Characterizing boundary layer turbulence using ACTIVATE observations over the Western North Atlantic Ocean: Implications for model evaluation and development


Motivation

The various interactions between aerosols, clouds, and meteorology (adopted from Sorooshian et al., 2019, BAMS).

There are a number of interactions between aerosols, clouds, and other processes (including turbulence pictured above).

Yet, the modeling of aerosols and cloud processes is still highly uncertain.

Turbulence, a small-scale process, needs to be parameterized in order to evaluate... (from Sorooshian et al., 2019, BAMS).

CLU BB is a higher-order moist turbulence scheme used in Earth system models (like the two that we evaluate here, see Methods).

CLU BB needs to use a bivariate Gaussian PDF that was fitted to subtropical and tropical clouds.

Here, we comprehensively use data from 40 research flights from the 2020 ACTIVATE deployments to characterize observed turbulence in order to evaluate model turbulence.

ACTIVATE

King Air: the High Spectral Resolution Lidar version 2 (HSRL-2), the Research Scanning Polarimeter (RSP), and dropsondes.

Falcon: stair-stepping maneuvers throughout the boundary layer. These are called level legs. A complete set of level legs is called an ensemble.

The flight strategy for the two aircraft used in ACTIVATE: the high-flying King Air and the HU-25 Falcon within the boundary layer for (a) cloudy and (b) clear ensembles.

Instrumental data used

From the Falcon, we use:

The Turbulent Air Motion Measurement System (TAMMS) to derive wind and temperature turbulence measurements.

The Langley Aerosol Research Group (LARGE) instrument suite of aerosol and cloud probes, and

The Fast Cloud Droplet Probe (FCDP) and 2DS provided by DLH. From the King Air, we use:

The HSRL-2 to derive mixed layer heights as a proxy for PBL heights and

RSP to derive cloud fraction.

Methods

Turbulent quantities are derived from the usual breakdown of a quantity \( x \) into its mean and turbulent components:

\[ x = \bar{x} + x' \]

where the means are made over each level leg.

From these three turbulent perturbations, we derive quantities like the wind variances \( \sigma_u^2 \), \( \sigma_v^2 \), and \( \sigma_w^2 \) (where \( \sigma \) is the average over a level leg).

Thus, turbulence kinetic energy

\[ \text{TKE} = \frac{1}{2} \left( \sigma_u^2 + \sigma_v^2 + \sigma_w^2 \right) \]

Global model simulations

The Community Atmosphere Model version 6 (CAM6) and CLU BB are higher-order moist turbulence parameterizations as being valid.

LES simulations

Weather Research and Forecasting (WRF) run in large eddy simulation (LES) mode:

a) 60 x 60 km domain for two horizontal resolutions, 153 layers up to 7 km with a vertical resolution of 33 m in the boundary layer.

b) Simulations on the three process study days: 28 February, 1 March, and 2 June 2020.

The LES is used as a tool to understand how TKE can be distributed throughout the boundary layer and to understand the difference between observational sampling and global model grid cell averages.

LES results

Domain averaged turbulence kinetic energy (TKE) profiles in the LES for the three process study days in 2020. Two different horizontal resolutions of the LES are shown: the original 300 m (black) and 100 m (red). Randomly sampled profiles of columns containing clouds in the 100-m resolution simulations are also provided (gray lines). Cloud layers are indicated by the gray (for 300-m resolution) or pink (for 100-m resolution) shading.

Maximum TKE can be absolutely highest within cloud or have a local peak within cloud.

How to characterize observed turbulence?

We characterize the observed turbulence by deriving distributions of frequencies of occurrence for various bins of turbulent quantities.

An example of such frequency distributions in TKE across four level legs types from cloudy ensembles in the 2020 winter deployment is given below.

These frequency distributions can be compared to those from ESM simulations like the right.

Frequency distributions of turbulence kinetic energy (TKE) in cloudy ensembles during the winter (February-March 2020) and summer (August-September 2020) flights. The numbers in the upper right of each panel indicate the number of level legs.

Where is TKE highest?

Frequency distributions of wind variances at two level legs in cloudy ensembles during the winter deployment (top) and from cloudy grid cells in the model (middle and bottom) winter simulations.

Model turbulence is weaker than observed (note the difference in the x-axes).

Simulated \( \sigma_u^2 \), \( \sigma_v^2 \), and \( \sigma_w^2 \) are wider than observed \( \sigma_u^2 \), \( \sigma_v^2 \), and \( \sigma_w^2 \) distributions being wider.

Returning of CLUBB parameters undertaken in the development of EAMv2 reduces the width of \( \sigma_u^2 \), \( \sigma_v^2 \), and \( \sigma_w^2 \) distributions.

Frequency distributions of turbulence kinetic energy (TKE) in cloudy ensembles during the winter (February-March 2020) and summer (August-September 2020) flights. The numbers in the upper right of each panel indicate the number of level legs.

Results

Implications for evaluating model turbulence

Is the bivariate normal PDF valid over the WNAO?

(Le t column) Bivariate frequency distributions between turbulent perturbations in liquid potential temperature \( \theta' \) and vertical velocity \( w' \). Distributions being wider.

Univariate marginal PDFs as seen in the normal-looking marginal distributions.

Bivariate frequency distributions consistent with bivariate Gaussian PDFs as seen in the normal-looking marginal distributions.

Conclusions

Maximum TKE is most often within cloud in observations but mostly below cloud by a factor of 2-3 in model.

Observations point to the binormal PDF assumed to close higher-order turbulence parameterizations as being valid.

Boundary layer turbulence simulated by global models is weaker than observed.

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