Observed Weakening of the Gulf Stream at Florida Straits over the Past Four Decades

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Today we'll try to convince you that—

- The Florida Current volume transport declined over the past four decades;

- The decline was "significant"—it was stronger than you'd expect from the null hypothesis of stationary noise; and,

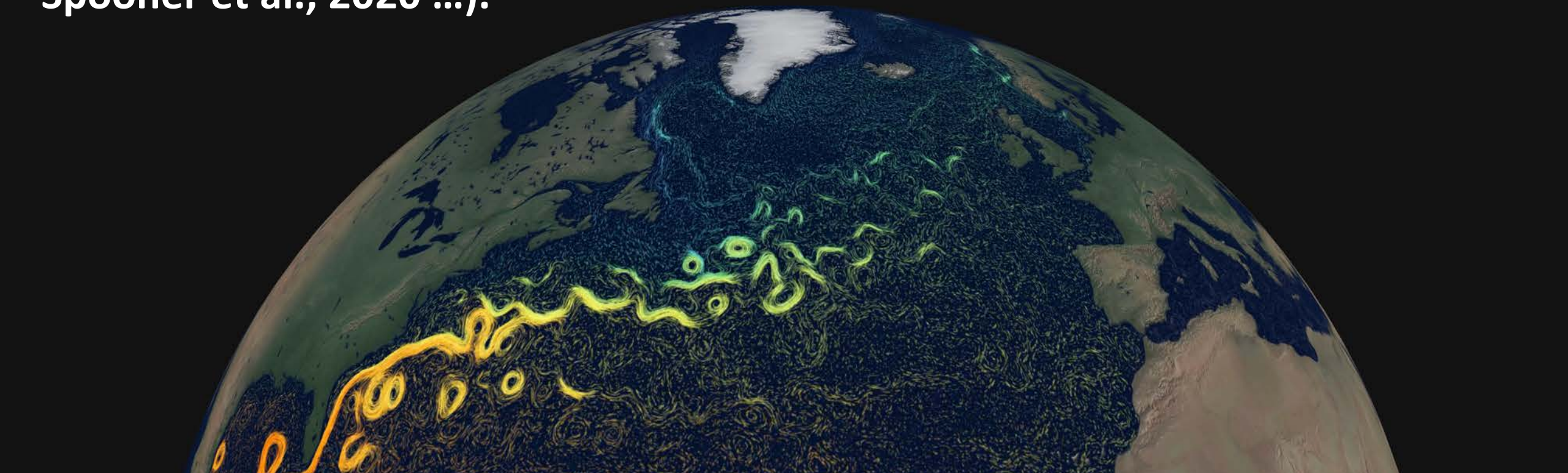
- The inference of a decline is supported by multiple instrumental observational time series.

All comments, critical or otherwise, are welcome!

Has the AMOC weakened? Is the AMOC weakening? Pro et Contra …

Some have interpreted a subset of available proxy reconstructions as supporting a decline in the AMOC since the Industrial Revolution

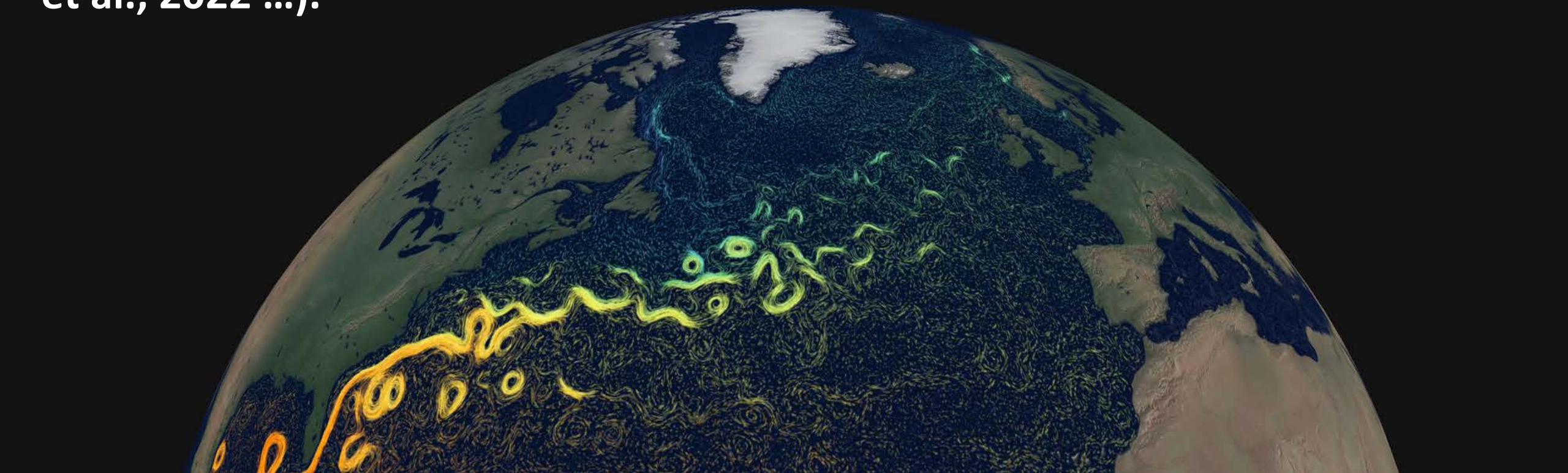
(e.g. Rahmstorf et al., 2015; Caesar et al., 2018; Osman et al., 2019; Thornalley et al., 2018; Thibodeau et al., 2018; Sherwood et al., 2011; Spooner et al., 2020 …).



Has the AMOC weakened? Is the AMOC weakening? Pro et Contra …

Others have challenged the interpretation of the records and argued that a more complete review of all available proxies suggests that recent changes in North Atlantic Ocean circulation remain uncertain

(e.g. Moffa-Sánchez et al., 2019; Keil et al., 2020; Little et al., 2020; Kilbourne et al., 2022 …).



Forget past centuries or millennia—the nature of AMOC changes is uncertain even during the past few decades!

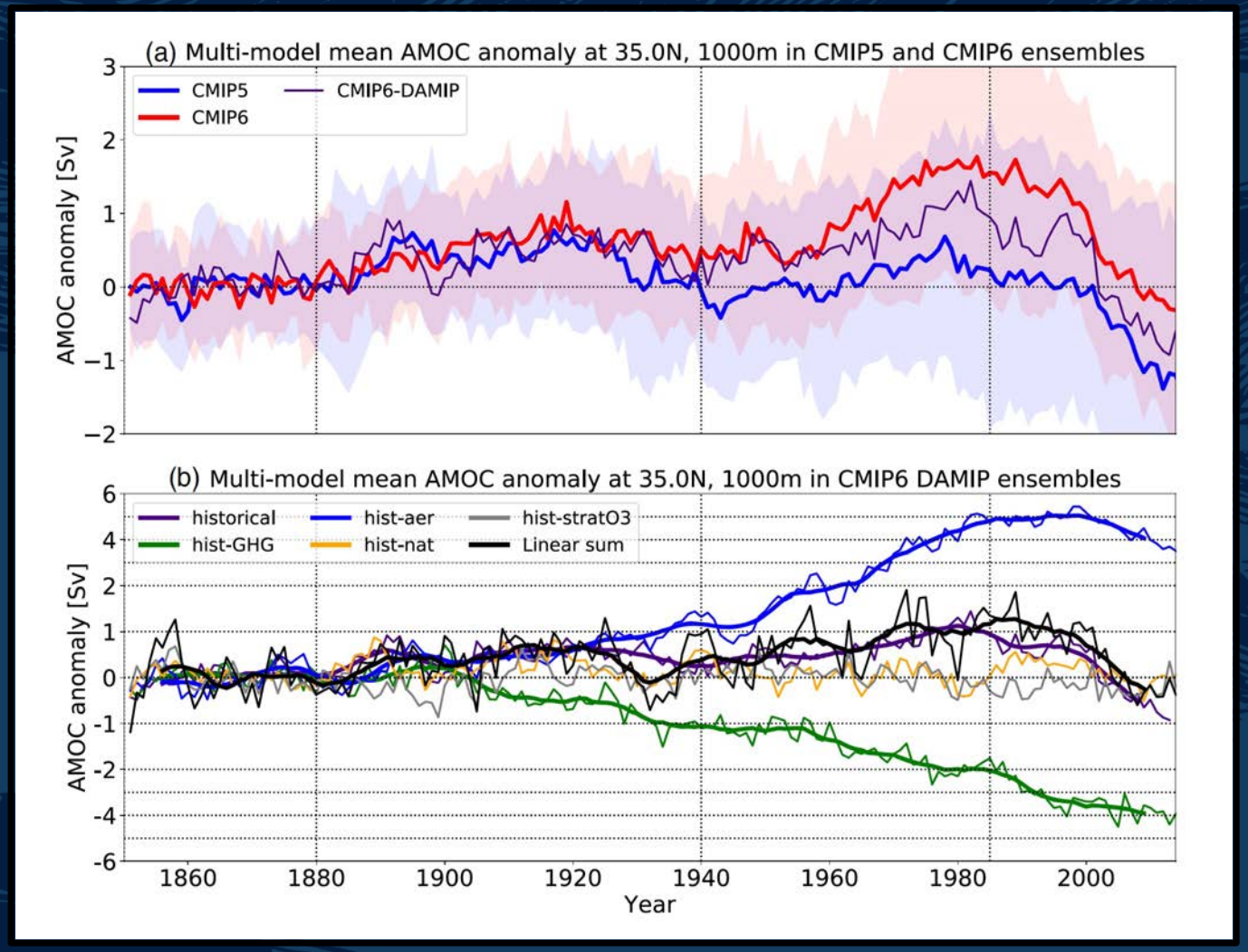


Figure from Menary et al. (2020). See also Cheng et al. (2013) and Weijer et al. (2020).

Model studies suggest that AMOC weakened during the past few decades in response to external forcing …

Forget past centuries or millennia—the nature of AMOC changes is uncertain even during the past few decades!

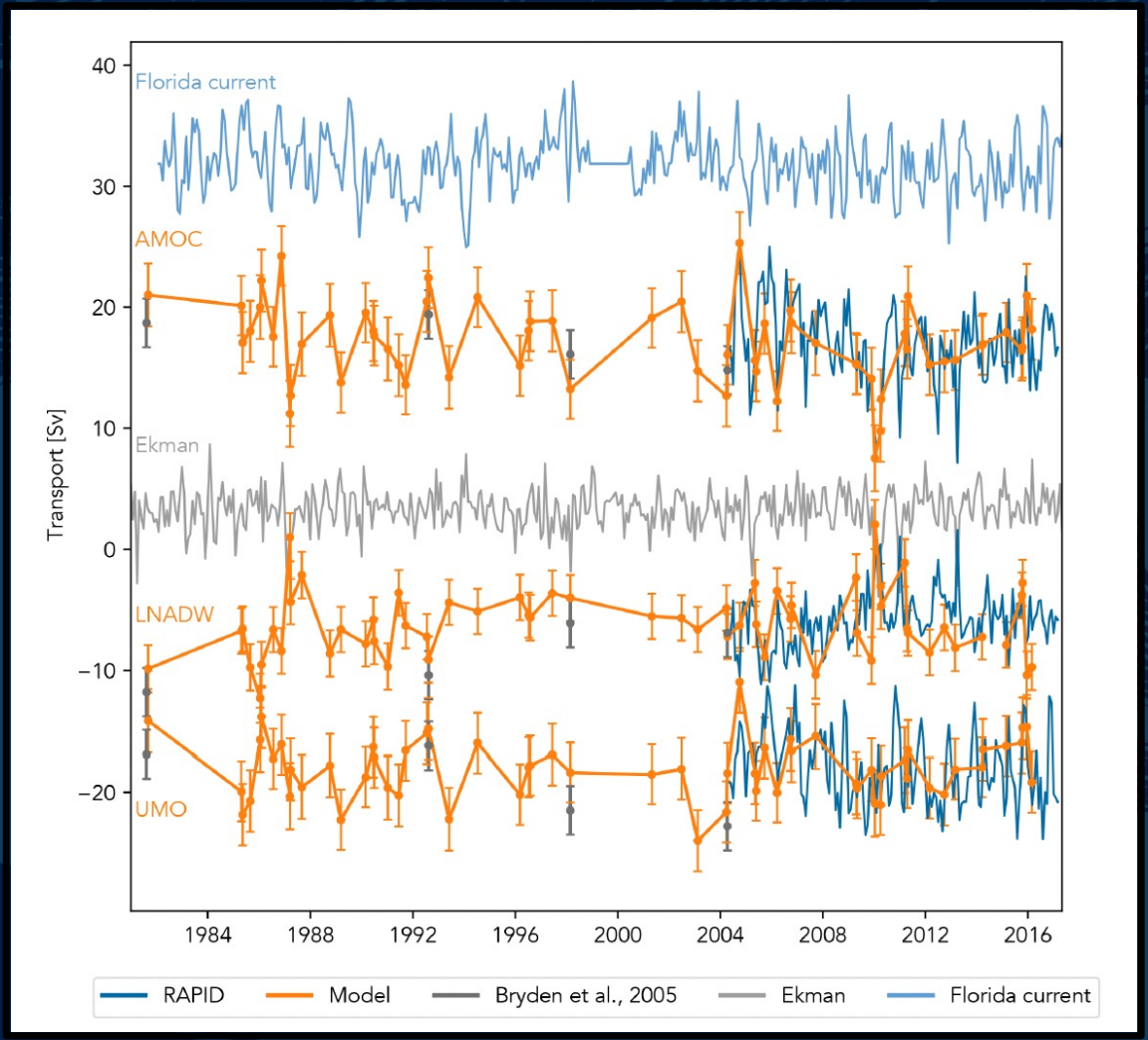


Figure from Worthington et al. (2021). See also Fu et al. (2020) and Caínzos et al. (2022)

… whereas observation-based studies argue that the AMOC was more or less stable during that time period.

What gives? Why the apparent model-data discrepancy?

Is the issue related to models (e.g. too-strong climate sensitivity) or data (e.g. aliasing of sparse hydrography)?

Or maybe the “signal” of the forced trend gets lost in the “noise” of natural variation?

“Such large interannual and decadal variability complicates the detection of long-term trends, but does not preclude a weakening associated with anthropogenic warming.” Jackson et al. (2022), ***Nat. Rev. Earth. Environ.***

Does the Florida Current offer any insights? It participates in the AMOC, and its volume transport is the best observed in the world:

- **Quasi-daily submarine telecommunication cable data since 1982;**
- **Quasi-quarterly *in situ* calibration cruise observations since 1982;**
- **Estimates every ~10 days based on satellite altimetry since 1993.**

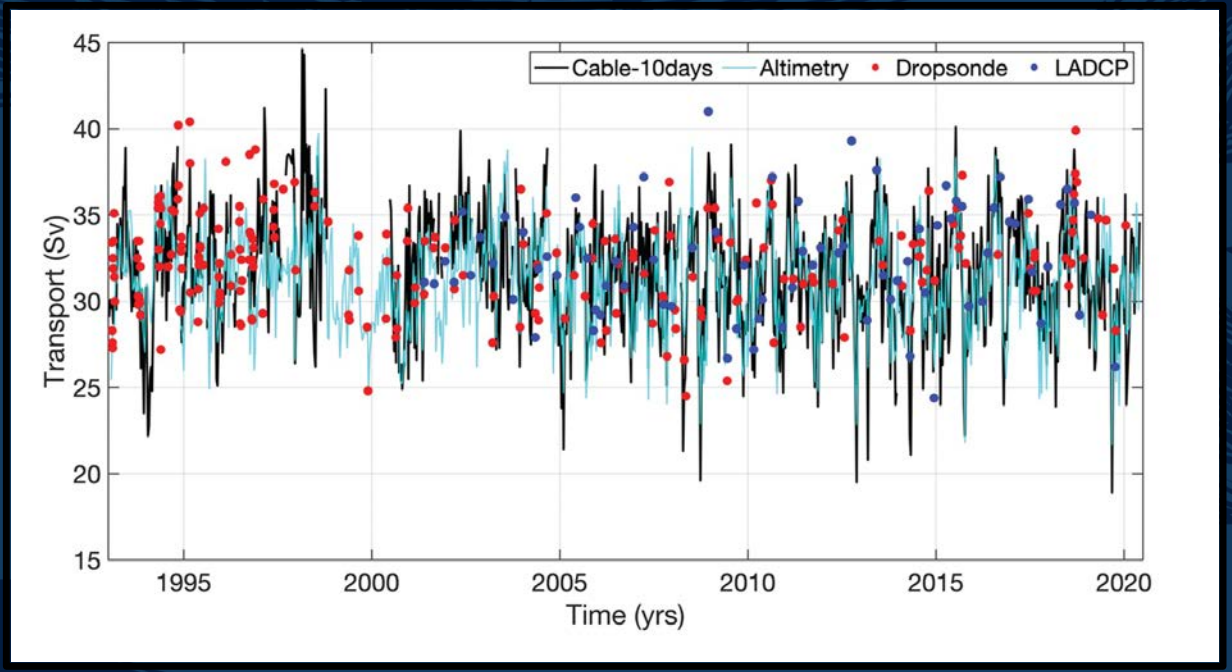


Figure from Volkov et al. (2020).
See also Meinen et al. (2010).

Models suggest that deep AMOC changes are compensated by Florida Current changes at long timescales (e.g., Gu et al., 2020).

—More data doesn't necessarily mean more certainty!—

Data Stream	Period	"Naïve" OLS Trend Fit
Cable	1982-2022	-0.3 ± ?? Sv/decade
Cruise	1982-2021	0.1 ± ?? Sv/decade
Altimetry	1993-2021	-0.1 ± ?? Sv/decade

Each data stream has its own pros and cons—

- Cruise data are accurate and precise, but infrequent, leading to an incomplete picture and potential aliasing;
- Cable data are voluminous, but feature non-trivial error structure (large, time-variable, and not independent);
- Altimetry provides a regular, stable measurement, but it observes sea-surface height, not the current transport.

—All data imperfectly observe same underlying reality!—

Approach: hierarchical Bayesian modeling—separate the common signal from the noise inherent to each dataset.

Decompose the scientific problem in to distinct "levels": Process Level, Data Level and Parameter (or Prior) Level.

Process/Data Levels specified as ARMA(p,q) models, e.g.,

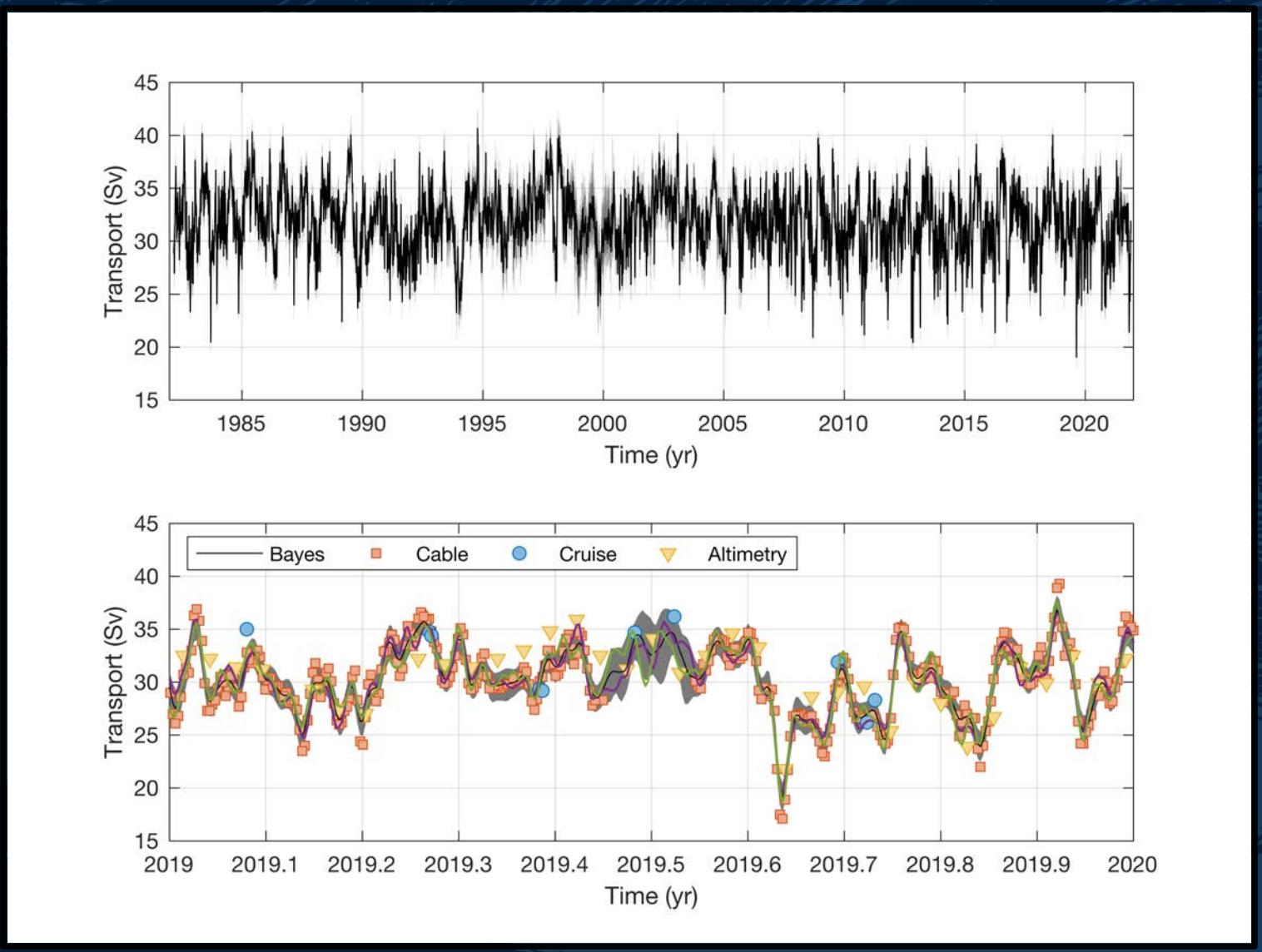
- Transport is the sum of mean, seasonal, trend, and AR(3) noise.
- Cable data represents the transport process plus MA(2) errors.

Use weak, uninformative priors at the Parameter Level.

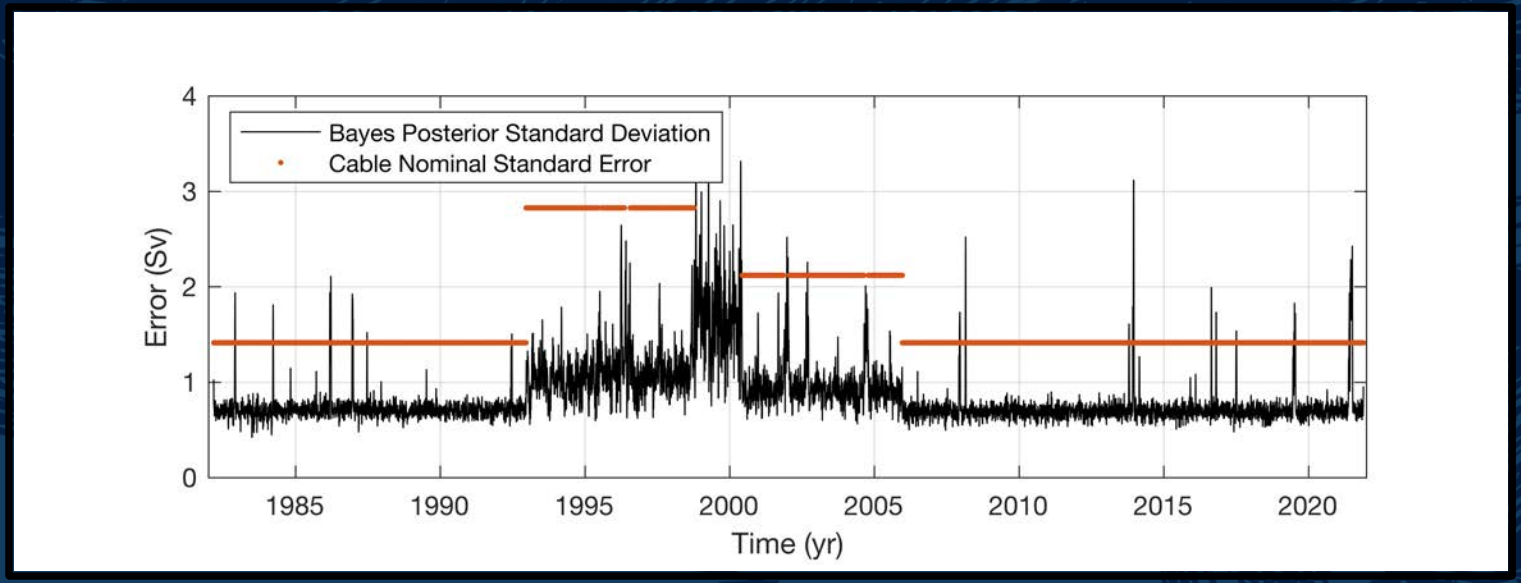
- AR(p), MA(q) coefficients, seasonal phases and amplitudes, etc.

Invert with Bayes' Rule, generate ensemble of posterior solutions for the process and parameters using numerical methods, and comprehensively propagate uncertainties.

A probabilistic reanalysis of Florida Current transport



A probabilistic reanalysis of Florida Current transport



Posterior uncertainties vary with time, and reflect the availability and accuracy of the assimilated data streams.

Mean standard deviation of transport solutions is ~0.9 Sv, which is about half of the value of ~1.7 Sv typically quoted as the standard error on the raw cable data (e.g., Meinen et al., 2010; Garcia & Meinen 2014; Volkov et al., 2020).

A probabilistic reanalysis of Florida Current transport

Run cross-validation experiments: how meaningful are error bars, and how well can the model predict the truth?

Data	Percent with 90% CI	Mean Prediction Error
Cable	97%	1.1 Sv
Cruise	83%	1.5 Sv
Altimetry	86%	2.3 Sv

Also—

- Residual analyses suggest that the algorithm's design is appropriate given the structure in the data (not shown).
- Numerical solutions converge and posteriors solutions are much narrower than prior assumptions (not shown).

A probabilistic reanalysis of Florida Current transport

Compute 40-year transport trends from different experiments that withhold different data types—

Experiment	40-y change (95% CI)	Fraction Weakening
All Data	-1.2 $\pm$ 1.0 Sv	>99%
No Altimetry Data	-1.2 $\pm$ 1.0 Sv	>99%
No Cruise Data	-1.2 $\pm$ 1.0 Sv	>99%
No Cable Data	-0.8 $\pm$ 0.9 Sv	>95%

The inference on a decline in transport is robust and not qualitatively dependent on any one observing system.

(NB: apparent weak strengthening in the raw section data occurs from aliasing. Such considerations also relevant to results of Fu et al., Worthington et al., and Caínzos et al.)

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Questions?

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