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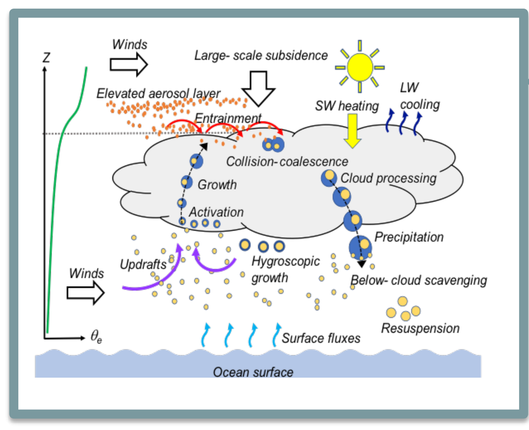
Characterizing boundary layer turbulence using ACTIVATE observations over the Western North Atlantic Ocean: Implications for model evaluation and development

Michael A. Brunke*, Lauren Cutler, Rodrigo Delgado Urzua, Andrea F. Corral, Ewan Crosbie, Johnathan Hair, Chris Hostetler, Simon Kirschler, Vincent Larson, Xiang-Yu Li, Po-Lun Ma, Annalisa Minke, Richard Moore, Claire E. Robinson, Amy Jo Scarino, Joseph Schlosser, Michael Shook, Armin Sorooshian, Kenneth Lee Thornhill, Christiane Voight, Hui Wan, Hailong Wang, Edward Winstead, Xubin Zeng, Shixuan Zhang, and Luke D. Ziemba

1 Motivation



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

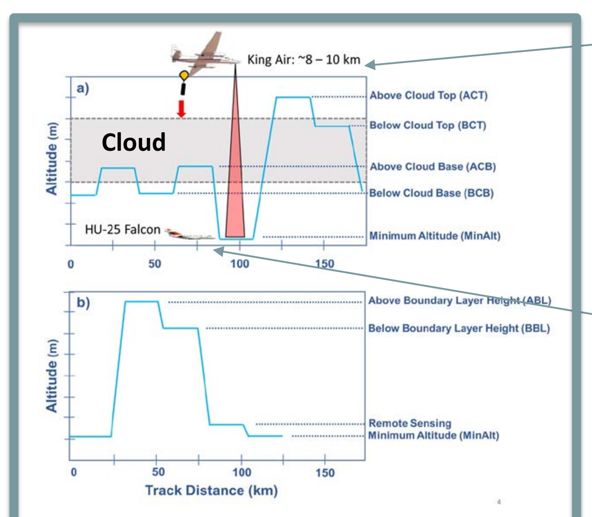
- There are a number of interactions between aerosols, clouds, and other processes including turbulence pictured above.
- Yet, the modeling of aerosols and cloud processes is still highly uncertain.

Turbulence, being a small-scale process, needs to be parameterized in E3SM:

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

2 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.

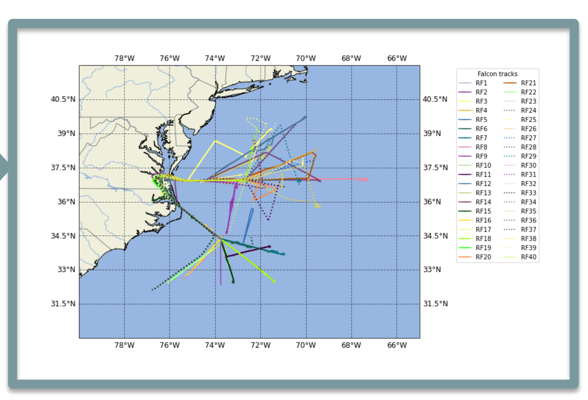
Instrumental data used

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.



Flight tracks of the 2020 ACTIVATE flights. Winter deployment flights are the solid lines, while the summer deployment flights are the dotted lines.

3 Methods

Turbulence processing

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 turbulent perturbations, we derive quantities like the wind variances $\langle u'^2\rangle$, $\langle v'^2\rangle$, and $\langle w'^2\rangle$ (where < > is the average over a level leg).

Thus, turbulence kinetic energy

$$\mathrm{TKE} = {}^1/_2\left(\langle u'^2\rangle + \langle v'^2\rangle + \langle w'^2\rangle\right)$$

Global model simulations

The Community Atmosphere Model version 6 (**CAM6**) and

The Department of Energy's Energy Exascale Earth System Model (E3SM) Atmosphere Model version 2 (**EAMv2**):

- These atmosphere models are run coupled to a land model with observed sea surface temperature (SST) for ocean forcing.
- 30-min timestep output for 15 days (19 February-5 March and 22 August-5 September) for 2004-2010

LES simulations

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

- 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.
- 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.

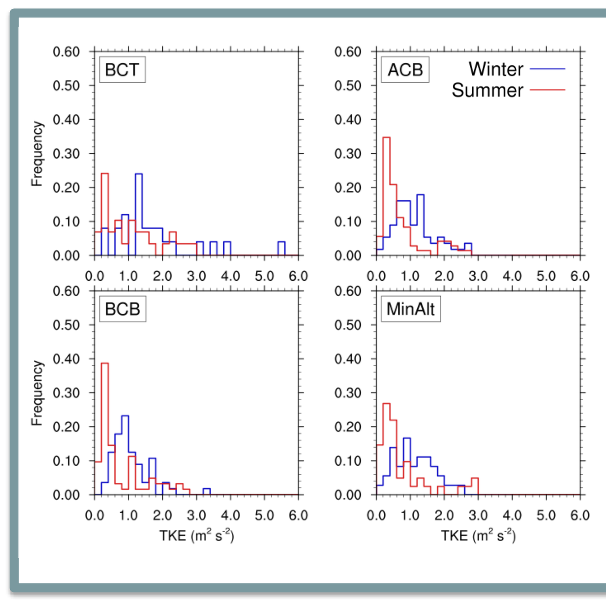
4 Results

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 Winter 2020 deployment is given below.

These frequency distributions can be compared to those from ESM simulations like on 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 of maximum TKE in ACTIVATE cloudy ensembles	Within cloud	Below cloud	MinAlt
Winter	36%	2%	27%
Summer	51%	4%	27%

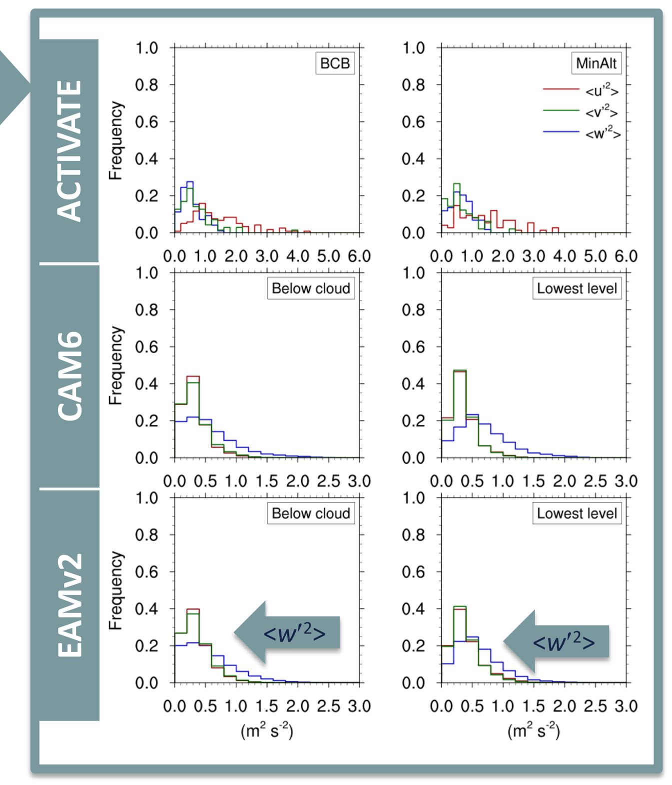
Frequency of maximum TKE in cloudy CAM6 columns	Within cloud	Below cloud	Lowest layer
Winter	3%	72%	25%
Summer	2%	59%	39%

Maximum TKE is within cloud most of the time in ACTIVATE observations, but CAM6 produces maximum TKE overwhelmingly below cloud.

Implications for evaluating model turbulence

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.

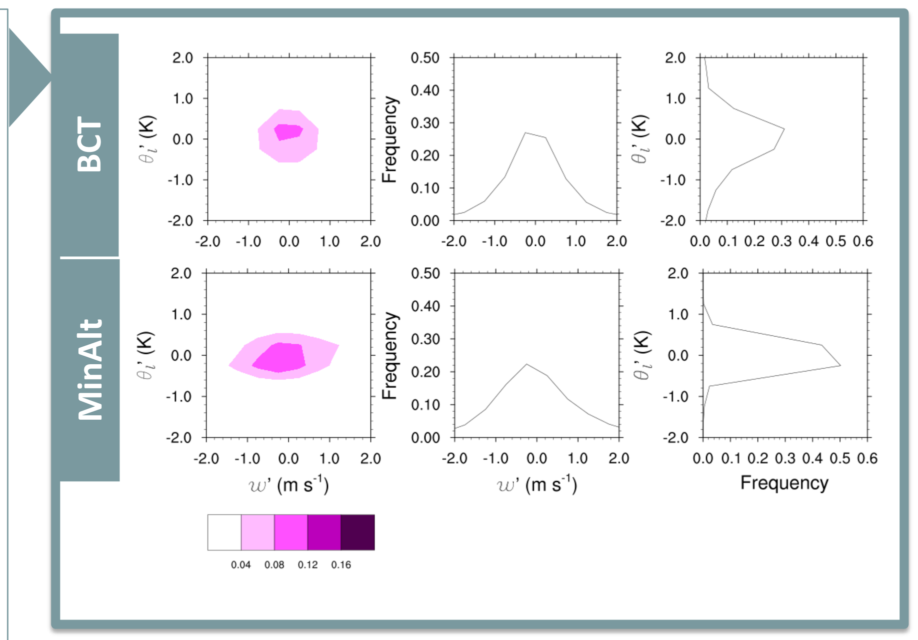
- *Model turbulence is weaker than observed* (note the difference in the x-axes).
- Simulated $\langle w'^2\rangle$ are wider than $\langle u'^2\rangle$ (red) and $\langle v'^2\rangle$, contrary to observed $\langle u'^2\rangle$ distributions being wider.
- Retuning of CLUBB parameters undertaken in the development of EAMv2 reduces the width of $\langle w'^2\rangle$ distributions.



Is the bivariate normal PDF valid over the WNAO?

(left column) Bivariate frequency distributions between turbulent perturbations in liquid potential temperature θ_l' and vertical velocity w' and univariate marginal distributions of (middle column) w' and (right column) θ_l' for two level legs during the winter deployment of ACTIVATE observations.

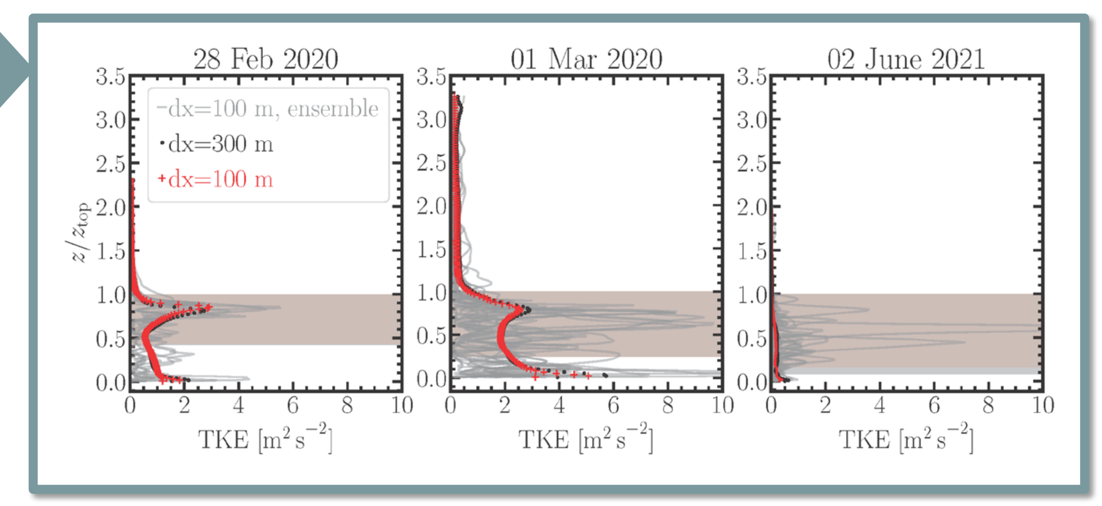
- *Bivariate frequency distributions consistent with bivariate Gaussian PDFs as seen in the normal-looking marginal distributions.*



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.



5 Conclusions

KEY POINTS

- Maximum TKE is most often within cloud in observations but mostly below cloud by a global model higher-order turbulence parameterization.
- 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.

FURTHER DISCUSSION

- CAM6 and EAMv2 turbulence may be improved by retuning CLUBB parameters.
- The full suite of ACTIVATE observations from all three years (2020-2022) can aid in providing an observational constraint on such retuning.

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***Contact information:**
brunke@arizona.edu