

Applications, Limits, and Challenges of Ocean Monitoring

Advanced Methods in Oceanography

Lecture 5

Application of Ocean Monitoring

At the end of this lecture you will be able to:

- Describe modern applications of ocean monitoring;
- Discuss the limit of monitoring;
- Raise some of the difficulties with sustaining long-term monitoring projects;

Application of Ocean Monitoring

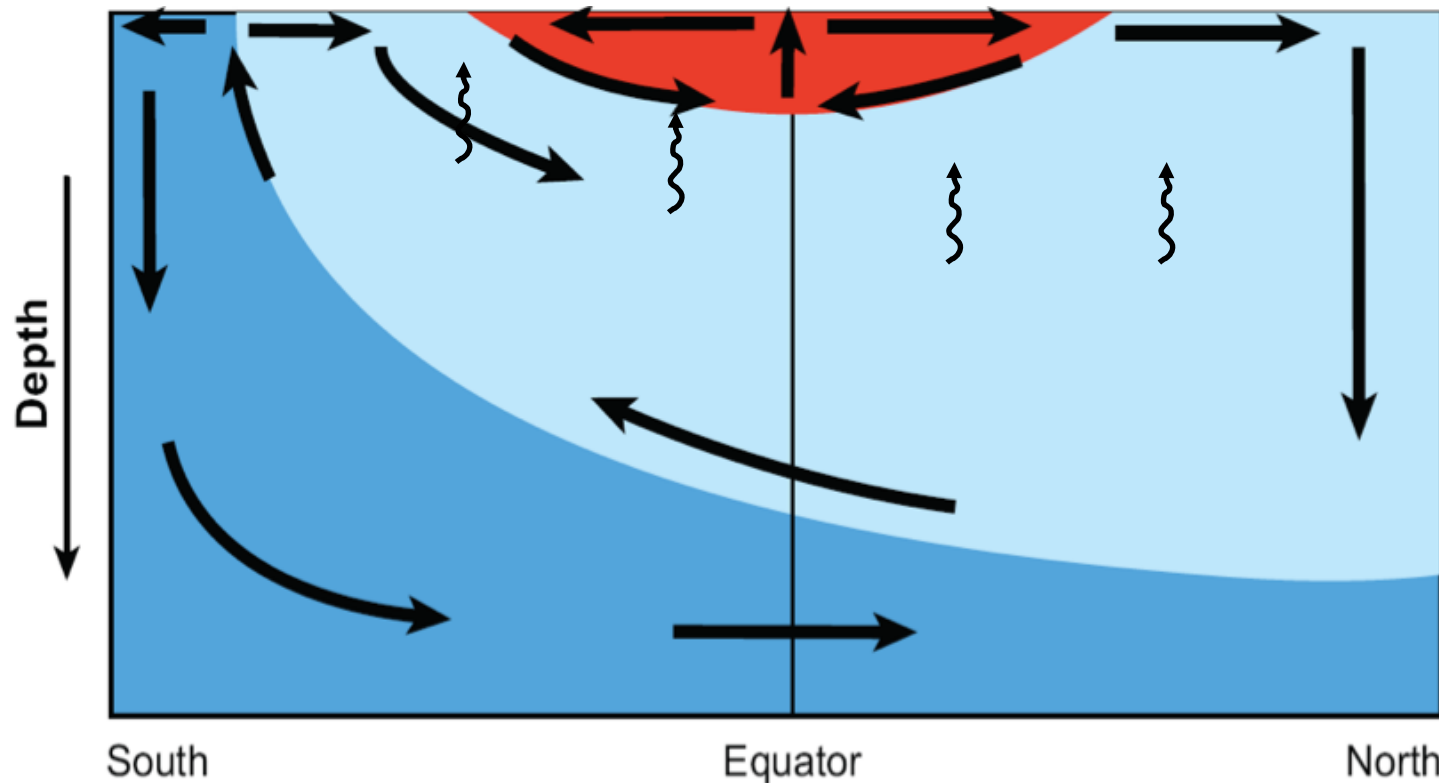
Lecture Outline:

1. Tracking vertical velocity from mooring
2. Inverse Model
3. Assimilation

Tracking vertical velocity

Why do we care about the vertical velocity?

- Bringing nutrient upward
- Lifting the dense water, and so sustaining the AMOC:



Tracking vertical velocity

How could we do that?

- Pb: Direct measurement is hard to do (vertical velocity is tiny).

Sol: Make an indirect measurement...

- Pb: Could be polluted by many “unwanted” vertical velocities:
 - Internal waves moving up and down do not transport mass

Sol: Monitor vertical velocity for a long time
(averaging effect of up and down motion)

Tracking vertical velocity

How could we do that? **by Using Mooring Data**

- Pb: Direct measurement is hard to do (vertical velocity is tiny).

Sol: Make an indirect measurement...

- Pb: Could be polluted by many “unwanted” vertical velocities:
 - Internal waves moving up and down do not transport mass

Sol: Monitor vertical velocity for a long time
(averaging effect of up and down motion)

Tracking vertical velocity

Mooring Data gives us

- **Long** and **frequent** measurements **all along the vertical** of
 - Temperature
 - Salinity
 - Pressure
 - Horizontal velocities (meridional and zonal)

We *just* need to find a way to track w from that!

Group challenge:

Find a way to relate $w(z,t)$ with $\rho(z,t)$, $u(z,t)$, and $v(z,t)$

To track missing information you need to add knowledge/constrain/equation(s)!

Tracking vertical velocity

Solution if one know over the vertical:

- the density
- and the horizontal velocities direction

$$w = -f \frac{R^2}{N^2} \partial_z \phi$$

Tracking vertical velocity

- Application (31°35'N, 54°56'W):

$$w = -f \frac{R^2}{N^2} \partial_z \phi$$

TABLE 1. Eastward and Northward Components, Speed, and Direction of the 243-Day Averaged Velocity for Each Current Meter on Mooring 612

Depth, m	Eastward Velocity, cm s^{-1}	Northward Velocity, cm s^{-1}	Speed, cm s^{-1}	Direction, rad
763	-0.85	1.66	1.86	2.044
913	-1.03	1.47	1.79	2.182
965	-0.93	1.35	1.64	2.174
1470	-1.23	0.86	1.50	2.531
1976	-0.83	0.77	1.13	2.394
2483	-0.41	0.86	0.95	2.016
4003	0.66	1.19	1.36	1.064

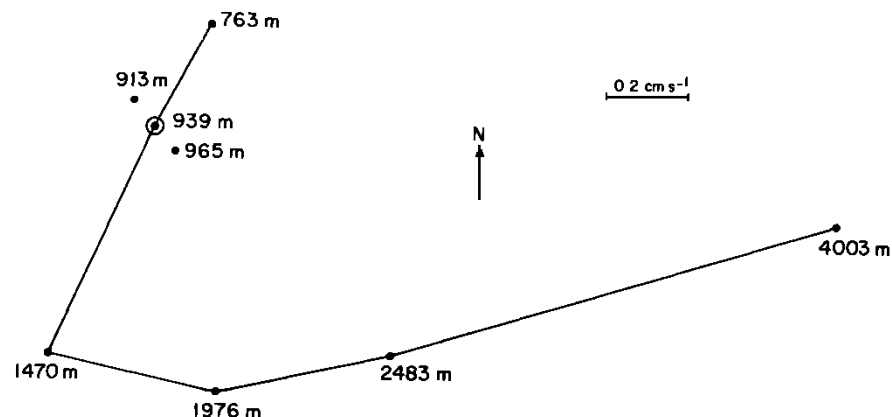


TABLE 2. Estimates of Vertical Velocity w , Vortex Stretching $f\partial w/\partial z$, and Advection of Planetary Vorticity βv at Mooring 612

Depth, m	$w, \times 10^{-4} \text{ cm s}^{-1}$
939	0.76
2483	-3.76

$\oplus$
(u, v) = (0, 0)

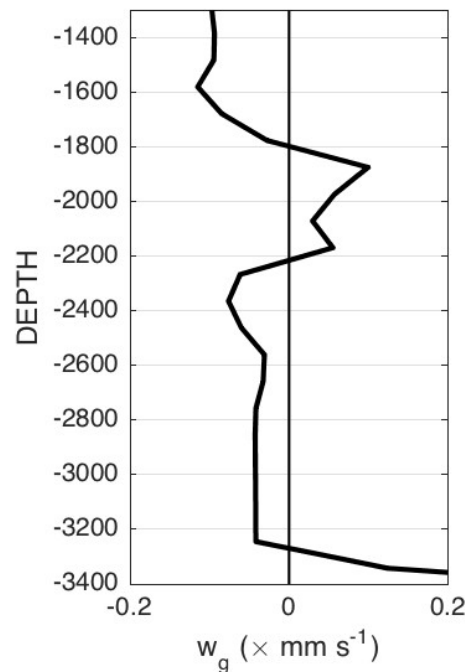
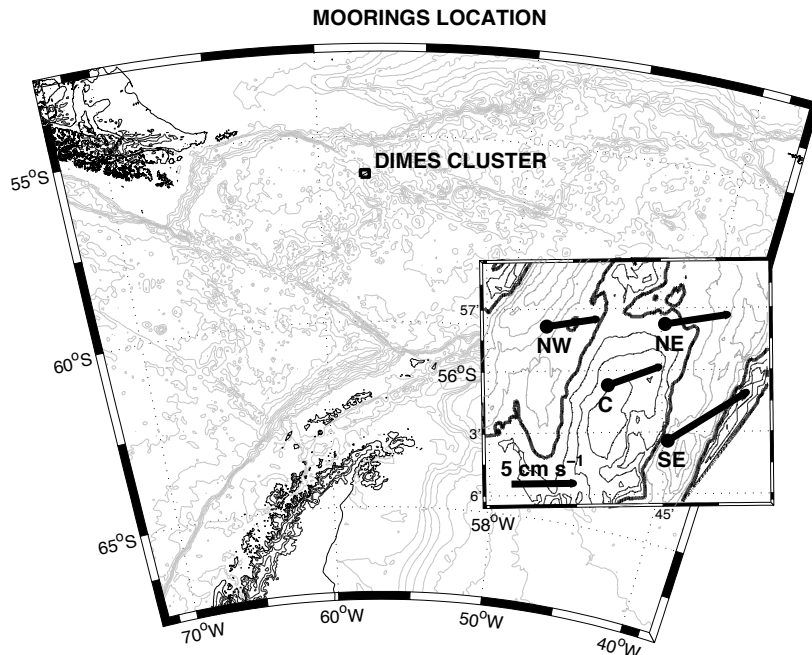
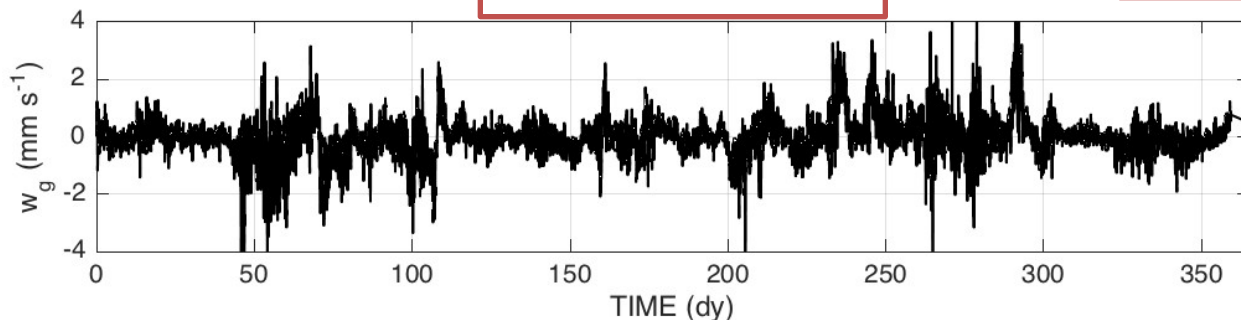
Fig. 1. Hodograph in depth of 243-day averaged velocities on mooring 612. At each depth the velocity vector is formed by connecting the tip of the vector denoted by solid dots to the origin denoted by cross in circle. The velocity at 939 m, denoted by an open circle, is the average of mean velocities at 913 and 965 m.

Tracking vertical velocity

- Application to the Drake passage:

$$w = -f \frac{R^2}{N^2} \partial_z \phi$$

$$W = -3 \times 10^{-5} \text{ m s}^{-1}$$



Inverse Modeling

What is an inverse problem?

In general:

$$f(\alpha) = \beta$$

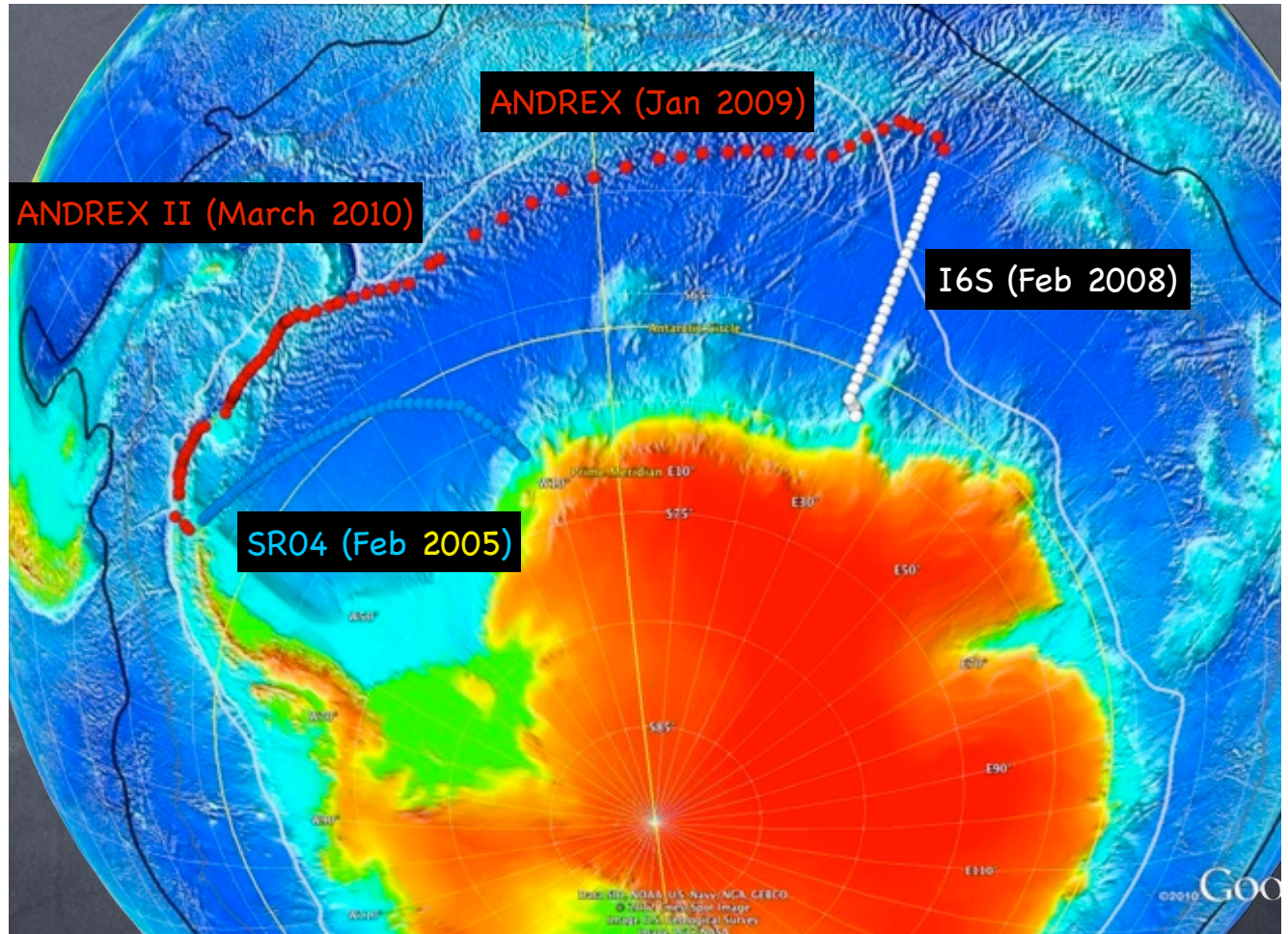
$$\alpha = f^{-1}(\beta)$$

But does f^{-1} exist?..

Finding a parameter or an unknown knowing the solution.

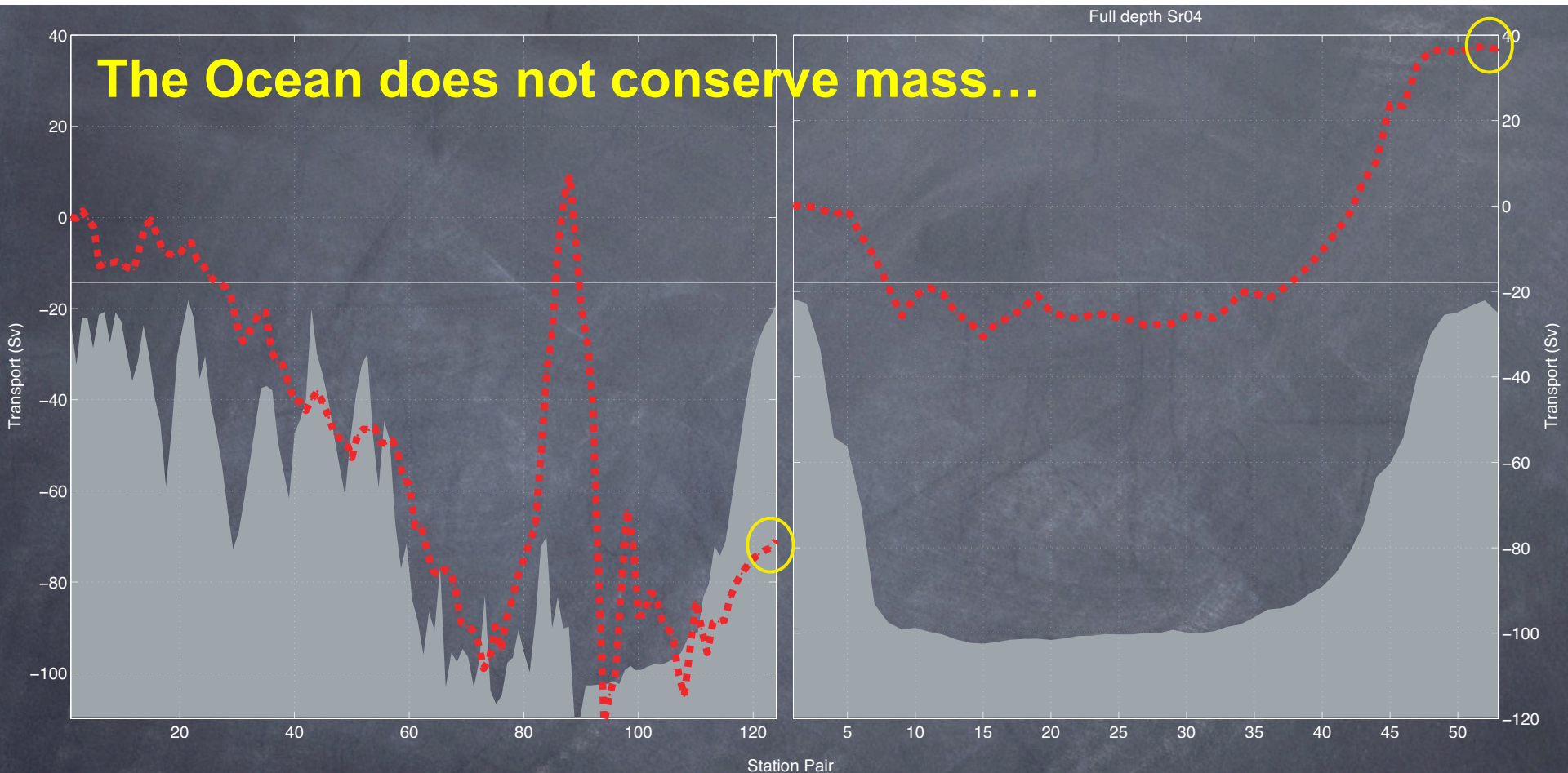
Inverse Modeling

Example of ANDREX?



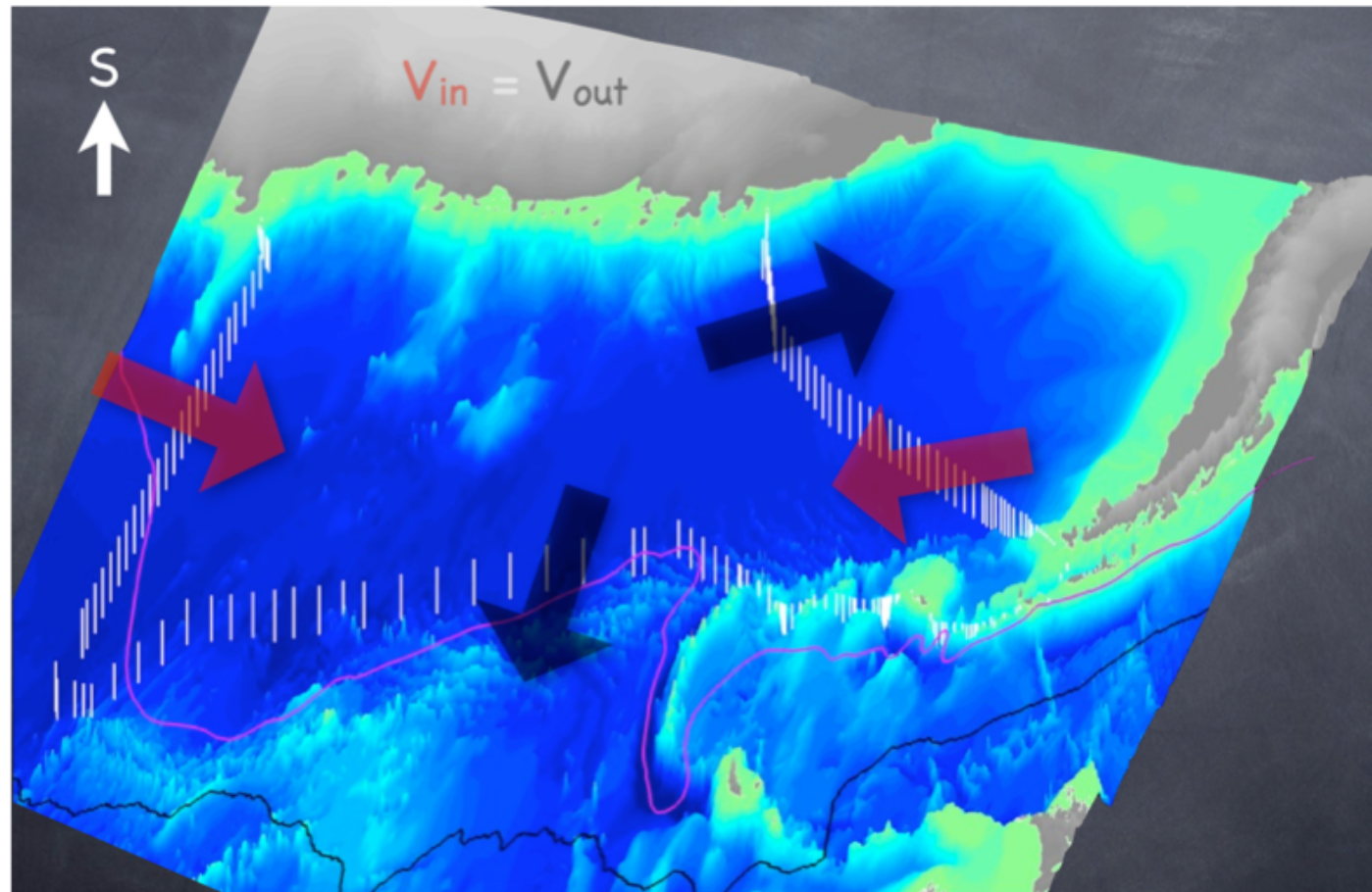
Inverse Modeling

The *a priori* mass transport estimate:



Inverse Modeling

Adding some knowledge (*i.e.* the function f):

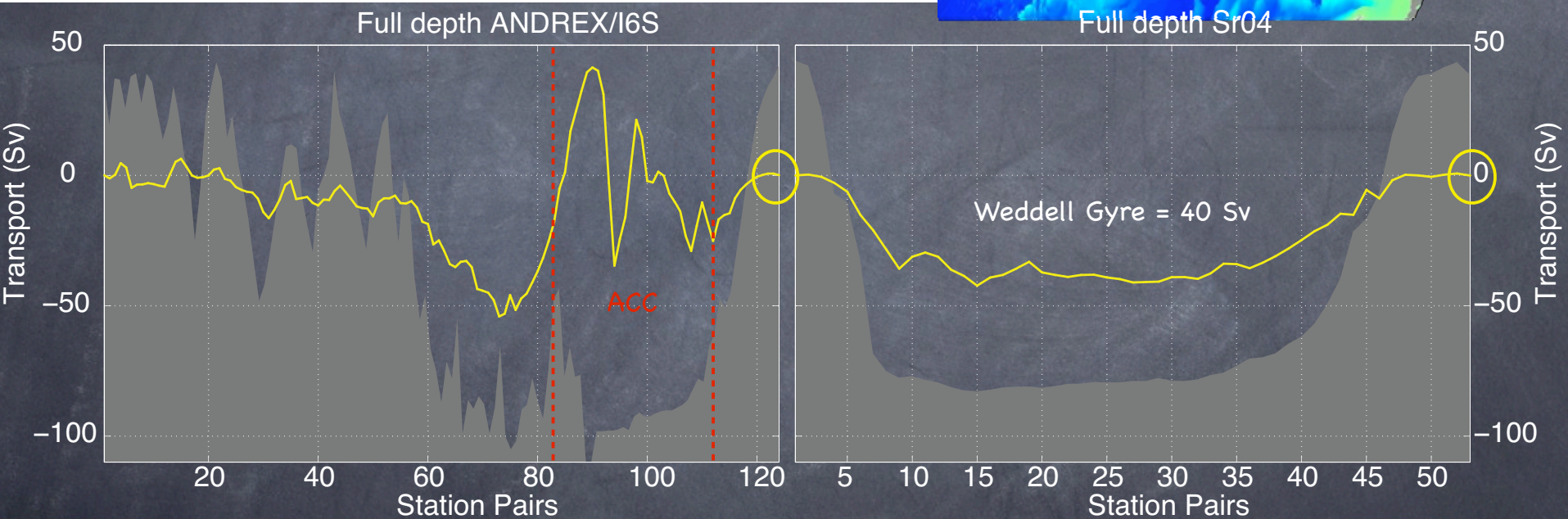
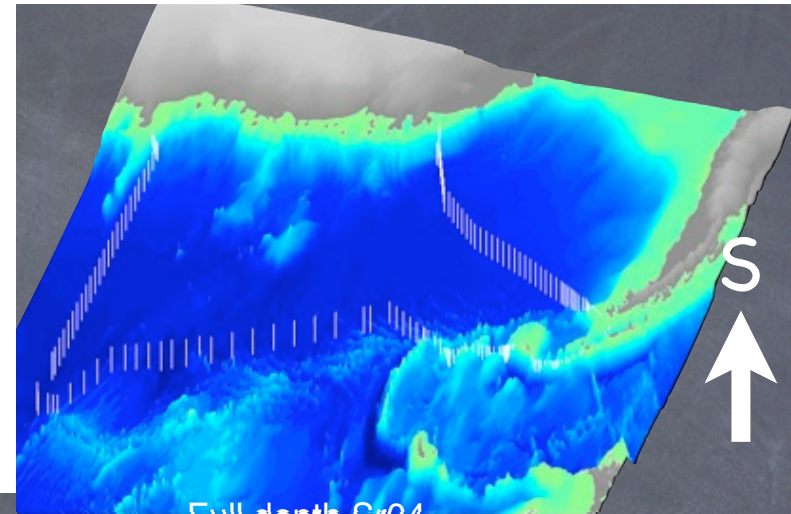


Inverse Modeling

The mass transport from the inverse solution:

- Assuming measurement errors.
- Constraining Mass conservation.

More Realistic!



Assimilation

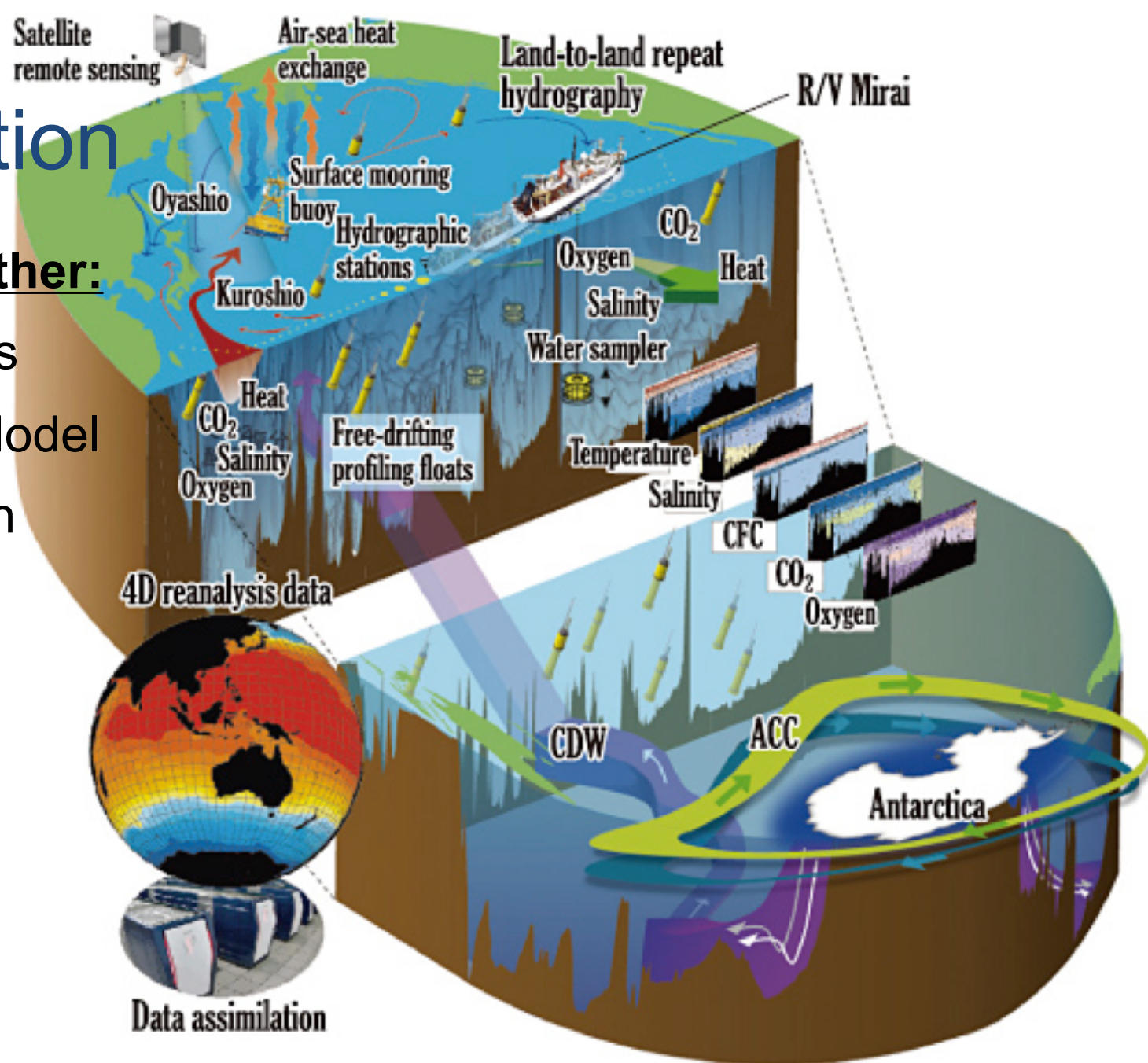
What is assimilation?

- **Extensively used in Operational Oceanography**
 - Observation (satellite & *in situ*)
 - Numerical Modelisation
- **Provide the “Best estimate” of the Ocean state**

Assimilation

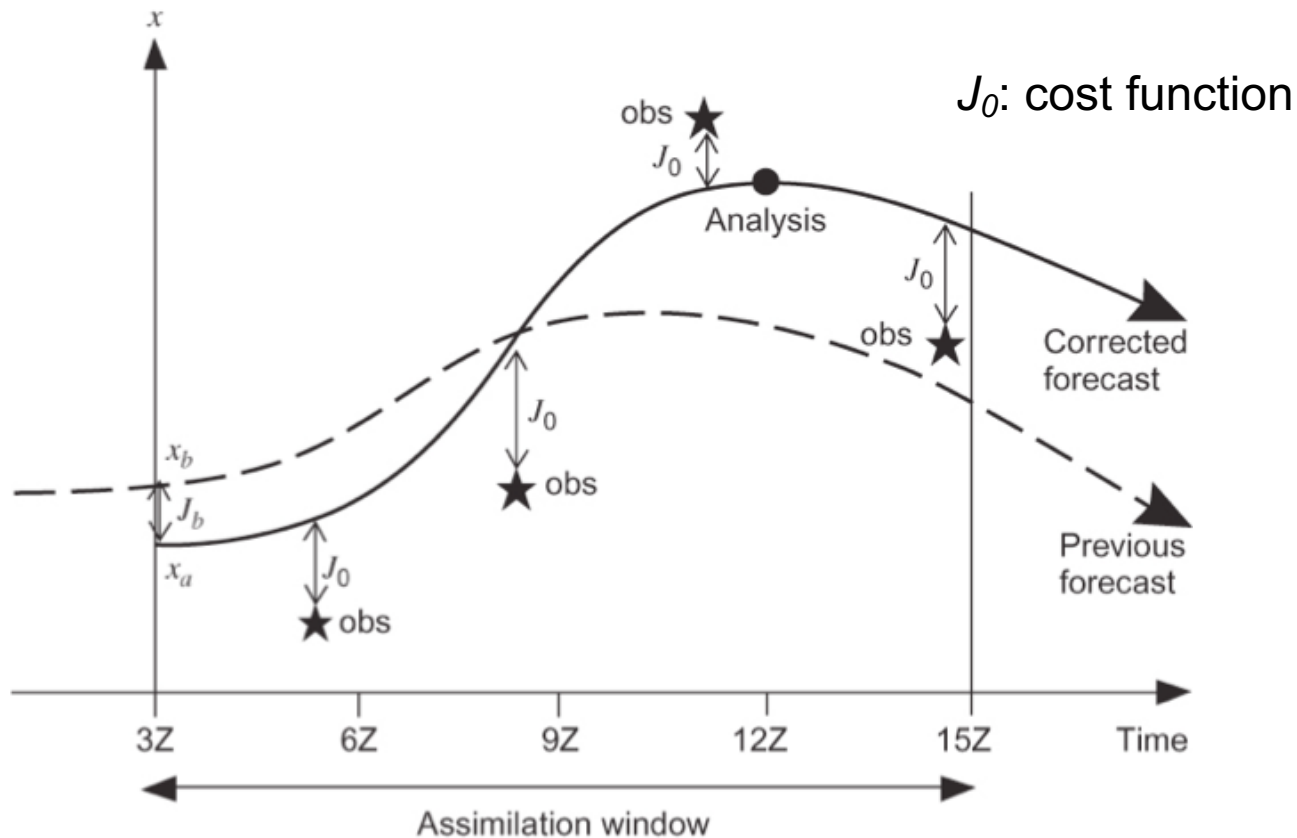
Bridging together:

- Observations
- Numerical Model
- Applied Math



Assimilation

Assimilation principle:

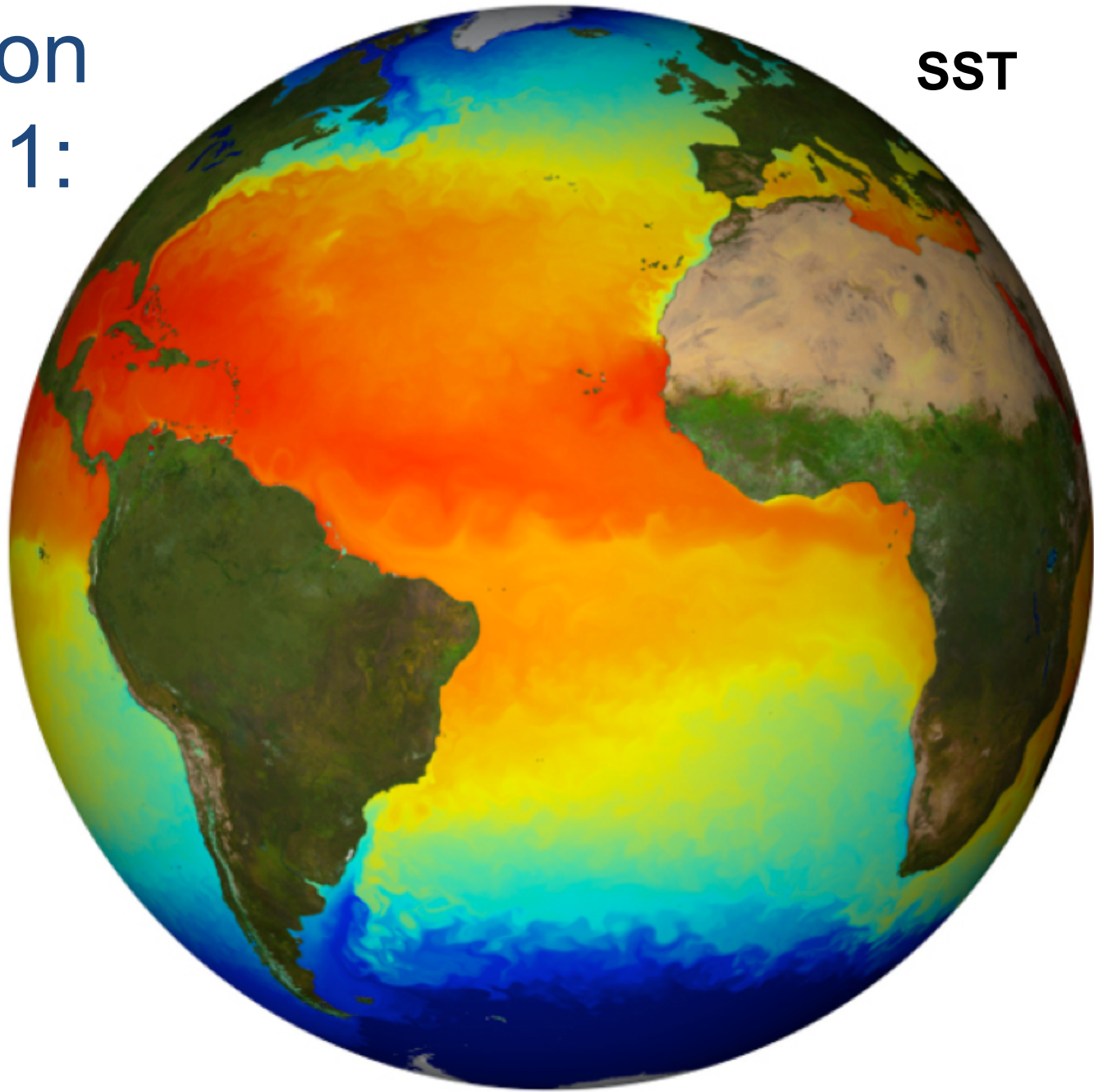


The model is used to *interpolate* observations.

Assimilation

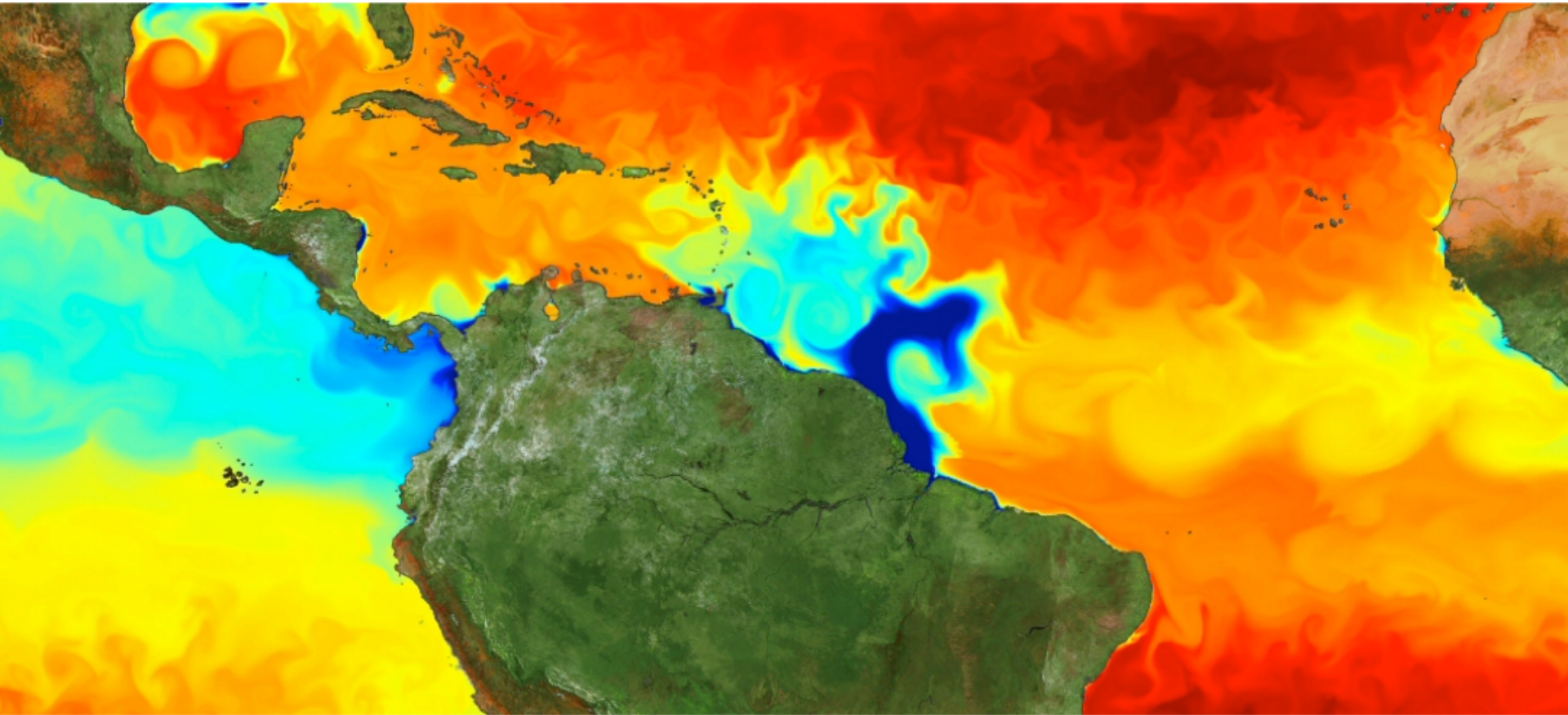
Example 1:

SST



Assimilation Example 2:

Sea Surface Salinity



Assimilation Criticism...

- Despite its tempting output the solution of assimilation is not based on physical principle only:
 - The mixture of observations & numerical model is hard to interpret.
 - One could interpret assimilation as numerical model constrain to follow observations by billion of *springs* (these *springs* do not have physical meaning).

Schema huius praeiudicis diuisionis Sphaerarum .

- Ptolemy (90-168) is back...
Good representation for the wrong reason. As scientist, should we be satisfied?..



Application of Ocean Monitoring

1. Tracking vertical velocity from mooring
 - Direct measurements are not always the best way...
 - Knowledge of the ocean/climate dynamics could be powerful.
2. Inverse Model
 - Incorporating knowledge and error increase consistency.
 - It allows finding unknown parameters.
3. Assimilation
 - Bridge Observations, Numerical Model, & Applied Math together.
 - Provide the “Best Estimate” of the Ocean State.

Ocean monitoring in the future

PART 2

Ocean monitoring in the future

The purpose of this lecture is to:

1. Discuss the limit of monitoring;
2. Summarize the role of long-term monitoring in oceanography;
3. Raise some of the difficulties with sustaining long-term monitoring projects;
4. Demonstrate why success of such projects depends as much on intellectual input into design and data analysis as on the quality of observations.

The Limit of Monitoring

Let's ask ourselves 2 questions:

1. What are the intrinsic limit of monitoring a system to understand it?
2. What are the limit of the nowadays Ocean Monitoring System?

The Limit of Monitoring

1. What are the intrinsic limit of Monitoring a system to understand it?

If you would like to study and understand a system, would you only look at it?

Imagine you have the perfect monitoring system of *this* wave. Would you know the dynamics of waves?

How other physical sciences deal with this fundamental issue?



The Limit of Monitoring

1. What are the intrinsic limit of Monitoring a system to understand it?

How other physical sciences deal with this fundamental issue?

- **They are making experiments...**
- **We have to use numerical model for this purpose.**

Observations are not enough by any mean. Scientists have to create a reproducible experiment to test their hypotheses.

The Limit of Monitoring

2. What are the limit of nowadays Ocean Monitoring System?

- a) The Time Scale
- b) The Spatial Scale

The Limit of Monitoring

2. What are the limit of nowadays Ocean Monitoring System?

a. The Time Scale:

The wave again:

- Gravity waves: 0.3s-30s
- Climate: 1yr-100yr, 3.1×10^7 s- 3.1×10^9 s

Ratio: $\sim 10^8$



A 1-h movie corresponds to 12,000-yr data... Impossible?

The Limit of Monitoring

2. What are the limit of nowadays Ocean Monitoring System?

b. The Spatial Scale:

Are we monitoring the system efficiently?

- Argo
- Satellite

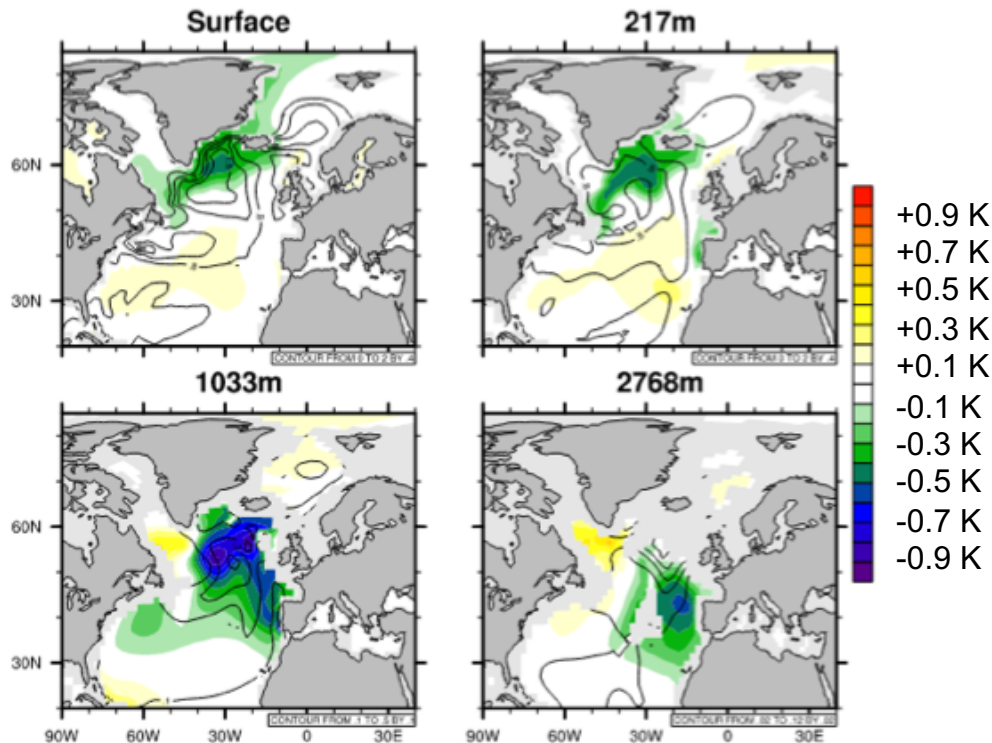
Are we missing something?

- **The Deep Ocean!**

The Limit of Monitoring

2. What are the limit of the nowadays Ocean Monitoring System? **The Deep Ocean!**

Sensitivity of Oceanic Heat Content to Anomaly:



Results:

- The deep ocean is key;
- Sensitivity extends well below 2,000 m.

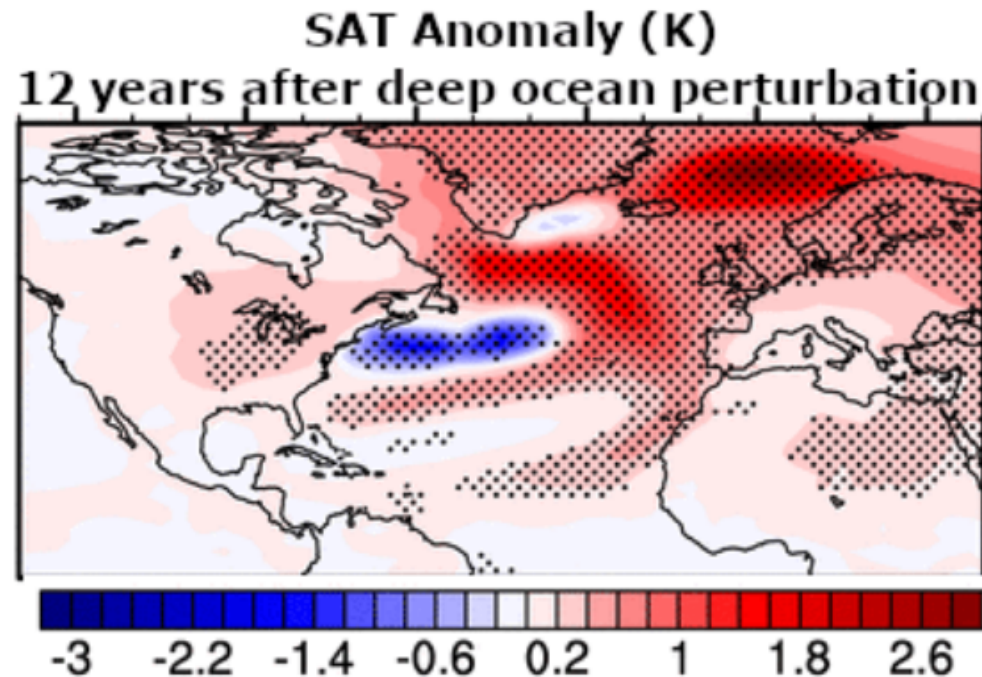
Sévellec and Fedorov (J. Clim., 2017)

The Limit of Monitoring

2. What are the limit of the nowadays Ocean Monitoring System? **The Deep Ocean!**

Impacts:

- An anomaly of **0.7 K** in the **deep ocean**
- leads to an anomaly of **~2 K** in the **surface atmosphere**
- after **~12 yr.**



Germe et al (J. Clim. Dyn, 2018)

For accurate prediction model initialization need accurate data below 2,000 m (~Argo floats)

The Limit of Monitoring

2. What are the limit of the nowadays Ocean Monitoring System?

a) The Time Scale

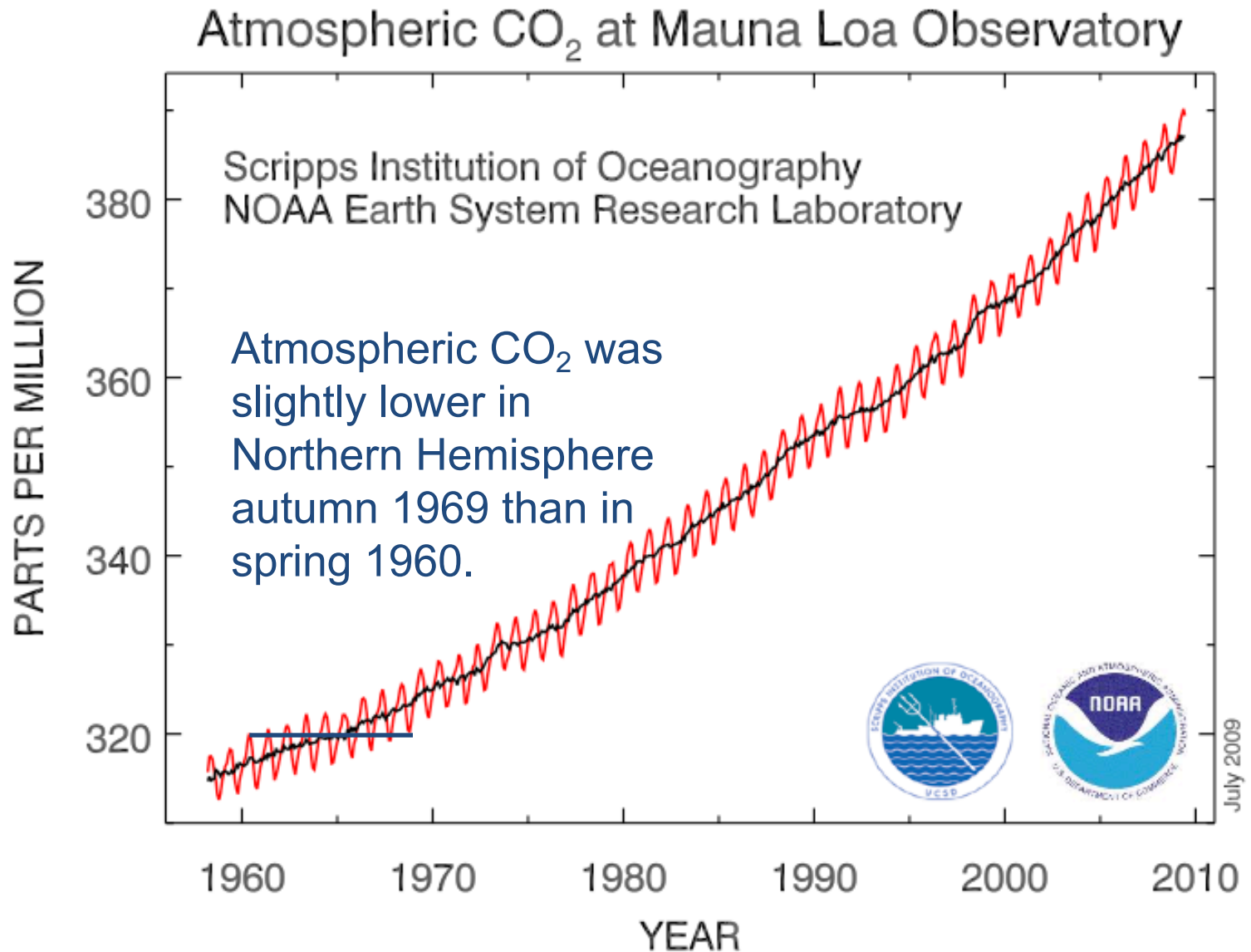
b) The Spatial Scale

“The understanding of climate is an inter-generational problem.”

(Carl Wunsch, 2010)

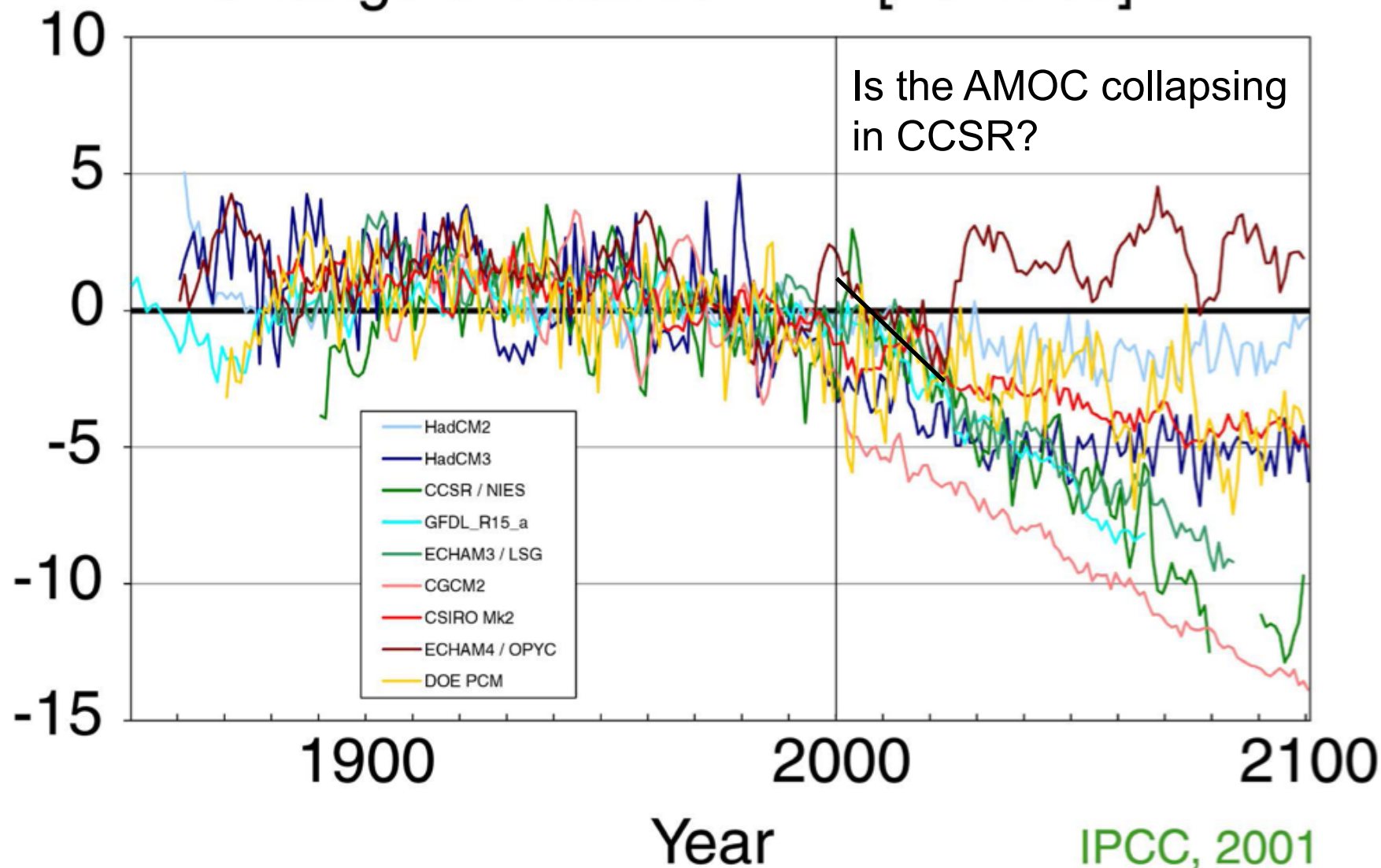
We need long, high temporal
resolution data sets...

The Role of long, high freq. Monitoring



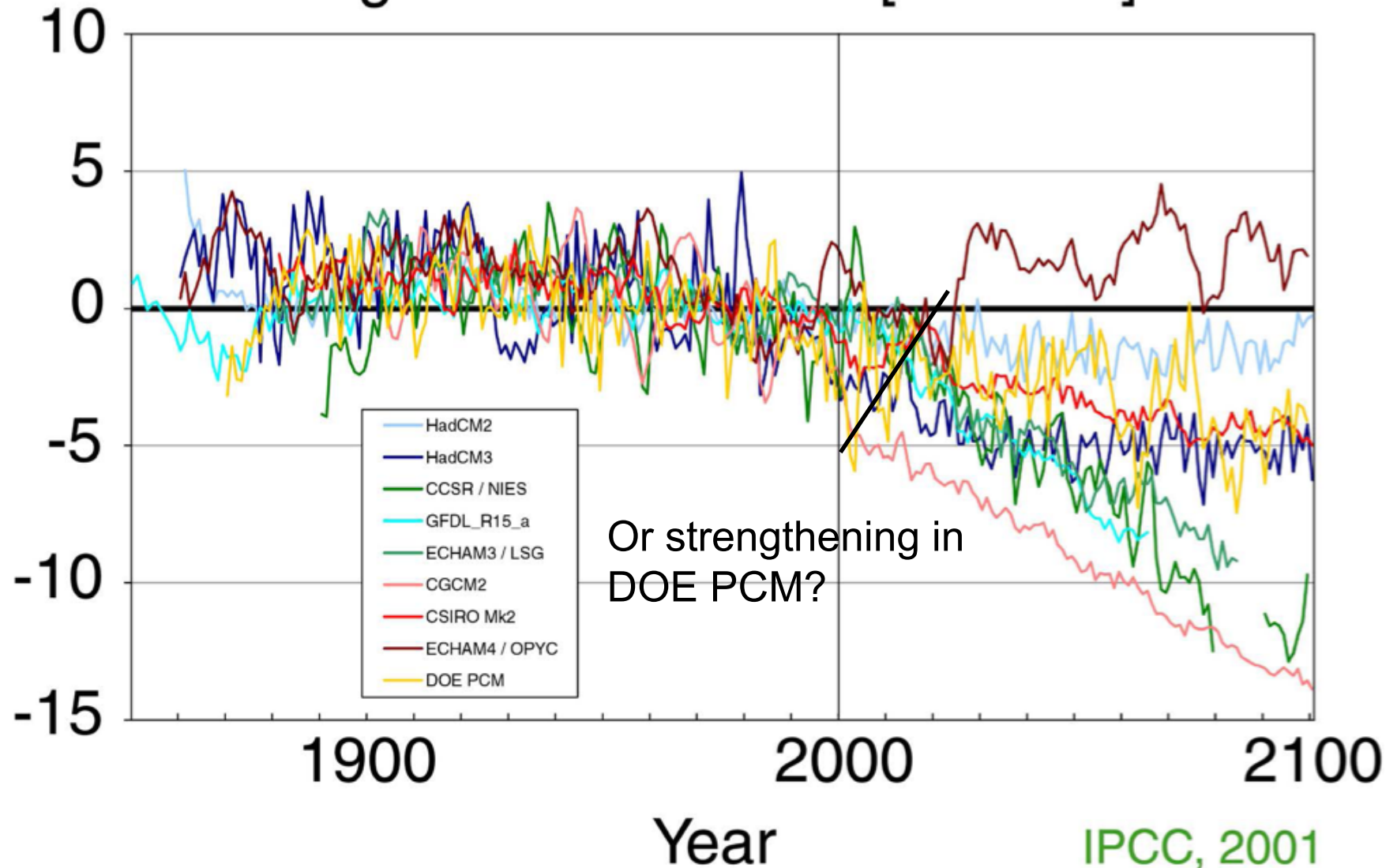
The Role of long, high freq. Monitoring

Change in Atlantic MOC [$10^6 \text{ m}^3/\text{s}$]



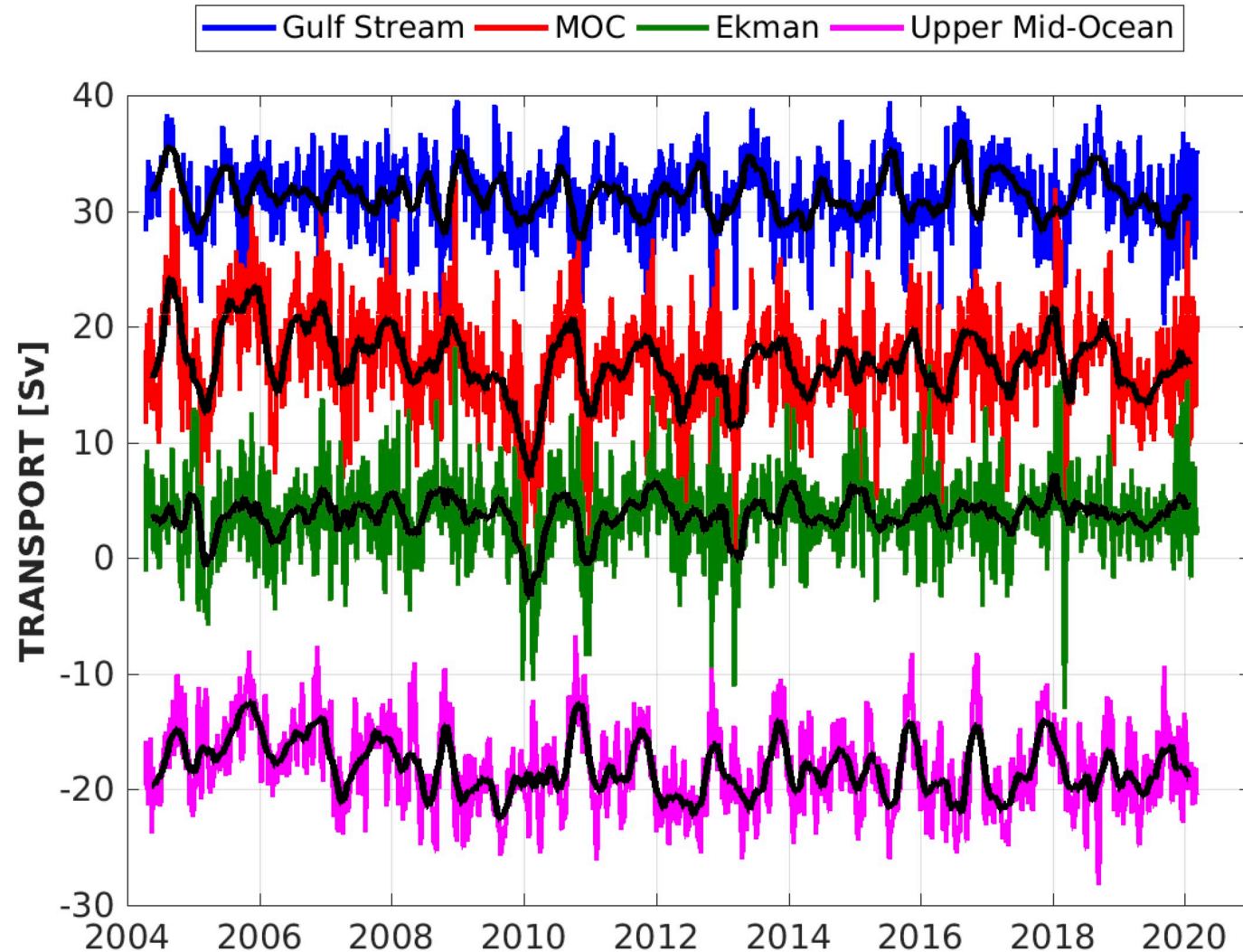
The Role of long, high freq. Monitoring

Change in Atlantic MOC [$10^6 \text{ m}^3/\text{s}$]



The Role of long, high freq. Monitoring

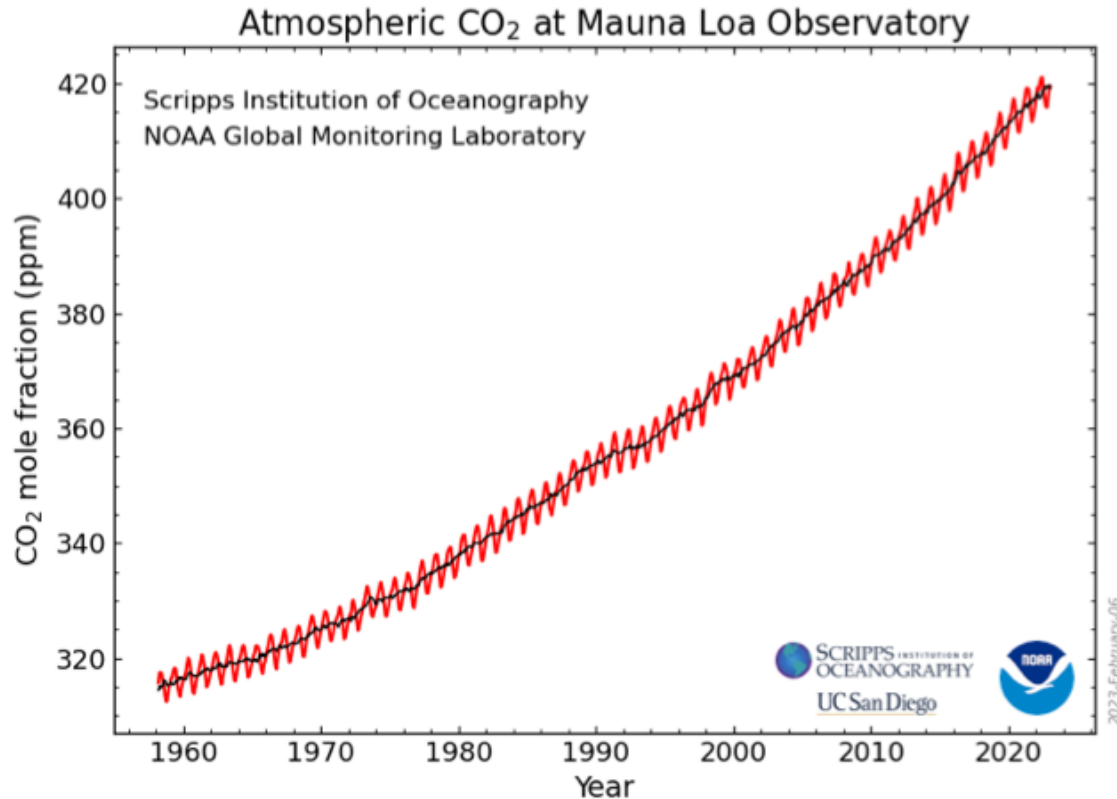
Variability of the observed MOC



We need long, high temporal
resolution data sets...

... but can we have them?

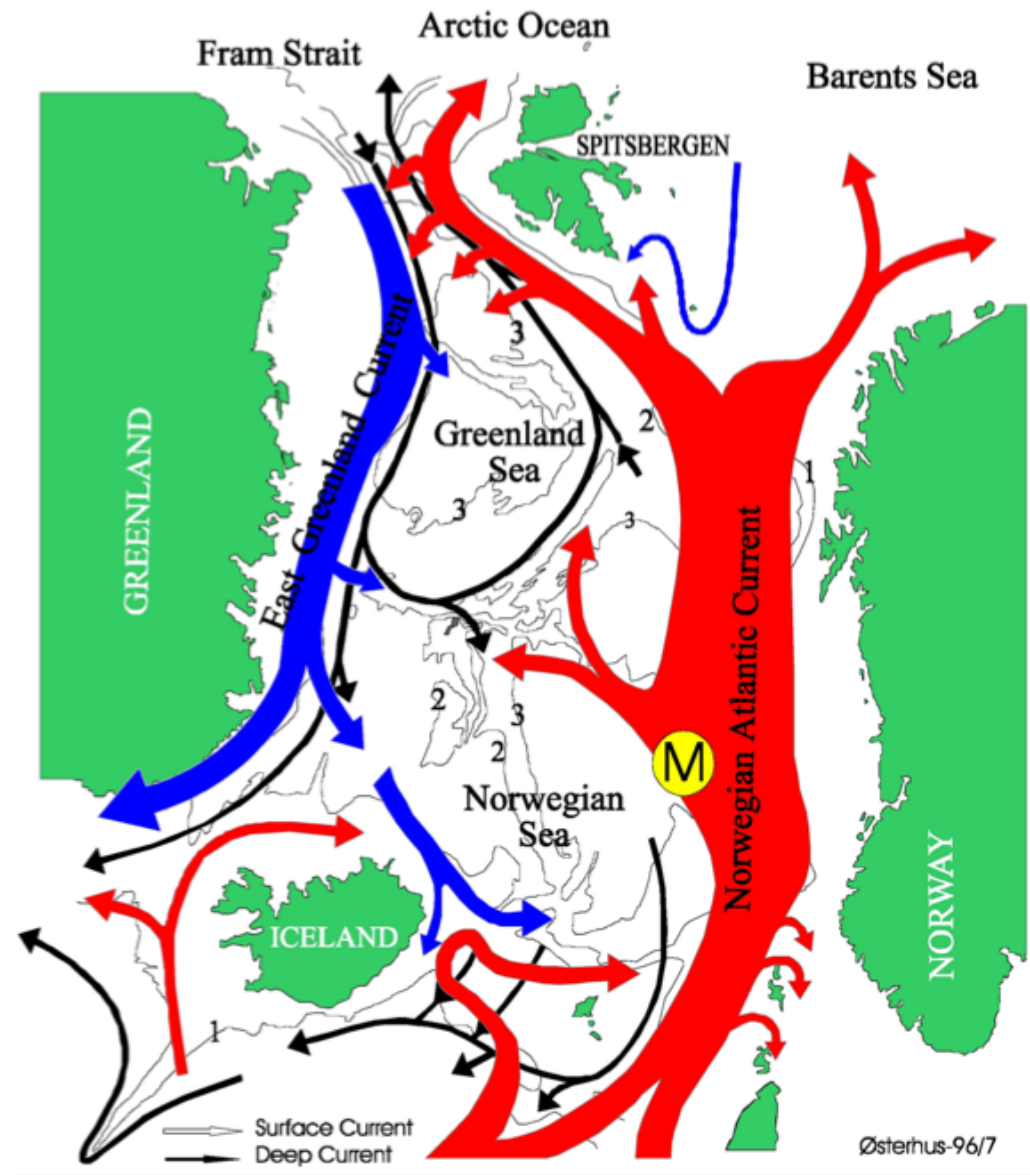
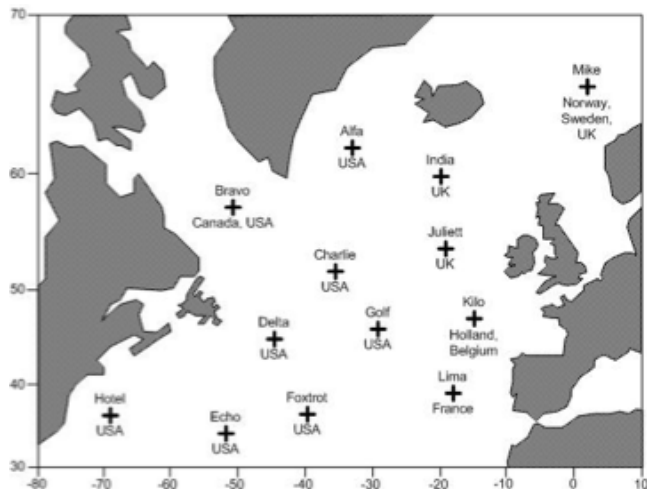
Funding the Keeling Curve



Charles Keeling, in the review article/autobiography "Rewards and Penalties of Monitoring the Earth", *Annu. Rev. Energy Environ.* (1998), explains the difficulties he faced in sustaining continuous observations, leading a second station at the South Pole to be abandoned.

Funding of Weather Ship stations

- 13 ocean weather stations planned in 1946
- Much more expensive than a buoys, but wider range of capabilities.
- Backing for most failed and only station "M" went on to produce a long timeseries of the subsurface ocean.
- Continued until 2010, replaced by a mooring.



Why is it hard to monitor the Earth?

- Monitoring is expensive
- Global monitoring requires international cooperation
- If a monitoring programme is to survive, there must be a steady stream of exciting results:

Low-hanging fruit near the start of a programme (new observations), but these will have been picked within a few years.

What to monitor & how to monitor it?

- 1) What are the big questions?
- 2) Can multiple big questions be addressed with the same monitoring system?
- 3) How do we resolve the trade-off between cost and spatial/temporal resolution?
- 4) How do we know whether a system will detect an important change if it occurs?
- 5) How do we ensure we get maximal value out of our existing monitoring systems?

Some big questions

- **Sea level** (coastal populations & ecosystems)
- **Ocean heat content** (the Earth is out of energy balance; most of the excess heat is stored in the ocean)
- **Sea surface temperature** (e.g. tropical cyclones)
- **Meridional overturning circulation** (Atlantic and European climate; carbon cycle)
- **Arctic sea ice** (ecosystems; albedo feedback; indigenous populations; MOC; trade routes)
- **Ocean pH** (ecosystems; fisheries; atmospheric CO₂)
- **Marine productivity** (ecosystems; fisheries; atm. CO₂)
- **Anthropogenic CO₂ uptake** (atm. CO₂, ocean acidification)

What could the following systems help with in **future**?

- Repeat hydrographic sections
- Satellites
- Moored instruments
- Argo floats & drifters
- Gliders
- AUVs

You may ignore technical limitations which could realistically be resolved in the near future (*e.g.*, depth/range).

What to monitor & how to monitor it?

Let's deal with the final three points...

3) How do we resolve the trade-off between cost and spatial/temporal resolution?

4) How do we know whether a system will detect an important change if it occurs?

5) How do we ensure we get maximal value out of our existing monitoring systems?

...in one go.

Observing vs. monitoring

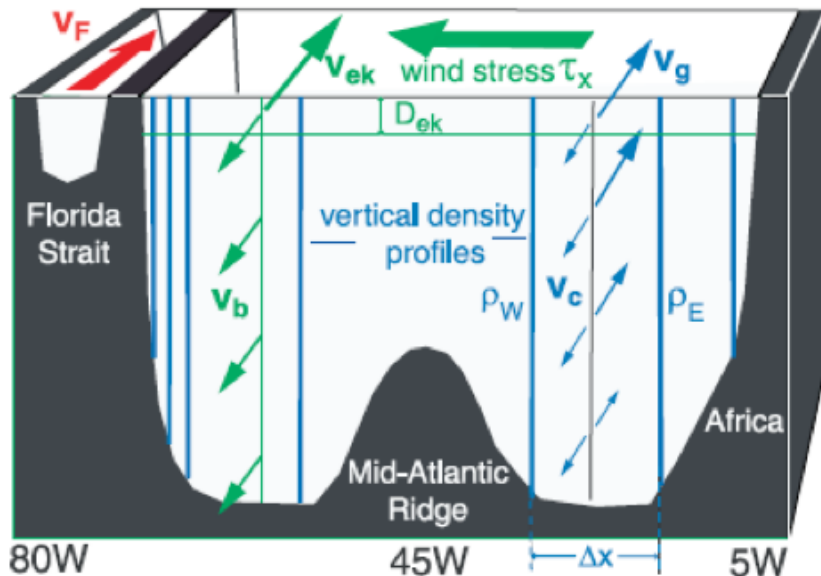
Reasons to observe the ocean:

- to test a hypothesis
- to gather the exploratory data necessary to form a useful hypothesis
- to map the ocean
- **to monitor the ocean**

It turns out that we need to test a hypothesis after all, the hypothesis being: **Our monitoring system will detect an important change in the ocean.**

Arguably, the optimal monitoring system is the cheapest one for which the answer is "yes".

Models as an aid to monitoring system design



Hirschi et al., Geophys. Res. Lett., 2003

Validation of the RAPID mooring array in an eddy-permitting model.

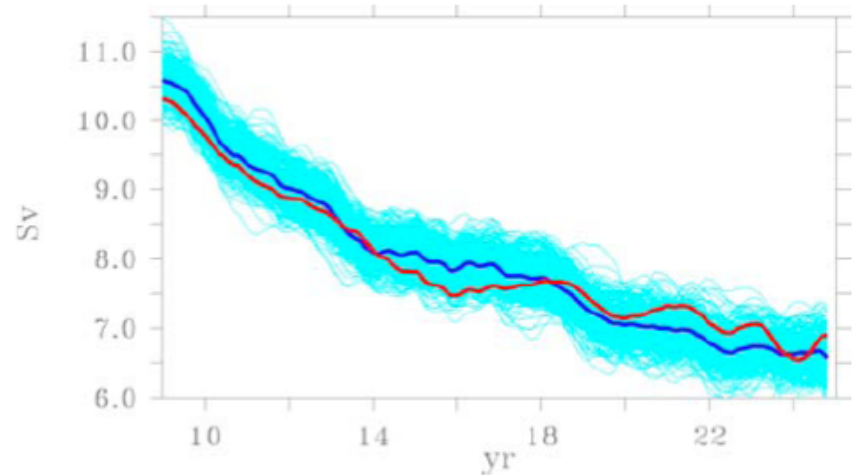
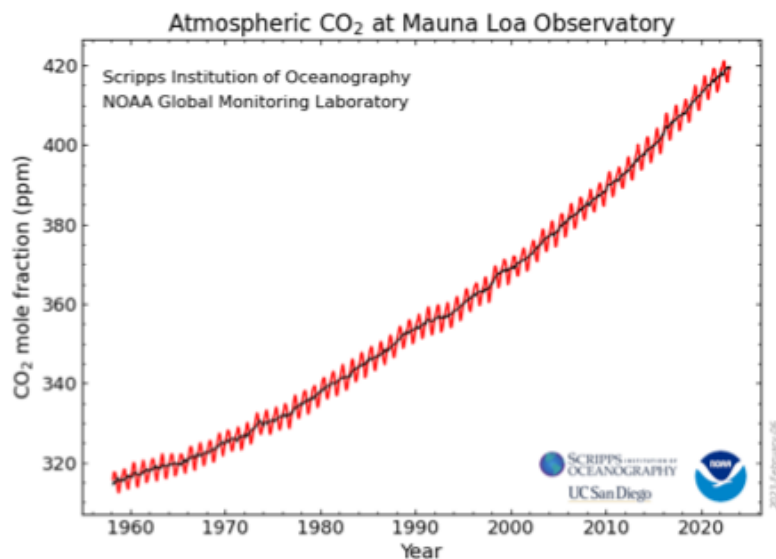


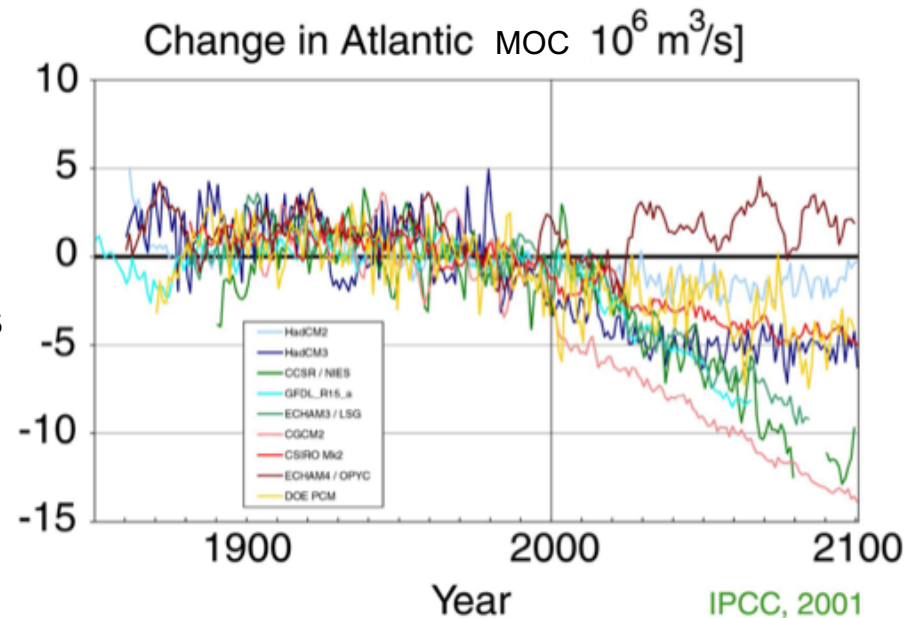
Figure 3. Evolution of maximum values for 300 estimates of the MOC (light blue lines) obtained with noise (standard deviation 1 Sv) added to the mass transport through Florida Strait and to the density field (standard deviation 0.01 kg/m^3) in OCCAM. The values are smoothed by a two year running mean. The solid blue line indicates the average of all reconstructions whereas the red line shows the maximum MOC values based on the full model information.

Detection – What do we measure?

Detecting trends is hard because of high frequency variability. If we find a relevant diagnostic variable with little high frequency variability, we can detect a change much more quickly.



versus



Monitoring is multidisciplinary

In the coming decades, it will not be sufficient to gather as much high quality data as we can, and carrying out straightforward analysis.

Numerical models, statistics, and applied math (dynamical system theory) will help us squeeze more out of our data.

Concluding remarks

- For ambitious monitoring programs, we should not spread ourselves too thinly. We must focus on big questions with relevance that can easily be conveyed to non-scientists.
- We need to find ways of getting **maximum** value out of observations, rather than being greedy.
- The **design** and **interpretation** of monitoring systems increasingly depend on models. This requires a good understanding of model and monitoring errors.
- Imaginative science must be carried out in the early years of a monitoring system.