Model development for E3SM at high resolutions

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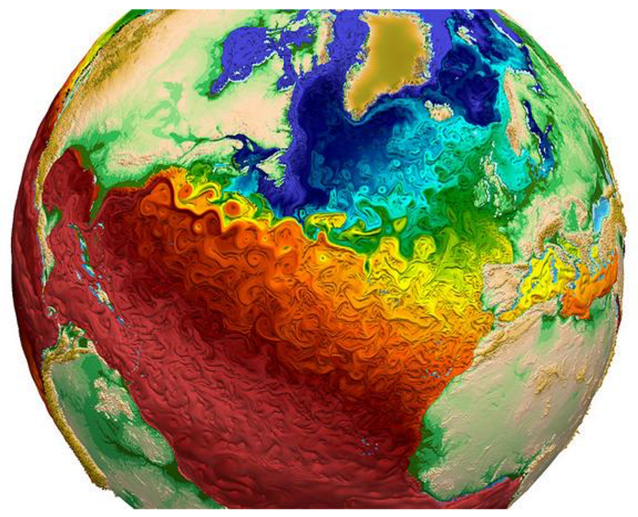
Introduction

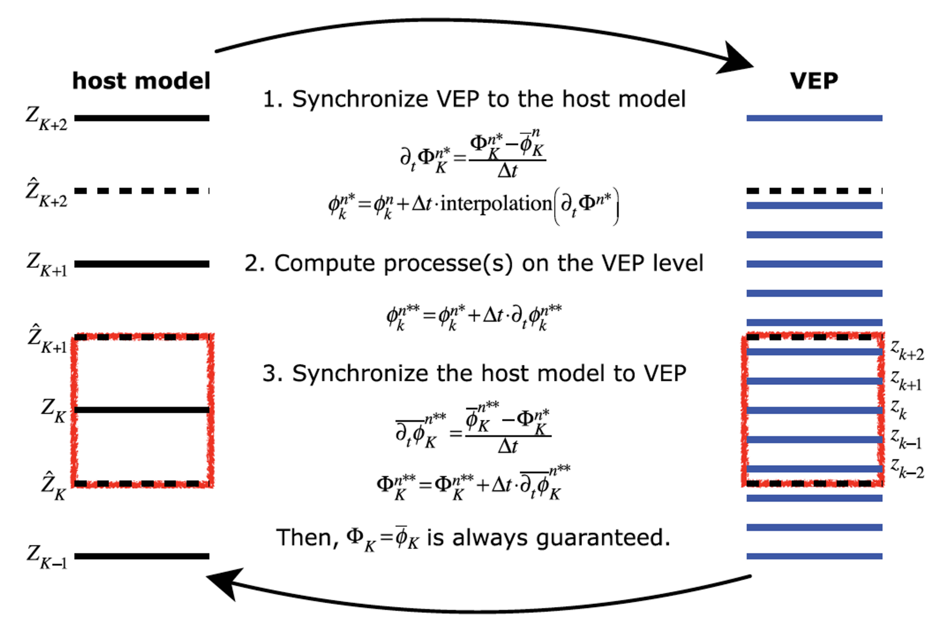


Inadequate model resolution in vertical and horizontal directions is a major cause of the underestimation of low-level shallow cloud in global circulation models, with important implications for climate studies. We have have achieved remarkable improvements in the representation of shallow clouds in U.S. DOE's Energy Exascale Earth System Model (E3SM) using eight-times or higher vertical resolutions in the boundary layer. To achieve an efficient vertical resolution enhancement, an adaptive vertical grid method, combined with the Framework for Improvement by Vertical Enhancement (FIVE), is under development for E3SM.

Our tasks for the model improvement:

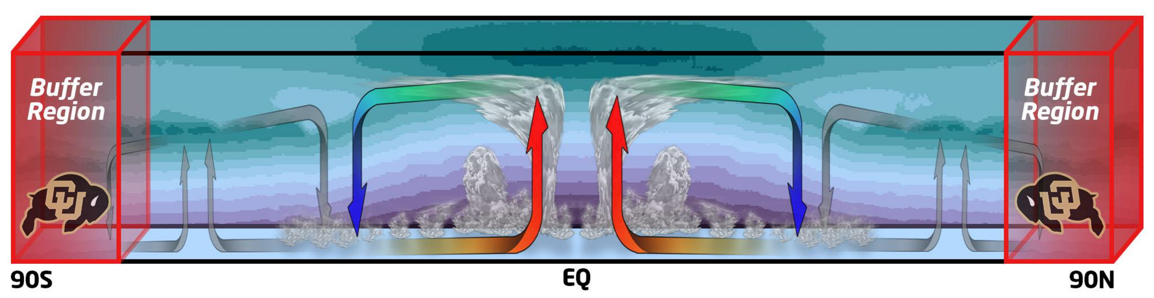
1. To further save computational costs, high-resolution vertical grids will only be turned on when and where necessary. Our solution is an application of neural networks for decision making on the meteorological conditions that are likely to benefit most from high-resolution vertical grids with respect to low cloud formation.

2. Testing the adaptive-FIVE and re-tuning model parameters will be necessary prior to climate simulations. However, these tasks are computationally too expensive to accomplish in full three-dimensional simulations given current computer resources. We propose a two-dimensional framework to address this issue.



▲ Fig. 1: A schematic for FIVE (Yamaguchi et al. 2017). Only physics schemes that are sensitive to the vertical profiles are calculated at high vertical resolution.

2. The two-dimensional framework as a testbed for high-resolution simulation



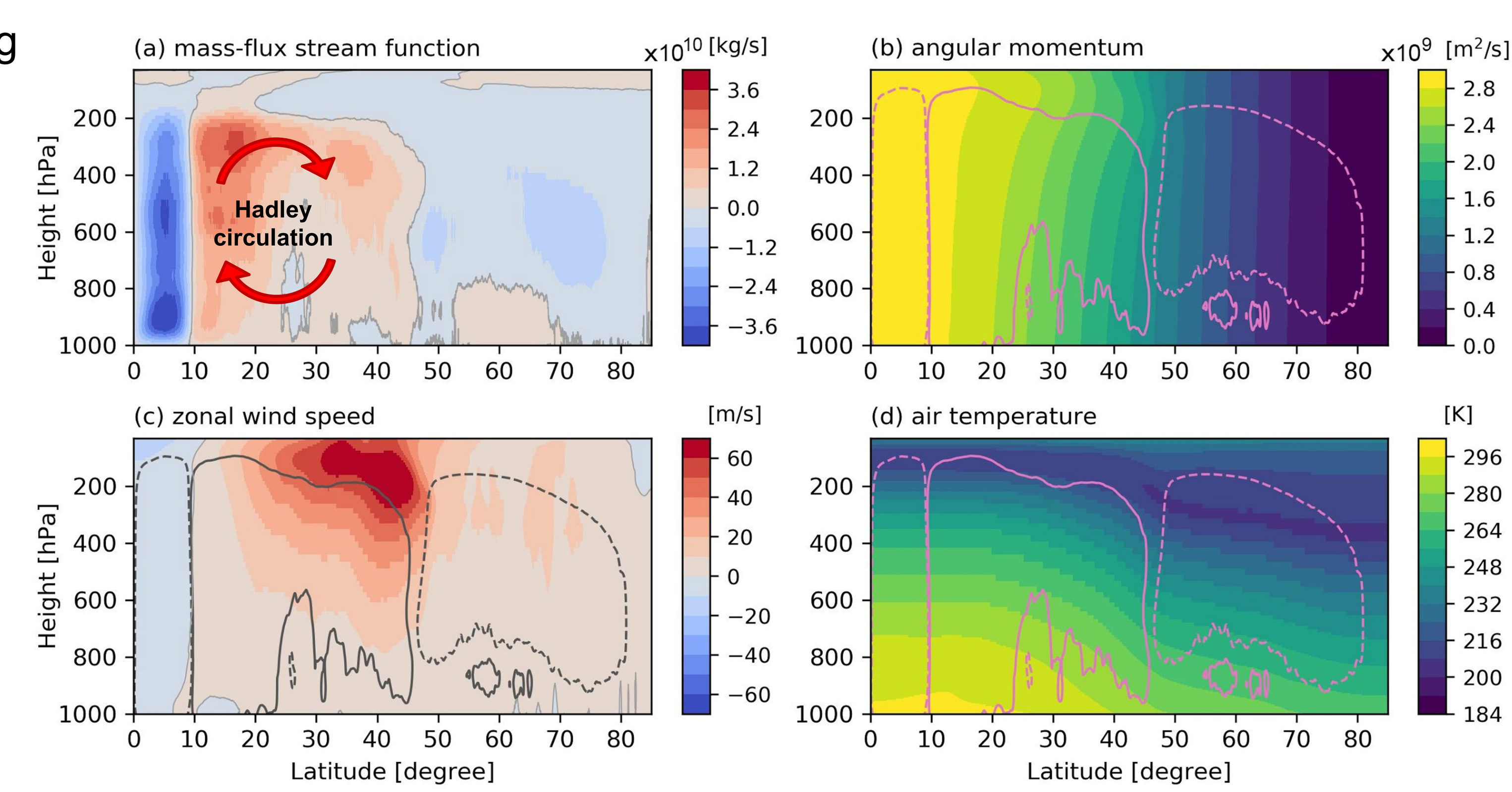
▲ Fig. 5: illustration of the north-pole to south-pole domain in vertical meridional two-dimensional (2-D) framework.

The Hadley circulation is a good representation of the Earth's climate that can be simulated in a two-dimensional framework (2-D). Various types of clouds and scale interactions embedded in the Hadley circulation are also simulated – which cannot be done by a single column model or a coarse-grid global model.

By neglecting the zonal direction, a large number of test simulations at high resolution becomes easily affordable. The computational and data resources are roughly 0.02 % of the global three-dimensional simulation with the same grid spacing.

A high-resolution 2-D simulation.
A 1000-day simulation with 2 km horizontal grid spacing with 128 vertical levels – extremely high resolution for global climate simulations – was carried out. The cost was 270 hours of CPU time using 512 cores of CPU with 8 nodes of a supercomputer.

The 2-D simulation produces the structurally equivalent Hadley circulation compared with real one.
The red-colored area from 10° to 40° in Fig. 6a (i.e. clockwise circulation) is the simulated Hadley circulation. Higher temperatures drive deep convection in the Tropics region; Concentrations of upward motion and their poleward outflows in the upper troposphere transport a higher angular momentum to the mid-latitudes (Fig. 6b), which accelerates westerly winds.



▲ Fig. 6: vertical-meridional cross sections averaged over the last 700 days. The average for north-hemisphere and south-hemisphere is shown.

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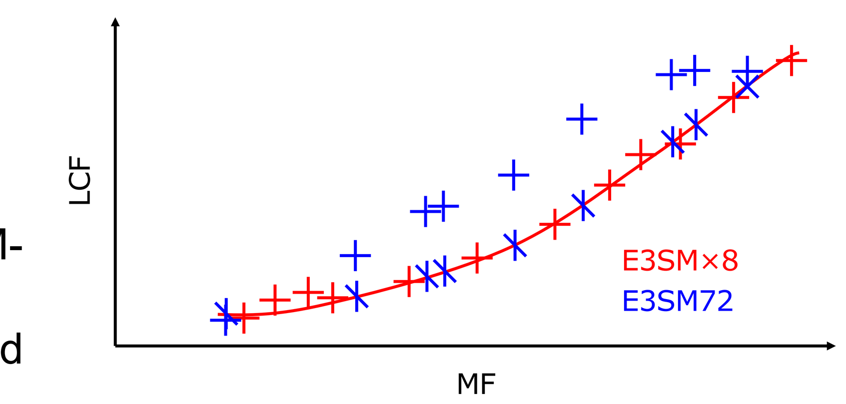
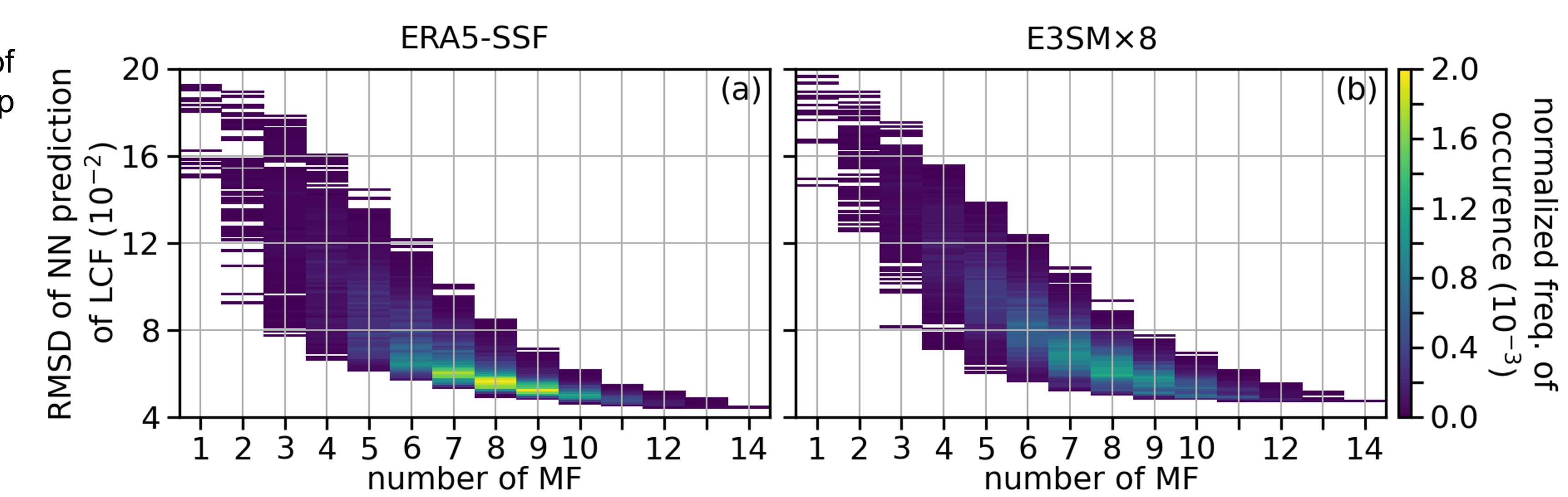
1. Application of neural networks for decision making

An adaptive vertical grid scheme needs to know whether the high vertical grid is a better choice for current atmospheric conditions in E3SM simulation with the default 72-layer vertical grid (E3SM72). We assume that the low cloud fraction (LCF) can be determined by a few meteorological factors (MFs). We trained neural networks (NNs) to capture the LCF–MF relationships for two data sets: E3SM-FIVE using 8-times vertical resolution (E3SM×8) and ERA5-SSF[1]. Then we use NNs as proxy models to estimate what the LCFs would be if the MFs in E3SM were to occur in E3SM×8 and ERA5-SSF. If NN predictions suggest that E3SM×8 can produce more realistic LCFs (compared with ERA5-SSF), the scheme will turn on 8-times vertical resolution. Early results show that, given the MFs produced by E3SM, changing to 8-times vertical resolution only slightly increases LCF, suggesting that the significant improvement of LCF in E3SM×8 simulations (Lee et al. 2021) is more associated with difference between MFs in E3SM×8 and in E3SM. On-going work is quantifying the shift in MFs and exploring other ideas for the adaptive scheme.

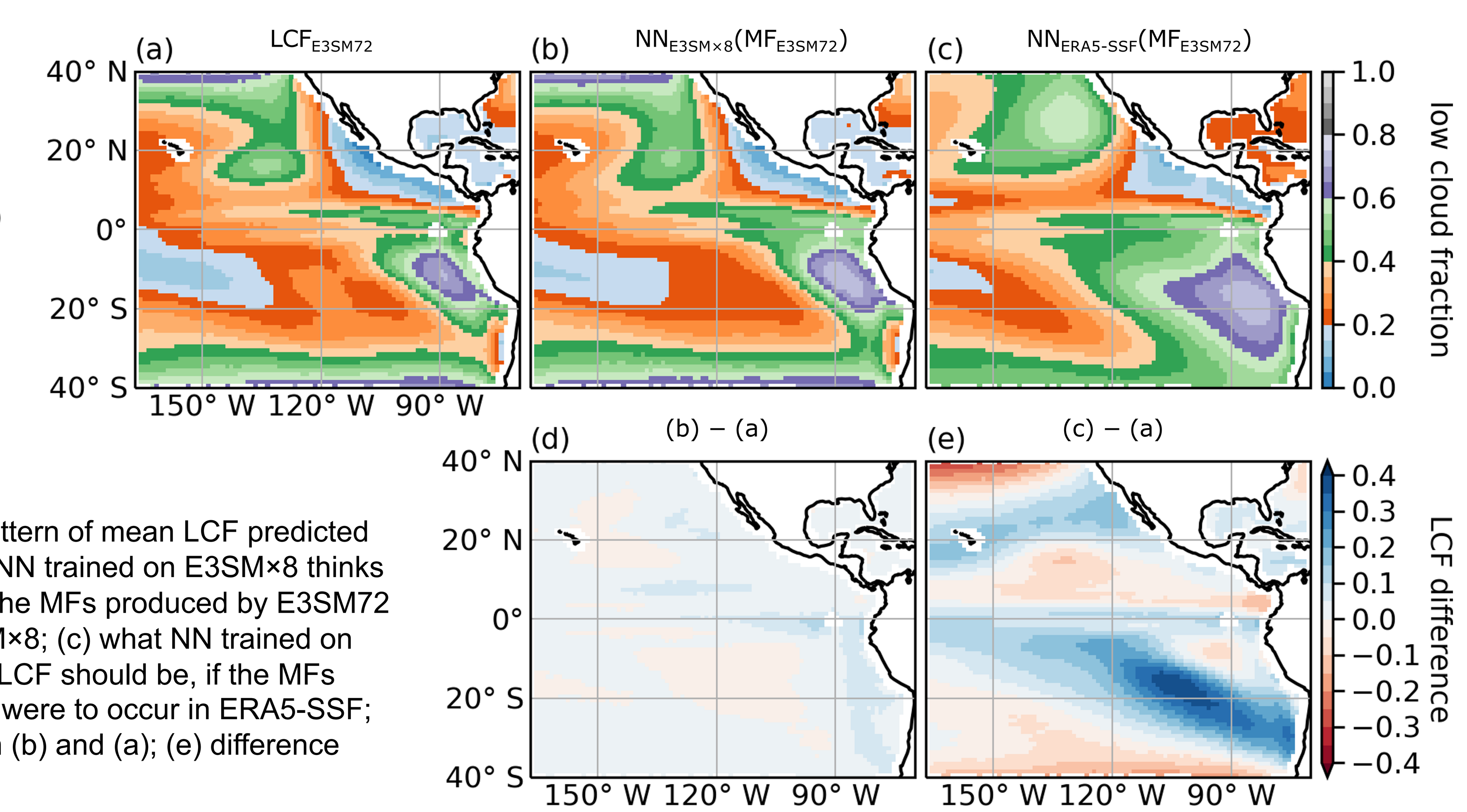


▲ Fig. 2 Schematic of the method (using E3SM×8 and E3SM72 as example).

▶ Fig. 3 Start with a pool of 14 MFs; train NNs that map subsets of MFs to LCF; pick an optimal MF subset based on the balance between (1) performance (root-mean-square deviation between NN prediction and true LCF) and (2) number of MFs required.



[1]ERA5-SSF data set contains MFs from ERA5 reanalysis (Hersbach et al. 2020) and LCF from CERES SSF1deg products (Minnis et al. 2021, Trepte et al. 2019).



▶ Fig. 4 (a) Spatial pattern of mean LCF predicted by E3SM72; (b) what NN trained on E3SM×8 thinks the LCF should be, if the MFs produced by E3SM72 were to occur in E3SM×8; (c) what NN trained on ERA5-SSF thinks the LCF should be, if the MFs produced by E3SM72 were to occur in ERA5-SSF; (d) difference between (b) and (a); (e) difference between (c) and (a).

Future work

We are addressing climate model performance improvement using efficient vertical resolution improvement and providing an efficient testbed to evaluate model performance.
Next steps:

- Assess the performance of FIVE in a two-dimensional Hadley circulation simulation.
- Apply neural networks for comprehensive model evaluation.