The Local Ensemble Tangent Linear Model: an enabler for coupled model 4DVAR

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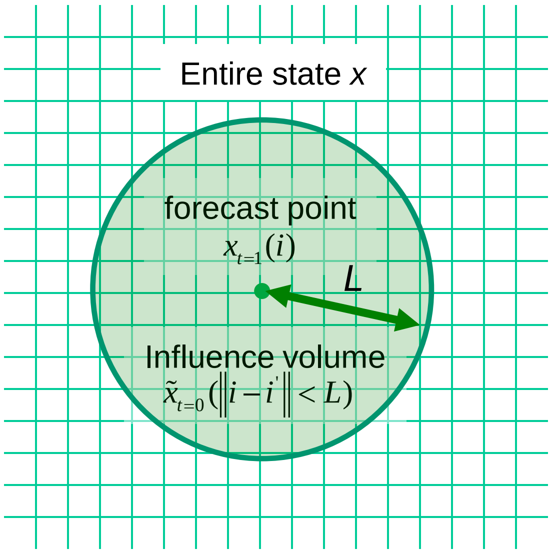
Dealing with the complexity of coupled models: the Local Ensemble TLM

- The prospect of maintaining accurate TLM and adjoints of coupled ocean-atmosphere-ice-aersol-LSM-chem models is daunting.
- Nevertheless, they are useful to have.
- True TLM perfectly predicts the difference between two nonlinear model trajectories whose initial state differs by an infinitesimal amount.
- Because of statements like “If A > 0 call parameterization”, environmental models do not have true TLMs. Artful approximations must be made. How to automate?

Local ensemble-based TLM

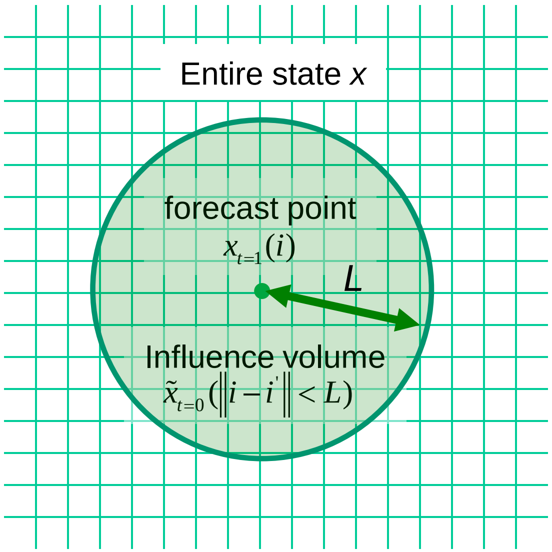


for each points "i" build an ensemble regression model

$$\underbrace{x_{t=1}(i)=\tilde{\mathbf{X}}_1}_{\text{Defined at the prediction point at future time step}}\underbrace{\left[\tilde{\mathbf{X}}_0^T\tilde{\mathbf{X}}_0\right]^{-1}\tilde{\mathbf{X}}_0^T\tilde{x}_0}_{\text{Defined for the influence volume at the previous time step}}$$

- Similar to finite difference models, ETLM updates each point based on the influence volume (stencil)
- Update is computed using an ensemble regression model for each point

Local ensemble-based TLM



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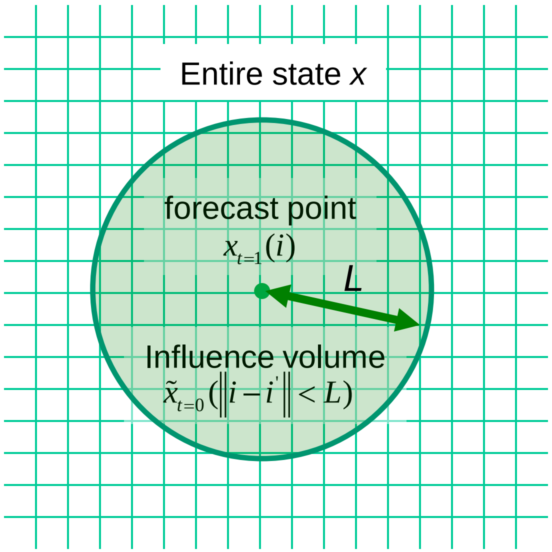
– Similar to finite difference models, ETLM updates each point based on the influence volume (stencil)

– Update is computed using an ensemble regression model for each point

– If number of ensemble members is greater than number of grid points in the stencil, the ETLM computation is exact.

Local ensemble-based TLM



for each points "i" build an ensemble regression model

$$x_{t=1}(i) = \tilde{\mathbf{X}}_1 \left[\tilde{\mathbf{X}}_0^T \tilde{\mathbf{X}}_0 \right]^{-1} \tilde{\mathbf{X}}_0^T \tilde{x}_0$$

Defined at the prediction point at future time step

Defined for the influence volume at the previous time step

- Similar to finite difference models, ETLM updates each point based on the influence volume (stencil)
- Update is computed using an ensemble regression model for each point
- If number of ensemble members is similar to the DOF that predict future state x_1 the ETLM computation is accurate.

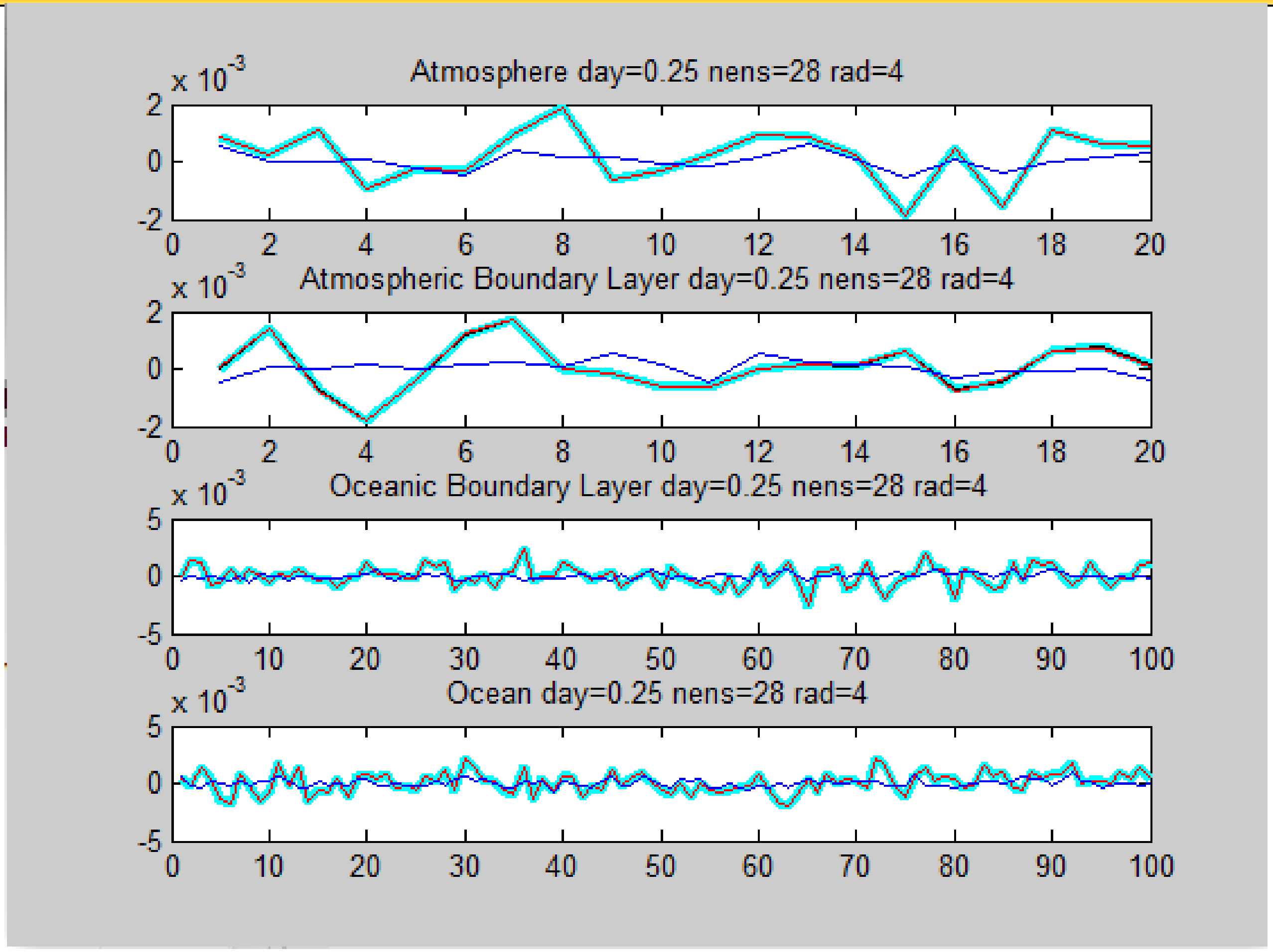
Outline

- Methods
- Applications:
  - four-layer coupled 1D model (model 1 of Lorenz)
  - 2D shallow water model (T21)
  - 3D low-resolution NAVGEM (T47)

Construction of Local Ensemble TLM (LETLM) for simple coupled model

- Simple coupled model (based on Model 1 of Lorenz, 2005) uses 2nd order Runge-Kutta time stepping. Vertical coupling via relaxation to neighbouring levels.
- Thus, patch size required 2-3 levels of 9 grid points.
- Hence, needed *K*>27 ensemble members to precisely describe the linear dynamics – regardless of total number of variables in the model (240).

Tests of coupled LETLM with *K*=28 ensemble members



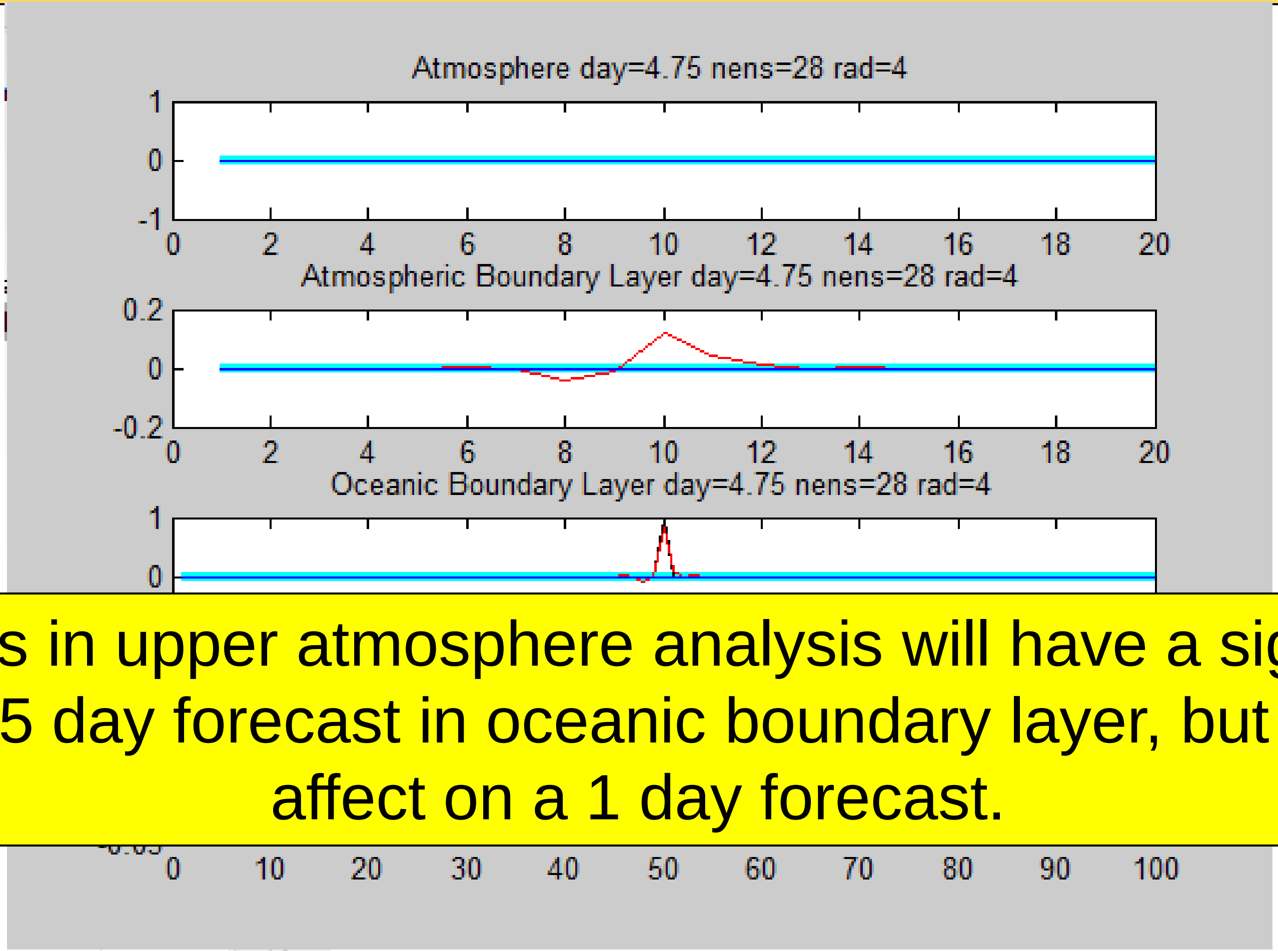
Black: Difference between 2 non-linear trajectories (target for the perfect TLM)

Cyan line is global ETLM with *K*=480 members: (Tracks black line perfectly)

Red line is LETLM with 28 members: (Often hidden by black line)

Blue line is global ETLM with 28 members: (Terrible performance)

Accurate LETLMs enable SVs and analysis and observation sensitivity

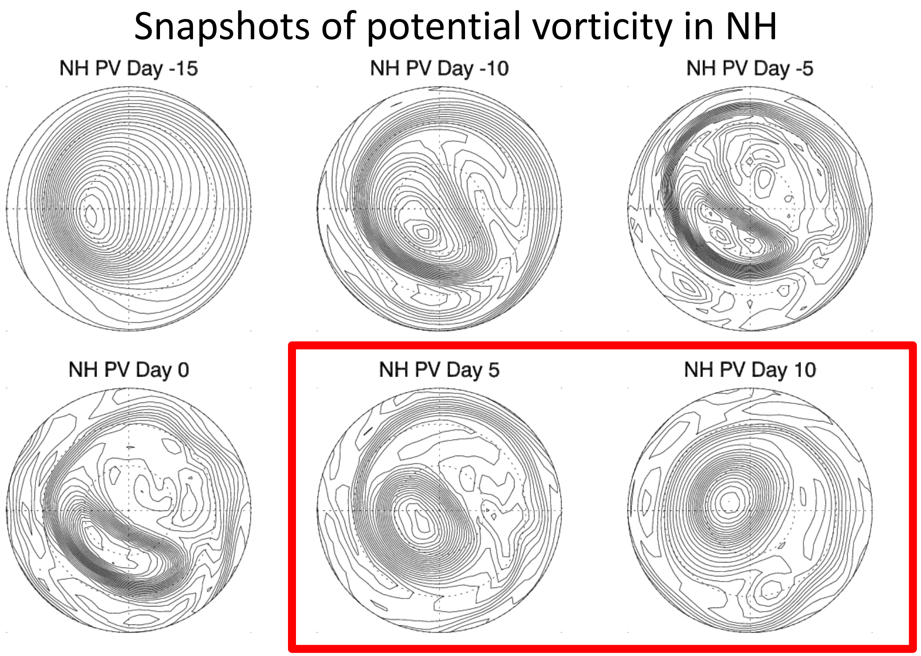


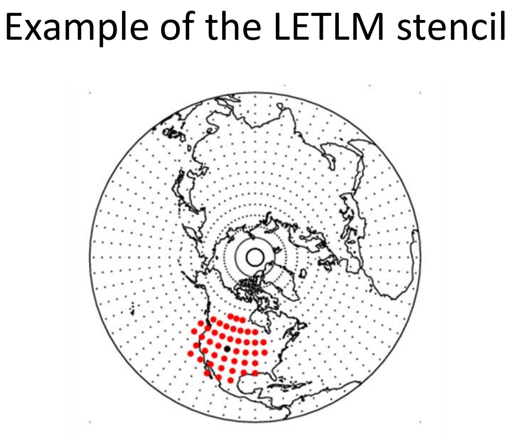
Changes in upper atmosphere analysis will have a significant affect on 5 day forecast in oceanic boundary layer, but very little affect on a 1 day forecast.

Black: Location of target grid point (verification time is t=5 days)

Red line is d(target variable)/d(local variable): (i.e. good places to observe to improve forecast of target grid point at t=5 days).

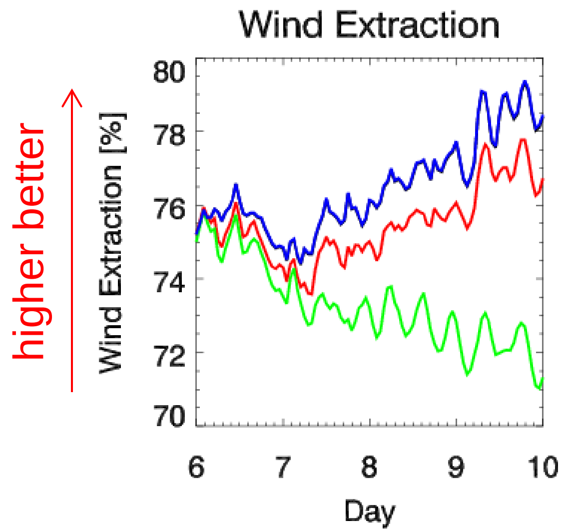
Shallow water model





- <u>System:</u>
  - Shallow water equation + ozone as a tracer
  - Spectral T21 resolution (5.8° lon spacing at equator)
  - Truth run with wave 1 topographic forcing (top left figure)
  - Experiment runs during day 5-10 (highlighted in red)
  - Perturbed observations EnKF with 100 members
  - Stencil size 1000km, LETLM timestep 1 hour

Testing of ETLM in a Hybrid-4DVAR system



Experiment	WEP
Hybrid-4DVar (with LETLM)	78.22
Hybrid-4DVar	78.17
Hybrid-3EnVar	76.71
NODATA	72.12

Method:

- Compare Hybrid-4DVar executed with traditional TLM and LETLM

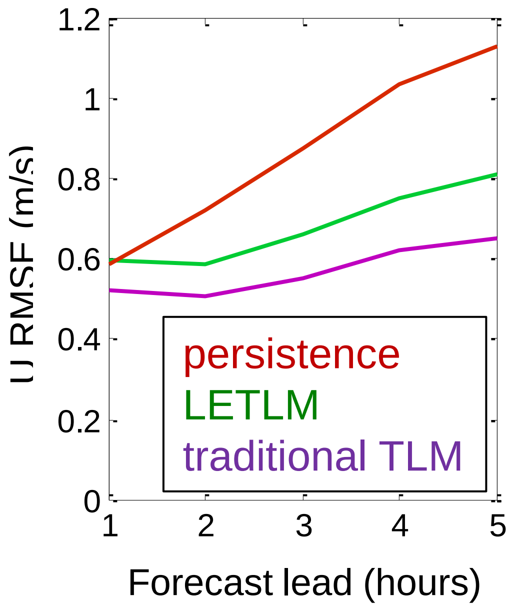
Results:

- Little difference between results with TLM and LETLM

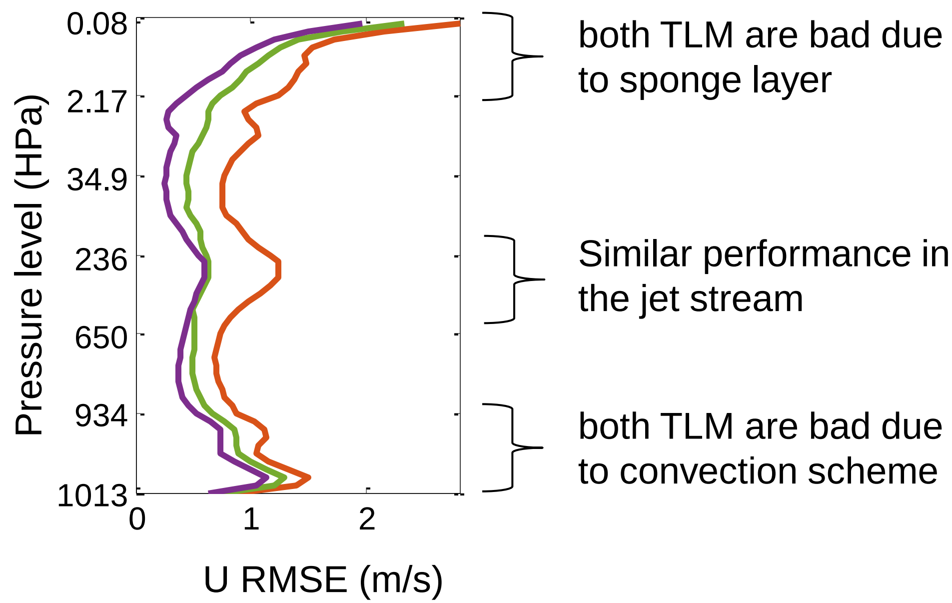
D. Allan et. al. (submitted MWR)

EARLY Results for 3D NAVGEM (illustrated for U velocity)

Error over time



Vertical profile of error



- LETLM has skill over persistence and is slightly worse than the traditional TLM
- LETLM is very young (~2 month of work) vs. traditional TLM (~6 years)

Summary

- Coupled ocean, wave, ice, atmosphere and aerosol models represent a quantum leap in complexity. TLM and adjoint maintenance for these systems is a daunting prospect. However, coupled model ensembles are readily available and, by construction, keep pace with the ever evolving components of coupled models.

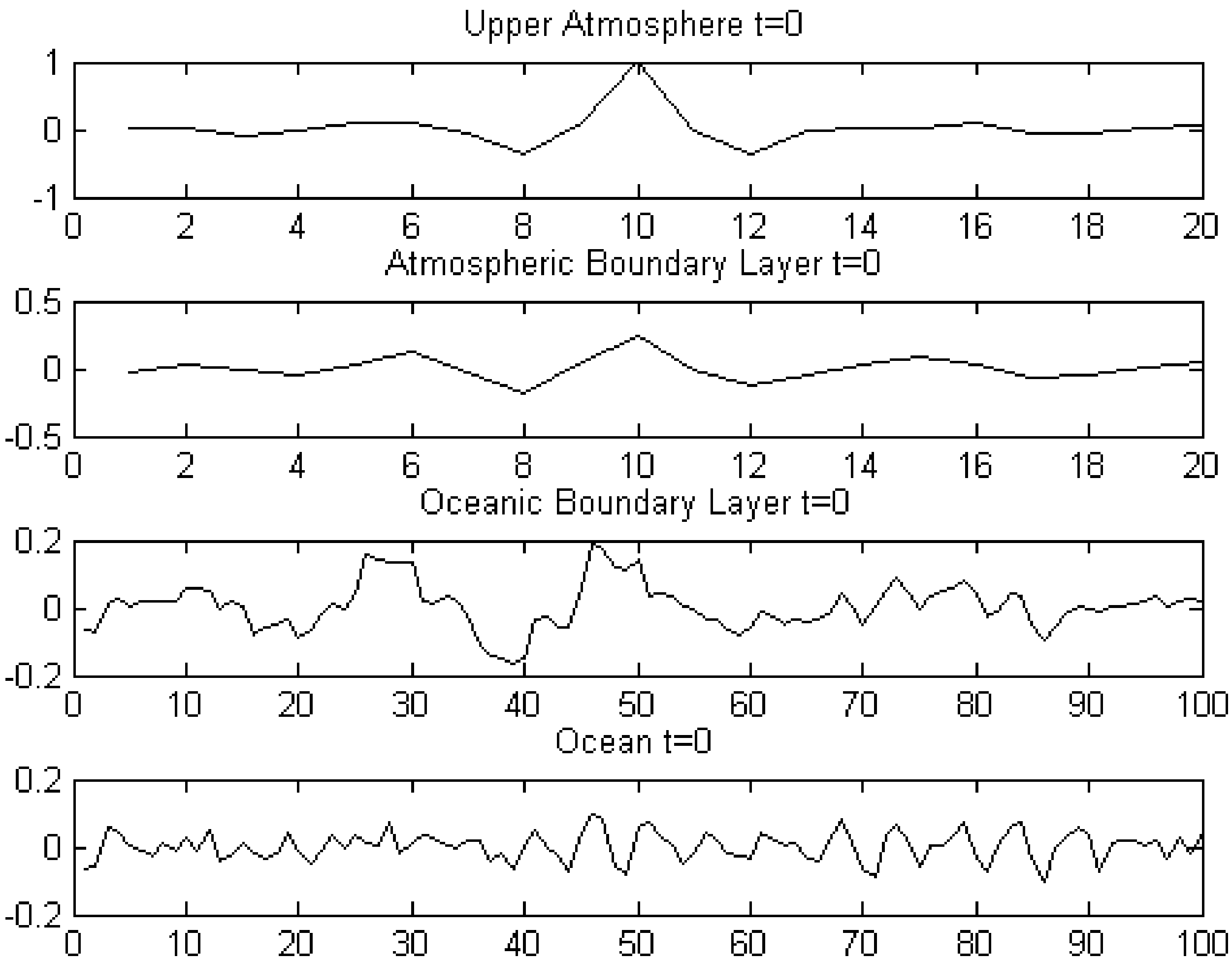
- Here, we have used an array of models to demonstrate:
  - Local Ensemble TLMs (LETLMs) of coupled models and their adjoints are easy to construct and can be precisely accurate provided the ensemble size exceeds the maximum number of independent variables that influence the evolution of model variables over a time step.
  - LETLMs and their adjoints can be used in 4DVAR data assimilation schemes (example in 1D and 2D) with indistinguishable results from traditional TLMs.
  - Promising results for LETLMs in complex 3D NWP models with physics.

Concluding remarks

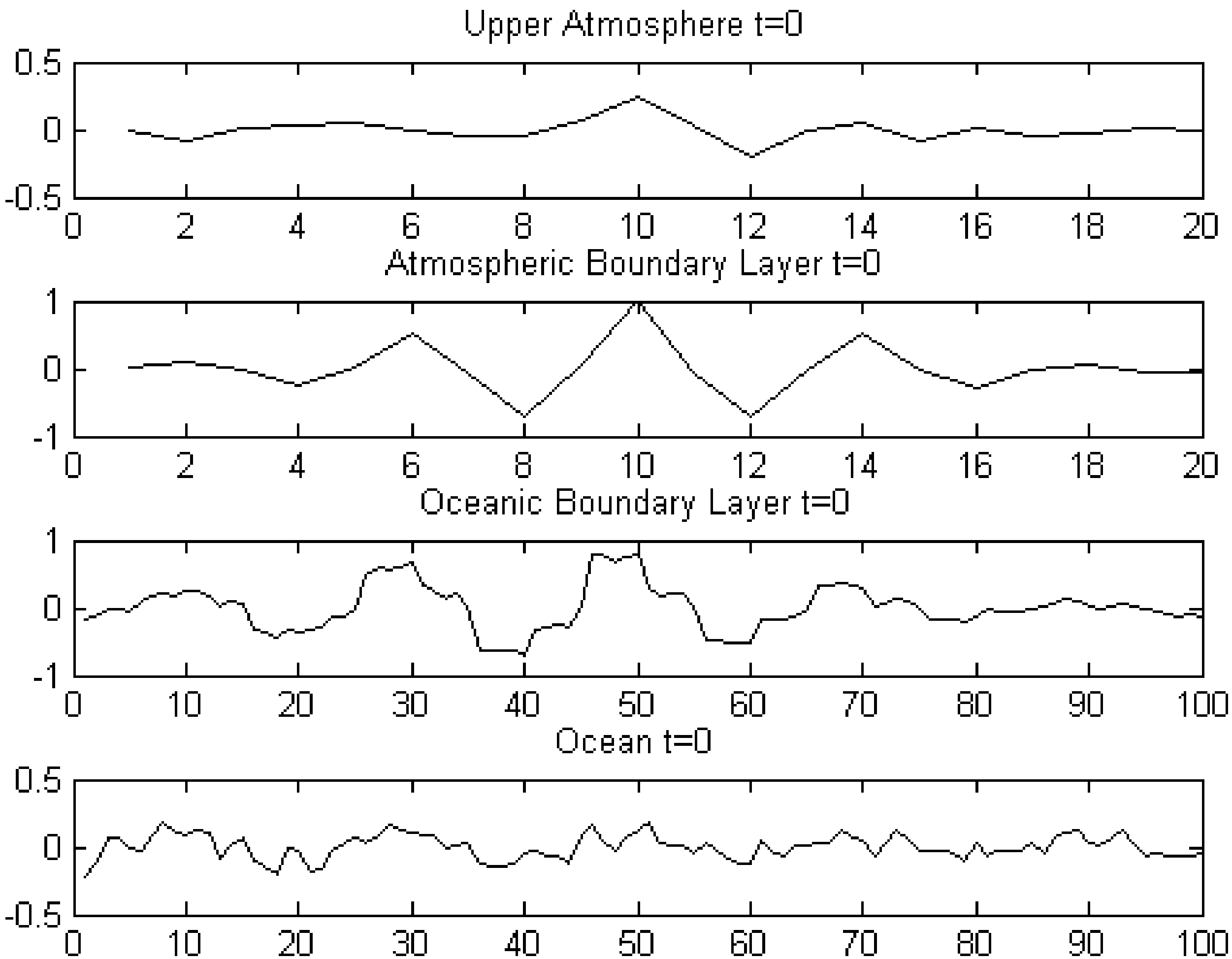
- Unlike traditional TLMs, LETLMs could be used in an interface solver.
- LETLM can be used to specify TLMs of the model coupler
  - Due to diffusive dynamics, it is likely that very few ensemble members will be needed to develop such an LETLM
  - LETLM for a coupler can be combined with a traditional (high-fidelity TLM) for the atmosphere (or ocean)

Extra slides

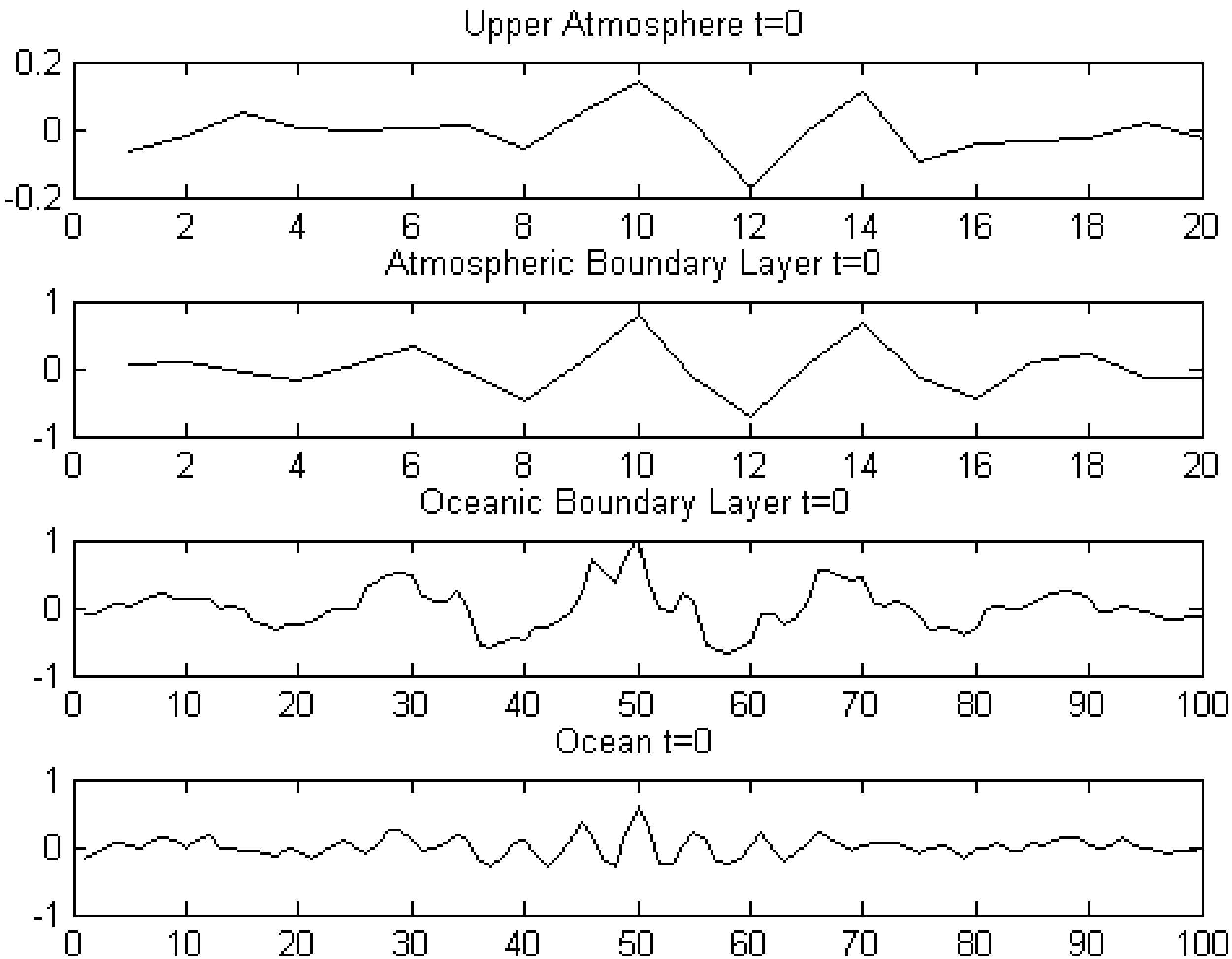
Climatological correlation function for upper atmosphere



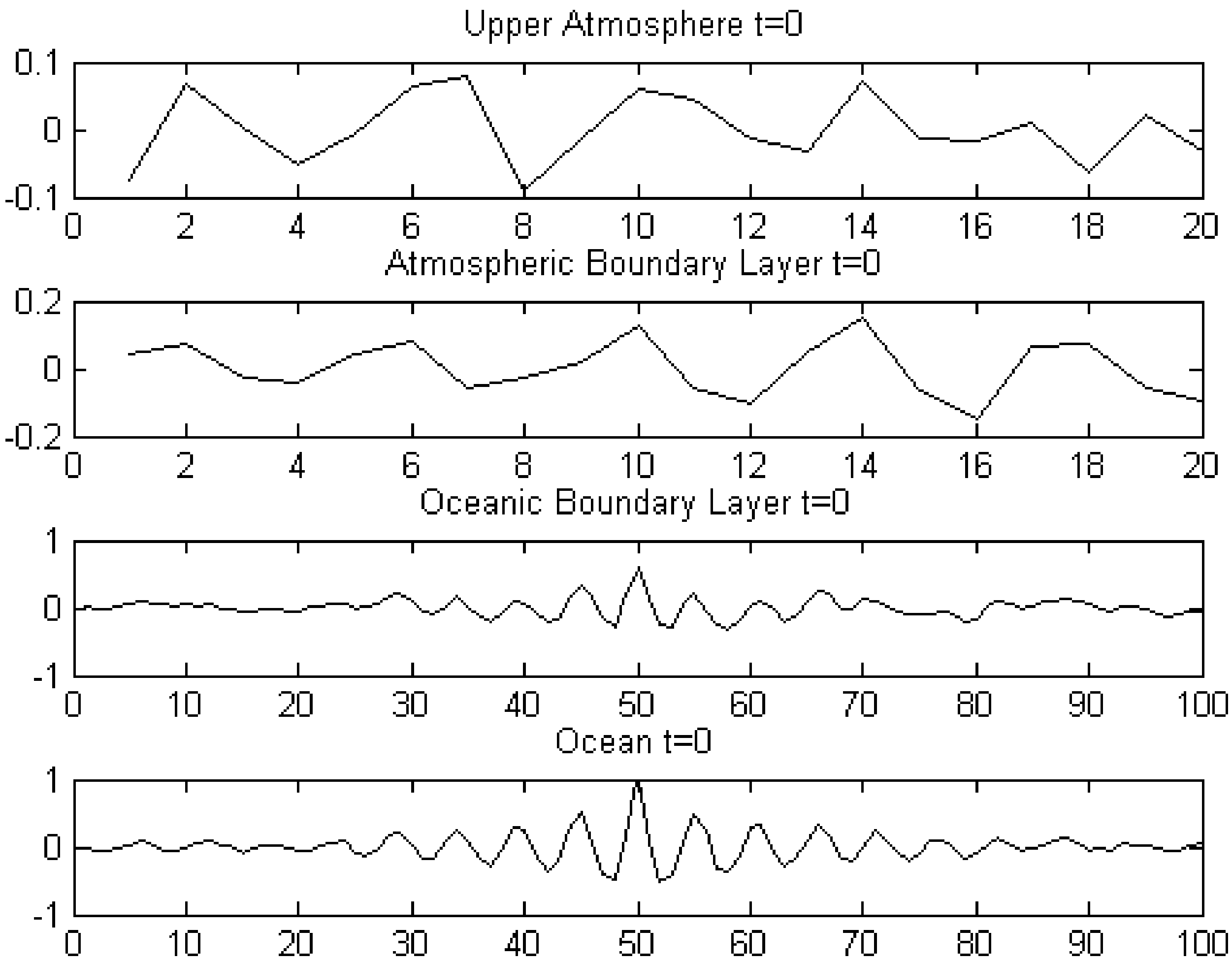
Climatological correlation function for atmospheric BL



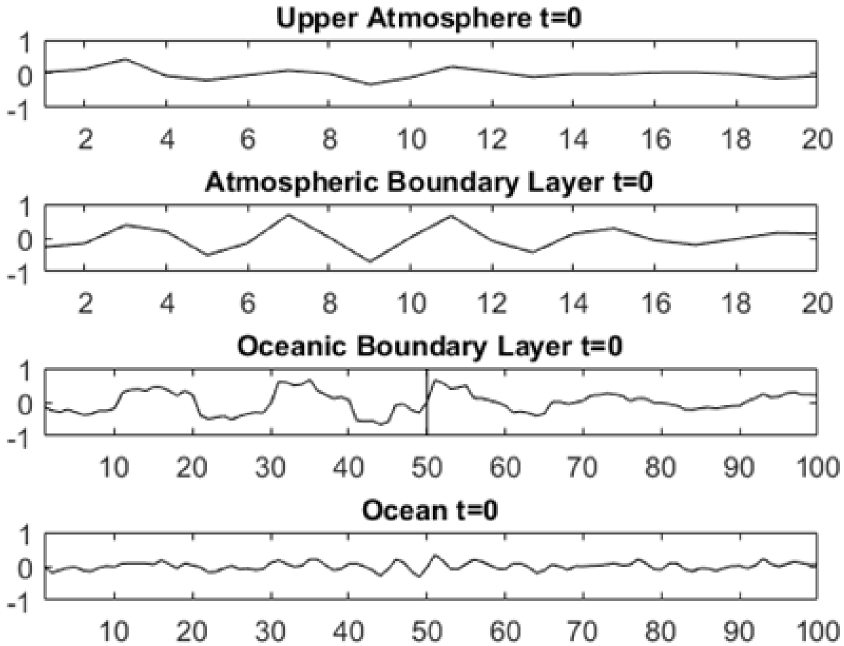
Climatological correlation function for oceanic BL



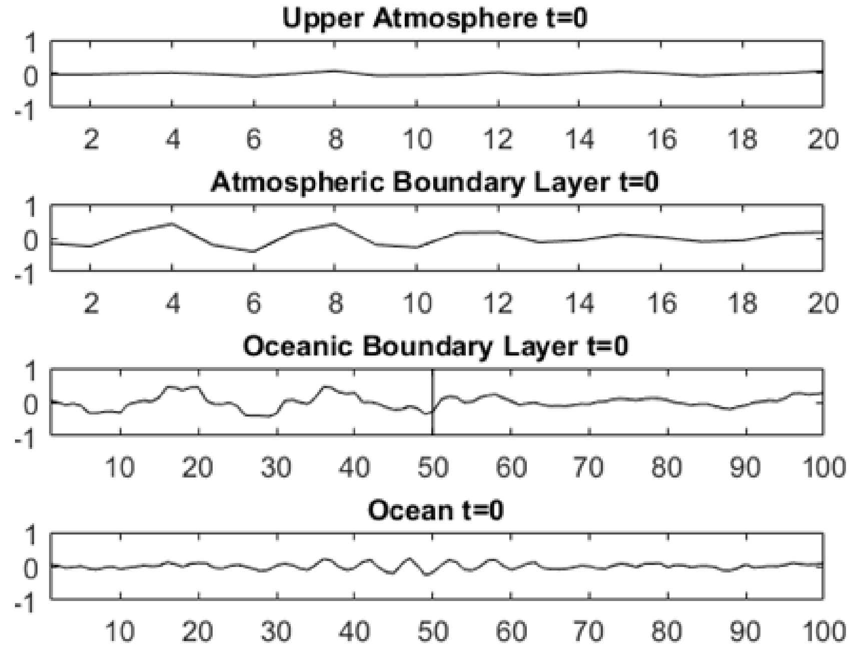
Climatological correlation function for ocean



Error correlation propagation: TLM (left panels) non-linear model (right panels)



Correlation function from TLM/adjoint



Correlation function from ensemble

The left panels show the LETLM predicted error correlation function between a 5 day forecast error of variable 50 of the oceanic boundary layer (indicated by the vertical line) and the initial time errors of every single model variable. Specifically, it is a 4D correlation function of a 480 member ensemble forecast made by propagating the initial ensemble perturbations forward in time using the LETLM. The right panels show the 4D correlation function of a 480 member ensemble forecast made from the same initial conditions as that used to generate the left panels but for the right panels, the non-linear model was used to generate the ensemble forecast.