Arctic Amplification of Anthropogenic Forcing: A Vector Autoregressive Analysis

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Literature

Parkinson & Comiso (2012):

Downward trend increases vulnerability of SIE to seasonal shocks

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Vavrus (2004), Winton (2013), Stuecker *et al.* (2018), McGraw (2019):

Feedback loops between climate variables, test them with Granger Causality tests

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Stroeve *et al.* (2012):

Recovering of SIE after extreme minima

→

So far:

Very sparse literature on VARs and climate-system.

↙

Our Contribution :

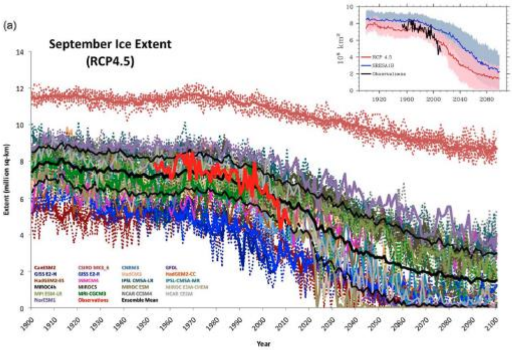
Amplification in the long-run: estimating and extrapolating the feedback process with Vector Autoregressions.

Motivation

- The minimum extent of arctic sea ice (SIE) in 2019 ranks second-to-lowest in history and is trending downward.
- There is an immediate need for flexible statistical modeling approaches that both *explain* endogenously the trend of SIE and permit its extrapolation to generate a long-run forecast.
- The VARCTIC is a compromise between fully structural/deterministic modeling and purely statistical approaches.
- It models dynamic interactions between some key variables without the need to specify a complete climate model, which can be useful in many situations.
- We use it to assess the importance of different internal variability mechanisms in amplifying SIE's response to CO_2 forcing.

CMIP5 & CMIP3 Projections

Stroeve et al. (2012):
dispersion is huge and the ensemble mean does not track recent observations so well.



Jahn et al. (2016): narrowing the dispersion to roughly 20 years

The VARCTIC can help pointing out understated mechanisms responsible for the discrepancy.

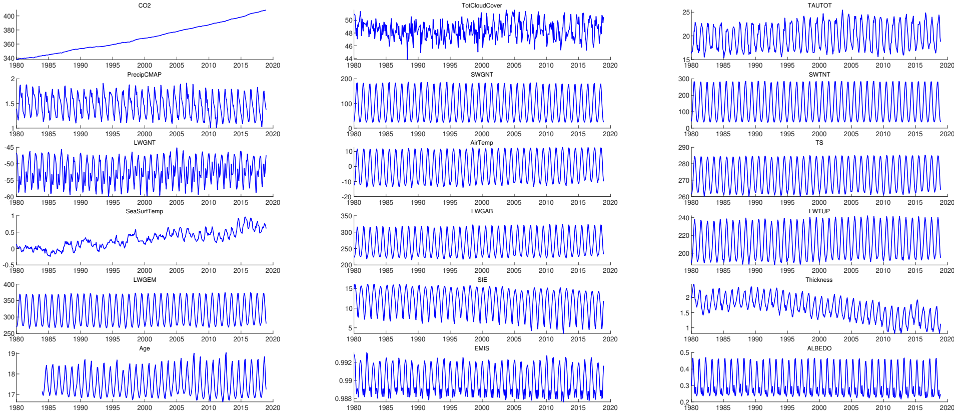
In Short

- We run an 8 variable Bayesian Vector Autoregression (VAR).
- Our "business as usual" completely unconditional forecast has SIE hitting 0 in September by the 2060's.
- Unsurprisingly, CO_2 is shown to be the main driver of the long-run evolution of SIE and conditioning on different RCPs can change the $SIE = 0$ date dramatically (2050's under RCP 8.5, never under RCP 2.6)
- We propose two ways of evaluating how the endogenous response of both sea ice albedo and thickness amplify the reaction of SIE to CO_2.
- Our results suggest that the thickness amplification channel could be of greater importance than that of albedo.

A look at the Raw Data

- Raw data $\boldsymbol{y}_t^{raw}$ is highly seasonal, and seasonality is only of second interest here as we wish to focus on phenomena that impact all seasons.

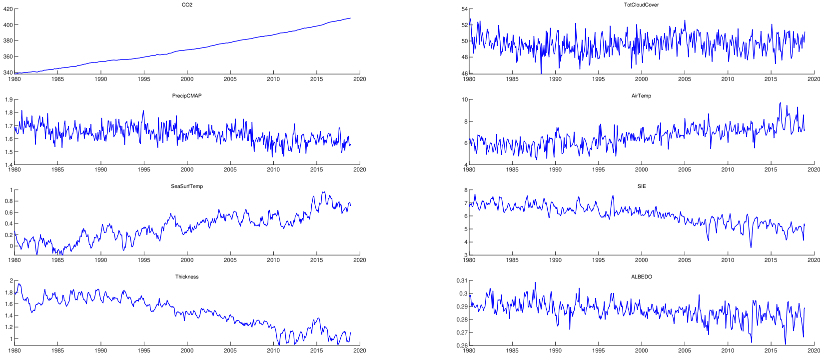
Figure: Raw Data: 18 Original Variables



A more productive look at the Data

- We take out seasonality with dummies.
- We later consider structural time series model-based seasonality extraction as a robustness check.

Figure: Deseasonalized Series: 8 Variables



Which Variables Did We Choose?

- Data Sources: We mostly follow **Stroeve & Notz (2018)** and regarded NSIDC, NOAA and the PIOMAS project among others as reliable data providers.
- Variable selection is based on compiling a sample, representing both external forcings and internal variability
- The chosen variables and their interactions with Arctic sea ice are all well-described in **Meier et al. (2014)**.

Table: Benchmark VARCTIC

Variable	**Data Source**
Sea Ice Extent	NSIDC Sea Ice Index
CO_2	NOAA/ESRL Global Trend
Total Cloud Cover	NCEP/NCAR 40-year Reanalysis Project
Sea Surface Temperature	Met Office Hadley Centre
Air Temperature	NCEP/NCAR 40-year Reanalysis Project
Precipitation	NOAA/OAR/ESRL
Thickness	PIOMAS
Sea Ice Albedo	MERRA-2

- If these variables constitute a diverging dynamic system of equations, the highest root will be >1.

VARs

- Let y_t stack our 8 variables of interest, then

$$A\boldsymbol{y}_t = \Psi_0 + \sum_{p=1}^{P} \Psi_p \boldsymbol{y}_{t-p} + \boldsymbol{\varepsilon}_t, \tag{1}$$

- Each of these variables is predicted by its own lags and lags of the $M-1$ remaining variables.
- The matrix A characterizes how the M different variables interact contemporaneously.
- The structural shocks/anomalies/disturbances are mutually uncorrelated disturbances with mean zero:

$$\boldsymbol{\varepsilon}_t = \left[\varepsilon_{1,t}, \ \ldots \ , \varepsilon_{M,t}\right] \ \sim \ N\left(0, \ I_M\right).$$

- An estimable version of the above is the reduced-form VAR

$$\boldsymbol{y}_t = \boldsymbol{c} + \sum_{p=1}^{P} \Phi_p \boldsymbol{y}_{t-p} + \boldsymbol{u}_t, \tag{2}$$

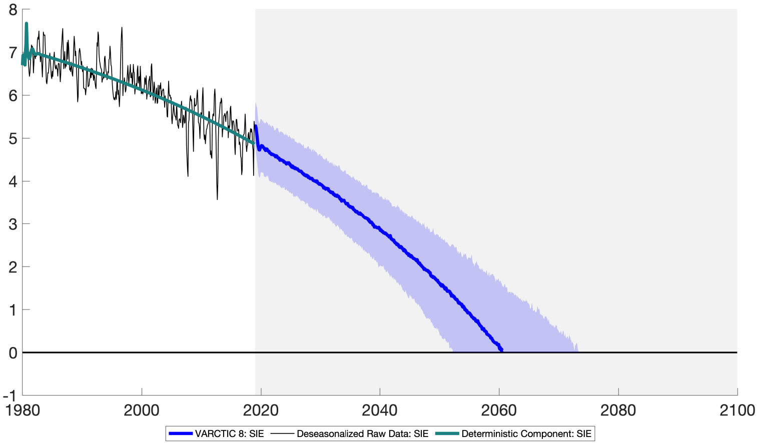
where $\boldsymbol{c} = A^{-1}\Psi_0$, $\Phi_p = A^{-1}\Psi_p$ and $\boldsymbol{u}_t$ are plain residuals.

Once the VAR is estimated, can do many things

- Get an unconditional long-run forecast
- Evaluate conditional forecasts based on different CO_2 scenarios
- Once the structural VAR is identified, we can look at how the dynamic system responds to certain shocks of interest, like CO_2 and temperature.
- Evaluate how certain channels amplify the response of SIE to CO_2
- A more in-depth explanation of those procedures as well as implementation details can be found in the paper.

Forecast obtained by iterating the VAR forward

Figure: Trend Sea Ice Extent, adjusted for September level



Impulse Response Functions in Detail

- The impulse response function of a variable m to a one standard deviation shock of $\varepsilon_{\tilde{m},t}$ is

  $$IRF(\tilde{m} \to m, h) = E(y_{m,t}|\boldsymbol{y_t}, \varepsilon_{t,\tilde{m}} = \sigma_{\varepsilon_{\tilde{m}}}) - E(y_{m,t}|\boldsymbol{y_t}, \varepsilon_{t,\tilde{m}} = 0).$$

- In a linear VAR with one lag ($P = 1$), the IRF of *all variables* is computed using

  $$IRF(\tilde{m} \to \boldsymbol{m}, h) = \Psi^h A^{-1} e_{\tilde{m}}$$

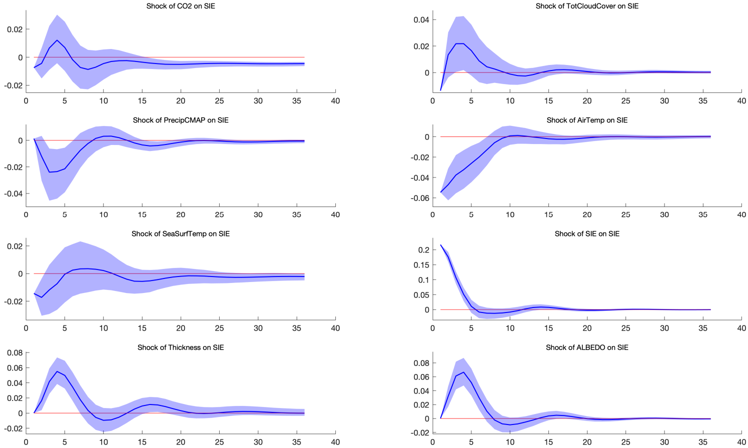
  where $e_{\tilde{m}}$ is vector with $\sigma_{\varepsilon_{\tilde{m}}}$ in position $\tilde{m}$ and zero elsewhere.
- This means we are looking at the individual effect of $\varepsilon_{\tilde{m}}$ while all other structural disturbances are shut down.
- For this paper's research question: how does variable z's channel contribute to $IRF(\tilde{m} \to m, h)$ $\longrightarrow$ formal statistical inquiry of the amplification hypothesis

How to obtain A: the Ordering

- External Forcings
  1. **CO_2**:
     most exogenous variable; not to be impacted by any other variable contemporaneously; rising levels due to anthropogenic stimulus (Dai et al. (2019), Notz and Stroeve (2016))
- Internal Variability
  - Fast Moving Variables
    2. **Total Cloud Cover**:
       → influencing the heat content of the surface
    3. **Precipitation**:
       → can cause immediate changes in temperature
    4. **Air Temperature**
  - Slow Moving Variables
    5. **Sea Surface Temperature**
       → lagged effect of both temperature series on 2. & 3.
    6. **Sea Ice Extent**
       → we assume an immediate impact on thickness and albedo
    7. **Thickness**:
       → crucial determinant of the albedo effect
    8. **Sea Ice Albedo**

IRFs: Response of Sea Ice Extent to different shocks

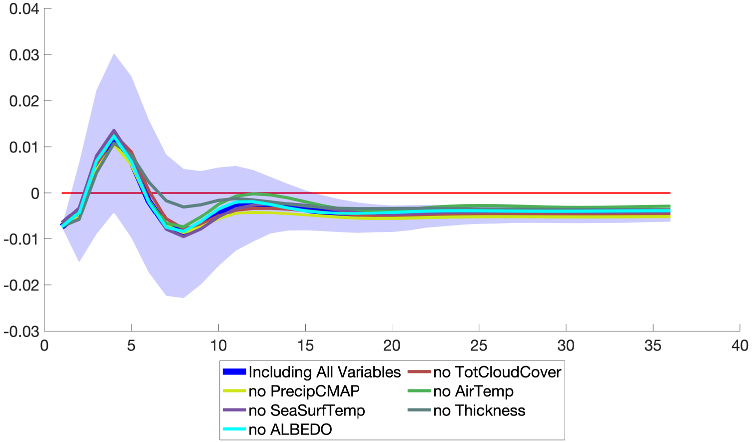
CO_2 shocks have a *permanent* downward effect → 2020 CO_2 anomaly could have a lasting positive impact on SIE – unless emissions pick up more strongly after the lockdown/recession.



Through which channels does CO_2 impact SIE?

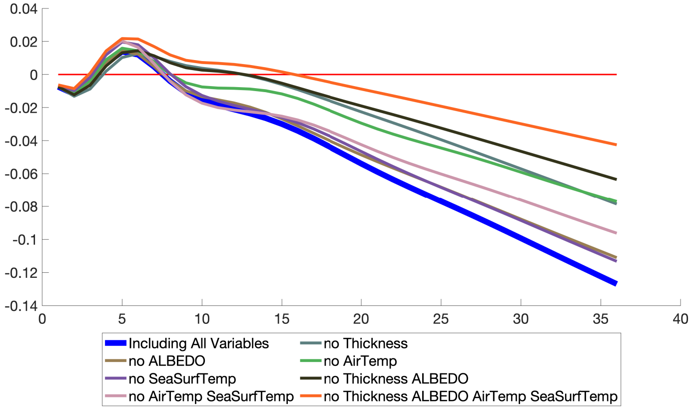
IRF decomposition

Figure: IRF Decomposition



Through which channels does CO_2 impact SIE?
Cumulative Impact

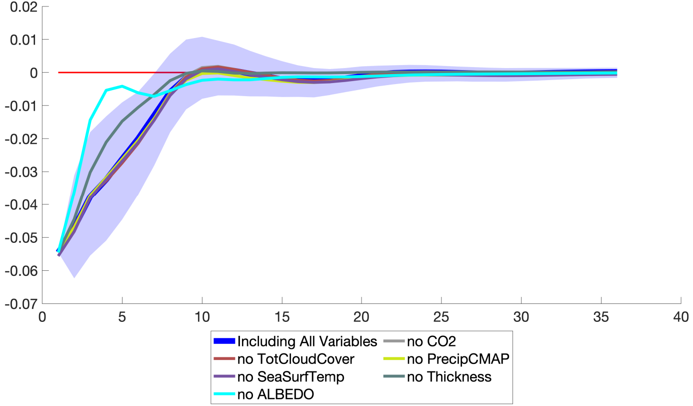
- Temperatures obviously matter.
- Thickness & Albedo together can double cumulative impact.
- Thickness' response seems much more important than Albedo.



How do Air Temperature shocks impact SIE?

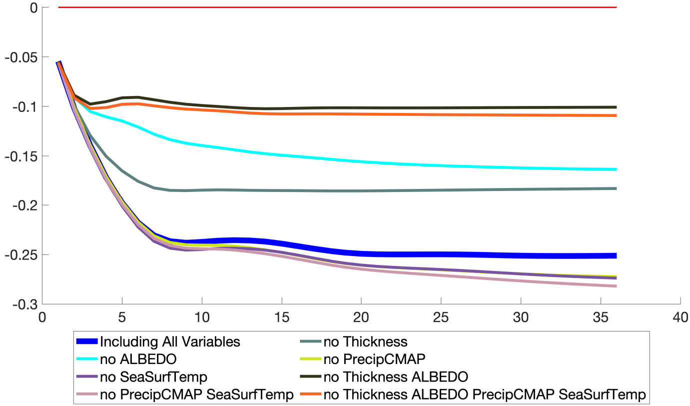
IRF decomposition

- Without the dynamic response of Albedo, the effect dies out really quickly (-0.005 after 5 months rather than -0.03)
- Thickness contributes, but to a lesser extent this time.



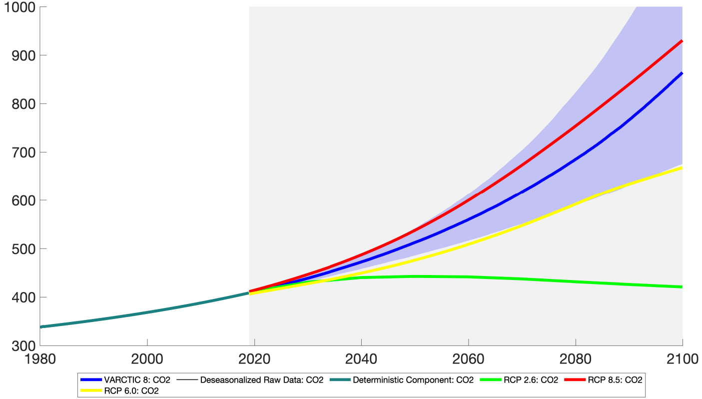
How do Air Temperature shocks impact SIE?
Cumulative Impact

- Cancel both Albedo & Thickness feedback and you get a much milder response that stabilizes quickly.



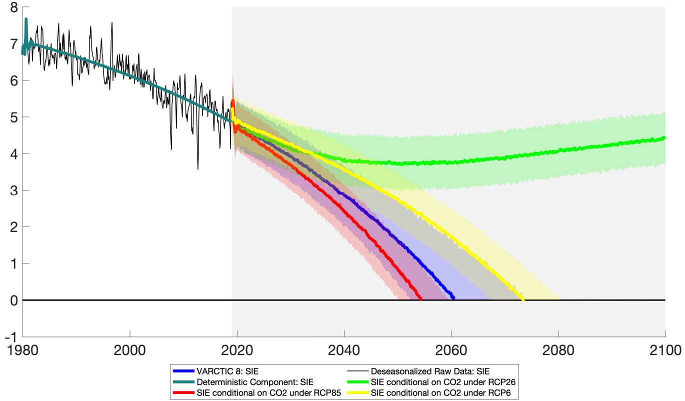
Identifying *systematic* transmission channels of CO_2

Scenarios



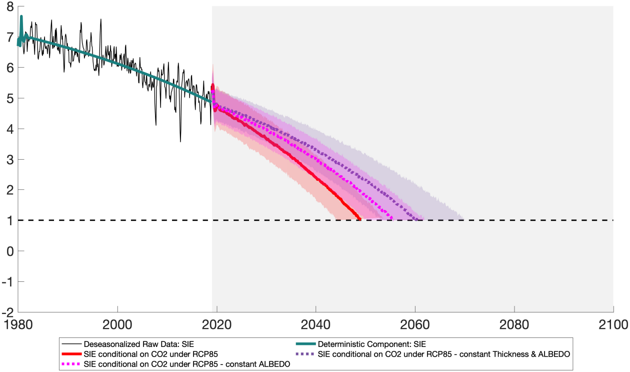
Identifying *systematic* transmission channels of CO_2

Forecasts Conditional on Different RCPs



Identifying *systematic* transmission channels of CO_2

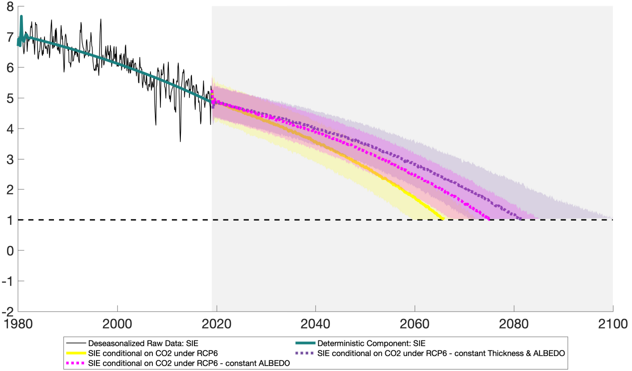
Decomposing Conditional Forecasts under RCP 8.5



Thought experiment:
stopping both SIE albedo and thickness from decreasing further would postpone $SIE < 1$ by 10 years – under RCP 8.5.

Identifying *systematic* transmission channels of CO_2

Decomposing Conditional Forecasts under RCP 6



Also roughly by 10 years under RCP 6.

Robustness Checks

- We consider many robustness checks
  - We consider de-seasonalizing the data using stochastic trends to allow for potentially evolving seasonality.
  - We report results with much looser priors
  - We also consider alternative orderings
  - We also consider a VAR with 18 variables, covering several measurements of long- & short-wave radiation
  - We see the impact of *upper-ocean heat* to be covered by SST
- In all instances, results remain unchanged.

Conclusion

Using a macroeconometric model estimated directly on the observational record, we find that

- The median scenario is SIE=0 in September around 2060;
- CO_2 anomalies have permanent effects on SIE, which are in part to their a mplification by thickness and albedo's responses;
- The concerted action of SI albedo and thickness feedback amplifies SIE's response to CO_2, likely bringing forward the disappearance of SIE by at least 20 years.