Laboratory for Atmospheric Dynamics
Yonsei University

Estimation of Turbulence Using Operational HVRRD and Comparison with Aircraft Turbulence Reports

Han-Chang Ko[1], Hye-Yeong Chun[1], Robert D. Sharman[2], Jung-Hoon Kim[3]

[1]*Department of Atmospheric Sciences, Yonsei University, Seoul, South Korea*
[2]*National Center for Atmospheric Research, Boulder, CO, USA*
[3]*School of Earth and Environmental Sciences, Seoul National University, Seoul, South Korea*

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Introduction

- **Aviation turbulence** is crucial to flight safety, including passengers, crew, and aircraft structures.
- It also can cause flight delays and excessive fuel consumption, leading to millions of dollars in losses to airlines every year *(Sharman et al., 2006; Wolff & Sharman, 2008)*.
- Therefore, many studies have been conducted to better understand and predict aviation scale turbulence, including:
  - (i) **case studies for turbulence sources and generation mechanisms** using numerical weather prediction (NWP) models and observations *(Lee & Chun, 2018; Kim et al., 2019; Bramberger et al., 2020; Trier et al., 2020; Kim et al., 2022)*,
  - (ii) **development of climatological turbulence distributions** retrieved from in-situ observations *(Wolff & Sharman, 2008; Kim & Chun, 2011; Sharman et al., 2014; Kim et al., 2020)*,
  - (iii) **forecasting of turbulence potential regions** using regional/global NWP model outputs *(Jaeger & Sprenger, 2007; Sharman & Pearson, 2017; Kim et al., 2018; Lee et al., 2022)*,
  - and (iv) investigations into **future variabilities in response to climate changes** *(Williams & Joshi, 2013; Williams, 2017; Storer et al., 2019)*.

Introduction

- Among these efforts, examining **climatological distributions of turbulence** using in-situ observations can **help to better understand turbulence characteristics**, such as location, time, frequency, and intensity *(Wolff & Sharman, 2008)*.

- **This information could be helpful for tactical and strategic guidance for mitigating turbulence encounters.** For example, observational turbulence distributions are an essential component of building and validating turbulence forecast systems, e.g., the **graphical turbulence guidance (GTG) system** *(Sharman et al., 2006; Sharman et al., 2014; Sharman & Pearson, 2017; Lee et al., 2022)*.

- **In-situ flight eddy dissipation rate (EDR)** is one of the major data sources of aviation turbulence, and is automatically computed from commercial aircraft using an onboard turbulence-estimation and reporting algorithm *(Cornman et al., 1995; Cornman, 2016; Sharman et al., 2014)*.

- However, the in-situ flight EDR data are only available **along the main flight routes** *(Sharman et al., 2014)*, and these commercial flights often **avoid turbulent convection areas and forecasted turbulence regions** *(Sharman et al., 2006; Kim & Chun, 2012; Sharman & Pearson, 2017)*.

- This hinders the construction of unbiased climatologies of aviation turbulence and the validation of aviation forecasting systems.

Introduction

- Recently, turbulence estimation using operational **high vertical-resolution radiosonde data (HVRRD)** based on the **Thorpe method** *(Thorpe, 1977)* has been conducted over vast regions and for long periods *(Nath et al., 2010; Muhsin et al., 2016; Ko et al., 2019; Kohma et al., 2019; Zhang et al., 2019a; 2019b; He et al., 2020; Geller et al., 2021; Lv et al., 2021; Ko & Chun, 2022)*.

- **Radiosondes drift freely** in the horizontal and vertical directions, and hence **cover a wide area** horizontally and vertically **without restriction of the aircraft routes**.

- EDR based on HVRRD (HVRRD-EDR) can be informative both in constructing climatologies of atmospheric turbulence and in validating aviation turbulence forecasting systems.

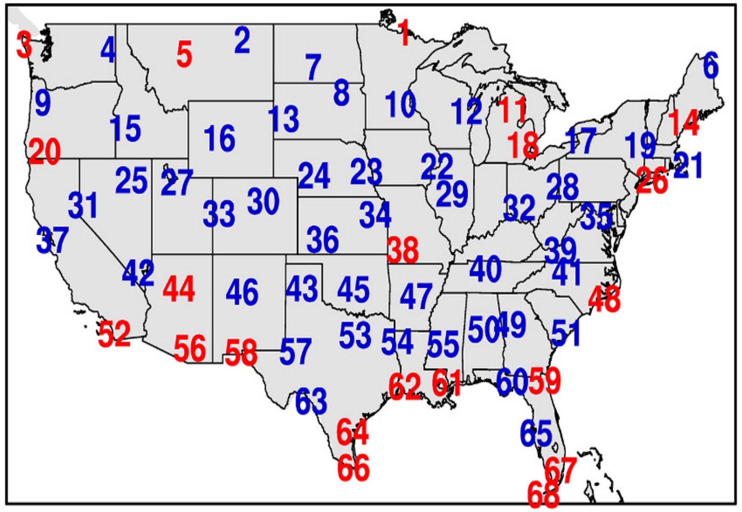
- As more and more operational radiosonde stations in the world archive high-resolution data *(Ingleby et al., 2016)*, **HVRRD-EDR can be obtained globally and operationally**, which can be **a valuable resource for atmospheric turbulence information** in the free atmosphere in general and **for aviation turbulence research** in particular.

- **This study compares the distribution of HVRRD-EDR and in-situ flight EDR in the USA as a first step toward applying HVRRD-EDR to aviation turbulence research.**

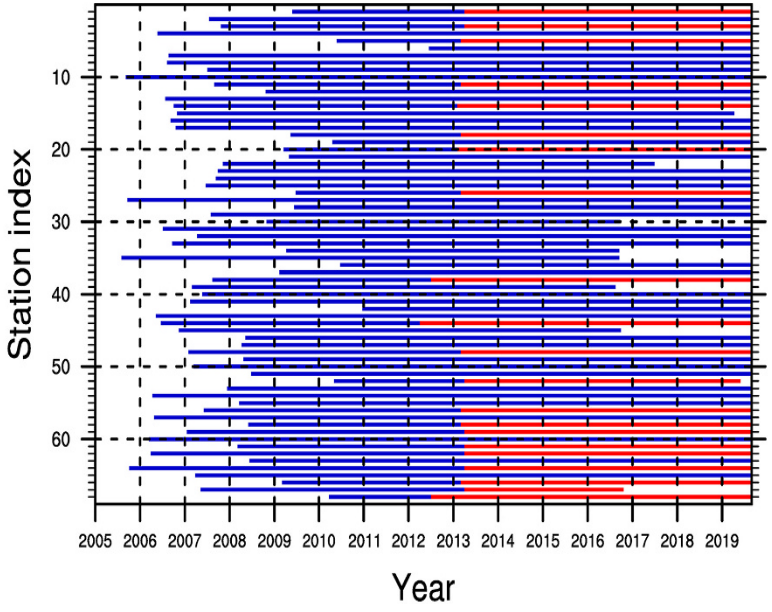
High Vertical-Resolution Radiosonde Data (HVRRD)

Ko and Chun (2022, AR)

	High vertical-resolution radiosonde data (HVRRD)
No. of stations	68
Resolution	**1 s** (~5 m, interpolated into **5 m**)
Observations	P, T, Rh, U, V, z
Launch frequency	twice a day (00 and 12 UTC)
Data period	2012 – 2017 (6 years)

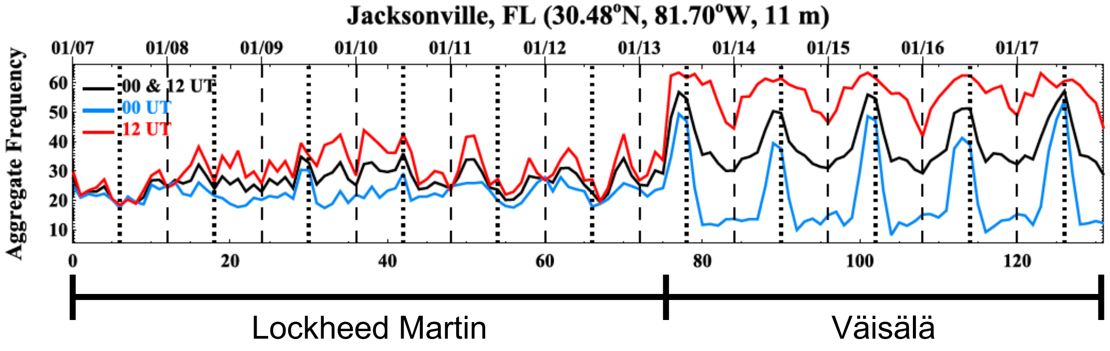


blue: radiosonde instrument has not been changed (47)
red: radiosonde instrument has been changed (21)

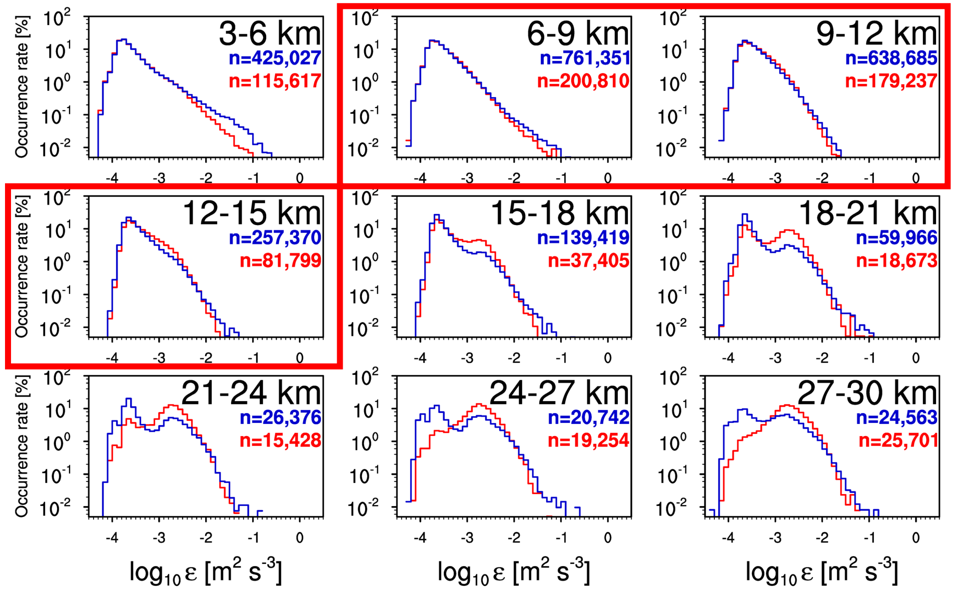


blue: Lockheed Martin, red: Väisälä

Monthly frequency of the occurrence of unstable layers between z = 15 and 25 km



Geller et al. (2021, MWR)

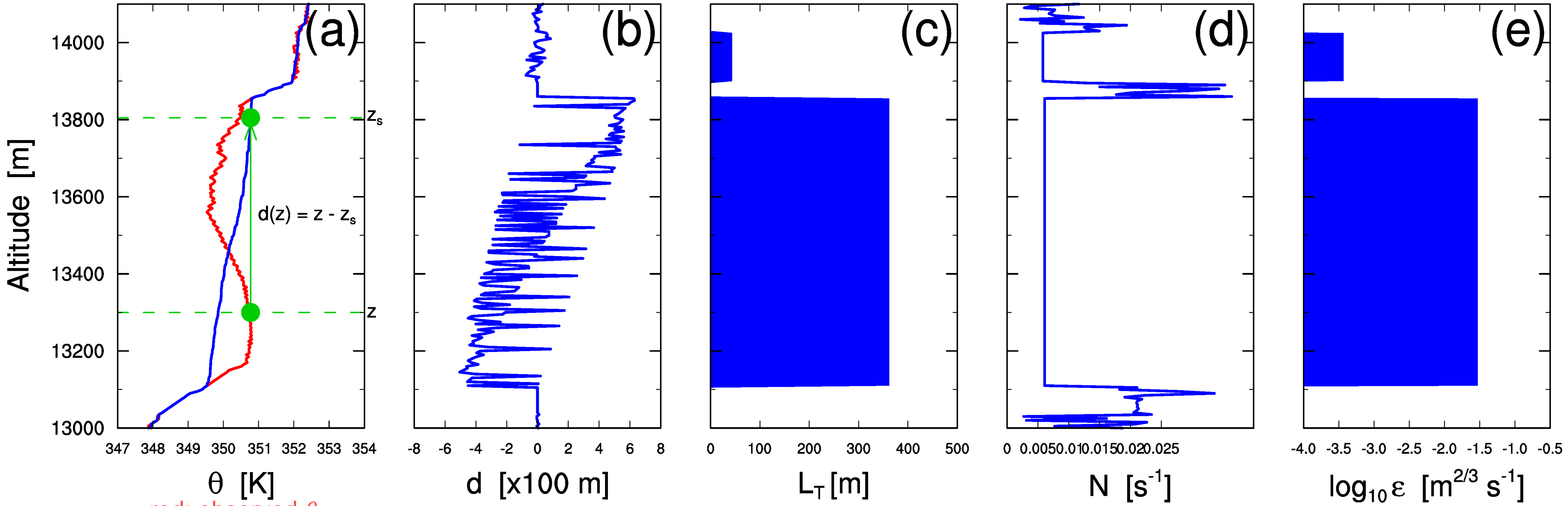


Ko and Chun (2022, AR)

blue: Lockheed Martin
red: Väisälä

This study use both datasets from Lockheed Martin and Väisälä

Thorpe method (Thorpe, 1977)



red: observed θ

blue: stably stratified (sorted) θ

- ✓ Thorpe displacement $d \equiv z - z_s$; **Thorpe scale $L_T \equiv d_{rms}$**
- ✓ **Assuming a linear relations** between the L_T and the **Ozmidov scale $L_O \equiv (\varepsilon/N^3)^{1/2}$**, an energy dissipation rate ε is calculated by

$$\varepsilon = C_K {L_T}^2 N^3$$

where $C_K = 1$ following Kantha and Hocking (2011) and Li et al. (2016), N is the Brunt-Vaisala frequency

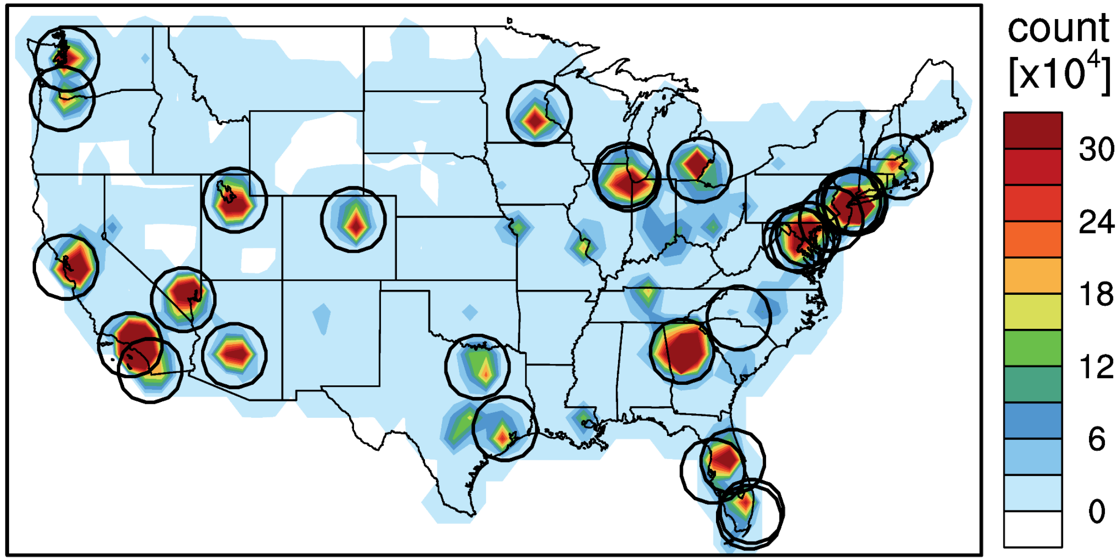
- ✓ Instrumental noise *(Wilson et al. 2010; 2011)* and moist-saturation effects *(Wilson et al. 2013)* are considered

Comparison of HVRRD-EDR ($= \varepsilon^{1/3}$) and flight-EDR

- **Flight-EDR** is produced from commercial aircrafts using vertical wind- or acceleration-based turbulence estimation and reporting algorithm implemented on aircrafts *(Corman et al. 1995, Corman 2016; Sharman et al. 2014)*.

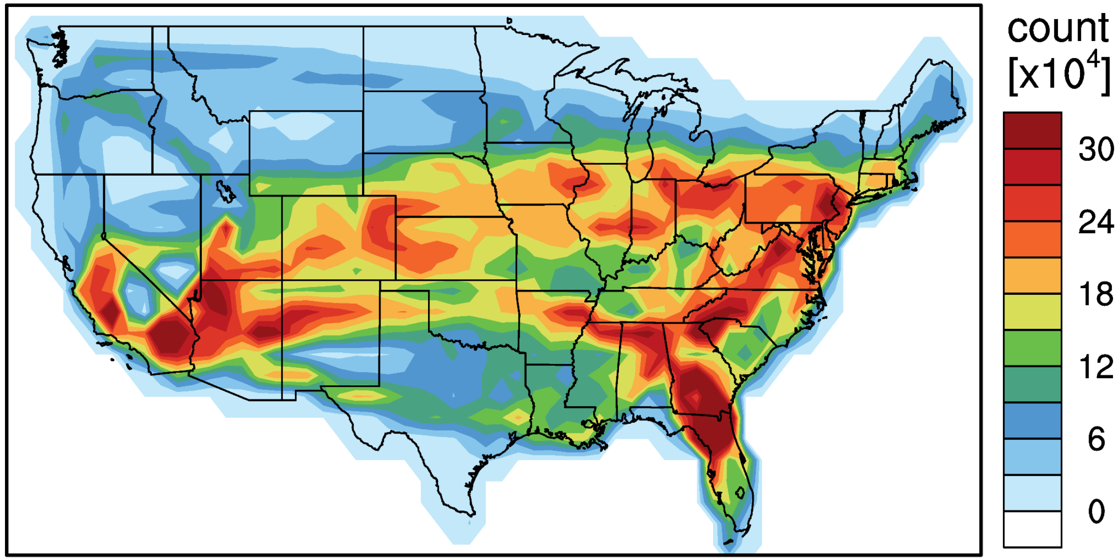
- This study used flight-EDR for 6 years (2012–2017). During this period, total number of flight-EDR is 214 857 394.
  - ✓ Delta Air Lines B737 / 767 / 777: 83 382 364 / 67 832 125 / 1 966 538
  - ✓ Southwest Airlines B737: 61 676 367

Flight-EDR 0-20 kft, 2012-2017



circles: locations of top 30 busiest airports by total passenger boardings (FAA, CY2017 Passenger Boarding Data)

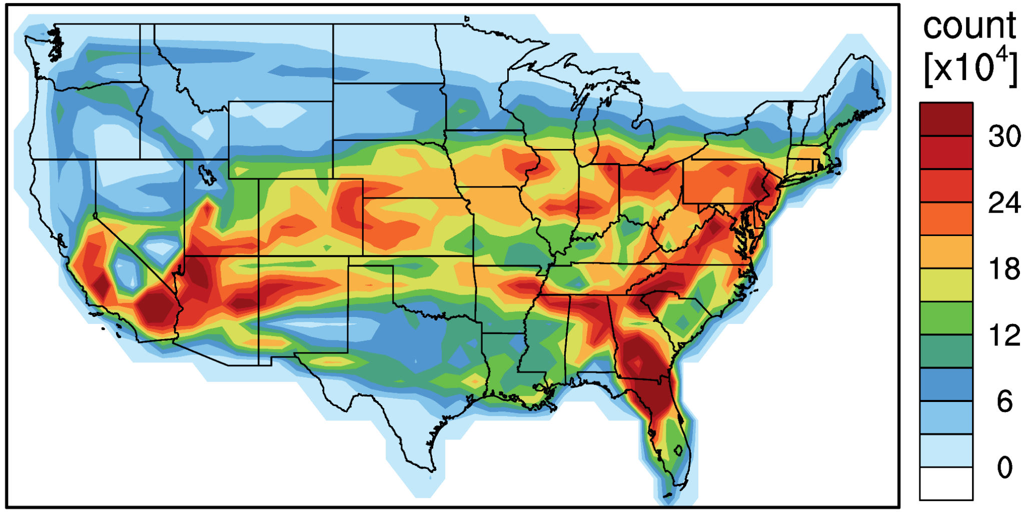
Flight-EDR 20-45 kft, 2012-2017



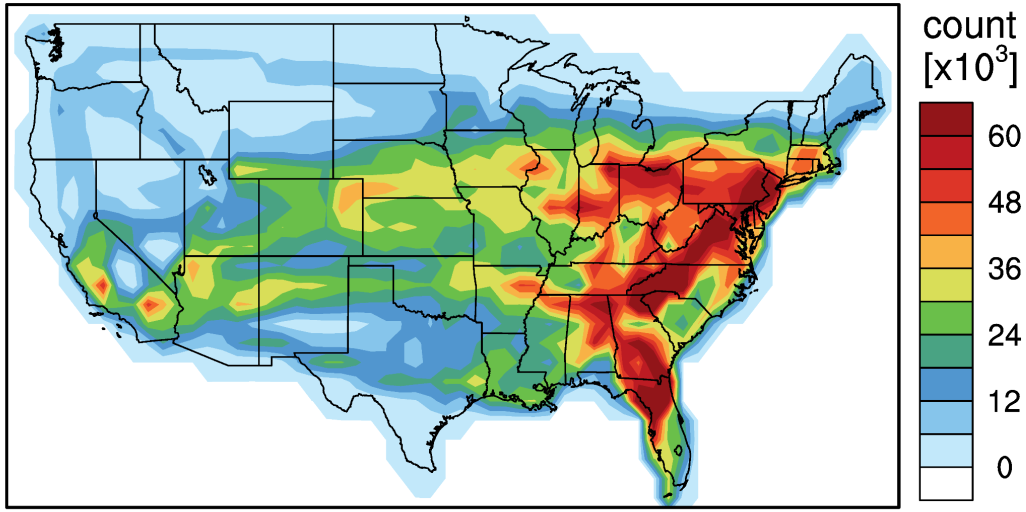
Note) 10 kft ~ 3 km

Area of comparison

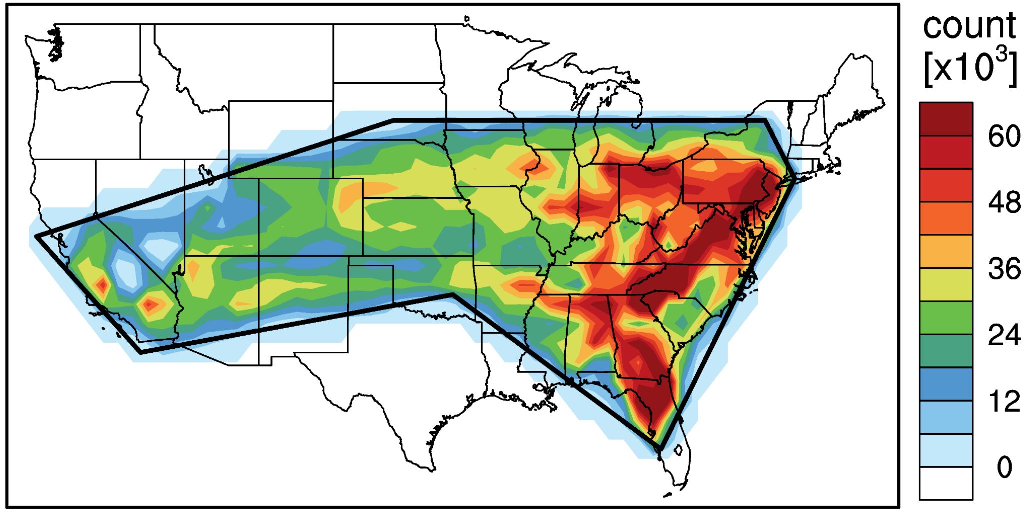
(a) Total counts (z = 20–45 kft)



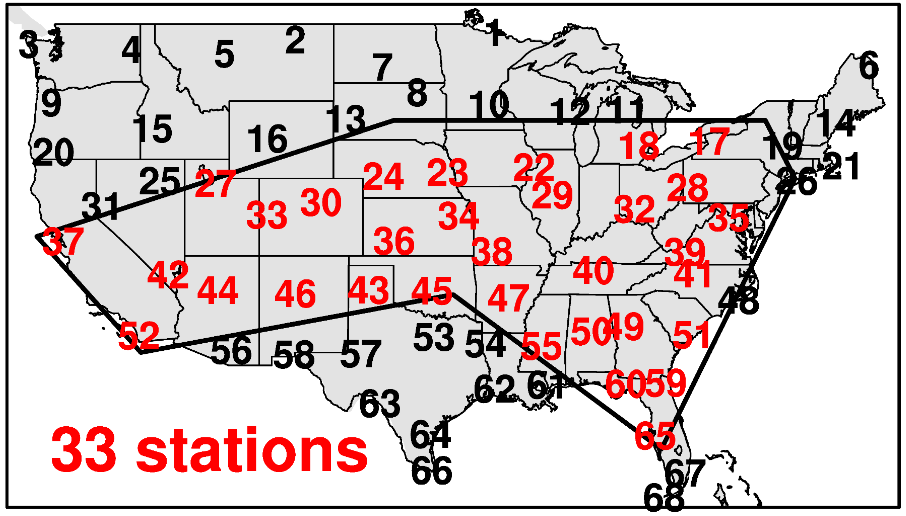
(b) ±1 hour from 00 and 12 UTC



(c) Main flight routes



(d) HVRRD stations within main flight routes

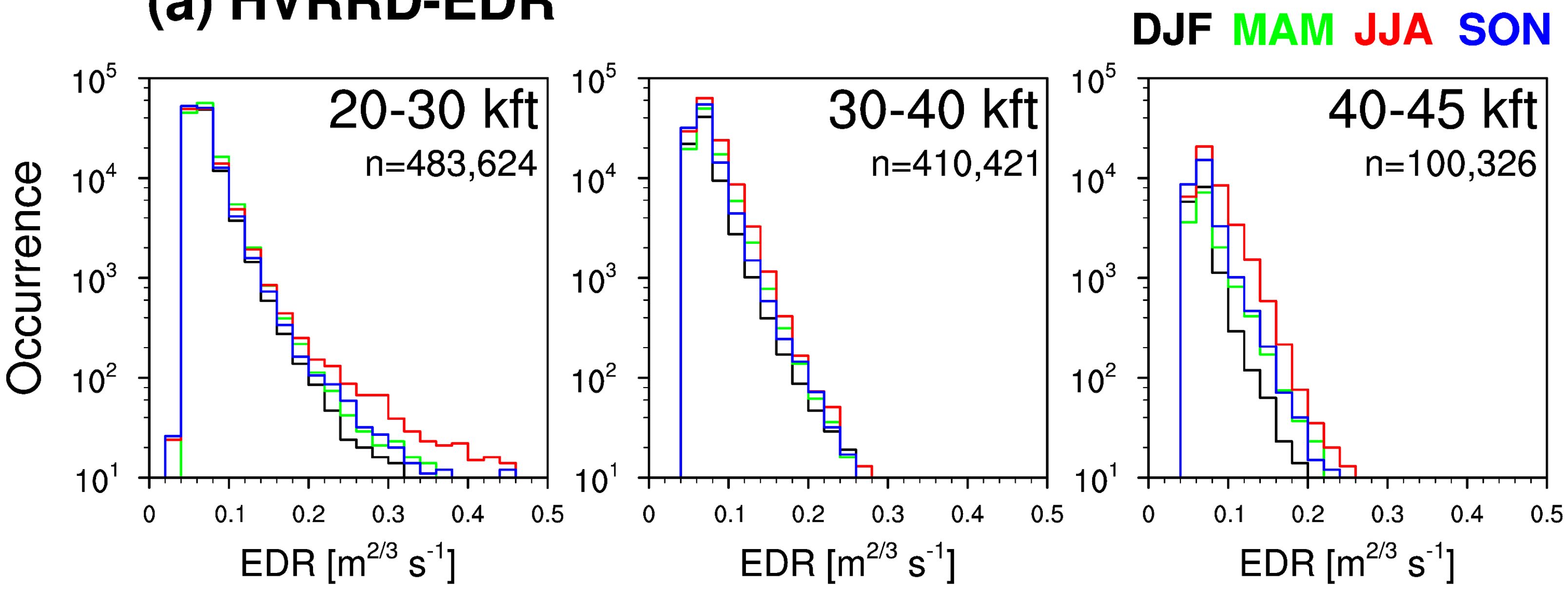


33 stations

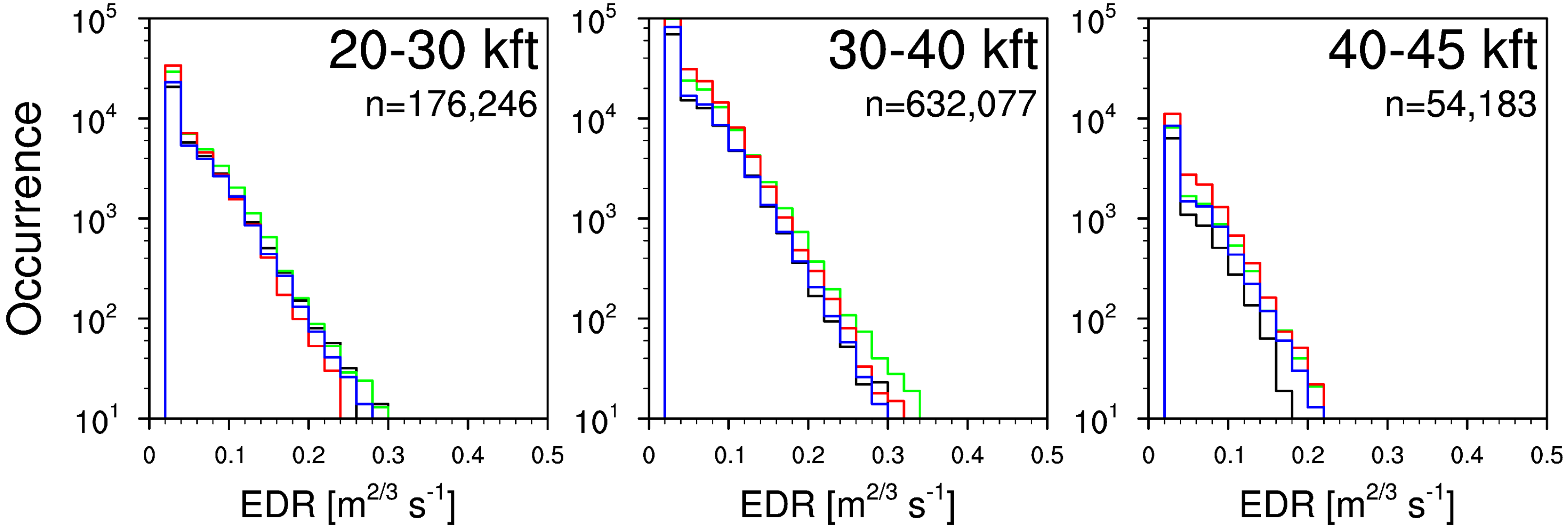
Comparison of HVRRD-EDR and flight-EDR

6 years (2012–2017)

(a) HVRRD-EDR

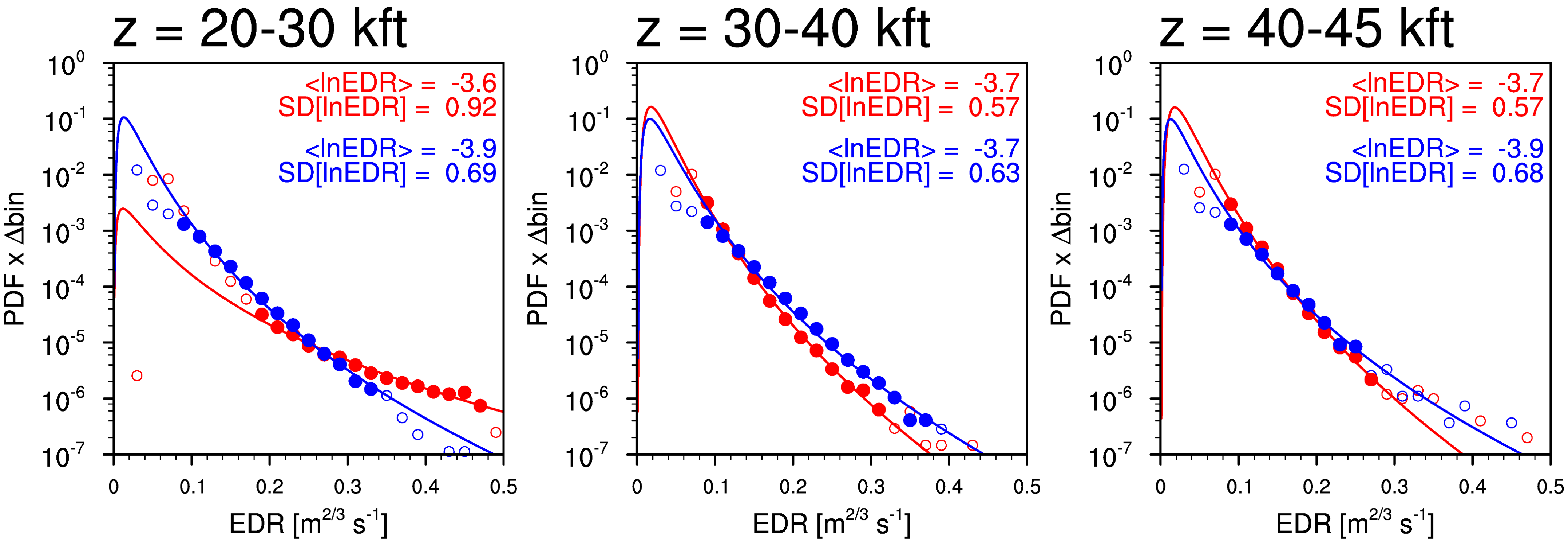


(b) flight-EDR



- **HVRRD-EDR**: the occurrence number is the **largest in JJA** and the **smallest in DJF**
- **At z = 20–30 kft,** the **maximum value of HVRRD-EDR** is approximately 0.45 $m^{2/3}$ s^{-1} in JJA and 0.35 $m^{2/3}$ s^{-1} in other seasons, **which is slightly larger than that of flight-EDR**
- **At z = 30–45 kft**, the **maximum value of HVRRD-EDR** is **comparable to** that of **flight-EDR**
- The total occurrence number of turbulence cases from HVRRD is much larger than those of flight-EDR at z = 20–30 kft and 40–45 kft.

Comparison of HVRRD-EDR and flight-EDR



red: HVRRD **blue: flight**

●: data used in the fit

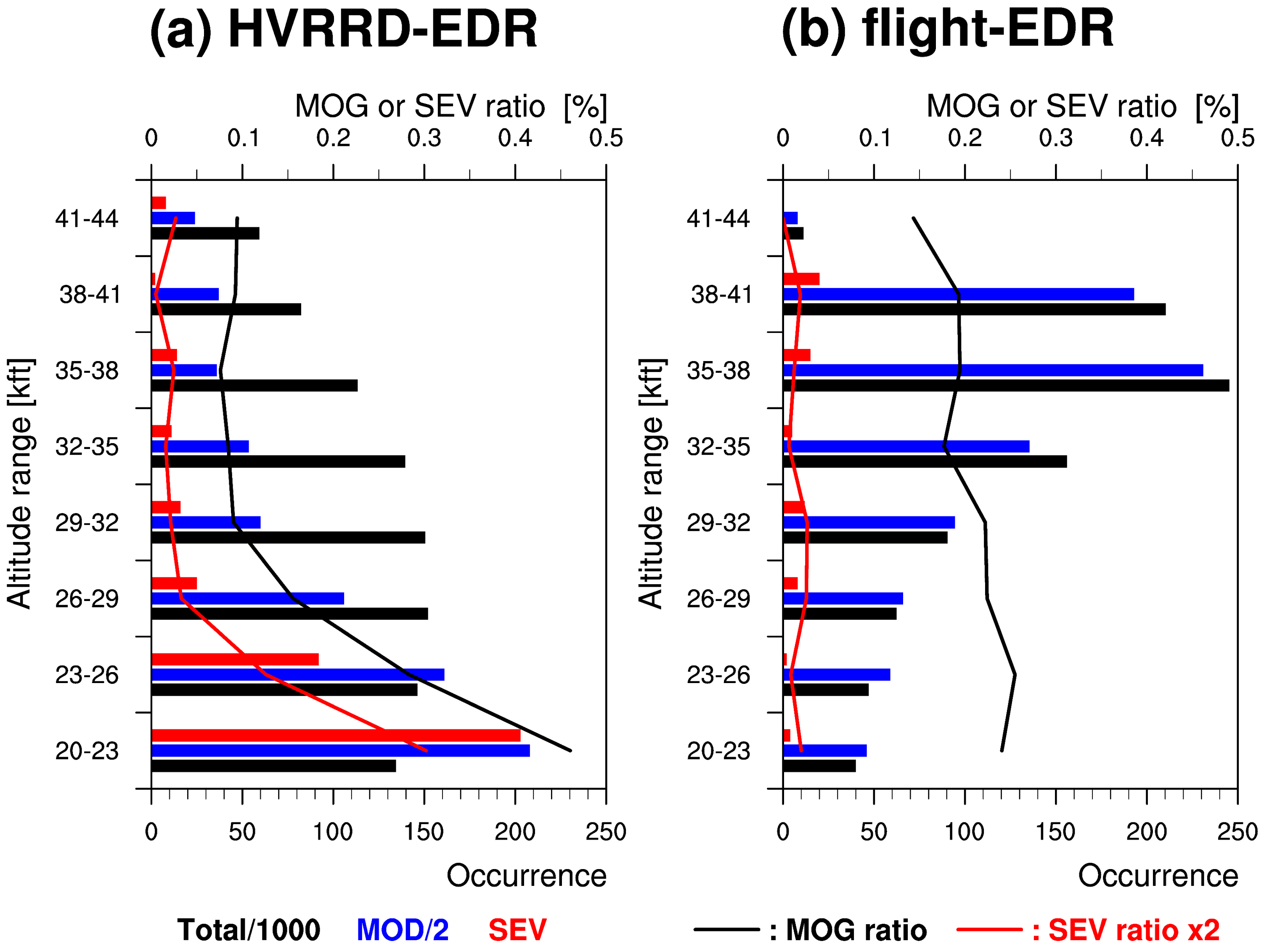
○: data excluded from the fit

- Both **HVRRD-EDR and flight-EDR fit well** by **lognormal PDFs**.

- At z = 20–30 kft, the lognormal PDFs of **HVRRD-EDR show more frequent distributions in the large values** than those of flight-EDR, while the distributions are consistent with each other at z = 30–40 kft and 40–45 kft.

- This larger values of HVRRD at z = 20–30 kft can be related to
  - 1) **HVRRD-EDR is mainly generated by low static-stability and convective environments** *(Ko & Chun, 2022)* and
  - 2) **aircraft avoid turbulence regions associated with convection** *(Sharman & Pearson, 2017)*.

Vertical distributions of HVRRD-EDR and flight-EDR

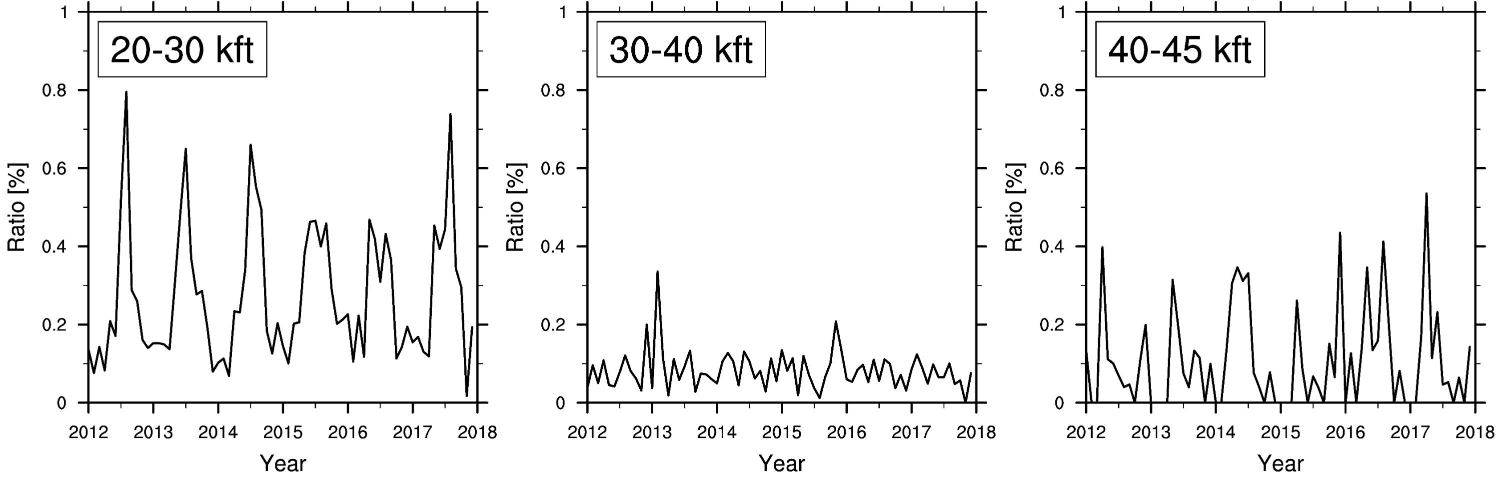


MOD (moderate): $0.22<EDR<0.34$ [$m^{2/3}$ s^{-1}]
SEV (severe): $0.34<EDR$ [$m^{2/3}$ s^{-1}]
following *Sharman and Pearson* (2017)

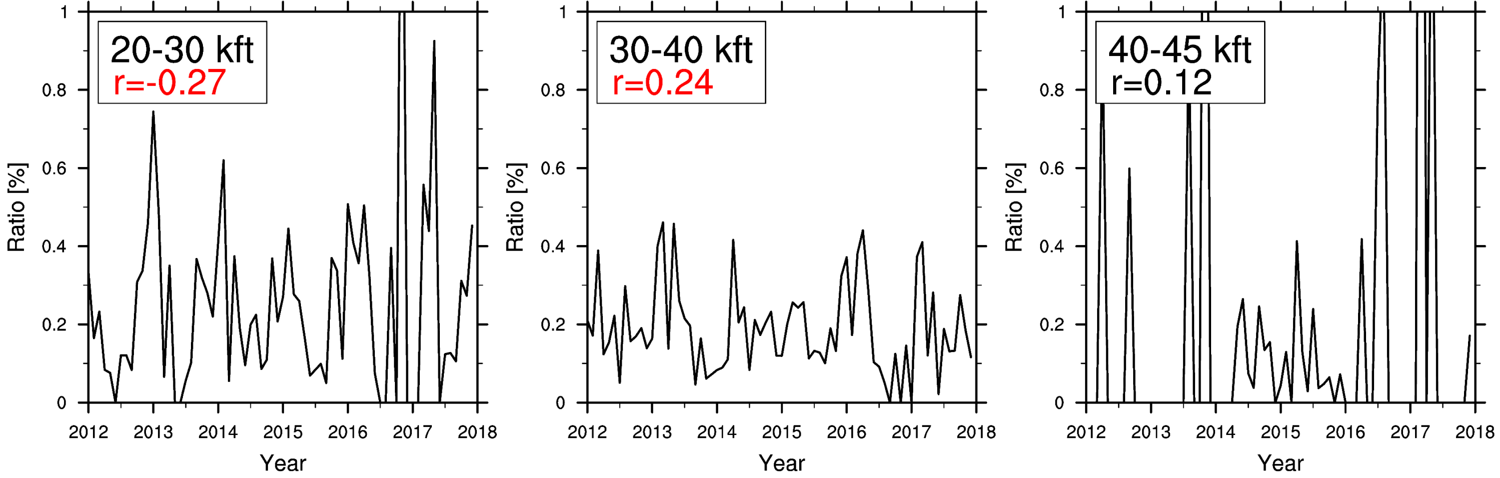
- **(a) HVRRD-EDR:** Maximum of MOG turbulence in 20–23 kft can be related to weak static-stability and convective environments *(Ko and Chun, 2022)*.
- **(b) flight-EDR**: The occurrence number is the largest at z = 35–38 kft (main cruising altitude).
- The MOG ratio of flight-EDR is **consistent** with that of HVRRD-EDR : larger below 32 kft than above, with the maximum at z = 23–26 kft
- The MOG and SEV ratios of flight-EDR at z = 20–26 kft are smaller than those of HVRRD-EDR : This might be due to aircraft avoiding turbulent regions related to convection *(Sharman & Pearson, 2017)*.

Time-series of monthly MOG ratio

(a) HVRRD-EDR



(b) flight-EDR



MOG ratio: $\frac{\text{moderate−or−greater occurrences}}{\text{total occurrences}}$

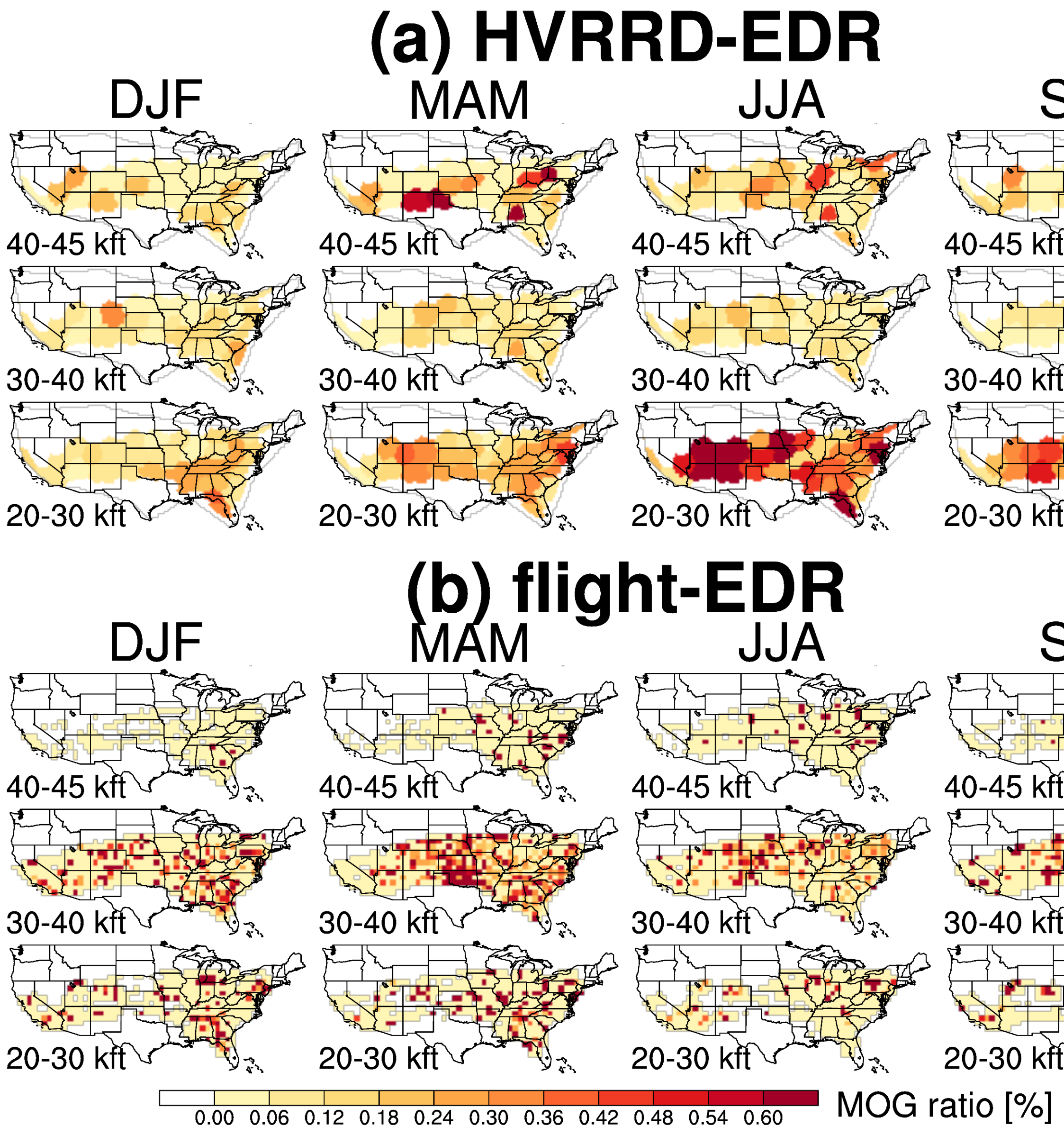
Red: statistically significant at the 95% confidence level

Max **Min**	20–30 kft	30–40 kft	40–45 kft
HVRRD	**JJA** **DJF**	**-**	**MAM** **SON**
flight	**DJF** **JJA**	**MAM** **JJA**	**MAM** **DJF**

HVRRD-EDR: low static-stability or convective conditions (Ko & Chun, 2022)
Flight-EDR: upper-level jet/front in DJF and convection in the lower altitudes in MAM–JJA (Sharman et al., 2014)

→ the results of negative correlation at lower altitudes and positive correlation at upper altitudes are somewhat unexpected.

Horizontal distributions of MOG ratio



- **z = 20–30 kft:** large MOG ratios over the Rocky Mountains. The clearly weaker MOG ratios of flight-EDR in JJA might be due to that the aircrafts avoid forecasted MOG turbulence regions related to convection.
- **z = 30–40 kft:** HVRRD-EDR has the minimum MOG ratio among three altitude ranges, while flight-EDR shows the maximum MOG ratio. Horizontally, both datasets revealed large MOG ratios mainly over the Rocky Mountains in all seasons except in SON of HVRRD-EDR.
- **z = 40–45 kft:** HVRRD-EDR shows peaks in several regions such as Texas, Alabama, and Ohio–Pennsylvania, while the flight-EDR shows a large MOG ratio in the eastern-USA.

Discrepancies between HVRRD-EDR and flight-EDR

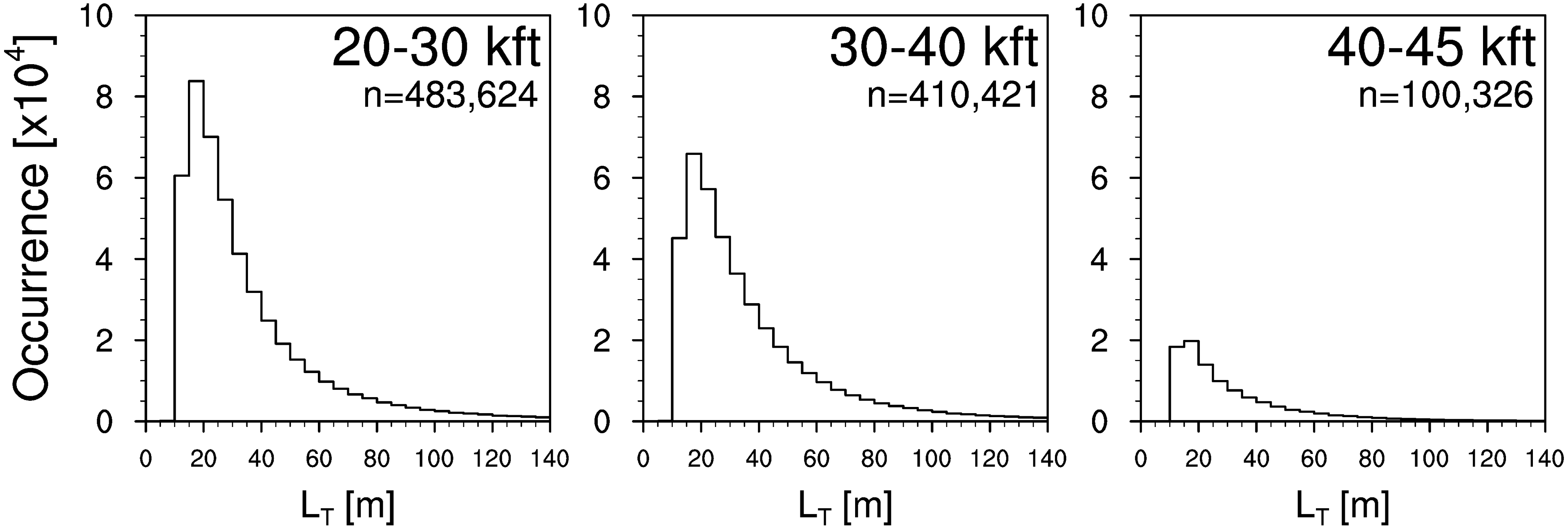
- First, **HVRRD-EDR and flight-EDR cannot detect the same volume of atmosphere** because the aircraft must not coincide with the radiosonde at the same location and time.
  - Therefore, a one-to-one match of the two datasets is not possible.
  - Nevertheless, if sufficient data are available, climatological characteristics of EDRs from in-situ flight observations and HVRRD may have some similarities.
  - Further investigation with more observational data, including different geographical locations, is required.

- Second, **HVRRD-EDR and flight-EDR may detect atmospheric turbulence caused by different sources**.
  - At cruising levels, flight-EDR is often related to clear-air turbulence (CAT) *(Wolff & Sharman, 2008; Kim & Chun, 2011)* because aircraft avoid intense convection either detected by the onboard radar or communicated from ground-based air traffic controllers or dispatchers *(Kim et al., 2011)*.
  - However, HVRRD-EDR is mainly generated under low static-stability conditions where convective activity is favorable *(Ko and Chun, 2022)*.
  - Specifically, **strong shear-induced turbulence** associated with upper tropospheric jets in the wintertime **under strong stability**, which is the main cause of MOG-level CAT reported by aviation turbulence research and forecasting centers *(e.g., Sharman et al., 2006; Kim & Chun, 2010; Kim & Chun, 2011; Kim & Chun, 2016; Lee & Chun, 2018)*, **is not captured by the Thorpe method**.
  - Future investigations including some modifications of the Thorpe method to consider VWS under stable conditions is required.

Discrepancies between HVRRD-EDR and flight-EDR

- Third, but not least, **aircraft measurements** may have **a limitation accounting for the response to fluctuations at smaller scales than the aircraft size**.
  - Examining the distribution of Thorpe scale L_T, **63%**, **79%**, and **89%** of the total cases have values less than **35 m**, **50 m**, and **70 m**, respectively.
    - Note that the size of **B737**, **B767**, and **B777** aircraft is 35 m, 50 m, and 70 m, respectively (https://www.boeing.com/).
  - **This implies that many cases of the HVRRD-EDR may be damped out in the aircraft response.**

Thorpe scale L_T



Summary

- This study compared the distributions of **EDR derived from operational HVRRD and in-situ flight observation from commercial aircrafts** in the United States for six years (2012–2017).

- Horizontal distributions of both EDRs from radiosonde data and flight data show **large values over the Rocky Mountains**. However, they show **large differences in vertical and temporal distributions** in terms of their peak location and timing.

- We attribute these differences to the followings:
  - First, **turbulence observed from the two datasets cannot be the same event**.
  - Second, **turbulence generated by strong wind shear under stable atmospheric condition is not captured by the Thorpe method**.
  - Third, **aircraft have limitations detecting fluctuation at scales smaller than the aircraft size**.

- Given the limited global data on atmospheric turbulence, **EDR estimated from operational radiosonde data can be a valuable resource** for research and development of **aviation industry** and **numerical weather forecasting models**.

Han-Chang Ko
gcinc@yonsei.ac.kr

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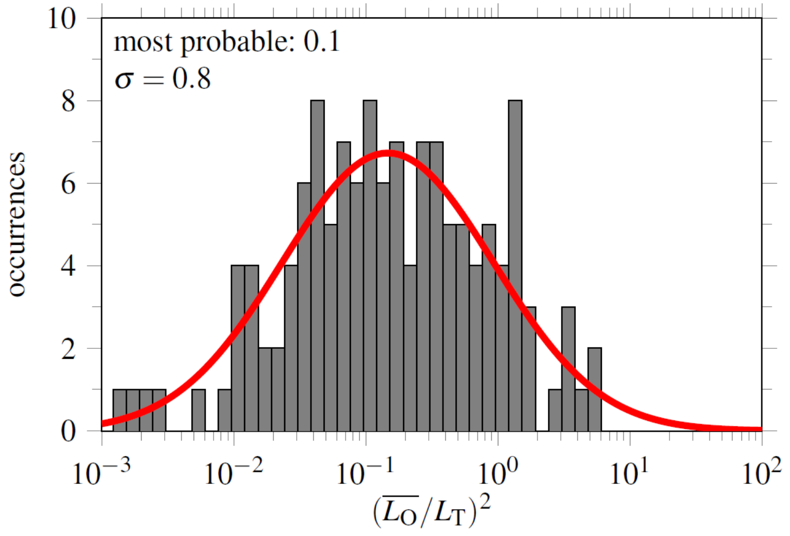
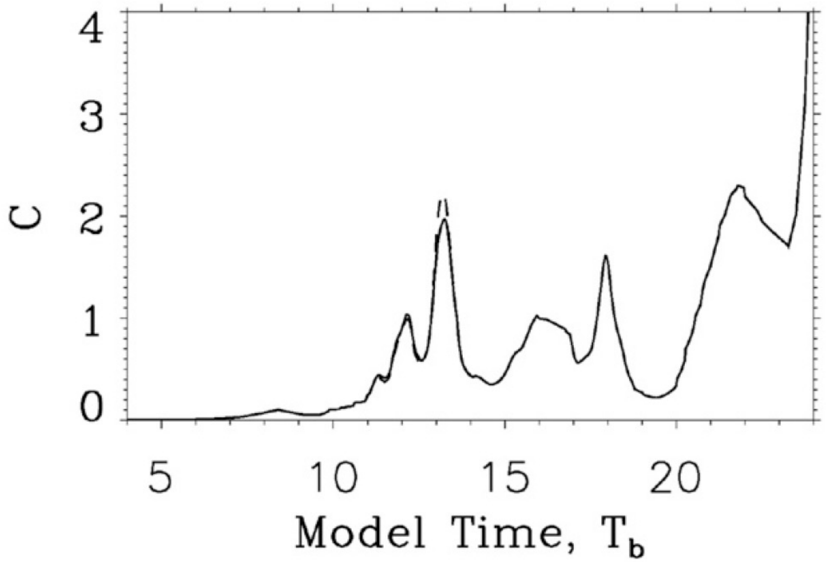
Supplementary figures

Issues in the L_o/L_T ratio

HVRRD-EDR is sensitive to the **L_o/L_T ratio:** $\varepsilon = C_K {L_T}^2 N^3$ where $C_K = c^2$, $c = L_o/L_T$

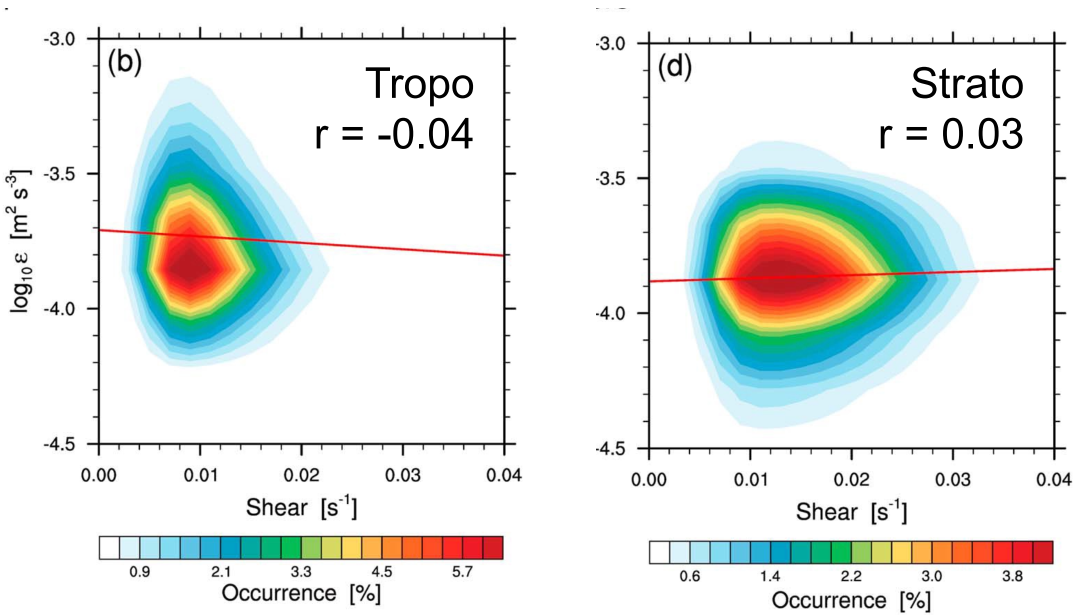
Schneider et al. (2015)





Fritts et al. (2016)

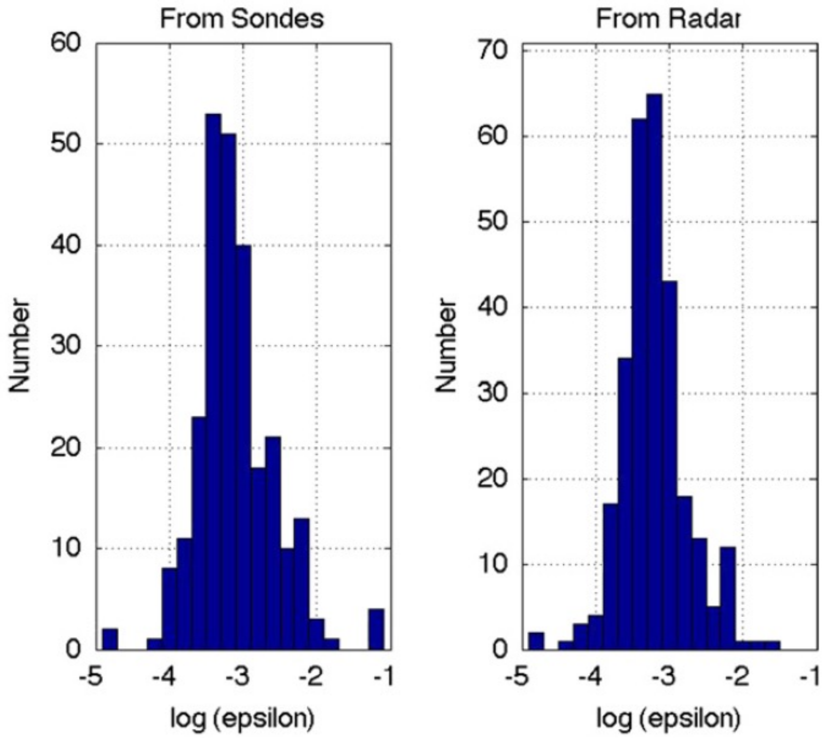
Ko et al. (2019)



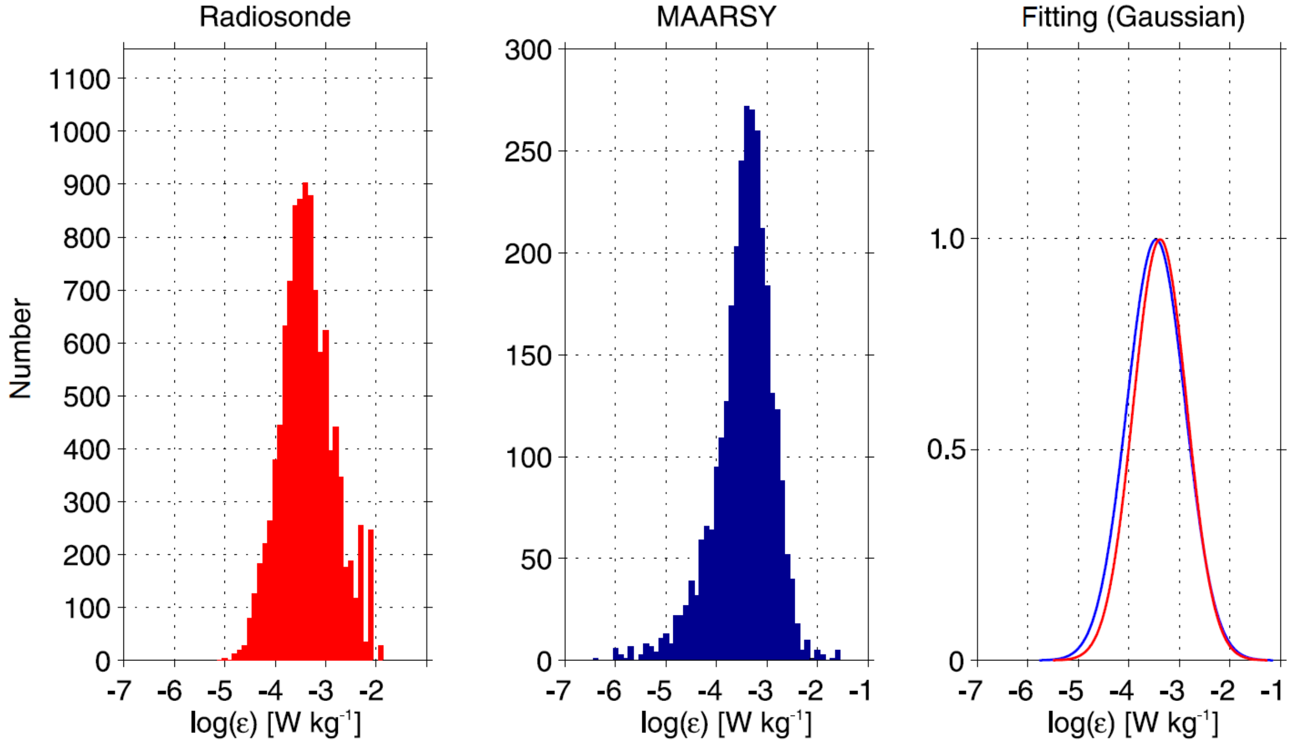
- ✓ Correlations between ε and VWS ~0, likely due to the mixing in the turbulence layer
- ✓ It is difficult to examine sources of turbulence using the radiosonde data, because **radiosonde data** is suitable for **representing local flows** that **already contain turbulence effects, not the background conditions**

Issues in the L_o/L_T ratio

Kantha and Hocking (2011)



Li et al. (2016)



- Following the results of Kantha and Hocking (2011) and Li et al. (2016) which compared the distributions of ε derived from HVRRD and radar, this study used L_O/L_T = 1.

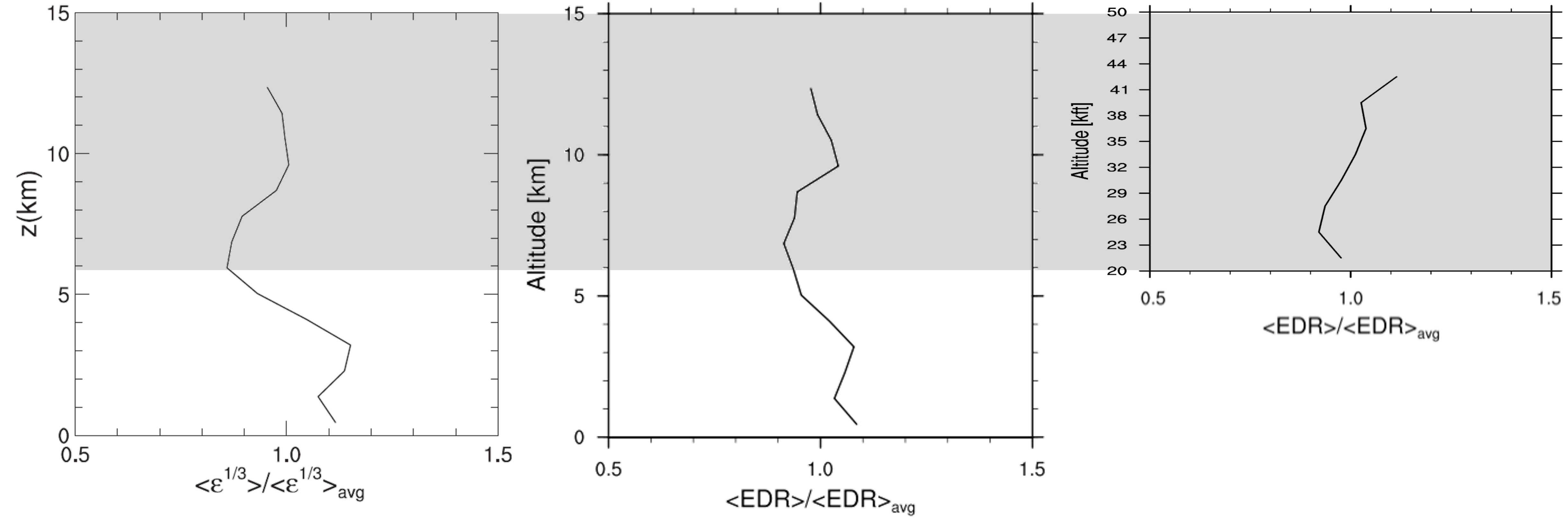
Vertical distributions of flight-EDR

grey shading: z = 20 – 50 kft

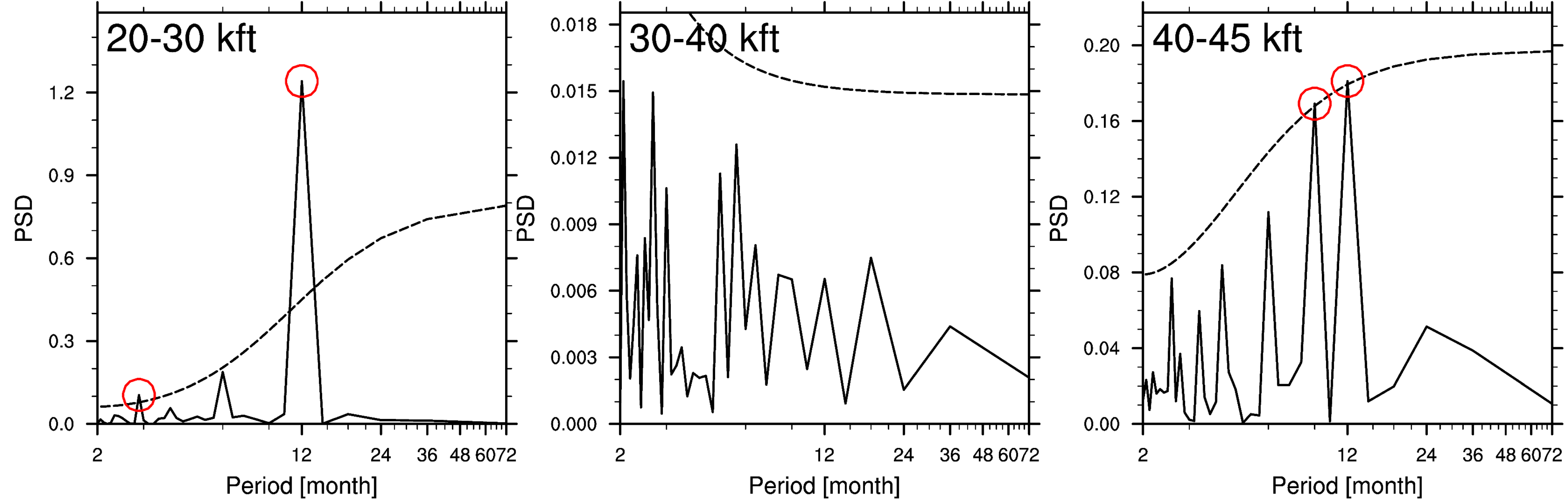
Sharman et al. (2017)
(2009–2013, DAL,
within entire CONUS)

Current study
(2012–2017, DAL,
within entire CONUS)

Current study
(2012–2017, DAL+SWA,
within main flight-route,
±1 hr from 00 and 12 UTC)



(a) HVRRD-EDR



(b) flight-EDR