Radiative Flux Divergence Observations during C-FOG

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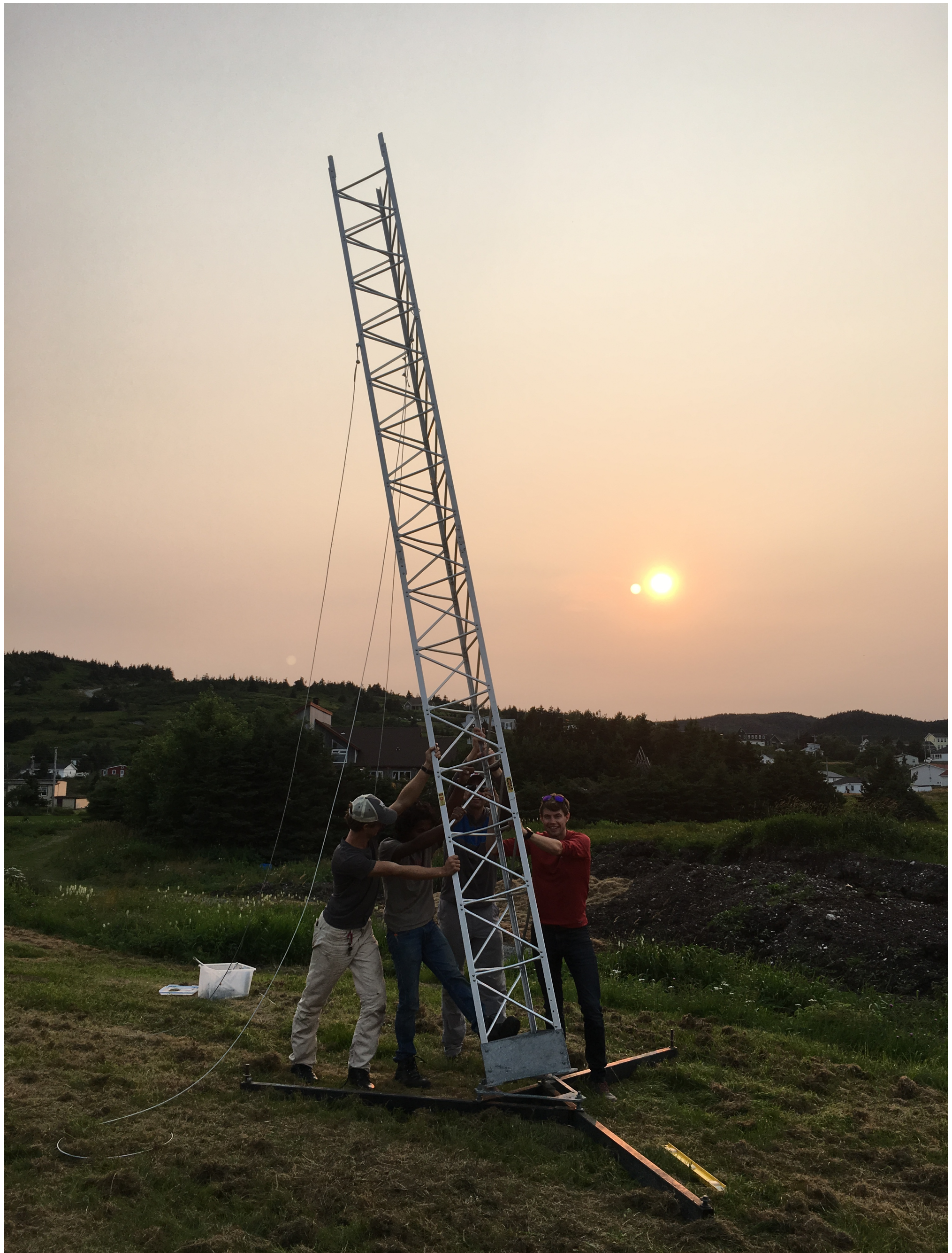


Report on observations & initial analysis from C-FOG

- Ceilometers
- Micro Rain Radars (MRRs)
- Radiation and Surface Energy Balance
- Radiative Flux Divergence (RFD)

Ceilometer Analysis

Several ceilometers (Vaisala CL31)were deployed during C-FOG

Blackhead

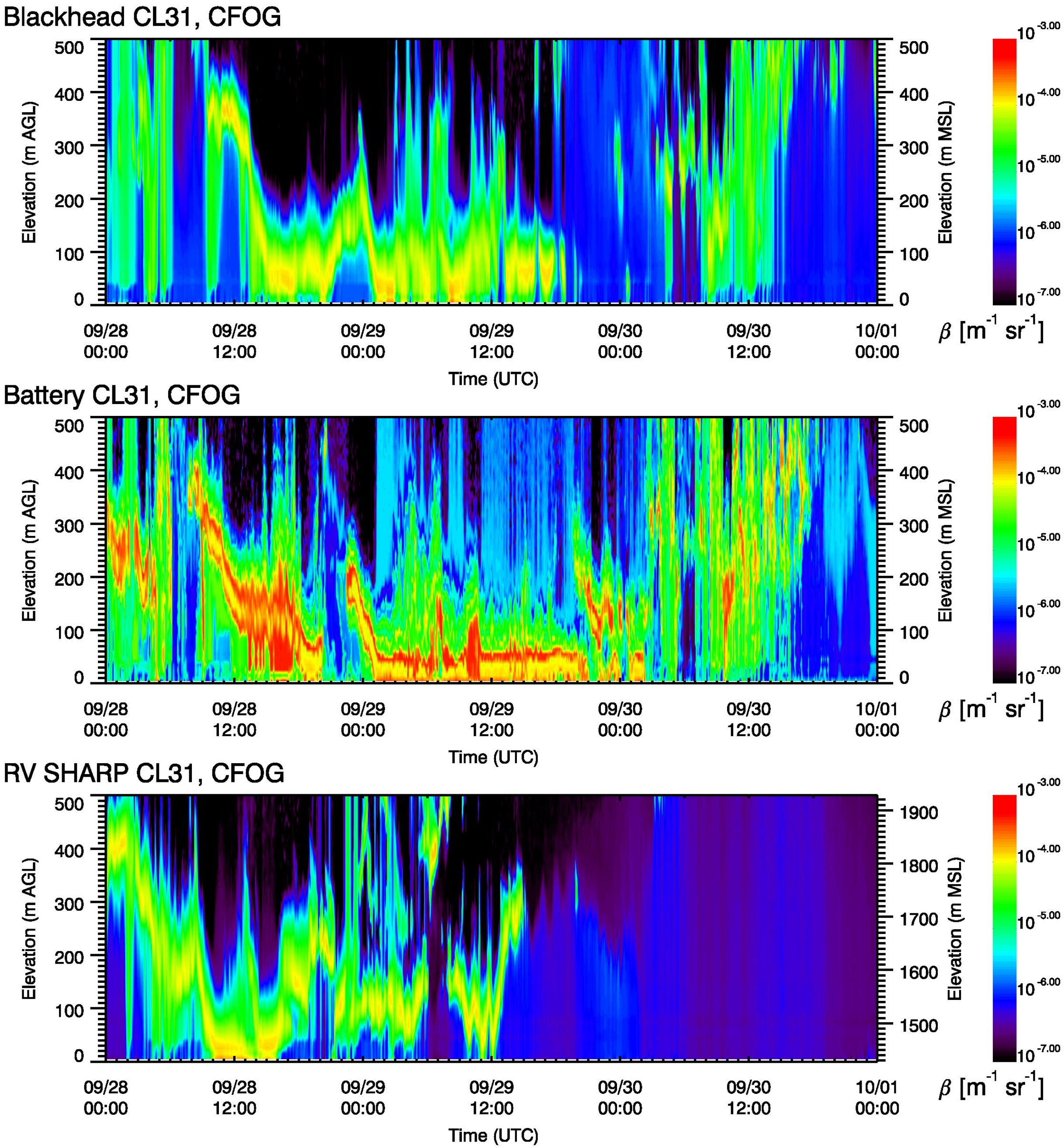
RV Sharp

Downs (Ferryland)

Battery (Ferryland)

Osborne Head (Halifax)

Example ceilometer comparison Super-IOP 10



Time-Height cross-section of backscatter coefficient

Temporal evolution similar over large spatial scales!

Micro Rain Radar (MRR) Analysis

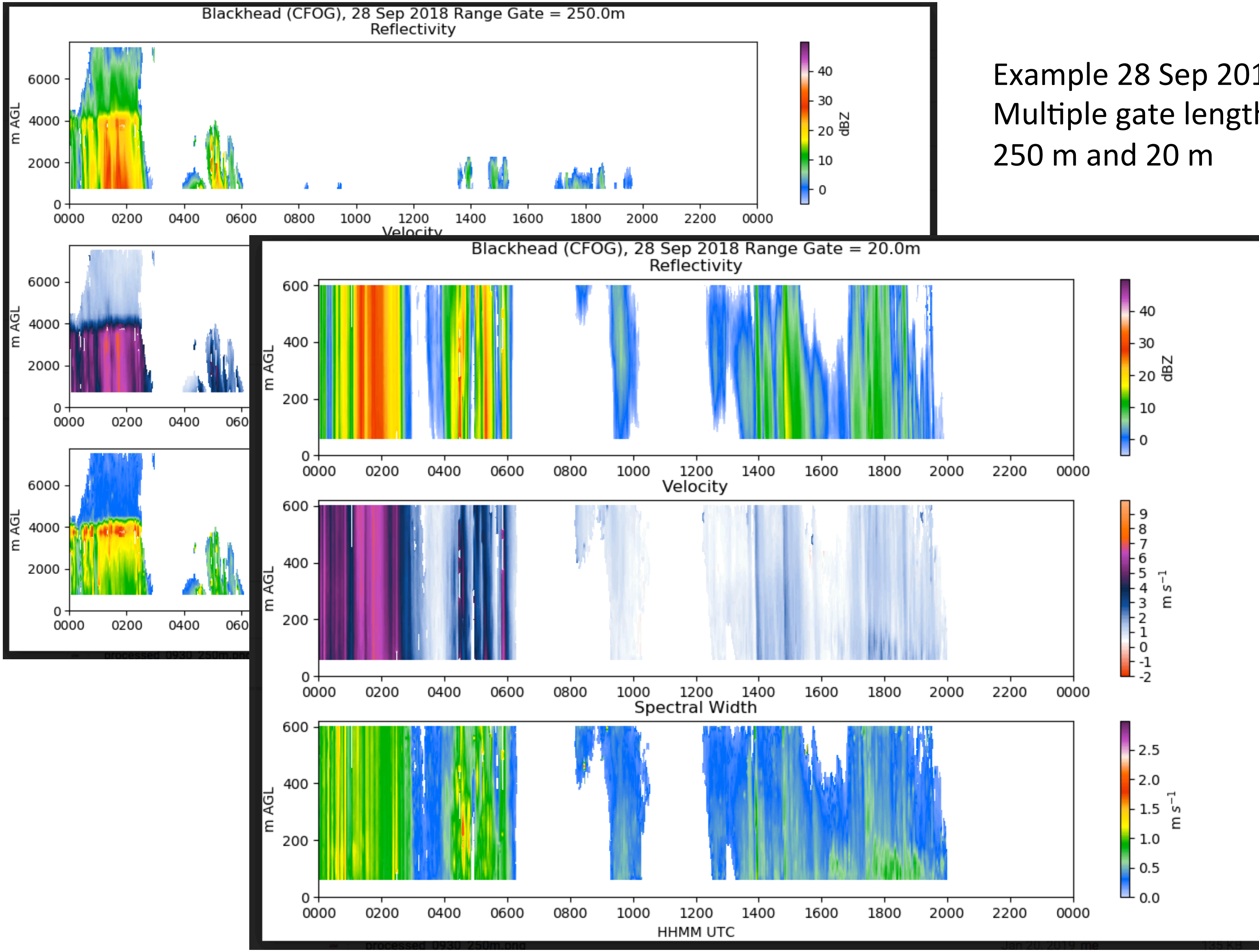
Several MRRs were deployed during C-FOG

Blackhead

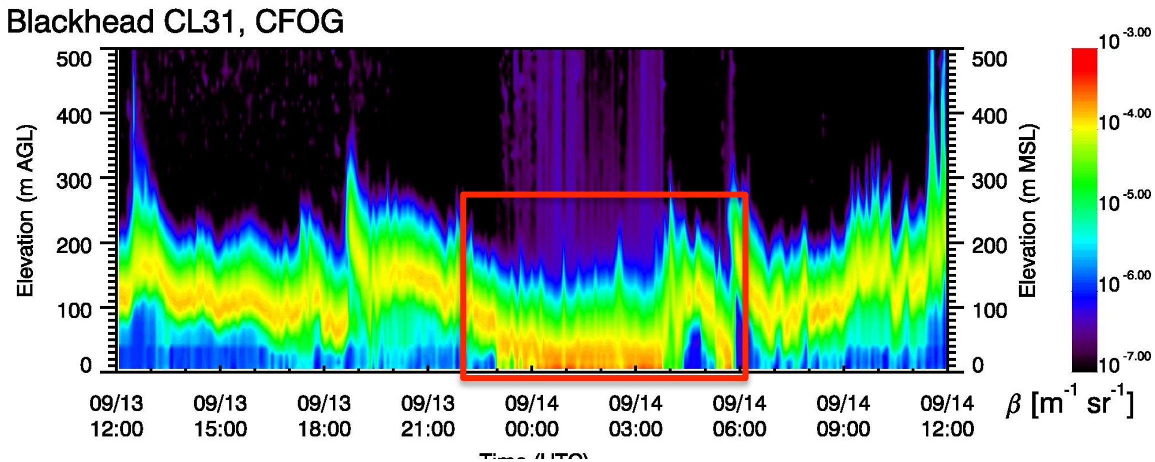
RV Sharp

Battery (Ferryland)

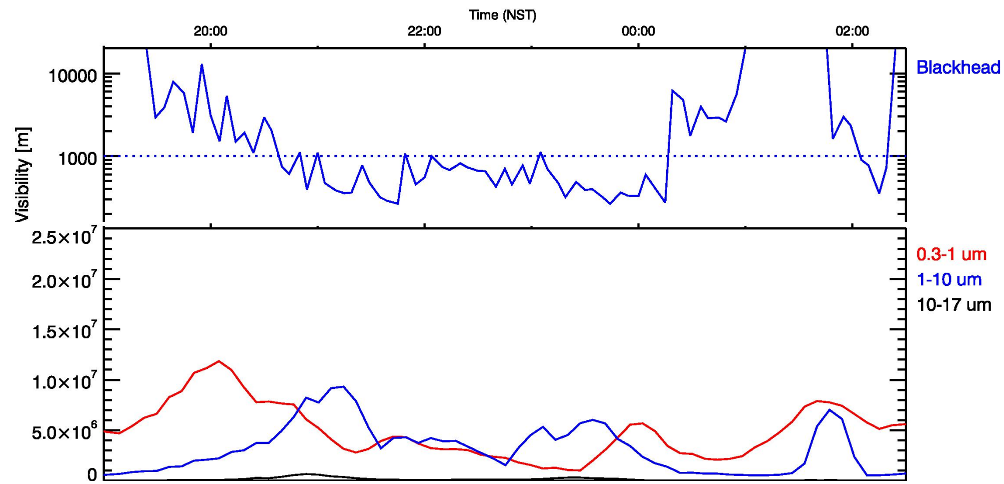
Example 28 Sep 2018: Multiple gate lengths 250 m and 20 m



Drizzle Formation during IOP 6

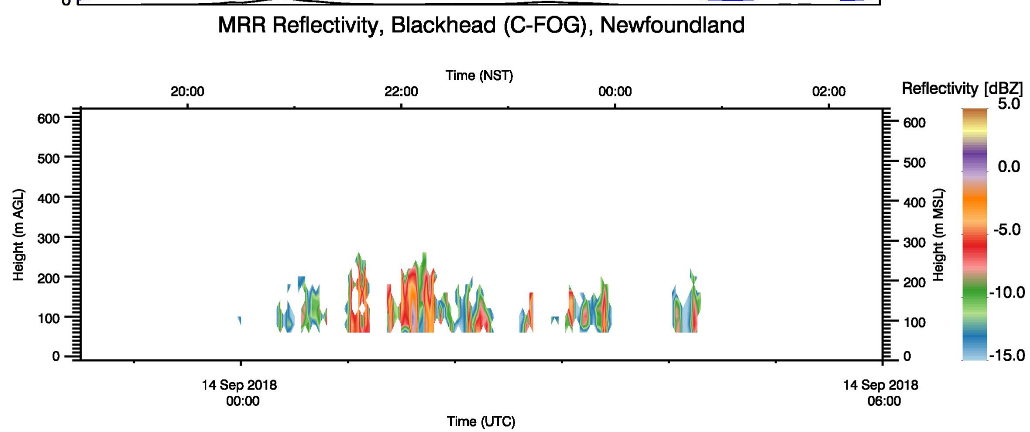


Ceilometer



PWD

OPC

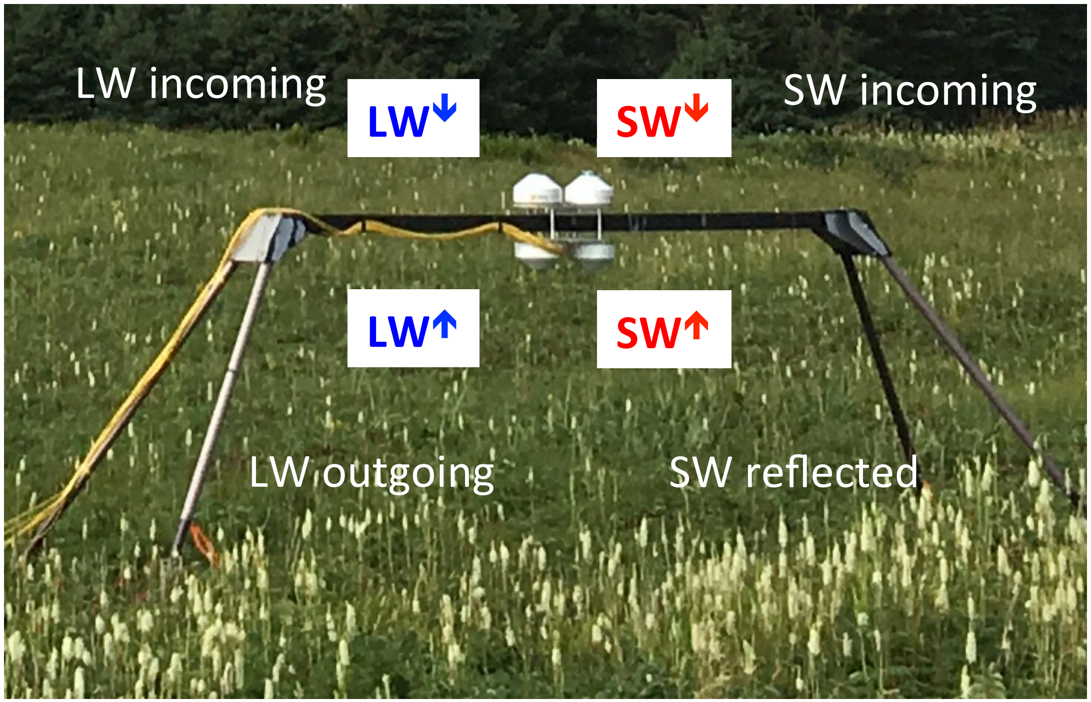


MRR (reflectivity)

Radiation Measurements / Radiative Flux Divergence

Surface Radiation Balance (SRB)

$NR = SW\downarrow - SW\uparrow + LW\downarrow - LW\uparrow$



Ferryland/Battery Site:

Kipp and Zonen CMP21 pyranometers (SW) and CGR4 pyrgeometers (LW) on sawhorse structure

- ventilated
- heated

Blackhead Site:

Kipp and Zonen CNR1 & CNR4 net radiometer

Surface Energy Balance (SEB)

To complete the SEB at ***Ferryland/Battery***, we measured

- sensible heat flux (H, 5 levels),
- latent heat flux (L, 2 levels), and
- ground heat flux (G).

At ***Blackhead***, we measured

- sensible heat flux (H, 3 levels),
- latent heat flux (L, 1 levels), and
- ground heat flux (G).

Radiation Measurements / Radiative Flux Divergence

Fog can form when the near-surface air is cooled below its dew-point temperature and when enough cloud or ice condensation nuclei are available.

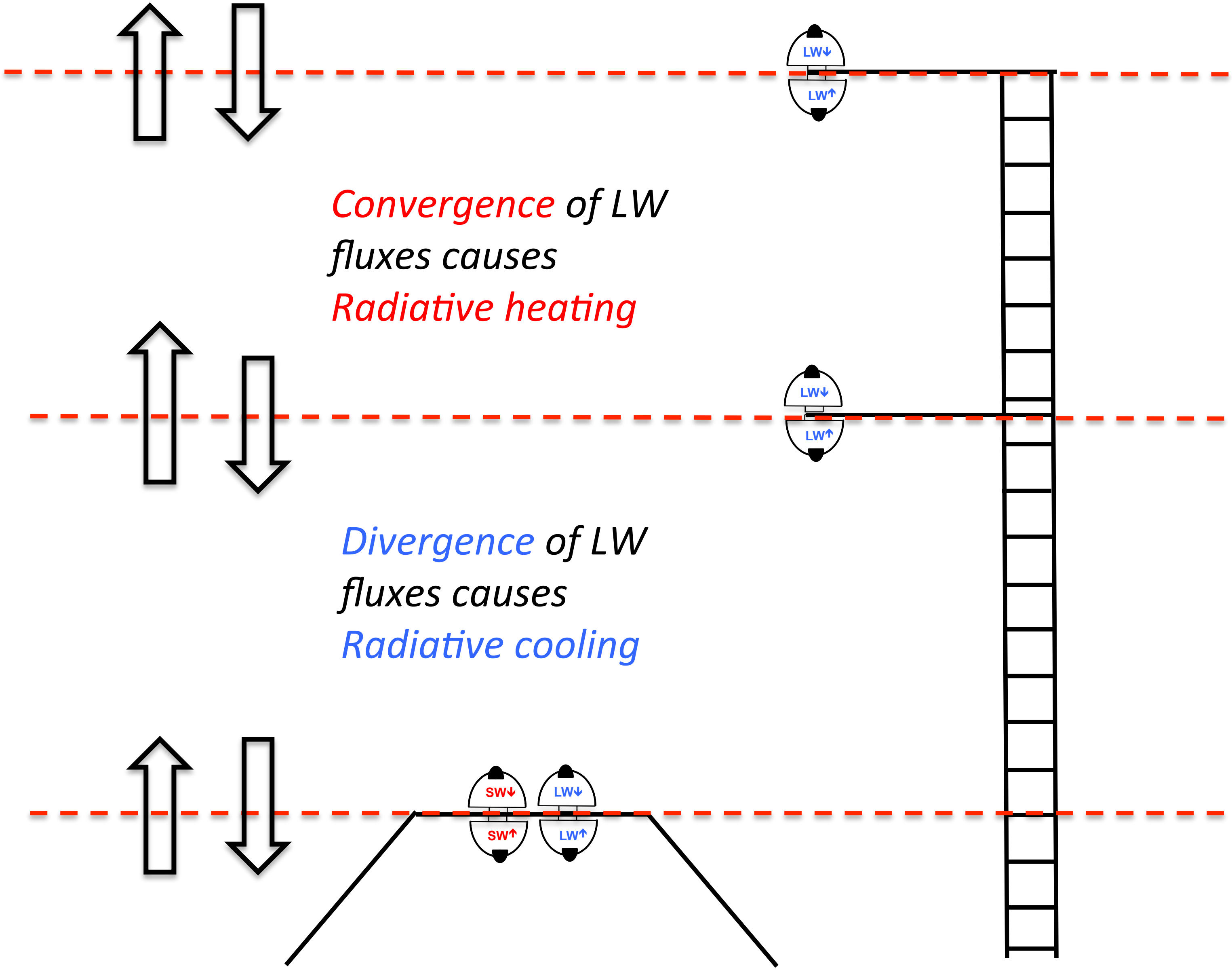
Condensation conditions can be reached by different mechanisms including local cooling and mixing processes of different air masses.

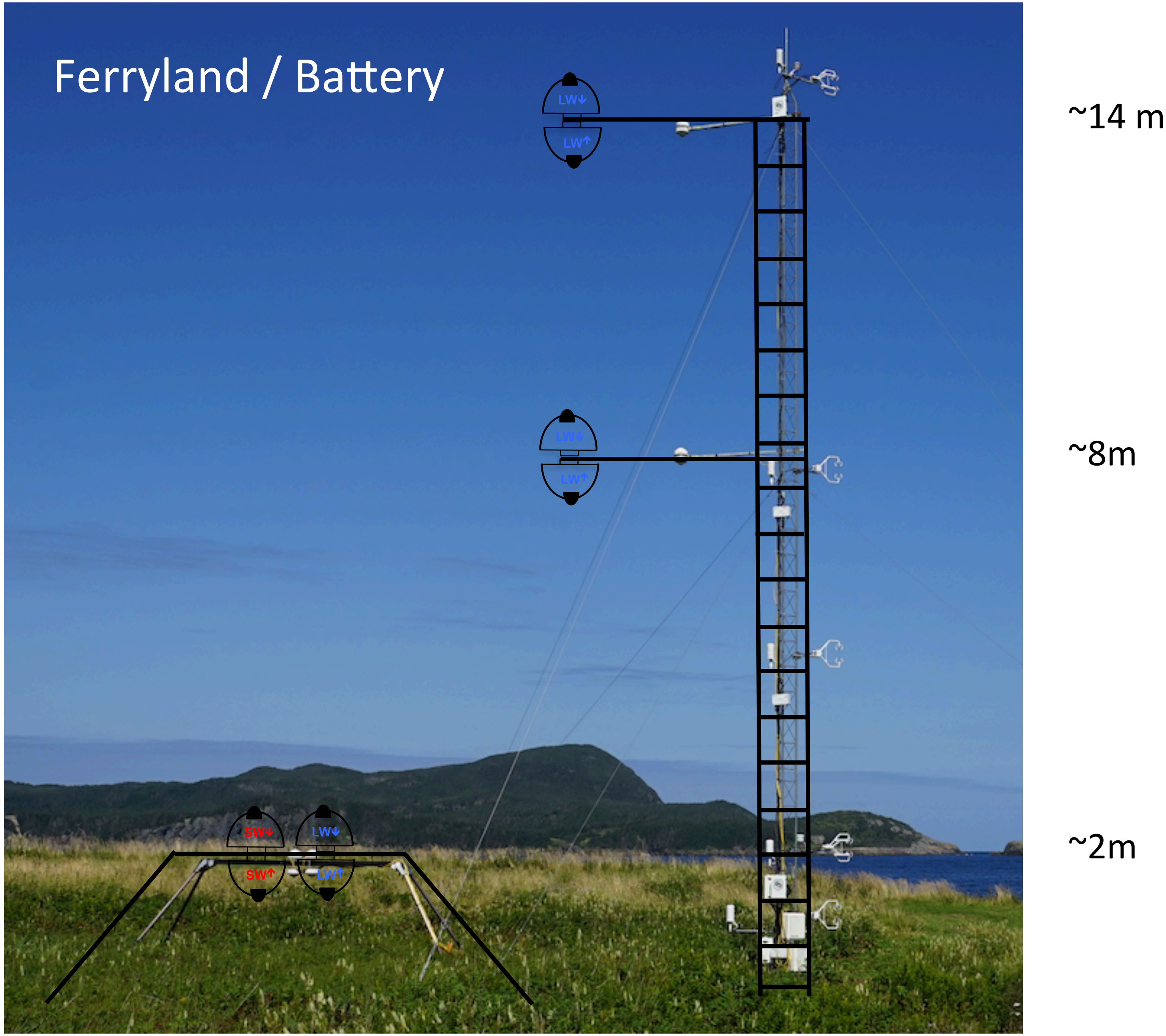
C-FOG observations were designed to directly measure the local cooling contributions.

$$\frac{\partial T}{\partial t} + \vec{v_h}\nabla_h T + w\frac{\partial T}{\partial z} = \nu_T \frac{\partial^2 T}{\partial z^2} - \frac{1}{\rho c_p}\left(\frac{\partial SW}{\partial z} + \frac{\partial LW}{\partial z} + \frac{\partial H}{\partial z}\right).$$

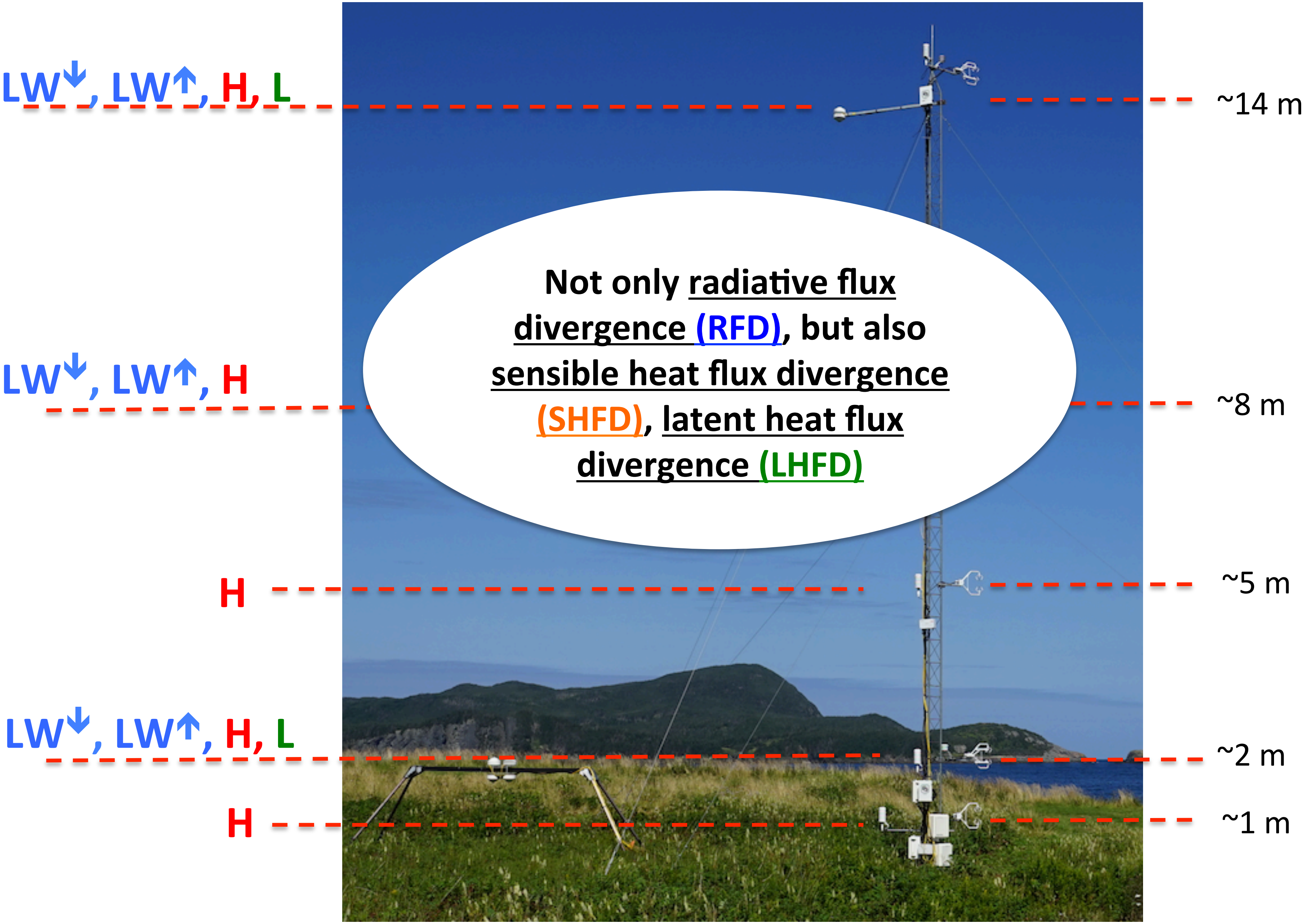
This research investigated the **role of *clear-air radiative cooling*** or ***Radiative Flux Divergence (RFD)*** in the surface layer and its relative importance under different conditions.

Radiation Measurements / Radiative Flux Divergence





Ferryland / Battery
LW↓
LW↑
LW↓
LW↑
SW↓
LW↓
SW↑
LW↑
~14 m
~8m
~2m

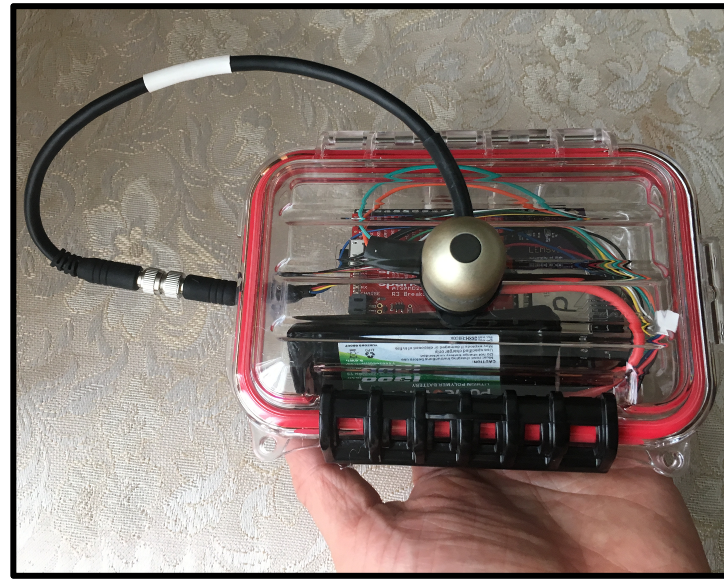


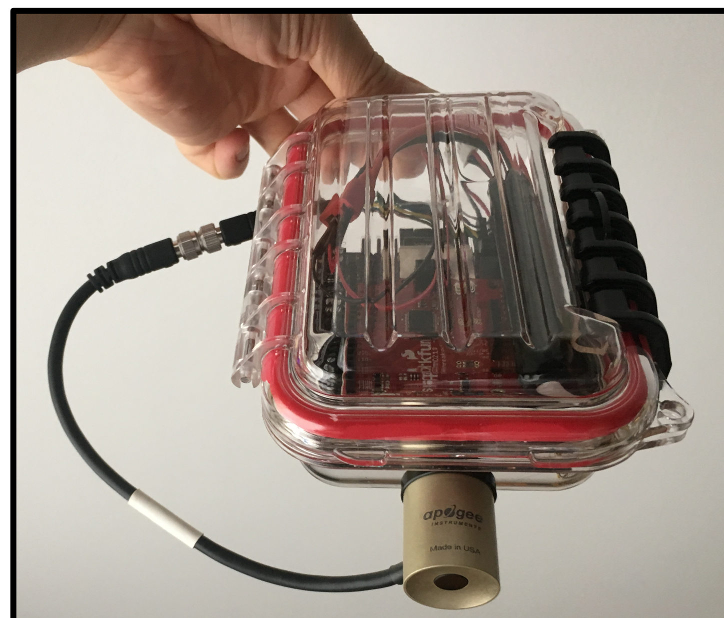
LW↓, LW↑, H, L
~14 m
Not only radiative flux divergence (RFD), but also sensible heat flux divergence (SHFD), latent heat flux divergence (LHFD)
LW↓, LW↑, H
~8 m
H
~5 m
LW↓, LW↑, H, L
~2 m
H
~1 m

Design of balloon-borne observations of RFD

- Arduino-based measurements and logging (LEMS)
- Based on Apogee SL-510 / SL-610 pyrgeometers
- For ARL ship-based TLS system

Nipun Gunawardena



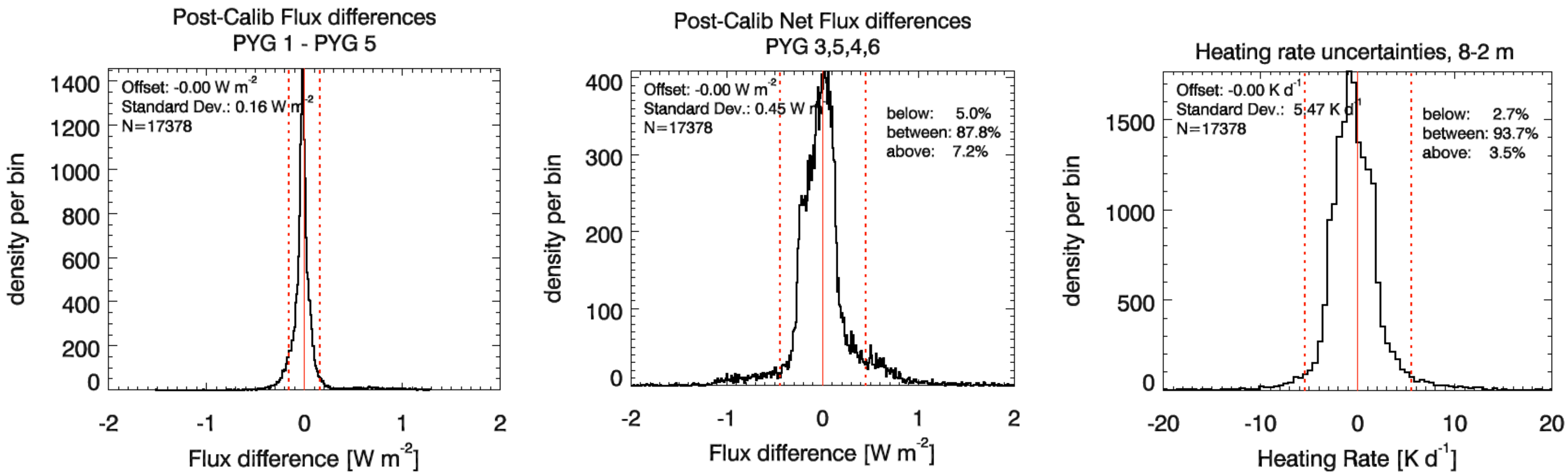


Radiative Flux Divergence - Challenges

- Small changes in LW fluxes need to be resolved
- Kipp and Zonen CGR4 research-grade pyrgeometers – at three levels
- To maximize instrument accuracy, sensors are ventilated with heated air.

Calibration setup at Ferryland/ Battery during C-FOG

➢ A careful ***Relative Calibration*** is necessary.

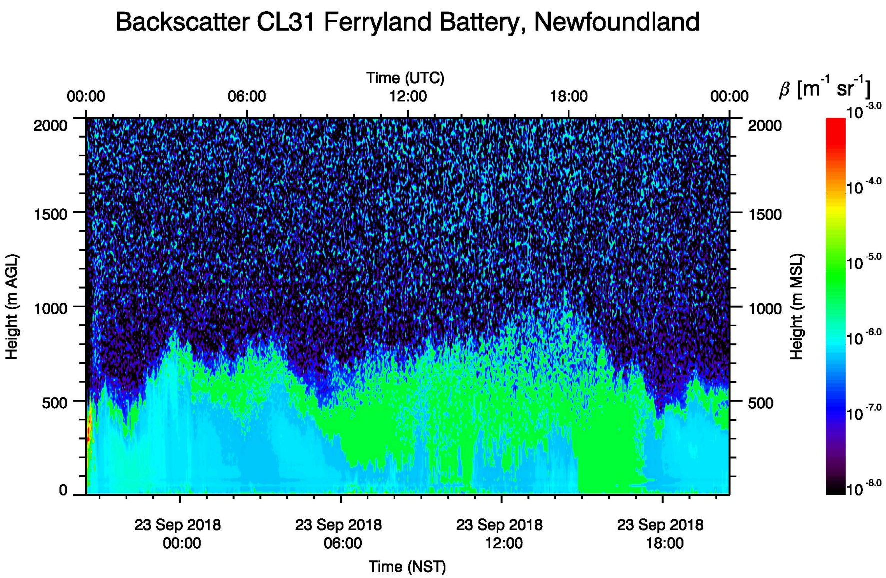


Flux Uncertainties	best pair	least good pair
LW in	± 0.38 W m^{-2}	± 0.56 W m^{-2}
LW out	± 0.16 W m^{-2}	± 0.70 W m^{-2}
LW net	± 0.42 W m^{-2}	± 0.61 W m^{-2}

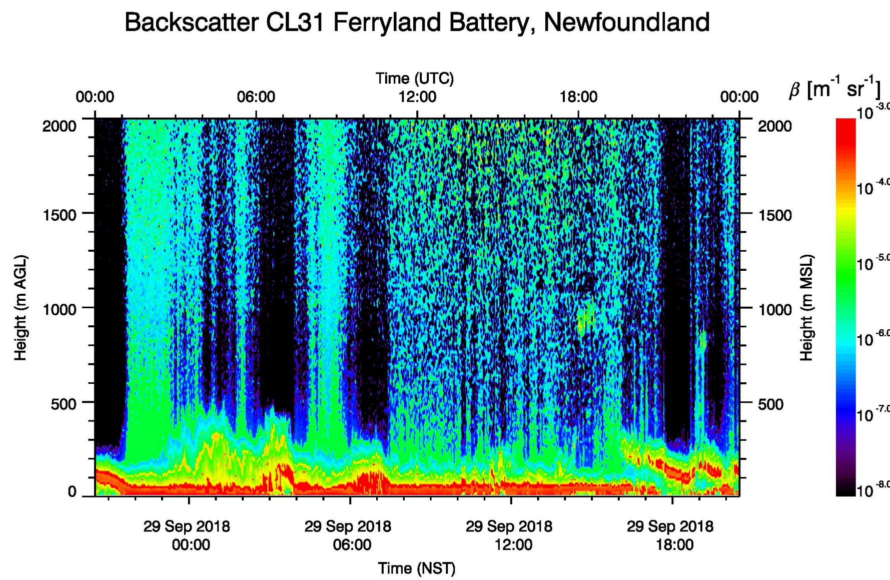
Uncertainties Heating Rate	
Full tower (14 - 2m)	± 2.4 K day^{-1}
Bottom (8 - 2 m)	± 5.5 K day^{-1}
Upper (14 - 8 m)	± 5.6 K day^{-1}

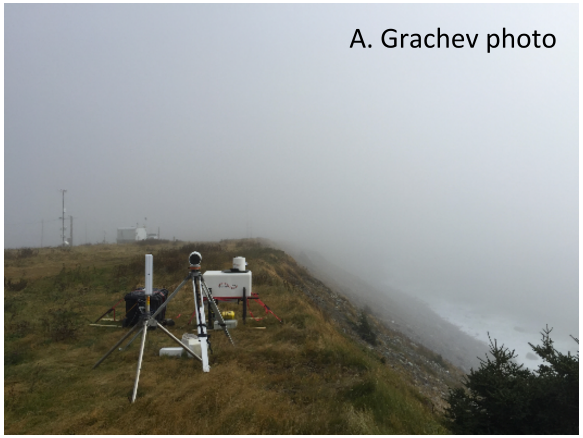
Radiative Flux Divergence – a first look

23 Sep 2018 (clear sky)

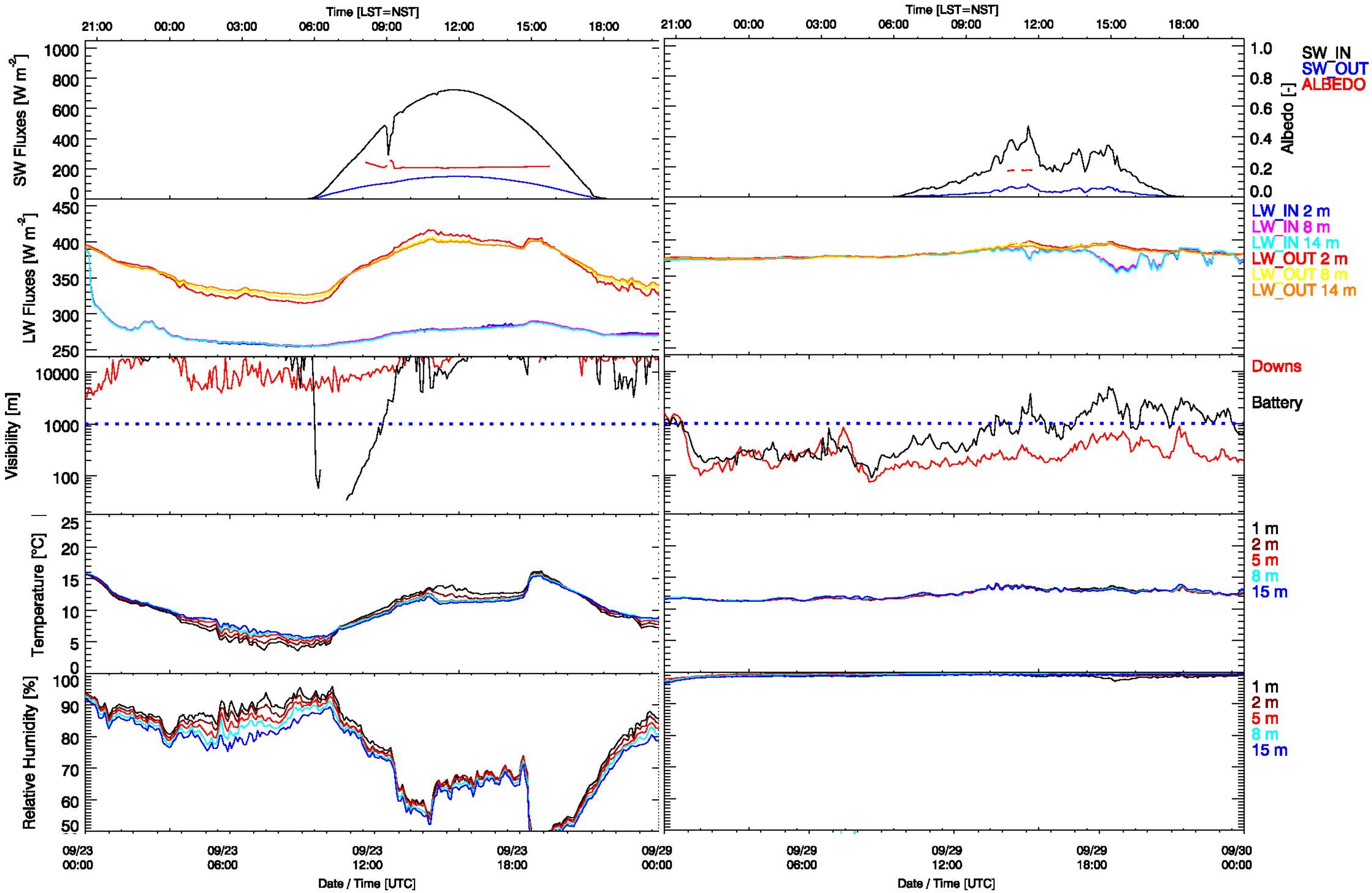


29 Sep 2018 (super-IOP10)

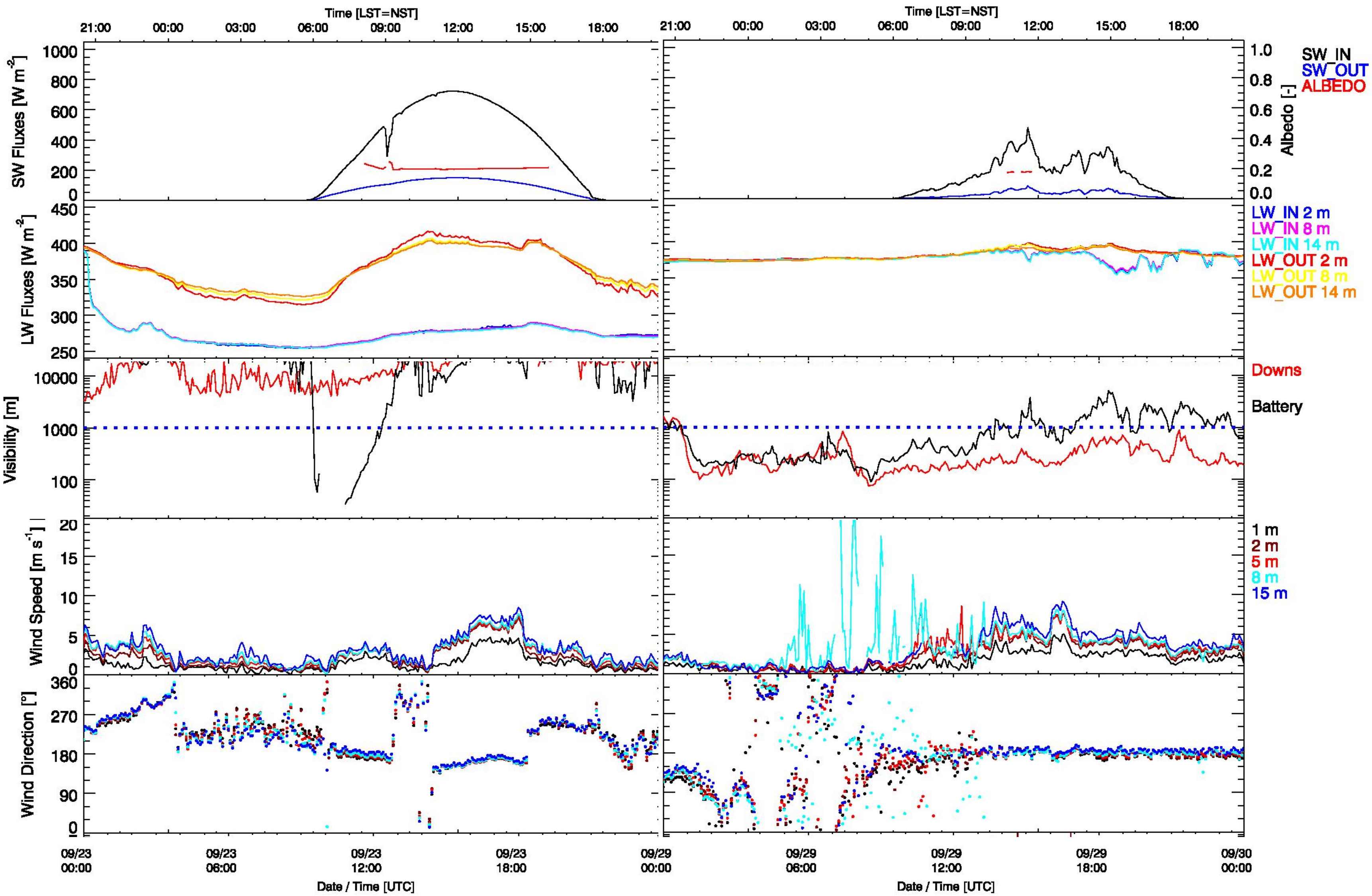




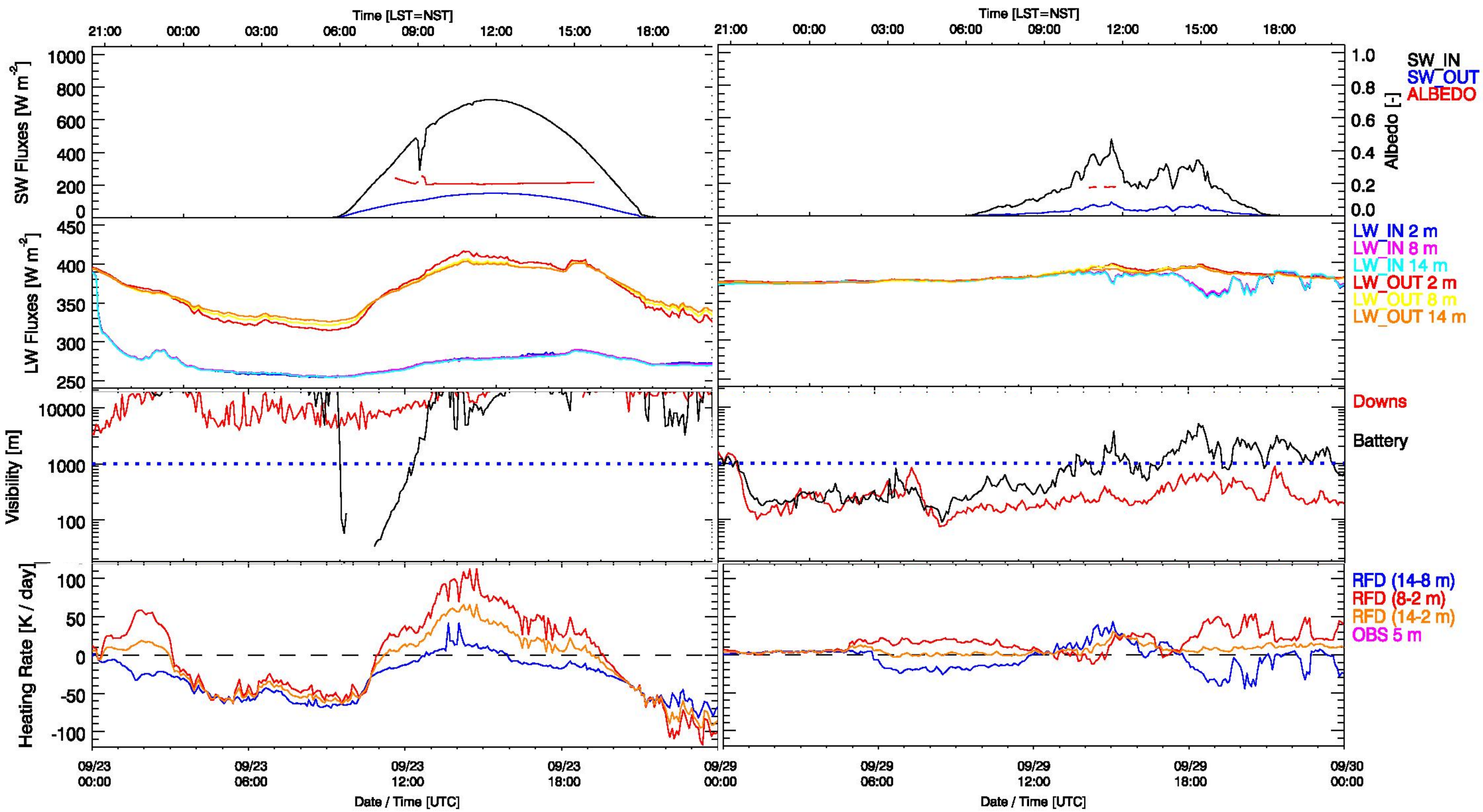
Radiative Flux Divergence – a first look



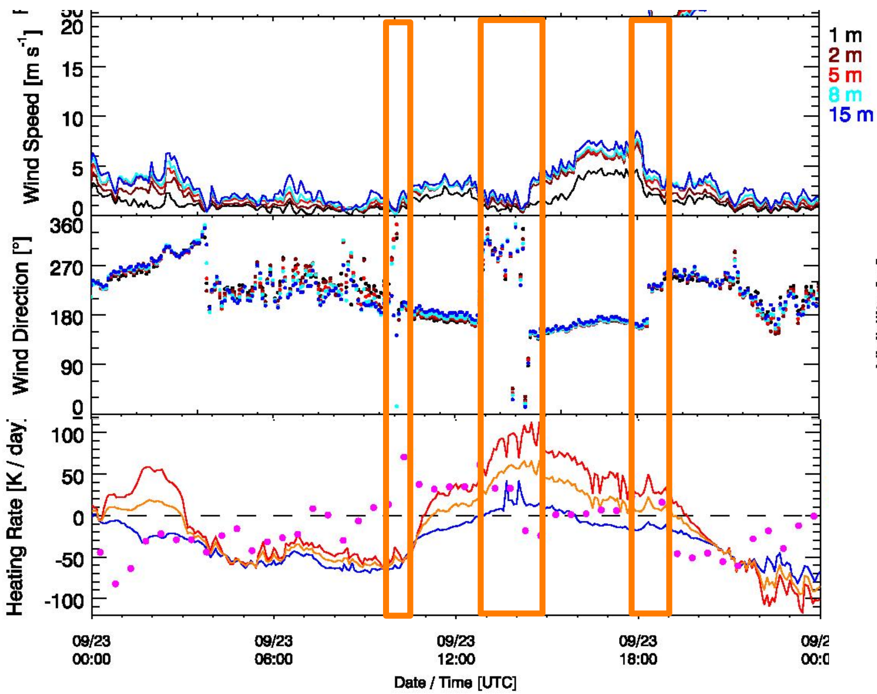
Radiative Flux Divergence – a first look

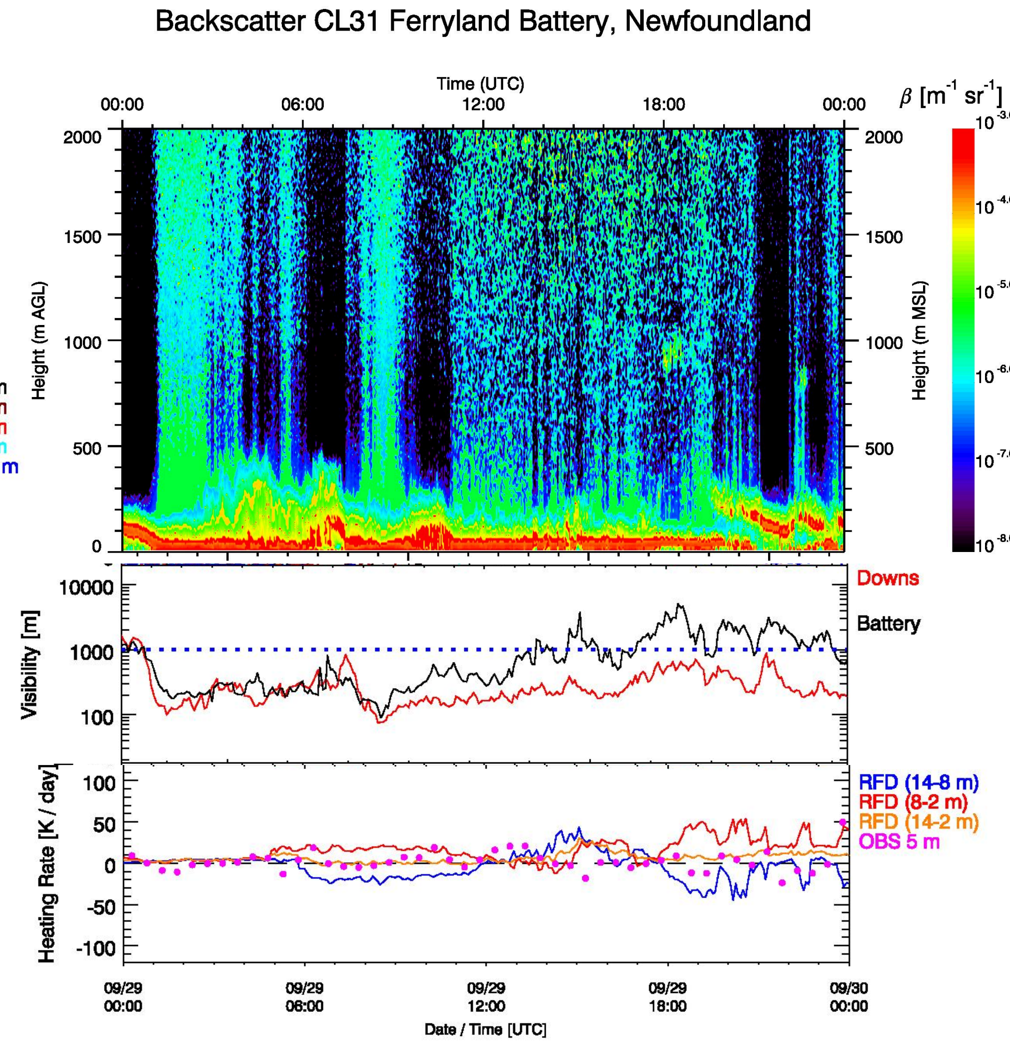


Radiative Flux Divergence – a first look

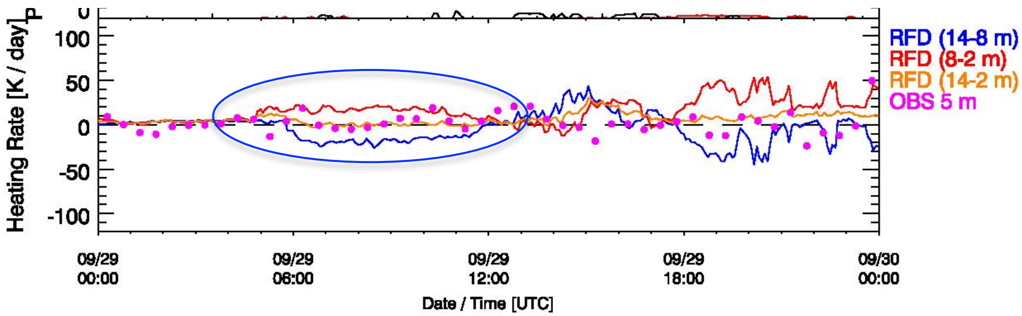


Radiative Flux Divergence – a first look

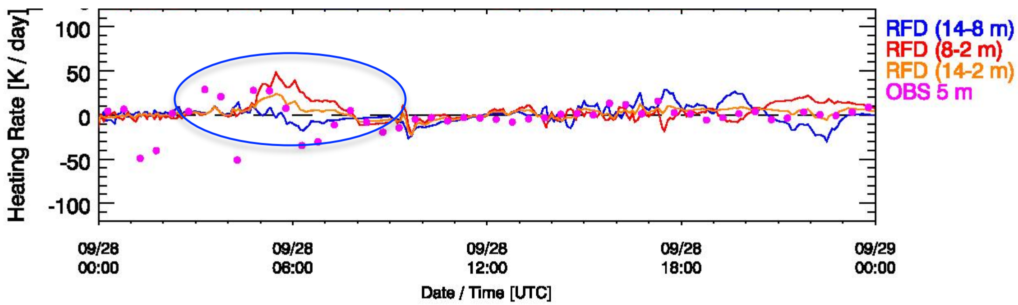




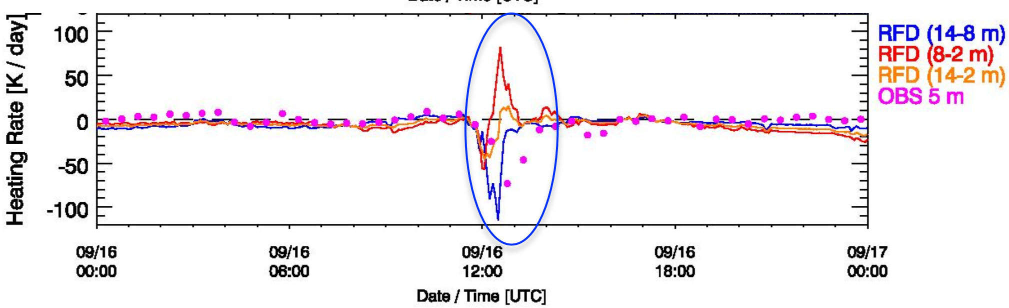
Advection / Sea Breeze Circulation seems to play an important role for local cooling



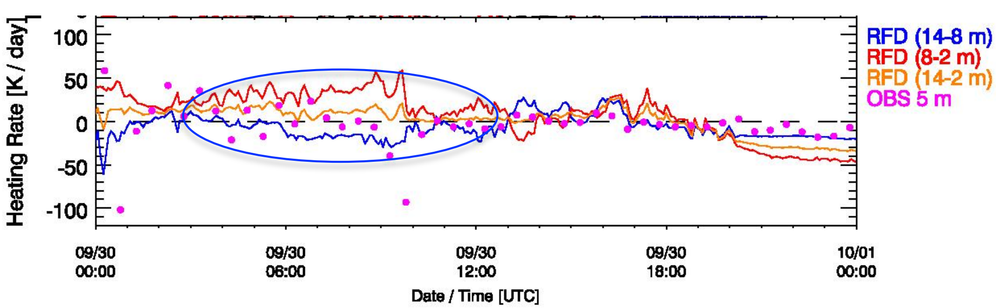
29 September



28 September



16 September



30 September

Summary

- C-FOG offered the unique opportunity to make direct measurements of longwave radiative flux divergence (clear air radiative cooling).
- Radiometers could be calibrated to a sufficient accuracy to resolve small flux differences in the near-surface layers.
- The magnitude of RFD is on the same order of the observed heating rate.
- RFD is suppressed under low stratus and fog conditions (compared to clear-sky conditions), but some interesting patterns are revealed.
- A rich dataset has been collected for further investigation …

Acknowledgements

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Entire C-FOG Team

Alexei Perelet
Travis Morrison
Nipun Gunawardena