Barcelona Supercomputing Center
Centro Nacional de Supercomputación
EXCELENCIA SEVERO OCHOA

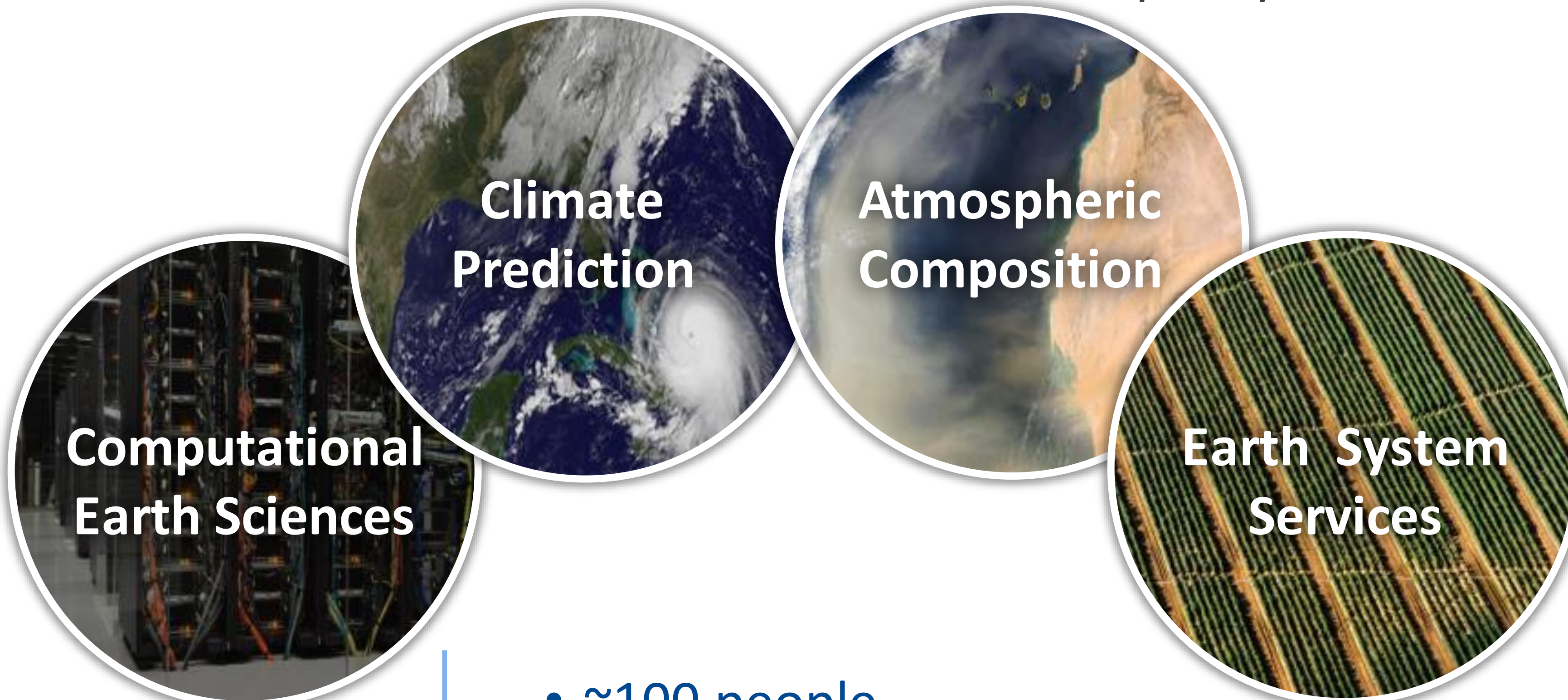
Earth Sciences Department: Ocean Activities

Pablo Ortega
Francisco J. Doblas-Reyes

ICREA

Earth Sciences Department

Environmental modelling and forecasting, with a particular focus on weather, climate and air quality



- ~100 people
- Funding from H2020, COPERNICUS, private contracts, ESA, Spanish and regional governments

BSC Barcelona Supercomputing Center
Centro Nacional de Supercomputación

Objectives

Mission:

Performing research on and developing methods for environmental forecasting, with a particular focus on the atmosphere-ocean-biosphere system. This includes managing and transferring technology to support the main societal challenges through models and data applications in HPC and Big data solutions.

Objectives:

Develop an **online chemical weather model** from global to urban scales to understand and predict the chemical composition of the atmosphere.

Implement the most reliable and skilful global **climate prediction system to cover time scales ranging from a month to three decades**.

Investigate the impact of weather/climate and atmospheric composition on socio-economic sectors through the development of **user-oriented services**.

Make **optimal use of cutting-edge HPC and big data technologies** to increment the efficiency, portability and user-friendliness of Earth system models, including the pre- and post-processing of environmental data.

Why these ones? Windows of opportunity driven largely by external funding

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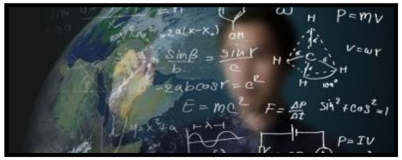
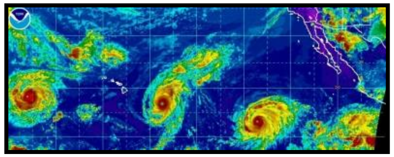
Ocean-related research lines

Model **computational efficiency**

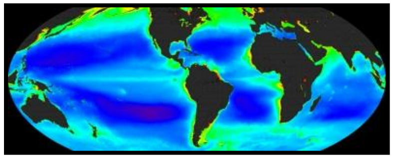
Sea ice and ocean variability, **prediction** and impacts



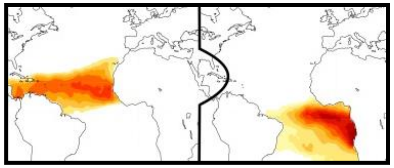
Climate model **initialization** and data **assimilation**



Tropical **cyclones**



Ocean **biogeochemistry** and climate feedbacks



Inter-basin teleconnections

Bias development and **initial shock** mechanisms

Climate model resolution

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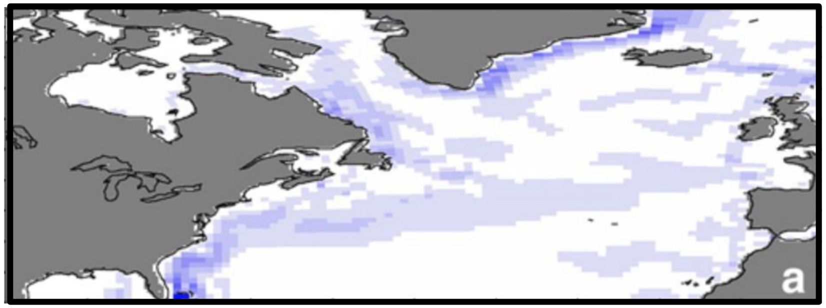
Increase in ocean resolution

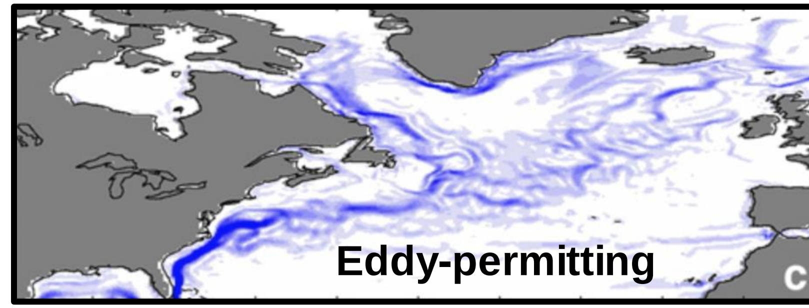
Marzocchi et al (2015)

Surfaces ocean velocities in 2007

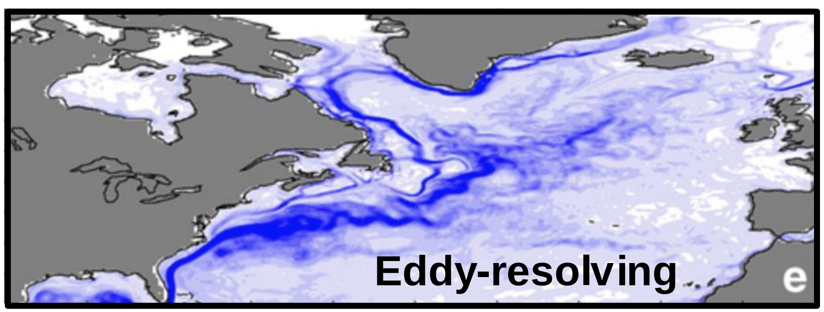
Standard Resolution ORCA1 (1º)



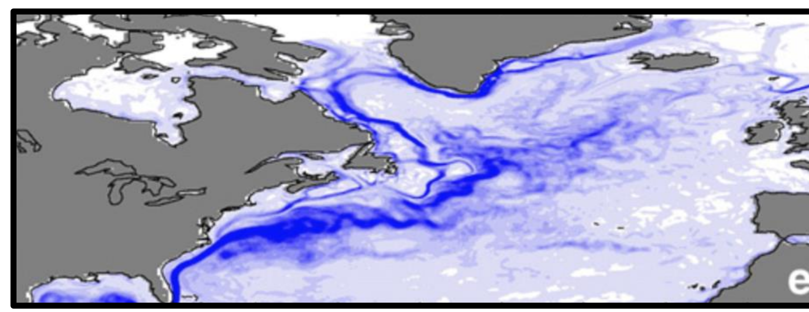
High Resolution ORCA025 (0.25º)



Very High Resolution ORCA12 (0.083º)



Satellite-based observations



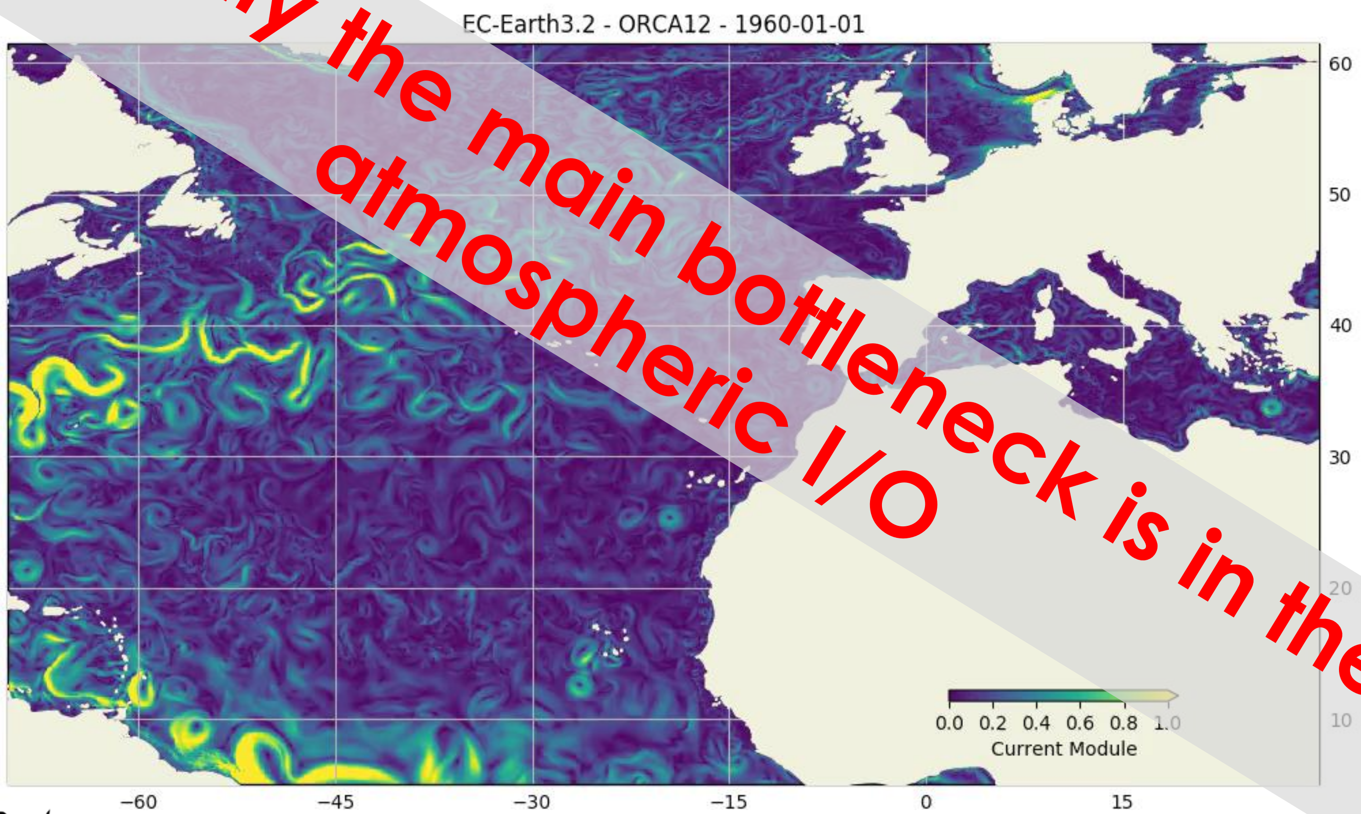
The **improvements in ocean resolution** translate in a **better representation of eddies** and **ocean currents**, which are key to describe more realistically decadal variability in the ocean

PRIMAVERA

Climate model resolution

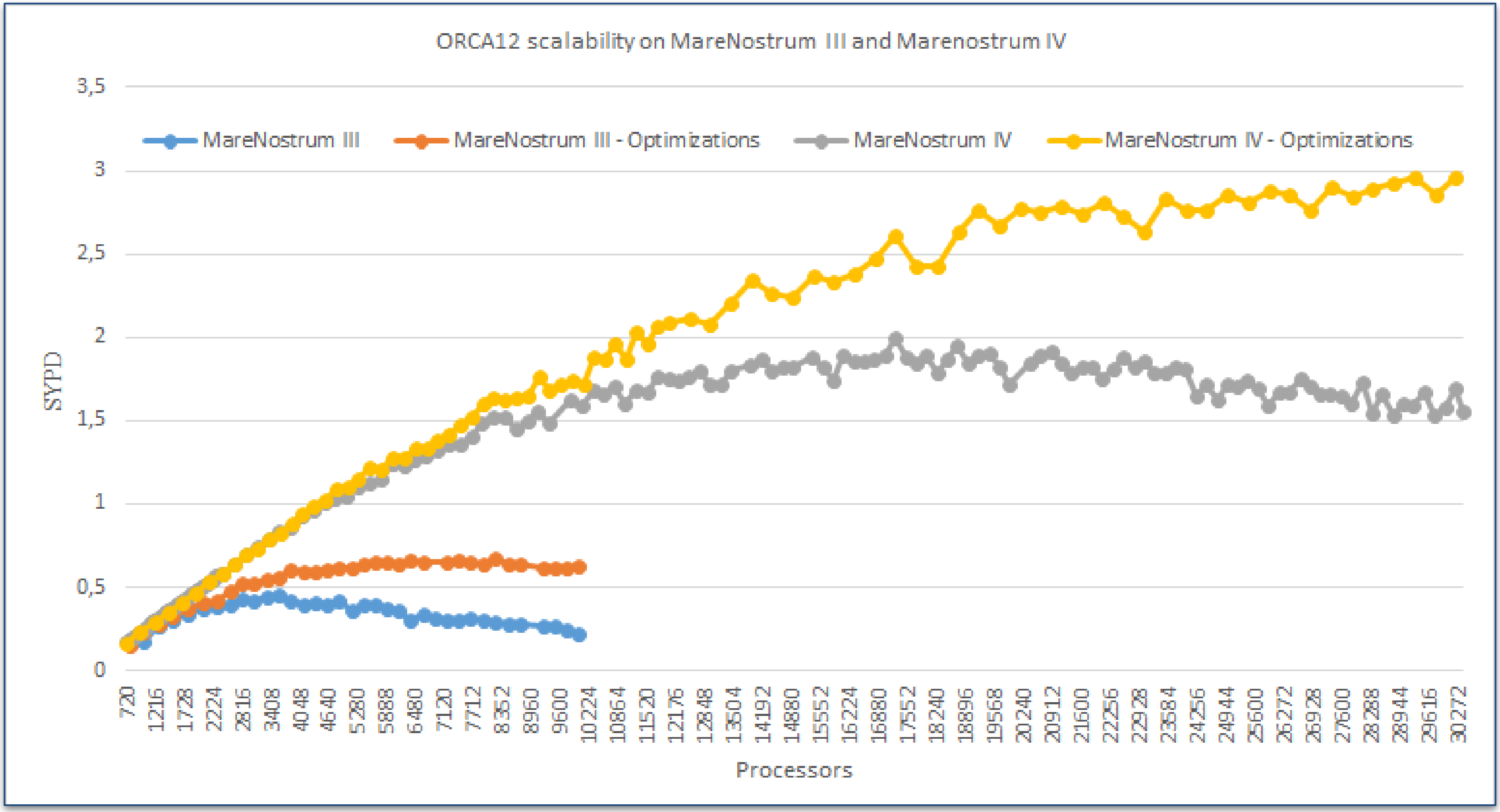
In the very high resolution configuration of EC-Earth runs at ~10 km the physical interaction between ocean and atmosphere is far more realistic. At these resolutions 220 kCPU hour per simulated year are needed (typical simulation is 150 years times several members). **Optimization is indispensable to increase the performance of these models**.

Currently the main bottleneck is in the atmospheric I/O



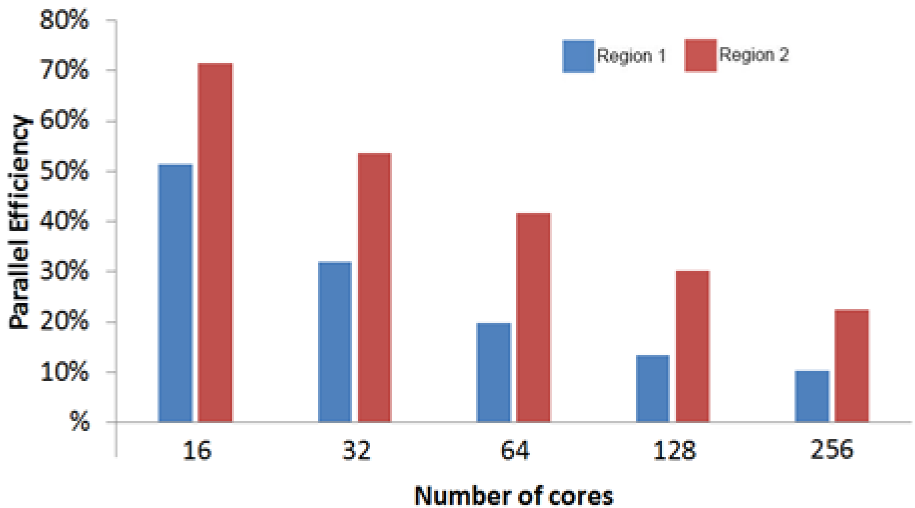
NEMO3.6 scalability

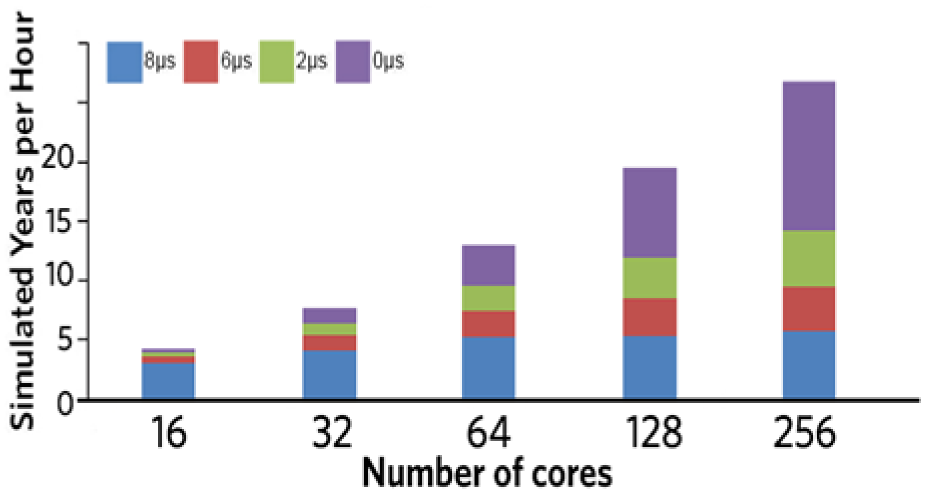
ORCA12-LIM3 scalability: NEMO 300s, LIM3 600s time step.



NEMO performance analysis

- Communications are the main performance problem. Even in the 16-core case parallel efficiency is really bad.
- The panel on the right shows how sensitive the model is to network latency.
- Communication efficiency drops much faster than computational efficiency.

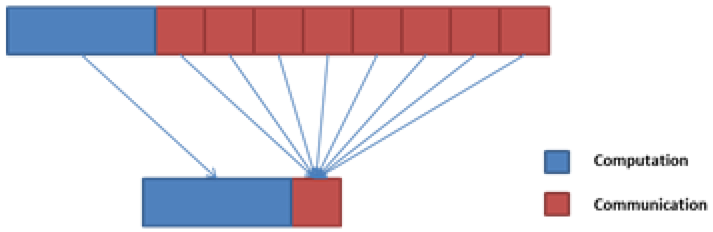




NEMO optimizations

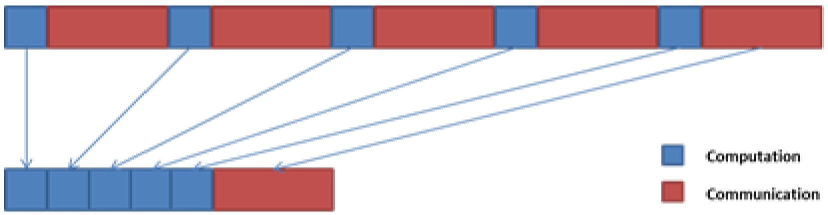
MPI message packing

Taking into account that NEMO is really sensitive to latency, message aggregation is the best way to reduce the time invested in communications. Therefore, consecutive messages have been packed wherever the computational dependencies allow to do so.



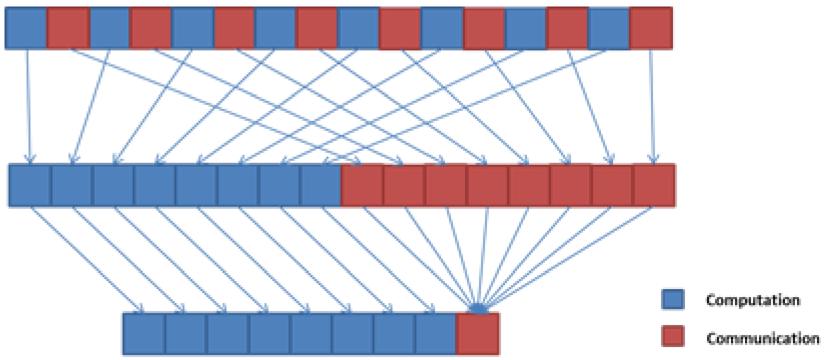
Convergence check reduction

Some routines use collective communications to perform a convergence check in iterative solvers. The cost of theseverifications is really high, reaching 66% of the time. Wherever the model allowed it, we reduced the frequency of these verifications in order to increase parallel efficiency.



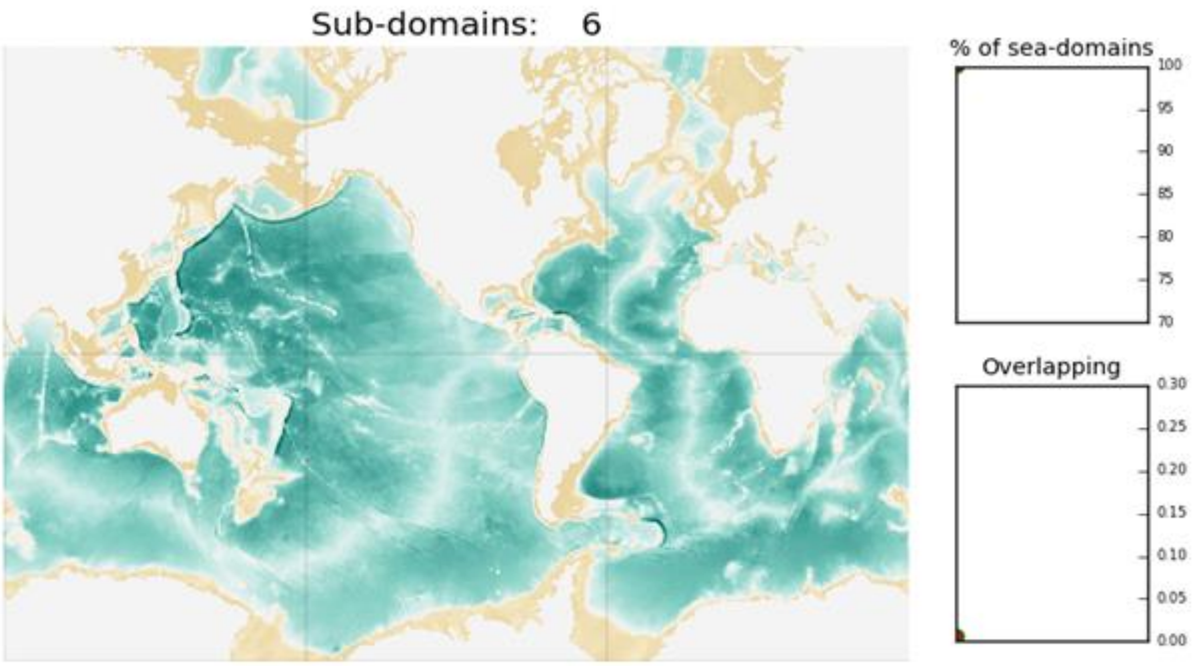
Reordering

In order to apply the message packing optimization to as many routines as it was possible, it was necessary to rearrange some computation and communication regions, taking into account the dependencies between them, to reduce the number of messages. This way it was possible to compute (and communicate) up to 41 variables at the same time, resulting in a dramatic reduction of the granularity.



NEMO optimizations

ELPiN allows to find the appropriate namelist parameters (jpni, jpnj, jpnij) to exclude land-only processes in NEMO simulations and save a substantial amount of resources.



Tintó et al. (2018)

NEMO optimizations

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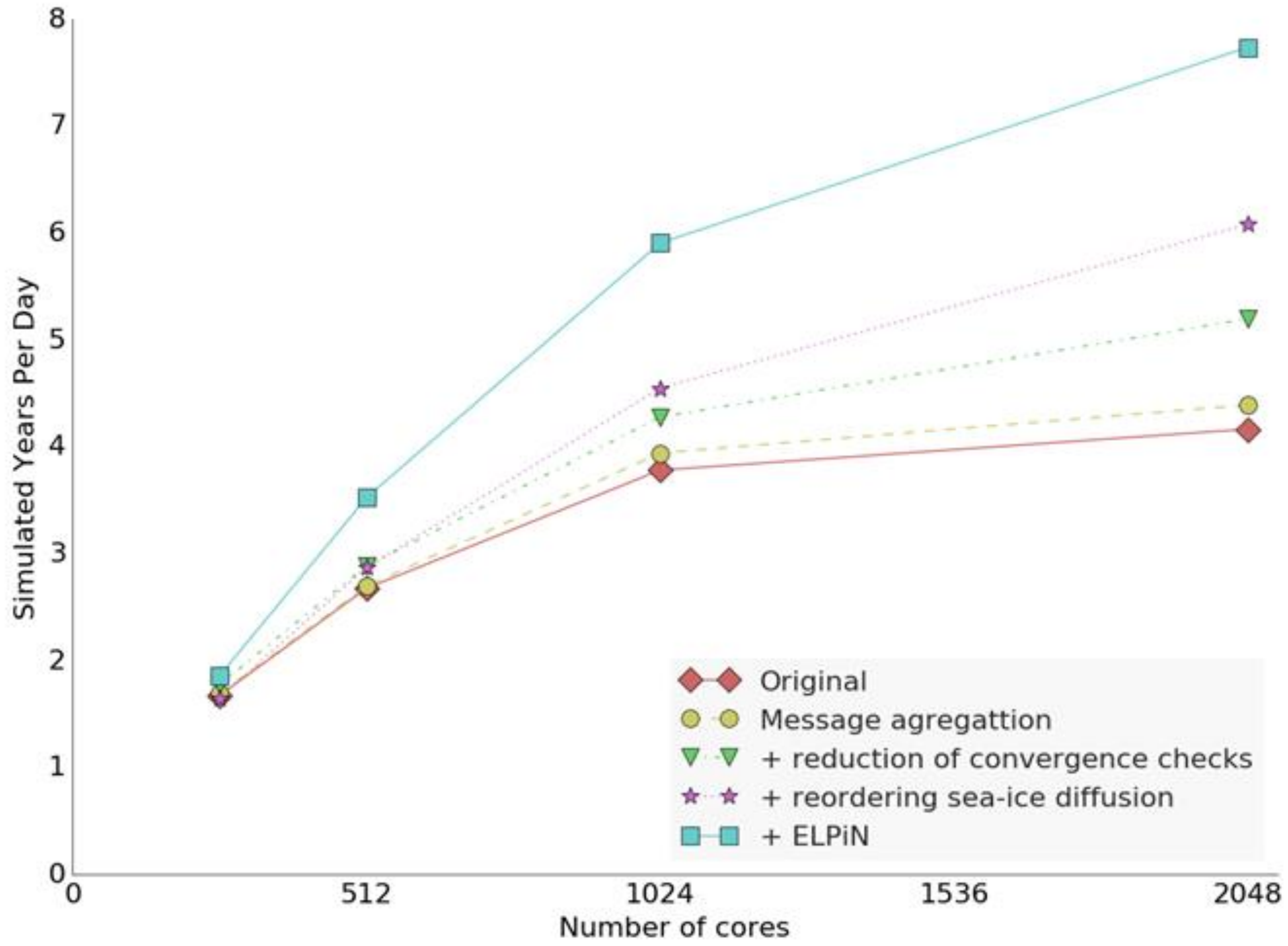
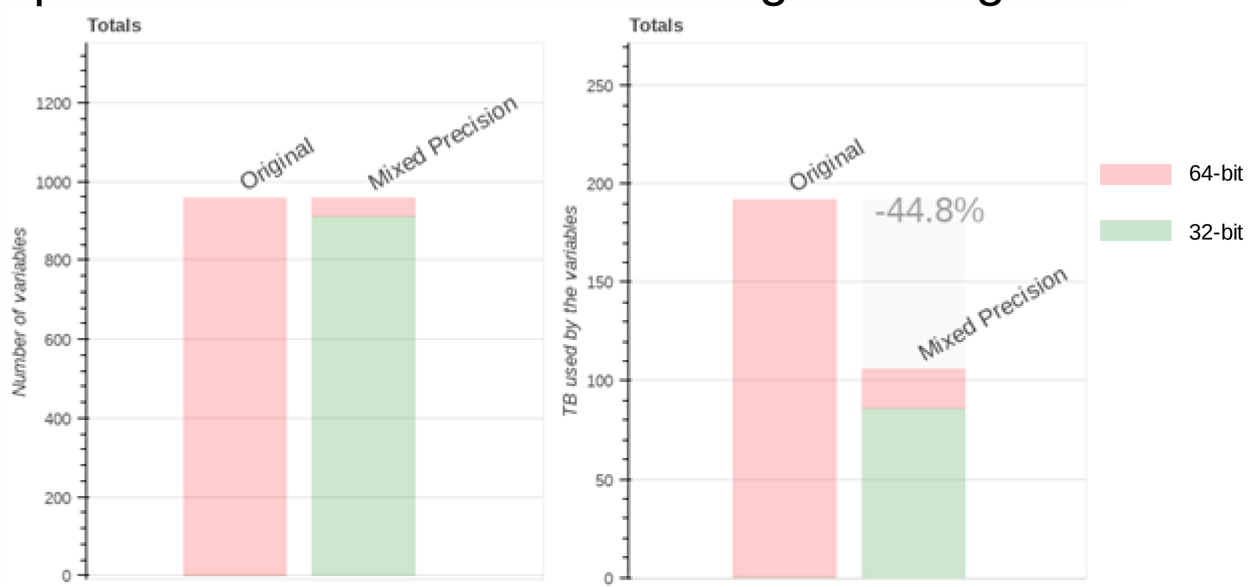
Impact of optimizations in SYPD for ORCA025-LIM3.



NEMO optimizations

Mixed precision: A method has been developed to adjust the numerical precision to minimize the resources used maintaining the accuracy of the model by identifying which variables require higher precision and which ones can effectively use less precision.

Impact estimation for NEMO using a 1 km grid.



Tintó et al. (2019)

NEMO performance timeline

TYPE-C ??

2019 — 2020 — 2021 — 2022

COPERNICUS CMEMS **Final report**: ORCA036 profiling

IMMERSE D4.1: Activities during 2019

IS-ENES3 **M8.4**: Definition of the optimization strategy
IMMERSE **MS25**: First setup of online diagnostics
ESiWACE2 D1.2: Model inter-comparison

NEMO 4.2 beta

IMMERSE **MS34**: Final setup of online diagnostics
ESiWACE2 D1.1: Production mode configurations

IS-ENES3 **D8.5**: Update NEMO code

IS-ENES3 **D4.3**: CPMIP metrics & performance
IMMERSE D4.3: AGRIF performance

ESiWACE2 D1.3: Scalability for pre-exascale systems

IMMERSE D4.4: Node performance
IMMERSE **D4.5**: Report online diagnostics

* Bold indicates BSC is the lead

EC-Earth as main prediction tool

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Model Components

IFS (Atmospheric Model):
T255 (0.75º) ~80km
L91 (top 0.01hPa) ~mesosphere
IFS-HTESSEL (Land Model)

NEMO (Ocean Model):
Nominal 1° Resolution
L75 levels (thousands km deep)
PISCES (Biogeochemistry Model)

LIM (Sea-ice Model):
Multiple (5) ice category

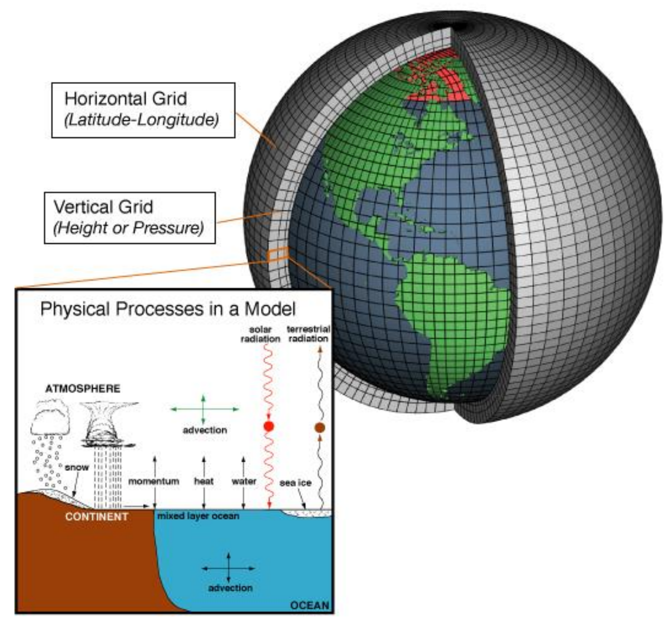
IFS-HTESSEL

EC-EARTH
Global Coupled model

produced in-house

Initial Conditions

Sea Ice reanalysis (**ESA**)	Atmosphere reanalysis (**ERA-Interim**)
Ocean reanalysis (**ORAS4**)	Land reanalysis (**ERA-Land**)



Generation of initial conditions

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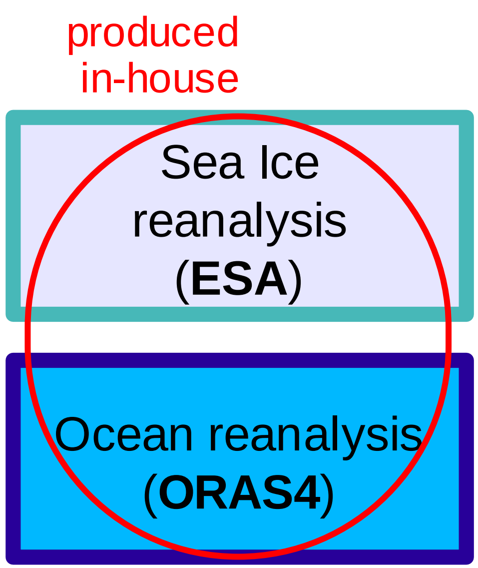
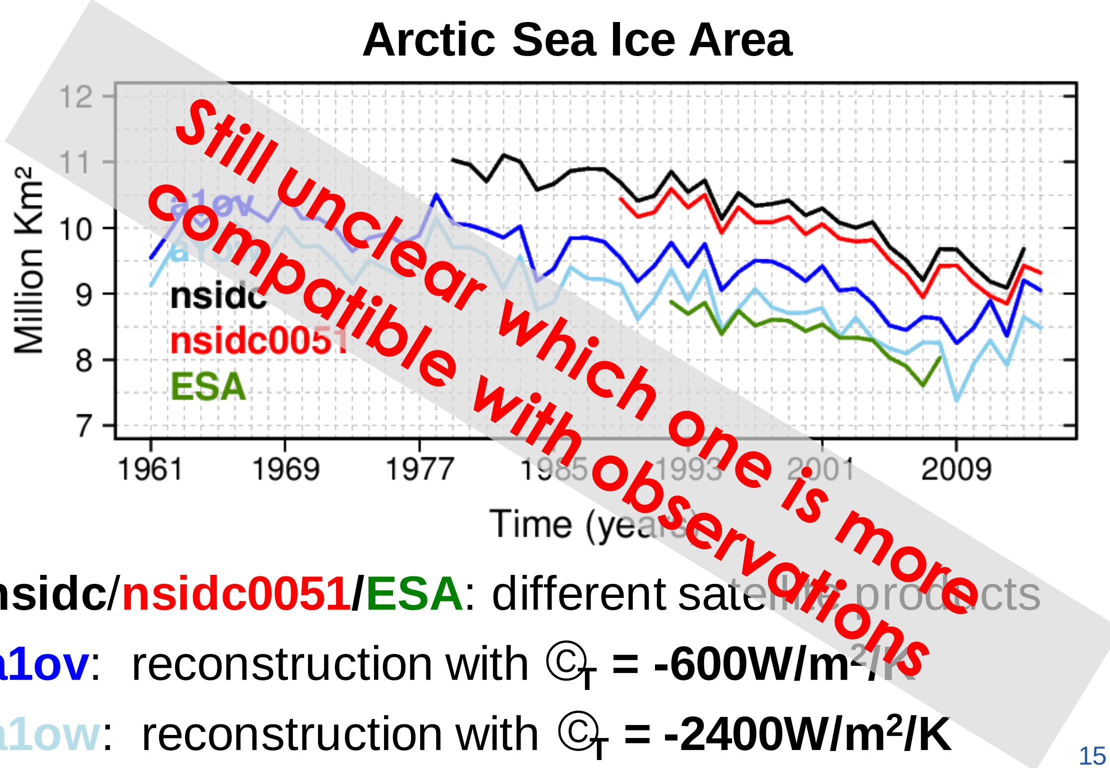
Historical reconstruction using **NEMO-LIM standalone**

- Forced with **DFS** atmospheric fluxes until 2015 and **ERA-Interim** afterwards
- **Nudged globally** towards 3D T and S from **ORAS4** [C_T = -40W/m²/K ; C_S = -150 kg/m2/s/psu]
- We are currently **testing** how different **relaxation coefficients** for **SST and SSS** affect the **realism of the sea ice evolution**

EUCP European Climate Prediction system   APPLICATE.eu





nsidc/**nsidc0051**/**ESA**: different satellite products

a1ov: reconstruction with C_T = **-600W/m²/K**

a1ow: reconstruction with C_T = **-2400W/m²/K**

Decadal prediction (I)

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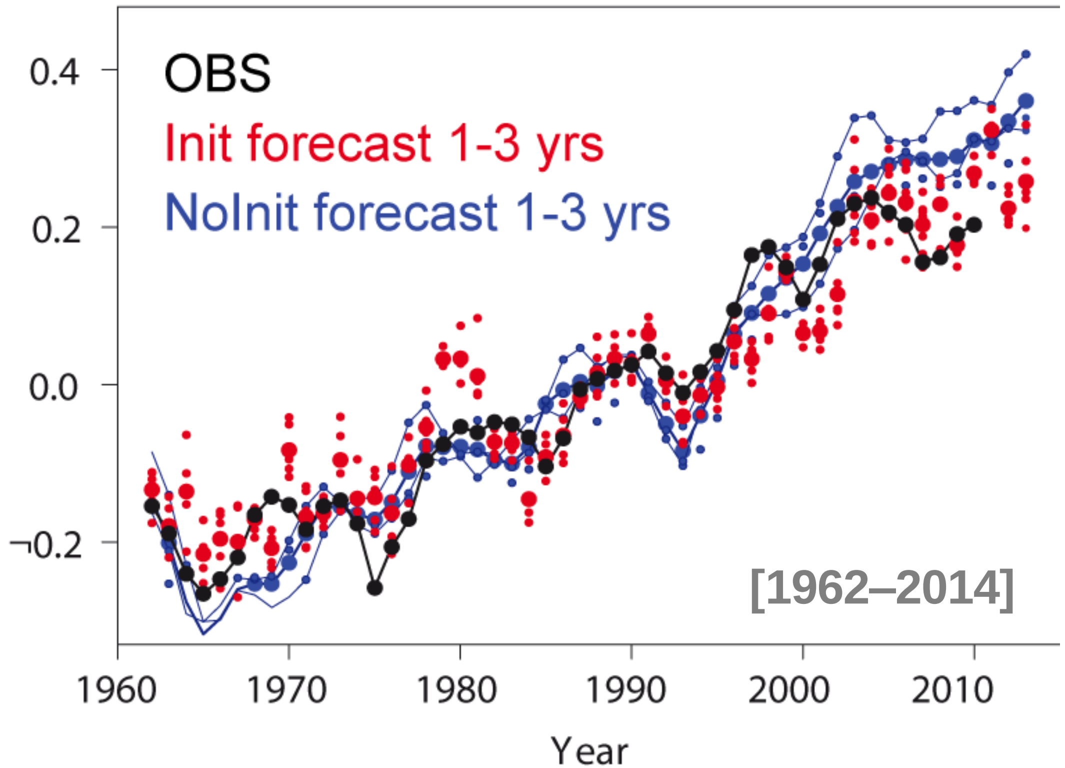
Predictive skill of **global mean surface-air temperature** (Ec-Earth2.3)

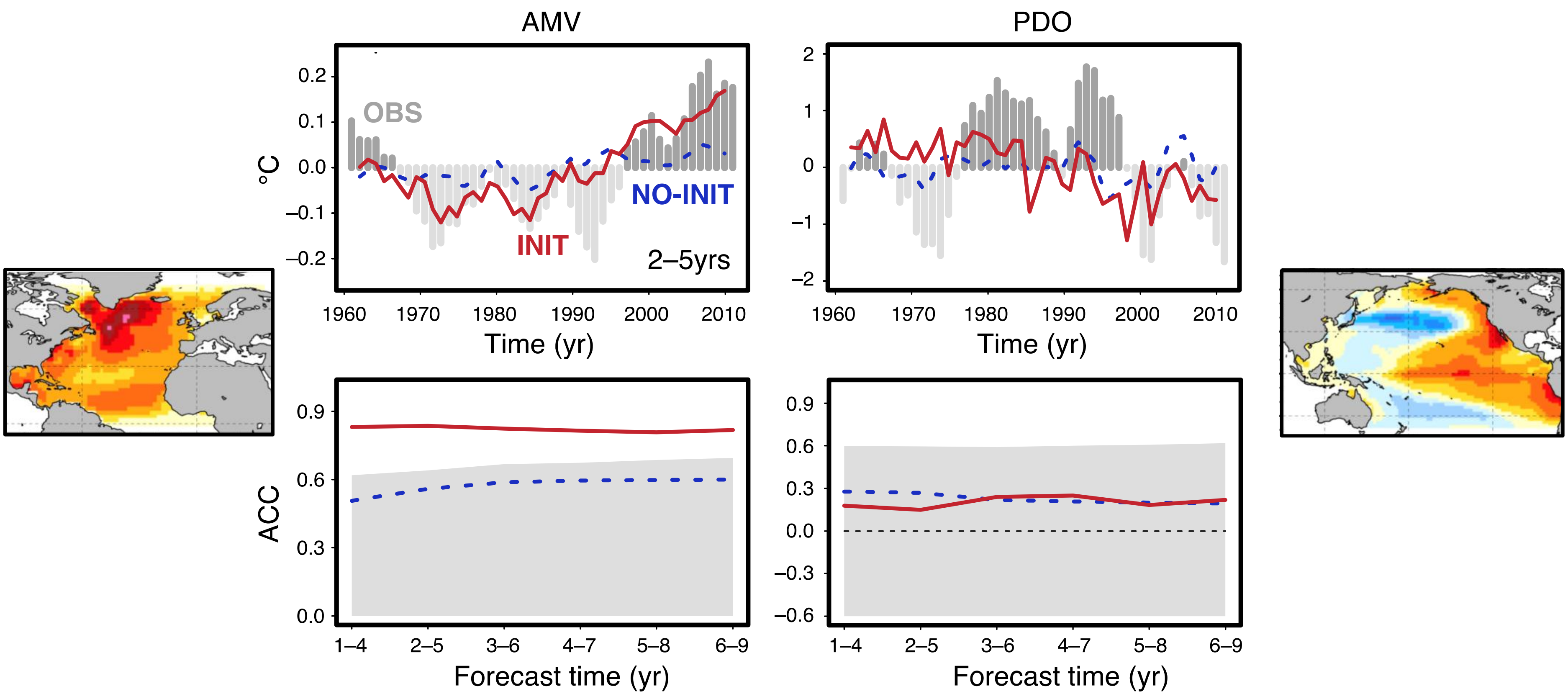


Initialised forecasts with EC-Earth reproduce the global temperature, and **describe more accurately** than the non-initialized ones the recent **HIATUS** period, which suggests a **key contribution of internal climate variability**

Guemas et al (Nat. Geo., 2013)

Decadal prediction (II)

Predictive skill of **modes of multi-annual climate variability** (in CMIP5)



Only in the **Atlantic Ocean**, the **initialized forecasts** show significant **predictive skill** and beat persistence, for forecast times of **up to 10 yrs**

Doblas-Reyes et al (Nat. Comm., 2013)

Decadal prediction (II)

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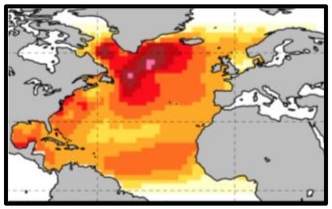
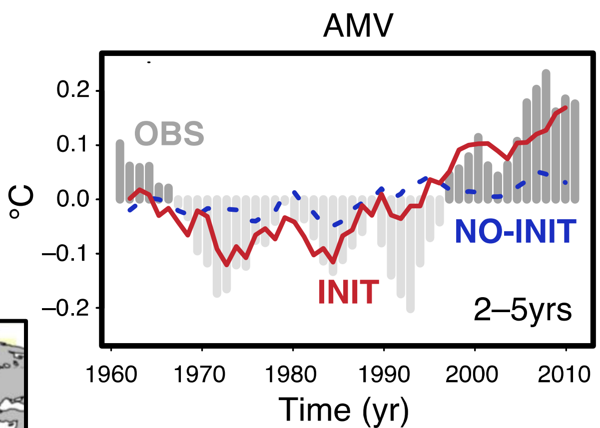
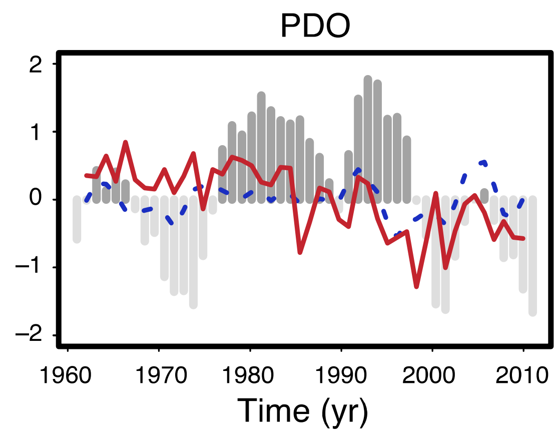
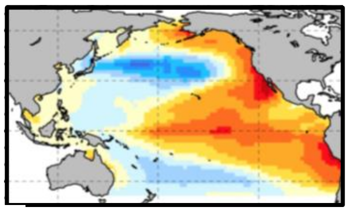
Predictive skill of **modes of multi-annual climate variability** (in CMIP5)

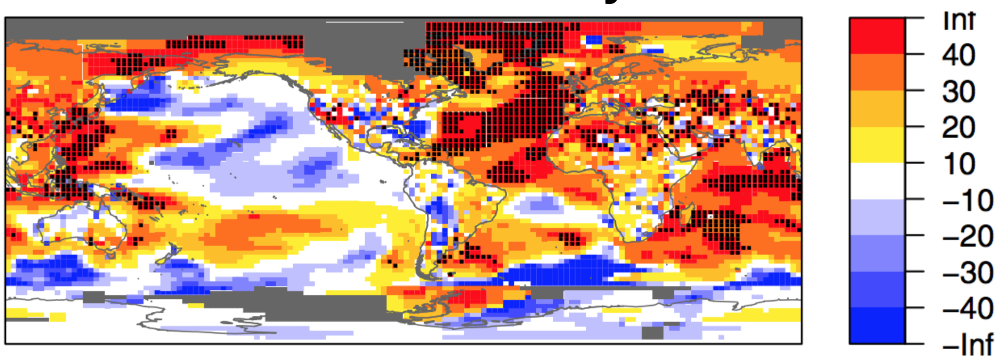








Multi-model skill in SAT 2-5 yrs lead time



The **grand challenge** of current **decadal prediction systems** is to improve the **predictive** skill over the **continents**

Doblas-Reyes et al (Nat. Comm., 2013)

Real-time decadal prediction

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2017 predictions for 2018-2022 SAT

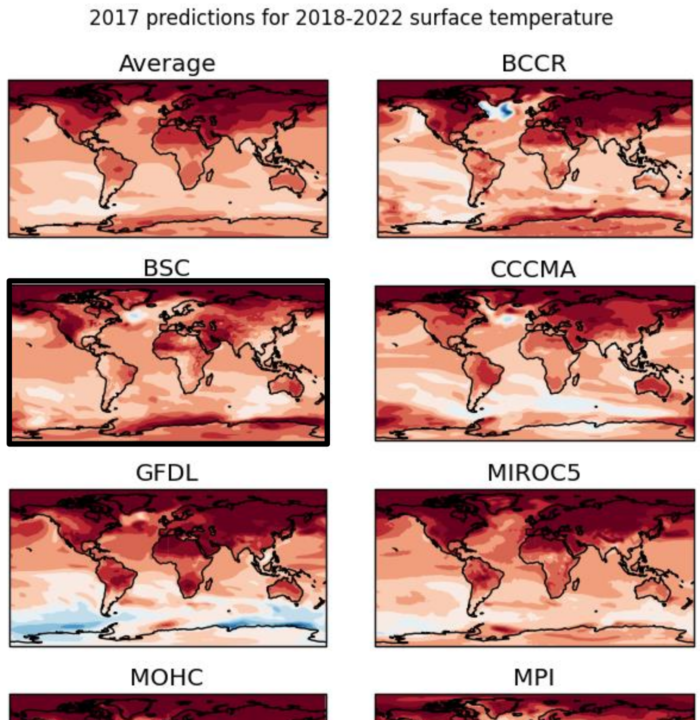
Multi-model decadal forecast exchange

The Met Office coordinates an informal exchange of near-real time decadal predictions. Many institutions around the world are developing decadal prediction capability and this informal exchange is intended to facilitate research and collaboration on the topic.

The contributing prediction systems are a mixture of dynamical and statistical methods. The prediction from each institute is shown below, alongside an average of all the models. When possible, observations for the period of the forecast are also shown. Currently three variables are included: surface air temperature, sea-level pressure and precipitation. These are shown as differences from the 1971-2000 baseline. More diagnostics, including ocean variables are planned for the future. Please use the drop-down menus below to explore the data collected to date.

This work is supported by the European Commission SPECS project.

SPECS
Seasonal-to-decadal climate Prediction for the improvement of European Climate Services



15 centers will contribute to Annual Decadal Climate Prediction Exchange
4 applied for WMO-designation (**BSC** the only non meteorological center)

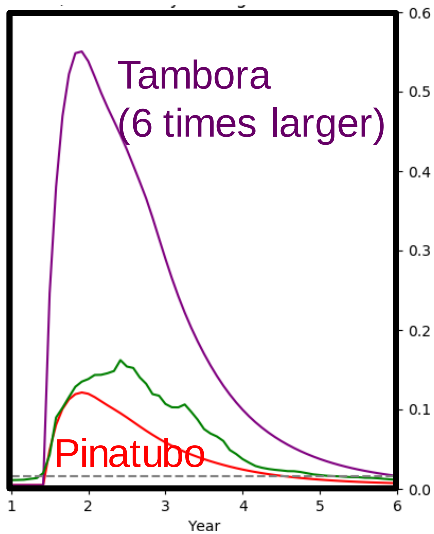
Impact of volcanoes on climate

Perfect model experiments with EC-Earth 3.2 *Martín et al (In Preparation)*

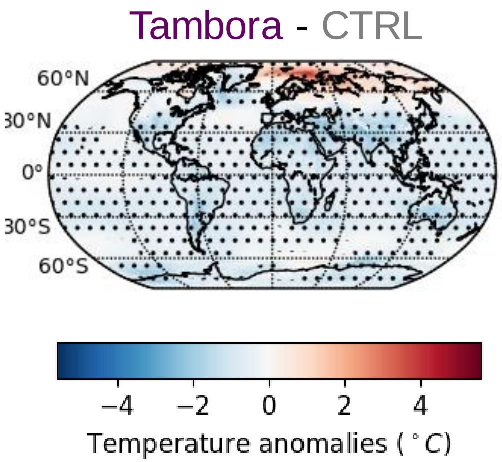
Idealised **Pinatubo** (1991 eruption)
Idealised **Tambora** (1815 eruption)
CTRL (background aerosols)

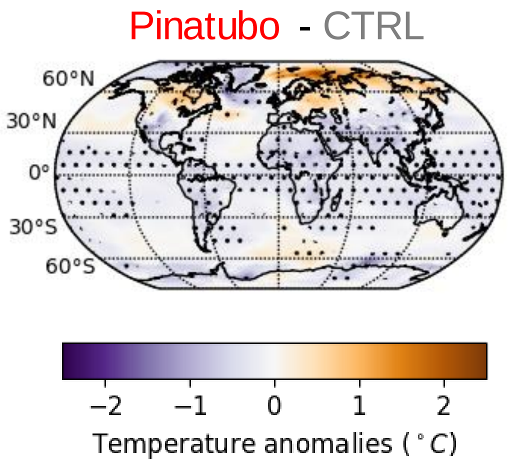
Initialized from **10 different initial states** (common to the three ensembles)

Zonally averaged total AOD



Predicted surface air temperature response (1st year)





Eruptions of different magnitude exert **similar climate impacts:** a **global cooling** and regional **warming over the Arctic**

VOLMIP CMIP
The World Climate Research Programme's Coupled Model Intercomparison Project

Impact of volcanoes on climate

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Perfect model experiments with EC-Earth 3.2 *Martín et al (In Preparation)*

Idealised **Pinatubo** (1991 eruption)
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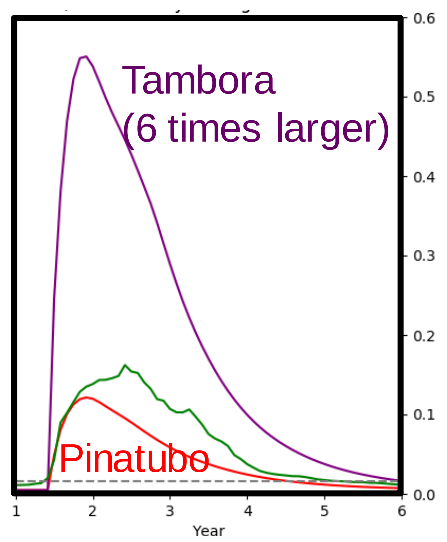
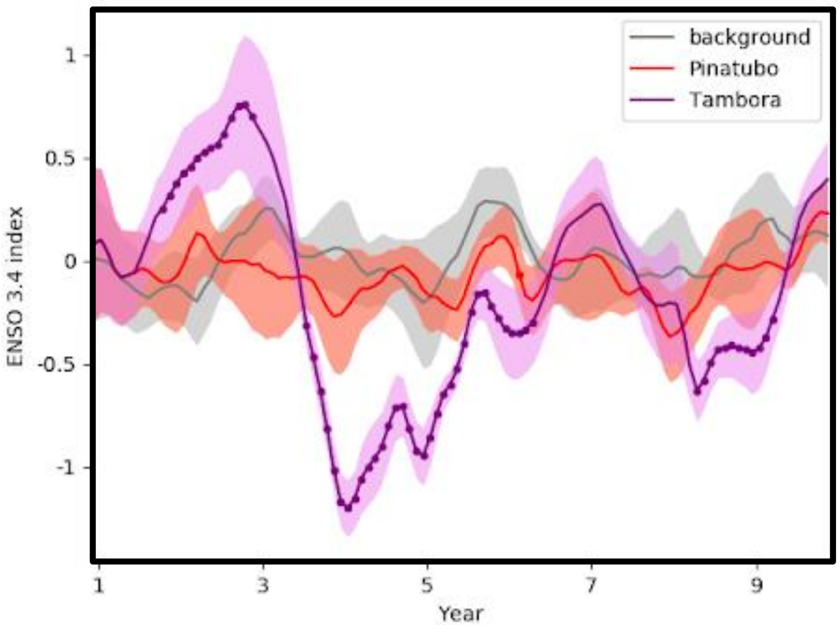


Eruptions of different magnitude exert **similar climate impacts:** a **global cooling** and regional **warming over the Arctic**

Predicted ENSO3.4 after the eruptions



Volcanic eruptions can however excite **non-linear responses**, as seen above for **El Niño region**

VOLMIP CMIP
The World Climate Research Programme's Coupled Model Intercomparison Project

Impact of the model resolution

Seasonal Forecasts **[1981–2010]** **➔ 10 members**

Standard resolution (**SR**)

[Atmos: T255 (~ 80 km)
Ocean: ORCA1 (~ 100 km)]

High resolution (**HR**)

[Atmos: T511 (~ 40 km)
Ocean: ORCA025 (~ 25 km)]

Impact of the model resolution

Seasonal Forecasts **[1981–2010]**

Standard resolution (**SR**)

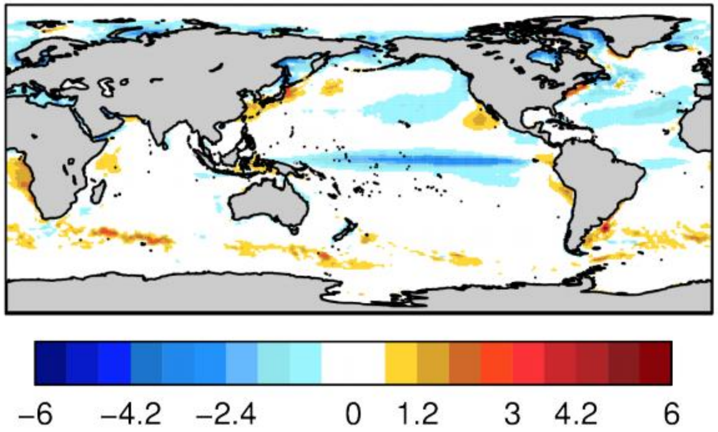
- Atmos: T255 (~ 80 km)
- Ocean: ORCA1 (~ 100 km)

High resolution (**HR**)

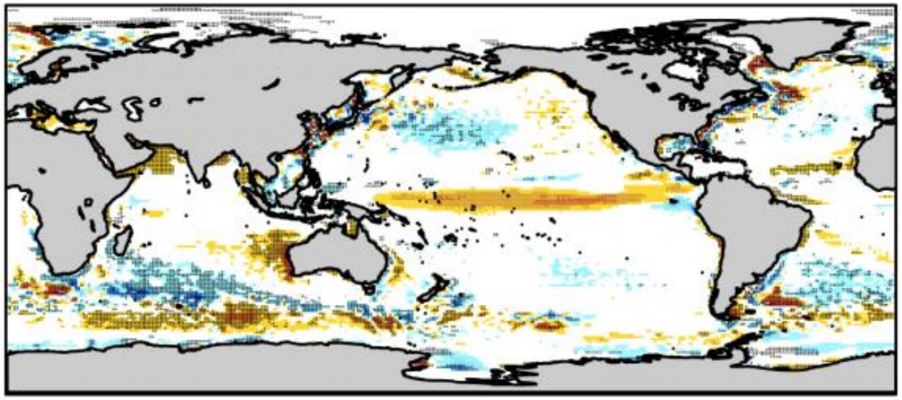
- Atmos: T511 (~ 40 km)
- Ocean: ORCA025 (~ 25 km)

Prodhomme et al (2016)

BIAS in SST [SR minus OBS]



Diff in SST [HR minus SR]



Increasing the **resolution** can help **reducing** some **model biases**

Impact of the model resolution

Seasonal Forecasts [1981–2010]

Standard resolution (**SR**)
- Atmos: T255 (~ 80 km)
- Ocean: ORCA1 (~ 100 km)

High resolution (**HR**)
- Atmos: T511 (~ 40 km)
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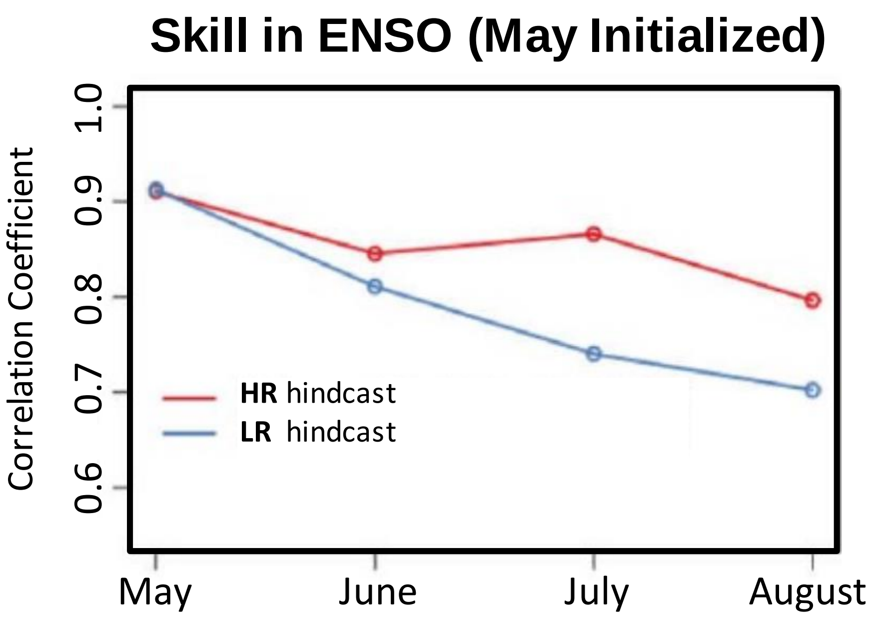
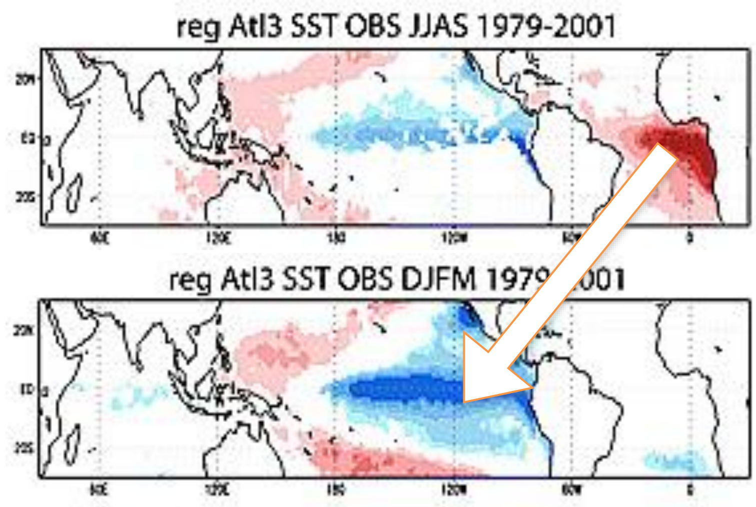


Increasing the **resolution** can also improve the **prediction skill** of key **modes of variability**

Interbasin teleconnections

Rodriguez-Fonseca et al (2009)

Observed teleconnection of Atlantic Niño with winter NIÑO

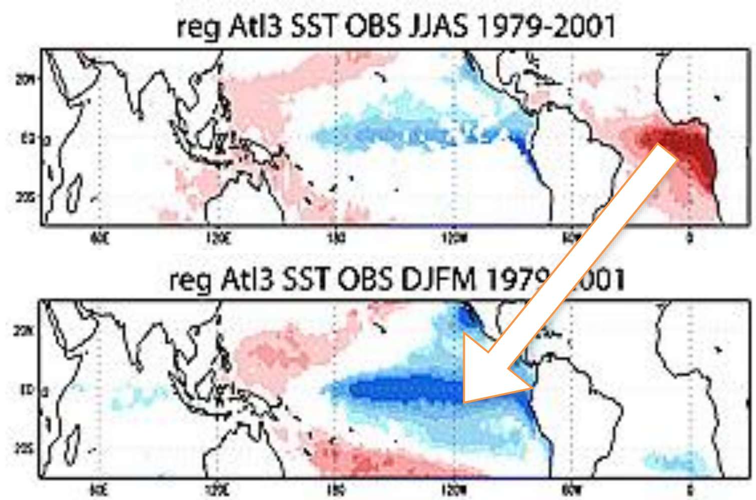


Observations show that the **summer tropical Atlantic (TA)** can influence the variability of **ENSO in the following winter (seasonal forecasts)**

Interbasin teleconnections

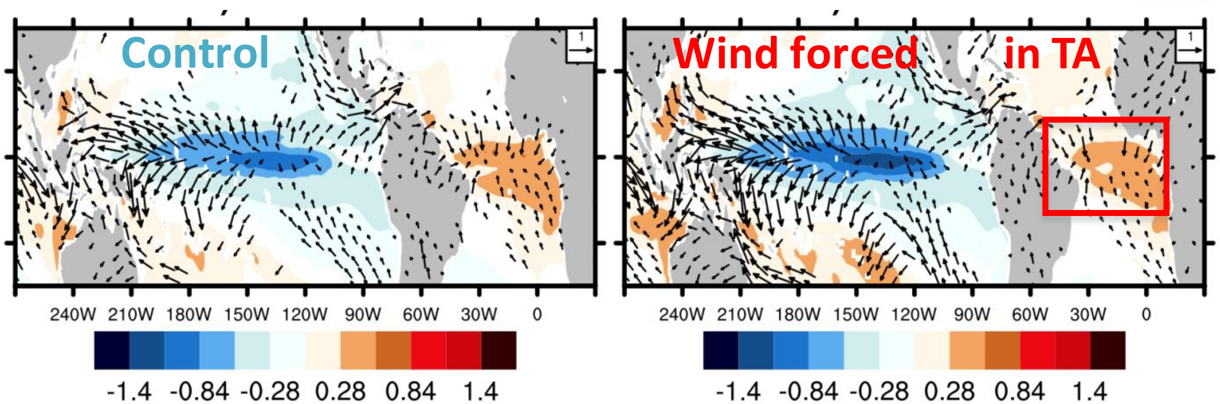
Rodriguez-Fonseca et al (2009)

Observed teleconnection of Atlantic Niño with winter NIÑO



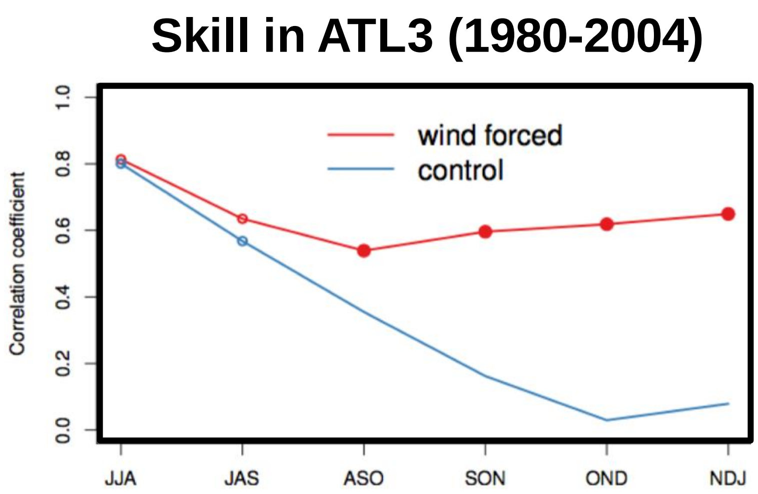
We show in two sets of **seasonal forecasts** with **EC-Earth** that this **linkage is strengthened** when current **biases in the Tropical Atlantic are corrected**

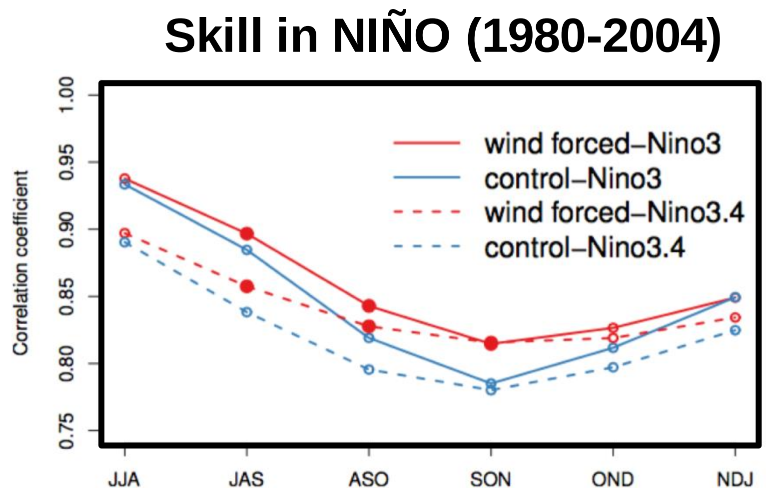
Regression JJA ATL3 vs SON SST



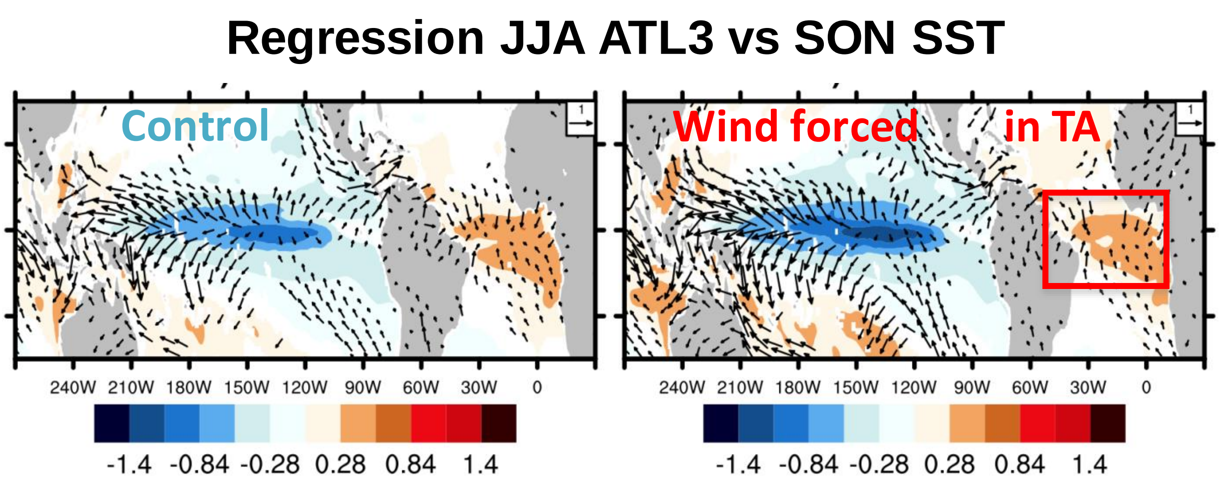
Exarchou et al (in preparation)

Interbasin teleconnections





Improved representation of **TA variability** can also **lead to better ENSO** skill



Exarchou et al (in preparation)

Understanding teleconnections

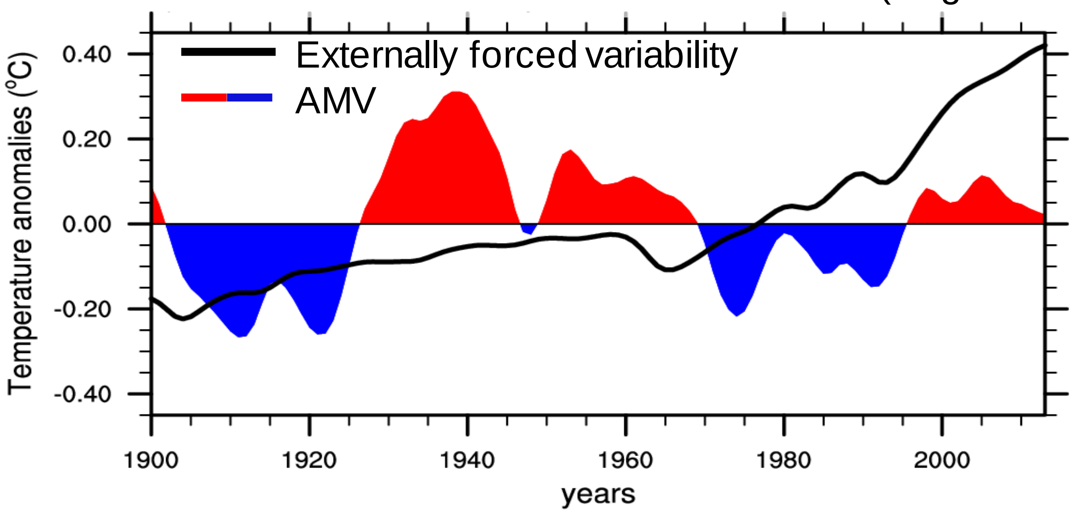
Boer et al (2016)

DCPP Component C: Predictability, mechanisms and case studies

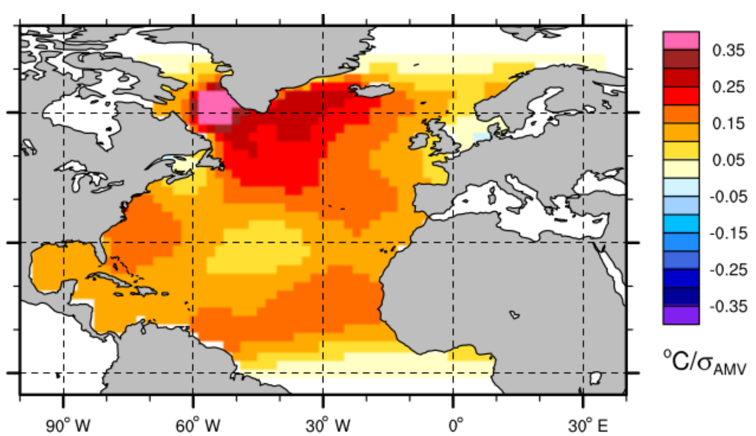
Attribution of observed decadal climate variability to Atlantic-Pacific SST variations

Idealized Atlantic Multidecadal Variability (AMV) experiments

North Atlantic SST time series (Ting et al. 2009)



AMV pattern



DCPP

CMIP The World Climate Research Programme's Coupled Model Intercomparison Project

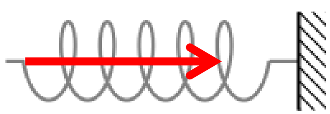
Restoring of SST through non-solar surface surface fluxes

$$\frac{\partial SST}{\partial t} = \ldots + \frac{\gamma_T}{\rho C_P h}\left(SST_{model} - SST_{AMV}\right)$$

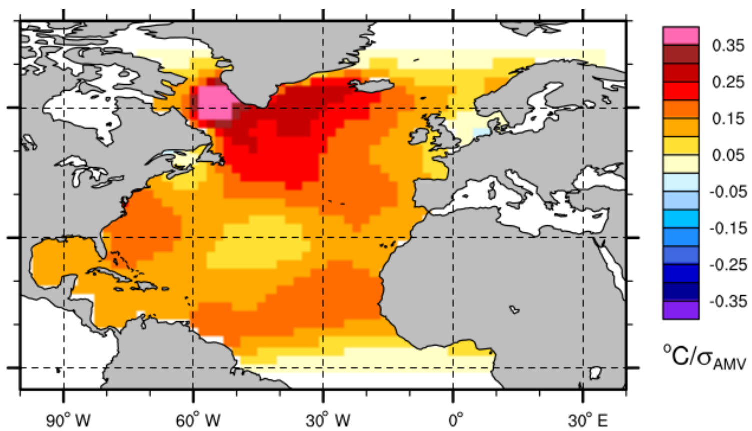
Restoring coefficient of γ_T **= -40W/m²/K** over North Atlantic (Eq-70ºN)

Free ocean-ice-land-atmosphere interactions outside of North Atlantic

SST_{AMV} = **Climatology + AMV pattern**



AMV pattern



By running this protocol in **coupled mode** we will be able to explore the **atmospheric linkages** responsible for the **AMV impacts** in the other basins.

DCPP

CMIP
The World Climate Research Programme's Coupled Model Intercomparison Project

Global carbon cycle: EC-Earth3-CC

Barcelona Supercomputing Center
Centro Nacional de Supercomputación
EXCELENCIA SEVERO OCHOA

EC-Earth3-CC
Earth System Model

Global Climate Model

Model Components

IFS (Atmospheric Model):
T255 (0.75º) ~80km
L91 (top 0.01hPa) ~mesosphere
IFS-HTESSEL (Land Model)

NEMO (Ocean Model):
Nominal 1° Resolution
L75 levels (thousands km deep)

LIM (Sea-ice Model):
Multiple (5) ice category

Global Carbon Cycle Model

PISCESv2 (Ocean Biogeochemical Model)*:*
Lower trophic levels of marine ecosystems

LPJ-GUESS (Dyn. Glob. Vegetation Model):
Process-based, plant functional types

TM5-CO2 (Atm. Chem. Transport Model):
34 layers, single-tracer version (CO2)

Atlantic upwelling predictability

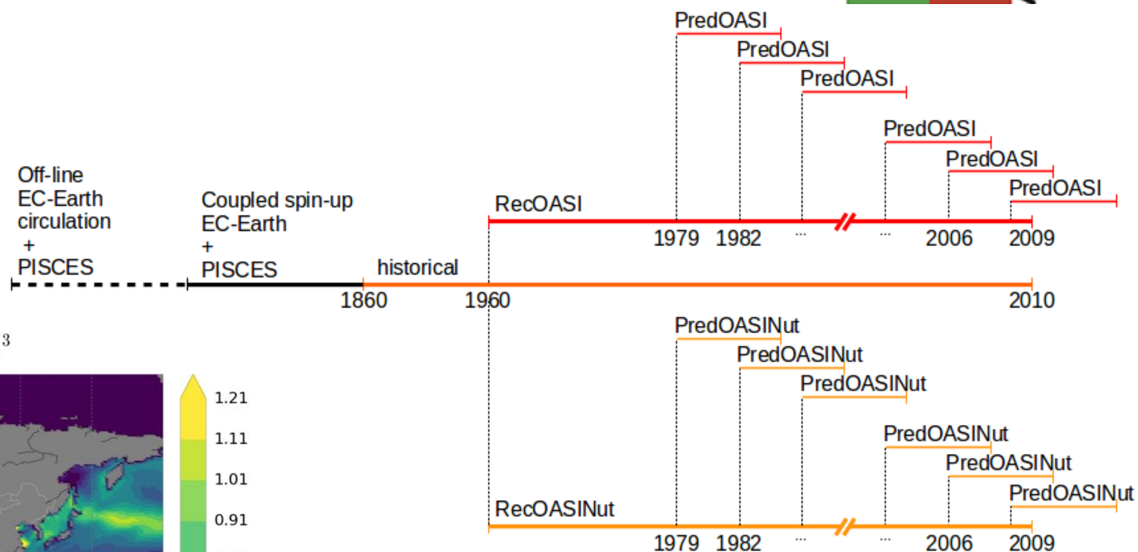
TRIATLAS

THE EU FRAMEWORK PROGRAMME FOR RESEARCH AND INNOVATION
HORIZON 2020
EXCELLENT SCIENCE
COMPETITIVE INDUSTRIES
BETTER SOCIETY

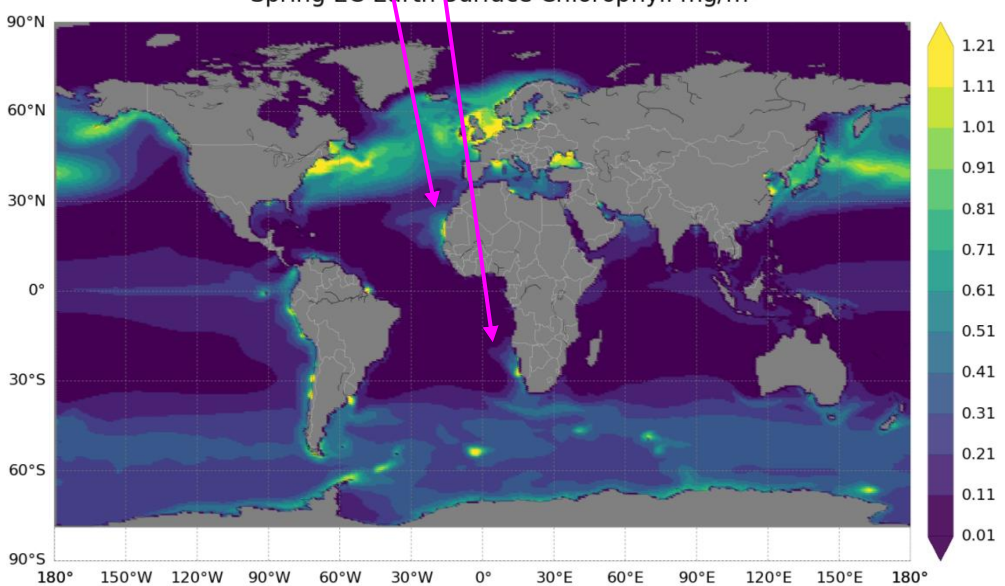
NeTNPPAO

ACTIONS

Investigating mechanisms of predictability of ocean biogeochemical properties



Validation using satellite obs



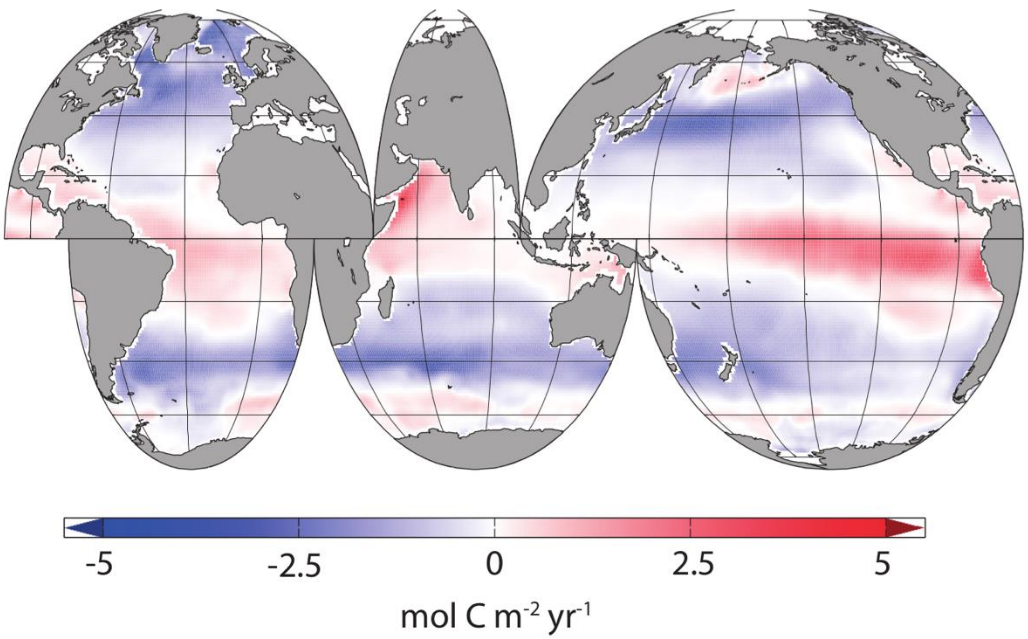
Retrospective decadal predictions using different initializations

Southern Ocean Carbon uptake

DeCUSO

Investigating mechanisms of variability of Southern Ocean Carbon uptake and the role of the Biological Carbon Pump

Validation using satellite obs-based reconstructions of air-sea CO2 flux



Transport Matrix Method (TMM) with NEMO for fast equilibration of bgc tracers

Retrospective decadal predictions of ocean carbon uptake

Impact of the BCP uncertainty on total carbon uptake estimates

Future carbon-climate interactions

Barcelona Supercomputing Center
Centro Nacional de Supercomputación

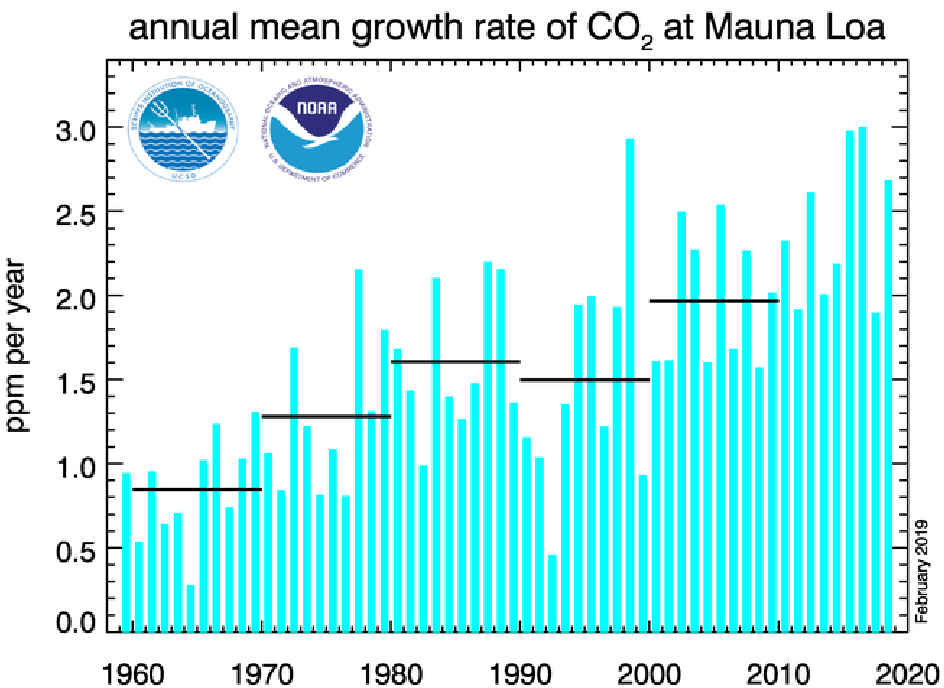
EXCELENCIA SEVERO OCHOA

CCiCC

Towards a near-term prediction of the climate and carbon cycle interactions in response to Paris Agreement emission trajectories

[Global **carbon stocktake** every **5 years]**

Variability in atm CO2 growth rate is mostly due to natural variability



Testing different ocean biogeochemical reconstructions as initial conditions

Retrospective decadal predictions of ocean and land carbon uptake

Idealized perfect-model experiments to investigate mechanisms of C uptake predictability in the ocean.

Organic C ocean sequestration

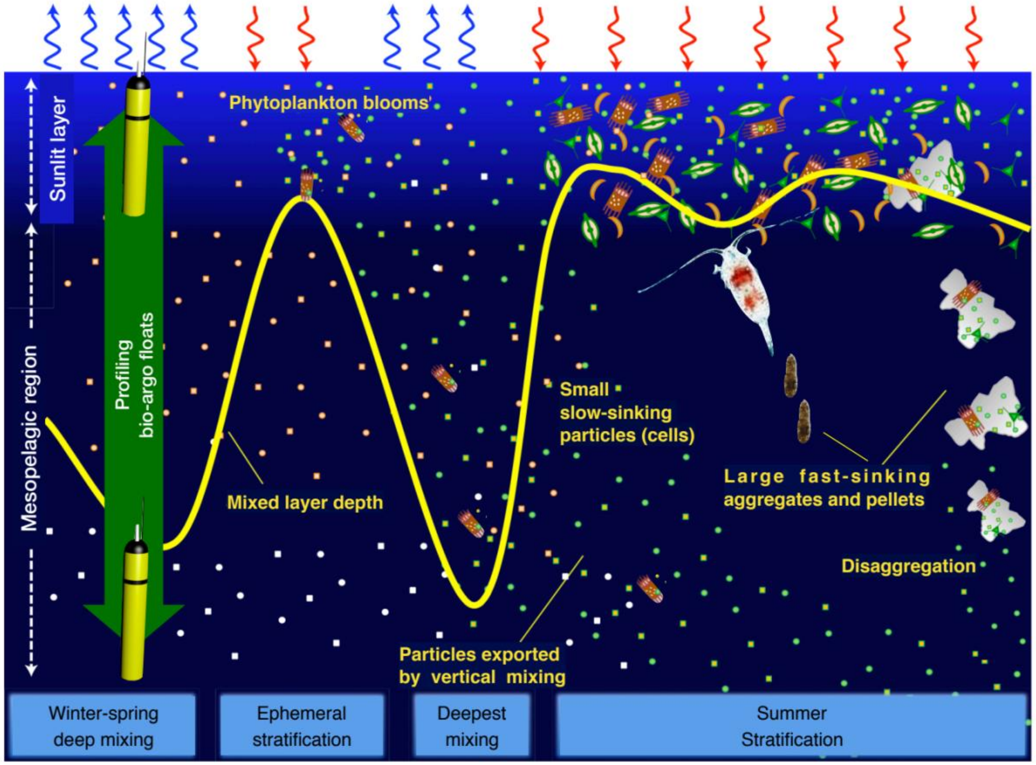
ORCAS

JuniorLeader

Postdoctoral Fellowships Programme

BEQUESCAIXA

Atmospheric CO2 is taken up by phytoplankton and exported to the the deep ocean in the form of sinking particles, where carbon can be sequestered for centuries.



Validate PISCES against novel high-resolution data from drifting underwater robots (bio-argo floats)

Test improved model formulations for particle supply and degradation in the oceans' twilight zone (200 to 1000 m depth)

Making a difference in environmental services

- BSC is a key developer of the Copernicus services.

	Referencia Exteri	Titulo proyecto	Presupuesto
1	87-GLOBAL-CMEMS-NEMO Lot 5: HPC ORCA36	HPC ORCA36	49.835,05
2	C3S 34a Lot2	MAGIC	170.000,00
3	C3S 441 Lot2	Climate for Energy	182.000,00
4	C3S 51 Lot3	Quality Assessment Strategies for Multi-model Seasonal Forecast	731.214,40
5	C3S 52 Lot2	SECTEUR	128.996,68
6	CAMS 50	Regional production	91.465,79
7	CAMS 81	Global and Regional Emissions	60.187,50
8	CAMS 84	CAMS 84 - Global and regional a posteriori validation, including focus on the Arctic and Mediterranean areas	176.000,00
9	CAMS 84 Phase 2	Global and regional a posteriori evaluation and quality assurance (EQC)	165.090,81
10	CAMS 95	CAMS 95 Use cases (second batch)	7.000,00
11	C3S 512	C3S 512: Quality Assurance for the Climate Data Store	1.504.275,81

Copernicus Europe's eyes on Earth

Climate Change Service

- The ESA CCI is another important, and underexploited, opportunity.

From research to services

Research field

Climate	Mineral Dust	Air Quality

Service user sectors

Climate	Mineral Dust	Air Quality
Renewable energy	Solar energy	Air quality and mobility planning
Agriculture	Aviation	Health
Insurance	Health	Heavy industry
Water management		
Forest fires		

The Earth System Services group facilitates technology transfer of state-of-the-art research from local, national to international levels

BSC