

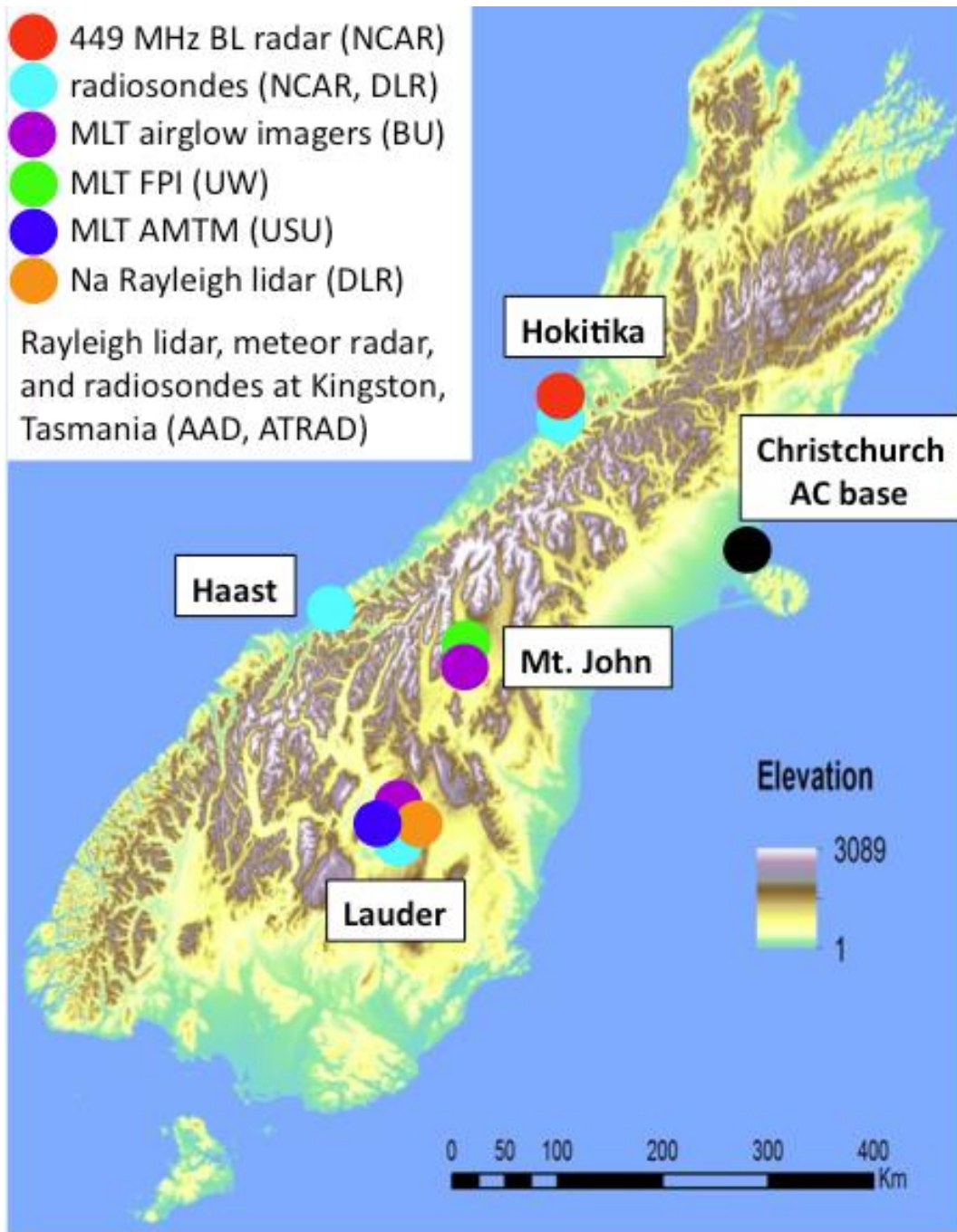
Investigating the 21-22 June Mountain Wave Breaking Event

Mike J. Taylor, P-D Pautet and Y Zhao
Utah State University

DEEPWAVE Science Team Meeting, Naval Postgraduate School, Monterey, CA, December, 2015

- 449 MHz BL radar (NCAR)
- radiosondes (NCAR, DLR)
- MLT airglow imagers (BU)
- MLT FPI (UW)
- MLT AMTM (USU)
- Na Rayleigh lidar (DLR)

Rayleigh lidar, meteor radar,
and radiosondes at Kingston,
Tasmania (AAD, ATRAD)



Hokitika

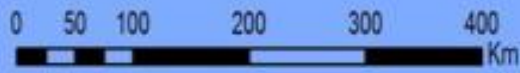
Christchurch
AC base

Haast

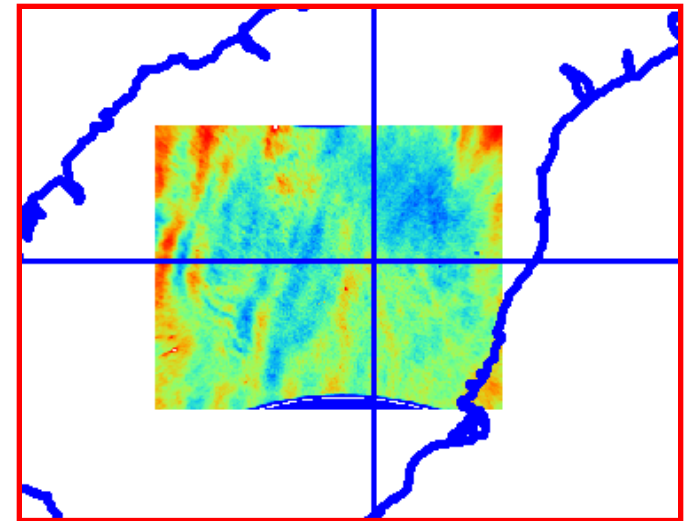
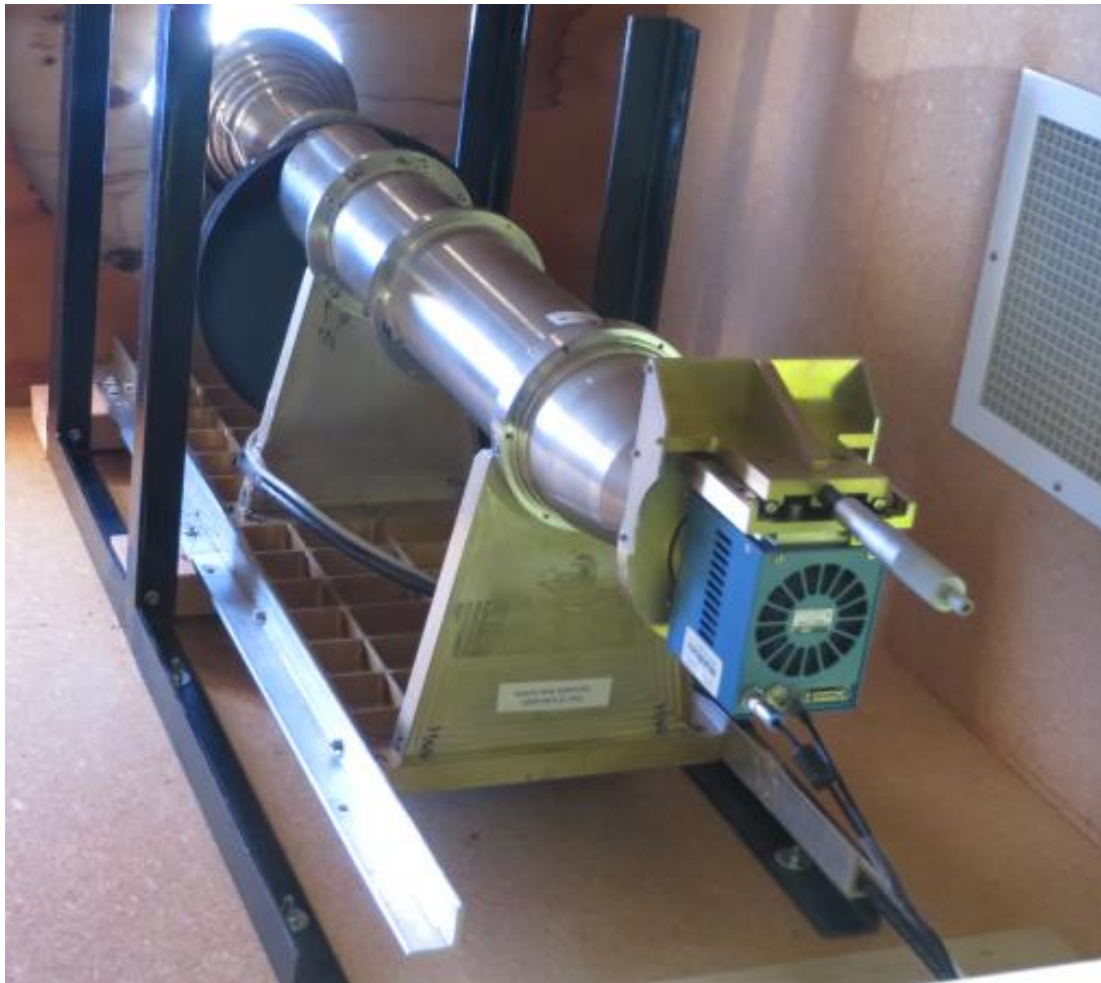
Mt. John

Lauder

Elevation



AMTM Installed at NIWA Lauder Observatory, 45°S, NZ, for Mission

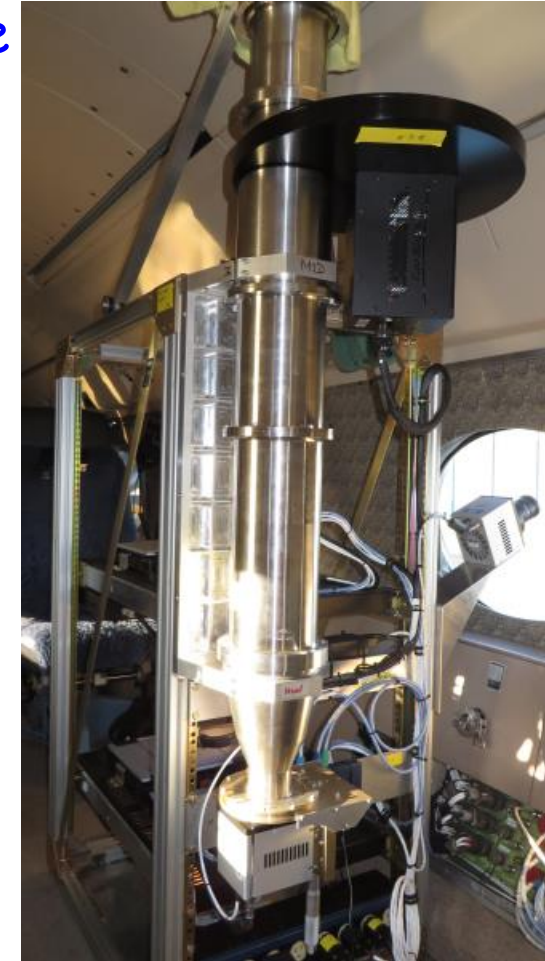


AMTM:

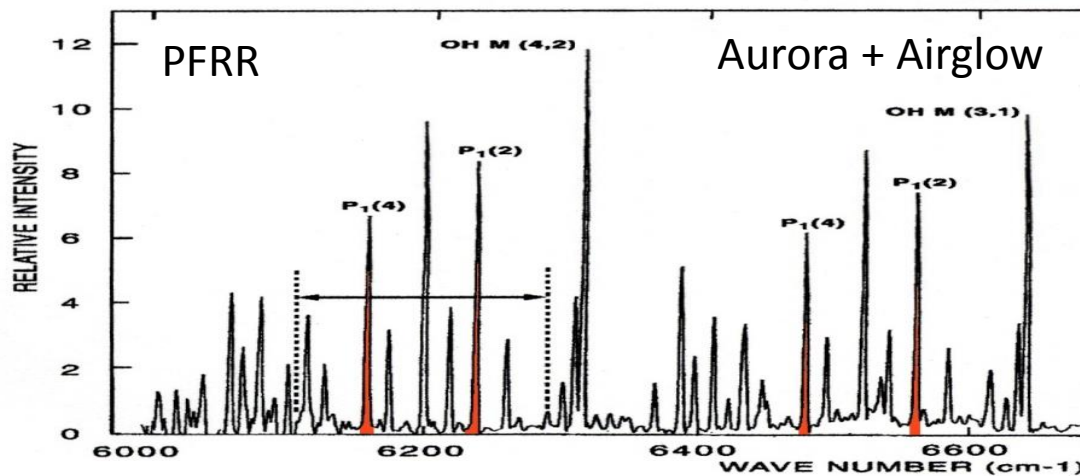
- 180 x 200 km temperature and intensity maps of the OH layer (~87km), centered at the zenith, every ~30s

GV Advanced Mesospheric Temperature Mapper (AMTM)

- New High-resolution mesospheric gravity wave intensity and temperature mapping.
- IR imager ($\sim 1.55\mu\text{m}$) OH (3,1) band, ~ 87 km.
- Medium format ($80^\circ \times 60^\circ$ FOV) fast (f/1) telecentric optics (120 km \times 80 km FOV).
- Operates at very high 4 sec cadence, 15 sec for temperature map, precision ~ 2 K.



AMTM on GV aircraft

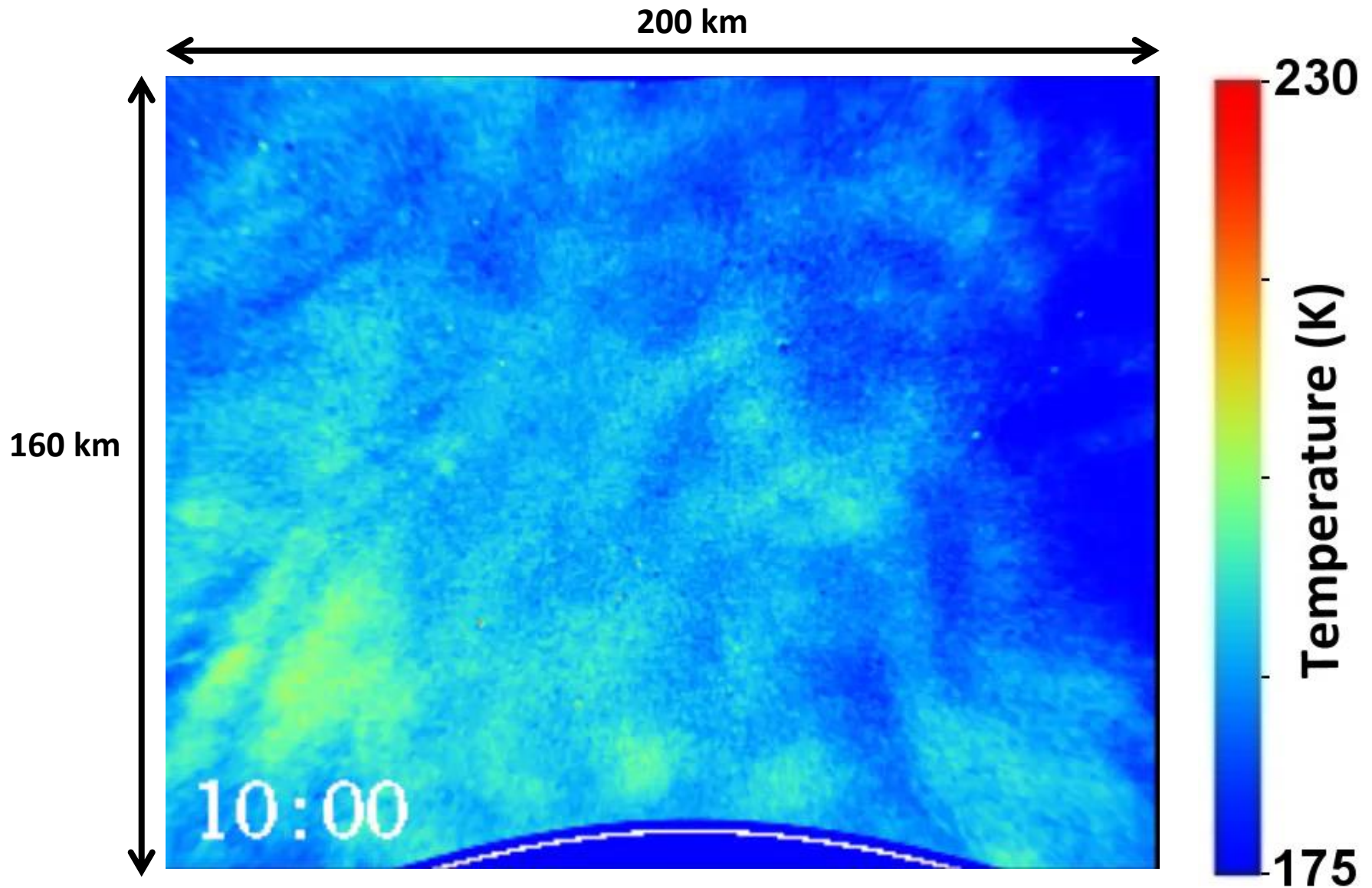


Temperature: ratio of P₁(2) and P₁(4) lines

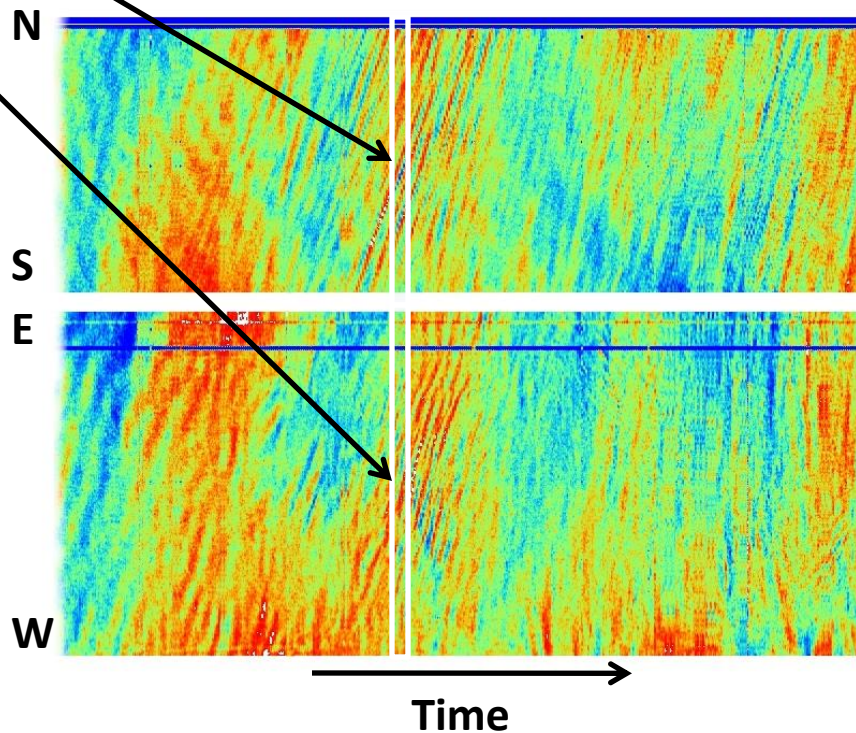
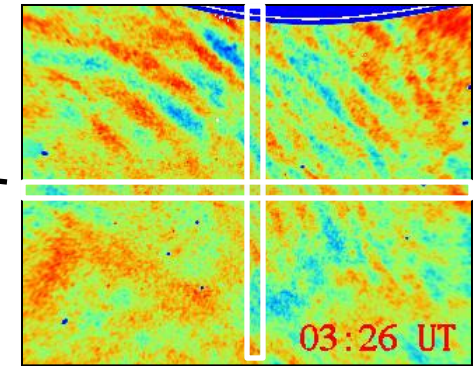
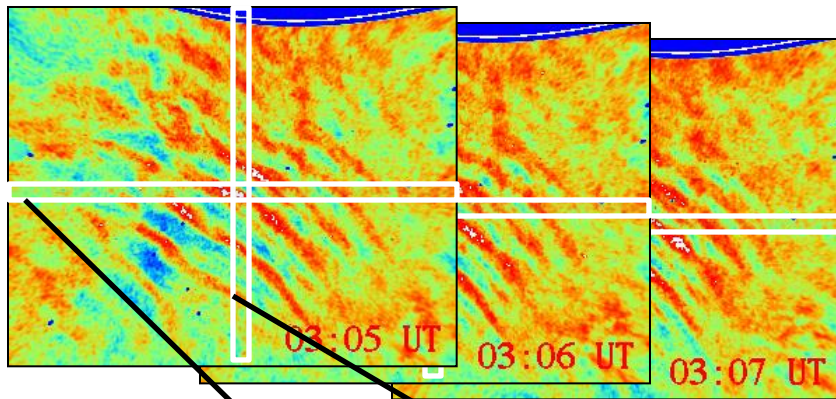
Selected Ground Based Nights

- GB1*
30/31 May Propagating and MW
- GB2
2/3 June Excellent wave activity
- GB3
18/19 June MW and coincident RF 6
- GB4*
21/22 June Breaking MW and sharp temperature gradients
- 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 and RF 23 coincidence

Temperature Movie, Jun 21-22 (5hrs)



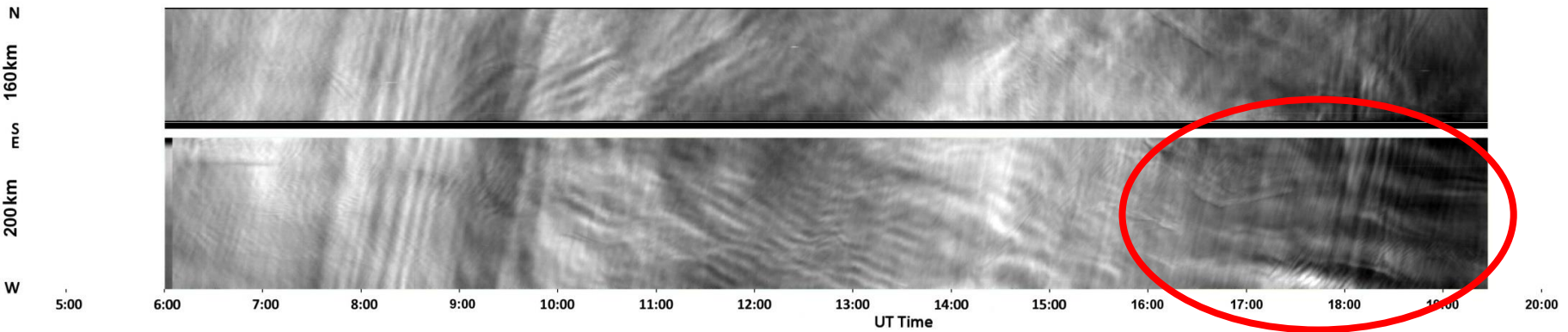
"Keogram" Technique to Study Broad Range of Wave Scales and Periods



Two Keograms:
summarizing
N-S and E-W
wave activity
vs. time.

Uses a
sequence of
temperature
maps

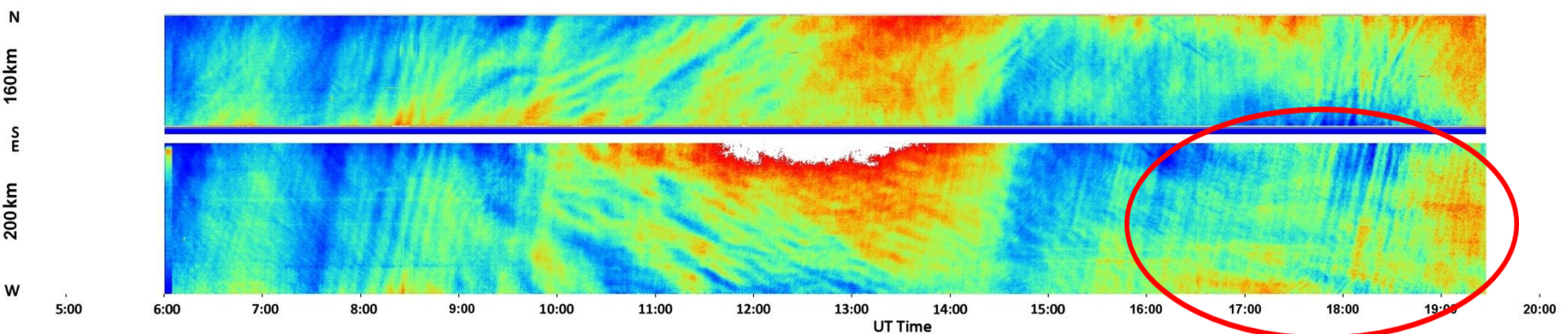
First AMTM Observations at Lauder, May 30-31



Propagating waves

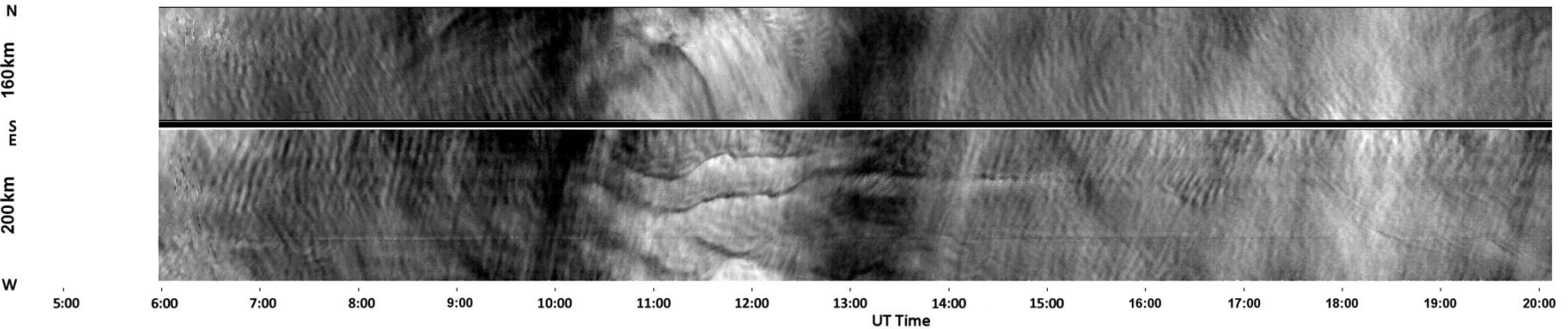


Low
velocity
(MWs)

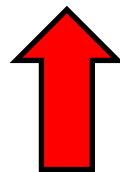
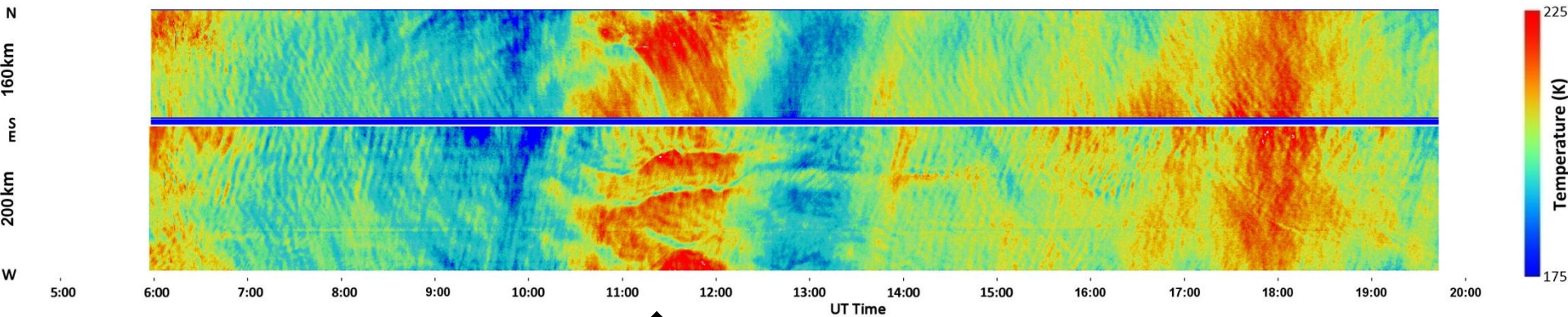


Breaking Mountain Waves, Jun 21-22

(No flight as forcing deemed to be insufficient)

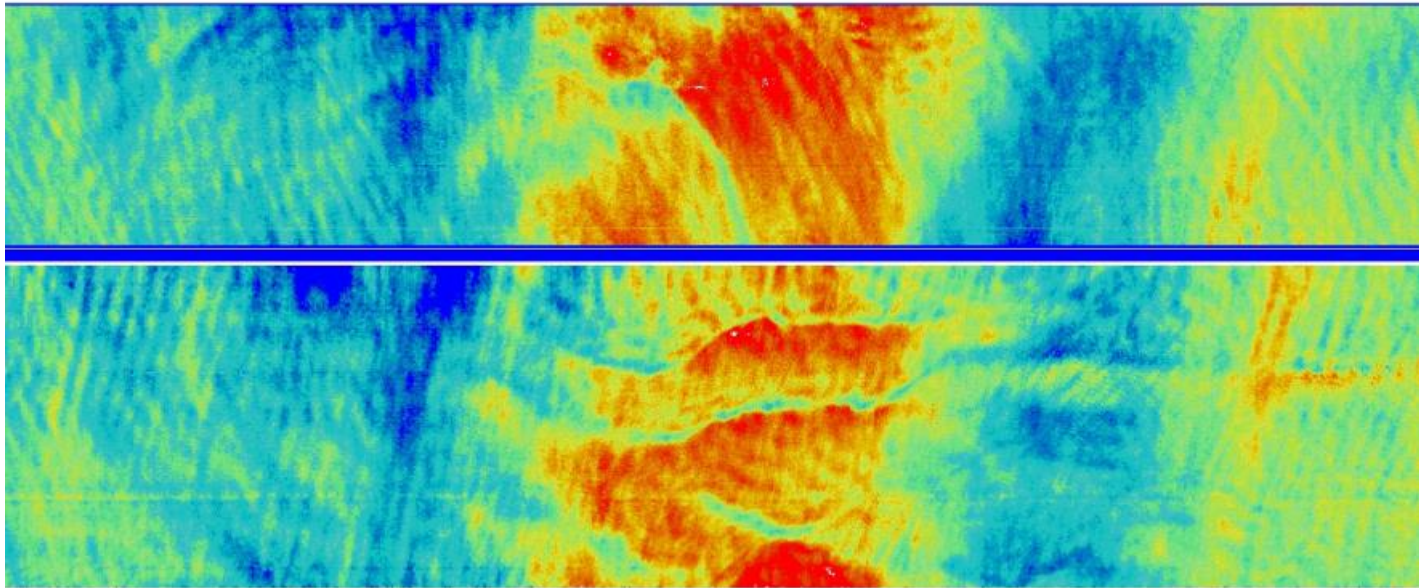
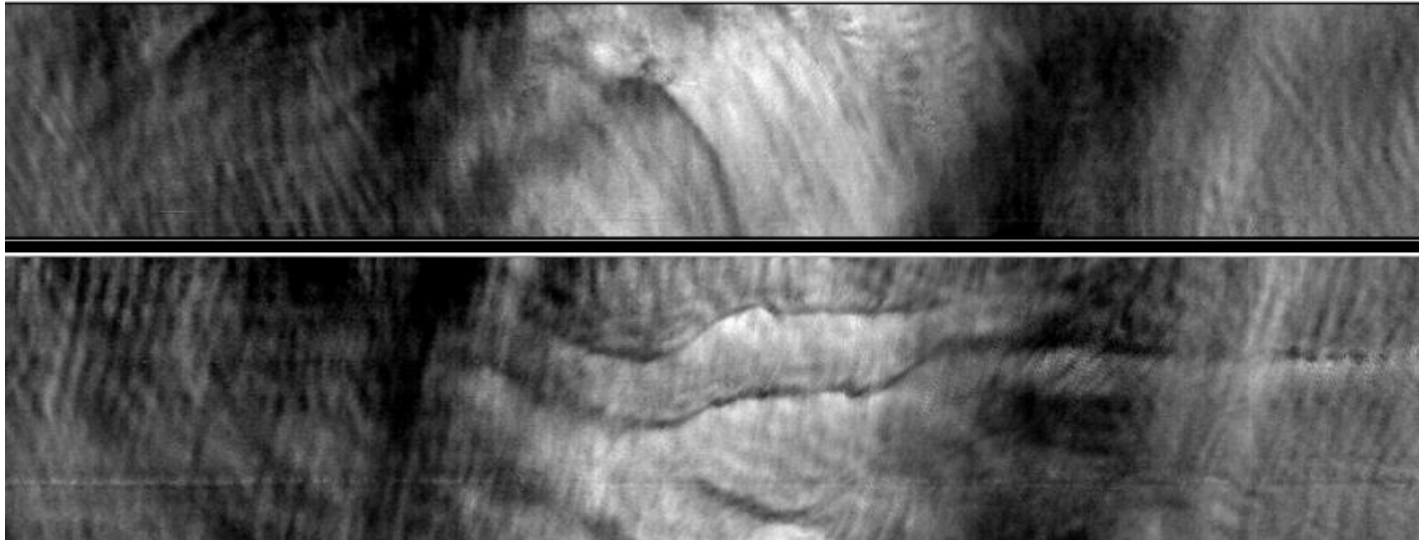


Continuous small scale waves interrupted by MW outburst



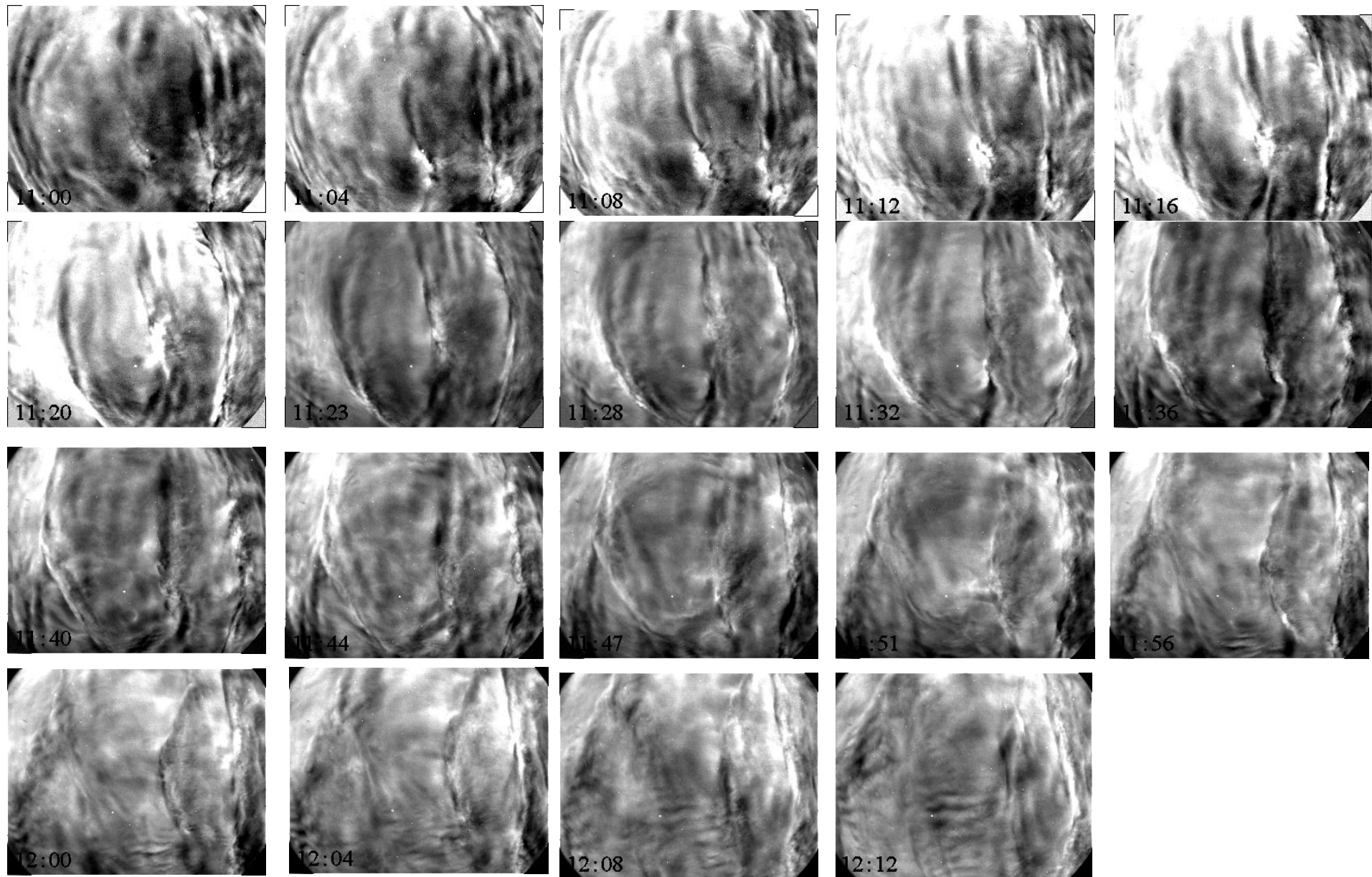
(~10-13 UT)

Complex Breaking MW Structure Jun 21-22



3:00 9:00 10:00 11:00 12:00 13:00 14:00
UT Time

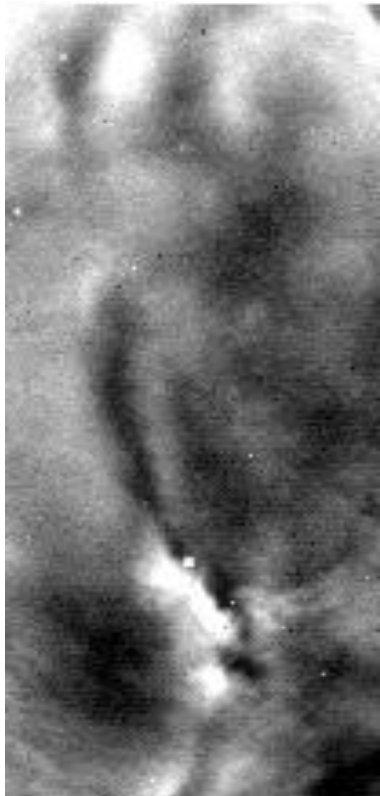
$P_1(2)$ Emission Evolution at 4 min Intervals (11:00-12:12 UT)



Development of instability Along Deep/Cold Troughs

(11:04-11:44 UT)

11:04 UT

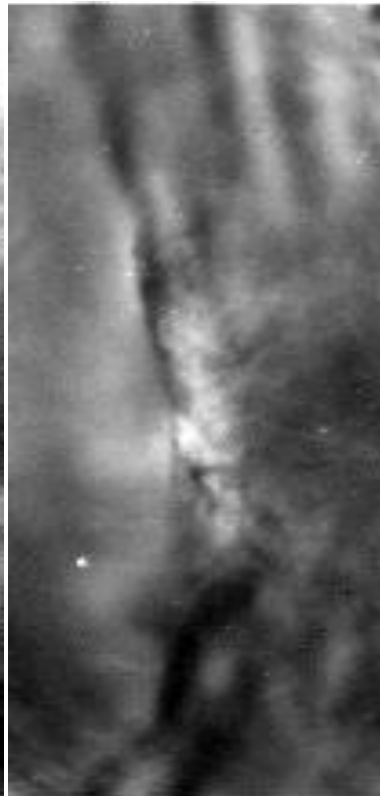


11:12 UT



Instability development

11:23 UT

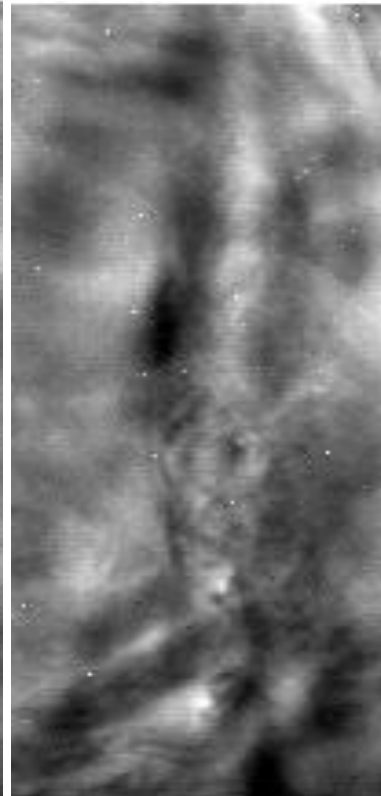


11:36 UT



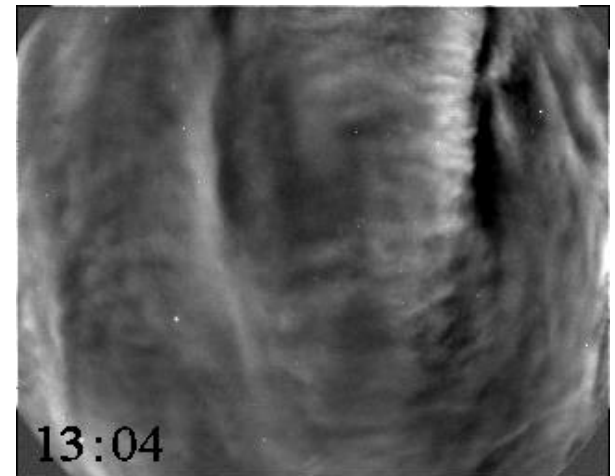
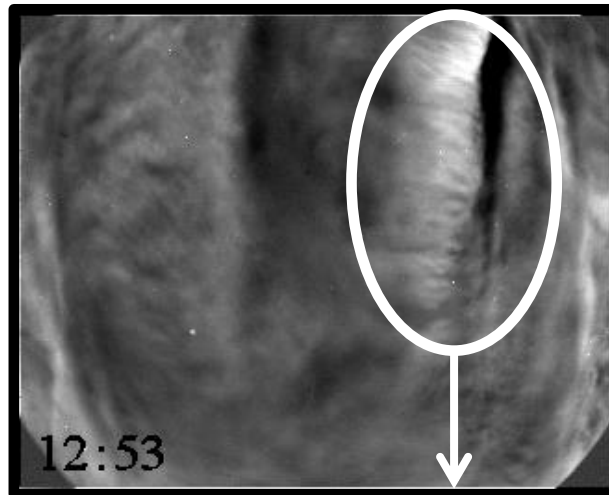
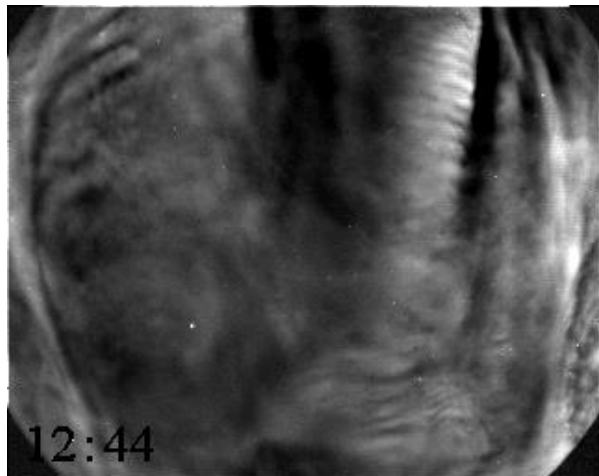
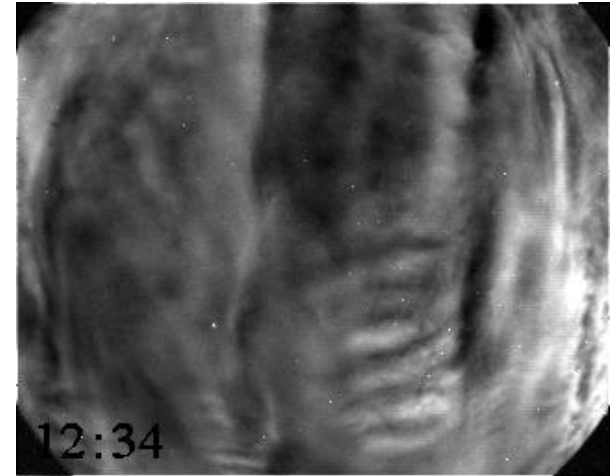
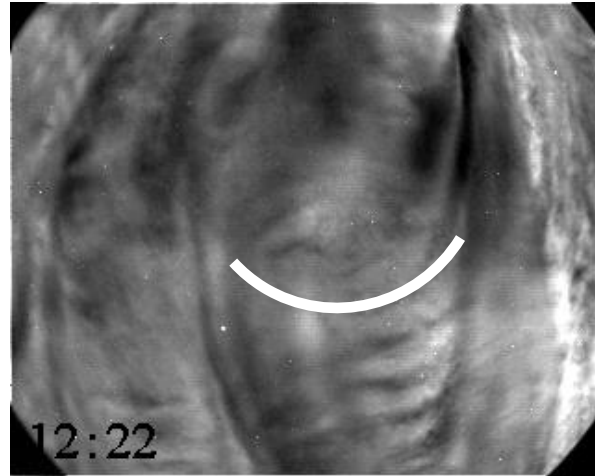
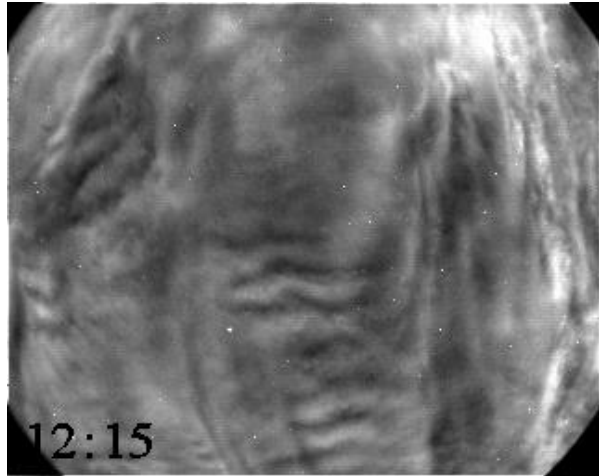
Cold trough development

11:44 UT



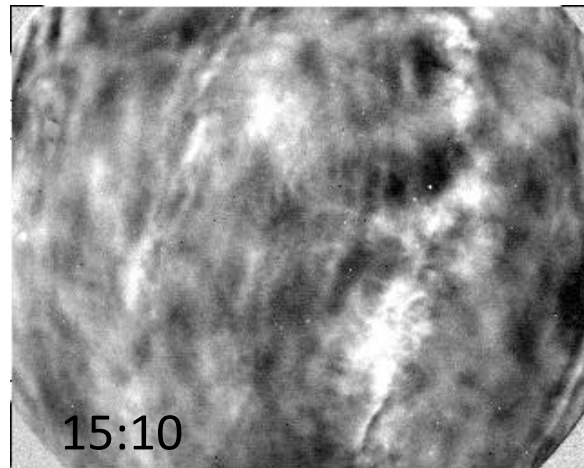
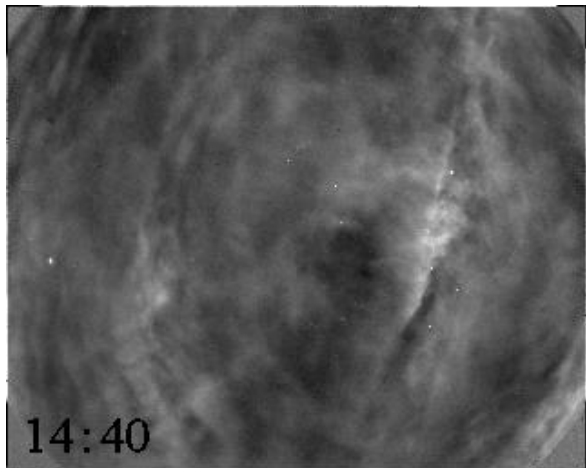
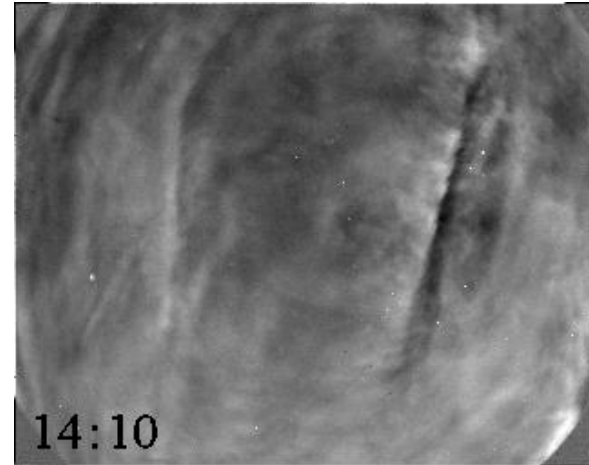
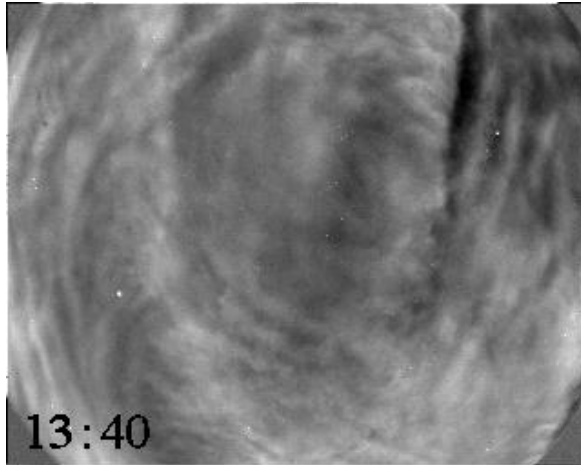
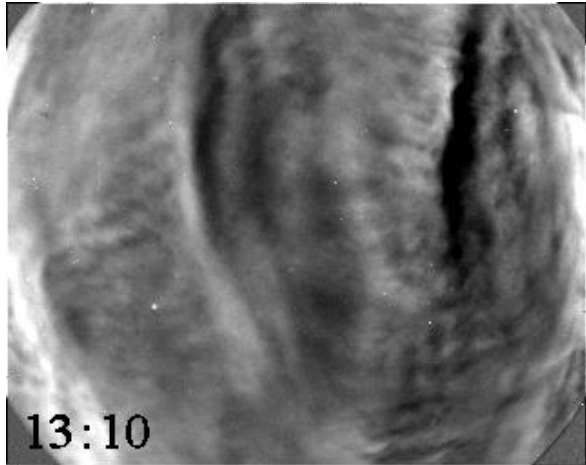
Development of Fine-Scale Waves and Twisting

(12:15-13:04UT)



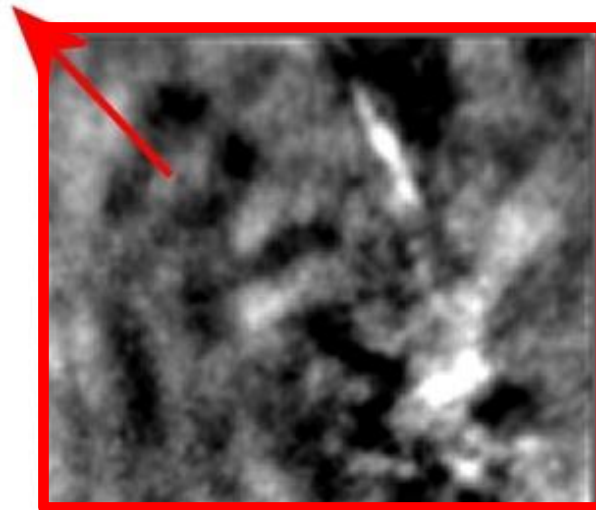
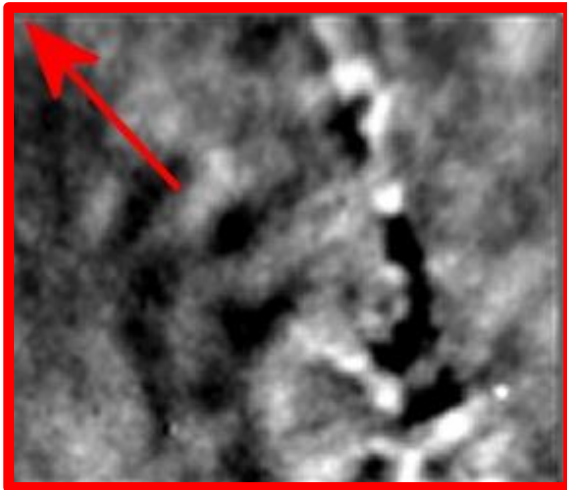
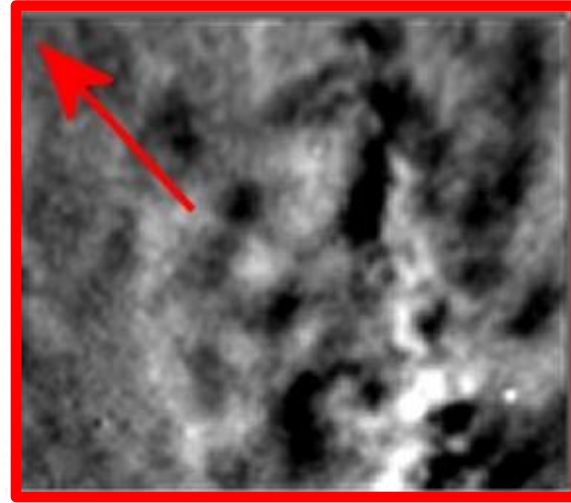
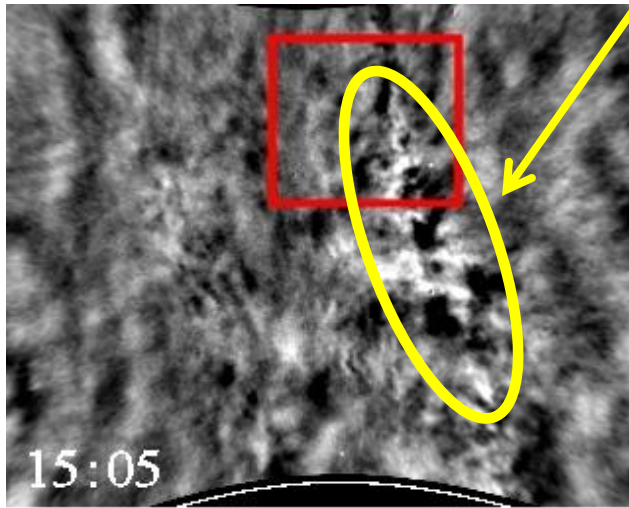
Vortex-like fine scale waves

MW Persistence Phase

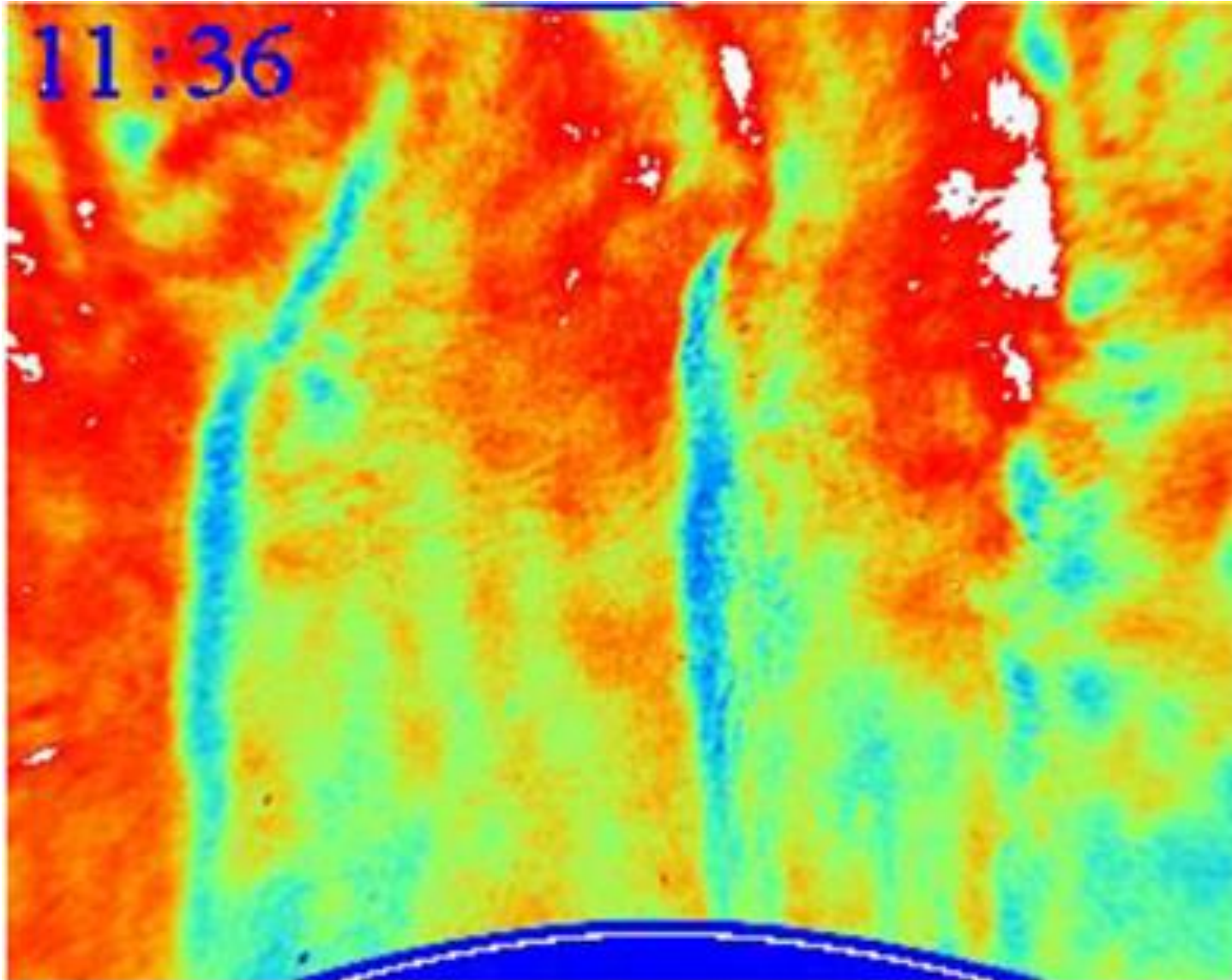


Secondary GW Generation

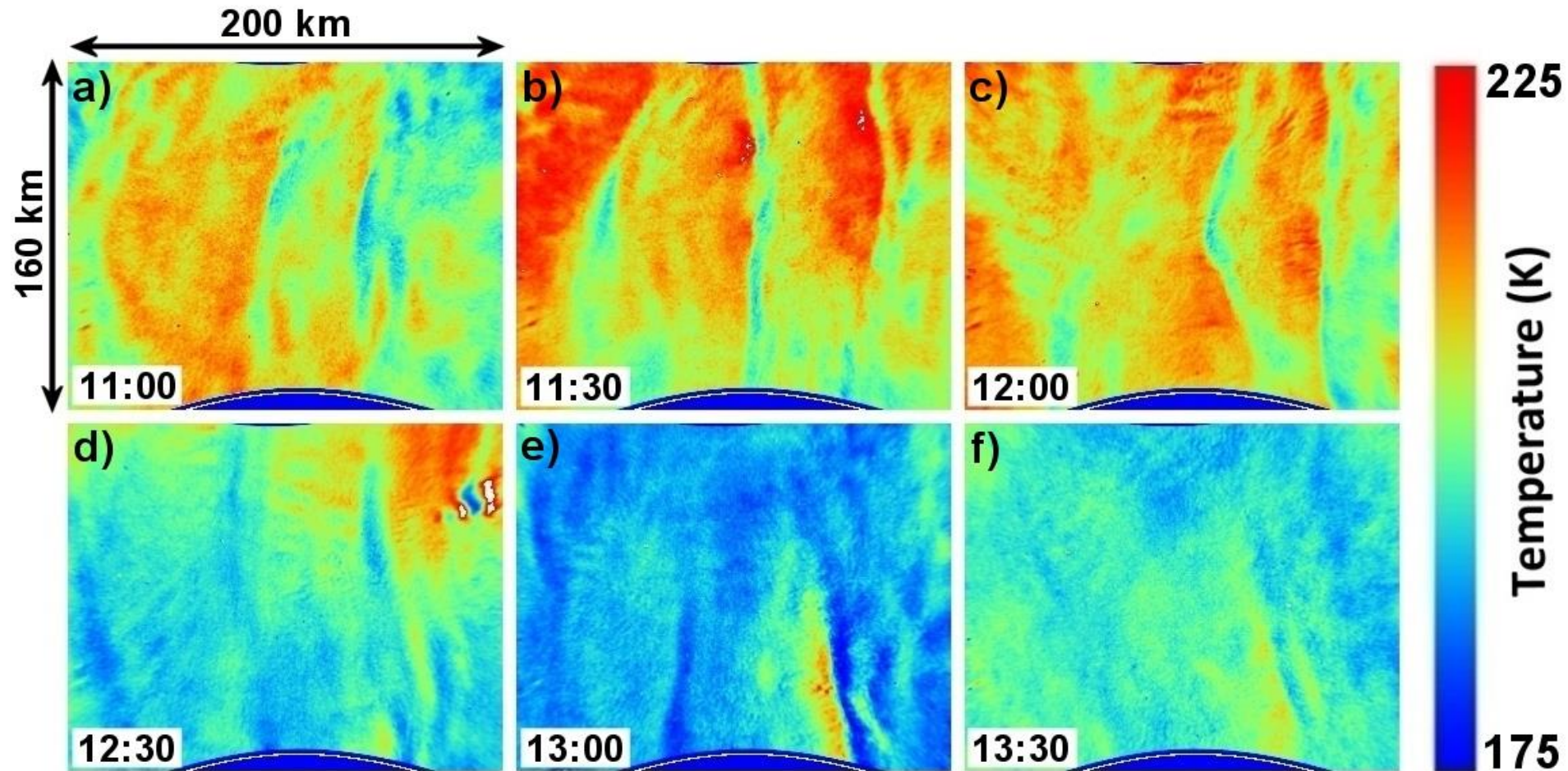
Region of overturning/intense GW breaking



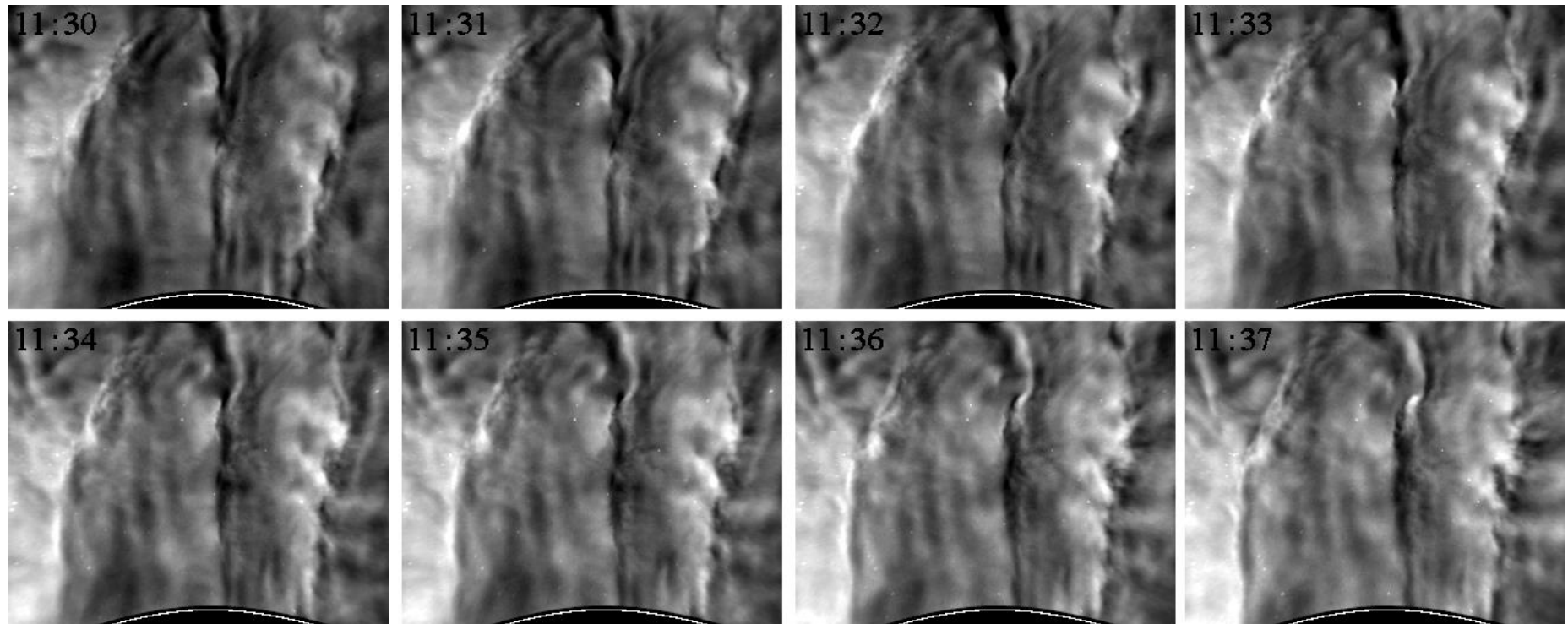
AMTM Temperature and Intensity Structure



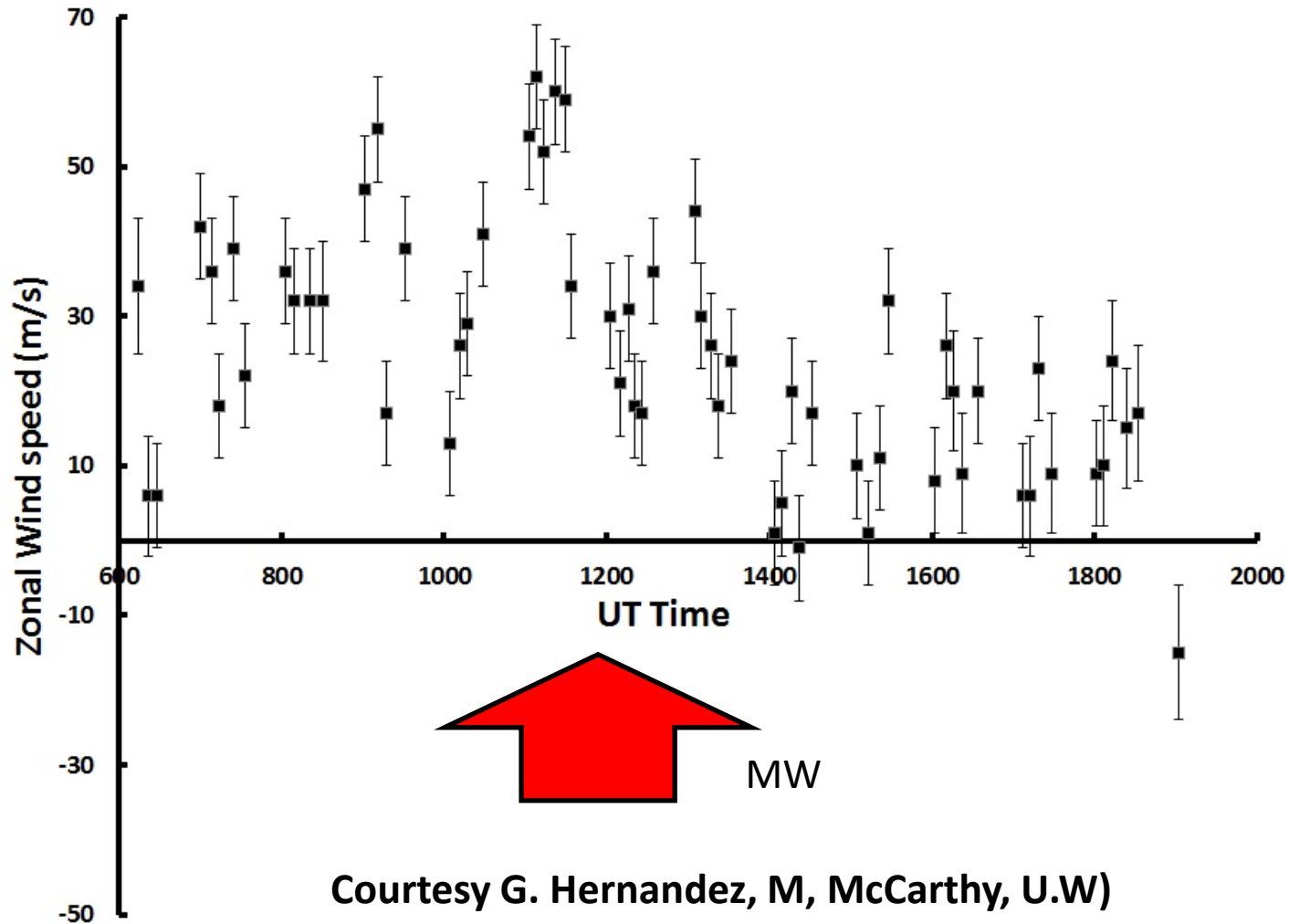
OH (3,1) Rotational Temperatures



OH (3,1) Band Intensity Showing Fine Scale Structuring (1 min intervals)



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



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

June 21-22 – Momentum Flux Estimate

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

(Fritts et al., 2014)

ω_i , intrinsic frequency

N , Brunt-Väisälä frequency (from Na lidar)

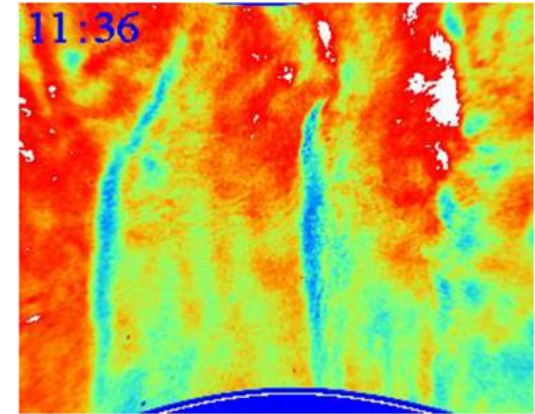
$\langle T' \rangle / T_0$, temperature perturbation (from AMTM)

C^2 , GW temperature variance reduction due to phase averaging for GW vertical wavelengths less than ~twice the OH layer FWHM:

$$C = \frac{\langle T' \rangle}{T'(z_0)} = \exp\left(-3.56 \frac{z_{\text{FWHM}}^2}{\lambda_z^2}\right)$$

dT ~ 10-15K
T ~ 208K
dT/T ~ 3-7%

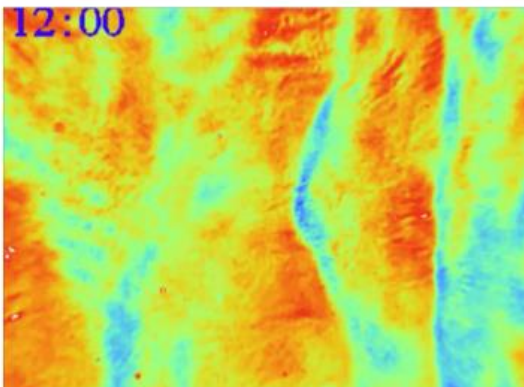
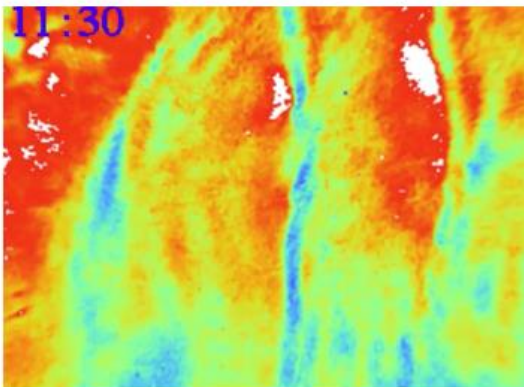
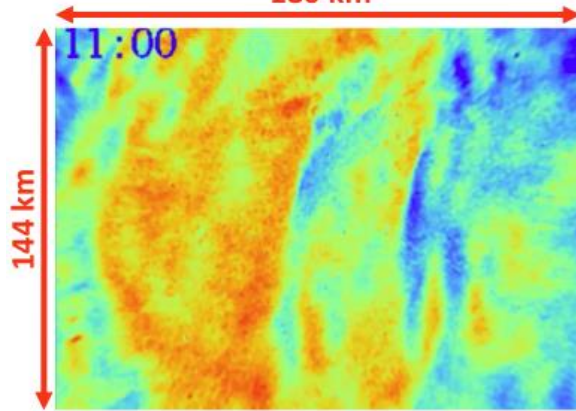
$$\langle u_h' w' \rangle = 60-300 \text{ m}^2/\text{s}^2$$



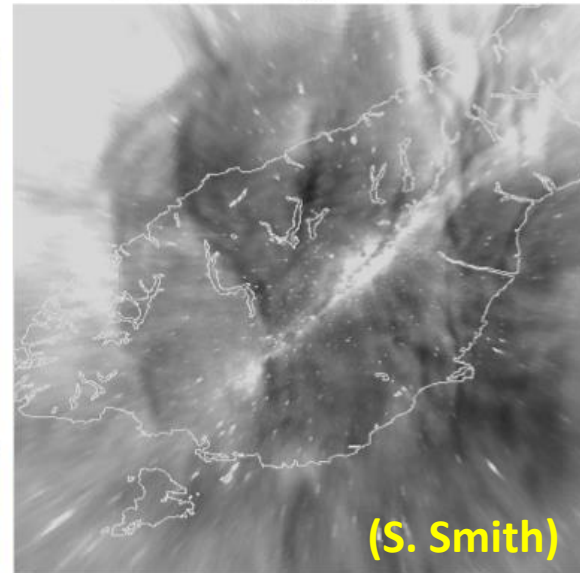
- Wind speed ~50m/s
- $\lambda_x \sim 55\text{km}$
- Direction ~95°
- Observed horizontal phase speed ~0 m/s
- dT/T ~3-7%
- -> $\lambda_z \sim 17\text{km}$

Lauder AMTM 11:49 UT

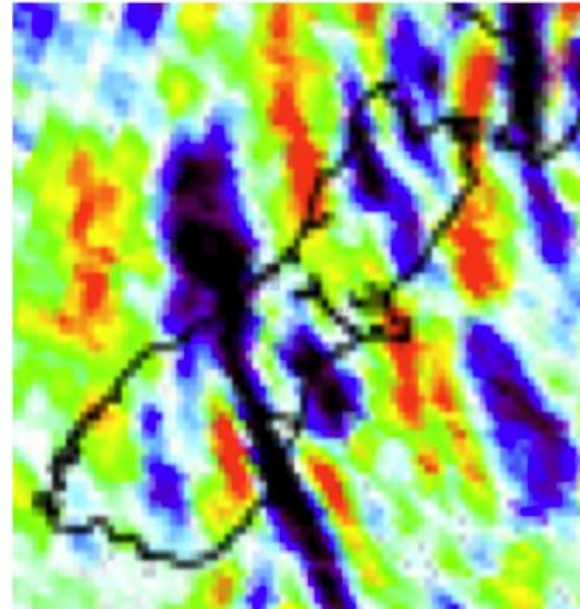
180 km



Lauder OH imager 11:49 UT

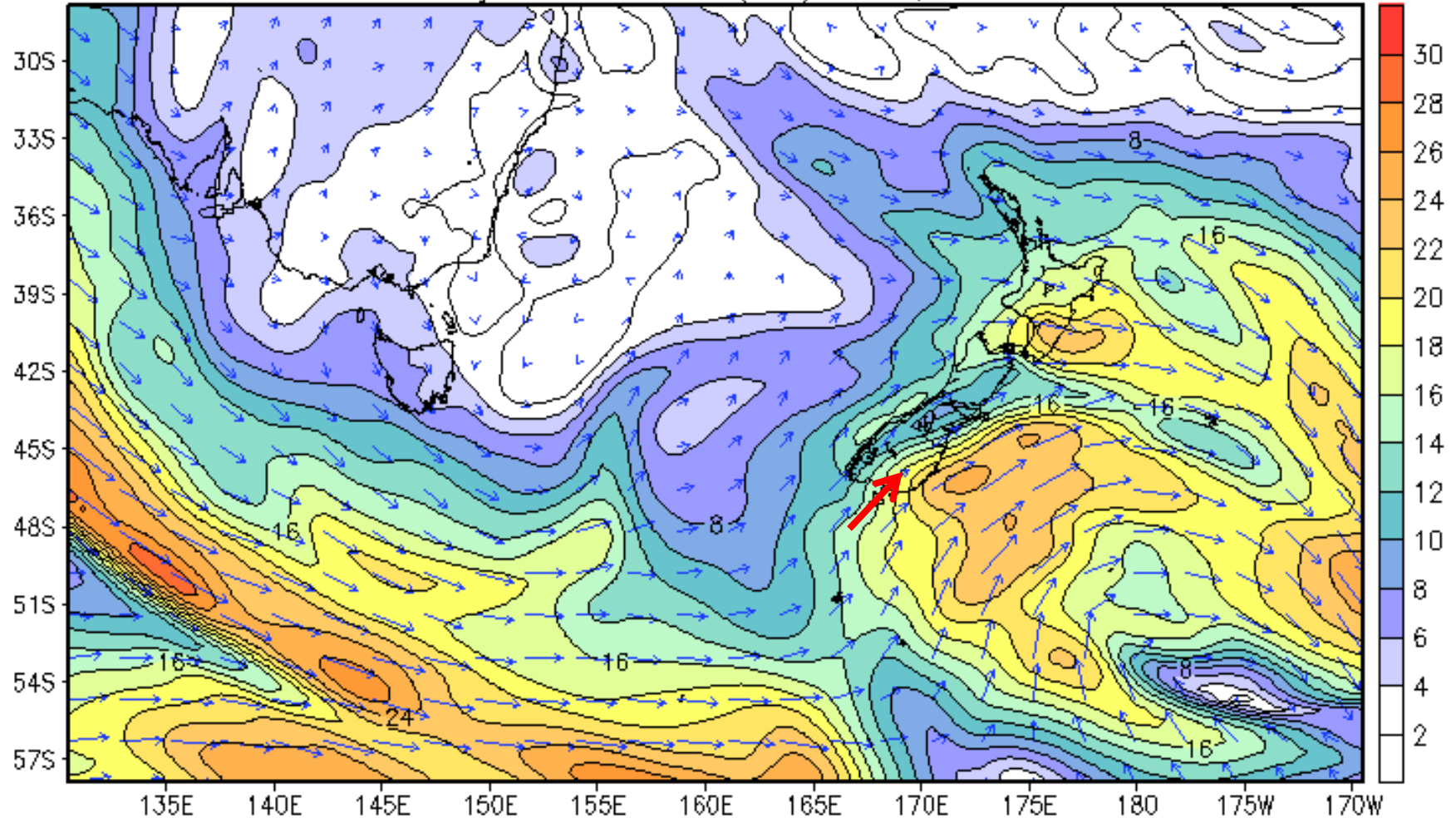


AIRS - 2 hPa 13:25 UT



June 21-22 – COAMPS Winds at 850mb

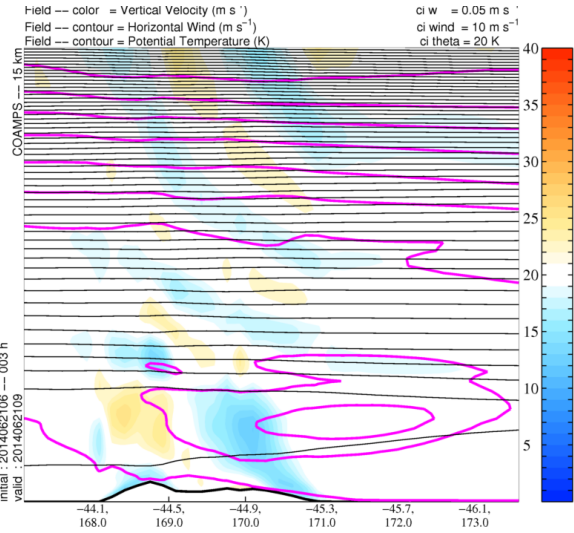
COAMPS Adjoint 850mb Winds (ms^{-1}) at 06h, 2014062106



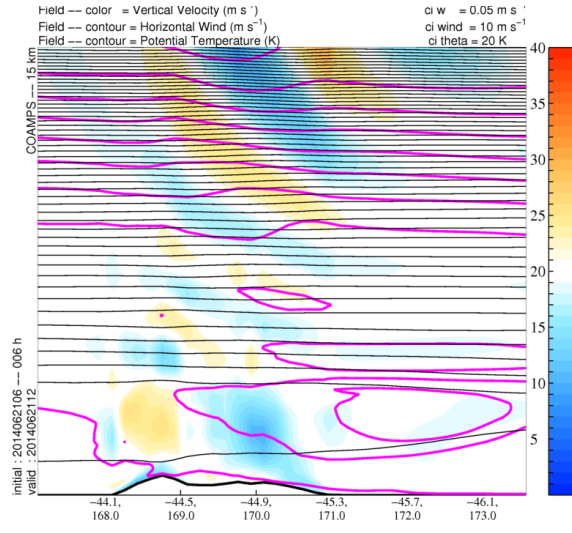
→
30

June 21-22 – Cross-Track Model Forecasts

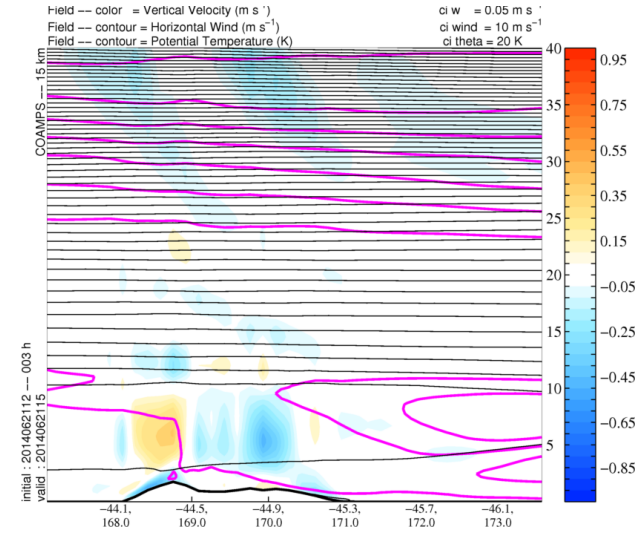
COAMPS vertical wind velocity



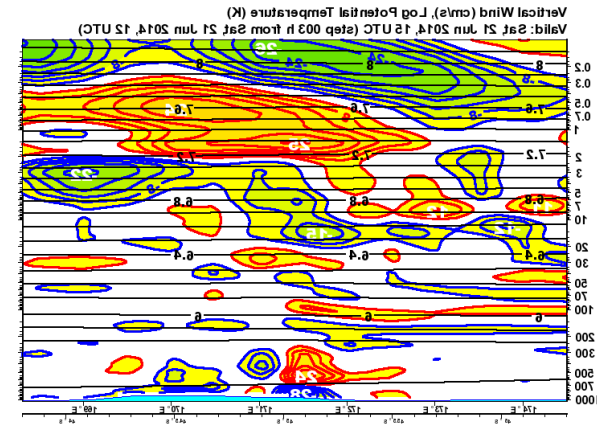
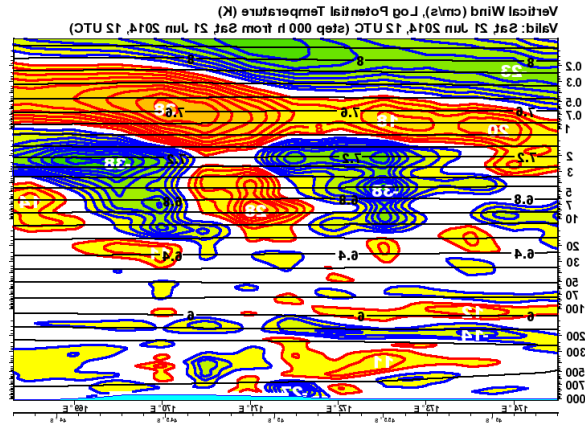
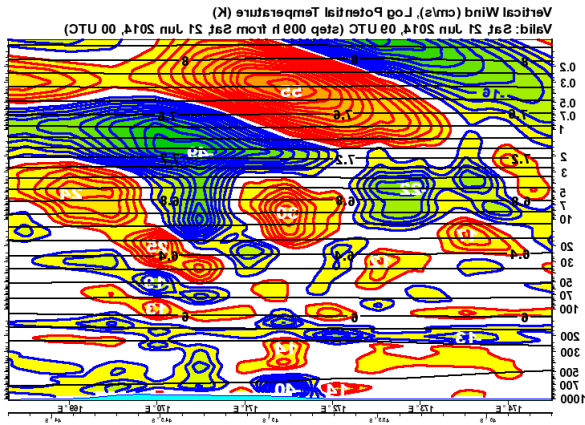
9UT



12UT

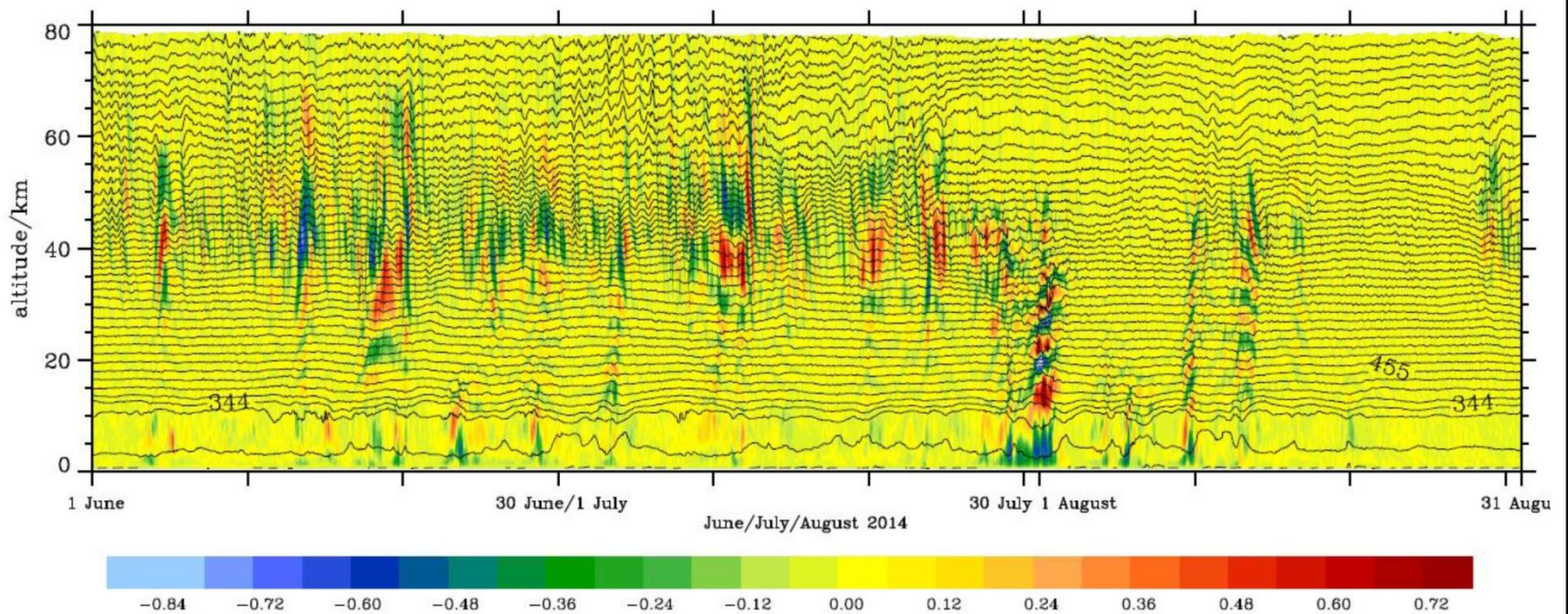


15UT



ECMWF vertical wind velocity

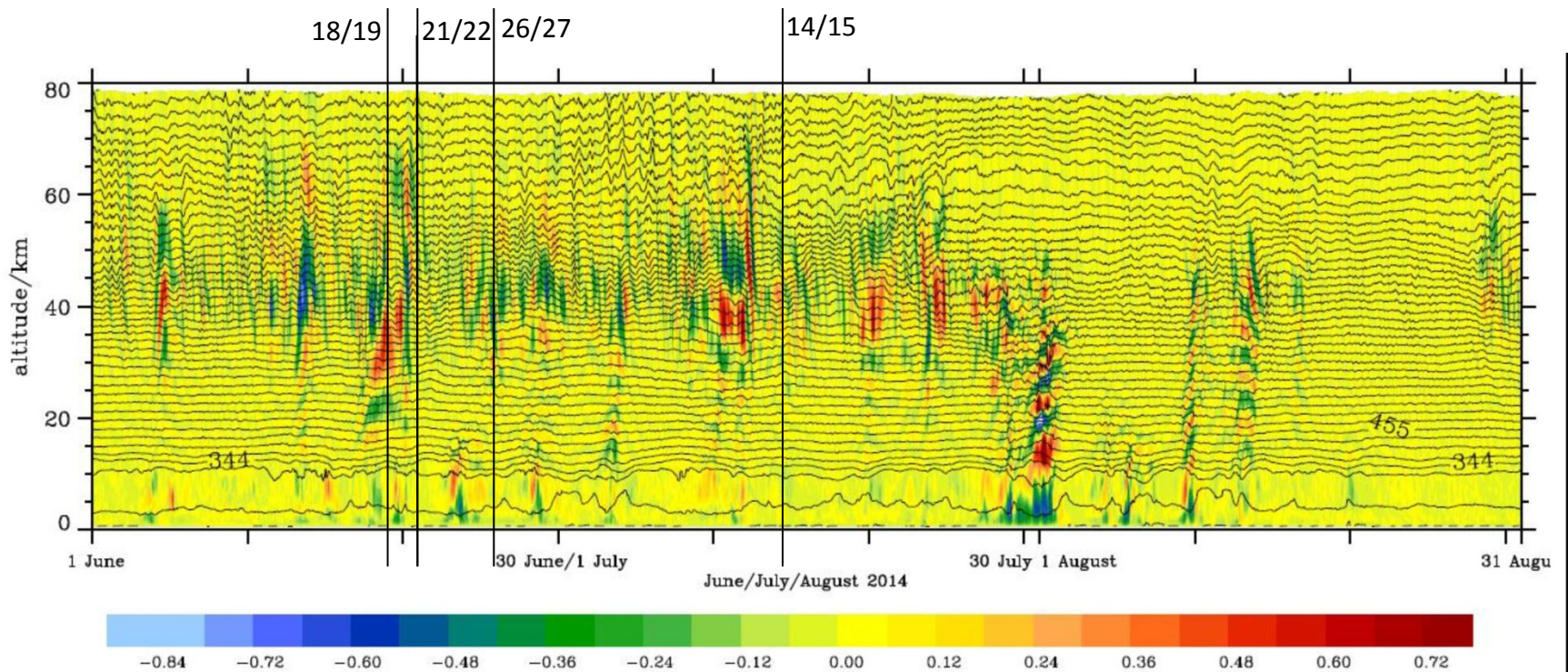
ECMWF Vertical Winds



ECMWF T1279/L137 operational analyses (6 h)
and 1 hourly high-resolution IFS predictions

w/ms^{-1}

ECMWF Vertical Winds & Strong MW Events



ECMWF T1279/L137 operational analyses (6 h)
and 1 hourly high-resolution IFS predictions

w/ms^{-1}

Mountain Waves over Lauder

Summary: Lauder AMTM GW/MW Observations:

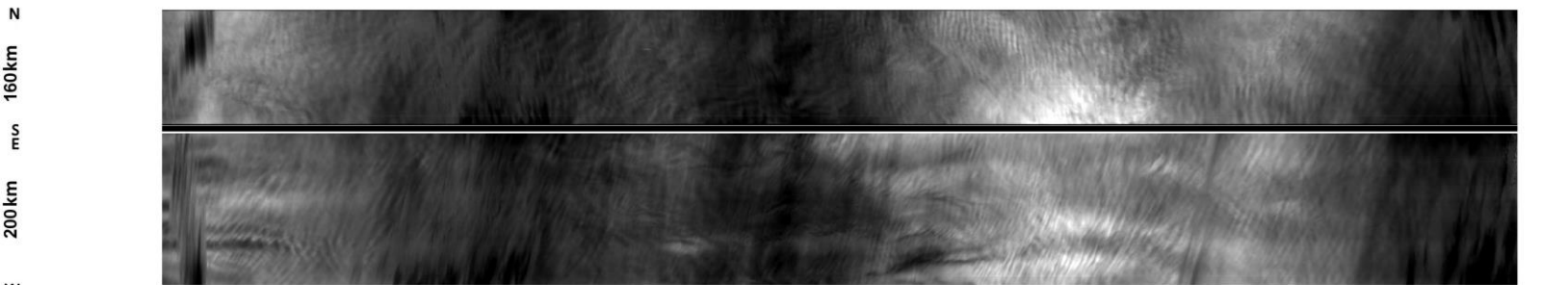
51 consecutive nights of observations from May 30th to July 21th:

- 15 clear nights
- 25 partially cloudy nights
- 11 nights totally cloudy

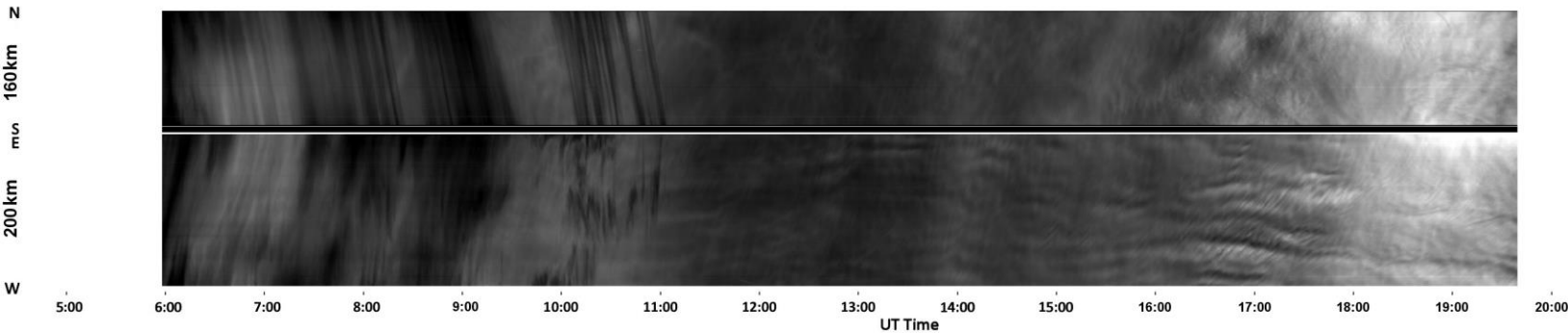
Amongst the 40 data nights:

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

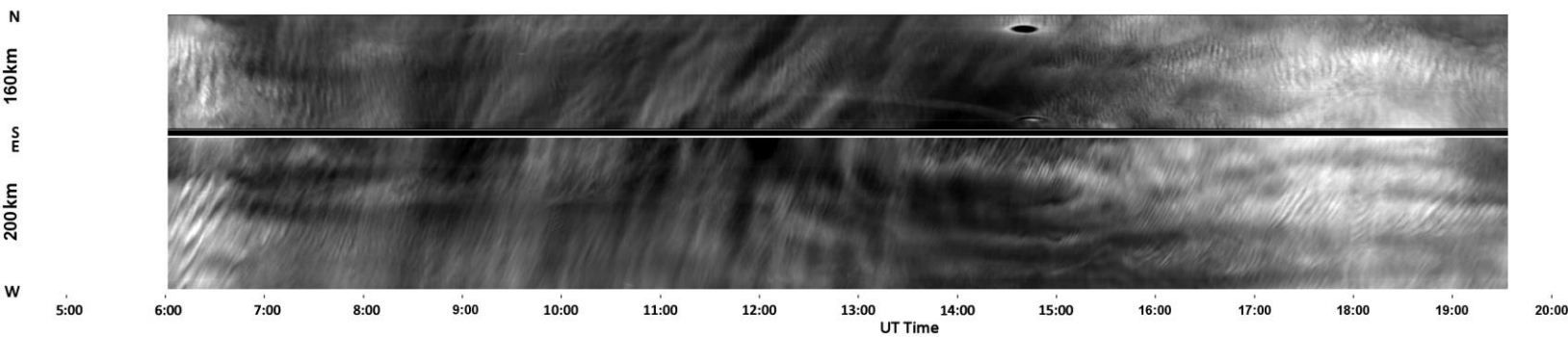
Keogram Examples of Extended Mountain Waves



June 26/27



June 27/28



July 14/15

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	Propagating GW					Standing GW			Propagating GW		Standing GW						
31-May	Propagating GW																
1-Jun				Standing GW			Propagating GW		Standing GW				Propagating GW				
2-Jun				Standing GW					Cloudy								
3-Jun	Cloudy																
4-Jun	Cloudy													Standing GW			
5-Jun	Propagating GW			Cloudy													
6-Jun	Cloudy													RF01			
7-Jun	Cloudy													Standing GW			
8-Jun	Cloudy																
9-Jun	Cloudy																
10-Jun	Cloudy													Propagating GW			
11-Jun	Propagating GW													RF02			
12-Jun	Propagating GW																
13-Jun	Standing GW			Propagating GW					Cloudy				Propagating GW		RF03		
14-Jun	Cloudy													RF04			
15-Jun	Propagating GW																
16-Jun	Cloudy			Propagating GW					Cloudy				Propagating GW		RF05		
17-Jun	Standing GW																
18-Jun	Standing GW													Cloudy		RF06	
19-Jun	Propagating GW							Standing GW			Cloudy			Propagating GW		RF07	
20-Jun	Propagating GW			Cloudy										RF08			
21-Jun	Standing GW			Propagating GW					Standing GW				Propagating GW				
22-Jun	Propagating GW			Standing GW			Propagating GW										
23-Jun	Propagating GW																
24-Jun	Cloudy													RF09			
25-Jun	Propagating GW			Cloudy					Propagating GW				Propagating GW		RF10		
26-Jun	Standing GW			Propagating GW					Standing GW				Propagating GW				
27-Jun	Standing GW			Cloudy					Standing GW				Propagating GW				
28-Jun	Standing GW			Cloudy					Standing GW				Propagating GW		RF11		
29-Jun	Cloudy													RF12			
30-Jun	Cloudy					Standing GW			Propagating GW		Propagating GW				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	Cloudy	Cloudy	Cloudy	Cloudy	Cloudy	Cloudy	Cloudy	Standing GW	Standing GW	Propagating GW	Propagating GW	Propagating GW	Propagating GW	Propagating GW	RF14
2-Jul	Cloudy	Cloudy	Cloudy	Cloudy	Cloudy	Cloudy	Cloudy	Cloudy	Cloudy	Cloudy	Cloudy	Cloudy	Cloudy	Cloudy	
3-Jul	Cloudy	Cloudy	Cloudy	Cloudy	Cloudy	Standing GW	Standing GW	Standing GW	Standing GW	Standing GW	Standing GW	Standing GW	Standing GW	Standing GW	
4-Jul	Propagating GW	Propagating GW	Cloudy	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	Cloudy	Cloudy	Cloudy	Propagating GW	Propagating GW	Standing GW	Cloudy	Cloudy	Cloudy	Cloudy	Cloudy	Cloudy	Cloudy	Cloudy	RF17
6-Jul	Propagating GW	Propagating GW	Propagating GW	Propagating GW	Propagating GW	Propagating GW	Propagating GW	Standing GW	Standing GW	Standing GW	Standing GW	Standing GW	Standing GW	Standing 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	Cloudy	Cloudy	Cloudy	Cloudy	Cloudy	Cloudy	Cloudy	Cloudy	Cloudy	Cloudy	Cloudy	Cloudy	RF19
9-Jul	Cloudy	Cloudy	Cloudy	Cloudy	Cloudy	Cloudy	Cloudy	Cloudy	Cloudy	Cloudy	Cloudy	Cloudy	Cloudy	Cloudy	
10-Jul	Cloudy	Cloudy	Cloudy	Cloudy	Cloudy	Cloudy	Cloudy	Standing GW	Standing GW	Standing GW	Standing GW	Propagating GW	Propagating GW	Propagating GW	RF20
11-Jul	Cloudy	Cloudy	Cloudy	Cloudy	Cloudy	Cloudy	Cloudy	Cloudy	Cloudy	Cloudy	Cloudy	Cloudy	Cloudy	Cloudy	RF21
12-Jul	Propagating GW	Cloudy	Propagating GW	Cloudy	Cloudy	Cloudy	Standing GW	Standing GW	Standing GW	Standing GW	Standing GW	Standing GW	Standing GW	Standing GW	
13-Jul	Cloudy	Cloudy	Cloudy	Cloudy	Cloudy	Cloudy	Cloudy	Cloudy	Cloudy	Cloudy	Cloudy	Cloudy	Cloudy	Cloudy	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	Cloudy	Cloudy	Cloudy	Cloudy	Cloudy	Cloudy	Cloudy	Propagating GW	Propagating GW	Propagating 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	Standing GW	Cloudy	Cloudy	Cloudy	Cloudy	Cloudy	Cloudy	Cloudy	Cloudy	RF25
19-Jul	Cloudy	Cloudy	Cloudy	Cloudy	Cloudy	Cloudy	Cloudy	Cloudy	Cloudy	Cloudy	Cloudy	Cloudy	Cloudy	Cloudy	
20-Jul	Cloudy	Cloudy	Cloudy	Cloudy	Cloudy	Cloudy	Standing GW	Standing GW	Standing GW	Standing GW	Standing GW	Standing GW	Standing GW	Standing GW	RF26
21-Jul	Cloudy	Cloudy	Cloudy	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

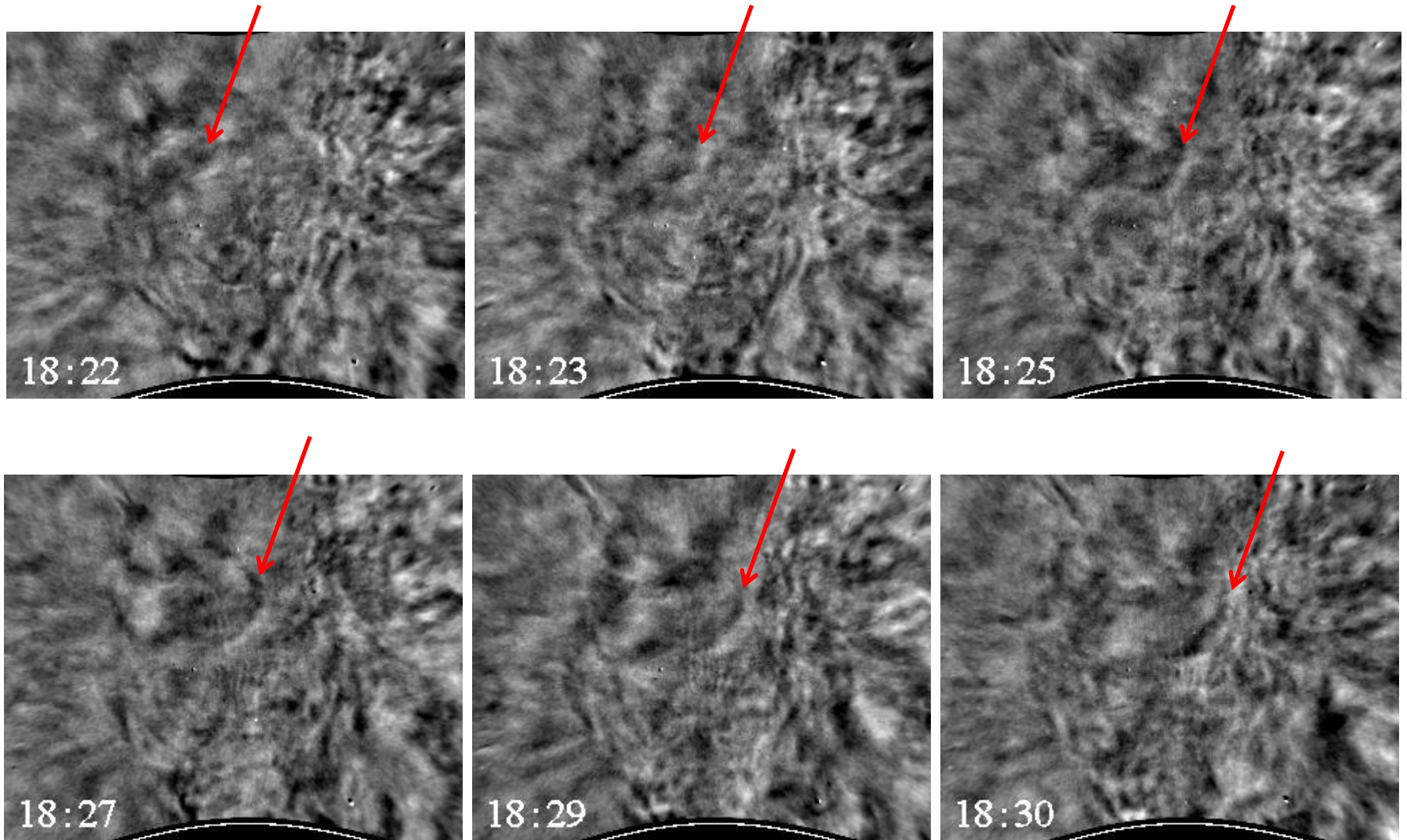
Summary AMTM Ground Observations

- 53 nights of observations, 20 cloudy
 - 33 nights with *GW* structure (partially cloudy)
 - 19 nights with extended *MW* activity
- Total ~100 hrs of mountain wave activity

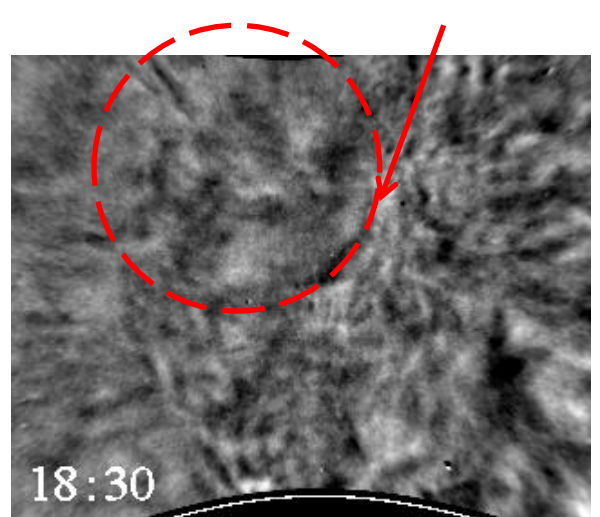
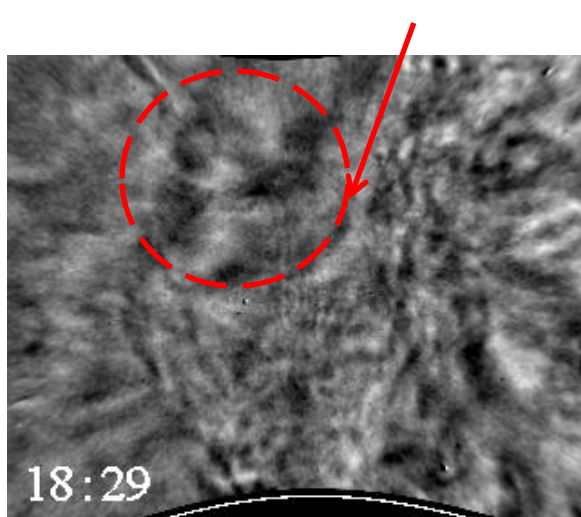
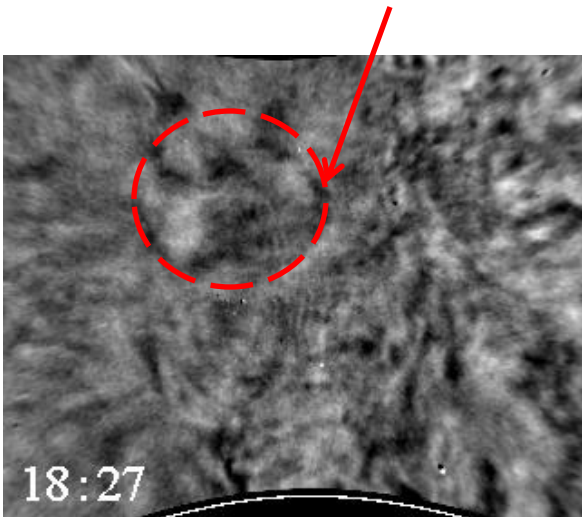
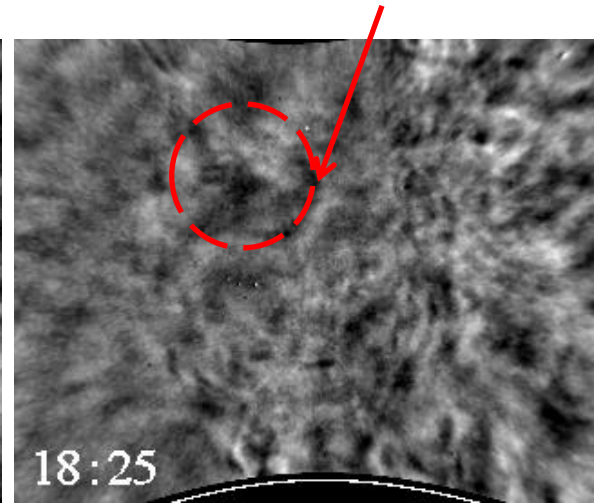
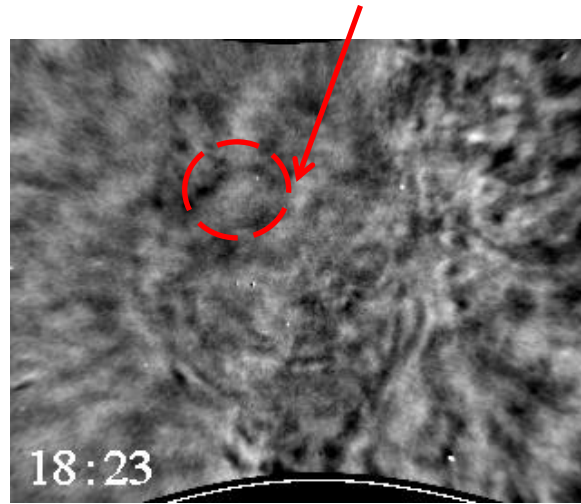
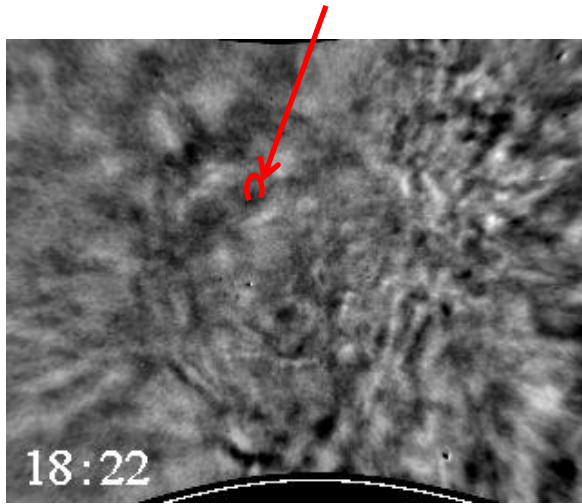
RF #	Date (UT)	comment	RF#	Date (UT)	comment
	May 30/31	First Night	RF 13	30/01	South Is
	June 1/2			July 3/4	
	June 2/3			6/7	
	June 4/5		RF20	10/11	Tasman Sea
	June 17/18		RF23	14/15	Auckland Is
RF06	June 18/19	Tasmania	F12	16/17	Falcon
	21/22*			17/18	
	23/24		RF25	18/19	South Ocean
	26/27				
RF11	27/28	Tasmania			
	28/29				

End

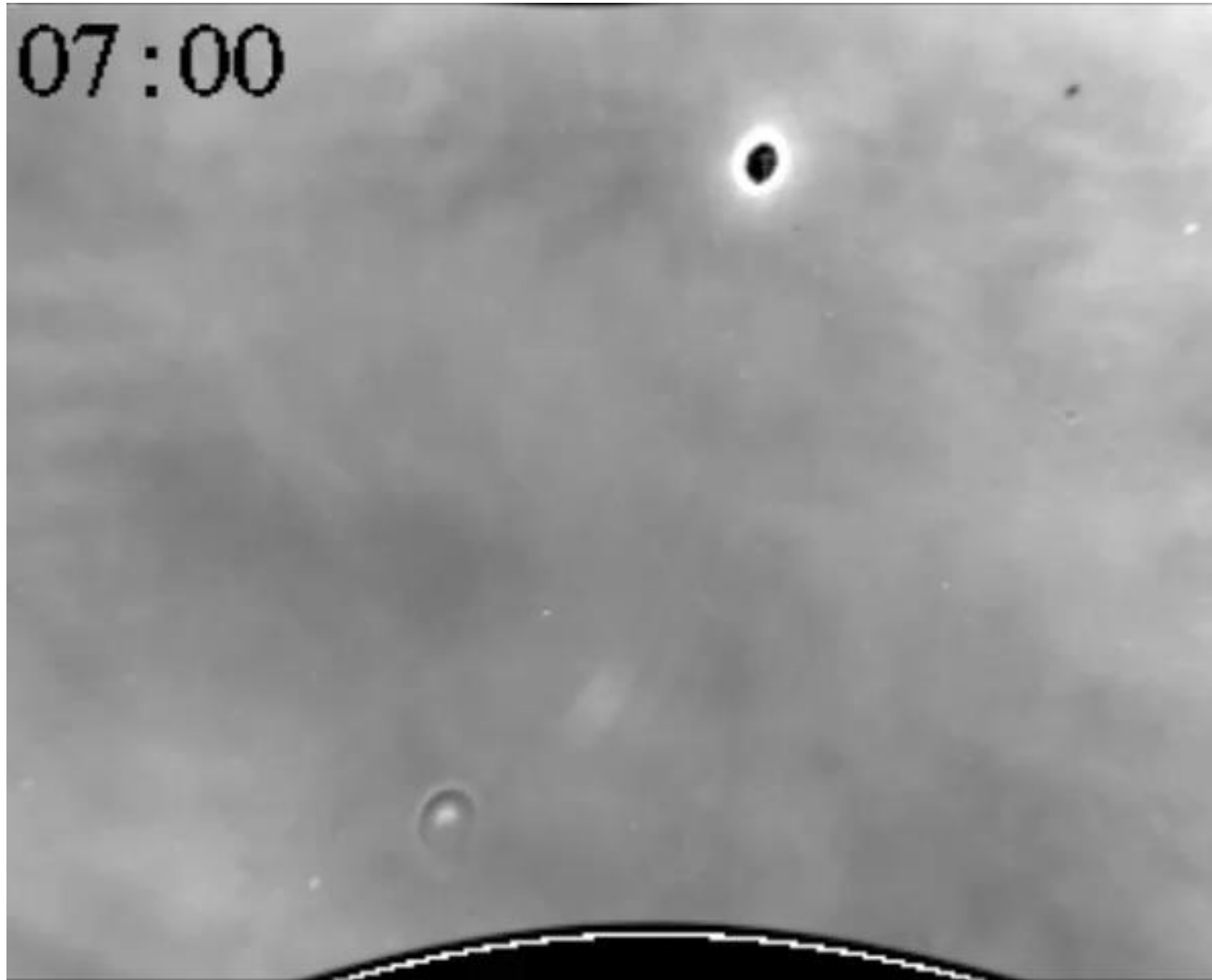
June 21-22 – Secondary GW Generation



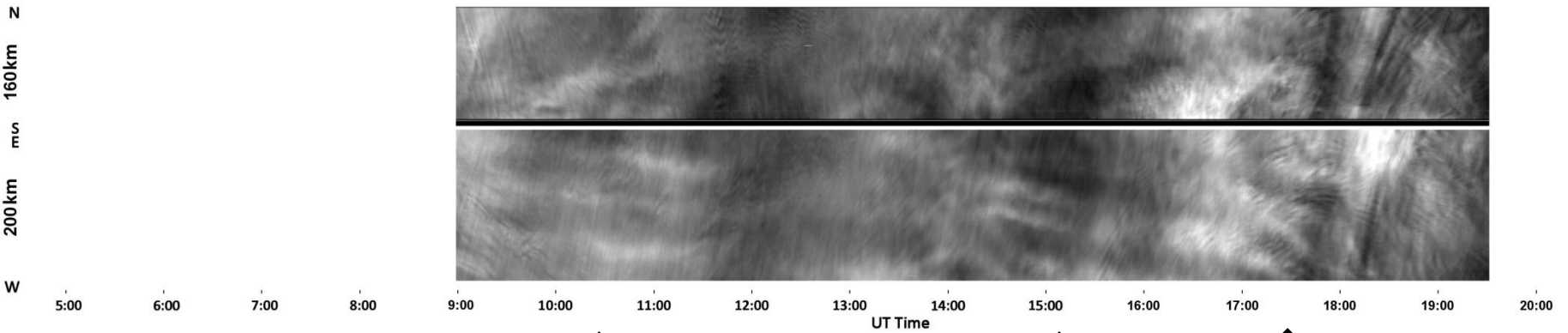
June 21-22 – Secondary GW Generation



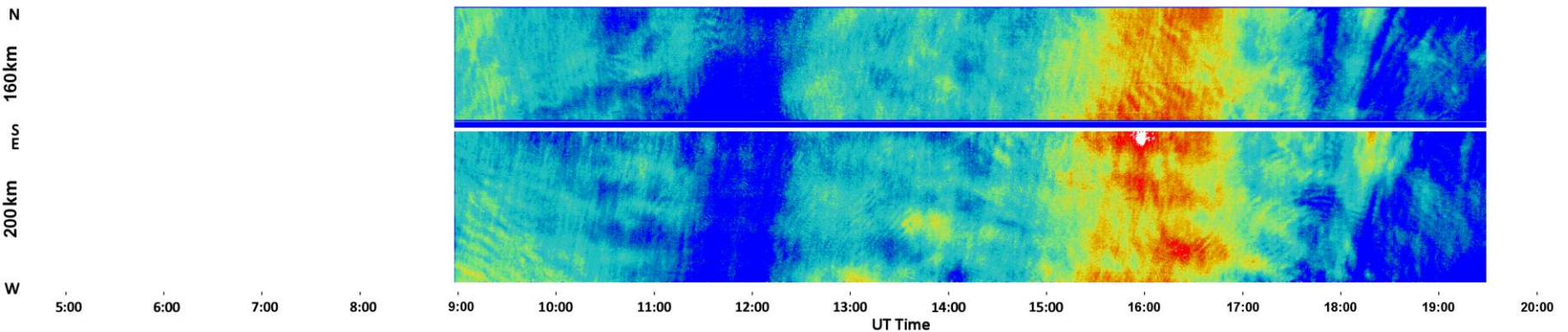
Secondary GW Generation, July 07-08



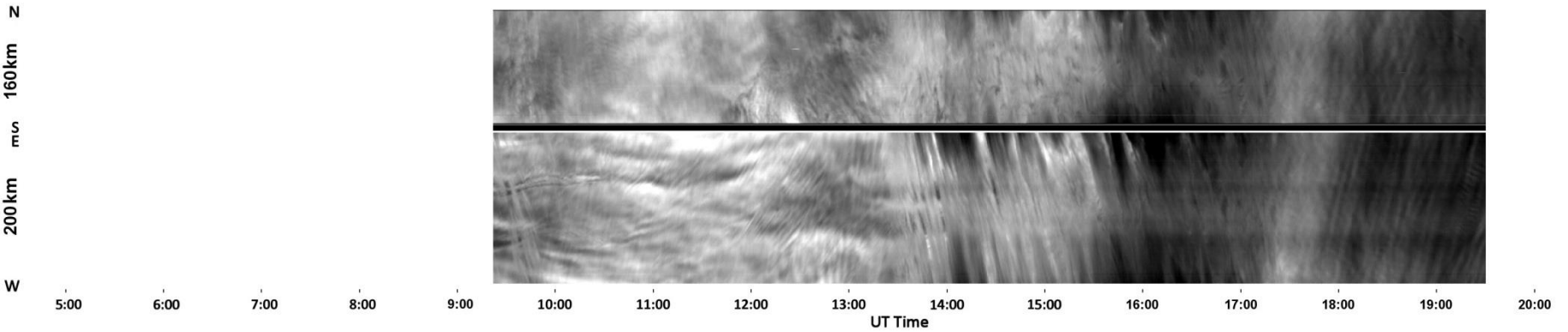
Intermittent MW over ~10 hours, June 01-02



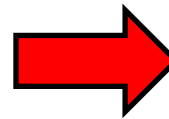
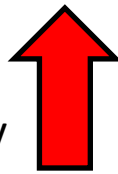
NS aligned low velocity waves appear as
quasi-horizontal stripes in WE Keograms



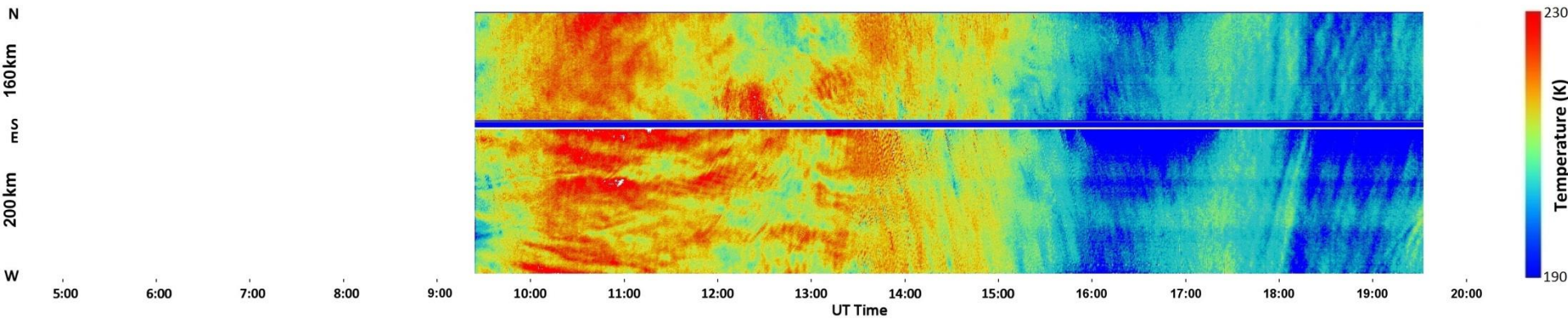
Strong MW, June 02-03



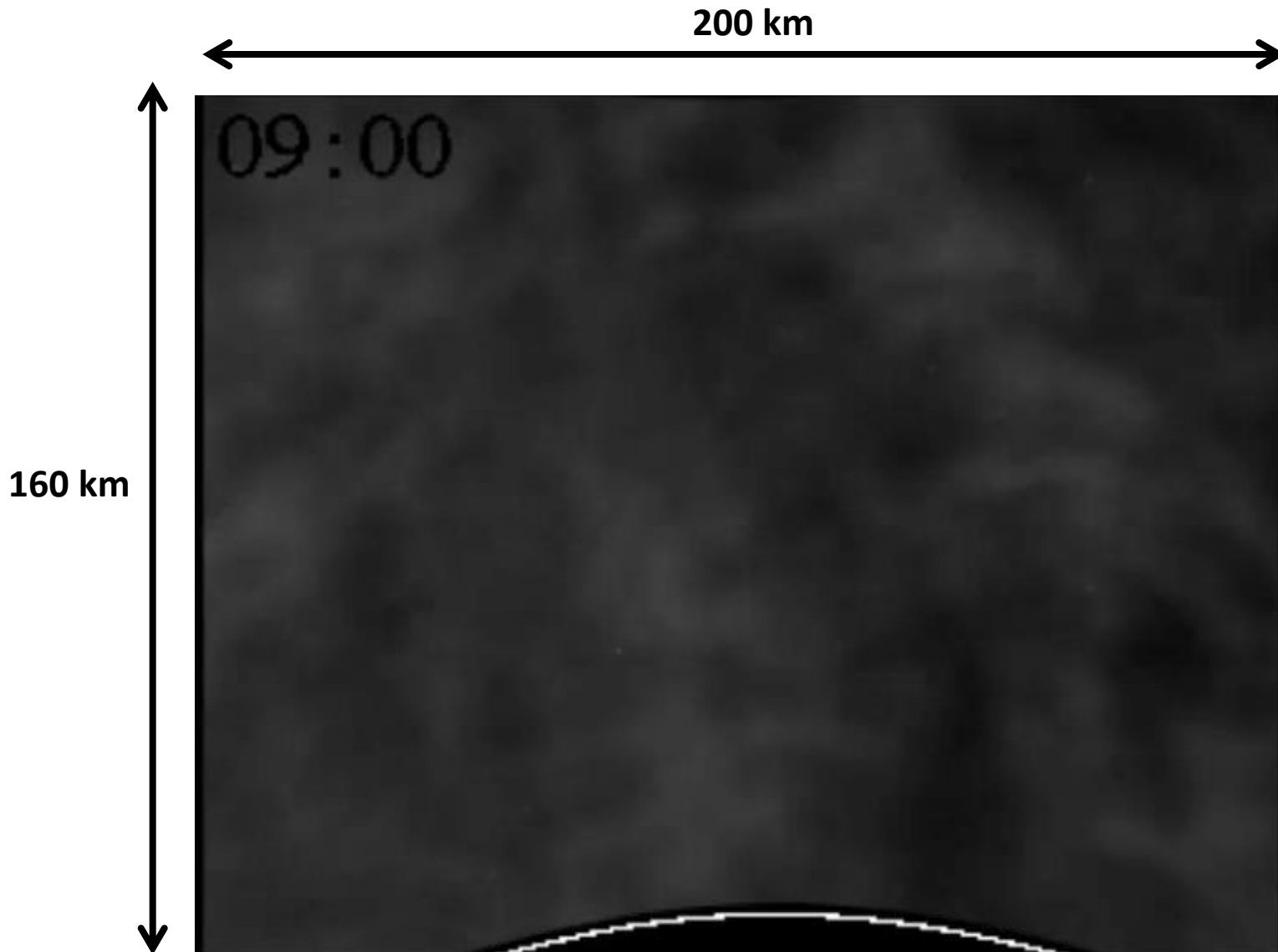
MW,
Low
velocity
waves



Tropospheric cloud



Intensity Movie, Jun 21-22 (~10hrs)



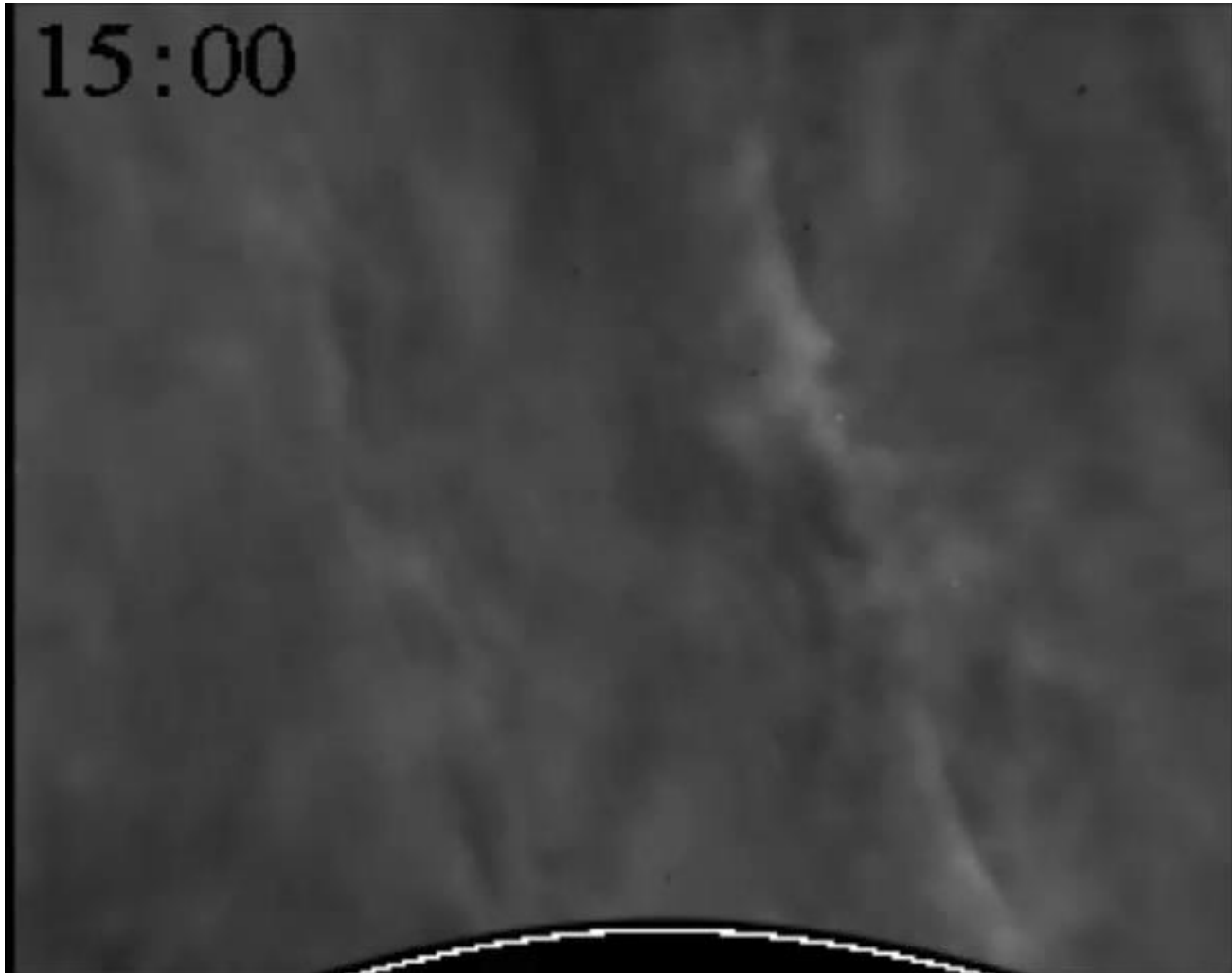
Secondary Wave Generation?

Jun 21-22

200 km



15:00

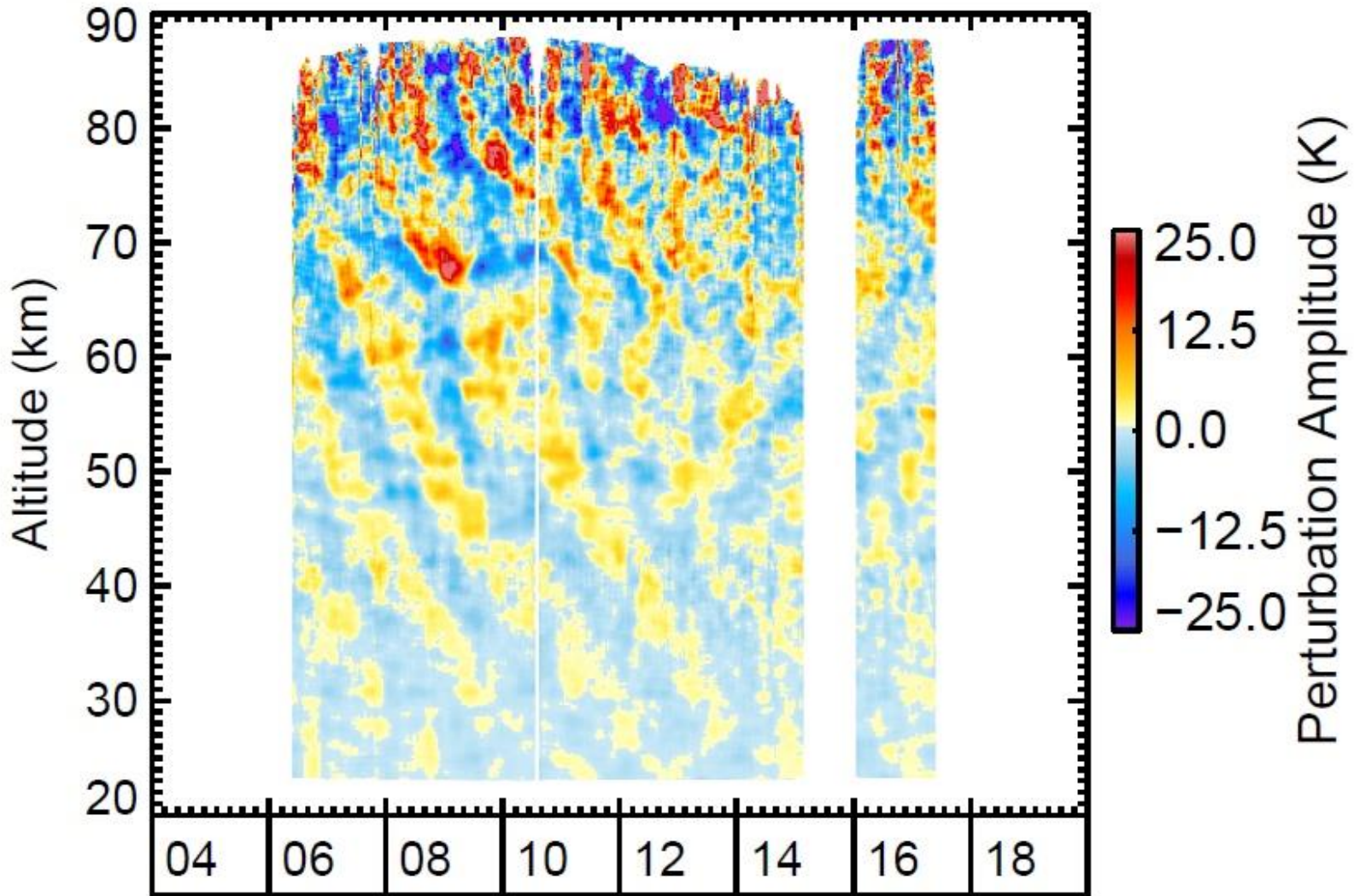


160 km



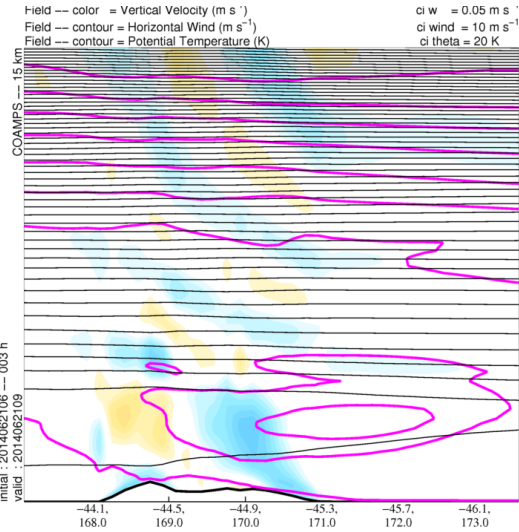
Rayleigh Lidar, July 07-08 (RF 18)

Mean 2h

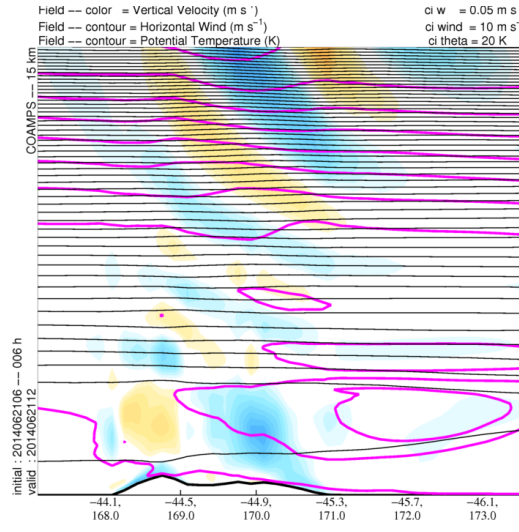


June 21-22 – Cross-Track Model Forecasts

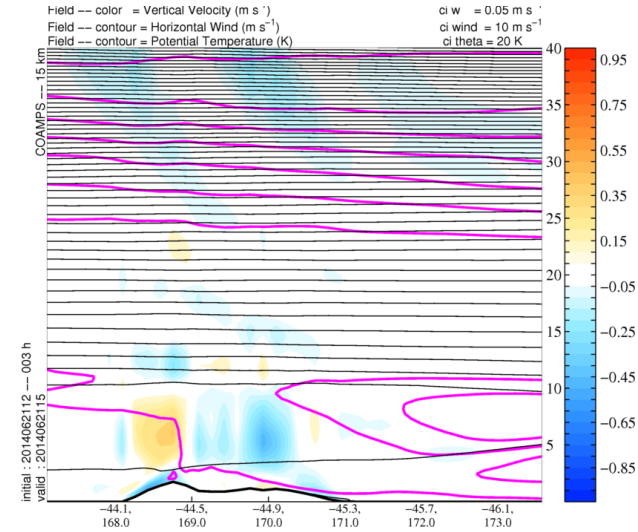
COAMPS vertical wind velocity



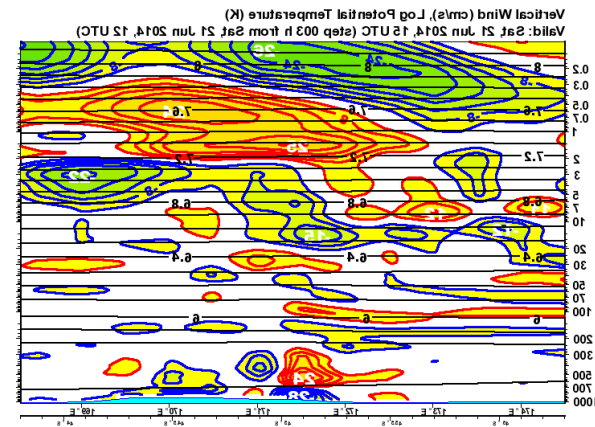
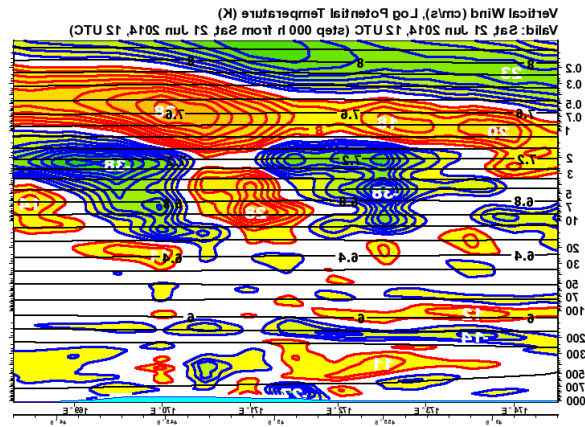
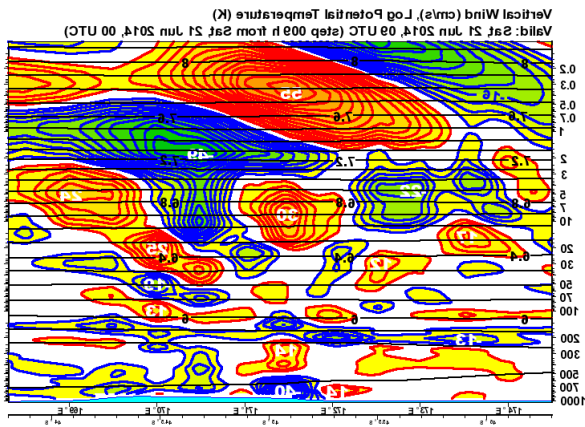
9UT



12UT



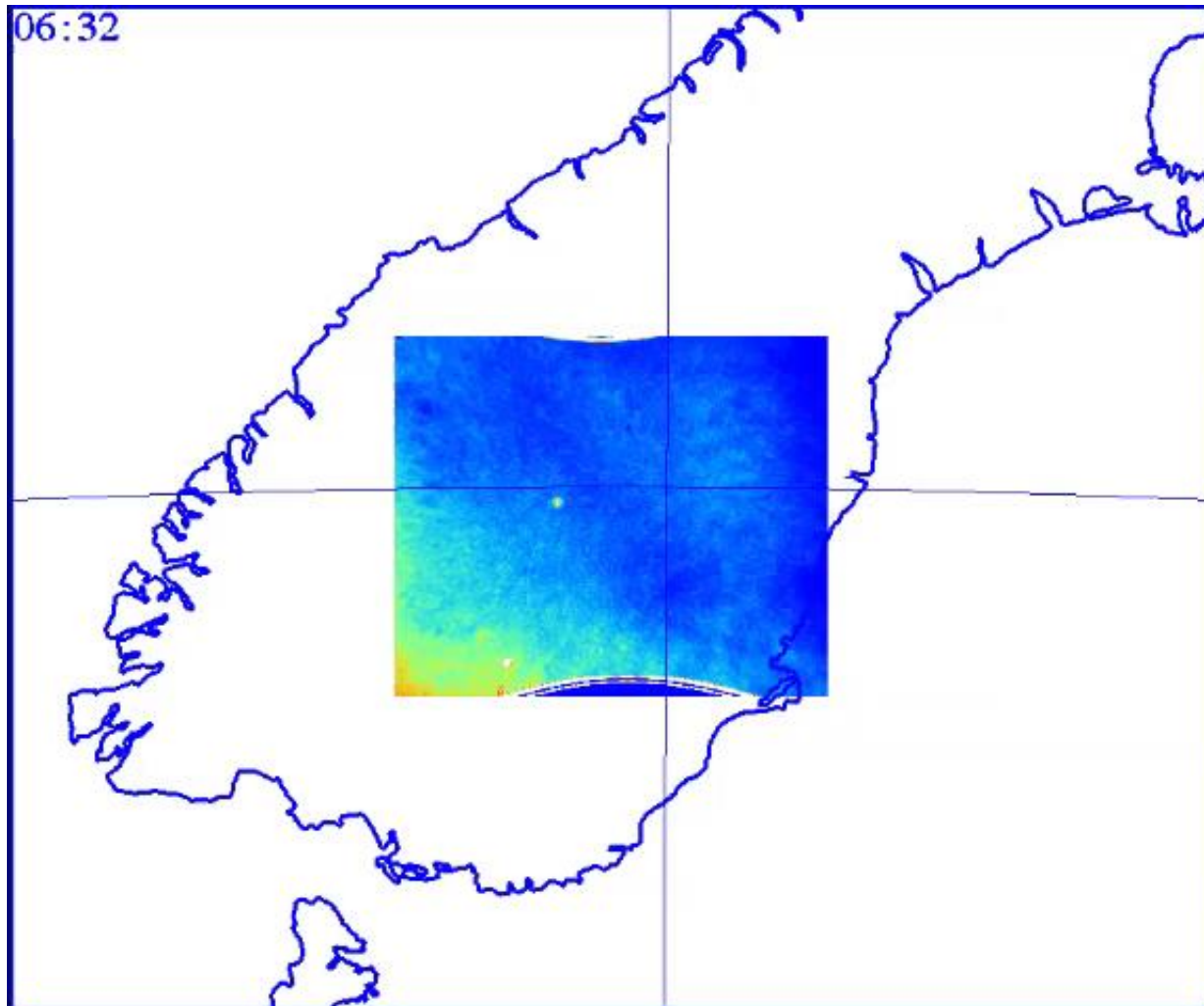
15UT



ECMWF vertical wind velocity

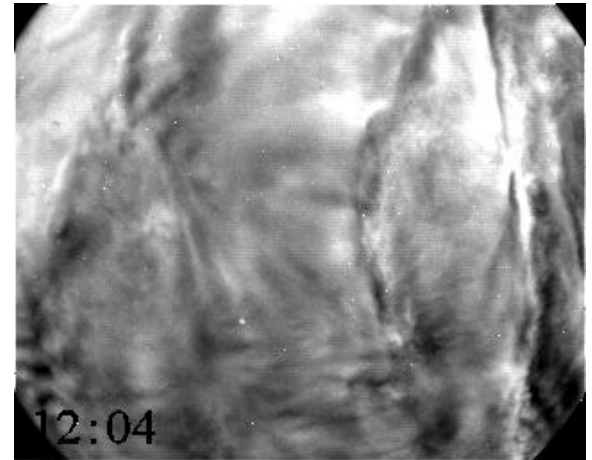
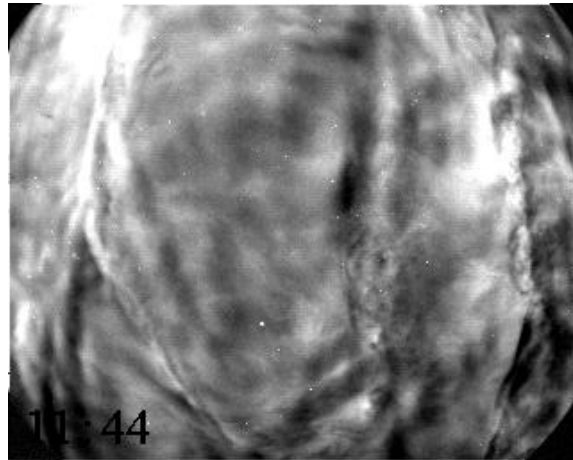
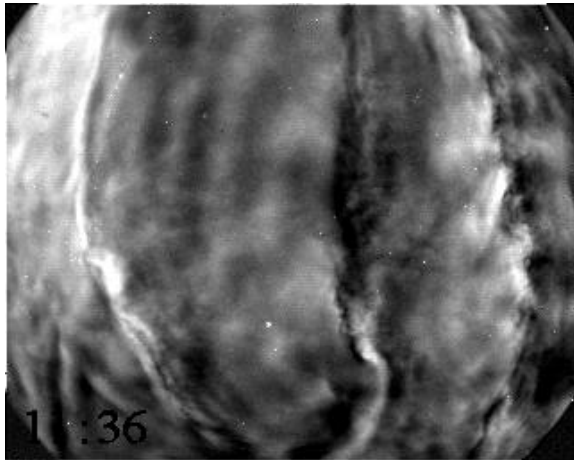
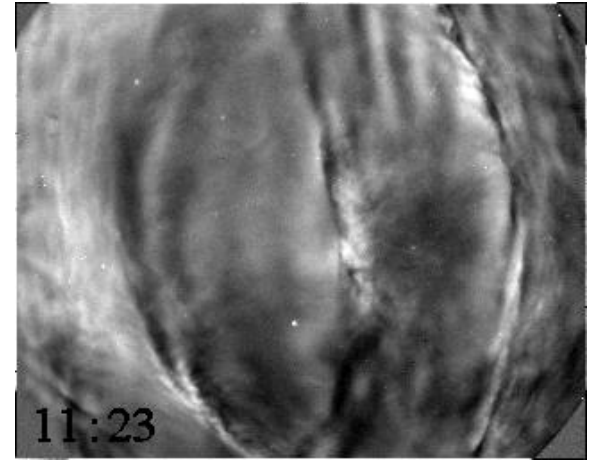
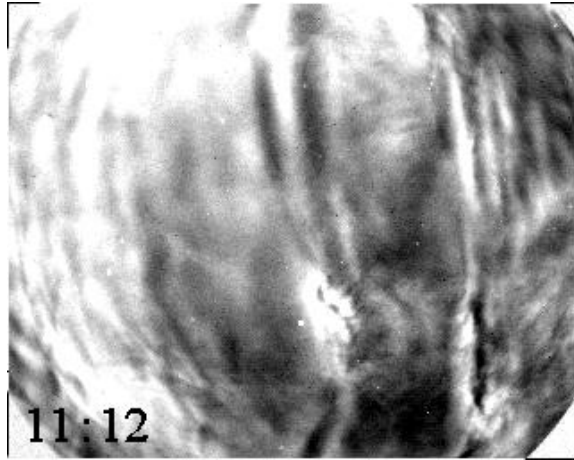
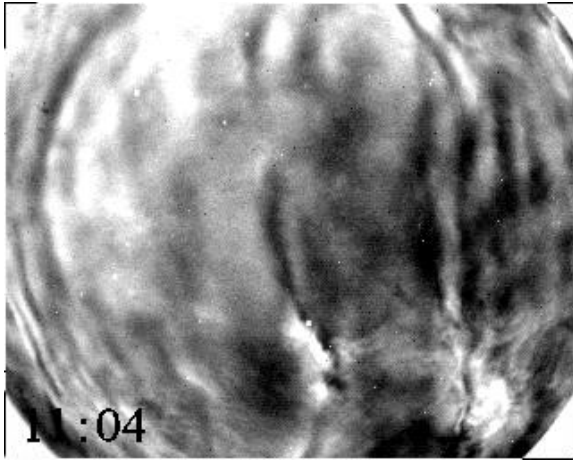
Temperature Movie - May 30-31

First Night!



Summary (to date)

- T-Mapper instrument suite worked very well. Enabled detailed measurements of the characteristics and dynamics of GW from the GV (lateral spatial coverage up to ~1000 km).
- Vast amount of data acquired! Currently in data reduction and geographic mapping phase....
- Coordinated measurements at Lauder indicate Mountain Wave activity on multiple nights...not always during strong forcing!
- Dominique to show data "nuggets"



Used to make slices

spare

