ODEN INSTITUTE
FOR COMPUTATIONAL ENGINEERING & SCIENCES

# CONSERVATION OF HEAT, FRESHWATER, AND MOMENTUM IN REANALYSES: WHY DO WE CARE?


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https://crios-ut.github.io
https://ecco-group.org

Applications of climate reconstructions / state estimates / “reanalyses”

Balancing the momentum, freshwater, and heat budgets

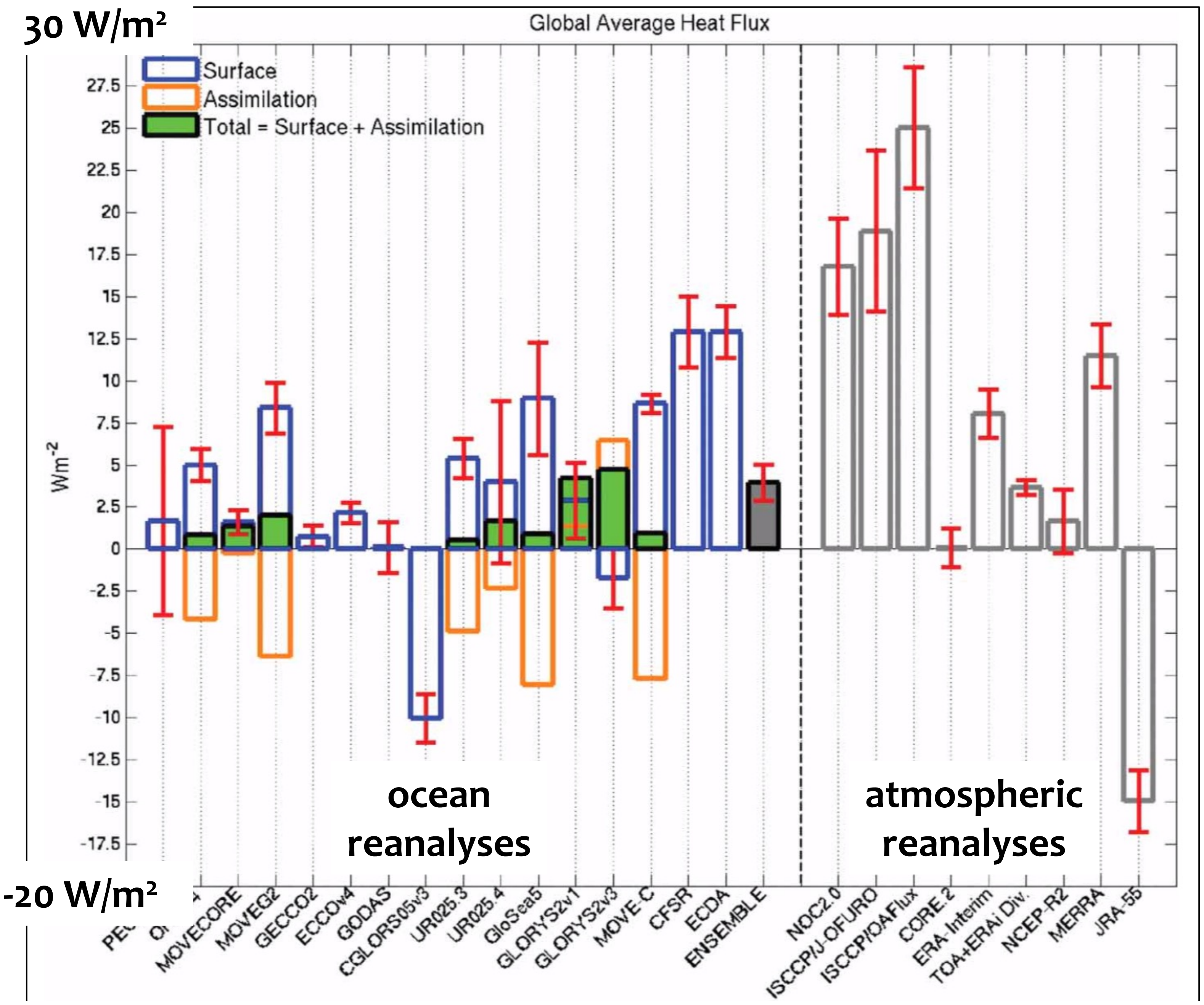
# Overview

**Five examples:**

1. Global mean net heat flux imbalances
2. AABW production in the Weddell Sea
3. Subtropical mode water formation
4. Impact of DA on vertical velocities in an eddy-resolving ocean model
5. Surface temperature “hiatus”

# Global net heat flux imbalance

Global mean air-sea fluxes *unrealistically large* in most reanalyses as a consequence of property *non-conservation*



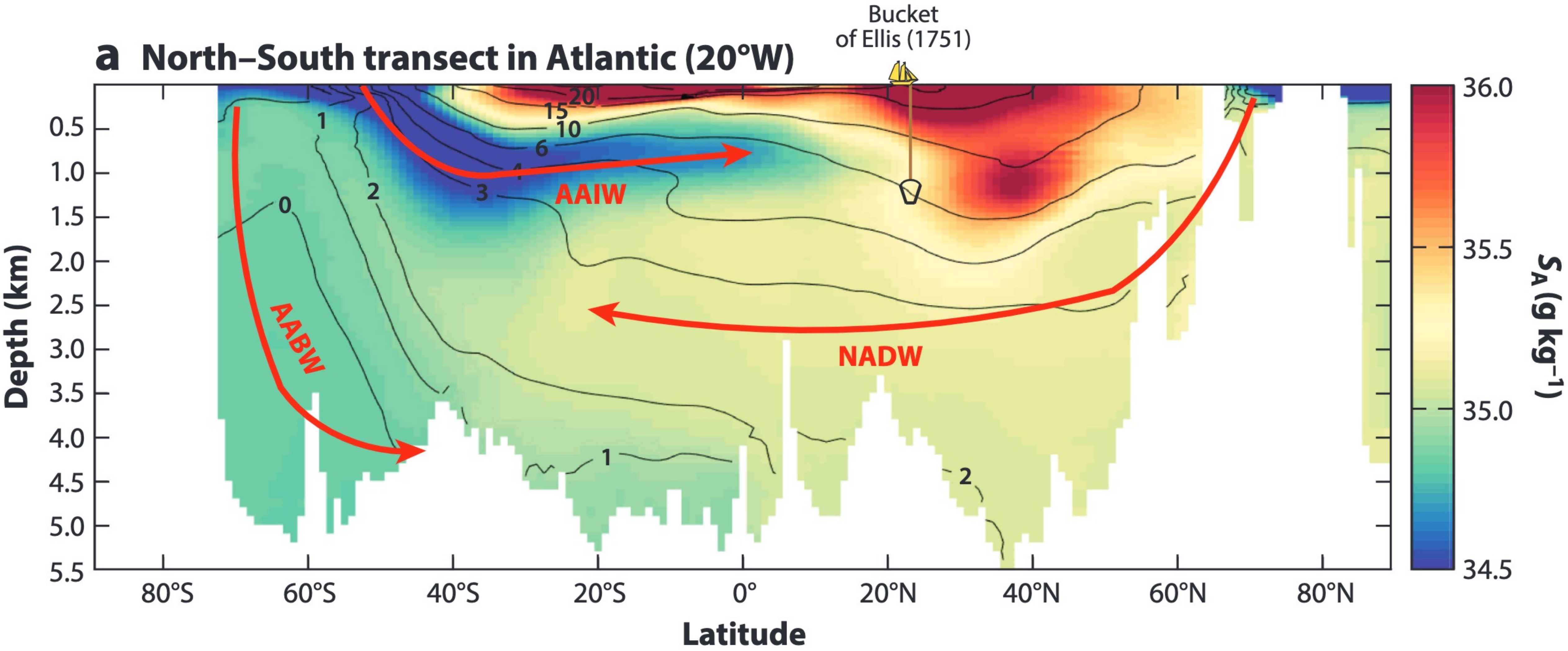

*Balmaseda et al. (2015): Ocean Reanalysis Intercomparison Project (ORA-IP)*

# Example Applications

## Gaining insight through quantifying time-evolving property budgets

Water mass transformation variability in the Weddell Sea in Ocean Reanalyses

***Bailey et al., EGUsphere (2022)***




Groeskamp et al. (2019)

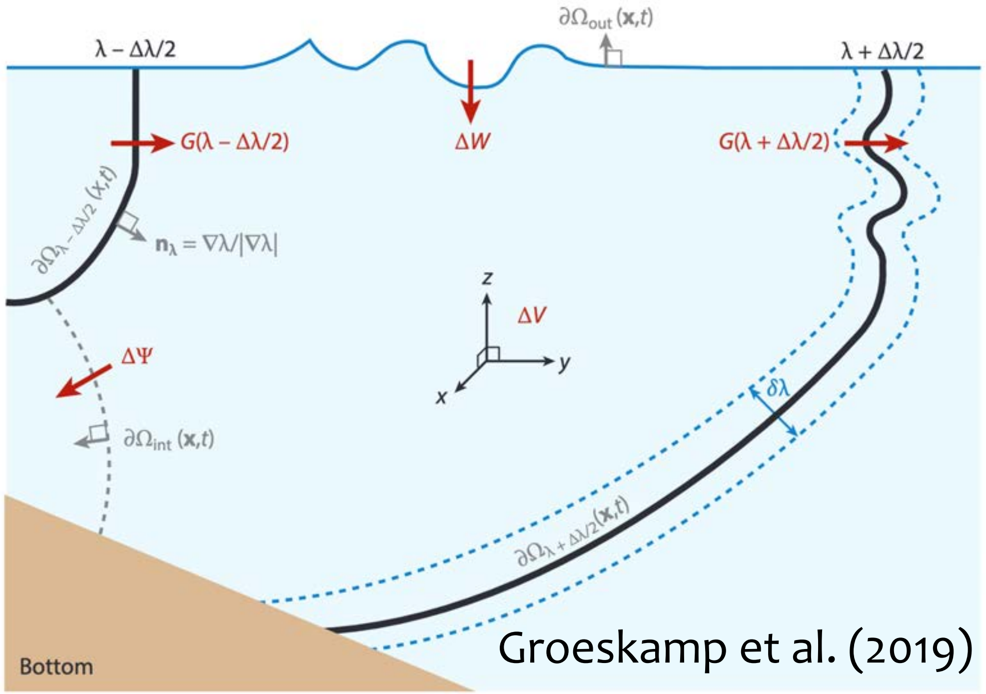
# Water mass transformation variability in the Weddell Sea in Ocean Reanalyses

***Bailey et al., EGUsphere (2022)***

Anomalous volume budget

$$\boldsymbol{dV/dt = \Psi + \Omega + R1}$$

- ***dV/dt***: time-rate of volume change
- ***Ψ***: transport through boundaries
- **Ω**: thermodynamic transformation
- ***R1***: residual due to discretization

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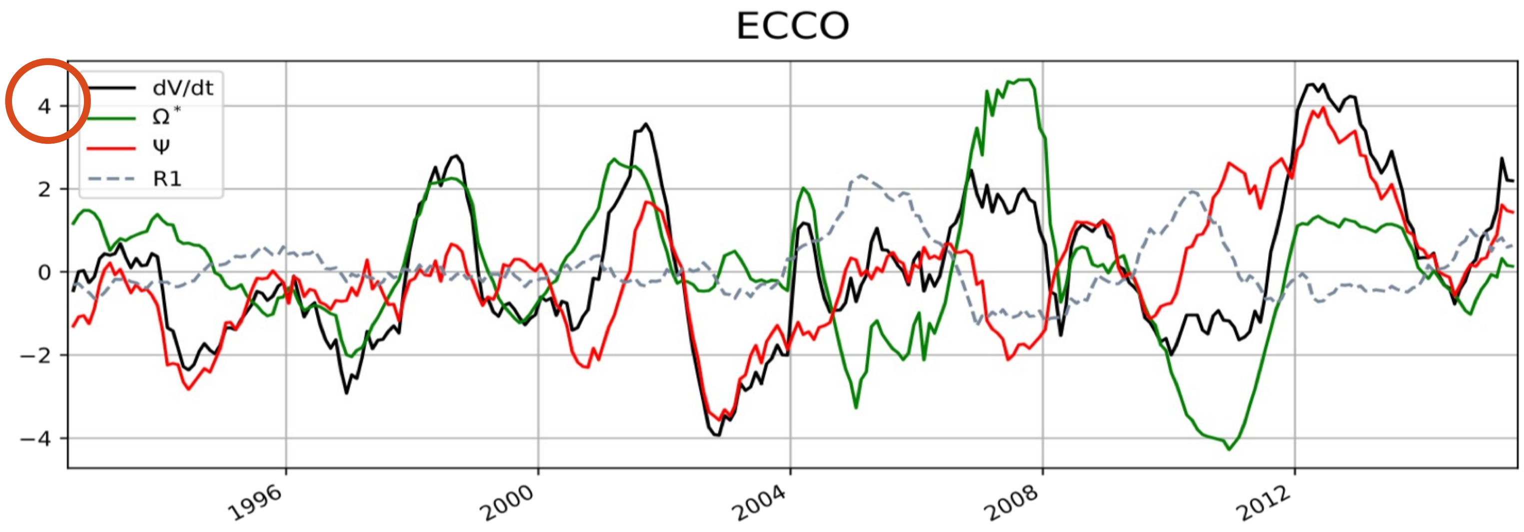
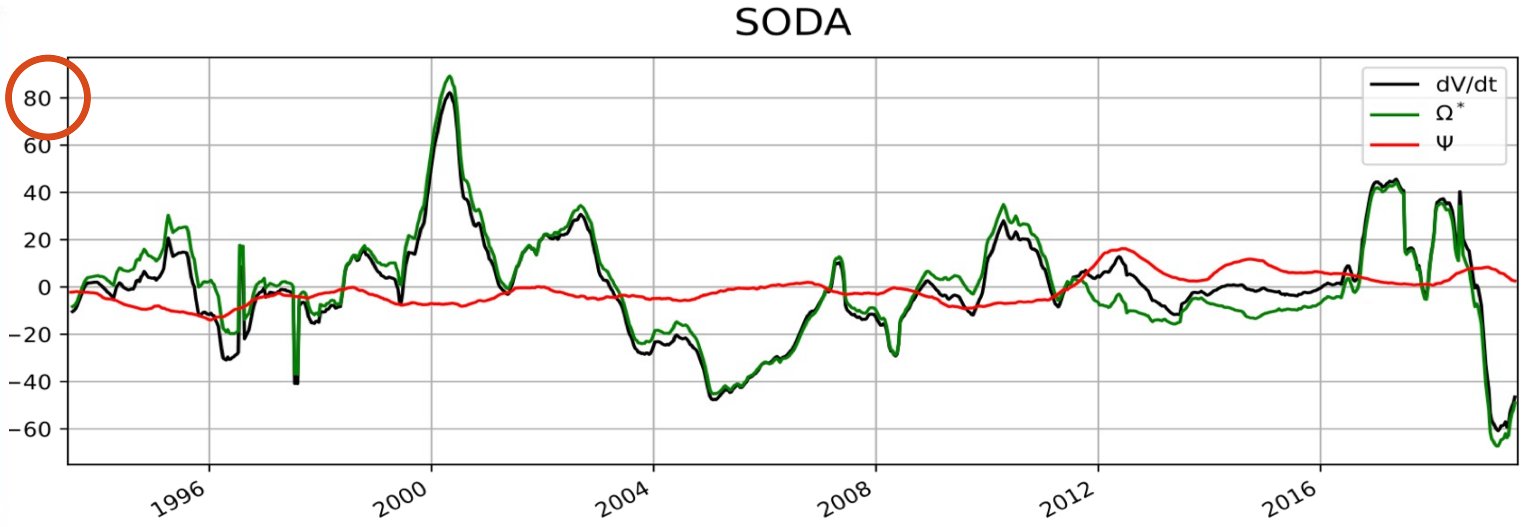
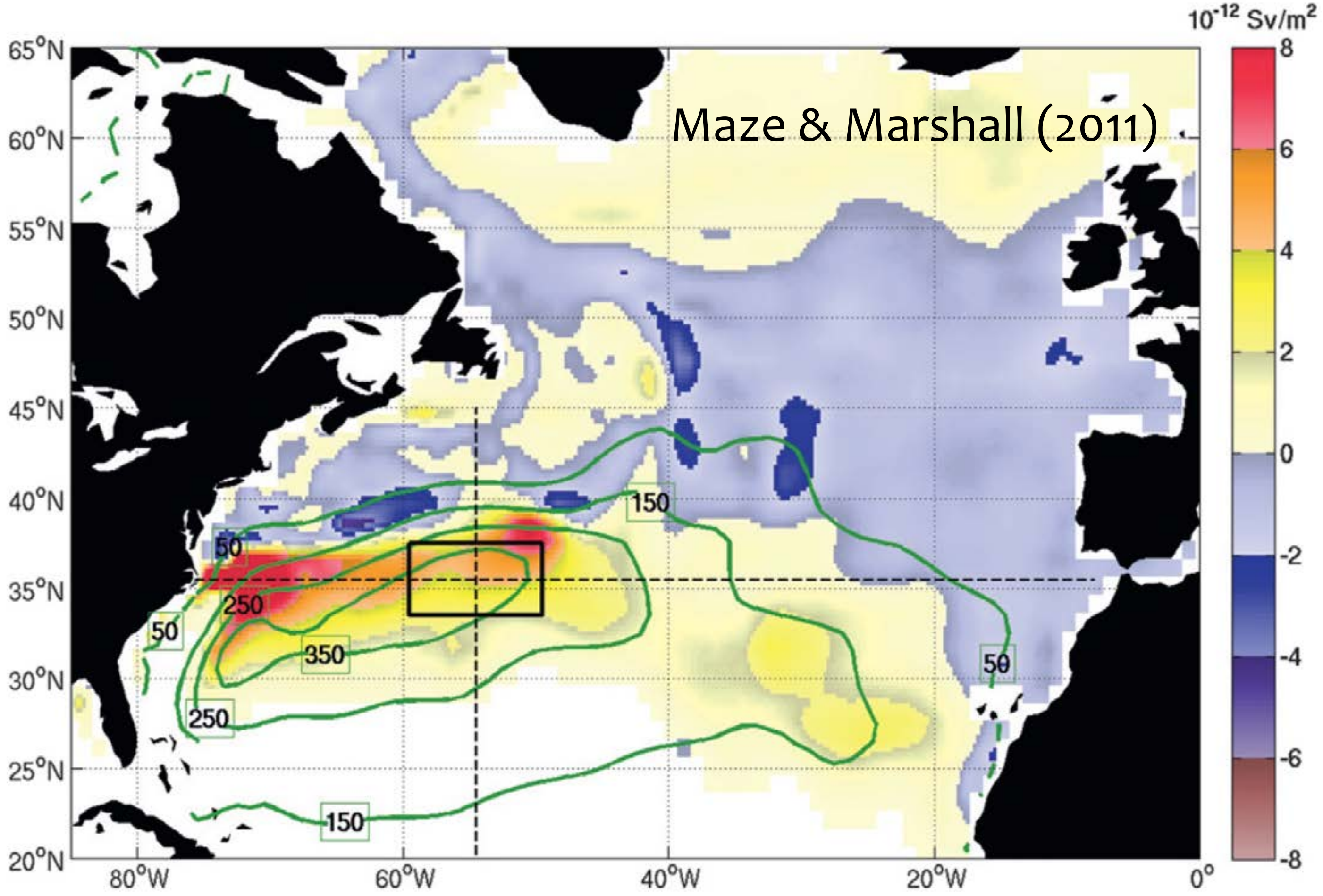


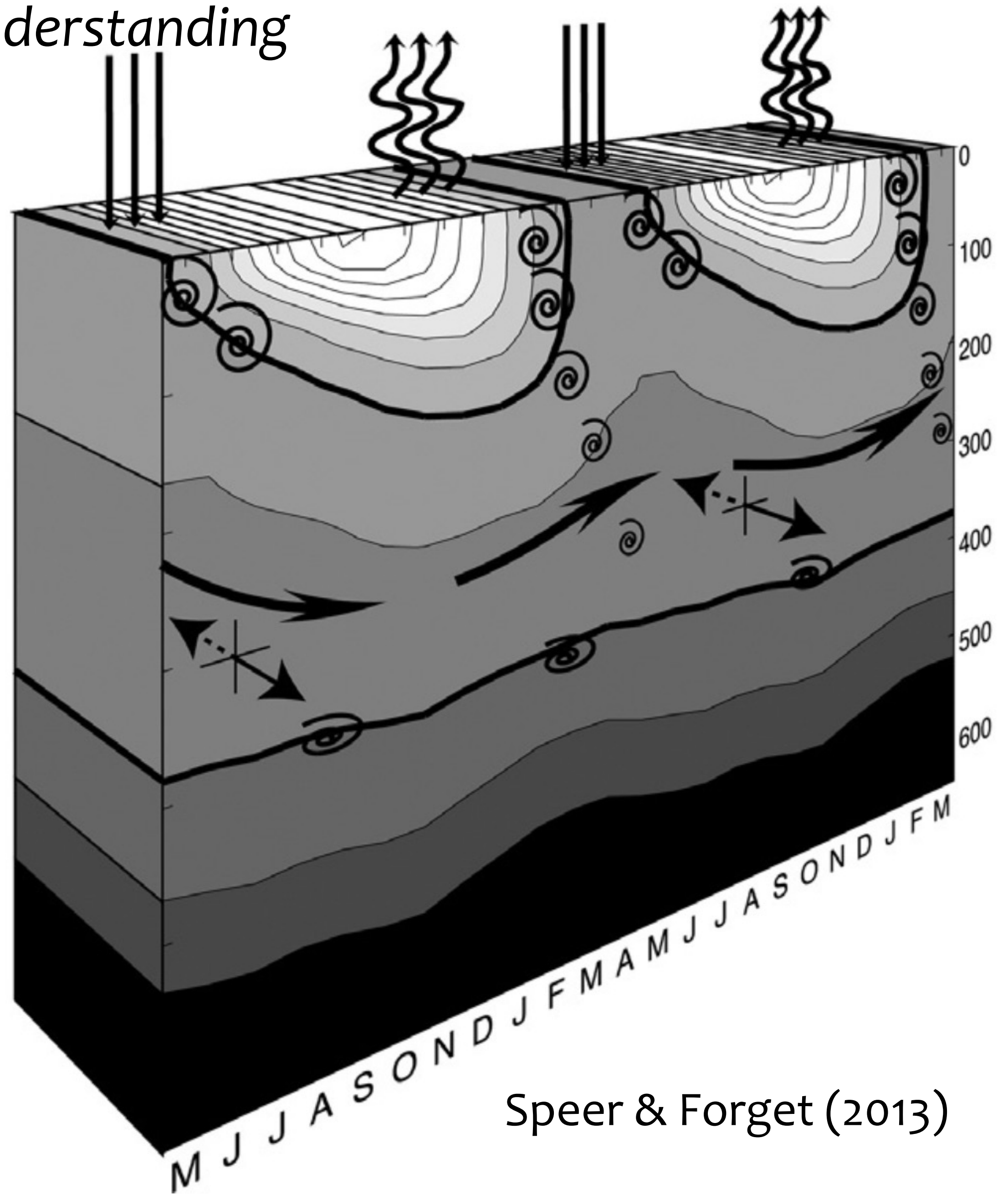



**Example use of state estimates:**

*Use of observations-only vs. state estimates for understanding*

Dynamics & variability of North Atlantic (Eighteen-degree) Mode Water formation



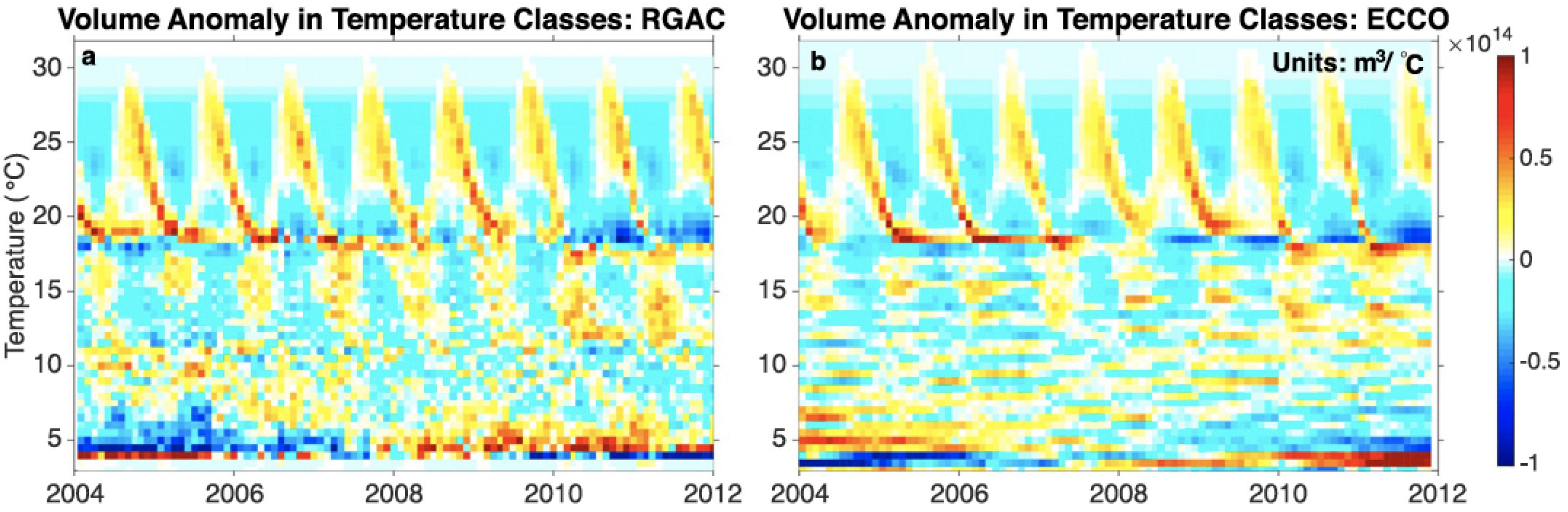

Speer & Forget (2013)

**Example use of state estimates:**

*Use of observations-only vs. state estimates for understanding*

Diabatic and adiabatic contributions to water mass volume variability in the North Atlantic subtropical gyre (26°N – 45°N)

***Evans et al., JPO (2017)***




**Roemmich & Gilson, 2009 (Argo)**

**ECCO version 4**

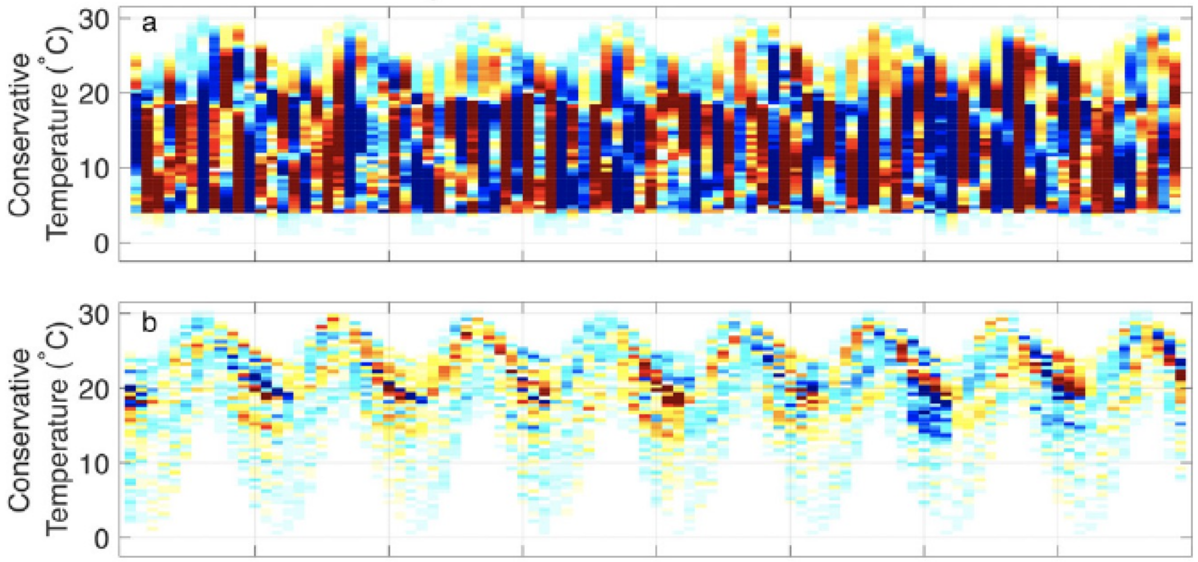
**Example use of state estimates:**

*Use of observations-only vs. state estimates for understanding*

# Diabatic and adiabatic contributions to water mass volume variability in the North Atlantic subtropical gyre (26ºN – 45ºN)

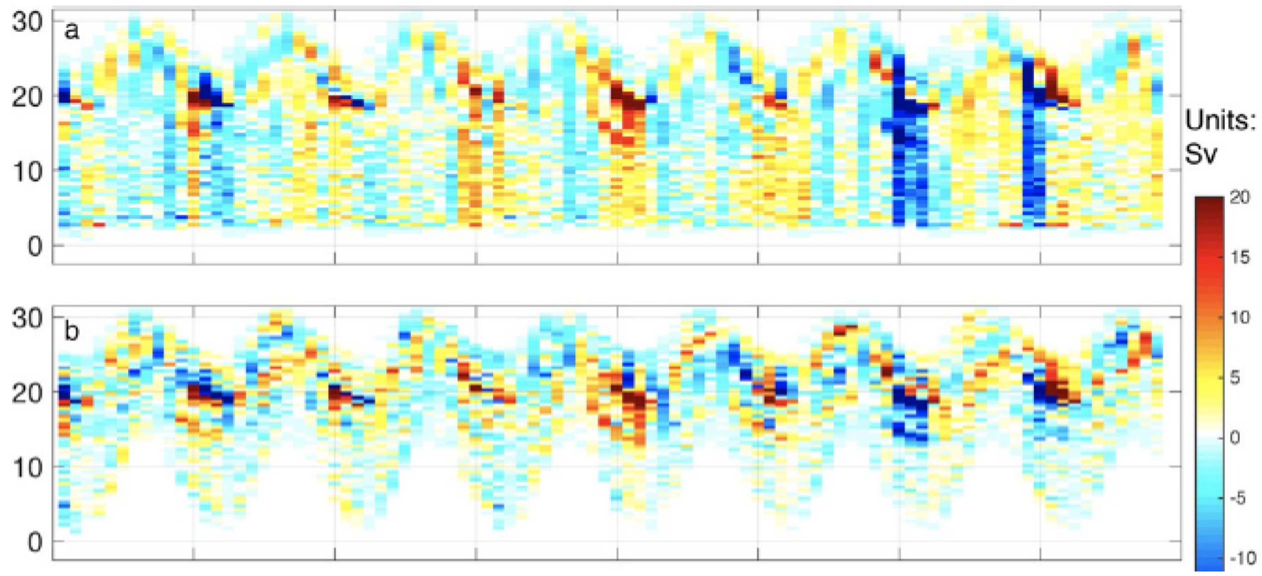
***Evans et al., JPO (2017)***

Total monthly ***dV/dt***, **Argo**




Monthly total & diathermal transformation due to air–sea heat fluxes
NCEP + Reynolds SST

Total monthly ***dV/dt***, **ECCO v4**



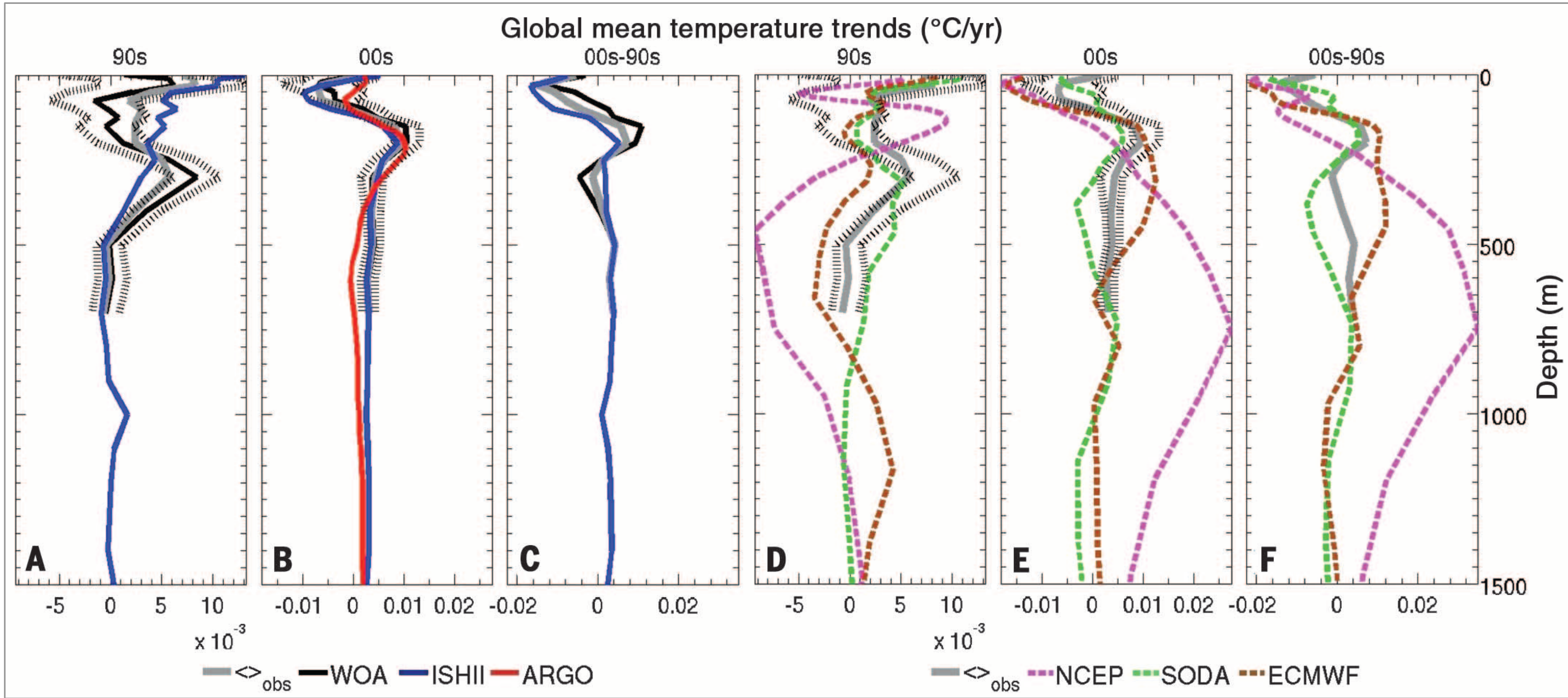

Monthly total & diathermal transformation due to air–sea heat fluxes
ECCO v4

**Example use of state estimates:**

*The ocean's role in the early 2000's Surface Warming Slowdown ("hiatus")*

- Hydrographic data suggest muted warming or cooling of top 100 m compensated by stronger subsurface warming down to 500 m
- Sizable differences among different hydrographies
- No info from Argo prior to ~2004!
- Discrepancies in several ocean reanalyses

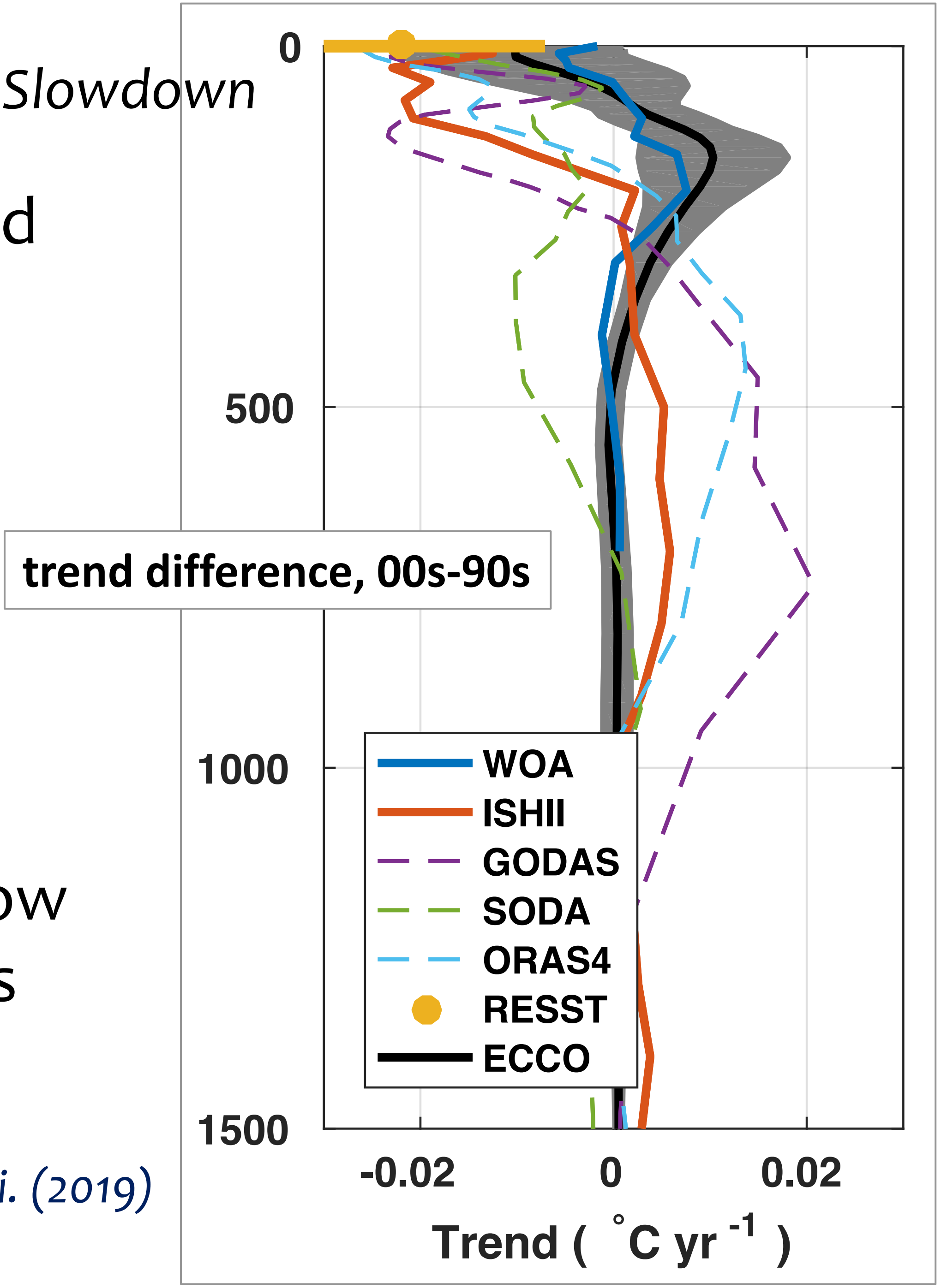
*Nieves et al., Science (2015)*



**Example use of state estimates:**

*The ocean's role in the early 2000's Surface Warming Slowdown*

- ECCO agrees well with WOA, within estimated uncertainties
- No uncertainties provided by *Nieves et al.* for hydrographic trends, 00s-90s
- Sizable differences among hydrographies
- Argo cannot constrain the 90s
- ECCO does not show large discrepancies below ~300 m, apparent in the 3 reanalysis products




*Heimbach et al., Front. Mar. Sci. (2019)*
*Piecuch (pers. comm.)*

Is it relevant for “short-window” DA?

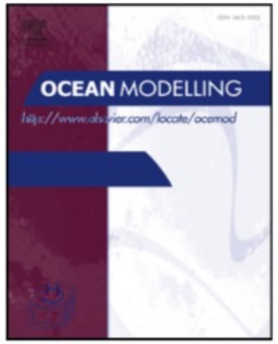
*Pilo et al., Ocean Modelling (2018)*

Ocean Modelling 131 (2018) 71–85

Contents lists available at ScienceDirect

Ocean Modelling

journal homepage: www.elsevier.com/locate/ocemod




# Impact of data assimilation on vertical velocities in an eddy resolving ocean model

Gabriela S. Pilo[*,a,b], Peter R. Oke[b], Richard Coleman[a,c], Tatiana Rykova[b], Ken Ridgway[b]

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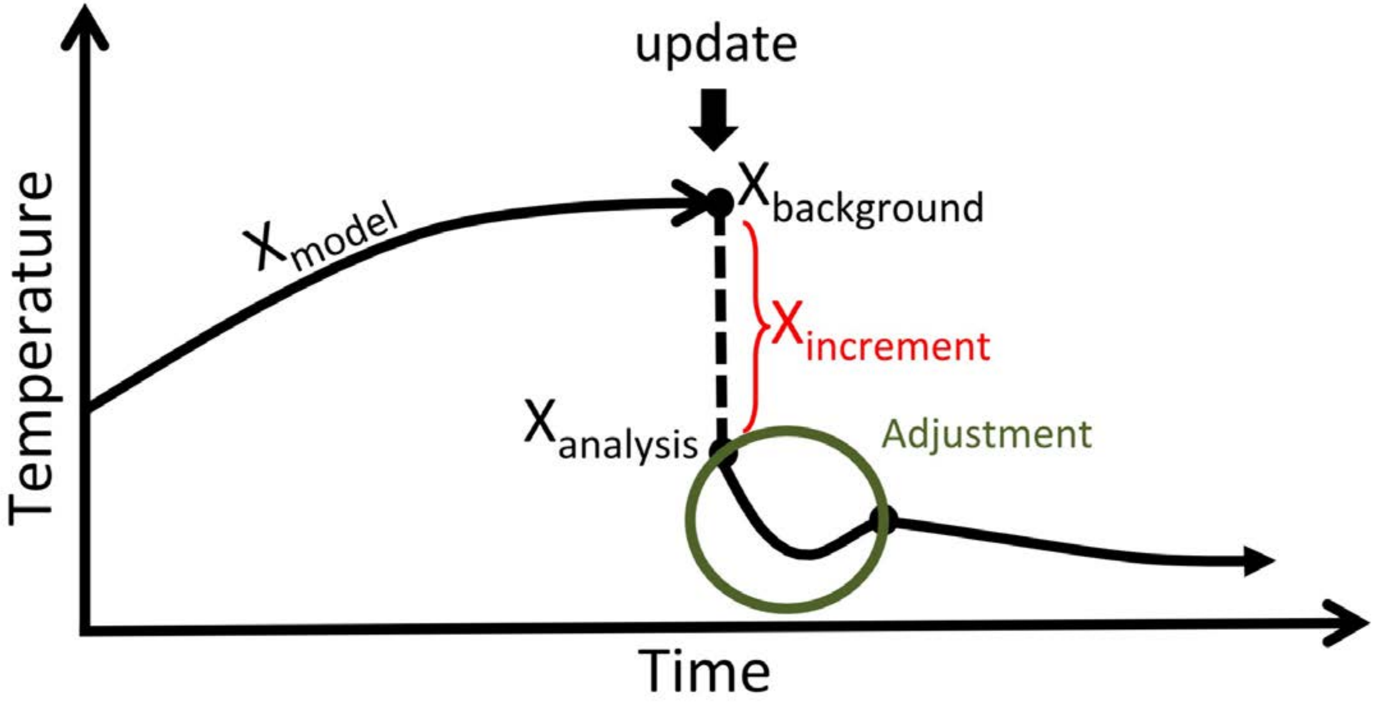
[c] *Antarctic Climate and Ecosystems CRC, Australia*

Is it relevant for "short-window" DA?

*Pilo et al., Ocean Modelling (2018)*

**In their words: "Sequential assimilation:"**

- explicit update of the model state at regular intervals
- updates to model state are not "dynamically consistent", i.e., they are generally not solutions to the model equations.
- can be regarded as a non-physical forcing term in the model equations
- Unphysical re-adjustments involve
  - inertial oscillations,
  - unrealistic mixing,
  - artificial baroclinic & barotropic adjustment

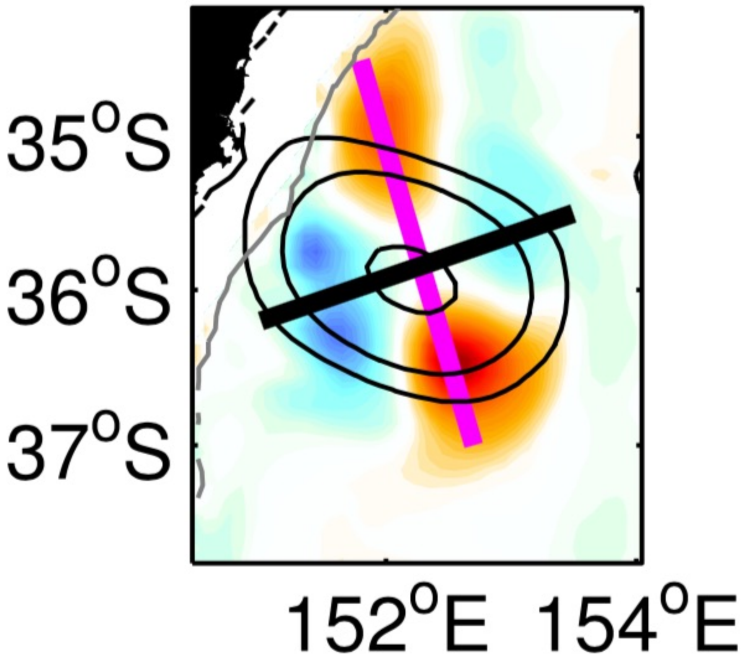


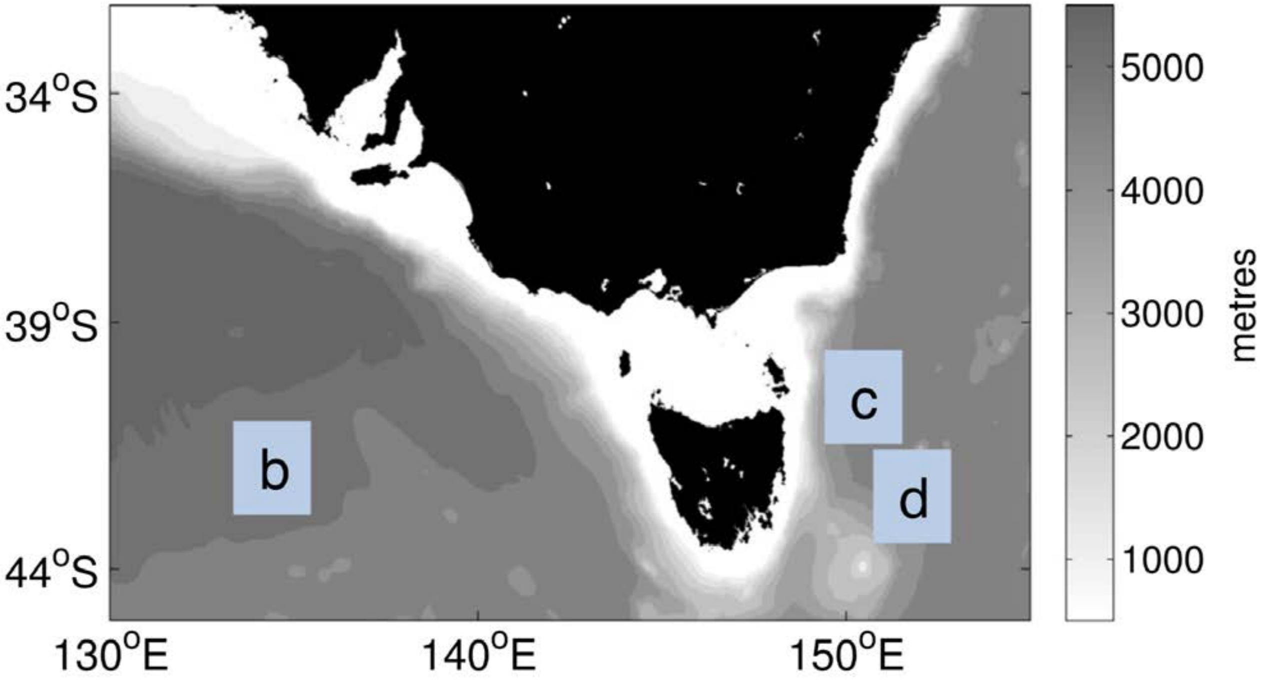
Is it relevant for "short-window" DA?

*Pilo et al., Ocean Modelling (2018)*

**Sequential assimilation:**

- Very few studies have assessed the integrity of the model's dynamical processes in a model run with DA.
- One way to gain insight into this issue is to look at behaviour of unobserved variable in the data-assimilating model
- Investigate vertical velocity field – pertinent to SWOT science
- Study of eddies in Tasman Sea



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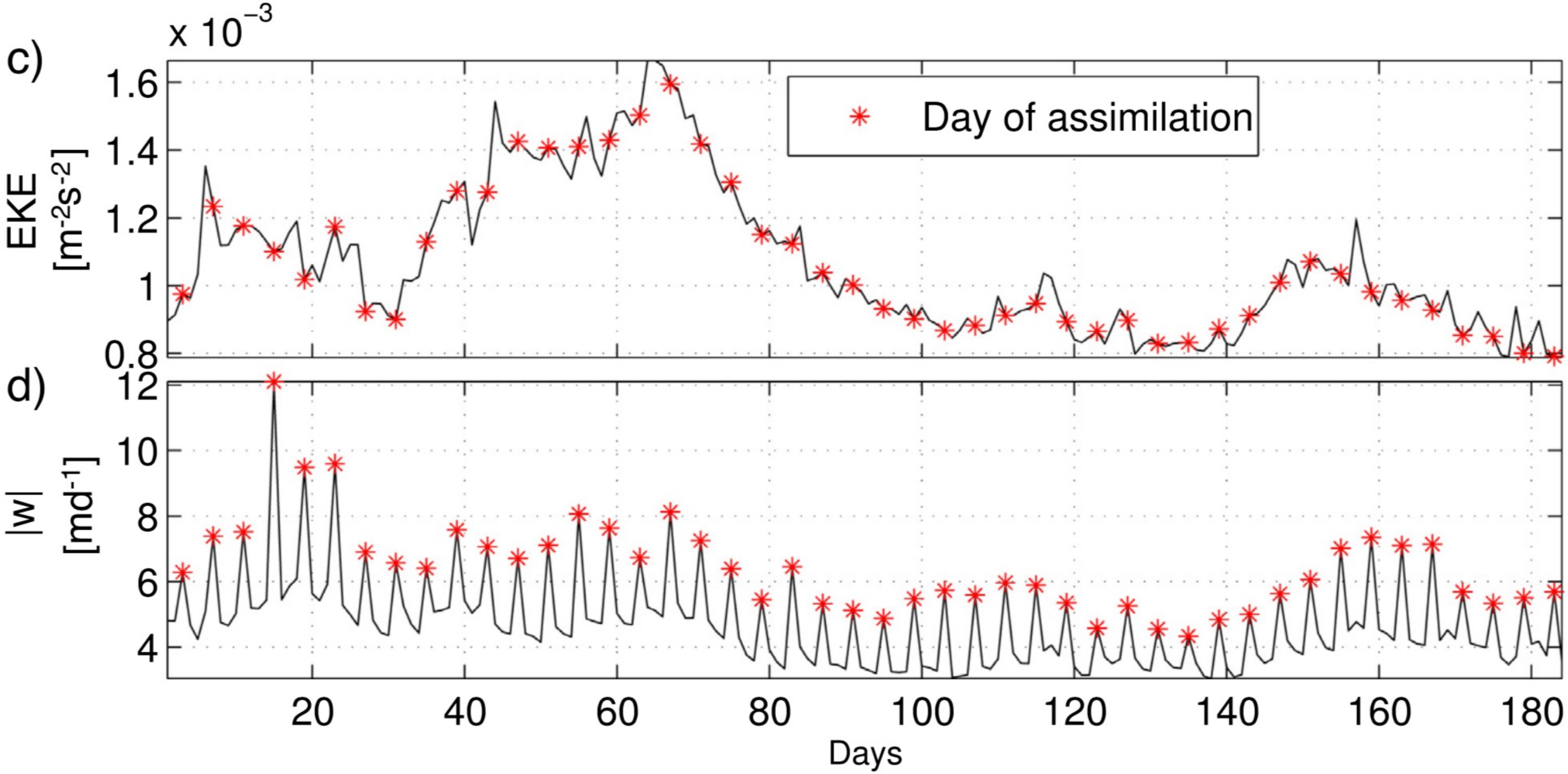


## Is it relevant for “short-window” DA?

***Pilo et al., Ocean Modelling (2018) – Verbatim***

- Analyses show that adjustment for vertical velocity is significant
- This also impacts *T* and *S* through vertical advection
- Vertical velocity appears to adjust within ~1 day
- Care should be taken when using vertical velocities “immediately” (i.e., one day) after assimilation
- Impact of artificial eddy distortion on the model’s *T* and *S* fields are typically smaller than the <u>increments</u> applied during the assimilation process itself

## Summary

- For mechanistic understanding & climate diagnostic dynamical & kinematical consistency often plays an essential role
- Climate diagnostics often seek small “signals” in noisy system
- Detailed investigation of property budgets from different terms in conservation equations for tracers are powerful diagnostic tools
  - but may be obscured by spurious effects from analysis increments
- Non-observed quantities also important for climate diagnostics or for driving offline models (e.g., biogeochemistry, ecosystems)
  - e.g., vertical velocity

Optimal tools for forecasting may not be optimal for reconstruction

- serious consideration for climate applications

# Filter vs. Smoother

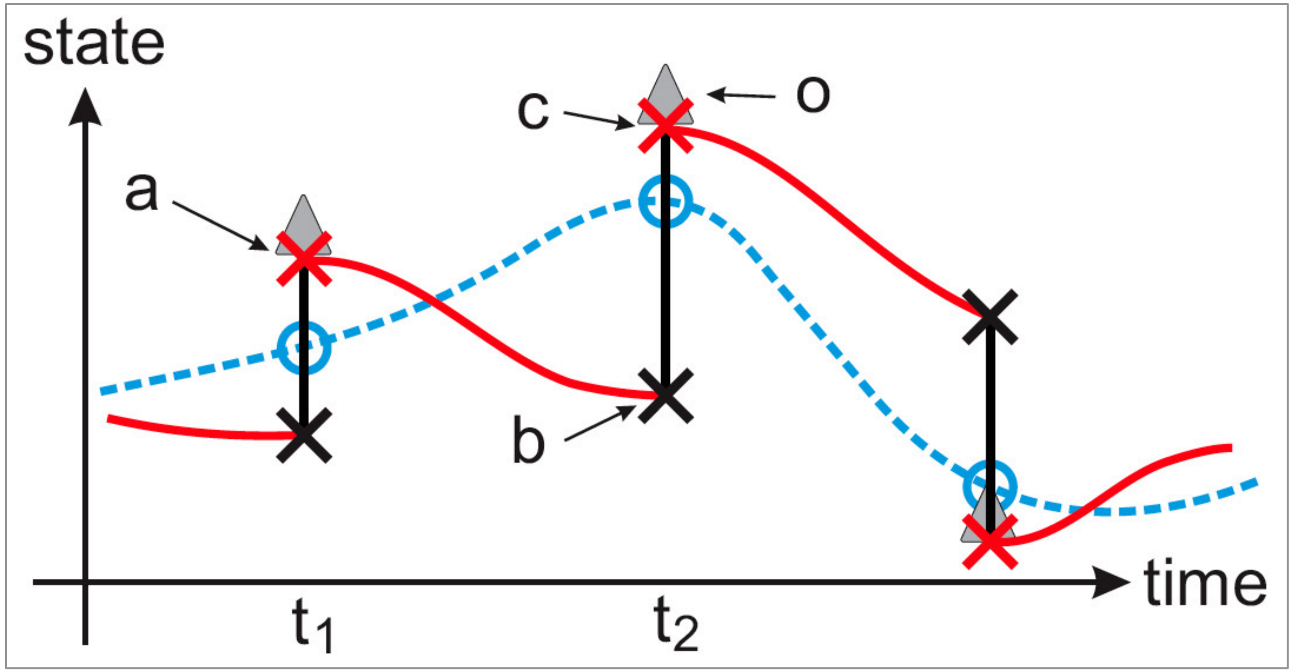
## The virtues of property-conserving estimation

**Some of the challenges:**

Why adjoints: dynamical & kinematical consistency in DA

## Numerical Weather Prediction (NWP) – a filtering problem

- Relatively abundant data sampling of the 3-dim. atmosphere
- NWP targets optimal forecasting
  - ➔ find initial conditions which produce best possible forecast;
  - ➔ *dynamical consistency or property conservation NOT required*



**Some of the challenges:**

Why adjoints: dynamical & kinematical consistency in DA

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## Ocean state estimation/reconstruction – a smoothing problem

- Sparse data sampling of the 3-D. ocean
- Understanding past & present state of the ocean is a major goal all by itself
  - ➔ use observations in an optimal way
  - ➔ *dynamic consistency & property conservation ESSENTIAL* for climate