	1.009	-1.448	8.506	98.38***	0.073	2.060
S_LND	0.061	1.022	0.047	2.615	0.399	0.054	2.037
S_OCN	0.093	0.978	0.377	2.988	1.447	0.116	1.908

Model 2

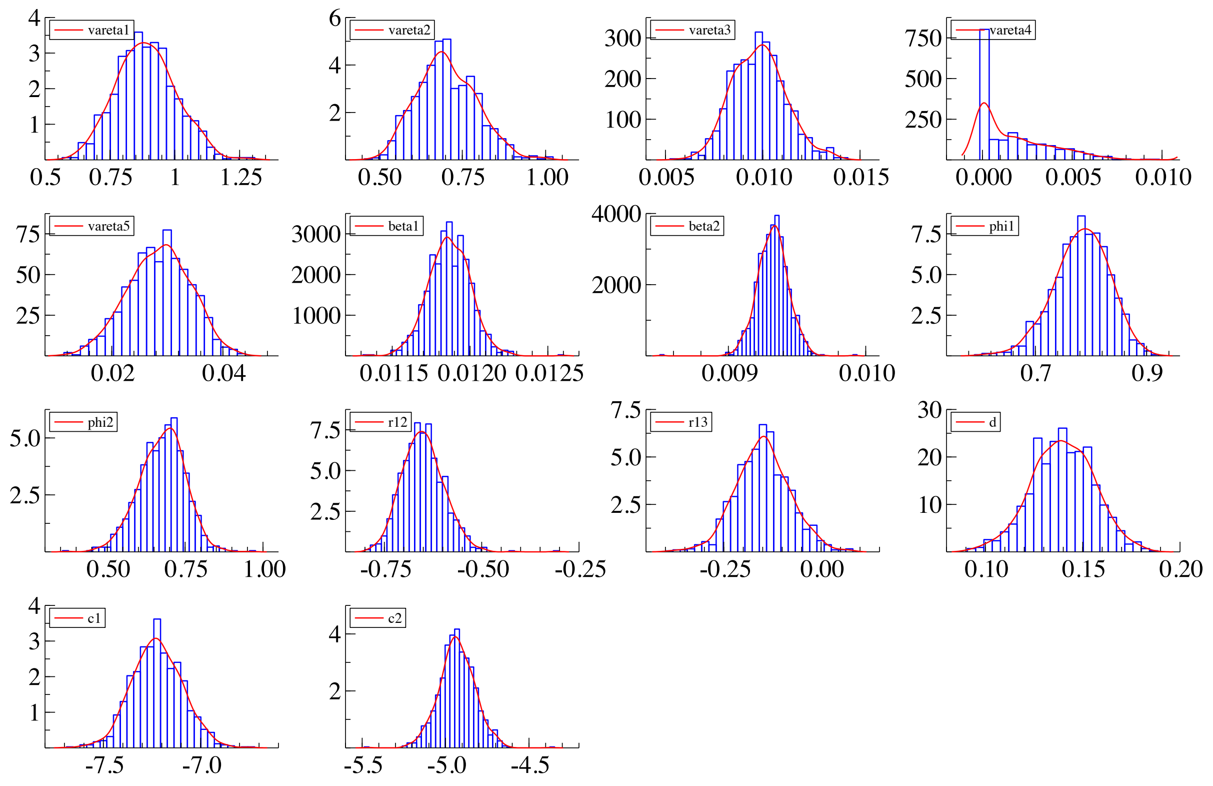
Residual	mean	std dev	skew	kurt	JB	LB(1)	DW
C	-0.140	0.979	0.167	3.272	0.471	0.350	1.840
E	0.004	0.983	-0.269	3.095	0.759	0.062	1.928
S_LND	0.164	0.995	0.285	2.530	1.387	0.223	2.111
S_OCN	0.120	0.951	0.440	3.394	2.360	0.648	2.191

SIMULATIONS OF MODEL 1

T=60

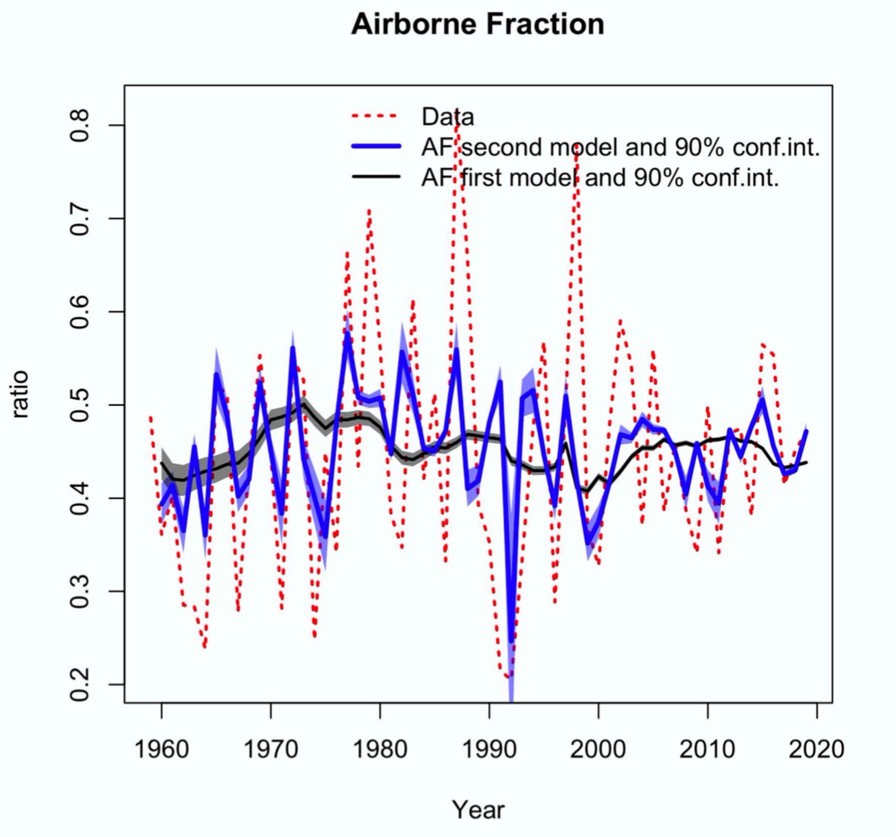


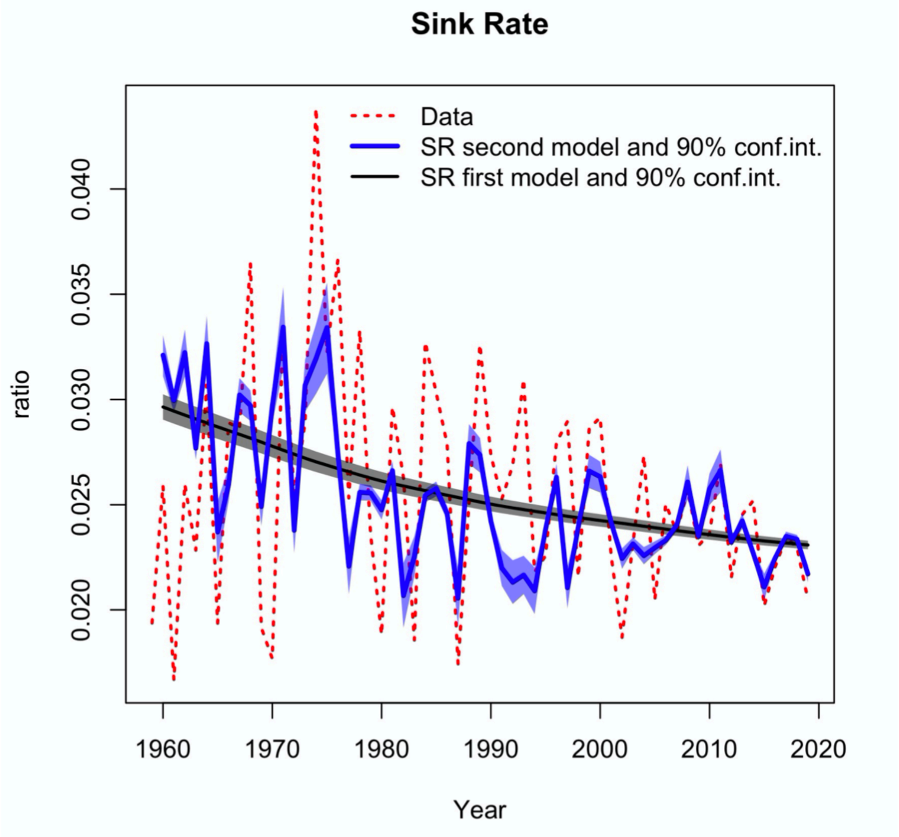
T=120



σ_4^2 exhibits "pile-up" problem (Stock and Watson 1998)

AIRBORNE FRACTION AND SINK RATE





$$AF = \frac{\Delta C}{E}$$

$$SR = \frac{S\_LND + S\_OCN}{C}$$

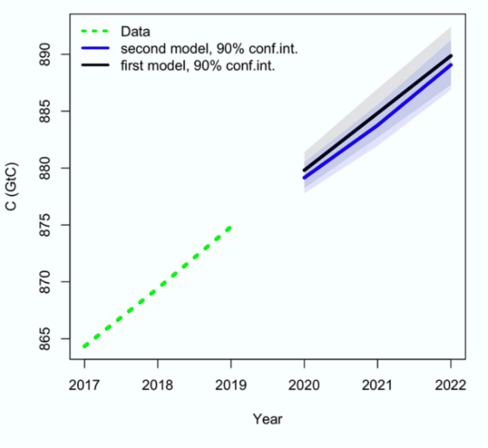
Raupach et al. (2014), Bennedsen, Hillebrand, Koopman (2019)

NOW-/FORECASTS

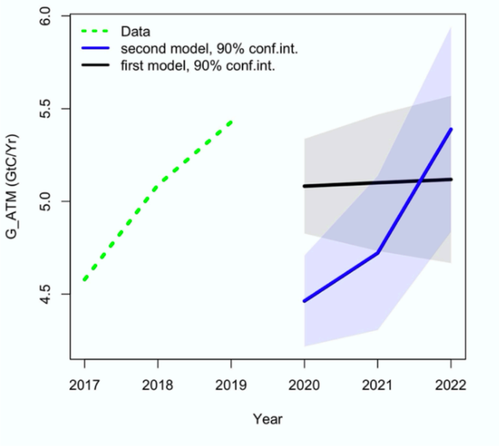
Forecasts of World GDP growth from IMF and World Bank

	2020	2021	2022
IMF	-3.5%	5.5%	4.2%
World Bank	-4.3%	4.0%	3.8%

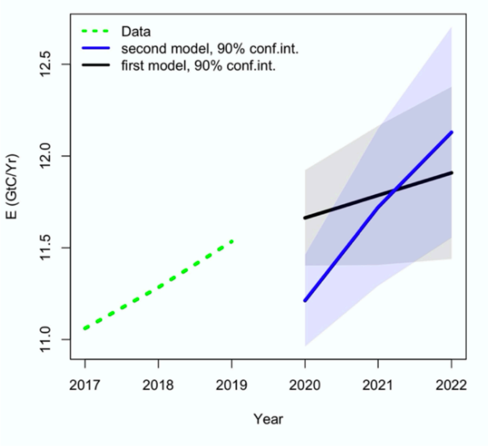
Forecasts of SOI from forecast model of monthly SOI data 1866-2020, with trigonometric seasonal and second-order trigonometric cycle w/ period about 4 years



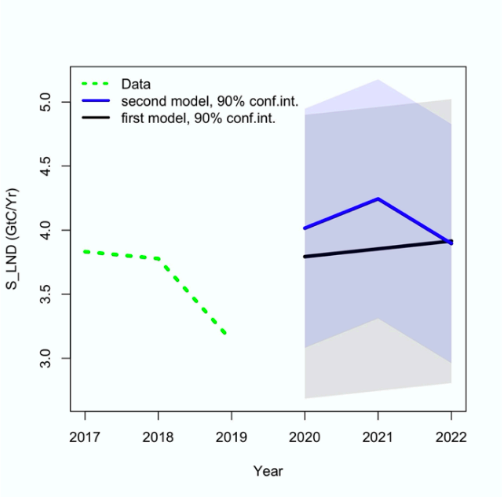
(A) C - IMF



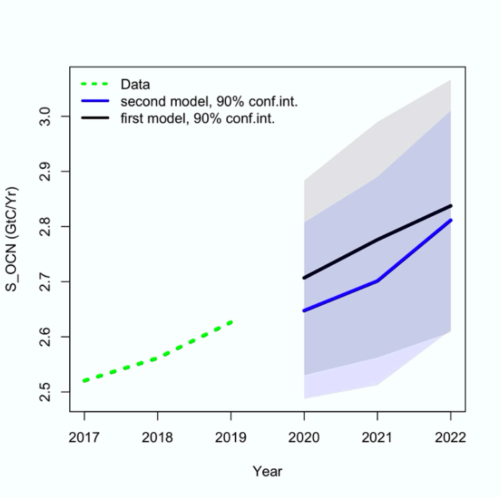
(B) G_ATM* - IMF



(C) E - IMF



(D) S_LND - IMF



(E) S_OCN - IMF

PROJECTIONS TO 2100

$$E^*_{t+1} = E^*_t + \beta_{5,t}\Delta GDP_{2010,t+1} + \beta_8 I1991 + X^E_t,$$

$$\beta_{5,t+1} = \beta_{5,t} + \eta_{5,t},$$

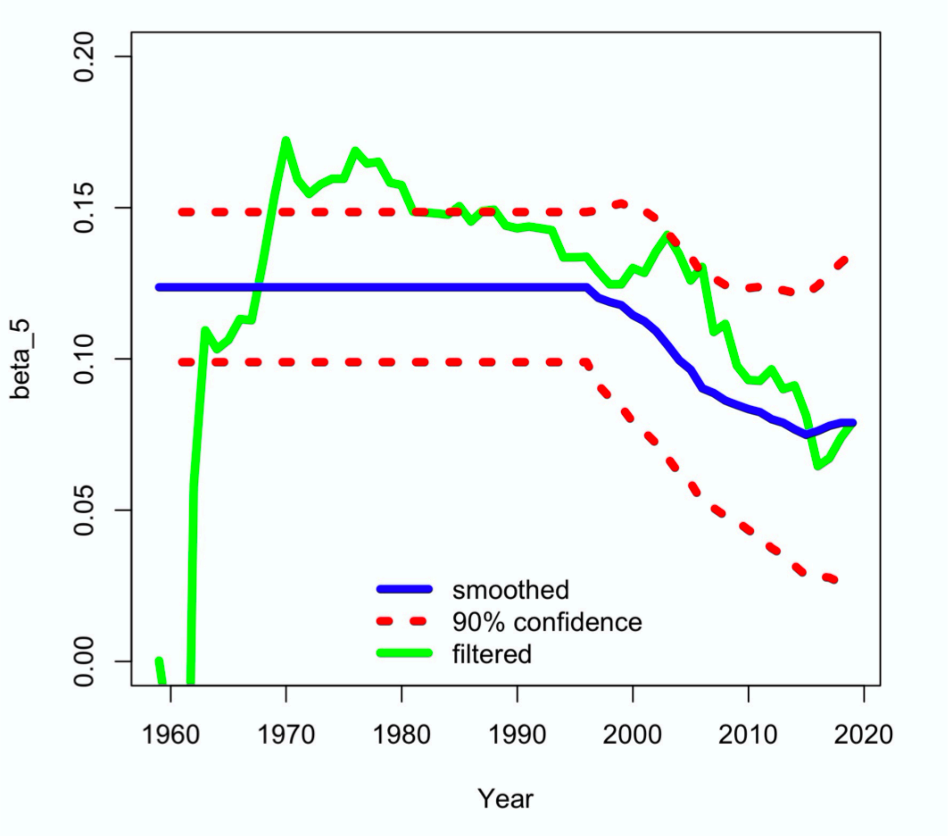
Scenarios:

GDP
- 1% growth
- 3.4% growth

IPCC SR15 (2018)
UNFCCC NDC Synthesis Report (2021)

1.5° warming
- 55% of 2010 emissions by 2030
- Net-0 by 2050
- $\beta_{5,t}$decreasing linearly to 0 by 2050

<2° warming
- 75% of 2010 emissions by2030
- Net-0 by 2070
- $\beta_{5,t}$decreasing linearly to 0 by 2070



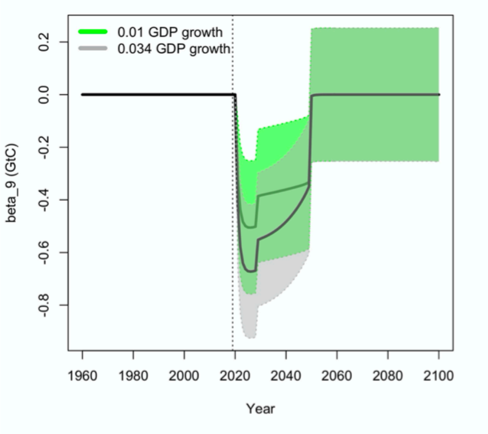
PROJECTIONS TO 2100

$$E^*_{t+1} = E^*_t + \beta_{9,t} + \beta_{5,t}\Delta GDP_{2010,t+1} + \beta_8 I1991 + X^E_t,$$

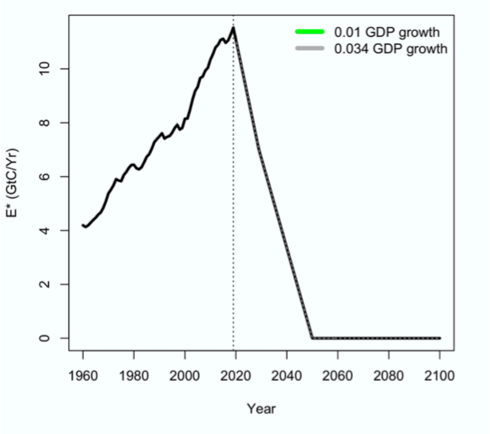
$$\beta_{9,t+1} = \beta_{9,t} + \eta_{6,t},$$

1.5° warming

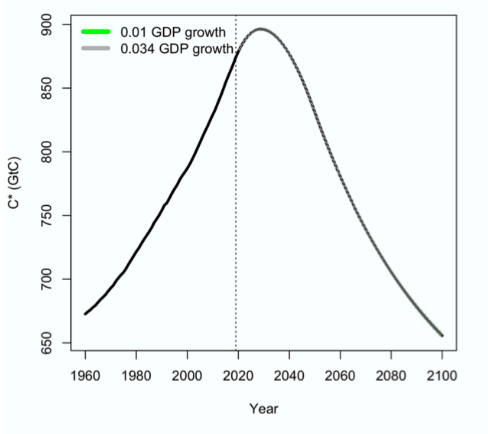
- 55% of 2010 emissions by 2030
- Net-0 by 2050
- $\beta_{5,t}$decreasing linearly to 0 by 2050



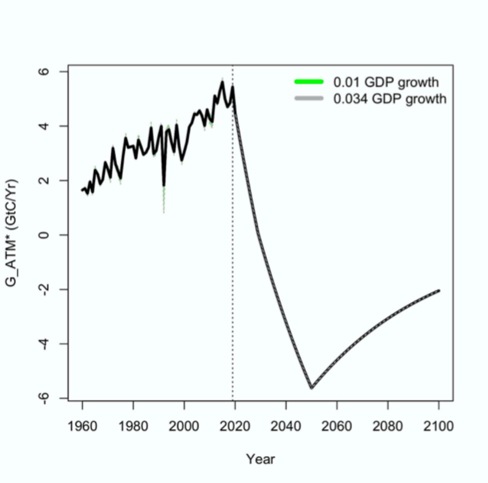
(A) Emission reductions $\beta_{9,t}$



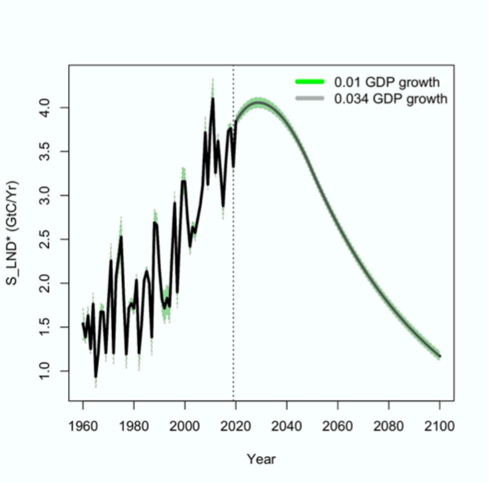
(B) E*



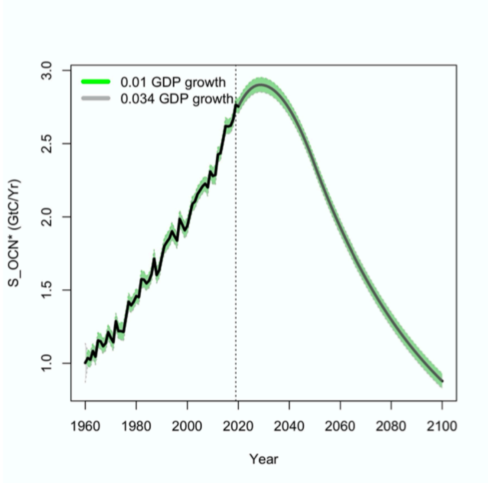
(C) C*



(D) G_ATM*



(E) S_LND*



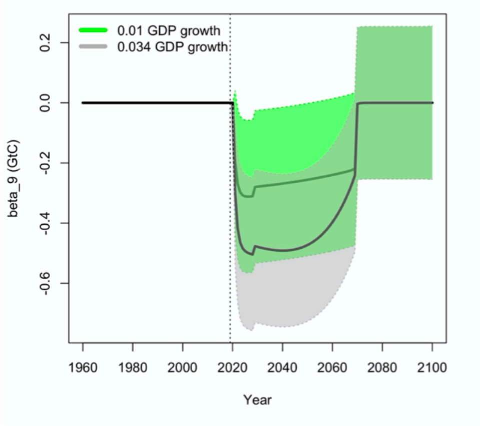
(F) S_OCN*

PROJECTIONS TO 2100

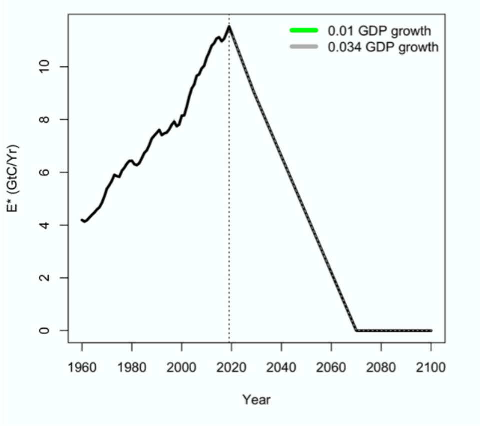
$$E^*_{t+1} = E^*_t + \beta_{9,t} + \beta_{5,t}\Delta GDP_{2010,t+1} + \beta_8 I1991 + X^E_t,$$

$$\beta_{9,t+1} = \beta_{9,t} + \eta_{6,t},$$

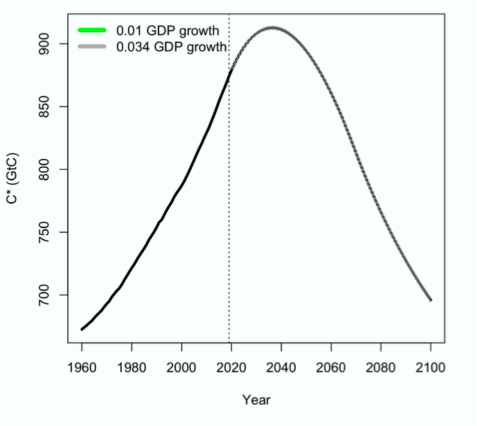
<2° warming
- 75% of 2010 emissions by2030
- Net-0 by 2070
- $\beta_{5,t}$decreasing linearly to 0 by 2070



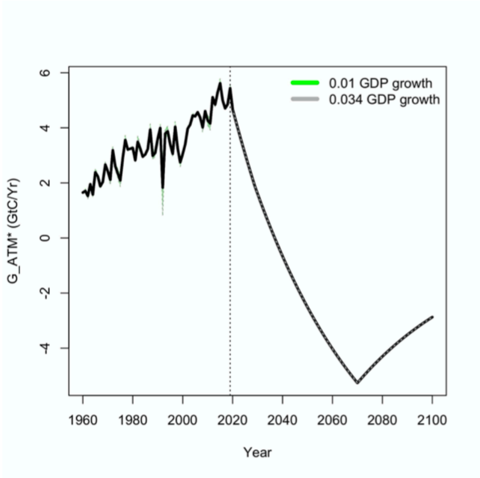
(A) Emission reductions $\beta_{9,t}$



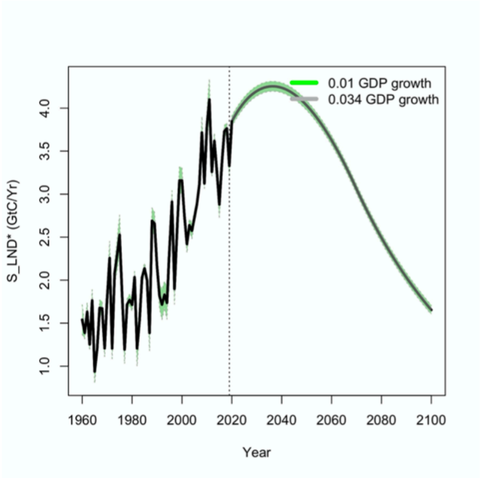
(B) E*



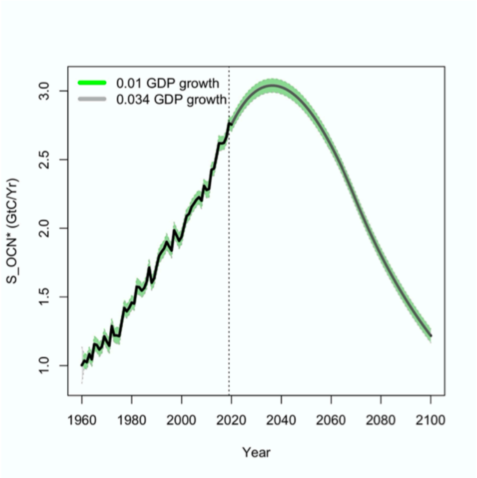
(C) C*



(D) G_ATM*



(E) S_LND*



(F) S_OCN*

CONCLUSIONS

- Specification of state-space model for Global Carbon Budget
- World GDP as driver in emissions
- Sinks: linear in CO2 concentrations and in SOI
- CO2 concentrations are I(1) ranging on I(2)
- Model allows for study of key variables such as airborne fraction and sink rate, forecasting, projecting necessary emission reductions

Future directions

- Include ensemble members for S_LND and S_OCN
- Factor model for drift in emissions using large macroeconomic dataset
- Higher resolution on Global Carbon Cycle module (MAGICC)
- Connection to temperatures (Energy Balance Models)
- Cointegration analysis

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EMISSIONS AND THE MACROECONOMY

ELSEVIER

Energy Economics
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Modeling, forecasting, and nowcasting U.S. CO_2 emissions using many macroeconomic predictors ☆

Mikkel Bennedsen [a], Eric Hillebrand [a], Siem Jan Koopman [b]

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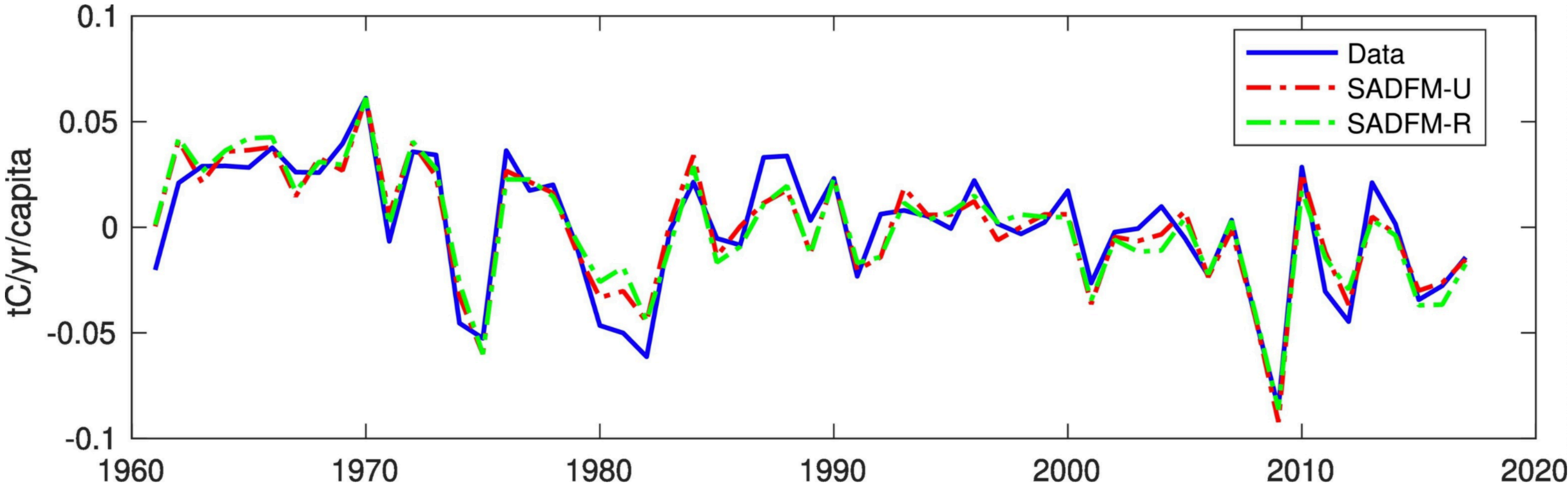
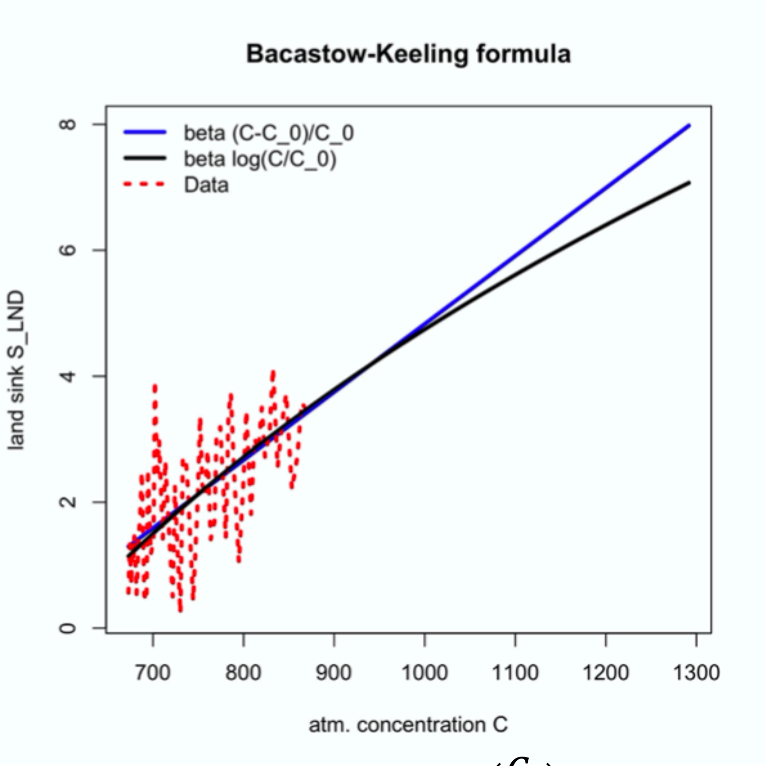
Log-differences of annual per-capita U.S. CO2 emissions explained by a structural augmented dynamic factor model of 226 macroeconomic variables



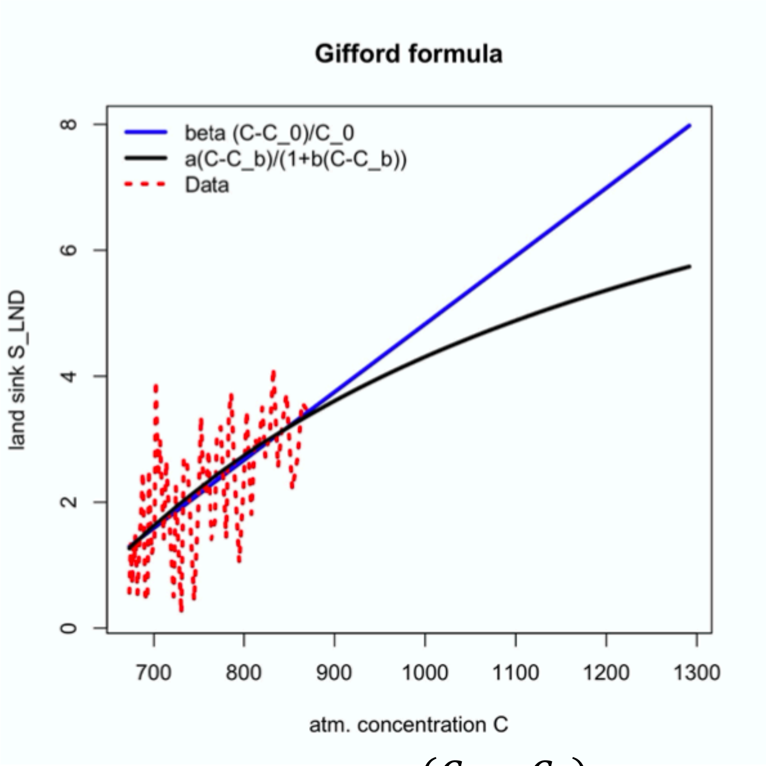
SINKS LINEAR IN CONCENTRATIONS



$$S\_LND_t = \beta \log\left(\frac{C_t}{C_0}\right)$$

C_0 pre−industrial concentration 593GtC or 279ppm

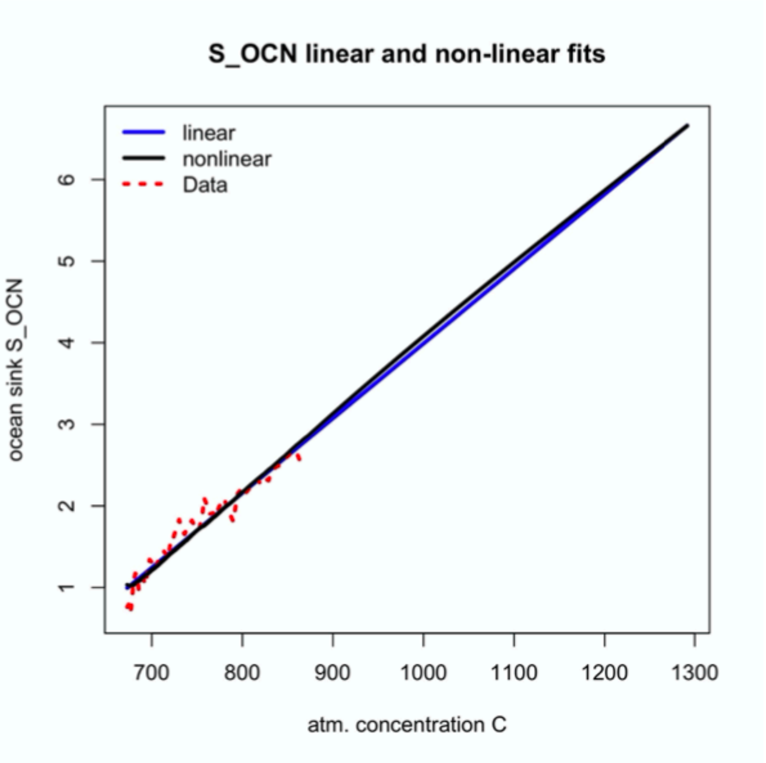
Bacastow and Keeling (1973)



$$S\_LND_t = \frac{a(C_t - C_b)}{1 + b(C_t - C_b)}$$

$C_b = 80$GtC NPP−zerolevel, $a, b > 0$

Gifford (1993)

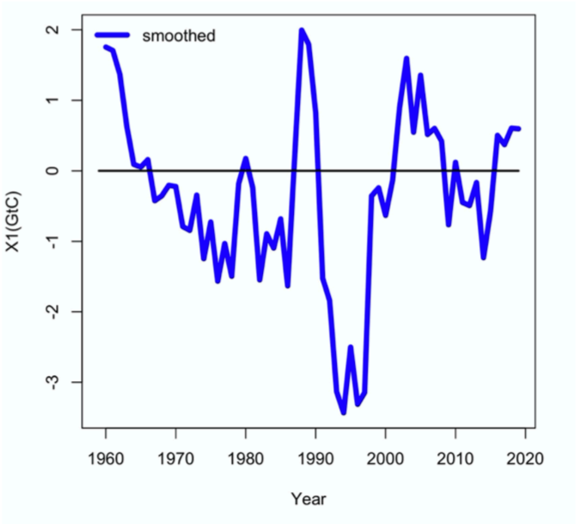


$$S\_OCN_t = k_O(pCO2_t^a - pCO2_t^s)$$

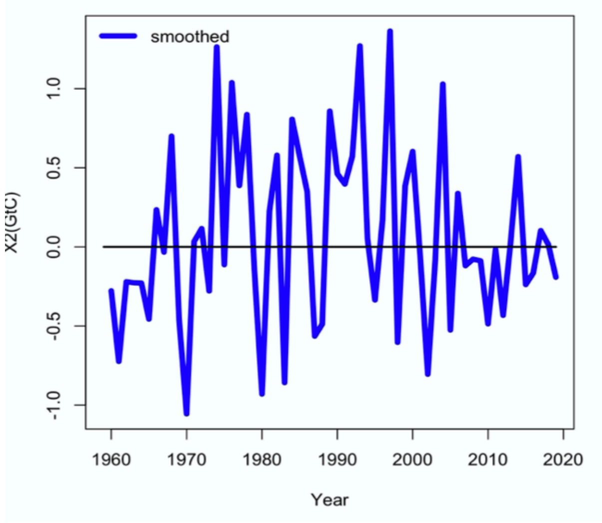
Joos et al. (1996, 2001)

RESIDUAL PROCESSES

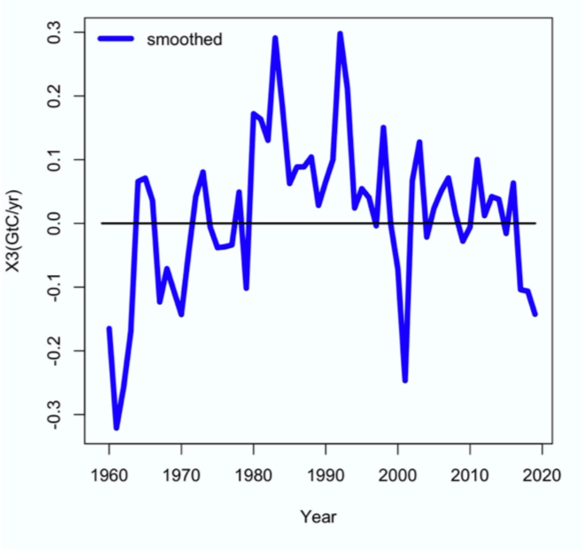
$X_{1,t}$ in C_t



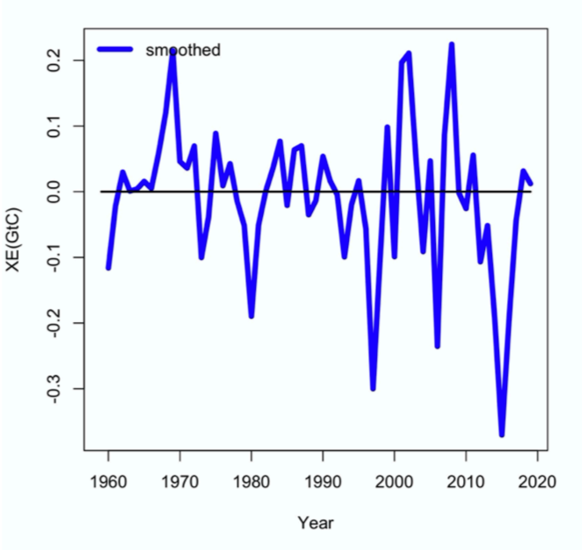
$X_{2,t}$ in S_LND_t



$X_{3,t}$ in S_OCN_t



X_t^E in E_t^*



PARAMETER ESTIMATES

Model 2

Coefficients	estimate	std err	Variances	estimate	std err
c_1 (filt.)	-6.70	0.04	$\sigma^2_{\eta 1}$	0.66	0.13
c_2 (filt.)	-4.63	0.03	$\sigma^2_{\eta 2}$	0.32	0.06
β_1	7.12	0.49	$\sigma^2_{\eta 3}$	0.01	0.002
β_2	4.99	0.29	$\sigma^2_{\eta 4}$	0.004	0.001
β_3 (filt.)	0.57	0.09	r_{12}	-0.60	0.09
β_4 (filt.)	-0.06	0.02	r_{13}	-0.01	0.12
β_5 (filt.)	0.11	0.01	s_E	2.28	0.51
β_6 (filt.)	0.39	0.06			
β_7 (filt.)	-2.04	0.66			
β_8 (filt.)	-0.29	0.06			
ϕ_1	0.77	0.08			
ϕ_3	0.62	0.12			
ϕ_E	0.39	0.12			

$$C^*_{t+1} = C^*_t + G\_ATM^*_{t+1} \qquad C_t = C^*_t + X_{1,t}$$

$$S\_LND^*_{t+1} = c_1 + \frac{\beta_1}{C_0} C^*_{t+1} + \beta_3 SOI_{t+1} \qquad S\_LND_t = S\_LND^*_t + X_{2,t}$$

$$S\_OCN^*_{t+1} = c_2 + \frac{\beta_2}{C_0} C^*_{t+1} + \beta_4 SOI_{t+1} \qquad S\_OCN_t = S\_OCN^*_t + X_{3,t}$$

$$E^*_{t+1} = E^*_t + \beta_5 \Delta GDP^{World}_{t+1} + \beta_8 I1991 + X^E_t$$

$$E_t = E^*_{t-1} + \beta_6 I1997$$

$$G\_ATM^*_{t+1} = E^*_{t+1} - S_{LND}{}^*_{t+1} - S_{OCN}{}^*_{t+1} + \beta_7 I1991$$

$$X_{1,t} = \phi_1 X_{1,t-1} + \eta_{1,t}$$

$$X_{2,t} = \eta_{2,t}$$

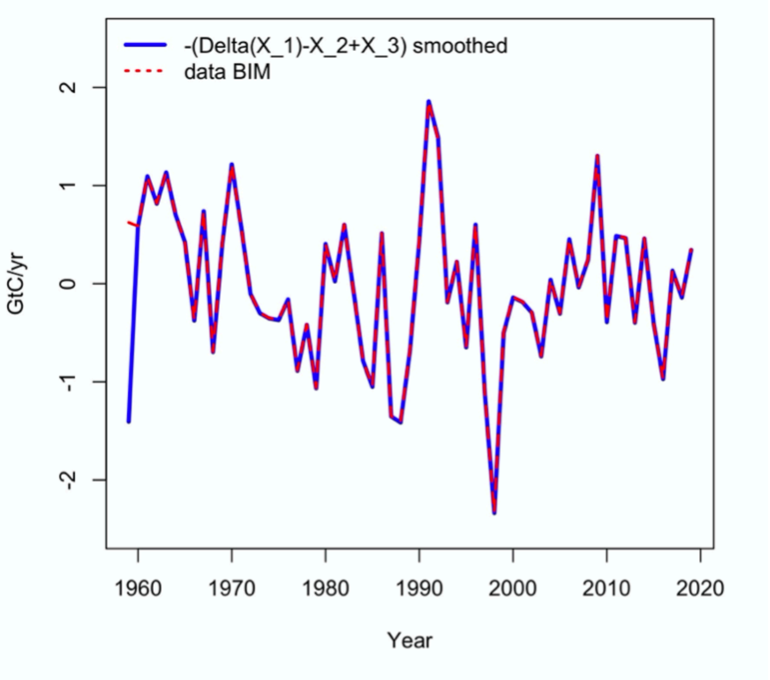
$$X_{3,t} = \phi_3 X_{3,t-1} + \eta_{3,t}$$

$$X^E_t = \phi_E X^E_{t-1} + \eta_{4,t}$$

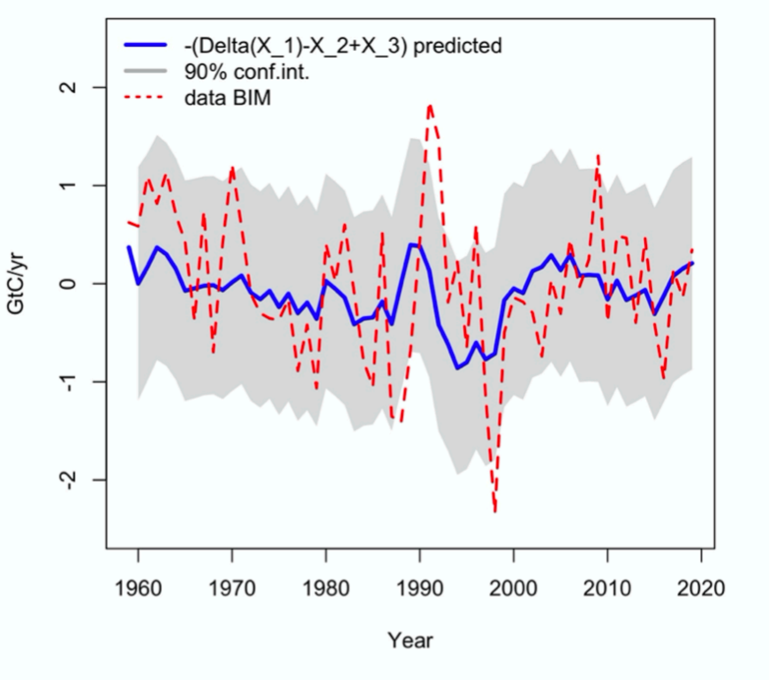
$$\begin{bmatrix} \eta_{1,t} \\ \eta_{2,t} \\ \eta_{3,t} \\ \eta_{4,t} \end{bmatrix} \sim N\left[0, \begin{bmatrix} \sigma_1^2 & r_{12}\sigma_1\sigma_2 & r_{13}\sigma_1\sigma_3 & 0 \\ r_{12}\sigma_1\sigma_2 & \sigma_2^2 & 0 & 0 \\ r_{13}\sigma_1\sigma_3 & 0 & \sigma_3^2 & 0 \\ 0 & 0 & 0 & \sigma_4^2 \end{bmatrix}\right]$$

$$\eta_{4,t} \sim N(0, \sigma_4^2\, s_E^2\, I_{t \geq 1996})$$

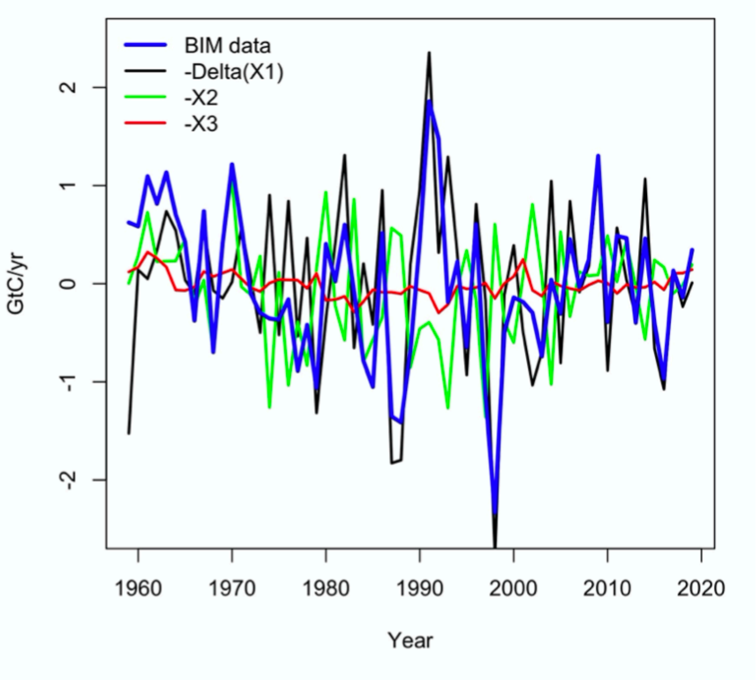
BUDGET IMBALANCE



(A) Smoothed $-(\Delta X_1 + X_2 + X_3) + \beta_6 I1997 - \beta_7 I1991$



(B) One-year ahead predictions

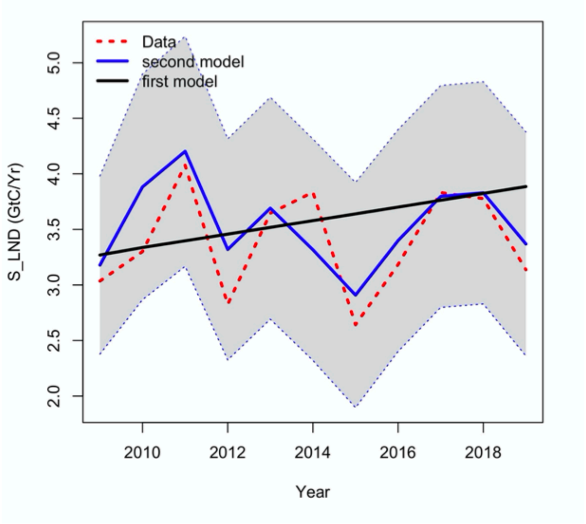


(C) Components $-\Delta X_1$, $-X_2$, $-X_3$

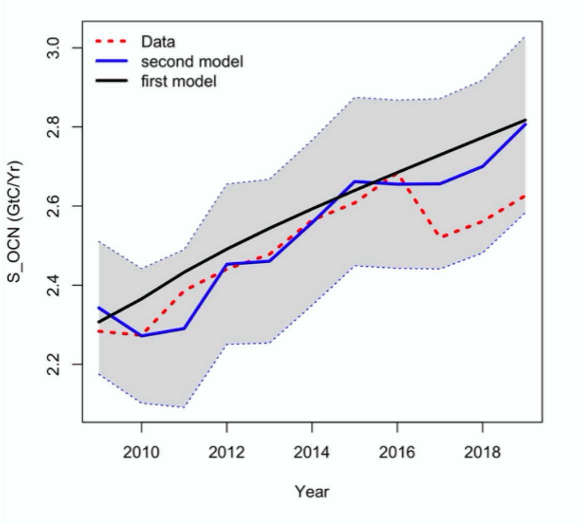
VALIDATION

Estimation of models on subsample
1959-2009

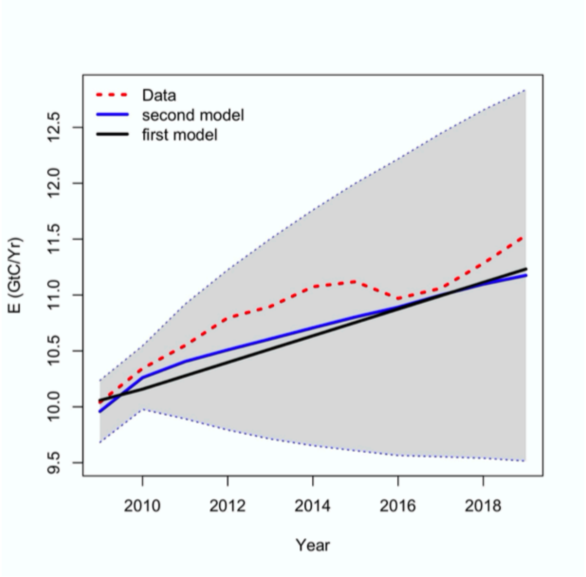
Iterating the models on subsample
2010-2019
given observations on World GDP and SOI



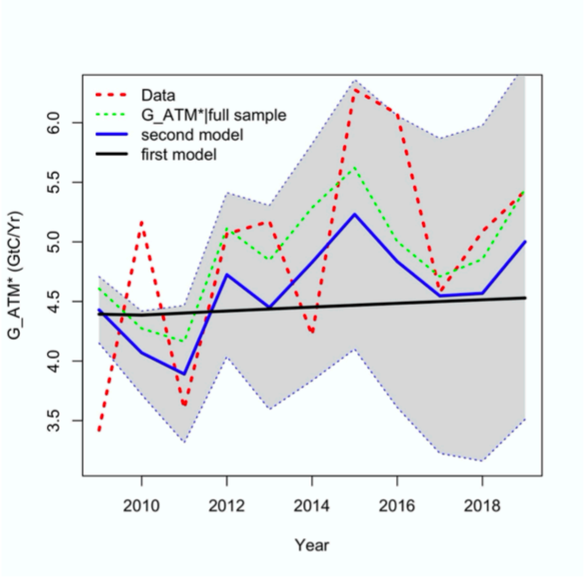
(A) S_LND



(B) S_OCN



(C) E



(D) G_ATM*