Recent upgrades to the coupled ocean - sea ice prediction system at ECMWF

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Ocean Modelling Team Lead

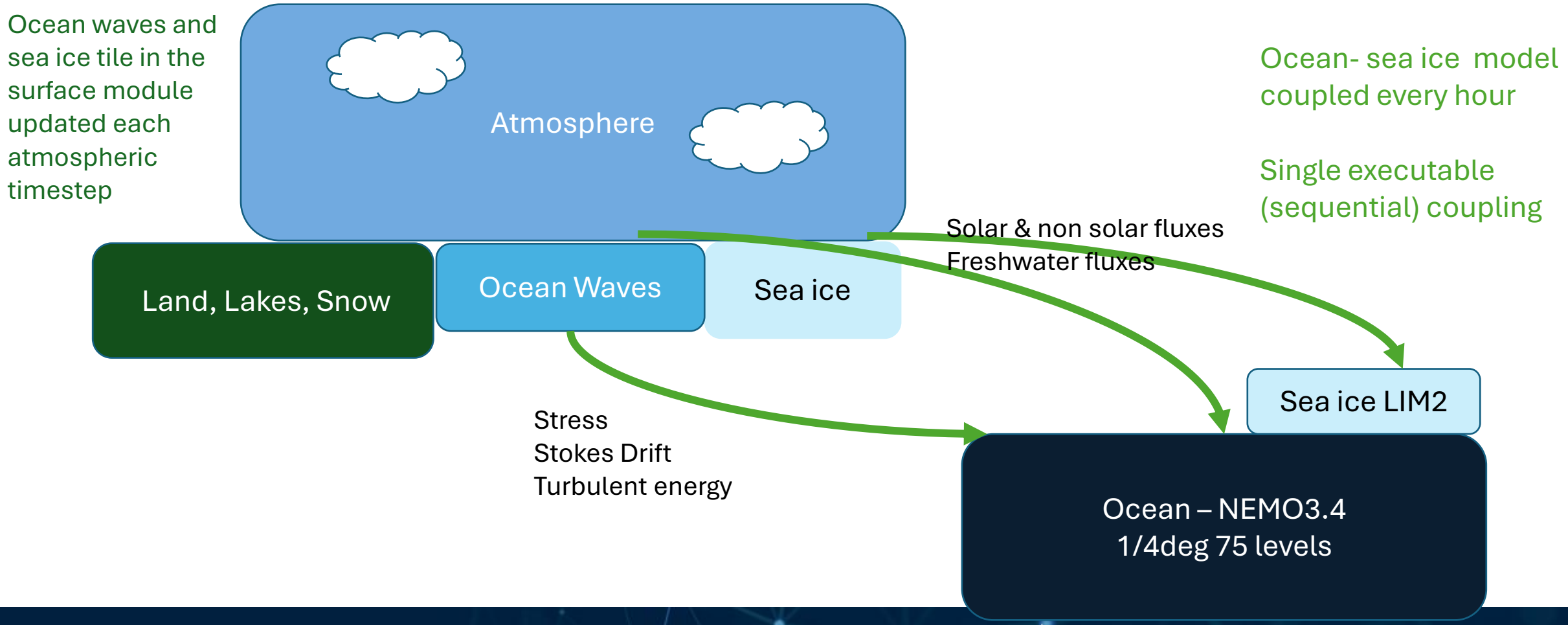
Sarah.Keeley@ecmwf.int

Operational model upgrades

and a quick look back

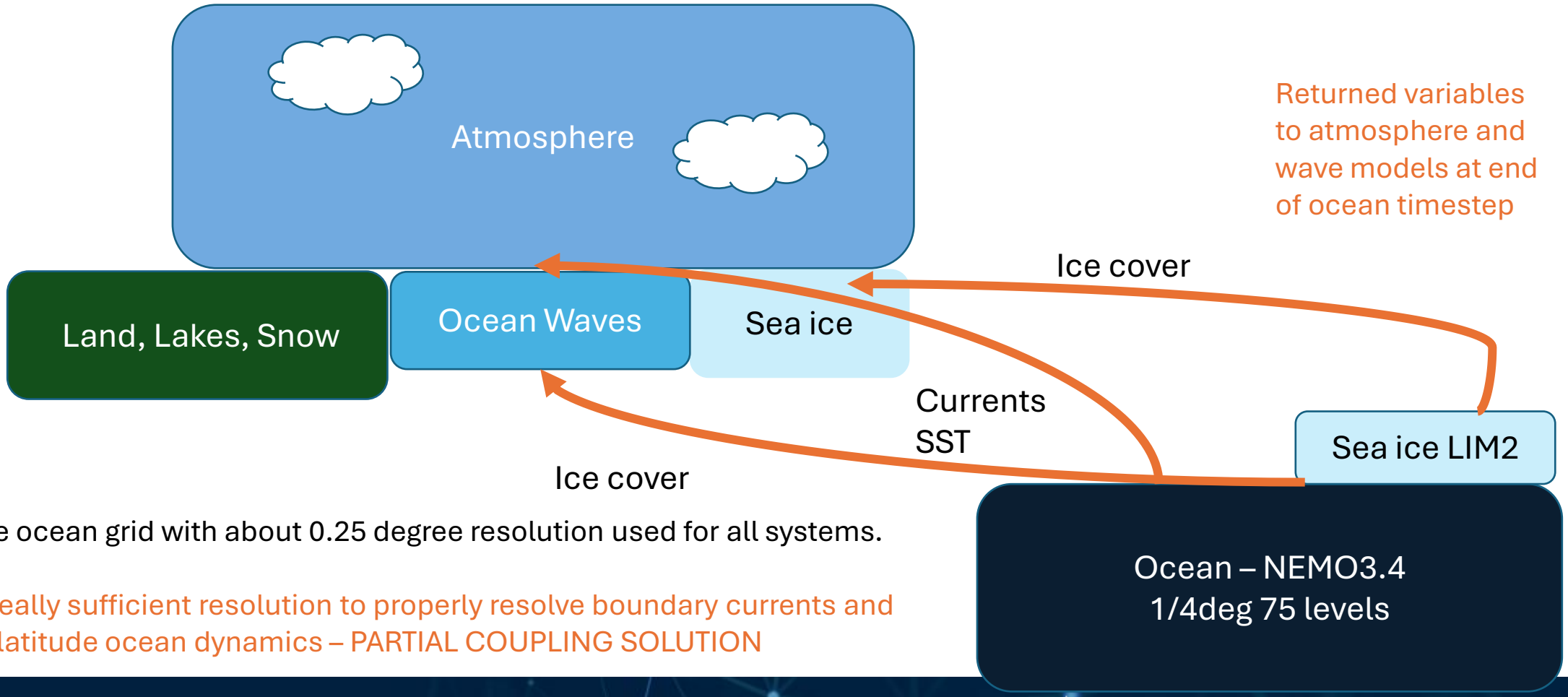
Marine model components

- Coupled ocean model in all our forecast systems
- Different modules have different coupling frequencies



Marine model components

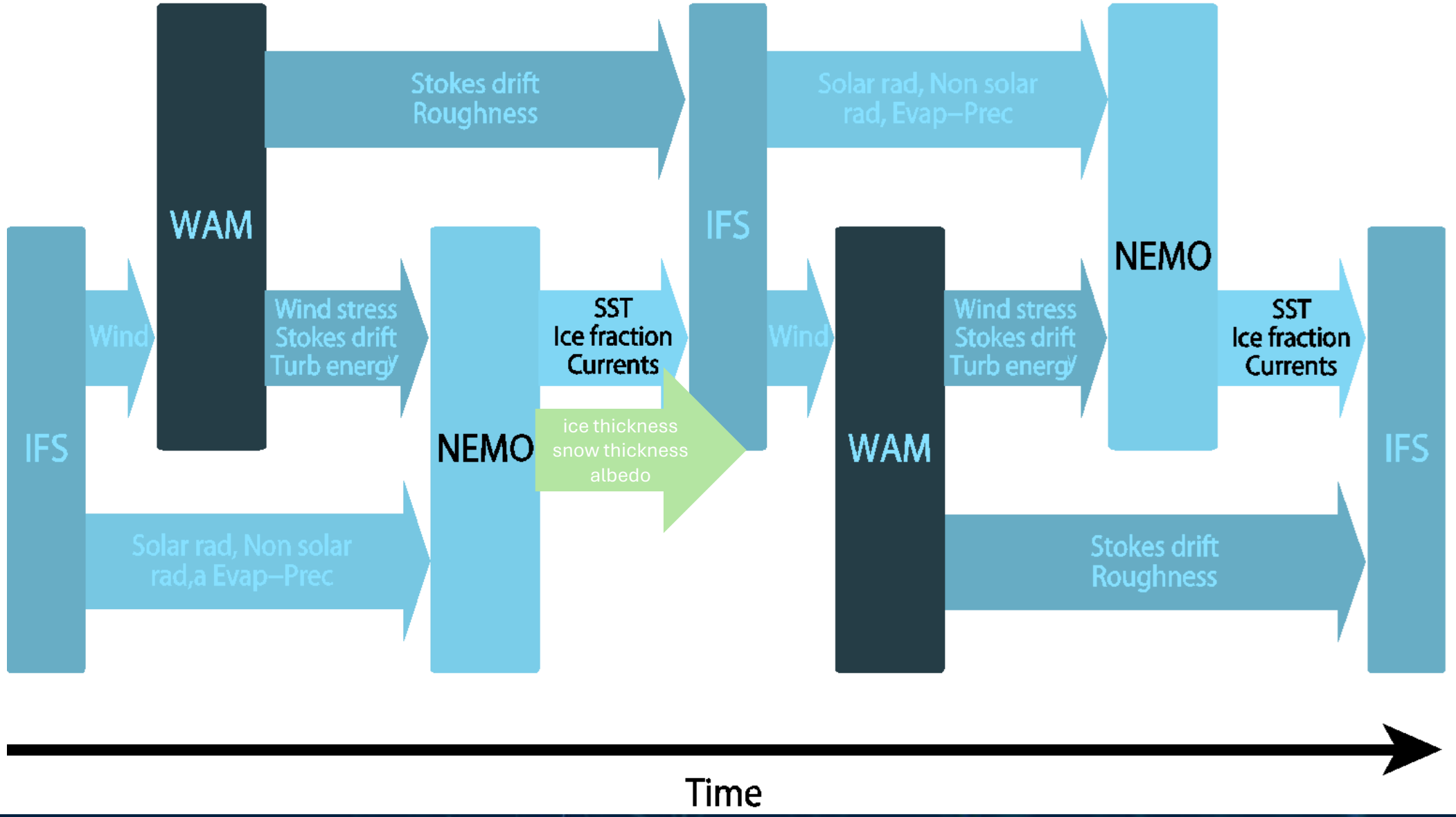
- Coupled ocean model in all our forecast systems
- Different modules have different coupling frequencies



Same ocean grid with about 0.25 degree resolution used for all systems.

Not really sufficient resolution to properly resolve boundary currents and high latitude ocean dynamics – PARTIAL COUPLING SOLUTION

Schematic overview of single executable coupled system (sequential coupling)

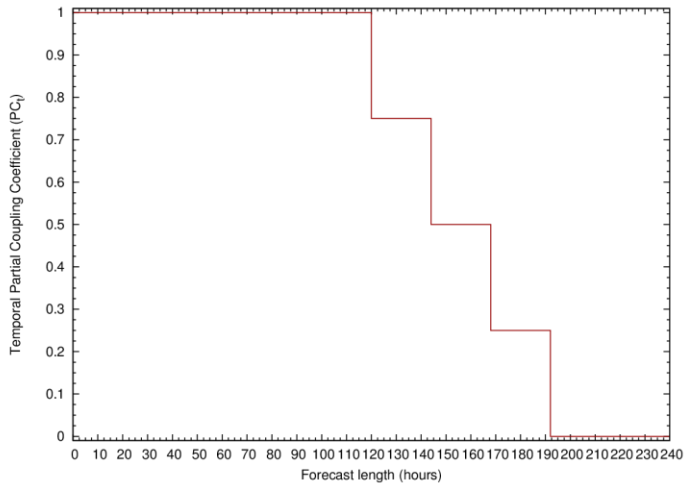


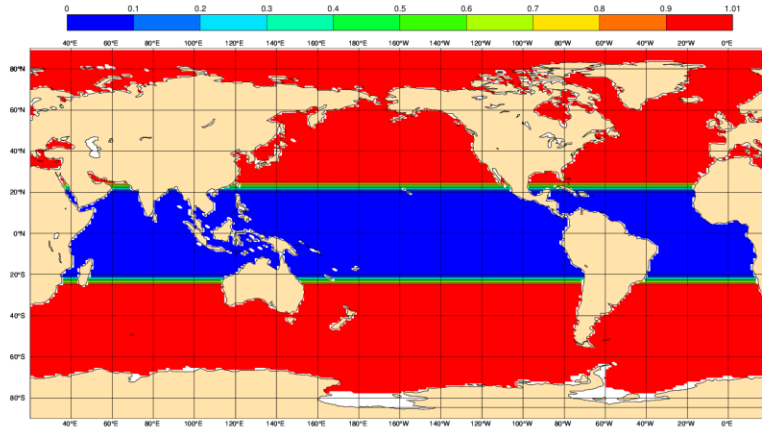
SSTs matter - partial coupling for an operational system

- The ORCA025 initial conditions do not have sufficient resolution to properly put the eddies in the right place
  - Example: The position of the Gulf Stream influences the weather over Europe
- To compensate for this we have introduced the concept of partial coupling where the SST used in the atmosphere model are:

  $$SST_{atmos}(t) = PC(t) * SST_{ostia}(0) - PC(t) * SST_{ocean}(0) + SST_{ocean}(t)$$

  - Where PC (0 to 1) depends on time (below left) and from 2018 onwards also on position (below right)
- Implemented when we introduced the coupled model with ORCA1 from day 0 in ENS (Nov 2013)
- However it is not nice approach since the fluxes computed in the atmospheric component are not consistent with the SST in the ocean component





Extra-tropics only

What's changed

	ORAS5	ORAS6
Ocean Model	NEMO3.4-LIM2 0.25 deg ORCA grid 75 vertical levels	NEMO4.0.6-SI3 0.25 deg eORCA grid 75 vertical levels Variable volume upper layer
Ice Model	Single category, 2 layer (+ 1 snow) ice model Constant salinity	Multi-category, 4 layer(+1snow) ice model Melt ponds Prognostic salinity
Output	netcdf (some variables in GRIB on atmos grid)	GRIB2 (restarts in netcdf)

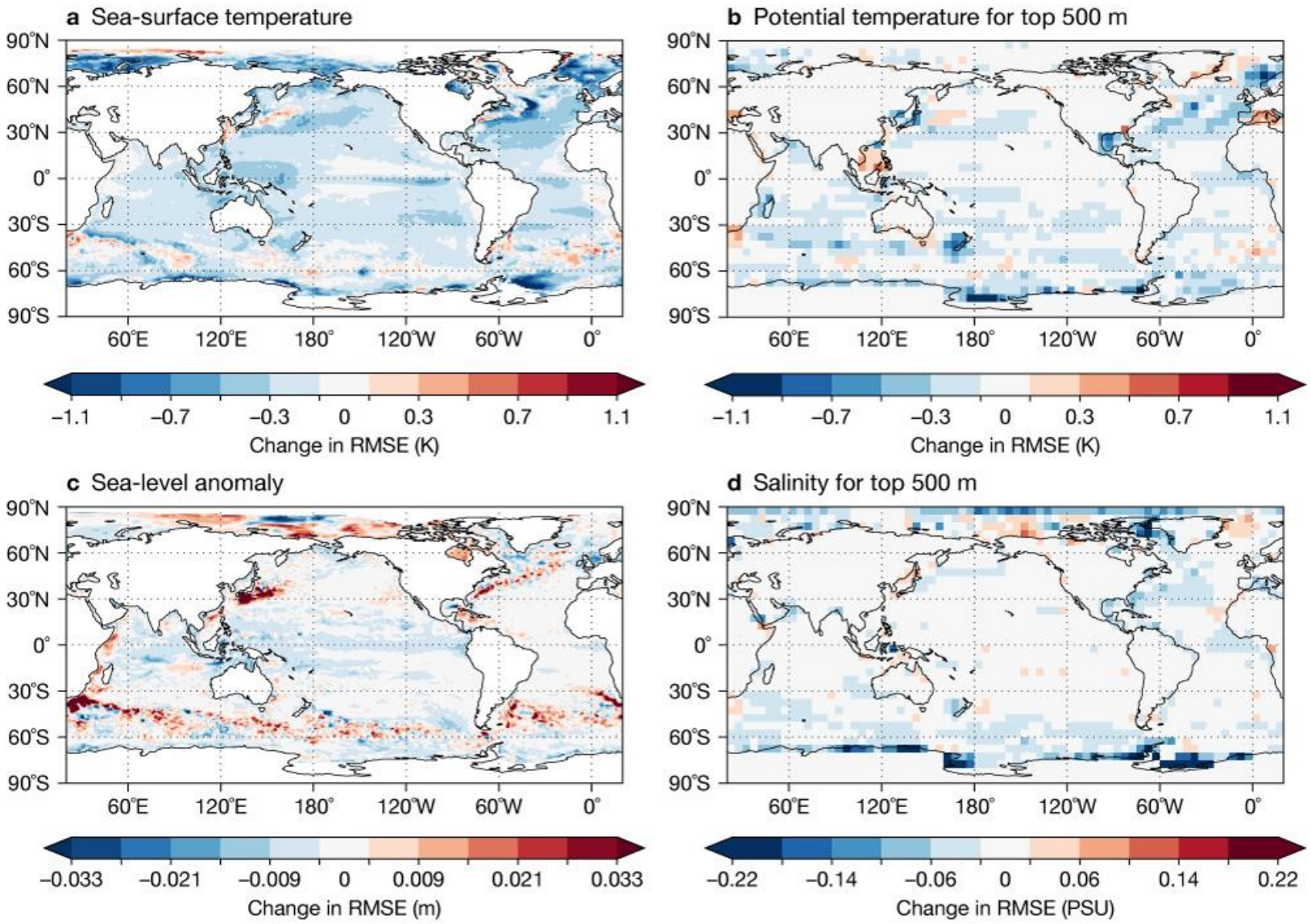
Features of the new ORAS6 system:

- Improved Western Boundary Currents (e.g. Gulf Stream) – aim to remove the partial coupling framework that is used in the first week of forecasts outside of the tropics currently.
- Multicategory sea ice model, with melt ponds is more responsive but tends to be biased too thin
  - No thickness assimilation in ORAS6
- Reduced the known SST warm bias in Southern Ocean

NEMO4 vs NEMO3.4

40 years from 1979, hourly ERA5 forcing, no data assimilation.

The evaluation focuses on the final 20 years after spin-up.

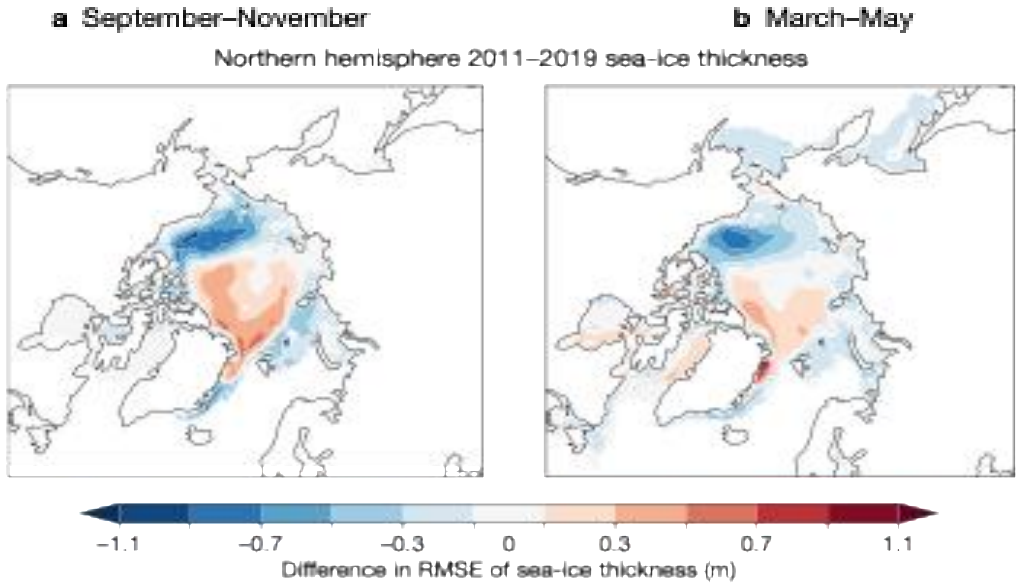


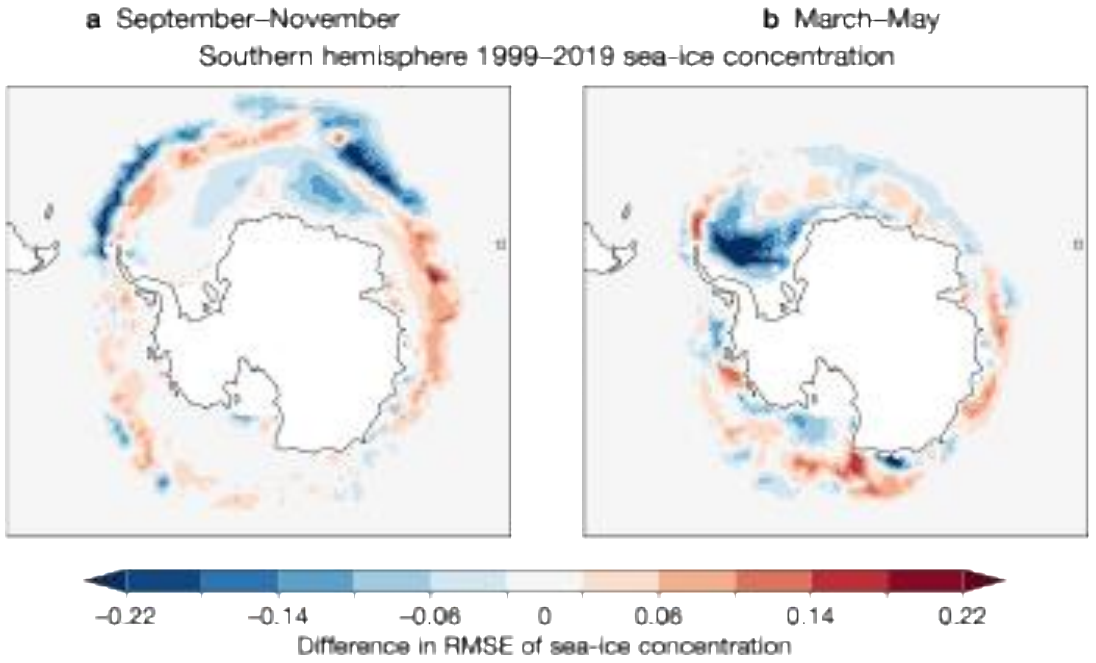
NEMO4 vs NEMO3.4

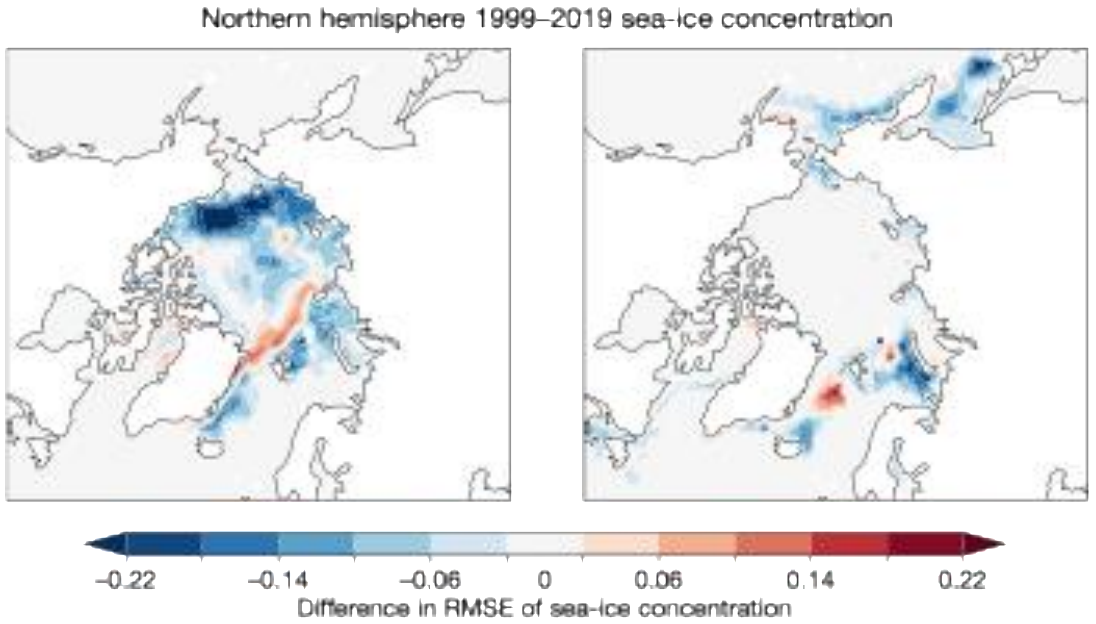
More emphasis given to Arctic performance.

Ice thinner year round
(no thickness assimilation in ORAS6)

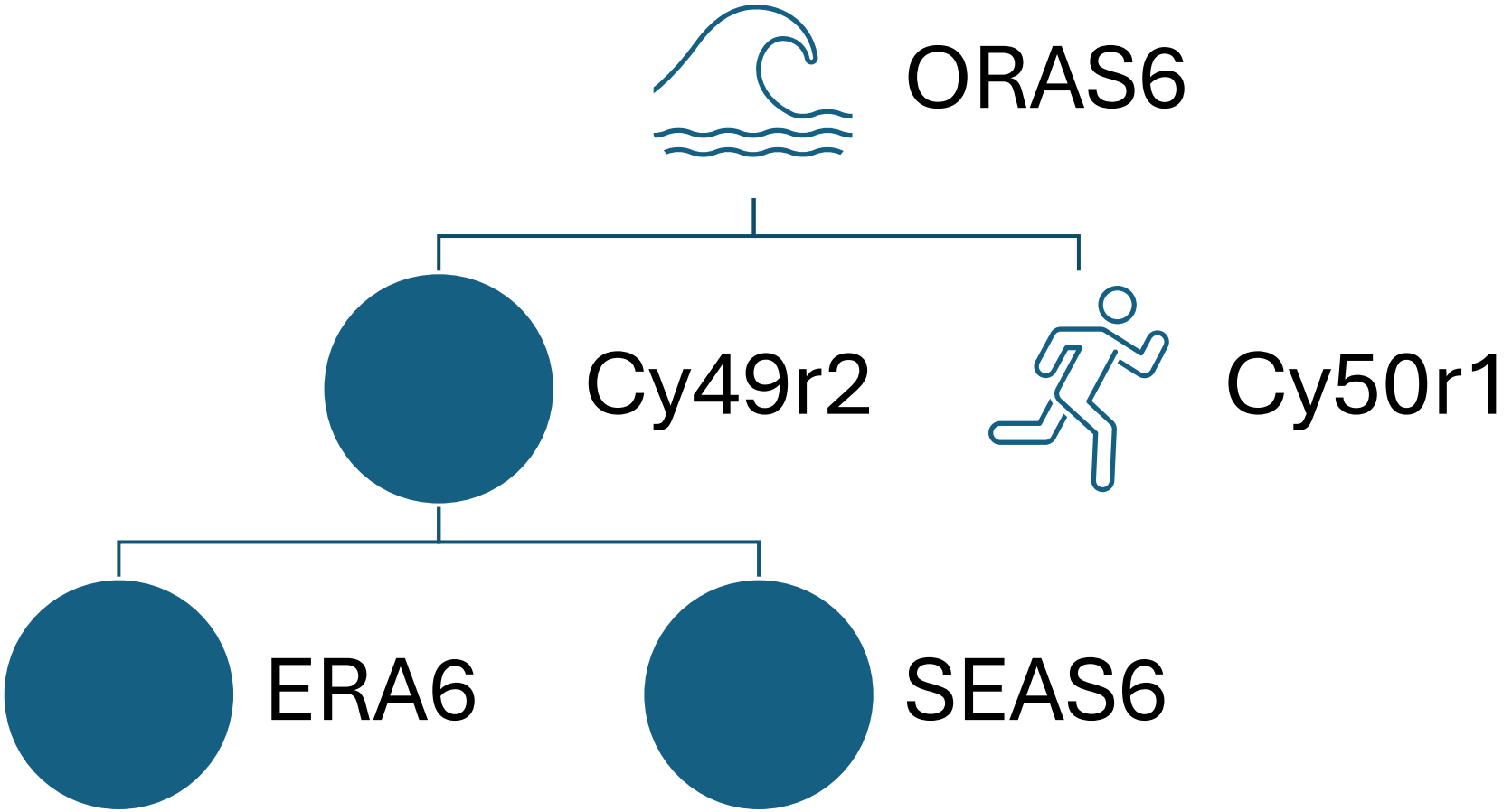
Tsz Yan poster for future developments



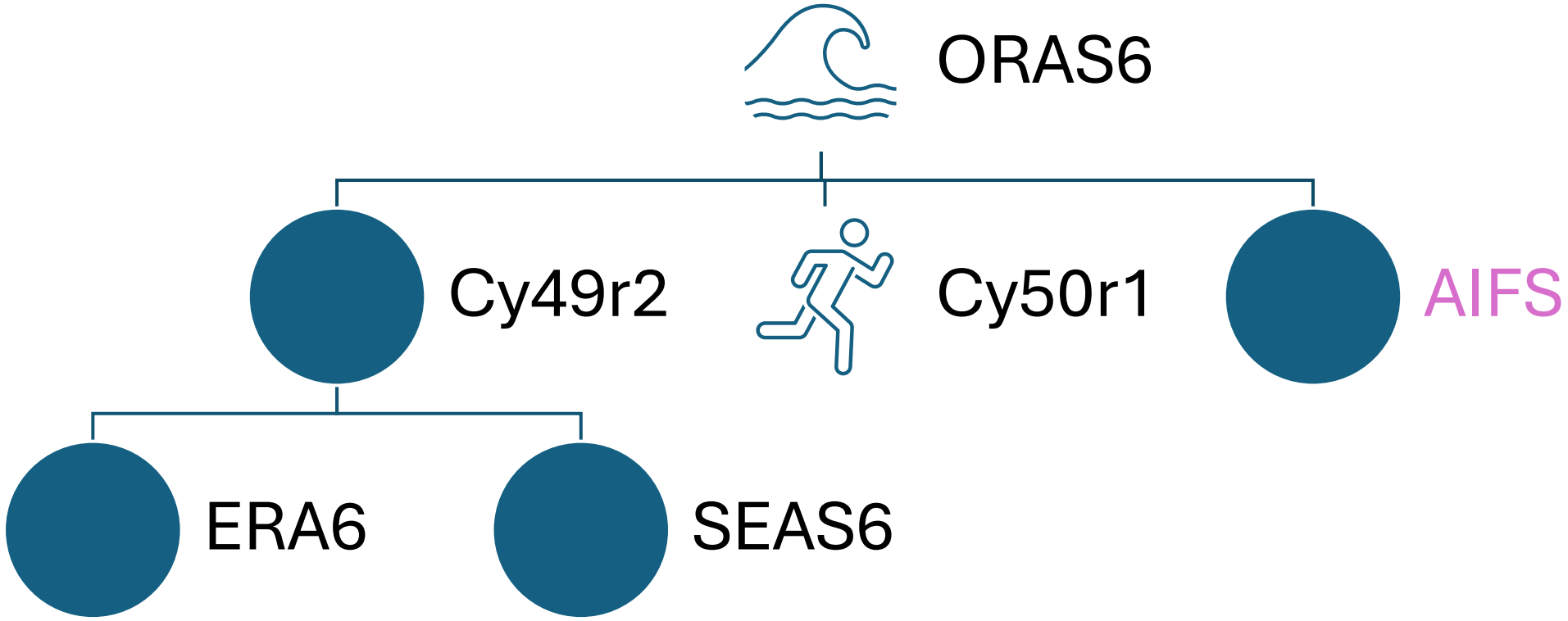




Cycle upgrades

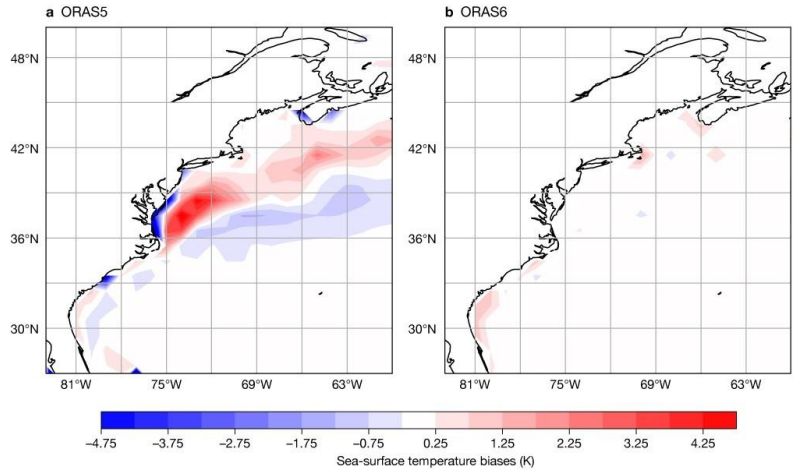


Cycle upgrades



Marine model components

- Coupled ocean model in all our forecast systems
- Sea ice model run each ocean time step



Returned variables to atmosphere and wave models at end of ocean timestep

Atmosphere

Land, Lakes, Snow

Ocean Waves

Sea ice

Ice cover, snow depth, ice thickness, albedo

Currents
SST

Ice cover, thickness

Sea ice SI3

Ocean – NEMO4.0.6
1/4deg 75 levels
Single Precision

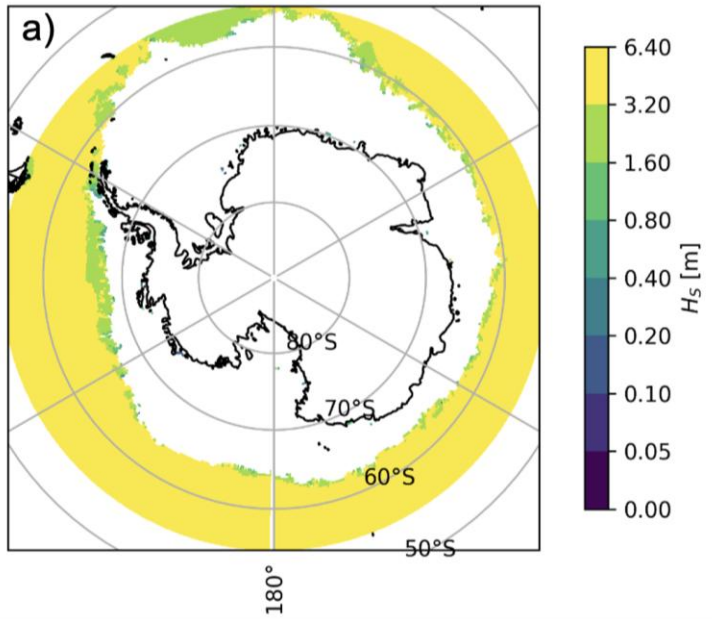
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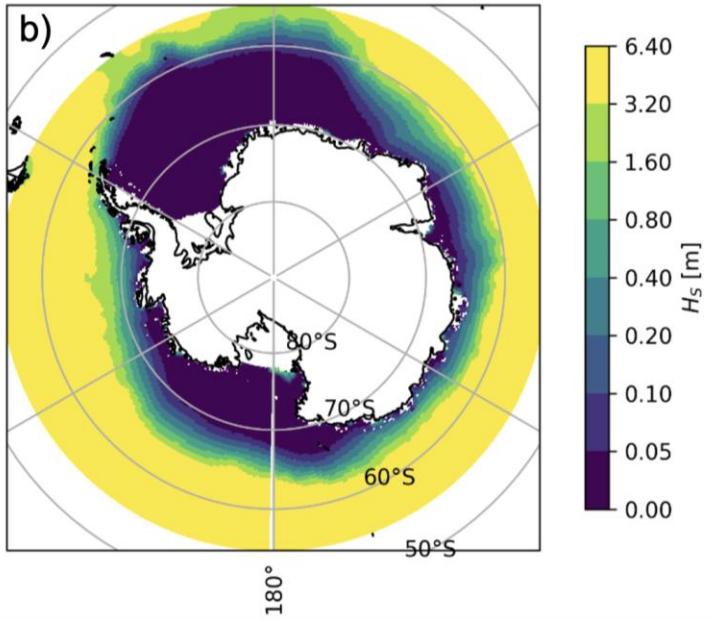
Cycle upgrade highlights

- 50r1
  - waves are attenuated in sea ice rather than “switched off”
  - opens pathway for wave feedback on ice
  - provides training datasets for data driven models

Pre May 2026



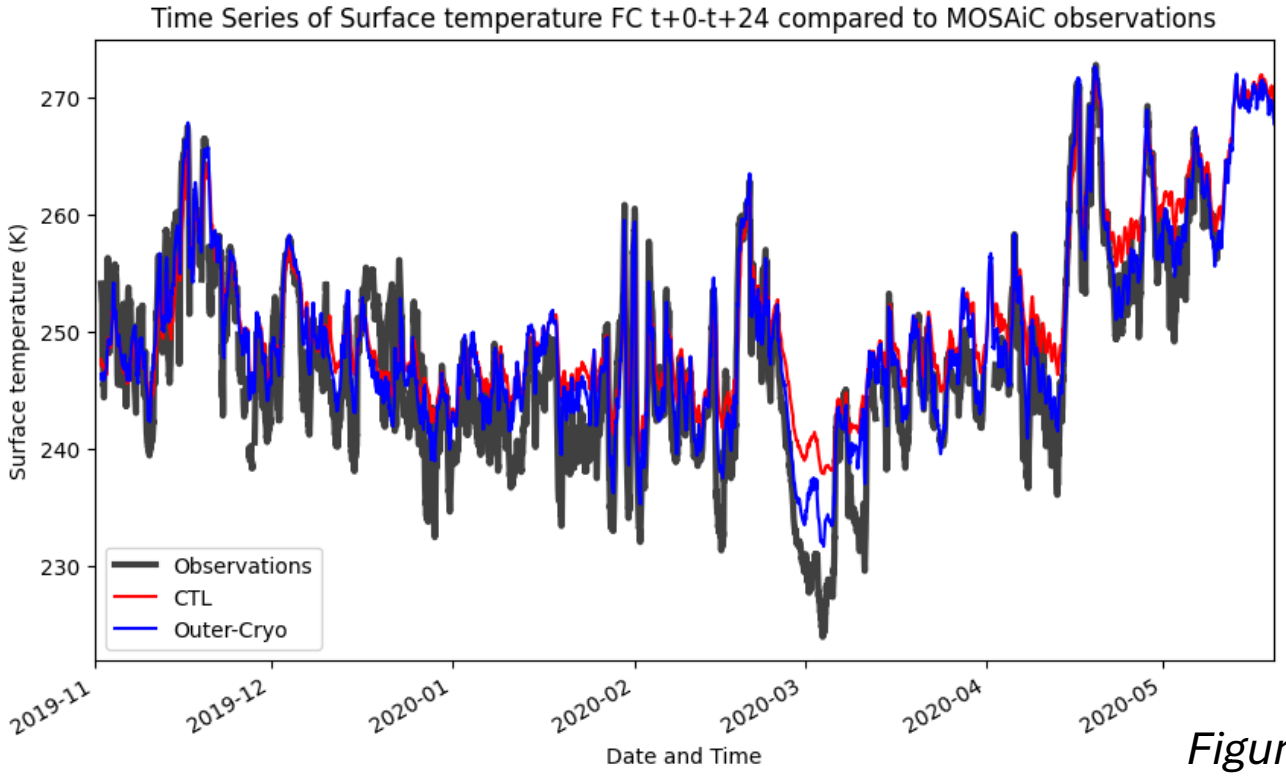
50r1 (May 2026)

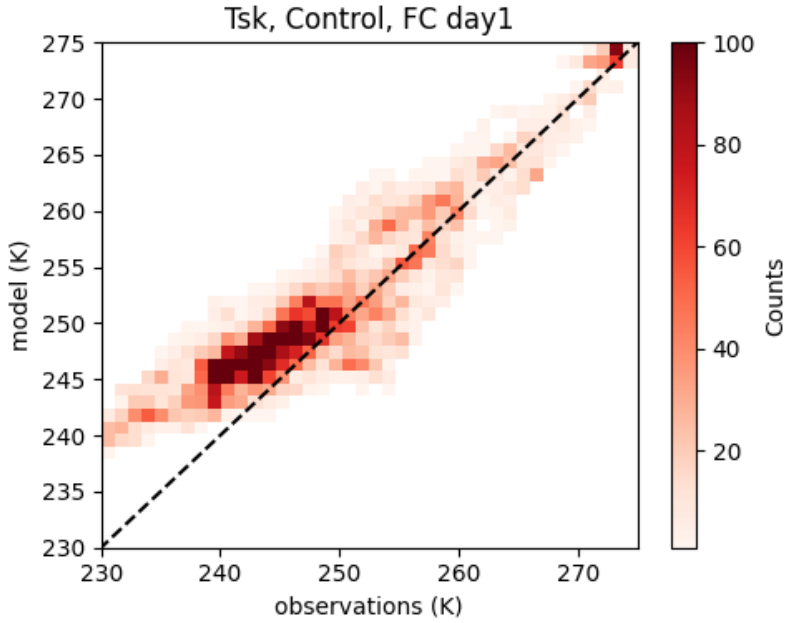


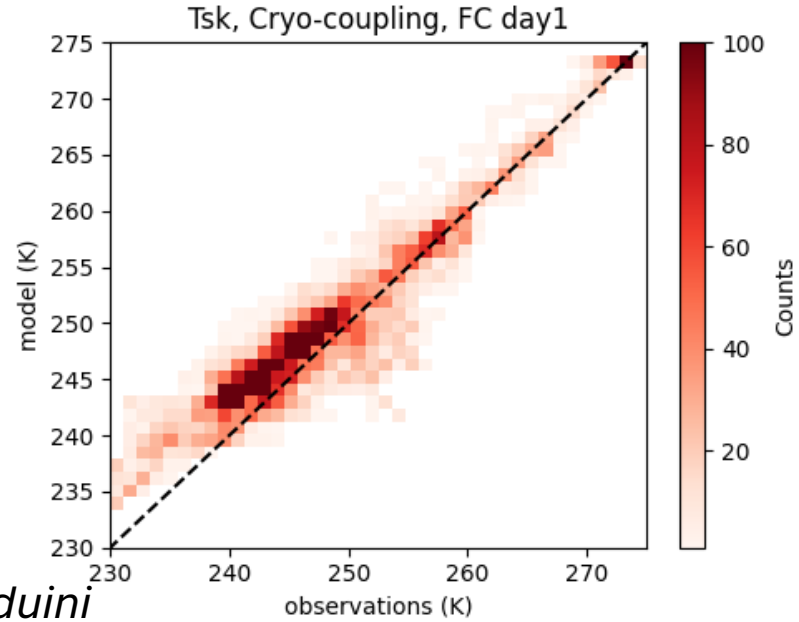
Figures from Josh Kousal

Cycle upgrade highlights

- ERA5 has known deficiencies in representing polar surface temperatures.
  - too warm in clear sky snow covered situations
- ERA6 – SEAS6 – 50r1 bringing snow on sea ice
  - using of ORAS6 snow depths, ice thickness, SI^3 albedo
  - compare MOSAiC data with ERA6 Tco799 v7 prototype
  - ongoing testing with field campaign data





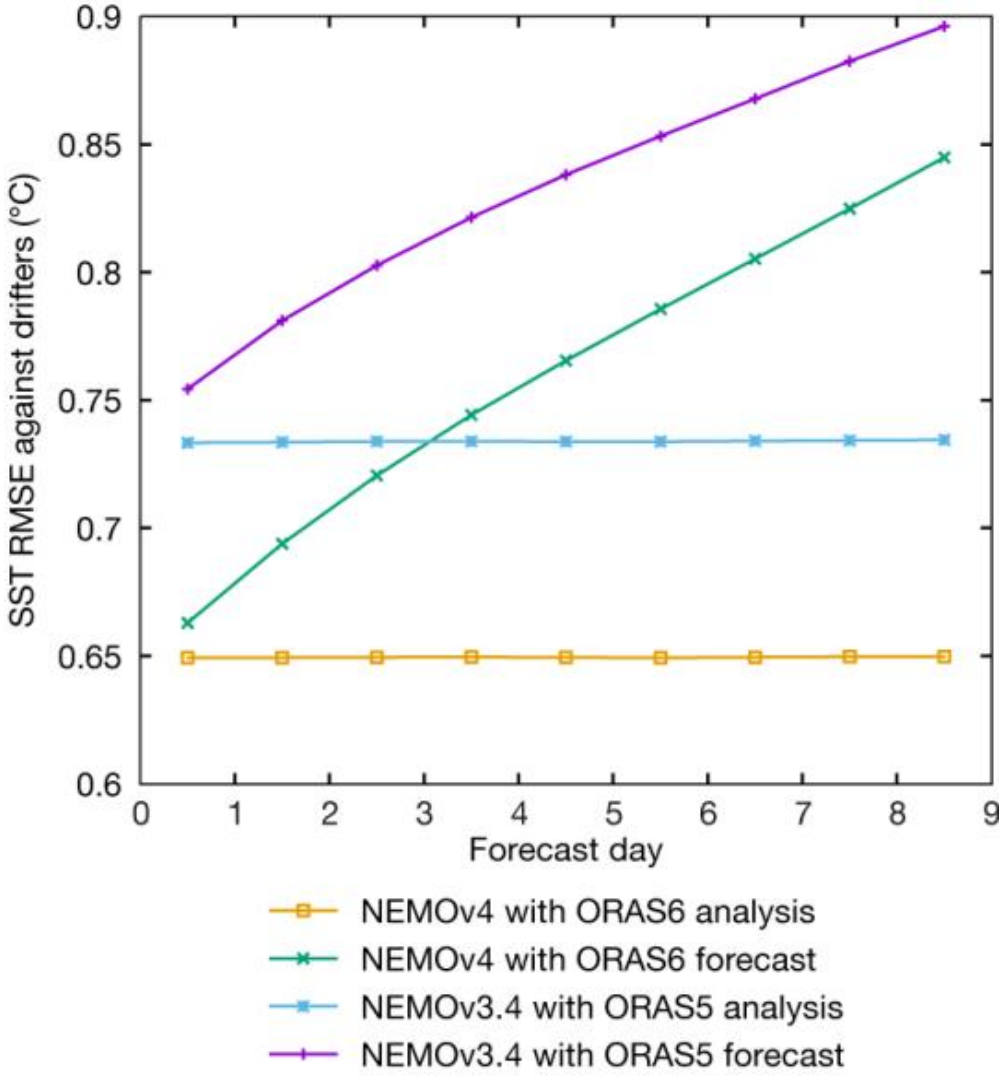


Figures from Gabriele Arduini

Model performance



Improvements at the medium range…



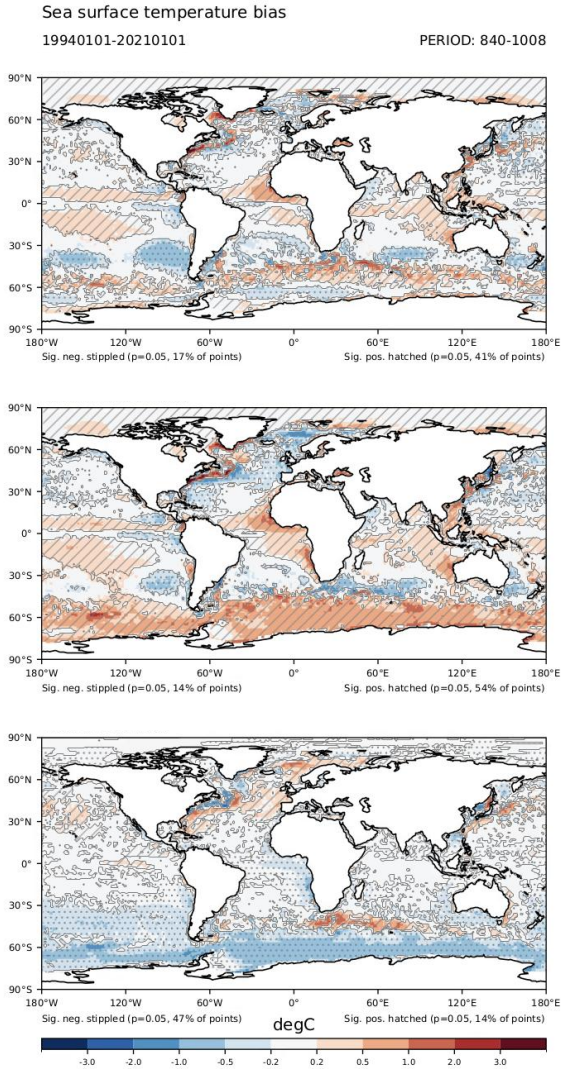
- Improved analysis against drifters compared to the previous system
- Leads to forecast system that is improved for the whole of the medium range forecast..

…at the subseasonal range

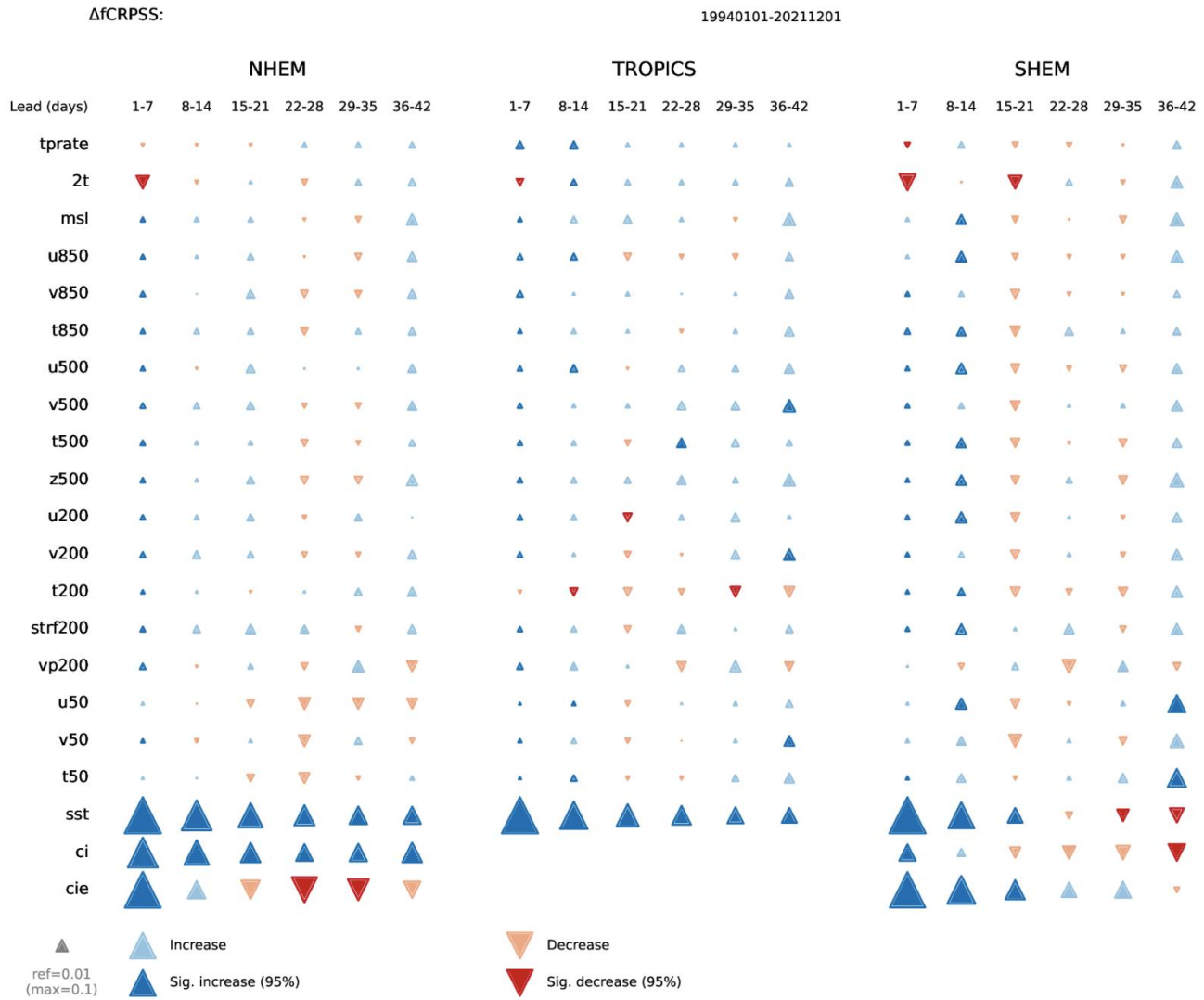
NEMO4 –ESA CCI

NEMO3.4 –ESA CCI

NEMO4 - NEMO3.4



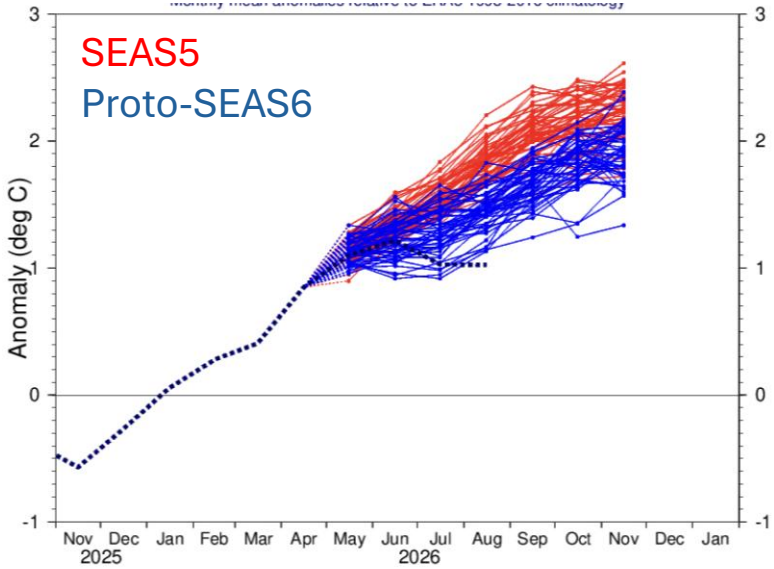
Atmospheric scorecard NEMO4 vs NEMO3.4



Improvements of coupled processes at seasonal time scales

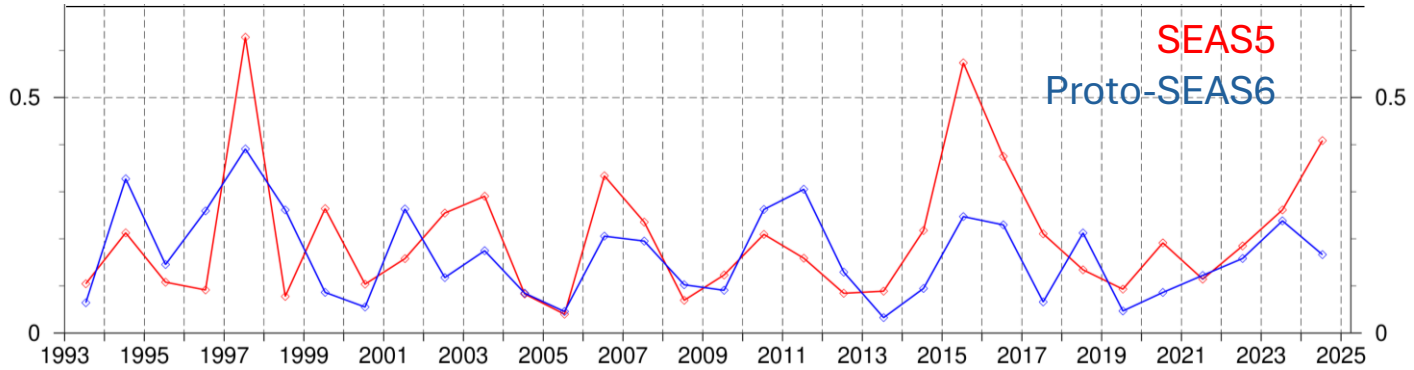
NINO4 SST forecast

1 May 2026



Equatorial Western Pacific JJA absolute error (ºC)

wrt ESA-CCI, 5N-5S, 150-190E (ºC)



Reforecasts from 1993-2024, 51 ensemble members, initialized on May. 1, month 2-4

- Improved variability in the Western Pacific, particularly JJA/SON
- ENSO skill maintained; longer and more frequent forecasts will add value
- Improved gulf stream separation area
- Improved equatorial upwelling in the eastern Pacific (Nino 1+2)

Figures from Stephanie Johnson

Summary and Conclusions

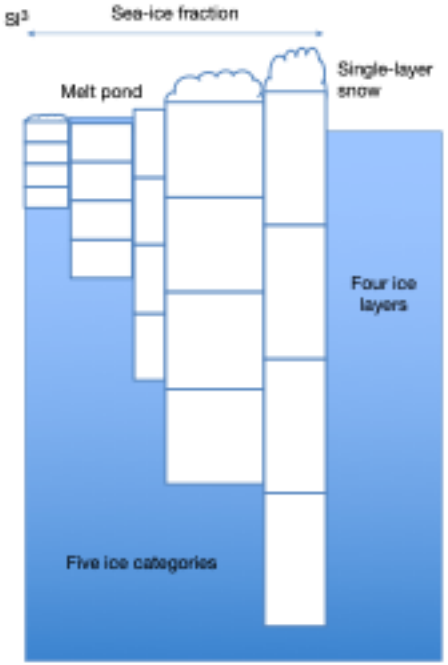
- We have produced a new reanalysis ORAS6 making use of NEMO4-SI3
  - highlights include better western boundary currents
  - 1950 - present day
  - removes the need for partial coupling
  - see Hao's talk
- ECMWF has implemented NEMO4-SI3 in operations for the medium and sub-seasonal time ranges with updates to the seasonal system coming soon.
- ERA6 will make use of ORAS6 to provide ocean and sea ice information.
- Improvements in the ocean model don't always translate into clear benefits in large scale scorecards
  - ongoing work to assess case studies and impact weather events
  - understanding the coupling limitations and budget analysis
  - see Chris Roberts's talk



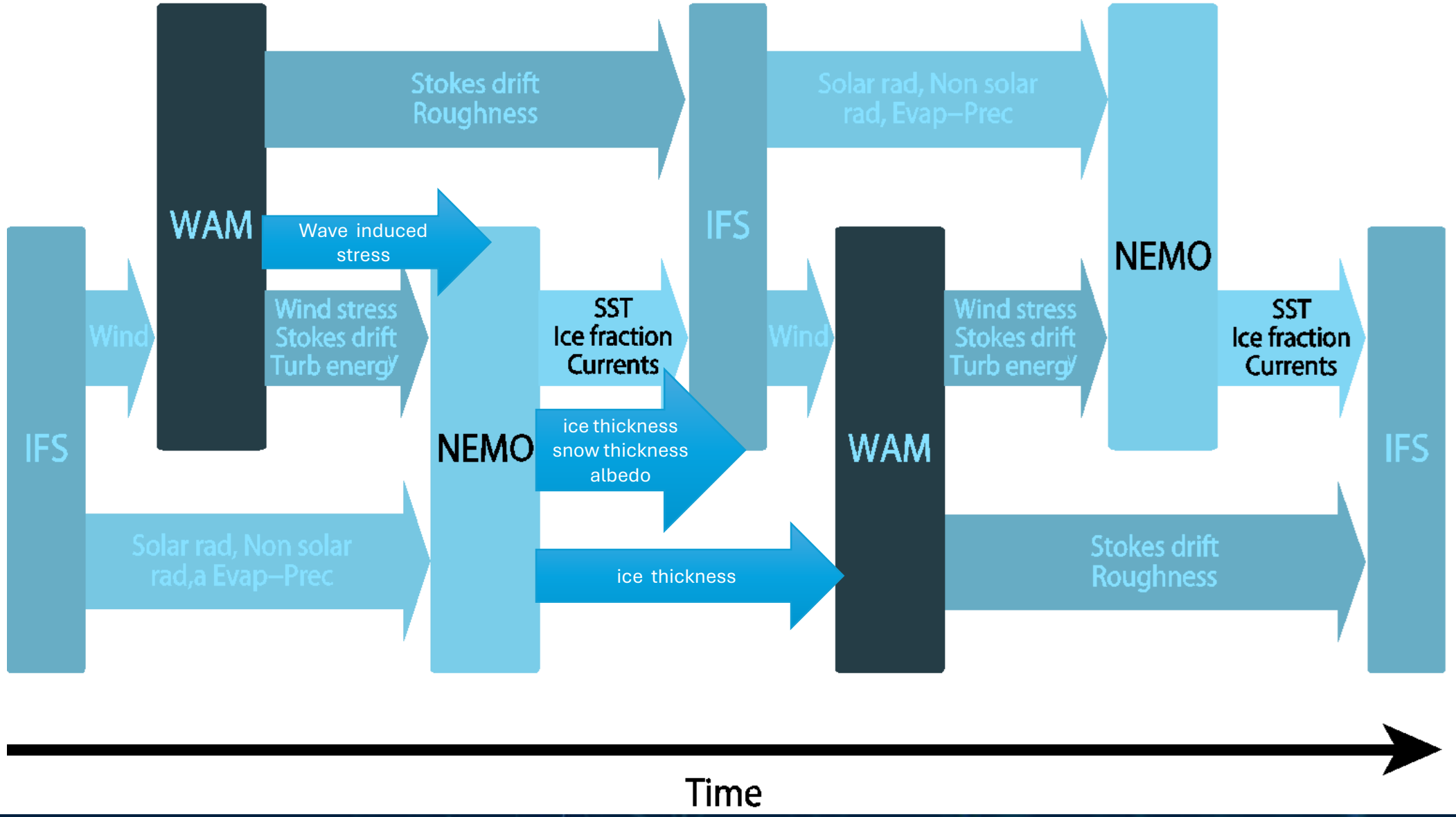
www.ecmwf.int

Updated Model – what does it bring

- What has changed:
  - **NEMO4.0.6 - SI³ – multicategory sea ice**
  - eORCA grid – more points further south
  - EVP rheology (previously VP)
  - melt ponds (level scheme)
  - 4 layers sea ice thermodynamics (previously 2)
  - prognostic salinity (previously constant)
  - ice timestep – 20mins (previously 1hr)
  - **coupling methodology to the IFS**
  - **data assimilation updates**
  - **output data format - now in GRIB2**
  - Single-precision forecast systems
  - new albedo formulation
- What has stayed the same:
  - Resolution – 0.25 eORCA grid
  - Single layer snow model
  - Hibler ice strength
  - restart files still in netCDF



Schematic overview of single executable coupled system (sequential coupling)



SI3 represents a distribution of ice thickness

ECMWF Newsletter 180, Summer 2024

Sea-ice representation	LIM2	SI3 configuration
Thickness categories	One	Five
Thermodynamic structure	Two ice layers + one snow layer	Four ice layers + one snow layer per category
Sea-ice salinity	Fixed	Varies in space and time
Melt ponds	None	Pond fraction and volume for each category
Dynamics	Viscous-plastic rheology	Elastic-viscous-plastic rheology

Thermodynamics operates by thickness category. Dynamics operates for the whole grid box, including ridging and rafting.

Source: Keeley et al. (2024), New sea-ice model and Box A

NEMO4 updates the ocean surface and forcing

ECMWF Newsletter 180, Summer 2024

Element	Change in NEMO4	Purpose
Ocean surface	Variable-volume upper layers	Improve surface realism and variability
Upper-ocean mixing	Attenuate wave effects under sea ice	Account for ice in turbulent mixing
Atmospheric forcing	Hourly ERA5 and revised bulk fluxes	Improve the diurnal cycle and flux consistency
Wave and current effects	Sea-state-dependent Charnock coefficient	More consistent surface momentum exchange

Resolution stays unchanged

Nominal 0.25° horizontal grid
75 vertical levels

The domain extends farther south

eORCA extends to 86°S.
Ice-shelf interactions remain a future option.

Source: Keeley et al. (2024), Main developments and Atmospheric forcing of the ocean

Standalone tests show gains and regional limitations

ECMWF Newsletter 180, Summer 2024

Both models: 40 years from 1979, hourly ERA5 forcing, no data assimilation.

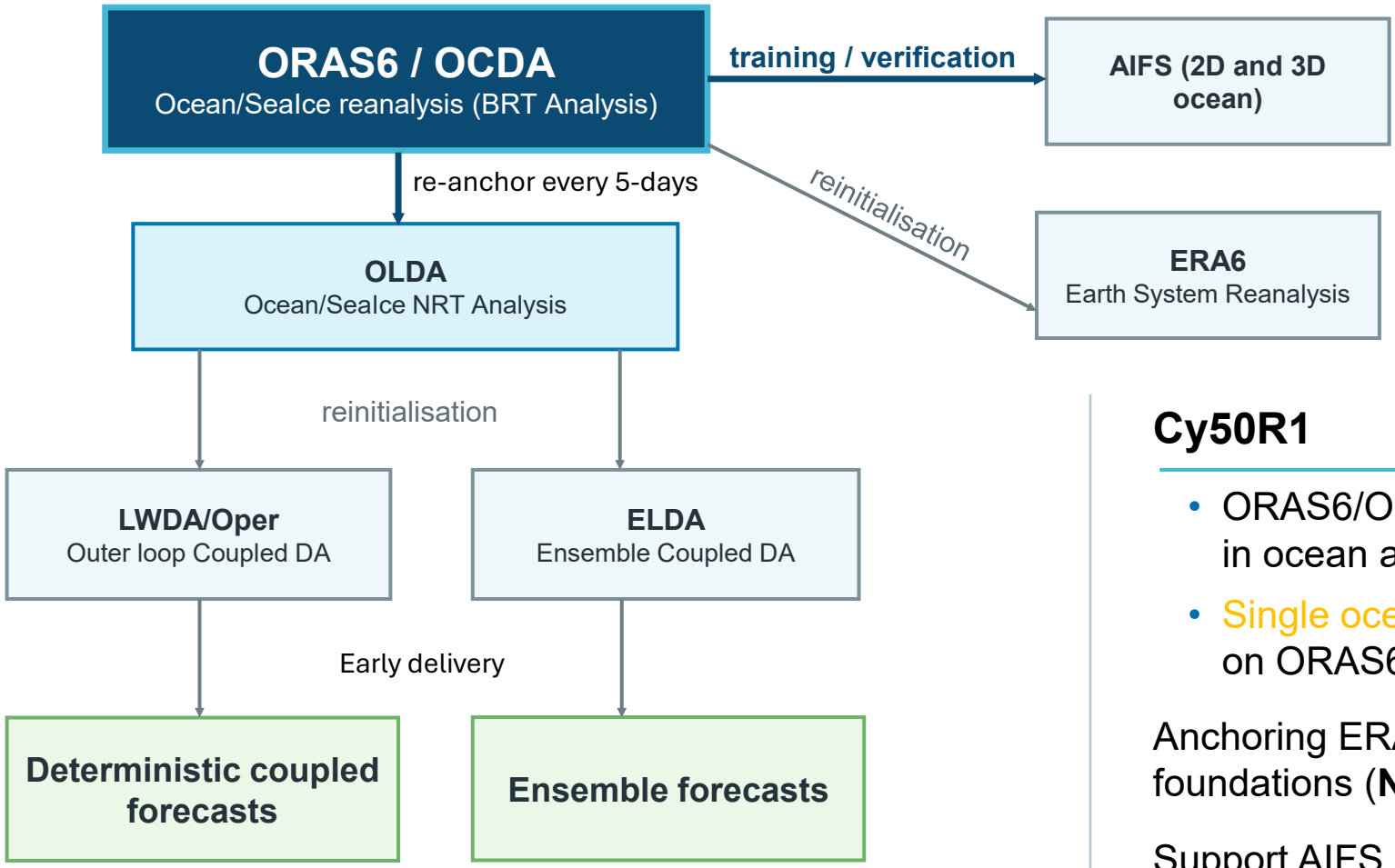
The evaluation focuses on the final 20 years after spin-up.

Diagnostic	Result reported in the article
SST and upper-ocean fields	Broadly lower errors. SST improves in the Southern Ocean and North Atlantic Current region.
Sea-level anomaly	Higher RMSE in eddy-rich regions.
Sea-ice concentration	Broad Arctic improvement. Antarctic results are mixed, with Davis Sea degradation and autumn Weddell Sea gains.
Arctic ice thickness	Thinner ice reduces the Beaufort Gyre thick bias but worsens the thin bias north of Greenland.

Source: Keeley et al. (2024), Comparing standalone NEMO4 with NEMO3.4, Figures 2–3

ORAS6 / OCDA anchors Cy50R1 and ERA6

The ocean–sea-ice reanalysis foundation feeds downstream cycling and AIFS training / verification.



Cy50R1

- ORAS6/OCDA anchors LWDA – to avoid drifts in ocean and sea ice
- Single ocean DA configurations (mostly) based on ORAS6 - **B**, **R**, **K**, BC, QC, …

Anchoring ERA6 – provide ocean and sea-ice foundations (**No ocean DA in ERA6**)

Support AIFS (2D and 3D ocean)