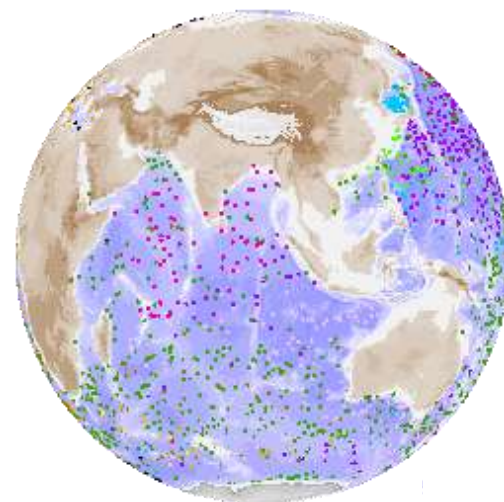


The international Argo programme: a revolution for ocean and climate observations



**Pierre-Yves Le Traon*, Ifremer
Coordinator NAOS Equipex Project**



** Acknowledgments: NAOS, French Argo, Euro-Argo/Argo international partners. Particular thanks to F. D'Ortenzio, H. Claustre, S. Le Reste, V. Thierry, S. Pouliquen, M. Babin and C. Marec*

Outline

- ❑ Ocean and Climate
 - ✓ The fundamental role of the oceans
 - ✓ Observing the global ocean: a vital necessity

- ❑ The Argo revolution
 - ✓ The development of Argo
 - ✓ Achievements

- ❑ Challenges for the next decade
 - ✓ New phase of Argo
 - ✓ French activities: NAOS Equipex

- ❑ Conclusions/Recommendations

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THE CONTRIBUTION OF COLLABORATIVE RESEARCH PROJECTS

Ocean and Climate

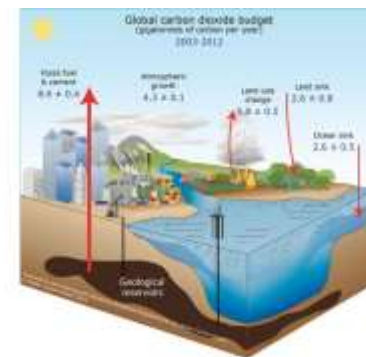
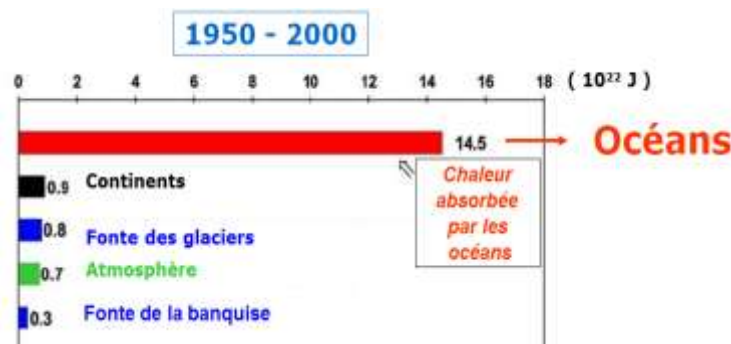


The fundamental role of the oceans

The oceans have a fundamental influence on the earth climate. A precise knowledge of the oceans is required to predict the evolution of our weather and climate.

The oceans have absorbed more than 90% of the Earth warming due to the anthropogenic increase of greenhouse gas concentration.

There are reducing the rate of climate change by absorbing about 30% of human emissions of carbon dioxide.



Climate Change impacts on the oceans

These buffering effects are not without consequences on the ocean physics, chemistry and ecosystems.

The oceans are getting warmer, sea level is rising, sea ice is melting.

The oceans are becoming more acidic due to CO₂ absorption and less oxygenated due to surface warming and increased stratification.

Impact on ecosystems and fisheries

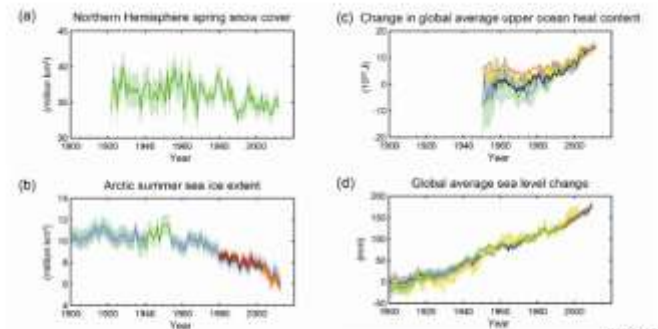


Fig. SPM.3

Warming in the climate system is unequivocal

IPCC Working Group I
Climate Change 2013: The Physical Science Basis

ipcc
INTERNATIONAL PANEL ON CLIMATE CHANGE
1995 2007 2013



Long-term observations of all oceans are imperative to better characterize climate change, understand and predict the role of the ocean on climate.

This is required to make informed political decisions on how to attenuate and adapt to climate change.

You cannot manage what you do not observe and do not understand.



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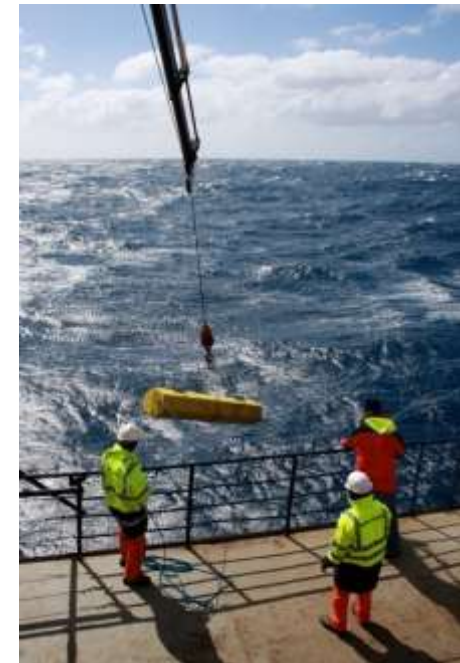
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The Argo revolution



Argo: a revolution in oceanography *the first global real time in-situ ocean observing system*

More than 3500 profiling floats worldwide measuring the temperature and salinity to a depth of 2000 m. A major contribution to the global ocean and climate observing system.



Argo is a long-term global array integrated with other elements of the climate observing system to:

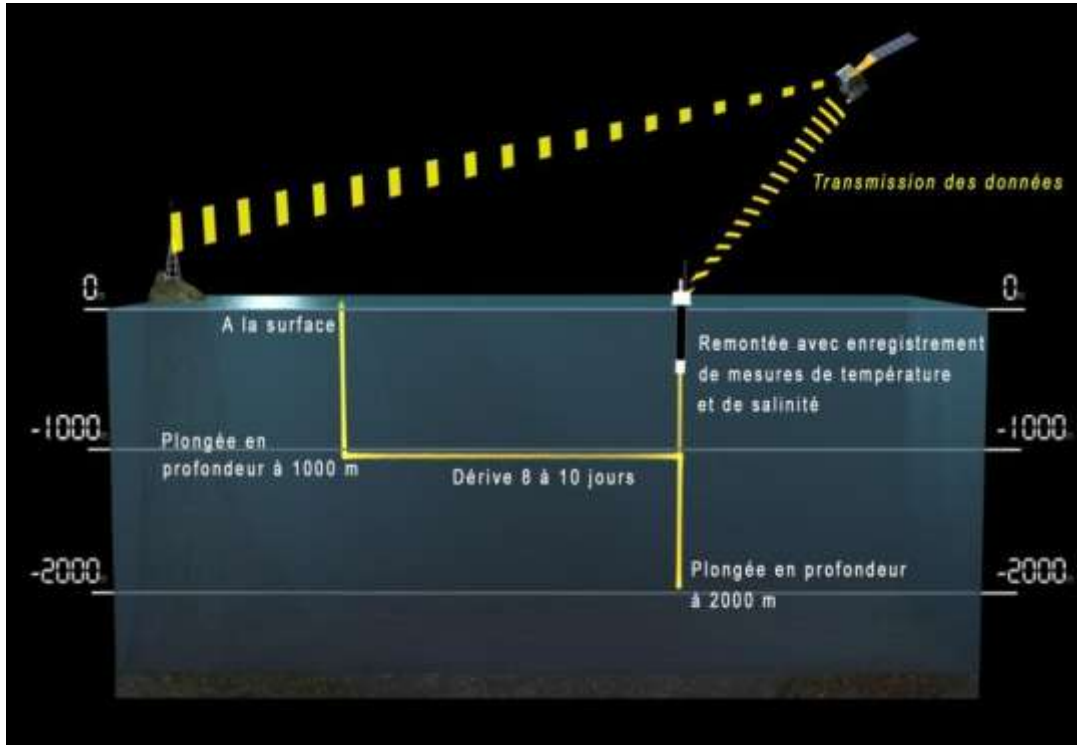
- ❑ **detect climate variability from seasonal to decadal scales and provide long-term observations of climate change in the oceans.** This includes regional and global changes in temperature and ocean heat content, salinity and freshwater content, sea level and large scale ocean circulation.
- ❑ provide data to **constrain global and regional ocean analysis and forecasting models**, to **initialize seasonal and decadal forecasting ocean/atmosphere coupled models** and to **validate climate models.**
- ❑ provide information necessary for the **calibration and validation of satellite data**

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How does an Argo float work ?

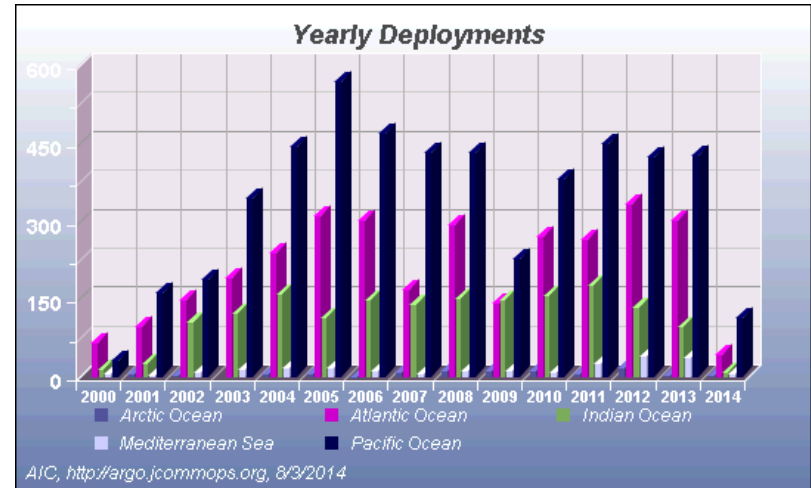
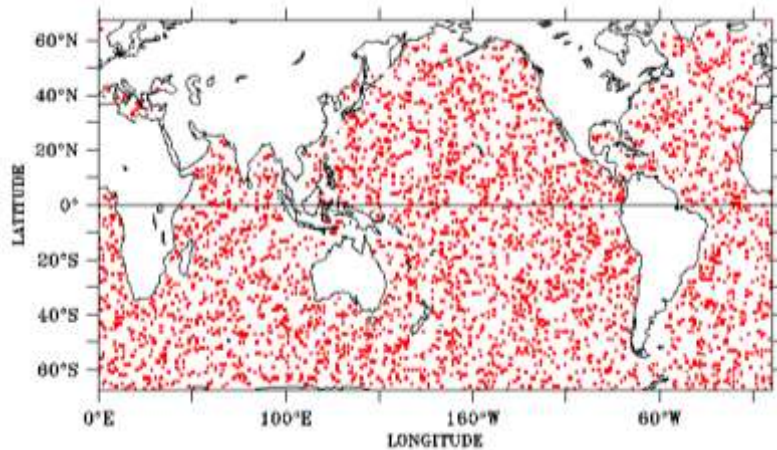


Cost of an Argo T,S profile \approx 120 euros
Cost of a WOCE T,S profile \approx 12000 euros

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Argo development from dream to reality



Initial Concept: 1998 (Argo Steering Team)

Annual deployments



Argo in 2015: 3800 floats, > 30 countries

Argo float deployment - 2014

The exceptional contribution of Argo to the global ocean observation

2000: start - end of 2007: 3000 floats. > 30 pays

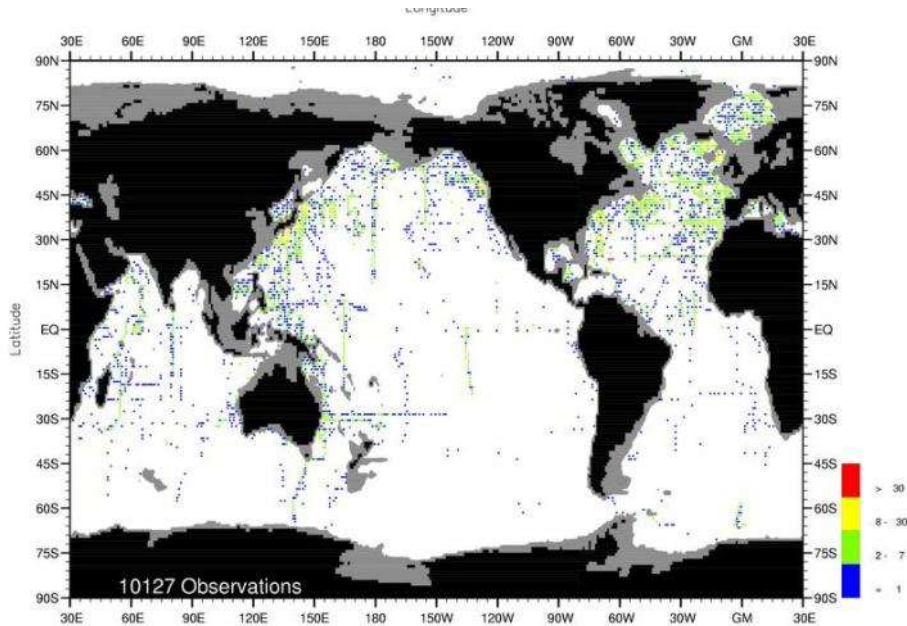
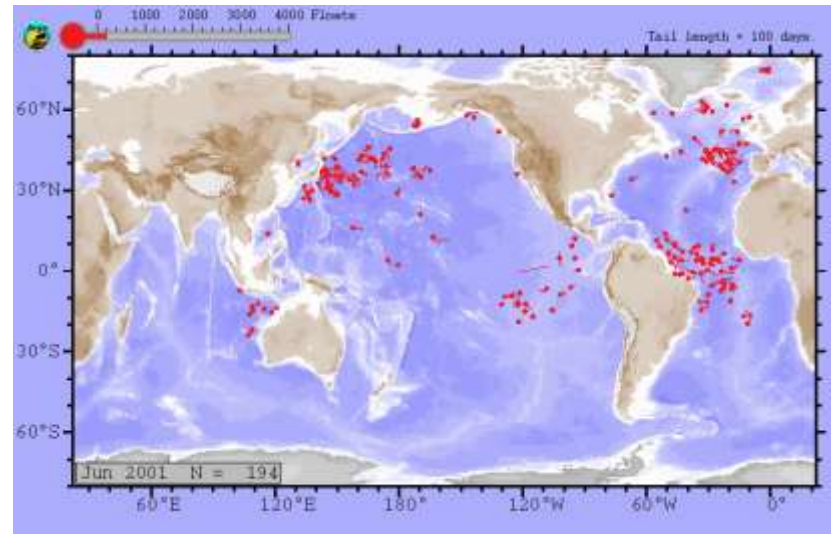


Fig. L1-24. July temperature observations at 1500 m. depth.

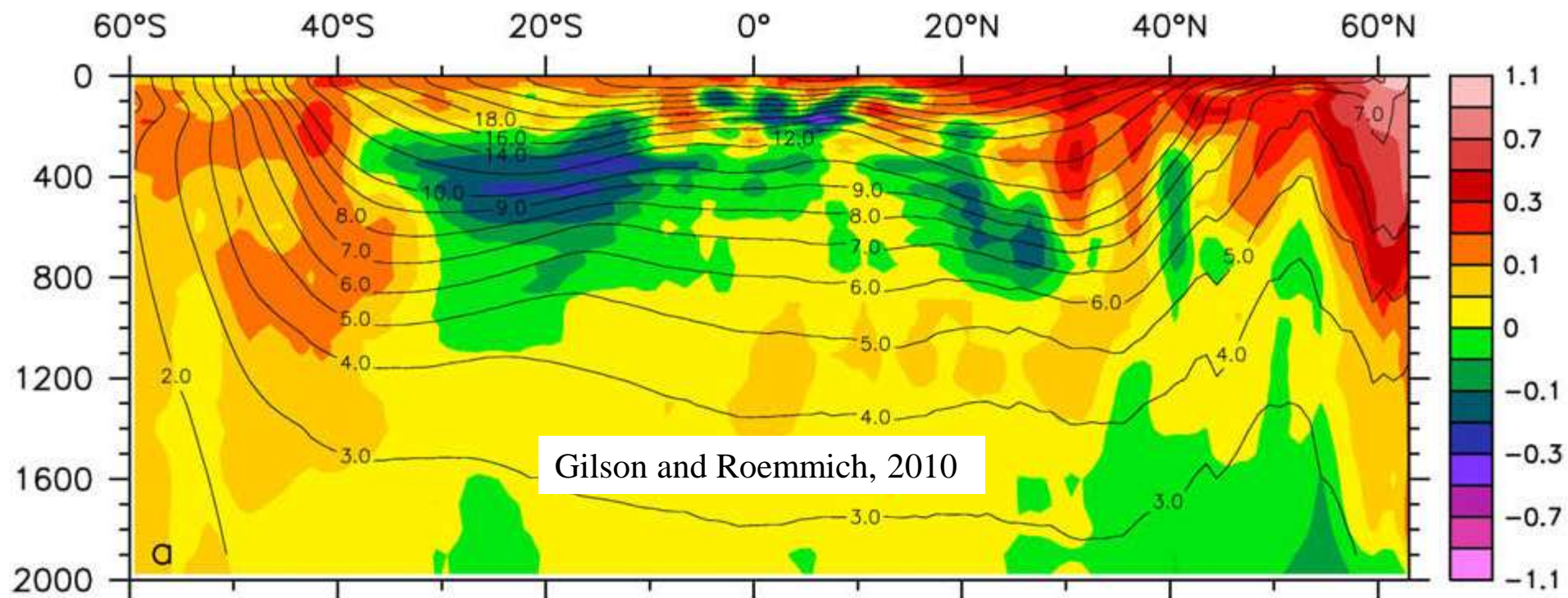
Temperature - July - 1500 m - 20th century



Argo float deployments (2001-2010)

20th century : 500 000 T/S profiles > 1000 m. **Argo**: 1 000 000 T/S profiles in 2012.

Argo years versus historical observations (temperature)



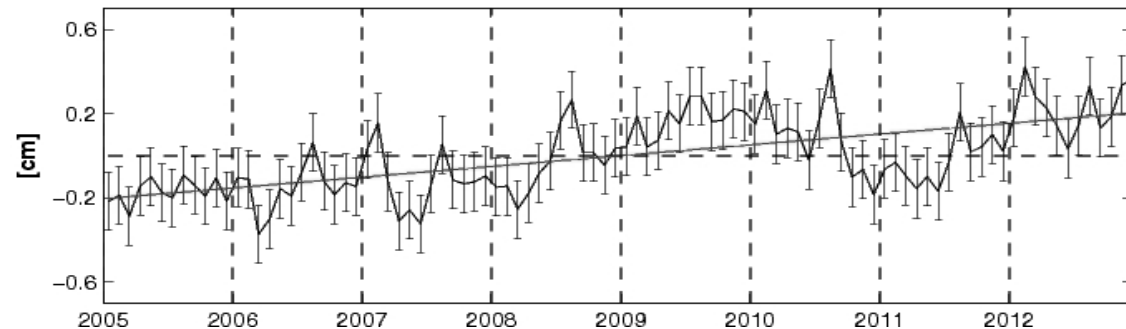
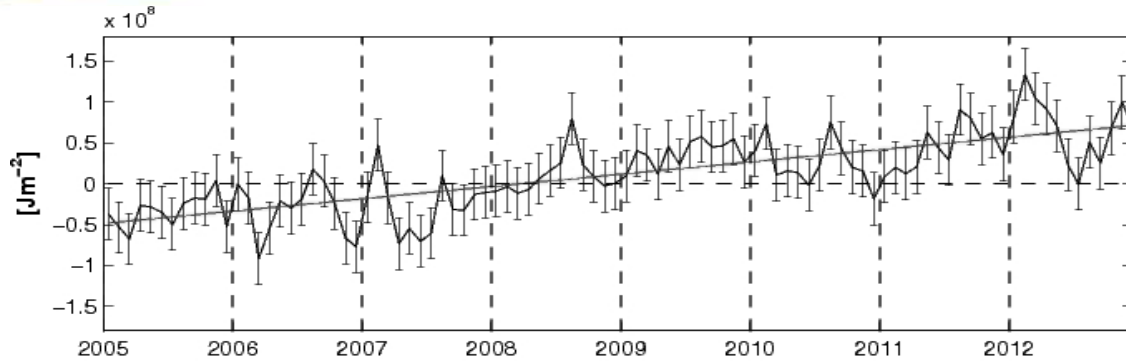
Warming at the surface but also at depth in mid-latitude/high latitudes

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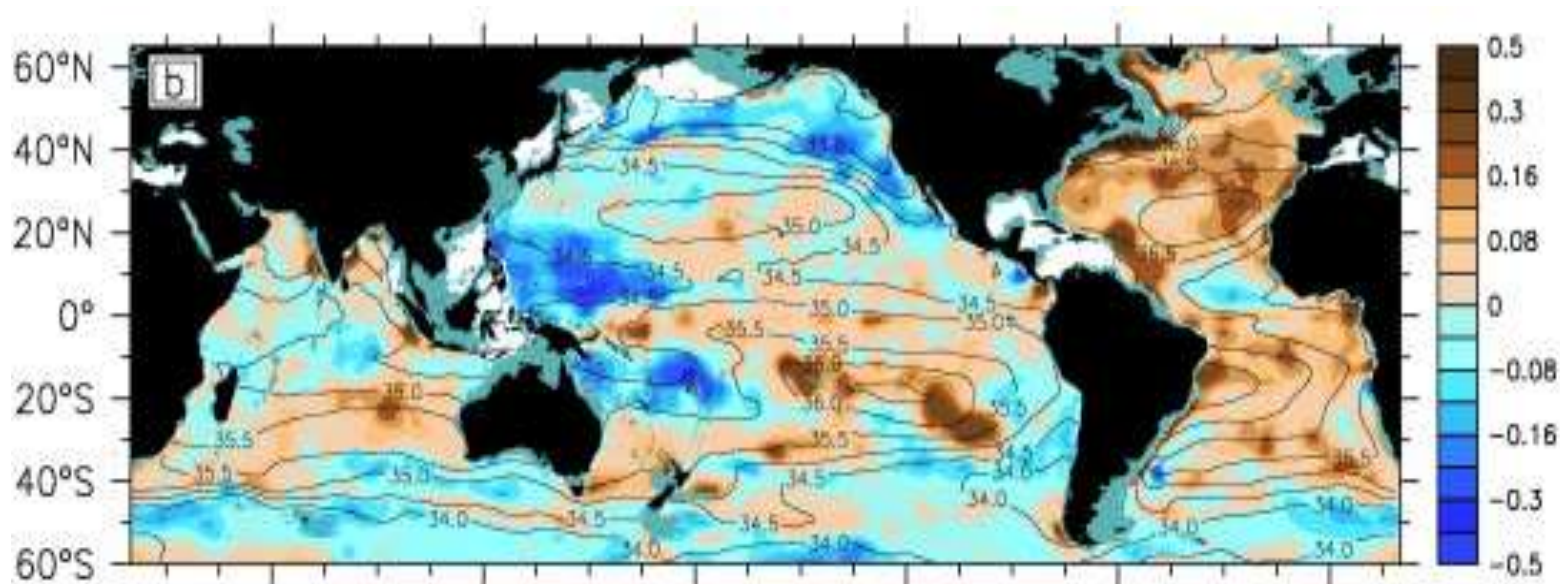
A major contribution of Argo is to provide much better estimation of heat stored by the oceans

Essential to a better understanding of earth energy imbalance and mean sea level rise mechanisms



Heat content and steric sea level rise (thermal expansion) (von Schuckmann et Le Traon, 2011; von Schuckmann et al., 2014)

Long term variations of salinity (Argo minus climatology)



Roemmich and Gilson, 2009; Durack and Wijffels, 2010; Pierce et al., 2012

Salinity variations are related to evaporation–precipitation and patterns suggest an intensification of the global water cycle above that predicted by models

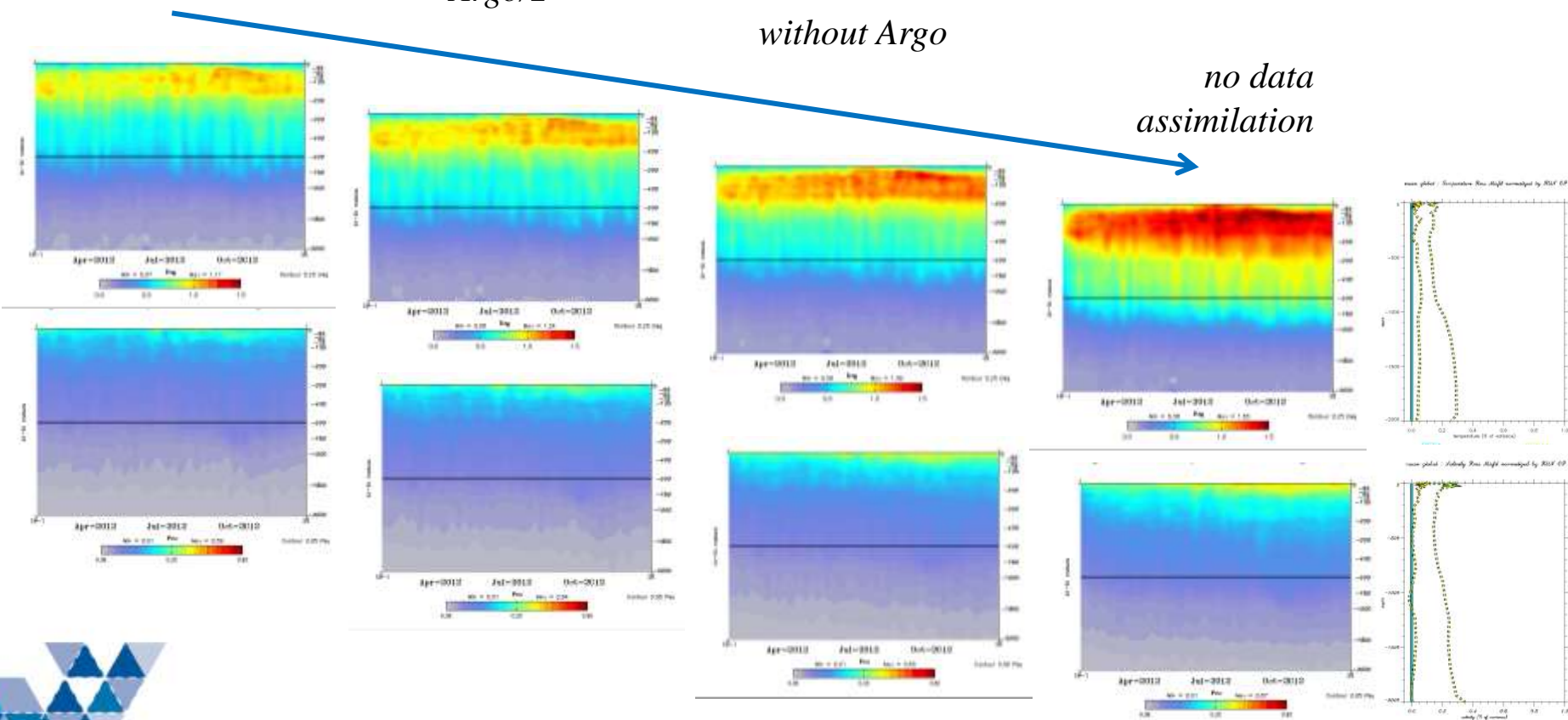
Major impact of Argo for global ocean analysis and forecasting

Mercator Ocean : observation - model forecast misfits for all in situ T,S data in 2012 (Turpin et al., 2015).
Operational Run

Argo/2

without Argo

no data assimilation



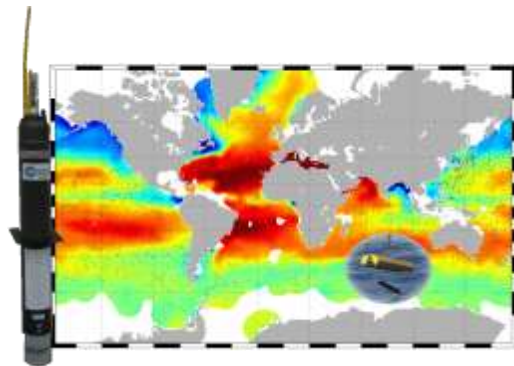
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The French contribution to Argo

- Argo France (TGIR, SO) part of the Coriolis 2014-2020 structure
- Instrumentation (Provior and Arvor floats)
- At sea operation : > 8% of the international efforts
- Data centers: one of the two global data centers
- Research: ocean, climate, biogeochemistry
- Operational oceanography: Mercator Ocean, Copernicus Marine
- European coordination: Euro-Argo ERIC hosted in France (Ifremer, Brest)
- Preparing the new phase of Argo : ERC Remocean, Equipex NAOS



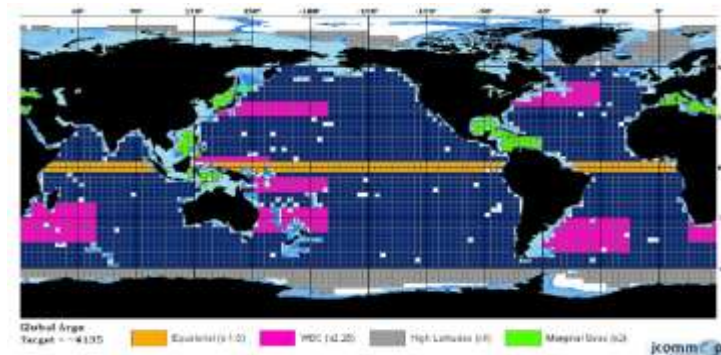
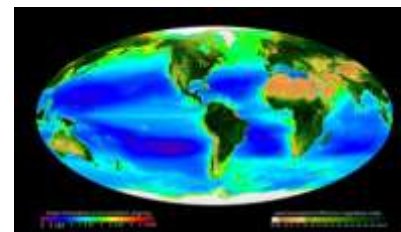
New challenges

Evolution of Argo for the next decade



Evolution of Argo for the next decade

- ❑ Proven concept. **Transition from research to sustained operational mode. 800 to 900 floats to be deployed per year .**
- ❑ Evolution of instrumentation (data transmission, hardware, lifetime)
- ❑ **The array needs to evolve over time. Extending the core mission.**
 - ❑ Under ice and high latitudes
 - ❑ Marginal seas
 - ❑ Sampling (e.g. WBC, tropics)
 - ❑ Deep ocean (Deep Argo)
 - ❑ New sensors and Bio-Argo (Oxygen, Chl-a, Nitrate, Carbon, pH)
- ❑ **Extension is on going** (pilot experiments) and long term plans are discussed



~4200 float array

Bio-Argo Science : global, climate change

- Ocean acidification
- Ocean deoxygenation
- Carbon sequestration and oceanic carbon biological pump

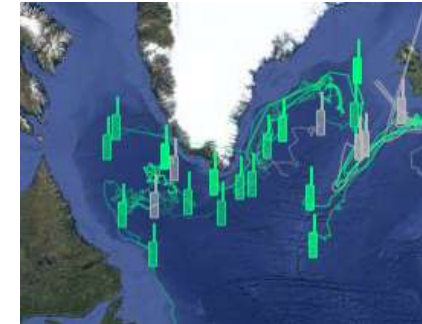
Bio-Argo integration: a component of future observing and forecasting systems

- Link with ocean colour remote sensing
- Link with biogeochemical & ecosystem models

Implementation : first target regional hotspots

- Oxygen Minimum zones
- North Atlantic sub-polar gyre

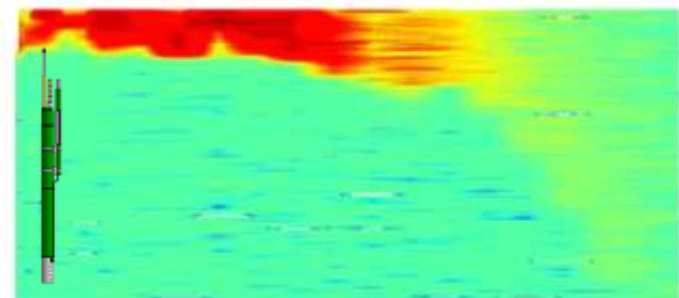
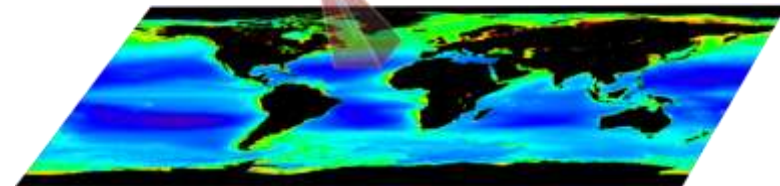
Mediterranean Sea



FP7 ERC remOcean (2010-2016) Bio-Argo pilot experiment in the North Atlantic (PI: H. Claustre)



Satellite: Global scale



Bio-Argo profiling float: Vertical dimension

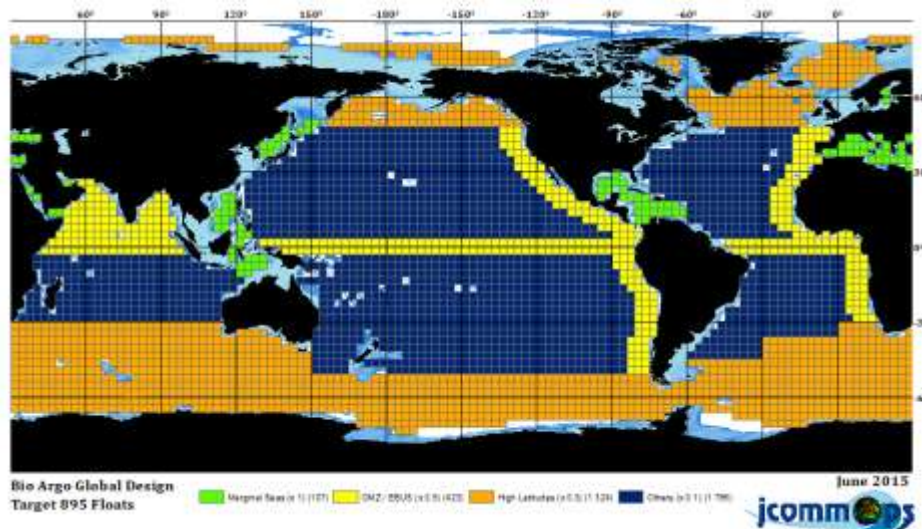
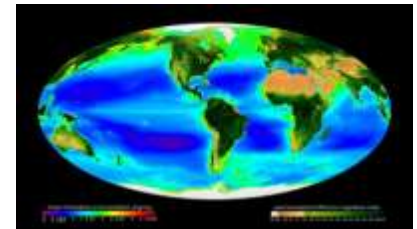
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From pilot projects, the Bio-Argo community is now involved in designing the network for the global scale

The variables already implemented on Bio-Argo

- Oxygen
- Nitrate
- pH
- Chlorophyll a
- Particulate (back)scattering
- Radiometry : $E_d(\lambda)$,
Photosynthetically Available Radiation (PAR)



From H. Claustre and Bio-Argo teams

Selection of these variables through an international consensus : IOCCG Working group "Bio-optical sensors on Argo floats Argo", OceanObs09

New Missions Deep Argo

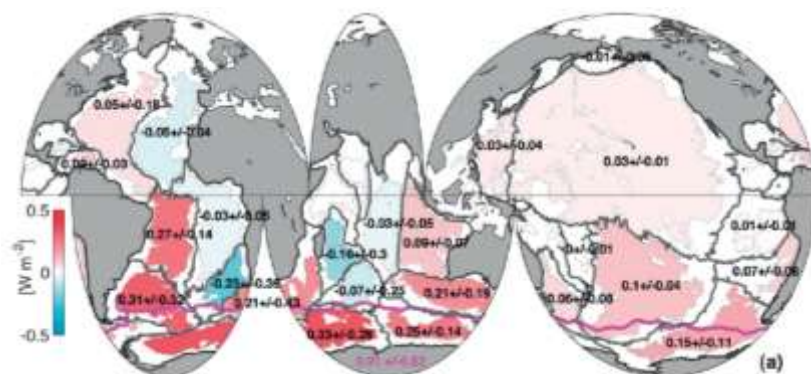
Requirements

- closure of the sea level, ocean mass, and heat / energy budgets on regional and global scales
- provide new information on ocean circulation and water mass formation and properties
- mitigate the lack of observations below 2000 m for ocean data assimilation modeling

Design issues : technological developments are progressing well, pilot experiments are on going or planned, design/implementation of a Deep Argo array is under discussion (global vs regional sampling, time/space sampling, number of floats, 4000/6000m, etc)

About of 50% of ocean volume only is observed today with Argo floats (2000 m). It is estimated they miss 0.1 W m^{-2} of ocean heat gain (about 20% of the total). **Deep Argo highly needed !**

Region	Global Heat Gain (W m^{-2})
Abyssal Ocean ($z > 4 \text{ km}$)	0.027 (± 0.009)
Southern Ocean ($1 > z > 4 \text{ km}$)	0.068 (± 0.062)
Total (Abyssal + Southern)	0.095 (± 0.062)



Bottom Water warming from 1990's to 2000's
 Purkey and Johnson (2010)

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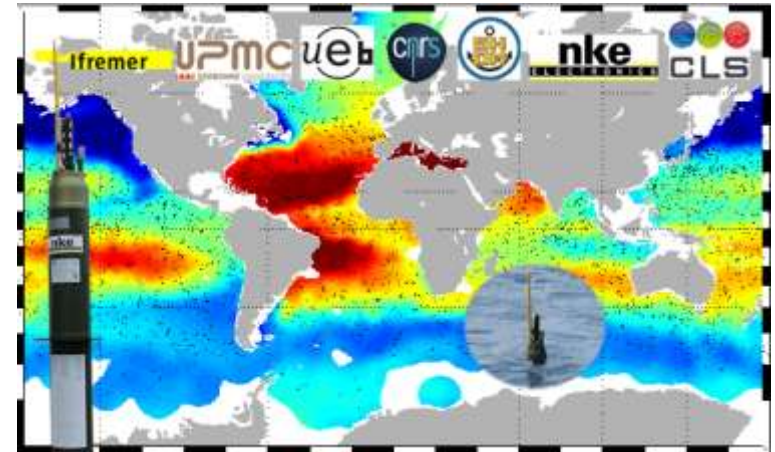
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The NAOS Equipex project



NAOS Equipex Project (2011-2019) New generation of French Argo floats

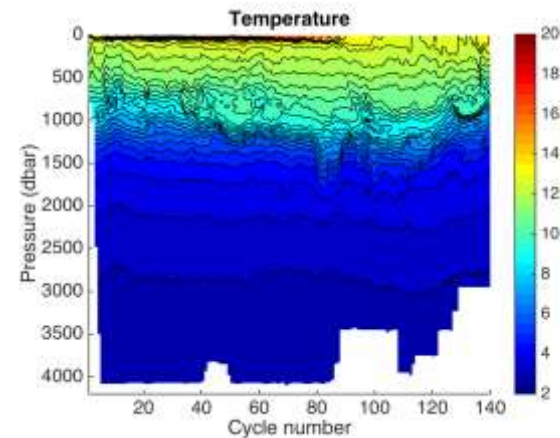
- Increased lifetime and performances incl. satellite communication and electronics
- Deep Ocean / Deep Argo.
- New sensors / Bio-Argo (Oxygen, Chl-a, Nitrate , Carbon). New sensors : density
- Under Ice operation
- Development of new float prototypes (almost completed)
- **Scientific pilot experiments** for the new phase of Argo :
 - Mediterranean Sea : biogeochemistry (on going)
 - North Atlantic : deep ocean and oxygen (starting)
 - Arctic: biogeochemistry (starting)



- More than 150 cycles 4000 m
- SBE41CP CTD + Oxygen
- Iridium & GPS - 26kg
- Two initial prototypes 3500 dbar (2012- 60 cycles, 2013-89 cycles).
- Two industrial prototypes (NKE) 4000 m deployed during the Geovide experiment (June, 2014).
- 24 floats (4000 m) to be deployed from 2015 to 2017 in the North Atlantic



Deep Arvor - Geovide (Juin, 2014)

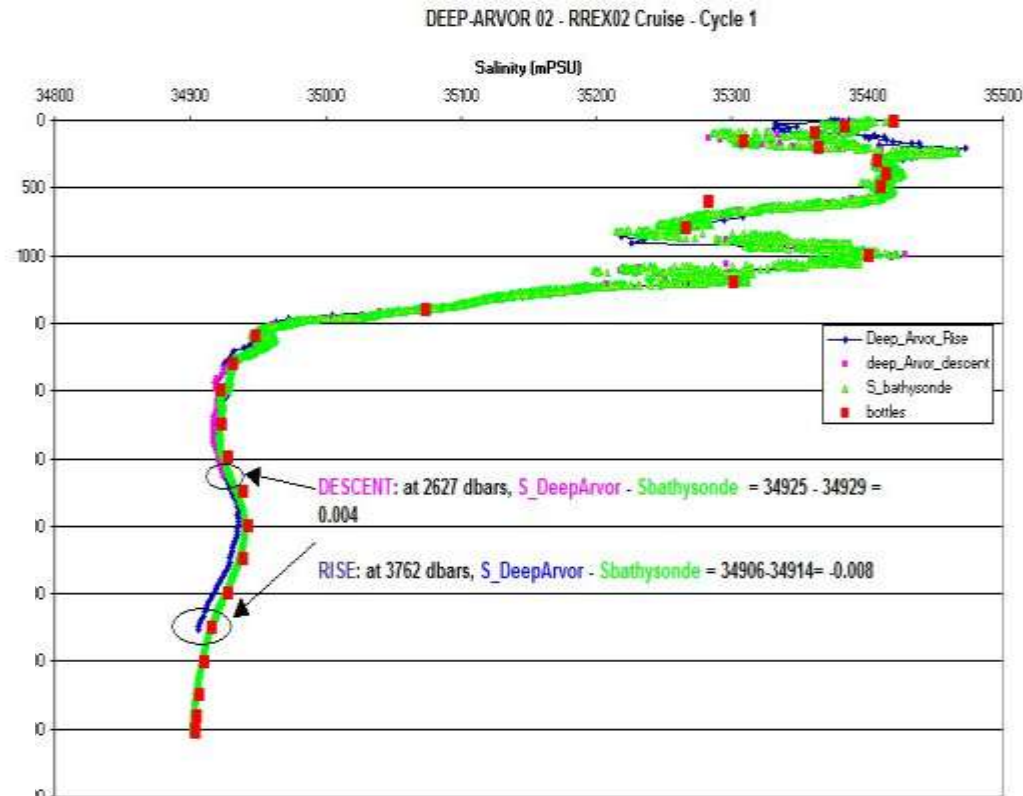
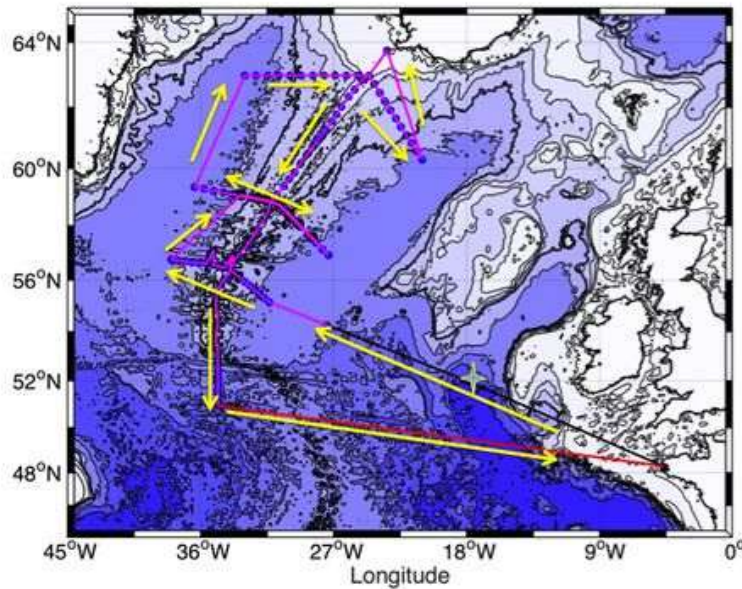


Deep-Arvor #4 : more than 140 cycles achieved (2 -day sampling)

Reykjavik Ridge experiment cruise (S. Le Reste/V. Thierry).

4 Deep-Arvor to be deployed

The first float was deployed on 8 June 2015
11 cycles achieved end of June. 3 other floats to be deployed in early July)



SBE41CP Salinity compared to CTD cast and sampling bottles. Differences within Argo specification (<0.01)

French Bio-Argo float

PROVBIO II is the “final” version of a series of models developed in France on the basis of the PROVOR T/S platform



PROVOR-DO: T/S, O₂



PROVBIO I: T/S, CHL, bb,
CDOM, Irr, POC,
IRIDIUM



PRONUTS: T/S, NO₃, IRIDIUM

PROVBIO V2



T/S, CHL, bb, O₂, CDOM, Irr,
PAR, NO₃, POC, IRIDIUM



F. D'Ortenzio, H. Claustre

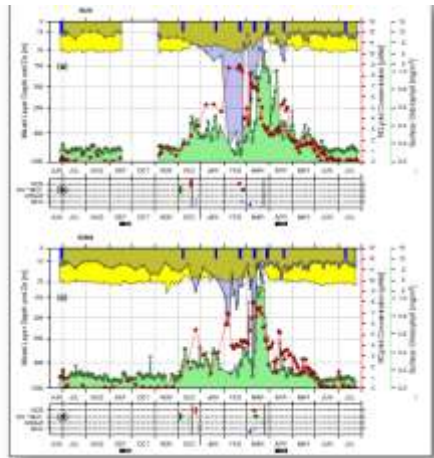
NAOS biogeochemical floats in the Mediterranean Sea (F. D'Ortenzio et al)

The first bio-Argo array in a regional sea

12 floats deployed between November 2012 and July 2013. More than 1900 profiles obtained. Unique data sets for the study of biogeochemical cycles in the Med Sea (Lavigne et al., 2013; D'Ortenzio et al., 2014)

12 new floats deployed in May/June 2016

- Two Nitrates floats operating in the NW Mediterranean Sea
- One year continuous profiling
- Strong complementarity with Ocean Color remote sensing
- Deep convection, NO₃ seasonal cycle, phytoplankton blooming

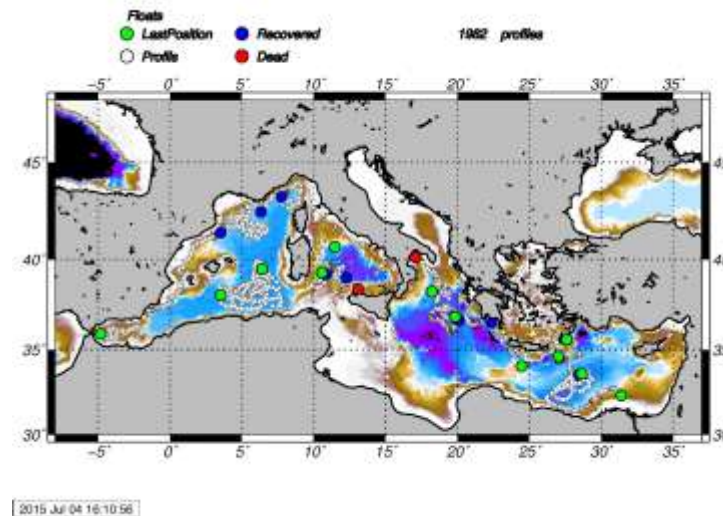


D'Ortenzio et al. 2014, CPL

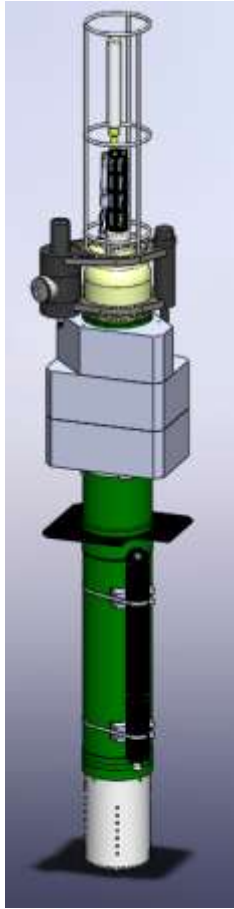
Mediterranean deep mixing, NO₃ uptake and bloom from NAOS floats (D'Ortenzio et al., 2014)



May-June 2016 deployments



Bio-Argo floats in Arctic Ocean



Provor CTS5 (NKE) + additional payload:

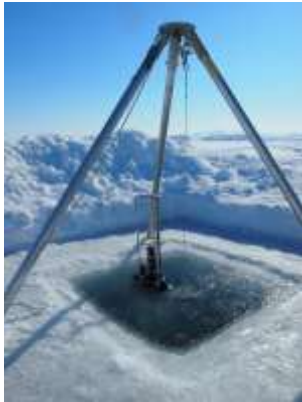
- ✓ SUNA (nitrates)
- ✓ OCR 504 (Ed 3 wavelengths: 380,410,490nm)+PAR (400-700nm)
- ✓ FLBB CD (fluo chl_a, fluo CDOM, backscattering)

- ✓ Sea Ice detection and avoidance (ISA) (+ optics, acoustic)
- ✓ Storage of data in case no surfacing is possible for transmission
- ✓ Modification of the mission without communication (date criteria)
- ✓ Protective frame for sensors

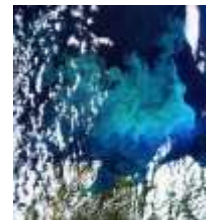
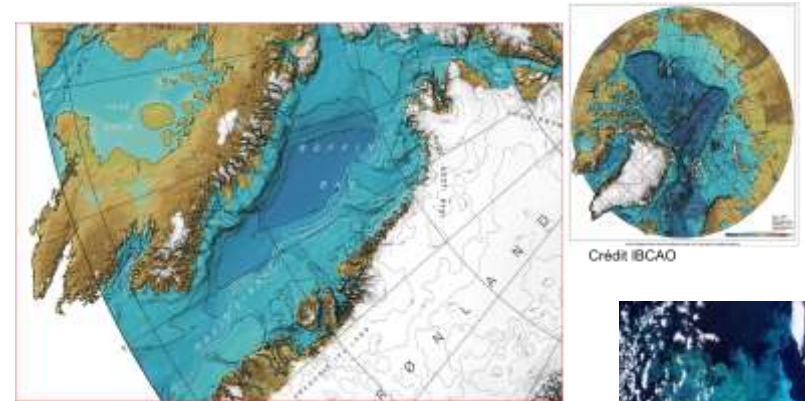


NAOS Bio-Argo floats in the Arctic ocean (Baffin Bay) (M. Babin, C. Marec)

Understanding the dynamics of the phytoplankton spring bloom in Arctic

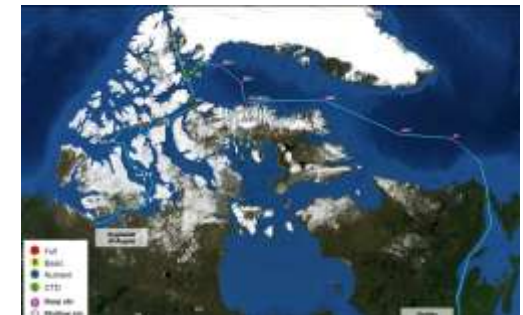


Bio-Argo float tests during GreenEdge 2015 Qikiqtarjuaq, Nunavut



Upcoming deployments: 20 floats (12 NAOS + 8 FCI)

- ✓ Summer 2015: 4 Pro-ice floats (stations BB4, BB2)
- ✓ Summer 2016 / summer 2017: 16 Pro-ice floats

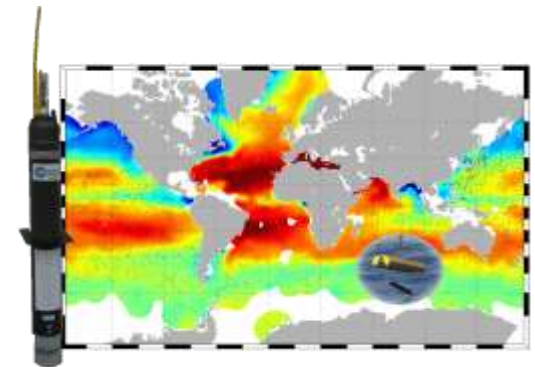
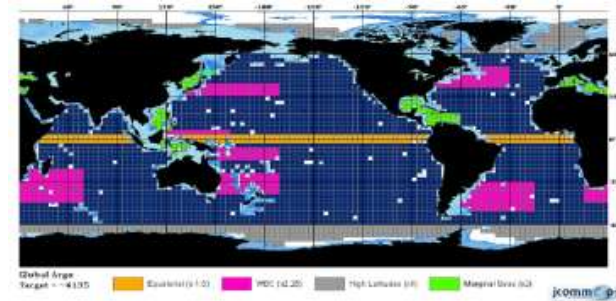


Argo : a revolution in oceanography

A major contribution to the ocean and climate research (more than 300 publications/year).

Essential observing system for climate change research (e.g. IPCC reports).

Why such an outstanding success ? Mature technology, complementarity with satellite observations and models, data policy, scientific steering team, international coordination



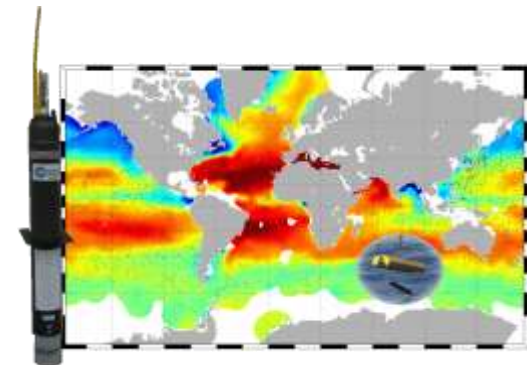
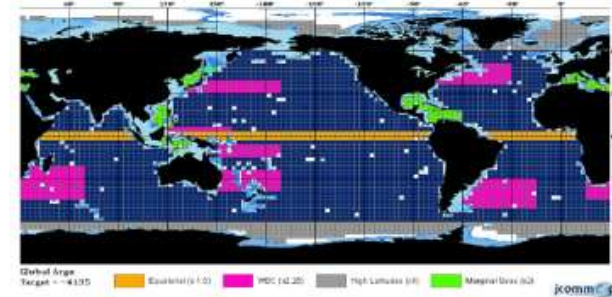
New challenges for Argo

Sustain the array for the next 10-20 years.

New scientific and long term monitoring challenges (deep ocean, biogeochemistry, Arctic).

Implementing a long term **Deep Argo programme** must now be a very high priority for climate change research. Required to understand/monitor how much heat (and where) the oceans are taking up.

Similarly implementing a long term **Bio-Argo programme** is required to better understand the coupling between physics and biology and to better assess the impact of climate change on ocean chemistry and ecosystems.



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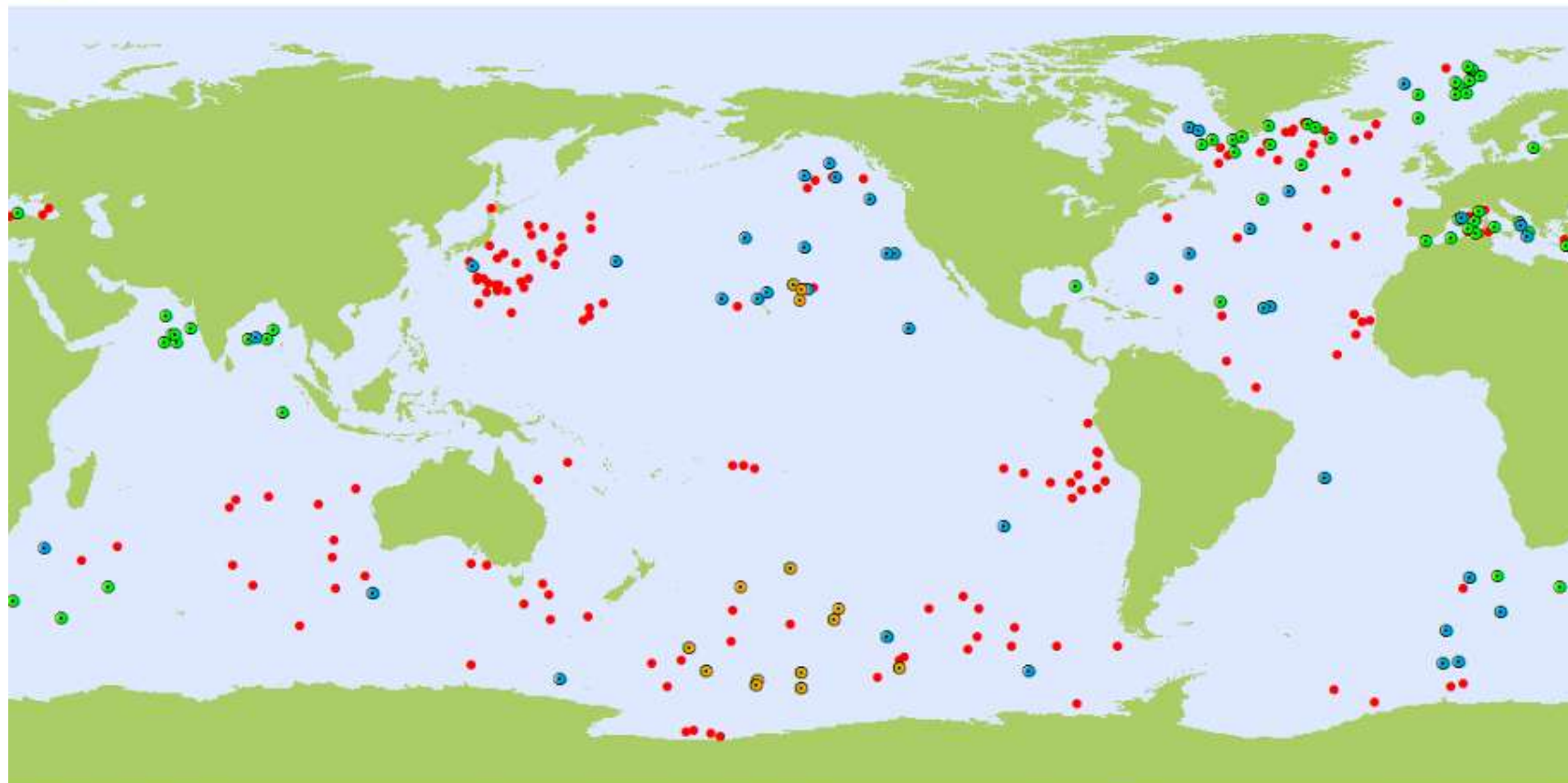
THE CONTRIBUTION OF COLLABORATIVE RESEARCH PROJECTS

Supplements



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THE CONTRIBUTION OF COLLABORATIVE RESEARCH PROJECTS



Bio-Argo (269)

• Dissolved Oxygen (252)

• Bio-optics (79)

• Nitrate (51)

• pH (14)

January 2015



The Euro-Argo European Research Infrastructure



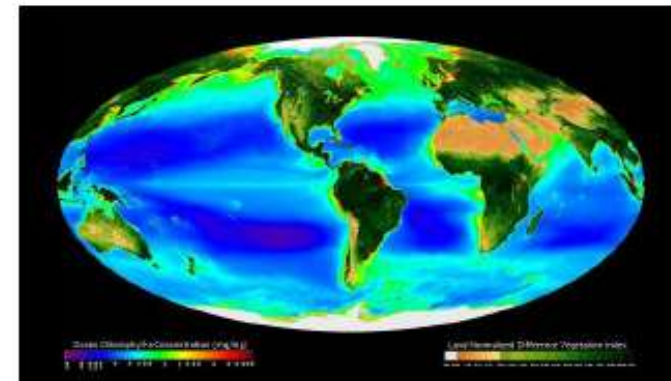
- Objective: ensure a long term European contribution to Argo
- Europe establishes an infrastructure for $\frac{1}{4}$ of the global array
 - ✓ Deploy about 250 floats per year to contribute to the Argo core mission including regional enhancements (Nordic seas, Mediterranean&Black seas) (maintain an array of 800 floats).
 - ✓ Prepare and contribute to the extension of Argo (e.g. marginal seas, biogeochemistry, deep ocean, polar regions).
 - ✓ Users and applications: ocean and climate research and operational oceanography (Copernicus Marine Service).
- A new European legal structure (Euro-Argo ERIC) set up in May 2014 that will allow European countries to consolidate and improve their contribution to Argo international.





Beside O₂, the biogeochemical community has identified the first variables ready to be implemented

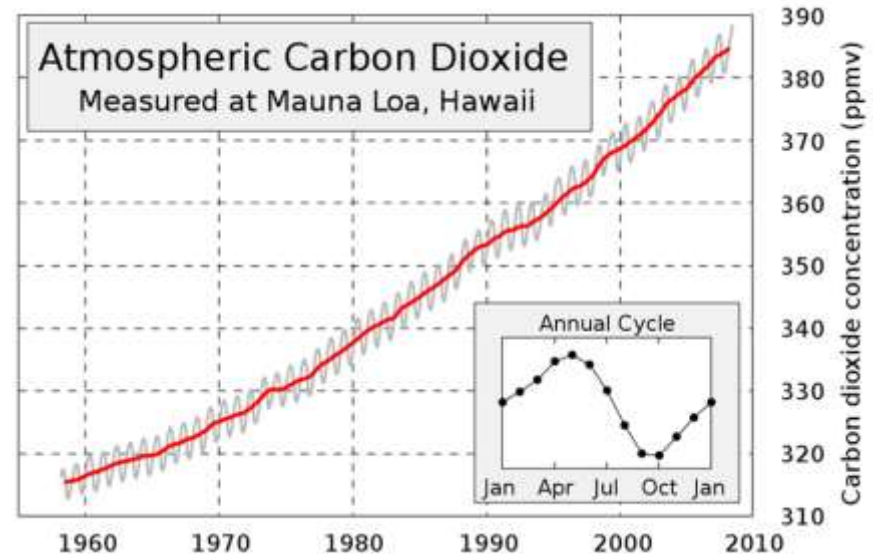
- Oxygen**: exchange with atmosphere, marine photosynthesis and respiration.
- Nitrate** : New production (build up of organic material) ; remineralization; potential for being a core variable for GCM/biogeochemical.
- Chlorophyll a** : Proxy of phytoplankton biomass, photosynthesis; required by spatial agencies (OCR); potential for being a core variable for GCM/biogeochemical.
- Particulate backscattering** : Stock of particulate matter (detrital and living). Proxy of Particulate Carbon. required by spatial agencies (OCR)_potential for being a core variable for GCM/biogeochemical.



Selection of these variables through an international consensus : IOCCG Working group "Bio-optical sensors on Argo floats Argo", OceanObs09

The oceanic carbon pump

- 10 Pg C emitted each year
- 5 Pg accumulate in the atmosphere
- 2.5 Pg absorbed by land
- 2.5 Pg absorbed by the ocean



Strong regionalization in ocean sources and sinks:

- ✓ Austral Ocean and North Atlantic are the main sinks

Strong interannual and decadal variability

- ✓ large uncertainties in estimation

Sources and sinks

- ✓ balance between physical processes (solubility pump) and biological ones (biological pump)

Deep-Sea Durafet pH sensors now operating on floats



pH (total) 25 C

