Characterizing Thunderstorm Gust Fronts near Complex Terrain

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Outline

1. Introduction
2. Study sites and instruments
3. Methods
4. Results
5. Discussion
6. Conclusions

1. Introduction

a. What are the characteristics of gust fronts (hereafter GFs) and cold pools?

- A gust front (GF) is the leading edge of cold air propagating horizontally away from a thunderstorm.
- The cold pools are resulted from evaporation and sublimation.
- The cold pool depth can range from 100 m to 4 km.
- As a GF passes over, the wind speed and direction change abruptly, the temperature decreases, and the humidity increases.

1. Introduction

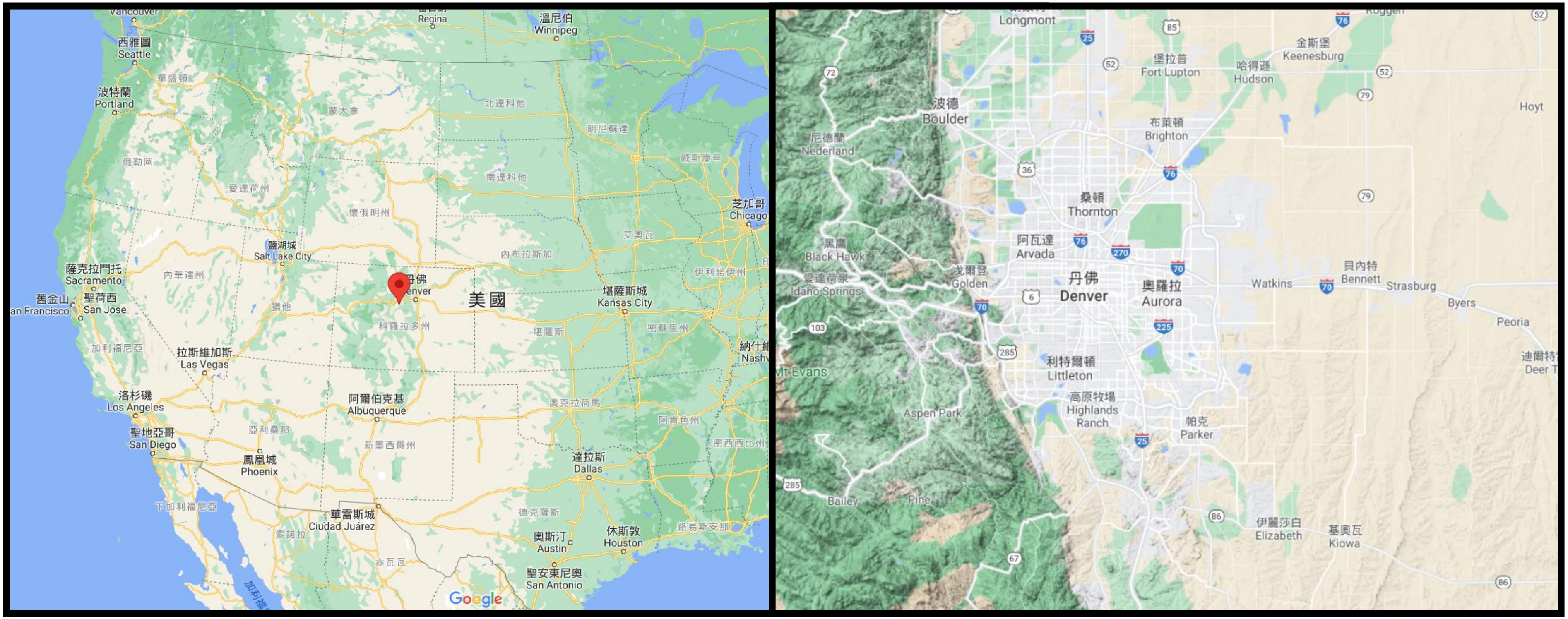
b. Why do we have to investigate GFs near complex terrain?

- Most observational GF studies focus on orographically flat regions such as U.S. Great Plains.
- Thunderstorms are less organized on complex terrain (single cell and multicell thunderstroms) than flat regions (supercells, squall lines, MCSs) due to reduced temperature, low-level moisture, and surface-based instability.
- GFs can have high impacts on **aviation**, **structural engineering**, **wind energy**, **wildland fire community**, and **emergency response community**.

1. Introduction

c. **How** do we investigate GFs near complex terrain?

- 24 GFs were observed near **Colorado Front Range.**
- The goal is to compare **near ground (0~300 m AGL)** GF properties (**wind, temperature, humidity, turbulence)** between flat and complex terrain.

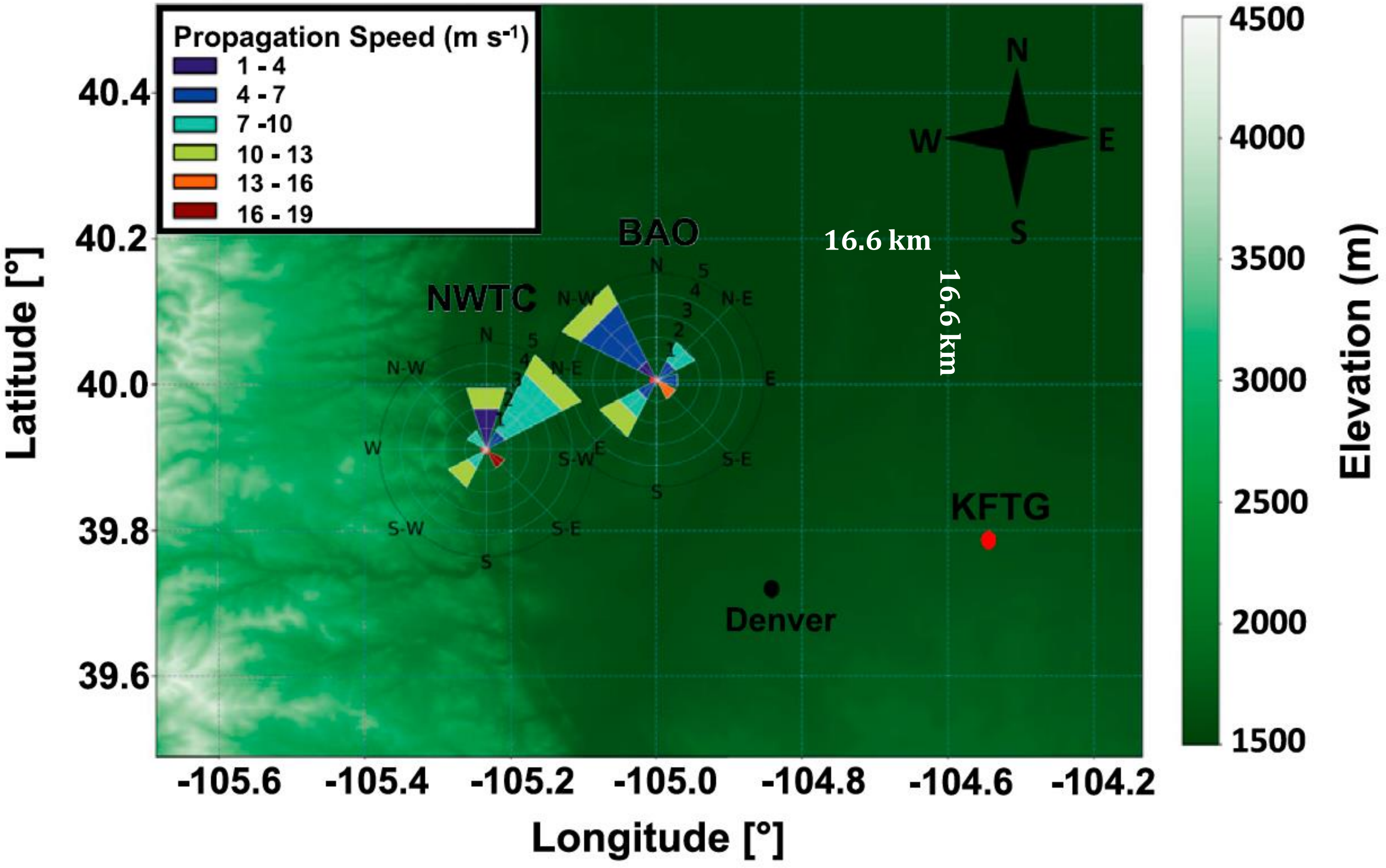


2. Study sites and instruments

a. Colorado study sites descriptions

BAO: Boulder Atmospheric Observatory (1584m)

NWTC: National Wind Technology Center (1852m)



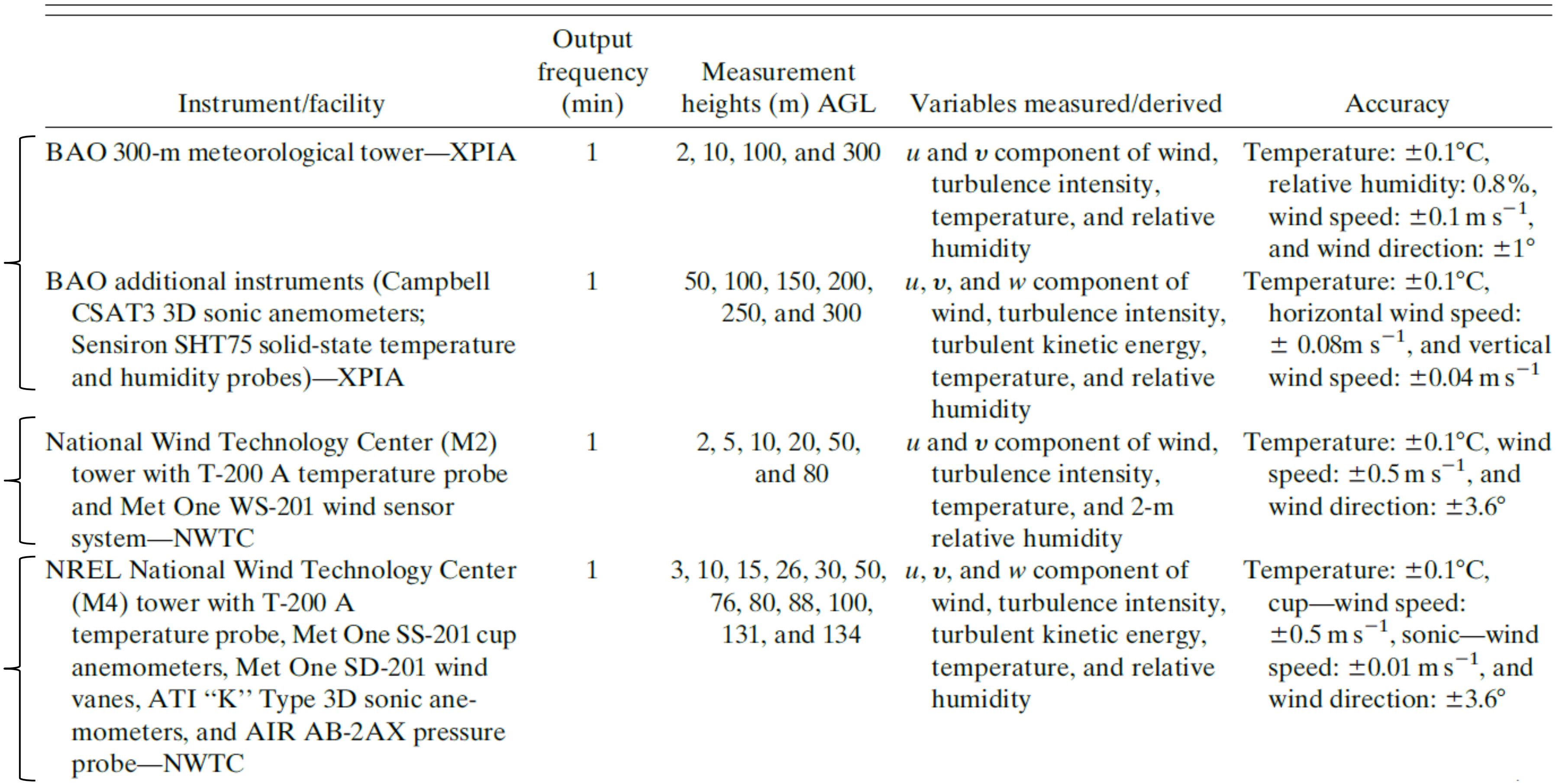
2. Study sites and instruments

b. Description of **in-situ** research instruments

Turbulence Intensity (TI): $\mathbf{TI} = \frac{\sigma_v}{\bar{V}}$

Turbulence Kinetic Energy (TKE): $\mathbf{TKE} = \frac{1}{2}(u'u' + v'v' + w'w')$

Both calculate mean and maximum **over 2-min interval**



	Instrument/facility	Output frequency (min)	Measurement heights (m) AGL	Variables measured/derived	Accuracy
1.	BAO 300-m meteorological tower—XPIA	1	2, 10, 100, and 300	u and v component of wind, turbulence intensity, temperature, and relative humidity	Temperature: ±0.1°C, relative humidity: 0.8%, wind speed: ±0.1 m s^{-1}, and wind direction: ±1°
	BAO additional instruments (Campbell CSAT3 3D sonic anemometers; Sensiron SHT75 solid-state temperature and humidity probes)—XPIA	1	50, 100, 150, 200, 250, and 300	u, v, and w component of wind, turbulence intensity, turbulent kinetic energy, temperature, and relative humidity	Temperature: ±0.1°C, horizontal wind speed: ± 0.08m s^{-1}, and vertical wind speed: ±0.04 m s^{-1}
2.	National Wind Technology Center (M2) tower with T-200 A temperature probe and Met One WS-201 wind sensor system—NWTC	1	2, 5, 10, 20, 50, and 80	u and v component of wind, turbulence intensity, temperature, and 2-m relative humidity	Temperature: ±0.1°C, wind speed: ±0.5 m s^{-1}, and wind direction: ±3.6°
3.	NREL National Wind Technology Center (M4) tower with T-200 A temperature probe, Met One SS-201 cup anemometers, Met One SD-201 wind vanes, ATI "K" Type 3D sonic anemometers, and AIR AB-2AX pressure probe—NWTC	1	3, 10, 15, 26, 30, 50, 76, 80, 88, 100, 131, and 134	u, v, and w component of wind, turbulence intensity, turbulent kinetic energy, temperature, and relative humidity	Temperature: ±0.1°C, cup—wind speed: ±0.5 m s^{-1}, sonic—wind speed: ±0.01 m s^{-1}, and wind direction: ±3.6°

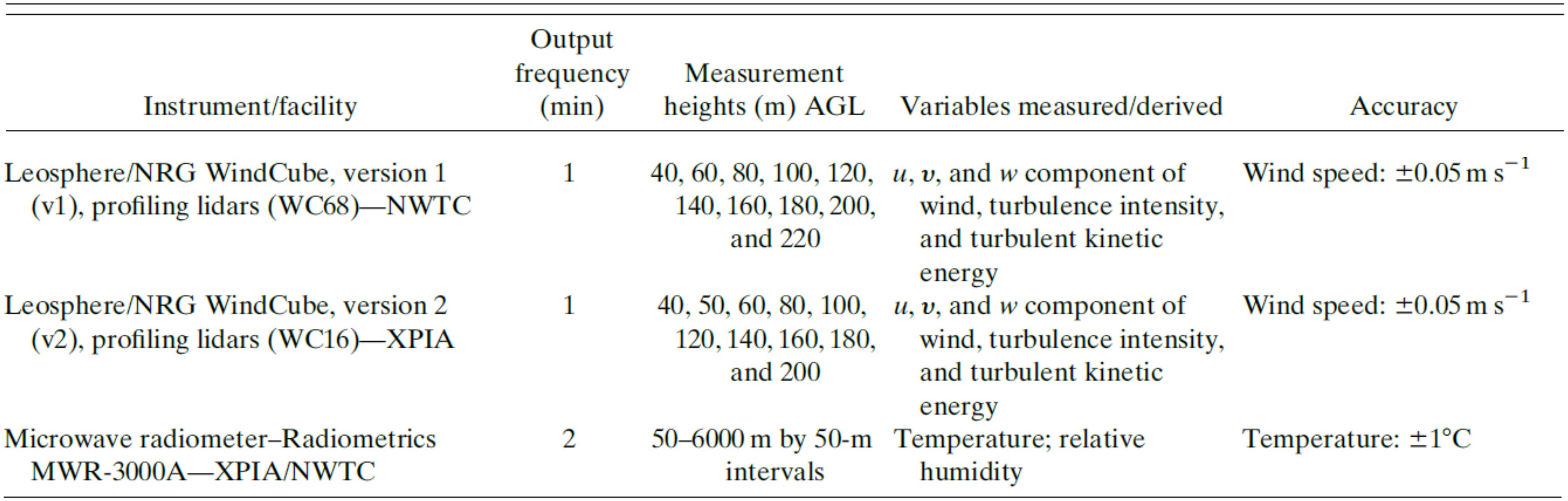
2. Study sites and instruments

c. Description of **remote sensing** research instruments

Turbulence Intensity (TI): $\mathbf{TI} = \frac{\sigma_v}{\bar{V}}$

Turbulence Kinetic Energy (TKE): $\mathbf{TKE} = \frac{1}{2}(u'u' + v'v' + w'w')$

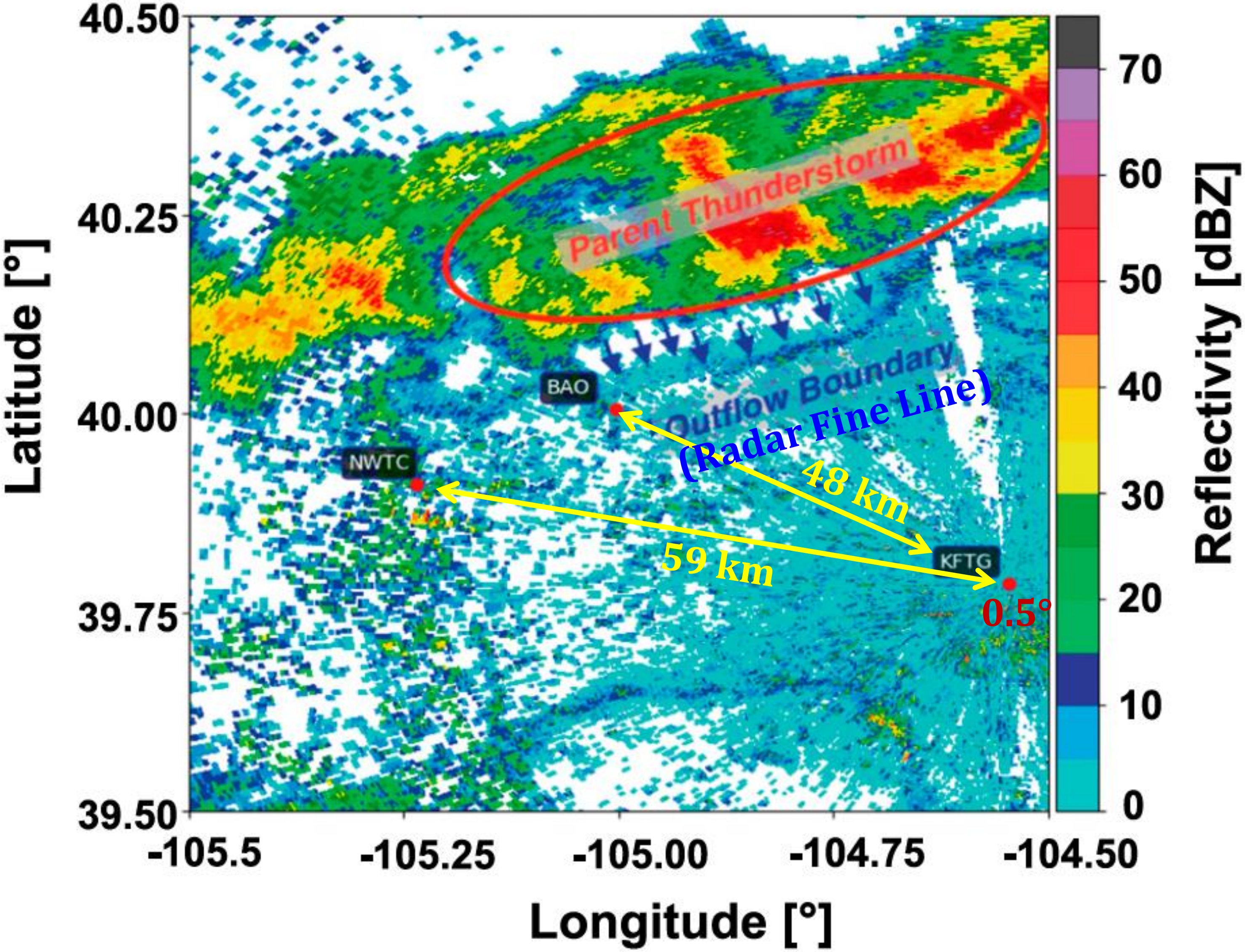
Both calculate mean and maximum over 2-min interval



Instrument/facility	Output frequency (min)	Measurement heights (m) AGL	Variables measured/derived	Accuracy
Leosphere/NRG WindCube, version 1 (v1), profiling lidars (WC68)—NWTC	1	40, 60, 80, 100, 120, 140, 160, 180, 200, and 220	u, v, and w component of wind, turbulence intensity, and turbulent kinetic energy	Wind speed: ±0.05 m s^{-1}
Leosphere/NRG WindCube, version 2 (v2), profiling lidars (WC16)—XPIA	1	40, 50, 60, 80, 100, 120, 140, 160, 180, and 200	u, v, and w component of wind, turbulence intensity, and turbulent kinetic energy	Wind speed: ±0.05 m s^{-1}
Microwave radiometer–Radiometrics MWR-3000A—XPIA/NWTC	2	50–6000 m by 50-m intervals	Temperature; relative humidity	Temperature: ±1°C

3. Methods

a. Parent thunderstrom and gust front detection using KFTG



3. Methods

a1. Parent thunderstroms detection using KFTG

At "**10 minutes prior to the first detection of radar fine line**":

- **Type**: single-cell, multicells, or supercell thunderstorms
- **Maximum Height**: radar echo tops of $Z \geq 18$ dBZ
- **Size**: the areal extent of $Z \geq 35$ dBZ at 0.5° elevation angle
- **Maximum Rainfall Rate**: $Z = 300R^{1.5}$

Definition of "**thunderstrom duration time**":

- "10 minutes prior to the first detection of radar fine line"

  to "dissipation ($Z < 20$ dBZ)"

3. Methods

a2. Gust fronts detection using KFTG

GF characteristics being detected:

- Propagation speed and direction
- The relative time GFs pass over the instruments
- The distance between parent thunderstrom at time of passage

Comparing observed GF propagation speed with theory (Benjamin, 1968):

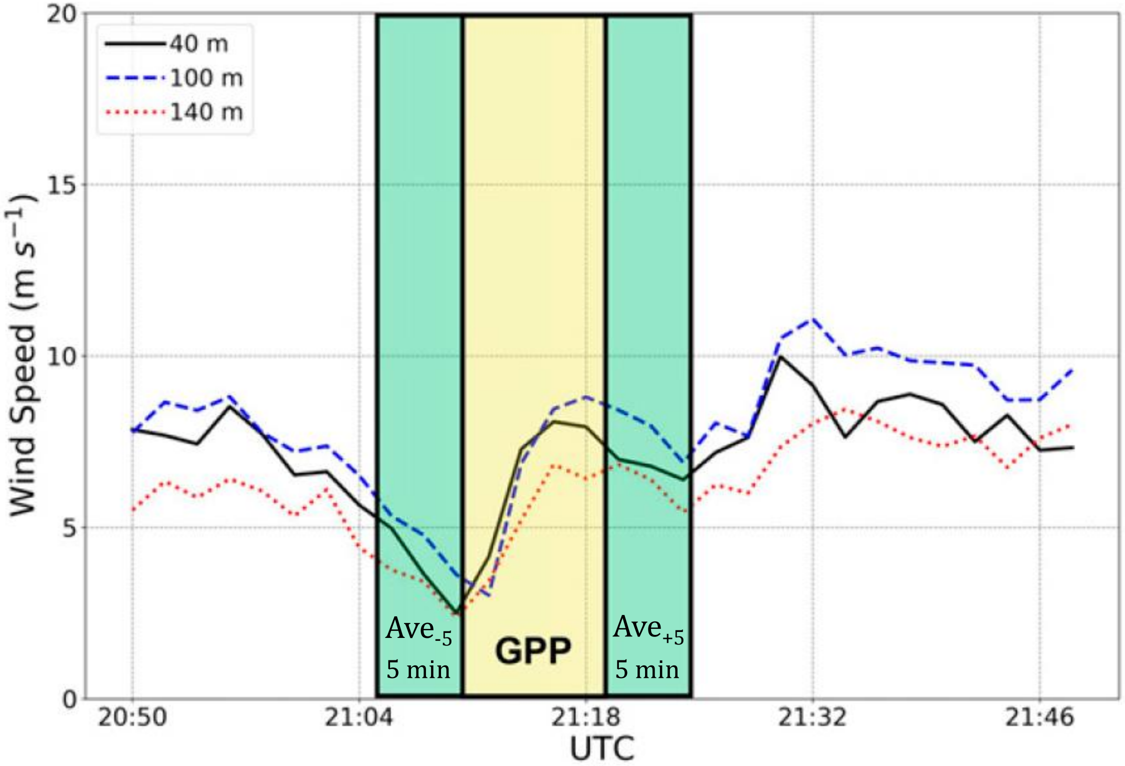
$$c = \sqrt{\frac{\Delta\theta}{\theta} gh}$$

where $\Delta\theta$ is measured at 10m and h is temperature change $> 1\,°\mathrm{C}$

3. Methods

b. The magnitude change and change rate of atmospheric properties

Properties: wind speed and direction, temperature, relative humidity



- **GPP**: GF Passage Period
- Magnitude Change

$$= Ave_{+5} - Ave_{-5}$$

- Change Rate

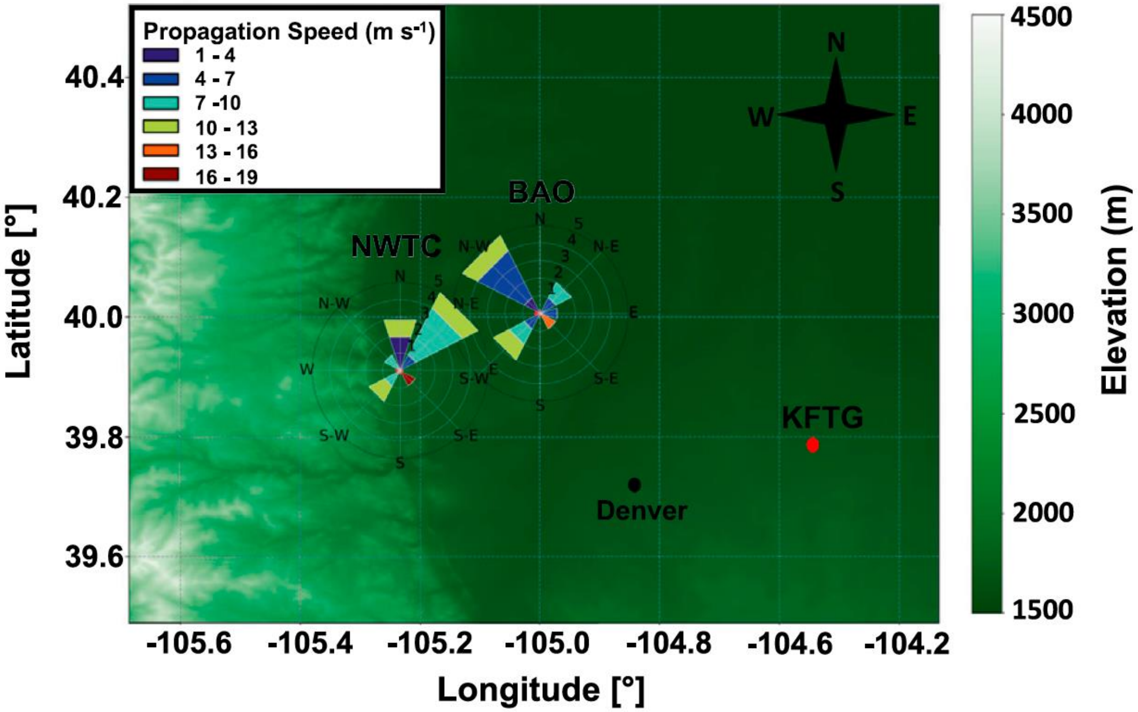
$$= \frac{Ave_{+5} - Ave_{-5}}{GPP}$$

The output: ”<u>atmospheric properties－height</u>” relationship for each event

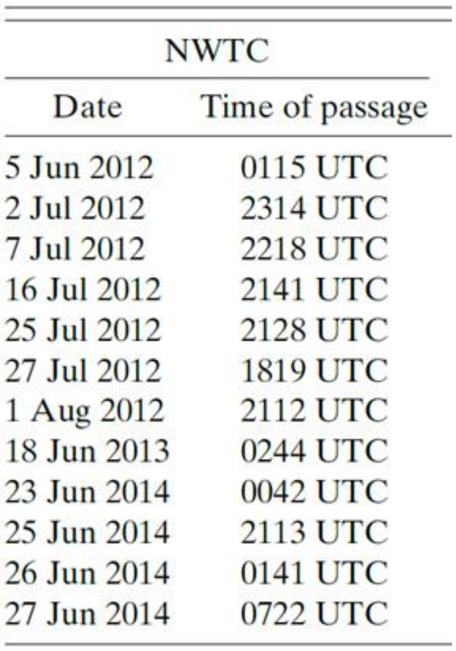
The goal: obtain “<u>median/interquartile range－height</u>” relationship for each property

4. Results / 5. Discussion

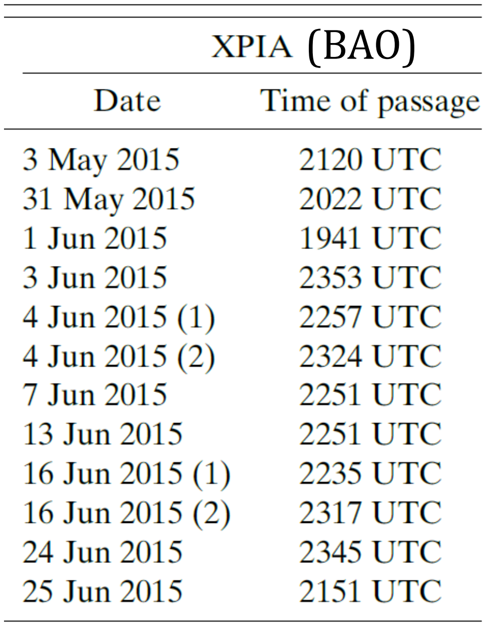
a. Parent thunderstorm characteristics



Types	Number	Percentage (%)
Single-cell	**10**	**42 %**
Multicell	**13**	**54 %**
Supercell	**1**	**4 %**
Total	**24**	**100%**



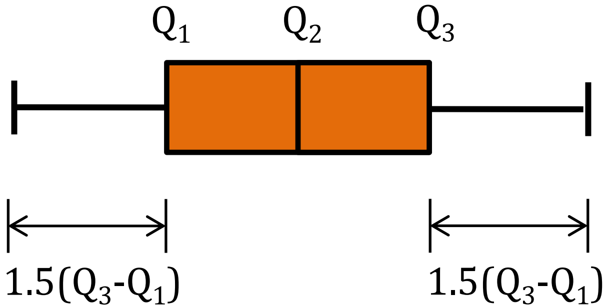
NWTC	
Date	Time of passage
5 Jun 2012	0115 UTC
2 Jul 2012	2314 UTC
7 Jul 2012	2218 UTC
16 Jul 2012	2141 UTC
25 Jul 2012	2128 UTC
27 Jul 2012	1819 UTC
1 Aug 2012	2112 UTC
18 Jun 2013	0244 UTC
23 Jun 2014	0042 UTC
25 Jun 2014	2113 UTC
26 Jun 2014	0141 UTC
27 Jun 2014	0722 UTC



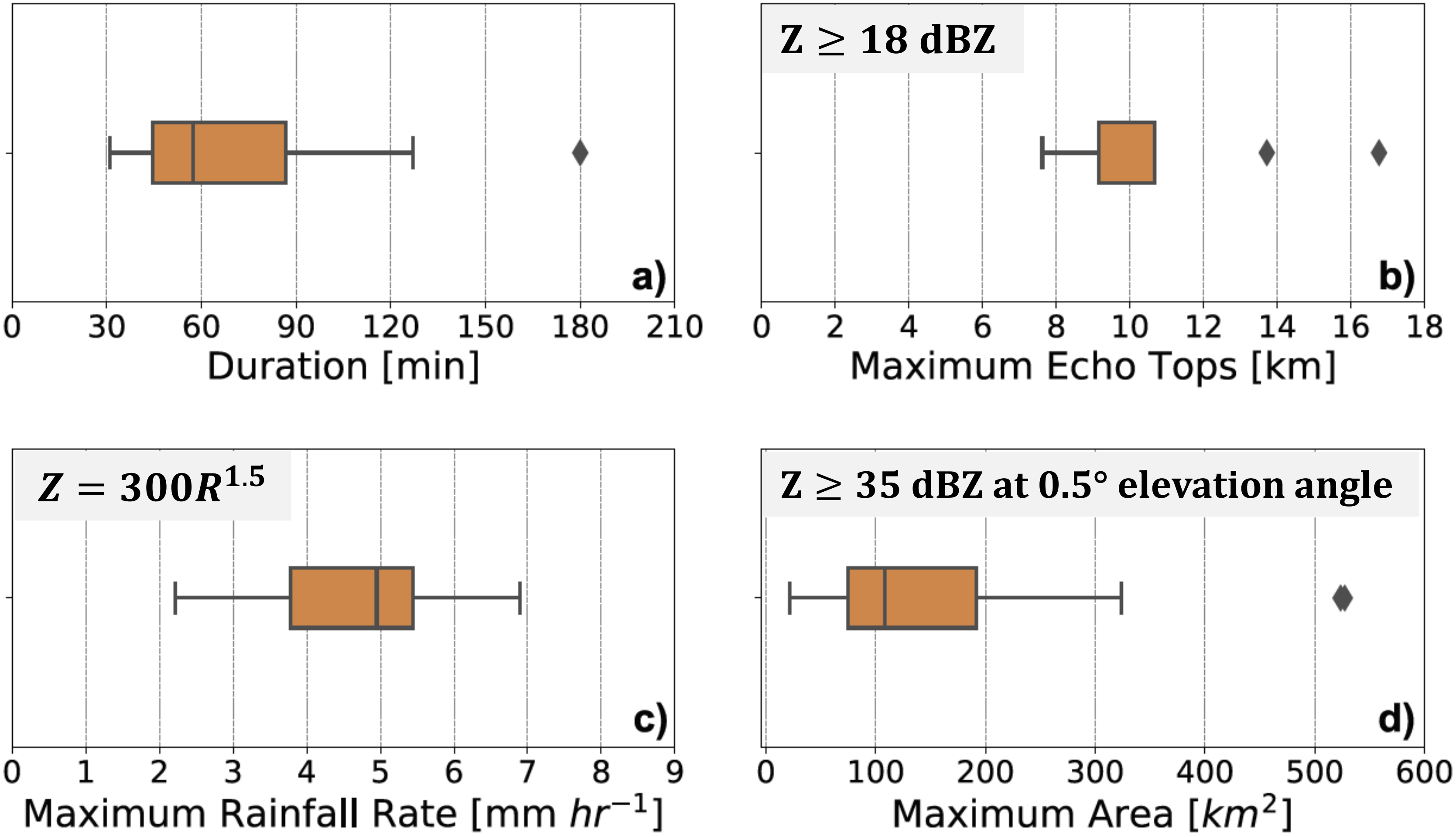
XPIA (BAO)	
Date	Time of passage
3 May 2015	2120 UTC
31 May 2015	2022 UTC
1 Jun 2015	1941 UTC
3 Jun 2015	2353 UTC
4 Jun 2015 (1)	2257 UTC
4 Jun 2015 (2)	2324 UTC
7 Jun 2015	2251 UTC
13 Jun 2015	2251 UTC
16 Jun 2015 (1)	2235 UTC
16 Jun 2015 (2)	2317 UTC
24 Jun 2015	2345 UTC
25 Jun 2015	2151 UTC

4. Results / 5. Discussion

a. Parent thunderstorm characteristics

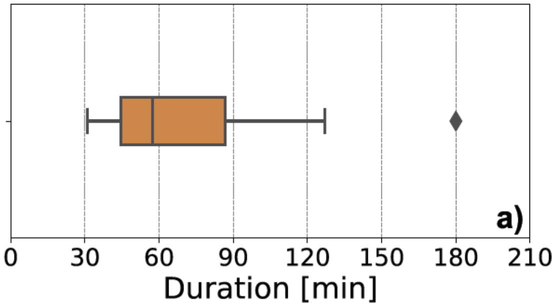


Duration : “10 minutes prior to the first detection of radar fine line” to “dissipation (Z < 20 dBZ)”

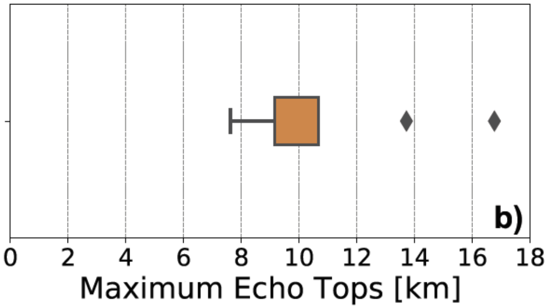


4. Results / 5. Discussion

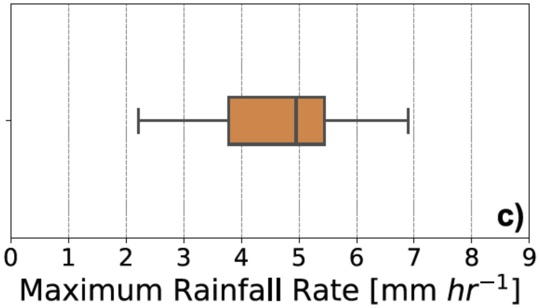
a. Parent thunderstorm characteristics



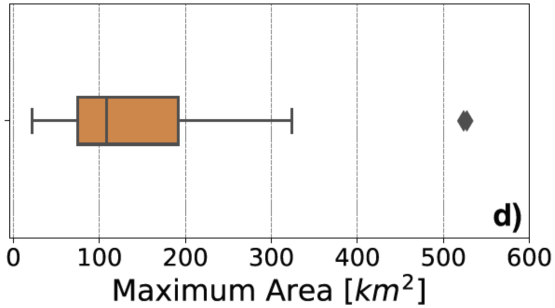
The Duration is typical for single cell and multi-cell thunderstroms.



The echo top may be subdued by lower CAPE in this region.



The maximum rainfall rate is typical to lower-reflectivity thunderstorms.

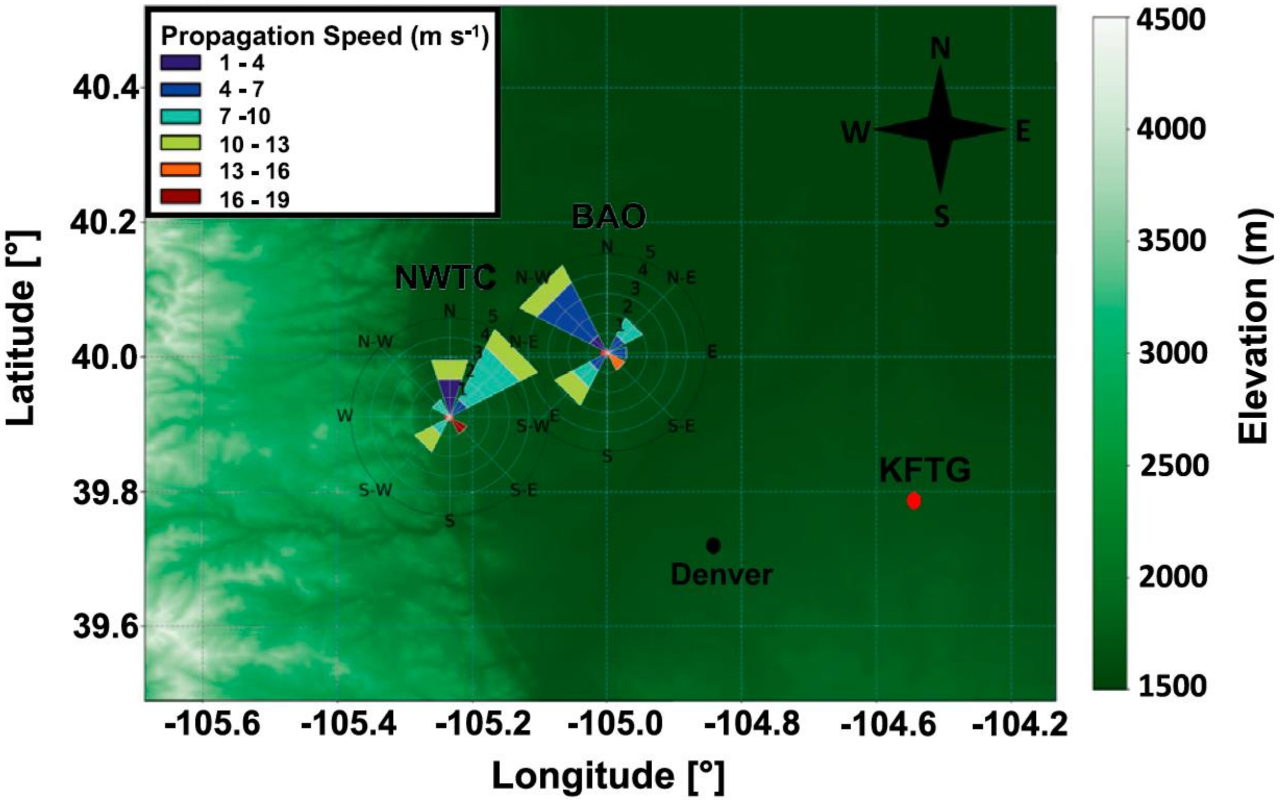


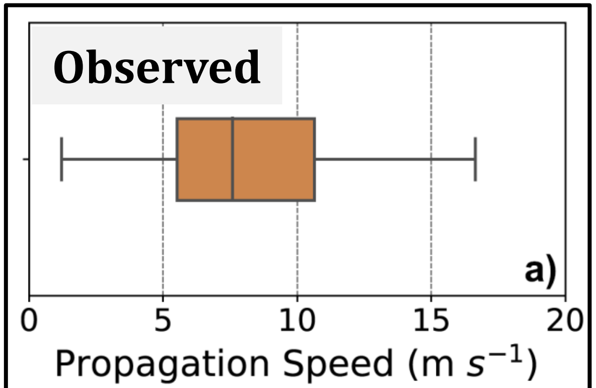
The maximum area is indicative of spatially smaller thunderstorms.

4. Results / 5. Discussion

b. Gust front characteristics

Propagate "from"	SW	SE	E	NE	N	NW	Total
Number	5	2	1	7	3	6	24
Percentage (%)	21 %	8 %	4 %	29 %	13 %	25 %	100 %





Theoretical ($c = \sqrt{\frac{\Delta\theta}{\theta} gh}$)

Min	4.7 m/s
Median	13.0 m/s
Max	24.6 m/s

$r = 0.36$

4. Results / 5. Discussion

b. Gust front characteristics

Question: Does prefrontal cross-front ambient wind matter?

- Theoretical propagation speed with cross-front ambient wind u_0:

  (Simpson and Britter, 1980)

$$c = k\sqrt{\frac{\Delta\theta}{\theta}gh} + bu_0$$

  where $b = 0.6$ and k is the internal Froude number (0.7~1.1, Koch 1984) and

- The theoretical propagation speed decreases with prefrontal cross-front ambient wind

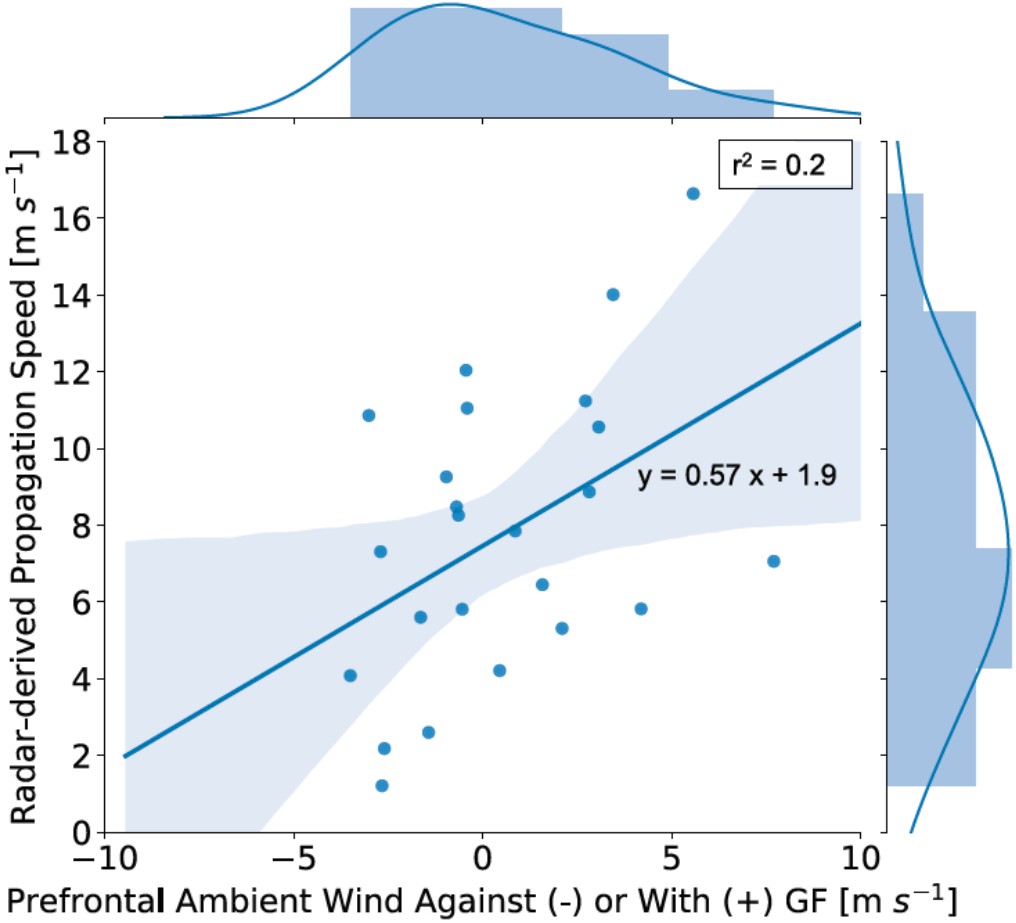
- The correlation between observed and theoretical propagation speed increases:

$$\boldsymbol{r = 0.36 \quad \rightarrow \quad r = 0.48}$$

4. Results / 5. Discussion

b. Gust front characteristics

Question: Does prefrontal cross-front ambient wind matter?

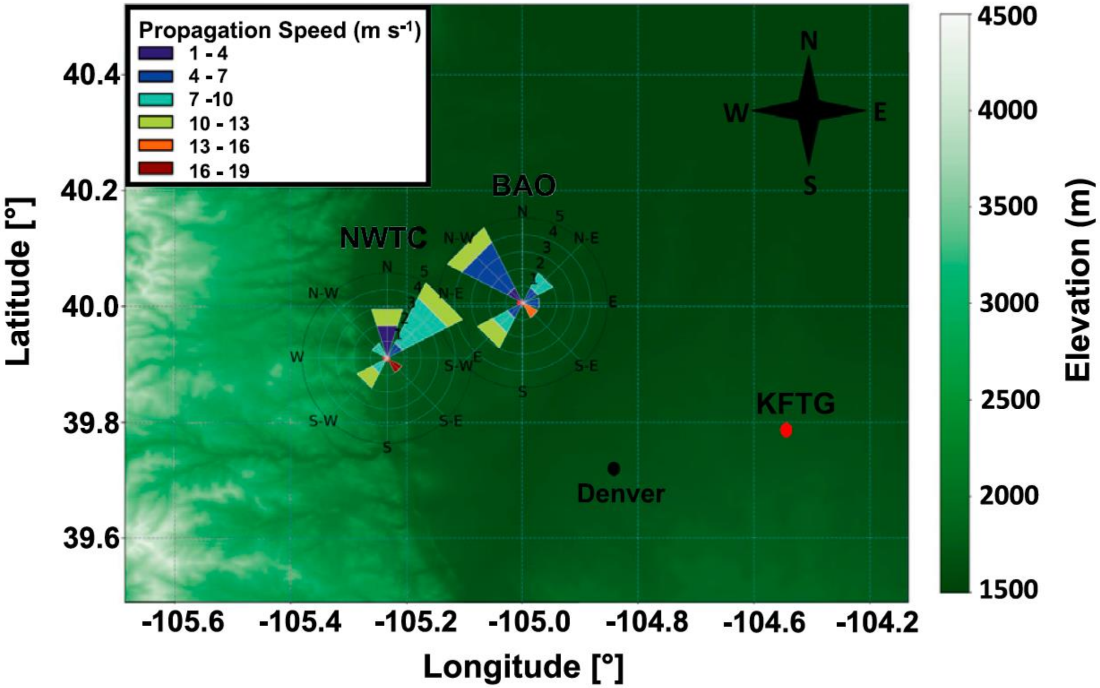


Result: Prefrontal cross-front ambient wind is not a strong determining factor.

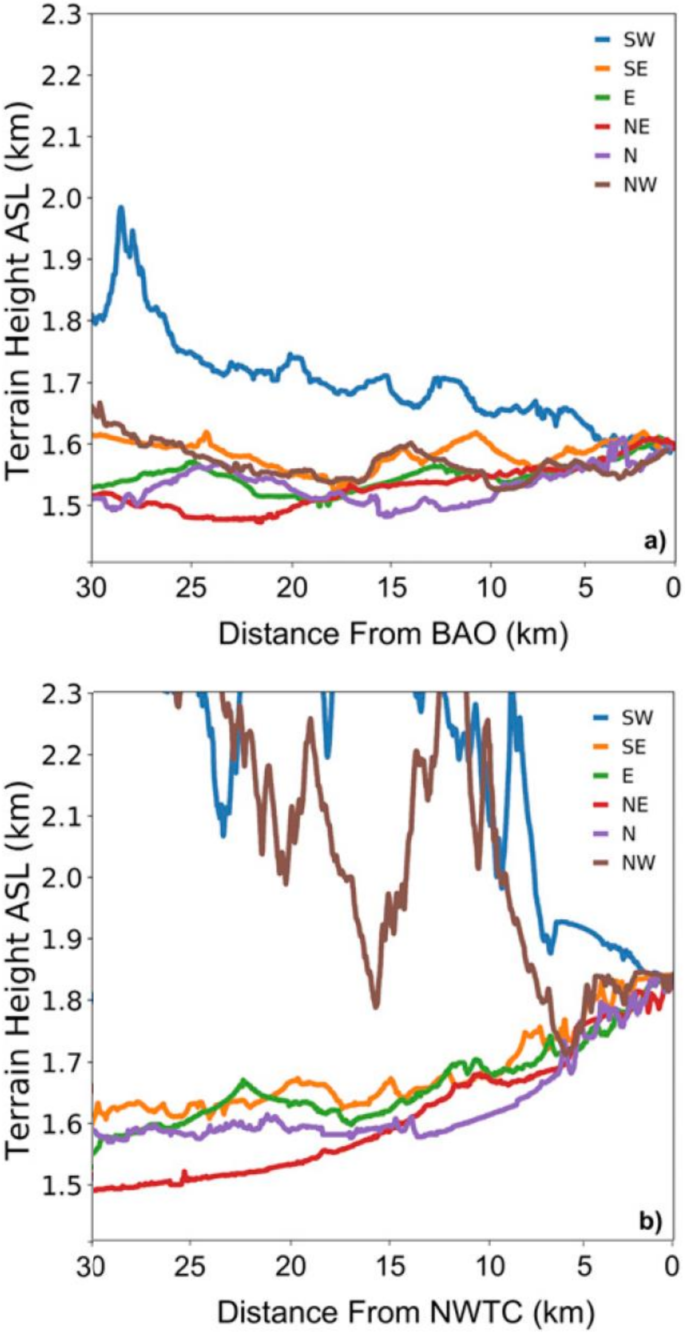
4. Results / 5. Discussion

b. Gust front characteristics

Question: Does topography drag matter?



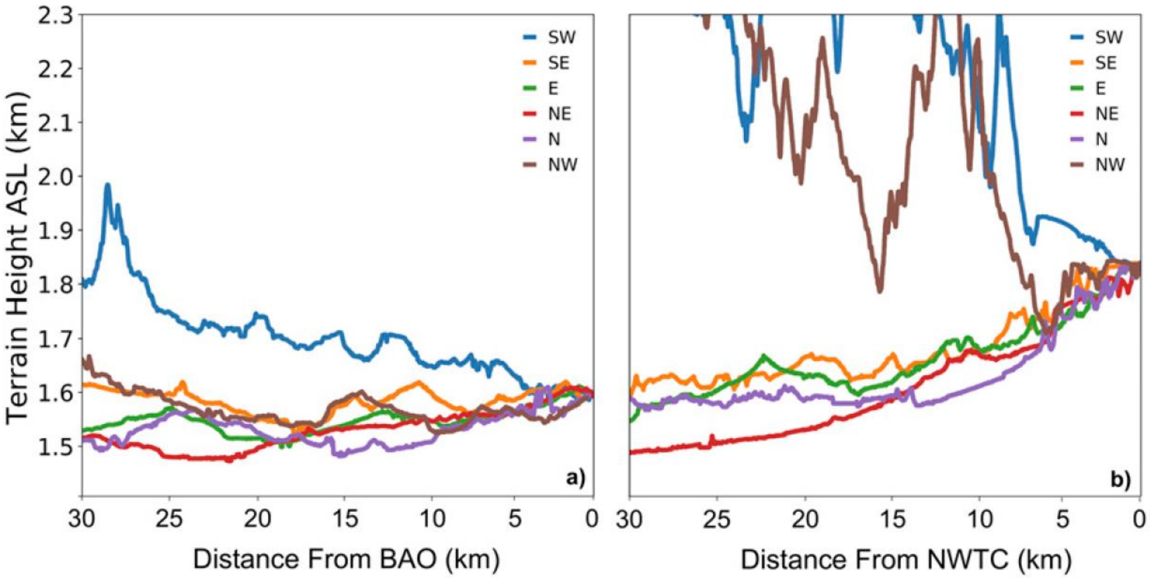
Types	Propagation Speed
Southward-moving GFs	$6.6 \pm 3.3\ m/s$
Other GFs	$10.1 \pm 3.8\ m/s$

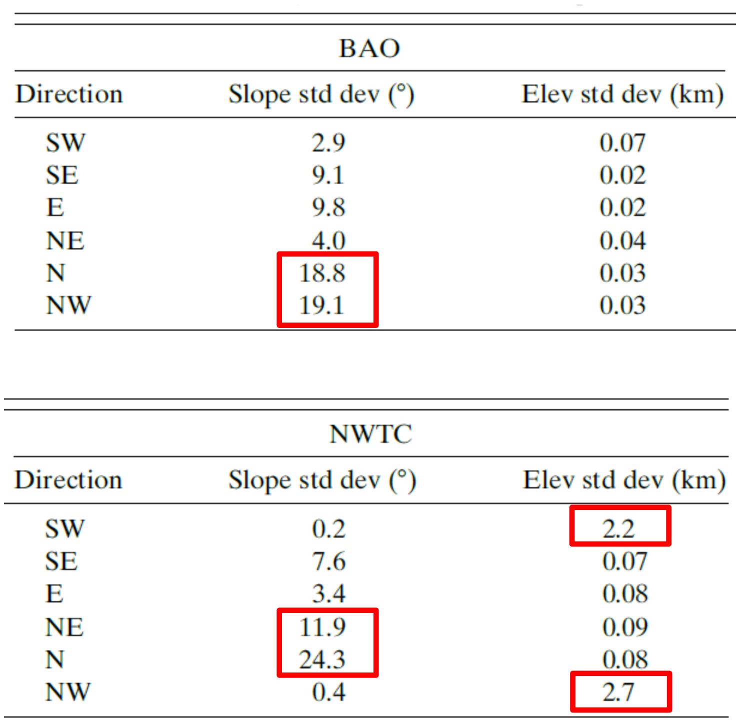


4. Results / 5. Discussion

b. Gust front characteristics

Question: Does topography matter?





BAO		
Direction	Slope std dev (°)	Elev std dev (km)
SW	2.9	0.07
SE	9.1	0.02
E	9.8	0.02
NE	4.0	0.04
N	18.8	0.03
NW	19.1	0.03

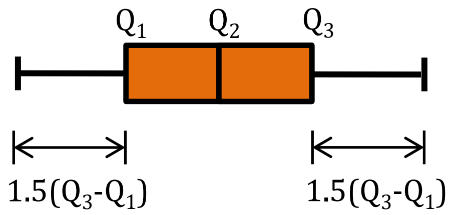
NWTC		
Direction	Slope std dev (°)	Elev std dev (km)
SW	0.2	2.2
SE	7.6	0.07
E	3.4	0.08
NE	11.9	0.09
N	24.3	0.08
NW	0.4	2.7

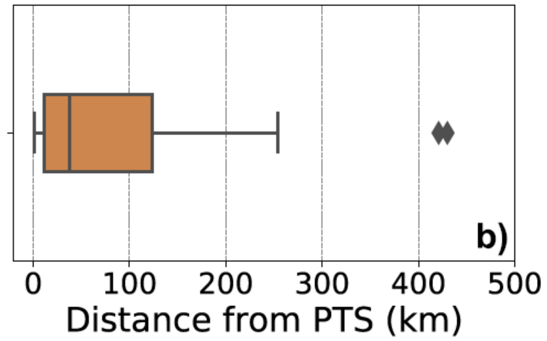
- 6 slowest GF events propagate from **N** and **NW**
- **NE**, **N** and **NW** slope variation are larger
- **SW** and **NW** elevation variation are larger

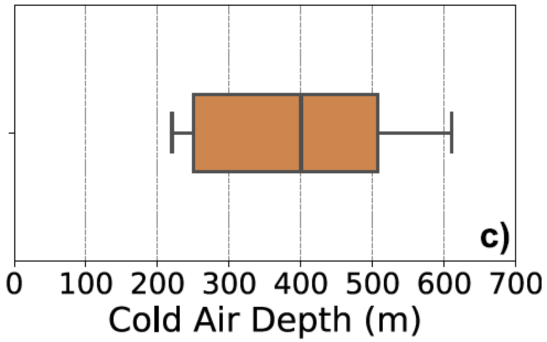
Result: Topography variation may contribute to the deceleration.

4. Results / 5. Discussion

b. Gust front characteristics







- **Mean cold air depth**

  In this study

  $$= 360\ m$$

  In flatter regions (Benjamin 1968; Craig Goff 1976; Mahoney 1988; Rotunno et al. 1988; Jorgensen et al. 2003)

  $$= 500 \sim 2000\ m$$

- Measuring at different GF stages and distances from parent thunderstrom (PTS) may cause difference.

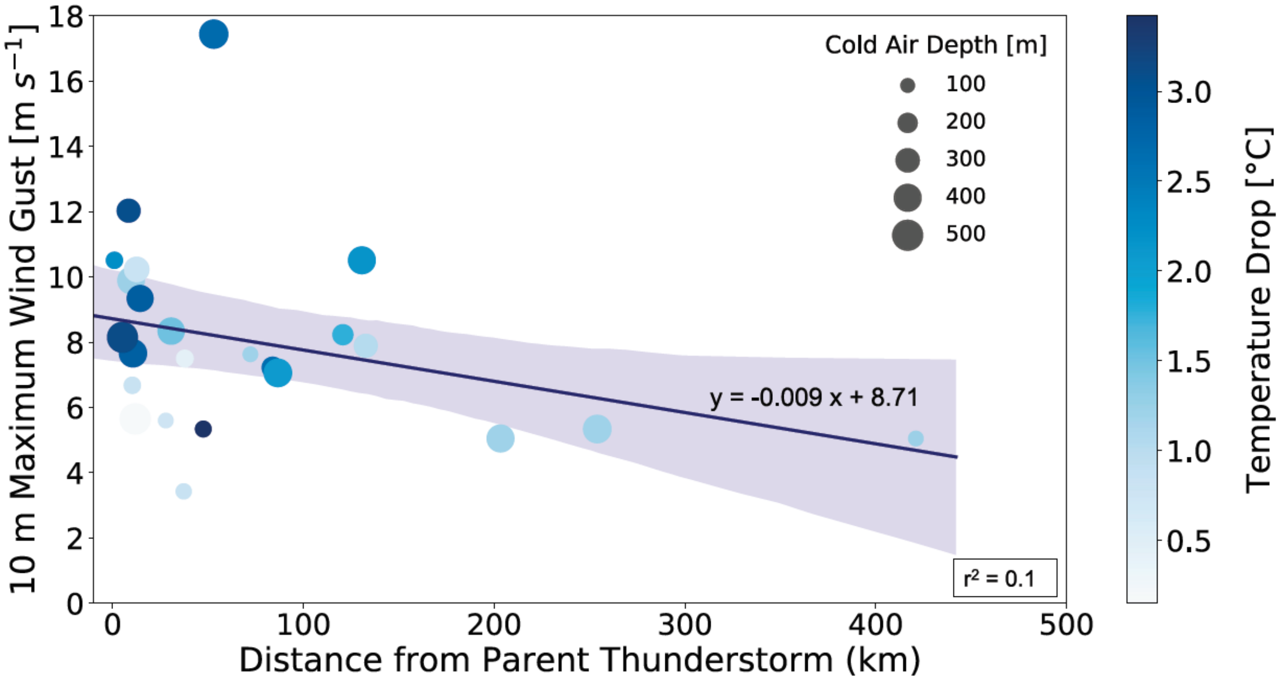
- In this study, the GFs are weaker, older and farther from PTS (median distance = 38 km).

4. Results / 5. Discussion

b. Gust front characteristics

- Deeper cold air can induce stronger horizontal wind gusts.
- Deeper cold air can lead to faster propagating GFs.

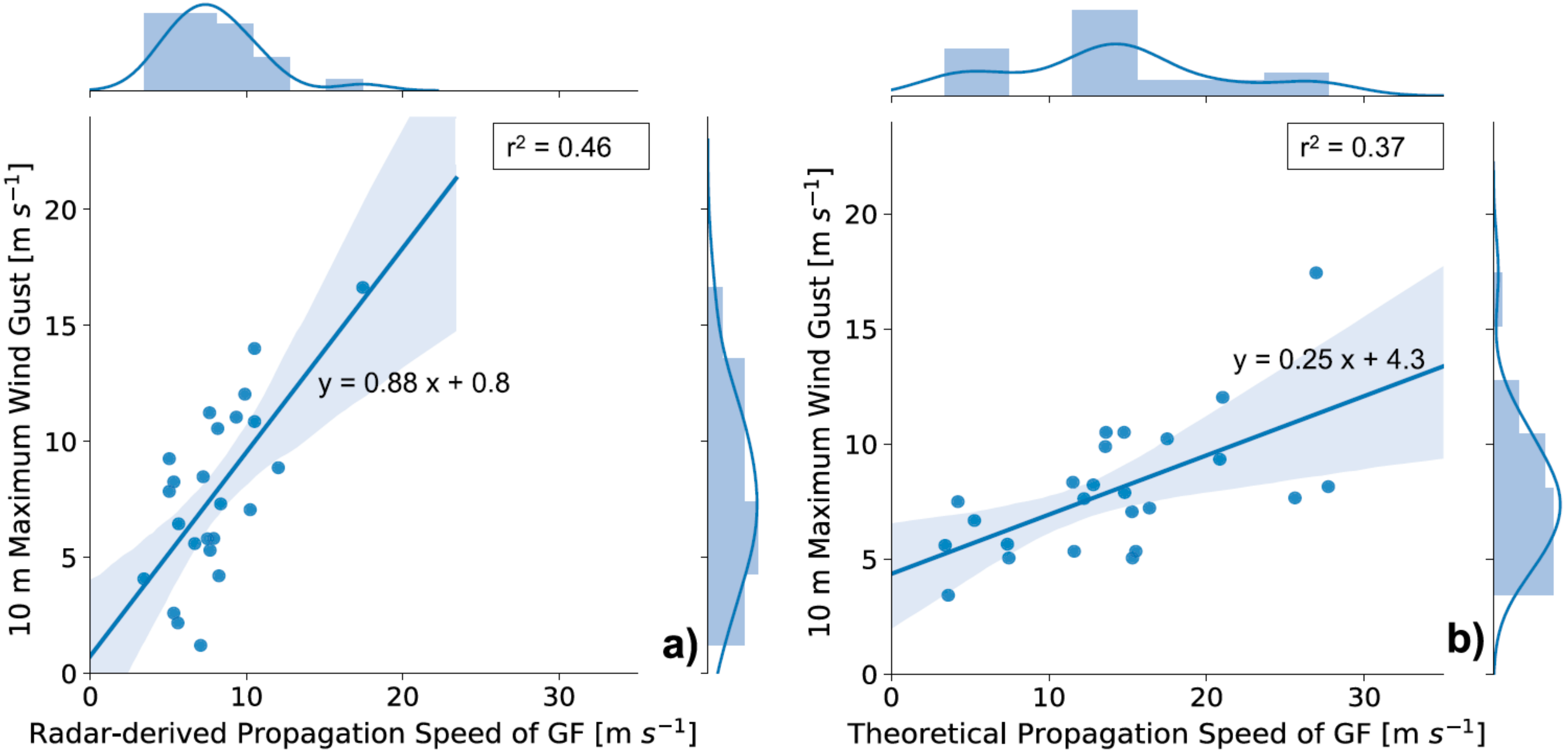
(Benjamin 1968; Rotunno et al. 1988; Jorgensen et al. 2003)



Correlation Coefficient	Maximum Wind Gusts	Temperature Drop	Theoretical Propagation Speed	Radar-derived Propagation Speed
Cold Air Depth	0.50	0.48	0.62	0.30

4. Results / 5. Discussion

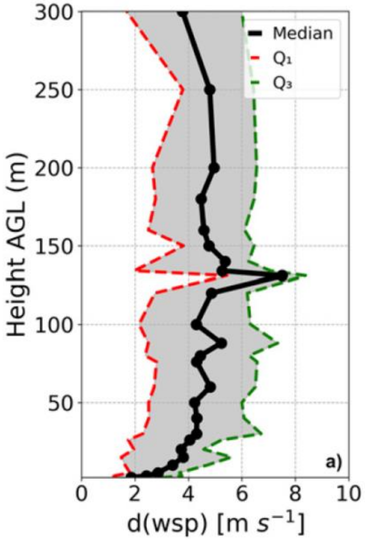
b. Gust front characteristics



Correlation Coefficient	Radar-derived Propagation Speed	Theoretical Propagation Speed
Maximum Wind Gusts	0.68	0.61

4. Results / 5. Discussion

c. Horizontal Wind Speed **(GPP = 7~13min)**



- 2013 Arizona Yarnell Fire GF accident (Karels and Dudley, 2013):

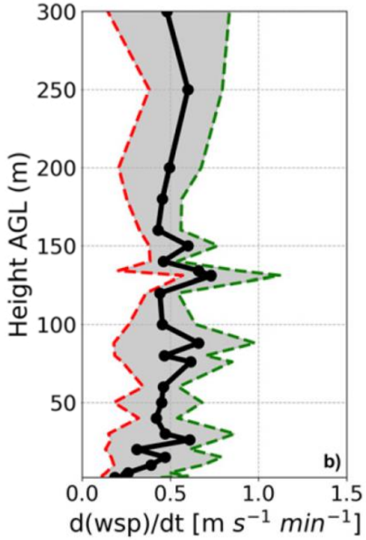
$$d(wsp) = 13{\sim}17\ m/s$$

- 1981 Florida Ransom Road Fire GF accident (Haines, 1988):

$$d(wsp) = 3{\sim}10\ m/s$$

- Similar jetlike structure at 120m is also observed and modeled.

  (Hjelmfelt 1988; Bowen 1996; Kwon and Kareem 2009; Kwon et al. 2012)



- 141 GFs at northern Mediterranean coastal plain over 10 min

  (Zhang et al. 2018):

  88 (63%) $\frac{d(wsp)}{dt} = 1.5{\sim}2.0\ m\ s^{-1}\ min^{-1}$

  53 (37%) $\frac{d(wsp)}{dt} = 2.0{\sim}3.5\ m\ s^{-1}\ min^{-1}$

- $\frac{d(wsp)}{dt}$ is lower than other studies.

4. Results / 5. Discussion

c. Horizontal Wind Speed (GPP = 7~13min)

Maximum Horizontal Wind Gusts:

- GFs in this study (mostly initiated from **single-cell and multi-cell thunderstorms**):

$$\boldsymbol{7.9\ m/s}$$

- 39 GFs initiated from organized **MCSs** in Oklahoma (Engerer et al. 2008):

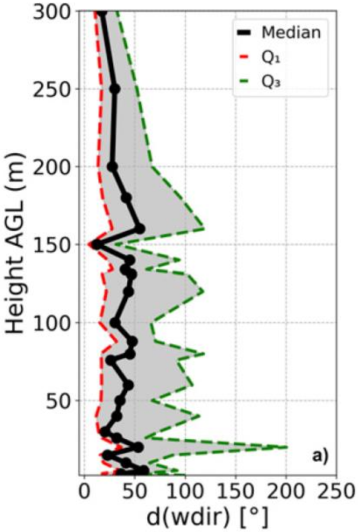
$$\boldsymbol{15\ m/s}$$

The reason why horizontal wind gusts weaker in this study:

- The thunderstorms are less organized near complex terrain, which make downdraft strength weaker.

4. Results / 5. Discussion

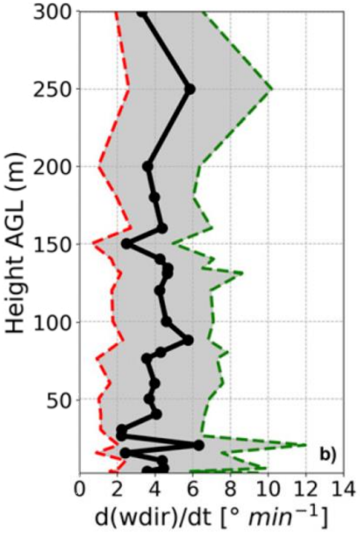
d. Horizontal Wind Direction (GPP = 7~16min)



- The magnitude change range between 10°~60°.
- 2013 Arizona Yarnell Fire GF accident (Karels and Dudley, 2013):

$$d(wdir) = 90°$$

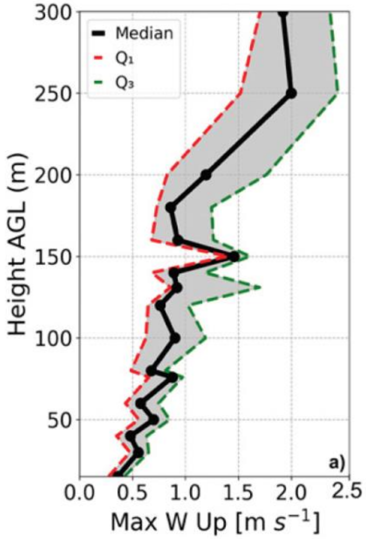
- Wind direction is critical in wild fire events, which change fire behavior and intensity.



- $\frac{d(wdir)}{dt}$ range from 1°~6° min^{-1}.
- $\frac{d(wdir)}{dt}$ is nearly uniform with height.

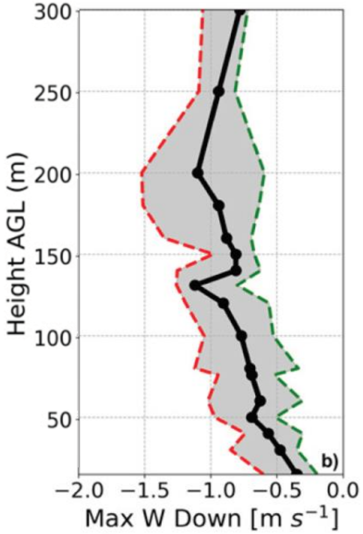
4. Results / 5. Discussion

e. Vertical Motion (Maximum Updraft and Downdraft)



- The median range between 0.4 and 2.0 m/s.
- Maximum updraft occur immediately prior to GF passage.
- Maximum updraft is followed by a spike in downward motion behind the leading edge boundary.
- The maximum updraft in organized MCSs often range from 6.0 to 15.0 m/s.

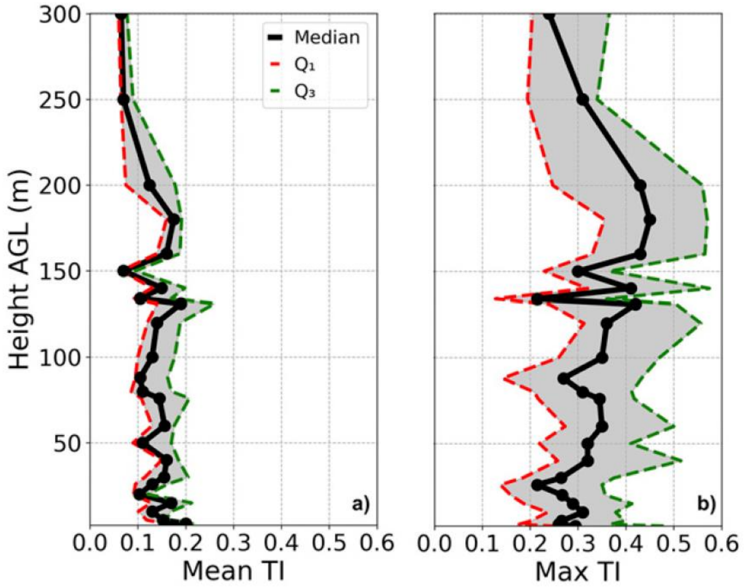
  (Charba 1974; Craig Goff 1976; Wakimoto 1982; Bryan and Parker 2010)
- The weaker updraft may due to shallower cold pool.

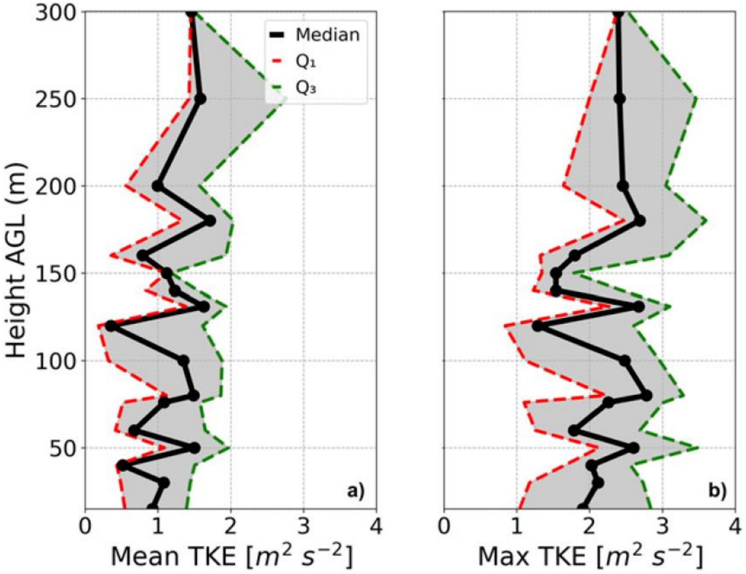


- The median range between -0.3 and -1.2 m/s.

4. Results / 5. Discussion

f. Turbulence (Mean and Maximum TI/TKE)





$$\mathbf{TI} = \frac{\sigma_v}{\overline{V}},\ \ \mathbf{TKE} = \frac{1}{2}(u'u' + v'v' + w'w')$$

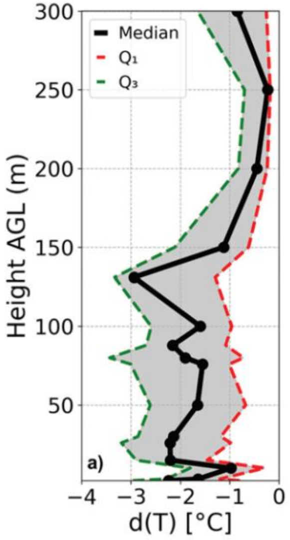
(average over 2 min)

- Turbulence increase during GF passage.
- Median mean TI range from 0.06 to 0.2.
- Median mean TKE range from 0.2 to 1.7 m^2s^{-2}.

- TI and TKE observed in this study is comparable to Zhang et al. 2018 along the northern Mediterranean coastline.

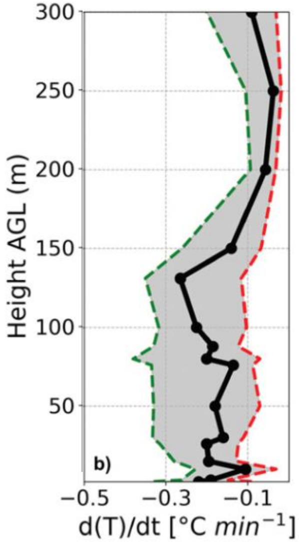
4. Results / 5. Discussion

g. Temperature (GPP = 5~10min)



- The magnitude change range from 0.2°C~3°C.
- The magnitude change of MCSs initiated GFs in Niger, Africa range from 1.8°C~13.1°C. (Provod et al. 2016)

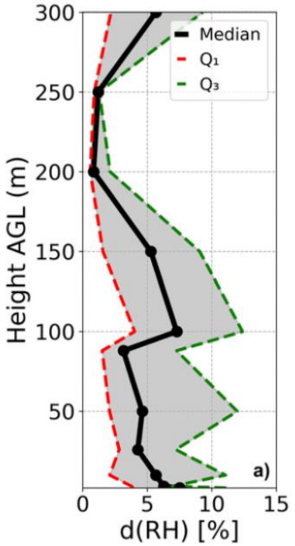
  (Calculating method different from here.)
- Shallower cold pool depth may associated to less temperature drop.



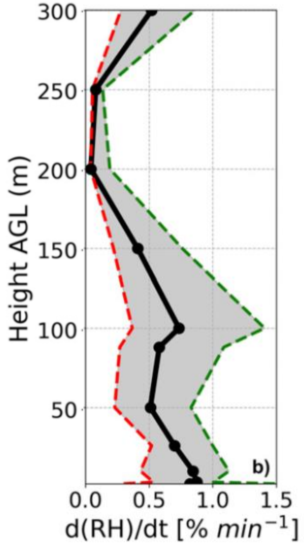
- $\frac{d(T)}{dt}$ range from $-0.04°\text{C}\sim -0.3°\text{C}\ min^{-1}$.
- $\frac{d(T)}{dt}$ does not vary too much with height.

4. Results / 5. Discussion

h. Relative Humidity (GPP = 10 min)



- The magnitude change range from 1% ~ 8%.
- The increase in RH may slow down the wildfire, however, the strengthen wind gusts would offset this effect.



- $\frac{d(RH)}{dt}$ range from 0.1%~0.8% min^{-1}.
- $\frac{d(RH)}{dt}$ vary a little with height.

6. Conclusions

The main finding in this study are:

- The influence of the prefrontal cross-front ambient wind component on GF propagation speed is negligible.
- GFs that encounter higher variability in terrain and slope propagate slower.
- The cold pool is shallower than organized MCSs in flatter terrain, which cause less change in atmospheric properties (wind speed, vertical motion, temperature, and RH).