Failure of Taylor’s hypothesis in the atmospheric surface layer and its correction for eddy-covariance measurements

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1. Background

- Taylor’s hypothesis plays a fundamental role in transforming commonly available temporal data into spatially-accessible spatial spectrum [Kaimal et al., 1972].
- Turbulent eddies convect at same velocity irrespective of eddy size [Taylor, 1938].
- Turbulent convection velocity may be related to eddy size [Krogstad et al., 1998].
- Turbulent fluxes are underestimated in surface energy balance [Foken, 2008].

2. Objective

2.1 To determine the relationship between turbulent convection velocity and eddy size

High resolution spatial and temporal data are needed. Previous studies were limited by spatial data length or spatial resolution.

2.2 To improve the eddy-covariance measurements by correcting the application of Taylor’s hypothesis in retrieving wavenumber spectrum by frequency spectrum

3. Method

3.1 Experiment setup

The temperature resolution was 0.16°C and 0.22°C before and after transfect respectively, which was calculated from the calibration baths using the standard deviation of bath temperature. Spatial resolution was 0.56 m and temporal resolution was 3 s.

3.2 Calculating convection velocity

\[ U(k_{1}) = \frac{\Delta \sigma}{k_{1} \Delta t} \]

\( k_{1} \) is streamwise wavenumber, \( U(k_{1}) \) is wavenumber dependent convection velocity, \( \Delta \sigma \) is the phase difference of Fourier transform of velocity between time \( t \) and \( t + \Delta t \) [Buxton et al., 2013].

4. Results

Convection velocity calculated by DTS data

Figure 2. a “averaged” and “smoothed and averaged” temporal data temperature for a fixed point in the transect. Temperature along the transect for a fixed time. The \( y \) axis is temperature minus the mean. c Temperature spectra in the time and space domain, \( u \) is frequency in the time domain, \( k_{1} \) is wavenumber in the spatial domain. \( k_{1} = l \) is streamwise wavenumber, \( z \) is optic fiber height above ground, \( l \) is Obukhov length, \( U \) is mean wind velocity, \( \sigma_{T} \) is power spectrum in frequency, \( \sigma_{T} \Delta t \) is power spectrum in wavenumber, \( \epsilon \) is turbulence variance of temporal or spatial data.

5. Conclusion

1. Convection velocity exhibits a \( k_{1}^{-1/2} \) dependence in the inertial subrange.
2. Random sweeping causes decorrelation (frequency broadening) at high wavenumber, which does not violate mean convection velocity.
3. It is the “frozen” hypothesis that is not correct in [Taylor, 1938] because eddies in the small limit of inertial subrange are decaying fast due to turbulent diffusion as they are advected.
4. Taylor’s hypothesis underestimates 10%-30% of turbulent energy in the inertial subrange.
5. A correction for eddy-covariance measurements is proposed.

References


PG would like to acknowledge funding from the National Science Foundation (NSF CAREER, EAR-1552104), and from the Department of Energy (DOE Early Career, DE-SC00142013). We would like to thank Nicki Hickman, Chris Martin, Andy Martin, Michael Bünsche, George Wu, John Schaut, Rod Soper, David Swank and Larry Swords of DOE’s ARM SGP site for the kind help in conducting the experiment and maintaining the equipment. We would like to thank Dr. Tyson Ochsenhirt for discussion in experiment setup. We are grateful to Chris Stabnau for maintaining the equipment and Jingdao Dong for downloading RBruto data and installing a solar panel. We are grateful to Oklahoma Mesonet for providing the meteorological data.

Figure 1. a Picture of the installation at the Oklahoma State University Range Research Station site. Four parallel 233-meter long optic fibers were maintained by tripods to measure air temperature in the direction of 50 degrees North of East. b Schematic of the DTS [Selker et al., 2000] transect and the fiber optic setup. The four water baths were used to calibrate the optic fiber temperature.

DTS data

The temperature resolution was 0.16°C and 0.22°C before and after transfect respectively, which was calculated from the calibration baths using the standard deviation of bath temperature. Spatial resolution was 0.56 m and temporal resolution was 3 s.

Figure 3. Ratios of different wavenumber components convection velocities and maximum convection velocity under different stability conditions. \( z \) is optic fiber height above ground, \( l \) is Obukhov length, \( k_{1} \) is one-dimensional streamwise wavenumber, \( U(k_{1}) \) is convection velocities of different wavenumber components, and \( U_{0} \) is maximum convection velocity. \( U \) is mean wind velocity. The maximum convection velocity rather than mean velocity is the denominator.

References


Figure 4. Ratios of different wavenumber components convection velocities and maximum streamwise velocity of LES data. \( l \) is the vertical height of the LES data, \( U_{0} \) is Obukhov length, \( k \) is one-dimensional streamwise wavenumber, \( U(k) \) is convection velocities of different wavenumber components, and \( \epsilon_{k} \) is mean streamwise velocity.

Figure 5. a Schematic relation between convection velocity and wavenumber indicated by Taylor’s hypothesis and this paper, b c d Normalized frequency spectrum (u/U0(k)), corrected normalized frequency spectrum (u/U0(k)) and measured normalized one-dimensional wavenumber spectrum (\( u_{k} \)). \( l \) is one-dimensional streamwise wavenumber in the spatial domain, \( U(k) \) is convection velocity of different wavenumber component, \( \epsilon_{k} \) is mean streamwise wind velocity, \( \epsilon_{k} \) is angular frequency, \( z \) is optic fiber height above ground, \( l \) is Obukhov length, \( \epsilon_{l} \) is power spectrum in wavenumber, \( \epsilon_{z} \) is temperature variance of spatial data or temporal data.

Wavenumber-dependent convection velocity and wavenumber spectrum