

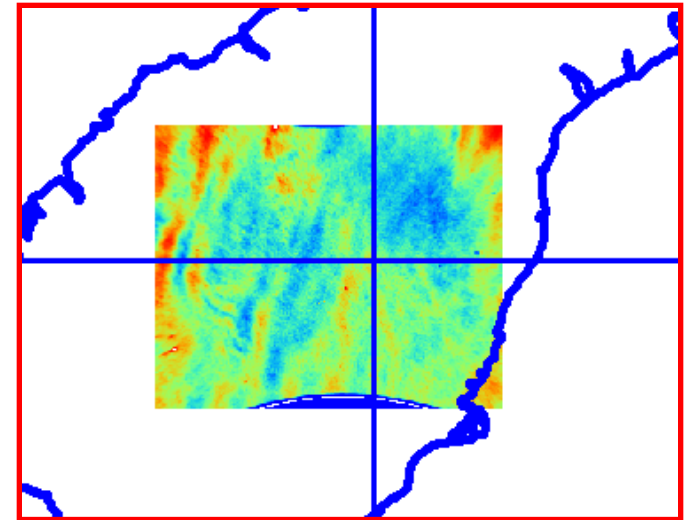
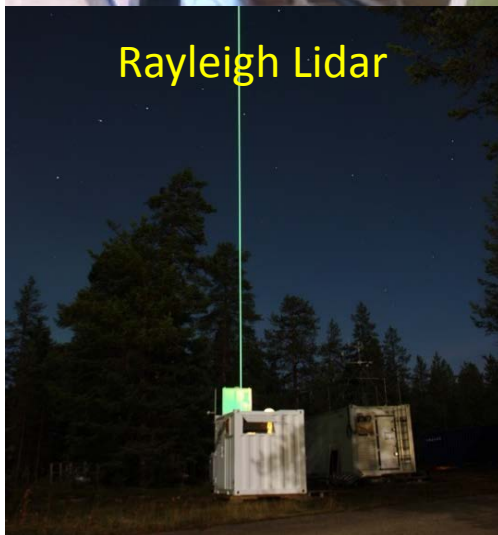
An aerial photograph of a research station situated on a grassy hillside. The station consists of several interconnected buildings with light-colored roofs and walls, some featuring external scaffolding or equipment. To the right, there is a white fence and a small, white, dome-shaped structure. The background shows rolling green hills under a clear blue sky.

DEEPWAVE: Investigating Mesospheric Mountain Wave Activity and Properties Over Lauder, NZ.

Mike J. Taylor, P-D Pautet , Y Zhao, B. Kaifler,
P. McLaughlin, D. Fritts, S, Smith, and
M. McCarthy,

DEEPWAVE Science Team Meeting, NRL, Monterey, CA, 9-10 December, 2016

AMTM Installed at NIWA Lauder Observatory, 45°S, NZ, (May 30th- Jul 21st)



AMTM:

- 180 x 200 km temperature and intensity maps of the OH layer (~87km), centered at the zenith, every ~30s

Mountain Waves over Lauder

Summary: Lauder AMTM GW/MW Observations:

51 consecutive nights of observations from May 30th to July 21th:

- 15 clear nights
- 25 partially cloudy nights

Total of 40 data nights:

- **280 nights with mountain (standing) waves (>100 hrs)**
(with durations from ~1-14 hrs).
- 12 nights with only propagating GWs

Dominant GWs Over Lauder - June 2014

UT Date	6-7	7-8	8-9	9-10	10-11	11-12	12-13	13-14	14-15	15-16	16-17	17-18	18-19	19-20	
30-May	Green	Green	Green	Green	Green	Blue	Green	Green	Green	Green	Blue	Blue	Blue	Blue	
31-May	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	
1-Jun				Blue	Blue	Blue	Green	Blue	Blue	Blue	Blue	Blue	Blue	Blue	
2-Jun				Blue	Blue	Blue	Blue	Blue	Blue	Blue	Blue	Blue	Blue	Blue	
3-Jun	Black	Black	Black	Black	Black	Black	Black	Black	Black	Black	Black	Black	Black	Black	
4-Jun												Blue	Blue	Blue	
5-Jun	Green	Green	Green												
6-Jun	Black	Black	Black	Black	Black	Black	Black	Black	Black	Black	Black	Black	Black	Black	RF01
7-Jun					Blue	Blue									
8-Jun															
9-Jun															
10-Jun					Green	Green								Green	
11-Jun			Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	RF02
12-Jun	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	
13-Jun	Blue	Blue	Green	Green	Green	Green	Black	Black	Black	Black	Green	Green	Green	Green	RF03
14-Jun	Black	Black	Black	Black	Black	Black	Black	Black	Black	Black	Black	Black	Black	Black	RF04
15-Jun	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	
16-Jun	Black	Black	Green	Green	Black	Black	Green	Green	Green	Green	Black	Black	Black	Black	RF05
17-Jun	Black	Black	Black	Black	Blue	Blue	Blue	Blue	Blue	Blue	Blue	Blue	Blue	Blue	
18-Jun	Blue	Blue	Blue	Blue	Blue	Blue	Blue	Blue	Blue	Black	Black	Black	Black	Black	RF06
19-Jun	Green	Green	Green	Green	Green	Green	Green	Green	Blue	Blue	Blue	Blue	Blue	Blue	RF07
20-Jun	Green	Black	Black	Black	Black	Black	Black	Black	Black	Black	Black	Black	Black	Black	RF08
21-Jun	Blue	Blue	Blue	Blue	Blue	Blue	Blue	Blue	Blue	Blue	Blue	Blue	Blue	Blue	
22-Jun	Green	Green	Green	Blue	Blue	Blue	Blue	Blue	Blue	Blue	Blue	Blue	Blue	Blue	
23-Jun	Black	Black	Black	Black	Black	Black	Black	Black	Black	Black	Black	Black	Black	Black	
24-Jun	Black	Black	Black	Black	Black	Black	Black	Black	Black	Black	Black	Black	Black	Black	RF09
25-Jun	Green	Black	Black	Black	Black	Black	Black	Black	Black	Green	Green	Green	Green	Green	RF10
26-Jun	Blue	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	Green	
27-Jun	Blue	Blue	Blue	Blue	Blue	Blue	Blue	Blue	Blue	Blue	Blue	Blue	Blue	Blue	
28-Jun	Blue	Blue	Black	Black	Black	Blue	Blue	Blue	Blue	Black	Black	Black	Green	Green	RF11
29-Jun	Black	Black	Black	Black	Black	Black	Black	Black	Black	Black	Black	Black	Black	Black	RF12
30-Jun						Blue	Blue	Green	Green	Black	Green	Green	Green	Green	RF13

	Cloudy		Propagating GW
	Standing GW		RF over the South Island

MW=16/24 nights

Dominant GWs Over Lauder - July 2014

UT Date	6-7	7-8	8-9	9-10	10-11	11-12	12-13	13-14	14-15	15-16	16-17	17-18	18-19	19-20	
1-Jul								Standing GW	Standing GW	Propagating GW	Propagating GW	Propagating GW	Propagating GW	Propagating GW	RF14
2-Jul															
3-Jul						Standing GW	Standing GW	Standing GW	Standing GW						
4-Jul	Propagating GW	Propagating GW			Propagating GW	Propagating GW	Propagating GW	Propagating GW	Propagating GW	Propagating GW	Propagating GW	Propagating GW	Propagating GW	Propagating GW	RF16
5-Jul				Propagating GW	Propagating GW	Standing GW									RF17
6-Jul	Propagating GW	Propagating GW	Propagating GW	Propagating GW	Propagating GW	Propagating GW	Propagating GW	Standing GW	Standing GW	Propagating GW	Propagating GW	Propagating GW	Propagating GW	Propagating GW	
7-Jul	Propagating GW	Propagating GW	Propagating GW	Propagating GW	Propagating GW	Propagating GW	Propagating GW	Propagating GW	Propagating GW	Propagating GW	Propagating GW	Propagating GW	Propagating GW	Propagating GW	RF18
8-Jul	Propagating GW	Propagating GW	Propagating GW												RF19
9-Jul															
10-Jul								Standing GW	Standing GW	Standing GW	Standing GW	Propagating GW	Propagating GW	Propagating GW	RF20
11-Jul															RF21
12-Jul	Propagating GW		Propagating GW				Standing GW	Standing GW	Standing GW						
13-Jul															RF22
14-Jul	Standing GW	Standing GW	Standing GW	Standing GW	Standing GW	Standing GW	Standing GW	Standing GW	Standing GW	Standing GW	Standing GW	Standing GW	Standing GW	Standing GW	RF23
15-Jul	Standing GW	Standing GW								Propagating GW	Propagating GW				RF24
16-Jul	Standing GW	Propagating GW	Propagating GW	Propagating GW	Propagating GW	Propagating GW	Propagating GW	Propagating GW	Propagating GW	Propagating GW	Propagating GW	Propagating GW	Propagating GW	Propagating GW	
17-Jul	Standing GW	Standing GW	Standing GW	Standing GW	Standing GW	Standing GW	Standing GW	Standing GW	Standing GW	Standing GW	Standing GW	Standing GW	Standing GW	Standing GW	
18-Jul	Standing GW	Standing GW	Standing GW	Standing GW	Standing GW										RF25
19-Jul															
20-Jul							Standing GW	Standing GW	Standing GW						RF26
21-Jul				Propagating GW	Propagating GW	Propagating GW	Propagating GW	Propagating GW	Propagating GW	Propagating GW	Propagating GW	Propagating GW	Propagating GW	Propagating GW	

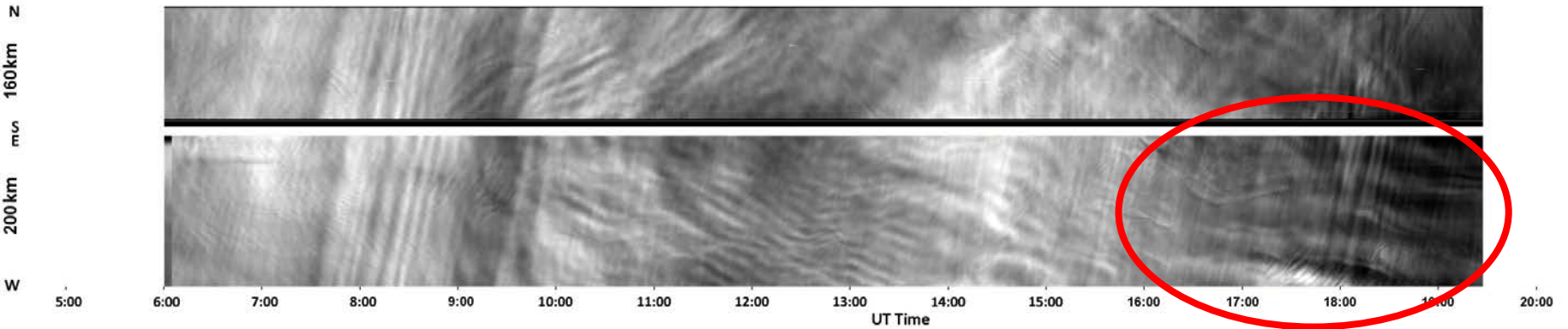
Cloudy	Propagating GW
Standing GW	RF over the South Island

MW = 12/17 nights

Lauder: Selected Ground Based Events Nights

- GB1*
30/31 May Numerous propagating and first MW event
- GB2
2/3 June Excellent wave activity
- GB3
18/19 June MW and coincident RF 6
- GB4*
21/22 June Breaking MW, sharp temperature gradients, lidar
- GB5
23/23 June Myriad small-scale and ducted waves
- GB6*
26/27 June Good MW and instabilities
- GB7
30/01 June good coordination with RF 13 MW data
- GB8*
14/15 July Excellent MW, breaking , lidar and RF 23 coincidence
- GB9 17/18 July Long duration (>all night) MW event, Lidar

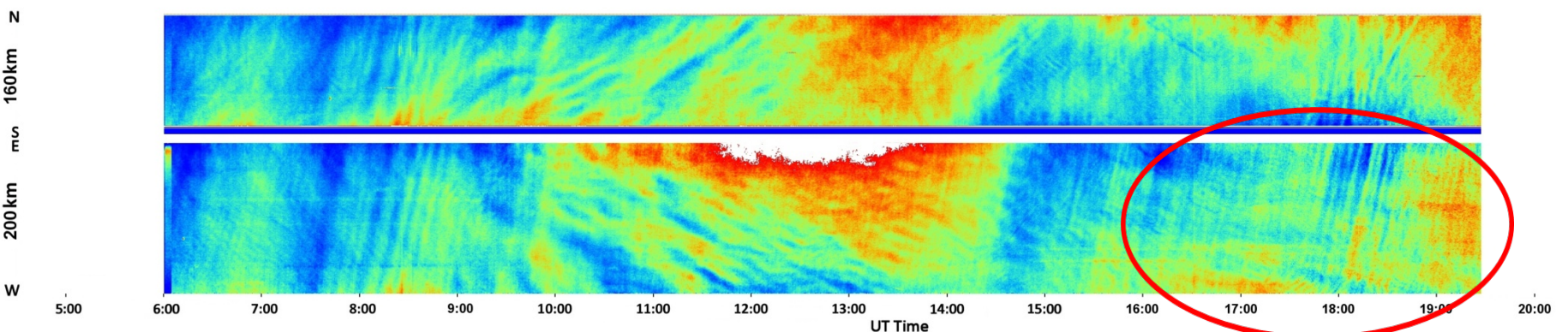
First AMTM Detection of Mesospheric Mountain Waves (Lauder, May 30-31, 2014)



Propagating waves



Mountain Waves

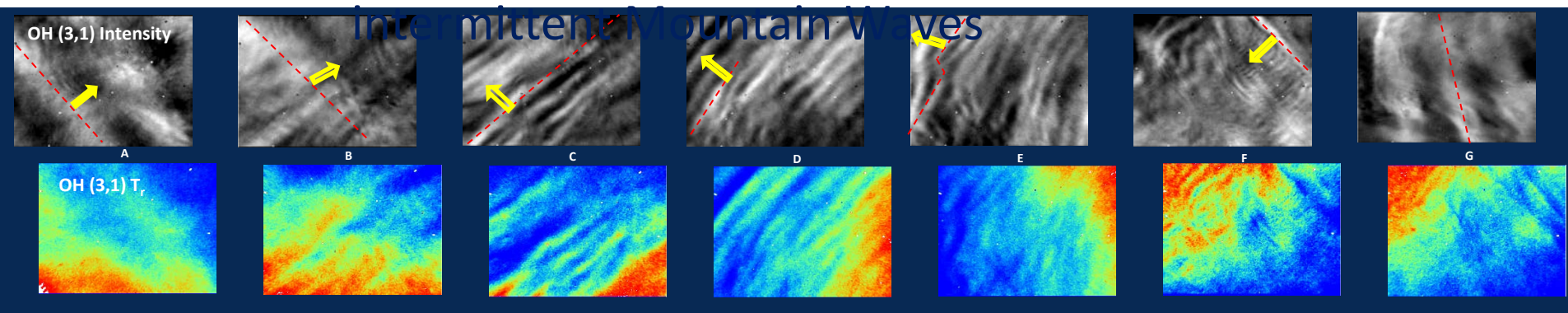


MW signature: near horizontal structures in E-W Keograms

Summary of the Rich GW Activity on the First Night of Data (May 30th)

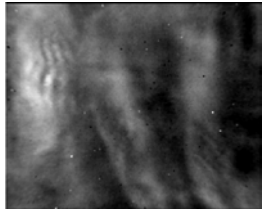
May 30th-7 hours of propagating, 4+ hours

Intermittent Mountain Waves

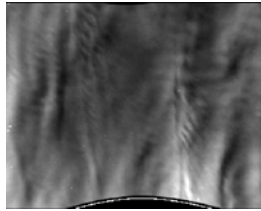


Event	Time	Wavelength [km]	Period [min]	ΔT [K]	Phase Velocity [m/s]	Θ [from North]	Duration [hours]
A	08:52 UT	46	6	~ 20	135 ± 3	52°	1.5
B	09:54 UT	57	9	~ 30	108 ± 2	49°	1
C	10:30 UT	23	27	~ 20	14 ± 1	319°	1
D	12:05 UT	18	28	~ 25	11 ± 1	304°	4
E	13:19 UT	21	26	~ 25	13 ± 1	300°	1
F	15:48 UT	13	45	~ 20	5 ± 1	225°	1.5
G	18:02 UT	50	-----	~ 20	~ 0	-----	>4

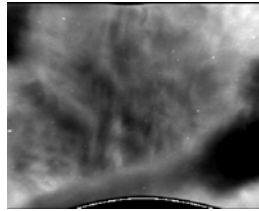
Summary of MW Events



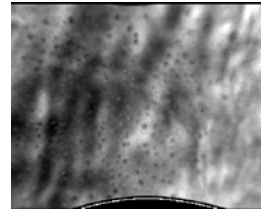
May 30-31
18:36 UT



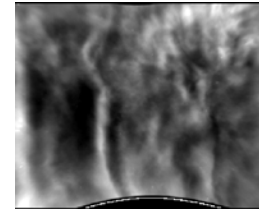
June 02-03
10:12



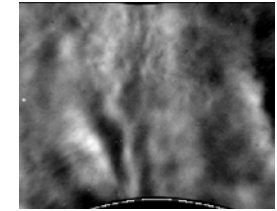
June 04-05
17:51



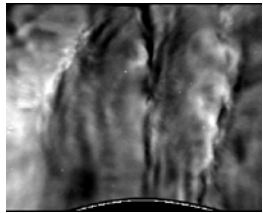
June 17-18
11:59



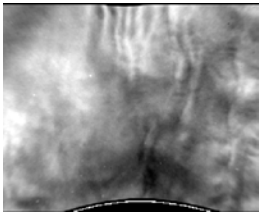
June 18-19
08:49



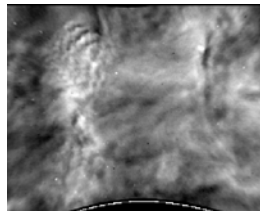
June 19-20
15:02



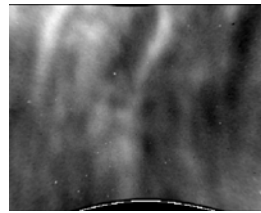
June 21-22
11:30



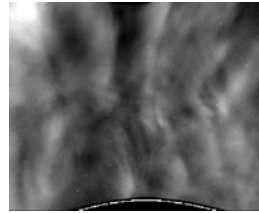
June 23-24
12:32



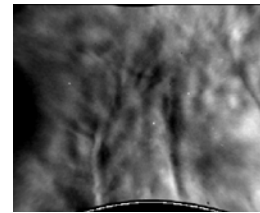
June 26-27
11:32



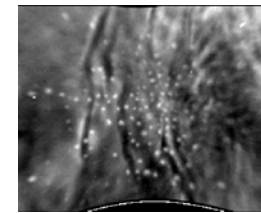
June 27-28
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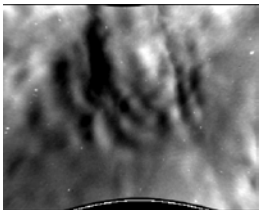
June 28-29
15:05



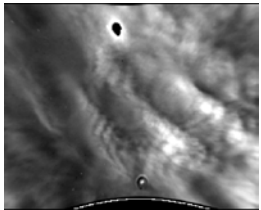
June 30-01
13:03



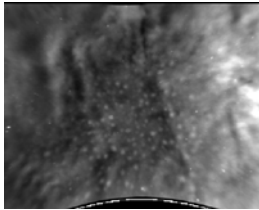
July 01-02
14:00



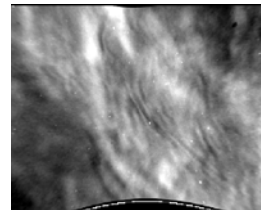
July 03-04
13:29



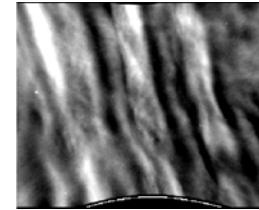
July 14-15
15:09



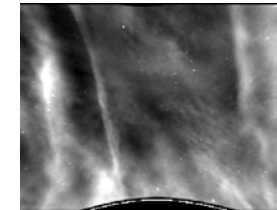
July 15-16
07:06



July 16-17
17:11



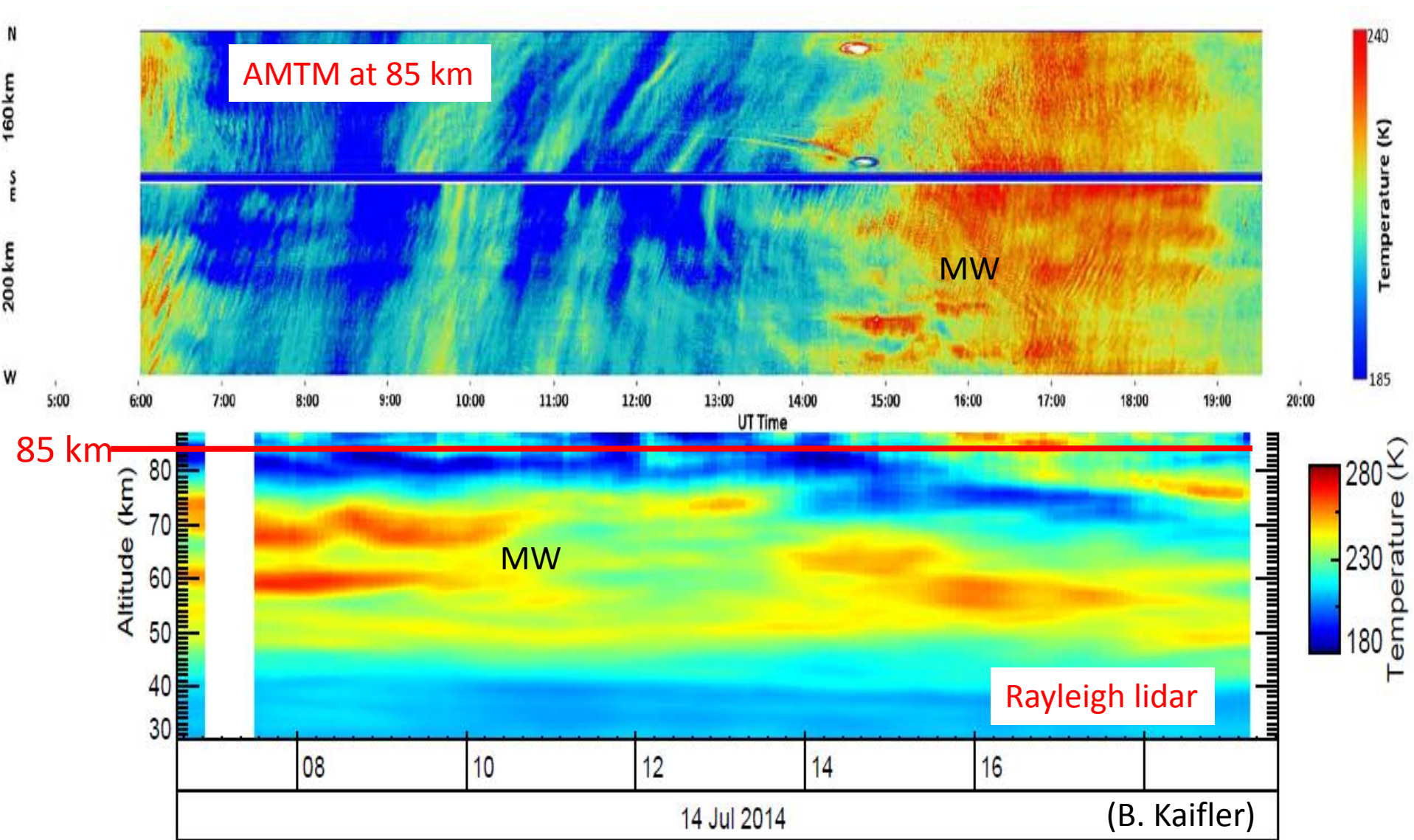
July 17-18
12:53



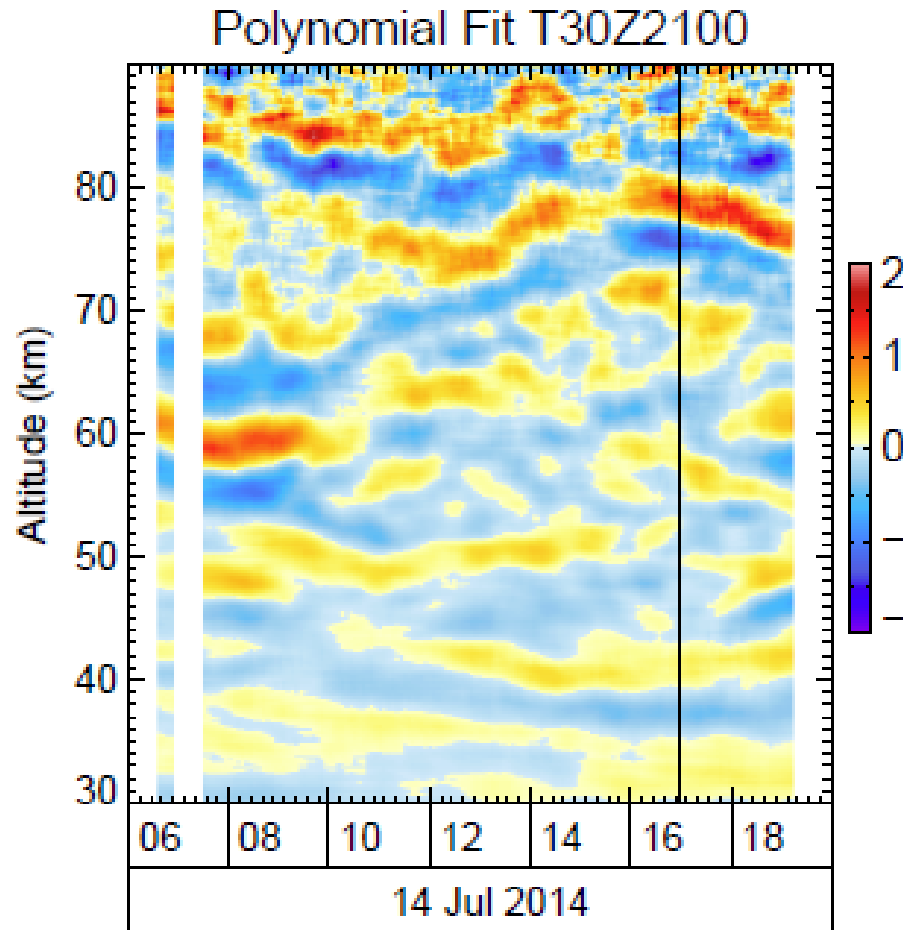
July 18-19
08:26

Wave breaking occurred on every night that MW were observed

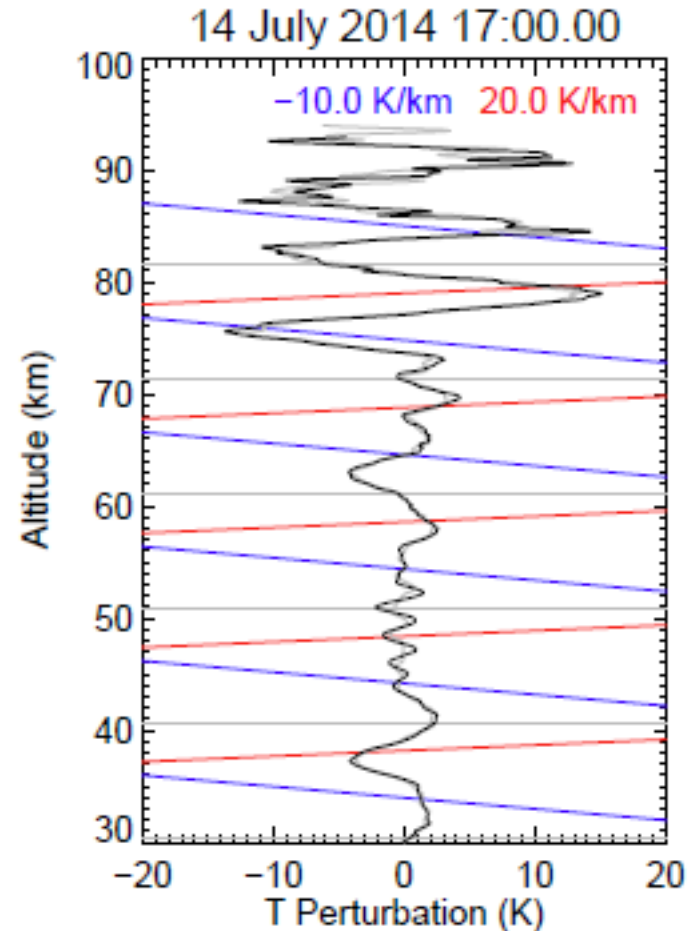
Comparison of AMTM and Rayleigh Lidar Data (July 14, 2014)



Rayleigh Lidar Mountain Waves (July 14, 2014)

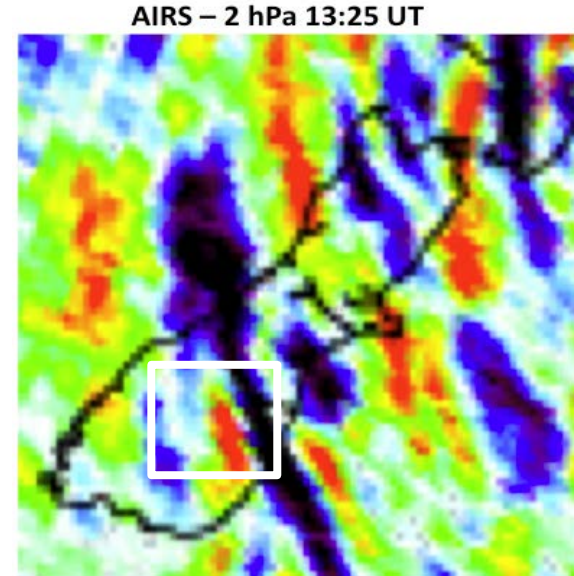
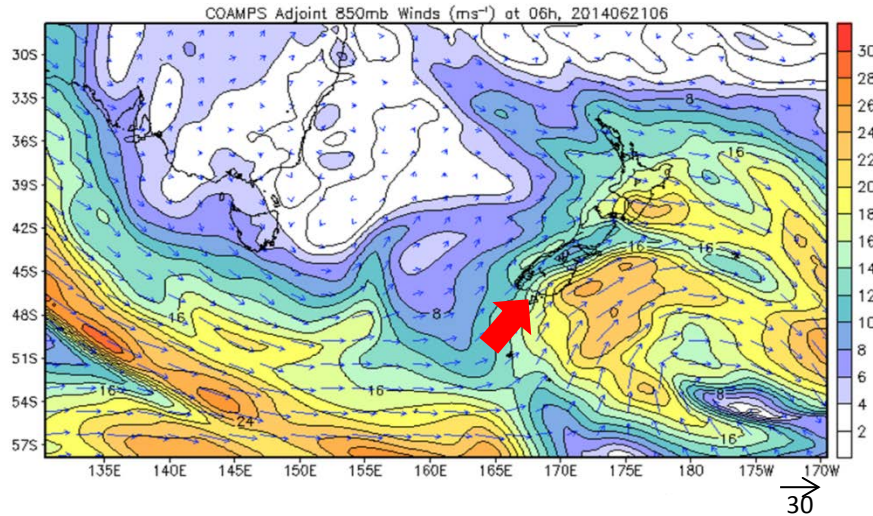


Temperature perturbations

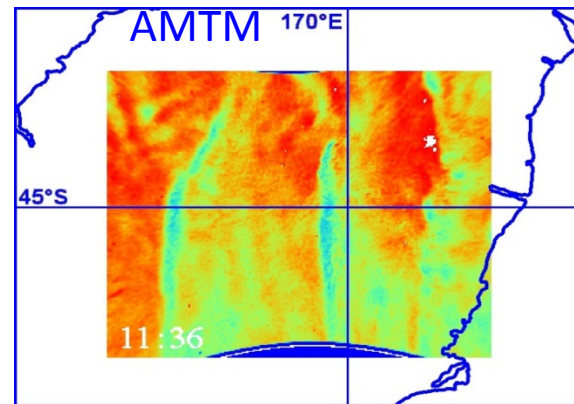
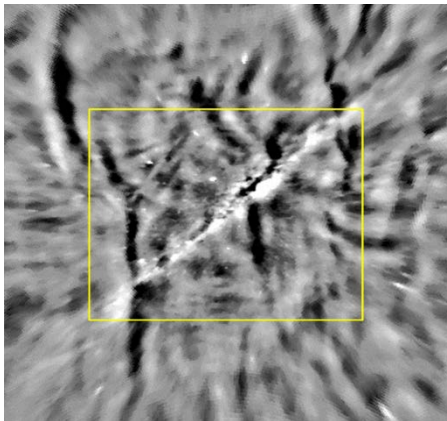


Strong (>10K amp.) MW detected in both Lidar and AMTM (16 -18UT)

Overview of 21/22 June MW Event



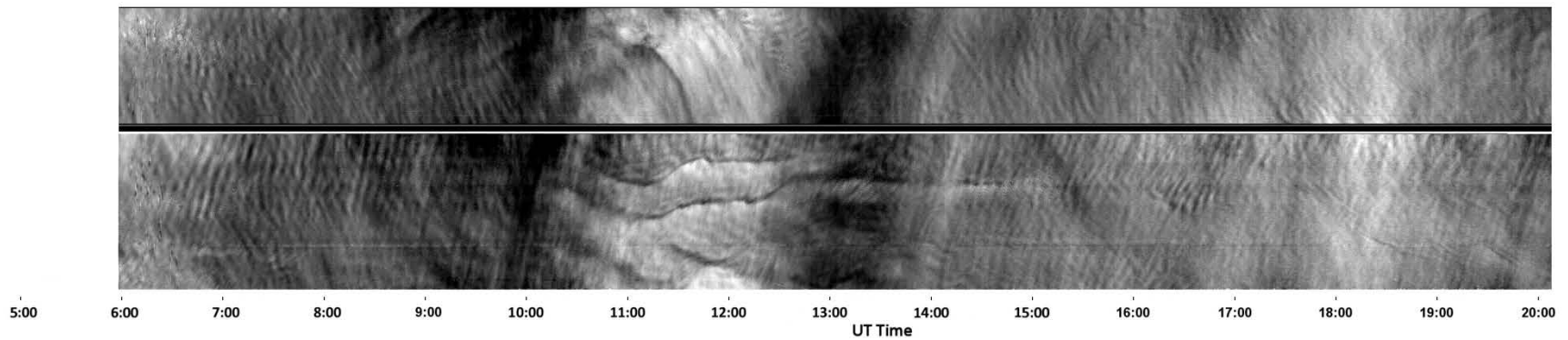
All-
sky
OH
Data



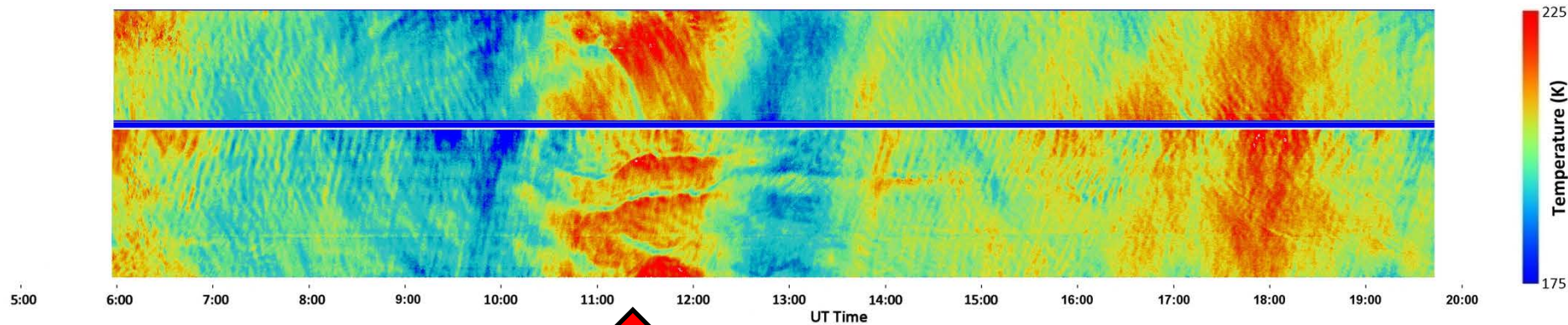
June 21-22 event: Prevailing tropospheric wind forcings over the Southern Alps and the resultant wave coupling into the stratosphere (AIRS data) and mesosphere (all-sky OH intensity and AMTM temperatures). Primary forcing was from the SW and the resulting MW where almost N-S aligned.

"Breaking" Mountain Wave Event, June 21/22

(No flight this night as forcing deemed to be insufficient)



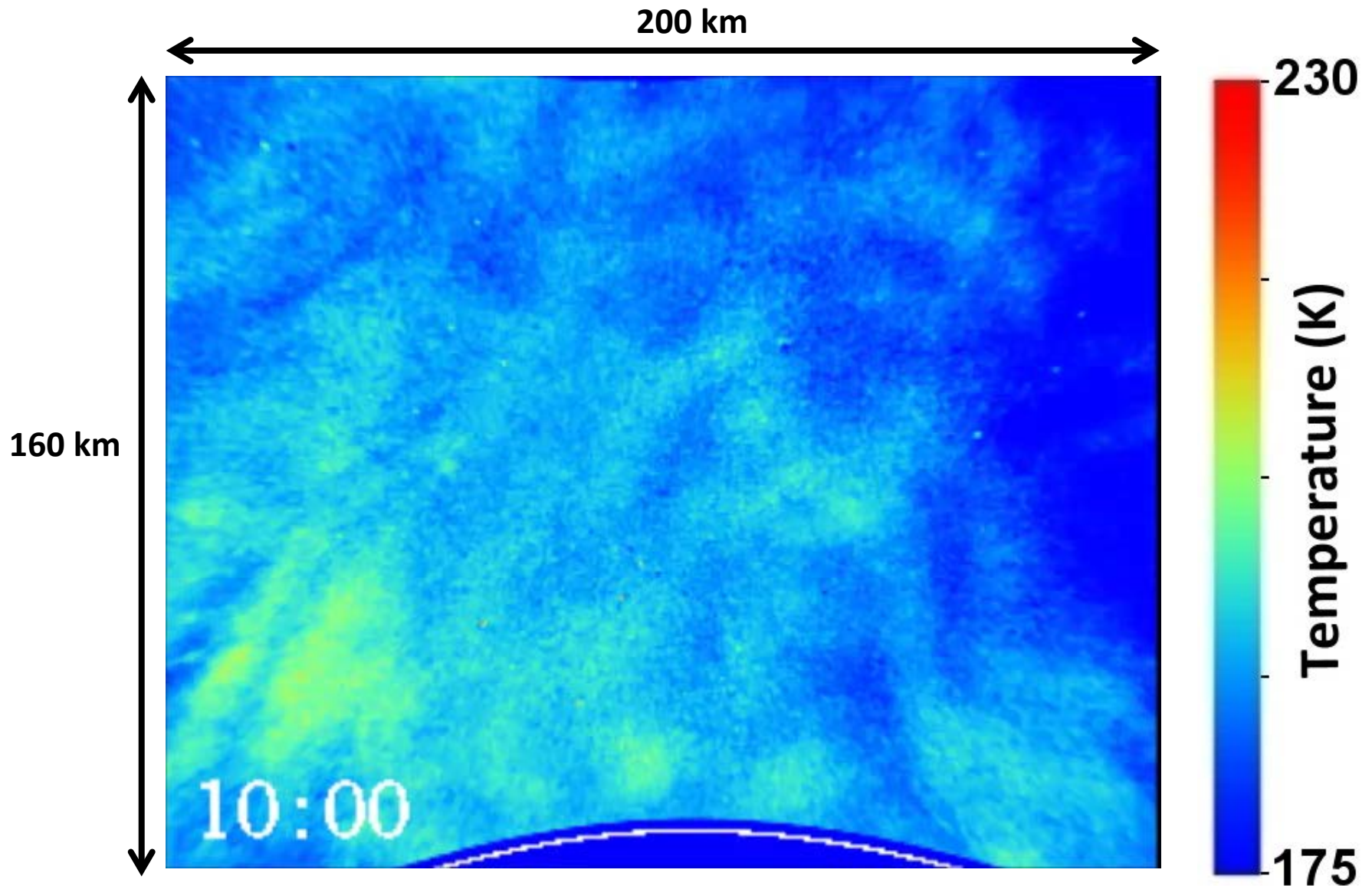
Continuous small-scale waves interrupted by MW outburst



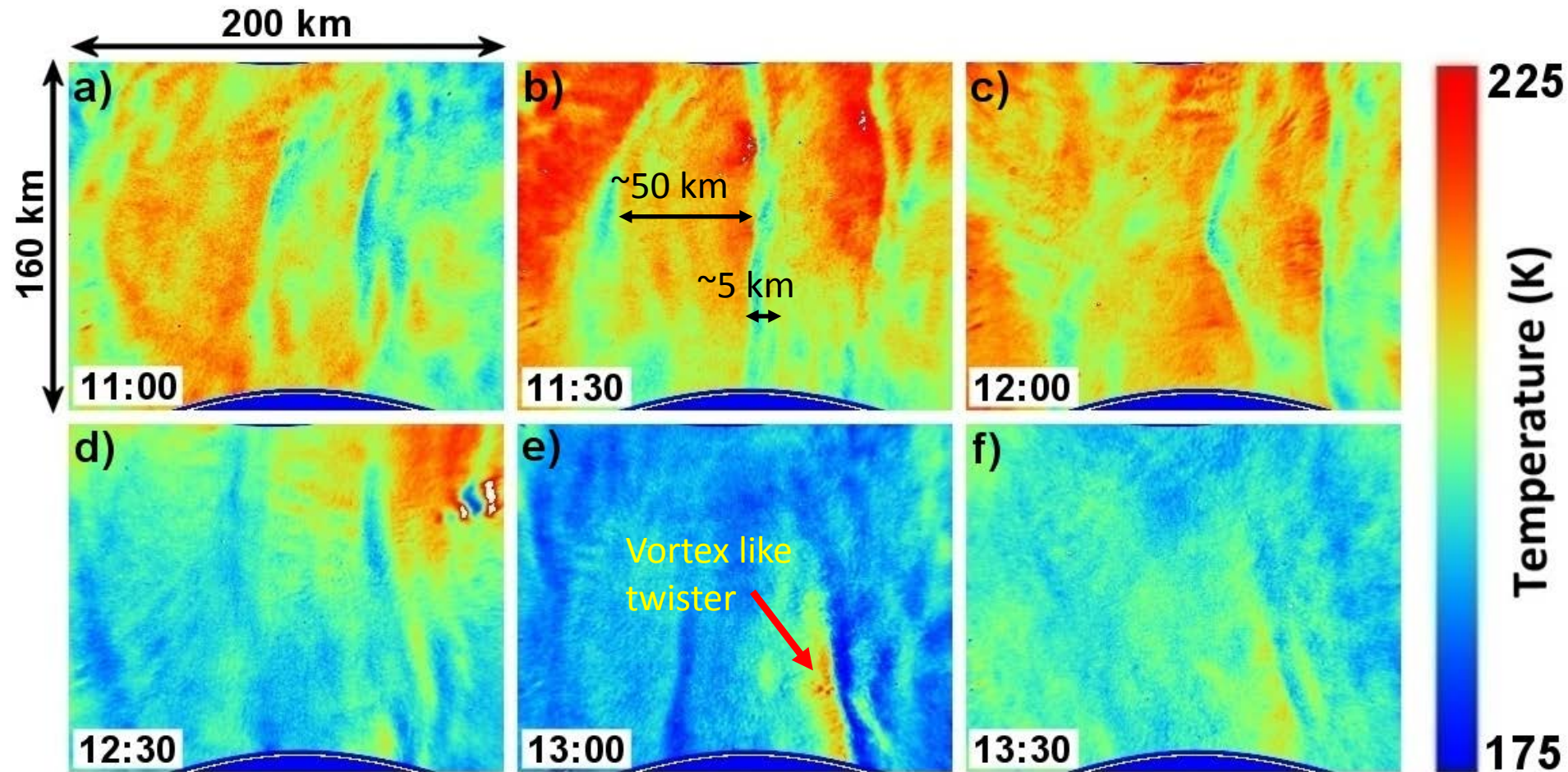
(MW Event ~10:30-13:30 UT)

OH Temperature "Mountain Waves" Movie

(Lauder, June 21-22 - OH Temperature, ~5hrs)



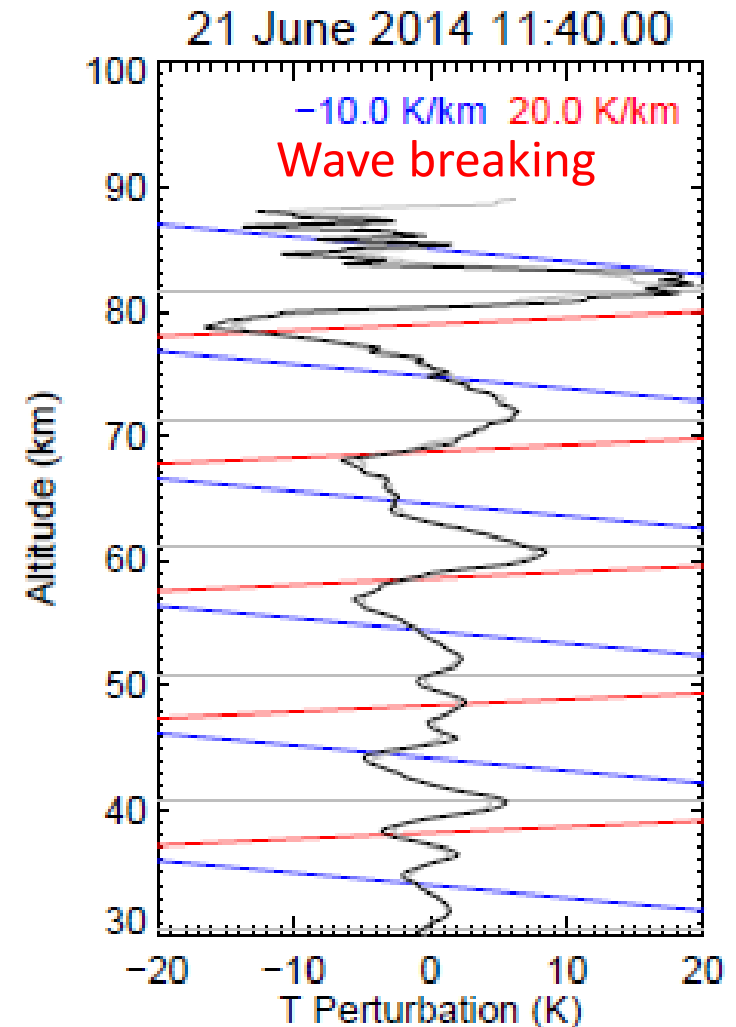
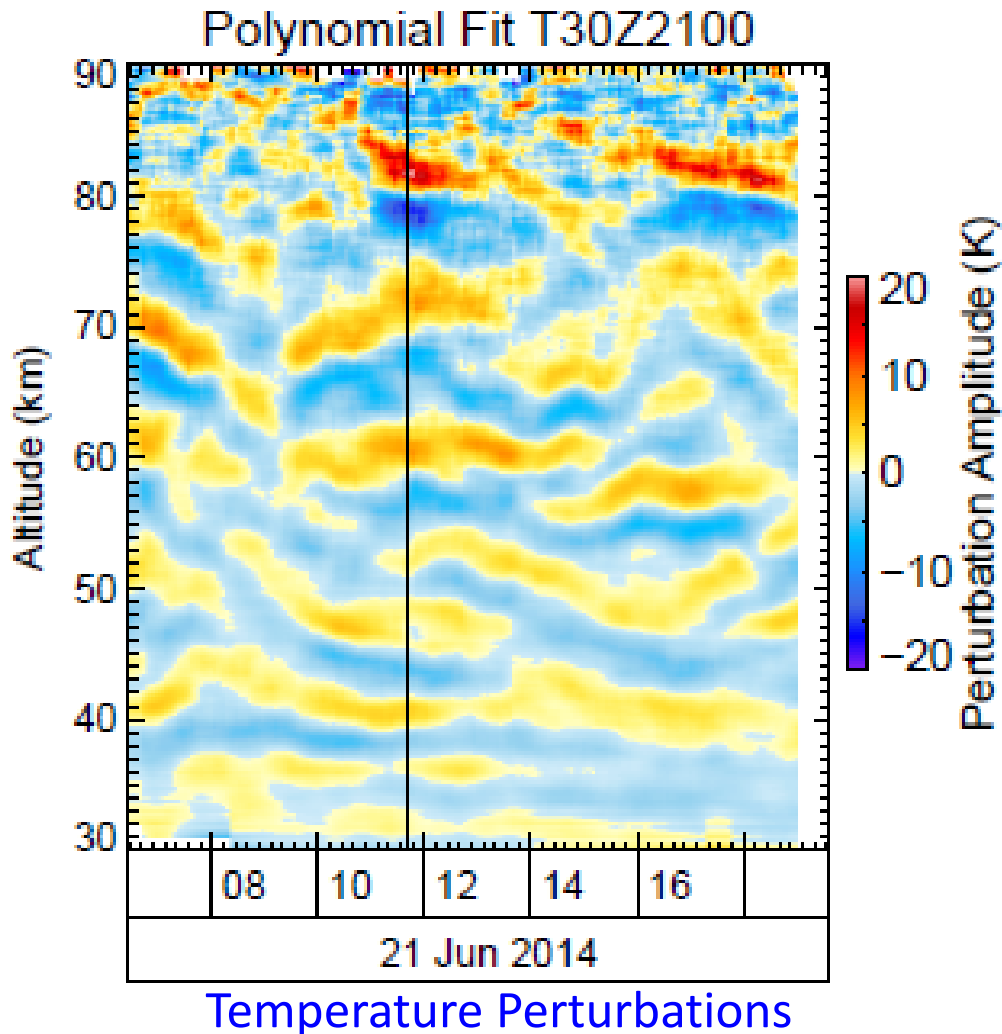
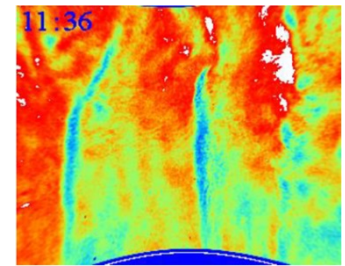
Snap-Shot Summary of MW Growth and Breaking Event (~2.5 hrs)



OH Temperature data, 21-22 June, 2014

Rayleigh Lidar: Breaking Mountain Waves

June 21/22, 2014

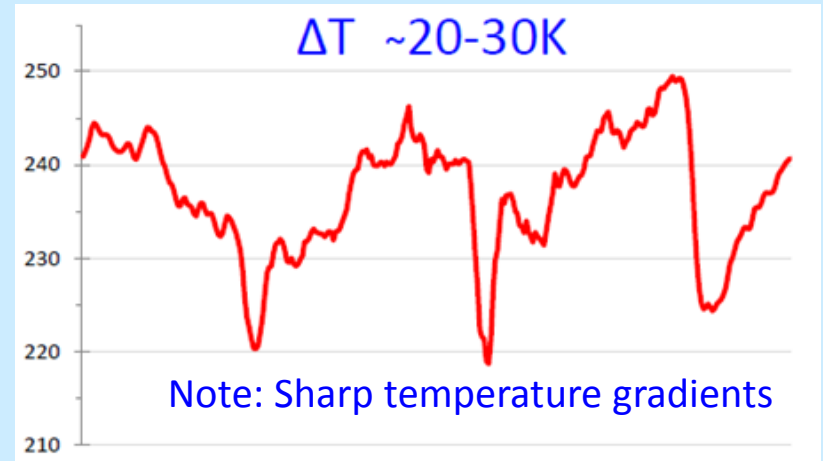
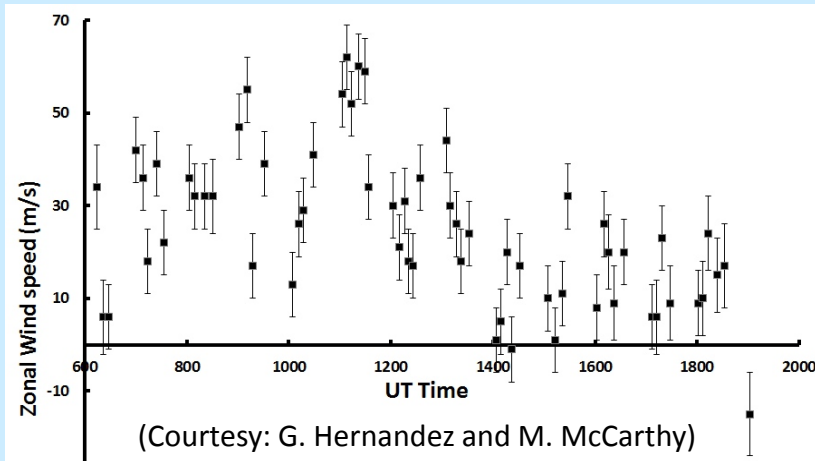
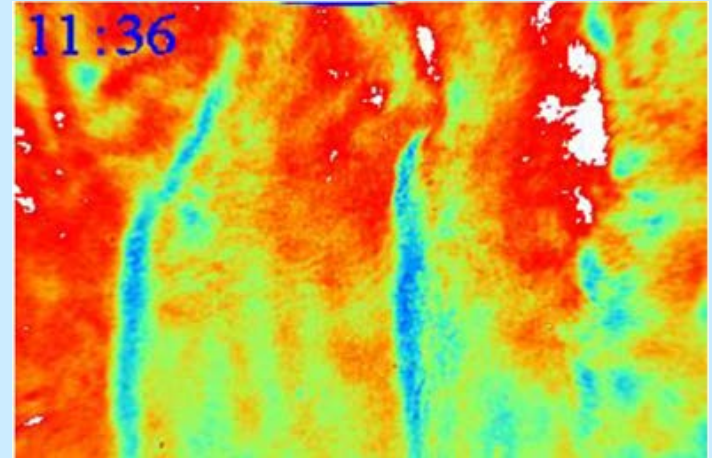


Large amplitude $\sim 15\text{K}$, breaking MW event, $\sim 10:30\text{-}13:30$ UT

Momentum Flux

$$\langle u_h'w' \rangle = \frac{g^2 \omega_i}{2N^3} \sqrt{1 - \frac{\omega_i^2}{N^2} \left(\frac{\langle T' \rangle}{T_0} \right)^2} \frac{1}{C^2}$$

(Fritts et. al, 2014)



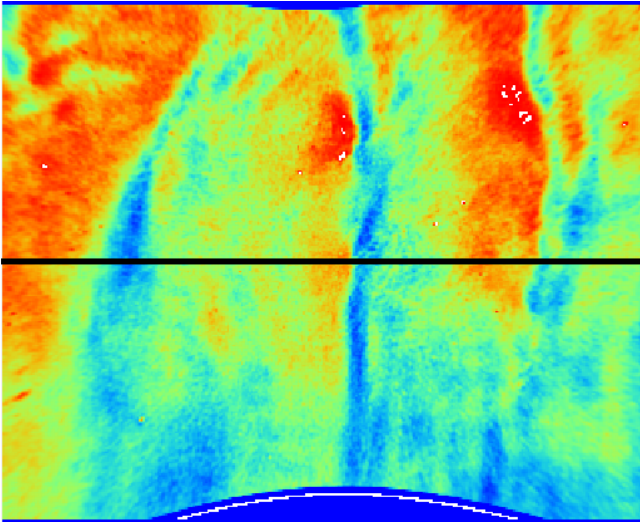
- Wind speed ~ 50 m/s
- $\lambda_x \sim 55$ km
- Direction $\sim 95^\circ$

- Horiz. phase speed ~ 0 m/s
- $\Delta T/T \sim 3-7\%$
- $\lambda_z \sim 17$ km

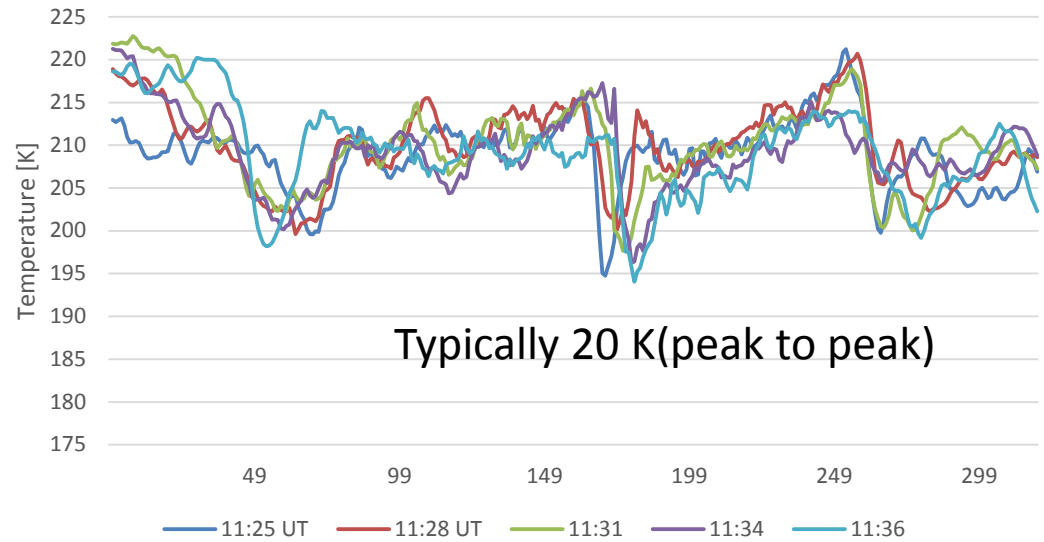
Estimated: $\langle u_h'w' \rangle = 60-300 \text{ m}^2/\text{s}^2$

New Temperature Scans

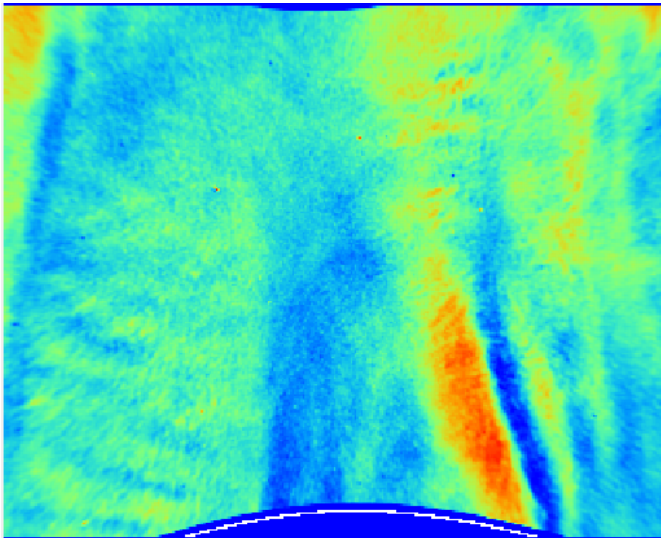
11:31 UT, June 21-22



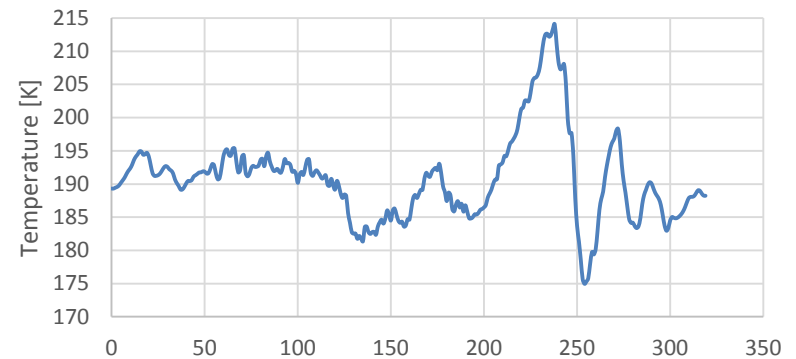
Temperature Profile



12:49 UT June 21-22



Temperate Profile



Maximum ~40K (peak to peak)

Development of Instabilities Along the Cold Troughs (40 min interval)

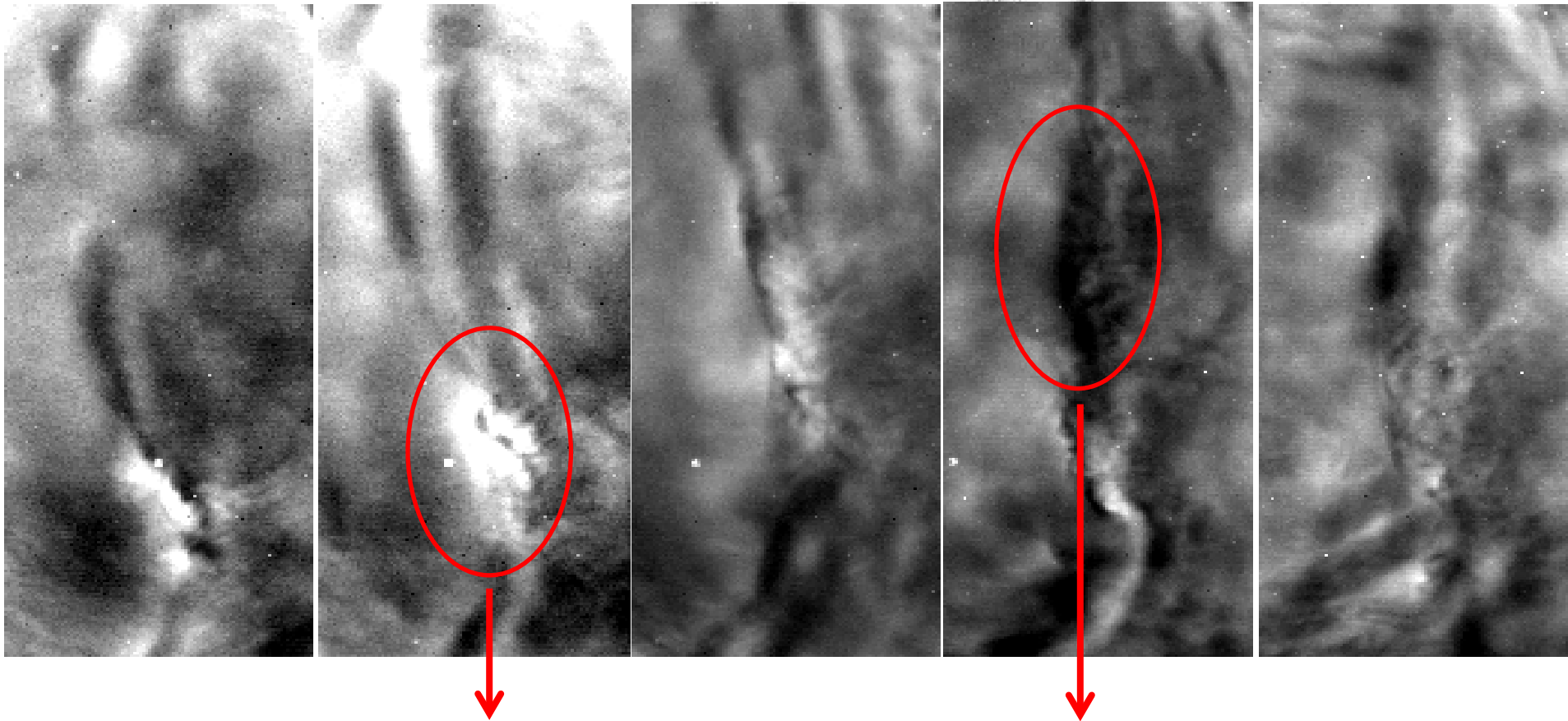
11:04 UT

11:12 UT

11:23 UT

11:36 UT

11:44 UT

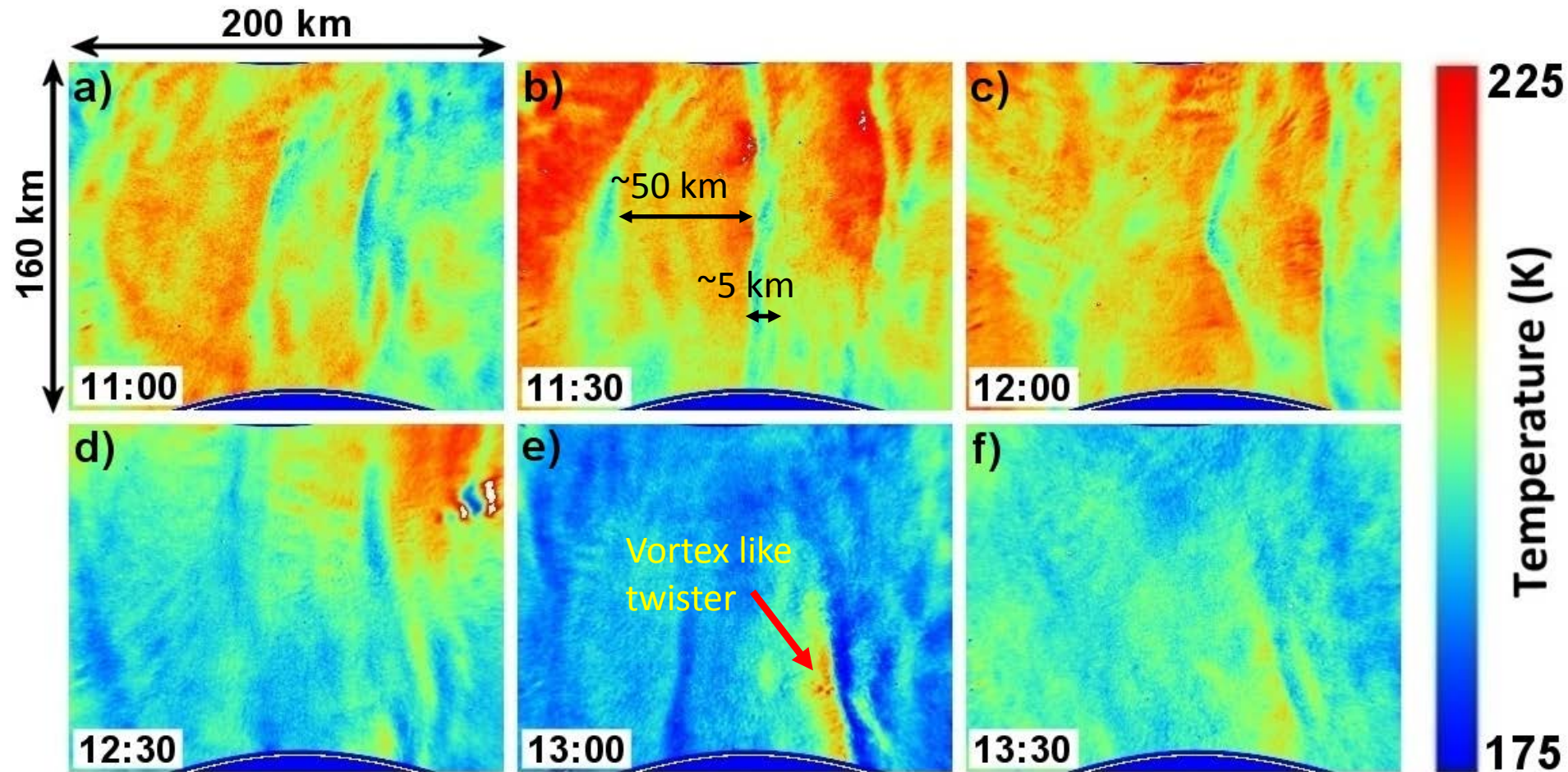


Instability development

Cold trough development

Basic characteristics of an MW breaking event-are they different to other GW?

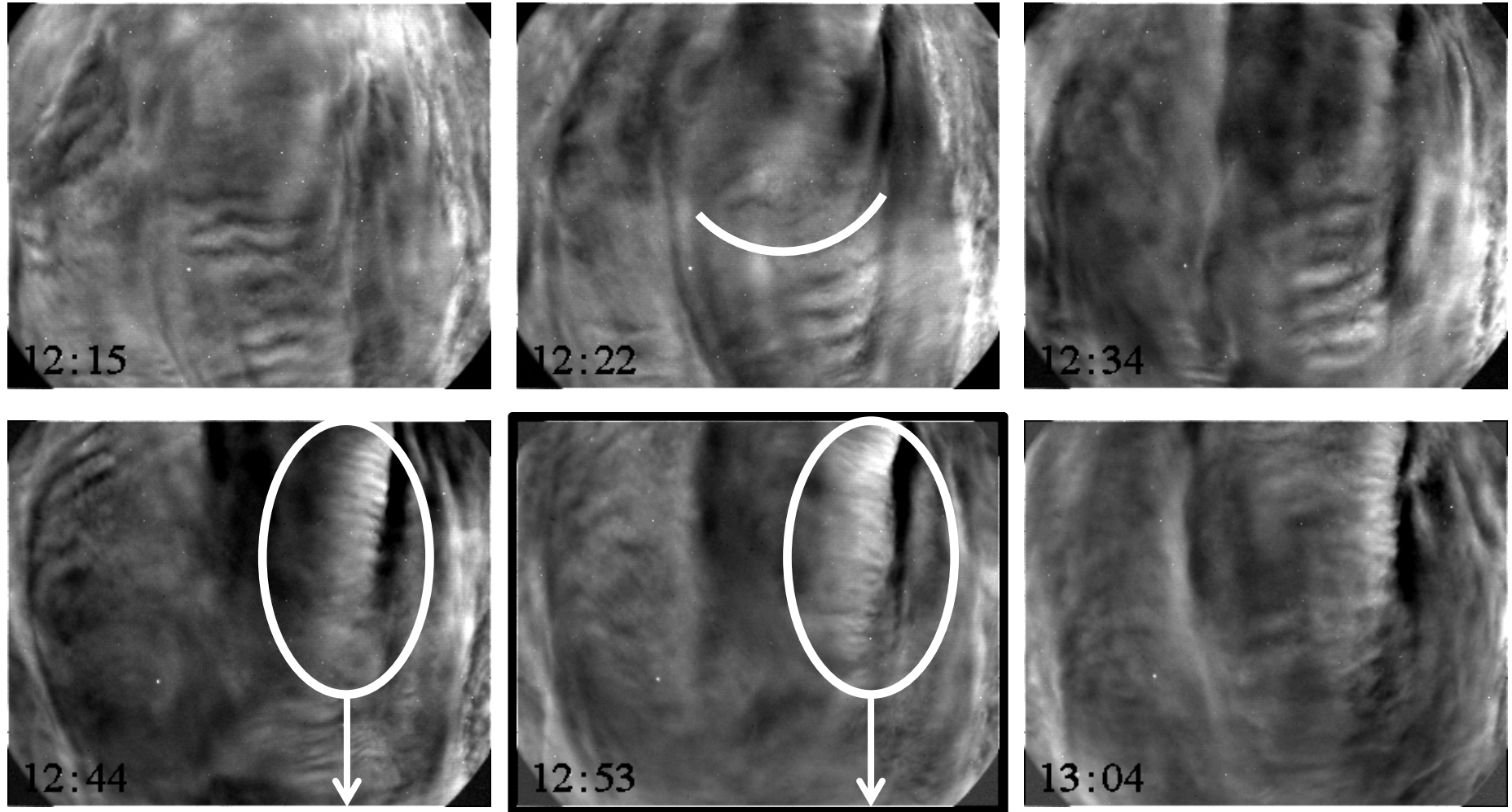
Snap-Shot Summary of MW Growth and Breaking Event (~2.5 hrs)



OH Temperature data, 21-22 June, 2014

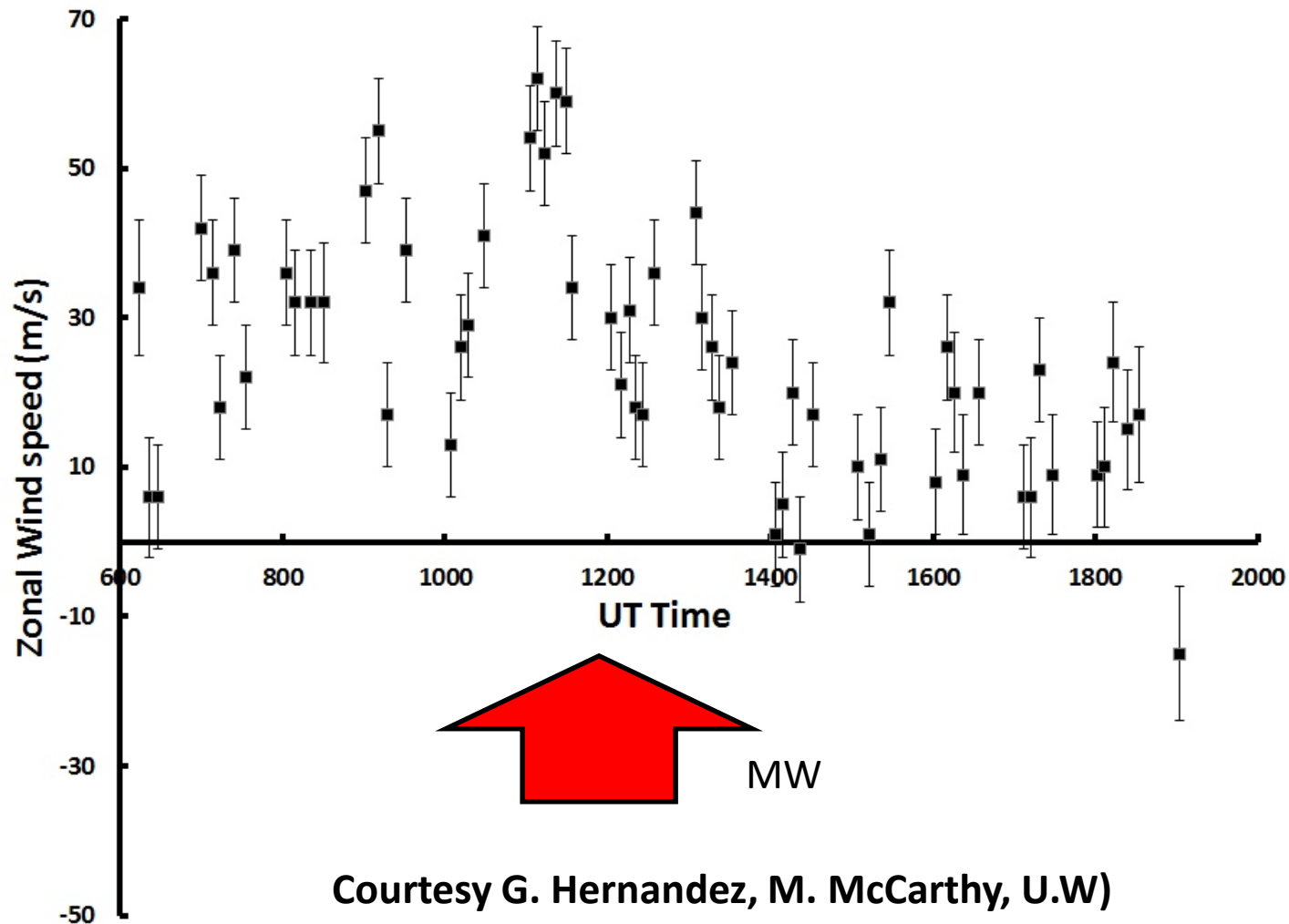
AMTM Development of Fine-Scale Waves and Twisting

Raw OH image data (12:15-13:04UT)



Growth of >12 “vortex-like” twisting fine-scale waves (~ 5 km)

FPI Mesospheric Winds, June 21-22 Mt. John Observatory (MJO)

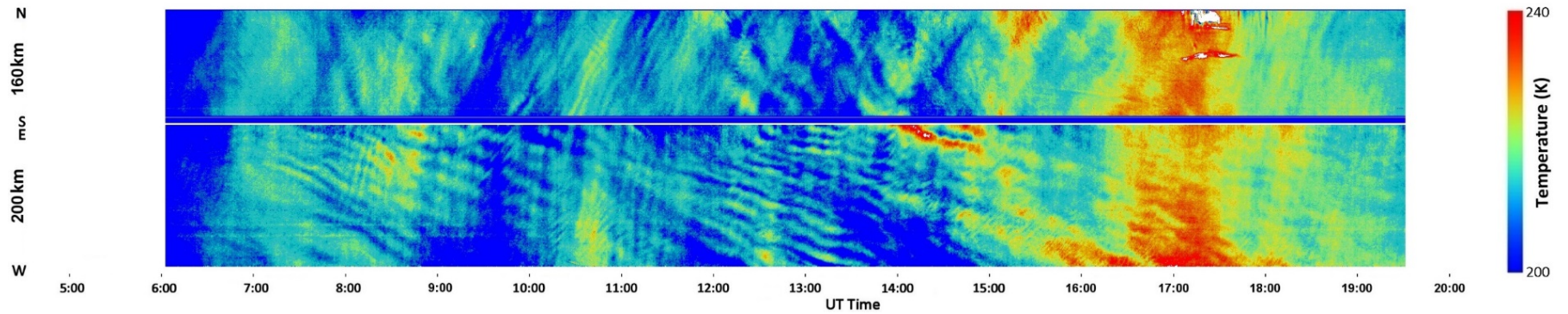
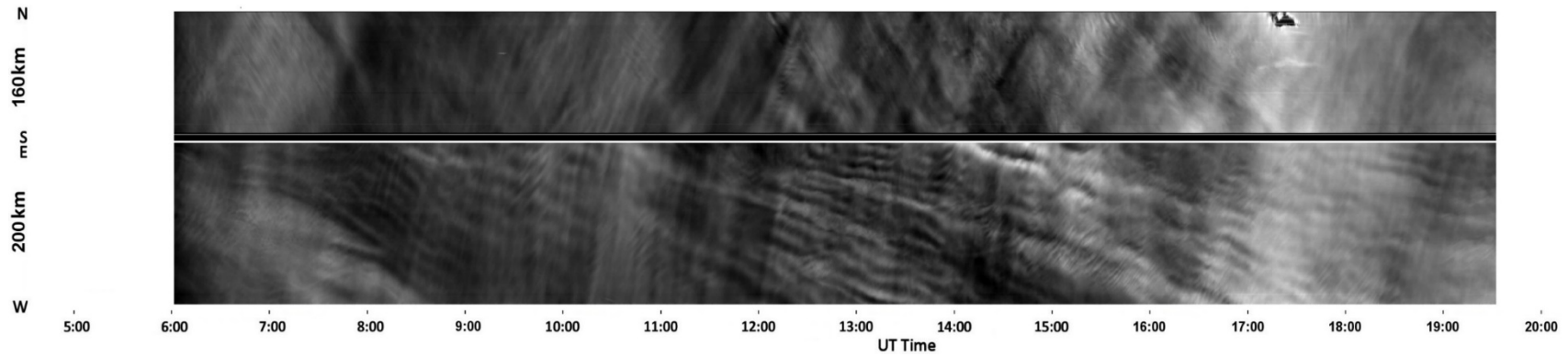


Courtesy G. Hernandez, M. McCarthy, U.W)

Summary of 21/22 June Event

- This was a very dynamic night. The addition of the lidar results makes the MW interpretation clear. Lots of wave breaking going on all the time.
- 2 papers identified:
- Summary of the event capturing its scales and dynamics. Wave temperature amplitudes and momentum flux estimates.
- Modelling the instability features
- Possible 3rd paper on the larger scale dynamic leading up to this event (using Airs data)
- Qu: concerning the almost constant MW activity during the campaign and its relation to forcing?

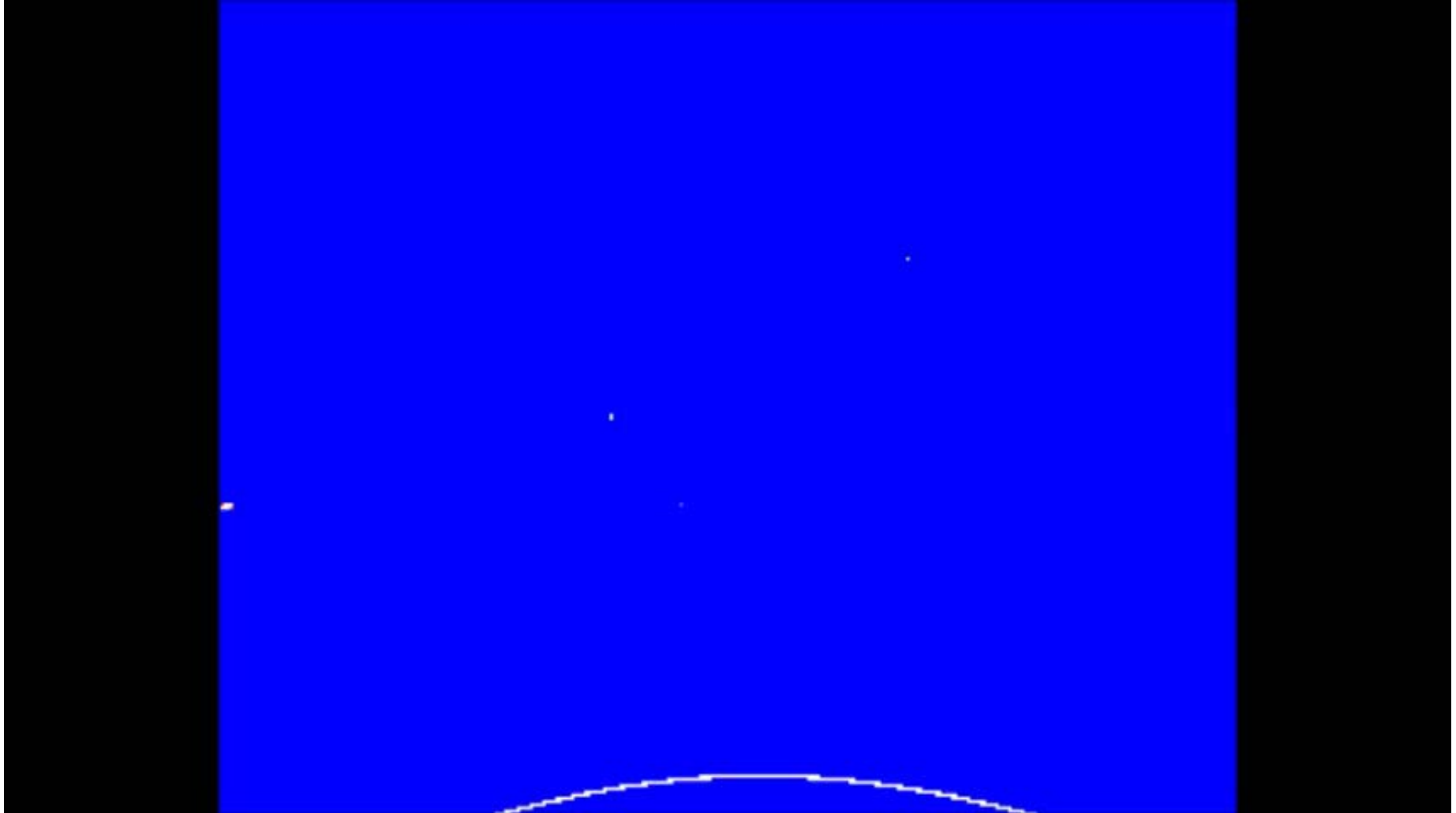
17 July Keogram



Constant fine scale MW activity all night

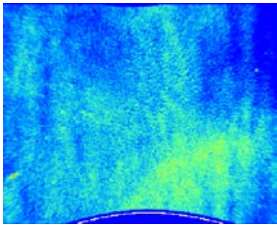
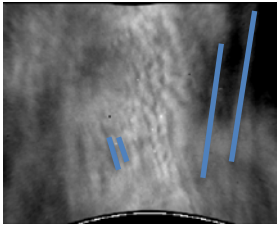
July 17-18 Movie

(Duration ~12 hrs)

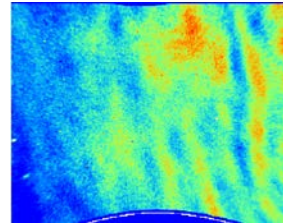
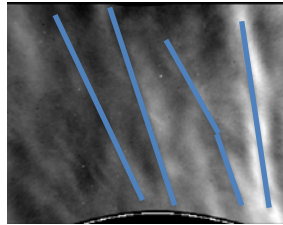


Snap-Shots of MW Activity

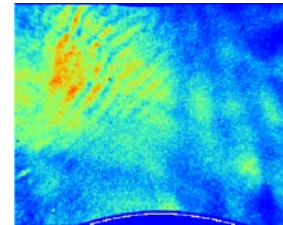
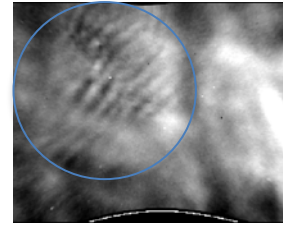
06:56



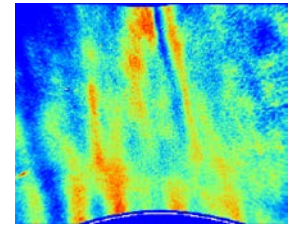
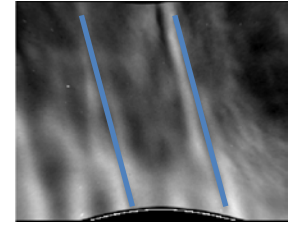
09:03



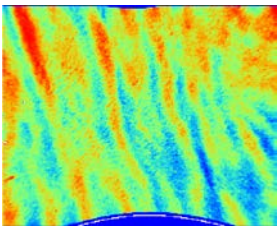
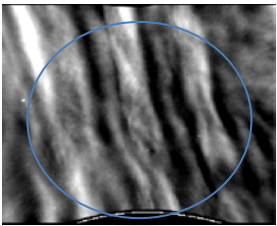
10:53



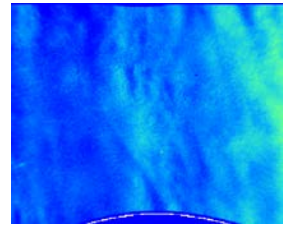
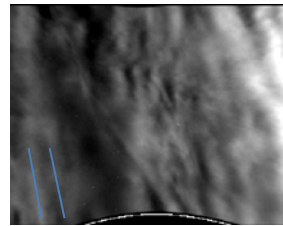
12:08



12:53

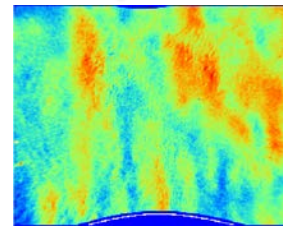
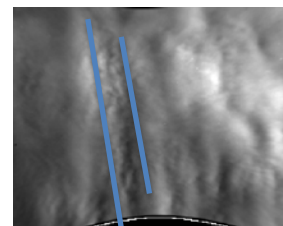


14:13

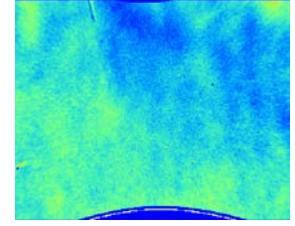
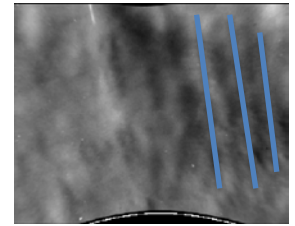


July 17-18

15:01

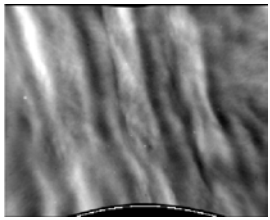


18:47

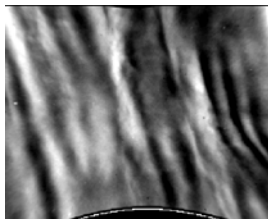


Continuous Narrow-Scale (~15km) MW Activity

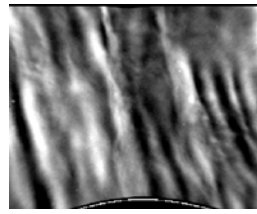
July 17-18 from 12:53-13:33 UT



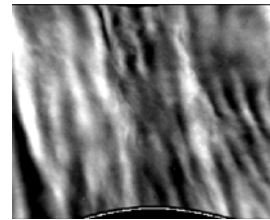
12:53



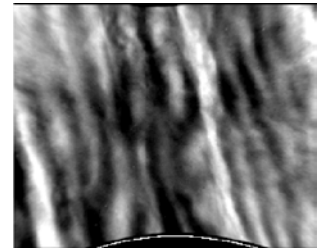
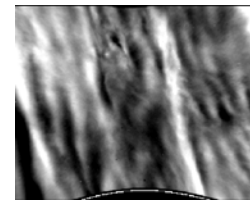
13:05



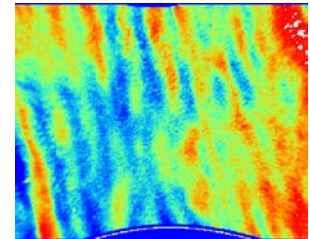
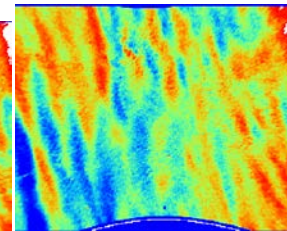
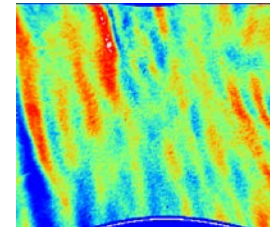
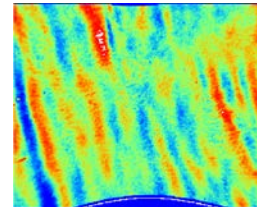
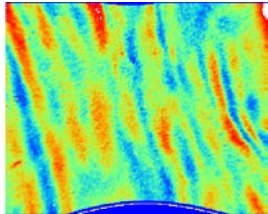
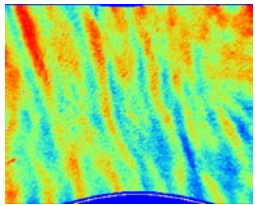
13:12



13:26

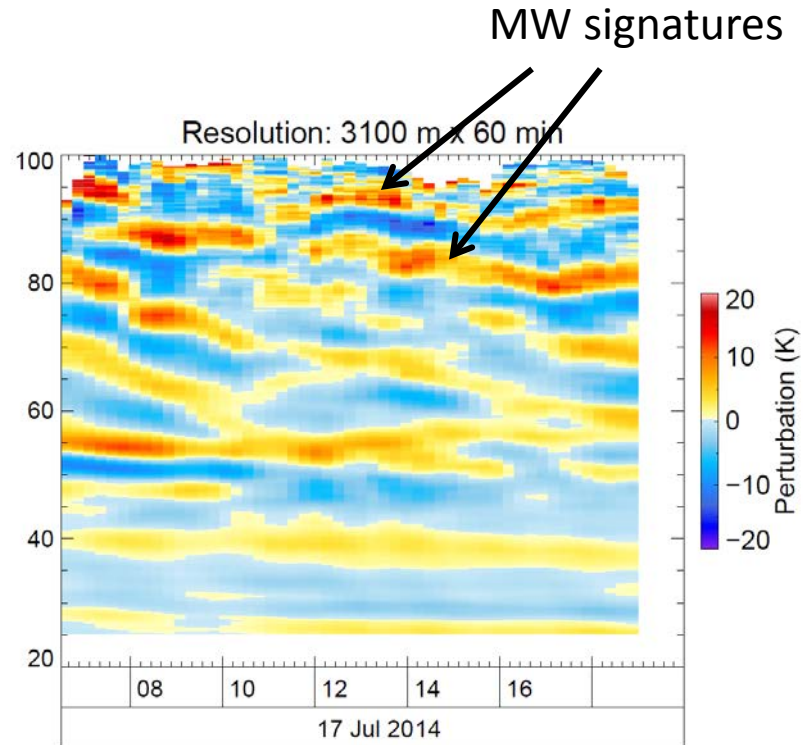
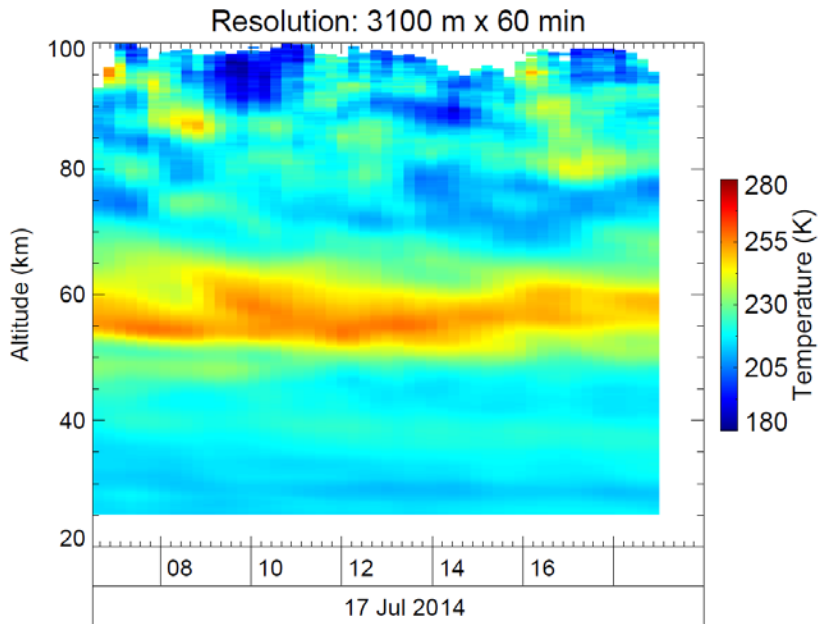


13:33

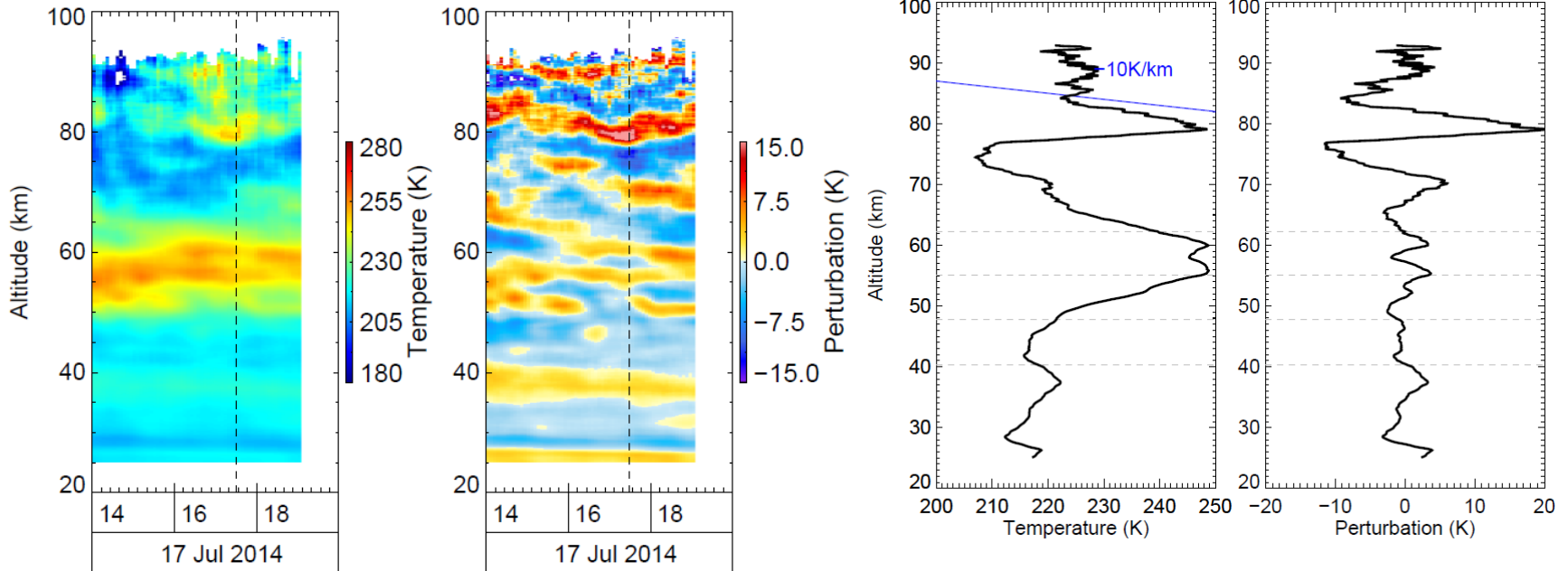


Time	Wavelength [km]	ΔT [K]
06:56	6, 19	~15
09:03	33, 35	~20
10:53	8-12	~15
12:08	71.9	~25
12:53	15-25	~20
14:13	17.7	~30
15:01	29.2	~30
18:47	26.3, 21.4	~20

Lidar at Lauder, 17 July 2014

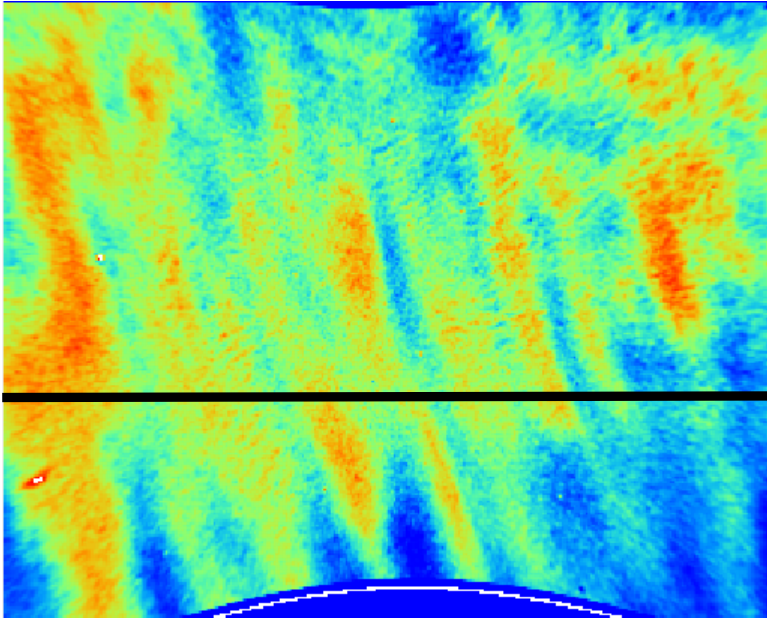


Lidar at Lauder, 17 July 2014

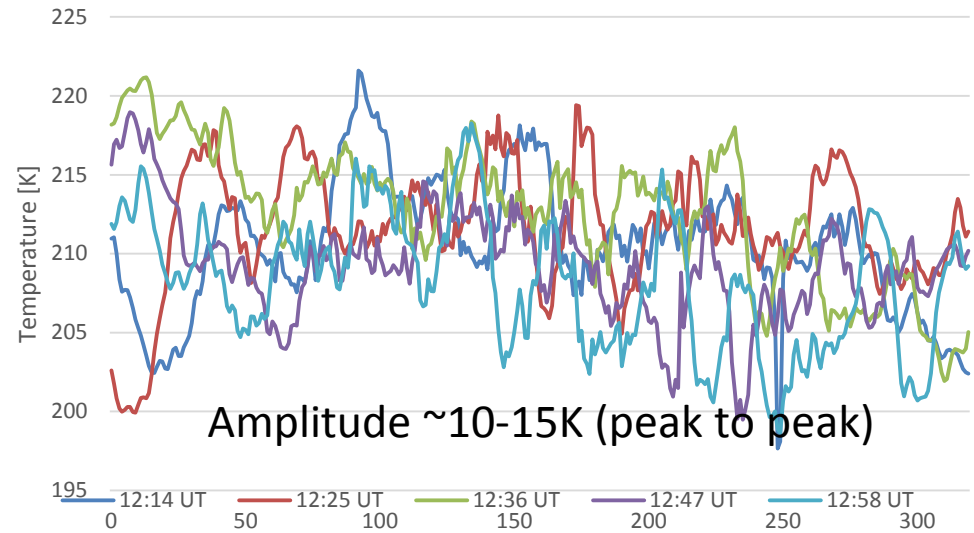


July 17, Temperature Scans

12:36

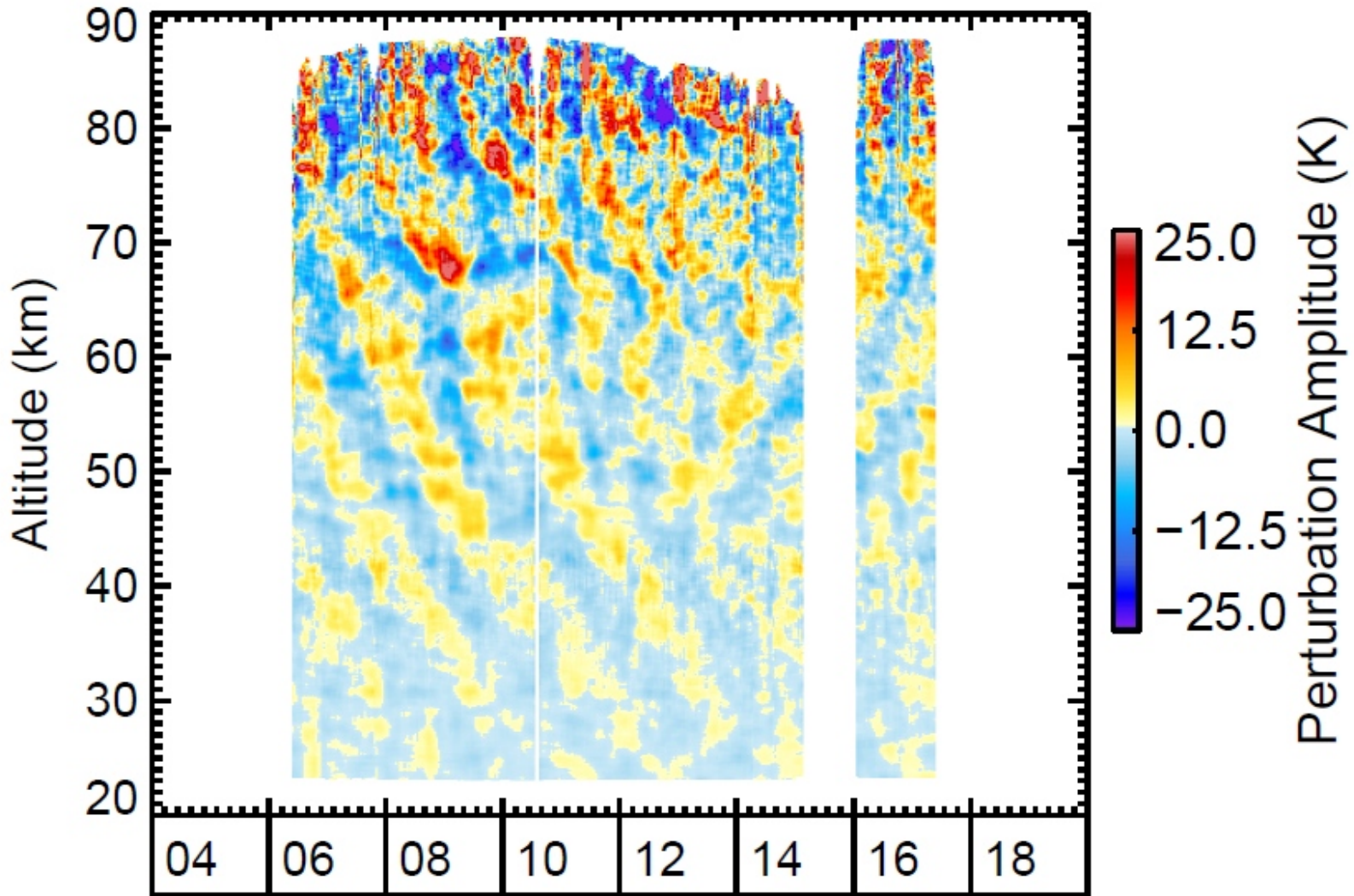


Temperature Profile



Rayleigh Lidar, July 07-08 (RF 18)

Mean 2h



Summary (to date..)

- AMTM measurements at Lauder indicated surprisingly large number (28) of nights with mesospheric MW activity, associated with weak to moderate wind forcing.
- Clear evidence for exceptionally **strong breaking MW events** were obtained on at least 4 occasions propagating into the mesosphere over the Southern Alps.
- So much wave breaking should have had a **significant effect on the state of the MLT region**. How to assess this?