A New Stochastic Ocean Physics Package and its Application To Hybrid-Covariance Data Assimilation

Andrea Storto[1,2], Panagiotis Andriopoulos[1]

[1] Centre for Maritime Research and Experimentation, La Spezia, Italy
[2] Institute of Marine Sciences, National Research Council, Rome, Italy

Contact: andrea.storto@cnr.it

Outline

- ***Motivation***
- ***Stochastic physics schemes***
- ***Use in hybrid ens-var data assimilation***
- ***Impact on global eddy activity***

Part of this work is supported by the Copernicus Climate Change Service (C3S)

Storto, A, Andriopoulos, P. (2021): A new stochastic ocean physics package and its application to hybrid-covariance data assimilation. *Q. J. R. Meteorol. Soc.*, **147**, 1691–1725 https://doi.org/10.1002/qj.3990

Data assimilation and ensemble generation

- Optimal ensemble generation is a key ingredient in EnKF, PF, hybrid ens-var methods
- Accounting for model uncertainty is achieved through physics perturbation (e.g. stochastic physics), input data perturbations, singular vectors (SV), breeding vectors (BV)
- Estimating model errors is also essential for WC-4DVAR (need of estimating **Q**)

Ensemble generation is also a key ingredient in

- Probabilistic (long-range) forecasts
- Uncertainty quantification (e.g. for reanalysis applications)
- Predictability studies
- Climate simulations and projections (climate signal versus uncertainty or noise)

Stochastic physics seems now generally preferred to techniques like SV because it implicitly accounts for non-linear effects, and can be more physical based (and also easier to maintain)

Stochastic physics

Stochastic physics enables a probabilistic description of the ocean model integration, and it is aimed in particular at spanning the uncertainty of all the processes that

- are not fully known (e.g. vertical turbulent mixing)
- are not well resolved (i.e. subgrid processes)
- or whose numerical implementation suffers from significantly approximate assumptions.

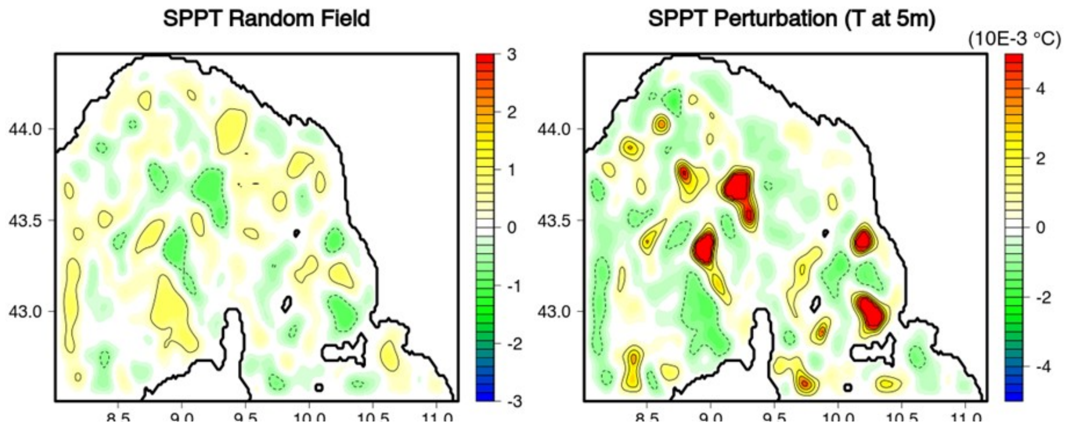
Here, we focus on three schemes now included in the STOPACK package for NEMO

- **SPPT: Stochastically perturbed parametrization tendencies**
- **SPP: Stochastically perturbed parameters**
- **SKEB: Stochastic Kinetic Energy Backscatter scheme**

SPPT (Stochastically perturbed parametrization tendencies)

In SPPT, tendencies that refer to unresolved processes ***P*** are perturbed collinearly to the unpertubed tendency.

$$\frac{\partial X}{\partial t} = D(X) + (1 + \xi_t)\, P(X)$$



In the NEMO experiments: horizontal and vertical mixing and solar radiation penetration are perturbed, although STOPACK allows a much larger range of processes.

Dynamics (***D***) is not perturbed (it is assumed to be well-known). The perturbation field is bounded between -1 and 1 to maintain the original sign of the tendency.

SPPT is implicitly resolution-dependent (i.e. for very high resolution configuration, the viscosity operator becomes unimportant and thus its tendency perturbation)

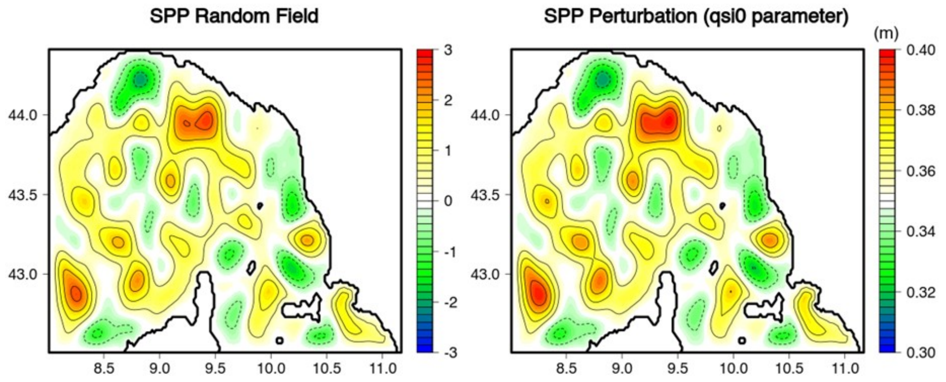
SPP (Stochastically perturbed parameters)

$$\hat{p} = p\, exp(\xi_t) \qquad \xi_t \sim N(-\frac{1}{2}\sigma^2, \sigma^2)$$

In SPP, parameters which are not well known, or for which the spatial homogeneity assumption is too strong, are perturbed according to the log-Normal pdf. This corresponds in practice to a stochastic spatio-temporal modulation of the parameters.

The list of parameters perturbed is quite long, and summarized in:

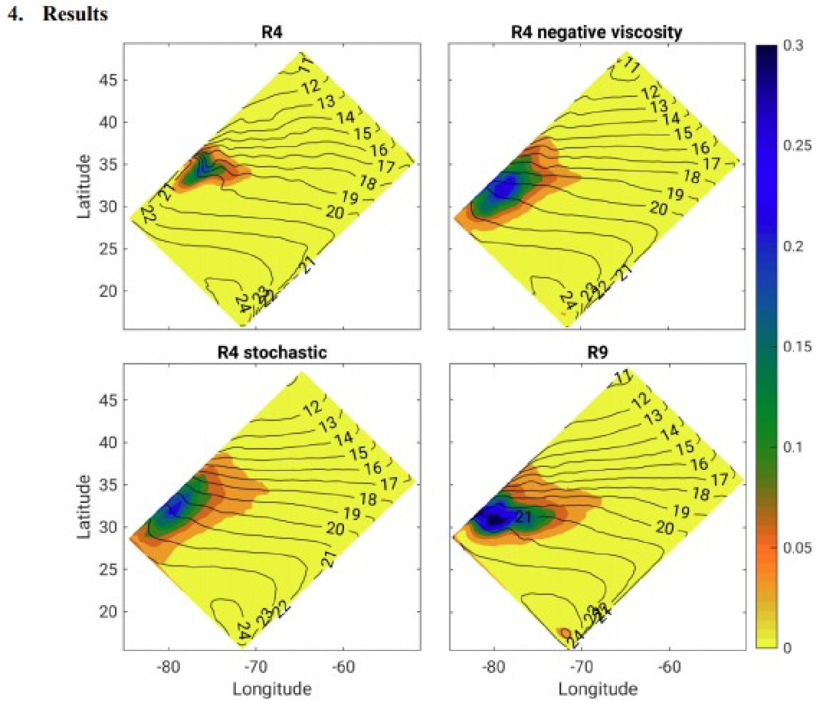
- Diffusivity and viscosity
- TKE parameter (Langmuir cell coeff.,etc.)
- Sea-ice albedo and strength
- Relative wind, geothermal flux, relax. time-scale
- Bottom friction
- Solar radiation extinction coeff.

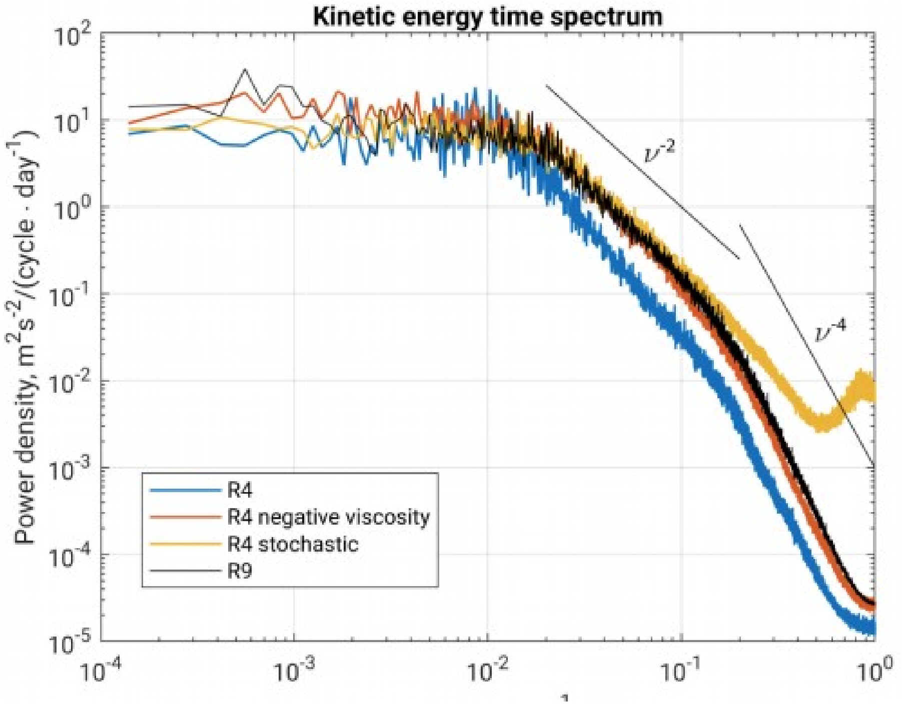


SPP does not depend on the resolution directly, strictly speaking, but on “our confidence about the choice of the parameters” (which is somehow resolution-dependent!)

SKEB (Stochastic Kinetic Energy Backscatter)

Eddy kinetic energy and the inverse energy cascade are known to be largely under-estimated in moderate resolution models (not fully eddy resolving). To lesser extent, this problem is also present in very high-resolution configuration (as long as numerical dissipation occurs).





From Perezhogin (2019, IOP): Deterministic and stochastic parameterizations of kinetic energy backscatter in the NEMO ocean model in Double-Gyre configuration

SKEB (Stochastic Kinetic Energy Backscatter)

SKEB aims at stochastically re-injecting the unrepresented scales of energy in the ocean models, through a “forcing streamfunction term”:

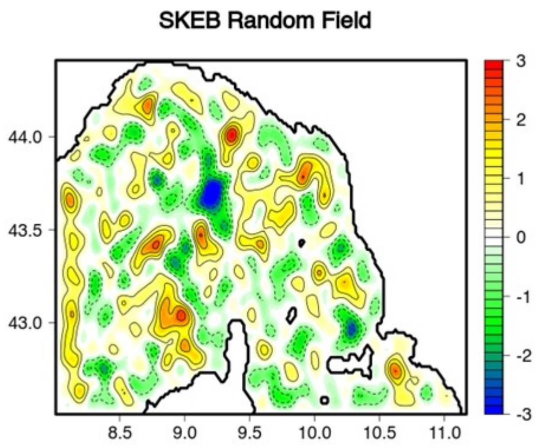
$$F'_{\psi} = F_{\psi}\,[b_r(\beta_n E_n + \beta_c E_c)]^{\frac{1}{2}}.$$

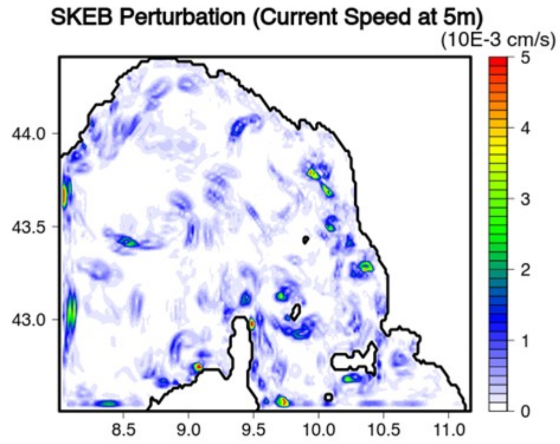
$$u' = \frac{\partial F'_{\psi}}{\partial y}; \quad v' = -\frac{\partial F'_{\psi}}{\partial x};$$

In STOPACK we calculate numerical (E_n) and convective (E_c) dissipated energy and re-inject it in the momentum equation.

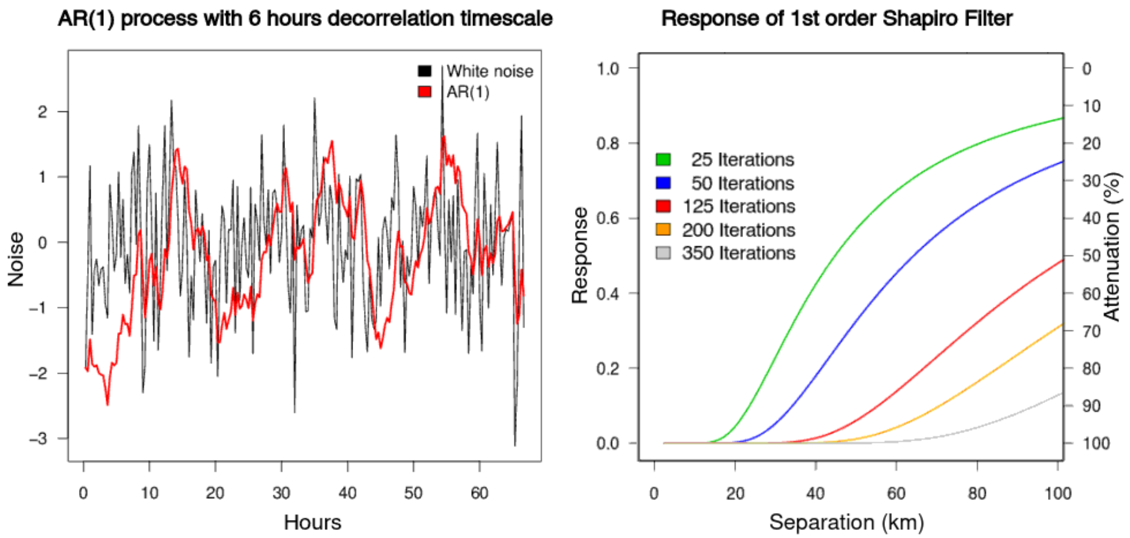
SKEB is strongly resolution dependent, and all the configurations presented here needed a specific tuning phase.

b_r represents the amount of dissipated energy reinjected





Generation of perturbation fields



Experiments

Ligurian Sea NEMO configuration (~1.8 km 91 vertical levels)

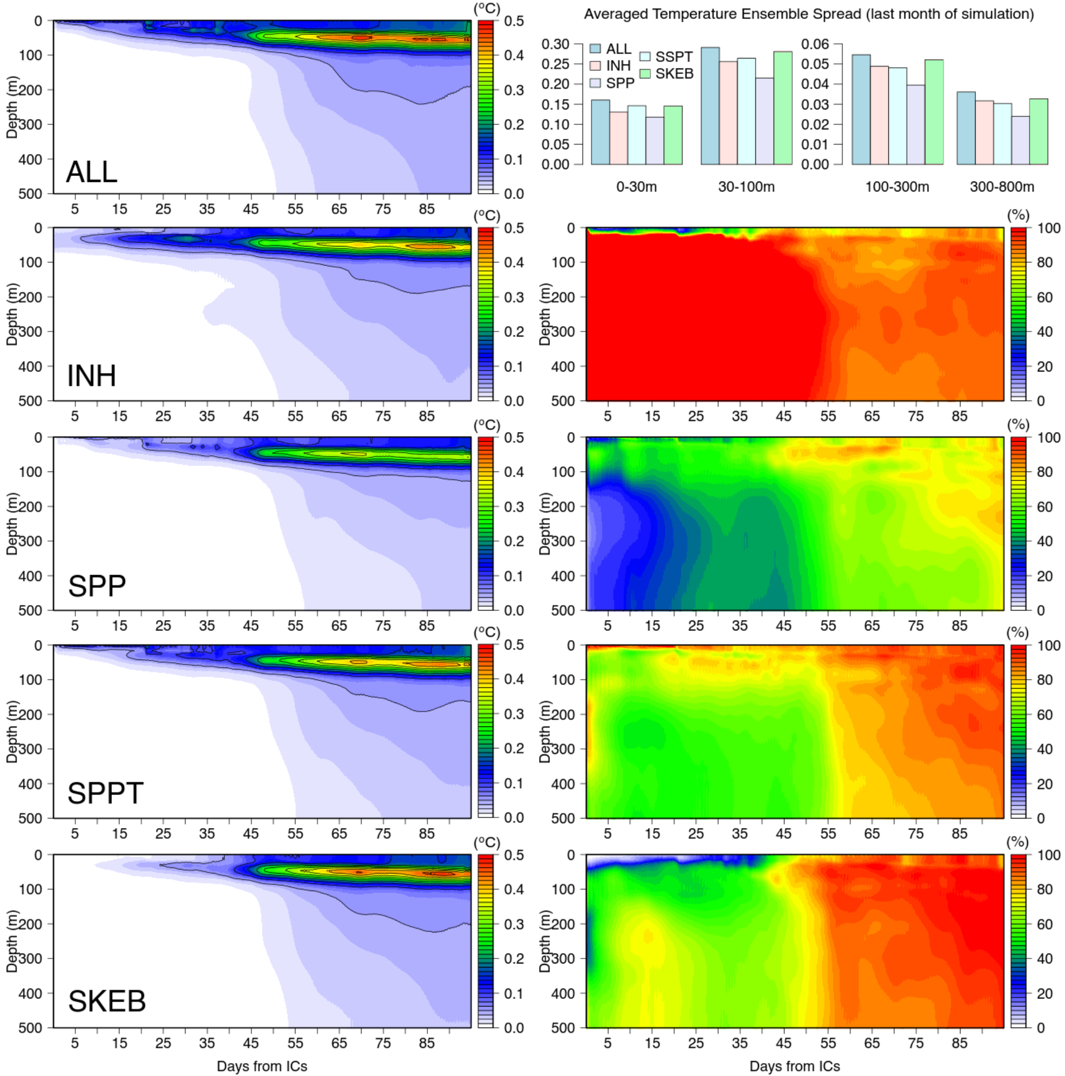
ORCA global NEMO configuration (ORCA1 and ORCA025)

Ensemble spread evolution

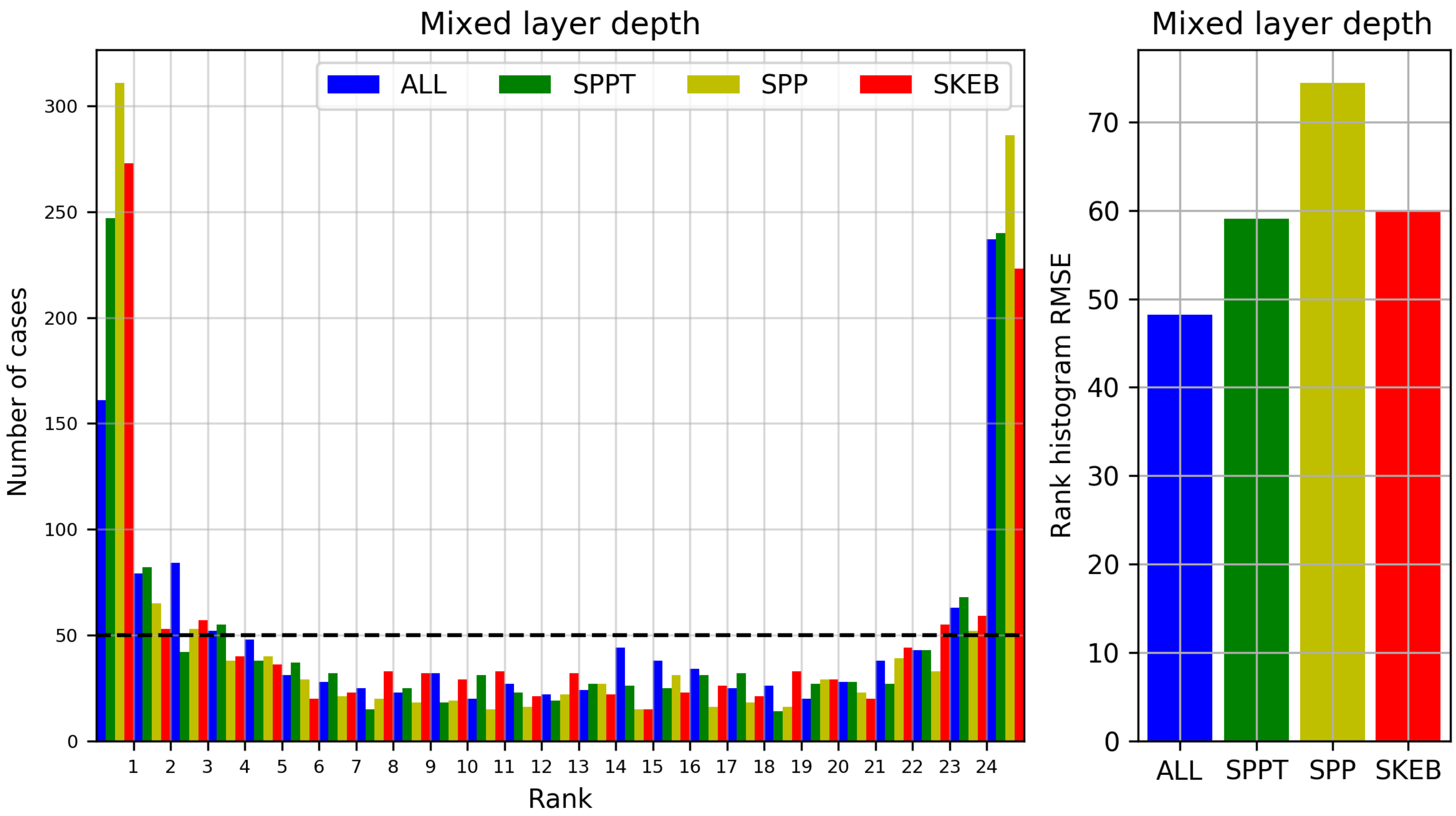
- Saturation of the ensemble spread

- ALL exceeding inherent uncertainty after ~ 2 months

- SPPT impacting immediately, SKEB later



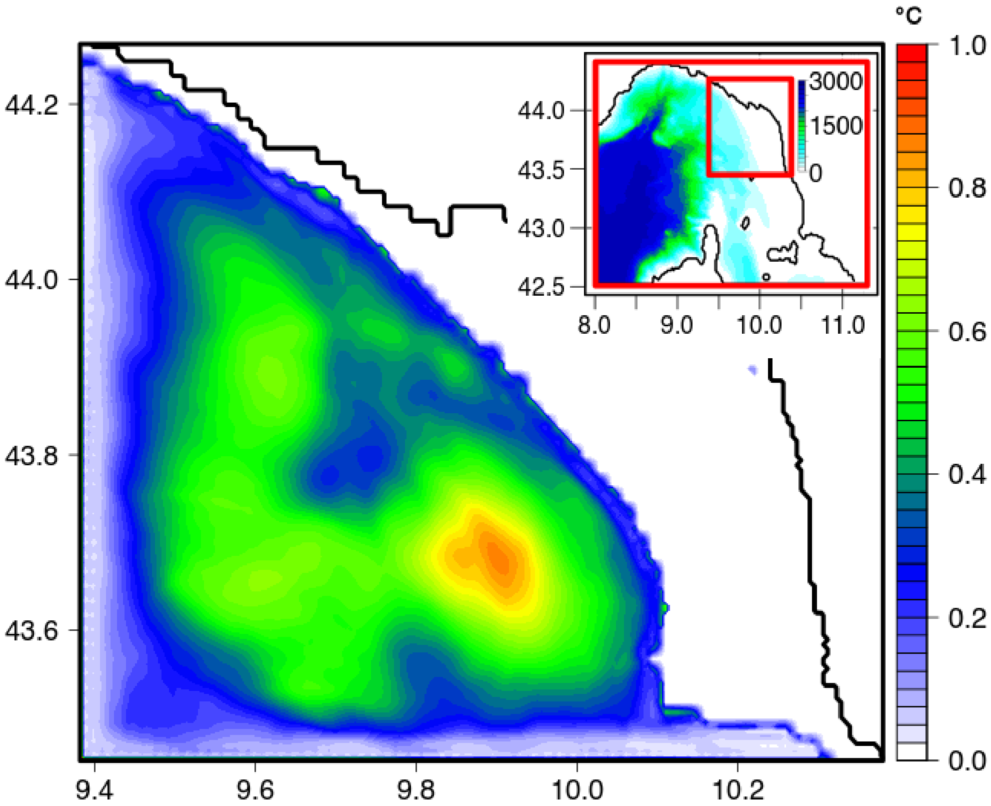
Reliability

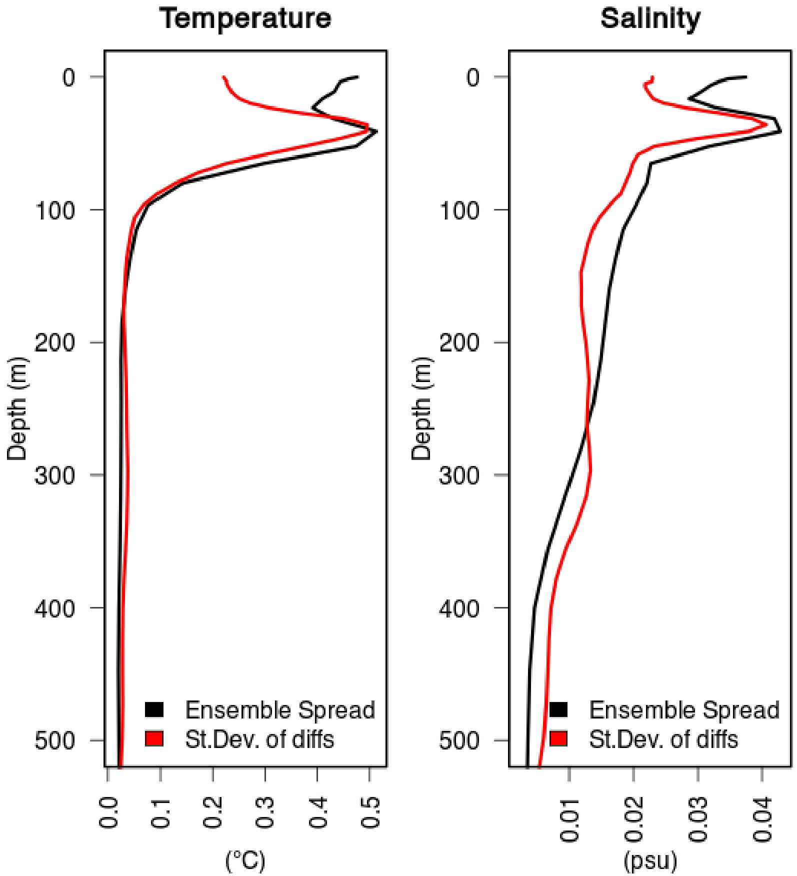


Under-dispersive ensemble because of the lack of forcing (surface and lateral) perturbations
Using all perturbation schemes improves the ensemble reliability

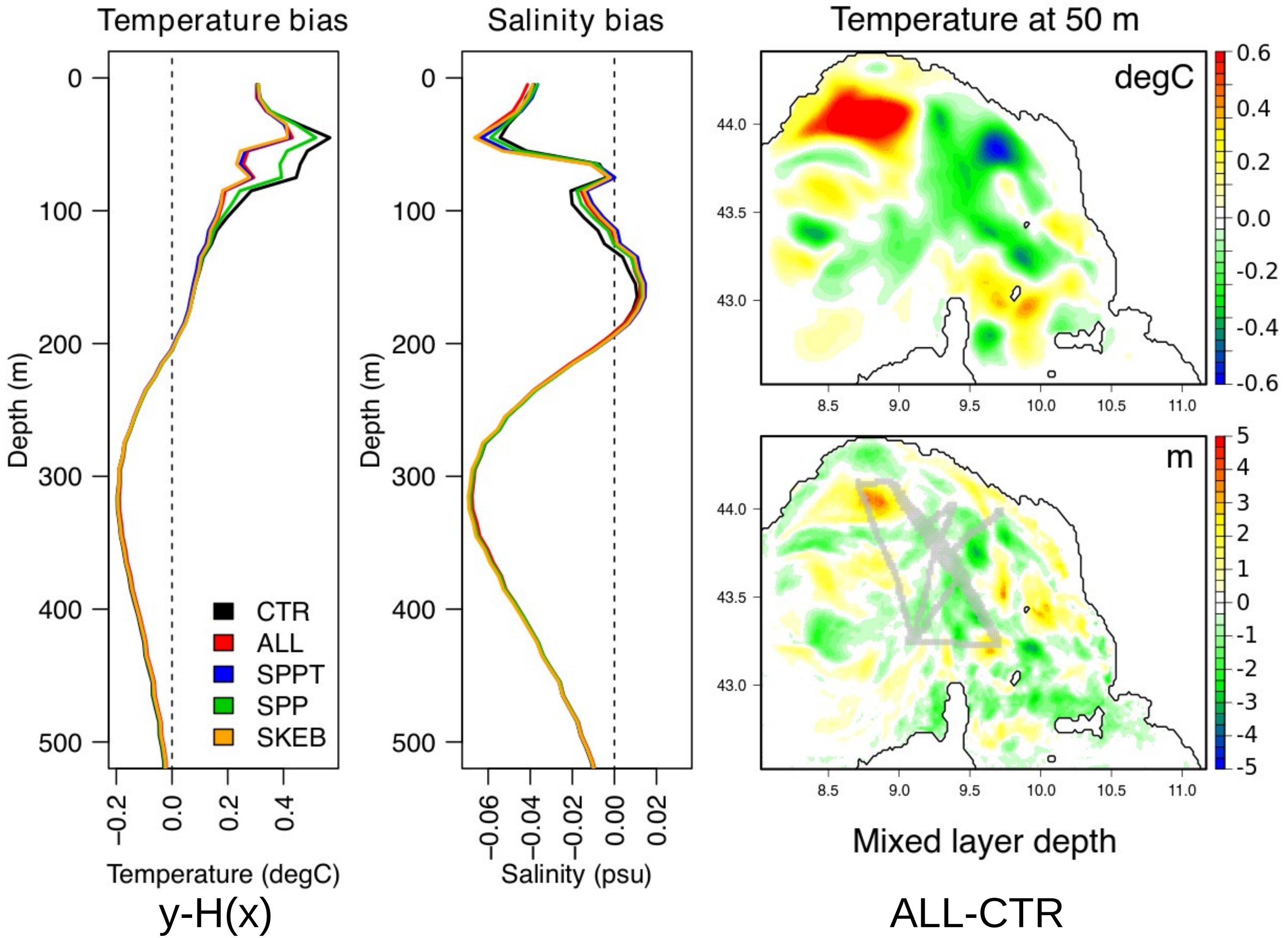
Validation

Posterior validation: comparison of the ensemble spread with RMSD versus “truth” (with unresolved scales), here a child model configuration with 3x higher resolution





Impact of stochastic physics on the ensemble mean

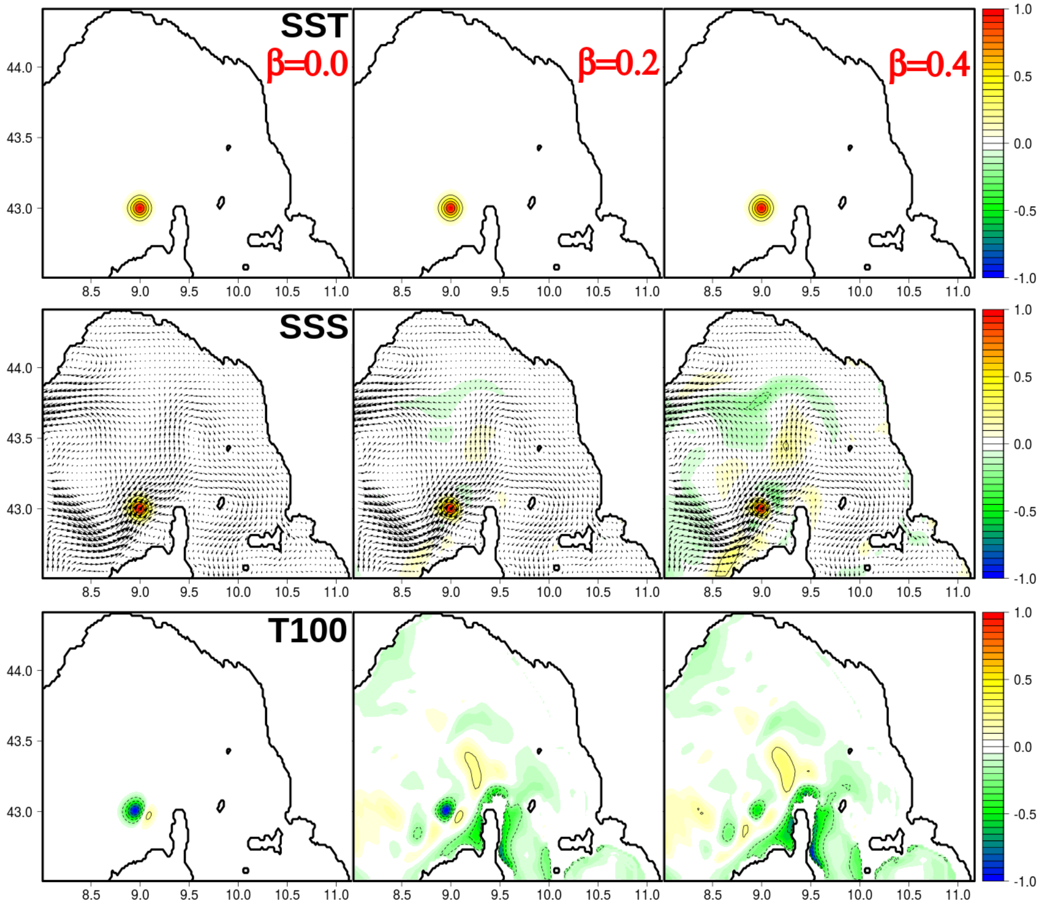


Non-linear rectification of the ensemble:

Enhanced vertical mixing attenuates warm biases

Hybrid data assimilation

The control vector is redefined as a sum of two components, associated to stationary and ensemble-derived covariances, respecitvely.



$$\hat{\mathbf{B}} = (k-1)^{-1}\, \mathbf{C}\, \hat{\mathbf{x}}\, \hat{\mathbf{x}}^{\mathrm{T}} \mathbf{C}^{\mathrm{T}}. \qquad \mathbf{C}\,\mathbf{C}^{-} x = x.$$

$\hat{\mathbf{B}} = \mathbf{Q}\, \Lambda \mathbf{Q}^{\mathrm{T}}$ Use 3D EOFs to model LS errors

$$\delta x = \alpha\, \mathbf{V}\, v + \beta\, \gamma\, \mathbf{C}^{-}\, \mathbf{Q}\, \mathbf{M}\, w \qquad \text{With } \beta = \sqrt{1-\alpha} \text{ and } \gamma = \sqrt{\frac{tr(\mathbf{B})}{tr(\hat{\mathbf{B}})}}$$

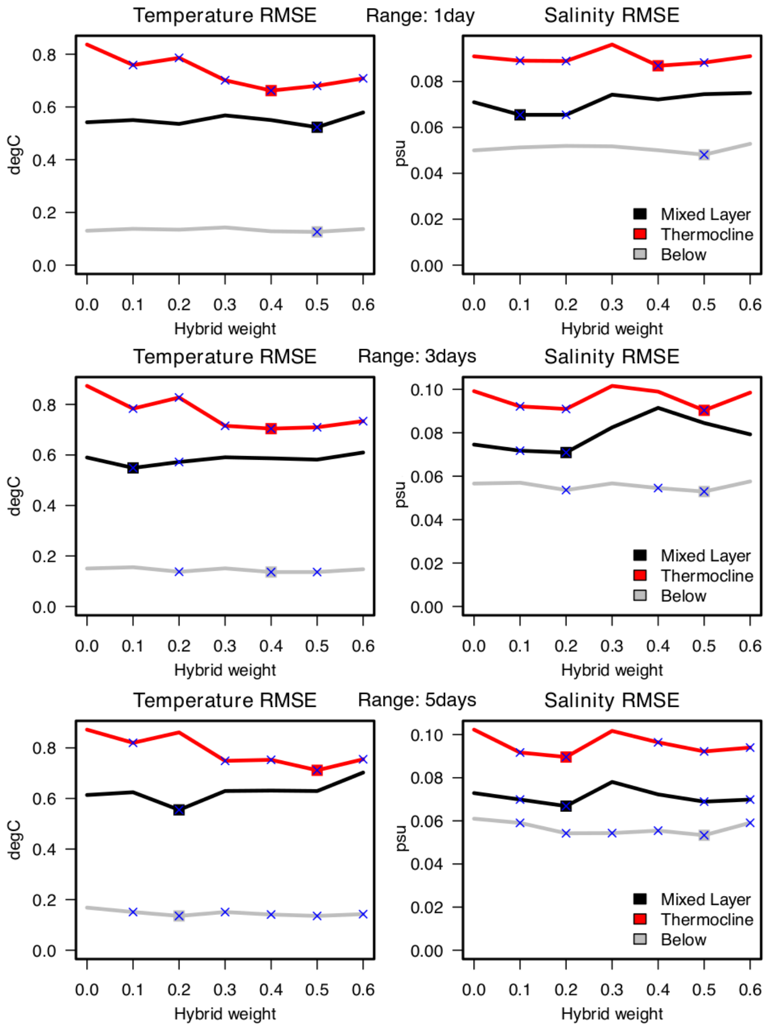
3D EOFs allow for some degree of anisotropy

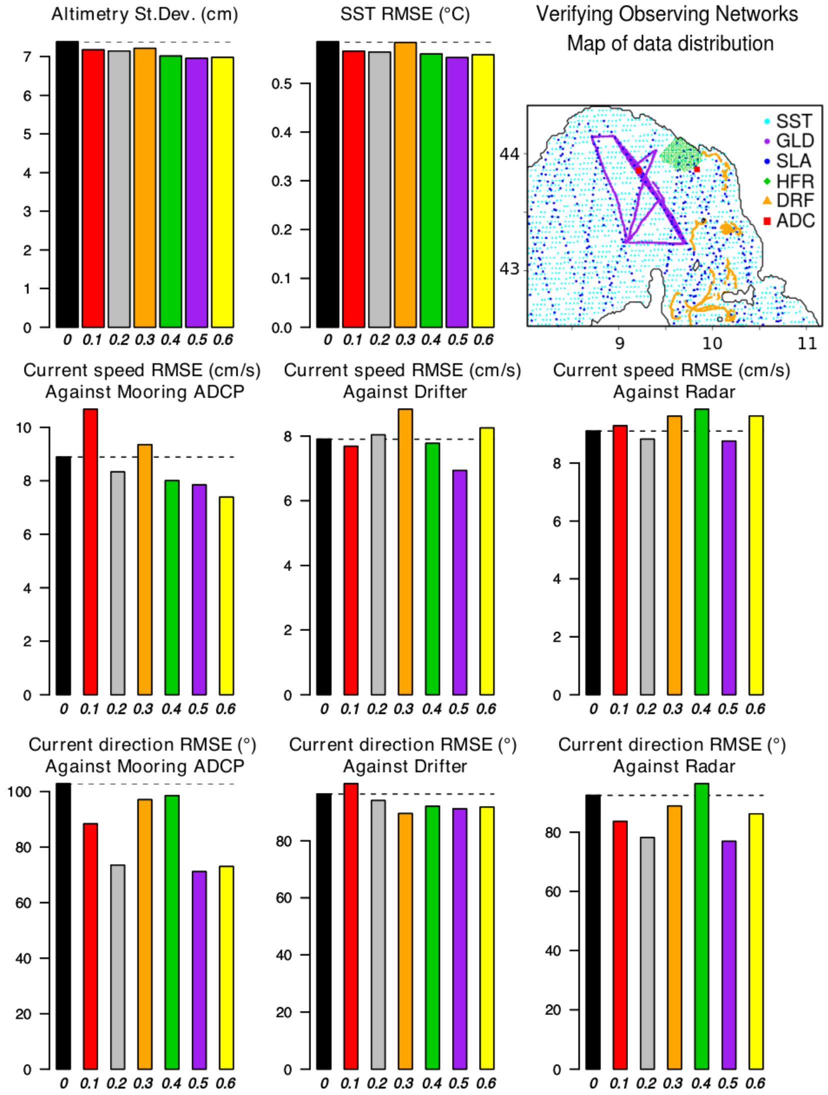
The cost function becomes:

$$J(v,w) = \frac{1}{2} v^{\mathrm{T}} v + \frac{1}{2} w^{\mathrm{T}} w + \frac{1}{2}(\mathbf{H}\,(\alpha\, \mathbf{V}\, v + \beta\, \gamma\, \mathbf{C}^{-}\, \mathbf{Q}\, \mathbf{M}\, w) - d)^{\mathrm{T}} \mathbf{R}^{-1} (\mathbf{H}\,(\alpha\, \mathbf{V}\, v + \beta\, \gamma\, \mathbf{C}^{-}\, \mathbf{Q}\, \mathbf{M}\, w) - d)$$

Hybrid DA verification

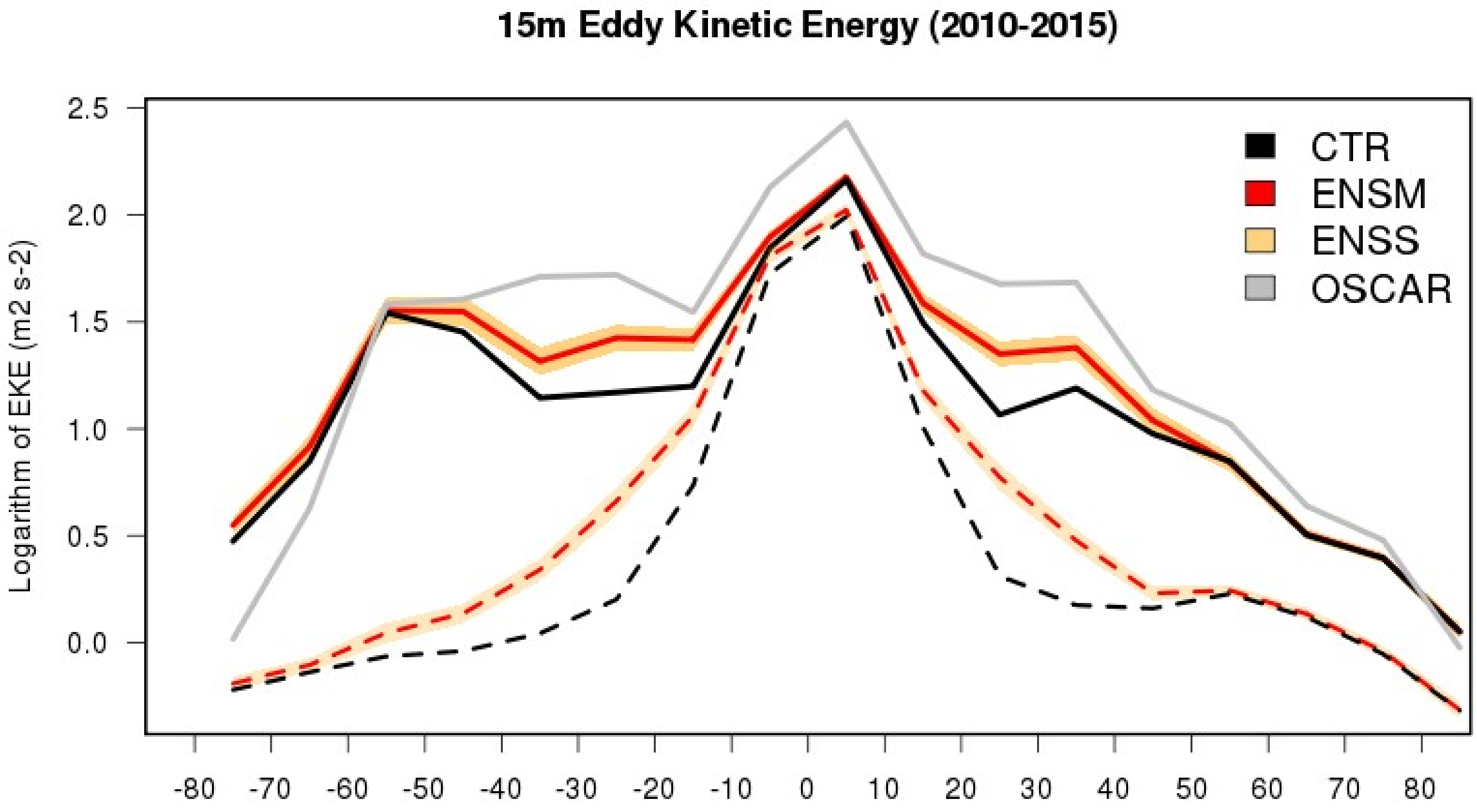
Skill scores all show neutral to positive impact of the new EOF-based error component





Eddy Kinetic Energy

Impact of stoch. phys. on EKE at both 1 and 0.25 deg resolution, in comparison with OSCAR data for the 2010-2015 (overlap) period



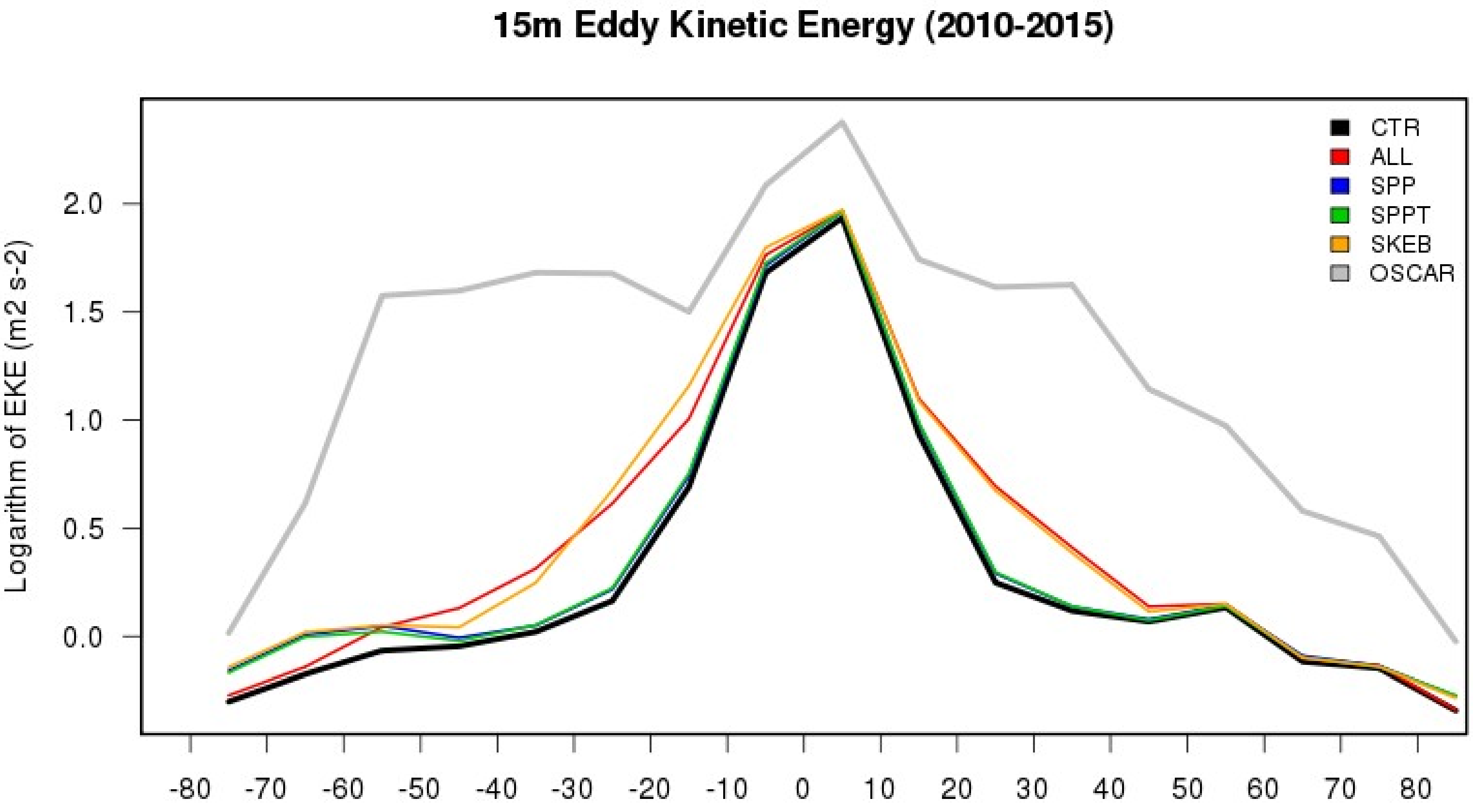
Solid lines: ORCA025 exps; Dashed line: ORCA1 exps.
ENSM is the ensemble mean of the EKE from the perturbed members
CTR is the unperturbed run

- **STOPHYS significantly (ENSM is greater than CTR by more than the ENSS) induces increase of EKE at mid latitudes, consistently in both model configurations**

Experiments with global NEMO configuration

Eddy Kinetic Energy

Impact of stoch. phys. on EKE at 1 deg resolution, in comparison with OSCAR data for the 2010-2015 (overlap) period



Solid lines: ORCA1 exps.
ENSM is the ensemble mean of the EKE from the perturbed members
CTR is the unperturbed run

- **At least at 1 degree resolution, SKEB is responsible for increase of EKE**

Experiments with global NEMO configuration

Summary

- ***Stochastic physics (and ensemble generation) is increasingly acknowledged as a crucial ingredient of data assimilation and prediction systems at multiple scales***

- ***A new package specifically developped for NEMO has been introduced, that includes SPPT, SPP and SKEB implementations for the ocean with different space-time decorrelation scales***

- ***The simultaneous use of all schemes benefits the ensemble reliability and the subgrid variability***

- ***Their use in a hybrid-covariance analysis systems provides positive impact in terms of verification skill scores***

- ***The implementation in a global eddy-permitting configuration suggests in particular that the SKEB stochastic scheme is able to increase the eddy activity at mid-latitudes***

Thank you for the attention

Contact:

andrea.storto@cnr.it

Material from this talk:

Storto, A, Andriopoulos, P. (2021): A new stochastic ocean physics package and its application to hybrid-covariance data assimilation. *Q. J. R. Meteorol. Soc.*, **147**, 1691–1725 https://doi.org/10.1002/qj.3990

Extra slides

SPP

Tendency name	Meaning	Default Switch
traxad	Tracer advection along x-direction	OFF
trayad	Tracer advection along y-direction	OFF
trazad	Tracer advection along z-direction	OFF
traldf	Tracer lateral diffusion	**ON**
trazdf	Tracer vertical diffusion	**ON**
traevd	Enhanced vertical diffusion	OFF
trabbc	Tracer bottom boundary condition	OFF
trabbl	Tracer bottom boundary layer parameterization	OFF
tranpc	Non-penetrative convection	OFF
tradmp	Tracer three-dimensional relaxation	OFF
traqsr	Solar radiation penetration	**ON**
transr	Surface boundary conditions for tracers	OFF
traatf	Asselin time filter on tracers	OFF
dynhpg	Horizontal pressure gradient	OFF
dynspg	Surface pressure gradient	OFF
dynkeg	Horizontal gradient of kinetic energy	OFF
dynrvo	Relative vorticity	OFF
dynpvo	Planetary vorticity	OFF
dynzad	Momentum vertical advection	OFF
dynldf	Momentum lateral diffusion	**ON**
dynzdf	Momentum vertical diffusion	**ON**
dynbfr	Bottom friction	OFF
dynatf	Asselin time filter on momentum	OFF
icehdf	Sea-ice (numerical) diffusion	OFF
icelat	Sea-ice lateral accretion	OFF
icezdf	Sea-ice vertical thermodynamics	OFF

Parameter name	Meaning	Default Perturbation type	Standard Deviation
avt	Vertical ocean diffusivity	**2**	0.4
avm	Vertical ocean viscosity	**2**	0.4
aht	Lateral ocean diffusivity	**2**	0.1
ahm	Lateral ocean viscosity	**2**	0.1
arnf	Vertical ocean diffusivity at river mouths	**2**	0.1
aevd	Enhanced convection vertical ocean diffusivity	**2**	0.1
tkelc	Langmuir cell coefficient in the TKE scheme	**2**	0.1
tkedf	Eddy diffusivity coefficient in the TKE scheme	0	-
tkeds	Kolmogorov dissipation coefficient in the TKE scheme	**2**	0.1
tkebb	Surface input of kinetic energy in the TKE scheme	0	-
tkefr	Fraction of surface kinetic energy transferred below the mixed layer in the TKE scheme	**2**	0.1
ahbbl	Bottom boundary layer lateral diffusivity	**2**	0.1
icealb	Sea-ice albedo	0	-
icestr	Sea-ice strength	0	-
geot	Geothermal heat flux	0	-
relw	Relative wind ratio	**5**	0.1
dqdt	SST damping coefficient	**2**	0.3
dedt	SSS damping coefficient	**2**	0.3
bfr	Bottom friction coefficient	**2**	0.05
qsl0	Short depth of extinction in the solar radiation penetration scheme	**2**	0.05

SKEB

$$E_n = k_h \Delta A \left(S^2 + T^2\right)^{3/2}$$

where k_f is the (dimensionless) tuning coefficient that accounts for the model resolution, ΔA is the gridcell area, and S and T are the shearing and tension strains, given respectively by:

$$S = \frac{\partial v}{\partial x} + \frac{\partial u}{\partial y}$$

$$T = \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y}$$

$$E_c = \frac{k_c M_k^2}{dz \, \rho_0^2}$$

Where k_c is a resolution-dependent parameter that quantifies the convection activity (in m s^{-1}), M_k is the mass flux across the k-th vertical level, and dz and ρ_0 are the vertical level thickness and reference density, respectively.

Data assimilation