Variability of Evaporative Duct Properties and EM Signal Propagation Utilizing Large Eddy Simulations

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***Abstract*— Large Eddy Simulation (LES) models can directly resolve dynamic and thermodynamic perturbations in the Marine Atmospheric Surface Layer (MASL) with a wide spectrum of eddy sizes from Energy Containing Eddies (ECEs) to some portion of turbulence in the inertial subrange. These resolvable-scale temperature and moisture perturbations result in corresponding perturbations in atmospheric refractivity and hence properties of the evaporative duct (ED). Here, we analyzed the characteristics of the ED using LES model results. The impact of small-scale refractivity variations on RF propagation are also investigated using the Variable Terrain Radio Parabolic Equation (VTRPE) propagation model.**

Keywords—Large Eddy Simulations, Evaporative Ducts, Electromagnetic ducting, Anomalous Propagation, Marine Atmospheric Surface Layer.

I. INTRODUCTION

Evaporative ducts are the most common and tactically relevant refractive phenomena that occur over the ocean surface. They exist due to a persistent/strong vertical gradient in water vapor that exists immediately above the air/sea interface and into the lowest 10s of meters of the MASL. The ED refracts EM waves downward and ultimately results in extended ranges to surface-based radars and communications systems.

The historical method of representing vertical MASL moisture gradients in a ED is to use surface layer models based on Monin-Obukhov Similarity Theory (MOST), of which spatial homogeneity and stationarity are primary assumptions. Therefore, this method is not capable of representing turbulent fluctuations on small scales while ED only represents mean ducting conditions.

Utilizing LES for MASL propagation modeling also allows us to account for the uncertainties associated with MASL turbulence when using a mean refractivity profile to quantify RF propagation. As a result, we can gain more insight into EM propagation through the turbulent MASL media by producing stochastic signal strength statistics, rather than a single/deterministic EM propagation assessment. Such knowledge on signal variability is an initial step towards ensemble EM propagation forecasts.

II. LES DATA

In this research, we used results from two LES models: the University of Minnesota and the Naval Research Laboratory – Monterey models, both simulated cases under different MASL thermal stabilities are currently being assessed. An initial evaluation of the model results was to compare them to the modified refractivity (*M*) profile calculated from the MOST-based theory, which gave us the confidence of the LES model results. As shown in the example in Fig. 1, many of the investigated cases produce realistic mean state variable profiles, and associated evaporative ducts.

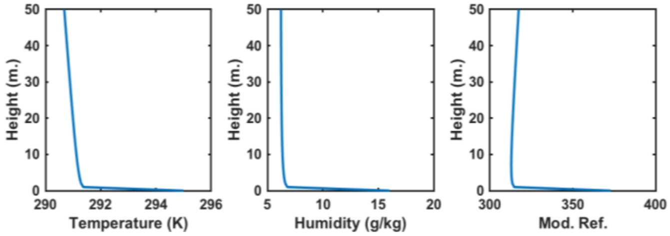

Fig. 1. Vertical mean profiles of temperature, specific humidity and modified refractivity from LES data.

Once mean LES properties are investigated and ensured to be physically realistic and internally consistent, the turbulent duct properties are assessed. The instantaneous LES state variables are used to calculate the turbulent *M* field. The height and value of *M* minima at each LES model grid point is determined and used to calculate instantaneous Evaporative Duct Height (EDH) and Evaporative Duct Strength (EDS), respectively. An example of the EDH field in the model domain is given in Fig. 2, where the 'instantaneous' EDH exhibits large spatial variability across the LES domain due to local moisture gradient perturbations imposed by ECEs.

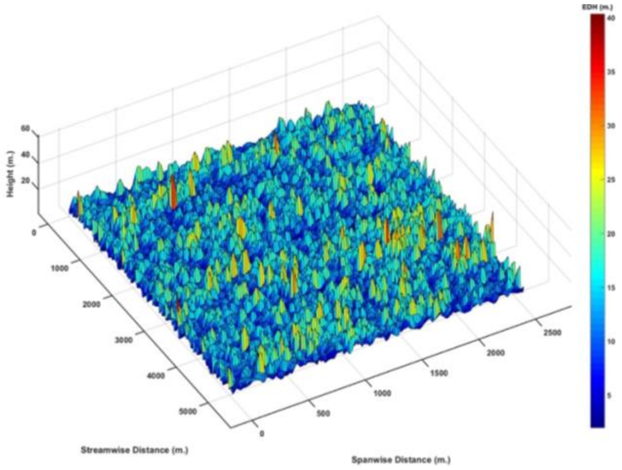

Fig. 2. Instantaneous EDH values occurring over a thermally unstable LES domain.

The variability of EDH and EDS on the LES grid scale allows for statistical depiction of these duct properties, a novel concept in RF propagation analyses to introduce small-scale variabilities. Fig. 3 gives histograms of EDH and EDS, respectively from one of the LES model runs. It is clear the EDH has a skewed distribution with the presence of some rather high ED values. The distribution of EDS appears more symmetric. Further analysis has shown that the buoyancy driven convective updrafts are responsible for the positively skewed tail of the EDH histogram, and the negatively skewed low EDS values, while compensating/continuity-driven subsidence accounts for the low EDH/high EDS instances.

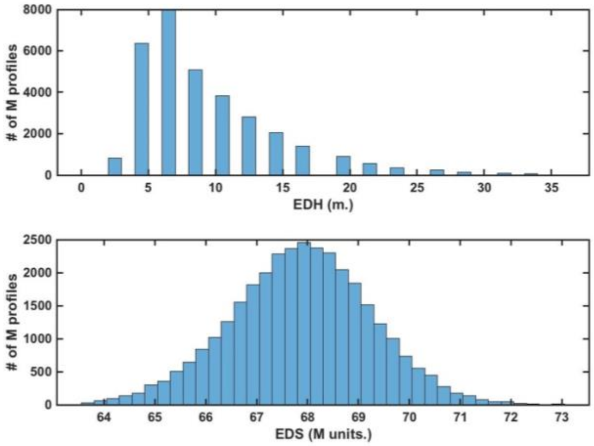

Fig. 3. Histogram of instantaneous EDH(top panel) and EDS (bottom panel) occurring over a thermally unstable LES domain.

III. PROPAGATION RESULTS

The goal of this portion of the study is to assess the range-integrated effect that the LES resolved turbulence field has on EM signal propagation. This is accomplished by constructing long/narrow LES corridors from concatenated LES segments (made possible by the LES periodic boundary condition), and ingesting the LES corridors into the VTRPE propagation model.

Fig. 4 illustrates the variability of propagation loss for a 9 GHz radar located within a 9 m. ED. The propagation loss values at a fixed range of 150km and at a fixed height above the duct (15 m) in the turbulent LES ensemble exhibit a large spread in values (blue bars), while the pink bar indicates the propagation loss resulting from an LES mean environment. The differences can be attributed to turbulent duct leakage, a process by which local duct perturbations leak energy from the ED with increasing propagation range.

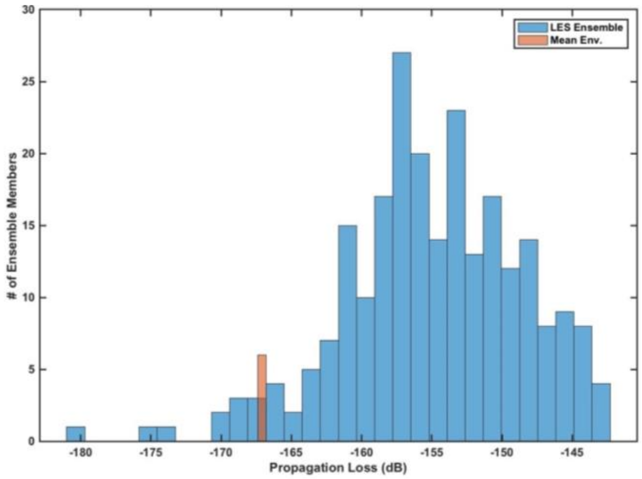

Fig. 4. Variations of propagaion loss calculated by VTRPE using LES refractivity field as input.

IV. CONCLUSIONS

We demonstrated here the importance of considering turbulent variations in EM propagation. LES models are great tools for generating the spatial refractivity field needed for this study.

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