Ocean reanalysis for the study of the evolution of the state of the ocean over the last decades

Aida Alvera-Azcárate

IV International Symposium on Marine Sciences

Vigo, 20 June 2018

cost
EUROPEAN COOPERATION
IN SCIENCE AND TECHNOLOGY

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Ocean reanalysis and the quest for truth

Aida Alvera-Azcárate

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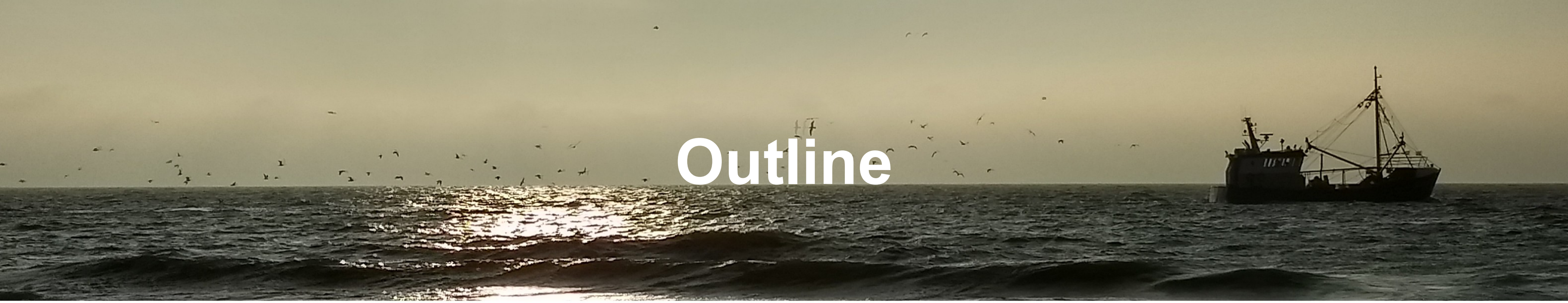
GONE WITH THE WIND



Outline

Introduction: the role of the ocean on climate

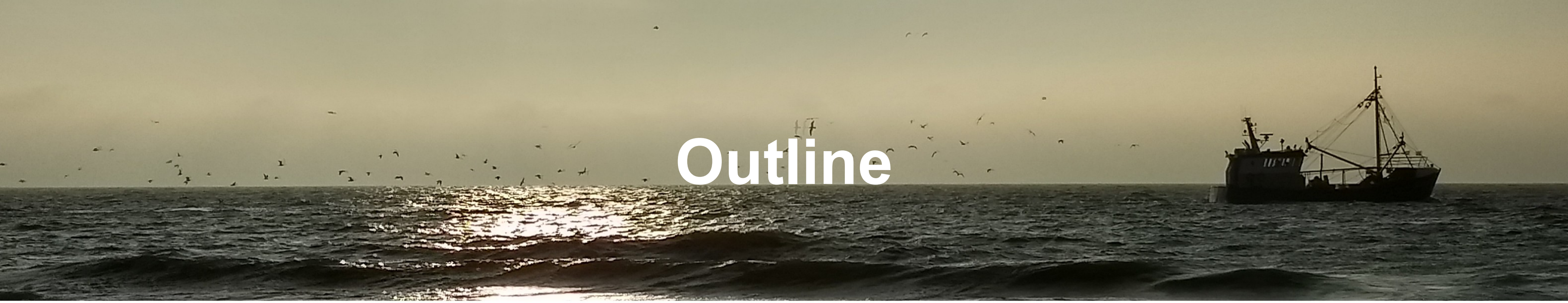
Estimating the state of the ocean:

- Gridding satellite data
- Gridding in situ data
- Ocean models and data assimilation

Ocean reanalyses

- Definition and applications
- COST Action EOS

Concluding remarks



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The ocean

→ largest heat capacity in the climate system: energetic buffer

→ controls the rate of climate change

→ Ocean circulation redistributes heat (and gases), and variability in that circulation determines seasonal to decadal variability in climate

- Consequences: sea level rise, rise of temperature, sea ice melting, de-oxygenation, acidification

→ Assessing the role of the ocean and sea ice on climate variability is critical for understanding global climate change

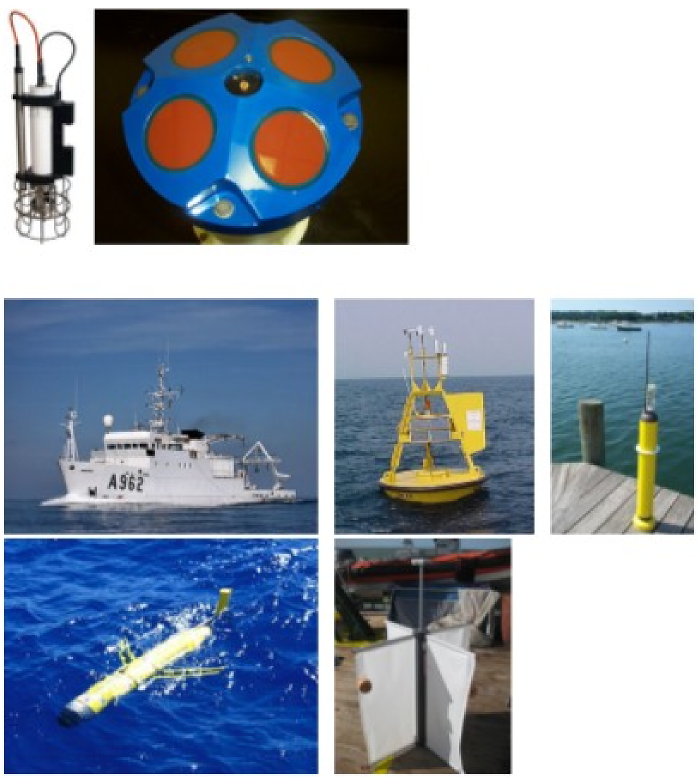
→ We need to know the **state of the ocean** and its evolution over the last decades to understand climate change

What is the state of the ocean?

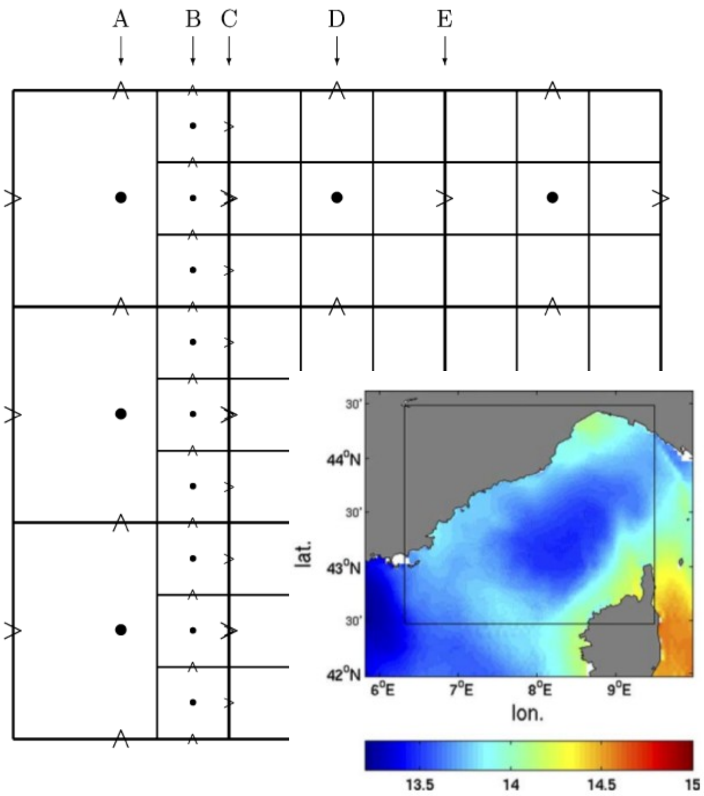
State of the ocean refers to the description of its temperature, salinity, density, elevation and currents, and its variation in space and time

To determine the state of the ocean, we can use:

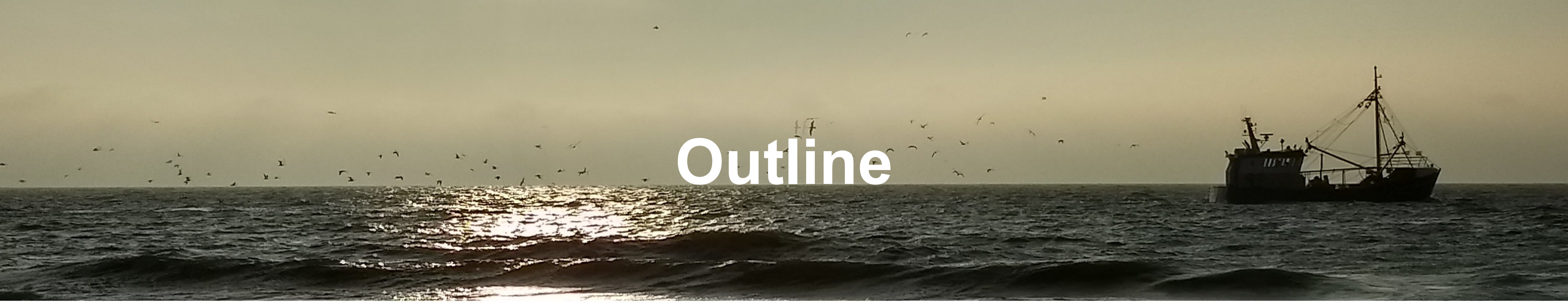
- Observations



- Models



A combination of both



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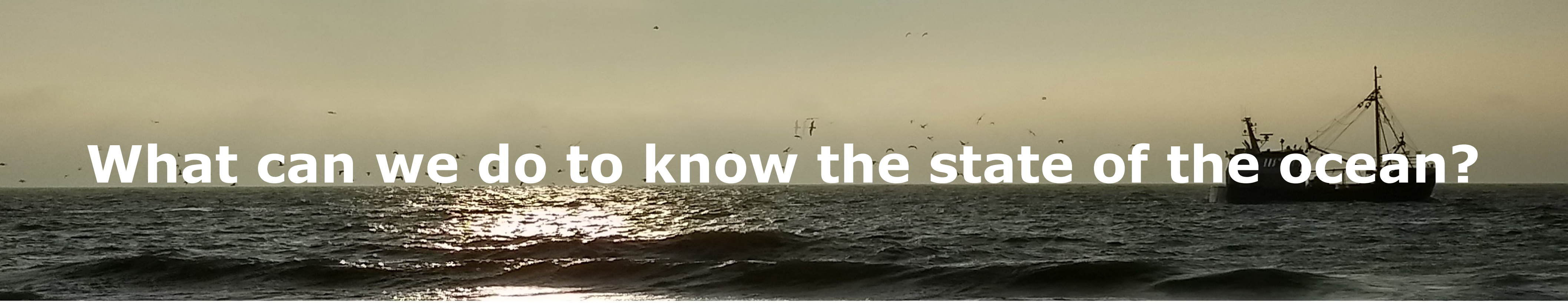
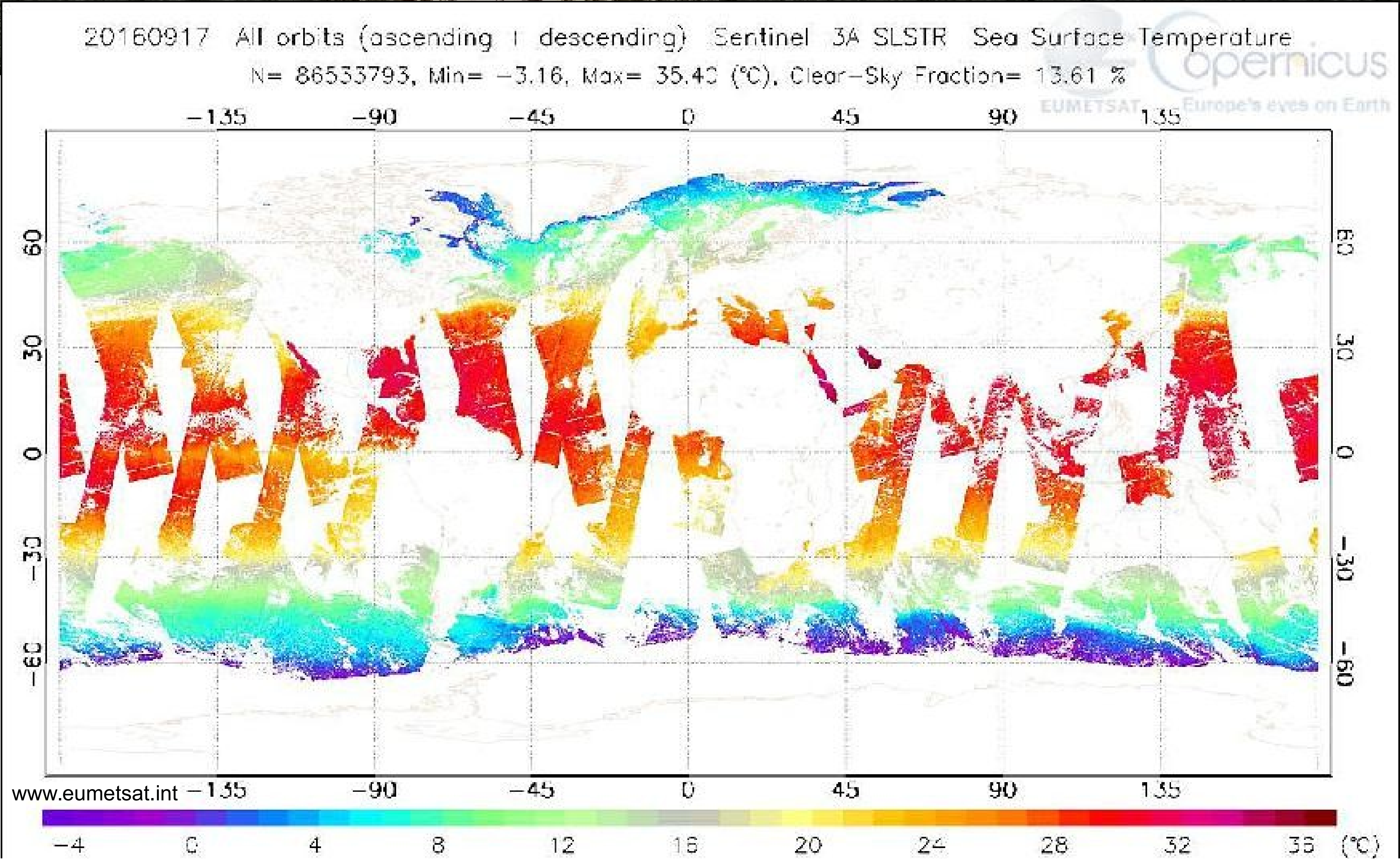


What can we do to know the state of the ocean?

Measure it!

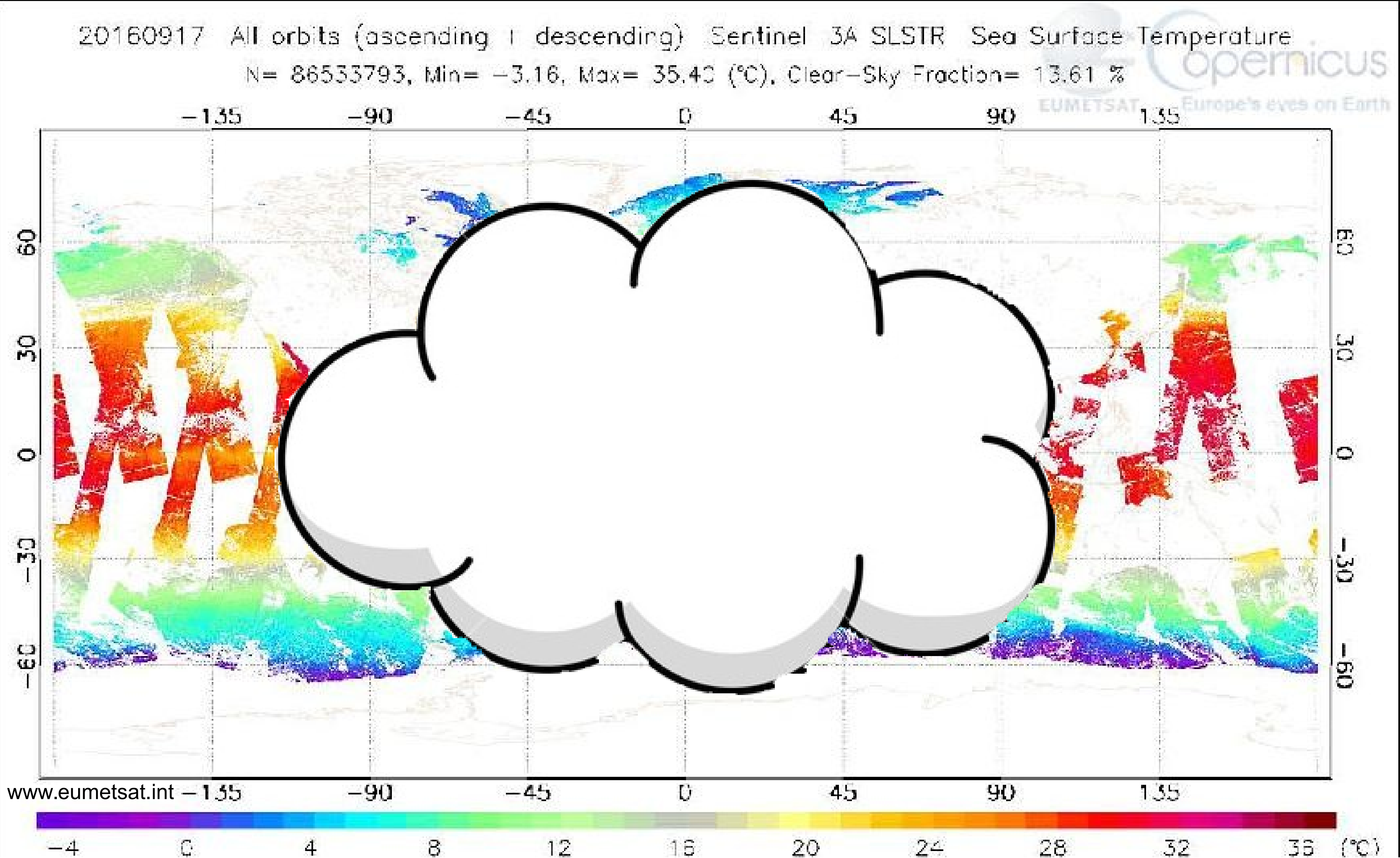
Observations: satellite

Observations: satellite



www.eumetsat.int

Observations: satellite

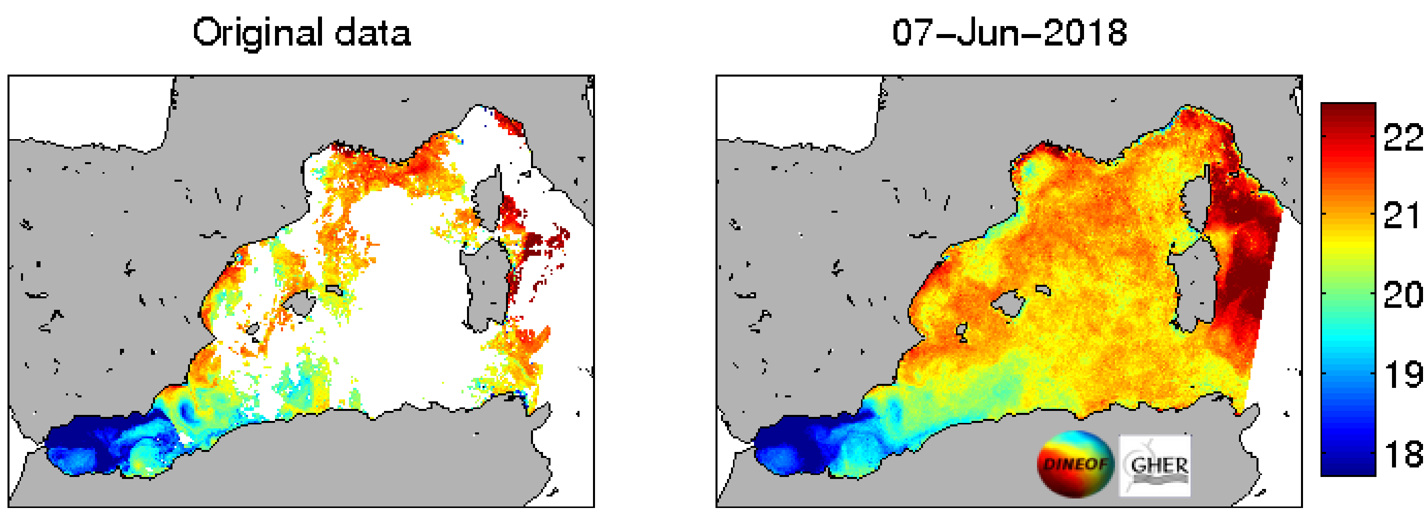


www.eumetsat.int

Continuous time series from satellite data

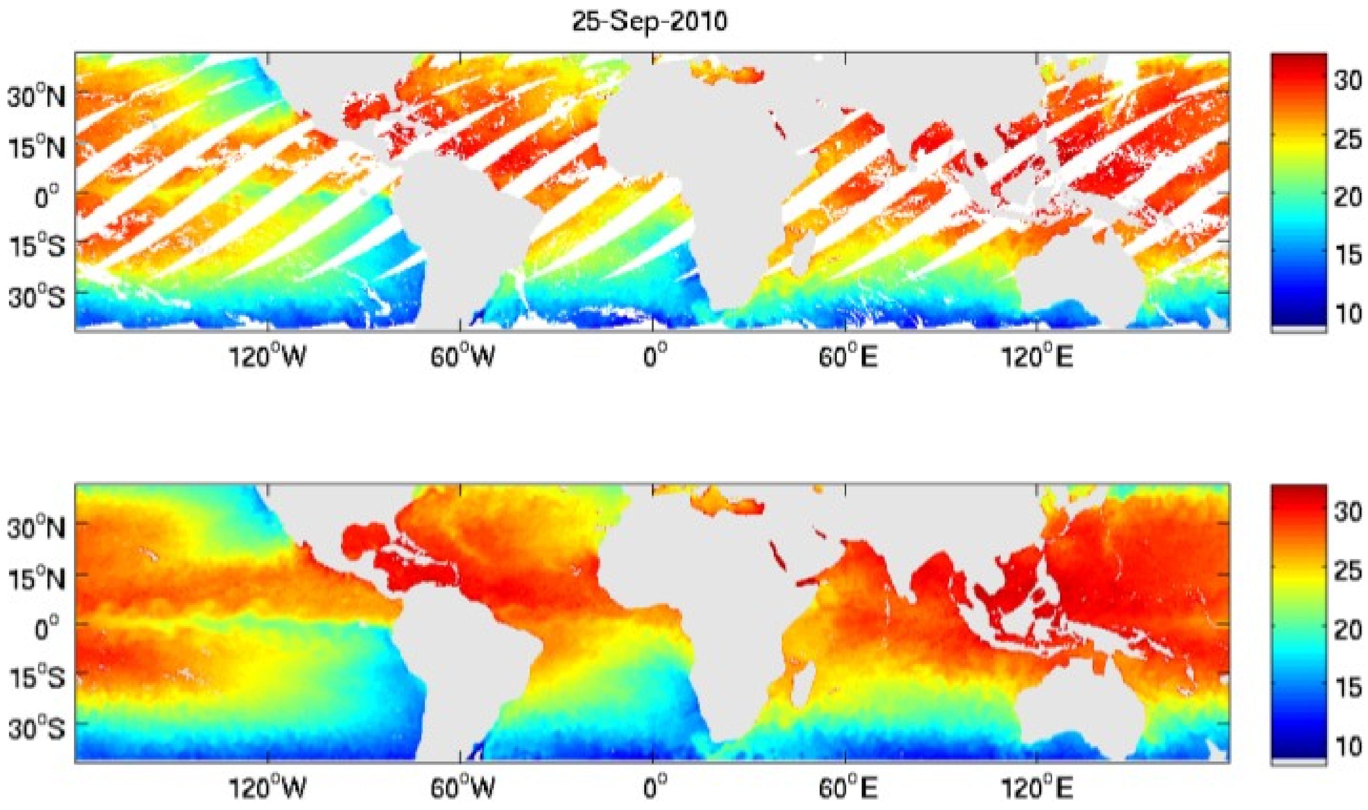
DINEOF: Data Interpolating Empirical Orthogonal Functions

- Technique to fill in missing data in geophysical data sets, based on an EOF decomposition
- Truncated EOF basis to calculate missing data (iterative method)
- EOFs extract main patterns of variability
- Reduced noise
- Optimal number of EOFs?: reconstruction error by cross-validation
- Uses EOF basis to infer missing data: non-parametric
- No need of a priori information (correlation length, covariance function...)
- Spatio-temporal coherence exploited to calculate missing values



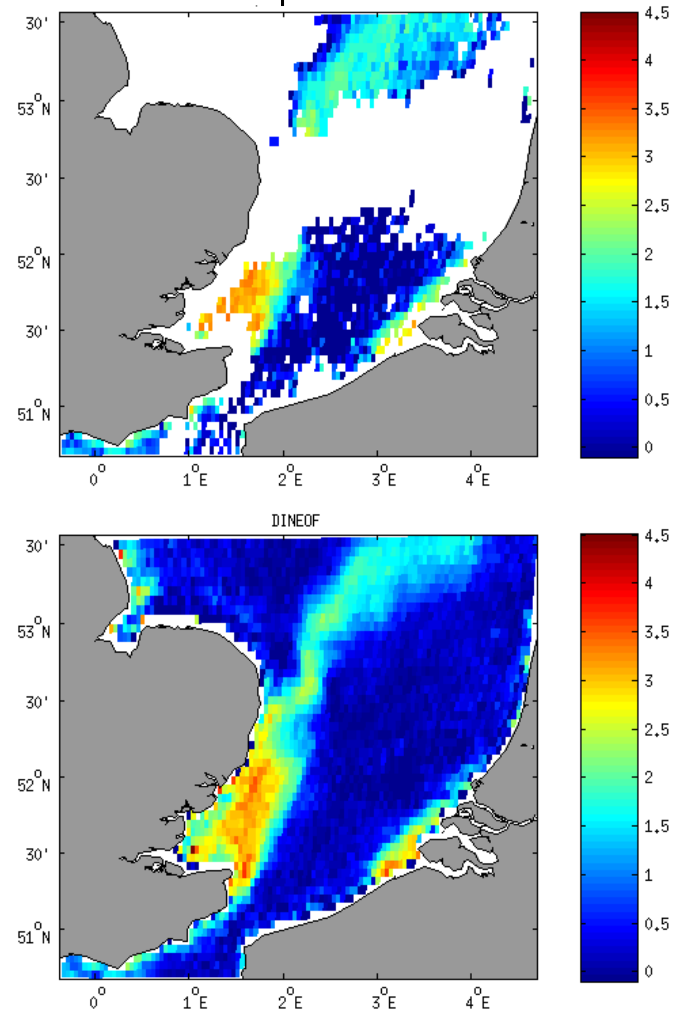
http://www.dineof.net/DINEOF/

Continuous time series from satellite data

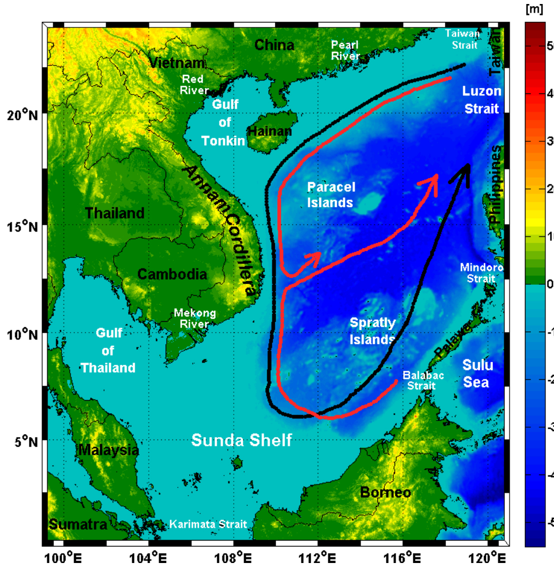


Global SST temperature, TMI on 25 September 2010

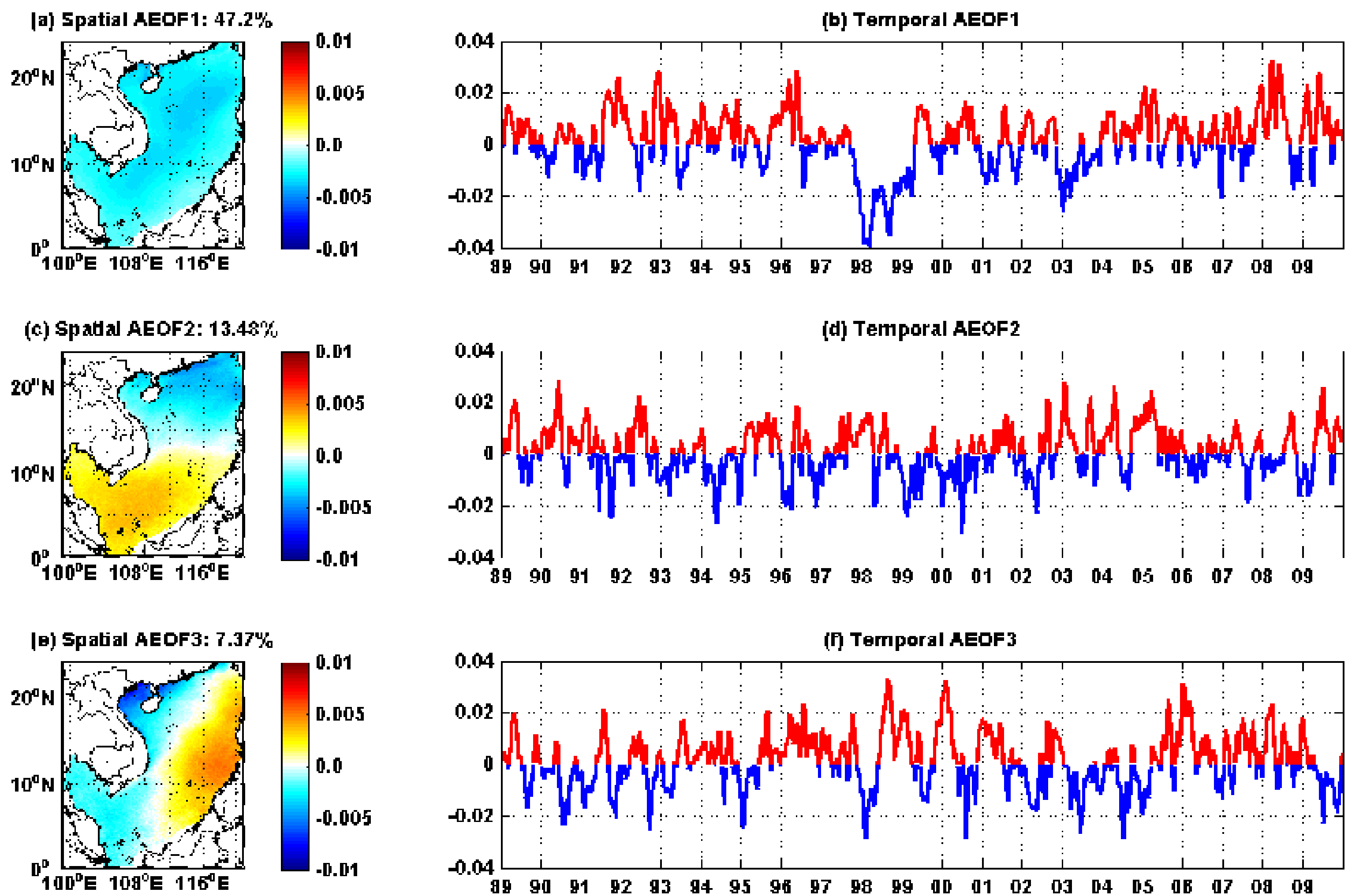
Turbidity in North Sea, SEVIRI
1 September 2008



Example of DINEOF reconstruction



20 years South China Sea SST, CHL and winds DINEOF reconstruction

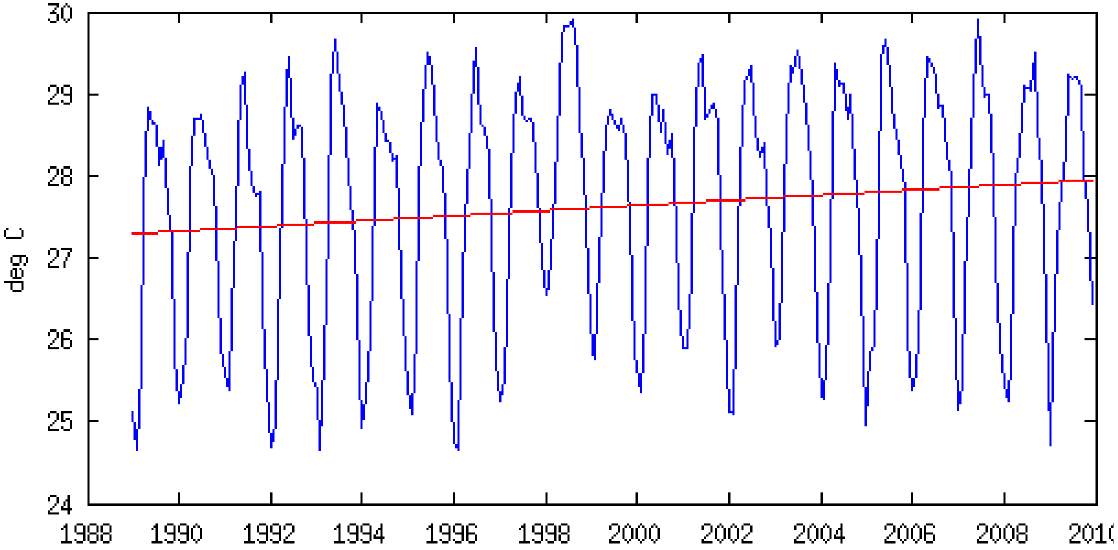


Study shows influence of monsoon and ENSO on SST

by PhD student Ngu Huynh (U. Liege)

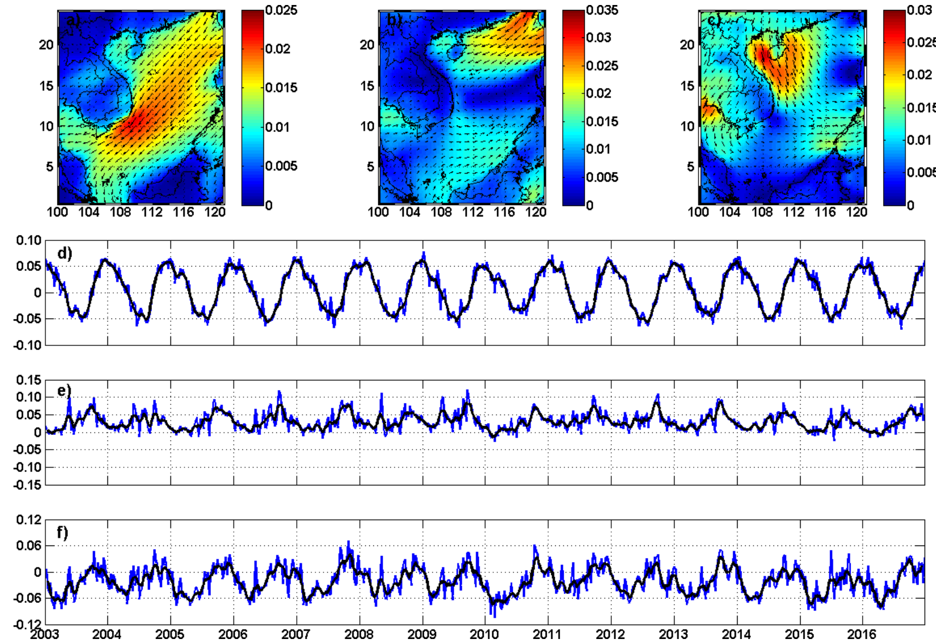
Huynh et al, 2016, Journal of Oceanography

Example of DINEOF reconstruction



Average SST over the South China Sea

Wind data



- An average of 88% of missing data in the initial dataset (multivariate analysis with wind)
- Calculating average value, correlations with other variables, or trends is not possible with such a high amount of missing data

Limitations of satellite data

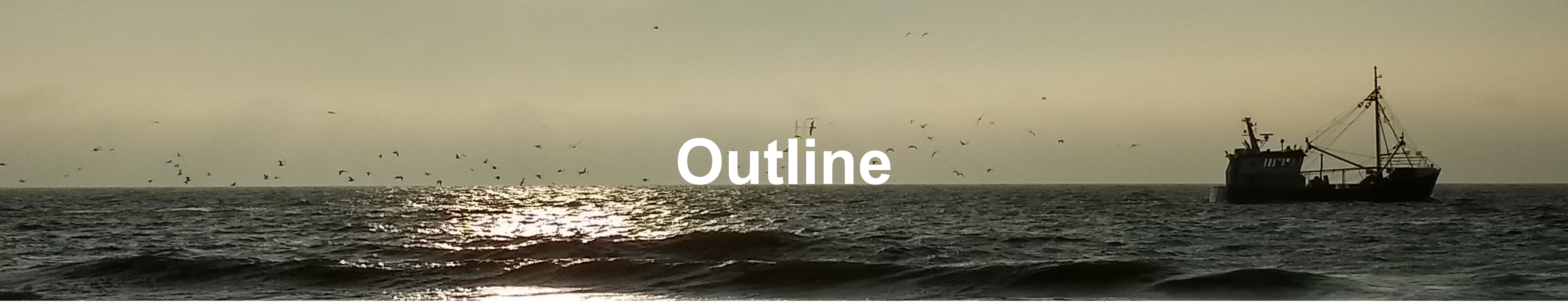
Limited to the last ~40 years (SST)

Not all variables are available (salinity only for 10 years, no direct currents measured so far)

Limited to the surface of the ocean

→ We need to estimate the 4D (space + time) variations in the ocean

→ We can then turn ourselves to **in situ measurements**



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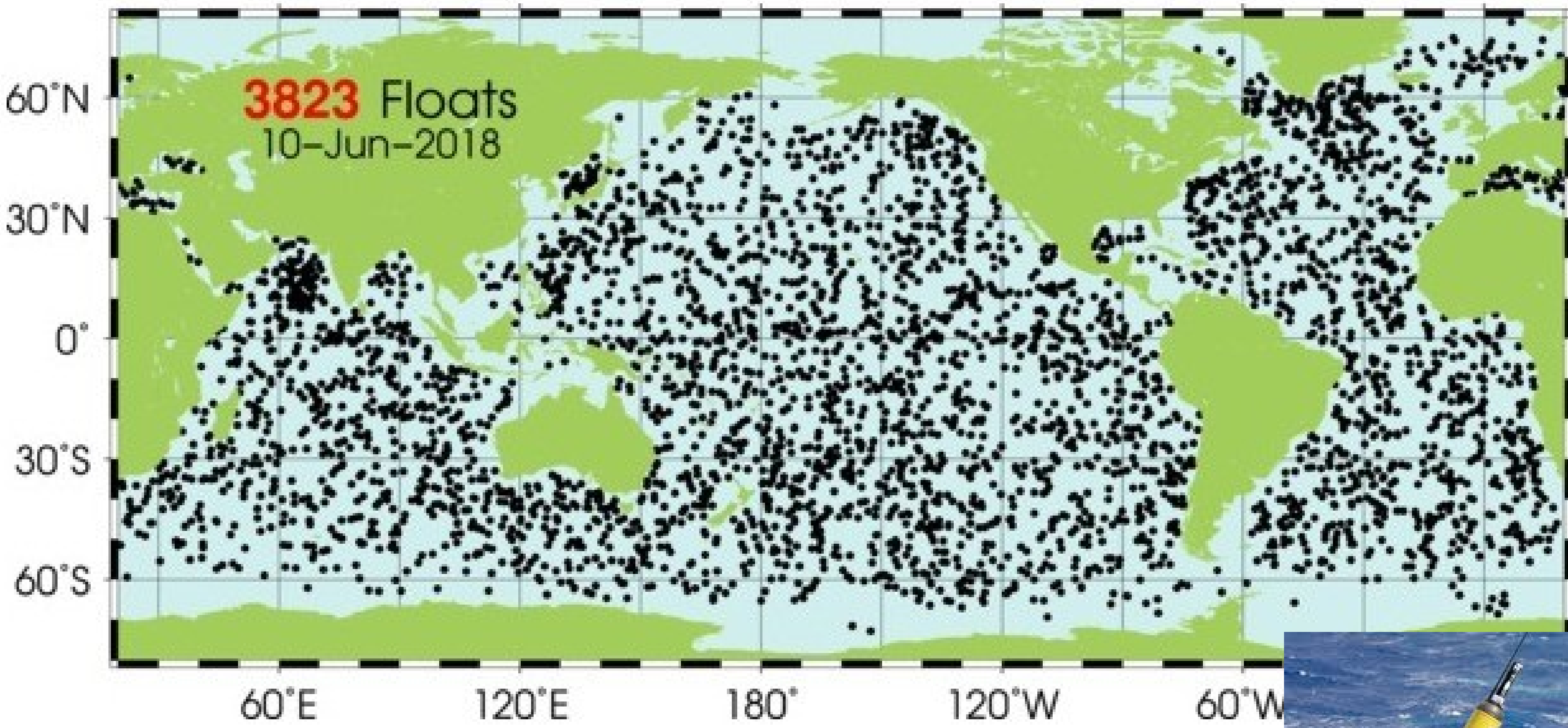
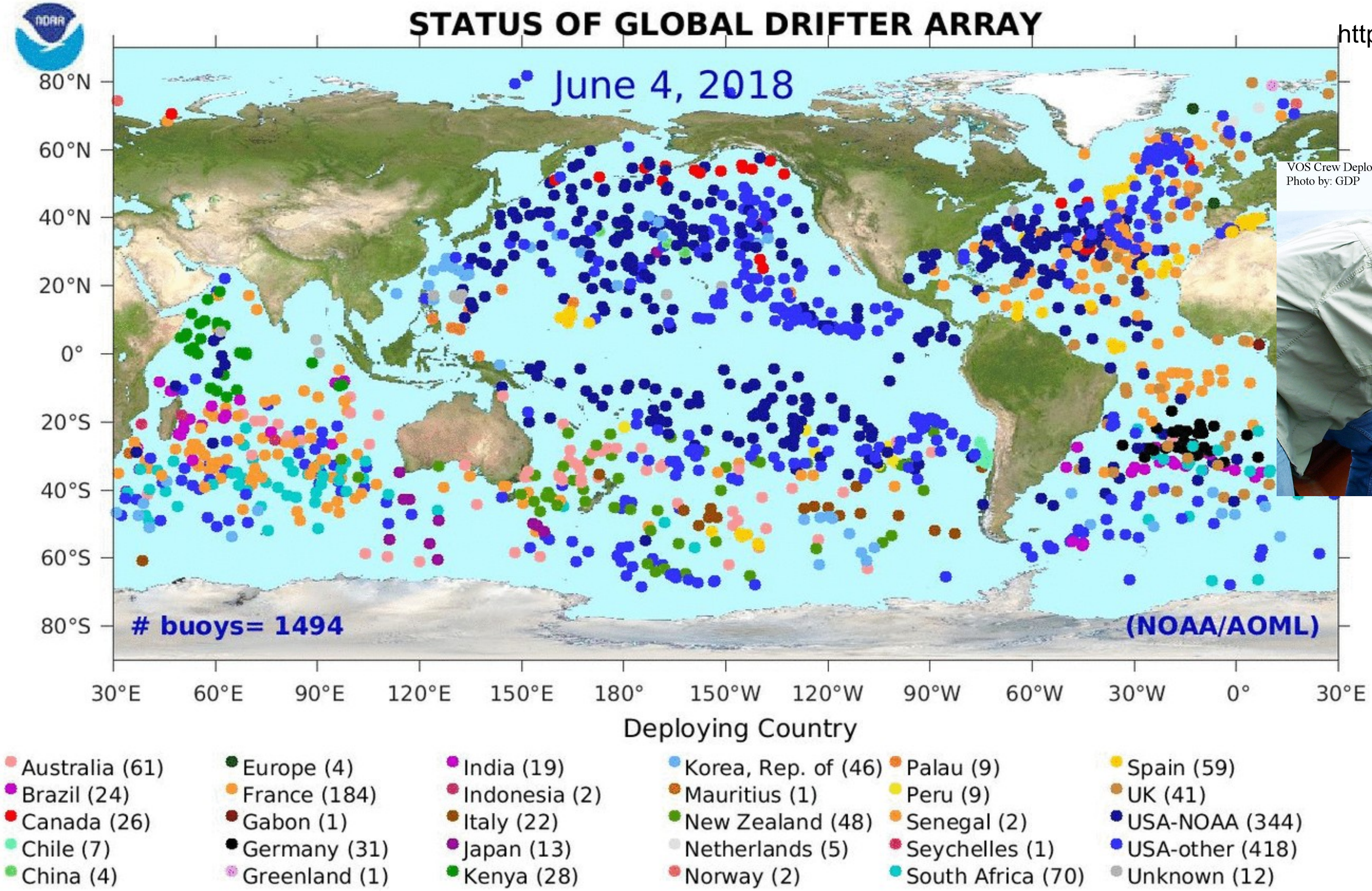
Observations: in situ



Argo array as of 10 June 2018

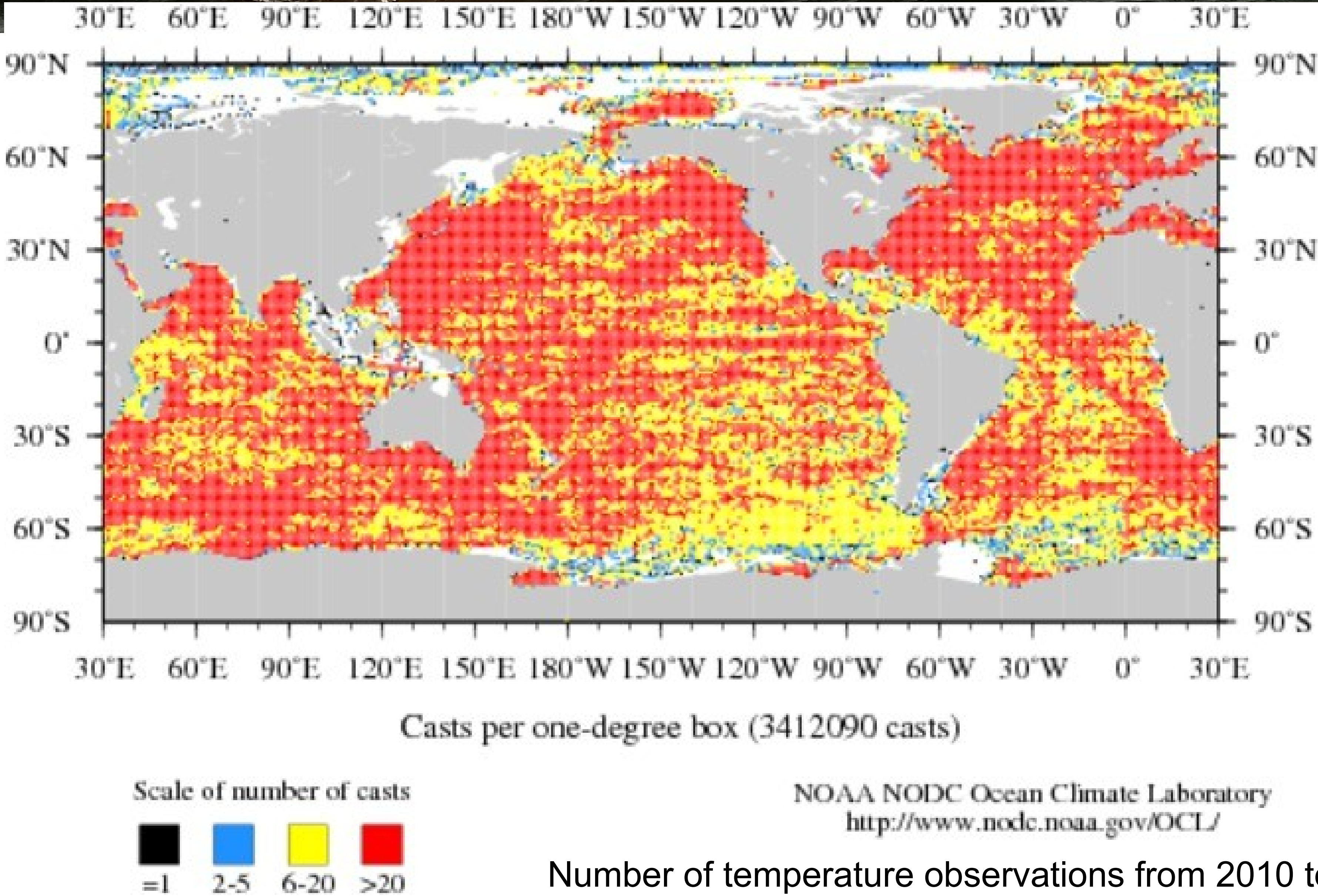
www.argo.ucsd.edu

Observations: in situ



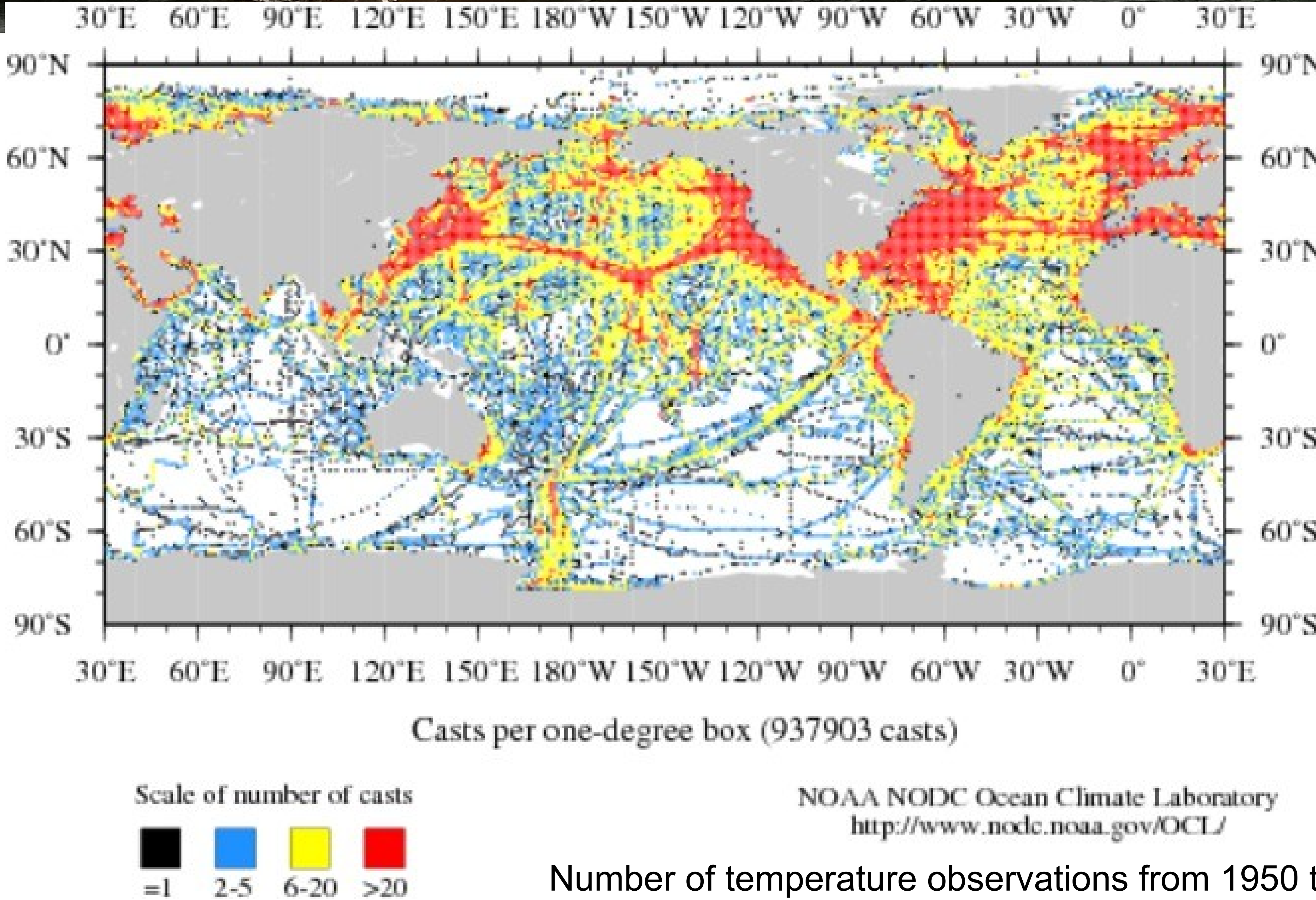
http://www.aoml.noaa.gov

Historical observations



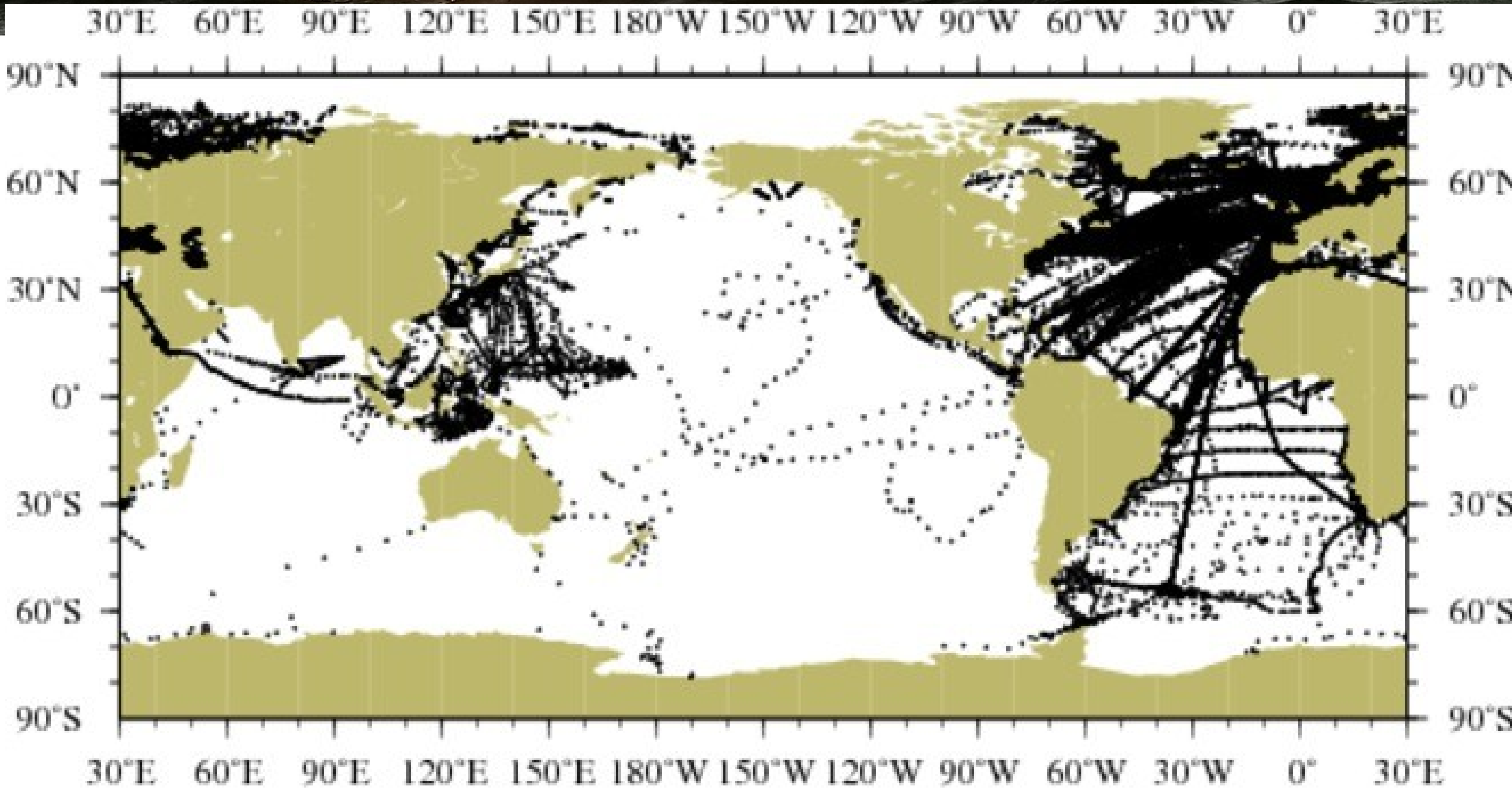
Number of temperature observations from 2010 to 2018

Historical observations



Number of temperature observations from 1950 to 1960

Historical observations



Geographic distribution of casts (73784 casts)

NOAA NODC Ocean Climate Laboratory
http://www.nodc.noaa.gov/OCL/

Temperature observations from 1920 to 1930

Observations: in situ

In situ observations are heterogeneously distributed, both in space and time

→ The scales of variability that we want to study might not be well resolved

→ we need to **grid** the data if we want a complete estimate

Observations have **errors**:

- **Instrumental errors** (limited precision or possible bias of the sensor)

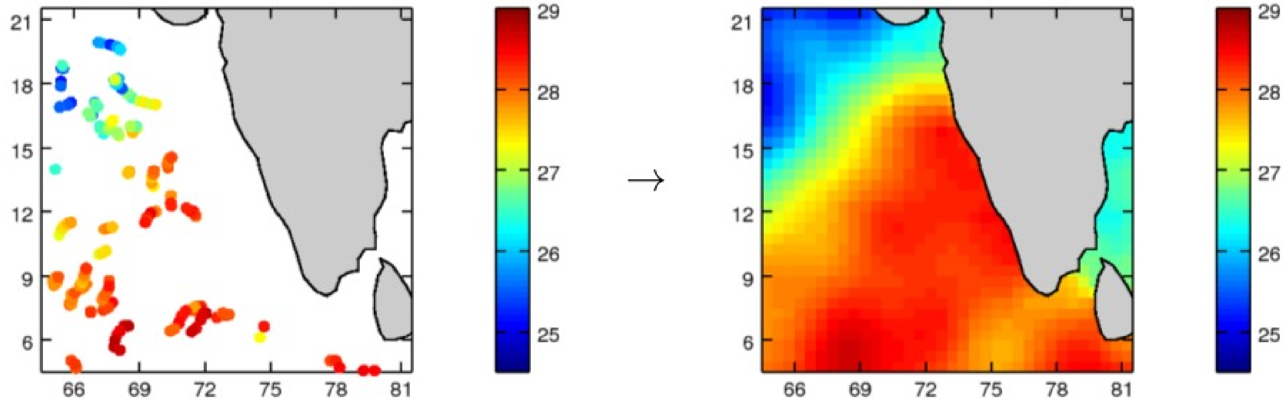
- **Representative errors:** the observations do not necessarily correspond to the field we want to obtain. For example, we want to have a monthly average, but the observations are instantaneous (or averages over a very short period of time).

- **Synoptic errors:** all observations are not taken at the same time.

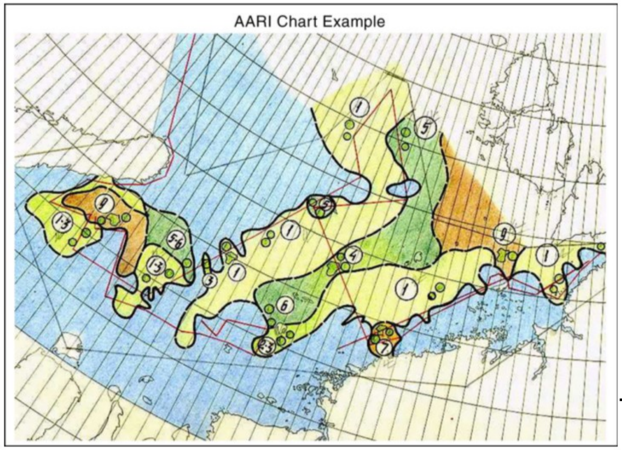
- Other errors sources: human errors (e.g. permutation of longitude and latitude), transmission errors, malfunctioning of the instrument, wrong decimal separators...

Observations: the gridding problem

How to go from here.............................. to here



- Subjective way (by hand...) →



from Walsh et al 2016

- More “objectively”, with a set of predefined mathematical operations

Gridding in situ data with DIVA

DIVA: Data Interpolating Variational Analysis

It uses the variational inverse method (VIM) or variational analysis (Brasseur et al., 1996, Troupin et al. 2012) to find a field with the following characteristics:

→ **smooth**
→ somewhat **close** to first guess (background climatology)
→ **close** to the observed values

This is achieved by defining a cost function which penalizes a field that doesn't satisfy those requirements.

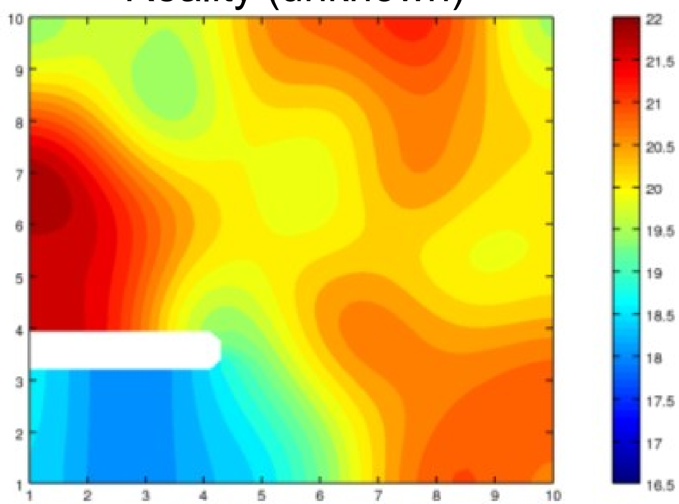
"smooth" is quantified by averaging the square of the first and second derivatives of the field (for a slowly varying field those derivatives are small) and a correlation length.

"close" is quantified using the RMS error and signal-to-noise ratio.

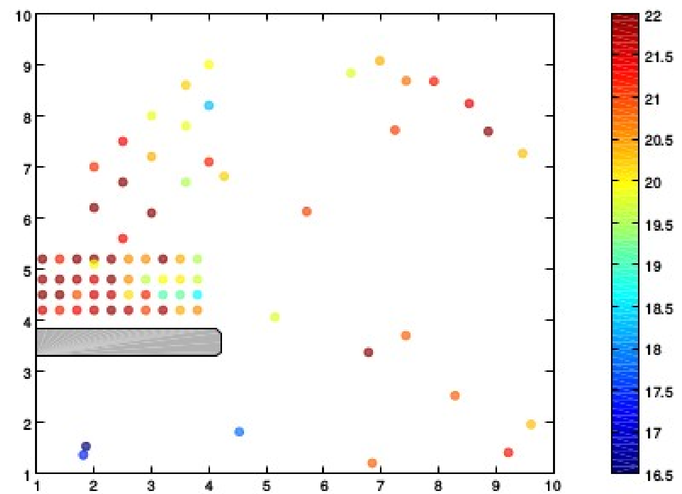
Those different requirements are **weighted** to define what is more important, a smooth field or a field close to observations.

Gridding in situ data with DIVA

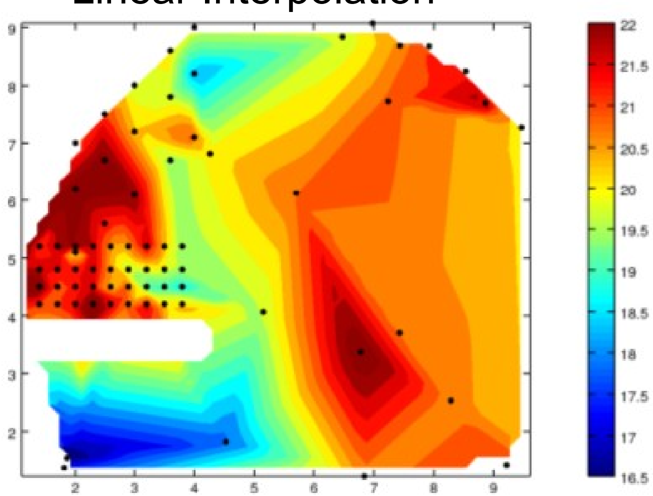
Reality (unknown)



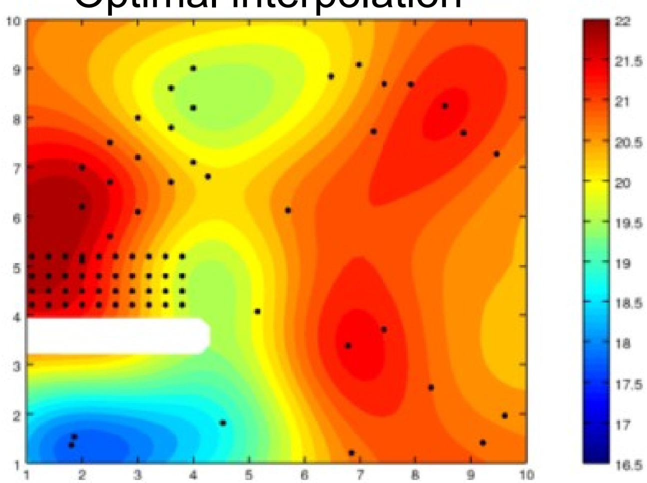
Observed reality (with noise/errors)



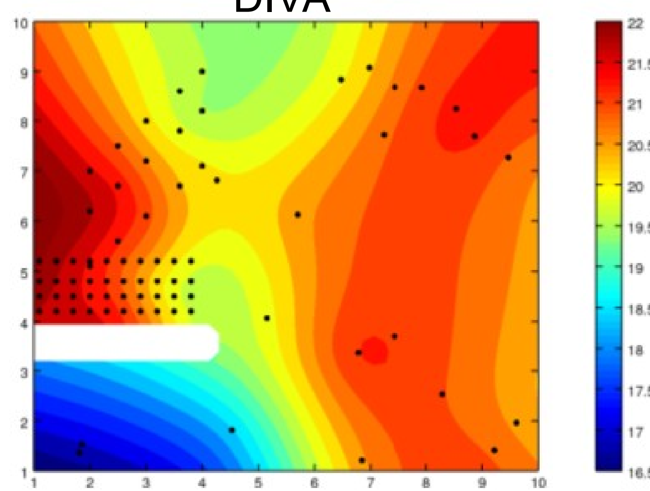
Linear Interpolation



Optimal interpolation

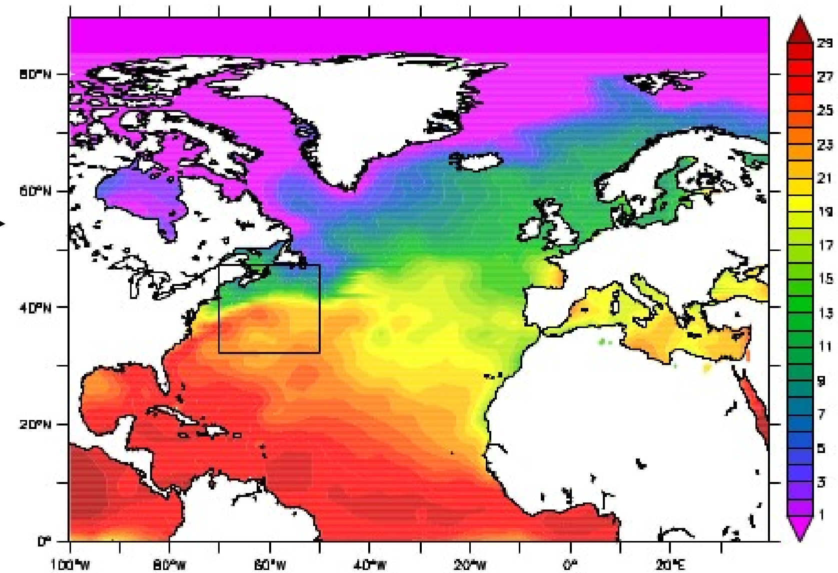


DIVA

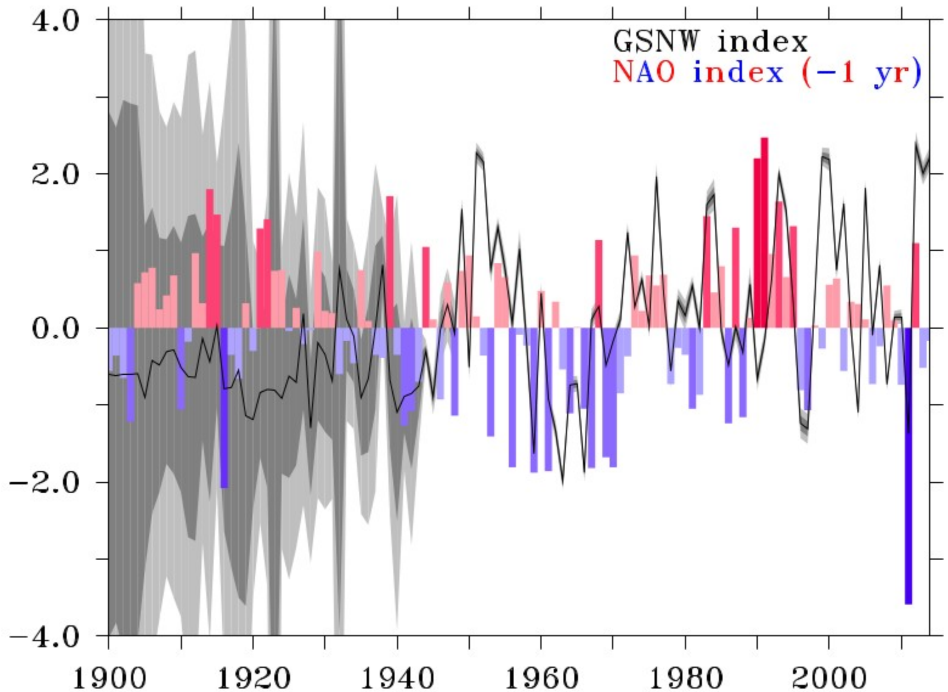


Example of DIVA analysis

- Study of the Gulf Stream response to the North Atlantic Oscillation since 1940
- 40 million data
- Monthly analyses of T & S over North Atlantic Ocean



SST for January 1984

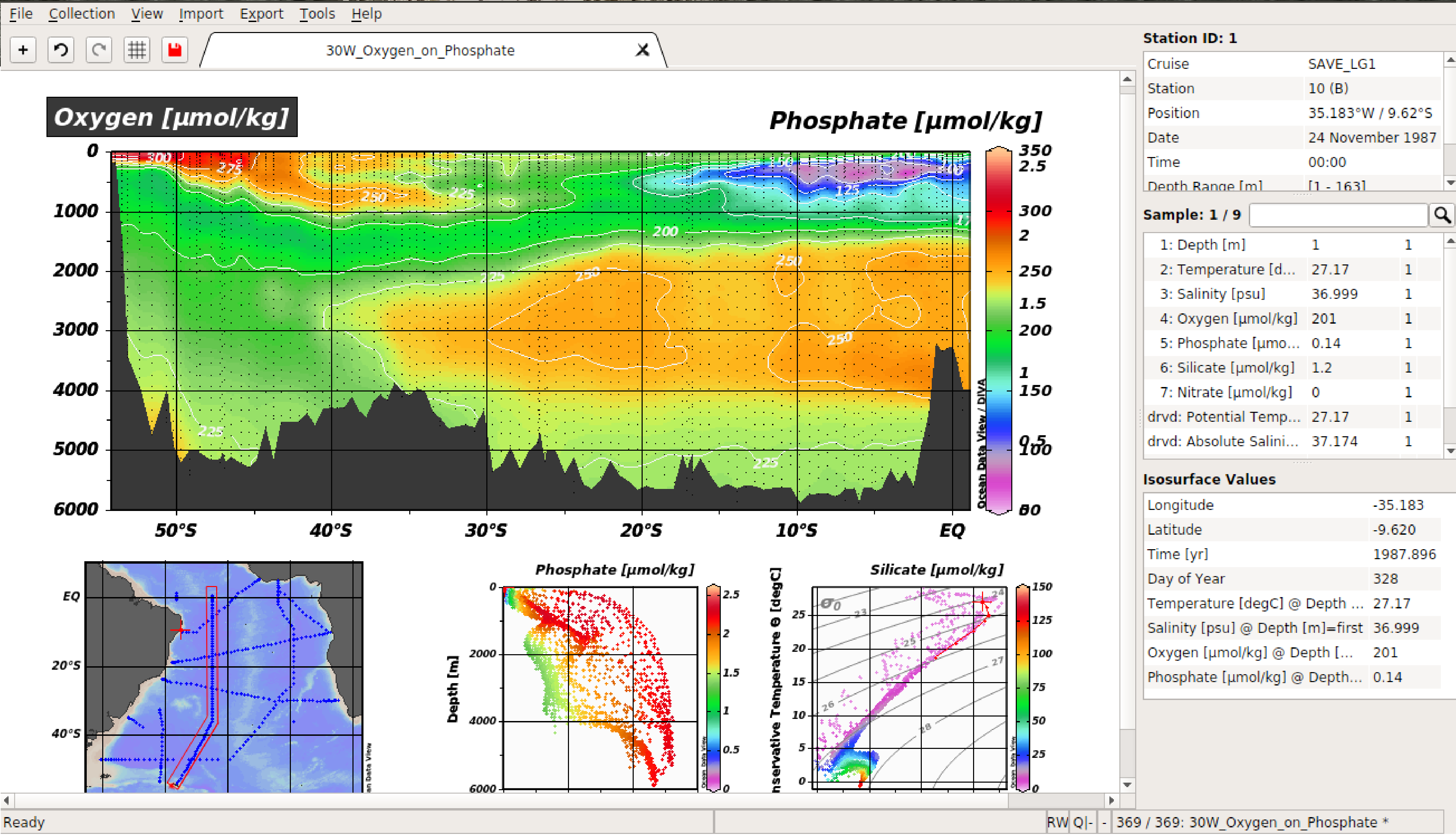


Main conclusion found a 1-year lag between NAO index and the position of the Gulf Stream

from PhD student Sylvain Watelet (U Liege)
- Watelet et al, 2017 (JPO)

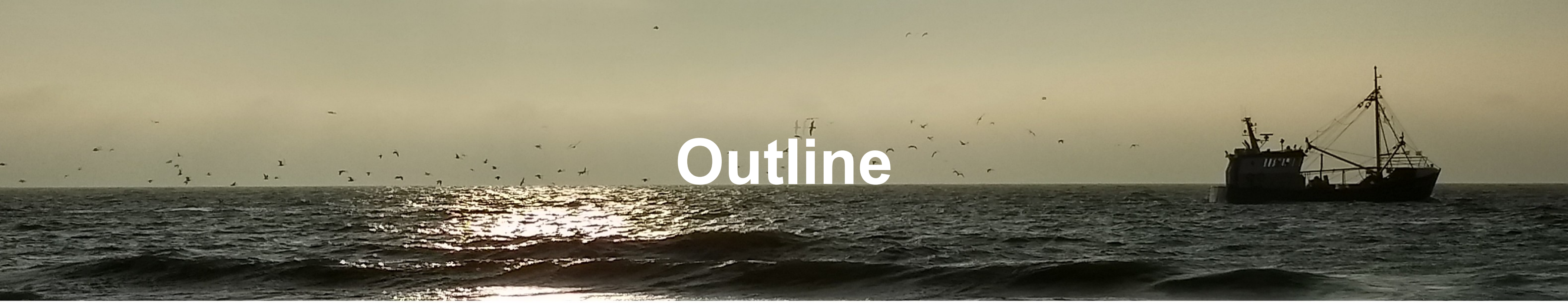
yeah, sounds great, but this is too complex...

DIVA for all



https://odv.awi.de/

Outline



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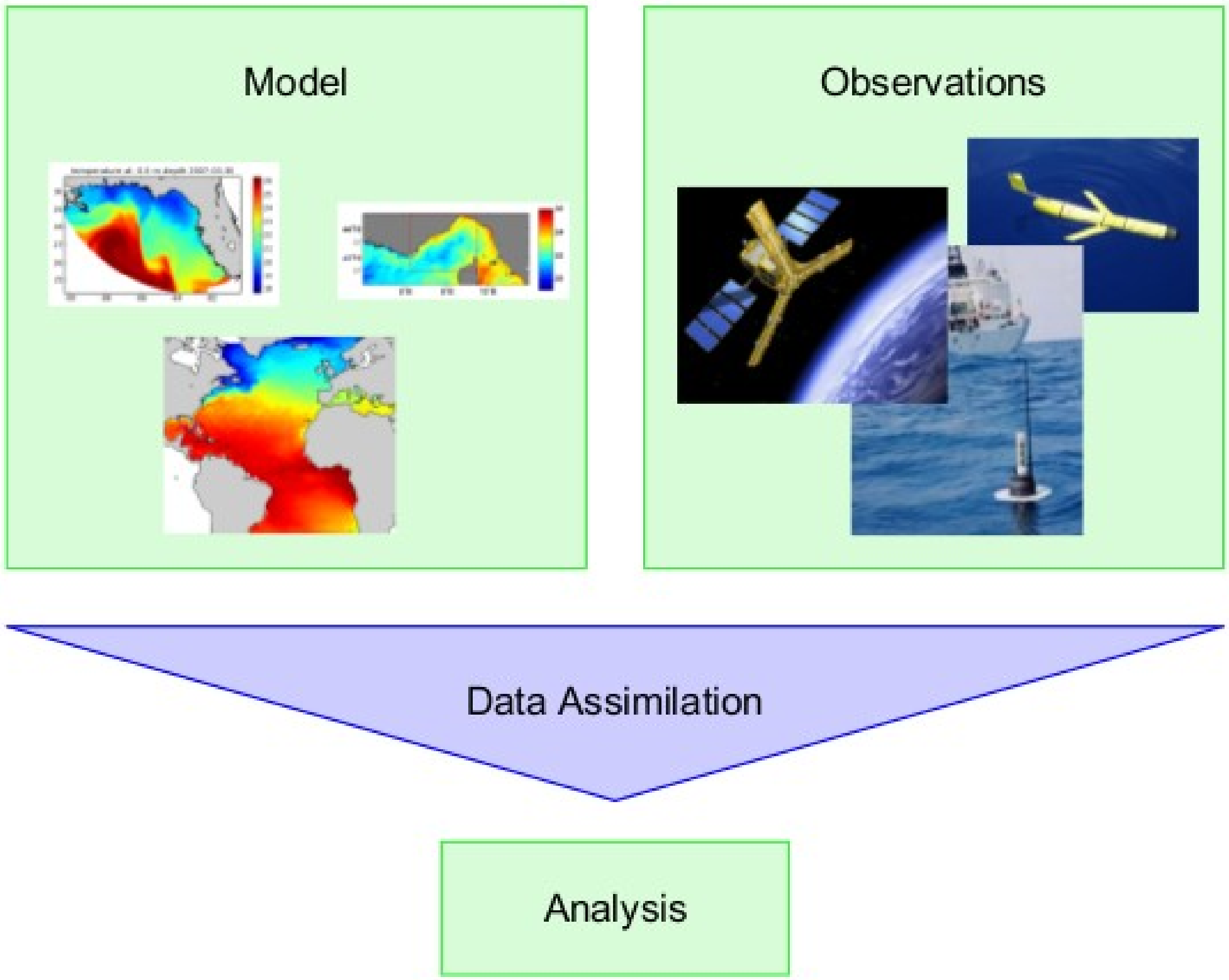
Next step: merge observations and models

Data assimilation



Data assimilation

Data assimilation:

Combine observations and model in an optimal way

Taking their uncertainties/errors into account

Errors in an ocean model might be due to
→ errors in initial conditions
→ errors in open ocean boundary conditions
→ errors in atmospheric fields (wind, air temperature, ...)
→ errors in bathymetry
→ inappropriate parametrizations
→ discretization error
…

Also, model and obs might have

mismatch in resolved scales
mismatch in resolved processes

It is essential to know how these uncertainties affect the results of the model.

Data assimilation can be used to reduce the effect of these error sources, i.e. **improve the knowledge of the ocean state**

Overview of data assimilation methods

Simple ad-hoc methods

→ Direct insertion
→ Nudging: adding a term to the model equation that pulls the model towards the observations

Statistical estimation (estimate the state with the lowest error)

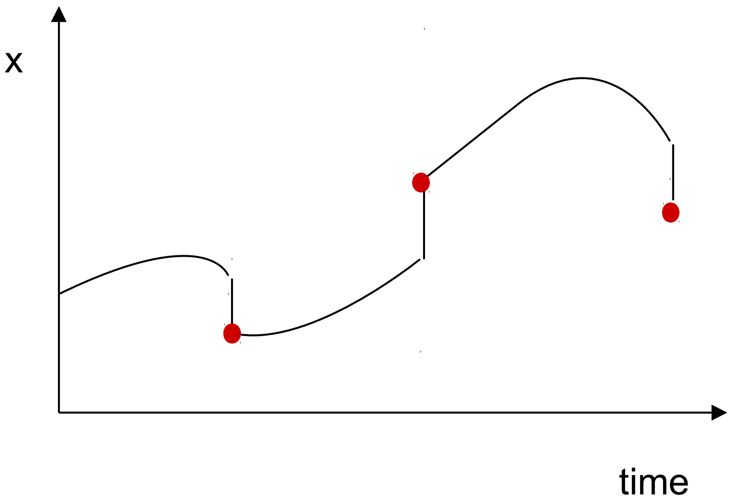
→ Optimal interpolation
→ Kalman Filter
→ Kalman Smoother

Variational methods (estimate the state with the highest probability)

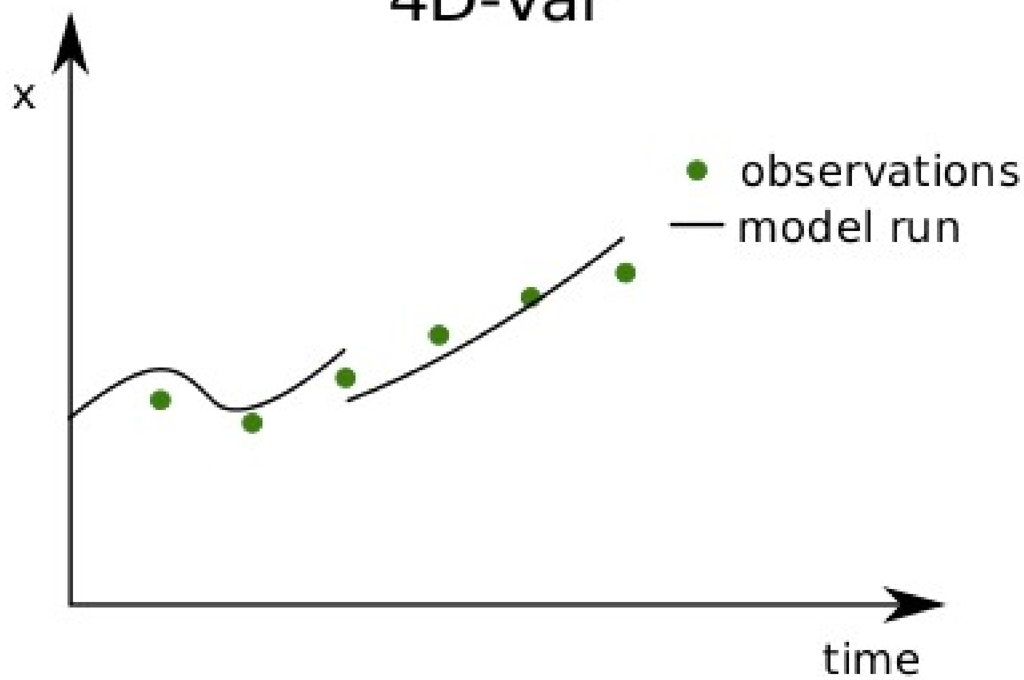
→ 3D-Var
→ 4D-Var (with time)

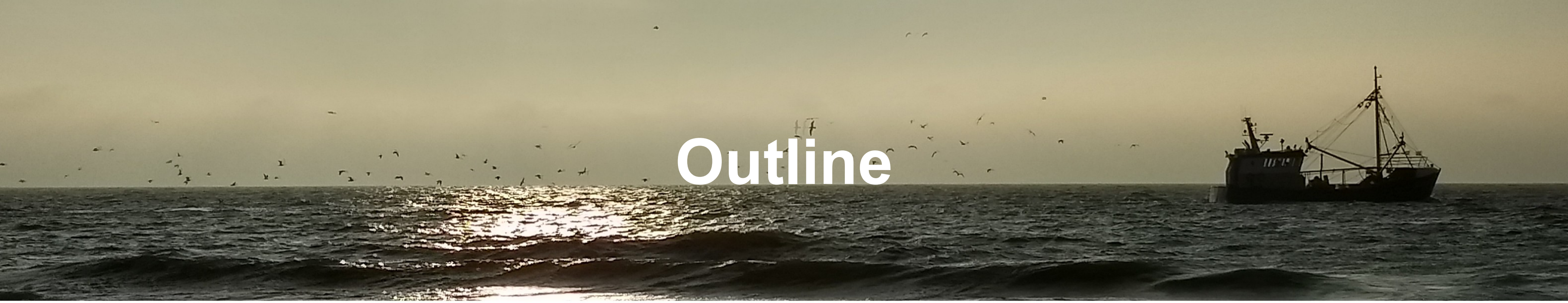
Overview of data assimilation methods

Direct insertion



4D-Var





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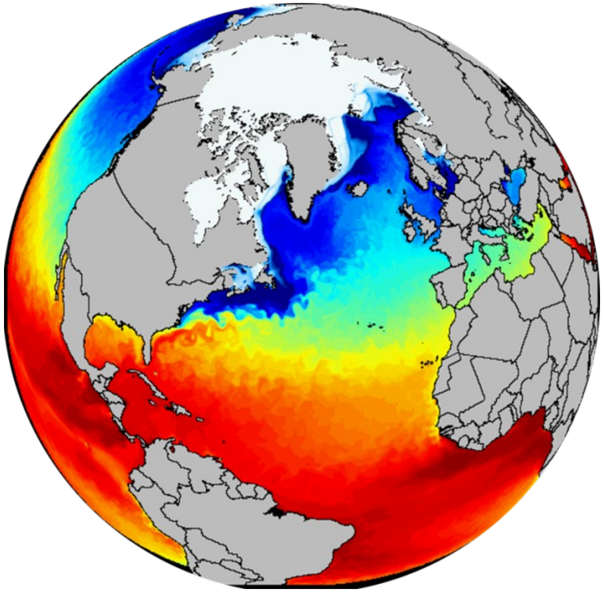
Ocean Reanalyses: long model runs

→ a comprehensive estimation of the state of the ocean state over the **last decades** (mainly temperature, salinity, sea level and currents)

→ calculated by merging hydrodynamic ocean models and all available observations using data assimilation

→ **Homogeneous**

Hydrodynamic model



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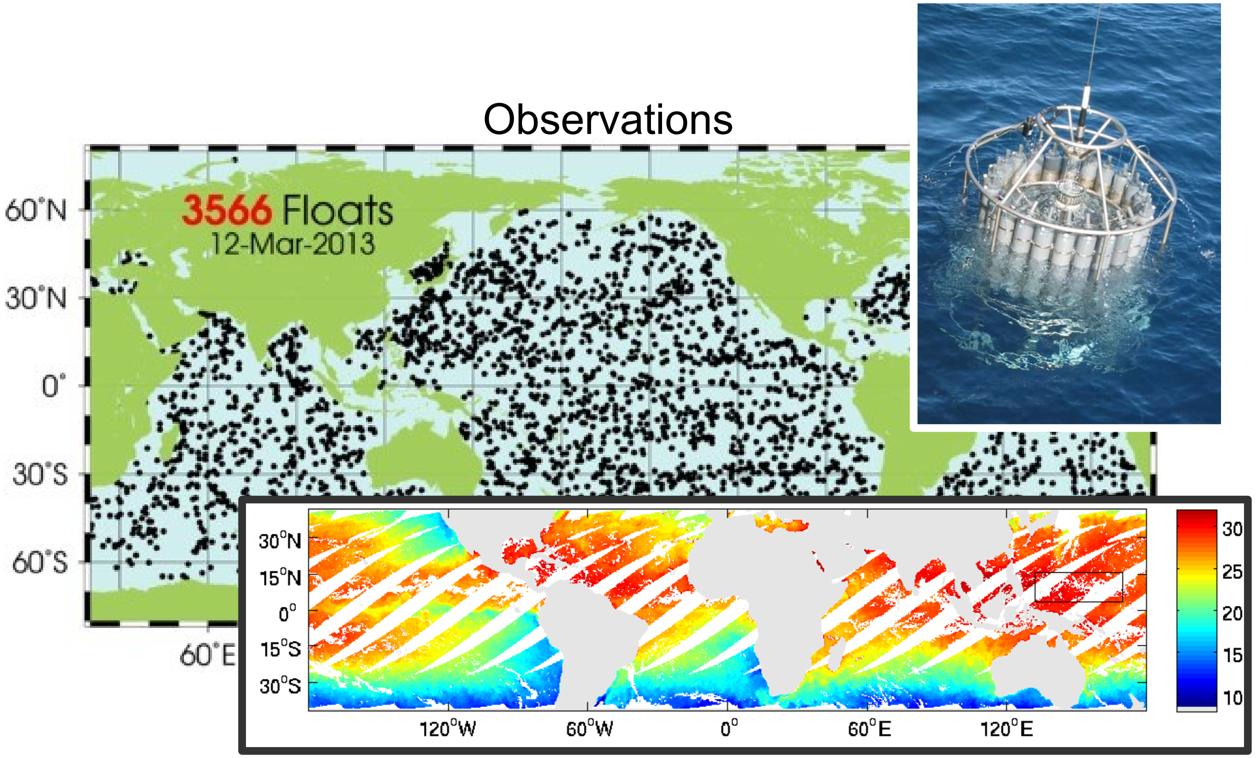
Observations



→ **Ocean reanalyses are critical to understand climate and to predict future change**

Applications of Ocean Reanalyses

→ Study long-term changes in the ocean

→ Initial conditions in hydrodynamic models:
- for operational forecasts of the ocean
- for short-term predictions (study of specific processes)
- for climate-related activities

→ Study of ocean-atmosphere interactions (heat balance, global water cycle)

→ Computation of transports across ocean basins and key straits (transport of heat)

→ Monitoring the ocean, near-real time climate signals

→ Serving Copernicus downstream services
- delivering products and services to manage and protect the environment and natural resources, and ensure civil security

Ocean Reanalyses

So what's the problem??... There can be:

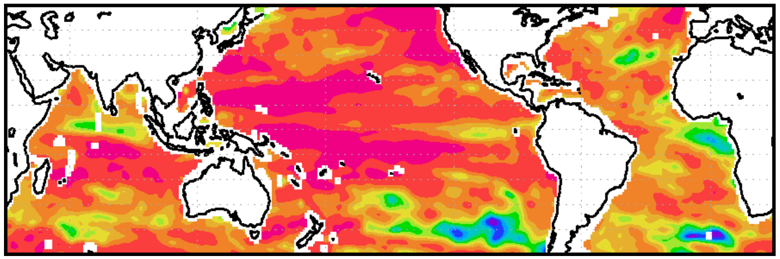
- Different hydrodynamic models
- Different data quality procedures
- Different data assimilation approaches
- Different spatial and temporal resolution
- Global of regional coverage

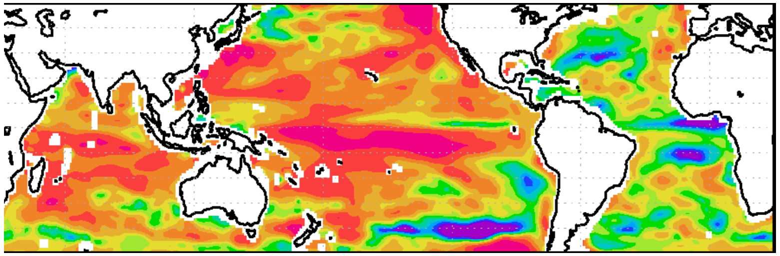
Let's make a parenthesis...

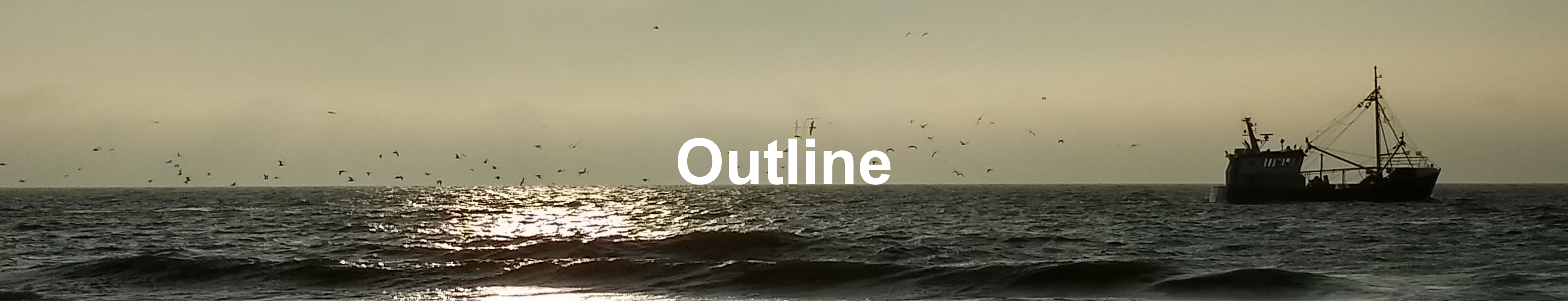

TOSHIRO MIFUNE
AKIRA KUROSAWA
RASHOMON

Evaluation of Ocean Syntheses

- A wide range of ocean syntheses exist, each created to fulfill specific objectives.
- Ocean syntheses have been **insufficiently evaluated** – products present significant differences!
- Lack of coordination between different efforts
- Users of ocean syntheses **do not know**:
    - Which specific product to use for their application
    - How good this product is
    - How a particular ocean synthesis differs from others







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COST

COST is an EU-funded programme that enables researchers to set up their interdisciplinary research networks in Europe and beyond. COST Actions are a **networking instrument** for researchers to cooperate and coordinate nationally funded research activities.

Bottom-up strategy, favour interdisciplinary projects

Provide **networking** opportunities

Special focus: early research scientists, inclusiveness target countries

→ Pan-European
→ **Open to all researchers**

Networking tools available through COST:
Workshops
Conferences
Training schools
Short-term scientific missions (STSMs)
Dissemination activities.

COST Action “Evaluation of Ocean Syntheses”

November 2014 to November 2018

Main objective: establish and consolidate a network of European scientists working on the generation and evaluation of ocean synthesis products, data providers, experts in data analysis, data assimilation and ocean modelling...

Support individual mobility, strengthen existing networks and foster collaboration between researchers.

↓

- compile an inventory of end-user requirements (quality and availability of ocean syntheses)
- improve the understanding of the value and use of ocean syntheses
- issue recommendations on which data products are the most suitable for which task.
- increase awareness of ocean synthesis products among end users

EVALUATION OF OCEAN SYNTHESES

COST Action ES1402

http://www.eos-cost.eu

A COST Action to **improve the coordination** of European efforts in the evaluation of ocean syntheses:

- better understanding of the value and use of ocean syntheses
- promote the use of ocean syntheses

Chairs:
Aida Alvera-Azcárate (University of Liège, BE)
Keith Haines (University of Reading, UK)

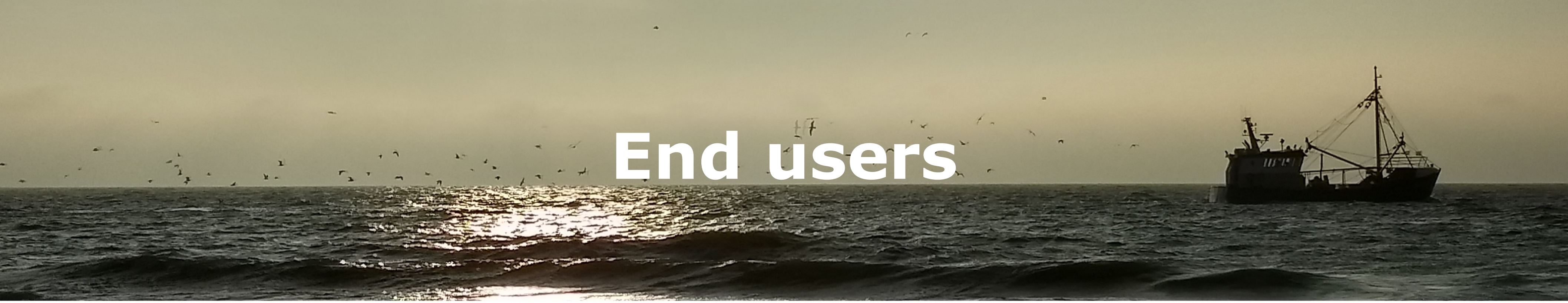
a.alvera@ulg.ac.be

cost
EUROPEAN COOPERATION IN SCIENCE AND TECHNOLOGY

Earth System Science and Environmental Management

EUROPEAN SCIENCE FOUNDATION

End users



Scientific community (ocean, weather, climate modellers, climate researchers, oceanographers) working in:

- national research centres
- operational centres (e.g. Mercator Ocean in France)
- national weather services (e.g. Met Office in the UK)
- climate research centres...

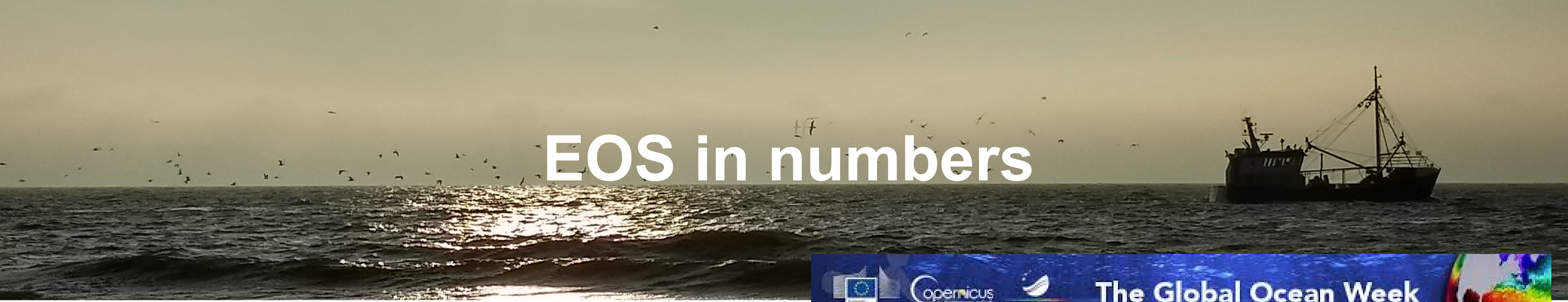
Public sector

- Policy makers
- Local authorities in coastal regions, marine safety
- National environmental agencies

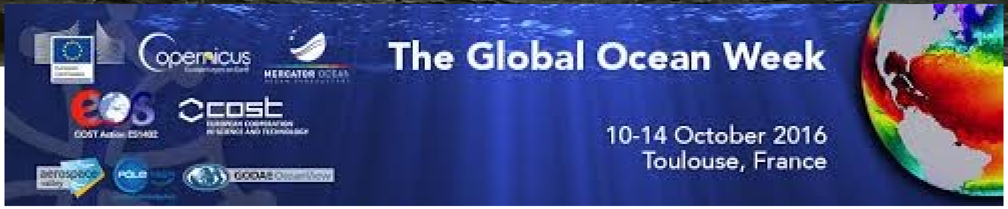
Private sector and other non-scientific representatives of the European society

- Fisheries management authorities
- Insurance companies
- Commercial shipping
- Offshore renewables as well as Oil and Gas

Plus all end users of ongoing European projects (MyOcean2, GODAE, CLIVAR/GSOP...)



EOS in numbers



4 international workshops

4 training schools (61 students funded by EOS)

10 working group meetings

5 Management Committee meetings

27 short-term scientific missions

So far, ~220 scientists have been funded by EOS

Network within the Network: Polar reanalyses

Polar regions reanalises Intercomparison Network
Polar regions are facing very rapid change over the last years, therefore are a special region of interest within EOS

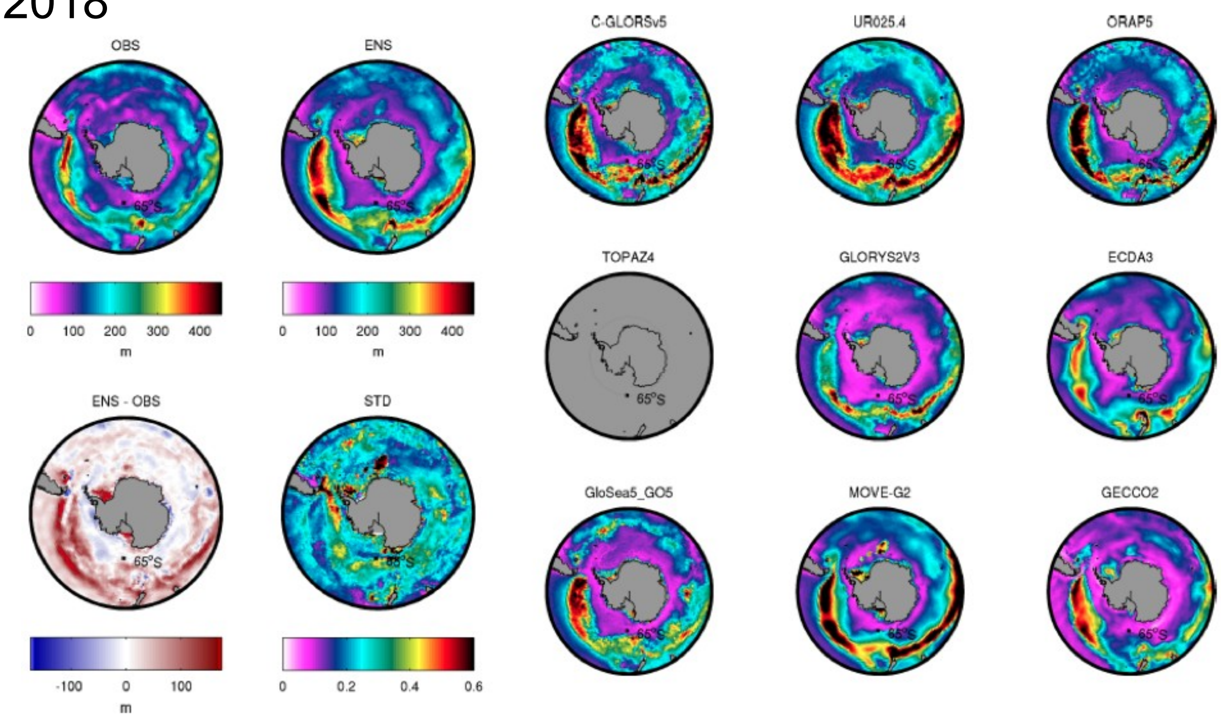
An intercomparison of 10 reanalyses in Arctic and Antarctic regions has been realised

“An assessment of ten ocean reanalyses in the polar regions”, Uotila et al, Climate Dynamics 2018

In the paper:

“...our best estimate of what the truth might look like”

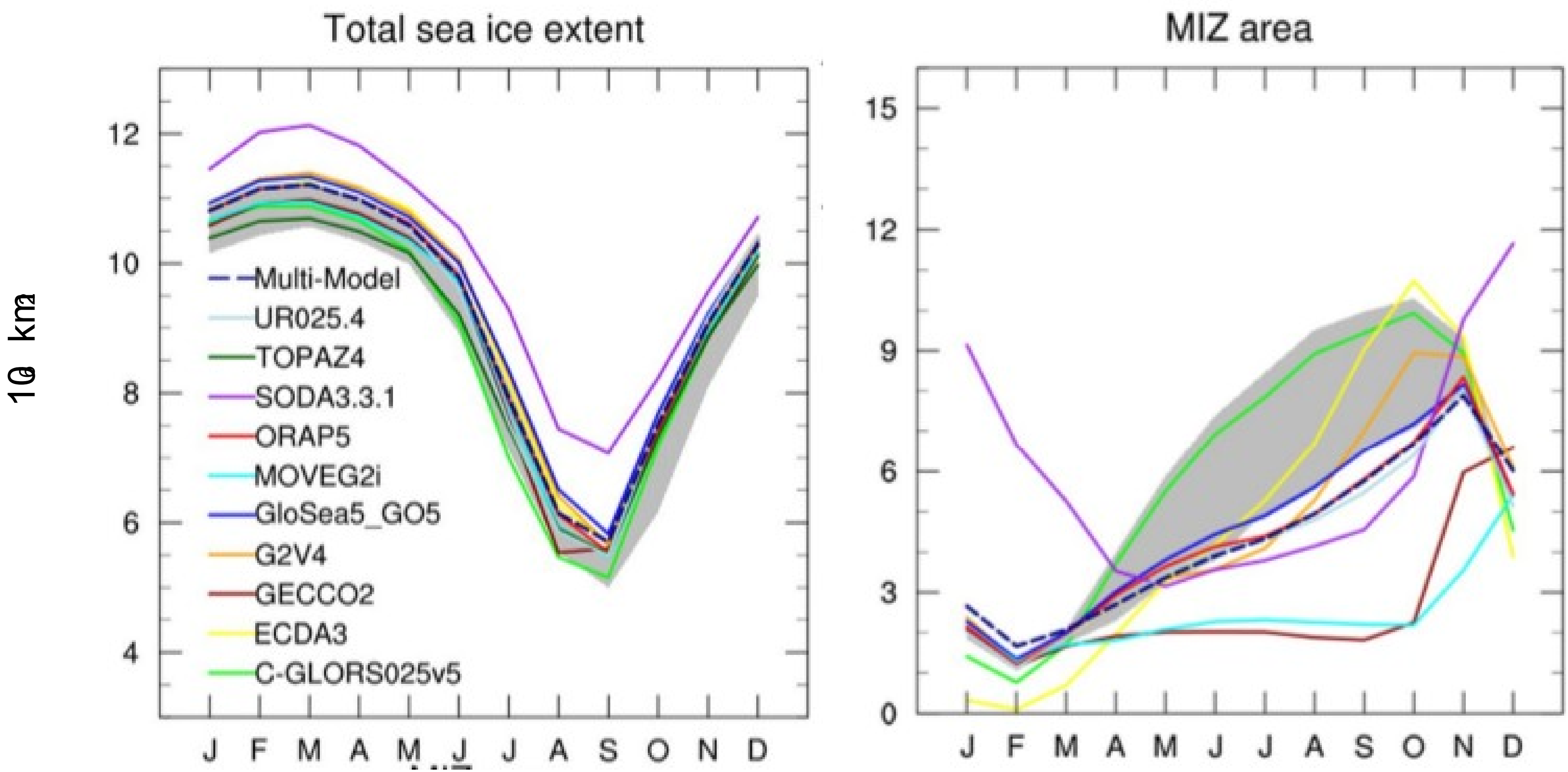
“...this paper does not seek to tell the user which reanalysis to use, but to show which are outliers for certain variables, which can still be very useful.”



Network within the Network: Polar reanalyses

Name	C-GLORS025v5	ECDA3	GECCO2	GLORYS2v4	GloSea5-GO5	MOVE-G2i	ORAP5	SODA3.3.1	TOPAZ4	UR025.4
Institution	CMCC	GFDL/NOAA	Hamburg University	Mercator Océan	UK MetOffice	MRI/JMA	ECMWF	University of Maryland	NERSC	University of Reading
Nominal horizontal resolution	0.25°	1°	1° × 1/3°	0.25°	0.25°	1° × 0.3° – 0.5°	0.25°	0.25°	12–16 km	0.25°
Vertical resolution	50 z-levels	50 z-levels	50 z-levels	75 z-levels	75 z-levels	52 z-levels	75 z-levels	50 z-levels	28 z-isopycnal layers	75 z-levels
Top-level thickness	~ 1 m	10 m	10 m	~ 1 m	~ 1 m	2.25 m	~ 1 m	~ 10 m	min 3 m	~ 1 m
Ocean-ice model	NEMO3.2-LIM2	MOM4-SIS	MITgcm	NEMO3.1-LIM2	NEMO3.4-CICE	MRI.COM3-CICE4	NEMO3.4-LIM2	MOM5-SIS	HYCOM-EVP SI	NEMO3.2-LIM2
Time period	1980–2015	1961–2012	1948–2014	1992–2015	1993–2012	1980–2012	1979–2012	1980–2015	1991–2016	1989–2010
Initialization	Spinup	Spinup	Cold start	Cold start	Spinup	Spinup	Spinup	Spinup	Cold start	Cold start
Source of atmospheric forcing data	ERA-Interim	Coupled	NCEP RA1	ERA-Interim	ERA-Interim	JRA-55[a]	ERA-Interim	NASA MERRA2	ERA-Interim	ERA-Interim
Ocean restoring	Large scale bias correction to EN3v2a	Fully coupled	None	T, S restoring towards EN4.1.1 for z > 2000 m and lat < 60°S (τ = 20 years)	Surface Haney SSS restoring (– 33.333 mm/day/PSU), 3D T/S to ENACT3 2004–2008 climatology (τ = 1 year)	Relaxing (by IAU) T/S to merged PHC3-WOA13 climatology (τ = 5 years)	Relaxation to OSTIA/NOAA OIv2d SST	Restoring to mean T and S (τ = 10 years). Relaxation to WOA SSS (τ = 3 months)	Relaxing T/S to merged PHC3–WOA13 climatology	None
Sea-ice DA method	Nudging	None (SST)	None (SST)	Reduced order KF	3DVAR	3DVAR	3DVAR-FGAT	None (SST)	EnKF	OI
Sea-ice DA variables	SIC, Arctic SIT	–	–	SIC	SIC	SIC	SIC	–	SIC, SIV	SIC
Sea-ice DA sources	NOAA OIv2d, PIOMAS	–	–	CERSAT	OSISAFv2	MGDSST	OSTIA, NOAA OIv2d	–	OSISAF	OSISAF
Ocean DA method	3DVAR	EnKF	4DVAR (adjoint)	Reduced order KF + 3DVAR large scale bias	3DVAR	3DVAR	3DVAR	OI	EnKF	OI

Network within the Network: Polar reanalyses



Network within the Network: North Atlantic

North Atlantic ORA-IP: intercomparison network aiming at better understand the differences between reanalyses of the North Atlantic. AMOC estimates

- Intercomparison of 12 reanalyses to determine variability, differences and reasons for them
- Can we learn what makes a reanalysis good at specific processes?

AMOC: Atlantic Meridional Overturning Circulation

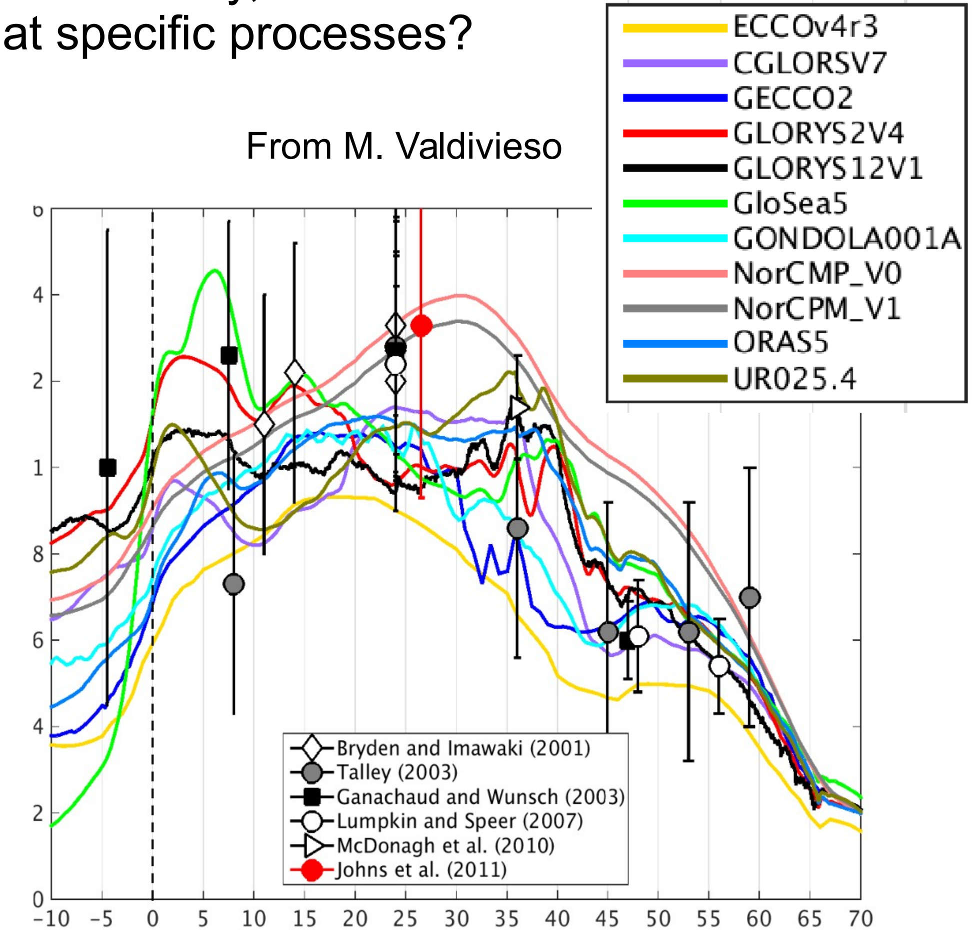
System of ocean currents driven by T & S differences

Transport of heat from tropics to north (& Europe)

Important component of climate system

Variability in AMOC drives changes in Europe's climate

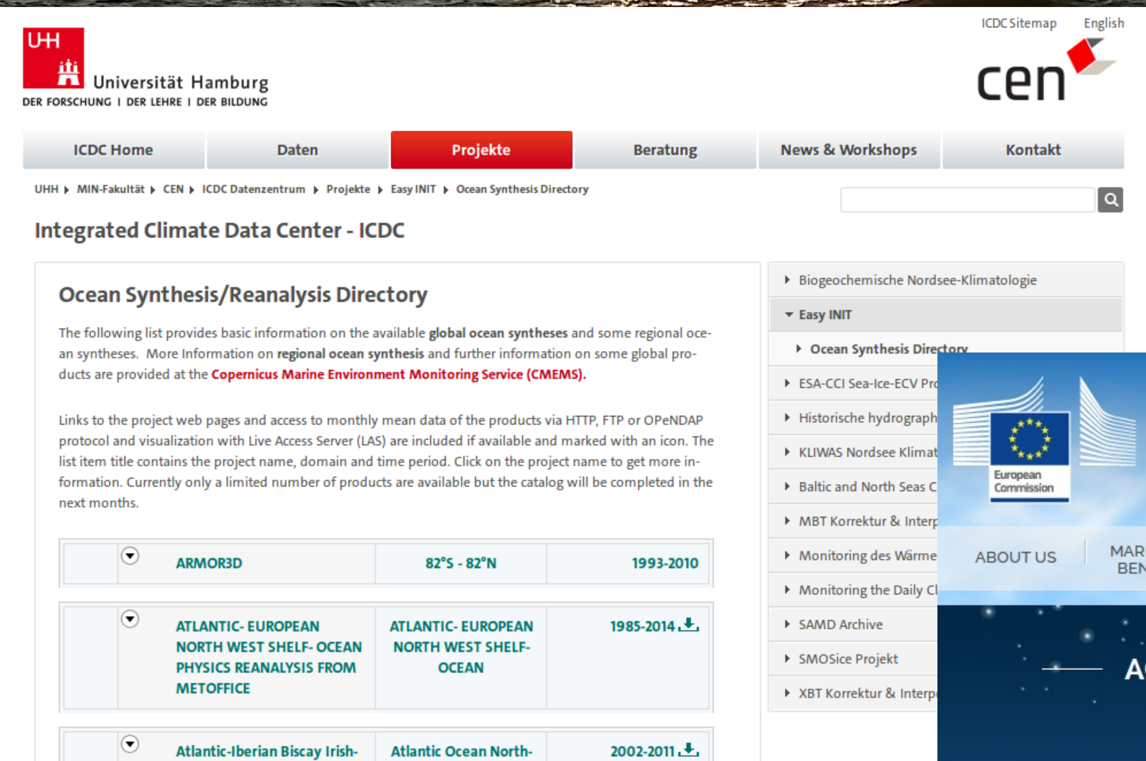
From M. Valdivieso



Meridional heat transport from reanalyses and climatologies, 1993-2000

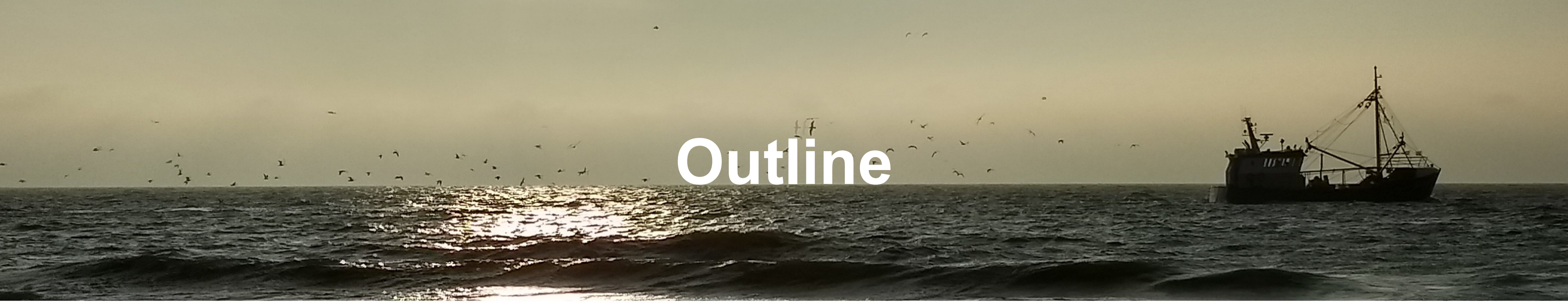
yeah, sounds great, but this is **really** too complex...

Where to access ocean reanalyses



EOS catalogue, http://www.eos-cost.eu/

CMEMS catalogue, http://marine.copernicus.eu/



Outline

Introduction: the role of the ocean on climate

Estimating the state of the ocean:

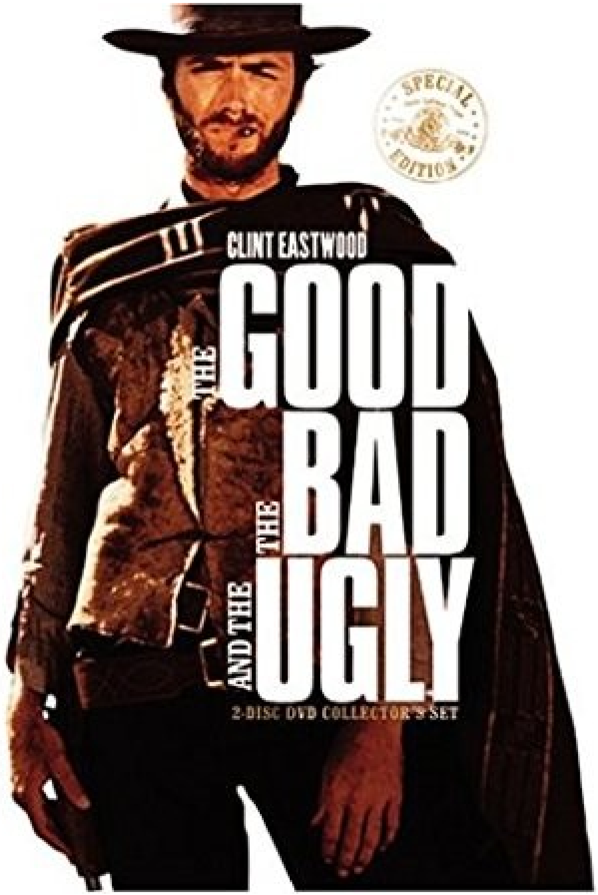
- Gridding satellite data
- Gridding in situ data
- Ocean models and data assimilation

Ocean reanalyses

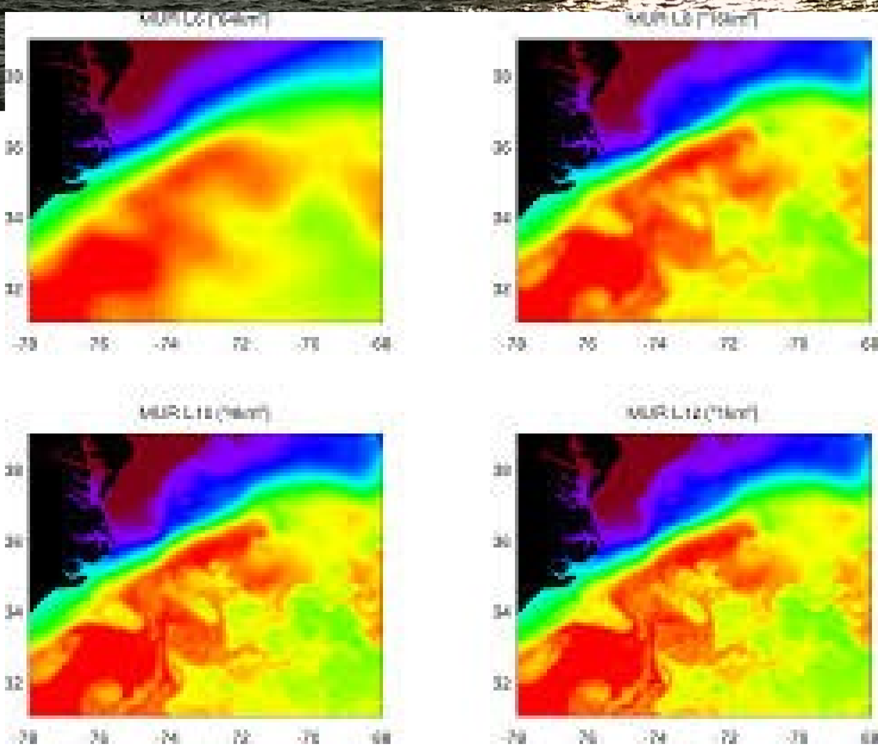
- Definition and applications
- COST Action EOS

Concluding remarks

On managing COST Actions



On validation of analyses and reanalyses



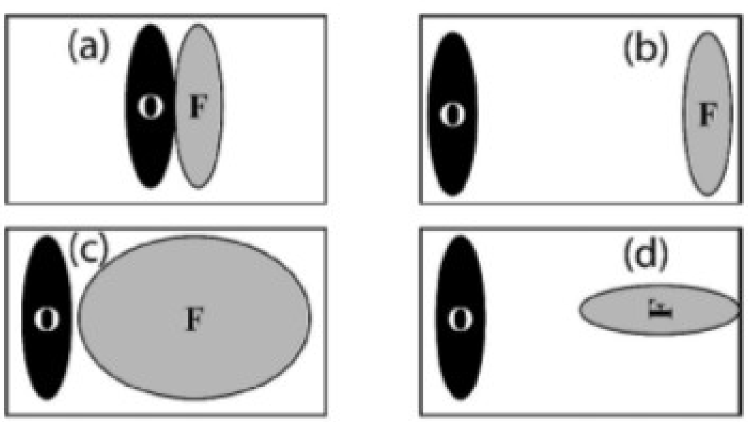
→ Processes present in model and data are not the same

→ Point measurements vs. area-averaged model results

→ Higher spatial resolution: double penalty effect

"Different" ways to validate a model/reanalysis

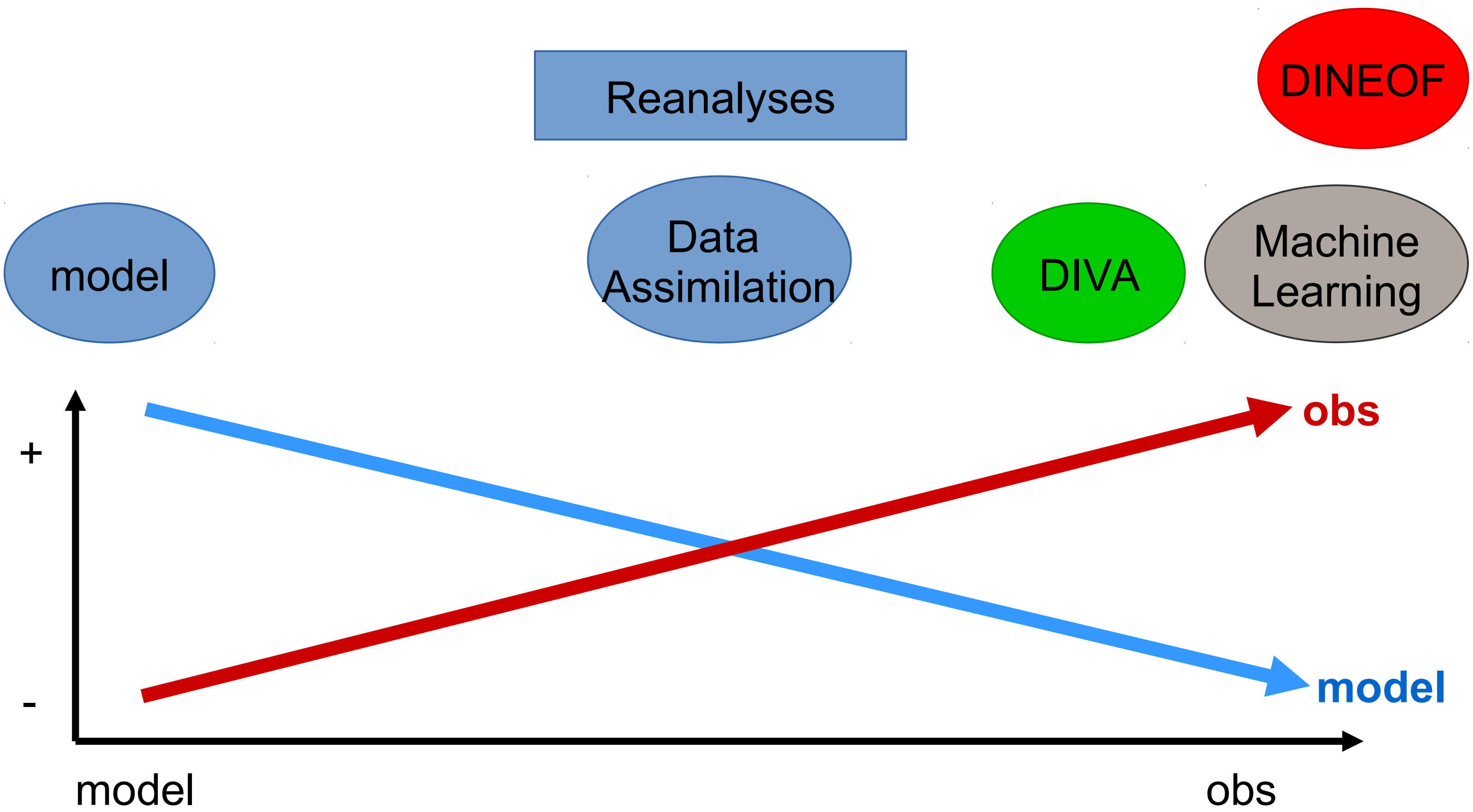
→ Neighbourhood methods that give credit for close forecasts
→ Scale separation methods that isolate scale-dependent errors
→ Object-based methods that evaluate attributes of coherent features
→ Field deformation methods that measure phase and amplitude errors.

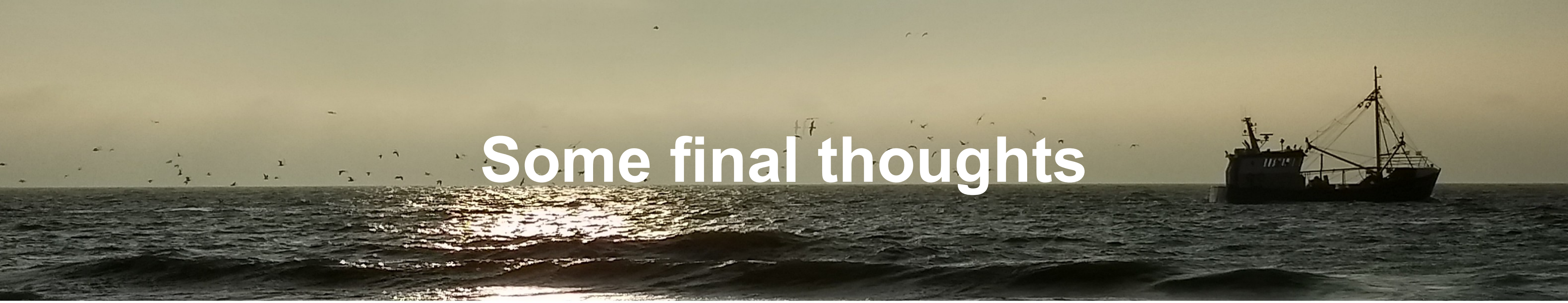


Fundel, An introduction to forecast verification

Also, an eddy in the wrong place, is it better than no eddy?

The data-model spectrum





Some final thoughts

The state of the ocean is impossible to know exactly

Uncertainties in the data
Uncertainties in the models
Lack of enough information

Ocean reanalyses are our best tool so far to study the state of the ocean, but many improvements necessary

A final though to all those scientists that, while knowing that the reality is impossible to know, they keep trying...

EVALUATION OF OCEAN SYNTHESES

COST Action ES1402

http://www.eos-cost.eu

A COST Action to **improve the coordination** of European efforts in the evaluation of ocean syntheses:

- better understanding of the value and use of ocean syntheses
- promote the use of ocean syntheses

Chairs:
Aida Alvera-Azcárate (University of Liège, BE)
Keith Haines (University of Reading, UK)

a.alvera@ulg.ac.be

cost
EUROPEAN COOPERATION IN SCIENCE AND TECHNOLOGY

Earth System Science and Environmental Management

European Science Foundation

Activities organized under EOS

Workshops:

- Workshop on the use of new satellite datasets in marine climate applications (Porto, Portugal, 29 March – 1 April 2016)

- Workshop on the use of models, reanalyses and observations to assess the health of the ocean environment (Liege, Belgium, 17 March 2017)

- Workshop on ocean reanalyses and inter-comparisons (Toulouse, France, 29-30 June 2017)

- Regional Climate System Modelling for the European Sea Regions (Palma de Mallorca, Spain, 14-16 March 2018)

Activities organized under EOS

Training schools:

1. School on Data Assimilation and Data Analysis Techniques (Lecce, Italy, 4-15 April 2016)

→ Fundamentals of combining physical data in an optimal way
→ Bayesian and Ensemble methods
→ Variational methods
→ Hybrid methods (ensemble + variational)
→ Reduced order methods
→ Optimal interpolation
→ Data-Interpolating Variational Analysis (DIVA)
24 students, 9 teachers by EOS-COST

2. The Global Ocean Week (Toulouse, France, 10-14 October 2016)

→ Outlook of Copernicus Marine Service and its added value for Blue Growth
→ Focus on Copernicus Marine Service global ocean products and practical exercises
→ Focus on downscaling of ocean syntheses
→ Intercomparisons of ocean syntheses available worldwide
→ Training on the evaluation of ocean syntheses
→ Opportunities for creating Science and SMEs Networking

21 students, 9 teachers by EOS-COST

Activities organized under EOS

3. Copernicus Marine Data in Ocean Models and Operational Applications (Hamburg, Germany, 5-9 February 2018)

This 1-week training school was organised in collaboration with EUMETSAT. Topics covered were, among others:

→ Learning what data and products the Copernicus Marine Data Stream provides.
→ Accessing and downloading data and products provided in the Copernicus Marine Data Stream (CODA, EUMETSAT Data archive, EUMETCast).
→ Reconstructing missing data in satellite datasets using DINEOF.
→ Use of CMEMS reanalysis products.

16 students, 4 teachers paid by EOS-COST (4 more students and 6 teachers by Eumetsat)

4. Training school ("Crash course") in data assimilation (Bergen, Norway, 22 to 25 May 2018)

→ 4-day school
→ aimed at PhD-level students and early stage scientists with beginner or no notions of data assimilation intending to apply data assimilation as part of their research.
→ It will cover the basic notions of data assimilation, focusing on ensemble methods, illustrated with real-scale / operational applications and with the aid of practical exercises.

What is the state of the ocean?

We don't know!