Data Assimilation Task Team (DA-TT)

MEETING

ABSTRACTS

CNR, Rome, Italy

9-11 May 2023

Status: 16 May 2023

DA-TT themes

Theme	Theme title	No of abstracts
1	Advances in DA methods (ensembles, algorithms, machine learning, downscaling, …)	
2	Error covariance modelling (B, Q and R, hybrid approaches)	
3	Observing systems: requirements, evaluation, design and associated DA developments	
4	Software infrastructure and efficient use of DA on HPCs	
5	Coupled Earth system DA (e.g., ocean/atmosphere/sea-ice, physics/biogeochemistry, physics/acoustics)	
6	Applications of DA in operational forecasting, reanalysis systems, digital twins and climate prediction.	

Abstracts (oral, poster and undefined; sorted by theme)

Please note that some abstracts have been submitted to multiple **theme categories**. Please check "theme category" column for details.

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2	**1.2**	Pierre	Brasseur	CNRS	Ensemble analysis and forecast of marine ecosystems in the North Atlantic using ocean colour observations and prior statistics from a stochastic NEMO-PISCES simulator
3	**1.3**	Andrea	Cipollone	CMCC	Joint assimilation of sea-ice concentration and thickness from remotely sensed observations
4	**1.4**	Andy	Moore	UC Santa Cruz	Weak Constraint 4D-Var Data Assimilation in the Regional Ocean Modeling System (ROMS) using a Saddle-Point Algorithm
5	**1.5**	Jozef	Skalala	PML	Uncertainty and observability of target ecosystem indicators within the operational system on the North-West European Shelf
6	**1.6**	Charles-Emmanuel	Testut	Mercator Ocean International	Towards a Mercator reanalysis and forecasting system using an Ensemble Kalman Filter
7	**1.7**	Norihisa	Usui	Meteorological Research Institute / Japan Meteorological Agency	Assimilation of high-resolution sea surface temperature into an eddy-resolving ocean model with a weak-constraint 4D-Var method
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10	**2.2**	Olivier	Goux	CERFACS	Accounting for correlated observation error in variational ocean data assimilation: application to wide-swath altimeter data

11	**2.3**	Anthony	Weaver	CERFACS	A scale-dependent hybrid background-error covariance model for global ocean data assimilation
DA - 3	**Algorithm development in support of data assimilation**				
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13	**3.2**	Matthew	Martin	Met Office	Assessing the impact of assimilating Total Surface Current Velocities in global ocean forecasting systems.
14	**3.3**	Andrea	Storto	CNR ISMAR	Assimilation of high-sampling rate altimetry for sea level studies in the Nordic Seas and Arctic Ocean
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21	**5.5**	Shastri	Paturi	Axiom@NOAA/NWS/NCEP/EMC	Towards a WCDA system for the GFSv17 at NCEP: Preliminary results for the ocean and sea-ice

22	**5.6**	Siva Reddy	Sanikommu	KAUSt	A Hybrid Ensemble Biogeochemical Data Assimilation System for the Red Sea: Development, Implementation and Evaluation
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DA – 1

Advances in DA methods (ensembles, algorithms, machine learning, downscaling, …)

Abstract 1.1: Sébastien Barthélémy, University of Bergen – ORAL (cat: DA - 1)

Hybrid covariance super-resolution data assimilation

Sébastien Barthélémy[1,3], Julien Brajard[2,3,4], Laurent Bertino[2,3], François Counillon[1,2,3]

[1]University of Bergen, Bergen, Norway
[2]Nansen Environmental and Remote Sensing Center, Bergen, Norway
[3]Bjerknes Center for Climate Research, Bergen, Norway
[4]Sorbonnes Université, Paris, France

This work extends the concept of "Super-resolution data assimilation" (SRDA, Barthélémy et al. 2022)) to the case of mixed-resolution ensembles pursuing two goals: (1) emulate the Ensemble Kalman Filter while (2) benefit from high-resolution observations. The forecast step is performed by two ensembles at two different resolutions, high and low-resolution. Before the assimilation step the low-resolution ensemble is downscaled to the high-resolution space, then both ensembles are updated with high-resolution observations. After the assimilation step, the low-resolution ensemble is upscaled back to its low-resolution grid for the next forecast. The downscaling step before the data assimilation step is performed either with a neural network, or with a simple cubic spline interpolation operator. The background error covariance matrix used for the update of both ensembles is a hybrid matrix between the high and low resolution background error covariance matrices. This flavor of the SRDA is called "Hybrid covariance super-resolution data assimilation" (Hybrid SRDA). We test the method with a quasi-geostrophic model in the context of twin-experiments with the low-resolution model being twice and four times coarser than the high-resolution one. The Hybrid SRDA with neural network performs equally or better than its counterpart with cubic spline interpolation, and drastically reduces the errors of the low-resolution ensemble. At equivalent computational cost, the Hybrid SRDA outperforms both the SRDA (8.4%) and the standard EnKF (14%). Conversely, for a given value of the error, the Hybrid SRDA requires as little as 50% of the computational resources of the EnKF. Finally, the Hybrid SRDA can be formulated as a low-resolution scheme, in the sense that the assimilation is performed in the low-resolution space, encouraging the application of the scheme with realistic ocean models.

Abstract 1.2: Pierre Brasseur, CNRS – ORAL (cat: DA - 1)

Ensemble analysis and forecast of marine ecosystems in the North Atlantic using ocean colour observations and prior statistics from a stochastic NEMO-PISCES simulator

Popov Mikhail, Capet Arthur, Brankart Jean-Michel, Cosme Emmanuel and Brasseur Pierre

The ocean analysis and forecasting systems operated in the OceanPredict community routinely deliver information about the "Green Ocean" based on satellite and *in situ* data combined with coupled physical-biogeochemical models. A key scientific question today is how to generate robust information on the uncertainties of estimated quantities, whether in real time, in delayed mode (reanalyses) and in forecast mode with a few days of lead time. In that perspective, a necessary step is the transition to probabilistic/ensemble methodologies, with the aim to provide more actionable information to help in decision-making and management of marine ecosystems.

In the framework of the H2020 SEAMLESS project, we have developed a new 4D, ensemble-based inverse approach that can be implemented in smoother-like mode over a time interval of several months. The algorithm is built on a separation between the prior ensemble generation which relies on the full model complexity, and the posterior pdf computation which makes the inverse problem simpler and avoids re-initialization and time-integration of the full coupled model within the assimilation period. Two options are available to compute the posterior ensemble distribution: one using a linear algorithm (LETKF), and one using a nonlinear iterative algorithm (MCMC sampler). Both options require applying anamorphic transformations given the non Gaussian nature of the problem.

The assimilation method has been implemented in regional sectors of the North Atlantic basin using L3 ocean colour data and a stochastic version of the NEMO-PISCES model in a global ¼° configuration. A prior 40-member ensemble is simulated based on stochastic parameterizations of uncertainty sources arising from (i) 7 critical biogeochemical model parameters of the PISCES formulation; (ii) sub-grid scale effects associated to the ¼°, eddy-permitting resolution, and (iii) the location of ocean mesoscale structures and associated advective/diffusive fluxes (Garnier et al., 2016; Leroux et al., 2022). The resulting ensemble represents a probabilistic view of the 2019 seasonal cycle of biogeochemical variables.

The posterior distribution is computed globally in time for model state variables related to surface chlorophyll concentration, as well as for a variety of targeted ecosystem indicators (e.g. NPP, phenology, trophic efficiency). In order to evaluate the relevance of the ensemble pdfs with respect to observed data, verification statistics are produced using the EnsScores library to check the consistency against L4 satellite products. The computed metrics include rank histograms, CRPS (decomposed into reliability and resolution skill scores) and RCRV.

In this presentation, we will discuss a variety of diagnostics including ensemble scores for phenology, trophic efficiency and downward flux of organic carbon, highlighting situations where the prior ensemble is consistent with uncertainty hypotheses made in the stochastic NEMO-PISCES model. We will further discuss the performances of the 4D inversion scheme to deliver probabilistic forecasts with a few days of lead time. We will finally show that such a 4D statistical analysis and forecast scheme can be seen as an additional by-product of an operational system which can be obtained at negligible cost as compared to ensemble simulations.

Garnier F., Brankart J.-M., Brasseur P. and Cosme E., 2016: Stochastic parameterizations of biogeochemical uncertainties in a 1/4° NEMO/PISCES model for probabilistic comparisons with ocean color data, J. Mar. Systems, 155, 59-72, https://doi.org/10.1016/j.jmarsys.2015.10.012

Leroux S., Brankart J.M., Albert A., Brodeau L., Molines J.M., Jamet Q., Le Sommer J., Penduff T., and Brasseur P., 2022: Ensemble quantification of short-term predictability of the ocean dynamics at kilometric-scale resolution: a Western Mediterranean test case, Ocean Sci., 18, 1619–1644, https://doi.org/10.5194/os-18-1619-2022.

Abstract 1.3: Andrea Cipollone, CMCC – ORAL (cat: DA - 1)

Joint assimilation of sea-ice concentration and thickness from remotely-sensed observations

Andrea Cipollone, Deep Sankar Banerjee, Doroteaciro Iovino, Ali Aydogdu, Simona Masina

CMCC

Despite the availability of different types of sea-ice remotely-sensed observations in the last decade, their joint assimilation in a multivariate framework is still an active research field. The reasons can be sought in the peculiar aspects of sea-ice variables that prevent a smooth ingestion in global analysis/reanalysis systems already in place. Sea-ice variables generally follow a bounded distribution that can peak over one of the two boundary values. Thickness measurements show limited accuracy (*Zygmuntowska et al., The Cryosphere, 8, 705–720, 2014*) with CryoSat-2 data providing high signal-to-noise ratio only for thick sea-ice, while SMOS data for thin one. Recently it has been shown (*Ricker et al., The Cryosphere, 11, 1607–1623, 2017)* that such datasets are complementary and can be merged yielding to an optimally-interpolated spatially-reconstructed thickness distribution CS2SMOS. However the straightforward ingestion of such maps can produce discontinuities in the sea-ice volume at the onset of the accretion period whether the observation errors are not properly tuned, thus spoiling the seasonal variability.

In this presentation we describe a new sea-ice module embedded in our 3DVar scheme (OceanVar) employed in the routinely production of CMCC global/regional analysis/reanalysis. Sea-ice concentration (SIC) and thickness (SIT) are treated through an anamorphosis operator that is included in the control vector transformation composing the B matrix. We showed that such transformation is also able to preserve the strong anisotropy of sea-ice fields close to sea-ice edge, thus helping future coupling with ocean variables.

A suite of global ocean/sea-ice experiments with different DA setup will be compared and discussed. The sole assimilation of SIC data provides a positive but small improvement in the representation of thickness field that can be potentially degraded in the case that the error assigned to SIC data is too small. The intermittent availability of SIT data along the year, together with the lack of off-diagonal elements in the R matrix, can generate jumps in the total volume that can spoil the seasonal variability and requires extra tuning. An independent validation against mooring data is also carried out showing that the joint initialization of SIT and SIC outperforms the other set up during the melting period, where no satellite thickness data are available (*Cipollone et al. 2023, submitted to Ocean Science*).

Abstract 1.4: Andy Moore, UCSC– ORAL (cat: DA - 1)

Weak Constraint 4D-Var Data Assimilation in the Regional Ocean Modeling System (ROMS) using a Saddle-Point Algorithm

Andrew M. Moore[1], Hernan G. Arango[2], John Wilkin[2] and
Christopher A. Edwards[1]

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2: Department of Marine and Coastal Sciences, Rutgers, The State University of New Jersey,
71 Dudley Road, New Brunswick NJ 08901

The saddle-point formulation of weak constraint 4-dimensional variational (4D-Var) data assimilation has been developed for the Regional Ocean Modeling System (ROMS) and is applied here to the California Current System (CCS). Unlike the conventional primal and dual forcing formulation of weak constraint 4D-Var, the saddle-point formulation can be efficiently parallelized in time which can lead to a substantial increase in efficiency. The performance of the ROMS saddle-point algorithm is assessed here and compared to that of the dual forcing formulation which is the current standard in ROMS. While the rate of convergence of the saddle-point formulation is slower than the dual forcing formulation, the increase in computational speed due to time-parallelization more than compensates for the additional inner-loop iterations required by the saddle-point algorithm in the CCS configuration considered here. Additional increases in performance can be achieved by running the 4D-Var inner-loop iterations at reduced resolution and/or reduced arithmetic precision. The results presented here indicate that in high performance computing environments, the saddle-point formulation of 4D-Var could significantly out-perform the forcing formulation for large data assimilation problems.

Abstract 1.5: Jozef Skalala, PML – ORAL (cat: DA - 1)

Uncertainty and observability of target ecosystem indicators within the operational system on the North-West European Shelf

Jozef Skalala

PML

We developed biogeochemical ensembles within the research and development (R&D) version of the coupled physical-biogeochemical operational system on the North-West European Shelf (NWES). Based on the ensembles we analyse the uncertainty of a selected set of target ecosystem indicators, such as net primary production, phytoplankton phenology and community structure, near-bottom oxygen, particulate organic carbon (POC) fluxes, trophic efficiency and pH. Performing data assimilation experiments with recently developed ensemble-3DVar system we determine how observable are these target indicators with the standard set of observations for surface total chlorophyll derived from the ocean color satellite data. Some conclusions for how to improve the target indicator observability are being discussed.

Abstract 1.6: Charles-Emmanuel Testut, MOi – ORAL (cat: DA - 1)

Towards a Mercator reanalysis and forecasting system using an Ensemble Kalman Filter

Testut Charles-Emmanuel[1], Giovanni Ruggiero[1], Mathieu Hamon[1], Laurent Parent[1], Jean-Michel Lellouche[1], Aliette Chenal[1,2] and Gilles Garric[1]

[1]*Mercator Ocean International, Toulouse, France*
[2]*CNES, Toulouse, France*

Mercator Ocean International (MOI) is in charge of the development and of the production of real time analysis and forecasts and reanalysis for the global ocean at the resolution of 1/12°. The current operational systems are all based on the ocean (NEMO3.6) and sea ice model (LIM3) and the multivariate data assimilation system SAM2 (Système d'Assimilation Mercator V2). The assimilation method is a reduced order Kalman filter based on SEEK/LETKF formulation with bias correction scheme for temperature and salinity and an Incremental Analysis Update. The background error covariance is represented by an ensemble of multivariate state vectors defining a subspace of the control space. However, the SAM2 background error statistics are built using a static approach based on a prior long multi-year free simulation.

Since few years, a new MOI system is under development coupled to more recent Nemo version (NEMO4.2) and using Ensemble approach based on LETKF scheme. The ensemble model simulations are based on method using stochastic perturbations of model parameters which are implemented in NEMO. The uncertainties have been tuned to represent the growing errors after the analysis but also to provide relevant extended forecast over a few weeks. An adaptative scheme is applied to improve internal statistical consistency of the analysis.

We will present recent technical and scientifical developments concerning the set-up of this future MOI System. With this framework, various hindcast experiments have been produced using a global sea-ice and ocean configuration at 1/4°. Finally, results and inter comparisons from free simulation, deterministic and ensemble data assimilation experiments will be presented.

Abstract 1.7: Norihisa Usui, MIR-JMA – ORAL (cat: DA - 1)

Assimilation of high-resolution sea surface temperature into an eddy-resolving ocean model with a weak-constraint 4D-Var method

Norihisa Usui, Nariaki Hirose, Yosuke Fujii, Ichiro Ishikawa

Meteorological Research Institute, Japan Meteorological Agency

Many ocean data assimilation systems use gridded sea surface temperatures (SSTs) produced by statistical interpolation methods such as the optimal interpolation. Such gridded SSTs are, however, spatio-temporally smoothed. Therefore, it is desirable for high-resolution assimilation systems to assimilate satellite Level-2 data directly, rather than the gridded data. In this study, we developed a method to analyze the SST field with high accuracy within the framework of the four-dimensional variational (4D-Var) method. In 4D-Var assimilation systems at eddy-resolving resolution, the assimilation window is usually set to about 10 days, and increments to the initial condition is optimized by minimizing the cost function. Although this setting is reasonable for analysis of ocean internal variations such as changes in ocean current and ocean internal temperature, it would not be appropriate for SST because the SST variability is influenced not only by the oceanic internal dynamics but also by the atmospheric forcing. In this study, we propose a new scheme based on weak-constraint 4D-Var to reproduce detailed spatial-temporal SST variations with guaranteed reproducibility of ocean internal variations. In the new scheme, daily SST increments within the assimilation window are added to control variables, and they are assumed to be independent from other control variables such as temperature and salinity increments to the initial condition. We implemented this scheme into the Meteorological Research Institute Multivariate Ocean Variational

Estimation (MOVE) system and conducted an experiment to assimilate Himawari SST together with altimeter data and in-situ temperature and salinity. In addition to details of the developed scheme, early results of the assimilation experiment will be presented.

Abstract 1.8: Yue Ying, NCAR – ORAL (cat: DA - 1)

Improving vortex position accuracy with a new multiscale alignment ensemble filter

Yue (Michael) Ying[1], Jeffrey Anderson[1], Laurent Bertino[2]

[1] *NCAR*
[2] *NERSC*

A multiscale alignment (MSA) ensemble filtering method was introduced by Ying (2019) to reduce nonlinear position errors effectively during data assimilation. The MSA method extends the traditional ensemble Kalman filter (EnKF) to update states from large to small scales sequentially, during which it leverages the displacement vectors derived from the large-scale analysis increments to reduce position errors at smaller scales through warping of the model grid. This study stress-tests the MSA method in various scenarios using an idealized vortex model. We show that the MSA improves filter performance as number of scales (Ns) increases in the presence of nonlinear position errors. We tuned localization parameters for the cross-scale EnKF updates to find the best performance when assimilating an observation network. To further reduce the scale mismatch between observations and states, a new option called MSA-O is introduced to decompose observations into scale components during assimilation. Cycling DA experiments show that the MSA-O consistently outperforms the traditional EnKF at equal computational cost. A more challenging scenario for the MSA is identified when the large-scale background flow and the small-scale vortex are incoherent in terms of their errors, making the displacement vectors not effective in reducing vortex position errors. Observation availability for the small scales also limit the use of large Ns for the MSA. Potential remedies for these issues are discussed.

DA – 2

Error covariance modelling (B, Q and R, hybrid approaches)

Abstract 2.1: Sébastien Barthélémy, University of Bergen – ORAL (cat: DA - 2)

Adaptive covariance hybridization for coupled climate reanalysis

Sébastien Barthélémy[1,3], François Counillon[1,2,3], Yiguo Wang[2,3]

[1]University of Bergen, Bjerknes Center for Climate Research, Bergen, Norway
[2]Nansen Environmental and Remote Sensing Center, Bjerknes Center for Climate Research, Bergen, Norway

Because of their very heavy computational burden, climate prediction systems that use ensemble data assimilation methods can afford only a few tens of members. Sampling error in the covariance matrix can introduce biases in the unobserved regions (e.g. in the deep ocean). Here, we assess the potential of hybrid covariance approach (EnKF-OI, Hamill and Snyder 2000) to counteract sampling error. The EnKF-OI combines the dynamical covariance to that of a large static/historical covariance (EnOI). We use the Norwegian Climate Prediction Model (NorCPM), which combines the Norwegian Earth System Model (NorESM) and the Ensemble Kalman Filter (EnKF) in an idealized twin experiment. We test the performance of reanalyses that assimilate synthetic SST observations monthly for the period 1980-2010. We use a dynamical ensemble of 30 members and a static ensemble size of 315 members sampled from a long stable pre-industrial run. We compare the performance of the EnKF to 1) an EnKF-OI with a global hybrid coefficient tuned empirically and 2) an EnKF-OI adaptive, with hybrid coefficient explicitly estimated in space and time (Ménétrier and Auligné, 2015). In the adaptive EnKF-OI, the hybrid coefficient remains stable through the course of the reanalysis with only a weak seasonal variability. Both EnKF-OI versions show comparable performance and cure the emergence of a bias in the deep ocean in the EnKF. The assimilation updates with the EnKF-OI adaptative are smaller, suggesting that it sustains a lower error level in between the assimilation cycle.

Abstract 2.2: Oliver Goux, CERFACS – ORAL (cat: DA - 2)

Accounting for correlated observation error in variational ocean data assimilation: application to wide-swath altimeter data

Oliver Goux

CERFACS

In variational data assimilation, the analysis is obtained by minimizing iteratively a cost function measuring the weighted least-square fit of an estimate of the state of the system to the background state and to the observations. The weights are determined by the respective error covariance matrices of the background and observations, **B** and **R**. In order to avoid explicitly building these matrices, the cost function is minimized using a **B**-preconditioned Conjugate Gradient, which only

involves matrix-vector products with **B** and $\mathbf{R}^{-1}$. While **B** has been thoroughly studied and is well represented in current data assimilation system, **R** is generally assumed to be diagonal to simplify the access to its inverse.

This assumption is not appropriate for all observation types, and is especially suspicious for high resolution satellite data. Not accounting for existing correlations in the observation error leads to overfitting of the observations at large spatial scales and underfitting them at small spatial scales. Common mitigation techniques involve thinning, *i.e.*, assimilating only a subset of distant observations, and artificially inflating variances to reduce the overfit at large scales (which amplifies the underfit at small scales). Both methods are detrimental to the extraction of small-scale features from the observations and limit the potential of high-resolution observations.

In order to use high resolution observations at their full potential, data assimilation algorithms need to be able to account for observation error correlations. In particular, we take the example of the SWOT mission, due to be launched in November 2022. SWOT will carry a wide swath altimeter which will provide sea level anomaly measurements at an unprecedented resolution. However, the error budget suggests that its observation error will contain substantial long range spatial correlations. Using simulated data from the JPL/CNES SWOT simulator, we characterize these correlations and suggest a method based on diffusion operators to account for them in variational data assimilation. Diffusion operators, originally designed to model correlations in **B**, have been recently adapted for observation error correlations. They provide an easy access to the inverse operator $\mathbf{R}^{-1}$ at a low computational cost even for large datasets and are suitable for unstructured data such as observations.

Abstract 2.3: Anthony Weaver, CERFACS – ORAL (cat: DA - 2)

A scale-dependent hybrid background-error covariance model for global ocean data assimilation

Anthony Weaver
CERFACS, Toulouse

Marcin Chrust
ECMWF, Reading

Ocean data assimilation systems are being applied to models with increasingly higher resolution and are incorporating observations, such as wide-swath altimetry, with unprecedented resolution. These advances have driven a need to adapt ocean data assimilation systems to be more effective at extracting information at multiple spatial scales. This presentation describes developments to the NEMOVAR ocean data assimilation system to account for scale dependency in ensemble formulations of the background-error covariance matrix (**B**). The approach taken is inspired by earlier work on Scale-Dependent covariance Localization (SDL). In the current work, the basic formulation of the SDL matrix is used to define a Scale-Dependent covariance Model (SDM). In turn, SDM can be combined with SDL to form a Scale-Dependent Hybrid covariance matrix (SDH). Different aspects of the methodology will be discussed including scale separation, scale-dependent covariance parameter estimation, normalization, and computational cost. The new multi-scale **B** formulation will be compared to the standard "single-scale" **B** formulation using single observation experiments and multi-year experiments with a global ¼ degree ocean model.

DA – 3

Algorithm development in support of data assimilation

Abstract 3.1: Azevedo Correia de Souza, Meteorological Service of New Zealand – ORAL (cat: DA - 3)

Assimilating innovative subsurface observations into an ocean forecast system: How fishers made the forecast better

Joao M. A. C. Souza, Colette Kerry, Julie Jakoboski

Meteorological Service of New Zealand

New Zealand has the 9th largest oceanic Economic Exclusive Zone and is the 52nd-largest national economy in the world. Therefore, it is key to efficiently use resources to support the development of a blue economy that is sustainable and resilient to climate change. While the seafood sector alone brings $4.18B to NZ annually, oil and gas offshore exploration provides about 30% of the country's consumption. Having a robust representation of the ocean dynamics allied with a reliable forecast system is strategic for the country's economy, environmental safety and resilience, and the community. The Moana project's objective is to provide state-of-the-art science to revolutionie ocean observing and modelling in New Zealand to support the Blue Economy by providing accurate ocean observations, models and data products. We are building a robust view of the past ocean behaviour to improve the understanding of the drivers of variability that impact ocean activities, such as commercial fishing and aquaculture. But to do this in an efficient way we need to partner with the communities that have been exploring these very resources for centuries, and we need to observe the ocean. By developing a new cost-effective water temperature and pressure sensor – the Mangōpare sensor – and deploying it in partnership with the fishing industry we built a new "nationwide ocean observing capability". This represents a step change in the availability of observations around New Zealand, roughly tripling the volume of sub-surface data in near-real-time and covering the shallow areas that Argo floats cannot reach. These observations are assimilated into our open-access ocean models to understand the past – reanalysis - and provide forecasts for the near future (7 days), increasing our capacity to plan and respond to emergencies and changes in the ocean environment. Here we present our forecast system based on a 4DVar data assimilative ocean model for New Zealand and results from Observing System Simulation Experiments to evaluate the contribution of the new temperature observations.

Abstract 3.2: Matthew Martin, Met Office – ORAL (cat: DA - 3)

Assessing the impact of assimilating Total Surface Current Velocities in global ocean forecasting systems

Matthew Martin[1], Jennifer Waters[1], Elisabeth Remy[2], Isabelle Mirouze[2], Lucile Gaultier[3], Clement Ubelmann[4], Robert King[1].

[1] Met Office, UK
[2] Mercator Ocean International, France
[3] OceanDataLab, France
[4] DATLAS, France

Accurate prediction of Total Surface Current Velocities (TSCV) are valuable for coupled ocean-atmosphere forecasting and applications such as shipping, search and rescue and offshore oil and gas operations. Presently, observations of surface velocities are not routinely assimilated in global ocean forecasting models, largely due to limited observation availability. New satellite concepts with the capability to observe TSCV are now being proposed. The aim of the ESA A-TSCV project is to focus on the design and implementation of TSCV assimilation and to report on the impact of the assimilation. The findings from this project will be used to develop requirements from the ocean forecasting community for future satellite missions.
The A-TSCV project has implemented a set of coordinated observing system simulation experiments (OSSEs) to test the assimilation methodology for TSCV data. We have used two operational global ocean forecasting systems at ¼ degree: the FOAM system run at the Met Office and the Mercator Ocean system. Synthetic observations were generated for all standard observation types (sea surface temperature, sea-ice concentration, sea level anomaly and profiles of temperature and salinity) from a 1/12th degree free running nature run. In addition, TSCV observations expected from a Sea surface KInematics Multiscale monitoring (SKIM) like satellite are simulated.
This presentation will provide an update on the final results of the project which is due to finish soon. We will provide a brief description of the data assimilation developments for global assimilation of satellite TSCV data and the results of the OSSEs from the two data assimilation systems which demonstrate the impact of TSCV assimilation. A discussion of the implications of these results for setting requirements for TSCV data from ocean forecasting systems will be included.

Abstract 3.3: Andrea Storto, CNR ISMAR – ORAL (cat: DA - 3)

Assimilation of high-sampling rate altimetry for sea level studies in the Nordic Seas and Arctic Ocean

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The inter-annual changes of the Arctic Ocean features are well-known proxies of global climate change, affecting the global climate through specific processes (e.g. dense water formation, meridional heat redistribution). The ocean circulation at high latitudes has significantly changed during recent decades, with an enormous impact on the socio-economic activities of the Nordic populations. Monitoring the Arctic environment is however non-trivial: the Arctic observing network is notably lacking the capability to provide a full picture of the changing ocean due to technological and economical limitations to sample the seawater beneath the ice or in the marginal ice zones. This leads to the obvious need of optimizing the exploitation of data from space-borne sensors. Among

these, altimetric radars measuring the sea level at millimetric precision have revolutionized our knowledge of the oceanic circulation, for more than 2 decades, at a large spectrum of scales ranging from the mesoscale activity to the slowly varying basin-wide dynamics. Technological solutions are continuously needed and pursued to enhance the spatial resolution of the altimetric signal and enable the solution of the mesoscale dynamics, either in the design of the altimeter itself (e.g. wide-swath altimeters) or in the combined use of altimeter data from multiple bands.
Newly reprocessed along-track measurements of Sentinel-3A, CryoSat-2, and SARAL/AltiKa altimetry missions (AVISO/TAPAS), optimized for the Arctic Ocean (retracking) and sampled at 5 Hz, have been recently produced in the framework of CNES AltiDoppler project. This study is devoted to the exploitation of such satellite altimetry data in high-latitude regions. We investigate the benefits of the reprocessed altimetry dataset at 5 Hz with augmented signal resolution in the context of ocean and sea-ice coupled short-range forecasts. In particular, we compare the effectiveness of this dataset to improve the mesoscale details of the forecasts in comparison to the conventional altimetry sampling dataset and the altimetry-blind experiments, to assess the added value of the enhanced altimetry reprocessing in Nordic Seas. This has in turn non-negligible impact on the high-latitude heat transports, whose mesoscale eddy component is enhanced. This comparison can motivate the assimilation of the high-resolution altimetry data in ocean re-analysis for the Arctic.

DA – 4

Hybrid data assimilation methods

Abstract 4.1: Hernan Arango, Rutgers University – ORAL (cat: DA - 4)

Introducing the ROMS-JEDI Interface

Hernan G. Arango[1], Andrew A. Moore[2], and John L. Wilkin[1]

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We will discuss the ROMS integration into JEDI as an alternative to advanced data assimilation applications. The adjoint-based algorithms have been available in ROMS for more than a decade (Moore *et al.*, 2004; 2011a, b, c; 2013; 2017). In addition to 4D-Var, the Ensemble Adjustment Kalman Filter (EAKF) is also available in ROMS (Moore *et al.*, 2020) with its interface to the DART system (Anderson *et al.*, 2009). Work on the interface to JEDI began in 2021, and all the elemental C^{++} and Fortran-2003 building blocks or object classes for OOPS, SABER, IODA, and UFO have been coded and tested with US West Coast applications. In this preliminary study, we will demonstrate the ROMS-JEDI interface progressively from 3D to 4D variational data assimilation: 3D-Var, hybrid 3D-Var, 3D-FGAT, 4D-Var, and hybrid 4D-Var. When possible, we will compare the ROMS-JEDI against the native ROMS 4D-Var solutions.

DART	Data Assimilation Research Testbed
IODA	Interface for Observation Data Access
JEDI	Joint Effort for Data Assimilation Integration
OOPS	Object-Oriented Prediction System
ROMS	Regional Ocean Modeling System
SABER	System-Agnostic Background Error Representation
UFO	Unified Forward Operator
YAML	YAML Ain't Markup Language

Abstract 4.2: Lars Nerger, AWI – ORAL (cat: DA - 4)

Ensemble Data Assimilation in NEMO using PDAF

Lars Nerger[1], Yuchen Sun[1], Wibke Düsterhöft-Wriggers[2], Yumeng Chen[3], Dale Partridge[4]

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NEMO itself does not provide full functionality for data assimilation. To enable data assimilation with NEMO, it was coupled with the Parallel Data Assimilation Framework (PDAF, https://pdaf.awi.de).

PDAF is open source software providing generic functionality for data assimilation (ensemble filters and smoothers, and variational schemes) as well as ensemble simulations, related diagnostics and tools. For computational efficiency the coupling to NEMO was performed by inserting a few subroutines in higher-level routines of NEMO, which call functions of PDAF. This scheme allows for an in-memory exchange of model fields with the data assimilation software, which lets us avoid excessive file outputs and model restarts. Alternatively, an offline-coupling using disk files is possible. Next to the NEMO ocean physics, also components like the sea ice or biogeochemical models can be handled, which allows for fully multivariate data assimilation. In addition, model parameters can be included in the data assimilation.

We discuss the structure and functionality of the implementation with a focus on ensemble filters. The application is exemplified using a setup of NEMO with the biogeochemistry model ERGOM configured at high resolution for the Baltic Sea *and a global eORCA1 configuration coupled with the FABM-MEDUSA biogeochemistry model*.

DA – 5

Coupled data assimilation

Abstract 5.1: Santha Akella, NASA – ORAL (cat: DA - 5)

Correlations across the air-sea interface for variables without direct analogs

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Error covariance information is essential for Data Assimilation (DA) and uncertainty quantification. However, this information is unavailable from nature, since we are presented with only one realization of the earth system trajectory, as opposed to many trajectories. In practice this information is either explicitly *calculated* using ensembles (though suffering from sampling errors), or alternatively *guessed (or specified)* as climatological relationships: former being the case in ensemble DA and latter in variational DA. While these approaches are common and serve as the basis for many DA systems, how do they extend to the case of Earth System Analyses (ESAs) with multiple components in a Coupled DA (CDA)? In this presentation I will focus on the correlations across components.

Most CDAs can be classified into either so-called *weakly* or *strongly* coupled, where cross-component correlations are entirely neglected or fully considered (I consider correlations at analysis time only, hence implicit generation of cross-component correlations via coupled model integration are not part of this study). Regardless of whether the CDA is *weak* or *strong*, any Earth System Model (ESM) has state variables that are directly connected across the coupling interface(s). For example, consider atmosphere-ocean ESA: atmospheric air temperature with surface and sub-surface temperature; winds with currents; sea level pressure and sea surface height (more generally pressure at any depth in the ocean), I refer to these as direct analogs. In contrast indirect analogs also exist, for example, atmospheric specific humidity or precipitation and ocean salinity; atmospheric air temperature and sea ice thickness. Only the strong CDA allows a treatment of correlations among all such variables. In this study I will demonstrate how such correlations for direct and indirect analogs vary when the ocean model vertical resolution changes (from coarse to fine). Specific focus will be on oceanic variables such as the sea surface temperature (SST), sea surface salinity (SSS) and sea surface height (SSH)- all of which can be constrained using a significant amount of available satellite data. It is expected that understanding the nature of such cross-component correlations will improve formulation of CDAs and implementation of ESA.

Abstract 5.2: Dan Lea, Met Office – ORAL (cat: DA - 5)

Adding ocean ensemble capability to the Met Office coupled NWP system

Daniel Lea[1], Matthew Martin[1], Jonah Roberts-Jones[1], Warren Tennant[1], Chris Harris[1], Martin Price[1], James While[1]

[1]*Met Office*

The Met Office coupled Numerical Weather Prediction (NWP) system uses weakly coupled data assimilation and the deterministic forecast uses a coupled model at N1280 (~10 km) resolution in the atmosphere and about 1/4 degree resolution in the ocean and sea-ice. A coupled ensemble is run with lower N640 (~20 km) atmospheric resolution, and the same ocean and sea-ice resolution as is used in the deterministic system. The atmospheric data assimilation is an ensemble of data assimilations (EDA) applying hybrid 4DEnVars to each member but in the ocean, at present, there is no ensemble data assimilation included and each ocean ensemble member is initialised using the deterministic ocean analysis. Additional perturbations, though, are added to the SSTs seen by the atmospheric ensemble members.

To add the ocean ensemble to the NWP system we updated the ocean model, NEMO to include stochastic model perturbations. An EDA approach is used whereby each ensemble member runs its own, 3DVar in this case, ocean data assimilation with perturbed observation values and locations. The system is capable of running hybrid-3DEnVar, whereby the background error covariances used in the data assimilation are a linear combination of the existing modelled error covariance and an ensemble-based error covariance. An ensemble inflation scheme based on the Relaxation to Prior Spread (RTPS) method is added to the ocean/ice ensemble system.

Here we present some results of 3 month trials of the coupled NWP system. To reduce computational cost, the atmosphere is run at lower resolution of N640 (deterministic) and N320 (ensemble) with the ocean resolution still 1/4 degree. We look particularly at the impact on the atmosphere including ensemble diagnostics like the CRPS (Continuous Reliability Probability Score). We also assess the performance of the ocean component and show that the ocean ensemble produces a reliable forecast (as has previously been shown in an ocean-only version of the system).

Abstract 5.3: Xiao Liu, SAIC @ NOAA/NWS/NCEP/EMC – ORAL (cat: DA - 5)

JEDI-based ocean color data assimilation for NOAA/NCEP's Unified Forecast System

Xiao Liu[1] (Xiao.Liu@noaa.gov), Avichal Mehra[2], Guillaume Vernieres[2], Daryl Kleist[2], Travis Sluka[3], Shastri Paturi[4], Hae-Cheol Kim[1], Eric Bayler[5]

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Ocean biogeochemical processes provide important geophysical feedback to the weather and climate systems through complex ocean biophysical and air-sea interactions. In recent years, multi-platform satellite observations provide nearly global coverage of surface ocean color with repeating daily cycles, enabling the assimilation of near real-time ocean color products (e.g. Chl-a, POC, Kd) in operational ocean forecast systems. Here we present the methodology and techniques to implement a JEDI-based assimilation of multi-source ocean color products in NOAA/NCEP's Unified Forecast

System (UFS) - a preoperational, fully coupled Earth modeling and prediction system. We conducted a suite of multi-year ocean analysis experiments with the system and evaluated the impact of ocean color data assimilation on ocean state predictions with a particular focus on skills at timescales of weeks to months. This work is in support of NOAA/NCEP's subseasonal to seasonal prediction project.

Abstract 5.4: Lars Nerger, AWI – ORAL (cat: DA - 5)

Coupled assimilation of satellite temperature and chlorophyll observations for improved ecosystem predictions in the Baltic Sea

Yuchen Sun, Sophie Vliegen, Lars Nerger

Alfred Wegener Institut, Bremerhaven, Germany

The CMEMS Monitoring and Forecasting Center for the Baltic Sea (BAL-MFC) uses NEMO coupled to ERGOM to compute reanalysis and forecasts for the Baltic Sea. Operationally, in situ observations of nutrients and oxygen are assimilated using the parallel data assimilation framework (PDAF, https://pdaf.awi.de) using a fixed ensemble read from model snapshots. In the EU-project SEAMLESS, the operational model setup builds the basis for enhancements by a fully dynamical data assimilation approach. For this, the coupled NEMO-ERGOM model system is augmented by the data-assimilation functionality of PDAF and NEMO-ERGOM is run in ensemble mode. Using an ensemble of 30 members, satellite surface temperature and chlorophyll observation are assimilated daily. We assess the impact of the assimilation on the forecast skill with a focus on the biogeochemical variables. In addition, additional ecosystem indicators, like tropic efficiency, pH, and phytoplankton community structure are analyzed. The developments on the data assimilation system are in wide parts generic and can also be applied with other model configurations or components. While the developments in SEAMLESS are independent from the BAL-MFC operational developments, it is planned to make them available to the operational service.

Abstract 5.5: Shastri Paturi, NOAA – ORAL (cat: DA - 5)

Towards a WCDA system for the GFSv17 at NCEP: Preliminary results for the ocean and sea-ice

Shastri Paturi[1], Guillaume Vernieres[2], Andrew Eichmann[3], Jakir Hossen[3], Hyun-Chul Lee[3], Xiao Liu[4], Travis Sluka[5], Daryl Kleist[2]

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The next planned upgrade for the Global Forecast System (GFS) for medium range and subseasonal-to-seasonal (S2S) forecast (GFSv17) is currently under development. One of the major differences with the current operational application (GFSv16) will be the use of a dynamically coupled forecast model. The coupled components will include the use of the Modular Ocean Model version 6 (MOM6)

for the ocean, the Los Alamos Sea-ice model version 6 (CICE6) for sea ice, and WAVEWATCHIII for waves. The land model will also be upgraded to the Noah-multi parameterization land surface model (noah-pm). The marine and land components will be initialized using the Joint Effort for Data Assimilation Integration (JEDI) system.

Here we present an overview and preliminary results of the Weakly Coupled Data Assimilation (WCDA) prototype of the GFSv17. The prototype uses a forecast model which is ½ the resolution of the operational atmospheric model (c384) and 0.25 deg for the ocean and sea-ice. Results will focus on the ocean and sea ice.

Abstract 5.6: Sivareddy Sanikommu, KAUST – ORAL (cat: DA - 5)

A Hybrid Ensemble Biogeochemical Data Assimilation System for the Red Sea: Development, Implementation and Evaluation

Sivareddy Sanikommu, Mohamad El Gharamti, Yixin Wang, Matthew Mazloff, Ariane Verdy, George Krokos, Rui Sun, Aneesh Subramanian, Benjamin K. Johnson, Angela Kuhn Cordova, Bruce Cornuelle, and Ibrahim Hoteit

A Hybrid ensemble system is implemented for data assimilation (DA) into coupled physical-biogeochemical ocean model of the Red Sea. The system comprises a Massachusetts Institute of Technology general circulation model (MITgcm) coupled with the Nitrogen-version of the Biologeochemistry, Light, Iron, Nutrients and Gases (N-BLING) model, both configured at 4km-resolution. The assimilation is based on the Data Assimilation Research Testbed (DART) and combines a time-varying ensemble generated using the Ensemble Adjustment Kalman filter (EAKF) with a pre-selected quasi-static (monthly varying) ensemble. The system is designed to assimilate observations of both physical (satellite sea surface temperature, altimeter sea surface height, and in situ temperature and salinity) and biological (satellite chlorophyll) variables. Two different assimilation experimental settings are tested: (1) Weakly coupled DA in which the physical and biological observations only update their respective states, and (2) Strongly coupled DA in which both the physical and biological observations are used to update both physical and biology states. Sensitivity experiments are conducted to assess the relative impact of assimilating physical and biology observations. The state estimates are evaluated against independent in situ Glider observations of temperature, salinity, chlorophyll, and oxygen. The results indicate that the strongly coupled DA generally performs better than the weakly coupled DA. The improvements are significant particularly in the subsurface layers. We further conducted identical twin experiments using strongly coupled DA with and without assimilating satellite chlorophyll observations to confirm the positive impact of assimilating chlorophyll observations on the estimation of biogeochemical fields.

Abstract 5.7: Zofia Stanley, CIRES/NOAA – ORAL (cat: DA - 5)

Guidance on Localization for Strongly Coupled Atmosphere-Ocean Data Assimilation

Zofia Stanley, Clara Draper, Sergey Frolov, Wei Huang, Laura Slivinski, Jeff Whitaker, Henry Winterbottom

We address the question of how to implement vertical localization in a strongly coupled atmosphere-ocean system, where observations of the atmosphere can directly impact the ocean and vice-versa. Localization serves to mitigate the impact of sampling errors on ensemble-derived estimates of background error covariance matrices and thus a properly specified localization scheme is essential. Vertical localization methods have been developed for multiple earth system components separately. However, guidance on how to localize the cross-domain error covariances used in strongly coupled systems is needed. In this work we use forecasts from a global 1-degree coupled atmosphere-ocean model to inform vertical localization strategies for strongly coupled atmosphere-ocean data assimilation systems. We compare errors associated with several "optimal" localization schemes.

Abstract 5.8: Anna Teruzzi, CIRES/NOAA – ORAL (cat: DA - 5)

One-way coupled physical-biogeochemical 1D data assimilation at basin wide distributed float locations in the Mediterranean Sea

Anna Teruzzi[1], Simone Spada[1], Laura Feudale[1], Stefano Salon[1], Gianpiero Cossarini[1]

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Marine biogeochemical assimilation can considerably benefit from subsurface observations, especially during stratification when biogeochemical processes are confined in the ocean interior. However, biogeochemical sensors are relatively expensive, and the availability of biogeochemical profiles (especially nitrate) is lower when compared to the one of temperature and salinity profiles. With the aim of maximizing available subsurface information, we developed a one-way strongly coupled physical-biogeochemical data assimilation method that updates temperature, salinity and nutrients assimilating temperature and salinity observed by Argo floats. A hybrid approach is adopted: temperature and salinity are updated using ensemble Kalman filter assimilation (EnKF), while a balancing scheme based on pre-computed covariances calculates increments on nutrients. The balancing scheme is based on the physical assimilation increments, and the nutrient increments are provided by precomputed density-nutrient covariances resulting from a statistical analysis on Mediterranean Argo and BGC-Argo floats.
The hybrid one-way strongly coupled physical-biogeochemical assimilation has been implemented in a one-dimensional assimilation tool at the 2019 BGC-Argo float locations in the Mediterranean Sea and compared with a set of alternative settings: an ensemble without assimilation (reference); EnKF assimilation with update of temperature, salinity, and nutrients (pure ensemble); EnKF assimilation with update limited to temperature and salinity (one-way weakly coupled assimilation). Comparing results with BGC-Argo nitrate observations, the one-way weakly coupled assimilation resulted very close to the reference simulation while the EnKF assimilation with updates also on nutrients (pure ensemble) showed a degradation on nitrate metrics. On the contrary, the hybrid one-way strongly coupled assimilation showed positive impacts on nutrients, with reduction of RMSDs with respect to BGC-Argo floats in subsurface layers up o 15%.
The nutrient degradation observed in the pure ensemble assimilation needs further investigation and can be related to non-fully optimized assimilation settings or suboptimal processes. On the other hand, the improvements on nutrient obtained by the balancing scheme seem related to the mitigation of possible discrepancies between assimilated physics and non-assimilated biogeochemistry, suggesting that also three-dimensional applications could benefit from the use of a similar hybrid one-way strongly coupled assimilation.

DA – 6

Use of novel observations and improved use of existing observations

Abstract 6.1: Ali Aydogdu, CMCC – ORAL (cat: DA - 6)

Recent data assimilation developments in the Mediterranean Sea Analysis and Forecasting System (MedFS)

Ali Aydogdu[1], Jenny Pistoia[1], Pietro Miraglio[1], Andrea Cipollone[1], Alessandro Grandi[2], Massimiliano Drudi[2], Emanuela Clementi[1], Simona Masina[1], Nadia Pinardi[3]

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The Mediterranean Sea Analysis and Forecasting System (MedFS) is continuously under development to provide improved ocean state estimates and daily forecasts through the Copernicus Marine Service. Since the beginning of the second phase of Copernicus Marine Service, there have been various upgrades in the data assimilation (DA) component of the MedFS and assimilated observations. MedFS consists of a NEMO-based modelling system coupled with WW3 for improved hydrodynamic representation and it is interfaced to OceanVar, the CMCC 3D variational ocean data assimilation scheme to incorporate observations. Here we present the most important novelties recently included in the operational system which consist in the use of a new observation-based Mean Dynamic Topography (MDT) and a new set of Empirical Orthogonal Functions (EOFs) computed from 35 years of Mediterranean high-resolution reanalysis both covering also the Atlantic side of the domain, as well as the ingestion of Sentinel-6A Sea Level anomaly (SLA) altimeter data. Moreover, we will show the impact of the assimilation of glider observations in the Mediterranean Sea with a focus on the western basin. Finally, we will outline future plans for Copernicus Marine Service towards an improved background representation and observation operators for satellite products.

Abstract 6.2: Marcin Chrust, ECMWF – ORAL (cat: DA - 6)

ECMWF 6th generation ocean and sea-ice reanalysis system (ORAS6)

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Ocean and sea-ice reanalyses are reconstructions of historical ocean and sea-ice states by ingesting observations into simulated model states through data assimilation methods. Reanalysis provides invaluable information for climate monitoring and is an essential component in long-term prediction such as seasonal to decadal forecasts. The Ocean ReAnalysis System-6 (ORAS6) is the 6th generation of ocean and sea-ice reanalysis system developed at ECMWF. Compared with the current ECMWF operational system-5 (ORAS5), the ocean and sea-ice model has been upgraded and is now driven by hourly atmospheric forcing. A new Ensemble-based variational ocean Data Assimilation (EDA) system has been developed. This new EDA system is constructed with a hybrid covariance model that provides flow-dependent background error variances and correlation scales, both of which are critical for better assimilation of sea surface observations.
Direct assimilation of L4 SST observations with ORAS6 EDA system greatly reduces SST biases, especially in critical regions around the Gulf Stream separation. Assimilation of L3 sea-ice concentration data within a multi-category sea ice model has been implemented as well and shows promising results in terms of sea ice spatial distribution and concentration. ORAS6 also includes a new freshwater budget closure scheme which allows to constrain the atmosphere-ocean freshwater fluxes using an external product.
This presentation will feature results from a prototype ORAS6 reanalysis and provide an overview of advances in the data assimilation methodology.

Abstract 6.3: Sergey Frolov, NOAA – ORAL (cat: DA - 6)

Consistent reanalysis: definition, challenges, and opportunities for collaboration

Sergey Frolov

NOAA PSL

Consistent reanalysis is set forth as the decadal aspiration for the U.S. Earth system reanalysis enterprise. This involves consistency in time, across the compartments of the Earth system, in storage access patterns, uncertainty estimates, and metrics for improvements. This presentation will focus on the scientific challenges that such requirement presents for the oceanic and sea ice components of the Earth system reanalysis. The presentation will also describe ongoing infrastructure investments by NOAA and NASA that aim to facilitate collaboration between reanalysis producing centers, including shared archive of Earth system observations and shared infrastructure for reanalysis diagnostics.

Abstract 6.4: Jean-Michel Lellouche, MOi – ORAL (cat: DA - 6)

Evolution of the Copernicus Marine Service global ocean analysis and forecasting high-resolution system: focus on data assimilation updates

Jean-Michel Lellouche[1], Eric Greiner[2], Giovanni Ruggiero[1], Romain Bourdallé-Badie[1], Charles-Emmanuel Testut[1], Olivier Le Galloudec[1], Mounir Benkiran[1], Gilles Garric[1]

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Since October 2016, and in the framework of Copernicus Marine Service, Mercator Ocean International delivers in real-time daily services (weekly analyses and daily 10-day forecasts) with a global 1/12° high resolution (eddy-resolving) system (Lellouche et al., 2018). Oceanic observations are assimilated in the model using a reduced-order Kalman filter method. Along track altimeter Sea Level Anomaly (SLA), satellite sea surface temperature (SST) and sea ice concentration, and in situ temperature and salinity vertical profiles are jointly assimilated to estimate the initial conditions for numerical ocean forecasting. A 3D-VAR scheme is also used to better control the slowly evolving large-scale biases in temperature and salinity.

A major release of this analysis and forecasting system is available since November 2022 with the following main changes and updates:

- A new version of NEMO ocean and sea ice models (new numerical schemes, coherent bulk formulation with the atmospheric forcing, multi-categories sea ice model);
- Higher spatial and temporal resolution (1/15° - 1 hour) atmospheric forcing from IFS ECMWF analyses and forecasts;
- A new assimilated SST observation (assimilation of L3 ODYSSEA SST high-resolution product instead of L4 OSTIA gridded product);
- A new Mean Dynamic Topography for SLA assimilation;
  An improved parametrization of the model error covariance with a new anomalies base deduced from the Mercator Ocean reanalysis at 1/12° (Lellouche et al., 2021);
  A 4D extension of the data assimilation scheme allowing a better spatiotemporal continuity of mesoscale structures;
  The assimilation of "super-observations" to filter out noisy data and scales that the model does not resolve;
  The use of satellite-based monthly estimates of the Global Mean Sea Level to better constrain the ocean mass and the steric height.
- An improvement of the parameterizations of the temperature and salinity bias correction method.

This presentation will describe all components of the system which have been revisited and will show how some identified weaknesses present in the previous system have been improved. It will also highlight the new system's performance in terms of analysis and forecast capacities, in the representation of mesoscale activity and water masses, and in the representation of the dynamics (particularly in the tropical band). The new system is very close to altimetric satellite observations with a forecast RMS difference below 5 cm (best analysis is around 4 cm). The description of the ocean water masses is also very accurate and departure from in situ temperature and salinity observations are generally below 0.3 °C and 0.05 PSU respectively. In addition, a global comparison with independent (not assimilated) velocity measurements shows that the location of the main currents is accurately represented.

Abstract 6.5: Andrea Storto, CNR – ORAL (cat: DA - 6)

Reconstructing historical ocean heat content from reanalyses: an uncertainty assessment

Andrea Storto and Chunxue Yang

Institute of Marine Sciences (ISMAR), National Research Council (CNR), Rome, Italy

Ocean heat content (OHC) variations respond to the energy imbalance caused by the human-induced increase in GHG concentration. As such, reconstructing OHC before the well-sampled period (before the Argo floats deployment) is crucial to understand the multi-decadal climate change in the ocean. Here, we use a large-ensemble ocean reanalysis (32 members) at moderate resolution (1/3°-1°) for the 1961-2022 period, to shed light on the OHC reconstruction, and its uncertainty, and identify the main sources of errors for the long-term trend. The ensemble system spans the uncertainty linked to the atmospheric forcing (input data and transfer coefficients estimation), observation bias-correction, initial conditions of the reanalysis period, and sea surface temperature data used at the sea surface; stochastic perturbation of model physics and observations is implemented as well.
Results indicate a 1961-2022 warming of 0.43 ± 0.08 W m^{-2}, in close agreement (in terms of both trend and uncertainty) with the latest independent estimates based on ensemble objective analyses, and an acceleration equal to 0.15 ± 0.04 W m^{-2} dec^{-1}. Over 11.6% of the global ocean, the year 2022 is that with the largest OHC, almost doubling any previous year. Major OHC uncertainty is found in the Tropics, while globally represents about 40% and 15% of the OHC variability before and after the Argo float deployment, respectively. The large acceleration and interannual variability compared to external objective analyses are found to depend on specific data assimilation settings rather than being a spurious artifact of the reanalysis system. Regional trends are mostly affected by observation procedure uncertainties (especially at high latitudes), and SST data uncertainty (especially at low latitudes).

Keywords: ocean synthesis, ocean warming, perturbations, stochastic physics, trend uncertainty, acceleration

POSTERS

Abstract P.1.1: Arthur Vidard, INRIA – POSTER (cat: DA-1)

Machine learning-based preconditioning for incremental variational data assimilation

Arthur Vidard[1] and Victor Trappler[1,2]

The Variational Data Assimilation problem, is usually solved by defining a succession of large and possibly ill-conditioned linear systems, constructed using linearizations of the forward model (the outer loop), and to solve them iteratively (the inner loop). In order to improve the convergence rate in the inner loop and reduce the computational burden, preconditioning techniques are often used to get better-conditioned linear systems, but constructing such preconditioners require additional computations.

The linear system that needs to be inverted depends on the current state, so we propose to construct a mapping from this state to an approximate inverse of the considered matrix using Deep Neural Networks. Once properly trained, this can be used as a state-dependent preconditioner in a variational data assimilation system, which can be constructed without any additional call to the forward model or linear tangent model.

Abstract P.3.1: Juliana Matranga, UCSC – POSTER (cat: DA-3)

Thinning techniques for remote sensing observations

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The increasing number of observations available to use in data assimilation brings computational and numerical difficulties. We evaluated the impact of thinning observations for a 4D-Var analysis of the ocean circulation along the U.S. West Coast using ROMS. We implemented two different thinning methods: an intelligent data thinning (IDT) algorithm to thin gridded satellite sea surface temperature observations, and a simple algorithm to reduce the volume of radial sea surface velocity measured by a network of high frequency radars. The IDT algorithm discards data in regions of low spatial variability and the simple algorithm averages neighboring radar observations in 'superobservations'. The statistical tools we used to compare the complete and thinned data sets results suggest that the thinned data sets do not significantly degrade the analysis, hence allowing the possibility to apply these techniques in a near real time forecasting system.

Abstract P.5.1: Lilian Garcia-Oliva, University of Bergen – POSTER (cat: DA-5)

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Assessing the Impact of Initialization Methods on Seasonal-to-Decadal Climate Predictions: Comparing Atmosphere and Ocean Constraints

Lilian Garcia-Oliva, Francois Counillon, Ingo Bethke, Lea Svendsen, Noel Keenlyside and Mao-Lin Shen

University of Bergen

The challenge in developing reliable seasonal-to-decadal climate predictions lies in finding the best combination of initialization methods that effectively constrain both the atmospheric and oceanic states, while also addressing the significant biases present in current models through either full-field initialization or anomaly initialization.

To address this, we compared several approaches using the Norwegian Climate Prediction Model, and the same experimental design: generating reanalysis and seasonal-to-decadal hindcasts for 1980-2010. Specifically, we compared a version with full-field atmospheric nudging (NudF), a version with anomaly atmospheric nudging (NudA), a version that assimilates ocean data with the Ensemble Kalman Filter (ODA), and a version that combines ODA and NudA (ODA-NudA).

Our findings indicate that full-field initialization performs best for short lead times (one month) and in specific regions (such as the tropical Atlantic Niño). However, anomaly initialization is preferable for longer lead times as it helps to limit drift and sustain prediction skill. Overall, ODA outperforms atmospheric initialized versions, but the latter is better at capturing specific events, such as the rapid North Atlantic subpolar Gyre shift. Combining the two methods did not yield optimal results as sustaining the reliability of the ensemble with atmospheric nudging proved to be a challenge, leading to a significant degradation of the ODA.

Abstract P.5.2: You Ying, NERSC – POSTER (cat: DA-5)

Assimilating observations of deformation to improve short-term ensemble forecasts of sea ice features

Yue Ying, Anton Korosov, Laurent Bertino

NERSC

Sea ice features such as open leads and ridges at kilometer scale are important information for the safety of sea navigation. However, short-term prediction of ice features is still challenging despite recent advancements in sea ice modeling and observation techniques. In this talk, we present some preliminary results from data assimilation experiments using deformation observations to improve sea ice feature prediction skill at day-to-day time scales. An ensemble of next generation sea ice model (neXtSIM) simulations are used to provide prior information. The boundary conditions of the stand-alone sea ice model are provided by the ERA5 atmospheric and TOPAZ4 ocean reanalyses. After the spin-up period, the ensemble developed a multivariate flow-dependent error covariance, the ensemble Kalman filter (EnKF) is used to assimilate deformation of ice drifts obtained from synthetic-aperture radar (SAR) satellite images to update neXtSIM ice drift and concentrations. Error reduction in the observed and unobserved model state variables are diagnosed with both spatial-average and feature-based metrics. Observation impact is evaluated in both the analysis and

ensemble forecast up to a one-week lead time. We will discuss issues in assimilating nonlinear features, especially due to large position mismatches between the simulated and observed ice leads, and discuss potential remedies from using the EnKF in a multiscale framework.

Abstract P.6.1: Shan Gao, NMEFC – POSTER (cat: DA-6)

Data assimilation experiment in the operational ecosystem models and forecasts for China coastal seas

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Under the influence of human activities and climate change, the coastal ecological environment is deteriorating, and the sustainable development of marine economy are seriously threatened. Therefore, it is of great significance to construct a high-resolution ecological operational forecasting system. In 2019, the National Marine Environmental Forecasting Center successfully constructed a high-resolution ecological environment forecasting system, covering the Bohai Sea, the Yellow Sea, South China Sea. And It has achieved stable and automatic operation. In order to further improve the accuracy of the ecological forecasting system, we use ENOI, ESTKF data assimilation to assimilate sea surface temperature, sea surface chlorophyll. The observation data used for assimilation are the SST of AVHRR and chlorophyll of OC-CCI. After data assimilation, the model results of sea surface temperature and sea surface chlorophyll are effectively improved.

Abstract P.6.2: Xin Li, BSH – POSTER (cat: DA-6)

Assimilation of satellite observations in BSH operational circulation model for the North Sea and Baltic Sea: recent implementation and results

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The German Federal Maritime and Hydrographic Agency (BSH) has been providing the operational forecasting service for the North and Baltic Sea, focusing on German coastal waters for more than 30 years. The service is based on its ocean-biogeochemical model HBM-ERGOM, which is further coupled to the parallel data assimilation framework (PDAF, https://pdaf.awi.de). The data assimilation component uses the Local Error Subspace Kalman Transform Filter (LESKTF) algorithm. Currently, sea surface temperature (SST), sea ice concentration (SIC) and sea ice thickness (SIT) can be assimilated in the model system. Two different SST satellite products can be used: 1. Advanced Very High Resolution Radiometer (AVHRR); 2. Copernicus Sentinel-3 SST. Additionally, sea ice concentration and thickness charts from the BAL MFC of CMEMS can be assimilated at the same or different time instants. Using different coupling regimes and different satellite data lead to different results. Here we will compare the influences of the assimilation of the different satellite products and will discuss the usage of data assimilation in the operational model system.
