# Recent developments on Superparmeterization in ocean modeling using general multiscale techniques: a deep-convection case study employing ESMF.

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## 1 Abstract

Multiscale approaches allow explicit modeling of the many different phenomena that are present in real ocean dynamics. In this work we use a multiscale-superparameterization approach to efficiently model oceanic deep-convection. We present results and methodology for a multiscale simulation in which several hundred high-resolution, two-dimensional, non-hydrostatic process models are coupled, as separate ESMF components, to a large-scale hydrostatic ocean model. One process model is embedded in each grid cell of the large-scale three-dimensional hydrostatic model. The process models take the place of conventional one-dimension empirical parameterizations, producing a simulation more accurately grounded in underlying physical equations. The individual process models, and the hydrostatic ocean model into which they are embedded, are implemented as ESMF components. The ESMF library is used to orchestrate data flows between components and to steer the overall computation, including spreading the workload over multiple parallel processors.

We measure the impact of our approach, in terms of both improved numerical accuracy and computational cost, by comparing quantitative metrics with respect to a fully resolved, three-dimensional, non-hydrostatic "ground-truth" simulation. In comparison with a purely hydrostatic numerical experiment, the time evolving state and statistics of the multiscale system are found to be significantly closer to the ground-truth model solution. For example, in the embedded simulation, the slanting of convective plumes due to large scale flow vertical shear is reproduced and higher order statistics, such as the variance and skewness of the model fields, are all much closer to the ground-truth model solution.

The improved accuracy of the multi-scale model is achieved for a computational cost far less than that of a fully resolved non-hydrostatic model. By exploiting parallelism amongst the embedded models, we can achieve a wall-clock time to solution that is a small multiple of a pure hydrostatic simulation.

The approach we have taken is by no means limited to parameterization of deep convection and can be generalized fairly broadly. For example mixed-layer processes, biogeochemical processes, eddy flux coefficients could all be estimated by appropriate local, prognostic sub-models that are then coupled to a larger scale model, provided the factors and analysis we described are appropriately considered.

## 2 Super-parameterization

### Motivations

Explicitly resolve sub-grid scale processes in each column of a large-scale, coarse resolution model

- concept from atmospheric superparameterization (with embedded Cloud Resolving Model)
- requires scales separation
- fine-grid embedded model may only cover part of the coarse grid column ; e.g., only 2-D in vertical plane.
- global/large-scale simulation at plume-resolving resolution is computationally very expensive. (e.g. Eddy-Resolving: $\Delta x \sim 2-10$ km ; Plume-Resolving: $\Delta x \sim 10$ m )

### Algorithm

- embed 2-D (x-z) plume-resolving model (fine-grid) in each column of coarse-grid, 3-D hydrostatic model.
- coupling

$$\text{Coarse}: \quad \frac{\partial \theta_c}{\partial t} = -\mathbf{v}_c \cdot \nabla\theta_c + F_{SGS}$$
$$\text{Fine}: \quad \frac{\partial \theta_f}{\partial t} = -\mathbf{v}_f \cdot \nabla\theta_f$$
$$\text{Coarse} \rightarrow \text{Fine} \;:\; [\theta_f]_c \;\leftarrow\; \theta_c(z)$$
$$\text{Fine} \rightarrow \text{Coarse} \;:\; F_{SGS} = [\partial\theta_f/\partial t]_c$$

- self orientation: orientation of 2-D model x axis is relaxed towards the direction of maximum vertical shear of the coarse-grid model
- coupling applies to potential temperature and horizontal momentum $(u, v)$.

### Implementation

- Generally applicable implementation not tied to a specific problem or model(s).
- cast computational formulation as a coupled modeling scheme and borrow Earth System Modeling Framework (ESMF) technology from the coupled modeling community.

### Efficiency

- $N$ = ratio of fine to coarse resolution. explicit computation: Coarse : Embedded : 3D Fine = $1 : N : N^2$
- 3-D NH pressure solver: less points and much smaller domain $\rightarrow$ converges much more rapidly + requires less exchanges.
- no direct connection between 2-D plume models $\rightarrow$ scales perfectly on large number of processors.

### Deep Convection test case

Starting from a uniformly stratified ($N = 3.10^{-4}s^{-1}$) oceanic box (40 x 40 x 2 km) at rest, a circular patch of uniform surface cooling (800 $W/m^2$) is applied at the center. 3 comparable set-up are compared:

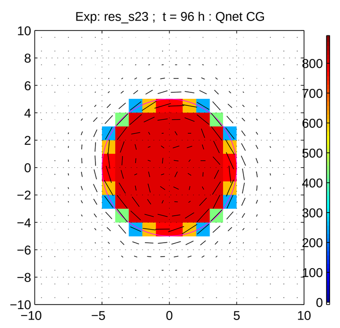
- 3-D High resolution ($\Delta x = \Delta y$ = 100m)
- 2-D embedded plume ($\Delta x_f$ = 100m) in 3-D coarse resolution ($\Delta x_c = \Delta y_c$ = 2 km)
- 3-D coarse resolution ($\Delta x = \Delta y$ = 2 km) with convective adjustment.

same vertical resolution ($\Delta z$ = 100m) and time-step (1.mn); same viscosity both in 2-D plume and 3-D High res. and also in the two 3-D coarse res.; same source code: **MITgcm**.

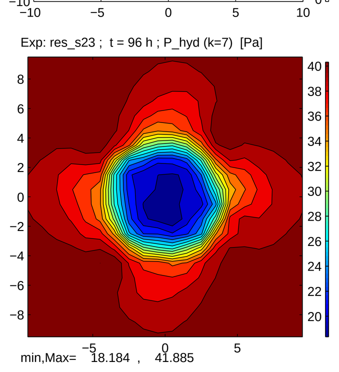
In addition a passive tracer is added at the surface (surface level concentration kept to 1)

## 3 Results (from Deep Convection test case)

strong baroclinic rim current develops at the edge of the cooling patch (aligns 2-D plume sub-models) and becomes baroclinicly unstable.

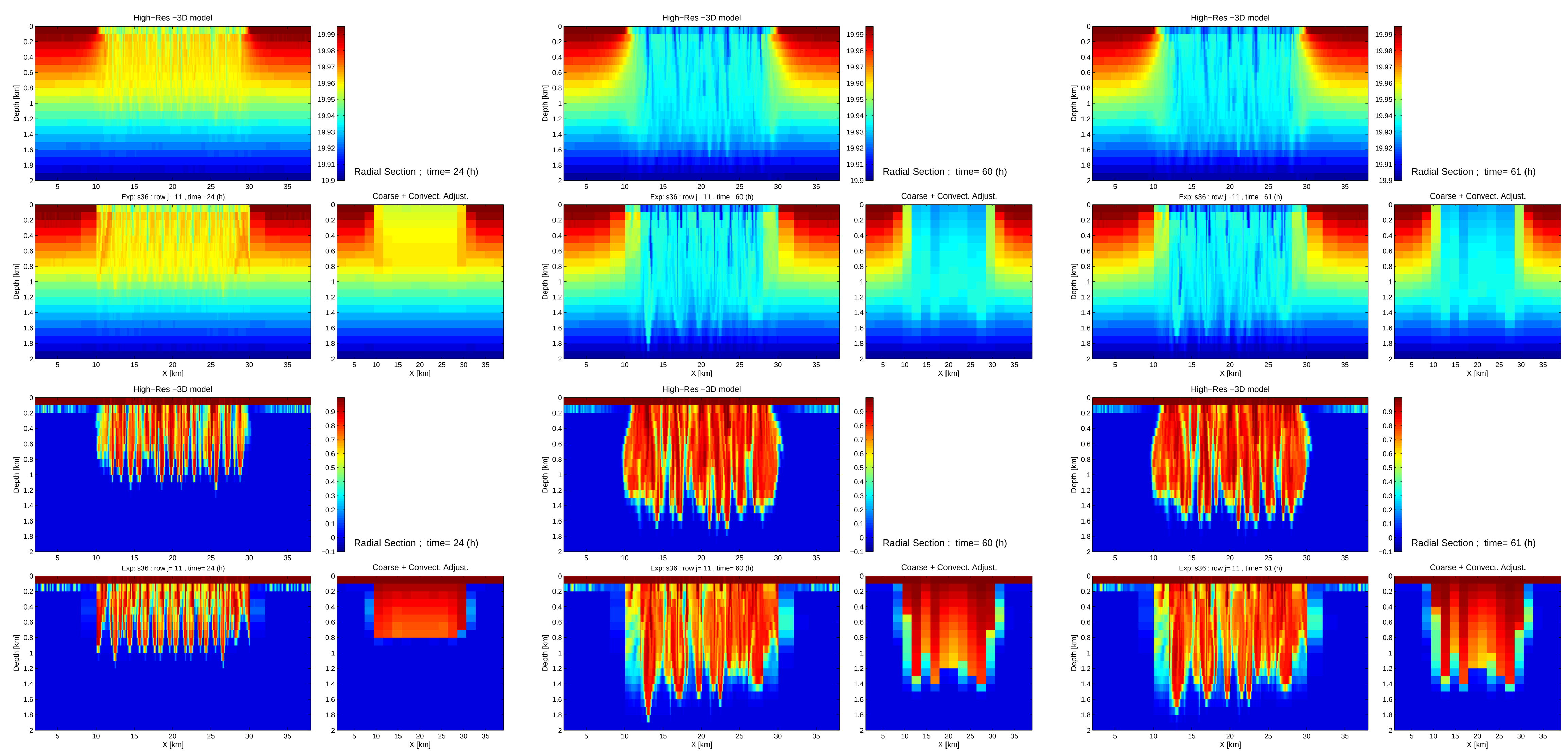


heat flux and 2-D plume orientation relative to coarse model grid

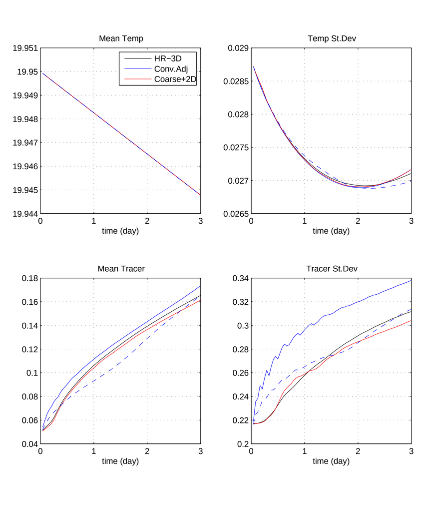


pressure at 700.m after 4.days to Coarse model grid

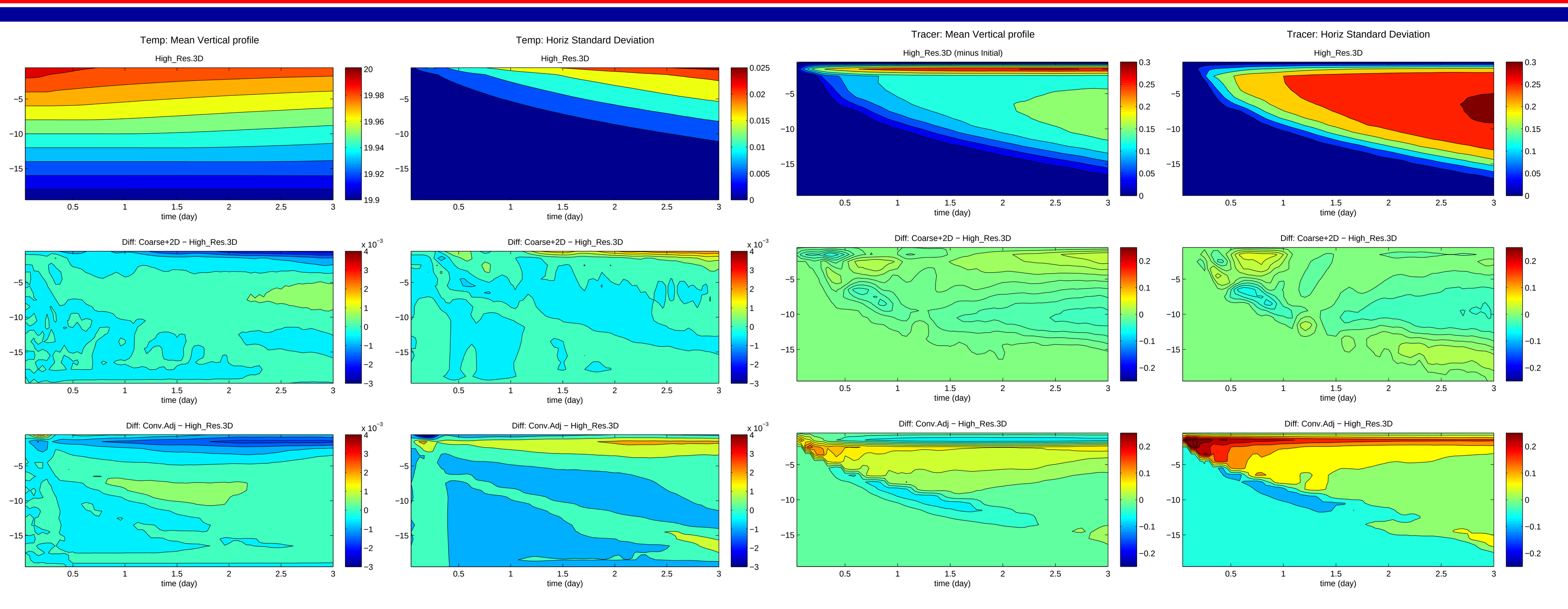
Temperature (Top) and Passive Tracer (Bottom) radial section for the 3 simulations, after 24.h, 60.h and 61.h




## 4 Analysis



Evolutions of temperature standard deviation, average tracer and tracer standard deviation (left) indicate a much closer agreement (with the High-Res case) for the 2.D embedded plume case relative to the convention convective adjustment case. Reducing the convective vertical diffusion (from 10 to 2.5 $m^2/s$) to match the average tracer concentration at t=3.days does not improve the tracer and temperature standard deviation (blue dash line). Evolutions of vertical profile are shown on the right and confirm previous analysis.




## 5 Turbulent Fluxes

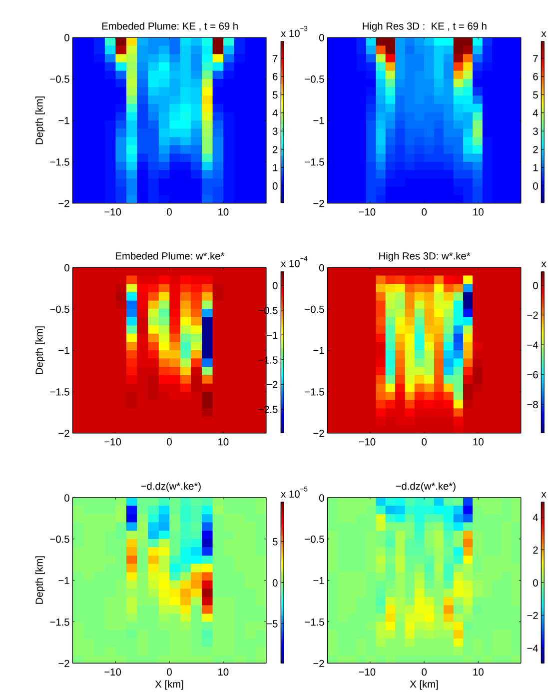
(Preliminary Analysis)

snap-shot, radial section
left: 2-D embedded plume
right: 3-D High Res.

total KE (top)

turbulent vertical flux of KE ($[w'.ke']$)(middle)

divergence of turbulent flux (bottom)



## 6 Conclusions

- Multiscale Approach has been successfully applied to a deep convection test case: Preliminary results show:
  - Qualitative agreement between the "super-parameterized" convective model and a reference 3-D non-hydrostatic plume resolving model;
  - specially compared to the simple convective adjustment simulation where transient responses are poorly represented.
  - explicitly resolving Sub-Grid-Scale model is only few times ($\sim$3-5) slower than model with convective adjustment, but far much faster ($>$10) than the 3-D non-hydrostatic plume resolving model.
  - multiple but almost independent 2-D plume set-up is highly scalable on large number of processors.
  - speed-up is expected to increase with the domain size.
- a way to improve traditional parameterization: e.g: importance of non local flux of TKE ? (from preliminary analysis)
- 2-D plume in global eddy-resolving model : appears feasible
- multiscale approach can be applied to other SGS processes (e.g.: internal wave breaking ?).